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Modification of jet structure in nuclear collisions: theory overview (and pp perspective)

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Abstract

This brief overview of jet structure in heavy-ion collisions touches on analytical and Monte Carlo methods for predicting jet substructure, as well as the question of how new and existing observables can be used to shed light on the dynamics of the interaction of a fragmenting parton with the quark-gluon plasma.

Keywords: Heavy-ion collisions, jets, quantum chromodynamics

1. Introduction

Bjorken's proposal [1] from over 35 years ago that jets might be quenched as they traverse a quark–gluon plasma initiated what, today, is a diverse field of both experimental and theoretical investigation, notably in light of the extensive observations by the RHIC and LHC experiments of quenching of high transverse-momentum hadrons and jets (for reviews, see e.g. Refs. [2, 3, 4]).

Early theoretical discussions of jet quenching, including Bjorken's, concentrated on the question of energy loss from a single parton that traverses the hot medium. However actual jets are composed of tens of hadrons, with a broad range of energies and angles with respect to the jet axis. The dynamics of jet quenching inevitably have an interplay with this rich jet structure, the traces of which may be left in the modifications of the jet structure.

The interplay takes place at several levels. The way in which a jet loses energy may depend on the sequence of QCD emissions that occurred just as the medium was being created, on timescales before a few tenths of a fermi after the collision. QCD radiation may be induced from partons as they receive kicks from the medium, adding emissions within (as well as outside) the jet, thus modifying its structure. Furthermore many articles talk of energy being transferred to the medium. In practice, experimentally, the definitions of what is "medium" and what is "jet" are operational definitions, and different choices may have an impact in differences in the observed structure of jets.

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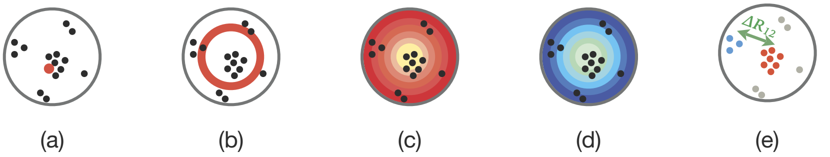

Fig. 1. Representation of different jet structure observables' sensitivity to the radiation inside a jet: (a) fragmentation function, (b) differential jet shape, (c) broadening or "girth", (d) jet mass (which may be groomed or ungroomed) and (e) soft-drop ΔR_{12} and z_g observables.

In brief proceedings such as these, it is impossible to thoughtfully cover all aspects of jet substructure in heavy-ion collisions, and indeed it would beyond my expertise. However I will try to bring a perspective on some key questions, a perspective necessarily coloured by my vacuum-QCD background.

2. Standard observables

There are many substructure observables in use and it may be helpful to recall the definitions of some key ones,

(a) Fragmentation function: $$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}} \tag{1}$$

(b) Differential jet shape: $$\rho(r) = \left\langle \frac{1}{p_{t,\text{jet}}\delta r} \sum_{\substack{k \text{ with} \\ \Delta R_{k,\text{jet}} \in [r, r+\delta r]}} p_{t,k} \right\rangle_{\text{jets}} \tag{2}$$

(c) Girth or Broadening: $$g = \frac{1}{p_{t,\text{jet}}} \sum_{k \in \text{jet}} p_{t,k}\, \Delta R_{k,\text{jet}} \tag{3}$$

(d) Jet mass (groomed or ungroomed): $$m^2 = \left(\sum_{i \in (\text{sub})\text{jet}} p_i^\mu \right)^2 \tag{4}$$

(e) Soft Drop z_g, ΔR_{12}: $$z_g = \frac{\min(p_{t1}, p_{t2})}{p_{t1} + p_{t2}}, \qquad \text{for} \quad z_g \left(\frac{\Delta R_{12}}{R} \right)^\beta > z_{\text{cut}} \tag{5}$$

The sensitivity of the various observables to different aspects of the jet structure is illustrated in Fig. 1. Some of the observables, such as the fragmentation function or differential jet shape are a function of some auxiliary variable, e.g. a momentum fraction z or a ring radius r and are typically used only as averages over an ensemble of jets.

Other observables, such as the girth, jet mass or soft-drop (SD) variables are usually evaluated on a jet-by-jet basis, and it is typical to examine their differential distributions. The girth (or broadening as it was originally called [5]) and jet mass effectively provide measures of the extent to which radiation is spread out in the jet, with the jet-mass weighting outer regions more prominently than the girth.

