Universidade de São Paulo Instituto de Física

Estudo da Modificação de Jatos em Colisões entre Íons-Pesados Relativísticos

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Study of Jet Modification in Relativistic Heavy-Ion Collisions

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It is the nature of the idea to be communicated, written, spoken, done. The idea is like grass it craves light, likes crowds, thrives on crossbreeding, grows stronger from being stepped on.

Ursula K. Le Guin, The Dispossessed

The most important step a man can take. It's not the first one, is it? It's the next one. Always the next step, Dalinar.

Brandon Sanderson, Oathbringer

Abstract

The study of jets, algorithmic representations of collimated sprays of particles, in relativistic heavy-ion collisions can illuminate the underlying physics of heavy ion experiments, as the ones in the Large Hadron Collider (LHC) and Relativistic Heavy-Ion Collider (RHIC). These experiments enable the production of the Quark-Gluon Plasma, a new state of matter characterized by its extreme energy density and temperature, which modifies the hard-scattered partons traveling through it and, consequently, the jets they produce. Analyses regarding jets as the main subject may recover information about the medium and implications to the Quantum Chromodynamics (QCD) theory.

This work applies the Monte Carlo event generators JEWEL (Jet Evolution With Energy Loss) and PYTHIA for the simulation of observables comparable to current experimental research. The impact of a realistic description of the medium, provided by the state-of-the-art (2+1)D v-USPhydro code, in the azimuthal distribution and energy modification of jets is the main focus of this study. All observables are presented for central and peripheral lead-lead collisions at 5.02 TeV, following the experimental setup of the LHC Run-2, for anti- k_T jets with multiple jet radii R.

The jet nuclear modification factor R_{AA} simulated presents good agreement with experimental data for central collisions only. The evolution of the results in terms of centrality and R indicates a possibility of better understanding of medium response in the JEWEL framework. The realistic hydrodynamics models behave differently to JEWEL's longitudinal-only expansion, mainly in the circumstances where less quenching is expected.

The correlation between the jet azimuthal distribution and those generated by soft particles resulting from the realistic medium profiles enables the event-by-event calculation of higher-order jet anisotropic flow coefficients that can be compared to experimental measurements. The simulations show a transverse momentum-dependent elliptic flow v_2 and, for the first time, a positive triangular flow v_3 .

Keywords: High Energy Physics; Quark; Quantum Chromodynamics; Heavy-Ion; Hydrodynamics.

Resumo

O estudo de jatos, representações algorítmicas de sprays colimados de partículas, em colisões de íons pesados relativísticos pode elucidar questões fundamentais de experimentos do *Large Hadron Collider* (LHC) e o *Relativistic Heavy-Ion Collider* (RHIC). Esses experimentos possibilitam a produção to Plasma de Quarks e Gluons, um novo estado da matéria caracterizado por sua extrema densidade de energia e temperatura, que modifica o comportamento dos *partons* de alta energia durante sua propagação no meio e, consequentemente, os jatos que eles produzem. Análises focadas em jatos podem trazer informações sobre o meio e implicações para a Cromodinâmica Quântica (QCD).

Este trabalho aplica os geradores de eventos Monte Carlo JEWEL (*Jet Evolution With Energy Loss*) e PYTHIA para a simulação de alguns observáveis. O impacto de uma descrição hidrodinâmica mais realista do meio, provida pelo código (2+1)D v-USPhydro, nas distribuições azimutais e fatores de modificação nuclear de jatos é o foco principal deste estudo. Todos observáveis são apresentados para colisões centrais e periféricas de chumbo-chumbo a 5.02 TeV, seguindo as configurações experimentais da Run-2 do LHC, para jatos anti- k_T com múltiplos raios R.

O fator de modificação nuclear para jatos R_{AA} simulado reproduz satisfatoriamente resultados experimentais apenas para colisões centrais. A evolução dos resultados em termos da centralidade e R indica a possibilidade de um melhor entendimento da resposta do meio com o JEWEL. Os modelos com hidrodinâmica realista se comportam de forma distinta do meio com expansão apenas longitudinal do JEWEL, principalmente em configurações nas quais é esperado que os jatos percam menos energia.

A correlação entre as distribuições azimutais de jatos e aquelas geradas por partículas de baixa energia resultantes dos meios mais realistas permite o cálculo evento-por-evento de coeficientes de fluxo anisotrópicos de jatos para altas ordens que podem ser comparados a medidas experimentais. As simulações mostram um fluxo elíptico v_2 dependente do momento transverso e, pela primeira vez, um fluxo triangular v_3 positivo.

Palavras-chave Física de Altas Energias; Quark; Cromodinâmica Quântica; Ions Pesados; Hidrodinâmica.

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Chapter 1

Introduction

In the last decades, experiments from the Large Hadron Collider (LHC) located in the Organisation Européenne pour la Recherches Nucléaires (CERN) and the Relativistic Heavy-Ion Collider (RHIC) from the Brookhaven National Laboratory (BNL) have been pushing the field of high energy physics with the investigation of a extremely hot and dense state of matter that is created in relativistic heavy-ion collisions [1, 2]. This medium is known as the Quark-Gluon Plasma, a liquid-like phase of strongly-interacting matter that achieves energy densities so intense to the point of breaking down the hadronic structure that confines the quarks and gluons [3]. Hydrodynamic models have been successful in deepening the understanding of experimental observations regarding the expansion and cooling down of the QGP, which generates low-energy particles in the final state regarded as the soft sector [4].

Furthermore, heavy-ion collisions also contain hard scatterings, high-momentum transfers between partons in the early stages of the nuclear interaction, that are described by perturbative Quantum Chromodynamics (QCD) [5]. These particles evolve through the medium in a cascade-like process called parton shower and, consequently, are expected to suffer modification from the QGP [2]. Measurements regarding the generated final state of their evolution, a new object called jet, may recover aspects of the medium, thus this new entities could be used as probes of the decoupled matter [6]. However, it is unknown if they would be sensible to finer particularities of the QGP and its evolution, since high-energy partons can escape the medium with little to no interaction with it. The study of jet distributions, specially when compared to in-vacuum hard scatterings of proton-proton collisions, are one of the main approaches in current heavy-ion research.

The aim of this work is to investigate the interplay between these two objects, jets and the medium, via the comparison between observables generated by cutting-edge Monte Carlo event generators and experimental data.

The models JEWEL (Jet Evolution With Energy Loss) [7] and PYTHIA [8] provide a framework capable of modeling the whole partonic development in heavy-ions collisions, from the initial hard scattering, in-medium shower evolution, gluon emission and hadronization, to the observed final state. JEWEL limits itself to a simplistic smooth medium with longitudinal-only expansion and, although the framework found success with this ideal hypothesis [7, 9, 10, 11], it is expected to be improved by a more realistic medium simulation [12]. The state-of-the-art v-USPhydro code [13], an implementation of the Smooth Particle Hydrodynamics Lagrangian method [14], fills that gap by solving the viscous hydrodynamic equations of the QGP in the transverse plane event-by-event for different initial conditions.

The chosen observables were the nuclear modification factor R_{AA} and the anisotropic flow coefficients $v_{n=2,3,4}$. The former presents a way of directly quantifying the mediuminduced modification of the jet transverse momentum distribution by comparing it to the jet spectrum generated by proton-proton, i.e. no medium, collisions. The latter measures the correlation between jet and soft's azimuthal distribution and may elucidate characteristics of their interaction, such as path-length dependence in the jet energy-loss mechanism and the presence of fluctuations in the QGP's initial conditions. Although the observables, which are discussed for multiple centralities, models and jet radii, are associated with general properties of the collision, this work develops the tools necessary to expand the simulations to more differential observables, e.g. jet substructure ones.

The fundamental aspects of the theory and inner workings of the models are presented in Chapters 2, with a brief discussion of QCD and techniques to describe its consequences, and 3, focusing on the details of different initial conditions and hydrodynamic evolution hypotheses used for the description of the generated medium. Chapter 4 introduces the necessary steps and particularities of to execute the simulation and apply the jet algorithm. Finally, Chapters 5 and 6 present and discuss the obtained results, making direct comparisons with current experimental data.

Chapter 2

Theory Introduction

2.1 Quantum Chromodynamics

Quarks and gluons interactions are described by the non-Abelian gauge theory of Quantum Chromodynamics (QCD), named after its associate charge known as color. Its Lagrangian density is [5, 15]

$$\mathcal{L}_{QCD} = \sum_{k}^{N_f} \bar{\mathbf{q}}_k (i\gamma^{\mu} D_{\mu} - m_k) \mathbf{q}_k - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a.$$
(2.1)

The first term refers to the dynamics of gluons and quarks, where the covariant derivative $D_{\mu} = \partial_{\mu} + igA_{\mu}^{a}\frac{\lambda_{a}}{2}$ has the coupling constant g, gluon field A_{μ}^{a} and Gell-Mann matrices λ_{a} using a = 1 to 8 as the color index. The quark fields \mathbf{q}_{k} with masses m_{k} and k = 1 to N_{f} as the flavor index, have three color components, such that

$$\mathbf{q}_{k} = \begin{pmatrix} q_{k}^{red} \\ q_{k}^{green} \\ q_{k}^{blue} \end{pmatrix}.$$
 (2.2)

Gluon field dynamics are present in the second term following the gluon field strength tensor

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f_{abc} A^b_\mu A^c_\nu, \quad \left\lfloor \frac{\lambda_a}{2}, \frac{\lambda_b}{2} \right\rfloor = i f_{abc} \frac{\lambda_c}{2}, \tag{2.3}$$

where f_{abc} are the anti-symmetric structure coefficients of the Lie group SU(3).

The interaction strength behavior in multiple energy scales Q can be expressed by the



Figure 2.1: Creation of a new quark-antiquark pair by the breaking of the gluon flux tube of a previous pair. Particle momentum represented by the arrows. Diagram from [15].

introduction of the running coupling constant [5]

$$\alpha_s(Q^2) = \frac{2}{b_0 \ln(-Q^2/\Lambda^2)}, \quad \alpha_s = \frac{g^2}{4\pi}.$$
 (2.4)

with the QCD scale parameter $\Lambda \approx 0.2 - 0.3$ GeV [16] and a positive constant b_0^{1} .

Differently from Quantum Electrodynamics (QED) [5], the positive sign of b_0 implies that α_s decreases with Q^2 . For high momentum transfers or short distances, $Q^2 \gg \Lambda$, the resulting force is so small that quarks are expected to behave as free particles, a phenomenon known as asymptotic freedom, which is a property of non-abelian gauge theories [5]. In this regime, a perturbative theory is valid for the description of QCD (pQCD).

Another intriguing aspect of the theory is color confinement. Quarks and gluons are not observed in nature, only their colorless bound states, i.e. hadrons [16]. This non-perturbative process, illustrated by Figure 2.1, starts with the gluon field forming a flux tube, also referred as "string", between a pair of color-charged particles. Energy is provided to separate them and the string is elongated until a point that, due to the scaling of α_s with distance, is energetically preferable to create a new quark-antiquark pair than continue the separation. If there is available energy, such in high energy collisions, this procedure is repeated multiple times. Instead of observing an isolated member of the original pair, one would measure a group of hadrons that composes a new physical object called jet.

 $^{{}^{1}}b_0 = \frac{1}{6\pi}(11N_c - 2N_f)$, thus positive for $N_c = 3$ colors and $N_f \leq 16$ active flavors.

2.2 Quark-Gluon Plasma

Asymptotic freedom brings forth some interesting considerations on QCD matter. Hadronic behavior is expected to disappear in hot and dense systems in favor of quarks and gluons becoming the relevant degrees of freedom [17]. This change in state of matter, i.e. a phase transition, was consolidated by the understanding of chiral symmetry spontaneous breaking in the QCD theory [3, 17] and defines the transition of a hadronic gas (HG) phase to a new state of deconfined matter: the Quark-Gluon Plasma (QGP).

Extensive research at CERN [1] and RHIC [2] showed that the necessary conditions for the creation of QGP is achieved in relativistic heavy-ion collisions. The high temperature limit indicates that the matter should follow the expected behavior of a weakly interacting gas, but experimental results introduced by RHIC [2] imply a resemblance closer to a strongly interacting liquid². Jet quenching and collective flow are some examples of those observed effects [2] that are explored in this work.

Collective flow refers to system-wide aspects of momentum distributions of different particles and are presumed to arise from the density distribution of the generated medium [2]. This discovery, specially regarding elliptic transverse flow, is a direct evidence of hydrodynamic nature of QGP and pushed the demand for numerical solutions of the relativistic ideal fluid equations [18] capable of modeling it. Its key concepts are further discussed in Section 2.2.1 and Chapter 6.

Jet quenching is the reduction of jet energy in nucleus-nucleus (AA) collisions when compared to proton-proton (pp) ones. The behavior of partons coming from the hard scattering of nucleons should be modified if they travel through a non-transparent medium, thus the measured suppression in the transverse momentum spectra of jet constituents is an evidence of the medium's existence. Furthermore, these hard scattered partons are produced in the early stages of the collision and are expected to acquire relevant information about the medium as they evolve through it, hence they can be studied as probes³ of the QGP's characteristics [6]. The ratio between jet transverse momenta spectrum on AA and pp collisions, with any necessary rescaling, quantifies the modification the partons suffer throughout their medium evolution and is known as the observable nuclear modification factor R_{AA} , which is properly introduced in Chapter 5.

A simplistic picture of the evolution process, displayed in Figure 2.2, can be outlined as follows [3]:

²QGP and the nominated strongly-interacting QGP (sQGP) will be used interchangeably.

³Justifying the denomination of "hard probes".



Figure 2.2: Representation of the evolution of the QGP and its multiple steps. Taken from [4].

