

Jet Quenching at RHIC and the LHC

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Abstract.

Relativistic heavy ion collisions allow one to study Quantum Chromodynamics (QCD) under extreme temperature and density conditions. A new form of matter formed at energy densities above $\sim 1 \text{ GeV}/\text{fm}^3$, Quark-Gluon Plasma (QGP), is predicted in Lattice QCD calculations. One of the most interesting experimental signatures of QGP formation is jet-quenching due to in-medium energy loss when hard-scattered partons pass through the QGP. Direct jet reconstruction in heavy ion collisions has opened a new era of precision studies of jet-quenching. In this summary talk, recent jet measurements in heavy ion collisions and their implications are reviewed and discussed.

1. Introduction

High-energy collisions of heavy ions allow one to study the fundamental theory of the strong interaction Quantum Chromodynamics (QCD) under extreme temperature and density conditions. A new form of matter [1, 2, 3, 4] formed at energy densities above $\sim 1 \text{ GeV}/\text{fm}^3$, accessible at high-energy heavy-ion collisions, is predicted in Lattice QCD calculations [5]. This quark-gluon plasma (QGP) consists of an extended volume of deconfined and chirally-symmetric quarks and gluons.

One of the most interesting experimental signatures which are suggested for QGP studies was the suppression of high-transverse-momentum(p_T) particles, often referred to as “jet-quenching”, resulting from in-medium energy loss when hard-scattered partons pass through the strongly interacting medium [6]. Results from nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) [7, 8, 9, 10] and the Large Hadron Collider [11, 12, 13] have shown evidence for the jet-quenching effect through the suppression of inclusive high- p_T hadron production and modification of high- p_T dihadron angular correlations when compared to proton-proton collisions.

However, high- p_T particle spectra by themselves give limited information on the underlying mechanism. There are three categories of models proposed to describe the observed magnitude of the suppression from RHIC and LHC data. The first group of models explains the parton energy loss by collinear and soft gluon emission which was the main idea of many pre-LHC calculations. The second group of PYTHIA [14] inspired models describe this phenomenon with medium induced branching which may contain hard gluon emissions. The third category of models based on AdS/CFT features wide angle gluon emissions or “QGP heating”. Recent reviews on the theoretical progress are available in [15, 16, 17, 18].

Direct jet reconstruction is becoming available at the RHIC and the LHC which opened a new era of the studies of the jet-quenching in heavy ion collisions. In this proceedings, recent

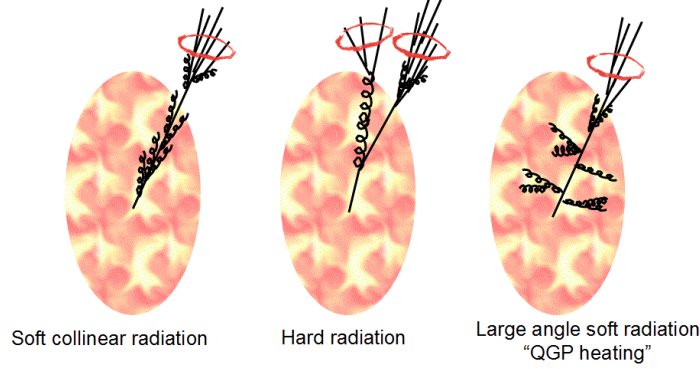


Figure 1. Scenarios of parton energy loss models

results related to jet-quenching measurements using direct jet reconstruction are summarized and discussed.

2. Nuclear modification factors of inclusive jets

To distinguish the scenarios demonstrated in Figure 1, one interesting way is to study the modification of jet p_T spectra using different resolution parameter (R) and check if one can collect the radiated energy back through jet reconstruction. Modifications of measured jet spectra are studied using the nuclear modification factors, the ratio of jet yields measured in the heavy ion collisions to the reference from pp (R_{AA}) or peripheral collisions (R_{CP}), normalized by the number of hard scatterings per collision. The raw jet spectra are typically corrected for jet energy scale and resolution using unfolding techniques. Results from RHIC and the LHC show that the high- p_T jet production is suppressed by a factor of 2-3 in the central CuCu [19], AuAu [20] and PbPb collisions [21, 22] compared to reference from pp collisions, which are summarized in Figure 2. This implies that a cone of $\Delta R \sim 0.2 - 0.5$ does not collect all the radiated energy back. The R_{CP} of jets reconstructed with $R=0.5$ is also found to be smaller than that with $R=0.2$ at the same jet p_T [21].

