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Exploring the time axis within medium-modified jets

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The fast evolution of the QGP makes its interaction with jets an inherently time-dependent process. However, this crucial dimension is missing from traditional jet quenching measurements, which hence provide a mere average quantification of the medium properties. Jet substructure observables provide an effective strategy to access the QGP time structure. By identifying the recursive steps of a novel jet clustering algorithm (the τ algorithm) with the sequence of branchings of the parton shower, it is possible to obtain an adequate proxy for a time axis within the medium. In this work we apply this technique to label jets according to their formation time and opening angle, defining populations with enhanced sensitivity to quenching effects. In doing so, we show how the formation time-based sampling of jets minimizes the bias of their initial transverse momentum spectrum.

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1. Introduction

The Quark Gluon Plasma (QGP) generated in Heavy Ion Collisions (HICs) experiences a very fast expansion, during which its properties are continuously modified. An appropriate strategy to study this evolution is to analyze its effect over hard probes such as jets, which, being generated early in the collision, experience the entire process. However, the picture evoked by traditional jet observables is one where quenching effects are implicitly integrated over the whole lifetime of the medium. Such an analysis thus fails to capture the complex time dependence of the interaction between the probe and its dynamical environment. In order to access this information, it is necessary to 1) define an experimentally measurable proxy for a time axis within the jet and 2) relate it to the underlying evolution of the medium. In this work we approach the first task in the context of p_T-differential jet energy loss in PbPb collisions.

The concept of 'time' is, in a sense, trivially built in all event generators. At the Monte Carlo level, the constituents of a jet originate from a sequence of partonic splittings implemented according to an algorithm (i.e. a parton shower) based on a certain ordering variable. This variable may be understood as providing an underlying time axis for the process, even if it is not an actual time scale. In fact, depending on the specific event generator employed, it might correspond to transverse momentum (used by e.g. PYTHIA 8), virtuality (PYTHIA 6), angle (HERWIG), etcetera.

When simulating a HIC, the ordering variable of the shower algorithm allows to implement the evolution of the background medium through its interaction with the jet at each consecutive value. Thus, the resulting jet modification implicitly depends on the development stage of the jet, labeled by the ordering variable. Given this theoretical picture, it is possible to use jet substructure observables to access the internal scales characterizing each splitting of the parton shower. This can be done through the unclustering process, where we recluster our jets and identify each step of the employed clustering algorithm with a partonic emission.

This method was presented by some of the authors of the present manuscript in [1], where it was shown that, by reclustering with the τ algorithm and applying Soft-Drop (SD) grooming [2], one obtains a good correlation between the extracted τ_{form} and the one within the primary branch of the parton shower. In the present work we apply this technique to Z-tagged jets simulated (without recoils) with the JEWEL Monte Carlo event generator [3]. We extract the formation time and the opening angle corresponding to their first SD splitting along the primary branch, and use this information to classify them according to their sensitivity to medium-induced energy loss. In doing so, we show how the τ_{form}-based sampling allows to quantify energy loss in a way that minimizes the bias on the initial p_T of the jets.

2. Jet (un)clustering

Let us start with some basic definitions. From a theoretical point of view, jets are bunches of collimated final state particles originated by the same hard parton. In practice, however, these particles have to be grouped according to a clustering algorithm of choice. These 'recipes' specify how to combine pairs of particles sequentially until they are all clustered into groups under a certain maximum size (i.e. the jet radius).

In this work we focus on the well known "generalized k_T-family" of clustering algorithms. On each iteration, we combine pairs of particles that minimize the following distance measure:

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \tag{1}$$

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ is the distance in the space defined by rapidity y and azimuthal angle ϕ. This function also depends on a couple of parameters: the jet radius R, which defines the maximum reach of the algorithm; and p, which controls the way in which d^{ij} depends on the transverse momenta of particles. Depending on the value given to p we will have different algorithms, like Cambridge/Aachen ($p = 0$), k_T ($p = 1$), or anti-k_T ($p = -1$). In this work, however, we employ a nonstandard clustering algorithm known as τ algorithm, which corresponds to setting $p = 0.5$. In this case, the clustering scale becomes:

$$d_{ij} \sim p_{T,i}\theta^2, \tag{2}$$

where the emission angle $\theta \approx \Delta R_{ij}^2/R$. In the soft and collinear radiation limit, this scale is approximately equal to the inverse of the formation time of the emitted particle, $1/\tau_{\rm form}$ (defined as the time it takes for the emitted parton to behave as an independent radiation source). As shown in [1], a special feature of this clustering algorithm is that it allows to establish an approximate one-to-one relation between each step of the clustering history and each splitting along the primary branch of the parton shower. This connection is established through the unclustering procedure.