- 1. Two Lorentz-contracted nuclei collide and deposit entropy at $^{4} \tau = 0$ fm/c.
- 2. The medium achieves local equilibrium at a thermalization time $\tau_{th} \sim 1 \text{ fm/c}$. From this point forward, the object can be seen as a complete entity, thus starting the fluid-dynamical evolution of the Quark-Gluon Plasma with $\tau_0 \approx \tau_{th}$.
- 3. Phase transition between QGP and HG. In the limit of vanishing baryonic chemical potential μ_B , which is justified in high-energy collisions [2], the non-perturbative formalism of lattice QCD (LQCD) predicts a critical temperature $T_C \approx 0.14 0.17$ GeV [17]. How this step happens is still not properly understood [17] and no mixed phase shall be considered is this study.
- 4. At around $\tau_{fo} \sim 10$ fm/c, known as freeze-out time, the system is diluted enough that the hydrodynamic picture is no longer valid. Both chemical equilibrium, where inelastic processes vanish and particle identity is fixed until decay, and kinetic freezeout, where particles stop interacting altogether, are contained in this stage [3].
- 5. Final-state particles are detected, $\tau \sim 10^{15}$ fm/c.



Figure 2.3: From left to right: collision of two nuclei with an impact parameter b (a), initial-state anistropy of the entropy deposited by the event (b), and its transformation into an anistropy in the measured momentum of final-state particles (c). Figure from [19].

2.2.1 Anisotropic Flow

The entropy deposition due to the nuclear collision defines an initial condition (IC) with geometric characteristics in the tranverse plane. As illustrated in Figure 2.3, asymetric behavior in the coordinate space, i.e. any divergence from an isotropic circular overlap, is expected to be transferred to the momentum space of the generated particles by the hydrodynamic evolution, also known as soft particles. Those anistropies are quantified by n^{th} -order eccentricity \mathcal{E}_n with intensity ε_n and direction Φ_n in the polar coordinates (r, ϕ) [20], such that

$$\mathcal{E}_n \doteq \varepsilon_n e^{in\Phi_n} = \begin{cases} -\frac{\{r^3 e^{i\phi}\}}{\{r^3\}}, & n = 1\\ -\frac{\{r^n e^{in\phi}\}}{\{r^n\}}, & n \ge 2 \end{cases},$$
(2.5)

where the average is taken over the initial transverse energy density $\{...\} \doteq \frac{\int dx dy \epsilon(x,y)(...)}{\int dx dy \epsilon(x,y)}$. Each eccentricity is named accordinly to its impact on the overall IC's geometry, with \mathcal{E}_2 known as ellipicity, \mathcal{E}_3 as triangularity, \mathcal{E}_4 as quadrangularity, etc. The first six orders are represented in Figure 2.4.

Analogously, the collective behavior of the final-state particles in the momentum space is quantified by the harmonic flow $V_n \doteq v_n e^{in\Psi_n}$, with intensity v_n and direction Ψ_n , the called n^{th} -order symmetry plane. The azimuthal distribution of soft particles can be written in a Fourier series, such that [22]

$$\frac{d^2 N}{dp_T d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))$$
(2.6)

⁴The definition $\tau \doteq \sqrt{t^2 - z^2}$ shall be adopted for the longitudinal proper time.



Figure 2.4: Geometrical characterization of the first n^{th} -order eccentricities in the initial conditions of a nucleus-nucleus collision. Image from [21].

These concepts are also useful for the study of hard scatterings: as the generated hard partons transverse the medium, its geometrical characteristics imply differences in the possible paths of the partonic evolution, thus anistropies should also impact the momenta of the final observed jets. Equation (2.6) can be applied to calculate new coefficients, $v_n^{jet}(p_T)$, that contain information about the path-length dependance of the QGP's energy-loss mechanism for partons.

2.3 Parton Showers

Partonic evolution is described with factorized soft and collinear splittings into other partons. This branching behavior develops the scattered parton into a cascade of secondary radiations, which could be medium-induced, until hadronization. The whole procedure, known as a parton shower, is often used in Monte-Carlo event generators to further understand QCD and QGP physics.

Consider an event that produces n partons with cross section σ_n . If a new emission is independent from previous configurations and dominated by a 2-splitting term⁵, then the differential cross section for the process with an additional parton in the final-state is [7]

$$d\sigma_{n+1} = \sigma_n \frac{dt dz \alpha_s(p_T^2)}{2\pi t} \hat{P}_{ba}(z), \qquad (2.7)$$

with $\hat{P}_{ba}(z)$ being the Altarelli-Parisi splitting function [5] of an original parton a into a new parton b with fractional momentum z. The process is dictated by the evolution parameter t that has a linear dependence with the parton's virtuality and arranges the order of calculations inside the shower. Its definition is set by the event generator, e.g. for PYTHIA ≥ 6.4 , $t = p_T^2$, resulting in a momentum-ordered evolution while HERWIG has $t = E^2 \theta^2$, with the parton energy E and angle of splitting θ , implying a angular-ordered

⁵Either the parton branches into two or nothing happens.

one [23].

To avoid the divergences in the collinear limit, i.e. $t \to 0$, an infrared cut-off t_c scale must be introduced with the partonic momentum $p_T^2(t_c) \approx 1 \text{ GeV}^2$. Moreover, it is reasonable to fix an upper bound t_0 defined by the initial hard scattering, since no process should surpass it. The range of t and its choice of definition imply a boundary of z, such that $t \in [t_c, t_0] \Rightarrow z \in [z_{min}, z_{max}]$.

Multiple branchings, with a defined order relation $t_i > t_1 > t_2 > ... > t_f$, can be inserted in (2.7), resulting in the whole description of the factorization⁶. Its probabilistic form is described by the Sudakov factor, which can be interpreted as the probability of no resolvable, i.e. $1 - z \in [z_{min}, z_{max}]$, emission between t_i and t_f :

$$\mathcal{S}_a(t_i, t_f) \doteq \exp\left[-\int_{t_f}^{t_i} \frac{dt}{t} \int_{z_{min}}^{z_{max}} dz \sum_b \frac{\alpha_s(p_T^2)}{2\pi} \hat{P}_{ba}(z)\right].$$
(2.8)

The Sudakov form factor contains all the information needed for calculating new splittings. With the insertion of parton distribution functions (PDFs) $f_a(x,t)$, which represents the probability of finding the parton a with fractional momentum x in the t scale at leading order, the master equation⁷ of the evolution is [23]

$$\frac{d}{d\ln t}\ln\left(\frac{f_a(x,t)}{\mathcal{S}_a(t_c,x)}\right) = \sum_{b\in[q,\bar{q},g]} \int_x^{z_{max}} \frac{dz\alpha_s}{2\pi z} \hat{P}_{ba}(z) \frac{f_b(\frac{x}{z},t)}{f_a(x,t)}.$$
(2.9)

2.3.1 Medium Interaction

The description of the interaction with the Quark-Gluon Plasma can be achieved by considering the medium as a collection of partonic scattering centers with screening mass of m_{scatt} and density n_{scatt} , followed by the calculation of $2 \rightarrow 2$ elastic collisions between those centers and the traveling parton. With a well-defined cross section, a Monte Carlo (MC) implementation of the shower can add the medium interaction as an intermediate step between splitting, thus the whole evolution is modified.

A minimal approach to modeling the medium is to consider it as an ideal gas of massless gluons with temperature T and d_g degrees of freedom. The scattering centers'

⁶Often referred as "hardness"-ordering [7, 24] or "strongly"-ordered [5] branchings.

⁷This equation is derived similarly to the Altarelli-Parisi evolution equations [5] considering the parton-shower cut-off t_c . Further details are presented in [23].

properties are [25, 17]

$$n_{scatt}(T) = d_g T^3 \frac{\zeta(3)}{\pi^2},$$
 (2.10)

$$m_{scatt}(T) = \frac{\mu_D(T)}{\sqrt{2}}, \quad \mu_D(T) \approx 3T,$$

$$(2.11)$$

with the Debye thermal mass μ_D and the Riemann Zeta function ζ . Note that the medium and, consequently, the shower modification are heavily dependent on the QGP's temperature profile, therefore it is expected that a realistic thermodynamical description of the medium is imperative for the success of this interpretation, which shall be further explored in Chapter 3.

In terms of the Madelstam variables⁸ \hat{s} and \hat{t} [15], the interaction of a parton a and a scattering center b, with PDFs $f_{(a/b)}(x,t)$, is presented as [7]

$$\sigma_a(E,T) = \int_0^{|\hat{t}_{max}(E,T)|} d|\hat{t}| \int_{x_{min}(|\hat{t}|)}^{x_{max}(|\hat{t}|)} dx \sum_{b \in [q,\bar{q},g]} f_b(x,\hat{t}) \frac{d\hat{\sigma}_b}{d\hat{t}}(x\hat{s},|\hat{t}|),$$
(2.12)

$$\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t}) = \frac{C_R \pi \alpha_s (|\hat{t}| + \mu_D^2)}{\hat{s}^2} \frac{\hat{s}^2 + (\hat{s} - |\hat{t}|)^2}{(|\hat{t}| + \mu_D^2)^2}, \quad C_R = \begin{cases} \frac{4}{9}, & qq\\ 1, & qg, \\ \frac{9}{4}, & gg \end{cases}$$
(2.13)

where the maximum momentum transfer due to a parton with energy E and virtual mass m_p is, neglecting the scattering center's momentum, $|\hat{t}_{max}(E,T)| = 2m_{scatt}(T)[E - m_p]$. The cross section also depends on the color factor C_R , which varies for the particles involved. A full leading order exchange should also account for the *u*-channel diagram, which could be interpreted as a deposition of energy enough to start the propagation of the scattering center, i.e. a swapping between the two objects, but is ignored since it would need a different approach for medium response.

2.3.2 JEWEL and Coherent Gluon Emission

Jet Evolution With Energy Loss (JEWEL) [26, 7] is a MC event generator based on the BDMPS-Z⁹ formalism [27] that implements calculations for simulating QCD jet evolution. It solves virtuality-ordered, i.e. $t \doteq Q^2$ being the virtual mass squared of the parton,

⁸Defined as $\hat{s} \doteq (p_a + p_b)^2 = (p_{a'} + p_{b'})^2$ and $\hat{t} = (p_a - p_{a'})^2 = (p_b - p_{b'})^2$, with the incoming/outgoing momentum of the parton *a* as $p_a/p_{a'}$ and $p_b/p_{b'}$ for the scattered center *b*, which shall be considered a parton.

⁹Baier-Dokshitzer-Mueller-Peigné-Schiff and Zakharov.

parton showers of massless quarks with medium interaction as discussed above.

MC implementations usually are applied for systems that are "memoryless", i.e. they do not violate the Markov property of being dependent only on the current simulation step and not the previous ones. Quantum interference breaks this assumption, hence it must be treated separately in the model. In the case of JEWEL, the overlap of the formation time of in-medium gluon production τ_f results in interference with subsequent scattering processes [7, 28], so it must categorize the interactions as coherent or incoherent [29].

Let k_T be the gluon momentum, ω its energy at creation, s_T the momentum transfer with the next scattering center, and ΔL a MC defined distance to the next interaction, then a simplified picture of the algorithm is [29]

$$\tau_f \sim \frac{E}{t} = \frac{2\omega}{k_T^2}, \quad \begin{cases} \Delta L > \tau_f \Rightarrow \text{ incoherence: gluon is formed.} \\ \Delta L < \tau_f \Rightarrow \text{ coherence: } k_T \to k_T + s_T, \text{ repeat the calculation.} \end{cases}$$
(2.14)

A formed gluon is then propagated in the shower as a new free parton. This prescription replicates the non-abelian¹⁰ Landau-Pomeranchuk-Migdal (LPM) effect, which predicts a suppression in the bremsstrahlung of high energy gluons via destructive interference.

2.4 String Model of Hadronization

To leave no space for ambiguities, hadronization shall define the process of transforming a partonic state into a hadronic final system. As presented in Section 2.1, confinement can be visualized with the help of a gluon field string and the formation of new hadrons by its snapping, as seen in Figure 2.1. This idea is the motivation of a broad group of hadronization models, called string models and includes the extremely popular Lund model [31], that are briefly introduced in this section.

Hadronic mass spectroscopy experiments and calculations from LQCD indicate a way to quantify the this string mechanism, as they imply that the potential between a quarkantiquark $(q\bar{q})$ pair is dominated by a linear term at large distances [31, 32]. A string tension κ is introduced such that

 $V(r) \to \kappa r, \quad \kappa \approx 1 \text{ GeV/fm.}$ (2.15)

¹⁰The original formulation [30] showed the effect for QED, an abelian theory, thus its QCD counterpart is usually referred as its non-abelian version.



Figure 2.5: The yo-yo model of a quark-antiquark system with its characteristics times. Full line for q trajectory, dashed for \bar{q} , and black dots for the vertices. Diagram from [33].

2.4.1 String Fragmentation

Let the string-pair dynamics be illustrated in the following scenario: consider the $q\bar{q}$ color-dipole with starting energy \sqrt{s} in the center-of-mass frame with allowed movement in the x direction, showed in Figure 2.5. At the start, the pair is close together and all the energy of the system is in their motion. As they distance themselves, their momenta is transferred to the string as potential of the field, up to (in light-cone coordinates) $t = \frac{\sqrt{s}}{2\kappa}$ where the string is fully extended and the quarks invert their motion. After $t = \frac{2\sqrt{s}}{\kappa}$, the system returns to its original condition, characterizing the period of a stable¹¹ harmonic motion. This is known as the hadronic¹² yo-yo model and its associate mass can be recovered with $m_h^2 = \kappa^2 A$, in which A is the area enclosed by an oscillation [31].

