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**Experimental studies of the muonic component of
extensive air showers**

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**Experimental studies of the muonic component of
extensive air showers**

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Abstract

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Ultra-High Energy Cosmic Rays (UHECR) can only be measured by the detection of Extensive Air Showers (EAS) created by the interaction of the cosmic ray particle with an atmospheric nuclei. The inference of some of the properties of UHECR, like their mass composition, is only possible by the comparison of measurements of EAS observables to predictions from Monte Carlo simulations. The most important source of uncertainties on the description of EAS by the simulations is the modeling of hadronic interactions. For many years it has been known that the hadronic interaction models fail on predicting the EAS observables related to their muonic component. The most evident manifestation of that is called *muon deficit problem* due to the fact that the number of muons in EAS with energies above 10^{18} eV predicted by simulations is smaller than the observed ones. The aim of this thesis is to approach this problem in three distinct fronts. First, a method is developed to interpret measurements of number of muons in terms of cosmic rays composition in despite of the muon deficit problem. Second, an EAS observable which is sensitive to the muon energy spectrum at ground and, consequently, can be used to constrain hadronic interaction models is proposed and tested. Third and final, the muon production in air showers is studied through measurements of hadron production spectra in pion-carbon interactions.

Keywords: Ultra-high energy cosmic rays. Extensive air showers. Muonic component of air showers. Air shower physics.

Resumo

PRADO, R. R. **Estudos experimentais da componente muônica de chuviros atmosféricos extensos**. 2018. 209p. Tese (Doutor em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

Raios Cósicos Ultra Energéticos (Ultra-High Energy Cosmic Rays, UHECR) somente podem ser medidos através da detecção dos Chuviros Atmosféricos Extensos (Extensive Air Showers, EAS) criados pela interação do raio cósmico primário com núcleos atmosféricos. A inferência de algumas propriedades dos UHECRs, como a composição de massa, é possível somente através da comparação entre medidas de observáveis dos EASs com previsões geradas por simulações de Monte Carlo. A fonte de incerteza mais importante na descrição de EAS por simulações é a modelagem das interações hadrônicas. Por muitos anos é sabido que os modelos de interação hadrônica falham na previsão de observáveis dos EASs relacionados a sua componente muônica. A manifestação mais evidente disso é chamada *problema do déficit de múons* devido ao fato que o número de múons em chuviros com energias acima de 10^{18} eV predito por simulações é menor que os observados. O objetivo desta tese é abordar este problema através de três frentes. Primeiramente, um método é desenvolvido para interpretar as medidas do número de múons em termos de composição de raios cósmicos considerando o problema do déficit de múons. Segundo, a proposta e o teste de um observável que é sensível ao espectro de energia dos múons na superfície e, conseqüentemente, pode ser usado para discriminar entre os modelos de interação hadrônica. Por último, a produção de múons em chuviros é estudada através de medidas do espectro de produção de hádrons em interações do tipo pión-carbono.

Palavras-chave: Raios cósmicos de altas energias. Chuviros atmosféricos extensos. Componente muônica de chuviros atmosféricos. Física de chuviros atmosféricos.

List of Figures

Figure 2.1 – Compilation of measurements of the cosmic ray energy spectrum from Ref. (13). Two of the spectrum features are indicated: the knee and the ankle.	30
Figure 2.2 – Compilation of measurements of the cosmic ray energy spectrum from Ref. (15). The flux is scaled by a factor $E^{2.6}$ and the main features of the spectrum are indicated (see text for details). The references to the data can be found in Ref. (15).	31
Figure 2.3 – Energy spectra of different components as measured by KASCADE (17) (top), around the first-knee energies, and by KASCADE-Grande (18) (bottom), around the second-knee energies. The hadronic interaction models used were QGSJET 01 and QGSJET II-04 for the KASCADE and KASCADE-Grande analysis, respectively.	33
Figure 2.4 – Hillas plot from Ref. (12). The sources shown are neutron stars (n-star), gamma-ray bursts (GRB), active galactic nuclei (AGN) split in radio-quiet Seyfert (Sy) and radiogalaxies (RG), supernova remnants (SNR), starburst galaxies and galaxy clusters.	34
Figure 2.5 – Energy loss lengths for protons and iron nuclei from Ref. (36).	35
Figure 2.6 – Average proton energy as a function of the propagation distance through the CMB. The numbers above the curves indicate the proton initial energy.	37
Figure 2.7 – UHECR spectrum as measured by Pierre Auger Observatory and Telescope Array. The Pierre Auger Observatory measurement combines several different data sets into one unique spectrum. (42) The Telescope Array measurement includes only the analysis of the surface detectors data. (43)	38
Figure 2.8 – Results of the combined fit of the spectrum and $X_{\max}$ distributions performed by Pierre Auger Observatory. (57) On the top plot the measured spectrum and the fitted contributions of different groups of primaries are shown. On the bottom plots the measured mean ($\langle X_{\max} \rangle$) and standard deviation ($\sigma[X_{\max}]$) of the $X_{\max}$ distributions are shown together with the results of the fit. The color codes for the groups of the primaries are indicated on the right side of the top plot. The hadronic interaction model used to describe the $X_{\max}$ distributions is EPOS LHC. (58) The results by using other models can be found in Ref. (57).	40

Figure 2.9 – Configuration of the Pierre Auger Observatory. The black dots represent stations of the standard surface detector, the gray dots represent the AMIGA stations and the blue and red lines indicate the field of view of each telescope which compose the fluorescence detector. The atmospheric monitoring devices (XLF, CLF and BLF) are represented by red dots. The blue circle shows the approximate area of the AERA setup.	41
Figure 2.10–Examples of the energy deposit longitudinal profile as measured by the FD (left plot) (64) and of the lateral distribution as measured by the SD (right plot). (3)	43
Figure 2.11–The attenuation curve derived from the SD data in which the reference zenith angle ($\theta = 38^\circ$) is indicated by a vertical dashed line (left) and the S_{38} - E_{FD} plot used in the standard energy calibration (right). Both figures were obtained from Ref. (3).	44
Figure 3.1 – Average longitudinal profiles of EAS obtained from simulations performed with CONEX (83) and the hadronic interaction models FLUKA (84) and EPOS LHC. (58)	49
Figure 3.2 – $\langle X_{\max} \rangle$ (left) and $\sigma[X_{\max}]$ (right) as a function of the primary energy obtained from air shower simulations performed with CONEX (83) and the hadronic interaction models FLUKA (84) and EPOS LHC. (58) . . .	50
Figure 3.3 – Energy distributions of the grandmother particles of muons that reaches the ground with lateral distances between 1000 and 2000 m in a proton initiated shower with primary energy 10^{19} eV. Plot reproduced from Ref. (88)	51
Figure 3.4 – Average N_μ as a function of the primary energy for a set of showers simulated with CONEX (83) and the hadronic interaction models FLUKA (84) and EPOS LHC. (58) The N_μ here is defined as all the muons which reach an observation level of 875 g/cm^2 with energy above 1 GeV. . . .	53
Figure 3.5 – Compilation of $\langle X_{\max} \rangle$ results reproduced from Ref. (125).	56
Figure 3.6 – $\langle X_{\max} \rangle$ and $\sigma[X_{\max}]$ as a function of the primary energy as measured by Pierre Auger Observatory.	57
Figure 3.7 – $\langle X_{\max} \rangle$ and $\sigma[X_{\max}]$ as a function of the primary energy as measured by Telescope Array experiment.	57
Figure 3.8 – Muon density as measured by HiRes/MIA (top-left) (129) and IceTop (bottom) (130) and number of muons as measured by Pierre Auger Observatory in highly inclined showers (top-right). (131)	60
Figure 3.9 – Muon attenuation length as measured by KASCADE-Grande experiments (left) (135) and the maximum muon production depth as measured by Pierre Auger Observatory (right). (136)	61

Figure 3.10–Risetime asymmetry (left) (139) and the delta parameter (right) (140) as measured by Pierre Auger Observatory.	62
Figure 3.11– $\langle \ln A \rangle$ as a function of energy for a set of observables measured by Pierre Auger Observatory. Only statistical uncertainties are shown. The hadronic interaction models EPOS LHC (top) and QGSJET II-04 (bottom) to perform the conversion represented by Eq. (3.3).	64
Figure 6.1 – Experimental setup of the NA61/SHINE experiment. (9)	93
Figure 6.2 – Illustration of the phase space binning used for the charged hadron analysis.	97
Figure 6.3 – Illustration of the phase space binning used for the V^0 analysis. The plot on the left shows the binning used for Λ and $\bar{\Lambda}$ and the plot on the right shows the binning used for K_S^0	98
Figure 6.4 – Illustration of the RST and WST definitions (see text for details). (145)	100
Figure 6.5 – dE/dx data used in this analysis. Positively and negatively charged tracks are shown respectively in (a) and (b) for the 158 GeV/c data set, and in (c) and (d) for the 350 GeV/c one. The solid curves show the $\langle dE/dx \rangle$ parametrization for each particle type.	101
Figure 6.6 – Examples of the fitted dE/dx distributions from the 158 GeV/c data set. On the top, the distributions of the (a) negatively and (b) positively charged tracks are shown for one phase space bin of the RST subset. On the bottom, the distributions of the (c) negatively and (d) positively charged tracks are shown for a different phase space bin of the WST subset. The values of the $\langle p \rangle$ and $\langle p_T \rangle$ for each phase space bin is indicated on the top of each plot. The black dots show the observed number of tracks, while the colored distributions are the results of the dE/dx fit of each particle type. On the bottom of each plot, we show the residual of the fit, defined as the difference between the observed and the expected number of tracks from the result of the fit, divided by the uncertainty of the observed number.	107
Figure 6.7 – χ^2/ndf of the dE/dx fit for the 158 GeV/c data set. The RST and WST are shown in (a) and (b), respectively.	108
Figure 6.8 – Calibration constants obtained from the dE/dx fit of the RST and 158 GeV/c data set.	109
Figure 6.9 – Shape parameters obtained from the dE/dx fit of the RST and 158 GeV/c data set.	110
Figure 6.10–Particle fractions obtained from the dE/dx fit of the RST and 158 GeV/c data set.	111

Figure 6.11—Examples of the parametrization of the particle fractions to be used to create the Simulated Data Ensembles. The plots in (a) and (b) refer to the 158 GeV/ c data set and in (c) and (d) to the 350 GeV/ c one. The particle type, the RST/WST subset and the $\langle p_T \rangle$ are indicated on the top of each plot. The black dots show the particle fractions obtained from the dE/dx fit and the red curves show the result of the fit of the Eq. (6.13) to these fractions. 112

Figure 6.12—Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f). 113

Figure 6.13—Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f). 114

Figure 6.14—Correction factors (c , see the definition in the text) for the RST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f). 115

Figure 6.15—Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 158 GeV/ c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot. 116

Figure 6.16—Impact parameter (b_r) distributions obtained with EPOS 1.99 simulations at 158 GeV/ c . The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). The efficiency of the cut is indicated by ε inside the plots. 121

Figure 6.17—Example of the relative uncertainty of the signal (σ_{S^*}/S^*) as a function of $L_{\text{decay}}^{\text{cut}}$, where the V^0 particle is Λ and the beam energy is 158 GeV. The $\langle p \rangle$ and $\langle p_T \rangle$ of the particular phase space bin is indicated on the plot. 122

Figure 6.18—Optimization of the $L_{\text{decay}}^{\text{cut}}$ for the 158 GeV/ c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). Individual phase space bins are shown as black markers, the average over p_T bins is shown as red markers. 122

Figure 6.19—Examples of the fitted m_{inv} distributions for the 158 GeV/ c data set with target inserted. Two phase space bins are shown for Λ in (a) and (d), for $\bar{\Lambda}$ in (b) and (e) and for K_S^0 in (c) and (f). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. Additionally, in green and purple we show the contributions of the two separated templates. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ and $\langle p_T \rangle$ of the phase space bin are indicated on the top of each plot.	124
Figure 6.20—Examples of the fitted m_{inv} distributions for the 158 GeV/ c data set with target removed. One p bin is shown for Λ in (a), for $\bar{\Lambda}$ in (b) and for K_S^0 in (c). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ of the phase space bin is indicated on the top of each plot.	125
Figure 6.21— χ^2/ndf of the m_{inv} fit of the 158 GeV/ c data set for the target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f).	125
Figure 6.22—Extracted signal S for the 158 GeV/ c data set with target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f).	126
Figure 6.23— β correction factor for the charged hadron analysis and for the 158 GeV/ c data set. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	128
Figure 6.24— β correction factor for the V^0 analysis and for the 158 GeV/ c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c).	129
Figure 6.25—Ratio between the uncorrected measured and generated spectra, R , as a function of p . The markers show different p_T bins. and the colored lines show the result of the parametrization (see text for details). On the bottom of each plot, we show the residuals, which are defined as the difference between the observed value of R and the parametrization, divided by the uncertainty on the observed one. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and the K_S^0 in (c).	130

- Figure 6.26—Examples of the double-differential spectra $\frac{d^2n}{dpdp_T}$ as a function of p_T for p bins. The $\langle p \rangle$ is indicated inside each plot. The black lines show the statistical uncertainties, while the gray bands show the systematic ones. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f). 135
- Figure 6.27—Examples of the double-differential spectra $\frac{d^2n}{dpdp_T}$ as a function of p_T for p bins. The $\langle p \rangle$ is indicated inside each plot. The black lines show the statistical uncertainties, while the gray bands show the systematic ones. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and the K_S^0 in (c) 136
- Figure 6.28—Differential spectra dn/dp of the charged hadrons as a function of p for the 158 GeV/ c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f). 137
- Figure 6.29—Differential spectra dn/dp of the charged hadrons as a function of p for the 350 GeV/ c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f). 138
- Figure 6.30—Differential spectra dn/dp of the V^0 particles as a function of p for the 158 GeV/ c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and K_S^0 in (c). 139
- Figure 6.31—Differential spectra dn/dp of the V^0 particles as a function of p for the 350 GeV/ c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and K_S^0 in (c). 139
- Figure 6.32—Systematic uncertainties on the differential spectra dn/dp of the charged hadrons as a function of p for the 158 GeV/ c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f). . . 140

Figure 6.33–Systematic uncertainties on the differential spectra dn/dp of the charged hadrons as a function of p for the 350 GeV/ c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f).	141
Figure 6.34–Systematic uncertainties on the differential spectra dn/dp of the V^0 particles as a function of p for the 158 GeV/ c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b), and the K_S^0 in (c).	142
Figure 6.35–Systematic uncertainties on the differential spectra dn/dp of the V^0 particles as a function of p for the 350 GeV/ c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b), and the K_S^0 in (c).	142
Figure A.1–Examples of the fitted dE/dx distributions from the 350 GeV/ c dataset. On the top, the distributions of the (a) negatively and (b) positively charged tracks are shown for one phase space bin of the RST subset. On the bottom, the distributions of the (c) negatively and (d) positively charged tracks are shown for a different phase space bin of the WST subset. The values of the $\langle p \rangle$ and $\langle p_T \rangle$ for each phase space bin is indicated on the top of each plot. The black dots show the observed number of tracks, while the colored distributions are the results of the dE/dx fit or each particle type. On the bottom of each plot, we show the residual of the fit, defined as the difference between the observed and the expected number of tracks from the result of the fit, divided by the uncertainty of the observed number.	162
Figure A.2– χ^2/ndf of the dE/dx fit for the 350 GeV/ c data set. The RST and WST are shown in (a) and (b), respectively.	163
Figure A.3–Calibration constants obtained from the dE/dx fit of the WST and 158 GeV/ c data set.	164
Figure A.4–Calibration constants obtained from the dE/dx fit of the RST and 350 GeV/ c data set.	165
Figure A.5–Calibration constants obtained from the dE/dx fit of the WST and 350 GeV/ c data set.	166
Figure A.6–Shape parameters obtained from the dE/dx fit of the WST and 158 GeV/ c data set.	167
Figure A.7–Shape parameters obtained from the dE/dx fit of the RST and 350 GeV/ c data set.	168

Figure A.8–Shape parameters obtained from the dE/dx fit of the WST and 350 GeV/ c data set.	169
Figure A.9–Particle fractions obtained from the dE/dx fit of the WST and 158 GeV/ c data set.	170
Figure A.10–Particle fractions obtained from the dE/dx fit of the RST and 350 GeV/ c data set.	171
Figure A.11–Particle fractions obtained from the dE/dx fit of the WST and 350 GeV/ c data set.	172
Figure A.12–Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	173
Figure A.13–Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	174
Figure A.14–Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	175
Figure A.15–Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	176
Figure A.16–Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	177
Figure A.17–Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	178
Figure A.18–Correction factors (c , see the definition in the text) for the WST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	179
Figure A.19–Correction factors (c , see the definition in the text) for the RST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	180

Figure A.20–Correction factors (c , see the definition in the text) for the RST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).	181
Figure A.21–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 158 GeV/ c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	182
Figure A.22–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 350 GeV/ c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	183
Figure A.23–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 350 GeV/ c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	184
Figure A.24–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 158 GeV/ c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	185
Figure A.25–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 158 GeV/ c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	186
Figure A.26–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 350 GeV/ c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	187
Figure A.27–Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 350 GeV/ c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.	188

Figure A.28—Optimization of the $L_{\text{decay}}^{\text{cut}}$ for the 350 GeV/c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). Individual phase space bins are shown as black markers, the average over p_T bins is shown as red markers. 189

Figure A.29—Examples of the fitted m_{inv} distributions for the 350 GeV/c data set with target inserted. Two phase space bins are shown for Λ in (a) and (d), for $\bar{\Lambda}$ in (b) and (e) and for K_S^0 in (c) and (f). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. Additionally, in green and purple we show the contributions of the two separated templates. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ and $\langle p_T \rangle$ of the phase space bin are indicated on the top of each plot. 190

Figure A.30—Examples of the fitted m_{inv} distributions for the 350 GeV/c data set with target removed. One p bin is shown for Λ in (a), for $\bar{\Lambda}$ in (b) and for K_S^0 in (c). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ of the phase space bin is indicated on the top of each plot. 191

Figure A.31— χ^2/ndf of the m_{inv} fit of the 350 GeV/c data set for the target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f). 192

Figure A.32—Extracted signal S for the 350 GeV/c data set with target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f). 192

Figure A.33— β correction factor for the charged hadron analysis and for the 350 GeV/c data set. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f). 193

Figure A.34— β correction factor for the V^0 analysis and for the 350 GeV/c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). 193

Figure A.35—Double-differential spectra $\frac{d^2n}{dpdp_T}$ of π^+ for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones. 194

Figure A.36–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of π^- for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	195
Figure A.37–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of K^+ for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	196
Figure A.38–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of K^- for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	197
Figure A.39–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of p^+ for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	198
Figure A.40–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of p^- for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	199
Figure A.41–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of π^+ for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	200
Figure A.42–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of π^- for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	201
Figure A.43–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of K^+ for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	202
Figure A.44–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of K^- for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	203

Figure A.45–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of p^+ for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	204
Figure A.46–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of p^- for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	205
Figure A.47–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of Λ for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	206
Figure A.48–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of $\bar{\Lambda}$ for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	206
Figure A.49–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of K_S^0 for the 158 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	207
Figure A.50–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of Λ for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	208
Figure A.51–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of $\bar{\Lambda}$ for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	208
Figure A.52–Double-differential spectra $\frac{d^2n}{dpdp_T}$ of K_S^0 for the 350 GeV/ c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.	209

List of Tables

Table 6.1 – Number of events after the event selection for the data and simulation sets and for both beam momenta, 158 and 350 GeV/ c	97
Table 6.2 – List of the V^0 particles of interest of this work, together with their masses and the properties of their relevant decay channel. (15)	117
Table 6.3 – List of α factor (see text) computed by using different hadronic interaction models and its average value.	128

Contents

1	INTRODUCTION	25
2	COSMIC RAYS AND THE PIERRE AUGER OBSERVATORY . . .	29
2.1	Overview of cosmic rays	29
2.1.1	Energy spectrum	29
2.1.2	Acceleration and sources	32
2.1.3	Propagation of UHECR	35
2.2	UHECR spectrum and composition	37
2.3	The Pierre Auger Observatory	40
2.3.1	AugerPrime	44
3	EXTENSIVE AIR SHOWERS	47
3.1	Phenomenology of EAS	47
3.1.1	Electromagnetic component and the $X_{\max}$	48
3.1.2	Hadronic component and muon production	50
3.2	Simulations of EAS	52
3.2.1	Simulation strategies	53
3.2.2	Hadronic interaction models	54
3.3	Measurements of EAS observables	55
3.3.1	Shower maximum and UHECR composition	56
3.3.2	Number of muons and the muon deficit problem	58
3.3.3	Further measurements	61
3.3.4	Summary	63
4	INTERPRETATION OF MEASUREMENTS OF THE NUMBER OF MUONS IN EXTENSIVE AIR SHOWER EXPERIMENTS . . .	65
5	A NEW AIR-Shower OBSERVABLE TO CONSTRAIN HADRONIC INTERACTION MODELS	79
6	HADRON PRODUCTION IN PION-CARBON INTERACTIONS . .	91
6.1	NA61/SHINE experiment	92
6.1.1	Beam	93
6.1.2	Beam detectors and trigger system	94
6.1.3	Time projection chambers	94
6.2	Data and simulation sets	95
6.3	Event selection	96

6.4	Phase space binning	96
6.5	Particle identification for the charged hadron analysis	97
6.5.1	Track selection	98
6.5.2	dE/dx measurements	99
6.5.3	dE/dx model	101
6.5.4	dE/dx fit strategy	103
6.5.5	dE/dx fit results	106
6.5.6	Simulated data ensembles, cuts and corrections	108
6.5.7	Particle identification results	114
6.6	V^0 analysis	117
6.6.1	V^0 selection	117
6.6.2	Signal extraction strategy	118
6.6.3	V^0 cuts	120
6.6.4	Signal extraction results	123
6.7	Monte Carlo corrections	127
6.7.1	Feed-down from weak decays	129
6.8	Spectra	131
6.8.1	Statistical uncertainties	131
6.8.2	Systematic uncertainties	132
6.8.3	Integration over p_T	133
6.9	Results	134
6.10	Summary, discussions and conclusions	134
7	SUMMARY	143
	REFERENCES	145
	APPENDIX	159
A	ADDITIONAL FIGURES	161

1 Introduction

The study of cosmic rays has been a very active field since the discovery of these particles by Victor Hess, in 1912. (1) Before the first accelerators were built during the 1950's, the only way to study elementary particle physics was through the detection of particles produced by cosmic ray interactions. The discovery of positrons, muons and pions are examples of the importance of cosmic rays for the development of the particle physics field. One of the most striking events of the history of cosmic rays was the discovery of Extensive Air Showers (EAS) by Pierre Auger, in 1938. (2) By measuring coincidences on the time of signals from detectors separated in space, he could confirm the hypothesis that cosmic ray particles can interact with atmospheric nuclei and start a cascade of secondary particles that can eventually reach the ground. After Auger's discovery, the idea of measuring the properties of cosmic rays through the detection of EAS with arrays of particle detectors at ground became a central concept for the experimental cosmic ray studies.

The advance of techniques to detect EAS and the construction of large detector arrays allowed us to extend cosmic ray studies up to the very high energy regions, where the flux of particles is very low. Currently, the cosmic ray energy spectrum is well known from 10^9 up to 10^{21} eV. Although this spectrum follows an overall power-law shape, a number of features are observed and the understanding of these features in terms of astrophysical phenomena is one of the motivations of the field. The main interest of this thesis is on the Ultra-High Energy Cosmic Rays (UHECR) region ($E > 10^{17}$ eV), where two spectrum features are observed: the *ankle*, which is a softening of the flux around 4×10^{18} eV and the *suppression*, which is an abrupt reduction of the flux above 4×10^{19} eV. Most questions about the nature of the UHECR are still open, and in particular, the actual nature of the ankle and the suppression are still a matter of discussions.

Measuring the properties of UHECR is the main goal of the largest cosmic ray experiment ever built, the Pierre Auger Observatory, located in Malargue, Argentina, and operating since 2004. (3) While its large collecting area (3000 km^2) guarantees a large event statistics, its hybrid detection system that includes surface detectors and fluorescence telescopes can provide precise measurements of the properties of the EAS. An overview of the current status of the UHECR field and an introduction to the Pierre Auger Observatory will be given in Chap. 2 of this thesis.

The precise inference of the properties of UHECR from EAS measurements requires a deep understanding of these objects. The most complete modeling of EAS is achieved by

means of Monte Carlo simulations. Among the known sources of uncertainties related to the simulation of EAS, the main one is the modeling of hadronic interactions. Because of the phenomenological nature of the hadronic interaction models, they are tuned to accelerator measurements and a number of problems with this process originate a substantial uncertainty on the predictions of the EAS properties by simulations.

The importance of EAS simulations comes mostly from the fact that some properties of UHECR, including its mass composition, can only be inferred by the comparison of EAS measurements to the predictions from simulations. The most reliable composition analysis at the UHECR regime are based on the shower maximum parameter ($X_{\max}$) which is defined as the atmospheric depth at which the shower reaches the maximum number of particles. Apart from the $X_{\max}$, shower parameters related to the muonic component of the showers are also sensitive to the cosmic ray composition, the most common one being the number of muons in the shower (N_{μ}). However, a number of measurements of the N_{μ} have shown that the comparison with predictions from simulations leads to inconsistent results. To be more precise, the N_{μ} observed is systematically larger than the ones predicted by EAS simulations using hadronic interaction models. Although this is traditionally known as *muon deficit problem*, further EAS measurements have shown that simulations also fail on predicting other properties of the muonic component. As a direct consequence, measurements of muonic observables cannot be properly used to infer cosmic ray composition. An overview of the EAS physics, simulations and a summary of measurements of EAS observables at the UHECR regime will be given in Chap. 3 of this thesis.

In this thesis, the problem of describing the properties of the muonic component of EAS by simulations is approached from an experimental perspective by three different fronts. The first one is presented in Chap. 4, where the Ref. (4) is reproduced, and it consists in the development of a method to interpret the energy evolution of the measured N_{μ} moments in terms of mass composition which takes into account the misprediction of the N_{μ} by the simulations. The method is tested by using a set of simulations and it is expected to be applicable for the analysis of future measurements of the N_{μ} by AugerPrime or other experiments. Preliminary stages of this work can be found in Refs. (5–7).

The second front is presented in Chap. 5 where the Ref. (8) is reproduced. The main idea is to explore the potentialities of using the measurements from muon detectors, similar to the ones of AugerPrime, to further constrain hadronic interaction models. By considering the operation of two distinct muon detectors, one at the surface and one buried a few meters below the ground, we have proposed a new observable that was shown to be sensitive to the properties of the energy spectrum of muons at ground. This observable was studied by using simulations and it can be seen that its measurements could provide

an efficient way to constrain hadronic models.

The third front, presented in Chap. 6, is the data analysis of the fixed target experiment NA61/SHINE at CERN Super Proton Synchrotron (9), aiming at the measurements of hadron production spectra in π^- -C interactions. These measurements are valuable for the understanding of the muon production in EAS (see Chap. 3) and they are an important part of the cosmic ray physics programme of NA61/SHINE experiment. A preliminary stage of this work can be found in Ref. (10). Finally, in Chap. 7 the summary of the thesis is presented.

2 Cosmic rays and the Pierre Auger Observatory

In this chapter, an overview of cosmic rays physics focusing on the UHECRs and an introduction to the Pierre Auger Observatory will be given. The goal of this chapter is to present the context and the motivation for this thesis. More detailed material about the current status of the cosmic ray field can be found in Refs. (11,12).

2.1 Overview of cosmic rays

2.1.1 Energy spectrum

The cosmic ray flux as a function of energy is the so-called *energy spectrum* and it plays a central role in the understanding of the astrophysical aspects behind these particles. A compilation of measurements of the cosmic ray energy spectrum over about 13 orders of magnitude in energy is shown in Fig. 2.1. One can see that from $\approx 10^{11}$ eV up to the highest energies the spectrum can be described approximately by a power law function, $d\phi/dE \sim E^{-\gamma}$, where the spectral index γ is not exactly constant over all the energy range but it changes only slightly, between 2.5 and 3.2. Because the cosmic ray spectrum extends over a very large energy range, it is expected that different astrophysical mechanisms at distinct length scales contribute to the production of these particles. An illustration of that comes from the fact that most of the modern models predict that the cosmic ray flux is dominated by particles produced inside our galaxy up to around 10^{17} - 10^{18} eV and, above these energies, they have extragalactic origin. The transition between these two components is currently one of the most active topics of discussion.

Because of the steepness of the spectrum, the particle flux changes over 27 orders of magnitude from 10^{11} to 10^{21} eV. As indicated in Fig. 2.1, while at 10^{11} eV the flux is about one particle per m^2 per second, at 10^{19} eV it drops to only one particle per km^2 per year. As a consequence, different experimental techniques have to be applied to detect cosmic ray particles at different energy ranges. Up to $\approx 10^{14}$ eV, the high flux allows us to use small area instruments installed in balloons or satellites to detect the particles before they interact with the Earth's atmosphere. Above this energy, the interaction with the atmosphere turns out to be necessary since we can measure the cosmic rays indirectly through the detection of the extensive air showers (see Chap. 3). For that, large arrays of detectors are used and their areas can vary substantially depending on the energy range they are intended to be sensitive to. As an example, the KASCADE experiment (14) is designed to measure particles from around 10^{14} to 10^{16} eV and it has an area of 4000 m^2 ,

Figure 2.1 – Compilation of measurements of the cosmic ray energy spectrum from Ref. (13). Two of the spectrum features are indicated: the knee and the ankle.

Source: SWORDY. (13)

Figure 2.2 – Compilation of measurements of the cosmic ray energy spectrum from Ref. (15). The flux is scaled by a factor $E^{2.6}$ and the main features of the spectrum are indicated (see text for details). The references to the data can be found in Ref. (15).

Source: PATRIGNANI. (15)

while the Pierre Auger Observatory (3) has an area of 3000 km^2 to measure particles above 10^{18} eV .

A few features of the cosmic ray energy spectrum can be identified by the small changes on the spectral index γ . To better visualize these changes, we show in Fig. 2.2 a compilation of measurements of the spectrum, starting at $\approx 10^{13} \text{ eV}$, in which the flux is scaled by a factor $E^{2.6}$. As indicated in Fig. 2.2, the lowest-energy feature is the so-called *first-knee* and it occurs around $3 \times 10^{15} \text{ eV}$. At this energy the index changes from $\gamma \approx 2.7$ to 3.0. Increasing the energy, the next feature is the so-called *second-knee*, around 10^{17} eV , where there is a further steepening and the index goes to $\gamma \approx 3.3$. The spectrum then becomes harder again at the *ankle*, around $5 \times 10^{18} \text{ eV}$, where the index changes to $\gamma \approx 2.6$. The final feature occurs at the highest energies, above $4 \times 10^{19} \text{ eV}$, where the value of the spectral index becomes very high ($\gamma > 4$), characterizing the so-called *suppression*.

