Jet Production at RHIC and LHC

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Abstract

Recent results on jet production in heavy ion collisions at RHIC and the LHC are discussed, with emphasis on inclusive jet yields and semi-inclusive hadron-triggered and vector boson-triggered recoil jet yields as well as their azimuthal angular correlations. I will also discuss the constraints that these observables impose on the opacity of the medium, the flavour dependence of energy loss, the interplay of perturbative and non perturbative effects and the change of the degrees of freedom of the medium with the resolution of the probe.

1. Introduction

The scope of the heavy ion jet physics program at RHIC and LHC is to understand the behaviour of QCD matter at the limit of high density and temperature via the study of the dynamics of the jet-medium interactions.

Jet physics in heavy ion collisions is a multiscale problem. Hard scales govern the perturbative production of the elementary scattering and subsequent branching in vacuum and in medium. While jet constituents may interact strongly with the medium at scales corresponding to the temperature of the plasma.

The characterization of medium modifications of jet distributions benefits from observables that are well-defined, that preserve the infrared and collinear safety of the measurement and thus allow for a direct connection to the theory. It also requires the control of the large combinatorial background present in heavy ion collisions.

The first generation of jet measurements are the jet production cross sections and their suppression relative to the vacuum proton-proton reference. These “disappearance” measurements indicate that a significant amount of energy is radiated out of the jet area but do not impose severe constrains on the dynamics of jet-medium interactions.

The second generation of observables are semi-inclusive jet rates, using hadrons, jets or vector-bosons as triggers. Coincidence measurements allow exploration of interjet broadening and inspection of low jet momenta and high resolution $R$. Vector-boson triggers allow for a quantification of the energy lost by the recoiling jet.

The third generation of observables are jet shapes. Possible modifications of the intrajet distributions are currently explored via the jet mass $M$, dispersion $p_T D$, angularities $\alpha$, fragmentation functions $f$ and jet-track correlations $r$. The role of color coherence in medium $C$ is explored by new observables like 2-subjetiness $J$, and soft drop subjet momentum balance $D$. Those two measurements were designed
to understand whether the subjet structure is resolved by the medium, depending on the angular scale, and consequently, determine whether subjets interact in the medium independently or coherently. The second and third generation observables can be combined in the measurement of substructure of recoiling jets, as it is done in [6]. Note as well that this third generation of jet observables won’t be discussed here since they were the subject of another talk [8].

Open questions include the flavour dependence of energy loss, the dependence of energy loss on jet substructure, the role of color-coherence effects, the interplay between weak and strong coupling effects, the role of the medium response or correlated background and the change with the probe resolution scale of the medium degrees of freedom.

2. Inclusive jet suppression

Inclusive jet yields have been measured in Pb-Pb collisions at the LHC over a wide kinematic range from a few tens of GeV to the TeV scale. The suppression of such yields relative to the binary collision-scaled proton-proton reference, is flat up to jet transverse momentum $p_T$ of 1 TeV for jet resolution $R = 0.4$. The strong suppression of 1 TeV jets is a striking observation, given the short size of the medium compared to the hadronization length of the shower of such energetic probes.

Fig. 1 (top left), shows ATLAS results for inclusive jet and hadron nuclear modification factor in Pb-Pb collisions at 5.02 TeV [9]. Data for prompt $J/\psi$ and $Z$ bosons are also shown. In Fig. 1 (bottom), the jet suppression is magnified and compared to 2.76 TeV results. There is no evidence of collision energy dependence. It should be noted that the magnitude of the suppression $R_{AA}$ is not a direct measure of the opacity of the medium to high $p_T$ probes, but rather depends on other elements such the the slope of the underlying hard parton spectrum and the quark/gluon fractions. A different medium opacity at the two colliding energies could manifest itself in a comparable $R_{AA}$.

The measurement of jet yields at forward rapidities is complementary to studying the $\sqrt{s}$ dependence, since it also offers the possibility to vary the medium density, the quark/gluon content and the spectral slope. It was predicted [10] that at forward rapidities and close to the kinematic limit where the spectrum becomes steep, the suppression of forward jets will increase relative to midrapidity. The ATLAS measurement, see Fig. 1 (top right), confirms this prediction qualitatively. At forward rapidity and high jet energy, the jet yields are suppressed relative to midrapidity by 30%.