3. Dijet and photon-jet momentum imbalance and azimuthal angle correlation

ATLAS and CMS collaborations has reported increasing dijet momentum imbalance in the central PbPb collisions [23, 24]. This again shows that there is momentum flow out of the jet

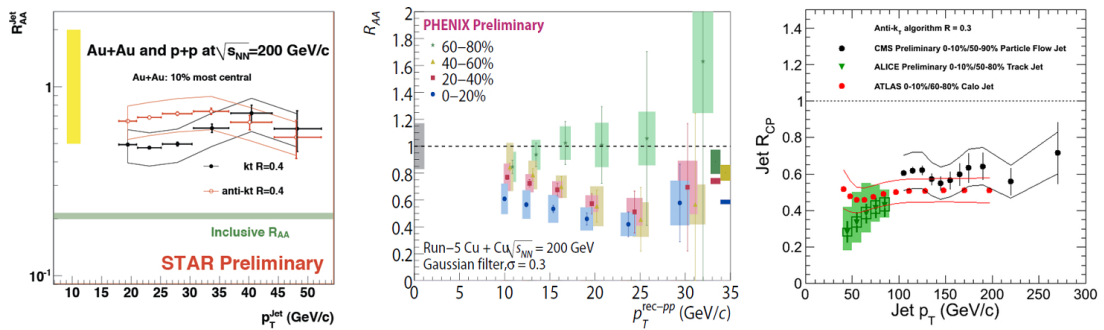


Figure 2. Jet nuclear modification factors measured in AuAu (left panel) [20], CuCu (middle panel) [19] and PbPb collisions (right panel) [21, 22].

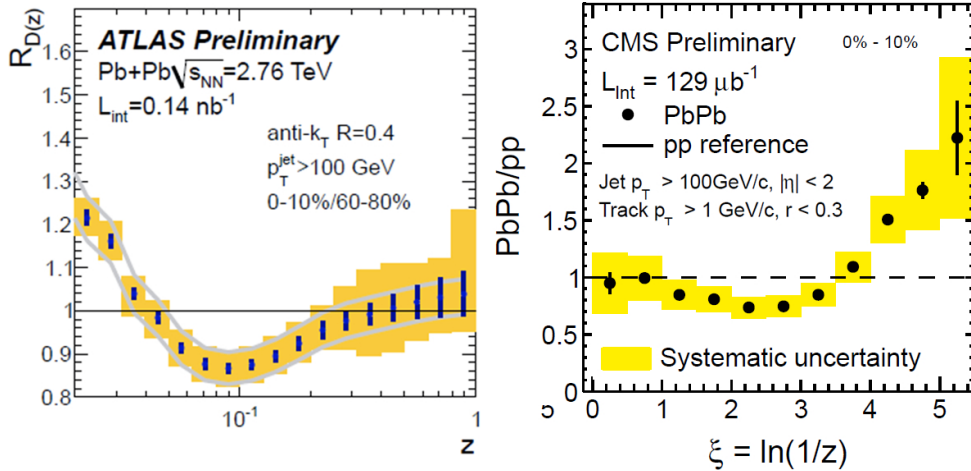


Figure 3. Jet fragmentation function ratios. (Left panel) Ratio of fragmentation function measured in central and peripheral PbPb collisions ($R_{D(z)}$) measured by ATLAS [31]. (Right panel) Ratio of fragmentation function measured in PbPb and pp collisions by CMS [30].

cone. CMS also reported the observed dijet asymmetry persists up to leading jet $p_T \sim 300$ GeV/ c and the modification of the mean dijet p_T ratio is around 10% [25]. On the other hand, the dijet azimuthal angle correlation is not largely modified, which may provide useful constraints to the hardness of the medium induced radiation.

