Jet Quenching in Small Systems

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Ever since the discovery of the Quark-Gluon Plasma in heavy-ion collisions, the study of jet quenching (i.e. the energy loss and modified branching of partons transversing dense media) has been at the forefront of current theoretical and experimental efforts in QCD.

Experimental data from both PbPb and XeXe collisions show significant signs of jet quenching, which is a strong indicator for QGP production. However, the question of whether these effects remain when we go to smaller colliding systems is still open. With this in mind, several light-ion collisions were simulated within the JEWEL framework, in order to fill the gap between what is already known from experiments. Therefore, the results will serve as predictions for future experiments involving these systems, like the OO collisions planned for the run 3 of the LHC.

The results show that the level of jet quenching remains rather similar across all simulated systems, until HeHe collisions, where a significant decrease in quenching is visible, but still not entirely negligible, like in pp collisions. The results also found a lower bound to the initial mean temperature of the medium for significant signs of quenching ($T_i \sim 300$ MeV). Finally, a sophisticated analysis of jet substructure is presented by looking at the kinematic Lund plane. This plane, even in a qualitative way, proves to be a powerful tool to distinguish between high and low quenched systems.
Keywords: QCD, Quark-Gluon Plasma, Jet Quenching, Small Systems.

I. INTRODUCTION

Heavy-ion collisions (HIC) have provided a lot of important insights regarding the hadronic structure of nuclei, but the golden nugget was the discovery of a new medium formed immediately after the collision of two heavy nuclei, the *Quark-Gluon Plasma* (QGP). This medium resembles a hot and dense soup of quarks and gluons, and it is believed that it was the same medium which filled the universe early on, only microseconds after the Big Bang. Nowadays, QGP is created and studied at the LHC with PbPb collisions reaching energies as high as 5.02 TeV per nucleon pair (and eventually reaching 5.50 TeV in the future run 3 of the LHC), and although a lot of insights were taken from these experiments, there is still a lot to be understood.

In the last couple of years, physicists started focusing on smaller system collisions, like pPb collisions, where signatures of QGP formation were found. These signatures sparked a new debate on which people argued if tiny droplets of QGP could be formed in those type of systems and if yes, what effects should we be able to see. Although many observables agree with the idea of QGP being formed in small systems, many other observables do not, which lead to a collaborative effort in trying to understand the exact conditions needed in order to form a QGP.

The thesis addresses one of the first and simplest questions that arise in this debate: *If QGP is formed in heavy-ion collisions and not in pp collisions, is there an intermediate system, i.e. the collision between lighter ions in which this transition occurs ?* Answering this question is no easy task, since there are a lot of elements to cover in the periodic table until we reach PbPb collisions. It is simply not feasible, from an experimental point of view, to perform experiments involving all these elements. Therefore, one must rely on computational simulations, based on state of the art Monte Carlo (MC) event generators, to accurately simulate small system collisions and narrow down the best candidates for which the transition may occur.

After the simulations of small system collisions are done, one can analyse the data and look for indicators of the presence of QGP. The ones that will be the focal point of the thesis are jets, more specifically, their modification due to the interaction with a medium. The modification of jets is usually referred to as *jet quenching* and the next section will bring more light on how this happens when a medium is present. The main goal of the thesis is to find how jet quenching effects change when we go to symmetric lighter colliding systems. We expect to see a significant reduction of these effects as we approach the size of a pp collision, where we know the jets are not modified. The bulk of the thesis will consist of finding the best strategies to identify these effects and distinguish them between systems. By doing this, we can make predictions for the future results from experiments involving small system collisions and help build a bridge between HIC and pp collisions.

II. QCD AND HEAVY-ION COLLISIONS

The goal of this section is to provide the necessary knowledge to understand all the results in the sections ahead. A more deep explanation of the underlying theory and historical background can be found in the thesis. All further knowledge is merely computational and should not be obstructive for easily reproducing the obtained results.

A. Quark-Gluon Plasma in Heavy-Ion Collisions

It has been the goal of research in QCD for the past twenty years to understand how hadronic matter behaves in extreme conditions, like the ones in the early universe. In other words, we know from the asymptotic freedom of QCD and results from heavy-ion collisions that hadronic matter can go through a phase transition in which the quarks and gluons stop being bounded into colourless states (i.e. hadrons) and start behaving as a collective medium known as the Quark-Gluon Plasma. This means that QCD has a phase diagram that needs to be filled by doing several experiments in different conditions. However, HIC only allow the scanning of a very limited region of the QCD phase diagram, and until today most of the regions in it remain to be fully understood both experimentally and theoretically.

Studying the thermal and hydrodynamical properties of QGP can give us a lot of important insights on the conditions of the early stages of the universe, but as one can imagine, it is not as simple as studying any other fluid. One can naively think that if we want to extract information on the medium that is created in these collisions, it is as simple as sending a probe to measure its properties. Unfortunately, the timescales that need to be measured are so small that direct probing of the QGP is not possible. We need to use indirect methods in order to fully understand the time evolution of the QGP. The probes that can actually be used are usually divided into two categories, soft and hard probes. Soft probes are low momentum particles that are the QGP direct byproducts. They usually reflect global characteristics of particle production like multiplicities, cross-sections, correlations and even hadro-chemistry. On the other hand, hard probes are high momentum particles, like *jets*, *heavy flavours* and *quarkonium states*, that are produced in a high momentum transfer process (i.e. a hard scattering very early on in the collision). Due to their large scale, they can be factorized from the medium evolution[1] and described analytically using perturbative methods.