A consistent interpretation of all these spectrum features requires the knowledge of the cosmic rays composition. Particularly in the energy region comprehending the first and second-knee, very efficient composition measurements were performed by KASCADE (14) and KASCADE-Grande (16) experiments. By using an experimental setup which includes

surface detectors able to measure both the number of charged particles and the number of muons in air showers, it was possible to measure the all particle spectrum as well as to infer the spectra of individual groups of particles. Results of both experiments are shown in Fig. 2.3 where the plots on the top show spectra measurements from KASCADE (17) around the first-knee energies and the ones on the bottom show measurements from KASCADE-Grande (18) around the second-knee energies. Although these results are strongly dependent on the choice of the hadronic interaction model due to the unfolding algorithm applied to estimate the individual spectra (17), it is still possible to conclude that: (a) the first-knee is the result of the suppression of the proton spectrum (17), (b) the suppression of the components heavier than proton are consistent with a rigidity dependent suppression (17) and (c) the second-knee coincides with the suppression of the heaviest group of particles, including iron nuclei. (19,20)

Although the rigidity dependent suppression as an explanation for the first-knee was a known hypothesis since suggested by Peters, in 1961 (21), the actual explanation is still a matter of discussion. The most simple model would assume that the suppression is a consequence of the maximum attainable energy by the sources. (22) Alternative models include explanations based on the effect of the drifting of cosmic rays in the galactic magnetic field (23,24) and on the escape of cosmic rays from the galaxy. (25) Most of the models, however, converge on the fact that the cosmic ray flux is dominated by a galactic component up to second-knee energies. The transition between this galactic and an extragalactic component would then occur at energies around the second-knee and the ankle. The measurements and the models concerning UHECRs will be presented in Sec. 2.2.

2.1.2 Acceleration and sources

The power-law shape of the energy spectrum indicates that cosmic rays are not accelerated in thermal processes. A stochastic acceleration mechanism was first proposed by Fermi, in 1949. (26) The main idea is that the multiple collisions of charged particles with moving magnetized regions could accelerate them up to high energies. Although a power-law spectrum can be derived from this mechanism, the overall acceleration efficiency is too low to explain the observed energy density of cosmic rays. The average energy gain is given by $\Delta E/E \sim \beta^2$, where $\beta = v/c$ and v is the velocity of magnetic cloud. Because of this second power of β , this mechanism is called *second order Fermi mechanism*.

A similar but more efficient mechanism was proposed almost two decades later. (27–30) The main idea of this mechanism is that charged particles collide with multiple shock waves and they gain energy by interacting with irregularities in the magnetic field. The average energy gain is $\Delta E/E \sim \beta$ and again a power law energy spectrum can be derived. The obtained spectral index is $\gamma = 2 - 2.3$, which means that propagation effects have to be

Figure 2.3 – Energy spectra of different components as measured by KASCADE (17) (top), around the first-knee energies, and by KASCADE-Grande (18) (bottom), around the second-knee energies. The hadronic interaction models used were QGSJET 01 and QGSJET II-04 for the KASCADE and KASCADE-Grande analysis, respectively.

Source: ANTONI.(top) (17); FUHRMANN.(bottom) (18)

responsible to account for the further steepening of the observed spectrum. This mechanism is called *first order Fermi mechanism* or, alternatively, *diffusive shock acceleration* (DSA), and it is the basis of most of the models that propose possible sources of cosmic rays. A detailed approach to the DSA theory can be found in Ref. (31).

The list of astrophysical objects usually considered as possible acceleration sites for cosmic rays includes neutron stars, active galactic nuclei (AGN), gamma ray bursts (GRB) and others. A review of the candidates for sources of cosmic rays can be found in Ref. (32). Independently of the details of the acceleration mechanisms in different types of astrophysical environments, it is possible to estimate the maximum energy at which a certain type of object is able to accelerate particles. This was first done by Hillas (33) and

Figure 2.4 – Hillas plot from Ref. (12). The sources shown are neutron stars (n-star), gamma-ray bursts (GRB), active galactic nuclei (AGN) split in radio-quiet Seyfert (Sy) and radiogalaxies (RG), supernova remnants (SNR), starburst galaxies and galaxy clusters.

Source: MOLLERACH. (12)

the idea is simply to consider that the Larmor radius of the particles must be smaller than the size of the site in which they are confined to be accelerated. As a result one obtain

$$\frac{E_{\max}}{10^{18} \text{ eV}} \approx \frac{\beta Z}{2} \frac{B}{\mu\text{G}} \frac{L}{\text{kpc}}, \quad (2.1)$$

where β is the typical velocity of the shock waves in units of c , Z is the charge of the particles, B is the magnetic field and L is the typical size of the site. The graphical illustration of this relation showing the astrophysical objects in a plane of their size *vs* their magnetic field is traditionally called *Hillas plot*. We show one version of it, focused on the candidate sources of UHECRs, in Fig. 2.4. The diagonal lines show the lower limits to accelerate protons and iron nuclei up to 10^{20} eV.

Regarding UHECRs, a famous family of models, generically called *top-down models*, assume that the particles are not accelerated by astrophysical objects, but instead they are the products of the decay of exotic super-massive particles. The origin of these exotic particles could be, for example, topological defects from early Universe phase transitions or dark matter. As a prediction of nearly all these models, a significant flux of ultra-high energy photons should be observed. However, measurements of Pierre Auger Observatory have shown that the upper limits of the photon flux is significantly lower than the

Figure 2.5 – Energy loss lengths for protons and iron nuclei from Ref. (36).

Source: BATISTA. (36)

predictions (34) and, therefore, the top-down hypothesis can be ruled out. A review of the top-down models can be found in Ref. (35).

2.1.3 Propagation of UHECR

At the ultra-high energy regime, cosmic rays suffer from a number of interaction processes during their propagation from the source to the Earth and the consequent energy losses have a large influence on the measured energy spectrum and composition. Four interaction processes take place: photopion production, electron pair production, photodisintegration and adiabatic losses due to the expansion of the universe. Since the latter affects equally all types of particles with no dependence on their energy, its influence on the energy spectra is the less relevant of all. Concerning the other three remaining processes, it is helpful to evaluate their effect separately for protons and nuclei. In Fig. 2.5 the energy losses of protons and iron nuclei are quantified by evaluating the energy loss length, which is defined as the average distance over which the particle energy decreases by a factor $1/e$, as a function of its energy.

The photopion production process (indicated by orange curves in Fig. 2.5) occurs mainly because of the interaction of the cosmic ray particle with photons from the cosmic microwave background (CMB). For protons, the processes that take place are $p + \gamma \rightarrow p + \pi^0$ and $p + \gamma \rightarrow n + \pi^+$, in which the energy threshold is given by the condition that the center-of-mass energy has to be larger than the rest mass of the pion. From Fig. 2.5 it is clear that photopion production processes dominate the proton energy losses at energies above $\approx 8 \times 10^{19}$ eV, and, as a consequence, it is expected that the proton spectrum be

strongly suppressed around this energies. This effect was proposed in 1966 by Greisen (37), Zatsepin and Kuzmin (38), and it is known as the *GZK suppression*. Also from Fig. 2.5, one can see that proton energy losses due to electron pair production dominate at energies between 5×10^{18} and 5×10^{19} eV.

It can be seen that the combined effect of these two processes, photopion production and electron pair production, on the energy spectrum of cosmic rays composed purely by protons can generate two evident features, a dip at $E \approx 5 \times 10^{18}$ eV and a sharp suppression above $E \approx 5 \times 10^{19}$ eV, that can explain the two features actually observed at the UHECR spectrum, the ankle and the suppression. (39,40) This scenario is called *dip model* (see also discussion in Sec. 2.2) and the pure proton composition predicted by it has two very relevant consequences to the possible identification of the sources of UHECRs. The first one is the so-called *particle horizon*, meaning that protons above a certain energy should be originated on average by sources inside a certain distance range. In Fig. 2.6 the particle horizon is quantified by curves that show the average energy of protons as a function of the propagation distance for three cases in which the particle left the source with 10^{20} , 10^{21} and 10^{22} eV. As a conclusion from this plot, one can see that protons reaching Earth with $E > 10^{20}$ eV are approximately limited to be originated at sources within 100 Mpc of distance. The second consequence is related to the particle deflections by magnetic fields. It is possible to show that heavier nuclei are so strongly deflected that their arrival direction does not contain information about the direction of the astrophysical source. On the other hand, since protons above $\approx 10^{19}$ eV are only slightly deflected, in this pure-proton scenario it would be possible to use the arrival directions to infer the sources distribution.

Unlike protons, nuclei also can suffer photodisintegration along their propagation. This means that they can interact with photons from the extragalactic background light (EBL) and be broken into lighter nuclei. In Fig. 2.5 it is also shown the energy loss due to this process for iron nuclei. One can see that photodisintegration dominates the energy losses over electron pair production or photopion production at all the energies. Because of photodisintegration, the resultant effect of the propagation of a combination of different nuclei on the energy spectrum turns out to be more complicated to evaluate than in the proton case. However, it is possible to show that for a mixed composition case, the energy spectrum would also suffer a suppression at the highest energies, mainly due to photodisintegration effects for heavy nuclei and photopion production for the light ones. This suppression can also be considered to be a manifestation of the above mentioned GZK suppression, since it would be a consequence of the propagation effects of cosmic ray particles.

Concerning the other spectrum feature, the ankle, it is not possible to reproduce it by considering nuclei propagation, instead of proton. The alternative explanation for

Figure 2.6 – Average proton energy as a function of the propagation distance through the CMB. The numbers above the curves indicate the proton initial energy.

Source: CRONIN. (41)

the ankle in the non-pure proton case is the effect of the transition between galactic and extragalactic component. In Sec. 2.2 we discuss the recent measurements of the UHECR spectrum and composition and how they constrain the above mentioned explanation for the ankle and the suppression.

2.2 UHECR spectrum and composition

At the ultra-high energy range, two very evident features can be observed in the spectrum: the ankle and the suppression. In Fig. 2.7 we show the most up to date spectrum as measured by Pierre Auger Observatory (42) and Telescope Array (43), where both features can be clearly seen. The ankle is a hardening of the spectrum at $E \approx 5 \times 10^{18}$ eV which was first observed in Haverah Park measurements in 1963 (44), and later confirmed in measurements by AGASA (45), HiRes (46), Pierre Auger Observatory (47) and Telescope Array. (48) The suppression is an abrupt softening of the flux at energies above 4×10^{19} eV which was measured first by Hires (46) and later confirmed by Pierre Auger Observatory (47) and Telescope Array. (48) The fact that the suppression was not observed on the AGASA spectrum (49) was a source of intense discussions along years. However, it is currently accepted that the AGASA measurements are not trustful because of systematic uncertainties in the primary energy estimation.

Figure 2.7 – UHECR spectrum as measured by Pierre Auger Observatory and Telescope Array. The Pierre Auger Observatory measurement combines several different data sets into one unique spectrum. (42) The Telescope Array measurement includes only the analysis of the surface detectors data. (43)

Source: By the author.

The most precise inferences of the composition of cosmic rays at this energy range are based on the X_{max}^* measurements performed by fluorescence telescopes. In Sec. 3.3, we present a detailed discussion about the X_{max} measurements, its composition interpretation, as well as further measurements of air shower observables that could, in principle, be used to infer composition. For now, it is only important to point out that the cosmic ray composition can be inferred by comparing the measured X_{max} distributions to predictions obtained from air shower simulations. This procedure can be done either by comparing only the moments of the X_{max} distributions, which gives only the average composition, or by comparing the whole distributions, which can provide the abundances of individual groups of primaries. In all cases, the composition interpretation is dependent on the hadronic interaction model used to generate the simulation predictions.

Although the energy spectrum with its both features can be successfully described by multiple hypothesis, the composition measurements must be used to further constrain the models. Concerning the ankle, most of the models associate it to the transition between the galactic and extragalactic flux, which can take place in energies between the second-knee and the ankle. The composition predictions by these models can vary substantially depending on the exact position of the transition and on the composition content of

* X_{max} is defined as the longitudinal depth in which the EAS reaches its maximum number of particles.

the extragalactic component. One historically relevant hypothesis to describe the ankle without the galactic-to-extragalactic transition assumption is the above mentioned dip model (39, 40), which proposes that the energy losses due to electron pair production along the particle propagation would cause the hardening of the spectrum around the ankle energies. It turns out that the success of the dip model actually requires a nearly pure proton composition around and above the ankle. Although at the time of the model proposal this composition assumption seemed to be fulfilled by the $X_{\max}$ measurements of HiRes experiments (50), recent measurements of Pierre Auger Observatory have proven that the composition is actually heavier than proton at ankle energies and above (51), which makes the dip model widely disbelieved by the UHECR community.

Concerning the suppression, the two currently most considered hypothesis to explain it are the GZK effect (see Sec. 2.1.3) and the limit of the acceleration power by the sources. While in the GZK hypothesis the composition can be either pure proton or mixed, the source limit hypothesis implies in a rigidity dependent suppression and consequently an increasingly heavier composition as the energy increases. Similarly to what happened to the dip model interpretation of the ankle, the composition measurements by HiRes supported the GZK hypothesis for many years, which was also changed after the $X_{\max}$ measurements by Pierre Auger Observatory were published.

Many scenarios which propose to explain the UHECR spectrum and composition can be found in the literature. (52–56) Two features are common to nearly all the recent models that are constrained by the Auger $X_{\max}$ measurements: the exact energy of the galactic-to-extragalactic transition (the energy in which both fluxes become equivalent) is around $1 - 3 \times 10^{18}$ eV and the suppression is mainly caused by a rigidity dependent cutoff due to the limit of the acceleration power of the sources. The observed mixed composition at the suppression energies and the confirmation that the suppression is not caused only by GZK effect with a pure proton composition has negative consequences, like the absence of correlation with nearby sources due to the deflection of heavy nuclei in magnetic fields and the absence of the GZK horizon. Those facts motivated the authors of Ref. (53) to name this generic scenario as *disappointing model*.

In a recent analysis done by Pierre Auger Collaboration, the measured spectrum and the $X_{\max}$ distributions were jointly fitted by using simulations which account for all the propagation effects. (57) We show in Fig. 2.8 the results of the fit by using the hadronic interaction model EPOS LHC (58) to predict the $X_{\max}$ distributions. The hypothesis of the limit of the acceleration power by the sources as the reason of the suppression is favored by the results of this analysis. However, the lack of information about the composition given by the $X_{\max}$ measurements at energies above 4×10^{19} eV is a limiting factor for this type of analysis, since the spectrum is measured up to above 10^{20} eV. Therefore, precise composition measurements at the highest energies are a requirement to refine the

Figure 2.8 – Results of the combined fit of the spectrum and $X_{\max}$ distributions performed by Pierre Auger Observatory. (57) On the top plot the measured spectrum and the fitted contributions of different groups of primaries are shown. On the bottom plots the measured mean ($\langle X_{\max} \rangle$) and standard deviation ($\sigma[X_{\max}]$) of the $X_{\max}$ distributions are shown together with the results of the fit. The color codes for the groups of the primaries are indicated on the right side of the top plot. The hadronic interaction model used to describe the $X_{\max}$ distributions is EPOS LHC. (58) The results by using other models can be found in Ref. (57).

Source: AAB. (57)

interpretation of the end of the cosmic ray spectrum.

2.3 The Pierre Auger Observatory

The Pierre Auger Observatory was designed to measure cosmic rays at the ultra-high energy range. It is located near the town of Malargue, Argentina, and its total area is approximately 3000 km². The average altitude of the experiment is 1420 m, which corresponds to a vertical atmospheric depth of approximately 880 g/cm². The construction of the observatory started in 2002 and finished in 2008. Its hybrid detection system, which

Figure 2.9 – Configuration of the Pierre Auger Observatory. The black dots represent stations of the standard surface detector, the gray dots represent the AMIGA stations and the blue and red lines indicate the field of view of each telescope which compose the fluorescence detector. The atmospheric monitoring devices (XLF, CLF and BLF) are represented by red dots. The blue circle shows the approximate area of the AERA setup.

Source: STREICH. (59)

combines a large surface detector and a set of fluorescence telescopes, is one of the most important experimental features of the observatory. A detailed overview of the experiment can be found in Ref. (3).

The standard surface detector (SD) is composed by a set of ~ 1660 water-Cherenkov detectors (WCD) which are regularly arranged in a triangular grid. The nearest neighbor distance of the stations for the standard array, which covers the full observatory area, is 1.5 km, while a small area of 23.5 km^2 called *SD infill* contains stations separated by 750 m. In Fig. 2.9 we show the configuration of the Pierre Auger Observatory, including the stations of the SD array indicated by black dots. Each WCD consists of a cylindrical tank with a diameter of 3.6 m, filled with 12 m^3 of ultra-high purity water, up to a height of 1.2 m. The particle detection is done by collecting the Cherenkov light produced by the passage of charged particle through the water. For that, three photomultiplier tubes (PMT) are installed on the top of each station and their signal are extracted and digitized using flash analog-to-digital converters (FADC) with a sampling rate of 40 MHz. Since the SD operation does not require any special environmental condition, its duty cycle turns out to be very close to 100%. More details about the SD can be found in Ref. (60).

The fluorescence detector (FD) is composed by 27 telescopes installed in 4 buildings

around the edge of the array. Each of these buildings contains a set of six telescopes with a field of view which covers 30° horizontally and goes from 1.5° to 30° vertically. The 24 telescopes of this kind were part of the original project of the observatory and they are designed to measure the fluorescence light emitted by the atmosphere during the development of air showers with primary energies above approximately 10^{18} eV. Another set of 3 telescopes that can operate with a vertical field of view going from 30° to 60° was later installed in one of the buildings. This enhancement is called HEAT (61) and it is designed to extend the lower limit of the fluorescence measurements to approximately 10^{17} eV. In Fig. 2.9 blue and red lines are used to show the horizontal field of view of the standard telescopes and the HEAT ones, respectively. Because of its sensitivity, the background light has to be avoided during the FD operation. This means that moonless nights with proper atmospheric conditions are required, implying in a duty cycle of about 13% for the FD measurements. More details about the FD can be found in Ref. (62).

The SD and FD measurements provide complementary information which can be combined to achieve a precise reconstruction of the properties of the air shower and the primary particle. However, because of the limited FD duty cycle, both information are only available to a fraction of the events. Because of that, two different event reconstruction modes are defined, the SD and the hybrid reconstruction.

The hybrid reconstruction uses the measurements of the fluorescence telescopes with only additional timing information from one SD station. From the time structure of the FD signal it is possible to reconstruct precisely the geometry of the shower and from the amount of light collected it is possible to reconstruct the longitudinal profile of the shower. A detailed procedure has to be applied at this point to convert the number of photons collected in the telescopes into energy deposit in the atmosphere by taking into account all the attenuation effects. One example of longitudinal profile as measured by Auger is shown on the left plot of Fig. 2.10. After obtained the energy deposit as a function of slant depth, a Gaisser-Hillas function (63) is fitted to that and the result is used to determine the shower maximum $X_{\max}$ and the calorimetric energy, which is given by the integral of the fitted function. This calorimetric energy is then corrected by the invisible energy due to neutrinos and high energy muons and the final FD energy (E_{FD}) is then obtained.

The SD reconstruction is based on the size and the times of signals registered by the individual stations. The geometry of the shower is first determined by fitting the time of the signals assuming a parabolic shape for the shower front. After obtaining the shower geometry it is possible to evaluate the lateral distribution, which is basically the evolution of the station signals with the distance to the shower axis. On the right plot of Fig. 2.10 we show one example of the lateral distribution function as measured by Auger. A function of the NKG type (65,66) is fitted and the evaluation of fitted function at a certain distance is

Figure 2.10 – Examples of the energy deposit longitudinal profile as measured by the FD (left plot) (64) and of the lateral distribution as measured by the SD (right plot). (3)

Source: AAB. (3, 64)

defined as shower size. For the standard array, with stations at 1500 m distance from each other, the signal is evaluated at 1000 m and the shower size is represented by $S(1000)$. The determination of the energy of SD reconstructed showers is done by means of an energy calibration procedure, in which a set of hybrid reconstructed showers are used to relate the shower size estimated from SD to the calorimetric energy estimated by FD.

The first step of the energy calibration is to correct the $S(1000)$ parameter for the atmospheric attenuation effects. This is done by following the constant instant cut (CIC) method (67) which, by assuming that the flux of cosmic rays above a certain energy is isotropic, correct the zenith angle dependence of $S(1000)$ by converting it to a certain reference zenith angle. For the standard array, this reference value is 38° and the corrected shower size is represented by S_{38} . On the left plot of Fig. 2.11 we show the evolution of $S(1000)$ with the zenith angle θ and the fitted CIC curve $f_{CIC}(\theta)$. The corrected shower size is then computed as $S_{38} = S(1000)/f_{CIC}(\theta)$, where θ is the measured zenith angle of the event. The next step was to select a sample of high quality hybrid events and use them to relate the S_{38} and E_{FD} . This relation is parametrized by a power law function of the type $E_{FD} = A(S_{38})^B$ which is fitted to the data. On the right plot of Fig. 2.11 we show one example of the S_{38} vs E_{FD} plot with the fitted function. The parameters resulting from the fit are used to determine the SD energy from the S_{38} parameter.

More details about the standard event reconstruction can be found in Ref. (3). Besides the SD and hybrid reconstruction, a special procedure is applied to highly inclined air showers, with zenith angle larger than 60° . The details about this reconstruction procedure can be found in Ref. (68).

Apart from the SD and FD, a number of other detectors are currently part of the Pierre Auger Observatory. The muon detector called AMIGA (69–71) (Auger Muons

Figure 2.11 – The attenuation curve derived from the SD data in which the reference zenith angle ($\theta = 38^\circ$) is indicated by a vertical dashed line (left) and the S_{38} - E_{FD} plot used in the standard energy calibration (right). Both figures were obtained from Ref. (3).

Source: AAB. (3)

and Infill for the Ground Array) and the radio detector called AERA (Auger Engineering Radio Array) (72) are already installed and operating. Moreover, prototypes of a recently developed muon detector named MARTA (73) will be installed in the near future.

2.3.1 AugerPrime

An example of the importance of the Auger spectrum and mass composition measurements of UHECRs was already given in Sec. 2.2, where the results of the combined fit were discussed. (57) Besides that, further recent analysis by Auger have provided very important results concerning the astrophysical origins of UHECRs. Two of these results are worthwhile mentioning: a large scale dipolar anisotropy of $\sim 6\%$ found for energies above 8×10^{18} eV (74) and evidences of anisotropy in the arrival directions of cosmic rays with $E > 10^{19}$ eV which indicates correlation with nearby extragalactic sources. (75) Even though these recent results represent a great progress on the understanding of the nature and origin of UHECRs, some of the main questions remain open.

An important piece of information to be provided experimentally that is still missing is the mass composition of cosmic rays above 3×10^{19} eV. Although the composition can be inferred trustfully from $X_{\max}$ measurements (see Sec. 3.3.1), the low duty cycle of the fluorescence telescopes prevents it to be used above the suppression energy. Overcoming this issue is the main goal of the upgrade of the Pierre Auger Observatory, called AugerPrime. (76,77) Besides elucidating the mass composition at the highest energies, the goals of AugerPrime also include searching for a flux contribution of protons up to the highest

energies and studying the properties of air showers and hadronic multiparticle production. The latter one is intrinsically related to the muon deficit problem (see Sec. 3.3.2), which is the main topic of this thesis.

The experimental configuration of AugerPrime consists of four components. The first one is the Surface Detector Electronics Upgrade (SDEU), intending to provide a large number of improvements to the SD electronics, which includes the increasing of analog-to-digital converter sampling rate from 40 MHz to 120 MHz. (78) The second component is the changing of the FD operation mode intending to increase its duty cycle up to 20%. The remaining two components are related to the detection of muons with surface detectors and they are the installations of the Scintillator Surface Detectors (SSD) and Underground Muon Detectors (UMD).

The SSD consists of scintillator detectors installed on the top of each existing WCD. Since the scintillator and water-Cherenkov tanks respond differently to the muonic and electromagnetic component of the shower, the combination of both measurements can be used to estimate the muon content. (79) The UMD consists of scintillator buried 1.3 m below the ground, near the SD stations, which are able to detect muons isolately with an energy threshold around 1 GeV. The design of the UMD will follow the same as the AMIGA detector (69–71) that has already been developed during the last years. While the SSD will cover the full standard array, with over 1600 stations, the UMD will be installed on the smaller area of the SD infill.

The precise measurements of the muonic component is surely one of the most relevant results to be provided by AugerPrime. As a consequence, it is expected a significant improvement on the current understanding of the air shower physics, and in particular the muon production. Both analysis in Chaps. 4 and 5 present methods that can be used to interpret and analyze data from muon detectors similar to the ones of AugerPrime.

3 Extensive air showers

In this chapter, we give an introduction to Extensive Air Showers (EAS). Although the physics behind these objects is very rich, in this text we will focus on the selected topics which are more relevant in the context of this thesis. More detailed and extended materials about the topic can be found in Refs. (80,81).

In Sec. 3.1 we start by a phenomenological description of the EAS development, focusing on the particle production in both electromagnetic and hadronic component of the cascade. In Sec. 3.2 we present the most relevant aspects of EAS simulations, which are currently necessary to study its physics and to interpret the measurements. Finally in Sec. 3.3 we present a compilation of measurements of EAS, focused on the UHECRs. At this point we approach the current inconsistency between measurements and simulations of the muonic related observables, which is the main motivation for this thesis.

3.1 Phenomenology of EAS

An EAS starts with the collision of the primary cosmic ray with an atmospheric nucleus. After this first interaction, the secondary particles produced also interact with the atmosphere producing more particles and so on. This succession of interactions with secondary production creates the cascade of particles that forms the EAS. For the sake of clarity, the description of the cascade is traditionally done by splitting it into different components: the *electromagnetic*, the *hadronic* and, possibly, the *muonic component*. It is also traditional to describe the EAS development in terms of its longitudinal and lateral profiles. The former refers to the shower development along the direction of its axis while the latter refers to the distribution of particles in a plane perpendicular to the shower axis.

The first interaction can produce tens to hundreds of secondary particles, which are nearly all hadrons with only an insignificant contribution of photons and leptons. Among the produced hadrons, the dominant contribution is by far from pions ($> 60\%$), followed by kaons and nucleons at similar proportions ($\sim 10\%$). Other types of mesons and baryons together count typically for less than 5% of the particles. (82) Besides that, a very small fraction of nuclei can be produced by the fragmentation of the target atmospheric nucleus or the primary (in case it is also a nucleus). After the first interaction, the following EAS development is mostly driven by the subsequent processes involving the secondary pions. The three types of pions (π^+ , π^- and π^0) are produced at similar proportions, which means that about 2/3 of them are charged and 1/3 is neutral. The charged ones will be responsible to create more hadrons and eventually muons, while the neutral ones will decay into photons, feeding the electromagnetic component of the shower. The latter case

is described in Sec. 3.1.1 and the former is described later in Sec. 3.1.2.

3.1.1 Electromagnetic component and the $X_{\max}$

Neutral pions can decay via the electromagnetic interaction into two photons ($\pi^0 \rightarrow \gamma + \gamma$) with a very short decay length ($c\tau_0 = 25$ nm). Since in the atmosphere this decay length is much shorter than the interaction one, nearly all the neutral pions end up decaying into photons. The high energy photons produced interact electromagnetically, being the dominant process the pair production ($\gamma \rightarrow e^+ + e^-$). The electrons* produced also interact electromagnetically, mainly through bremsstrahlung, which produces more photons. The succession of these two electromagnetic processes creates a self-sustainable cascade of photons and electrons that forms the electromagnetic component of the EAS. Since more neutral pions are produced in hadronic interactions of secondary particles with atmospheric nuclei (again in the 1/3 proportion wrt the charged pions), the same chain of electromagnetic interactions takes place again and new lower energy electromagnetic cascades are produced. This means that the energy carried by the hadronic particles is partially, but continuously, transferred to electromagnetic particles. After a few generations of hadronic interactions (~ 6), about 90% of the primary energy is carried by the electromagnetic component.

The length scale of the bremsstrahlung interaction, responsible to produce photons out of electrons, is given by the radiation length, X_0 , that is the average distance needed to electrons to lose all but $1/e$ of its energy. In the atmosphere $X_0 \approx 37\text{g/cm}^2$. On the other hand, the length scale of pair production is of the same order of X_0 , only slightly larger ($\approx 1.3X_0$). Because of the short length scale given by X_0 , the electromagnetic shower develops very rapidly, which implies a fast increase of the number of particles and a fast decrease of their average energy. The lower the energies of the particles, more relevant are the energy losses due to ionization. The critical energy in which the ionization losses becomes equivalent to the bremsstrahlung ones is $E_c = 85$ MeV in the atmosphere. After the average energy of electrons becomes of the order of E_c , the number of particles starts to decrease, which creates the peaked shape of the longitudinal profile of the electromagnetic component.

In the left plot of Fig. 3.1 we show the average longitudinal profile of the number of photons (N_γ) and electrons (N_e) in EAS initiated by protons and iron nuclei. It is also shown for comparison the longitudinal profile of the deposited energy (dE/dX) in the atmosphere by all the charged particles. Because the number of particles in the shower is dominated by the electromagnetic component, one can see that the shape of the dE/dX profiles is basically the same as the N_e one. The depth correspondent to the maximum of these both profiles is called the shower maximum and it is symbolized by $X_{\max}$. In EAS experiments, the dE/dX profile can be accessed by telescopes which measure the

* In this text the term *electrons* actually refers to electrons and positrons.

fluorescence light emitted by the interaction of the EAS with the atmosphere. The $X_{\max}$ can then be determined from the dE/dX profile.

Figure 3.1 – Average longitudinal profiles of EAS obtained from simulations performed with CONEX (83) and the hadronic interaction models FLUKA (84) and EPOS LHC. (58)

Source: By the author.

The dependencies of $X_{\max}$ with the primary energy (E_0) and with the nuclear mass of the primary particle (A) can be expressed by the relation

$$\langle X_{\max} \rangle = \lambda_I(A) + D_{10} \log_{10} \left(\frac{E_0}{A} \right), \quad (3.1)$$

where λ_I is the mean free path of the first interaction. The quantity $D_{10} = d\langle X_{\max} \rangle / d \log_{10} E_0$ is called *elongation rate* and it does not depend on E_0 and A . Although the Eq. (3.1) is derived by simplistic analytic models (85), it can be certified by using full Monte Carlo simulations that this relation is valid to a very good approximation.

On the left plot of Fig. 3.2 we show the $\langle X_{\max} \rangle$ as a function of the primary energy for a set of simulated EASs. The logarithmic energy dependence is clear, as well as the separation between proton and iron initiated showers. This dependence of $\langle X_{\max} \rangle$ on the primary mass comes from both terms on the right side of Eq. (3.1). The λ_I term decreases with increasing A , because the interaction cross section is larger for heavier nuclei. The second term, $\log_{10} \left(\frac{E_0}{A} \right)$, is a manifestation of the so called *superposition principle*, which says that an air shower initiated by a nuclei of mass A of energy E_0 is actually equivalent to a superposition of A showers initiated by protons with primary energies E_0/A . Since $X_{\max}$ is a longitudinal quantity, it is not affected, on average, by the superposition of showers and it turns out that the term $\log_{10} \left(\frac{E_0}{A} \right)$ is actually equivalent to only one proton shower with energy E_0/A .