The soft-drop variables [6] are special in that they examine the properties of subjets obtained from declustering a Cambridge-Aachen (C/A) [7, 8] clustering sequence, repeatedly following the higher-p_t branch and stopping when the condition $z_g\,(\Delta R_{12}/R)^\beta > z_{\text{cut}}$ is satisfied. The version with $\beta = 0$ was introduced in Ref. [9], there called modified mass-drop tagger, and then subsequently generalised and given the name soft drop [10]. Recent work on further generalising the concept of soft-drop observables is discussed in section 6.

In any discussion of jet structure, the diversity of observables that one has to hand is important: each brings sensitivity to somewhat different aspects of the jet's structure. By examining many variables, one can gain confidence that a given approach to predicting jet-structure modifications isn't improving one variable's description while simultaneously worsening another's.

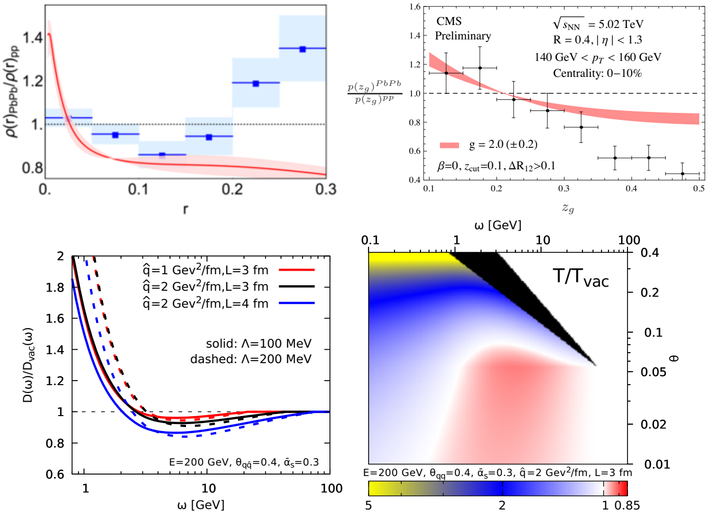

Fig. 2. Results for $\rho(r)$ and the z_g the distribution from Refs. [11, 12] (top row) and for the fragmentation function (bottom left) with an analysis of contributing phase-space regions [13] (bottom right).

3. Analytical calculations

Of the two main practical approaches to making theoretical predictions for comparison to HI collision data, we will first discuss (semi-)analytical methods.

Figure 2 shows results from (semi)-analytical calculations for $\rho(r)$, the z_g distribution, and the fragmentation function. Each comes from a different group, using distinct underlying calculational methods, respectively: a holographic approach [11]; soft-collinear effective theory [12], and a method that emphasises the role of the pattern of emission angles and energies induced by parton showering shower in determining medium interactions [13].

A weakness of analytical approaches in an environment as complicated as that of heavy-ion collisions is that it can be difficult to account for all relevant physical effects. This may be the origin of the limited agreement with data in both of the upper figures, which has been attributed (see notably Refs. [14, 15]) to a lack of "recoil" effects, i.e. the modification of the pattern of energy-flow in the heavy-ion background due to the jet's interaction with it.

On the other hand, a strength of analytical approaches is that for the effects that they can calculate, one can gain considerable insight and understanding into the relevance of the different physical effects and phase-space regions that are accounted for. This is illustrated in the bottom-right plot of Fig. 2 [13], which shows the degree of modification of the emission pattern shown as a function of two variables, the angle and energy of the emission. The distinct regions of that plot are identified in terms of an understanding of the different time and length scales that emerge in a double-logarithmic analysis of showering in the medium.

4. Monte Carlo tools

In contrast to analytical approaches, Monte Carlo simulation tools (including the ambitious Jetscape project [16]) have the potential to produce a far more complete description of heavy-ion collision events, with the potential drawback that it can sometimes be more difficult to understand which given physical effect and phase-space region is responsible for which phenomenon (though to some extent this can be diagnosed by switching off individual elements of the simulation).