The creation of a new yo-yo occurs whenever the string snaps. Let $q_0\bar{q}_0$ be the initial pair of the string. Assuming the production of massless quarks without transverse momentum, i.e. $m_T^2 \doteq m^2 + p_T^2 = 0$, multiple breaking vertices will generate each a new pair $q_j\bar{q}_j$, such that new hadrons are formed by coupling neighbor quarks, as seen in Figure 2.6.

For the case $m_T^2 > 0$, $q_j \bar{q}_j$ of flavor f cannot be generated in a point vertex, since the energy necessary for the creation must come from the string itself. The pair must be able to tunnel between the associate string length of m_{Tf}/κ . The probability of this tunneling

¹¹Not considering particle decay.

¹²This is a simplified model for mesons. More complex descriptions [31], including baryons, follow the same inspiration.



Figure 2.6: Multiple string snappings generated from a high-energy $q\bar{q}$ pair. The final state presents n yo-yos. Figure from [31].

process is [31], applying the WKB approximation,

$$P_f \propto \exp(-\pi m_{Tf}^2/\kappa) = \exp(-\pi m_f^2/\kappa) \exp(-\pi p_T^2/\kappa).$$
(2.16)

The string fragmentation defines the stopping point of the hadronization. After multiple decays, no energy will be available for new hadrons. Note that (2.16) rapidly falls as m_f increases and implies a suppression in heavy quarks production via hadronization¹³.

 $^{^{13}}u\bar{u}: d\bar{d}: s\bar{s}: c\bar{c} \approx 1:1:0.3:10^{-11}$ [32].

Chapter 3

Heavy-Ion Physics

Section 2.3.1 illustrates the necessity of a good description of the Quark-Gluon Plasma to analyze its impact on the partonic shower. In current research, different approaches are applied to model the entropy deposition by two colliding nuclei at the initial point of the interation and its evolution [34].

The chapter starts with the modelling of the transverse initial conditions (IC) of medium. A quick revision on the distribution of nucleons, i.e. constituents of a nucleus, is presented, followed by the IC hypotheses applied in this work. Subsequently, the methodologies to evolve the transverse profile are introduced.

3.1 Initial Conditions

The initial temperature profile in the transverse plane must be defined to describe the complex nature of the Quark-Gluon Plasma evolution.

In this section, multiple models capable of illustrating nucleus-nucleus collisions are introduced with a quick glance at the underlying physics of each. From their hypotheses, the theoretical development is presented until a certain quantity (e.g. entropy or particle multiplicity) of the model is found. The temperature transverse profile can be calculated by its proportinality to the presented quantity, as discussed in [34, 13].

3.1.1 Nuclear Density Distributions

Before calculating any initial energy densities in a collision, the spatial nucleon distribution within a nucleus must be defined. For a symmetric nucleus of atomic mass A, the probability density of finding a nucleon in a certain position \vec{r} is [17]

$$\rho_A(\vec{r}) = \frac{n_A(\vec{r})}{A},\tag{3.1}$$

where $n_A(\vec{r})$ is the number of nucleons per unit of volume. Since $\rho_A(\vec{r})$ is a probability density function, it must be normalized [17], i.e.

$$\int d^3 r \rho_A(\vec{r}) = 1 \Rightarrow \int_0^\infty r^2 dr n_A(\vec{r}) = \frac{A}{4\pi}.$$
(3.2)

Two common choices for $n_A(\vec{r})$ are:

• Hard sphere

$$n_A(\vec{r}) \doteq \begin{cases} n_0, & r \le R_A \\ 0, & r > R_A \end{cases}$$
(3.3)

which describes the nucleus as an unvarying dense sphere of nucleons with radius R_A . This distribution does not allow interactions between nuclei at distances larger than their radii, hence should be only used as tool for simplistic calculations [4].

• (two-parameter) Woods-Saxon distribution

$$n_A(\vec{r}) \doteq \frac{n_0}{1 + \exp(\frac{r - R_A}{a})},$$
(3.4)

where the nuclear skin-depth a is introduced. Differently from (3.3), the WS distribution presents a continuous drop for $r \approx R_A$, with sharpness defined by a, and a non-zero tail that enables $r > R_A$ interactions. Tuning the parameters to charged nuclear density data, one arrives at $a \approx 0.54$ fm for lead (varies with atomic mass) [17], and note that $a \to 0$ fm recovers the hard sphere.

It has been used with success to describe large nuclei with A > 16 [4, 17]. A discussion of its three-parameter version can be found in [17].

3.1.2 Glauber Nuclear Overlap Model

The number of binary collisions that a nucleon at (x, y) participates while traversing a nucleus along the beam axis z can be calculated with the help of thickness functions [35]

$$T_A(x,y) \doteq \int_{-\infty}^{\infty} n_A(\vec{r}) dz = \int_{-\infty}^{\infty} n_A(x,y,z) dz.$$
(3.5)

This concept can be expanded to nucleus-nucleus (AB) collisions, resulting in the



Figure 3.1: Transverse diagram of a nucleus-nucleus collision. Figure from [17].

nuclear overlap function

$$T_{AB}(b) \doteq \int d^2 s T_A(\vec{s}) T_B(|\vec{b} - \vec{s}|), \qquad (3.6)$$

where the impact parameter \vec{b} connects the center of the nuclei and $\vec{s} = \vec{s}(x, y)$ points from the center of A to a point (x, y) in B, shown in Figure 3.1.

For a total inelastic nucleon-nucleon cross section σ_{NN} , the probability of a nucleon not interacting with a certain nucleon *i* of A is

$$p_i(ncol = 0, b) = 1 - p_i(ncol = 1, b) = 1 - \frac{\sigma_{NN}T_A(b)}{A}$$
 (3.7)

for indistinguishable nucleons. The probability of the nucleon becoming a participant in the collision is simply the probability of interacting with at least one of the A nucleons available, thus

$$p(ncol \neq 0, b) = 1 - p_i(ncol = 0, b)^A$$
$$= 1 - \left[1 - \frac{\sigma_{NN}T_A(b)}{A}\right]^A$$
$$\Rightarrow p(ncol \neq 0, b) \approx 1 - \exp(-\sigma_{NN}T_A(b)).$$
(3.8)

The last step is justified due to $\lim_{n\to\infty} \left(1+\frac{x}{n}\right)^n = \exp(x)$ and this study is focused on lead-lead collisions, in which $A = 208 \gg 1$.

With well-defined probabilities of interaction, the density of participants is [35]

$$n_{AB}(b; x, y) = T_A(\vec{s}) \left[1 - \exp(-\sigma_{NN} T_B(|\vec{b} - \vec{s}|)) \right] + T_B(|\vec{b} - \vec{s}|) \left[1 - \exp(-\sigma_{NN} T_A(\vec{s})) \right],$$
(3.9)

where the first term refers to nucleons of A interacting with the nucleus B, whilst the second one is the complementary.

Consider the collision to be of type AA. Since the energy density in the transverse plane $\epsilon(b; x, y)$ is proportional to $n_{AA}(b; x, y)$ [9],

$$\frac{\epsilon_{AA}(b;x,y)}{\epsilon_i} = \frac{n_{AA}(b;x,y)}{\langle n_{AA}(b=0) \rangle} \quad \Rightarrow \quad \frac{\epsilon_{AA}(b;x,y)}{\epsilon_i} \approx n_{AA}(b;x,y) \frac{\pi R_A^2}{2A}.$$
 (3.10)

Note that $\langle n_{AA}(b=0)\rangle \approx \frac{2A}{\pi R_A^2}$ because all nucleons of both nuclei are expected to participate over the overlap circular area of a totally central collision. A discussion of the calculation of the energy density of an ideal gas of quarks and gluons ϵ_i is showed at [17].

For a given constant central initial temperature $T_i \doteq T(b = 0; x = y = 0)$, and applying the ideal gas relation, with vanishing chemical potential, $T \propto \epsilon^{\frac{1}{4}}$ [17], the initial conditions can be achieved by

$$\frac{T(b;x,y)}{T_i} = \left(\frac{\epsilon_{AA}(b;x,y)}{\epsilon_i}\right)^{\frac{1}{4}}$$

$$\therefore T(b;x,y) \approx T_i \left(n_{AA}(b;x,y)\frac{\pi R_A^2}{2A}\right)^{\frac{1}{4}}.$$
 (3.11)

Final temperature profiles of this model are displayed in Figure 3.2(first column) for multiple centrality classes, i.e. impact parameters. For PbPb collisions at 5.02 TeV, T_i was chosen to be 0.59 GeV, following [10, 34], which results in significantly higher temperatures than other models in this study.

3.1.3 T_RENTo

The Reduced Thickness Event-by-event Nuclear Topology (T_RENTo) [36] is a Glauberbased parametric initial conditions model for high energy collisions. It only assumes that the eikonal overlap of the thickness functions T_A and T_B produces entropy via a scalar field $f(T_A, T_B)$. Both experimental and theoretical insights [36] help to postulate f as a generalized mean, called reduced thickness. Those assumptions are summarized in the



Figure 3.2: Initial temperature conditions for random profiles in multiple centrality classes (rows) and models (columns) for PbPb at 5.02 TeV. Maximum temperature of each panel is written in white, length scale in fm and proper time scale in fm/c.
relation

$$\frac{dS}{dy} \propto f(T_A, T_B) \doteq T_R(p; T_A, T_B) = \left(\frac{T_A^p + T_B^p}{2}\right)^{\frac{1}{p}},\tag{3.12}$$

with p as a free continuous parameter.

The first step of the procedure is to determine which nucleon in the collision is to be considered a participant. This is achieved by sampling the collision probability $P_{i,j}$ for each nucleon pair (i, j). Let $\rho_n(\vec{r})$ be the nucleon density function, taken as gaussian and without substructure¹, then the nucleon density at the spatial coordinates of *i* is $\rho_i = \rho_n(x_i \pm b/2, y_i, z_i)$. Hence

$$P_{i,j} = 1 - \exp\left[-\sigma_{gg} \int dx \int dz \rho_i \int dz \rho_j\right], \qquad (3.13)$$

with the effective parton-parton cross section σ_{gg} tuned such that the total cross section matches the experimental results for σ_{NN} .

Each participant nucleon has a thickness function described as a weighted version of equation (3.5),

$$T_n(x,y) \doteq w \int \rho_n(\vec{r}) dz, \quad P_k(w) = \frac{k^k}{\Gamma(k)} w^{k-1} e^{-kw}.$$
(3.14)

The weighting w of each participant, that follows the gamma distribution $P_k(w)$, is added to mimic large multiplicity fluctuations observed in pp collisions. The final nuclear thickness function $T_A(b)$ is the sum of the $T_{n,i}$ of each participant i, considering the Woods-Saxon nucleon density distribution (3.4).

With T_A and T_B defined, the entropy profile is calculated using (3.12).

Final results are shown in 3.2(second column), where the Monte Carlo sampling of colliding nucleons is visually reflected in fluctuations in the transverse plane. The choices of simulation parameters are presented in Appendix A.

3.1.4 MC-KLN

Another option is to the define the initial condition based on the Color Glass Condensate (CGC) formalism [37, 16], where the nuclei are seen as sheets of gluons.

A key concept of the model is the fraction of longitudinal momentum carried by a parton compared to its hadron, defined as the Bjorken-x variable. For high-energy

¹The $T_R ENTo$ software is also capable of defining *m* nucleon constituents, resulting in the final distribution to be fragmented into *m* gaussians.



Figure 3.3: Transverse partonic distribution as a function of $\ln(1/x)$ and $\ln(Q_s^2)$, along with the evolution equations that describe each region, $Q_s(x)$ is given by the bold curve. Figure from [16].

collisions, the small x limit is valid and shall be adopted for the rest of the section.

The main motivation of the CGC was given by HERA results [37, 4], which indicated that the transverse density of gluons of the system rises faster than the total cross section as x decreases. Gluons of a certain size scale must be packed together inside the hadron until a point of saturation, described by the characteristic momentum scale $Q_s(x, \vec{r})$. As represented in Figure 3.3, the parton distribution inside a nucleon is dominated by gluons and their overlap leads to the interpretation of the nucleus as a coherent gluon condensate [4, 16].

The Kharzeev-Levin-Nardi (KLN) [37, 38] deploys the unintegrated gluon distribution as^2

$$\phi(x, p_T; \vec{r}) \propto \frac{1}{\alpha(Q_s^2)} \frac{Q_s^2}{\max(Q_s^2, p_T^2)}.$$
 (3.15)

The Monte Carlo implementation of KLN (MC-KLN) [38] parametrizes the saturation scale as

$$Q_{s,A}^2(x,\vec{r}) = 2 \text{ GeV}^2\left(\frac{T_A(\vec{r})}{1.53p_A(\vec{r})}\right) \left(\frac{0.01}{x}\right)^{\lambda},$$
(3.16)

where $p_A(\vec{r}) = p(ncol \neq 0, r)$ of (3.8) using a sampling area $S^{-1} = \lim_{T_A \to 0} \frac{T_A}{p_A}$ instead of $T_A(r)$. The thickness function is calculated by sampling nucleons following the WS distribution for each nucleus. Once $Q_{s,A/B}$ are well-defined so are the distributions (3.15),

²For the region $Q_s^2 \gg \Lambda^2$.

and the gluon multiplicity can be achieved by

$$\frac{dN_g}{dyd^2r} \propto \int \frac{d^2p_T}{p_T^2} \int d^2k_T \phi(n_a)\phi(n_b), \qquad (3.17)$$

with $n_{A/B}$ being the density of participants of A/B.

Examples of the temperature profiles are shown in Figure 3.2(third column) and indicate a lower maximum temperature of the model compared to Glauber-based results.