Given a collision event, one first identifies the jets (typically by clustering with the anti-k_T algorithm), then selects the jets to be analyzed (e.g. the leading jets in dijet events), and recluster them with the τ algorithm. In this work we also use this step to remove soft contamination by imposing the SD condition. Finally, going over the reclustering history, one extracts the kinematic information of each splitting, substituting it in the following formula (valid in the high energy limit only):

$$\tau_{\rm form} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}, \tag{3}$$

thus obtaining a sequence of formation times. In the same way, one may also extract a sequence of opening angles (denoted simply as ΔR from now on). This method was applied in [1] to Monte Carlo-generated dijet events at $\sqrt{s_{NN}} = 5.02$ TeV, and it was shown that it indeed provides an appropriate proxy for the formation time at each splitting (and that it does so independently of the ordering scheme of the parton shower).

3. Results

We use the procedure outlined above to extract both the formation time $\tau_{\rm form}$ and the opening angle ΔR of the first SD splitting of jets. We focus our study on JEWEL-generated Z+jet events at $\sqrt{s_{NN}} = 5.02$ TeV, where we require a minimum transverse momentum of 60 GeV for the Z-boson and 30 GeV for the reconstructed jet.

Z+jet processes are known to provide a clean and well calibrated environment for energy loss studies. The mean reason for this is that the boson is largely unaffected by the medium, and therefore,

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its momentum is a good proxy for the initial momentum of the jet. This is specially advantageous when compared to other event topologies where we do not have a handle of the initial p_T of the jet (e.g. dijet events). In the case of Z+jet events, however, this effect is minimized. Another attractive feature of boson-tagged events is that we can quantify energy loss straightforwardly through the momentum imbalance between jet and boson: $x_{j,Z} = P_{j\perp}/P_{Z\perp}$.

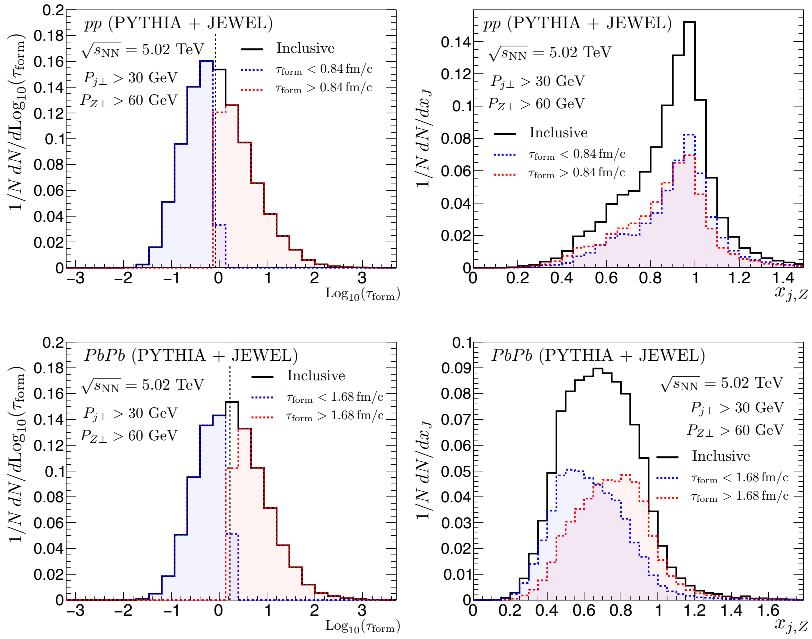

Figure 1: LEFT PANELS: $\mathrm{Log}_{10}(\tau_{\mathrm{form}})$ spectra of 'early' (blue dashed lines), 'late' (red dashed lines) and inclusive (full black lines) jets in pp (top) and PbPb (bottom) collisions. RIGHT PANELS: Comparison of the corresponding $x_{j,Z}$ distributions.

In the top panels of Fig. (1) we show the $x_{j,Z}$-distributions corresponding to pp collisions (right panel, distinctively peaked at one), as well as the distribution of τ_{form} values extracted from the first SD splitting (left panel). We use this information to classify jets according to their sensitivity to medium modifications. For this, we find the median of the τ_{form}-distribution τ_m, and define an 'early' class of jets with those whose first SD splitting takes place before τ_m; and a 'late' jet group with those that start fragmenting after τ_m. We do this in order to have each jet sample contain approximately half of the total population. We perform similar operations over PbPb events, obtaining the bottom panels of Fig. (1).

As can be seen in the pp $x_{j,Z}$ spectra, we are selecting samples that are basically indistinguishable. This suggests that, in the vacuum, there is no discernible correlation between our jet selection criteria and the momentum imbalance observed in the resulting classes. However, in the case of PbPb collisions, our selection yields a much clearer separation between our samples. This can be interpreted simply in terms of τ_{form}: the 'early' class, which contains jets that spent more time inside the medium, have lost more energy on average, with the opposite being true for the 'late' group.