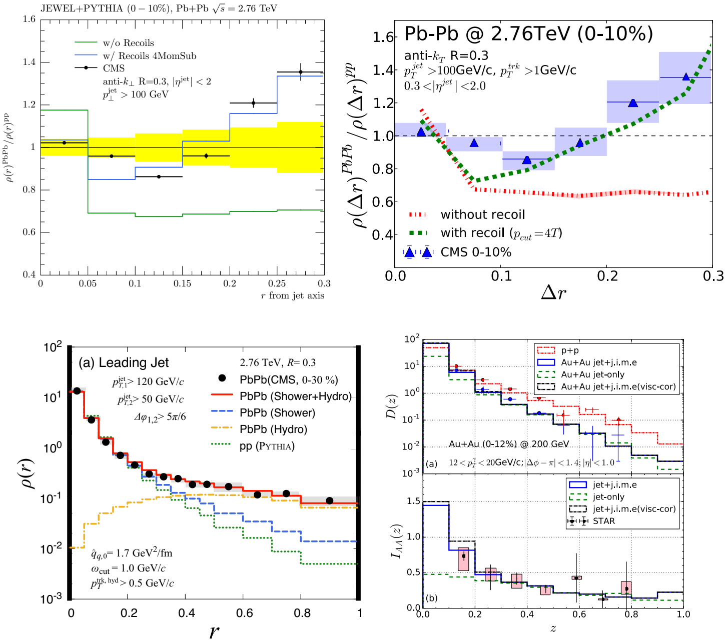

Fig. 3. Results from Monte Carlo simulations compared to data from the LHC and RHIC: Jewel [17] (top left), Martini [18] (top right), and Tachibana et al. [19] (bottom left) for the jet shape $\rho(r)$ (or its nuclear modification factor) and from the LBT approach [20] for the fragmentation function (bottom right).

A theme that has characterised many of the Monte Carlo studies recently is that of understanding the medium response, or equivalently recoil. Its impact is shown in Fig. 3, within several Monte Carlo approaches, for the jet shape $\rho(r)$ and the fragmentation $D(z)$. In particular, for the jet shape one sees a remarkably similar pattern from Jewel [17] (top left), Martini [18] (top right), and Tachibana et al. [19] with medium Mach cones (bottom left), where the medium recoil contribute at larger values of r. The LBT approach [20] is shown for the fragmentation function and, again, the effect of medium recoil ("j.i.m.e.") is relevant, now for small z.

A further great advantage of Monte Carlo approaches is that they can be used to calculate a wide range of observables. This was illustrated very nicely with the Jewel comparisons [17] to all of the observables mentioned in section 2. To obtain confidence in one's tools and the physics one may learn from them, it is important to see agreement with data for all these different observables. Still, there are some subtleties in such comparisons. Notably, as the tools stand currently, it is difficult to carry out analyses that directly mirror the experimental analyses, notably as concerns the subtraction of the underlying event.

5. An aside about underlying event subtraction

One question about any jet-related observable in heavy-ion collisions is that of how one should define it with respect to the subtraction of the underlying event.

In pp collisions with tens or hundreds of pileup collisions, an environment with an "underlying event" that can be as noisy as that of a heavy-ion collision, there is a unique physical answer to the analogous question, because the single pp collision is a well defined concept: with a perfect detector, one could imagine identifying the collision vertices for all charged and neutral particles, and so separate the event into distinct pp collisions, then pulling out only the one that is of interest. The best subtraction procedure is whichever one comes closest to this ideal definition.

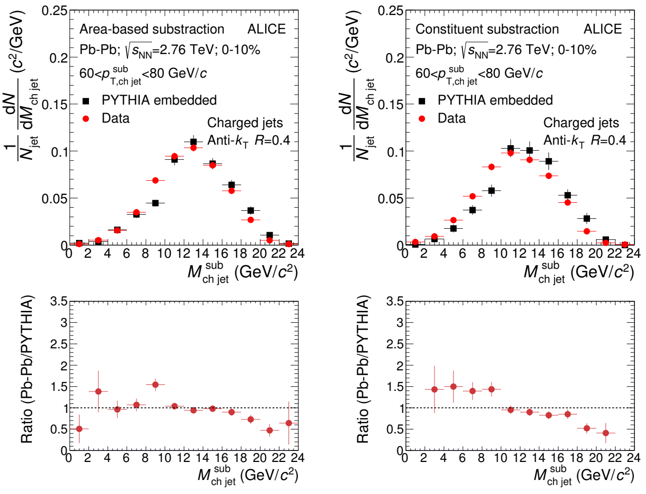

Fig. 4. The subtracted jet-mass distribution for a *pp* event embedded in a *PbPb* background [21], comparing area [22] and constituent subtraction [23] methods.

In heavy-ion collisions, there is no unique physical definition of what belongs to the hard scattering and what belongs to the background. For example if a low-energy gluon from the hard collisions scatters off a gluon from the medium, then there is no unambiguous assignment as to which of the two resulting outgoing gluons belongs to the medium and which to the hard scattering. An underlying event subtraction procedure is then an intrinsic part of the definition of any observable: it is a prescription for declaring which part of the momentum flow is to be considered hard-scattering-like and which part underlying-event-like.