Medium Evolution 3.2

The initial conditions presented in the last section need to be coupled with a hydrodynamic model to describe the evolution of the system with time, which necessary definitions were introduced in Section 2.2. The discussion starts with a simple longitudinal-only approach, associated with J. D. Bjorken [39], and then is complemented with the stateof-the-art transverse hydrodynamic model v-USPhydro [13].

3.2.1**Bjorken Longitudinal Expansion**

Let $u^{\mu} = (u_t, u_{\rho}, u_{\phi}, u_z)$ be the fluid 4-velocity defined in a cylindrical coordinate system. Heavy-ion collisions are expected to be symmetrical in the azimuthal direction, hence $u_{\phi} = 0$, and it shall be assumed that the evolution is mostly in the longitudinal region, thus $u_{\rho} \approx 0$. Given those constraints and $u^{\mu}u_{\mu} = 1$, the scalar V is introduced such that [4, 17]

~ - -

$$u^{\mu} \doteq (\cosh V, 0, 0, \sinh V).$$
 (3.18)

Note that

$$\partial_{\mu}u^{\mu} = \sinh V \frac{\partial V}{\partial t} + \cosh V \frac{\partial V}{\partial z}$$

$$u^{\mu}\partial_{\mu} = \cosh V \frac{\partial}{\partial t} + \sinh V \frac{\partial}{\partial z}.$$
 (3.19)

The entropy current conservation can be described as

$$\partial_{\mu}(u^{\mu}s) = 0$$

$$s\partial_{\mu}u^{\mu} + u^{\mu}\partial_{\mu}s = 0$$

$$\partial_{\mu}u^{\mu} + u^{\mu}\partial_{\mu}\ln s = 0$$

$$\partial_{\mu}u^{\mu} + \frac{u^{\mu}}{c_{s}^{2}}\partial_{\mu}\ln T = 0,$$
(3.20)



Figure 3.4: Charged particle pseudorapidity distribution in central AuAu collisions for multiple energies. Result from the PHOBOS Collaboration [40].

where $\frac{d \ln T}{d \ln s} \doteq c_s^2$ was applied in the last step to express the relation between temperature and entropy density to the speed of sound in the medium c_s , valued at around $1/\sqrt{3}$ for an ideal gas of massless particles [17].

The last equation shows that a complete description of V is enough to calculate the temperature profile of the system in any moment. For such, the Bjorken scaling initial condition is introduced [17]

$$V(y, \tau_0) = y,$$
 (3.21)

and shall be expanded to be true for any $\tau \geq \tau_0$. The motivation behind it is the assumption that a Lorentz boost along the beam axis should not modify the rapidity distribution of produced particle at the mid-rapidity region, hence $\frac{dN}{dy}|_{y\sim0}$ is constant [39]. This "central-plateau" structure results in all thermodynamic quantities being functions only of the proper time τ and the transverse coordinates [4], and it can be observed in Figure 3.4. In contrast, one could assume the Landau initial condition, where the hydrodynamic evolution starts from a system at rest, so $V(y, \tau_0) = 0$, which would ensue the rapidity distribution to be gaussian-like in the laboratory frame [17]. A comparison between the two approaches regarding experimental data at the RHIC energy level is found at [4].

The new coordinate system (τ, y) shall follow the standard definitions of the light-cone variables

$$y \doteq \frac{1}{2} \ln \frac{t+z}{t-z} \qquad \qquad t = \tau \cosh y \\ \tau \doteq \sqrt{t^2 - z^2} \qquad \qquad \Rightarrow \qquad \qquad z = \tau \sinh y$$
(3.22)



Figure 3.5: Temperature evolution applying Bjorken (top row) and v-USPhydro (bottom row) expansions for a random T_RENTo central (0-10%) initial profile in different proper time steps (columns) for PbPb at 5.02 TeV. Maximum temperature of each panel is written in white, length scale in fm and proper time scale in fm/c.

$$\Rightarrow \quad \frac{\partial}{\partial t} = \cosh y \frac{\partial}{\partial \tau} - \frac{\sinh y}{\tau} \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} = -\sinh y \frac{\partial}{\partial \tau} + \frac{\cosh y}{\tau} \frac{\partial}{\partial y}.$$
(3.23)

Applying (3.23) and (3.21) to (3.19)

=

$$\partial_{\mu}u^{\mu} = -\frac{\sinh^2 y}{\tau} + \frac{\cosh^2 y}{\tau} = \frac{1}{\tau}$$

$$u^{\mu}\partial_{\mu} = \cosh^2 \frac{\partial}{\partial\tau} - \sinh^2 \frac{\partial}{\partial\tau} = \frac{\partial}{\partial\tau}.$$
(3.24)

Thus (3.20) in the new coordinates is

$$\frac{1}{\tau} + \frac{1}{c_s^2} \frac{\partial}{\partial \tau} \ln T = 0$$
$$\frac{\partial \ln T}{\partial \ln \tau} = -c_s^2$$
$$\therefore T(\tau) = T(\tau_0) \left(\frac{\tau}{\tau_0}\right)^{-c_s^2}.$$
(3.25)

An example of this model can be seen in Figure 3.5(top row). Note that, since the expansion is longitudinal-only, any geometric property of the initial condition is maintained throughout the process.

3.2.2 v-USPhydro

The equations of motion of the fluid with the inclusion of shear ζ and bulk Π viscosity are [13]

$$\gamma \frac{\partial}{\partial \tau} \left[\frac{\epsilon + p + \Pi}{\sigma} u^{\mu} \right] - \frac{1}{\sigma} \partial^{\mu} (p + \Pi) = 0$$
(3.26a)

$$\gamma \frac{\partial}{\partial \tau} \left(\frac{s}{\sigma} \right) + \left(\frac{\Pi}{\sigma} \right) \frac{\theta}{T} = 0 \tag{3.26b}$$

$$\gamma_{\Pi}\left(\frac{\Pi}{\sigma}\right) + \frac{\Pi}{\sigma} + \frac{\zeta}{\sigma}\theta = 0,$$
 (3.26c)

where s, ϵ and σ refer to the densities of entropy, energy and local fluid, p and T to the pressure and temperature of the system. The fluid expansion rate $\theta \doteq \frac{\partial_{\mu}}{\tau}(\tau u^{\mu})$ and the relaxation time τ_{Π} are also necessary for the description.

These equations can be solved in the transverse plane by the Lagrangian method called Smoothed Particle Hydrodynamics (SPH) [14]. The fundamental idea of the formalism is to introduce a set of Lagrangian coordinates, called "SPH particles", which flow with the fluid. The chosen boost-invariant field can be reconstructed in terms of these mesh-free carriers and, consequently, also any of its extensive thermodynamical quantities, such as entropy [14, 13]. Some advantages of a Lagrangian approach over a Eulerian (fixed-grid) one are its adaptability to geometrical changes and computational scalability over the increase of the system size, both properties desirable in heavy-ion collisions since the QGP evolves from a highly compressed system and multiple initial conditions can be easily implemented [14].

Firstly, let $W[\vec{r};h]$ be positive definite kernel function normalized as

$$\int W[\vec{r};h]d^2\vec{r} = 1,$$
(3.27)

described with a width parameter h and $\lim_{h\to 0} W[\vec{r};h] = \delta^2(\vec{r})$.

For a given reference density σ , there is a corresponding density in the space-fixed frame such that [14]

$$\tau\gamma\sigma = \sigma^*(\vec{r},\tau) = \sum_{i=1}^{N_{SPH}} \nu_i W[\vec{r} - \vec{r_i}(\tau);h]$$
(3.28)

in which N_{SPH} is the number of SPH particles and ν_i can be seen as the proportion of the quantity carried by each particle, illustrated by $\int \sigma^*(\vec{r},\tau) d^2\vec{r} = \sum_{i=1}^{N_{SPH}} \nu_i$.

Let $a(\vec{r},\tau)$ be other extensive density. The formalism dictates [14]

$$a^*(\vec{r},\tau) = \sum_{i=1}^{N_{SPH}} \nu_i \left(\frac{a}{\sigma}\right)_i W[\vec{r} - \vec{r_i}(\tau);h], \quad \left(\frac{a}{\sigma}\right)_i \doteq \frac{a(\vec{r_i}(\tau))}{\sigma(\vec{r_i}(\tau))} = \frac{a^*(\vec{r_i}(\tau))}{\sigma^*(\vec{r_i}(\tau))} \tag{3.29}$$

Thus the complete calculation of dynamical quantities of each SPH particle recovers the system's extensive properties and, consequently, its temperature profile. The stateof-the-art code viscous Ultrarelativistic Smoothed Particle hydrodynamics (v-USPhydro) [13] solves equations (3.26) numerically following the described mechanism in the transverse plane (2+1) and assumes the Bjorken scaling (3.21) for the longitudinal direction.

The model enables the study of event-by-event heavy-ion collisions for multiple initial condition hypotheses, which one example is presented in Figure 3.5(bottom row). The direct comparison to the Bjorken expansion of the same profile shows how different the medium can become with the addition of transverse evolution as time progresses.

Chapter 4

Method Description

4.1 Overview

The previous chapters indicate the necessity of multiple theories to describe jet evolution. To achieve this complex goal, different models are applied for each step in a somewhat modular fashion, illustrated in Figure 4.1. The simulation overview is:

- 1. The simulation begins by generating a hard scattering between nucleons, for a given nuclear mass, via PYTHIA 6.4¹ [8, 41].
- 2. The event proceeds with the parton evolution of the scattering, following Section 2.3 with PDFs provided by the LHAPDF 5 package [42], from an initial vertex.
- 3. Parton shower calculations:
 - (a) For heavy-ion collisions, the parton shower interacts with a medium following Section 2.3. JEWEL's default medium is a simple Glauber+Bjorken (Sections 3.1.2 and 3.2.1), and this study also used more realistic alternatives such as T_RENTo+v-USPhydro and MC-KLN+v-USPhydro (Sections 3.1.3, 3.1.4 and 3.2.2).
 - (b) For proton-proton collisions, the parton shower is evolved in vacuum.
- 4. Once the partons achieve on-shell mass or leave the medium, they are handed back to PYTHIA for hadronization, following the ideas introduced in Section 2.4, and decays. This results in the final hadronic configuration of the event.

¹JEWEL sightly modifies the original PYTHIA code.



Figure 4.1: Diagram of the steps taken in the simulation and observables' calculations. Arrows represent interactions between different models, codes and frameworks.

5. The Monte Carlo event is loaded on the Rivet 2.7.2 framework [43], where jets are reconstructed using the Anti-kt algorithm provided by the FastJet package [44] and, finally, observables are obtained.

The coupling between JEWEL 2.0.2 and new medium profiles was originally developed and studied in [12]. Differently from JEWEL's default configuration, new media is defined by a discrete set of points $T(x, y, \tau)$, the spatial grid has a size of 0.15 fm whilst the temporal part evolved with steps of 0.1 fm/c. For calculation in any given point, a crucial aspect of the framework, the grid is interpolated bicubically in space and linearly in time [12]. An user-defined critical temperature T_C limits the range of medium interactions, such that $T(x, y, \tau) < T_C$ implies no QGP is found at the region and no interaction is calculated, i.e. a mixed phase is not considered. The v-USPhydro medium profiles were provided by Jacquelyn Noronha-Hostler and are categorized in different centrality classes given the multiplicity of soft charged pions their particularization yields [13]. Differently, the centralities of Glauber, i.e. JEWEL default, media are user-defined.

Free parameters for each model were tuned by matching the jet modification factor R_{AA} of central (0-10%) PbPb collisions at 5.02 TeV to experimental results from ATLAS [45]. Some details are different from the expected JEWEL tuning [7] and the process is explained in Section 4.3.

Details of the analyses, such as kinematics cuts and centrality classes, are presented in Table 4.1 for each observable. All simulations in this study used a center-of-mass

Simulation details				
Observable	Models	Centrality (%)	Kinematics cuts	Jet radius R
R_{AA}	Default,	0-10, 10-20, 20-	p_T interval: 63 to	0.2, 0.3, 0.4,
	Tv, Mv	30, 30-40, 40-50,	630 GeV; $ y < 2.8$	0.6, 0.8, 1.0
		50-60	and $ \eta < 3.2 - R$	
$v_{n=2,3,4}$	Default,	0-10, 10-20, 20-	p_T interval: 71 to	0.2, 0.3, 0.4,
	Tv	40, 40-60	630 Gev; $ \eta < 1.2$	0.6, 0.8, 1.0

Table 4.1: Simulations details for each jet observable studied. Default model refers to JEWEL's original Glauber+Bjorken, Tv to $T_RENTO+v$ -USPhydro and Mv to MC-KLN+v-USPhydro.

energy of 5.02 TeV and JEWEL's mode with recoils active, explained in Section 4.2.2. A complete list of the parameters applied in the simulations can be found in Appendix A.

4.2 Jet Reconstruction

As argued in Chapter 2, partons are notorious objects in the understanding of QCD and QGP physics, but they cannot be directly observed. After suffering through illdefined procedures of evolution, fragmentation, hadronization and final-state decays, they are transformed into a collection of collimated hadrons in the azimuth-(pseudo)rapidity space: a jet. Albeit jets are directly rooted in what is expected from the theory, only a qualitative picture of this new object is described at that level. Consensus between theory and experiments must be achieved for the jet definition, i.e. sets of rules that dictate how final-state particles are clustered together to form jets [47]. These so-called jet algorithms should respect the following general properties [48], known as the Snowmass Accord of 1990,

- 1. Simple to implement in an experimental analysis.
- 2. Simple to implement in the theoretical calculation.
- 3. Defined at any order of perturbation theory.
- 4. Yields finite cross section at any order of perturbation theory.
- 5. Yields a cross section that is relatively insensitive to hadronization.

