Splitting Functions and Subjet Distributions in Heavy Ion Collisions

Yang-Ting Chien[a] & Ivan Vitev[b]

[a] Center for Theoretical Physics, Massachusetts Institute of Technology

[b] Theoretical Division, Los Alamos National Laboratory

ytchien@mit.edu, ivitev@lanl.gov

Abstract

We present the first calculations of the momentum sharing and angular separation distributions between the leading subjets inside a reconstructed jet, as well as the jet mass distribution modification in heavy ion collisions. These observables are sensitive to the early and late stages of the in-medium parton shower evolution and allow us to probe the quark-gluon plasma across a wide range of energy scales. We use the medium-induced splitting functions obtained in the framework of soft-collinear effective theory with Glauber gluon interactions to calculate the subjet distributions. Qualitative and in most cases quantitative agreement between theory and preliminary CMS measurements suggests that the parton shower in heavy ion collisions can be dramatically modified early in the branching history. Predictions for the subjet angular distribution is also presented which will illuminate the nature of the medium-induced radiations.

Introduction

The jet quenching phenomenon has been an essential tool to study the properties of the quark-gluon plasma (QGP) produced in ultrarelativistic nucleus-nucleus (A+A) collisions. The emergence of the in-medium parton branching is at the heart of all jet modification studies. Although the traditional energy loss picture has been very successful in describing the suppression of jet and hadron production cross section, to disentangle the detailed jet formation mechanisms in the medium requires comprehensive studies of jet substructure observables. In the past few years there has been a proliferation of jet substructure measurements in A+A, which gave differential and correlated information about how quark and gluon radiation is redistributed due to medium interactions. It is now established that the jet shape and the jet fragmentation function, which describe the transverse and longitudinal momentum distributions inside jets, are modified in heavy ion collisions. Both of these observables depend strongly on the partonic origin of jets, and their nontrivial modification patterns are partly due to the increase of the quark jet fraction in heavy ion collisions [1, 2].

To better understand the jet-by-jet modifications of jet observables, in this work we calculate the groomed momentum sharing which probes the hard branching in the jet formation. Given a jet reconstructed using the anti-k_T algorithm with radius R, one reclusters the jet using the Cambridge-Aachen algorithm and goes through the branching history, grooming away the soft branch at each step until the following condition is satisfied,

$$z_{cut} < \frac{\min(p_{T_1}, p_{T_2})}{p_{T_1}+p_{T_2}} \equiv z_g \, , \quad (1)$$

One could also demand that the angular separation between the two branches be greater than the angular resolution Δ,

$$\Delta < \Delta R_{12} \equiv r_g \, . \quad (2)$$

By selecting the angular separation r_g, one could also examine the momentum sharing distribution $p(z_g)$ at different splitting angles and the $p(r_g)$ distribution.

One of the nice properties of this observable is the insensitivity to the partonic origin of jets in $p+p$ collisions. Therefore it is not strongly affected by the change of the quark/gluon jet fractions in A+A collisions and its modification can be used to directly probe the medium effects on each jet. More generally, the grooming procedure removes the wide-angle, soft radiation inside jets which allows us to examine how soft radiations contribute to jet observables. As we will see, by selecting the angle between the two leading subjets one focuses on a specific jet sample with two-prong structures. The differential subjet distributions will then allow us to examine the modification of these wide-angle, hard branchings and reveal the detailed nature of bremsstrahlung radiations.