In HIC, the high momentum particles must propagate through the QGP that is formed during the same collision. Therefore, due to interactions with the medium, the exiting jet can lose energy, forward momentum but also pick up momentum transverse to its original direction [1]. The energy "lost" by the jet is deposited in the medium and gives birth to many soft particles after the QGP falls apart. Effects like this energy loss are often referred to as *jet quenching* and until now they have only been observed in AA collisions.[2]

Given our lack of understanding on how these interactions work and how exactly is the jet modified by its passage through the QGP, it is vital that we use jet reconstruction algorithms and study all the scattering history, during the jet evolution, in order to obtain some insights on how these interactions happen and ultimately, determine properties of the QGP itself.

By reconstructing a jet in HIC, we can measure its properties and see how they are affected by the presence of an interacting medium. Besides jet measurements like its transverse momentum or mass, there are also intra-jet measurements, also referred to as jet substructure, that allow us to know the history of the jet regarding its radiation pattern. Classifying which splittings are induced from an interaction with the QGP and which are caused by the usual splitting probability of vacuum parton showers is a crucial step towards understanding how these interactions work. Fortunately, there is a great way of visualizing and classifying these splittings by using a simple and general kinematic plane of QCD.

B. Lund Diagrams

Jet substructure, at its most fundamental, is the study of vacuum QCD in the near-soft (low-energy) and collinear (small-angle) limits. It was shown in the thesis that the probability of a propagating quark to emit a gluon is given by:

$$P(z,\theta^2)dzd\theta^2 = \frac{\alpha_S C_F}{\pi} d(\log z) d(\log \theta^2)\,, \tag{1}$$

where $z = \frac{E_g}{E_q+E_g}$ is the gluon energy fraction, θ is the angle between the emitted gluon and quark, C_F is the Casimir colour factor in the representation of the fundamental quarks, and α_S is the coupling of the strong interaction.

Equation 1 suffers from a problem that most particle physicists are already very familiar with: In the soft ($z \to 0$) and collinear ($\theta \to 0$) limits, the probability diverges. Dealing with infinities can frustrate a lot of people, but in times like this, it is important to think about the system represented by the equation. In these limits, there is really no distinction between a system of a quark emitting a zero energy (or zero angle) gluon from a system of a quark emitting no gluons. In fact, the system is exactly the same as one quark emitting an indefinite number of soft/collinear gluons. We call these systems degenerate with each other and by the *Kinoshita-Lee-Nauenberg theorem* [2, 3]: results and predictions in degenerate perturbation theory are only finite if we sum

[1] The separation between production of the hard probe and propagation through the medium is under theoretical control.

[2] AA is used as a system of two heavy nuclei, like PbPb, colliding with each other

up all degenerate states. Therefore, $P(z,\theta^2)dzd\theta^2$ should not be interpreted as a probability, but rather as an expectation value of the number of soft/collinear gluons emitted from the quark.

Once again, looking at equation 1, the emissions of soft/collinear gluons are uniformly distributed on the ($\log z$,$\log\theta^2$) plane. By exploiting this, it is possible to fill this plane with a point regarding each emission along the fragmentation pattern of a jet, since each emission can be characterized by these two phase space variables. This plane is called the *Lund plane*. If only the primary splittings of a jet are considered, we call the plane a *primary Lund plane*. If the secondary splittings are also considered, then we would get a perpendicular plane, for each secondary splitting and so on and so forth. The diagram that has all these planes represented is the same place is called the *Lund diagram* and although it can easily get very messy to visualize, it can contain all the information regarding jet substructure. A complete Lund diagram would be filled with every point (z,θ) associated with each splitting in a jet's fragmentation pattern.

The picture becomes more complicated however, when the plane is filled with information from a full heavy-ion event. The presence of a medium changes the fragmentation pattern of a jet, and it becomes difficult to see which splittings were induced from the interactions with the medium itself and which ones were natural vacuum QCD splittings. Furthermore, the medium-induced splittings no longer obey equation 1, meaning that they will not be uniformly distributed across the plane. It is also not practical to single out information regarding one jet alone, and in order to maintain statistical relevance, usually the plane is filled with the information of several jets, usually one per event of interest which can lead to a lot of points in a sample of one million generated events. This altogether makes the plane very difficult to analyse. However, by filling the plane with every jet of interest, one can analyse its global structure in a qualitative way and compare it with the one filled for different systems. For example, it is possible to see enhancements of certain kinematic regions of the plane when comparing with the ones filled from pp collisions, where the medium is not present.

It was suggested in [4] that by using the kinematic Lund plane, we can distinguish emissions/splittings that happen inside the medium from those that occur outside, considering we know the medium's length. Furthermore, we can even separate the region corresponding to emissions inside the medium into three smaller regions: Pure vacuum splittings inside the medium, in-medium splittings that are never resolved by medium interactions and finally a region where the splitting kinematics is dominated by medium effects and therefore the probability of splitting is no longer described by equation 1. This is, however, not applicable in a realistic noisy heavy-ion background but nevertheless, provides an interesting view on the capabilities of the Lund plane.

Lund diagrams provide an excellent tool to observe jet substructure and although a lot of work needs to be done in order to better understand them beyond the qualitative level, several techniques are being implemented nowadays to filter the important information and give an accurate view on how the jet fragmentation pattern looks when is modified by the presence of QGP. One of the goals of this thesis is to help narrow down specific configurations of the Lund plane that allow a better distinction (even if only on a qualitative level) between high quenched systems and low quenched systems, as well as the evolution between them. Until now, these planes were only used for analysing high quenched systems, like PbPb collisions and systems with no quenching, like pp collisions. Hopefully, by seeing how the planes look in intermediate systems, we will have a better understanding on which techniques to use, in order to extract the relevant information, that will ultimately allow us to know how and in which systems the QGP is formed in the first place.

