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Citation: Chien, Yang-Ting et al. "Probing the Hardest Branching within Jets in Heavy-Ion Collisions." Physical Review Letters 119, 11 (September 2017): 112301 © 2017 American Physical Society

As Published: http://dx.doi.org/10.1103/PhysRevLett.119.112301

Publisher: American Physical Society

Persistent URL: http://hdl.handle.net/1721.1/114558

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Probing the Hardest Branching within Jets in Heavy-Ion Collisions

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(Received 9 September 2016; revised manuscript received 27 June 2017; published 12 September 2017)

Heavy ion collisions present exciting opportunities to study the effects of quantum coherence in the formation of subatomic particle showers. We report on the first calculation of the momentum sharing and angular separation distributions between the leading subjets inside a reconstructed jet in such collisions. These observables are directly sensitive to the hardest branching within jets and can probe the early stage of the jet formation. We find that the leading-order medium-induced splitting functions, here obtained in the framework of soft-collinear effective theory with Glauber gluon interactions, capture the essential many-body physics, which is different from proton-proton reactions. Qualitative and in most cases quantitative agreement between theory and preliminary CMS measurements suggests that hard parton branching in strongly interacting matter can be dramatically modified. We also propose a new measurement that will illuminate its angular structure.

DOI: 10.1103/PhysRevLett.119.112301

The dramatic suppression of hadron and jet cross sections observed at the Relativistic Heavy Ion Collider (RHIC) [1–6] and the Large Hadron Collider (LHC) [7–14] signals the strong modification of parton showers within strongly interacting matter. This 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 in-medium parton branching, qualitatively different from the one that governs the jet formation in $e^+ + e^-$, $e^- + p$, and $p + p$ collisions, is at the heart of all jet modification studies. This phenomenon is driven by many-body quantum coherence effects [15] and is of interest to many subfields of physics. Although the traditional energy loss picture has been very successful in describing the suppression of 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 $A+A$ collisions [16–21], 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 [22] and the jet fragmentation function [23], 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 [24–26]. To better understand the jet-by-jet modifications for these observables, one can devise strategies to isolate purer quark or gluon jet samples.

Recently, a novel jet substructure observable, called the groomed momentum sharing, has been studied using the soft drop jet grooming procedure [27,28]. It probes the hard branching in the jet formation and is dominated by the leading-order Altarelli-Parisi splitting functions [29]. Given a jet reconstructed using the anti-k_T algorithm [30] with radius R, one reclusters the jet using the Cambridge-Aachen algorithm [31,32] and goes through the branching history, grooming away the soft branch at each step until the following condition is satisfied

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

i.e., the soft branch must carry more than a $z_{\rm cut}$ fraction of the sum of the transverse momenta to not be dropped. Note that by definition $z_{\rm cut} < z_g < \frac{1}{2}$ and the groomed momentum sharing is not sensitive to soft radiation by design. Because of detector granularity one also demands that the angular separation between the two branches be greater than the angular resolution Δ,

$$\Delta < \Delta R_{12} \equiv r_g. \tag{2}$$

More generally, by selecting the angular separation ΔR_{12}, defined as the groomed jet radius r_g, one could also examine the momentum sharing distribution $p(z_g)$ at different splitting angles and the $p(r_g)$ distribution.

For jets with small radii [33–36], the z_g distribution can be described by the collinear parton splitting functions. At leading order, for a parton i with collinear momentum $p = (\omega, 0, 0)$ [37] splitting into partons j, l with momenta $k = (x\omega, k_\perp^2/x\omega, k_\perp)$ and $p - k$, the splitting functions in vacuum $\mathcal{P}^{\rm vac}_{i\to jl}(x, k_\perp)$ are well known. The z_g distribution is calculated by integrating the splitting functions over the partonic phase space constrained by R, Δ, and z_{cut} as follows, which corresponds to the soft drop and algorithm implementations in the fixed order calculation,

$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \bar{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{\mathrm{cut}}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \bar{\mathcal{P}}_i(x, k_\perp)}. \tag{3}$$

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

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

Note that for anti-k_T jets the angle θ between the two final state partons satisfies $\Delta < \theta < R$. The effect of running coupling can be taken into account by setting $\mu = k_\perp$ in the splitting function. The final z_g distribution is then weighted by the jet production cross sections,

$$p(z_g) = \frac{1}{\sigma_{\mathrm{total}}} \sum_{i=q,g} \int_{\mathrm{PS}} d\eta dp_T \frac{d\sigma^i}{d\eta dp_T} p_i(z_g), \tag{4}$$

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

The z_g distributions for quark-initiated and gluon-initiated jets are very similar throughout the whole z_g region. The color factors $C_F = 4/3$ and $C_A = 3$ for quarks and gluons cancel and the distributions follow approximately $1/z_g$, the leading $1/x$ behavior of the splitting functions in Eq. (3) for $x < 1/2$. The insensitivity of z_g to the partonic origin of jets implies that its modification in heavy ion collision is not significantly affected by the change of the quark and gluon jet fraction as one observes in the jet shape and the jet fragmentation function.