We reach similar conclusions by extracting ΔR instead of τ_{form}. In this case, analogously to

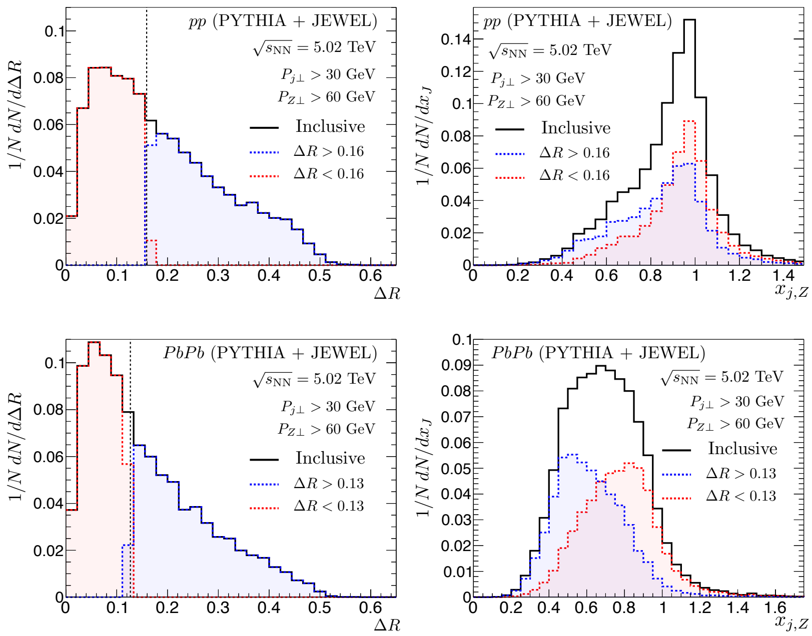

Figure 2: LEFT PANELS: ΔR spectra of wide (blue dashed lines), narrow (red dashed lines) and inclusive (full black lines) jets in pp (top) and PbPb (bottom) collisions. RIGHT PANELS: Comparison of the corresponding $x_{j,Z}$ distributions.

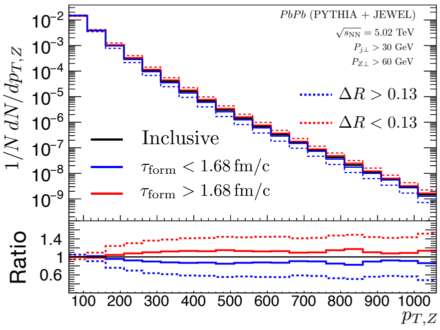

Figure 3: p_T spectra of Z bosons (which we identify with the initial p_T spectra of the recoiling jet). The full colored lines correspond to 'early' (blue) and 'late' (red) jets, sampled according to their τ_{form}, whereas the dashed curves represent the 'wide' (blue) and 'narrow' (red) jets, sampled according to their ΔR. The inclusive spectra is shown in solid black.

our τ_{form}-based selection, we define classes of 'wide' and 'narrow' jets according to the kinematics of their first SD splitting. As can be seen in the bottom right panel of Fig. (2), there is indeed a correlation between the initial opening angle of jets and their medium-induced energy loss. The origin of this correlation can be explicitly stated when expressing τ_{form} as:

$$\tau_{\text{form}} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})} \approx \frac{1}{zE\Delta R^2}. \tag{4}$$

From this, it is clear that we can expect a correlation between smaller values of τ_{form} and larger opening angles (and viceversa). Exploiting this correlation, in Fig. (2) we have defined jet classes that seem to be almost identical to those binned in τ_{form} and show the same signs of sensitivity to energy loss. At this point, it is worth questioning whether we are actually selecting the exact same jets in Fig. (1) and Fig. (2). In order to see this, one may examine the initial p_T-spectra of the jet samples defined through their τ_{form} and ΔR values. This is shown in Fig. (3). As can be seen in this plot, when we use ΔR to bin our jets, we obtain a significant shift with respect to the inclusive spectra (shown as a solid black line). This poses a fundamental problem: the energy loss that we quantify with ΔR-based binning is implicitly biased, as it is correlated to the initial p_T. On the other hand, when we perform a binning in terms of τ_{form}, the observed correlation is minimized, thus providing a measurement of energy loss that is less sensitive to the initial p_T of the jet.

4. Conclusions

We used the τ algorithm presented in [1] to extract the formation time τ_{form} and the opening angle ΔR corresponding to the first SD splitting inside jets. We showed that one can use this information to discriminate between jets according to their sensitivity to medium-induced energy loss, and applied this technique in an analysis of JEWEL-generated Z+jet events at $\sqrt{s_{NN}} = 5.02$ TeV. We observed that, by selecting jets according to τ_{form}, we minimize the bias of their initial transverse momentum spectrum (which is a dominant effect when binning in ΔR). This allows to interpret the energy loss of jets unambiguously in terms of their formation time and independently of their initial p_T.

The results presented in this manuscript are part of an ongoing effort to explore the features, limitations, and potential applications of the τ algorithm. Many future studies are foreseen as part of this endeavor. For example, it would be desirable to confront the present results with a more realistic simulation of the interaction with the medium. This can be achieved by including medium response in JEWEL (more specifically, by employing the newly released background subtraction algorithm [4]). We also plan to expand this study to include other jet substructure observables, such as the jet mass. Crucially, we also intend to examine the connection between the extracted τ_{form} and the actual lifetime of the medium. This will be a definite step towards a tomographic study of the QGP.

References

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