Framework

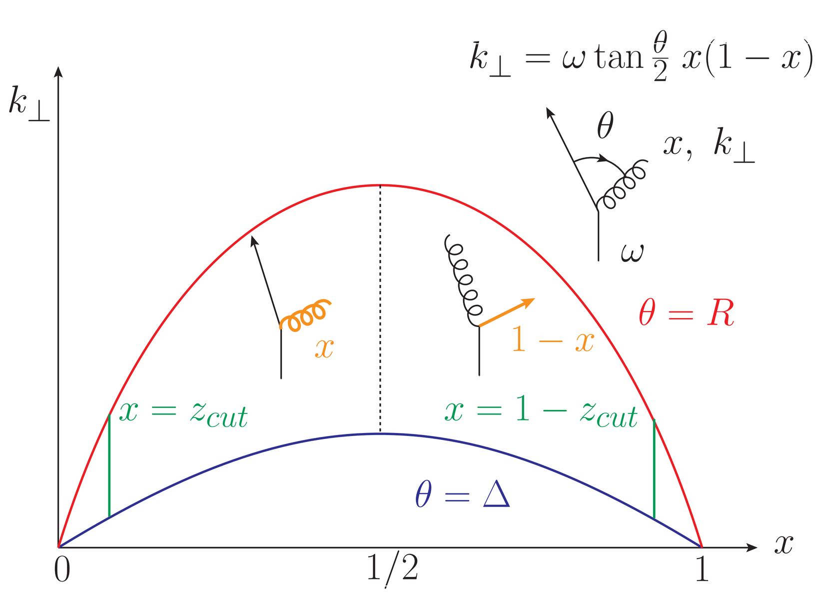

Figure 1: Illustration of the phase space regions for the z_g distribution calculation at leading order.

For jets with small radii, the z_g distribution can be described by the collinear parton splitting functions. At leading order, in lightcone coordinates for a parton i with collinear momentum $p = (\omega, 0, 0)$ splitting into partons j, l with momenta $k = (x\omega, k_\perp^2/x\omega, k_\perp)$ and $p - k$,

$$\mathcal{P}_{i\to jl}(x, k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x, k_\perp) + \mathcal{P}^{med}_{i\to jl}(x, k_\perp) \, , \quad (3)$$

which is the sum of the vacuum and medium-induced splitting functions. The z_g distribution is calculated by integrating the splitting functions over the partonic phase space constrained by R, Δ and z_{cut} and shown in FIG. 1,

$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)} \, . \quad (4)$$

Here, $k_\Delta = \omega x(1-x)\tan\frac{\Delta}{2}$, $k_R = \omega x(1-x)\tan\frac{R}{2}$ and

$$\overline{\mathcal{P}}_i(x, k_\perp) = \sum_{j,l} \Big[\mathcal{P}_{i\to j,l}(x, k_\perp) + \mathcal{P}_{i\to j,l}(1-x, k_\perp)\Big]. \quad (5)$$

The final z_g distribution is then weighted by the jet production cross sections,

$$p(z_g) = \frac{1}{\sigma_{\rm total}} \sum_{i=q,g} \int_{PS} d\eta\, dp_T \frac{d\sigma^i}{d\eta\, dp_T} p_i(z_g) \, , \quad (6)$$

with the phase space cuts (PS) on the jet p_T and η as imposed in the experiment.

The medium-induced splitting functions were calculated using soft-collinear effective theory with Glauber gluon interactions ($\mathrm{SCET_G}$) [3, 4] in a QGP model consisting of thermal quasi-particles undergoing longitudinal Bjorken-expansions. $\mathrm{SCET_G}$ is an effective field theory of QCD suitable for describing jets in the medium. It goes beyond the traditional parton energy loss picture in the soft gluon limit, and it provides a systematic framework for resumming jet substructure observables and consistently including medium modifications.

Results

We compare our calculations to the preliminary data taken by the CMS collaboration at the LHC Run II at $\sqrt{s_{\rm NN}} = 5.02$ TeV [5]. In both proton-proton and lead-lead (Pb+Pb) collisions, the jets are reconstructed using the anti-k_T algorithm with $R = 0.4$. They are then groomed using the soft-drop jet grooming procedure. The groomed momentum sharing z_g and its normalized distribution $p(z_g) = 1/N_{\rm jet}\, dN/dz_g$ are measured, and the in-medium momentum sharing modification is quantified by taking the ratio of the z_g distributions in lead-lead and proton-proton collisions,