The difference between $\langle X_{\max} \rangle$ for proton and iron initiated showers is $\sim 100 \text{ g/cm}^2$, as can be seen on the left plot of Fig. 3.2. It is also clear that the elongation rate D_{10} is nearly constant with energy and does not depend on the primary mass. For using $X_{\max}$ measurements to infer the primary composition of cosmic rays, both the differences on $X_{\max}$ for different primaries and the constancy of D_{10} are relevant features. By comparing the

Figure 3.2 – $\langle X_{\max} \rangle$ (left) and $\sigma[X_{\max}]$ (right) as a function of the primary energy obtained from air shower simulations performed with CONEX (83) and the hadronic interaction models FLUKA (84) and EPOS LHC. (58)

Source: By the author.

measured $\langle X_{\max} \rangle$ with simulation one can infer the average composition and by measuring the D_{10} one can verify if the composition is changing with energy or not.

Besides the $\langle X_{\max} \rangle$, the fluctuations of $X_{\max}$ also carry relevant information about the primary cosmic rays. On the right plot of Fig. 3.2 we show the standard deviation of the $X_{\max}$ distribution, $\sigma[X_{\max}]$, as a function of the primary energy for proton and iron initiated showers. Concerning $\sigma[X_{\max}]$, a consequence of the superposition principle is that the fluctuations of the $X_{\max}$ of showers initiated by nuclei are smaller than the fluctuations of proton showers. It is also necessary to take into account the smaller fluctuations on the depth of the first interactions in nuclei showers. As a result, we can see on the right plot of Fig. 3.2 that the differences between $\sigma[X_{\max}]$ of proton and iron initiated showers is about $\sigma^p[X_{\max}] - \sigma^{Fe}[X_{\max}] \approx 40 \text{ g/cm}^2$.

The study of cosmic rays composition by using the $\langle X_{\max} \rangle$ and $\sigma[X_{\max}]$ is usually called $X_{\max}$ moments analysis. The $X_{\max}$ measurements and their composition interpretation are approached in Sec. 3.3.1.

3.1.2 Hadronic component and muon production

Unlike the neutral pions, the charged ones can only decay via weak interaction, with a much longer decay length ($c\tau_0 = 7.8 \text{ m}$) than the electromagnetic π^0 decay. Thus, at high energies, their interaction length is much smaller than the decay one. This means that most of the charged pions actually interact with atmospheric nuclei producing more particles at similar proportions as the ones produced in the first interaction. While the neutral pions produced fed the electromagnetic shower, as explained above, the charged ones can keep interacting and producing more hadrons. The hadrons produced by this chain of hadronic interactions compose the hadronic component of the shower.

The lower the charged pions energies, larger the probability that they decay instead

of interacting again. The dominant decay channel for charged pions is into muons and neutrinos ($\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$) and the critical energy in which the probability of decaying is equivalent to the probability of interacting is 85 GeV. These decays are responsible to produce the great majority of the muons in EAS. The typical number of interactions of charged pions before decaying into muons is 4-8. (86)

Apart from pion decays, a considerable fraction of the muons reaching the ground is produced by the decay of charged kaons. In Refs. (86,87) the muon production in EAS was studied in detail and it was found by using simulations that $\sim 90\%$ of the muons come from the decay of charged pions and $\sim 10\%$ of charged kaons. While these particles are called *mother*, the particles which interacted hadronically with an atmospheric nucleus to produce them are called *grandmother*. Thus, concerning the properties of the grandmother particles, it was found that more than 70% of them are pions, $\approx 20\%$ are nucleons and $\approx 6\%$ are kaons. In Fig. 3.3 the energy distributions of the grandmother particles are shown and we can see the contribution from these different types of particles. (88) The dominance of pions as grandmother particle is clear, as well as the fact that most of the interactions of the grandmother particles occur at energies of order of $\sim 100\text{GeV}$.

Although the interaction of the grandmother particle is very important, it has to be noted that the whole chain of hadronic interactions, which are mostly pion-air interactions, influence the muon production. This means that any EAS observable related to the muonic component is sensitive to the properties of hadronic interactions which occur along the shower. The particle production in these hadronic interactions is particularly important and, in the context of this thesis, it is worthwhile to point out the effect of (anti)baryon production. Most of the (anti)baryons produced are nucleons (p , $\bar{p}$, n and $\bar{n}$) and they are all produced in similar proportions. Since these particles are stable and can only interact again, their energy surely fed the hadronic component, which means that it is partially converted into muon production. Because of that, the increase of (anti)baryon production in hadron-air interactions has been considered a very important mechanism to

Figure 3.3 – Energy distributions of the grandmother particles of muons that reaches the ground with lateral distances between 1000 and 2000 m in a proton initiated shower with primary energy 10^{19} eV. Plot reproduced from Ref. (88)

Source: MARIŞ. (88)

increase the total number of muons in the

EAS. (89,90) Then, in view of the muon deficit problem, which is presented in Sec. 3.3.2, understanding the particle production in pion-air interactions turns out to be very important. Therefore, the Chap. 6 of this thesis is dedicated to the measurement of the hadron production in pion-carbon interactions.

Besides increasing the number of muons, increasing the (anti)baryon production in hadron-air interactions also affects the energy spectra of the produced muons. It was argued in Ref. (89) that larger (anti)baryon production implies in shifting the muon energy spectra to lower energies. Since accessing the energy spectra of muons at the ground is very challenging experimentally, in Chap. 5 we propose a new observable to be used for that considering experiments with two different muon detectors.

On the right plot of Fig. 3.1 we show the average longitudinal profile of the number of muons, as well as the muon production, for proton and iron initiated showers. First we can see that the number of muons in iron initiated showers is substantially larger than in proton showers. The reason for that is the fact that the first interaction of a heavier primary produces a larger number of secondary hadrons, which means that more hadronic sub-showers are generated and consequently more muons are produced. Second, we can see by comparing both plots of Fig. 3.1 that, after reaching its maximum, the muonic component is much weakly attenuated than the electromagnetic counterpart. Thus, the number of muons after the maximum depth decreases very slowly and after a certain atmospheric depth, only the muonic component survives to the attenuation.

The number of muons (N_μ) observed at a given atmospheric depth is a characteristic quantity of the shower. A relation between N_μ and the primary energy (E_0) and mass (A) can also be obtained from simplified analytic models (85) and confirmed by full Monte Carlo simulations. (91) This relation is

$$\langle N_\mu \rangle \approx A^{1-\beta} E_0^\beta, \quad (3.2)$$

where $\beta \approx 0.9$. (91) The energy and primary mass dependence of $\langle N_\mu \rangle$ can be seen in Fig. 3.4, where we show the $\langle N_\mu \rangle$ as a function of energy, again for proton and iron initiated showers. Results of measurements of N_μ , as well as other observables related to the muonic component will be presented in Sec. 3.3.

3.2 Simulations of EAS

In this section we give a short overview of the topic of EAS simulations, including a description of the most used simulation codes (Sec. 3.2.1) and an overview of the hadronic interaction models used by them (Sec. 3.2.2). Besides the hadronic interaction models, the EAS simulation codes also make use of electromagnetic interaction models. The commonly used one is EGS4 (92) Since the electromagnetic processes are assumed to be properly

described by quantum electrodynamics (QED), their modeling is not considered to be a significant source of uncertainties on the EAS simulations. Because of that, we will only focus here on the hadronic interaction models, which, in turn, are the most relevant source of uncertainties. More detailed approaches to the topic can be found in Refs. (93–95).

3.2.1 Simulation strategies

To simulate an EAS taking into account all the relevant aspects is surely a very complex task. All the particles produced have to be propagated 3-dimensionally through the atmosphere and their interactions with atmospheric atoms have to be properly modeled. The effect of the structure of the atmosphere with changing density and the earth magnetic field also have to be taken into account. Furthermore, the extremely large number of particles at high energies makes the computational cost of an EAS simulation extremely large. Because of that, the full simulation turns out to be impossible for practical purposes and, thus, special strategies have to be developed by simulation softwares to reduce the complexity of the problem.

The most complete softwares apply Monte Carlo methods to simulate the 3-dimensional propagation of the particles and their interactions along the whole shower development. This class of software includes MOCCA (96), AIRES (97) and CORSIKA (98), being the latter the one used in this thesis. To reduce the computing time, an algorithm called *statistical thinning* is usually applied. (96,99) Instead of following all the particles, by using the thinning algorithm only a number of them are selected to be followed and a weight is given to these particles which corresponds to the number of particles that are not being followed anymore.

A few parameters are usually needed to set up the thinning configuration. As an example, in CORSIKA the maximum particle energy in which the thinning algorithm is applied is set by the ε_{th} parameter, which is actually the fraction with relation to the energy of the primary. This parameter can be set separately for electromagnetic and hadronic

Figure 3.4 – Average N_μ as a function of the primary energy for a set of showers simulated with CONEX (83) and the hadronic interaction models FLUKA (84) and EPOS LHC. (58) The N_μ here is defined as all the muons which reach an observation level of 875 g/cm² with energy above 1 GeV.

Source: By the author.

particles and typical values are between $10^{-2} - 10^{-7}$. As smaller the values of ε_{th} , more precise the simulation will be, but with the cost of longer computing time. The maximum weight allowed is also a parameter to be set and its typical values lie between 100-10000. Since the thinning algorithm removes the important information of the geometrical spread of the particles, for some analysis a *dethinning* algorithm has to be applied. (100)

A second class of simulation softwares, called *hybrid*, makes use of Monte Carlo techniques to simulate only the interactions at the highest energies and, below a certain energy threshold, cascade equations are applied (101) to compute the number of each type of particle as a function of the atmospheric depth. This means that the solution of the cascade equation gives only a 1-dimensional description of the shower and all the information about the lateral distributions of the particles is lost. Since for many applications only the longitudinal profile of the shower is needed, this class of software turns to be very useful. The very short computing time required to solve the cascade equations makes these softwares very fast. One of the most used code of this kind is CONEX (83), which is used in this thesis. The SENECA code (102) also makes use of cascade equations but includes a re-sampling algorithm to recover the lateral particle distributions in the final stages of the shower. It is worthwhile mentioning that the current version of the CORSIKA software can also simulate showers in the hybrid mode, similar to CONEX or SENECA.

3.2.2 Hadronic interaction models

The models used to describe the hadronic interactions at high energies are by far the most relevant source of uncertainties on the prediction of EAS observables by simulations. Although the strong interactions can be successfully described by *quantum chromodynamics* (QCD), we are still not able to compute the bulk of hadronic particle production processes from first principles.

The hadronic interactions are described by first considering hadrons as constituted by point-like particles called *partons*. Then, the interactions between partons are treated differently depending on the transfer momentum: *hard* and *soft* processes, in which there is a large and small momentum transfer, respectively. While the properties of hard processes can be properly computed by means of perturbative QCD, the soft ones require either lattice calculations or phenomenological models to be described. Because of the long processing time required by lattice calculations, distinct phenomenological approaches are applied by hadronic interaction models.

All the currently used hadronic models for high-energy interactions are based on Gribov's Reggeon Field Theory (103, 104), in which hadron-hadron, hadron-nucleus and nucleus-nucleus scattering are described by the exchanging of objects called *reggeons* and *pomerons*. Other examples of common features of all models are the application of minijet

and string fragmentation models. An intrinsic feature of these phenomenological models is the large number of parameters that cannot be determined theoretically, but they have to be tuned instead. For that, a large number of accelerator measurements are used. The problem with this strategy is that the accelerator measurements cover only a small fraction of the energy range and particle production phase space that is relevant for describing EASs.

The problem with the model tuning can be split in three parts. First, the highest energy collisions studied in accelerators ($\sqrt{s} = 13$ TeV reached by LHC) is still much lower energy than the interaction of a high energy cosmic ray ($\sqrt{s} \approx 400$ TeV for a 10^{20} eV primary proton). Second, there is a lack of measurements of particle production at the forward region, which is the most relevant to understand particle production in soft interactions and also the most relevant for the EAS development. Finally, there is a lack of accelerator data concerning some colliding systems that are very important for EAS physics, e.g. hadron-nucleus interactions.

As a consequence of the phenomenological nature of the models in combination with the problems with accelerator data listed above, the predictions of EAS simulations with different hadronic interaction models turns out to be discordant. Because of that, it is a common approach to compare the EAS measurements to simulations with a number of different models and to treat the differences between them as a systematic uncertainty of theoretical nature.

For EAS studies, the most currently used models for high energy interactions are QGSJET II-04 (105), EPOS 1.99 (89), EPOS LHC (58), SIBYLL 2.1 (106), SIBYLL 2.3 (107) and DPMJET 3.06. (108) Among these, QGSJET II-04, EPOS LHC and SIBYLL 2.3 are updated to take into account recent LHC data.

Below a certain energy threshold (~ 100 GeV), the hadronic interactions in EAS simulations are described by the so called *low energy models*, which are much simpler than the high energy ones. The particle production, for example, is usually modeled by means of empirical parametrizations. The most used low energy models are UrQMD (109), GHEISHA (110) and FLUKA (84). A review of these models can be found in Ref. (111). The influence of the low energy models on the number of muons in EAS have been shown in Ref. (112). We show in Chap. 5 that they are also relevant for the spectrum of the muons at ground.

3.3 Measurements of EAS observables

In this section, a compilation of measurements of EAS observables is presented. The main focus is on the high energy cosmic rays range ($E > 10^{17}$ eV). We start in Sec. 3.3.1 by the X_{max} measurements which are the most reliable observable to be used to infer

composition of cosmic rays. In Sec. 3.3.2, measurements of the N_μ are presented and the muon deficit problem is introduced. In Sec. 3.3.3 we briefly mention further observables recently measured. A summary is finally presented in Sec. 3.3.4.

3.3.1 Shower maximum and UHECR composition

The $X_{\max}$ (see Sec. 3.1.1) can be measured directly by fluorescence telescopes, which can measure the energy deposited by the EAS along the atmosphere. This technique was first successfully applied by Fly's Eyes experiment (113), posteriorly followed by HiRes (114) and recently it has been used by Telescope Array (115) and Pierre Auger Observatory. (3,64) Another technique commonly used in the past to measure the $X_{\max}$ are the non-imaging Cherenkov detectors. From the lateral profile of the Cherenkov light measured in surface detectors, it is possible to infer the longitudinal position of the shower maximum. (116,117) This method was used by Tunka (118,119), Yakutsk (120,121) and CASA-BLANCA. (122) In Fig. 3.5 we show a compilation of $\langle X_{\max} \rangle$ measurements from $10^{15.0}$ eV up to the highest energies and in Figs. 3.6 and 3.7 we show the most up to date $X_{\max}$ results of Pierre Auger Observatory (123) and Telescope Array. (124) The $\sigma[X_{\max}]$ is also shown together with the $\langle X_{\max} \rangle$.

Figure 3.5 – Compilation of $\langle X_{\max} \rangle$ results reproduced from Ref. (125).

Source: KAMPERT. (125)

The colored curves in Fig. 3.5 show the $\langle X_{\max} \rangle$ predictions from Monte Carlo simulations. It is traditional to show the predictions for the lightest primary expected, protons, and for the heaviest, iron nuclei. By comparing the $X_{\max}$ measurements with the Monte Carlo predictions, one can obtain information about the average composition of the primary cosmic rays. Besides the comparison of the $X_{\max}$ moments, the full $X_{\max}$

distributions can be compared and the fractions of different groups of primaries can be fitted. This procedure has been applied by Pierre Auger Observatory in Ref. (126).

Figure 3.6 – $\langle X_{\max} \rangle$ and $\sigma[X_{\max}]$ as a function of the primary energy as measured by Pierre Auger Observatory.

Source: BELLIDO. (123)

Figure 3.7 – $\langle X_{\max} \rangle$ and $\sigma[X_{\max}]$ as a function of the primary energy as measured by Telescope Array experiment.

Source: HANLON. (124)

The composition interpretation of the $X_{\max}$ measurements is only possible because this observable is well described by Monte Carlo simulations using hadronic interaction models. From Fig. 3.5, we can first see that the measured $\langle X_{\max} \rangle$ lies always in between the predictions for protons and iron nuclei. Furthermore, it is important the fact that

the Monte Carlo predictions with different hadronic interaction models do not diverge substantially, which reduces the model dependencies on the composition interpretations of the measurements.

Another important feature of the $X_{\max}$ analysis is that the detector biases can be fully removed and the measured values of the $\langle X_{\max} \rangle$ and $\sigma[X_{\max}]$ can be directly compared to the ones from shower simulations, without the requirement of simulating the detection process. The Pierre Auger Observatory remove most of the detector biases by using the so called *fiducial volume cuts*, which reduces significantly the number of events. (64) On the other hand, because of the lack of statistics, Telescope Array opt for not to perform any strategy to unbiased the $X_{\max}$ moments. Instead, the measurements are compared to simulation that include all the detector effects. As a consequence, the $X_{\max}$ moments as measured by both experiments cannot be compared to each other directly.

From Figs. 3.6 and 3.7, the composition interpretation of both Auger and Telescope Array $X_{\max}$ data seem to be incompatible. The Auger data shows a clear changing of the average composition from a very light composition around $10^{18.3}$ eV to an intermediate one around $10^{19.5}$ eV. This trending is confirmed by the fits of $X_{\max}$ distributions shown in Ref. (126). The Telescope Array data, on the other hand, shows a constant composition which is dominantly light, between proton and helium nuclei on average, from $10^{18.2}$ eV up to the highest energies. This apparent inconsistency has been studied by a working group formed of members of both collaborations and the most recent conclusion is that, taking into account the detector effects intrinsic of the Telescope Array measurements and all the systematic uncertainties, the results of Telescope Array are actually compatible with the composition inferred from Auger data up to 10^{19} eV. (127) Above this energy it was not possible to take any conclusion because of the lack of statistics of the Telescope Array measurements.

3.3.2 Number of muons and the muon deficit problem

In this section we present measurements of both the number of muons (N_{μ}) and the muon density (ρ_{μ}) in EAS. Measurements of N_{μ} or ρ_{μ} at ground can be done with several different types of surface detector arrays. However, the muon measurements are strongly affected by specific features of each experimental setup and, therefore, it is not possible in general to compare the measurements from different experiments. The experimental features which affect the most the muon measurements are the muon energy threshold, the lateral distance interval in which the muons are detected and the observation level.

To be able to detect isolated muons, the detectors are usually shielded so the electromagnetic component is absorbed before being detected. This can be done either by placing a layer of a heavy material on the top of the detector or by burying it few meters below the ground level. It turns out that low energy muons also end up being

absorbed, and as a consequence, each experiment measures muons above a different energy threshold and the N_μ is different. The lateral distance range in which the muons are detected is also a specific feature of each experiment that affects strongly the N_μ . Since the experiments are always made of granular arrays, the distance between the detectors usually determine in which lateral distance the N_μ is estimated. Lastly, the observation level of the experiment affects N_μ because of the atmospheric attenuation, which affects much strongly the electromagnetic component, but it is still relevant for muon detection.

Among the results of measurements of N_μ and ρ_μ in EAS experiments, we have selected three to present here. The first one are the measurements by HiRes/MIA experiments of the density of muons at the ground in EAS initiated by cosmic rays of energy approximately in the range between 10^{17} eV and 10^{18} eV. The experimental setup consisted of a set of fluorescence telescopes of the HiRes experiment (114) combined with a detector array of MIA. (128) The surface detectors were formed by scintillator counters buried about 3 m below the ground level, which implies in an energy threshold for muons of around 850 MeV. The density of muons at a lateral distance of 600 m ($\rho_\mu(600)$) was reconstructed and compared to simulations. On the top-left plot of Fig. 3.8 we reproduce the plot of $\rho_\mu(600)$ as a function of the primary energy as published in Ref. (129). By comparing the measured muon density with predictions from Monte Carlo simulations, it was found that the $\rho_\mu(600)$ in data was larger than the predictions for the heaviest primaries expected, iron nuclei. This result was clearly inconsistent in terms of composition and the conclusion that could be taken is that the Monte Carlo simulations are deficient in muon production. This was the first manifestation of what is usually called *muon deficit problem*, in 1999.

The second measurement to be presented was performed by IceTop detector (132), part of the IceCube experiment (133), by using ice-Cherenkov surface detectors. The primary energy range of these measurements goes from 10^{15} eV to 10^{17} eV and the density of muons at 600 and 800 m from the shower axis was estimated as muon content observable. On the bottom plot of Fig. 3.8 we reproduce the result from the Ref. (130) which shows the ρ_μ as a function of energy compared to simulation predictions by using the SIBYLL 2.3 as hadronic interaction model. The muon deficit can be again seen at energies around 10^{17} eV. Although these are still preliminary results, it is worthwhile to present it here because they show that the muon deficit problem is still existing at relatively low energies ($<10^{18}$ eV), even by using modern hadronic interaction models like SIBYLL 2.3.

The third and final measurement presented here is the one performed by Pierre Auger Observatory. (3) Even though its standard surface array does not contain muon detectors, the number of muons can be measured by Auger in highly inclined showers ($\theta > 60^\circ$). For this type of showers the electromagnetic component is almost totally attenuated by the atmosphere and the signal at the water-Cherenkov tanks is dominated by muons. On the top-right plot of Fig. 3.8 we show the average N_μ as measured by Auger

Figure 3.8 – Muon density as measured by HiRes/MIA (top-left) (129) and IceTop (bottom) (130) and number of muons as measured by Pierre Auger Observatory in highly inclined showers (top-right). (131)

Source: ABU-ZAYYAD.(top-left) (129);DEMBINSKI.(bottom) (130);AAB.(top-right) (131)

compared to simulations as published in Ref. (131). The primary energy range here is above $10^{18.6}$ eV and the muon deficit is clear at the whole energy range. It is important to point out that both models which are shown for comparison are recent versions, updated with LHC results. In Ref. (134) another Pierre Auger result that confirms the muon deficit at energies around 10^{19} eV can be found, in which showers with $\theta < 60^\circ$ were used.

In conclusion, the muon deficit problem is known for almost two decades and at the moment it prevents us to do composition studies based on the measurements of the N_μ in EAS. In Chap. 4 we present a method to interpret the energy evolution of the moments of the N_μ measurements in terms of cosmic rays composition, taking into account the muon deficit problem.

3.3.3 Further measurements

In this section we briefly mention four further measurements of EAS observables, the first one made by KASCADE-Grande experiment (16) and the remaining three by the Pierre Auger Observatory.

The KASCADE-Grande experiment can measure both number of charged particles and number of muons in EAS with primary energy between $10^{16.0}$ eV and about $10^{17.5}$ eV. In a recent analysis, the KASCADE-Grande collaboration has studied the evolution of the N_μ with the zenith angle of the shower by using a parameter called muon attenuation length (Λ_μ). Since the atmospheric attenuation of the muonic component depends on the energy of muons, the parameter Λ_μ turns out to be sensitive to the muon energy spectra. Thus, by comparing the measurements to Monte Carlo predictions it is possible to test muon production properties of the hadronic interaction models. On the left plot of Fig. 3.9 we reproduce the plot from Ref. (135) that compares the measured value of Λ_μ with simulations and what can be seen is that none of the currently used models can describe properly the muon attenuation. The primary energy range of this analysis is similar to the one of IceTop shown in the previous section.

Figure 3.9 – Muon attenuation length as measured by KASCADE-Grande experiments (left) (135) and the maximum muon production depth as measured by Pierre Auger Observatory (right). (136)

Source: APEL.(left). (135); AAB.(right) (136)

The second measurement to be presented is the longitudinal depth of the maximum of the muon production profile ($X_{\max}^\mu$), which can be measured by using the temporal structure of the water-Cherenkov detectors of Pierre Auger Observatory in highly inclined showers. (136) The main result is the energy evolution of $\langle X_{\max}^\mu \rangle$ that is show on the right plot of Fig. 3.9. Although the composition interpretation of these measurements depends strongly on the hadronic interaction model, it can be seen that for both QGSJET II-04 and EPOS LHC the inferred composition would be much heavier than the expected from

the $\langle X_{\max} \rangle$ measurements. The EPOS LHC case is even worse because it implies in a composition even heavier than iron nuclei. In Refs. (137,138) it was shown that $X_{\max}^{\mu}$ is very sensitive to the properties of the pion-air interactions and therefore its measurements can be effectively used to constrain hadronic models.

The third and fourth observables to be mentioned are related to the quantity called risetime that is defined as the time difference between the water-Cherenkov detectors reach 10 and 50% of their total signal. This quantity is sensitive to both the electromagnetic and muonic component of the EAS. In Ref. (139) an analysis of the azimuthal asymmetry of the risetime was published where a parameter called *risetime asymmetry*, $\sec(\theta)_{\max}$, was defined. In a second analysis, published in Ref. (140), the so called *delta method* was applied in which the risetime dependence on the lateral distance is used to define a parameter called Δ_s . In Fig. 3.10 we show the main results of both analysis. The conclusions from both analysis are similar, being that the composition extracted directly from $\sec(\theta)_{\max}$ and Δ_s are not compatible with the one inferred from $X_{\max}$ measurements. However, the inconsistency is not as strong as in the case of N_{μ} and $X_{\max}^{\mu}$. This intermediate behavior can be understood by the fact that the risetime parameter is not sensitive to only the muonic content of EASs, but instead, to a combination of the electromagnetic and muonic components. It was shown in Ref. (140) that the Δ_s parameter can be calibrated by using the $X_{\max}$ measurements and as a result consistent composition inferences can be done.

Figure 3.10 – Risetime asymmetry (left) (139) and the delta parameter (right) (140) as measured by Pierre Auger Observatory.

Source: AAB. (139,140)

3.3.4 Summary

We can divide the EAS measurements presented here in three categories: pure electromagnetic, pure muonic and mixed. The only pure electromagnetic measurement discussed is the $X_{\max}$ one, which can be used to study cosmic rays composition because, among other reasons, the predictions from EAS simulations are consistent with the data.

The pure muonic measurements include number (or density) of muons (N_μ), maximum of the muon production depth ($X_{\max}^\mu$) and the muon attenuation length (Λ_μ). The conclusion concerning these measurements is that the Monte Carlo simulations fail on describing properly the muonic component. As a consequence, observables like N_μ and $X_{\max}^\mu$ cannot be used to infer cosmic rays composition. One particular manifestation of this inconsistency between data and simulations is the so called muon deficit problem, which is observed from 10^{17} eV up to the highest energies.

The mixed measurements presented are the ones related to the risetime parameter, the risetime asymmetry ($\sec(\theta)_{\max}$) and the delta parameter (Δ_S). In these cases, the composition interpretation of the measurements does not imply in non-physical conclusions (average nuclear mass heavier than iron nuclei), however, it is not, in general, compatible with the composition inferred from the $X_{\max}$ measurements. This behavior is expected also because of the failure of the simulation to predict the muonic component properly.

An usual method to compare the composition interpretation from several measurements is to convert their average value to the average of the logarithm of the nuclear mass, $\langle \ln A \rangle$. This conversion can be performed for observables that correlates linearly with $\ln A$, through the relation

$$\langle \ln A \rangle = \frac{\langle p_{\text{data}} \rangle - \langle p_{\text{MC}}^{\text{proton}} \rangle}{\langle p_{\text{MC}}^{\text{iron}} \rangle - \langle p_{\text{MC}}^{\text{proton}} \rangle}, \quad (3.3)$$

where p is an arbitrary observable and p_{MC} is obtained from Monte Carlo simulations. In Fig. 3.11 we show the $\langle \ln A \rangle$ as a function of primary energy for all the observables measured by Pierre Auger Observatory presented in this section. The upper plot refers to the hadronic model EPOS LHC, while the lower one to QGSJET II-04.

Figure 3.11 – $\langle \ln A \rangle$ as a function of energy for a set of observables measured by Pierre Auger Observatory. Only statistical uncertainties are shown. The hadronic interaction models EPOS LHC (top) and QGSJET II-04 (bottom) to perform the conversion represented by Eq. (3.3).

Source: By the author.

4 Interpretation of measurements of the number of muons in extensive air shower experiments

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Interpretation of measurements of the number of muons in extensive air shower experiments

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ABSTRACT

In this paper we analyze the energy evolution of the muon content of air showers between $10^{18.4}$ and $10^{19.6}$ eV to be able to determine the most likely mass composition scenario from future number of muons measurements. The energy and primary mass evolution of the number of muons is studied based on the Heitler–Matthews model and Monte Carlo simulation of the air shower. A simple model to describe the evolution of the first and second moments of number of muons distributions is proposed and validated. An analysis approach based on the comparison between this model's predictions and data to discriminate among a set of composition scenarios is presented and tested with simulations. It is shown that the composition scenarios can be potentially discriminated under the conditions imposed by the method. The discrimination power of the proposed analysis is stable under systematic changes of the absolute number of muons from model predictions and on the scale of the reconstructed energy.

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1. Introduction

The energy spectrum of ultra high energy cosmic rays (UHECRs) has been measured recently with high precision and two major features were confirmed. The ankle ($\log(E/\text{eV}) \sim 18.7$) and the flux suppression ($\log(E/\text{eV}) \sim 19.5$) have been undoubtedly established by HiRes [1], the Pierre Auger Observatory [2,3] and Telescope Array [4]. However, the astrophysical interpretation of these structures cannot be inferred with complete certainty mainly because of the lack of knowledge on the UHECR composition at these energies. In a light abundance scenario, the ankle could be interpreted as the modulation resulting from the particle interaction with radiation backgrounds [5,6]. On the other hand, it could also be explained as the transition from galactic to extra-galactic cosmic rays [7]. The flux suppression can be equally well described by the energy losses of extra-galactic particles due to interactions with CMB photons [8] or by the maximum reachable energy of the astrophysical acceleration mechanisms in nearby sources [9]. In each one of these astrophysical scenarios, the energy evolution of the UHECR composition is significantly different.

The UHECR measurements are done indirectly through the detection of extensive air showers. Therefore, the determination of

the composition depends strongly on the data analysis capability to correlate the measured properties of the shower to the primary particle type. This correlation is achieved using air shower simulations. However, intrinsic fluctuations of the showers and uncertainties in the high energy hadronic interaction models for energies above 10^{17} eV prevent us from a definitive conclusion about the primary particle type for each event. Statistical analysis and evolution trends [10,11] are used to minimize the fluctuation effects, nevertheless an unique interpretation of the data is not possible because of the hadronic interaction model uncertainties. Currently, the most reliable observable to investigate composition at higher energies is X_{max} , the atmospheric depth at which the shower reaches the maximum number of particles [12]. A second very powerful observable sensitive to primary particle mass is the number of muons (N_{μ}) in the showers. However, the lack of knowledge of the high energy hadronic interactions and the systematic uncertainties in the energy determination limit the interpretation of N_{μ} data in terms of composition in a more severe way than they do for X_{max} . There are several indications that the current most often used hadronic interaction models fail at predicting the muonic component features of air showers [13,14]. Moreover, as N_{μ} scales directly with shower energy, the systematic uncertainty in energy reconstruction (typically $\sim 10 - 20\%$) represents also a difficult challenge to overcome in the interpretation of the N_{μ} data. As a consequence, it is not straightforward to envisage a data analysis procedure that extracts the mass abundance from the N_{μ} data.