Another crucial property of jet algorithms is Infrared and Collinear (IRC) safety². Hard partons are expected to experience multiple collinear splittings or soft emissions in

²One can state that IRC safety is a direct expansion of the Snowmass statements, since soft and



Figure 4.2: Experimental example of a dijet event in a PbPb collision at 2.76 TeV from CMS [46].

both the perturbative and non-perturbative realms, some that are not yet fully understood. It is reasonable to favor algorithms capable of generating final results insensible to those emissions. Given this motivation, it is defined [49]

- Infrared (IR) Safety: the algorithm is infrared safe if the final jet configuration is not affected by adding an infinitely soft parton.
- Collinear (C) Safety: the algorithm is collinear safe if the final jet configuration is not affected by replacing any parton with any corresponding collinear set of partons.

If both conditions are satisfied, the algorithm is called infrared and collinear (IRC) safe. Various algorithms were discarded or updated in order to achieve IRC safety, since it is a useful tool in theoretical pQCD calculations and enables a better structure to explore detector physics, such as noise and granularity [47].



Figure 4.3: Partonic event with random soft particles clustered with the k_T , Cambridge/Aachen, and anti- k_T algorithms from left to right. Jets are represented in various colors. Image from [47].

4.2.1 The Anti-kt Algorithm

Consider a set of final-state particles³ *i* in the azimuth-rapidity plane, such that each has a position (y_i, ϕ_i) and transverse momentum $p_{T,i}$. The distance between a pair (i, j) is defined as $\Delta R_{ij}^2 \doteq (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and new quantities d_{ij} and d_{iB} , that depends on the parameters *p* and *R*, are defined as [47]

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$
 and $d_{iB} = p_{T,i}^{2p}$. (4.1)

This quantity allows the clusterization of the particles i into jets through the following algorithm:

- 1. Calculate all possible d_{ij} and d_{iB} .
- 2. Find minimum of d_{ij} and d_{iB} :
 - (a) d_{ij} is minimum: recombine *i* and *j* into a new particle. Return to first step.
 - (b) d_{iB} is minimum: declare *i* as a jet and remove it from the list of particles. Return to first step.
- 3. Stop when no particle remains⁴.

collinear emissions are closely related to the appearance of divergences in cross sections (item 4) and non-perturbative effects that includes hadronization (item 5). A discussion can be found in [47].

³The algorithm should be capable of clustering through a plethora of entities in the (y, ϕ) -plane, e.g. final-state particles, parton configurations, detector constructed objects [44]... The term "particles" was kept for the sake of simplicity.

⁴Note that this implies that all particles will be constituents of a jet.

Step 2a uses a recombination scheme, which describes how two particles are merged into a new one. The most popular choice, known as E-scheme, is to simply add their 4-momenta together. Alternatives, including one proposed in the Snowmass Accord, are found in [48, 44].

The IRC safe sequential clustering anti- k_T algorithm is defined when p = -1 and implies that the clustering is preferred to happened around hard particles, in contrast to favoring soft particles (p = 1, the k_T algorithm) or positional-only clusterings (p = 0, the Cambridge/Aachen algorithm) [47]. Figure 4.3 shows these different algorithms applied for the same partonic configuration, where one can note that the anti- k_T algorithm results in circular jets with well-defined boundaries even when an overlap occurs.

The jet radius parameter R regulates the area of the reconstructed jets. It is expected that the variation of R shall impact the inclusion of originally dispersed energy from the parton fragmentation evolution, thus giving insights regarding the jet quenching mechanism and medium modifications along with possible constraints for models [50]. In this work, observable analyses capable of varying the radius were written and studied for R = 0.2, 0.3, 0.4, 0.6, 0.8 and 1.0, expanding the discussion beyond the usual range R = 0.2 to 0.4 applied by experiments [51, 45].

4.2.2 Thermal Background Subtraction

JEWEL implements a weakly-coupled approach to medium response regarding the parton shower interactions. As the traveling partons evolve through the medium, they interact with scattering centers via $2 \rightarrow 2$ processes, which generates new "recoiling" partons to be added to the simulation [26]. These recoils evolve freely, i.e. no medium interaction, until they hadronize [11]. Unfortunately, this implies that contributions from the original shower and medium response in the final state cannot be distinguished. JEWEL enables to save the thermal information⁵ of these scattering in the form of fake particles, i.e. merely soft momentum-carriers in the azimuth-rapidity space, since one expects the removal of thermal contributions via background treatment in the laboratory. Therefore, in order to make reliable comparisons between the model and experiments, a new algorithm must be defined at analysis level [11].

The subtraction procedure applied in this work was the gridless⁶ 4MomSub, which goes as follows [11]:

⁵This is an option when running the JEWEL code usually referred as "recoils on" mode. On the other hand, there is the opposite option "recoils off", where medium response is ignored.

⁶No new hypothesis regarding the detector resolution must be assumed.

- 1. Apply the chosen jet algorithm to final state.
- 2. Given a jet, iterate through its constituents. If the distance between the constituent and a fake particle $\Delta R < 10^{-5}$, then that fake particle is part of the thermal background.
- 3. Sum all the momenta of the thermal background.
- 4. Subtract the background's 4-momentum from the initial jet's 4-momentum, achieving the corrected final 4-momentum of the jet.
- 5. Generate observables using the new collection of jets.

There is not a clear path to the validation of the recoiling background methodology, nevertheless JEWEL has found overall success in some observables using the 4MomSub technique [11] and it is physically motivated, therefore it was applied for the results of this work. Note that this methodology does not consider any impact of the recoiling parton's removal to the medium evolution and its particularization, i.e. recoils do not affect soft particle distributions. Current research is also exploring a strongly-coupled medium response approach that goes beyond what is possible in JEWEL, with the jet being modified by the medium and, simultaneously, depositing energy in it to the point of altering the hydrodynamic evolution [52, 53].

Recoils were considered, using the 4MomSub method, for all simulations presented in this work.

4.3 Free Parameters Tuning

Monte Carlo event generators often have free parameters that need to be defined for a given experimental setup before making comparisons, specially in high-energy physics, where some experimental steps do not translate directly into the simulation framework and are heavily detector-dependent [7, 8]. JEWEL originally regulated the Debye mass (2.11) with a free scaling parameter s_{μ} , such that

$$\mu_D(T) \approx 3T \Rightarrow \mu_D(T) = 3s_\mu T, \tag{4.2}$$

and, by adjusting the parameter to describe single-inclusive hadron suppression at RHIC, s_{μ} was found to be 0.9 [7, 10].



Figure 4.4: Nuclear modification factor resulting from different Debye mass scale factor s_{μ} and critical temperature T_C configurations. The best match, i.e. the curve that presented the smaller χ^2 over the degrees of freedom when compared to ATLAS data [45], is emphasized for each model.

Since this study heavily changes the medium hypotheses from the expected default model, the critical temperature T_C was also treated as a free parameter to enable any physical effects near freeze-out, fixed at $T_{fo} = 0.15$ GeV, to be observed in v-USPhydro profiles' results, in contrast to JEWEL's default fixed 0.17 GeV. As discussed in Section 2.2, LQCD predicts T_C between 0.14 and 0.17 GeV, limiting our variation space to [0.15, 0.16, 0.17] GeV. The Debye mass scale factor is expected to be close to one, so its variation space was chosen to be [0.9, 1.0, 1.1].

The observable used to perform the tuning of these parameters was the jet nuclear modification factor $R_{AA}(p_T)$, which is further explained with the simulation details in Chapter 5, for central 0-10% PbPb collisions at $\sqrt{s} = 5.02$ TeV measured by ATLAS [45]. The R_{AA} is the default choice for tuning since it was extensively studied by multiple collaborations in the LHC [45, 50, 51] and provides a general overview of the jet quenching process. Therefore, any model modification should impact this observable. Furthermore, the ATLAS collaboration has measured the central R_{AA} for a wide range of transverse jet momentum, from 100 to 1000 GeV, and a valid rapidity region of the model, |y| < 2.8, for anti- k_T jets with R = 0.4 [45]. Most of the results of this work also follow the measuring capabilities of the ATLAS detector.

After calculating the R_{AA} for all possible configurations of s_{μ} and T_C within the variation space, illustrated in Figure 4.4, the best pair is chosen by minimizing the χ^2 over the degrees of freedom for each model, as seen in Figure 4.5. Once the pair is found, its corresponding model is considered tuned and all subsequently simulations use them



Figure 4.5: χ^2 over the degrees of freedom when compared with ATLAS central jet R_{AA} [45] for each free parameter choice and model. The minimal values are circled in red. The tuning parameters are: $s_{\mu} = 0.9$ for Glauber+Bjorken, $s_{\mu} = 1.0$ for T_RENTo+v-USPhydro, $s_{\mu} = 1.1$ for MC-KLN+v-USPhydro, with $T_C = 0.15$ GeV for all.

as initial parameters, which can be verified in Appendix A.

Although simplistic, the method validates all models regarding their R_{AA} . JEWEL's default medium seems to undershoot the observable for all free parameters configurations, but achieves a better fit for $p_T < 200$ GeV. On the other hand, both v-USPhydro models consistently presents a higher R_{AA} than expected with a better match for $p_T > 200$ GeV. All models favor a lower critical temperature then JEWEL's original setup. Interestingly, the expected maximum temperature order relation between the initial conditions $T_{max}^{\text{Glauber}} > T_{max}^{\text{T}_{\text{R}}\text{ENTo}} > T_{max}^{\text{MC-KLN}}$, as indicated in Figure 3.2, reflects the choice of optimal $s_{\mu}^{\text{Glauber}} < s_{\mu}^{\text{T}_{\text{R}}\text{ENTo}} < s_{\mu}^{\text{MC-KLN}}$, since the factor can be interpreted as a direct temperature regulator in equation (4.2).

Chapter 5

Nuclear Modification Factor R_{AA}

One of the main pillars of heavy-ion physics is to study the impact of the Quark-Gluon Plasma on the momentum spectrum of an object, such as jets, highly energetic hadrons or specific particles. When compared to the production given by a pp collision, i.e. no medium, one can quantify that impact due to the medium created in a AA experiment. This measurement is named the nuclear modification factor R_{AA} and is one of the most popular observables in the whole high energy physics community [4, 54, 2, 51, 50, 45].

The chapter starts with the definition and simulation details of the observable. Section 5.2 compares the results to ATLAS data for various centralities and R = 0.4, whilst Section 5.3 varies the jet radii for central collisions presented with ALICE and CMS observations. At the end of the chapter, the simulated R_{AA} for all configurations for each model are displayed in Figures 5.9 and 5.10 (Glauber+Bjorken)¹, 5.11 (T_RENTo+v-USPhydro) and 5.12 (MC-KLN+v-USPhydro).

As described in Chapter 4, all simulations refer to anti- k_T jet reconstruction in PbPb 5.02 TeV collisions, using JEWEL recoil subtraction algorithm 4MomSub.

5.1 Definition

Given the differential jet yield $\frac{dN}{dp_T}$ normalized by the number of events N_{evt} events, then

$$R_{AA}(p_T) \doteq \frac{1}{\langle N_{coll} \rangle} \frac{\frac{1}{N_{evt}} \frac{dN}{dp_T} \Big|_{AA}}{\frac{1}{N_{evt}} \frac{dN}{dp_T} \Big|_{pp}},$$
(5.1)

¹Glauber+Bjorken data was separated into two images for better visualization.

note that the ratio is also rescaled for the number of binary collisions expected in the nucleus-nucleus interaction $\langle N_{coll} \rangle$, which is calculated using the Glauber model. This implies that the jet spectrum of a AA collision per hard scattering is directly compared to the production in pp, thus any modification is associated with the medium. In JEWEL, only one hard scattering occurs per event², hence $\langle N_{coll} \rangle = 1$ and, as in any Monte Carlo generator, the events must be counted considering their associated probabilistic weights.

This is a simple, yet powerful, tool to understand general properties of the collision, in which $R_{AA} < 1$ implying a suppression whilst $R_{AA} > 1$ means the production was enhanced for a p_T cut, but it does not convey any finer details of the jet modification. As showed in Section 4.3, this observable is incredibly useful for constraining models.

Following Table 4.1, two (pseudo)rapidity cuts were applied: $|y_{jet}| < 2.8$, for direct ATLAS comparisons, and $|\eta_{jet}| < 3.2 - R$, with jets reconstructed with the anti- k_T algorithm with R = 0.2 to 1.0. The jet transverse momentum spectra are simulated over a range of 63 to 630 GeV. The observable was calculated using 5 millions collisions for all models per centrality class of 0-10%, 10-20%, 20-30%, 30-40%, 40-50% and 50-60%. For v-USPhydro results, 1000 medium profiles, with 5000 hard scatterings each, were sampled for each centrality class. Only the statistical uncertainty of the observable was considered, and a more comprehensive discussion regarding errors in the JEWEL framework can be found in [55, 7].

The LHC collaborations have different methodologies and detector limitations, hence different choices of kinematic cuts, jet radii, centralities and even jet definitions. The original results of ALICE [51, 56], CMS [50] and ATLAS [45] are illustrated in Figure 5.1 for central collisions and R = 0.4 jets, compared to the realistic T_RENTo+v-USPhydro³. Comparisons were made between the simulations and experiments using different (pseudo)rapidity cuts, since the R_{AA} was shown in [57] to be insensible to the choice; whenever the data is presented alongside with ATLAS results, |y| < 2.8 following the methodology of [45], otherwise $|\eta| < 3.2 - R$, the most inclusive pseudo-rapidity cut, is presented.