Another interesting question that rises when exploring jet production at the TeV scale is the role of nuclear effects. At midrapidity, for $E = 1$ TeV and $\sqrt{s_{NN}} = 5$ TeV, the parton momentum fraction is $x_t = 2E/\sqrt{s_{NN}} = 0.4$ and EMC effects may emerge.

3. Semi-inclusive recoil jet yields and momentum balance

Semi-inclusive trigger-jet coincidence measurements provide several advantages:

- Analysis based on semi-inclusive coincidence measurements allow for a precise subtraction of the background uncorrelated to the hard scattering, without imposing fragmentation bias on the jet population. When such background is removed, full correction of the yields can be achieved down to low jet $p_T$ and large $R$.

- When the trigger is a vector boson that does not interact strongly with the medium, the momentum imbalance between the trigger and the recoil jet provides a direct measurement of the energy lost out of the jet area.

- Different choices of trigger bias towards different recoil jet flavour, allowing for the exploration of the flavour dependence of energy loss. The different trigger choices also vary the geometric bias.

- Semi-inclusive measurements are self-normalized and as a consequence they don’t need an interpretation of event activity in terms of geometry. This is an advantage when studying energy loss in small systems as was shown [11].
The STAR collaboration has reported the semi-inclusive yields of track-based jets recoiling from high $p_T$ hadrons ($9 < p_T^{\text{tag}} < 30$ GeV) \cite{12}. A key aspect of the analysis is that uncorrelated background is removed via event mixing and the fully corrected jet yields are measured down to nearly zero $p_T$ for $R$ up to 0.5. The central and peripheral corrected yields are shown in Fig. 2 (top left) together with a PYTHIA and an NLO calculation, and their ratio, $I_{CP}$ is shown in the lower panel of the same figure.

ALICE has also measured the distribution of track-based jets recoiling from a high $p_T$ trigger track \cite{13}. To remove combinatorial background, the difference of two exclusive trigger track classes is taken and a new observable is defined $\Delta_{\text{Recoil}}$. The trigger track class subtraction is proven to be effectively equivalent to the event mixing except for the treatment of multiple parton interactions at low $p_T$, MPIs, that are not subtracted in the latter \cite{12}. The ratio of central Pb-Pb $\Delta_{\text{Recoil}}$ to PYTHIA $\Delta_{\text{Recoil}}$ is shown in Fig. 2 (top right) down to $p_T = 20$ GeV and $R = 0.5$.

In Fig. 2 (bottom), the ratio of the recoil jet distributions measured with $R = 0.2$ relative to those measured with $R = 0.5$ is shown both by STAR (left) and ALICE (right). ALICE data reveals no in-medium redistribution of energy within $R = 0.5$ compared to the vacuum reference.

The finite suppression of the recoil jet distributions in Fig. 2 together with the low infrared cut-off of these measurements, indicates that the medium-induced energy loss arises predominantly from radiation at angles larger than 0.5 relative to the jet axis. The lost energy is reflected in the magnitude of the spectrum shift under the assumption of negligible trigger track energy loss and it is estimated to be $8 \pm 2$ GeV at ALICE, in the jet momentum range of 60 to 100 GeV while STAR results indicate approximately 4 GeV in the jet momentum range of 10 to 20 GeV.

CMS and ATLAS have measured jet production in association with isolated $\gamma$ and $Z$ bosons in proton-proton and Pb-Pb collisions \cite{14,15,16,17}. The $\gamma$ and $Z$ triggers have $40 < p_T^{\gamma} < 60$ and $p_T^{Z} > 60$ respectively, while the recoiling jets have $p_T^{\text{jet}} > 30$ GeV with $R = 0.3$ and $R = 0.4$, respectively.
measurement of $R_{J\gamma}$, the number of jet coincidences per $\gamma$ trigger, is shown in Fig. 3 (top left). The central Pb-Pb data is below the vacuum reference (proton-proton results smeared by background fluctuations) indicating that a significant fraction of the recoil jets lose energy and their momentum is shifted below the 30 GeV threshold. The hardening of the recoil jet yield with increasing photon momentum is reflected in the increasing trend of $R_{J\gamma}$.