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In this paper we propose a new approach to interpret N_μ data which accommodates the systematic uncertainties of the high energy hadronic interaction models and of the energy reconstruction. The analysis proposed here is based on the energy evolution of the first ($\langle \log_{10} N_\mu \rangle$) and second ($\sigma[\log_{10} N_\mu]$) moments of the $\log_{10} N_\mu$ distribution. There are two central features of the proposed procedure: (a) a simplified model to describe the energy and mass evolution of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ which minimizes the hadronic interaction model dependencies, and (b) a comparison between the predictions of this model for a set of given composition scenarios and the data integrated in energy to maximize the discrimination power.

First in Section 2 we propose a simplified model to describe the energy and mass evolution of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$. We argue that to a very good approximation only two parameters (a and b) summarize all uncertainties of the currently used high energy hadronic interaction models. This simplification of the description of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ with energy and mass is an important step in the analysis procedure because it minimizes the dependencies on hadronic interaction models in the interpretation of the data. In Section 3.1 we use shower simulations to study the energy and mass evolution of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ and to validate the model proposed in Section 2. We also introduce in Section 3.1 the algorithm developed to build the large set of simulations used in this paper. This simulation process is complemented in Appendix A.

In Section 4 we introduce a set of six benchmark composition scenarios defined by the percentage of proton, helium, nitrogen and iron nuclei as a function of energy. Four composition scenarios are astrophysical motivated (based in Refs. [6–9,15]) and two were derived from the $X_{\max}$ measurements performed by the Pierre Auger Collaboration (based on Ref. [16]). By using simulations we also study the energy evolution of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ for each one of these scenarios and evaluate the effects of the uncertainties on the energy scale and on the absolute N_μ due to the misprediction by the hadronic interaction models.

In Section 5 we show how the model proposed in Section 2 can be used to discriminate between these representative composition scenarios. The comparison of the model predictions for the composition scenarios with the data in an energy range is the important step of the analysis procedure proposed here because it maximizes the discrimination power allowing us to identify the most likely scenario that generated a set of N_μ data. This comparison is done by the traditional χ^2 , which assumes the minimal value for the composition scenario which best describes the data. We use simulations to test our approach and show that it is possible to achieve a good discrimination between the chosen scenarios supposing a realistic case with the statistic to be collected during 3 years of data taking with the Pierre Auger Observatory Upgrade – AugerPrime. We also show that the systematic uncertainties in the energy reconstruction and on the absolute scale of the number of muons do not mix the composition scenarios. Hence we conclude in Section 6 that by using only the energy evolution of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ it would be possible to identify, by comparing the composition scenarios to the data, the scenario which best describes the measurements of N_μ .

2. A model for the energy and mass evolution of $\log_{10} N_\mu$ moments

In this section we present a model to describe the energy and primary mass evolution of the $\log_{10} N_\mu$ first and second moments. The Heitler–Matthews model [17] is a semi-empirical description of the shower development which describes the dependencies of

the mean N_μ as

$$\langle N_\mu \rangle_A = A^{1-\beta} N_\mu^p \quad (1)$$

and

$$\langle N_\mu \rangle_E = \left(\frac{E}{\zeta_c^\pi} \right)^\beta, \quad (2)$$

where N_μ^p is the number of muons in a proton shower and ζ_c^π is the pion critical energy, assumed to be equal to 20 GeV in [17]. β is often taken to be constant because its value is shown to vary in a small interval from 0.85 to 0.92 [17,18].

Both equations define a clear linear relation of $\langle \log_{10} N_\mu \rangle$ with energy and mass that can be summarized as

$$\langle \log_{10} N_\mu \rangle_{E,A} = a + D_A \cdot \ln(A) + D_E \cdot (\log_{10} E - 19.0), \quad (3)$$

where $D_E = \beta \simeq 0.85 - 0.92$, $D_A = (1 - \beta) \cdot \log_{10} e \simeq 0.434 \cdot (1 - \beta) \simeq 0.0347 - 0.0651$, and the energy E is given in eV. Because of our lack of knowledge of the hadronic interactions at the highest energies, the value of a is highly model dependent and presents a large variability. It can be written as $a = \log_{10}(N_\mu^p) - \beta \log_{10}(\zeta_c^\pi)$ and varies approximately from 6.5 to 8.0, depending on the hadronic interaction model. These values of a were obtained using the simulations described in Section 3.

In addition to the $\langle \log_{10} N_\mu \rangle$, the $\sigma[\log_{10} N_\mu]$ could also be modeled by the same approach. However, no analytic model has been proposed to describe the shower-to-shower fluctuations and our study relies on simulations to propose a similar description of $\sigma[\log_{10} N_\mu]$ evolution with energy and mass. We propose that the $\sigma[\log_{10} N_\mu]$ can be described as

$$\sigma[\log_{10} N_\mu]_A = \sigma[\log_{10} N_\mu]_{Fe} + b \cdot [\ln(A) - \ln(56)]^2, \quad (4)$$

where $\sigma[\log_{10} N_\mu]_{Fe}$ is the $\sigma[\log_{10} N_\mu]$ for iron nucleus initiated showers. Two main assumptions were used in this proposal: a) for a fixed primary (A), the $\sigma[\log_{10} N_\mu]$ does not depend on energy and b) a quadratic dependency of $\sigma[\log_{10} N_\mu]$ with $\ln(A)$. These assumptions are justified in Section 3 via Monte Carlo simulation of the air shower.

The description of the $\sigma[\log_{10} N_\mu]$ is analogous to the deduction of $\langle \log_{10} N_\mu \rangle$ using the Heitler–Matthews models in the following way. We will show in Section 3 that, for the purposes of this paper's analysis, $\sigma[\log_{10} N_\mu]_{Fe}$ can be taken to be constant, in other words, the small model dependence of $\sigma[\log_{10} N_\mu]_{Fe}$ can be ignored. On the other hand, b changes significantly with the hadronic interaction model, which reflects the theoretical uncertainties concerning the muonic component description.

Eqs. (3) and (4) summarize the first step of this paper. These equations offer a simple, but good description of the two first moments of the $\log_{10} N_\mu$ distribution with energy and mass. The uncertainties due to hadronic interaction model descriptions are only significant for two parameters, a and b , while for the further parameters there is a good agreement between their predictions. The quality of the description given by Eqs. (3) and (4) is going to be numerically studied in the next section.

For a mixture of primaries in which each primary particle type, i , has mass A_i and contributes to the total flux with a fraction given by f_i , we can show that $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ of the mixture (mix) can be calculated as follows

$$\langle \log_{10} N_\mu \rangle_{mix} = \sum_i f_i \cdot \langle \log_{10} N_\mu \rangle_{A_i} \quad (5)$$

$$\langle \log_{10} N_\mu \rangle_{mix} = a + D_A \cdot \langle \ln(A) \rangle_{mix} + D_E \cdot (\log_{10} E - 19.0),$$

and

$$\sigma^2[\log_{10} N_\mu]_{\text{mix}} = \sum_i f_i \cdot \left[(\langle \log_{10} N_\mu \rangle_{A_i} - \langle \log_{10} N_\mu \rangle_{\text{mix}})^2 + \sigma^2[\log_{10} N_\mu]_{A_i} \right]. \quad (6)$$

Using Eq. (3) we can write

$$\sigma^2[\log_{10} N_\mu]_{\text{mix}} = \sum_i f_i \cdot \left[D_A^2 \cdot (\ln(A_i) - \langle \ln(A) \rangle_{\text{mix}})^2 + \sigma^2[\log_{10} N_\mu]_{A_i} \right]. \quad (7)$$

Note that $\sigma^2[\log_{10} N_\mu]_{\text{mix}}$ does not depend on a . The dependence on b is implicit in the $\sigma^2[\log_{10} N_\mu]_{A_i}$ term.

3. Simulation studies of $\log_{10} N_\mu$ moments

In this section we briefly describe the procedure adopted to produce simulated $\log_{10} N_\mu$ distributions that are extensively employed in the following sections of this paper. The present discussion is complemented by Appendix A where more details about the simulations are given. Furthermore, in this section we also use the simulated showers to validate the $\log_{10} N_\mu$ moment descriptions proposed in Section 2 and to study the energy evolution of $\log_{10} N_\mu$ moments for a set of mass composition scenarios.

3.1. Simulation technique

In our analysis we aim to assess the number of muons measured in UHECR experiments. A combination of detector technology, observatory altitude, spatial configuration of the detectors and analysis procedures determines the lateral distance range and the energy threshold of detectable muons. To avoid saturation of the detectors (close to the shower axis) and large statistical fluctuations (far from the shower axis), a fiducial lateral distance range is commonly defined to get the lateral distance function integrated. Therefore, the measured number of muons (N_μ^{meas}) is not the total number of muons at the ground but only a sample of them above an energy threshold and within a distance range.

In this paper N_μ^{meas} is defined as the number of muons with energy above 0.2 GeV reaching the ground (1400 m above sea level, the Auger mean altitude) at a distance between 500 m and 2000 m from the shower axis. This choice is motivated by the design of the main current high energy cosmic ray experiments, for example, the Pierre Auger Observatory [19] and Telescope Array [20].

The muons spatial and energy distributions at the ground can be evaluated by CORSIKA [21] (version 7.4000), which is a full Monte Carlo code able to perform 3D shower simulations. N_μ^{meas} could be determined by CORSIKA, in despite of its high computational cost [22]. CONEX [23] (version 2r4.37) is a very fast hybrid simulation code which combines full Monte Carlo with solutions of one-dimensional cascade equations. From CONEX simulations it is possible to determine the total number of muons at the ground above 1 GeV (N_μ^{tot}).

N_μ^{tot} and N_μ^{meas} can be simultaneously obtained from full simulated showers (CORSIKA), allowing us to parametrize the relation between them. We propose the following parametrization:

$$N_\mu^{\text{meas}} = R(E, X_{\text{max}}) \cdot N_\mu^{\text{tot}}, \quad (8)$$

where the conversion factor R should be determined for each primary and depends on the energy and X_{max} . The parametrization of $R(E, X_{\text{max}})$ is explored in detail in Appendix A. The X_{max} dependence of the factor R ensures that the parametrization takes into account the shower-to-shower fluctuations due to the variance of the first interaction depth. Furthermore, the most relevant physical

processes responsible for muons production in showers are reliably reproduced by the CONEX simulations, and consequently they should also be represented in N_μ^{meas} . As shown in Appendix A, the N_μ^{meas} distributions obtained based on the proposed parametrization are in very good agreement with the ones obtained from full Monte Carlo simulation.

The parametrization was done only for shower at 38° zenith angle. The zenith angle dependence can be taken into account by simulating other primaries with the corresponding arrival direction and by dividing the data in zenith angle intervals.

3.2. Simulating $\log_{10} N_\mu$ moments

We generated 60,000 CONEX (version 2r4.37) showers with energies between $10^{18.4}$ and $10^{19.6}$ eV, for four primaries (proton, helium, nitrogen and iron) and two hadronic interaction models (EPOS-LHC [24] and QGSJetII-04 [25]). The showers are distributed uniformly in $\log_{10}(E)$ and the zenith angle is fixed at 38° . From the $R(E, X_{\text{max}})$ parametrization of Appendix A, the CONEX showers were converted into a set of N_μ^{meas} .

Fig. 1 shows the evolution of $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ with the primary mass for three energy intervals. Lines are the result of a linear fit which demonstrates the dependence of $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ with mass as proposed in Eq. (3). The fits resulted in $D_A \simeq 0.034 - 0.037$ and $a \simeq 6.64 - 7.70$, with errors from the fit less than 0.0005 and 0.005, respectively.

The energy evolution of $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ is shown in Fig. 2, where one can note the linear behavior as proposed in Eq. (3). The fits resulted in $D_E \simeq 0.915 - 0.928$, with errors from the fit less than 0.0003. The energy evolution of $\sigma[\log_{10} N_\mu^{\text{meas}}]$ is shown in Fig. 3. Note the flatness of $\sigma[\log_{10} N_\mu^{\text{meas}}]$ and the coincidence of the $\sigma[\log_{10} N_\mu^{\text{meas}}]$ constant value of iron initiated showers for both hadronic interaction models. These figures validate both assumptions made in Section 2 concerning $\sigma[\log_{10} N_\mu^{\text{meas}}]$.

The primary mass dependence of $\sigma[\log_{10} N_\mu^{\text{meas}}]$ can be seen in Fig. 4 for three energy intervals and both hadronic interaction models. The dashed lines are the quadratic curves shown in Eq. (4) fitted to the points. The fits resulted in $\sigma[\log_{10} N_\mu]_{\text{Fe}}$ being indeed nearly constant, varying from 0.0258 to 0.0275, with errors from the fits less than 0.003. The fit also resulted in $b = 0.0024 \pm 0.0002$ for QGSJetII-04 and $b = 0.0033 \pm 0.0003$ for EPOS-LHC. The simulations shown in this section confirmed all the assumptions made in Section 2.

4. Mass composition scenarios and the energy evolution of the $\log_{10} N_\mu$ moments

In this section we simulate the energy evolution of $\log_{10} N_\mu^{\text{meas}}$ moments for six mass composition scenarios, which are defined by setting the fractions $f_i(E)$ of the total flux corresponding to each particle with mass A_i . Given $f_i(E)$ and A_i we can calculate $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_\mu^{\text{meas}}]$ as a function of energy using the procedure described in Sections 2 and 3.

The mass composition scenarios we used are divided in two groups. The first one includes the astrophysical motivated scenarios, which are labeled by the letter A. The second group includes two scenarios obtained from the X_{max} distributions fit performed by the Pierre Auger Collaboration [11,16] and they are labeled by the letter X. Below, we present a brief description of the composition scenarios, which can be skipped by the reader that is familiar with the subject.

Scenario A1: This scenario proposes a pure proton flux. It was the first model proposed to explain the dip in the energy spectrum as the effect of pair-production in the propagation of the UHECR. This model is described in Refs. [5,8] and was also explored in Refs. [6,15] (labeled as Model B in Ref. [15]).

Fig. 1. $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ as a function of $\ln(A)$ for both hadronic interaction models, (a) EPOS-LHC and (b) QGSJetII-04 and three energy intervals. The dotted lines are the results of the linear fit, represented in Eq. (3). The statistical error bars are smaller than the markers.

Fig. 2. $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ as a function of $\log_{10}(E)$ for both hadronic interaction models, (a) EPOS-LHC and (b) QGSJetII-04, and four primaries (proton, helium, nitrogen and iron). The dotted lines are the results of the linear fit, represented in Eq. (3). The statistical error bars are smaller than the markers.

Fig. 3. $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ as a function of $\log_{10}(E)$ for both hadronic interaction models, (a) EPOS-LHC and (b) QGSJetII-04, and four primaries (proton, helium, nitrogen and iron). The dotted lines are the results of the fit of a constant energy function. The statistical error bars are smaller than the markers.

Scenario A2: This scenario assumes a mixed source composition with abundances similar to the data at lower energies. It was proposed by Allard et al. (labeled as Model A in Ref. [15]). In this model the ankle is explained as the transition in the predominance of the flux from the galactic to the extra-galactic component. The abundances are originally given for five groups of nuclei, however, in this paper the fluxes of the two heaviest groups were summed into the iron component.

Scenario A3: Biermann and de Souza [9] have proposed a model in which the observed cosmic ray energy spectrum from $10^{15.0}$ to $3 \times 10^{20.0}$ eV is explained by the galactic and only one extra-galactic source, the radio galaxy Cen A. In this model the element abundances from extra-galactic origin are similar to the galactic ones, but shifted up in energy because of the relativistic shock in the jet emanating from the active black hole. The abundances are originally given for six groups of nuclei, however, in this paper the flux of

Fig. 4. $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ as a function of $\ln(A)$ for both hadronic interaction models, (a) EPOS-LHC and (b) QGSJetII-04, and three energy intervals. The dotted lines are the results of the fit of Eq. (4). The statistical error bars are smaller than the markers.

the element group Ne–S was summed into the nitrogen flux and the flux of the Cl–Mn group was summed into the iron group flux.

Scenario A4: The model proposed by Globus et al. [7] describes the whole cosmic ray spectrum by superposing a rigidity dependent galactic component and a generic extra-galactic component. This model gives an adequate description of the energy spectrum and the moments of the X_{max} distribution measured by the Pierre Auger Observatory.

Scenario X1: It has been shown by the Pierre Auger Collaboration that the measured X_{max} distributions can be well described by a combination of four components [11,16]. By fitting the X_{max} simulated distributions to the data, the abundances of the separate components were obtained as a function of energy. This scenario is based on the abundances obtained by using the hadronic interaction model QGSJetII-04. However, the abundances obtained with Sibyll2.1 are also very close to the one we used. In order to minimize point-to-point fluctuations, we used here a smooth curve fitted to the fractions obtained in the Auger analysis [16].

Scenario X2: This scenario was obtained by fitting X_{max} distributions measured by the Pierre Auger Observatory using showers simulated with the EPOS-LHC hadronic interaction model. The procedure is the same as the one adopted for Scenario X1.

The merging of components done for models A2 and A3 is necessary to allow us to use the parametrization elaborated in Section 3. Since we present in this paper only the analysis procedure, verified with simulations, this choice has no limiting consequence. Besides that, the systematic uncertainties of the abundances obtained from the scenarios are also going to be neglected here. Figs. 5 and 6 show the abundances for each scenario in the energy range from $10^{18.4}$ to $10^{19.6}$ eV as explained above. Scenario A1 is not shown because it assumes a 100% proton flux.

Fig. 7 shows the energy evolution of the $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ for all mass composition scenarios. The error bars correspond to the one sigma fluctuation of the mean value considering the statistics from 3 years of AugerPrime data (3000 km² of muon detectors). The all particle flux was taken from Ref. [3]. Fig. 7a shows the mean normalized to the proton simulation for better visualization.

5. Discrimination between mass composition scenarios

Given the theoretical uncertainties on the N_{μ} predictions and the systematic uncertainties on the energy reconstruction, the

Fig. 5. The composition component abundances as a function of $\log_{10}(E)$ for the mass composition scenarios A2, A3 and A4 (see text).

question we would like to answer in this section is how it is possible to discriminate between the mass composition scenarios shown above using the evolution of the $\log_{10} N_{\mu}^{\text{meas}}$ moments with energy. Examining Fig. 7 it might seem easy to differentiate

Fig. 6. The composition component abundances as a function of $\log_{10}(E)$ for the mass composition scenarios X1 and X2 (see text).

the scenarios by using the absolute value or the evolution of the $\log_{10} N_{\mu}^{\text{meas}}$ moments with energy. However, if we include in this figure the uncertainties in the hadronic interaction model and systematic in energy reconstruction the interpretation of the data is not straightforward.

Fig. 8 shows how the uncertainties on the hadronic interaction model predictions and on the energy reconstruction influence the interpretation of the $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ in terms of composition. We show in this figure the extreme composition scenarios (A1 and A3), since the other four scenarios lie within them. In Fig. 8a we calculate $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ for scenarios A1 and A3 adding arbitrarily 20% more muons to the simulation predictions to mimic the theoretical uncertainties in the hadronic interaction model predictions [14]. Even the extreme models A1 and A3 would overlap if the uncertainty is considered. In Fig. 8b we calculate $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ for scenarios A1 and A3 and changed the simulated energy by $\pm 15\%$ in order to evaluate the effect of the systematic uncertainty in the energy reconstruction. Once more it is clear that even the extreme

scenario cases cannot be distinguished anymore. Moreover a combination of both uncertainties in the N_{μ} predictions and energy applied to this analysis would make the discrimination between the scenarios even harder. The conclusion is clear: the measurement of N_{μ} does not lead to a straightforward interpretation of the data in terms of composition if all the uncertainties are considered.

It is worthwhile to remember here how the interpretation of the X_{max} measurement is done. The Pierre Auger Collaboration, for example, fits f_i to the measured X_{max} distribution in bins of energy [16]. The calculation of f_i depends on simulation and therefore on the hadronic interaction model. However, because the electromagnetic cascade of the shower dominates the determination of the X_{max} position, the discrepancy between the hadronic interaction model X_{max} predictions is minimized. The difference in $\langle X_{\text{max}} \rangle$ is at most 20 g/cm² and in $\sigma[X_{\text{max}}]$ is 6 g/cm² for the most often used hadronic interaction models (EPOS-LHC, Sibyll2.1 and QGSJetII-04) [11]. Given the small differences in the predictions of X_{max} and its consistency with data, the fit of f_i leads to acceptable differences in the calculation of f_i for different hadronic interaction models and then to mass composition scenarios which are physically consistent.

Unfortunately, the same procedure cannot be applied to N_{μ} because of the discrepancies between the hadronic interaction model predictions and the inconsistency between simulations and data. It is known that the simulations are off by at least 20% in the calculation of N_{μ} [13,14]. A fit of f_i based on the N_{μ} distribution would lead to non-physical results. Therefore we propose an alternative analysis to discriminate between composition scenarios. The idea is to fix f_i , choosing a mass composition scenario, and fit the data with the energy evolution of $\log_{10} N_{\mu}^{\text{meas}}$ moments to search for the scenarios which better describe the data.

If the composition (f_i) were known by an independent measurement, this procedure would allow us to calculate a and b and constrain the hadronic interaction models by limiting fundamental properties of the interactions. This hypothesis needs to be explored further by using the results from the X_{max} measurement to fix f_i .

We propose here a procedure that allows a statistically robust test of composition scenarios against data. The method starts by using the model proposed in Section 2 to predict the energy evolution of $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ for a given composition scenario. Here, all the parameters of the model are fixed, except a and b . The next step is to compare these predictions with data and find the values of a and b which make the model most similar to the data. This can be done by a χ^2 minimization. The minimal values of χ^2 determine which scenario best describes the data. Since a and b take all the hadronic interaction model dependence, the

Fig. 7. Energy evolution of (a) $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ and (b) $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ for the six composition scenarios described in the text. The values of $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ are divided by the corresponding value of pure proton composition for better visualization. The hadronic interaction model used was EPOS-LHC.

Fig. 8. Energy evolution of $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ for 2 mass composition scenarios, A1 and A3. The dashed lines show the effects of (a) an increase of 20% in the N_{μ} and (b) a variation of $\pm 15\%$ in energy. The values of $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ are divided by the corresponding value of pure proton composition for better visualization. The hadronic interaction model used was EPOS-LHC.

Fig. 9. Black dots show the simulated (a) $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ and (b) $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ using scenario A1 as the true one. The colored lines show the results of the fit for each one of the test scenarios. The values of $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ are divided by the corresponding value of pure proton composition for better visualization.

composition scenario can be tested independently of hadronic interaction model limitations.

We explored this analysis proposal by choosing a composition scenario as if it would represent the true measurement, and we name it *true scenario*. We generate the $\log_{10} N_{\mu}$ moments as a function of energy for the *true scenario* using the simulation described in Section 3 in order to emulate the real data. Here, the energy bins are defined by 12 intervals of width $\Delta \log_{10}(E/\text{eV}) = 0.1$, from $10^{18.4}$ to $10^{19.6}$ eV. This choice is mainly motivated by the Auger experimental acceptance, which reaches a 100% efficient trigger probability around $10^{18.4}$ eV [26]. The number of events in each bin is determined by considering 3 years of data taken by the full array of Auger, following the energy spectrum of Ref.[3].

It is important to note that the simulations used here do not take into account any detector effects or zenith angle dependence. Although in this paper we do not intend to approach these issues because the focus here are on the general aspects of the analysis, it is clear that in practical applications of the method one should deal with these experimental difficulties. The detector effects, like resolution and limited acceptance, could be addressed by unfolding or unbiasing techniques once the detector response is well known. One example of these process is the Auger analysis of X_{max} moments [11]. The zenith angle dependence could be addressed in a conservative approach by dividing the data in zenith angle intervals or by correcting the data using a *constant intensity cut* (CIC) method [27–29]. This later class of method has been successfully used, for example, to determine the shower size

parameter by Pierre Auger [30] and KASCADE-Grande Collaboration [31] and to correct the N_{μ} parameter by KASCADE-Grande Collaboration [32]. The systematics uncertainties from these procedure are usually small ($<10\%$) and should be taken into account in a realistic approach of our method.

In next step, we perform a χ^2 fit using the model described by Eqs. (5) and (7), with a and b as free parameters of the fit, for all the composition scenarios. The scenarios which are not the true one are named *test scenarios*. Fig. 9 shows one realization of these fits in which scenario A1 was used as the *true scenario* to generate the black dots. The fit of the $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ with energy (Fig. 9) sets the best value of a and the minimal value of $\chi^2(a)$. The fit of the $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ with energy (Fig. 9) sets the best value of b and the minimal value of $\chi^2(b)$. In all fits, $D_E = 0.920$, $D_A = 0.0354$ and $\sigma[\log_{10} N_{\mu}]_{\text{Fe}} = 0.0265$. Each line in Fig. 9 is the fit of one out of the six composition scenarios. We compared all scenarios (*test scenarios*) to the *true scenario*.

A simple χ^2 comparison finds the *test scenarios* which best fit the data generated with the *true scenario*. The average value of χ^2 as a function of the fitted parameters a and b is shown in Fig. 10 for a set of 500 realizations. In this case, it is clear that the scenario A1 better describes the $\langle \log_{10} N_{\mu}^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_{\mu}^{\text{meas}}]$ evolution with energy because of the smaller values of $\chi_{\text{min}}^2(a)$ and $\chi_{\text{min}}^2(b)$. Fig. 11 shows the plots of $\chi_{\text{min}}^2(a)$ vs $\chi_{\text{min}}^2(b)$ for all six scenarios as the *true scenarios*. The error bars represent one standard deviation around the mean for 500 realizations. All scenarios,

Fig. 10. χ^2 as a function of the parameters a (a) and b (b) for all the scenarios. The scenario A1 is the *true scenario*. The colored bands represent one standard deviation around the mean for a set of 500 realizations.

Fig. 11. $\chi^2_{\min}(a)$ vs $\chi^2_{\min}(b)$ for all composition scenarios.

Fig. 12. $\chi^2_{\min}(a)$ vs $\chi^2_{\min}(b)$ for the true scenario A1 with (a) $\alpha_{N_\mu} = 1.3$ and (b) $\alpha_{N_\mu} = 1.6$ and for the true scenario X1 with (c) $\alpha_{N_\mu} = 1.3$ and (d) $\alpha_{N_\mu} = 1.6$ (see text).

except in X1 case, can be discriminated by the smallest $\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$. In other words, the *true scenario* is the one with the $\chi^2_{\min}(a) - \chi^2_{\min}(b)$ point closer to the left-down corner. Note that only $\chi^2_{\min}(a)$ or only $\chi^2_{\min}(b)$ cannot alone discriminate most of the scenarios. In the case of X1 as *true scenario* one can see that, even if it is not possible to discriminate scenario X1 and X2, it is still possible to discriminate the $X_{\max}$ scenarios from the astrophysical ones.

5.1. Sensitivity to the systematic uncertainties on energy scale and absolute number of muons

As mentioned above, the greatest obstacles in interpreting N_μ data currently are the systematic uncertainties in the theoretical description and reconstruction of air showers. In this section we demonstrate that the procedure proposed in the previous section to discriminate between composition scenarios is stable under systematic changes of absolute N_μ prediction and of energy scale.

The systematic uncertainties in N_μ scale were tested by applying the rescaling factor α_{N_μ} in N_μ^{meas} generated by simulations. The examination of Eq. (3) shows that a rescaling factor on N_μ corresponds to an additive term in a . This is how the systematic effect on N_μ^{meas} is incorporated in the simple description of $\langle \log_{10} N_\mu^{\text{meas}} \rangle$. Eq. (4) shows that b does not depend on α_{N_μ} . If only $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ changes by an additive term when α_{N_μ} is applied, it is clear that $\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$ are independent of α_{N_μ} . Fig. 12 shows the values of $\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$ for true scenarios A1 and X1 and $\alpha_{N_\mu} = 1.3$ and 1.6, as examples. One can see that the values of $\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$ are stable under systematic changes in N_μ^{meas} .

The energy scale effect was tested by including a rescaling factor α_E in simulated energy of each shower. The same analysis of Eqs. (3) and (4) reveals that a and b accommodate the sys-

tematic effects in energy as additive terms. All additive terms are canceled in the χ^2 comparison resulting in the independence of the conclusions under systematic effects. In Fig. 13 we show the $\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$ for true scenarios A1 and X1 and for $\alpha_E = 0.85$ and 1.15, which represents a systematic uncertainties of 15% in energy. Again, it can be observed that the values of $\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$ would not lead to a different conclusion, and therefore, the results of the method would be stable under energy shifts.

6. Conclusion

In this paper, we have analyzed the muon content of air showers, proposed a parametrization of the first two moments of the number of muons with energy and primary particle mass and showed how the measured mean and σ of $\log_{10} N_\mu$ can be used to discriminate between composition scenarios.

We proposed a model to describe $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_\mu^{\text{meas}}]$ as a function of energy and primary particle mass (A). This model was conceived to keep the most relevant hadronic interaction uncertainties concentrated in only two parameters (a and b). We have validated the model with Monte Carlo simulation of the air shower and its capability to describe the $\log_{10} N_\mu^{\text{meas}}$ moments was proven.

Six composition scenarios were considered. The particle flux predicted by these scenarios was transformed into the corresponding $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_\mu^{\text{meas}}]$ evolution with energy. The $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_\mu^{\text{meas}}]$ evolution with energy was fitted using the proposed parametrization. A comparison of the $\langle \log_{10} N_\mu^{\text{meas}} \rangle$ and $\sigma[\log_{10} N_\mu^{\text{meas}}]$ model using a simple χ^2 test allows the discrimination between the scenarios. The discrimination is effective even considering the systematic uncertainties on the N_μ prediction and on energy scale uncertainty.

Fig. 13. $\chi^2_{\min}(a)$ vs $\chi^2_{\min}(b)$ for the true scenario A1 with (a) $\alpha_E = 0.85$ and (b) $\alpha_E = 1.15$ and for the true scenario X1 with (c) $\alpha_E = 0.85$ and (d) $\alpha_E = 1.15$ (see text).

The effect of the systematic in the N_μ number and energy reconstruction was studied for constant values of the uncertainty with energy. This choice is justified by the narrow energy interval used in the analysis. Abrupt changes of the systematic uncertainties with energy could change the conclusion drawn here since $\log_{10} N_\mu^{\text{meas}}$ is assumed to be fixed in the proposed model.

The upgrade of Telescope Array [33] and Pierre Auger Observatory [34], to be constructed in the next few years, will for the first time allow precise measurements of the muon component of air showers for energies above 10^{18} eV. This will open up a new window of analyses and tests in astroparticle physics. Once data is acquired, the parametrization proposed here could be tested and if proven to be right, the analysis method proposed in Section 5 could be used to find the most probable composition scenario in the energy range from $10^{18.4}$ to $10^{19.6}$ eV.