C. Small System Collectivity

The story of small system collisions started recently, in 2010, when momentum anisotropies were measured in systems like pA or even high multiplicity pp collisions [5–8]. These momentum anisotropies were comparable with the ones from HIC. In HIC, physicists had already established that matter in the QGP behaves as a nearly inviscid fluid that efficiently translates initial spatial anisotropies into correlated momentum anisotropies among the particles produced, creating a common velocity field pattern known as collective flow.

When similar anisotropies were measured in small systems like pA collisions, people started thinking if this could be an indication of the presence of QGP, something that until now was exclusively possible in HIC. In fact, the expectations were that the volume and lifetime of a medium produced in these collisions would be too small to form a QGP. This opened up a lot of new discussions on which systems would actually be possible the formation of a QGP and which probes could be used to verify its presence. By understanding this, a bridge could be built between HIC and pp collisions that would allow the extension of the heavy-ion standard model to small systems.

Several other observables, directly related with collectivity, were measured using soft and hard probes. Most of the soft probes show a good agreement with the idea of QGP being formed in these systems as well [9]. However, hard probes, like jets don't seem to be modified in these systems and that is a fundamental problem in the view of tiny droplets of QGP being produced in small systems, since jet quenching effects are a crucial evidence of the interaction between high energy particles, produced in the collision, and the medium itself. Even considering the smaller scale of the medium (when compared with AA collisions), the effects should be noticeable.

Asymmetric collision systems (like pA collisions) are, however, much more complicated to study and if the goal is to establish a bridge between HIC and pp collisions, it makes sense to look first at symmetric collision systems. The first fundamental question that arises when one looks at the problem in this way is: *If QGP is formed in HIC and not in pp collisions, is there an intermediate system in which the QGP stops being formed ?* Since jet quenching effects are a necessary condition for the existence of QGP, one can study these effects in symmetric lighter system collisions, chosen in a way such that they could provide a good coverage of the periodic table and see in which system the effects start to be negligible.

The goal of the thesis is to simulate these small system collisions and analyse observables sensitive to jet quenching effects, in order to check in which systems these effects are significant and in which they start to be more reminiscent of a pp collision. This is a crucial step towards the verification of QGP being formed in these systems or not. By answering questions like these, we put ourselves one step closer of understanding how the universe was during this unconfined phase of QCD.

D. Model Description

The main framework adopted throughout the thesis was the Monte Carlo generator JEWEL [10]. JEWEL is an event generator that can simulate QCD jet evolution in HIC. It is based on one of the general-purpose event generators used in particle physics simulations, PYTHIA 6 [11], and it handles exclusively the final-state parton shower routine. One can think of JEWEL as a general MC generator for particle physics that has the option of embedding a medium model in the collision, in order to simulate a realistic environment for HIC. JEWEL treats the interplay of QCD radiation and re-scattering in a medium with fully microscopic dynamics in a consistent perturbative framework with minimal assumptions (for further details on the inner workings of JEWEL see [12]).

JEWEL has two modes of operation: *simple* and *vacuum*. One can think of these modes as an on/off button for the medium. In the absence of the medium JEWEL reduces to an ordinary virtuality ordered parton shower similar to the virtuality ordered shower in PYTHIA 6. This means that simulating a PbPb collision using the vacuum mode is the equivalent of simulating $\langle N_{coll}\rangle$ pp collisions, where $\langle N_{coll}\rangle$ is the average number of pp collisions that happen in a PbPb collision. The same would happen for different colliding systems and if all the parameters are kept the same, the only difference would be the number of pp collisions that are simulated, which of course depends on the system itself. The medium is therefore somewhat independent from the colliding system, at least from a computational point of view and it is viewed by the jet as a collection of partons in the form of scattering centers. These scattering centers will induce extra radiation, characteristic of a typical HIC.

The medium properties are inferred from hydrodynamical calculations, in order to have a close correspondence between the colliding system and the QGP that is formed in a realistic experiment. The expansion of the medium is governed by a classic Bjorken expansion [13] in the Stefan-Boltzmann limit of the QCD equation of state [14]. After several calculations (which can be found in the thesis), one arrives at the final set of equations that allow the estimation of the input parameters for the characterization of the medium embedded in JEWEL:

$$T_i = \left(\frac{15}{c\pi^3 R_A^2 n_{dof}} \cdot N_{part} \cdot 0.46 \cdot (\sqrt{s_{NN}})^{0.4}\right)^{1/3}\,, \tag{2a}$$

$$\tau_i = \frac{1}{T_i}\,, \tag{2b}$$

where T_i and τ_i are the initial (mean) temperature and formation time of the medium, which will be given to JEWEL as input parameters. R_A is the atomic nuclear radius of the colliding nucleus (which can be found in [15]), $n_{dof} = 47.5$ is the number of degrees of freedom for a system with gluons and three quark flavours, N_{part} is the average number of participants in the collision, estimated by the *Glauber Model* [16] and $\sqrt{s_{NN}}$ is the center-of-mass energy of the colliding nuclei, which can be estimated for an accelerator like the LHC by knowing its $\sqrt{s}$.