Fig. 2. Top: STAR semi-inclusive charged jet yields recoiling from a high $p_T$ track in central and peripheral collisions at $\sqrt{s} = 200$ GeV and their ratio $I_{CP}$ (left). Ratio of ALICE $\Delta R_{Recoil}$ observable in central relative to PYTHIA at $\sqrt{s} = 2.76$ TeV (right). Bottom: Ratio of recoil jet distributions measured with $R = 0.2$ relative to those measured with $R = 0.5$. STAR (left) and ALICE (right) results are shown.

The momentum asymmetry $x_{JB}$, the ratio of the jet and boson momentum, would be a $\delta$ function only at LO. Higher-order corrections broaden its distribution. A shift in the mean of this distribution is used to quantify the average energy lost by the recoil jets.

Fig. 3 (top right) shows the average fraction of the photon momentum carried by the recoiling jets as a function of centrality. One can see that in the most central bin, the average shift between Pb-Pb data and the smeared pp reference is compatible with $\approx 10$ GeV of energy radiated out of the jet area. In Fig. 3 (bottom left) the asymmetry distribution (in this case for Z-triggered recoiled jets) is shown for central Pb-Pb collisions compared to several theory models. It should be noted that the data points are not fully corrected (not unfolded for background fluctuations and detector effects) so theory predictions are consistently smeared with parametrizations of the response provided by the experiment.

In the absence of a consistent theoretical model incorporating weakly and strongly coupled energy loss, both limits are compared independently to data. JEWEL [19] is a Monte Carlo model that considers elastic
Fig. 3. $R_{jj}$, average momentum imbalance $\lt x_{jj} \gt$, the $x_{jj}$ distribution in central Pb-Pb events and the ratio of beauty dijet and dijet momentum imbalance versus centrality.

and radiative energy loss in the medium in a weakly coupled framework. In the Hybrid model [20] parton showers are generated by Pythia and the interactions with the medium are implemented by changing the momenta of the partons using an analytical calculation of the lost energy according to strong coupling expectations from string calculations in the gauge/gravity duality. Its prediction is the green curve in plot.

To explore the sensitivity of the observable to the details of energy loss, two parametric perturbative limits for the energy loss are also considered, one proportional to the third power of the temperature, as expected from radiative losses, one proportional to the squared of the temperature, as expected from collisional losses. One can see that the differences between the different approaches are not significant enough to discriminate between the details of the energy loss process as implemented in the models. Other purely perturbative calculations [22] reproduce boson-tagged jet data fairly well.

$Z$ and $\gamma$ triggers enhance the sample of quark recoiled jets compared to jet triggers, so these data may illuminate the parton-flavour dependence of energy loss.

At high jet $p_T$ where quark mass effects are negligible, a $b$-jet is essentially a quark jet. Triggering on $b$-dijets is interesting because the requirement of a large azimuthal gap between the dijet system suppresses the contribution to $b$-jet production of gluon splitting. Such a contribution confuses the flavour and color charge of the object propagating in the medium. The beauty dijet sample is consequently a cleaner measurement of prompt heavy quark flavour than inclusive beauty jet $R_{AA}$. In Fig. 3 (bottom right) one can see that the momentum imbalance of the $b$ dijet system is consistent with that of the inclusive dijet system across all centrality bins for trigger and recoil jets of $p_T > 100$ and $p_T > 40$ GeV respectively. Since the jet-triggered recoil jet population is expected to be gluon-dominated, the previous plot points to no significant differences in quark and gluon energy loss in the given kinematic regime.

4. Medium-induced acoplanarity

The combined analysis of jet energy loss and momentum broadening can constrain the underlying mechanism of energy loss. In the perturbative BDMPS formalism [13], for instance, energy loss and momentum
broadening are linearly coupled by a single parameter, the transport coefficient \( \hat{q} \). On the contrary, in the limit of strong coupling [21], energy loss and broadening are uncorrelated.