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Appendix A. Parametrization of $R(E, X_{\max})$

As mentioned in Section 3, the parametrization of $R(E, X_{\max})$ can be done by means of full air shower simulations. In this paper, we choose CORSIKA [21] as the full Monte Carlo code.

First, a set of 200 CORSIKA (version 7.4000) showers for each primary (proton, helium, nitrogen and iron), fixed energy ($E = 10^{18.5}, 10^{19.0}, 10^{19.5}$ eV) and high energy hadronic interaction model (EPOS-LHC [24] and QGSjetII-04 [25]) were generated. The low energy hadronic interaction model is Fluka [35] in all cases. Furthermore, the zenith angle was set fixed to 38° for all showers. This is clearly a simplification, and then it should be stressed that, in a more realistic analysis, the N_μ zenith angle dependence must be treated.

In Fig. A.1 the factor R is shown as a function of $X_{\max}$ for all primaries, one primary energy, $10^{19.0}$ eV, and one hadronic interaction model, EPOS-LHC. The observed behavior suggests a linear parametrization of the form,

$$R(E, X_{\max}) = p_1(E) \cdot X_{\max} + p_0(E), \quad (\text{A.1})$$

where p_0 and p_1 have to be also parametrized as a function of energy. The values of p_0 and p_1 for each primary and energy were determined from the linear fit, shown in Fig. A.1 by a dotted red line.

In Fig. A.2 p_0 and p_1 are shown as a function of logarithmic energy for all primaries and the hadronic interaction model EPOS-LHC, as an example. Again, we are able to perform a linear parametrization of p_0 and p_1 as a function of $\log_{10}(E)$, in the form

$$\begin{aligned} p_0(E) &= \alpha_0 \cdot \log_{10}(E/\text{eV}) + \beta_0, \\ p_1(E) &= \alpha_1 \cdot \log_{10}(E/\text{eV}) + \beta_1. \end{aligned} \quad (\text{A.2})$$

The dotted lines in Fig. A.2 show the function from Eq. (A.2) fitted to the point obtained from CORSIKA simulations. The values of α_0 , β_0 , α_1 and β_1 for all primaries and hadronic interaction models are presented in Table A.1.

Fig. A.1. Conversion factor R as a function of $X_{\max}$ for $E = 10^{19.0}$ eV showers with EPOS-LHC as hadronic interaction model. The black dots are individual showers, the blue circles are the profile and dotted red line is the linearfit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. A.2. p_0 and p_1 as a function of $\log_{10}(E)$ (see text) for EPOS-LHC as the hadronic interaction model. The dashed lines are the linear fits represented in Eq. (A.2).

A comparison between $\log_{10} N_{\mu}^{\text{meas}}$ distributions achieved directly from CORSIKA showers and from the simulated method described in this work can be seen in Fig. A.3. The energy is fixed at $E = 10^{19.0}$ eV and the hadronic interaction model is EPOS-LHC. The discrepancies in the mean values and in the σ of the distributions are less than 2% and 5% respectively, for any combination of primary and hadronic interaction model. Indeed, considering the differences between the approaches assumed by both software, CORSIKA and CONEX, these observed discrepancies are really satisfactory. Among the several physical effects which are treated differently we can highlight the lack of geomagnetic field and muon multiple scattering in CONEX.

Although there is a small discrepancy between our method's and CORSIKA's $\log_{10} N_{\mu}^{\text{meas}}$ distributions, we do not expect to find any loss in the development of this paper. This can be assured because the method proposed here is not dependent on the comparison between our simulations and any other set of simulated showers.

Table A1
Fitted parameters α_0 , β_0 , α_1 and β_1 given in Eq. (A.2).

Had. int. model	Primary	α_0	β_0	$\alpha_1(10^{-5} \text{g}^{-1} \text{cm}^2)$	$\beta_1(10^{-5} \text{g}^{-1} \text{cm}^2)$
EPOS-LHC	proton	0.0303	-0.00635	-3.20	38.0
	helium	0.0385	-0.147	-4.14	53.6
	nitrogen	0.0337	-0.0721	-3.90	50.5
	iron	0.0259	0.0613	-3.04	35.8
QGSJetII-04	proton	0.0216	0.130	-2.04	17.3
	helium	0.0143	0.264	-1.20	1.35
	nitrogen	0.0167	0.209	-1.60	9.94
	iron	0.0245	0.0427	-2.99	38.5

Fig. A.3. Comparison between the normalized $\log_{10} N_{\mu}^{\text{meas}}$ distributions generated by CORSIKA and by this work's algorithm. The energy is $E = 10^{19.0}$ eV and the hadronic interaction model is EPOS-LHC. The primary particles are (a) proton, (b) helium, (c) nitrogen and (d) iron.

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5 A new air-shower observable to constrain hadronic interaction models

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A new air-shower observable to constrain hadronic interaction models

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ABSTRACT

The energy spectrum of muons at ground level in air showers is studied and a new observable is proposed to constrain hadronic interaction models used in air shower simulations. An asymmetric Gaussian function is proposed to describe the muon ground energy spectrum and its parameters are studied regarding primary particle, energy and hadronic interaction models. Based on two realistic measurements of the muon density at a given distance from the shower axis, a new observable (r_μ) is defined. Considering realistic values of detector resolutions and number of measured events, it is also shown r_μ can be successfully used to constrain low and high energy hadronic interaction models. The study is focused in the energy range between $10^{17.5}$ and $10^{18.0}$ eV because of the importance of this interval for particle physics and astrophysical models. The constraining power of the new observable is shown to be large within current experimental capabilities.

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1. Introduction

The interaction of ultra high energy cosmic rays with atmospheric nuclei allows us to access hadronic interactions at energies much beyond the reach of man-made accelerators. However several properties of the cosmic ray phenomena and of the detection techniques impose limitations on the available information to study the highest energetic interactions. Experiments are only able to measure the air shower produced by the interaction of the cosmic particles with the nucleus of atoms in the atmosphere. The study of elementary properties of particle physics is done by relating global shower parameters to the properties of the hadronic interactions.

The depth at which the shower reaches its maximum number of particles ($X_{\max}$) and the muon component are the most used shower features related to properties of particle interactions. At the same time, they are also strongly sensitive to the type of the shower primary particle [1]. Given that the primary particle type cannot be determined on event-by-event basis, different primary compositions must be considered in the study of the interaction properties. Usually, the large possibility of primary particles, from proton to iron nuclei, makes it impossible to disentangle the mass of the cosmic particle from particle interaction properties.

This paper proposes an analysis procedure to constrain hadronic interaction models by the measurements of the muon density by two different detectors. The idea proposed here is to compare the

predictions of the models to measurements based on the muon density at ground level. It will be shown in Section 4 that the muon ground energy spectrum has valuable information, which allow to discriminate among different hadronic interaction models.

Hadronic interaction models used in Monte Carlo simulations of air showers are limited to phenomenological approaches tested and tuned to collider data [2]. Three hadronic models for high energy interaction (>80 GeV) and three hadronic models for low energy interaction (<80 GeV) were investigated. A new and realistic air-shower observable based on two measurements of the muon density by different detectors is proposed in this paper and it is demonstrated to be powerful enough to constrain the hadronic interactions models.

The analysis procedure proposed here does not aim to infer properties of the particle interactions, instead, the new proposed parameter has power to test the predictions of the hadronic interaction models within realistic experimental conditions. By comparing the prediction of the models to future measurements of the new parameter, it will be possible to select the best model and guide the way towards a better understanding of the underlying assumptions taken by that model.

The work is based on Monte Carlo simulations of air showers. The new proposed parameter is studied in the energy range from $10^{17.5}$ to $10^{18.0}$ eV. The energy range is limited in order to minimize the effect of systematic uncertainties in energy reconstruction and also because of the importance of this range, which is the transition energy range from collider data to the extrapolation domain. It is shown that the new parameter can be used to test hadronic interaction models without knowledge on the primary composition.

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The paper is organized as follows: Section 2 describes the simulations, Section 3 shows a study on the energy spectra of muons at the ground level, Section 4 proposes the new parameter and studies its behavior with relation to primary mass, energy and detector properties, Section 5 quantifies the constraining power of the new parameter and Section 6 concludes the work.

2. Simulations

Extensive air showers were simulated using the Monte Carlo code CORSIKA v7.500 [3]. The applied thinning factor was 10^{-2} for the electromagnetic component and 10^{-4} for the hadronic component, with the maximum weight for any particle set to 100. It was verified that the choice of this thinning configuration does not result in a bias in the present analysis. The energy of the primary particles was sampled continuously between $10^{17.5}$ and $10^{18.0}$ eV, following a power law energy spectrum with index -3 . The arrival directions were sampled following a uniform distribution in solid angle, up to a maximum zenith angle of 60° . Three primaries were simulated: proton, nitrogen nucleus and iron nucleus. The minimum energy of particles simulated in air showers were set to 0.3 GeV for hadrons and muons, and 0.003 GeV for electrons and photons. Three hadronic interaction models were used for high energies interactions (>80 GeV): QGSJetII-04 [4], EPOS-LHC [5,6] and Sibyll2.3 [7], and three for low energies (<80 GeV): FLUKA [8], GHEISHA [9] and UrQMD [10]. For each selected combination of hadronic interaction model and primaries particle, 1200 showers were generated. The ground altitude (1400 m above sea level) was chosen to be the one at the Pierre Auger Observatory.

The energy spectrum of muons at ground level is the shower feature to be considered in this paper. The energy spectra were built by collecting from the simulated air showers all muons reaching ground in a lateral distance between 425 and 475 m from the shower axis. Although a full detector reconstruction is not applied, in Section 4.1 the detector effects are taken into account by artificial smearing the shower observables around its simulated values. Detector thresholds and geometry are considered as well.

To sample showers at the same stage of development, the commonly used DX parameter is used. DX is the slant atmospheric depth between the shower maximum and the ground. It is given by

$$DX = \frac{X_{\text{gr,vert}}}{\cos \theta} - X_{\text{max}}, \quad (1)$$

where $X_{\text{gr,vert}}$ is the vertical slant depth of the ground,¹ θ is the zenith angle of the shower axis and X_{max} is the depth in which the shower reaches its maximum. For each simulated event, the θ corresponds to the true zenith angle as set in the input of the simulation and X_{max} was taken directly from the Gaisser–Hillas function fitted to the longitudinal energy deposit profile.

3. Characterization of the muon ground energy spectrum

In this section, the simulations described in Section 2 are used to characterize the energy spectrum of muons at ground level and to study its relations with primary mass and hadronic interaction models.

Fig. 1 shows examples of the ground energy spectrum of muons for six simulated events, which differ by the primary particle and the shower geometry. The low and high energy hadronic interaction models are FLUKA and QGSJetII-04, respectively. Examples have been selected to illustrate the general shape of the muon spectrum for different primary particles and extreme values of DX . The left-hand column shows deep showers, with relatively small

DX values, while the right-hand column shows shallow showers, with relatively high values of DX . The normalization and the mean of the distributions are clearly different but the overall shape is very similar.

As shown by the red lines in Fig. 1, the ground energy spectrum of muons is well described by the following asymmetric Gaussian function

$$\frac{dN_\mu}{dx} = \begin{cases} N_0 \exp \left[-\frac{1}{2} \left(\frac{x-\eta}{\sigma} \right)^2 \right], & \text{if } x < \eta \\ N_0 \exp \left[-\frac{1}{2} \left(\frac{x-\eta}{\alpha\sigma} \right)^2 \right], & \text{if } x > \eta \end{cases} \quad (2)$$

where $x = \log_{10}(E/\text{GeV})$. N_0 is the normalization parameter and it is correlated with the total number of muons in the shower. η is the mode of the energy distribution, and it is strongly correlated with the average energy of muons reaching ground between 425 and 475 m distance from the shower axis. σ and α give the width of the distribution, α being the parameter that measures the degree of asymmetry of the distribution.

Muon energy spectra of all simulated showers were fit by the function presented in Eq. (2), in which N_0 , η , σ and α were taken as free parameters. The fitting was performed using a binned maximum likelihood method with Poissonian probability distribution functions.

Since the ground energy spectrum of muons is well described by the asymmetric Gaussian function, one may study its dependencies on the energy, primary particle and hadronic interaction models through the evolution of the parameters N_0 , η , σ and α with DX . Fig. 2 shows the DX evolution of the four parameters for three different energy intervals, Fig. 3 for three primary particles and Fig. 4 for five combinations of high and low energy hadronic interaction models.

It is clear from Fig. 2 that the normalization (N_0) is the only property of ground muon energy spectrum which shows a significant dependence on the primary energy. As expected, N_0 also depends strongly on the primary particle and hadronic interaction model (see Figs. 3 and 4), which reflects the very known behavior of number of muons in air showers. Concerning the peak position of the distributions, η , a strong evolution with DX is observed, revealing the shift of the average energy of muons to higher values with increasing DX . Besides normalization and peak positions, changes on the overall shape of the energy spectrum of muons can be evaluated through the parameters σ and α . These parameters clearly show a very weak evolution with DX , and a nearly null dependence on the primary energy and primary particle and a relatively very small dependence on the hadronic interaction models.

The analysis of Fig. 4 also repeats known though less popular lessons: the effect of low energy hadronic interaction models are as important as the high energy one regarding the description of the muonic component in air-shower simulations [11]. The differences of N_0 between QGSJetII-04/FLUKA and QGSJetII-04/UrQMD or GHEISHA are of the same order or larger than the largest difference between the high energy interaction models. The average energy of muons, correlated with η , is larger for GHEISHA, followed by UrQMD and then FLUKA. The differences in η due to the low energy hadronic interaction models are as large as the differences due to the high energy hadronic interaction models. Regarding σ and α parameters, one can see in Fig. 4 they show the same weak DX evolution for all the hadronic model combinations. Furthermore, the effect of low energy hadronic models is again clear as shown by the difference between FLUKA and GHEISHA, or UrQMD.

Finally, the analysis of Fig. 4 also opens new possibilities. It turns out that η is strongly sensitive to the hadronic interaction models, and at the same time, it does not show any significant dependence on the primary energy and on the primary particle. The lack of primary energy dependence is important experimen-

¹ $X_{\text{gr,vert}} = 870 \text{ g/cm}^2$ for the Pierre Auger Observatory.

Fig. 1. Example of the ground muon energy spectrum for six simulated showers. Shower parameters are shown in each panel. The energy spectra were built by collecting from the air-shower simulation all muons hitting the ground in a lateral distance between 425 and 475 m from the shower axis. The low and high energy hadronic interaction models are FLUKA and QGSJetII-04, respectively. Red lines are the result of fitting Eq. (2) to the data points. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tally to eliminate effects from the experimental energy scale, while the lack of primary particle dependence is an essential property to disentangle the hadronic interaction effects from the primary composition determination. The evolution of η with DX is simple (linear) and strong, which makes easy to study showers in different evolution stages.

All of these are indications that accessing experimentally the information carried by η could be successfully used to constrain the hadronic interaction models. In the next section a new observable which is strongly correlated to η is studied and its constraining power in realistic experimental conditions is tested.

4. An observable to test hadronic interaction models

Accessing η directly is not possible for any running or planned UHECR experiment. Therefore, instead of proposing an unrealistic parameter, this study starts from a realistic experimental scenario and aims to find an observable which correlates to η . A generic experimental set-up is considered with two muon detector arrays with different amount of shielding leading to two energy thresholds. With such an experimental set-up, it is possible to measure the integral of the energy spectrum or the energy density of muons above two energy thresholds.

Using the simulations described in Section 2 the density of muons in the lateral distance from 425 to 475 m from the shower axis was calculated for a surface (S_{μ}^{sur}) and a buried (S_{μ}^{bur}) detectors and a new parameter is defined:

$$r_{\mu} = \sec^{\beta} \theta \frac{S_{\mu}^{\text{bur}}}{S_{\mu}^{\text{sur}}}, \quad (3)$$

where θ is the zenith angle of the primary particle. The term $\sec^{\beta} \theta$ compensates the zenith dependence on the energy threshold and the effective area of the buried detectors. The surface detector (S_{μ}^{sur}) is considered to have 10 m² and the buried detector (S_{μ}^{bur}) to have 30/cos θ m², which are motivated by water-Cherenkov stations and flat buried scintillators respectively. β was determined to minimize the primary mass dependence of r_{μ} . In Fig. 5 the r_{μ} dependence on β is shown for one hadronic interaction models, which justify the choice of $\beta = 0.6$ as the value that minimize the difference between primaries. The detector features considered is described in the next section.

Figs. 6 and 7 show the distributions of r_{μ} for several energy thresholds of the buried detector. Three cases are shown in which the vertical muon energy threshold of the buried detector ($E_{\text{vert},\mu}^{\text{th}}$) is changed. The effective energy threshold for a muon with incident zenith angle θ_{μ} is $E_{\text{vert},\mu}^{\text{th}}/\cos \theta_{\mu}$. For the surface detectors, the energy threshold is kept fixed at 0.3 GeV. Fig. 6 compares the

Fig. 2. (a) N_0 , (b) η , (c) σ and (d) α as a function of DX for three energy intervals. Same number of p, N and Fe showers are considered. The hadronic interaction models used are FLUKA and QGSjetII-04.

Fig. 3. (a) N_0 , (b) η , (c) σ and (d) α as a function of DX for three primary particles. The energy interval for all primaries is $17.5 < \lg_{10}(E/eV) < 18.0$. The hadronic interaction models used are FLUKA and QGSjetII-04.

Fig. 4. (a) N_0 , (b) η , (c) σ and (d) α as a function of DX for five combinations of hadronic interaction models. The energy interval for all primaries is $17.5 < \log_{10}(E/\text{eV}) < 18.0$. Same number of p, N and Fe showers are considered.

Fig. 5. $\langle r_\mu \rangle$ as a function of β for one small DX interval and for three different primaries. $\beta = 0.6$ was chosen to minimize the dependence of r_μ with primary particle.

distributions for different high energy hadronic interaction models and Fig. 7 for different low energy hadronic interaction models. The different degrees of separation of the hadronic interaction models with different energy threshold is clear, pointing to the possibility to constrain the hadronic interaction models using r_μ . In the next sections, the constraining power of r_μ is estimated and its correlation with η is shown.

4.1. r_μ Determination including detector characteristics

In this section, the effect of detector geometry, muon energy thresholds, detector resolutions and systematic uncertainties on r_μ are studied. To include the detector features in the proposed analysis, the general characteristics of the muon detectors of the Pierre Auger Observatory are considered. A surface detector with 10 m² of effective area is considered to measure muons with energies above 0.3 GeV. Its general characteristics are inspired in the AugerPrime [12–14] design of water-Cherenkov stations with plastic scintillators on top. A second detector is considered based on

Fig. 6. r_μ distributions of the three high energy hadronic interaction models. Each panel shows the distributions for a given energy thresholds of the buried detector, $E_{\text{vert},\mu}^{\text{th}} = 0.65, 2.6, 8.13$ GeV from left to right. Low energy hadronic interaction model is FLUKA.

Fig. 7. r_μ distributions of the three low energy hadronic interaction models. Each panel shows the distributions for a given energy thresholds of the buried detector, $E_{\text{vert},\mu}^{\text{th}} = 0.65, 2.6, 8.13$ GeV from left to right. High energy hadronic interaction model is QGSJetII-04.

Fig. 8. Mean r_μ as a function of $\langle\eta\rangle$ for $325 < DX/(g/cm^2) < 375$. β was set to 0.6. See Eqs. (2) and (3) for definitions of the parameters. Detectors effective area and threshold were considered according to Section 4.1. Five combinations of hadronic interaction models is shown for three primary particles. A nearly linear correlation is seen and a clear separation of many hadronic interaction models is visible.

Fig. 9. $\langle r_\mu \rangle$ as a function of DX for different values of S_μ^{sur} and S_μ^{bur} resolution. The mean value $\langle r_\mu \rangle$ is calculated over 2000 realizations in which the detector resolution was applied to each simulated shower. Points were artificially shifted in DX for clarity.

the general characteristics of the Auger AMIGA detector [15,16]. Those are 30 m² flat scintillator detectors buried 2.5 m below the ground. The muon energy threshold for the buried detectors depends on the incident zenith angle of the particle and it is given by $E_{\text{th}} = \beta \rho h / \cos \theta_\mu$, where $\beta = 1.808$ MeV cm² g⁻¹ is the fractional energy loss per depth of standard rock, $\rho = 1.8$ g cm⁻³ is the soil density, $h = 2.5$ m is the vertical depth of the detectors and θ_μ is the zenith incidence angle of the muon. Because of its flatness, the effective collection area of the detector decrease by a factor $\cos \theta$, where θ is the zenith angle of the shower. The reconstruction of the muon density by an AMIGA-like detector has been shown to be satisfactorily possible for events with $\theta < 45^\circ$ [17–19].

From now on, the results were obtained by considering the detector features shown above to calculate the muon density from the simulated air showers explained in Section 2. In this way, the most important properties of the detectors are considered without the need to perform a full detector simulation.

Fig. 8 shows the relation between the average value of r_μ ($\langle r_\mu \rangle$) and the average value of η ($\langle \eta \rangle$) for showers with $325 < DX/(g/cm^2) < 375$ according to the detector properties explained above. Five combinations of low and high energy hadronic interaction models are shown in different colors and three primaries are shown in different marker styles. From Fig. 8, one can see a nearly linear relation between $\langle r_\mu \rangle$ and $\langle \eta \rangle$. Furthermore, the relatively large separation between the hadronic interaction model combinations by $\langle r_\mu \rangle$ is clear, which shows r_μ is a good observable to constrain hadronic interaction properties.

The resolutions on the muon density reconstruction were taken into account by applying a Gaussian smearing on the true signal

obtained from the simulations. S_μ^{sur} resolution was considered to vary in the range from 10% to 20% [12,14] and S_μ^{bur} resolution in the range from 5% to 10% [18,19]. Fig. 9 shows the effect of the resolution in the calculation of $\langle r_\mu \rangle$. The Gaussian smearing were performed 2000 times and the $\langle r_\mu \rangle$ is shown as a function of DX . The standard deviation of r_μ distributions is shown by the error bars. Three cases are shown in which the resolution on both S_μ^{sur} and S_μ^{bur} vary. The systematic effect of the detector resolution in the determination of $\langle r_\mu \rangle$ is smaller than 5%.

Besides the experimental resolutions, systematic uncertainties on S_μ^{sur} and S_μ^{bur} can be originated from the detection and reconstruction procedures. Typically the most significant systematic uncertainty on muon density measurements are due to systematic uncertainties on the shower energy determination, which affects both S_μ^{sur} and S_μ^{bur} in the same magnitude. To evaluate the effect of systematic uncertainties on r_μ , the simulated S_μ^{sur} and S_μ^{bur} were shifted artificially and the resulting r_μ were calculated. First it was considered the shifts on S_μ^{sur} and S_μ^{bur} are totally correlated, which means the same magnitude and direction. This case represents the energy reconstruction uncertainty effect. Fig. 10 shows the r_μ as a function of DX , for one hadronic interaction models combination, for different cases in which S_μ^{sur} and S_μ^{bur} were shifted by a factor $1 + \delta^{\text{top}}$ and $1 + \delta^{\text{bur}}$ respectively. In Fig. 10 left panel it is shown the effect of a 10% shift on both muon density at the same direction. Clearly, correlated systematic uncertainties on S_μ^{sur} and S_μ^{bur} have an insignificant effect on r_μ . In Fig. 10 right panel it is shown the effect of systematic shifts of 2.5% on S_μ^{sur} and S_μ^{bur} in opposite directions. The magnitude of the $\langle r_\mu \rangle$ deviation is of order 0.05.

Fig. 10. $\langle r_\mu \rangle$ as a function of DX for different combinations of the systematic uncertainties on S_μ^{sur} and S_μ^{bur} . δ^{top} and δ^{bur} are defined in Section 4.1. All simulated primary particles are included (p, N, Fe). Bottom panel shows the difference with relation to the average value. The hadronic interaction model combination used is QGSJetII-04/FLUKA. Points were artificially shifted in DX for clarity.

Fig. 11. $\langle r_\mu \rangle$ as a function of DX for three energy intervals. All simulated primary particles are included (p, N, Fe). Bottom panel shows the difference with relation to the average value. The hadronic interaction model combination used is QGSJetII-04/FLUKA. Points were artificially shifted in DX for clarity.

Fig. 12. $\langle r_\mu \rangle$ as a function of DX for three primary particles (pr, N, Fe). All simulated energies are included. Bottom panel shows the difference with relation to the average value. The hadronic interaction model combination used is QGSJetII-04/FLUKA. Points were artificially shifted in DX for clarity.

The consequences of this deviation on the separation between different hadronic interaction models is discussed in Section 5.

4.2. r_μ Dependence on primary mass and energy

For the following analysis, the DX range was defined to preserve a good statistics in all DX bins and it goes from 100 to 600 g/cm² divided in 5 bins of 100 g/cm². The upper bound of 600 g/cm² is highly influenced by the shower zenith angle limitation at $\theta < 45^\circ$ due to the buried detector features.

Fig. 11 shows the evolution of $\langle r_\mu \rangle$ as a function of DX for different energy ranges. All simulated primary particles are include (p, N and Fe). Hadronic interaction model combination here is QGSJetII-04/FLUKA. A better visualization of the differences in $\langle r_\mu \rangle$ is seen in the bottom panel of Fig. 11, where Δr_μ are the differences with relation to the average value of $\langle r_\mu \rangle$ for the three energy ranges considered. The differences of $\langle r_\mu \rangle$ in all energy intervals is smaller than 1% for the entire DX range. The energy independence of $\langle r_\mu \rangle$

is expected, since S_μ^{sur} and S_μ^{bur} evolve similarly with energy in the range from $10^{17.5}$ to $10^{18.0}$ eV. The lack of energy dependence is an advantage because it allows the analysis of events in a large energy interval, increasing significantly the available statistics. Furthermore, it also contribute to diminishing any effect due to the experimental energy scale.

The primary mass dependence of the $\langle r_\mu \rangle$ is shown in Fig. 12. The hadronic interaction model combination shown is again QGSJetII-04/FLUKA. Very similar results were obtained for all combinations of models. The bottom panel shows the $\Delta\langle r_\mu \rangle$. The observed primary mass dependence is below 2%. The dependence of $\langle r_\mu \rangle$ with the primary particle was minimized by choosing $\beta = 0.6$. The lack of $\langle r_\mu \rangle$ dependence on the primary particle is a great advantage because it disentangles the study of the hadronic interaction properties from the determination of the primary particle type.

Fig. 13. $\langle r_\mu \rangle$ as a function of DX for three high energy hadronic interaction models. All simulated energies are included. All simulated primary particles are included (p, N, Fe). Bottom panel shows the difference with relation to the average value. Low energy hadronic interaction model is FLUKA. The detector resolution is set to 20% for S_μ^{sur} and 10% for S_μ^{bur} . Points were artificially shifted in DX for clarity.

5. Results: constraining hadronic interaction models with r_μ parameter

In this section, the capacity to constrain hadronic interaction models by measuring r_μ is demonstrated by studying the DX evolution of $\langle r_\mu \rangle$ for different combinations of low and high energy hadronic models. Detector resolution is taken into account as explained above. The effect of a limited number of events is considered here. The total number of simulated air showers used (3500) is approximately the number of hybrid events to be measured by the Pierre Auger Observatory infill array in 2 years of operation. The infill array consists of 750 m spaced water-Cherenkov stations spread over an area of 23.5 km². In this same area the AMIGA-Grande and AugerPrime muon detectors are going to be installed. Considering the duty cycle of the fluorescence detectors to be 14%, the total exposure of this experimental set-up is 4.32 km².sr.yr. Taking into account the cosmic-rays flux between 10^{17.5} and 10^{18.0} eV, the expected number of events to be measured per year is 1806.

Figs. 13 and 14 show the $\langle r_\mu \rangle$ as a function of DX for different combinations of hadronic interaction models. In Fig. 13 the three high energy hadronic models are shown in combination with one low energy hadronic interaction model: FLUKA. In Fig. 14 the three low energy hadronic models are shown in combination with one high energy hadronic interaction model: QGSJetII-04. The bottom panels show the $\Delta\langle r_\mu \rangle$. The worst case for the detector resolution was considered: 10% for S_μ^{bur} and 20% for S_μ^{sur} . Figs. 13 and 14 show that even with a relatively poor detector resolution a clear separation between hadronic interaction models is achieved. In Fig. 13 it is observed that EPOS-LHC can be distinguished from QGSJetII-04 and Sibyll2.3, while in Fig. 14 it is seen that GHEISHA can be distinguished from UrQMD and FLUKA.

To better quantify the discriminating power of $\langle r_\mu \rangle$, the commonly used Merit Factor can be used. It is defined as:

$$\text{Merit Factor} = \frac{|\langle r_\mu \rangle_a - \langle r_\mu \rangle_b|}{\sqrt{\sigma_a^2 + \sigma_b^2}}, \quad (4)$$

Fig. 14. $\langle r_\mu \rangle$ as a function of DX for three low energy hadronic interaction models. All simulated energies are included. All simulated primary particles are included (p, N, Fe). Bottom panel shows the difference with relation to the average value. High energy hadronic interaction model is QGSJetII-04. The detector resolution is set to 20% for S_μ^{sur} and 10% for S_μ^{bur} . Points were artificially shifted in DX for clarity.

where a and b refer to any two hadronic interaction model combination and the σ 's are the standard deviations of $\langle r_\mu \rangle$.

Fig. 15 shows the Merit Factor as a function of DX for the same experimental resolutions and statistics described above. The left-hand panel refers to hadronic model combinations with different high energy models, and on the right-hand panel with different low energy models. The best Merit Factor is 3.0 between EPOS-LHC and QGSJetII-04 and 2.3 between FLUKA and GHEISHA.

Figs. 16 and 17 show the Merit Factor as a function of the number of events and detector resolution for one particular DX bin: 300 < DX (g/cm²) < 400. The resolutions on S_μ^{sur} and S_μ^{bur} were re-scaled by a common factor f , being that $\sigma_{\text{bur}} = 0.1fS_\mu^{\text{bur}}$ and $\sigma_{\text{top}} = 0.2fS_\mu^{\text{top}}$. The effect of the number of events was calculated by re-scaling the standard deviation of the muon densities by a factor $\sqrt{N_{\text{sim}}/N}$, where N_{sim} is the number of simulated showers and N is the number of showers in each case.

Fig. 16 shows that it is possible to reach large Merit Factor values (>5) for the separation between EPOS-LHC and QGSJetII-04/Sibyll2.3 using a reasonably small number of events (<6000) considering realistic detector resolutions ($\sigma_{\text{bur}}/S_\mu^{\text{bur}} < 0.06$ and $\sigma_{\text{top}}/S_\mu^{\text{top}} < 0.13$). On the other hand, the separation between Sibyll2.3 and QGSJetII-04 is small for any resolutions and number of events, which is expected because of their similar values of η . The same conclusions can be drawn about the low energy hadronic interactions models from Fig. 17. $\langle r_\mu \rangle$ provides a very good separation between FLUKA and GHEISHA/UrQMD, but the separation power is limited for GHEISHA and UrQMD.