5.2 Centrality Dependence

The energy deposition in the medium changes according to the impact parameter of the system. As the collisions become more peripheral, the energy density decreases, hence

²Hard scatterings are considered to be independent of each other.

³As presented along this chapter, the v-USPhydro models behave very similarly for this centrality and jet radii configuration.



Figure 5.1: Jet nuclear modification factor for $T_RENTO+v$ -USPhydro compared to multiple collaborations results: ATLAS [45], CMS [50] and ALICE [51, 56]. Anti- $k_T R = 0.4$ jets with color-coded specifications in central collisions.

the medium temperature and lifetime is expected to diminish as well, as exemplified in Figure 3.2. The observations in AA collisions seem to be dominated by the hard parton interaction with the medium [54], therefore the behavior of R_{AA} at different centralities convey information about the generated medium. One should expect the measured jet momenta to be less suppressed in peripheral collisions than central ones, with the R_{AA} approaching unity.

Figure 5.2 shows the models' R_{AA} for central (0-10%), semi-central (20-30%) and peripheral (40-50%) systems. As consequence of the tuning process, all models have good descriptions of central collisions from ATLAS. For the other centrality classes, the models' results seem to raise slightly but not as much as the experiments. The qualitative behavior of the curves, increasing for $p_T < 300$ GeV and saturating for $p_T > 300$ GeV is consistent for all centralities. Complete comparisons with the ATLAS data are found in Figures 5.4 (Glauber+Bjorken), 5.5 (T_RENTo+v-USPhydro) and 5.6 (MC-KLN+v-USPhydro). The presence of transverse expansion does affect the results, e.g. v-USPhydro models achieves $R_{AA} \sim 0.7$ the Bjorken approach reaches ~ 0.6 for $p_T > 300$ GeV in the most peripheral collisions, difference that is not enough to describe the measured centrality evolution. T_RENTo and MC-KLN results are compatible for all simulations.

Since the R_{AA} was used to tune the models, one must be careful to differentiate the physical effects and consequences of the tuning method. It is unclear if Figure 5.2 shows an improvement with the v-USPhydro or the non-central curves are closer to the experimental results because the models with realistic hydrodynamics overshoot the R_{AA} in the tuning process, as discussed in Section 4.3. An auxiliary observable R_{CP} is introduced to better illuminate the question, such that

$$R_{CP}(p_T) = \frac{R_{AA}(p_T)\big|_{\text{central}}}{R_{AA}(p_T)\big|_{\text{peripheral}}},$$
(5.2)

where the nuclear modification factor is written in terms of central/peripheral instead of AA/pp. This new observable should be less tuning-dependent, since both spectra are affected by the chosen free parameters.

Figure 5.3 displays the R_{CP} varying the centrality when compared to the spectrum generated in 50-60% collisions for R = 0.4. The Bjorken and v-USPhydrocurves behavior are distinct for $p_T < 200$ GeV jets in central collisions, and become more undifferentiated as p_T and centrality increases. This is an indication of hydrodynamic modification: low p_T jets escape the medium after suffering higher modification, thus they are expected to be better conveyors of the medium properties. The ATLAS R_{AA} data does not seem to



Figure 5.2: Jet nuclear modification factor for all models compared to ATLAS results [45] for multiple centralities, from left to right: 0-10%, 20-30% and 40-50%.

suggest the characteristic presented by JEWEL's default medium, favoring the realistic hydrodynamics ones.

5.3 Jet Radius Dependence

Larger jets should be more inclusive to medium response effects and recover any energy scattered in the azimuth-(pseudo)rapidity plane [54]. The naive approach is to expect that, as the jet radius R increases and, consequently, the area of a anti- k_T jet, the R_{AA} increases until unity. This line of thought is up to discussion since R-dependence research in heavy-ions is still in early development: CMS observed an increase in R_{AA} for $p_T < 500$ GeV [50], while no conclusive dependence was found in ALICE [51] and consensus cannot be achieved in models [50]. Detector characteristics and increasing difficulty to handle background for large areas limits the range of available experimental data for comparisons, but novel Machine Learning (ML) techniques in ALICE [58, 56] shall enable more broader measurements in the future.

Figure 5.7 shows the models' R_{AA} for 0-10% collisions varying the jet radius R. Both ALICE and CMS have measured the nuclear modification factor for multiple radii in central collisions, justifying the choice of centrality class. For R = 0.2, simulated jets are consistently more modified than the experiments show, but statistically compatible with ALICE. For R = 0.4, all models are compatible with ALICE (low p_T) measurements, however CMS (high p_T) favors v-USPhydro models. In the last panel R = 0.6, all models are able to replicate CMS results. ATLAS compatibility is not discussed since its



Figure 5.3: R_{CP} for all models and multiple centralities, from left to right: 0-10%, 20-30% and 40-50%, compared to 50-60%.



Figure 5.4: Jet nuclear modification factor for Glauber+Bjorken compared to ATLAS results [45] for multiple centralities, color-coded.



Figure 5.5: Jet nuclear modification factor for $T_RENTo+v$ -USPhydro compared to AT-LAS results [45] for multiple centralities, color-coded.



Figure 5.6: Jet nuclear modification factor for MC-KLN+v-USPhydro compared to AT-LAS results [45] for multiple centralities, color-coded.



Figure 5.7: Jet nuclear modification factor for all models compared to ALICE [51] and CMS [50] central 0-10% results for multiple jet radii R, from top to bottom: 0.2, 0.4 and 0.6.



Figure 5.8: Nuclear modification factor ratio for all models as a function of jet R with respect to R = 0.2 for multiple centralities, from left to right: 0-10%, 20-30% and 40-50%. Central values are compared to CMS results [50], note its different kinematic cuts to the simulations.

measurements for this system were used for the tuning process.

The jet radii dependence is explicitly characterized in Figure 5.8, in which a wider $316 < p_T < 501$ GeV (all panels) cut was chosen to better address the CMS $400 < p_T < 500$ one for central collisions. For R = 0.3 and 0.4, no noticeable differences are observed among the models, however large jet areas accentuate the models' distinctions, favoring the realistic hydrodynamics when compared to the CMS experiment. Similar to the indications in centrality dependence, v-USPhydro shows improvement against Bjorken, specially regarding the MC-KLN initial conditions, but not enough to describe the experiment.

As R increases (Figures 5.9 and 5.10), Glauber+Bjorken swaps the expected behavior of R_{AA} increasing with p_T for a decreasing one, even showing jet enhancement for some configurations. The same effect is illustrated, although diminished, for the v-USPhydro models with $R \ge 0.8$ in Figures 5.11 and 5.12. This observation should be due to medium response. The larger area jets with small momentum should have contributions of recoils more prominent, before thermal subtraction, and the effect is intensified for hotter ($T_{max}^{\text{Glauber}} > T_{max}^{\text{T}_{\text{R}}\text{ENTo}} > T_{max}^{\text{MC-KLN}}$) and central initial conditions. The anomaly is probably triggered by JEWEL's treatment of the recoils, either in the parton shower or analysis level (4MomSub). Experimental results in this region may better constrain the framework.



Figure 5.9: Jet nuclear modification factor for configurations of Glauber+Bjorken varying centrality with $R \leq 0.4.$



Figure 5.10: Jet nuclear modification factor for configurations of Glauber+Bjorken varying centrality with $R \geq 0.6.$



Figure 5.11: Jet nuclear modification factor for configurations of $T_RENTo+v$ -USPhydro varying R and centrality.



Figure 5.12: Jet nuclear modification factor for configurations of MC-KLN+v-USP hydro varying R and centrality.

Chapter 6

Anisotropic Flow Coefficients v_n

As stated in Section 2.2.1, the coefficients v_n^{jet} can be studied to better understand the path-length dependence of the medium-induced jet energy loss. Differently from the soft flow phenomenon, associated with the distribution of low energy particles generated by the hydrodynamic evolution of the collision, jet anisotropic flow is the interplay of two mechanisms: QGP's geometrical properties and the modifications that partons suffer while traveling through it [59, 60]. For example, as the collisions become more peripheral, the ellipicity of the initial collisions rise, implying an increase in v_2 with centrality, but the jets escape the medium less quenched, hence decreasing any anisotropic jet coefficient in the same conditions.

The model applied for the study of jet v_n should englobe the dialogue between the soft and jet physics [61, 62], aspect lacking in JEWEL's original formulation¹. Furthermore, Glauber+Bjorken shows a completely smooth medium profile, i.e. it does not have the event-by-event fluctuations that are understood to be responsible for non-zero odd $v_{n>1}$ [54]. However, the coupling of JEWEL with T_RENTo+v-USPhydro medium hypotheses enables a complete simulation of v_3 for jets.

The chapter starts with the necessary definitions for the calculation of the coefficients, including the steps taken to make the observables comparable to experimental data, closely following [62]. Section 6.2 presents the correlation between the jet and soft sectors, with final results for v_2 in Section 6.3 and $v_{n>2}$ in Section 6.4, where comparisons with preliminary results of ATLAS [59] are presented for various centralities and R = 0.2.

As described in Chapter 4, all simulations refer to anti- k_T jet reconstruction in PbPb 5.02 TeV collisions, using JEWEL recoil subtraction algorithm 4MomSub.

¹JEWEL's final state is only composed by jet constituents.

6.1 Definition

Multiple hard scatterings collisions are separately simulated using a T_RENTo+v-USPhydro medium profile. To avoid ambiguities between a hydrodynamic event, i.e. the medium, and a hard scattering event, the coupling between all hard scatterings and its medium profile shall be called a hydro-event. One must be able to calculate, for a given transverse jet momentum p_T cut, the symmetry plane $\Psi_n^{jet}(p_T)$ and Fourier coefficients of the azimuthal distribution of jets $v_n^{jet}(p_T)$ of each hydro-event. For jets, equation (2.6) is written as [62]

$$\frac{R_{AA}(p_T,\phi)}{R_{AA}(p_T)} = 1 + 2\sum_{n=1}^{\infty} v_n^{jet} \cos(n(\phi - \Psi_n^{jet}(p_T))),$$
(6.1)

with

$$\Psi_n^{jet}(p_T) = \frac{1}{n} \tan^{-1} \left(\frac{\int_0^{2\pi} d\phi \sin(n\phi) R_{AA}(p_T, \phi)}{\int_0^{2\pi} d\phi \cos(n\phi) R_{AA}(p_T, \phi)} \right),$$
(6.2)

and

$$v_n^{jet}(p_T) = \frac{1}{2\pi} \int_0^{2\pi} \cos(n(\phi - \Psi_n^{jet}(p_T))) \frac{R_{AA}(p_T, \phi)}{R_{AA}(p_T)}.$$
(6.3)

By applying those definitions for a jet yield distribution $\frac{d^2N_i}{dp_Td\phi} \propto R_{AA}(p_T, \phi)_i$ of a hydro-event *i*, exemplified in Figure 6.1, one can obtain $\Psi_{n,i}^{jet}(p_T)$ and $v_{n,i}^{jet}(p_T)$. The v-USPhydro code provides the soft counterpart, $\Psi_{n,i}^{soft}$ and $v_{n,i}^{soft}$, along with the total multiplicity of soft particles M_i [13].

Experimentally, jet anisotropy measurements are possible with the calculation of particle's reference planes, e.g. charged hadrons in the ATLAS detector [63], which implies that experimental results approach jet-soft correlations instead of the expected jet-jet ones [61, 64]. Thus, experimental measurements should be compared to the correlation between jets and soft particles [61, 62, 20]

$$v_n^{exp}(p_T) = \frac{\langle v_n^{soft} v_n^{jet}(p_T) \cos(n(\Psi_n^{soft} - \Psi_n^{jet}(p_T))) \rangle}{\sqrt{\left\langle \left(v_n^{soft} \right)^2 \right\rangle}},$$
(6.4)

with

$$\langle \dots \rangle \doteq \frac{\sum_{i} M_i R_{AA}(p_T)_i(\dots)}{\sum_{i} M_i R_{AA}(p_T)_i}.$$
(6.5)

This imply that the theoretical calculation of the anisotropic flow coefficients must include information of the soft distribution, which is not calculated in JEWEL. For



Figure 6.1: Fourier harmonics of the azimuthal jet distribution for a random $T_RENTO+v-USPhydro 20-40\%$ profile.

Glauber+Bjorken, the auxiliary variable $v_n^{jet,GB}(p_T)$ is introduced to better understand the effects of v-USPhydro versus a longitudinal-only expansion, such that

$$\frac{d^2N}{dp_T d\Delta\phi_n} = A \left[1 + 2v_n^{jet,GB} \cos(n\Delta\phi_n) \right], \quad \Delta\phi_n \doteq |\phi - \Psi_n^{jet,GB}(p_T)| \tag{6.6}$$

where the normalization constant A and $v_n^{jet,GB}(p_T)$ are calculated by applying a simple non-linear least squares fit to the differential jet yield, similarly to the procedure used in ATLAS [59]. As a consequence of the symmetries of Glauber+Bjorken in the transverse plane, the symmetry planes points to direction of the impact parameter [20], thus $\Psi_n^{jet,GB}(p_T) = 0.$

Following Table 4.1, the rapidity cut chosen was $|y_{jet}| < 1.2$ for direct comparison with ATLAS [59], with jets reconstructed using the anti- k_T algorithm with R from 0.2 to 1.0. The jet transverse momentum spectra are simulated over a range of 71 to 630 GeV, for the centralities classes of 0-10%, 10-20%, 20-40% and 40-60%. To achieve convergence in the calculations of $\Psi_n^{jet}(p_T)$, 800 thousands hard scatterings were generated for each v-USPhydro medium, in which 100 profiles were sampled per centrality.