These estimations should apply for any colliding system, and they will be extensively used when simulating lighter systems. However, one should take them with a grain of salt, since they only apply for an idealistic scenario in which the QGP is modelled as an ideal gas of quarks and gluons that undergo a classic Bjoken expansion. With this in mind, the following results shall bring more light into the validity of both the model embedded in JEWEL, as well as the theoretical considerations involved in the estimations of the model parameters.

III. JET QUENCHING IN PBPB COLLISIONS

Before applying an analysis to a system for which a few or no experimental data exists, it is important to validate the analysis with results from real experiments. With this in mind, two well-known systems were simulated, in this section, using the JEWEL framework: PbPb and pp collisions. The "pp collisions" simply correspond to the simulation of a PbPb collision in vacuum mode, as already explained in the previous section. The initial medium parameters were determined accordingly with equation 2 and the full list of parameters can be found in Appendix B of the thesis. Most of these parameters are general to all simulations (even the simulations for the next section) and the ones that will change, shall be stated explicitly.

A. Processes

In order to save computational time, MC generators usually allow the selection of different processes of interest, which means one can select the production channel through which the fundamental particles will interact. This will be useful when simulating events for a specific process. Throughout this thesis, two processes were analysed: Z+Jet and Dijet.

The Z+Jet process requires a Z boson to be produced back to back with a jet. As for the Dijet process, the only requirement is to have two back to back jets being produced. The JEWEL framework allows the selection of both processes, by restricting the hard scattering to one in which a Z boson is produced together with a quark or a gluon (in the Z+Jet case) and to QCD processes only, where the resulting particles must be quarks or gluons, in order to each form a jet on their own (in the Dijet case).

These two processes are among the most useful for dealing with jet modification since both will produce noticeable asymmetries due to interactions with the medium. In the case of Z+Jet, the Z boson will not interact with the medium, since it does not have colour charge and therefore will not be modified by it. This means we can define ratios, using the information on the Z boson as baseline and have a frame of reference for which energy the jet should have if the medium was not present. As for the Dijet type events, we can measure asymmetries regarding the leading and subleading jets[3] and understand how these asymmetries change in the presence of an interacting medium. The full description of how the analysis was done and the results of some baseline and control measurements can be found in the thesis.

B. Observables

Having established the relevant processes, we need to define observables that are sensitive to jet quenching effects. As already mentioned at the beginning of this section, these observables often reflect asymmetries between objects which interact differently with the medium, usually in the form of ratios.

One of the first and most commonly used observables is the *nuclear modification factor*:

$$R_{AA}(p_T) = \frac{\frac{dN^{AA}}{dp_T}}{\langle N_{coll} \rangle \frac{dN^{pp}}{dp_T}} , \tag{3}$$

where $\frac{dN^{xx}}{dp_T}$ is the number of particles (or jets) produced in a xx collision with a given p_T and $\langle N_{coll} \rangle$ is the number of pp collisions expected to happen in a AA collision.

[3] Leading and subleading jet is used to distinguish between the highest p_T jet and the second highest in the away side, respectively.

This observable allows the comparison between the number of jets in a AA collision and the number of jets that would be expected from an analogous number of pp collisions, without the presence of QGP. In terms of the analysis, selecting the nucleon PDF and simulating in the vacuum mode of JEWEL is the equivalent of simulating $\langle N_{coll} \rangle$ pp collisions. Therefore, the ratio is obtained simply by diving the jet spectrum of an AA collision with the jet spectrum of the same AA collision in vacuum mode. A ratio smaller than 1 indicates that due to interactions with the medium, the number of jets produced at a given p_T is reduced in AA collisions and considering the steepness of the spectrum[4], a small fractional energy loss corresponds to a large suppression in R_{AA}. This makes the nuclear modification factor a very sensitive observable to jet energy loss.

This observable can be used when analyzing both processes, but the way it is calculated is different. On the Z+Jet analysis, only the back to Z jets contribute to the jet spectrum used to calculate the ratio, while in the Dijet analysis all the jets that survive the kinematic cuts contribute to the total inclusive jet spectrum and therefore enter the ratio. This means that the nuclear modification factor will not be the same for each process, as it is shown in figure 1. Nevertheless, they both show a clear suppression in jet production for heavy-ion collisions, compatible with the results from the LHC [17].

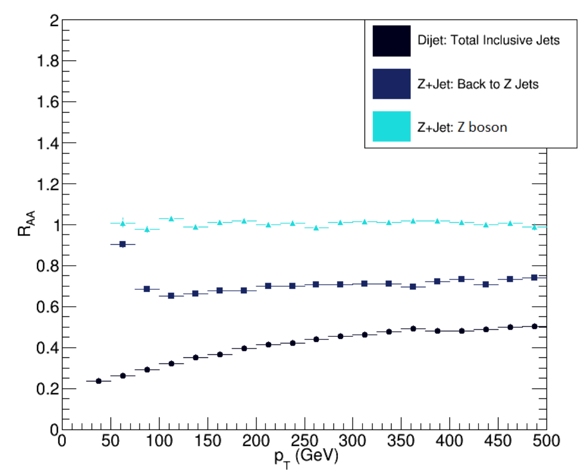

FIG. 1. Nuclear modification factors for Z+Jet and Dijet processes.

Another useful observable is the *momentum fraction* in the Z+Jet process, which is defined in the following way:

[4] At mid-rapidity, the probability of jet production scales roughly with p_T^{-6}.

$$x_{JZ} = \frac{p_{T,jet}}{p_{T,Z}} \,. \tag{4}$$

As already explained, the Z boson will not interact with the medium and therefore will normalize the amount of transverse momentum lost by the back to Z jet. This means that we expect a ratio compatible with 1 for pp collisions, where we know QGP is not formed and a ratio smaller than 1 for PbPb collisions.