6. Conclusions

This paper studies the ground muon energy spectrum of air showers and proposes an analysis procedure to constrain hadronic interaction models used in Monte Carlo simulations. In Section 3, it was shown that the energy distribution of muons at ground level can be well described by an asymmetric Gaussian function with four parameters. The study of the evolution of the four parameters with DX concluded that the overall shape of the energy spectrum of muons does not depend strongly on the combination of low and

Fig. 15. Merit Factor calculated for two different hadronic interaction model combination as a function of DX . Left panel shows the cases in which the high energy hadronic interaction models are different and the low energy one is the same, FLUKA. The legend indicates the two hadronic models considered to calculate the Merit Factor. Right panel shows the cases in which the low energy hadronic interaction models are different and the high energy one is the same, QGSJetII-04.

Fig. 16. Merit Factor as a function of the number of events and detector resolution. Detector resolution are defined as $\sigma_{bur} = 0.1fS_{\mu}^{bur}$ and $\sigma_{top} = 0.2fS_{\mu}^{sur}$. The Merit Factor is given in the color scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 17. Merit Factor as a function of the number of events and detector resolution. Detector resolution are defined as $\sigma_{bur} = 0.1fS_{\mu}^{bur}$ and $\sigma_{top} = 0.2fS_{\mu}^{sur}$. The Merit Factor is given in the color scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

high energy hadronic interactions models. Also, it was verified that the average muon energy, or the parameter η , is sensitive to the model combination and presents a strong evolution with DX .

However, η is not an easy parameter to be measured. Therefore in Section 4 a new and experimentally motivated parameter (r_{μ}) is proposed and its correlation with η is shown. r_{μ} dependencies on the primary mass and energy were proven to be insignificant which allows on to disentangle the composition and the hadronic interaction studies as well as minimize the effect of systematic uncertainties in the energy reconstruction.

The general properties of the current and proposed muon detectors of the Pierre Auger Observatory are considered to study r_{μ} under realistic experimental limitations. Section 5 shows that the discrimination power of r_{μ} is significantly large. EPOS-LHC can be separated from Sibyll2.3 and QGSJetII-04 with large Merit Factor (>5) using a reasonably small number of events (<6000). Sibyll2.3 and QGSJetII-04 show similar average muon energy at ground and therefore can, in the best case, be discriminated with Merit Factor ~ 2 with about 9000 events. As for the low energy hadronic

models, FLUKA can be separated from GHEISHA and UrQMD with large Merit Factor (>5) using a reasonably small number of events (<6000). GHEISHA and UrQMD can, in the best case, be discriminated with Merit Factor ~ 0.8 with about 9000 events. It was shown that correlated systematic uncertainties on S_{μ}^{sur} and S_{μ}^{bur} have insignificant influence on $\langle r_{\mu} \rangle$. Uncorrelated opposite systematics of order of 2.5% can generate a systematic uncertainty on $\langle r_{\mu} \rangle$ of the same order of the separation between the hadronic interaction models. This means that for a realistic application of r_{μ} analysis, the systematic uncertainties on the muon densities measured by the two detectors have to be correlated (more realistic case). If the systematic uncertainties of the two detectors are in opposite directions (less realistic case) they have to be smaller than 2.5% in order to keep the discrimination power of the hadronic interaction models.

It was also shown that r_{μ} is a very robust parameter which can be used irrespective of ignorance of the primary mass composition to test the hadronic interaction models. Constraints imposed by an analysis based on r_{μ} can in a short period of time contribute to the

solution of the known problems with muon production in extensive air shower [20,21].

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6 Hadron production in pion-carbon interactions

In this chapter we present the analysis of hadron production in π^- -C interactions measured by the NA61/SHINE experiment at CERN SPS. In Sec. 3.1.2 we have stressed the importance of $\pi^\pm$ -air interactions for the EAS development and particularly for the muon production. The carbon target was selected here because of its similarity with air nuclei in terms of nuclear mass and because its experimental advantages with respect to nitrogen or oxygen targets.

Our goal is to measure the production spectra of $\pi^\pm$, $K^\pm$, $p(\bar{p})$, $\Lambda(\bar{\Lambda})$ and K_S^0 . Although our measurements of the $p(\bar{p})$ spectra can impact directly the current understanding of the EAS physics, all the particle spectra measured here will be surely valuable for the testing of the hadronic interaction models and for the tuning of their next generation. Besides that, the $\Lambda(\bar{\Lambda})$ and K_S^0 spectra have also an important role on reducing the systematic uncertainties on the $p(\bar{p})$ spectra.

The unprecedented π^- -C data analyzed here were taken by the NA61/SHINE detector at two beam momenta, 158 and 350 GeV/c. The large detector acceptance that covers a large region of the forward phase space makes the NA61/SHINE the ideal detector for this kind of study. A previous analysis of the π^- -C data with the measurements of resonance mesons was published in Ref. (141). In particular, the obtained ρ^0 spectra is also relevant for EAS physics and muon production.

The analysis presented in this chapter can be essentially split in two parts. One of them is dedicated to the measurements of the $\pi^\pm$, $K^\pm$ and $p^{\pm*}$ spectra and the other to the $\Lambda(\bar{\Lambda})$ and K_S^0 spectra. The former will be labeled along the text as the *charged hadron analysis* and its most challenging step includes the particle identification through the measurements of the deposit energy of the particles. On the other hand, the analysis of the latter group of particles will be labeled by *V^0 analysis*, being the signal extraction based on m_{inv} spectra the most challenging step. Although the two analyses were in practice done separately, the analysis steps that are conceptually the same will be presented here only once.

The charged hadron analysis was already in development at the time this work started. The previous stages of the analysis can be seen in Refs. (88, 142–144). Particularly, the event and track selection used here was based on previous works of Martin Ruprecht (145) and the dE/dx fit strategy was based on previous works of Hans Dembinski.

* Throughout this text protons and anti-protons will eventually be represented by p^+ and p^-

Concerning the V^0 analysis, there was no previous development and the whole analysis was done by the author of this thesis in collaboration with Dr. Michael Unger. A preliminary stage of the present analysis was published in Ref.(10).

The NA61/SHINE experiment is first described in Sec. 6.1 and the data and simulations used for this analysis in Sec. 6.1. In Sec. 6.3 and Sec. 6.4 we present the event selection and the phase space binning, respectively. The particle identification step for the charged hadron analysis and the V^0 analysis are presented in Sec. 6.5 and Sec. 6.6, respectively. In Sec. 6.7 we describe the Monte Carlo correction step, in Sec. 6.8 we describe the derivation of the particle spectra and finally in Sec. 6.9 we show the results. We summarize and conclude in Sec. 6.10.

6.1 NA61/SHINE experiment

The NA61/SHINE (9) is a fixed target experiment located in the North Area of the CERN SPS. Its proposal was accepted in 2006, a pilot run took place in 2007 and the first physics run in 2009. Most of its detector components were inherited from the NA49 experiment (146), which was shut down in 2003.

The physics programme of NA61/SHINE is very rich, including heavy ion, neutrino and cosmic ray physics. All these different fields have in common the need for precise hadron production measurements, which can be provided by NA61/SHINE experiment. The main goals of the heavy ion programme is the study of the properties of the onset of deconfinement (discovered by NA49 (147)) and the search for the critical point of strongly interacting matter. Concerning the neutrino physics programme, the hadron production spectra in hadron-nucleus collisions measured by NA61/SHINE are required to improve the neutrino flux predictions for the T2K experiment (148). Finally, the goal of the cosmic rays physics programme is to study the properties of the π -C interactions, which is of highly value for the better understanding of the EAS physics and, in particular, the muon production (see Chap. 3 for more details).

Its large acceptance is the main experimental feature of the NA61/SHINE detector. A set of five Time Projection Chambers (TPCs) can provide a high efficiency charged particle tracking. A magnetic field partially covering the TPCs allows the reconstruction of the particle momenta and charge while the energy loss measurements by the TPCs allows for the particle identification. At the bottom of Fig. 6.1 we show the configuration of the beam detectors as set for the π^- -C data taken and on the top we show the configuration of the main part of the NA61/SHINE detector. The coordinate system used in all NA61/SHINE analysis is also shown in Fig. 6.1. The axis defined by the beam direction is represented by the z coordinate, while the x-y plane is the perpendicular to this direction.

A brief description of the beam and the detector components relevant for the present

analysis follows in the next sections. Some important components, like the Time-of-Flight detectors, are not described here for the sake of brevity. A detailed description of the experiment is given in Ref. (9).

Figure 6.1 – Experimental setup of the NA61/SHINE experiment. (9)

Source: ABGRALL. (9)

6.1.1 Beam

The CERN SPS is able to provide to the North Area experiments primary proton or ion beams of maximum energy of 450 GeV/u. To generate the π^- secondary beam, a primary proton beam of 400 GeV from SPS is first collided against a 10 cm long beryllium target. This collision occur about 500 m upstream the NA61/SHINE detector. The secondary charged particles produced are then transported through the H2 beamline. During the transportation, a number of collimators and magnets are responsible for selecting the momentum of the beam particles as well as controlling their intensity and trajectory. For the data analyzed in this work, the π^- beam was generated with two beam momenta, 158 and 350 GeV/c.

6.1.2 Beam detectors and trigger system

The beam detectors and the components of the trigger system are shown on the bottom of Fig. 6.1. Most of them are placed upstream of the target, being the S4 the only exception. A set of three plastic scintillation counters are labeled as S1, S2 and S4. The components V0, V1 and $V1^p$ are called veto detectors and they are also scintillation counters but with a role in the beam trajectory. These veto detectors are used in the trigger system in anti-coincidence so the beam particles that pass away from the expected beam trajectory are removed.

Two trigger modes defined based on the scintillation counter measurements are relevant for this work. The first one is the *beam trigger*, denoted in this text as T1 and defined as $S1 \wedge S2 \wedge \overline{V0} \wedge \overline{V1} \wedge \overline{V1^p}$, which means that S1 and S2 are considered in coincidence and V0, V1 and $V1^p$ in anti-coincidence. The second relevant trigger is the *interaction trigger*, denoted as T2 and defined as $T1 \wedge \overline{S4}$. The S4 detector in anti-coincidence removes events in which a beam particle crossed the target without interacting. Evidently, a small fraction of the inelastic interactions can produce a high energy particle that reaches S4 and in these cases, the event is not accepted. The resultant bias is taken into account on the Monte Carlo correction step (see Sec. 6.7).

The three Beam Position Detectors, indicated as BPD in Fig. 6.1, are proportional chambers that are able to measure the traverse position of the beam particles. Two important functions of the BPDs are to constrain the traverse position of the interaction vertex and to define the incident angle of the beam particle on the target. Besides that, the information about the spread of the beam particles on the tranverse plane is used as a offline cut to assure the selection of good quality events (see Sec. 6.3).

A further beam detector is the CEDAR, that is also shown in Fig. 6.1. It is a Cherenkov detector and its functionality is to identify the beam particle. After the secondary beam particles are selected and transported to the NA61/SHINE detector, the purity of the π^- beam is about 95% and 100% for the 158 and 350 GeV/c case, respectively. The CEDAR information is then used as an offline cut to assure that the interacting particle is indeed a π^- .

6.1.3 Time projection chambers

In Fig. 6.1 one can see the position of the five TPCs, which form the main part of the NA61/SHINE detector. Two of them are the vertex TPCs, called VTPC-1 and VTPC-2. Placed in between VTPC-1 and VTPC-2 there is the GAP-VTPC (or only GTPC). The other ones are the left and right components of the main TPCs, which are called MTPC-L and MTPC-R.

The VTPC-1 and VTPC-2 are located inside two superconducting dipole magnets.

The produced magnetic field is responsible for bending the particle trajectories, which allows us to measure the sign of the particle charge as well as its momentum. To optimize the geometrical acceptance, the intensity of the magnetic field is set depending on the beam momentum. For the π^- -C data taken at 158 and 350 GeV/ c , the magnetic field was set to 1.5 and 1.1 T in the first and second magnets, respectively.

All the TPCs are filled with a gas mixture of Ar/CO₂ in the proportion of 90/10 for the VTTCs and GPTC and 95/5 for the MTTCs. The particle tracking is possible by collecting the electrons freed by the ionization of the gas atoms because of the passage of the charged particle. These electrons are drifted along the y direction under the influence of an electric field and collected by a set of readout pads on the top of the TPCs. The electrons collected in the pads are grouped in time to form the so called clusters. While the position of the pads gives the x and z coordinates of the cluster position, the y coordinate is reconstructed by its drifting time. By combining the position of many clusters measured along the TPCs, we can reconstruct the trajectory of the charged particles. The combination of the clusters associated to one particle is called track.

Besides the particle tracking, the TPCs can also measure its ionization energy loss. These measurements are done by combining the total charge of all the clusters that compose a track and a unique value of dE/dx is defined for each particle. The dE/dx measurements allow the main particle identification procedure applied in NA61/SHINE analyses (more details about that are given in Sec. 6.5.2). A technical description of the TPCs of the NA61/SHINE can be found in Refs. (9, 149).

6.2 Data and simulation sets

The π^- +C data were collected by NA61/SHINE in 2009 at two beam momenta: 158 and 350 GeV/ c . The carbon target consisted of an isotropic graphite plate with 2 cm thickness along the beam axis, with density of $\rho = 1.84$ g/cm³. The target position was set to 80 cm upstream of VTTC-1. To estimate the contribution of interactions that occur with the detector material, about 10% of the data were taken with the target removed. In Sec. 6.8 we describe the procedure applied to subtract the effect of the out-of-target interactions from the measured spectra. The calibration of the π^- +C data followed the standard NA61/SHINE procedure, described in Ref. (150).

The Monte Carlo simulation sets used in the present analyses were produced by the NA61/SHINE Collaboration. They were created by first generating the primary interactions using hadronic interaction models and then by passing the produced particles through a detailed detector simulation based on GEANT3 package. (151) Three hadronic interaction models were used: EPOS 1.99 (89), DPMJET 3.06 (108) and QGSJET II-04. (105) For each beam momentum and hadronic interaction model, a simulation set was produced with approximately the same number of events as in data. Both data and simulations were

reconstructed by the standard NA61/SHINE reconstruction chain. (152)

6.3 Event selection

The event selection can be divided into upstream and event cuts. The upstream cuts are based on the measurements of the beam detectors and, since these detectors are not implemented in the Monte Carlo simulations, these cuts were applied only to the data. The upstream cuts are:

- (i) the *CEDAR cut* to identify the beam particle type and then remove the contributions from non-pion particles;
- (ii) the *WFA cut* that uses the time information from the S1 detector to exclude events in which a second beam particle was detected within a time interval shorter than $2\ \mu\text{s}$;
- (iii) the *BPD cut* that uses the information from the three BPD detectors to assure a good quality measurements of the beam position at the target plan.

More details about the upstream cuts can be found in Ref. (145).

The event cuts that were applied to both data and simulations are:

- (i) the *trigger cut* to select events of the T2 type (see Sec. 6.1.2 for the trigger definitions);
- (ii) the *main vertex cut* to remove events in which the main vertex was not properly fitted in the event reconstruction;
- (iii) the *main vertex z-position cut* (or only *vertex z cut*) to remove events in which the z coordinate of the fitted main vertex is farther than 17 cm from the main vertex position measured by the BPD detectors.

The vertex z cut (item (iii)) was applied to reduce the contribution of interactions that occur out of the target. Because of the resolution on the fitted main vertex z position, a small fraction of interaction which occurred in the target are also removed by this cut. This bias effect is estimated and corrected in the Monte Carlo correction step (see Sec. 6.7). In Tab. 6.1 we show the number of events after the event selection for the data and simulation sets.

6.4 Phase space binning

Both charged hadron and V^0 analyses were performed by splitting the data into 2-dimensional phase space bins of the p and p_T variables. For the charged hadron analysis a unique phase space binning was defined. The p intervals are nearly uniform in $\log_{10} p$.

Table 6.1 – Number of events after the event selection for the data and simulation sets and for both beam momenta, 158 and 350 GeV/c.

	158 GeV/c	350 GeV/c
Data (target inserted)	2.78×10^6	2.59×10^6
Data (target removed)	6.80×10^3	6.12×10^3
EPOS 1.99	3.59×10^6	3.04×10^6
DPMJET 3.06	3.89×10^6	3.46×10^6
QGSJET II-04	3.56×10^6	2.95×10^6

Source: By the author.

Only small adjustments were done to move the crossing points of the energy deposit function of different particles closer to the center of the bins. Since some of these bins in the crossing regions will be removed from the analysis (see Sec. 6.5.6), this strategy has shown effective to reduce the number of removed bins. The average width of the $\log_{10} p$ intervals is $\Delta \log_{10} p = 0.1$. Concerning the p_T intervals, the bin width increases with p_T , being the width of the shorter and the longer ones $\Delta p_T = 0.1$ and $\Delta p_T = 0.5$, respectively. In Fig. 6.2 we show the phase space binning used for the charged hadron analysis.

Figure 6.2 – Illustration of the phase space binning used for the charged hadron analysis.

Source: By the author.

Because the V^0 analysis is done independently for the three target particles, the phase space binning is not required to be unique. However, because the statistics is similar for Λ and $\bar{\Lambda}$, the same binning was defined for these two particles. For either $\Lambda(\bar{\Lambda})$ or K_S^0 the p intervals vary from $\Delta \log_{10} p = 0.2$ to 0.3 . Concerning the p_T intervals, the widths vary from $\Delta p_T = 0.2$ to 0.8 . In Fig. 6.3 we show the binning used for the V^0 analysis.

6.5 Particle identification for the charged hadron analysis

In this section we present the particle identification analysis to obtain the spectra of $\pi^\pm$, $K^\pm$ and $p^\pm$. This step is done in a track basis through the dE/dx measurements,

Figure 6.3 – Illustration of the phase space binning used for the V^0 analysis. The plot on the left shows the binning used for Λ and $\bar{\Lambda}$ and the plot on the right shows the binning used for K_S^0 .

Source: By the author.

being the aim here to determine the fraction of tracks which correspond to each particle type on every phase space bin. The track selection is first described in Sec. 6.5.1 and a brief overview of the dE/dx measurements is then given in Sec. 6.5.2.

The dE/dx measurements only allow the particle identification to be done statistically by fitting the dE/dx distributions with a combination of particle types. Because of the complicated dependence of the dE/dx distributions on the particle momentum, track properties (e.g. number of clusters) and detector properties (e.g. resolution and calibration), the dE/dx fit turns to be a very challenging step. The first requirement to perform is the development of an appropriate dE/dx model. This step is described in Sec. 6.5.3.

Having in hands the dE/dx model, the measured dE/dx distributions can be fitted to determine the particle fractions. However, the usual large number of model parameters, added to the overlap of the dE/dx distributions of different particles in certain phase space regions, can make this fit very hard to perform. Our fit strategy developed to overcome these difficulties is shown in Sec. 6.5.4 and the results of the fit in Sec. 6.5.5. A new tool developed in this work to evaluate the fit performance and estimate biases and statistical uncertainties of the fit is presented in Sec. 6.5.6. This tool is called *Simulated Data Ensembles* and it is also used to define cuts on problematic phase space bins and to compute correction factors. Finally, in Sec. 6.5.7, we show the results of the particle identification analysis, including the particle fractions of $\pi^\pm$, $K^\pm$ and $p^\pm$.

6.5.1 Track selection

A set of selection criteria were applied to the measured tracks aiming to ensure the quality of their reconstruction. The list of selection criteria is the following.

- (i) The reconstructed track must be contained in the detector acceptance, that is defined based on two criteria. First, Monte Carlo simulations are used to define regions of the (ϕ, p, p_T) phase space in which the selection efficiency is larger than 90%. Second, the measured tracks are used to define regions of the same phase space in which the tracks hit directly the S4 detector. The final acceptance is then defined by the (ϕ, p, p_T) bins which do not satisfy any one of these two criteria. (145)
- (ii) The total number of clusters on the track must be greater than or equal to 25.
- (iii) The sum of clusters on both VTPCs must be greater than or equal to 12, or the number of cluster on the GTPC must be greater than or equal to 6.
- (iv) The distance between the extrapolated track to the interaction plane and the interaction point must be smaller than 4 cm on both horizontal and vertical plane.

The acceptance selection (item (i)) is important because it was observed that the Monte Carlo simulations cannot describe accurately the detector efficiency in the phase space regions in which this efficiency is relatively low ($<90\%$). (145) Since the detector acceptance is the dominant effect to be corrected at the Monte Carlo correction step, this discrepancy between data and simulations could significantly bias the resultant spectra if the acceptance selection was not applied.

After the track selection, the measured tracks were split into two subsets called Right Side Tracks (RST) and Wrong Side Tracks (WST). The former group is defined as the tracks that bend away from the beam axis, while the latter as the tracks that bend towards the beam axis. Given the track ϕ angle and its charge q , the two groups can be defined by the sign of the product $q \times \cos(\phi)$, where RST have positive sign ($q \times \cos(\phi) > 0$) and WST have negative ones ($q \times \cos(\phi) < 0$). The distinction between the two track topology is motivated by the fact that a right and a wrong side track, with the same p and p_T , cross different regions of the detector, which in turn have important implications on the particle identification step based on the dE/dx measurements (see Sec. 6.5). In Fig. 6.4 we illustrate the RST and WST definitions.

6.5.2 dE/dx measurements

The dE/dx is defined as the energy lost by the particle to the medium per unit of length. In NA61/SHINE, the dE/dx is measured by the TPCs, which collect the freed electrons from the ionization of the gas by the passage of the charged particles. The determination of the dE/dx from the signal recorded at the TPCs requires a complex and detailed procedure that has been very well established by the NA49 and NA61/SHINE experiment along the last decades. Since the detailed description is out of the scope of this text, only the general idea and the most important aspects will be presented in the next paragraphs. More complete and detailed approaches can be found in Refs. (153–155).

Figure 6.4 – Illustration of the RST and WST definitions (see text for details). (145)

Source: RUPRECHT. (145)

Several processes can contribute to the energy loss of charged particle due to its interaction with atoms of the gas in the TPCs, being the emission of electrons by ionization the most relevant one. The electrons emitted are drifted through the chamber and collected in the readout pads, which records the signal as ADC charges. A cluster is defined as a set of consecutive charges. The total charge measured for each cluster is related to the dE/dx of each track. However, numerous detector effects have to be corrected at the cluster level before grouping the clusters in one unique dE/dx value. The simplest correction accounts for the geometrical differences due to the particle incident angle in the pad and the pad widths. More complicated corrections account for differences in the electronic gain and gas pressure/temperature of the pads, differences in the sector gains and losses of electrons during the drift in the chambers and in the readout pad. A detailed description of the correction procedure can be found in Ref. (156).

The track dE/dx is then determined by the combination of the corrected charges from all track clusters. Because of the well known Landau-like shape of the energy loss probability distribution, the average and the variance of the measured charges are not well behaved for typical number of clusters ($\sim 20-150$). This makes the simplest approach, by defining the track dE/dx as the average charge over all cluster, not suitable. To overcome this issue and to obtain a satisfactory dE/dx resolution, the method of the truncated mean is applied, in which only a subset of the clusters is selected to compute the average. The selected clusters are defined by ordering the values of the charge and then selecting the ones inside a given fractional interval. For the NA61/SHINE experiment it was found the optimal interval being the 50% of the clusters with the smallest charges. (155)

It is important to point out that, although the dE/dx associated to a track is proportional to the energy lost by the particle, these two quantities are not exactly the same. This means that the measured $\langle dE/dx \rangle$ as a function of p does not follow the theoretical Bethe-Bloch function, but it does behave in a very similar way. Because of this

similarity, the functional form of the Bethe-Bloch function is used here to parametrize the $\langle dE/dx \rangle$ evolution with p . In Fig. 6.5 we show the distribution of the measured dE/dx as a function of the track p together with the $\langle dE/dx \rangle$ parametrization for several particle types. This parametrization was developed for this analysis and it is an important element for the dE/dx model and the dE/dx fit presented in Secs. 6.5.3 and 6.5.4.

Figure 6.5 – dE/dx data used in this analysis. Positively and negatively charged tracks are shown respectively in (a) and (b) for the 158 GeV/c data set, and in (c) and (d) for the 350 GeV/c one. The solid curves show the $\langle dE/dx \rangle$ parametrization for each particle type.

Source: By the author.

6.5.3 dE/dx model

To perform the dE/dx fit, a model to describe the dE/dx distributions of different particle types as a function of their momenta is required. While experiments like ALICE (157) and CMS (158) opt for modeling the dE/dx distributions with templates (159,160), the NA49 and NA61/SHINE experiments traditionally adopt an analytic model, which will also be adopted by us. Although the model chosen for our analysis is based on previous studies from NA49 and NA61/SHINE collaborations (154,155), it contains particular features that we have found to be the most suitable for the present analysis.

For clarification, we first present the notation adopted along this text. The particle types are represented by the index i , which can be one of the five particles $i = e, \pi, K, p$ or d . The positive and negative charges are indexed by j , so that $j = +$ or $-$. In addition, n_{cl} is used to represent the number of cluster of a track and the dE/dx is replaced by ε , for shortening.

The first element of our model is the probability density function of ε for a given particle type and charge, which is called here $f_{i,j}(\varepsilon)$. Because ε is obtained by averaging the measured charge over a certain number of clusters, it is natural to assume that the shape of $f_{i,j}(\varepsilon)$ depends on n_{cl} . To be more precise, the width of $f_{i,j}(\varepsilon)$ (or the ε resolution) should decrease with increasing n_{cl} , and vice-versa. Furthermore, the mean of $f_{i,j}(\varepsilon)$ is expected to evolve with the particle momentum p by following a Bethe-Bloch-like function. Given its n_{cl} and p dependencies, f can be taken as a conditional probability function, so it can be written as $f_{i,j}(\varepsilon|p, n_{\text{cl}})$.

It has been verified that $f_{i,j}(\varepsilon|p, n_{\text{cl}})$ can be well represented by an asymmetric Gaussian function. (155) Thus, we can write

$$f_{i,j}(\varepsilon|p, n_{\text{cl}}) = \frac{1}{\sqrt{2\pi}\sigma_{i,j}} \exp \left[-\frac{1}{2} \left(\frac{\varepsilon - \mu_{i,j}}{\delta \sigma_{i,j}} \right)^2 \right], \quad (6.1)$$

with

$$\delta = \begin{cases} 1 - d, & \varepsilon \leq \mu_{i,j} \\ 1 + d, & \varepsilon > \mu_{i,j}, \end{cases} \quad (6.2)$$

where μ is the mode of the distribution, σ is its resolution and d is the asymmetry parameter. The p and n_{cl} dependencies are implicit on the parameters μ and σ , as will be explained next. The mode μ is related to the mean of ε ($\langle \varepsilon \rangle$) by

$$\mu_{i,j} = \langle \varepsilon \rangle_{i,j} - \frac{\sigma_{i,j}}{\sqrt{2\pi}} \left[(1 + d)^2 - (1 - d)^2 \right]. \quad (6.3)$$

The Bethe-Bloch parametrizations shown as colored curves in Fig. 6.5 give the $\langle \varepsilon \rangle$ as a function of p for a given particle type. In this model, this parametrization is used for reference and the value of $\langle \varepsilon \rangle$ from the parametrization is denoted by $\langle \varepsilon \rangle^{\text{BB}}$. To account for deviations from $\langle \varepsilon \rangle^{\text{BB}}$, our model includes a set of parameters called *calibration constants*, which are denoted by the symbol X . These parameters act as logarithmic shifts of the $\langle \varepsilon \rangle$ around $\langle \varepsilon \rangle^{\text{BB}}$ and they can in principle be applied to each particle and charge separately. However, to reduce the complexity of the model, we assume one global calibration constant for each charge, that follows the $\langle \varepsilon \rangle$ of the π distribution, and individual calibration constants for the other particle types, which are common for both charges. The $\langle \varepsilon \rangle$ for a given i and j is then given by

$$\langle \varepsilon \rangle_{i,j} = \begin{cases} \langle \varepsilon \rangle_i^{\text{BB}} e^{X_i^j} & (i = \pi) \\ \langle \varepsilon \rangle_i^{\text{BB}} e^{X_\pi^j} e^{X_i^j} & (i \neq \pi). \end{cases} \quad (6.4)$$

In total, the model includes 6 calibration constants: X_π^+ , X_π^- , X_e , X_K , X_p and X_d . The $\langle \varepsilon \rangle$ from Eq. (6.4) is used in Eq. (6.3) to compute $\mu_{i,j}$, which is in turn used in Eq. (6.1) to compute $f_{i,j}(\varepsilon|p, n_{\text{cl}})$.

The last ingredient of Eq. (6.1) to be described is the resolution $\sigma_{i,j}$. Its n_{cl} dependence is assumed to be of the form $\sigma \sim 1/\sqrt{n_{\text{cl}}}$. Besides that, $\sigma_{i,j}$ is also assumed to depend on the $\langle \varepsilon \rangle$ by a power law relation. The overall scale of $\sigma_{i,j}$ is given by its normalization parameter σ_0 , which is actually defined separately for each charge (σ_0^j). The final expression for the resolution is,

$$\sigma_{i,j} = \frac{\sigma_0^j}{\sqrt{n_{\text{cl}}}} \langle \varepsilon \rangle_{i,j}^\alpha, \quad (6.5)$$

in which 3 more parameters are included to the model: σ_0^+ , σ_0^- and α .

By combining Eqs. (6.2) to (6.5) with the Eq. (6.1), we obtain the probability density function of ε for each particle i and charge j . Apart from the 6 calibration constants, the model also includes a set of 4 *shape parameters*: σ_0^+ , σ_0^- , α and d . Altogether, there are 10 parameters that can be used as free parameters to perform the fit of the ε distributions.

6.5.4 dE/dx fit strategy

The fitting procedure is performed by means of a binned maximum-likelihood method. In the general case, 10 particle fractions (5 particle types and 2 charges) and 10 model parameters are taken as free parameters of the fit. Special cases in which one or more particle fractions are fixed to zero will be described later.

The ε data is first divided in bins of $\log_{10}\varepsilon$ of width $\Delta \log_{10}\varepsilon = 0.01$. The index k will be used to indicate these $\log_{10}\varepsilon$ bins. By using the standard Poissonian probability distribution function in which $n_{j,k}$ and $\nu_{j,k}$ are the observed and expected number of tracks in a given bin k and charge index j , the log-likelihood is then written as

$$l_0 = 2 \ln \mathcal{L} = 2 \sum_{j=+,-} \sum_{k=1}^K (\nu_{j,k} - n_{j,k} \ln \nu_{j,k}), \quad (6.6)$$

where $\mathcal{L}$ is the likelihood function, K is the number of $\log_{10}\varepsilon$ bins and the constant terms were neglected.

The expected number of tracks $\nu_{j,k}$ is computed by using the ε model. Since $f_{i,j}(\varepsilon|p, n_{\text{cl}})$ depends on p and n_{cl} , it has to be convoluted with the p and n_{cl} distributions of the measured tracks. To do that, the measured tracks are first split in bins of the variables $q = \log_{10}p$ and $z = 1/\sqrt{n_{\text{cl}}}$. These variables were chosen to provide a better sampling of the data along their bins. The distributions of the original variables, p and n_{cl} , contain undersampled tails which are not suitable for the convolution procedure.