The observables' uncertainties were estimated using the Jackknife resampling technique [65], such that the variance of the estimator $\bar{\mathcal{X}}$ over all events is



Figure 6.2: Alignment of Ψ_n^{jet} (71 < p_T < 251 GeV) and Ψ_n^{soft} for multiple centralities as a function o jet radius R.

$$\operatorname{Var}(\bar{\mathcal{X}}) = \frac{n-1}{n} \sum_{i=1}^{events} (\bar{\mathcal{X}}_i - \bar{\mathcal{X}})^2$$
(6.7)

where $\bar{\mathcal{X}}_i$ is the estimator being calculated along the subset of measurements excluding the hydro-event *i*.

6.2 Jet-Soft Correlations

Equation (6.4) shows that the model's anisotropic flow is directly associated to its capacity to align the symmetry planes of the jet and soft sectors. Without medium, the jets are uniformly distributed in the azimuth plane, thus $\Psi_n^{jet}(p_T)$ never converges to a value. A path-dependent energy-loss mechanism should cause the distribution to approach the fixed values of the medium's soft symmetry planes, but the final flow coefficients are also affected by the nuclear modification factor, which was shown to be heavily dependent of collision centrality and jet radius for various p_T regions in Chapter 5.

Figure 6.2 displays the evolution of the hydro-event averaged $\xi_n \doteq \langle \cos(n(\Psi_n^{soft} - \Psi_n^{jet}(p_T))) \rangle$ as a function of R for jets with transverse momentum in the range $71 < p_T < 251$ GeV. For n = 2, the alignment seems to increase for more peripheral collisions, which

could be an indication of decorrelation in central collisions due to the recoil methodology², and slightly decrease with jet radius, with $0.5 < \xi_2 < 0.9$. The odd harmonic n = 3becomes significantly more uncorrelated with R, as ξ_3 goes from ~ 0.35 for small areas to 0 for the largest computed jets. No correlation is observed for n = 4 in all configurations. Overall, the order of harmonic appears to be crucial for the symmetry plane alignment, quickly changing from a moderately correlated scenario $\xi_2 \sim 0.5 - 0.8$ to completely uncorrelated $\xi_4 \approx 0$, resulting in a larger suppression in higher-order $v_n^{exp}(p_T)$.

The correlation for peripheral collisions is further explored in Figure 6.3 in terms of v_2^{jet} and v_2^{soft} . The Pearson factor r is shown for each panel to quantify the relation of the two variables: a strong positive linear correlation is indicated with r = 1, while uncorrelated quantities results in with r = 0 and strong negative one in r = -1. The elliptic flow correlations seem to behave similarly to the second-order symmetry planes in Figure 6.2. Their linearity is smaller than calculations for high energy hadrons [61] and heavy-flavored particles [21], that could be due to processes that randomly spread the parton shower's energy in the azimuth-rapidity plane, such as hadronization or gluon bremsstrahlung, thus adding fluctuations to v_2^{jet} insensible to medium geometry. An investigation of jet structure observables may shine some light on the effect.

6.3 Elliptic Flow v_2

The influence of the initial condition and hydrodynamic evolution choice in the jet azimuthal distribution's second harmonic is observed in Figures 6.4 and 6.5.

Glauber is perfectly circular, hence isotropic, for ultra-central collisions and becomes more elliptical as the centrality increases, as seen in Figure 3.2. Furthermore the Bjorken expansion conserves any geometrical aspect of the IC along the evolution, as pointed in Section 3.2.1. Ergo $v_2^{jet} \approx 0$ for 0-10% and a clear centrality dependence are justified, with an expectation to exceed the values from more realistic simulations in lower centralities. The centrality dependence is affected by jet radii, diminishing for larger R.

v-USPhydro breaks down any structure in the IC by letting the energy flow in the transverse plane, implying in smaller coefficients than the expected from a longitudinalonly expansion. For R = 0.2, $v_2^{jet} \approx 0.02$ for all centralities in the lower p_T ranges and diminishes as p_T increases, which is expected because higher p_T jets escape the medium less modified. The model displays a dependence with centrality and R, similar

²Recoiling partons do not interact with the medium after their creation, differently from the original parton shower, hence may increase the decorrelation as more are generated, which happens in central systems.


Figure 6.3: Event-by-event correlation between v_2^{jet} (71 < p_T < 251 GeV) and v_2^{soft} for jet radius R = 0.2 (left), 0.6 (middle) and 1.0 (right) and centralities 10-20% (top) and 40-60% (bottom).

to JEWEL's default medium but less intense.

The analyses of v_2^{jet} and ξ_2 enables a better understanding of the discrepancies between v_2^{exp} and ATLAS data [59], represented in Figures 6.6 and 6.7. The simulated results are consistently below the experimental ones for all centralities with R = 0.2. The model's v_2^{exp} has a p_T -dependence that becomes accentuated in the more peripheral collisions classes of 20-40% and 40-60%. The centrality-dependence is illustrated 6.8, in which the v_2^{jet} results were added to explicitly show that the gap between experimental data and theoretical calculations is not explained by the misalignment of Ψ_2^{jet} and Ψ_2^{soft} . This is evidence that another unknown effect may be responsible for the suppression observed. The *R*-dependence displayed in Figure 6.8 follows the one observed in Figure 6.5

The complete results for v_2^{exp} for all configurations are found in Figure 6.9.

6.4 Higher-order Harmonics

As indicated in Figure 6.2, the $v_{n>2}^{exp}$ are highly suppressed by the misalignment between the jet and soft symmetries planes. Both v_3^{exp} and v_4^{exp} are within the uncertainties of the results from ATLAS, shown in Figure 6.10, and the observables' dependence on centrality and jet radius are manifested in the simulations.

The results for triangular flow coefficient for R = 0.2 is displayed in Figure 6.11.



Figure 6.4: Model comparison of the jet azimuthal distribution coefficient v_2^{jet} for different centralities.



Figure 6.5: Model comparison of the inclusive jet azimuthal distribution coefficient v_2^{jet} for different centralities and jet radii.



Figure 6.6: Comparison between the calculated v_2^{exp} and ATLAS results [59] for all centralities with R = 0.2.



Figure 6.7: The calculated v_2^{exp} and v_2^{jet} compared to ATLAS results [59] for the inclusive p_T bin as a function of centrality with R = 0.2.



Figure 6.8: Inclusive elliptic flow coefficient v_2^{exp} for different centralities and jet radii.



Figure 6.9: Elliptic flow v_2^{exp} for all configurations of $T_RENTO+v$ -USPhydro varying jet radius and centrality.



Figure 6.10: Comparison between the calculated $v_{n>2}^{exp}$ and ATLAS results [59] for all centralities with R = 0.2.



Figure 6.11: The calculated v_3^{exp} for all centralities with R = 0.2.

The v_3^{exp} is calculated for the all centralities, which is positive for $p_T < 300$ GeV and goes to zero as the jet transverse momentum increases, i.e. p_T -dependent, for 10-20%, 20-40% and 40-60%, but the most central result is inconclusive. The R and centrality dependence is better depicted in Figure 6.12 for the inclusive p_T bin, where this observable seems to increase as the collisions become more peripheral and decrease with R, achieving zero for the largest jets. The values of v_3^{jet} demonstrate that the R-dependence is not only due to the the cosine term in equation (6.4). This could be indication that the medium's fluctuations, responsible for odd harmonics in the azimuthal distribution, are being averaged out as the parton shower evolves and increases its angular region, which would be more visible in larger areas jets. Overall, the jet distributions convey information about the event-by-event fluctuations of v-USPhydro, resulting in v_3^{exp} around one order of magnitude smaller than v_2^{exp} .

The quadrangular flow coefficient's calculations are shown in Figures 6.13 and 6.14. Even though a positive v_4^{jet} is observed, the high suppression $\xi_4 \approx 0$ lowers the v_4^{exp} to zero for 20-40% and 40-60% centralities and all jet radii. The results for the more central collisions are inconclusive, with the coefficients fluctuating between 0.002 and -0.002.

When discussing higher-order harmonics, one must recall that jets, differently from particles, are not point-like objects. As mentioned in Section 4.2.1, anti- k_T are circles in the azimuth-rapidity space with radius R, thus occupying a region of 2R in the azimuth



Figure 6.12: The calculated v_3^{exp} and v_3^{jet} for the inclusive p_T bin as a function of centrality with R = 0.2 (left), 0.6 (middle) and 1.0 (right).



Figure 6.13: The calculated v_4^{exp} for all centralities with R = 0.2.



Figure 6.14: The calculated v_4^{exp} and v_4^{jet} for the inclusive p_T bin as a function of centrality with R = 0.2 (left), 0.6 (middle) and 1.0 (right).

line, if overlaps are ignored. The distance between two peaks of a n^{th} -order harmonic oscillation is $\frac{2\pi}{n}$, as depicted in Figure 6.1. Hence, for large enough R and n, full oscillations occur inside the jet area. Aspects of the jets' substructure that could contribute to a higher-order v_n^{exp} may be discarted in a large area clustering, e.g. if the energy deposition inside a large area jet is distributed in two clusters centered around ϕ' and ϕ'' , a high-enough order modulation (in terms of R) should be able discern between the clusterings, but the information is lost when applied the jet algorithm and the ϕ_{clusters} are represented by a single ϕ_{jet} . This could contribute to a suppression on ξ_n , thus v_n^{exp} , as seen in Figure 6.14 but further studies regarding jet substructure are necessary to better understand the impact of this effect.

The complete results for v_3^{exp} and v_4^{exp} for all configurations are found, respectively, in Figures 6.15 and 6.16.



Figure 6.15: Triangular flow v_4^{exp} for all configurations of T_RENTo+v-USPhydro varying jet radius and centrality.



Figure 6.16: Quadrangular flow v_4^{exp} for all configurations of T_RENTo+v-USPhydro varying jet radius and centrality.

Chapter 7

Final Remarks

This work discusses two necessary aspects for the understanding of Quantum Chromodynamics and the Quark-Gluon Plasma physics: jet quenching and jet-soft correlations. Expanding on the implementation of custom medium profiles into JEWEL, the framework was improved to enable an in-depth study on the partonic evolution and its mediuminduced modifications. The results presented provide an extensive description of crucial general observables in heavy-ion collisions research, which elucidate the importance of a realistic event-by-event hydrodynamic evolution of the medium.

The chosen observables, nuclear modification factor $R_{AA}(p_T)$ and anisotropic flow coefficients $v_n(p_T)$, provide general information about the jet distribution and were used as a first assessment of the model, emphasizing that the study of higher-order anisotropic flow (n > 2) was only possible by the coupling of JEWEL with v-USPhydro and the analysis of jet-soft correlation developted throughout this work, yielding the first-time calculations of jet v_3 . Both observables were calculated in a wide transverse momentum range for various centralities and jet radii, using the anti- k_T algorithm, to better demonstrate the alterations caused by different medium evolution hypotheses.

For the R_{AA} , all models are unable to replicate experimental data for peripheral collisions, with little improvement for v-USPhydro simulations. Moreover, the study of large area jets demonstrated substantial model-dependent behavior. A detailed study regarding the event-by-event fluctuations in the jet-soft correspondence was made, enabling the calculations of v_n for multiple configurations and resulting in a description of the observable dependences with centrality, jet radius R and model similar to the observations on R_{AA} . Measurements for different R is a new trend among the LHC collaborations and this work provides a plethora of unprecedented predictions regarding it. The combination of simulations of JEWEL, PYTHIA, T_RENTo and v-USPhydro enabled the first theoretical result for a positive jet v_3 , which shows that jet evolution is a viable indicator of the medium's hydrodynamic characteristics.

The comprehensive study of these general observables presented paves the way to new possibilities to further explore aspects of heavy-ion physics within the JEWEL framework: medium response and the thermal background subtraction method surrounding it, jet substructure observables, the introduction of heavy-flavor phenomena, etc.

Bibliography

- U. Heinz and M. Jacob, "Evidence for a New State of Matter: An Assessment of the Results from the CERN Lead Beam Programme," pp. 1–7, 2000.
- [2] STAR Collaboration, "Experimental and theoretical challenges in the search for the quark-gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions," *Nuclear Physics A*, vol. 757, no. 1-2 SPEC. ISS., pp. 102–183, 2005.
- [3] J. Letessier and J. Rafelski, *Hadrons and Quark–Gluon Plasma*. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Cambridge University Press, 2002.
- [4] W. Florkowski, Phenomenology of Ultra-relativistic Heavy-ion Collisions. World Scientific, 2010.
- [5] M. Peskin, An Introduction To Quantum Field Theory. CRC Press, 2018.
- [6] X. N. Wang, "Hard probes in high-energy heavy-ion collisions," Progress of Theoretical Physics Supplement, no. 129, pp. 45–59, 1997.
- [7] K. C. Zapp, F. Krauss, and U. A. Wiedemann, "A perturbative framework for jet quenching," *Journal of High Energy Physics*, vol. 2013, no. 3, 2013.
- [8] T. Sjöstrand, S. Mrenna, and P. Skands, "PYTHIA 6.4 physics and manual," Journal of High Energy Physics, vol. 2006, no. 5, 2006.
- K. C. Zapp, "Geometrical aspects of jet quenching in JEWEL," *Physics Letters*, Section B: Nuclear, Elementary Particle and High-Energy Physics, vol. 735, pp. 157– 163, 2014.
- [10] R. K. Elayavalli and K. C. Zapp, "Simulating V+jet processes in heavy ion collisions with JEWEL," *European Physical Journal C*, vol. 76, no. 12, pp. 1–9, 2016.
- [11] R. Kunnawalkam Elayavalli and K. C. Zapp, "Medium response in JEWEL and its impact on jet shape observables in heavy ion collisions," *Journal of High Energy Physics*, vol. 2017, no. 7, 2017.
- [12] F. Canedo, "Study of Jet Quenching in Relativistic Heavy-Ion Collisions," may 2020.