$$R_{AA}^{p(z_g)} = p(z_g)^{PbPb}/p(z_g)^{pp} \, . \quad (7)$$

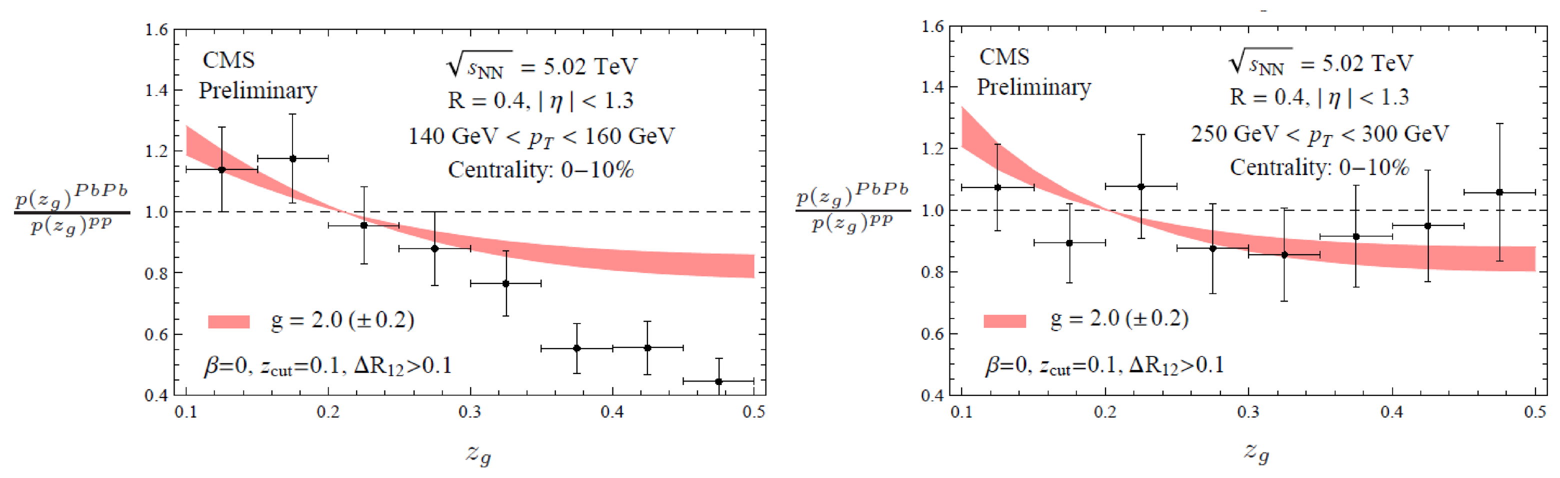

Figure 2: Comparison of theoretical calculations and preliminary CMS data for the ratio of momentum sharing distributions of inclusive anti-k_T $R = 0.4$ jets in 0-10% central Pb+Pb and p+p collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Jets are soft-dropped with $\beta = 0$, $z_{cut} = 0.1$ and $\Delta R_{12} > 0.1$. Bands correspond to the theoretical uncertainty estimated by varying the coupling between the jet and the medium ($g = 2.0 \pm 0.2$). Left panel: modification for jets with $140\ {\rm GeV} < p_T < 160$ GeV and $|\eta| < 1.3$. Right panel: modification for jets with $250\ {\rm GeV} < p_T < 300$ GeV and $|\eta| < 1.3$.

In FIG. 2, the preliminary CMS data shows a strong modification of the momentum sharing distribution for jets with lower p_T in central collisions, and the modification decreases quite quickly when the jet p_T becomes higher. We find that the modification does decrease as the jet p_T increases. However, the p_T dependence in our theory calculation is not as strong as suggested in the preliminary CMS measurements, with the amount of modification around $z_g = 0.5$ underestimated in our calculation for lower p_T jets. For jets with higher p_T, our calculation is consistent with the preliminary CMS data within the experimental uncertainties.