Being l and m respectively the indexes for the bins of the variables q and z , the number of measured tracks in one (q, z) bin, for a given charge j , is denoted by $N_{j,l,m}$ and

the center of the bins are denoted by $\hat{q}_l$ and $\hat{z}_m$. In the next step, the partial cumulative distribution function in one k bin relative to one (q, z) bin is computed as

$$F_{i,j,k,l,m} = \int_{k^{\text{th}} \text{ bin}} f_{i,j}(\varepsilon | \hat{q}_l, \hat{z}_m) d\varepsilon, \quad (6.7)$$

where the limits of the integral are given by the $\log_{10} \varepsilon$ limits of the k th bin. Note that, instead of the original p and n_{cl} variables, the variables q and z are used to evaluate f .

The total cumulative distributions $C_{i,j}$ is computed by summing the contributions of all (q, z) bins, weighted by its respective number of measured tracks, as

$$C_{i,j} = \sum_{l=1}^L \sum_{m=1}^M N_{j,l,m} F_{i,j,k,l,m}, \quad (6.8)$$

where L and M are the number of l and m bins, respectively. The number of mathematical operations in this step can become very large depending on how large are L and M . As a consequence, the computing time can be impracticably long. On the other hand, too small number of bins can imply in an undesirable loss of precision in the results of the fit. In this work, it was found that $L = 5$ and $M = 15$ are suitable choices. The limits of the q and z binning were defined automatically by using the smallest and the largest values found on data.

Finally, the expected number of tracks in one k bin of charge j is computed by summing the contributions of all particle types weighted by its respective fraction $Y_{i,j}$,

$$\nu_{j,k} = \sum_{i=e,\pi,K,p,d} Y_{i,j} C_{i,j}. \quad (6.9)$$

This expression is then combined to Eq. (6.6) to determine l_0 .

In addition to l_0 , the final log-likelihood function, l , will also include terms of Gaussian constraints for the model parameters. (161) These are, by definition, Gaussian probabilities functions multiplying the original likelihood function $\mathcal{L}$. In terms of the log-likelihood functions, these constraints turn into quadratic terms of the form $[(b - b_c)/\sigma_b]^2$ added to l , where b can be one of the model parameters and b_c and σ_b are its estimated mean value and standard deviation, respectively. It is important to constrain the model parameters because the number of tracks in the ε distribution can be eventually very low for a number of phase space bins. In these cases, the lack of statistics combined to the large number of free parameters can make the fit impracticable if the constraints are not applied. Furthermore, the constraints are also important, even for bins with large statistics, in which the proximity of the position of ε distributions for two particles can create a partial degeneracy between the respective calibration constants, and consequently generate large instabilities in the fitting procedure.

The b_c and σ_b were estimated by performing the fit without including the Gaussian constraints and then evaluating the mean and standard deviation of the fitted model

parameters using the phase space bins in which the fit converged properly. By construction the mean value of the calibration constants are zero. An additional term was included to constrain the difference between global calibration constants for both charges (X_π^+ and X_π^-) aiming to avoid solutions in which one of the charges is largely shifted with relation to the other. The sum of the constraints on the model parameters are given by,

$$c_m = \left(\frac{X_\pi^+}{0.01}\right)^2 + \left(\frac{X_\pi^-}{0.01}\right)^2 + \left(\frac{X_e}{0.005}\right)^2 + \left(\frac{X_K}{0.005}\right)^2 + \left(\frac{X_p}{0.005}\right)^2 + \left(\frac{X_\pi^+ - X_\pi^-}{0.01}\right)^2 + \left(\frac{\sigma_0^+ - 0.4}{0.2}\right)^2 + \left(\frac{\sigma_0^- - 0.4}{0.2}\right)^2 + \left(\frac{\alpha - 0.75}{0.1}\right)^2 + \left(\frac{d - 0.05}{0.03}\right)^2 \quad (6.10)$$

Because of the very low fraction of deuterons, their fractions ($Y_{d,+}$ and $Y_{d,-}$) may not be well determined by the fit. As a consequence, we observed that for a number of phase space bins the fitted deuteron fractions do not make physical sense, which leads to a bias on the other particle fractions. To avoid this problem, the parameters $Y_{d,+}$ and $Y_{d,-}$ were also constrained. Their mean value is set to zero and their standard deviation to 0.02. Since the fraction for deuterons is always expected to be smaller than 0.01, the constraints are assumed not to bias the fit, being important only to forbid non-physical results in which $Y_{d,+}$ or $Y_{d,-}$ is much larger than this value. The term added is given by

$$c_d = \left(\frac{Y_{d,+}}{0.02}\right)^2 + \left(\frac{Y_{d,-}}{0.02}\right)^2. \quad (6.11)$$

The final log-likelihood function to be maximized is then given by

$$l = l_0 + c_m + c_d, \quad (6.12)$$

where l_0 , c_m and c_d are given by Eqs. (6.6), (6.10) and (6.11).

The maximization of l was performed by using the MINUIT package. (162) When fitting models with large number of free parameters, it is important to define suitable starting parameters to assure the convergence of the maximization and reduce the computing time needed for that. The starting parameters here are defined by means of preliminary fitting phases, in which a simplified fitting procedure is performed. In the first phase, only the model parameters are set free for the likelihood maximization and the fractions are computed in each step, for a given set of model parameters, by an analytic minimization of the χ^2 . In the second phase, the model parameters are fixed to the values obtained by the solution of the first phase and the fractions are obtained by the likelihood fit, which is performed separately for each charge. The starting parameters for the main fit is given by the model parameters obtained in the first phase and the fractions obtained in the second phase.

To simplify the fit and reduce the uncertainties on the fraction of particle of interest ($\pi^\pm$, $K^\pm$ and $p^\pm$), the fractions of deuterons and electrons were fixed to zero for phase

space bins with momentum above a certain limit. These limits were defined based on their asymptotic behavior observed by performing the fit setting all fractions free and the values are 3 and 70 GeV/ c for deuterons and electrons, respectively.

The RST and WST subsets were fitted separately (see Sec. 6.5.1 for the definitions). This is motivated by the fact that, for the same phase space interval, these two types of tracks are detected by different parts of the TPCs. Since the model parameters, mainly the calibration constants, are related to detector features, it is expected that the solutions of RST and WST present differences on the fitted parameters.

Since the number of tracks measured with the target removed is too small, the fitting procedure described above is not suitable for the this data set. The complexity of the model (or the large number of free parameters) combined with the poor statistics would strongly reduce the precision of the results, or even prevent the convergence of the maximization algorithm. To overcome this problem, the particle fractions from the target removed data were obtained by means of χ^2 minimization, in which all the model parameters were fixed to the value obtained from the target inserted data set fit. Since the model prediction is linear on the particle fraction, the minimization could be performed analytically.

6.5.5 dE/dx fit results

Examples of the fitted dE/dx distributions are shown in Figs. 6.6 and A.1. Although the fit was performed by the maximum likelihood method, the χ^2/ndf can still be used to evaluate the goodness of fit. In Figs. 6.7 and A.2, we show the χ^2/ndf distributions. One can see that the χ^2/ndf follow the expected trend, with average value around 1 and few bins with $\chi^2/\text{ndf} \sim 2 - 2.5$. Therefore, we conclude that the dE/dx model provides a good description of the data.

Examples of the calibration constants obtained by the fit of the RST and 158 GeV/ c data set are shown in Fig. 6.8. The remaining cases are shown in Figs. A.3 to A.5. As expected, in general they exhibit small deviations from zero. Furthermore, we can observe a systematic dependence with the phase space region, in particular with p_T . This dependence makes evident that there is indeed small differences on the dE/dx calibration in different regions of the TPCs. Therefore we can conclude that a single Bethe-Bloch parametrization would not provide a suitable description of the dE/dx data, which justify the inclusion of the calibration constants. Additionally, the RST and WST results are different, which proves the necessity of performing the dE/dx fit separately for both data sets.

Examples of the shape parameters for the RST and 158 GeV/ c data set are shown in Fig. 6.9 and the remaining cases are shown in Figs. A.6 to A.8. The parameters σ_0^+ and σ_0^- present only a weak phase space dependence, exhibiting values centered at 0.4,

Figure 6.6 – Examples of the fitted dE/dx distributions from the 158 GeV/c data set. On the top, the distributions of the (a) negatively and (b) positively charged tracks are shown for one phase space bin of the RST subset. On the bottom, the distributions of the (c) negatively and (d) positively charged tracks are shown for a different phase space bin of the WST subset. The values of the $\langle p \rangle$ and $\langle p_T \rangle$ for each phase space bin is indicated on the top of each plot. The black dots show the observed number of tracks, while the colored distributions are the results of the dE/dx fit of each particle type. On the bottom of each plot, we show the residual of the fit, defined as the difference between the observed and the expected number of tracks from the result of the fit, divided by the uncertainty of the observed number.

Source: By the author.

Figure 6.7 – χ^2/ndf of the dE/dx fit for the 158 GeV/c data set. The RST and WST are shown in (a) and (b), respectively.

Source: By the author.

and rarely smaller than 0.35 or larger than 0.5. Concerning the parameters α and d , a peculiar behavior is observed: a region of mid- p and mid- p_T clearly stands out from the average behavior. In this region, the asymmetry parameter d assumes negative values and the exponent α assume values smaller than the average. Since the source of this behavior is not well understood, a contribution to the systematic uncertainties due to that will be estimated. For that, the dE/dx fit was repeated with the parameters α and d fixed to their average values, one at a time, and the differences on the particles fractions were taken as the systematic uncertainty. See Sec. 6.8.2 for more the details.

Examples of the particle fractions for RST and 158 GeV/c with target inserted are shown in Fig. 6.10 and the remaining cases are shown in Figs. A.9 to A.11. From the fraction of the particle types π , K and p, it is clear that there are few p bins, between 1 and 5 GeV/c, in which the fitted fractions stand out from the overall behavior. This happens because of the overlap between the dE/dx distributions of two particle types can be too large, creating a degeneracy between their fractions in the fit. Since the particle fractions of these p bins are clearly not reliable, a special strategy had to be developed to approach this problem. In the next section we describe our strategy. The fractions from the target removed data set are shown in Sec. 6.5.7.

6.5.6 Simulated data ensembles, cuts and corrections

The Simulated Data Ensembles (SDEs) are large sets of simulations that reproduce the most relevant features of the data and are fitted by following exactly the same fit strategy described in Sec. 6.5.4. By analyzing the fit results of the SDEs, we can evaluate the fit performance in a statistical basis and then estimate biases and statistical uncertainties of the particle fractions.

The construction of one individual simulation set of a SDE starts by creating a new simulated track for each data track reproducing its properties like p , p_T and n_{cl} . This

Figure 6.8 – Calibration constants obtained from the dE/dx fit of the RST and 158 GeV/c data set.

Source: By the author.

means that the number of tracks contained in a phase space bin, as well as their p , p_T and n_{cl} distributions, is identical in the simulation and in the data. The second step is to associate a particle type to each simulated track. To do that we sample randomly one of the five possible types by assigning them weights that are derived from the particle fractions obtained from the dE/dx fit of the data. To avoid the statistical fluctuations on the fitted fractions, a smoothing process was performed in which a 2-dimensional fourth-degree polynomial function was fitted to the fractions. The fitted function is given

Figure 6.9 – Shape parameters obtained from the dE/dx fit of the RST and 158 GeV/ c data set.

Source: By the author.

by

$$f(p, p_T) = \sum_{n=0}^{n < 4} \sum_{m=0}^{m < 4} a_{nm} (\log_{10} p)^n p_T^m, \quad (6.13)$$

where a_{nm} are free parameters to be fitted. The fit was performed by using a traditional χ^2 method. In Fig. 6.11 we show few examples of the p_T projections of the fractions and the fitted polynomial function.

After sampling a particle type, the dE/dx associated to each track is sampled by following the dE/dx model. The model parameters are set as the ones obtained by the dE/dx fit of the data, which are shown in Sec. 6.5.5. A set of approximately 1000 simulation sets, for each beam momentum, was created by following the description above and fitted afterwards. As the result, we obtain the distributions of the fitted particle fractions for each phase space bin.

From the SDEs results, we can first evaluate the relative standard deviation of the fractions, defined as $\sigma_r = \sigma_Y / \langle Y \rangle$, where σ_Y is the standard deviation of the fraction Y and $\langle Y \rangle$ is its average value. In Fig. 6.12 we show one example of σ_r for the RST and 158 GeV/ c case. The remaining cases are shown in Figs. A.12 to A.14. Only $\pi^\pm$, $K^\pm$ and $p^\pm$ are shown because these are the particles of interest of this analysis. Second, we can evaluate the relative bias, defined as $\delta_r = \langle \Delta Y / Y \rangle$, where ΔY is the difference between

Figure 6.10 – Particle fractions obtained from the dE/dx fit of the RST and 158 GeV/c data set.

Source: By the author.

Figure 6.11 – Examples of the parametrization of the particle fractions to be used to create the Simulated Data Ensembles. The plots in (a) and (b) refer to the 158 GeV/c data set and in (c) and (d) to the 350 GeV/c one. The particle type, the RST/WST subset and the $\langle p_T \rangle$ are indicated on the top of each plot. The black dots show the particle fractions obtained from the dE/dx fit and the red curves show the result of the fit of the Eq. (6.13) to these fractions.

Source: By the author.

the fitted and the true fraction, being the former computed at the moment the particle types of the simulated tracks are sampled. In Fig. 6.13 we show examples of δ_r for the RST and 158 GeV/c case, while the remaining cases are shown in Figs. A.15 to A.17.

From the σ_r one can clearly see that for few p bins, mainly between 1 and 10 GeV/c, the fitted fractions present a very large relative standard deviation in comparison to the remaining phase space regions. This is because of the proximity between the mean of the dE/dx distribution of two particle types that cause a partial degeneracy between their fractions. The result of the dE/dx fit at these phase space bins are evidently not suitable and, because of that, they were removed from our analysis. To this aim, the bins with σ_r larger than 0.15 for $\pi^\pm$, and 0.25 for $K^\pm$ and $p^\pm$ were removed.

From the δ_r we can observe that there are regions of the phase space which presents a significant relative bias on the fractions. These regions are mainly the low statistic and the high p bins. In the latter case, the fractions are biased because the dE/dx distributions of all particle types approach to each other following the relativistic rise behavior of

Figure 6.12 – Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 158 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

the deposit energy function. Attempts were made to eliminate this bias by changing the fit strategy, however, we found no effective solution. Therefore, we have decided for a correction procedure based on the δ_r obtained from the SDEs. A multiplicative correction factors, called c , was computed and we show it in Fig. 6.14 for the RST and 158 GeV/c case, while the remaining cases are shown in Figs. A.18 to A.20. The phase space bins removed because of the large σ_r are shown as white bins.

Besides the cuts and corrections, the SDEs can also be used to compute the statistical uncertainties of the particle fractions. This was done by computing the standard deviation of fractions obtained from the SDEs. It is decided to use these values of standard deviation as the final statistical uncertainties of the fractions, instead of the the ones resulting from the fit procedure.

Figure 6.13 – Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 158 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

6.5.7 Particle identification results

After applying the cuts and corrections discussed in Sec. 6.5.6 we obtain the final particle fractions to be used to compute the spectra. In Fig. 6.15 we show examples of the particle fractions for the RST and 158 GeV/c data set, while the remaining cases are shown in Figs. A.21 to A.23. Only the three particle types of interest are shown: π , K and p. Each plot shows the fractions as a function of p for one p_T bin. The equivalent plots for the target removed data set are shown in Figs. A.24 to A.27.

Figure 6.14 – Correction factors (c , see the definition in the text) for the RST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure 6.15 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 158 GeV/c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

6.6 V^0 analysis

In this section we describe the part of our analysis focused on the identification of Λ , $\bar{\Lambda}$ and K_S^0 , which are also called here V^0 particles. Neutral weakly decaying particles with average decay length ($c\tau$) of order of few or tens of centimeters can be detected by NA61/SHINE experiment through their charged decay products. This type of particle is called V^0 particles because of the V -shape of the decay and their neutral charge. Although the V^0 particle itself does not create a track in the TPCs, the products of its decay may do, allowing us to reconstruct the position of the decay vertex and, by using the properties of the daughter tracks, identify the mother V^0 . Therefore, the detector acceptance depends strongly on geometrical factors because both daughter particles must create tracks on the TPCs and they must be well reconstructed. In Tab. 6.2 we list the three V^0 particles of interest of the present work together with the properties of their decay channel which is used here (daughter particle types and branching ratio).

The description of the standard algorithms applied by NA61/SHINE experiment to find and reconstruct the V^0 's can be found in Refs. (163, 164), while the particular V^0 selection applied to our analysis is described in Sec. 6.6.1. The identification of the V^0 particles is done by means of its invariant mass, which is given by

$$m_{\text{inv}} = \sqrt{m_+^2 + m_-^2 + 2(E_+E_- - \vec{p}_+\vec{p}_-)}, \quad (6.14)$$

where the indexes $+$ and $-$ refer to the positively and negatively charged daughter particles. Because of the large combinatorial background, which means that many tracks can be randomly combined and reconstructed as V^0 particles, a signal extraction step is needed. This is usually done by fitting the measured m_{inv} distribution with a model that includes the signal and the background components. Our signal extraction strategy is presented in Sec. 6.6.2, the V^0 cuts in Sec. 6.6.3 and the signal extraction results in Sec. 6.6.4.

Table 6.2 – List of the V^0 particles of interest of this work, together with their masses and the properties of their relevant decay channel. (15)

V^0 particle	mass [GeV/ c^2]	decay products	branching ratio
Λ	1.1157	$p + \pi^-$	63.9%
$\bar{\Lambda}$	1.1157	$\pi^+ + \bar{p}$	63.9%
K_S^0	0.4976	$\pi^+ + \pi^-$	69.2%

Source: By the author.

6.6.1 V^0 selection

The V^0 selection criteria are the following.

- (i) The selected vertex must be identified as a V^0 type vertex.

- (ii) The number of daughter tracks of the vertex must be equal to 2.
- (iii) Both daughter tracks must be of opposite charges.
- (iv) The total number of cluster has to be greater than 30 for both tracks
- (v) At least one track has to have more than 15 clusters in the VTPCs

These selection criteria are standard ones in NA61/SHINE analyses. (165,166) Besides the above selection, two further V^0 cuts will be applied to the V^0 candidates before the signal extraction. Since these cuts were optimized to improve the signal extraction and they might depend on the phase space region, we will describe them separately in Sec. 6.6.3.

Unlike in the case of the track selection for the charged hadron analysis (see Sec. 6.5.1), it is not possible to define a detector acceptance selection for the V^0 's. Therefore, the possible discrepancies between the acceptance of the data and simulations will be accounted on the systematic uncertainties (see Sec. 6.8.2). Since the border of the acceptance contains typically short tracks (small number of clusters) the systematic uncertainty will be estimated by varying the minimum number of clusters on both tracks from 30 to 20.

6.6.2 Signal extraction strategy

The signal extraction is done by fitting the m_{inv} distribution with a model that includes the signal and the background contributions. Traditionally in NA61/SHINE analyses the signal is modeled by analytic functions like Breit-Wigner or Gaussian functions. (165,166) However, because of difficulties in describing properly the K_S^0 signal, we have decided to use here Monte Carlo templates instead. Moreover, it was found that for few K_S^0 phase space bins, the signal description is very poor when using only one single template. As a solution, a double template approach was preferred. The simulations used to build the templates were described in Sec. 6.2 and they include most of the expected detector effects. It was observed that the choice of the hadronic interaction model has an insignificant impact on the shape of the templates. Because of that, the templates were filled with the three of them to increase the template statistic. For the background description we have decided for the standard approach, using generic polynomial functions. It was observed that a second-degree polynomial function provides a satisfactory description of the background. A third-degree polynomial function was used to estimate the systematic uncertainties of the background shape description (see Sec. 6.8.2).

The fit is performed by a likelihood method assuming Poissonian distributions for the entries of the m_{inv} distribution. The log-likelihood to be maximized is analogous to the one shown in Eq. (6.6), however the notation is simpler because the only index is the one that refers to the m_{inv} bin. This index will be represented by i , the total number of m_{inv} bin by I and the value of m_{inv} in the center of the bin by m_i . Also, the expected

value of the particle mass is represented by m_0 . Thus, being n and ν the observed and expected number of entries, respectively, the log-likelihood function is given by

$$l_0 = 2 \ln \mathcal{L} = 2 \sum_{i=1}^I (\nu_i - n_i \ln \nu_i). \quad (6.15)$$

The expected number ν_i is given by the sum of the signal and background model as

$$\nu_i = T_i + f_i^{\text{BG}}, \quad (6.16)$$

where T_i is given by the templates and

$$f_i^{\text{BG}} = p_0 + p_1(m_i - m_0) + p_2(m_i - m_0)^2. \quad (6.17)$$

The contribution of one template evaluated at a given mass m is represented by $t[m]$. The templates contain the same number of bins as the data distribution (I) and $t[m]$ is computed by a linear interpolation of the two bins with closest centers to m . To allow for the shifting of the templates, an offset parameter δm was added. In the end, after summing the contributions of the two templates, T_i is computed as

$$T_i = S_{\text{fit}} \left(\alpha t[m_i + \delta m^0] + (1 - \alpha) t[m_i + \delta m^1] \right), \quad (6.18)$$

where S_{fit} , α , δm^0 and δm^1 are free parameters to be fitted. The parameter α can be interpreted as the fraction of the signal that is attributed to one of the templates. Since the templates are normalized, S_{fit} gives directly the amount of signal in the distribution.

By combining the Eqs. (6.16) to (6.18) with Eq. (6.15) we have the log-likelihood function l_0 with 7 free parameters, which are p_0 , p_1 and p_2 for the background and S_{fit} , α , δm^0 and δm^1 for the signal.

Similarly to what was done for the dE/dx fit, here we also include Gaussian constraints to improve the fit stability. The parameters to be constrained are the mass offsets (δm^0 and δm^1) and the fraction α . In the former case the intention is to avoid solutions of the fit in which the templates largely shift. It is expected offsets of order of few MeV/ c only and it was observed that, without the constraints, there could be solutions with offsets much larger than this, which are physically unacceptable. The constraint on the α parameter is important for cases in which the signal is well described by one template only and consequently α becomes degenerated. The constraint term is given by

$$c = \left(\frac{\delta m^0}{0.001} \right)^2 + \left(\frac{\delta m^1}{0.003} \right)^2 + \left(\frac{\alpha}{0.2} \right)^2, \quad (6.19)$$

where the δm^0 and δm^1 is given in GeV/ c^2 units. Finally, the log-likelihood to be maximized is given by

$$l = l_0 + c, \quad (6.20)$$

where l_0 and c are given by Eq. (6.20) and Eq. (6.19), respectively.

The maximization of l was done by using the MINUIT package. (162) The width of the m_{inv} bins was 1.5 and 3.0 MeV/ c^2 for $\Lambda(\bar{\Lambda})$ and K_S^0 , respectively, and the mass range was $[1.095 \text{ GeV}/c^2, 1.160 \text{ GeV}/c^2]$ and $[0.42 \text{ GeV}/c^2, 0.580 \text{ GeV}/c^2]$ again for $\Lambda(\bar{\Lambda})$ and K_S^0 , respectively. For each beam momentum data set, the templates were filled with the three simulation sets, generated by different hadronic interaction models.

As results of the fit, we obtain the estimated signal S_{fit} , and the average background B_{fit} , which is the integral of the background function over all the mass range of the fit. To avoid possible bias due to misdescription of the signal by the templates, the final signal will not be taken as S_{fit} . Instead, we compute it as $S = N - B_{\text{fit}}$, where N is the total number of entries in the m_{inv} distribution. By doing this, we assume that the background estimation is more precise than the signal one. The statistical uncertainty on S is given by $\sigma_S = \sqrt{N + \sigma_{B_{\text{fit}}}^2}$, where Poissonian fluctuations are assumed for N and $\sigma_{B_{\text{fit}}}$ is obtained as a result of the fit.

To determine suitable starting parameters for the fit, a preliminary phase was performed by means of a χ^2 fit. In this case, the signal model is simplified and only one template is used without allowing for any offset. In this way the whole model turns to be linear on the fitting parameters and the χ^2 minimization can be done analytically. The results of the χ^2 fit is then used to compute the respective parameters to start the final fit.

Because the number of selected V^0 's is substantially smaller at the target removed data set, a special strategy for the signal extraction is required. First, the phase space binning was changed, so all the original p_T bins were merged into one unique bin for each p interval. Second, the m_{inv} fit was performed by means of an analytic minimization of the χ^2 in which only one template is used for the signal modeling, without allowing for a mass offset. Although it is known that this fitting procedure can produce biased results, it is only acceptable in this context because the statistical uncertainties due to the low statistics is surely much larger than the bias. After obtaining S from the m_{inv} fit, the target removed signal for each original p and p_T bin is obtained by assuming that the target removed data follows the same p_T dependence observed in the target inserted one.

6.6.3 V^0 cuts

The V^0 cuts were applied to the m_{inv} data to reduce the relative amount of background events, increasing the precision of the signal extraction. Two quantities are used here for the V^0 cuts, the radial impact parameter of the V^0 particle (b_r) and its decay distance (L_{decay}). The b_r is defined as $b_r = \sqrt{(0.5b_x)^2 + b_y^2}$, where b_x and b_y are the coordinates x and y of the projection of the V^0 particle trajectory at the target plane. The factor 0.5 on b_x is included because the spread of b_x is approximately 2 times larger than b_y . In Fig. 6.16 we show the b_r distribution separately for signal and background obtained

from simulations for all the phase space bins. We can observe that the b_r parameter of signal V^0 's are more concentrated at small values while the background ones show a longer tale. Because of that, an upper cut on b_r was defined to increase the signal-to-background ratio. This cut value is called b_r^{cut} and it was chosen to be 2 cm. The efficiency of this cut was observed to be larger than 90% for all the phase space bins.

Figure 6.16 – Impact parameter (b_r) distributions obtained with EPOS 1.99 simulations at 158 GeV/c. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). The efficiency of the cut is indicated by ε inside the plots.

Source: By the author.

The L_{decay} is defined as the distance between the position of the V^0 vertex and the main vertex. Since a large amount of the background V^0 's are formed by the combination of tracks that are actually produced in the main vertex, the background L_{decay} distribution tends to be more concentrated at small values. Therefore, an lower cut was imposed to L_{decay} to increase the signal-to-background ratio. The value of the cut is called $L_{\text{decay}}^{\text{cut}}$. Because of the physical dependence of the L_{decay} on the momentum of the particle, $L_{\text{decay}}^{\text{cut}}$ was defined as a function of the V^0 momentum and it was optimized to minimize the statistical uncertainty of the extracted signal. The optimization was done by first performing the m_{inv} fit with many values of $L_{\text{decay}}^{\text{cut}}$ and then evaluating $S^* = S/\varepsilon$ and its uncertainty σ_{S^*} , where ε is the efficiency due to the V^0 cuts (b_r and L_{decay} cut). Next, we found the value of $L_{\text{decay}}^{\text{cut}}$ that minimizes the relative uncertainty σ_{S^*}/S^* , which is denoted by $L_{\text{decay}}^{\text{cut, opt}}$. One example of σ_{S^*}/S^* as a function of $L_{\text{decay}}^{\text{cut}}$ is shown in Fig. 6.17, where $L_{\text{decay}}^{\text{cut, opt}}$ is indicated. The $L_{\text{decay}}^{\text{cut, opt}}$ found for all the phase space bins are shown in Figs. 6.18 and A.28 as a function of the V^0 momentum and the average over the p_T bins are shown as red markers. A fit of a linear function of $\log_{10} p$ to the average $L_{\text{decay}}^{\text{cut, opt}}$ is shown as a red curve. This function shows to describe in first order the momentum dependence of $L_{\text{decay}}^{\text{cut, opt}}$, and because of that, we have decided to use it to define the $L_{\text{decay}}^{\text{cut}}$.

The signal extraction described in Sec. 6.6.2 was performed using the m_{inv} distributions obtained after applying both V^0 cuts described above. The signal loss due to these cuts were taken into account at the Monte Carlo correction step, described in Sec. 6.7.

Figure 6.17 – Example of the relative uncertainty of the signal (σ_{S^*}/S^*) as a function of $L_{\text{decay}}^{\text{cut}}$, where the V^0 particle is Λ and the beam energy is 158 GeV. The $\langle p \rangle$ and $\langle p_T \rangle$ of the particular phase space bin is indicated on the plot.

Source: By the author.

Figure 6.18 – Optimization of the $L_{\text{decay}}^{\text{cut}}$ for the 158 GeV/c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). Individual phase space bins are shown as black markers, the average over p_T bins is shown as red markers.

Source: By the author.

6.6.4 Signal extraction results

Examples of the fitted m_{inv} distributions are shown in Figs. 6.19 and A.29 for the target inserted data set and in Figs. 6.20 and A.30 for the target removed one. The reduced χ^2 of the m_{inv} fit of the target inserted data sets are shown in Figs. 6.21 and A.31. Since the values of χ^2/ndf are in all phase space bins around 1 and very few bins show $\chi^2/\text{ndf} \sim 1.5$, we can conclude that the measured m_{inv} distributions are well described by our m_{inv} model. The extracted signal S for the target inserted and removed data sets are shown in Figs. 6.22 and A.32.

Figure 6.19 – Examples of the fitted m_{inv} distributions for the 158 GeV/c data set with target inserted. Two phase space bins are shown for Λ in (a) and (d), for $\bar{\Lambda}$ in (b) and (e) and for K_S^0 in (c) and (f). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. Additionally, in green and purple we show the contributions of the two separated templates. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ and $\langle p_T \rangle$ of the phase space bin are indicated on the top of each plot.

Source: By the author.

Figure 6.20 – Examples of the fitted m_{inv} distributions for the 158 GeV/c data set with target removed. One p bin is shown for Λ in (a), for $\bar{\Lambda}$ in (b) and for K_S^0 in (c). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ of the phase space bin is indicated on the top of each plot.

Source: By the author.

Figure 6.21 – χ^2/ndf of the m_{inv} fit of the 158 GeV/c data set for the target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f).

Source: By the author.

Figure 6.22 – Extracted signal S for the 158 GeV/c data set with target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f).

Source: By the author.