- [13] J. Noronha-Hostler, G. S. Denicol, J. Noronha, R. P. Andrade, and F. Grassi, "Bulk viscosity effects in event-by-event relativistic hydrodynamics," *Physical Review C -Nuclear Physics*, vol. 88, no. 4, pp. 1–23, 2013.
- [14] C. E. Aguiar, T. Kodama, T. Osada, and Y. Hama, "Smoothed particle hydrodynamics for relativistic heavy-ion collisions," *Journal of Physics G: Nuclear and Particle Physics*, vol. 27, no. 1, pp. 75–94, 2001.
- [15] O. Nachtmann, A. Lahee, and W. Wetzel, *Elementary Particle Physics: Concepts and Phenomena*. Theoretical and Mathematical Physics, Springer Berlin Heidelberg, 2012.
- [16] Y. Kovchegov and P. Levin, *Quantum Chromodynamics at High Energy*. Cambridge Monographs on Particle Physics, Nuclear Physics an, Cambridge University Press, 2014.
- [17] R. Vogt, Ultrarelativistic Heavy-Ion Collisions. Elsevier Science, 2007.
- [18] U. Heinz and R. Snellings, "Collective flow and viscosity in relativistic heavy-ion collisions," Annual Review of Nuclear and Particle Science, vol. 63, pp. 123–151, 2013.
- [19] R. Nouicer, "Review article New State of Nuclear Matter : Nearly Perfect Fluid of Quarks and Gluons in Heavy Ion Collisions at RHIC Energies,"
- [20] M. Luzum and H. Petersen, "Initial state fluctuations and final state correlations in relativistic heavy-ion collisions," *Journal of Physics G: Nuclear and Particle Physics*, vol. 41, no. 6, 2014.
- [21] C. Prado, Heavy-flavor nuclear modification factor and event-by-event azimuthal anisotropy correlations in heavy ion collisions. 07 2018.
- [22] A. M. Poskanzer and S. A. Voloshin, "Methods for analyzing anisotropic flow in relativistic nuclear collisions," *Physical Review C - Nuclear Physics*, vol. 58, no. 3, pp. 1671–1678, 1998.
- [23] S. Höche, "Introduction to parton-shower event generators," in Theoretical Advanced Study Institute in Elementary Particle Physics: Journeys Through the Precision Frontier: Amplitudes for Colliders, pp. 235–295, 2015.
- [24] T. Sjostrand and P. Z. Skands, "Transverse-momentum-ordered showers and interleaved multiple interactions," *Eur. Phys. J. C*, vol. 39, pp. 129–154, 2005.
- [25] K. Zapp, G. Ingelman, J. Rathsman, and J. Stachel, "Jet quenching from soft QCD scattering in the quark-gluon plasma," *Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics*, vol. 637, no. 3, pp. 179–184, 2006.
- [26] K. Zapp, "JEWEL 2.0.0: Directions for use," European Physical Journal C, vol. 74, no. 2, pp. 1–14, 2014.

- [27] R. Baier, Y. L. Dokshitzer, A. H. Mueller, and D. Schiff, "Medium-induced radiative energy loss; equivalence between the BDMPS and Zakharov formalisms," *Nuclear Physics B*, vol. 531, no. 1-3, pp. 403–425, 1998.
- [28] K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, and U. A. Wiedemann, "A Monte Carlo model for 'jet quenching'," *European Physical Journal C*, vol. 60, no. 4, pp. 617–632, 2009.
- [29] K. Zapp, J. Stachel, and U. A. Wiedemann, "A local Monte Carlo implementation of the non-abelian Landau-Pomerantschuk-Migdal effect," no. 1, pp. 1–5, 2008.
- [30] A. B. Migdal, "Bremsstrahlung and pair production in condensed media at high energies," *Physical Review*, vol. 103, no. 6, pp. 1811–1820, 1956.
- [31] B. Andersson, *The Lund Model*. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Cambridge University Press, 2005.
- [32] A. Buckley, J. Butterworth, S. Gieseke, D. Grellscheid, S. Höche, H. Hoeth, F. Krauss, L. Lönnblad, E. Nurse, P. Richardson, S. Schumann, M. H. Seymour, T. Sjöstrand, P. Skands, and B. Webber, "General-purpose event generators for LHC physics," *Physics Reports*, vol. 504, no. 5, pp. 145–233, 2011.
- [33] Bierlich Christian, Rope Hadronization, Geometry and Particle Production in pp and pA Collisions. 2017.
- [34] C. Shen and U. Heinz, "Collision energy dependence of viscous hydrodynamic flow in relativistic heavy-ion collisions," *Physical Review C - Nuclear Physics*, vol. 85, no. 5, 2012.
- [35] K. Eskola, K. Kajantie, and J. Lindfors, "Quark and gluon production in high energy nucleus-nucleus collisions," *Nuclear Physics B*, vol. 323, no. 1, pp. 37–52, 1989.
- [36] J. S. Moreland, J. E. Bernhard, and S. A. Bass, "Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions," *Physical Review C Nuclear Physics*, vol. 92, no. 1, pp. 1–6, 2015.
- [37] D. Kharzeev, E. Levin, and M. Nardi, "Onset of classical QCD dynamics in relativistic heavy ion collisions," *Physical Review C - Nuclear Physics*, vol. 71, no. 5, pp. 1–4, 2005.
- [38] H. J. Drescher and Y. Nara, "Eccentricity fluctuations from the color glass condensate in ultrarelativistic heavy ion collisions," *Physical Review C - Nuclear Physics*, vol. 76, no. 4, pp. 1–9, 2007.
- [39] J. Bjorken, "Highly relativistic nucleus-nucleus collisions: The central rapidity region," *Physical Review D*, vol. 27, no. 1, 1983.
- [40] Back, B. B. and PHOBOS Collaboration, "Charged-Particle Pseudorapidity Distributions in Au+Au Collisions at sqrt(s_NN)=62.4 GeV," pp. 1–6, 2005.

- [41] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, "An introduction to PYTHIA 8.2," *Computer Physics Communications*, vol. 191, no. 1, pp. 159–177, 2015.
- [42] M. R. Whalley, D. Bourilkov, and R. C. Group, "The Les Houches accord PDFs (LHAPDF) and LHAGLUE," HERA and the LHC: A Workshop on the Implications of HERA for LHC Physics, HERA-LHC 2005 - Proceedings, pp. 575–581, 2005.
- [43] C. Bierlich, A. Buckley, J. Butterworth, C. H. Christensen, L. Corpe, D. Grellscheid, J. F. Grosse-Oetringhaus, C. Gutschow, P. Karczmarczyk, J. Klein, L. Lönnblad, C. S. Pollard, P. Richardson, H. Schulz, and F. Siegert, "Robust Independent Validation of Experiment and Theory: Rivet version 3," *SciPost Physics*, vol. 8, no. 2, 2020.
- [44] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual," The European Physical Journal C, vol. 72, no. 3, pp. 1–69, 2012.
- [45] ATLAS Collaboration, "Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV with the ATLAS detector," *Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics*, vol. 790, no. March, pp. 108–128, 2019.
- [46] CMS Collaboration, "CMS collision events: from lead ion collisions." CMS Collection., Nov 2010.
- [47] G. P. Salam, "Towards jetography," European Physical Journal C, vol. 67, no. 3, pp. 637–686, 2010.
- [48] J. E. Huth et al., "Toward a standardization of jet definitions," in 1990 DPF Summer Study on High-energy Physics: Research Directions for the Decade (Snowmass 90), 12 1990.
- [49] M. H. Seymour, "Jet shapes in hadron collisions: Higher orders, resummation and hadronization," Nuclear Physics B, vol. 513, no. 1-2, pp. 269–300, 1998.
- [50] CMS Collaboration, "First measurement of large area jet transverse momentum spectra in heavy-ion collisions," feb 2021.
- [51] ALICE Collaboration, "Measurements of inclusive jet spectra in pp and central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV," *Physical Review C*, vol. 101, sep 2019.
- [52] Y. Tachibana, A. Angerami, S. A. Bass, S. Cao, Y. Chen, J. Coleman, L. Cunqueiro, T. Dai, L. Du, R. Ehlers, H. Elfner, D. Everett, W. Fan, R. Fries, C. Gale, Y. He, M. Heffernan, U. Heinz, B. V. Jacak, P. M. Jacobs, S. Jeon, K. Kauder, W. Ke, E. Khalaj, M. Kordell, A. Kumar, T. Luo, M. Luzum, A. Majumder, M. McNelis, J. Mulligan, C. Nattrass, D. Oliinychenko, D. Pablos, L. G. Pang, C. Park, J. F. Paquet, J. H. Putschke, G. Roland, B. Schenke, L. Schwiebert, C. Shen, A. Silva,

C. Sirimanna, R. A. Soltz, G. Vujanovic, X. N. Wang, R. L. Wolpert, Y. Xu, and Z. Yang, "Hydrodynamic response to jets with a source based on causal diffusion," vol. 00, pp. 1–4, 2020.

- [53] S. Floerchinger and K. C. Zapp, "Hydrodynamics and jets in dialogue," European Physical Journal C, vol. 74, no. 12, pp. 1–11, 2014.
- [54] M. Connors, C. Nattrass, R. Reed, and S. Salur, "Review of Jet Measurements in Heavy Ion Collisions," pp. 1–52, 2017.
- [55] A. Andronic, J. Honermann, M. Klasen, C. Klein-Bösing, and J. Salomon, "Impact of scale, nuclear PDF and temperature variations on the interpretation of mediummodified jet production data from the LHC," arXiv, 2020.
- [56] R. Haake, "Machine learning based jet momentum reconstruction in Pb-Pb collisions measured with the ALICE detector," *Proceedings of Science*, vol. 364, pp. 0–6, 2019.
- [57] ATLAS Collaboration, "Measurements of the Nuclear Modification Factor for Jets in Pb+Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector," *Physical Review Letters*, vol. 114, no. 7, pp. 0–19, 2015.
- [58] R. Haake and C. Loizides, "Machine-learning-based jet momentum reconstruction in heavy-ion collisions," *Physical Review C*, vol. 99, no. 6, pp. 1–8, 2019.
- Pb+Pb [59] "Measurements of Jet Azimuthal Anisotropies in colli-TeV," sions at $\sqrt{s_{NN}}$ 5.02tech. rep., CERN, Geneva, Jun 2020. figures including auxiliary All figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-019.
- [60] ALICE Collaboration, "Azimuthal anisotropy of charged jet production in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions," sep 2015.
- [61] J. Noronha-Hostler, B. Betz, J. Noronha, and M. Gyulassy, "Event-by-Event Hydrodynamics+Jet Energy Loss: A Solution to the RAA - V2 Puzzle," *Physical Review Letters*, vol. 116, no. 25, pp. 1–7, 2016.
- [62] J. Noronha-Hostler, B. Betz, M. Gyulassy, M. Luzum, J. Noronha, I. Portillo, and C. Ratti, "Cumulants and nonlinear response of high pT harmonic flow at $\sqrt{s_{NN}}=5.02$ TeV," *Physical Review C*, vol. 95, no. 4, 2017.
- [63] ATLAS Collaboration, "Measurement of the azimuthal anisotropy of charged particles produced in $\sqrt{s_{_{\rm NN}}} = 5.02$ TeV Pb+Pb collisions with the ATLAS detector," *Eur. Phys. J. C*, vol. 78, no. 12, p. 997, 2018.
- [64] J.-F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, and C. Gale, "Production of photons in relativistic heavy-ion collisions," *Phys. Rev. C*, vol. 93, no. 4, p. 044906, 2016.

[65] B. Efron and C. Stein, "The Jackknife Estimate of Variance," The Annals of Statistics, vol. 9, no. 3, pp. 586 – 596, 1981.

Appendix A

Simulation Parameters

For the sake of replicabality, the relevant models parameters used are presented in this appendix.

In the case of JEWEL's configuration files: name of files, random seeds, number of events and centrality-specific entries are excluded, any other unspecified parameter used JEWEL 2.0.0's default ones, found in [26].

JEWEL CONFIGURATION FILE				
	R_{AA}	v_n		
PTMIN	20	70		
PTMAX	1200	800		
ETAMAX	4.2	3.2		
SQRTS	5020.	5020.		
KEEPRECOILS	Т	Т		
WRITESCATCEN	Т	Т		
WRITEDUMMIES	Т	Т		

Table A.1: Parameters used in JEWEL configuration for runs of of each observable.

JEWEL MEDIUM CONFIGURATION FILE					
	Glauber+Bjorken	$T_RENTO+v-USPhydro$	MC-KLN+v-USPhydro		
TI	0.59	*	*		
TAUI	0.4	0.6	0.6		
TC	0.15	0.15	0.15		
MDSCALEFAC	0.9	1.0	1.1		
SIGMANN	7.0	7.0	7.0		

Table A.2: Medium parameters used in JEWEL configuration for each medium model. *v-USPhydro profiles do not use an initial temperature TI since JEWEL is not responsible for generating them.

The same presentation is showed for $T_R ENTo$ parameters, following the default parameters (if unspecified) discussed in [36] for PbPb 5.02 TeV collisions. For MC-KLN, the only altered parameter was the nucleon-nucleon cross section, chosen to be 7.0 fm².

T _R ENTo CONFIGURATION FILE			
Projectile	Pb		
Projectile	Pb		
Reduced Thickness	0.0		
Fluctuation	1.6		
Cross Section	7.0		
Grid Max	12		
Grid Step	0.06		

Table A.3: Parameters used in $\mathrm{T}_{\mathrm{R}}\mathrm{ENTo}$ initial conditions.