Momentum broadening can be studied experimentally via intrajet shapes sensitive to the redistribution of jet momentum and constituents to wider angles [23] and it can be studied as a change in the jet direction as a whole [24]. Here we focus on the second approach and we inspect momentum broadening via the azimuthal angular correlation of dijet systems.

4.1. Broadening of the primary peak of the azimuthal angular correlation

In a purely perturbative framework, there are two ingredients that contribute to the azimuthal decorrelation of the recoil jet: one is the vacuum soft and collinear radiation and other is the medium-induced effect. The latter are described as random kicks of momentum at each scattering of the partonic projectile with the medium. The multiple kicks result in a total accumulated momentum \( Q_s = \hat{q} \cdot L \) where \( L \) is the medium length.

The relative contributions of vacuum and in-medium effects to the decorrelation measured at RHIC and LHC has being studied theoretically using resummation techniques [24]. Fig. 4 shows the vacuum contribution to momentum broadening for the different kinematic choices of trigger hadrons and recoil hadrons/jets in hadron-hadron and hadron-jet correlations at RHIC and LHC. One can see that at the LHC kinematics the vacuum distributions are broader than at RHIC and thus medium-induced broadening, which would be combined in quadrature with these distributions, would be more difficult to measure. Fig. 5 shows the hadron-jet angular correlations measured at RHIC [12] and at LHC [13] for different kinematic choices for the trigger and recoil jet momentum, compared to the calculations that also incorporate medium-broadening, parameterized as \( \langle \hat{q}L \rangle \). One can see that as kinematic cuts select harder scatterings, the sensitivity to different choices of broadening parameter is decreased.

In the strongly coupled limit [21] there is no notion of scattering centers or of multiple discrete scatterings. However, under some limits, coloured excitations acquire transverse momentum according to a gaussian with width \( Q^2 = \hat{q}L \) where \( \hat{q} = KT^3 \) and \( K \) is a free parameter of the theory. In Fig. 6(left), one can see that very different choices for the broadening parameter lead to negligible changes in the azimuthal correlation for the kinematics selected by the CMS cuts. Fig. 6(right) shows the azimuthal angular correlation for \( Z \)-jet pairs compared to purely perturbative JEWEL model and to the hybrid model with different assumptions for the energy loss rate. The four curves can describe the data and the conclusion is that this observable, with the given kinematic cuts, is not very sensitive to the details of the microscopic dynamics of the interaction with the medium.

4.2. Tails of the azimuthal correlation

The main peak of the azimuthal angular correlation helps to constrain the average momentum broadening while the tails of such distribution might encode fundamental information on the dynamics of the degrees
of freedom of the medium. Recent calculations [25] show that the probability of large angle and semi-hard parton deflections in medium, the so-called Moliere regime, is parametrically larger in the case of quasi-particle than in the case of strongly-coupled degrees of freedom. This is shown in Fig. 7 (left).

The calculations are done in terms of transverse momentum $k_T$ and in the limit of infinite parton energy. More realistic calculations will open a very interesting possibility of measuring an excess of large angle and semi-hard jet azimuthal angular correlation compared to models with different assumptions on the energy loss mechanism.

Unfolding in 2D will help to correct simultaneously the $p_T$ of the jet and the azimuthal angle between the jet and the trigger hadron or boson, allowing for fully corrected measurements of $\Delta \phi$ at significantly smaller jet $p_T$.

**5. Conclusions**

A large sample of differential jet measurements is currently available for systematic comparisons to the theory models. Most of the jet results from LHC Run 2 can be described simultaneously by weakly coupled and strongly coupled theory models, implying lack of sensitivity to discriminate among different
microscopic pictures for jet energy loss. However, several of the experimental measurements have strong cuts on jet $p_T$ that might be biased to a kinematic regime dominated by vacuum effects, whereby medium effects become a small perturbation that is difficult to disentangle. The access to low jet $p_T$ and to more differential intrajet measurements will open new possibilities in the data-theory comparison.

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