6.7 Monte Carlo corrections

The measured number of events, tracks and V^0 particles in a given phase space bin are naturally biased by multiple detector effects. To determine the final spectra, these effects must be corrected, and that is done by applying a correction factor obtained from Monte Carlo simulations. This factor is called here C_{MC} . For a given phase space bin, C_{MC} is basically the ratio between the generated and measured spectra and it is written as

$$C_{\text{MC}} = \left(\frac{n^{\text{gen}}}{N^{\text{gen}}} \right) / \left(\frac{n^{\text{sel}}}{N^{\text{sel}}} \right). \quad (6.21)$$

where N refers to number of events and n can be either the number of tracks, for the charged hadron analysis, or the number of V^0 's, for the V^0 analysis. The indexes “gen” and “sel” refer respectively to generated and selected quantities and, while the former is obtained directly from the Monte Carlo generators, the latter is obtained from the detector simulations, in which the reconstruction algorithm and selection criteria are exactly the same as the ones applied to data. For the sake of clarity, the C_{MC} can be split in the event and track/ V^0 contributions, which will be refereed as α and β . In this way, C_{MC} becomes

$$C_{\text{MC}} = \left(\frac{N^{\text{sel}}}{N^{\text{gen}}} \right) / \left(\frac{n^{\text{sel}}}{n^{\text{gen}}} \right) = \alpha / \beta. \quad (6.22)$$

The α factor is a property of the data set as a whole and, therefore, it is the same for both charged hadron and V^0 analyses. On the other hand, the β is a property of the phase space bin and it depends on the particle type ($\pi^\pm$, $K^\pm$ or $p^\pm$ for the charged hadron analysis and Λ , $\bar{\Lambda}$ or K_S^0 for the V^0 analysis).

The C_{MC} was determined here by using the three simulation sets generated with different hadronic interaction models (see Sec. 6.2). The α factor obtained is summarized in Tab. 6.3, where we show the values for each simulation set and their average value, which will be used in this work. The observed differences in the α factor due to the hadronic interaction models are expected mainly because of the large discrepancy between them in terms of particle multiplicities. As an illustration, we can take the DPMJET 3.06 case, in which the average multiplicity is fairly larger than the others and consequently the α is also significantly larger. This relation is caused mainly by two effects. First, the interaction trigger probability is larger on average because of the larger number of particles crossing the detector. Second, the vertex z cut (see Sec. 6.3) tends to remove less events since, with more detected particles, the fit of the main vertex tends to be more precise. The model dependence of the α will be accounted on the systematic uncertainties in Sec. 6.8.2.

The β factor for $\pi^\pm$, $K^\pm$ and $p^\pm$ is computed by the ratio of the generated and measured number of tracks. In Figs. 6.23 and A.33 we show the β for these particles. For the V^0 particles, $\Lambda(\bar{\Lambda})$ and K_S^0 , the β is computed as the ratio between the V^0 particles generated and measured in a given phase space bin. In Figs. 6.24 and A.34 we show the β

Table 6.3 – List of α factor (see text) computed by using different hadronic interaction models and its average value.

	158 GeV/c	350 GeV/c
EPOS 1.99	0.875	0.744
DPMJET 3.06	0.949	0.848
QGSJET II-04	0.868	0.721
Average	0.897	0.771

Source: By the author.

for these V^0 particles. It is important to note that the β factor for the V^0 particle also includes the effect of the V^0 cuts, presented in Sec. 6.6.3.

Figure 6.23 – β correction factor for the charged hadron analysis and for the 158 GeV/c data set. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure 6.24 – β correction factor for the V^0 analysis and for the 158 GeV/c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c).

Source: By the author.

The geometrical acceptance of the detector is the dominant contribution to the β factor for both charged hadrons and V^0 analysis. Smaller effects, but still significant, are related to the event selection, track and V^0 reconstruction efficiency, bin migration and feed-down from re-interactions and weak decays. The latter case means that a fraction of the measured particles are not produced in the main target interaction, but instead, in processes like interactions of secondary particles inside the target or in the detector material, or the decay of unstable particles which are produced in the main interaction. A special treatment to the feed-down from weak decays will be given in Sec. 6.7.1.

The model dependence of the β factor is only significant ($> 1\%$) for the contributions of the event selection and feed-down from weak decays. Concerning the event selection, the differences between the three models can reach up to 10% for few phase space bins, in which the contribution of both the T2 selection and the vertex z cut are accounted for. These differences will be taken into account on the systematic uncertainties of the spectra (see Sec. 6.8.2). The model dependencies of the β contributions due to feed-down from weak decays will be approached in next section.

6.7.1 Feed-down from weak decays

For the charged hadrons, the contribution of weak decays is null for the $K^\pm$ and can reach up to 20% for $\pi^\pm$ and $p^\pm$. Depending on the hadronic interaction model, the decay of K_S^0 can represent from 70 to 90% of the feed-down contribution of $\pi^\pm$, while the decay of $\Lambda(\bar{\Lambda})$ account for 5-10%. In the $p^\pm$ case, from 75 to 100% is due to the decay of $\Lambda(\bar{\Lambda})$. Since the $\Lambda(\bar{\Lambda})$ and K_S^0 production varies substantially among the hadronic interaction models, the model dependence on the β correction for $\pi^\pm$ and $p^\pm$ would be very large, which would also imply in large systematic uncertainties. To avoid that, the measured spectra of $\Lambda(\bar{\Lambda})$ and K_S^0 will be used here to correct the feed-down contribution from these particles.

The procedure adopted for that is based on a re-weighting of the simulated particles

which are produced from the decay of $\Lambda(\bar{\Lambda})$ and K_S^0 . This weight is determined by the ratio between the measured and the generated spectra of these particles for a given model. To also account for $\Lambda(\bar{\Lambda})$ and K_S^0 which were themselves produced by the decay of other weakly decaying particles, the ratio is computed by using the uncorrected spectra, which means basically the number of particles in a certain bin divided by the number of events. In Fig. 6.25 we show examples of the ratios for the three V^0 particles for the model EPOS 1.99 and beam momentum of 158 GeV/c. A parametrization of the ratio as a function of p and p_T was performed by using a log-normal function of p in which its parameters are interpolated as a function of p_T by a second-degree polynomial function. The result of the parametrization is also shown in Fig. 6.25.

Figure 6.25 – Ratio between the uncorrected measured and generated spectra, R , as a function of p . The markers show different p_T bins, and the colored lines show the result of the parametrization (see text for details). On the bottom of each plot, we show the residuals, which are defined as the difference between the observed value of R and the parametrization, divided by the uncertainty on the observed one. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and the K_S^0 in (c).

Source: By the author.

The weight given for the simulated particles is then computed by using the parametrization of the ratio between measured and generated spectra. A small model difference on the β due to feed-down from weak decay still remains after this re-weighting procedure because of the contribution of decay of particles which are not $\Lambda(\bar{\Lambda})$ or K_S^0 . These differences will be accounted on the systematic uncertainties of the spectra (see Sec. 6.8.2).

Concerning the feed-down from weak decays on the V^0 particle spectra, the effect is null for K_S^0 and can reach up to 25% for $\Lambda(\bar{\Lambda})$, in which the decaying particles are mostly $\Xi^\pm$, Ξ^0 , $\Omega^\pm$ (and their anti-particles). The model dependencies are also significant in this case and it will be accounted for on the systematic uncertainties of the spectra (see Sec. 6.8.2).

6.8 Spectra

The final double-differential spectra for each phase space bin is computed as

$$\frac{d^2n}{dpdp_T} = \frac{1}{\Delta p \Delta p_T} C_{MC} \frac{n^I - Bn^R}{N^I - BN^R}, \quad (6.23)$$

where:

- Δp and Δp_T are the widths of the phase space bin;
- C_{MC} is the Monte Carlo correction factor (see Sec. 6.7);
- The indexes I and R refer to target inserted and removed data sets, respectively;
- N is the number of events;
- n is the number of measured particles inside the phase space bin. For the charged hadrons ($\pi^\pm$, $K^\pm$ and $p^\pm$), n has to be computed by combining the results of the dE/dx fit of the RST and WST data sets. This was done by first computing the number of measured particles in each data set, which is given by the particle fraction obtained from the dE/dx fit multiplied by the total number of tracks in a bin. Second, we summed this measured number of particles of both data sets to obtain the final n . For the V^0 particles, n is directly given by the signal obtained from the signal extraction procedure;
- B is the target removed factor and it is meant to normalize both target inserted and removed data set to the same number of beam particles. Given the number of interaction events N_{T2} and the probability of a beam particle produce a interaction event P_{T2} , the number of beam particles for a given data set can be computed as $N_{beam} = N_{T2}/P_{T2}$. Thus, in this work, we compute the B factor as N_{beam}^I/N_{beam}^R and its values are 5.1 and 5.2 for the 158 and 350 GeV/c data sets, respectively. This procedure to subtract the target removed contribution follow the standard approach of NA61/SHINE analyses. More details can be found in Ref. (156).

In the Secs. 6.8.1 and 6.8.2 we describe the determination of the statistical and systematic uncertainties on the spectra and in Sec. 6.8.3 we describe the procedure to integrate the double-differential spectra over p_T .

6.8.1 Statistical uncertainties

The dominant contribution to the statistical uncertainties of the spectra is the uncertainty on the particle identification step for the charged hadrons and on the signal extraction step for the V^0 particles. Since the number of target removed tracks is substantially smaller than the target inserted ones, the statistical uncertainties on n^R was

neglected. The contribution of the C_{MC} because of the limited number of simulated events was taken into account, however, it is relatively very small.

6.8.2 Systematic uncertainties

The sources of systematic uncertainties will be listed separately for charged hadrons and V^0 analyses. First, the list of systematic uncertainties accounted for in the spectra of the charged hadrons is the following.

- The uncertainties related to the dE/dx model used for the dE/dx fit were estimated by redoing the fit with a different configuration of the model parameters and comparing the resultant spectrum to the standard one. The size of the uncertainties were taken as the differences between the extreme cases and the standard one. The new parameter configuration tested include cases in which (a) the center of the Gaussian constraints of the all the calibration constants were separately moved 2 standard deviation for both directions, (b) the parameter d was fixed to zero, (c) the parameter p was fixed to 0.7 and (d) both parameters d and α were fixed at the same time.
- The model dependence on the Monte Carlo correction factors due to the T2 event selection. Since both the number of events and tracks are affected by this selection, the model differences were estimated by combining both α and β factors. To compute the systematic uncertainties, we first isolated the contributions of the T2 selection on the correction factor, α_{T2} and β_{T2} , and then we computed the factor α_{T2}/β_{T2} for all the three models separately. The relative differences between the extreme values of α_{T2}/β_{T2} and the average one were used to define the relative systematic uncertainties.
- The model dependence on the Monte Carlo correction factors due to the vertex z cut in the event selection. The procedure here is totally analogous to the one described for the T2 selection.
- The model dependence on the Monte Carlo correction factor due to the feed-down from weak decays. Since the feed-down is corrected at the track level, only the β factor has to be taken into account. Because the feed-down correction was done by using the measured $\Lambda(\bar{\Lambda})$ and K_S^0 spectra (see Sec. 6.7.1), this contribution is very small. Similarly to what is done for the previous contributions, the factor β due to feed-down was computed isolated (β_{FD}) for all the models. Then, the relative differences on the factor $1/\beta_{FD}$ were used to define the systematic uncertainties.
- The differences on the spectra obtained by using only RST and WST data set separately. Since the dE/dx fit is already done separately, only the Monte Carlo

correction has to be repeated. The differences observed between RST and WST spectra are small, reaching 3% at most for few phase space bins, and they come from systematic differences between data and simulations. The systematic uncertainties here were estimated by taking the relative differences between RST/WST spectra and the combined one.

Second, the sources of systematic uncertainties accounted for in spectra of the V^0 particles are the following.

- The model dependence on the Monte Carlo correction factors due to the T2 event selection. The procedure here is exactly the same described for the charged hadron analysis.
- The model dependence on the Monte Carlo correction factors due to the vertex z cut in the event selection. The procedure here is exactly the same described for the charged hadron analysis.
- The model dependence on the Monte Carlo correction factor due to the feed-down from weak decays. The procedure here is exactly the same described for the charged hadron analysis.
- The shape of the background used on the m_{inv} fit step was changed from a second-degree to a third-degree polynomial function. In this case, only the signal extraction step had to be repeated and the systematic uncertainty were computed as the relative difference between the particle multiplicity obtained by the new background function and the standard one.
- The minimum number of cluster required on the daughter tracks on the V^0 selection was changed from 30 to 20. In this case, both the signal extraction and the Monte Carlo correction had to be repeated for the new V^0 selection. Again the systematic uncertainty was computed as the relative difference between the particle multiplicity obtained by the new selection and the standard one.

In Sec. 6.9, both statistical and systematic uncertainties are shown separately for the particle spectra.

6.8.3 Integration over p_T

The single differential spectra dn/dp can be obtained by integrating the double-differential spectra, given by Eq. (6.23), over p_T . Since the measured spectra do not cover all the p_T range, an extrapolation is needed to perform the integration. This was done by fitting the double-differential spectra as a function of the p_T for each p bin and then using the integral of the fitted function to extrapolate the measured spectra. In this work, we

have decided to use a function defined by a Gaussian function convoluted to an exponential one. The p_T integrated spectra is then computed by summing the measured spectra over all the available p_T bins and adding to it the integral of the fitted function over the remain p_T range. The final p_T integrated spectra results were limited to the p bins in which the fraction of the extrapolation is smaller than 5% of the total for the charged hadrons and 20% for the V^0 particles.

6.9 Results

Examples of the double-differential spectra are shown in Fig. 6.26 for the charged hadrons and in Fig. 6.27 for the V^0 particles. The full set of measurements are shown in Figs. A.35 to A.46 for the charged hadrons and in Figs. A.47 to A.52 for the V^0 particles. The statistical and systematic uncertainties are shown separately as black lines and gray bands, respectively. In red curves we show the fitted functions used to perform the extrapolation in p_T (see Sec. 6.8.3). These functions are shown only for p bins in which there are more than 3 measured p_T bins. Otherwise, it was not possible to perform the fit.

The p_T integrated spectra are shown in Figs. 6.28 and 6.29 for the charged hadron and in Figs. 6.30 and 6.31 for the V^0 particles. Again, the statistical and systematic uncertainties are shown separately as black lines and gray bands, respectively. In colored curves, the predicted spectra by the most currently used hadronic interaction models are also shown for comparison. The simulated spectra were computed by using the CRMC software (167) and the models shown are EPOS 1.99 (89), DPMJET 3.06 (108), SIBYLL 2.1 (106), SIBYLL 2.3 (107), QGSJET II-04 (105) and EPOS LHC. (58)

One can clearly see in the p_T integrated spectra that the p region covered by the measurements depends on the type of particle. For the charged hadron analysis, the main reason for that is the removal of phase space bins during the particle identification step (see Sec. 6.5.6). It was observed that the particle fractions obtained from the dE/dx fit are not reliable for these bins. For the V^0 analysis, the main reason is the lack of statistics, which imply on the impossibility to perform the signal extraction. Besides that, in both charged hadron and V^0 analysis the double-differential spectra were limited to phase space bin where the relative statistical uncertainty is smaller than 0.5.

The different contributions to the systematic uncertainties on the p_T integrated spectra can be seen in Figs. 6.32 and 6.33 for the charged hadron and in Figs. 6.34 and 6.35 for the V^0 particles.

6.10 Summary, discussions and conclusions

In this chapter we have presented the analysis of the hadron production in π^- -C interactions measured by NA61/SHINE experiment. The spectra of $\pi^\pm$, $K^\pm$ and $p^\pm$ were

Figure 6.26 – Examples of the double-differential spectra $\frac{d^2n}{dp dp_T}$ as a function of p_T for p bins. The $\langle p \rangle$ is indicated inside each plot. The black lines show the statistical uncertainties, while the gray bands show the systematic ones. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f).

Source: By the author.

obtained by means of a particle identification method based on the dE/dx measurements and the $\Lambda(\bar{\Lambda})$ and K_S^0 by means of the m_{inv} spectra analysis. Two data sets were analyzed with beam momenta 158 and 350 GeV/c.

Our results can be summarized by the Figs. 6.28 to 6.31, which show the differential spectra dn/dp as a function of p for $\pi^\pm$, $K^\pm$, $p^\pm$, $\Lambda(\bar{\Lambda})$ and K_S^0 . One can clearly see from these spectra the significant discrepancy between data and models, as well as between models themselves. The main reason for that is the previous non-existence of this kind of measurements to be used to tune the hadronic models. Therefore, the most important

Figure 6.27 – Examples of the double-differential spectra $\frac{d^2n}{dp dp_T}$ as a function of p_T for p bins. The $\langle p \rangle$ is indicated inside each plot. The black lines show the statistical uncertainties, while the gray bands show the systematic ones. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and the K_S^0 in (c)

Source: By the author.

contribution of this work is to provide unprecedented measurements that will be of great importance for the tuning of the next generation of models. As a consequence, the model predictions of the muon related EAS observables will surely become more precise.

For now, the implications of our results on the muon production in EAS can be roughly estimated. To do that, we can start by analyzing the $\pi^\pm$ production in π^- -C interactions. Although most of muons are produced by the decay of $\pi^\pm$, we can see in plots (a) and (b) from Figs. 6.28 and 6.29 that there is a great agreement between data and models, and therefore, no significant improvement on the muon production simulations is expected due to our $\pi^\pm$ spectra. The only model that shows not to be consistent with the $\pi^\pm$ spectra is DPMJET 3.06, which overproduce $\pi^\pm$ at low momenta regions.

Concerning the $K^\pm$ production, the observed data-model discrepancies are very significant. However, since only a small fraction ($< 10\%$) of the muons in EASs are produced by the decay of $K^\pm$, no strong effect on the number of muons is expected after the models are tuned by using our $K^\pm$ spectra.

The most relevant case to be discussed is surely the $p(\bar{p})$ spectra, since one of the hypothesis considered to explain the muon deficit in simulations is the potential underproduction of (anti)baryons in π -air interactions by the models. (89) From the plots (e) and (f) in Figs. 6.28 and 6.29 one can see that the shape of the p and $\bar{p}$ spectra is very different. This is explained by the fact that a large number of low momentum p are produced by the fragmentation of the target nucleus. Apart from this contribution from the target fragmentation, the p and $\bar{p}$ should be very similar. Because of that, to isolate the spectra of produced $p(\bar{p})$, we can take our conclusions from the spectra of $\bar{p}$ only. Thus, what we can observe is a very good agreement of the model EPOS 1.99 with our measurements, an underestimation of the $\bar{p}$ production by SIBYLL 2.1, SIBYLL 2.3 and QGSJET II-04, and an overestimation by EPOS LHC and DPMJET 3.06.

Figure 6.28 – Differential spectra dn/dp of the charged hadrons as a function of p for the 158 GeV/c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f).

Source: By the author.

Because there are models which agree very well with our measured $\bar{p}$ spectra, and also models which overestimate the $\bar{p}$ production, we can conclude that the simple hypothesis of the underproduction of (anti)baryons is very unlikely to explain the problem of the deficit of muons in EAS simulations.

Concerning our measured spectra of $\Lambda(\bar{\Lambda})$ and K_S^0 , apart from their relevance on the future tuning of the hadronic models, it is important to note their role on the reduction

Figure 6.29 – Differential spectra dn/dp of the charged hadrons as a function of p for the 350 GeV/c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f).

Source: By the author.

of the systematic uncertainties on the charged hadron spectra, in particular on the $p(\bar{p})$ ones. From plots (f) of Figs. 6.32 and 6.32 we can see that the systematic uncertainties on $\bar{p}$ spectra is now of order of 10%, due to the feed-down correction done by using the measurements of $\Lambda(\bar{\Lambda})$ spectra. By doing this correction using the Monte Carlo spectra, the systematic uncertainties would be of order of 20%. These differences can be observed by comparing the results presented here with the ones in Ref. (10).

Figure 6.30 – Differential spectra dn/dp of the V^0 particles as a function of p for the 158 GeV/c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and K_S^0 in (c).

Source: By the author.

Figure 6.31 – Differential spectra dn/dp of the V^0 particles as a function of p for the 350 GeV/c data set. The black circles show the measurements, while the black vertical lines shows the statistical uncertainties and the gray band shows the systematic ones. The colored curves show the predictions of the hadronic interaction models. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b) and K_S^0 in (c).

Source: By the author.

Figure 6.32 – Systematic uncertainties on the differential spectra dn/dp of the charged hadrons as a function of p for the 158 GeV/c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f).

Source: By the author.

Figure 6.33 – Systematic uncertainties on the differential spectra dn/dp of the charged hadrons as a function of p for the 350 GeV/c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The π^+ case is shown in (a), the π^- in (b), the K^+ in (c), K^- in (d), the p^+ in (e) and p^- in (f).

Source: By the author.

Figure 6.34 – Systematic uncertainties on the differential spectra dn/dp of the V^0 particles as a function of p for the 158 GeV/c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b), and the K_S^0 in (c).

Source: By the author.

Figure 6.35 – Systematic uncertainties on the differential spectra dn/dp of the V^0 particles as a function of p for the 350 GeV/c data set. The black circles show the total uncertainties and the colored symbols show the contributions of each source separately. The Λ case is shown in (a), the $\bar{\Lambda}$ in (b), and the K_S^0 in (c).

Source: By the author.

7 Summary

In this thesis the muon deficit problem was approached in three different fronts. In Chaps. 4 and 5 we presented simulation studies aiming to the development of methods to be applied in the analysis of measurements of future experiments with the presence of muon detectors, which includes AugerPrime. In Chap. 6 we presented the measurements of hadron production spectra in pion-carbon interactions by NA61/SHINE experiment. The importance of these type of interaction for muon production in air showers were pointed out in Sec. 3.1.2.

The main idea of the method presented in Chap. 4 is to explore the energy evolution of the moments of the N_μ to interpret the measurements in terms of composition in despite of the N_μ misprediction by the simulations. The first step of the method is the development of a model to describe the energy and the primary mass evolution of the moments of $\log_{10} N_\mu$ ($\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$) which capture the common behavior to the simulations with different hadronic interaction models (Sec. 2 of Chap. 4). This model also contains free parameters that represent the features which are discrepant with relation to the models (α and β). Second step is the selection of a set of composition scenarios that can be motivated by astrophysical models or by the measurements of other observables, like $X_{\max}$. These scenarios should predict the energy evolution of the abundance of different groups of primaries (Sec. 4 of Chap. 4). The next and final step is to compare the measurements of $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ with the prediction of the model considering different composition scenarios. The comparison is performed by a χ^2 parameter for $\langle \log_{10} N_\mu \rangle$ and $\sigma[\log_{10} N_\mu]$ separately and the free parameters of the model are used then to minimize the χ^2 . The minimum values of the χ^2 ($\chi^2_{\min}(a)$ and $\chi^2_{\min}(b)$) can be compared for different composition scenarios and the true scenario can be identified by the smallest values (Sec. 5 of Chap. 4).

To illustrate and test the method, a large set of simulated showers were used. Two simulation codes were applied, CONEX and CORSIKA. An algorithm to convert the N_μ from CONEX, which counts all the muons at ground above 1 GeV, to the one that takes into account a limited lateral distance range (between 500 and 2000 m) and a different muon energy threshold of 0.2 GeV, was developed by using CORSIKA showers to parametrize their relation (Sec. 3 of Chap. 4).

A consistency test of the method was performed by using these large simulation set. As a result, it was shown that the method can provide a very efficient identification of the true composition scenario. The muon deficit problem was considered by testing

the method using simulations in which the N_μ was artificially scaled by a given factor. Furthermore, the uncertainties due to the energy scale were also considered by scaling the shower energies in the simulations. The result of the method was shown to be stable under these both tests (Sec. 5 of Chap. 4).

In the analysis presented in Chap. 5, a set of CORSIKA simulations were first used to characterize the muon energy spectrum at ground and to study its dependencies on the energy and primary mass of the primary and on the hadronic interaction model. It was observed that the most relevant feature of the muon energy spectrum at ground to discriminate between hadronic models is given by its mode parameter (η), which evolves strongly with the DX of the shower. Next step was the proposal of a new observable (r_μ) which correlates with η and which can be measured by an experimental setup including two types of muon detectors, one at the surface and one buried few meters below the ground. These two types of detectors were based on the designed of the AugerPrime detectors.

By using CORSIKA simulations it was possible to test the applicability of r_μ measurements under realistic experimental conditions. For that, it was considered an array of the area of Auger infill and the experimental resolution on the measurements of the muon signal were considered based on simulation studies from the literature. As a final result, it was shown that the evaluation of the measured $\langle r_\mu \rangle$ as a function of DX can be efficiently used to constrain hadronic interaction models.

The last part of this thesis, presented in Chap. 6, contains the measurements of hadron production spectra in pion-carbon interactions by NA61/SHINE experiment. The main steps of the analysis are the event selections, particle identification, Monte Carlo correction and the computation of the spectra. The particle identification step was done separately for charged hadrons, by means of the fit of the dE/dx distributions, and for V^0 particles, by means of the signal extraction from the m_{inv} spectra.

The final results include the production spectra of $\pi^\pm$, $K^\pm$, $p(\bar{p})$, $\Lambda(\bar{\Lambda})$ and K_S^0 at two collision energies, 158 and 350 GeV. The spectra of $p(\bar{p})$ are of particular interest for muon production in air showers since one of the hypothesis to explain the muon deficit problem is that the current hadronic interaction models under-produce (anti)baryon in hadron-air interaction. From our results, it can be seen that a few current models actually predict well the p spectra, which is an indication that the underproduction of (anti)baryons is not the reason of the muon deficit problem. However, the strongest impact of our hadron production measurements on the muon production in air shower by simulations will be seen by the performance of the next generation of hadronic interaction models.

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Appendix

A Additional figures

Figure A.1 – Examples of the fitted dE/dx distributions from the 350 GeV/c dataset. On the top, the distributions of the (a) negatively and (b) positively charged tracks are shown for one phase space bin of the RST subset. On the bottom, the distributions of the (c) negatively and (d) positively charged tracks are shown for a different phase space bin of the WST subset. The values of the $\langle p \rangle$ and $\langle p_T \rangle$ for each phase space bin is indicated on the top of each plot. The black dots show the observed number of tracks, while the colored distributions are the results of the dE/dx fit or each particle type. On the bottom of each plot, we show the residual of the fit, defined as the difference between the observed and the expected number of tracks from the result of the fit, divided by the uncertainty of the observed number.

Source: By the author.

Figure A.2 – χ^2/ndf of the dE/dx fit for the 350 GeV/c data set. The RST and WST are shown in (a) and (b), respectively.

Source: By the author.

Figure A.3 – Calibration constants obtained from the dE/dx fit of the WST and 158 GeV/ c data set.

Source: By the author.

Figure A.4 – Calibration constants obtained from the dE/dx fit of the RST and 350 GeV/ c data set.

Source: By the author.

Figure A.5 – Calibration constants obtained from the dE/dx fit of the WST and 350 GeV/ c data set.

Source: By the author.

Figure A.6 – Shape parameters obtained from the dE/dx fit of the WST and 158 GeV/ c data set.

Source: By the author.

Figure A.7 – Shape parameters obtained from the dE/dx fit of the RST and 350 GeV/ c data set.

Source: By the author.

Figure A.8 – Shape parameters obtained from the dE/dx fit of the WST and 350 GeV/ c data set.

Source: By the author.

Figure A.9 – Particle fractions obtained from the dE/dx fit of the WST and 158 GeV/c data set.

Source: By the author.

Figure A.10 – Particle fractions obtained from the dE/dx fit of the RST and 350 GeV/c data set.

Source: By the author.

Figure A.11 – Particle fractions obtained from the dE/dx fit of the WST and 350 GeV/c data set.

Source: By the author.

Figure A.12 – Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 158 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.13 – Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 350 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.14 – Relative standard deviation (σ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 350 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.15 – Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 158 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.16 – Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the RST and 350 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.17 – Average relative bias (δ_r , see the definition in the text) of the particle fractions obtained with the SDEs for the WST and 350 GeV/c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.18 – Correction factors (c , see the definition in the text) for the WST and 158 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.19 – Correction factors (c , see the definition in the text) for the RST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.20 – Correction factors (c , see the definition in the text) for the RST and 350 GeV/ c case. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.21 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 158 GeV/c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.22 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 350 GeV/c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.23 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 350 GeV/c data set, with target inserted. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.24 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 158 GeV/c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.25 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 158 GeV/c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.26 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the RST and 350 GeV/c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.27 – Particle fractions obtained from the dE/dx fit, after applying the cuts and corrections (see Sec. 6.5.6), of the WST and 350 GeV/c data set, with target removed. Markers with different colors show particle types and negatively (positively) charged particles are shown in full (open) symbols. The $\langle p_T \rangle$ is indicated on the top of each plot.

Source: By the author.

Figure A.28 – Optimization of the $L_{\text{decay}}^{\text{cut}}$ for the 350 GeV/c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c). Individual phase space bins are shown as black markers, the average over p_T bins is shown as red markers.

Source: By the author.

Figure A.29 – Examples of the fitted m_{inv} distributions for the 350 GeV/c data set with target inserted. Two phase space bins are shown for Λ in (a) and (d), for $\bar{\Lambda}$ in (b) and (e) and for K_S^0 in (c) and (f). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. Additionally, in green and purple we show the contributions of the two separated templates. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ and $\langle p_T \rangle$ of the phase space bin are indicated on the top of each plot.

Source: By the author.

Figure A.30 – Examples of the fitted m_{inv} distributions for the 350 GeV/c data set with target removed. One p bin is shown for Λ in (a), for $\bar{\Lambda}$ in (b) and for K_S^0 in (c). The black markers show the measured m_{inv} distributions. The colored curves show the results of the fit, being the signal in blue, the background in red and the total in gray. On the bottom of each plot we show the residual distributions, being Δ the difference between observed and fitted number of entries and σ the uncertainties of the observed number. The $\langle p \rangle$ of the phase space bin is indicated on the top of each plot.

Source: By the author.

Figure A.31 – χ^2/ndf of the m_{inv} fit of the 350 GeV/c data set for the target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f).

Source: By the author.

Figure A.32 – Extracted signal S for the 350 GeV/c data set with target inserted (upper plots) and removed (lower plots). The Λ cases are shown in (a) and (d), the $\bar{\Lambda}$ in (b) and (e) and the K_S^0 in (c) and (f).

Source: By the author.

Figure A.33 – β correction factor for the charged hadron analysis and for the 350 GeV/c data set. The π^+ case is shown in (a), π^- in (b), K^+ in (c), K^- in (d), p^+ in (e) and p^- in (f).

Source: By the author.

Figure A.34 – β correction factor for the V^0 analysis and for the 350 GeV/c data set. The Λ case is shown in (a), $\bar{\Lambda}$ in (b) and K_S^0 in (c).

Source: By the author.

Figure A.35 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of π^+ for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the grey bands show the systematic ones.

Source: By the author.

Figure A.36 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of π^- for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.37 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of K^+ for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.38 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of K^- for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.39 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of p^+ for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.40 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of p^- for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.41 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of π^+ for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.42 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of π^- for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.43 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of K^+ for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.44 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of K^- for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.45 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of p^+ for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.46 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of p^- for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.47 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of Λ for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.48 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of $\bar{\Lambda}$ for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.49 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of K_S^0 for the 158 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.50 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of Λ for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.51 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of $\bar{\Lambda}$ for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.

Figure A.52 – Double-differential spectra $\frac{d^2n}{dp dp_T}$ of K_S^0 for the 350 GeV/c data set. Each plot shows one p bins and the value of $\langle p \rangle$ is indicated inside it. The black lines show the statistical uncertainties, while the gray bands show the systematic ones.

Source: By the author.