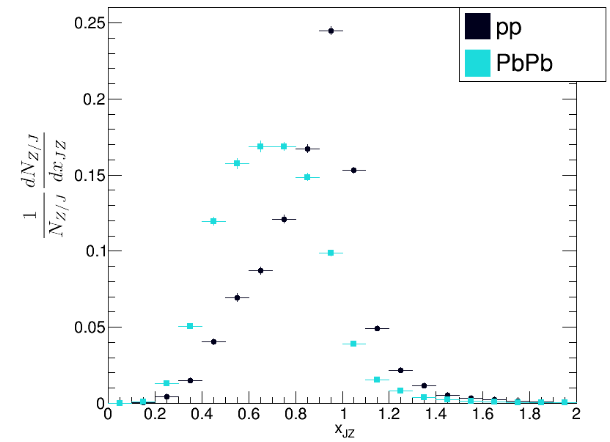

FIG. 2. Momentum fraction in the Z+Jet process.

The momentum fraction in figure 2 seems to be in agreement with the results from [18], showing a peak for both PbPb and pp collisions. This reflects the fact that the denominator in the ratio remains the same, even in the presence of QGP. This means that instead of looking at the entire distribution, we can give a bit of rest to our eyes and only look to the mean value of the distribution as represented in figure 3.

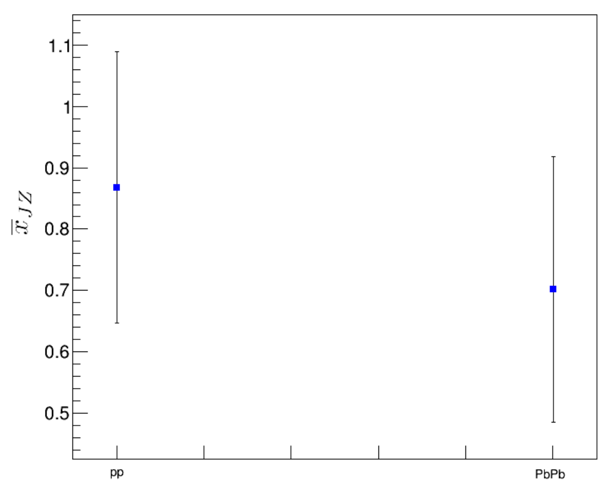

FIG. 3. Mean momentum fraction in the Z+Jet process.

By looking at the mean values of the distributions, one can clearly see that the ratio in a pp collision is very close to 1 ($\overline{x}_{JZ} \sim 0.87$), while the ratio in a PbPb collision is much smaller ($\overline{x}_{JZ} \sim 0.7$), showing a close agreement with the results from [18]. Both values are represented with error bars up to one standard deviation ($\sigma \sim 0.22$), which is calculated for the discrete distributions in figure 2. The mean error of the distribution is around 0.6% of the mean value, reflecting the statistical relevance of the results.

As for the asymmetry between the leading and subleading jets in the Dijet process, it can be measured with an observable called *dijet asymmetry*, which reflects the asymmetry in transverse momentum of both jets, in a given Dijet event, normalized to unity:

$$A_J = \frac{p_{T,jet1} - p_{T,jet2}}{p_{T,jet1} + p_{T,jet2}} \,, \tag{5}$$

where the labels 1 and 2 correspond to the leading and subleading jet, respectively.

$A_J \approx 1$ indicates a huge asymmetry, while $A_J = 0$ means that the leading and subleading jet have exactly the same transverse momentum. Without the presence of QGP, one makes expects to see a peak in event probability around zero asymmetry, since these are the most likely events and a decrease towards values of higher asymmetries, effectively reaching zero probability before $A_J = 1$, since this value would mean the subleading jet had $p_{T,jet2} = 0$ and by definition this is not considered to be a Dijet event.

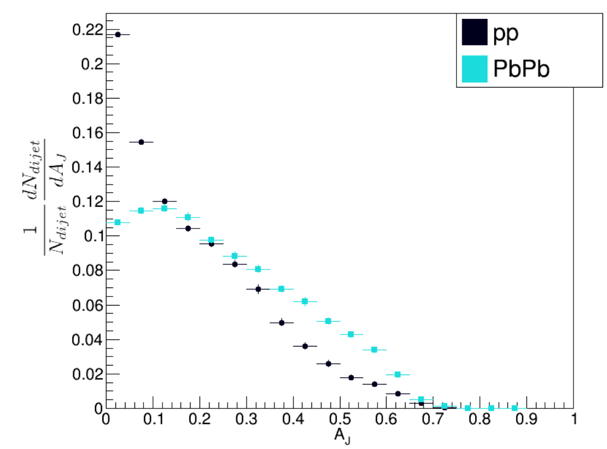

FIG. 4. Dijet asymmetry.

Looking at the results from figure 4, we can see that the behaviour in a pp collision is exactly what one should expect from the absence of an interacting medium. However, in a PbPb collision, there is a significant decrease in probability for low asymmetric Dijet events, just like the results in [19]. This, once again, reflects the fact that both jets will interact with the medium and lose energy. Coupling this with the fact that both jets will most likely lose different amounts of energy (mainly due to the larger fragmentation pattern of the subleading jet) and we have an increase in event probability for higher values of A_J. In fact, this observable shows that in the presence of a medium, most of the events will have a leading jet with a p_T around 25% higher than the subleading one. Furthermore, this observable allows us to distinguish between systems with and without jet quenching effects by comparing the results of other colliding systems with the ones in figure 4 and see if the behaviour is more similar to the pp case or PbPb case.