Triggering on a high p_T jet selects a subset of di-jet events which contain a jet passing through a smaller in-medium path-length and losing smaller amount of energy. Therefore, this selection usually biases the position of the hard scattering to the surface of the QGP. It has been shown that the inclusive isolated photons are unmodified in the PbPb collisions with respect to pp reference measurements within the experimental uncertainty [26]. Therefore, requiring a high $p_{T, \text{photon}}$ isolated photon does not bias the location of the hard scattering inside QGP. Moreover, isolated photons also serve as an unmodified tag for the initial parton energy in the away side in a photon-jet event. CMS has published the first photon-jet analysis [27]. Isolated photons with $p_T^\gamma > 60$ GeV/ c were correlated with jets with $p_T^{\text{jet}} > 30$ GeV/ c to determine the jet/photon transverse momentum ratio, $x_{J\gamma} = p_T^{\text{jet}}/p_T^\gamma$, and the fraction of photons with an associated jet. The observed momentum ratio $x_{J\gamma}$ is $\sim 13\%$ lower than PYTHIA prediction and 20% of the isolated photons lost the associated away-side jet. ATLAS preliminary results [28] on the photon-jet correlation also show a consistent picture as the CMS measurement.

4. Dijet missing p_T analysis

Given the large transverse momentum imbalance observed in dijet and photon-jet events, one obvious quest is to measure the distribution of the radiated energy. Information about the overall momentum balance in the dijet events can be obtained using the projection of missing p_T of reconstructed charged tracks onto the leading jet axis. For each event, this projection can be calculated as $p_T^\parallel = \sum_i -p_T^{i, \text{track}} \cos(\phi_i^{\text{track}} - \phi_{\text{leadingJet}})$ using tracks with $p_T > 0.5$ GeV/ c . Studies of p_T^\parallel reported by CMS have shown that the overall momentum balance can be recovered if all tracks in the event with $p_T > 0.5$ GeV/ c are included in the calculation. In the PbPb data a large fraction of the balancing momentum is carried by tracks having $p_T < 2$ GeV/ c . Comparing the momentum balance using only tracks inside and outside of cones of $\Delta R = 0.8$ around the leading and subleading jet axes demonstrates that a large contribution to the momentum balance in data arises from soft particles radiated at $\Delta R > 0.8$ to the jets. [24].

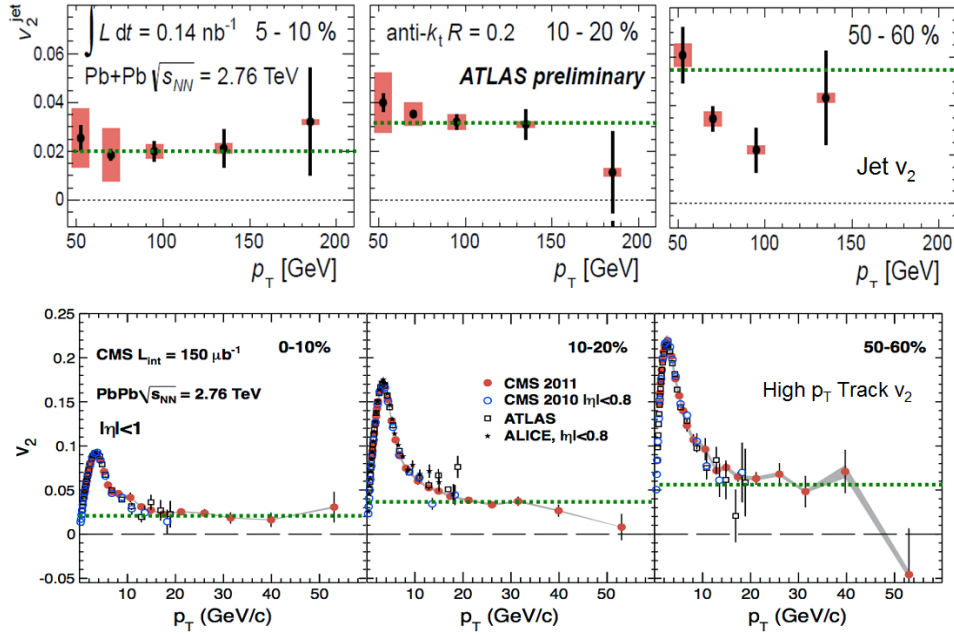


Figure 4. Azimuthal anisotropy measured with jets by ATLAS [33] and high p_T tracks by CMS [34].

Future p_T^{\parallel} analyses with tracks inside and outside of jet cones with different sizes will give a complete map of the radiated energy and medium response to the hard scattering.