Is the field at the level of precision where this matters? Fig. 4 shows two subtraction methods applied to the jet mass for hard *pp* events embedded in a heavy-ion collision. There is a hint that they yield different results. In the case of *pp* with pileup, there would a unique meaningful target to which to unfold, the single *pp* event, and such differences between two subtraction procedures would be expected to vanish after unfolding. However if one defines the result of an experimental analysis to be, say, the jet mass after a specific subtraction procedure, as one will eventually have to do in heavy-ion collisions, then it will become important that theory calculations and experimental measurements define their observables with the same subtraction procedure. The discussion of these questions has started within the community, reflected in a recent workshop, `https://www.bnl.gov/jets18/`, and also in its study in theoretical work [17], and one can expect it to gain prominence as data and calculations become more precise.

6. New observables

The observables outlined in section 2 are but a small subset of the large number of observables that are being considered by the *pp* community, as reviewed recently [27]. In discussing observables, it is useful to ask oneself what one is trying to learn from them and how closely one can tie the observables to the underlying picture one has of the physics that takes place as a jet traverses and showers inside the medium.

A common feature of many theory discussions is that the underlying phase space has two key variables, as represented for example in Fig. 2 (bottom right). The particular pair of variables that is chosen depends on the authors, but to a first approximation different choices can be straightforwardly translated to each other. One natural choice, proposed long ago by the Lund group for studies of vacuum emissions, is the transverse momentum of an emission relative to its emitter, and the angle of the emission [28], both on a logarithmic scale. The corresponding phase-space representations have come to be known as Lund diagrams. Fig. 5(left) shows a jet, and the distribution of emissions (the coloured subjets) in the Lund-like variables $\ln 1/\theta$ and $\ln z\theta$

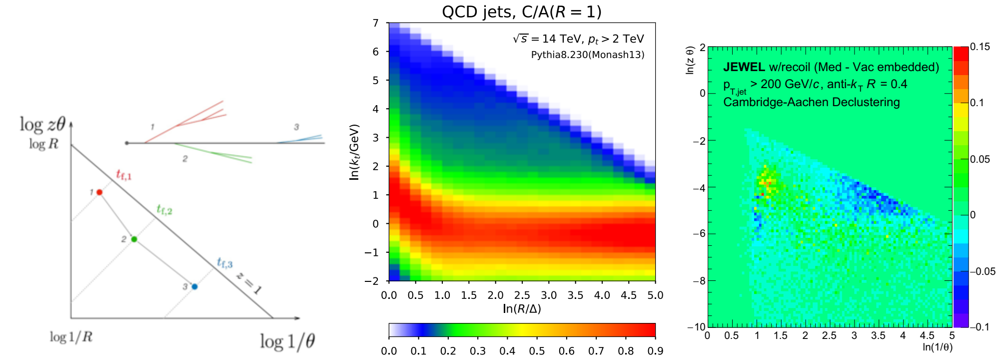

Fig. 5. Left: representation of a jet's primary emissions in the Lund plane (from Ref. [24]). Middle: the averaged Lund-plane emission density in pp jets [25], as simulated with Pythia [26]. Right: degree of modification of the Lund plane in heavy-ion collisions compared to pp with Jewel (from Ref. [24]).

(z being the momentum fraction carried by the emission; $z\theta$ is effectively a relative transverse momentum, normalised to the momentum of the emitting parton). Upward diagonal lines correspond roughly to contours of constant formation time. Yet other contours can be identified associated with other key parameters in a heavy-ion context.

Recently it has been observed [25, 24] that the pattern of emissions in the Lund plane can effectively be obtained jet-by-jet, by repeatedly declustering a C/A-clustered jet, adding an entry in the Lund plane for the kinematics of the softer branch at each stage, and then continuing the declustering for the harder branch. In fact, such an algorithmic definition of the Lund plane provides a powerful generalisation of a range of quantities obtained with the soft-drop algorithm, such as the z_g and ΔR_{12} distributions, each of which can be derived from the averaged Lund plane density. Fig. 5(middle) shows this average density of emissions in the Lund plane for pp jets (using relative k_t of emissions rather than $z\theta$ on the vertical axis), with an enhanced band near $k_t = 1\,\text{GeV}$ reflecting the fact that the density is roughly proportional to $\alpha_s(k_t)$, which is large at low scales. Fig. 5(right) shows the difference in the averaged Lund-plane density in heavy-ion collisions versus embedded pp, as simulated with Jewel relative to a Pythia baseline [24], revealing the kinematic regions where the differences appear. Related results have been shown also in Refs. [29, 30].

Outlook

Though the field of jet quenching has been vibrant for a good twenty years, today the myriad opportunities offered by the study of the internal structure of jets are opening a new era, both in terms of the experimental measurements than can be performed, and of the theoretical developments that are called for in order to grasp the simultaneous dynamics of partons fragmenting while passing through the quark-gluon plasma.

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