C. Lund Analysis

In the previous section, it was explained how analyzing jet substructure could provide insightful knowledge on the changes in the fragmentation pattern due to medium-induced interaction. It was shown how the Lund plane could contain all the information regarding jet fragmentation and therefore be used as a powerful tool to distinguish between high and low quenched systems. This section will show how the primary Lund plane looks when it is filled with jets from PbPb collisions and from pp collisions. The full explanation on how to reconstruct this plane can be found in the thesis as well as some important insights regarding the reconstruction algorithms used.

In theory, several combinations of the Lund plane are possible, and at this stage, it is very difficult to choose which one works the best for visualizing quenching evolution. However, by showing an example of a primary Lund plane filled with jets from PbPb and pp collisions we can already have a general idea of the main kinematic regions that are affected by the presence of a medium. One possible configuration of the plane is represented in figure 5, in which the plane was filled with the back to Z jets from the Z+Jet process.

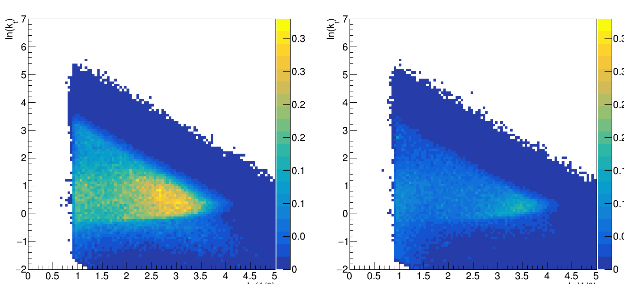

FIG. 5. Primary Lund planes filled with back to Z jets from pp collisions (left side) and PbPb collisions (right side). The plane was reconstructed with the C/A algorithm and spanned by $\ln(1/\theta)$ and $\ln(k_T)$. The plane is also scaled by a factor of 10^3.

By comparing the two planes, one can see that there is a significant reduction of emissions in the middle region of the plane when the medium is present. This kinematic region corresponds to soft/collinear emissions, which are highly enhanced in vacuum due to QCD divergences (see equation 1). This means that the presence of an interacting medium suppresses these divergences somehow and the probability of emission is no longer ruled by equation 1, as one already expected. As far as the qualitative distinction in quenching intensity, one can argue that the more this region is suppressed, the more intense the medium is, and if a small system collision presents a primary Lund plane with a strong fingerprint in the soft/collinear region, then the quenching effects are most likely negligible.

IV. JET QUENCHING FROM HEAVY TO LIGHT

This section aims to highlight the main results achieved during the thesis, based on simulations using the JEWEL framework. It is important to notice that many of the lighter systems that were studied still do not have any experimental data to compare with, which means that the obtained results will serve as predictions for future experiments involving lighter system collisions, like OO collisions at the LHC, which are planned for 2023 [20]. This means that the following results are only valid within the models embedded in the JEWEL framework and if later experimental evidence from lighter system collisions diverges from the results obtained in here, then either the models in JEWEL need to be readjusted or the theoretical predictions for the parameters do not apply in these type of systems and we need to rethink how to accurately describe them in terms of a strongly coupled QGP.

A. Model Testing

Given the lack of experimental data on these systems, is it difficult to know what to expect from the results. That is why it is important to start with a test of the model in order to know how it behaves, regarding each of the parameters. By doing this, it will be possible to have a better understanding of the results once we go to realistic simulations of lighter system collisions.

The first thing one needs to do is to establish a baseline system that will serve as a frame of reference for every parameter that is changed. This system needs to be compatible with experimental results in order to serve as a beacon of truth in the sea of the unknown. The chosen system is, without much surprise, PbPb collisions (or *baseline med* as it appears in the results) with parameters that give compatible results to the ones at the LHC: $T_i = 406$ MeV, $\tau_i = 0.48$ fm and $\sqrt{s}_{NN} = 5.5$ TeV. The other baseline system is the vacuum itself, as generated by JEWEL, based on the simulated PbPb collision in vacuum mode.

Several parameters were tested (all presented in the thesis), but the most notorious result was the impact of the initial temperature of the medium in the jet quenching effects. Figure 6 shows how the dijet asymmetry changes for five different initial temperatures. Other observables, like the mean momentum fraction in the Z+Jet process, are presented in the thesis.

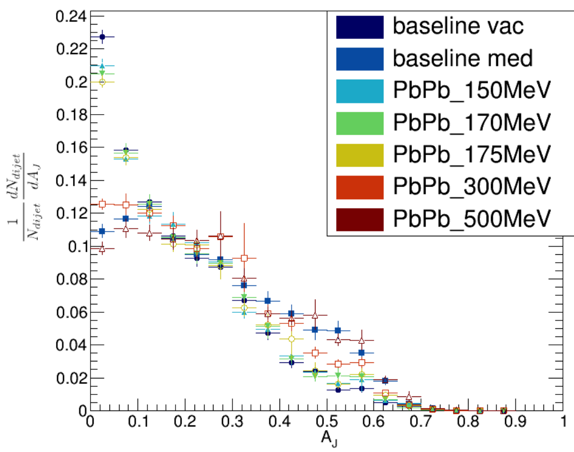

FIG. 6. Initial temperature evolution for the dijet asymmetry.