5. Jet shapes and fragmentation functions

Medium induced radiation may redistribute the momenta carried by particles in the jet. The fragmentation function is presented as a function of the variables $z = p_{\parallel}^{\text{track}}/p^{\text{jet}}$ and $\xi = -\ln z$. CMS has measured the ratio of jet shapes and fragmentation functions between PbPb and pp data [29, 30], while ATLAS compared the fragmentation function measured in central and peripheral PbPb collisions [31]. As shown in Figure 3, an excess in high ξ (low z) particles in jets with $p_T > 100$ GeV/c is observed in central PbPb collisions. This implies that for central collisions the spectrum of particles in a jet has an enhanced contribution of soft particles compared to one from pp collisions. At low ξ (high z) region, the fragmentation function is not largely modified. ALICE also reported the measurement of jet like near side correlation using charged particles with background subtraction [32]. It is shown that the correlation peak is widened in central collisions.

Detailed studies of jet fragmentation functions and their fluctuations using high statistics dijet and photon-jet events will give a more detailed picture of in-medium jet modification.

6. Jet azimuthal anisotropy

Path length dependence of parton energy loss can be studied by the measurement of jet yields as a function of azimuthal angle with respect to the event plane. The second Fourier harmonics (v_2) of jet azimuthal distribution is measured by ATLAS [33] up to jet $p_T = 200$ GeV/c, remains significantly larger than zero at all measured jet p_T . As shown in Figure 4, the magnitude of the jet v_2 is in agreement with the high p_T track v_2 measurement from CMS [34]. Preliminary results from STAR [35] also show non-zero jet v_2 and the magnitude is similar to results from LHC experiments.

The observed positive jet v_2 at RHIC and the LHC may indicate that high- p_T partons suffer from larger energy loss in the direction of larger transverse path-length in the medium.

7. b-jet fraction

Modification to jets in high-energy heavy-ion collisions is expected to depend on the flavor of the fragmenting parton and the flavor dependence of jet quenching is a crucial test ground for various parton energy loss models. In QCD, quarks carry a smaller color factor compared to gluons, so that the in-medium energy loss for quarks is expected to be smaller than for gluons. Moreover, compared to light quarks, heavy quarks are expected to suffer from smaller radiative energy loss when passing through the medium because gluon radiation is suppressed at angles smaller than the ratio of the quark mass M to its energy E [36], thus further attenuating the effect of the medium.

To disentangle this flavor dependence, jets from heavy quark fragmentation are identified for the first time in heavy ion collisions [37]. Jets are first tagged by their secondary vertices and the contribution from bottom quarks is extracted using template fits to their secondary vertex mass distributions. The bottom quark jet to inclusive jet ratio is measured with the CMS detector from PbPb and pp collisions at a center-of-mass energy of 2.76 TeV per nucleon. This b-jet fraction is measured in the range of $80 < p_T^{\text{Jet}} < 200$ GeV/c in PbPb collisions and found to be compatible with the pp b-jet fraction, within sizable uncertainties. The measurement is sufficiently precise to demonstrate that b-jets are subject to jet quenching, although a precise comparison of light and b-jet quenching would require a reduction of the statistical and systematic uncertainties.

8. Summary

The new data from RHIC and the LHC have brought new insights to the jet quenching mechanism. Models which feature soft collinear gluon radiation need mechanism to transport the radiated energy out of the jet cone [38]. Hard gluon radiations and modification of splitting function are constrained by dijet and photon-jet azimuthal angle correlation measurements. Also the distributions of dijet and photon-jet momentum ratio as well as inclusive jet v_2 provide constraints to the path-length dependence of the parton energy loss. The data from RHIC and the LHC can be qualitatively described by models associated with wide angle radiative energy loss. However quantitative comparisons between data and models are needed.

From those studies, we are now in a better position to validate our theoretical understanding of in-medium parton energy loss. It is expected that PbPb collisions at 5.5 TeV will be delivered by the LHC and precision measurements such as $Z^0(W^\pm)$ -jet correlations, b-jet quenching, multi-jet correlations, the azimuthal anisotropy of high p_T jets, and top production may bring us beyond the qualitative observation [39, 40, 41, 42, 43, 44, 45, 46, 47]. Coming implementations of parton energy-loss in realistic event generators, that can be directly compared to the experimental data from RHIC and the LHC, will allow us to go beyond a "mechanistic" understanding of in-medium parton energy loss, and reach our final goal of determining the thermodynamical and transport properties of hot and dense QCD matter via "jet tomography" measurements.

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