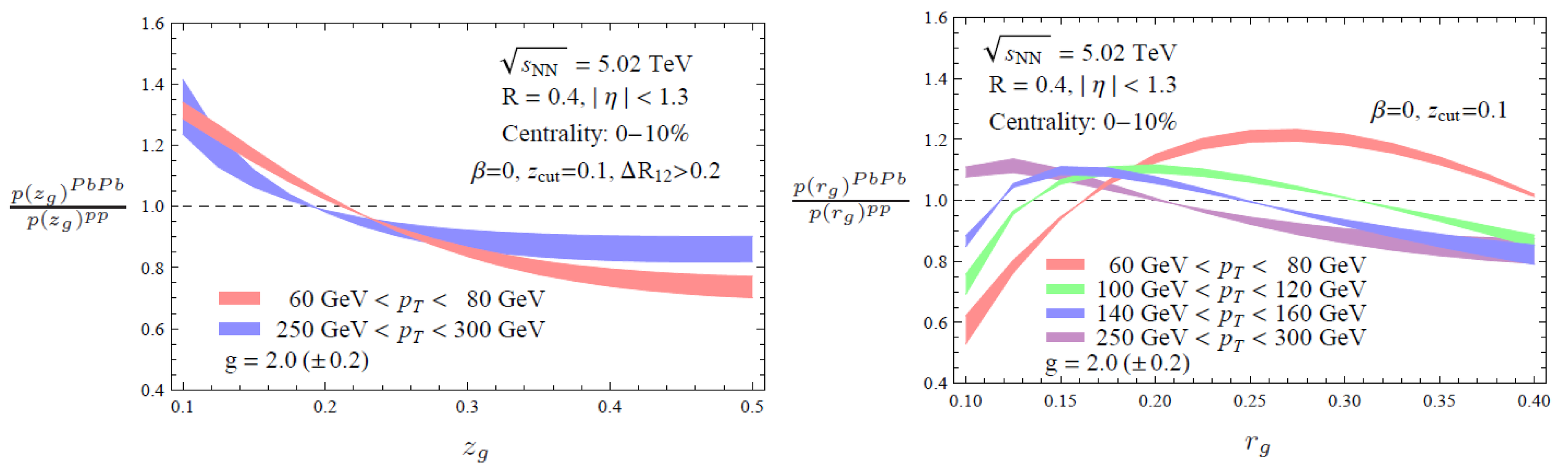

Figure 3: Left panel: theoretical calculations for the momentum sharing distribution ratio of inclusive jets in central lead-lead and proton-proton collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Jets are soft-dropped with $\beta = 0$, $z_{cut} = 0.1$ and $\Delta R_{12} > 0.2$. We study its jet p_T dependence and provide results for $60\ {\rm GeV} < p_T < 80$ GeV (red band) and $250\ {\rm GeV} < p_T < 300$ GeV (blue band). Right panel: theoretical calculations for the groomed jet radius modification of inclusive jets in proton-proton and central lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The soft drop parameters $\beta = 0$, $z_{cut} = 0.1$ and $\Delta R_{12} > 0.1$ are used. Shown are results for four p_T bins with $60\ {\rm GeV} < p_T < 80$ GeV (red band), $100\ {\rm GeV} < p_T < 120$ GeV (green band), $140\ {\rm GeV} < p_T < 160$ GeV (blue band) and $250\ {\rm GeV} < p_T < 300$ GeV (purple band).

An important new observable that we propose to study in heavy ion collisions is the angular separation distribution $r_g \equiv \Delta R_{12}$ of the leading subjets inside a groomed jet. At leading order,

$$p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x) \overline{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)} \, , \quad (8)$$

and $k_\perp(r_g, x) = \omega x(1-x)\tan\frac{r_g}{2}$. The power of this observable is that it is sensitive to the medium modification of the hardest branching inside jets, rather than the soft radiation which can be transported to larger angles through different mechanisms, e.g. QGP excitation. Predictions for the momentum sharing distribution ratios for inclusive jets in central lead-lead and proton-proton collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with a more stringent cut $\Delta R_{12} > 0.2$ are shown in the left penal of FIG. 3. We find that the modification increases (decreases) with ΔR_{12} for low (high) p_T jets, rendering a stronger p_T dependence in the modification pattern. In the right panel, we predict the angular separation modification for the leading subjets in the $\mathrm{SCET_G}$ framework. The same jet selection cuts and soft drop parameters are used as in the preliminary CMS momentum sharing measurements. We examine the p_T dependence of the angular region where the distribution is enhanced, which shifts to smaller values when the jet p_T increases. The peak of this distribution corresponds to the characteristic r_g where the medium enhancement of large-angle splitting for hard branching processes is most significant.

Conclusions

We presented the first calculation of the momentum sharing distribution in heavy ion collisions. This observable allows us to probe the early stages of the QGP evolution. The z_g distribution is significantly modified in the medium. This suggests that the parton shower modification in the QGP starts early. We also proposed a new measurement of the angular separation distribution between the leading subjets inside a groomed jet which encodes the angular distribution of the hard splitting, and we present theoretical predictions for its behavior.

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References

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