Figure 6 shows that for higher initial temperatures the dijet asymmetry resembles very much the baseline system in which the medium is present, even reaching smaller values of low asymmetric events than the baseline one (406 MeV), in the case of the 500 MeV system, which is reasonable, since it has a higher initial temperature. As one should expect, the systems which have initial temperatures equal or smaller than the critical temperature (170 MeV) show negligible quenching effects that are compatible with the vacuum ones. However, the interesting feature of these results is the fact that even for temperatures slightly higher than the critical one, the quenching effects are still negligible. In fact, the 175 MeV system is still compatible with the vacuum baseline and only at temperatures near 300 MeV the effects start to be noticeable. This indicates that the system probably needs some time above the critical temperature before the parton-medium interactions start, and in order to see quenching effects, the initial temperature of the medium needs to be above a certain threshold.

B. Observable Evolution

Now that the model was tested, it is time to get to the meat and potatoes of the thesis. It is time to see how the observables sensitive to jet quenching behave under realistic simulations of small system collisions. Four new systems were simulated: SnSn, ArAr, OO and HeHe collisions. All simulations were done in a similar way to the ones in the previous section, but using the new parameters for both the colliding system, as well as the medium itself (see table I).

Element	$\sqrt{s_{NN}}$ (TeV)	N_{part}	R_A (fm)	τ_i (fm)	T_i (MeV)
Pb	5.50	356	5.5	0.48	406
Sn	6.00	210	5.1	0.54	362
Ar	6.30	66	3.7	0.64	307
O	7.00	27	1.8	0.53	374
He	7.00	6	1.7	0.84	235

TABLE I. Parameter table for the small system sample generation.

In order to have a frame of reference for an unquenched system, all the results will also be compared with the ones from a standard "pp collision", which is basically a PbPb collision simulated using the vacuum mode in JEWEL. Any other vacuum system would be equivalent (see Appendix A of the thesis) in simulating the so-called "pp collisions", and the choice of using the vacuum from PbPb was merely to retain consistency with the previous results.

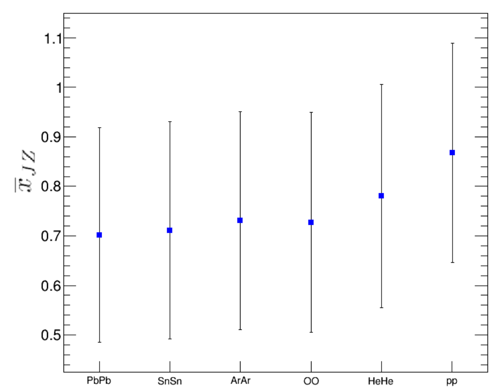

FIG. 7. Mean momentum fraction evolution through all generated samples.

Figure 7 shows how the mean momentum fraction evolves for each system. There is a slight increase in the values of x_{JZ} as the system gets smaller, meaning that the quenching effects start to resemble the ones from a pp collision as we go to the lighter systems, like HeHe. However, the increase is not sufficient enough to say it is compatible with the vacuum, and the effects are still noticeable and compatible with the ones from a PbPb collision. Even a system like HeHe, that is much closer in size to a pp collision, shows significant quenching ($\overline{x}_{JZ} \sim 0.78$). In fact, the value for x_{JZ} is closer to the one from PbPb ($\overline{x}_{JZ} \sim 0.7$) then the one from pp collisions ($\overline{x}_{JZ} \sim 0.87$).

The results from the nuclear modification factors and the dijet asymmetry (see thesis) also corroborate the idea of a compatible level of quenching across all systems, except HeHe collisions, where there is a noticeable decrease in quenching, but it is still not entirely negligible like in pp collisions. This could mean that the transition we were looking for might actually be between pp collisions and HeHe collisions and if that is the case, a lot of effort needs to be put in order to understand why all systems can produce QGP except a collision between two protons.

C. Lund Evolution

Having this in mind, it was one of the goals to narrow down which configuration works the best and after an extensive look at all possible planes, the configuration that proved to be the most reliable was the one that uses the C/A algorithm and has a set of coordinates $[\log 1/\theta, \log k_T]$. It is possible that another configuration works better for a different binning and coordinate disposition. However, this one proved to be the most reliable during all tests, in which different binnings and axis ranges were experimented on.

We could dwell into the primary Lund planes filled with the leading and subleading jets (like it was done in the thesis), but since we are only concerned with the evolution between systems, it is sufficient to show how the planes look when filled with the back Z jets in Z+Jet processes (see figure 8).

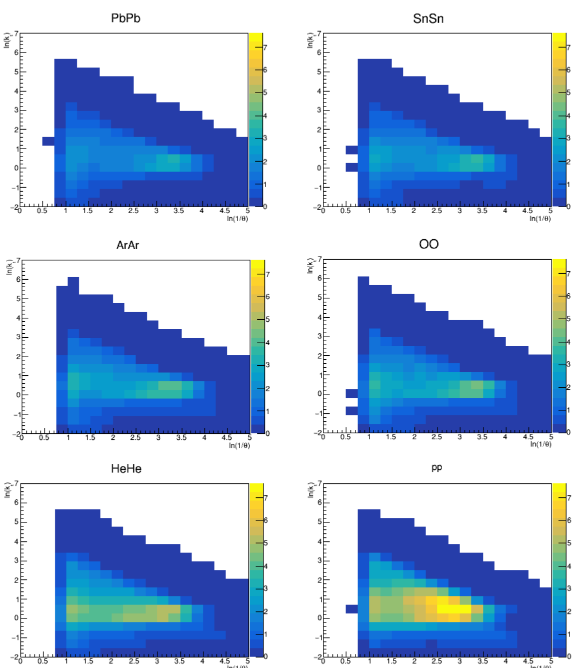

FIG. 8. Primary Lund plane evolution through each generated sample. The planes were filled with the back to Z jets from Z+Jet processes.

Figure 8 shows that the jet substructure remains practically the same for the heavier systems and only when we reach a very light system like HeHe, the plane starts to resemble the one from pp collisions. Nevertheless, there is a slight increase in the soft/collinear region of the plane as the system gets lighter, across all planes. However, it is very diluted in the current scale, which is maximized by the pp plane (i.e. the z-axis is fixed in all planes). If we only compared the four heavier systems, the scale would be adjusted, and these changes should be more noticeable. They would most likely reflect the tendency already seen in the results of the observables, which is to have a slight decrease in quenching as the system gets lighter. There is still a visible quenching fingerprint in HeHe collisions but, as far as the results go, the jets that come from Z+Jet events, only start to be significantly modified in OO collisions and the modifications remain rather equivalent until PbPb collisions.

Looking at the Lund plane results alone leads to one of the two conclusions, regarding the transition:

- The threshold for the QGP formation is somewhere between an OO collision and a HeHe collision and the decrease of soft/collinear radiation in HeHe is attributed to something else.

- The threshold for the QGP formation is between an HeHe collision and a pp collision, and although a QGP is formed in HeHe collisions, it is very short-lived, when compared with the ones from heavier systems, but it still produces noticeable effects.

However, since the observable results also show significant signs of quenching for HeHe collisions, the most likely scenario is that the transition is between HeHe and pp collisions.

V. CONCLUDING REMARKS

The goal of the thesis was to address the question of how jet quenching effects change from a heavy system to a light one, also called small system. We know, from experiments, that QGP is formed in heavy colliding systems, like PbPb and XeXe collisions and not in pp collisions. By keeping the colliding system symmetric, one expected to see a smooth transition in the observed quenching as the system gets lighter, eventually reaching the point of negligible quenching. However, the results show that instead of a smooth transition, the jet quenching effects remain rather similar across all systems until HeHe collisions, where the effects decrease significantly but are still not entirely compatible with the ones from pp collisions.

In principle, this would mean that QGP is formed in every colliding system besides pp collisions, which indicates an unknown mechanism for QGP formation that needs to be further explored. However, one cannot simply ignore that these results were obtained in the context of the medium model embedded in JEWEL. By using a framework which deals with the medium simulation as an on/off mechanism, it should make sense that no matter how light the colliding system is, if the simulation is done with the "simple" mode of JEWEL, then the quenching effects will be noticeable, since the medium is there by default. Ideally, we would have a MC that deals with the medium simulation in a more sophisticated way, by letting the colliding system "decide" if a medium would be produced or not. However, this would require a deep knowledge of what exactly are the initial conditions needed to form QGP, something we do not have at the moment.

Nevertheless, several important results were discovered, like the threshold value of the initial temperature of the medium for visible signs of quenching ($T_i \sim 300$ MeV), which was significantly higher than the QGP's critical temperature ($T_i = 170$ MeV). This could be an artefact of JEWEL's medium model, but it further enlightens why significant quenching effects were seen in all systems, since the estimated initial temperatures were all above 300 MeV (except He, which had $T_i = 235$ MeV and that is why this was the only system showing a significant reduction in quenching). This means that, if jet quenching effects are not observed in an experiment involving one of these small systems, the medium model in JEWEL is not necessarily wrong. Maybe, the theoretical assumptions used in the estimate of the initial parameters given to JEWEL need to be reconsidered in order to give values of T_i significantly lower than the threshold for quenching effects. Nevertheless, in the absence of quenching in small systems, the most likely scenario is that the model in JEWEL needs to be revisited and upgraded in order to accurately predict this behaviour. Therefore, the results obtained regarding the small system simulations will serve as predictions for the future experiments, like the OO collisions planned for the run 3 of the LHC and will help to narrow down the possible outcomes of what needs to be revisited.

Although several important insights were taken from the results of this thesis, there is still a lot of work that could be done while we wait for the results from the future experiments involving small system collisions. Besides further tests of the JEWEL model and the validation of the theoretical assumptions involved in the estimation of the initial medium parameters, it could also be very useful to further develop techniques to explore the Lund planes besides their qualitative nature, which was the main type of studies done here. For example, one could use some type of "filtering" technique to select very specific jets of interest and take quantitative information on the kinematic region that is filled and that could be useful to understand what exactly is the difference between a quenched Lund plane and an unquenched one.

It could also be interesting to look at the Lund planes besides the primary one. By considering secondary splittings, one can have a better idea of how exactly the fragmentation pattern of a jet is modified by the presence of a dense medium. However, this comes at the cost of visualization, since secondary splittings would fill a new plane perpendicular to the primary one. Nevertheless, n-dimensional analysis and feature recognition is a hot topic in the modern age of machine learning techniques, and probably the field could use some insights from this area to be able to extract relevant information from a fully-fledged Lund diagram.

All this goes to show that there is still a lot of room for improvement of the current methods of analysis and although progress is usually made by taking little steps, the problem of extending the heavy-ion standard model to small system collisions is right around the corner to be solved. Hopefully, with the future experimental data on these collisions, it will possible to end the debate on QGP formation in small systems and ultimately, gain an all-new perspective on the QCD phase diagram and the theory of QCD as an accurate description of the strong interaction.

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