In the presence of the medium,

$$\mathcal{P}_{i\to jl}(x, k_\perp) = \mathcal{P}_{i\to jl}^{\mathrm{vac}}(x, k_\perp) + \mathcal{P}_{i\to jl}^{\mathrm{med}}(x, k_\perp), \tag{5}$$

which is the sum of the vacuum and medium-induced splitting functions. The later were calculated using soft-collinear effective theory [38–43] with Glauber gluon interactions (SCET$_G$) [44–47] in a QGP model consisting of thermal quasiparticles undergoing longitudinal Bjorken expansion [48], and by taking into account the Glauber geometry of the collision. Assuming parton-hadron duality, the parton density is constrained from the measured charged hadron pseudorapidity density. 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 and provides a systematic framework for resumming jet substructure observables and for consistently including medium modifications. The same medium-induced splitting functions used in this Letter have been previously constrained and applied to describe and predict several hadron and jet observables in heavy ion collisions [25,49,50]. To evaluate their significance in the splitting function modification, we also study collisional energy loss effects on the two subjets by allowing the QGP quasiparticles to recoil away from the jet. We constrain the collision centrality by matching the experimentally measured number of participants, $\langle N_{\mathrm{part}}\rangle = 360$ for the 0%–10% centrality class and $\langle N_{\mathrm{part}}\rangle = 110$ for the 30%–50% centrality class, in 5.02 TeV Pb + Pb reactions.

It can be seen analytically and confirmed numerically that, in the region $x < 1/2$ in Eq. (3), the leading behavior of the medium-induced component of the splitting functions follows approximately $1/x^2$ [46]. The momentum sharing distribution will show enhancement at the smallest values of z_g and suppression near $z_g = 1/2$.

With the full collinear parton splitting functions in the medium at hand, Eqs. (3) and (4) are completely general and can be used to calculate the momentum sharing distribution in heavy ion collisions. The jet cross section is calculated by incorporating the jet energy loss due to out-of-cone radiation, with the small cold nuclear matter effects as in Refs. [25,51]. However, since z_g is insensitive to the flavor of jet-initiating partons, the effect from the change of quark and gluon jet fractions due to the different amounts of cross section suppression is minor.

For the cross section calculations we use the CTEQ5M parton distribution functions [52] and the $O(\alpha_s^2)$ QCD partonic cross sections. We use the two-loop running of the strong coupling constant with $\alpha_s(m_Z) = 0.1172$. We estimate the theoretical uncertainty by varying the coupling between the jet and the QCD medium $g = 2.0 \pm 0.2$ as in Ref. [25]. Note that a different QGP model, e.g., 3 + 1D hydro, might require a different range for the coupling g [53].

The great utility of the momentum sharing distribution in heavy ion collisions lies in the fact that one can select the jet transverse momentum and the angle between the two leading subjets to ensure large splitting virtuality and, consequently, a branching that happens shortly after the hard scattering inside the QGP. Indeed,

$$\tau_{\mathrm{br}}[\mathrm{fm}] = \frac{0.197\ \mathrm{GeV\,fm}}{z_g(1-z_g)\omega[\mathrm{GeV}]\tan^2(r_g/2)} \tag{6}$$

suggests that for typical jets with $\omega = 2p_T = 400$ GeV, $r_g = 0.1$, and $z_g = 0.1$, the branching time $\tau_{\mathrm{br}} < 2$ fm. This is considerably smaller than the size of the QGP created in Pb + Pb collisions at the LHC, of $O(10)$ fm, and allows us to test whether the medium modification of parton branchings happens early in the jet formation.

We compare our calculations to the preliminary data taken by the CMS Collaboration at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [21] at the LHC. In both proton-proton and lead-lead (Pb + Pb) collisions, jets are reconstructed using the anti-k_T algorithm with $R = 0.4$ [30]. They are then groomed using the soft-drop jet grooming procedure [27]. The parameters chosen in the CMS measurements are $\beta = 0$, which simplifies the soft drop condition to Eq. (1), and $z_{\rm cut} = 0.1$. Another cut on $\Delta R_{12} > 0.1$, where ΔR_{12} is the distance between the two branches in the pseudorapidity-azimuthal angle plane, is imposed due to the detector resolution. This requirement also effectively selects jets with the hardest branching angle greater than 0.1. The groomed momentum sharing variable z_g and its normalized distribution

$$p(z_g) = \frac{1}{N_{\rm jet}} \frac{dN}{dz_g} \tag{7}$$

are measured. Jets are selected with the following cuts on the jet transverse momentum p_T and pseudorapidity η: $p_T > 140$ GeV and $|\eta| < 1.3$. The in-medium momentum sharing modification is quantified by taking the ratio of the z_g distributions in lead-lead and proton-proton collisions,

$$R_{AA}^{p(z_g)} = p(z_g)^{\rm PbPb} / p(z_g)^{pp}. \tag{8}$$

The modification patterns are examined across a wide range of p_T bins with different collision centralities.

Figure 1 shows the result for the ratio of the momentum sharing distributions of inclusive jets in 0%–10% central Pb + Pb and $p + p$ collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. We consider two p_T bins $140 < p_T < 160$ GeV (Fig. 1, upper panel) and $250 < p_T < 300$ GeV (Fig. 1, lower panel) to study the modification pattern as a function of the jet transverse momentum. The preliminary CMS data show significant modification of the momentum sharing distribution for jets with lower p_T in central collisions, and the modification decreases when the jet p_T becomes larger [54]. The purple (red) bands correspond to the theoretical calculations with (without) collisional energy loss, with the variation of $g = 2.0 \pm 0.2$. We find that collisional energy loss effects slightly decrease the splitting function modification [55]. The physical reason is that $\Delta p_T^{\rm coll}/p_T \sim c(\ln p_T)/p_T$ has a stronger effect on the lower p_T subjet, thereby reducing the value of z_g. To match the experimental measurements, the medium induced splitting functions need to be evaluated at slightly higher z_g, where the distributions are flatter and their overall contribution in Eq. (5) is smaller. We further find that the modification of the momentum sharing distribution does decrease as the jet p_T increases. However, the p_T dependence in our theory calculation is not as strong as suggested by the preliminary CMS measurements, with the amount of modification around $z_g = 0.5$ underestimated in our calculation for lower p_T jets [56]. For jets with higher p_T, our calculation is consistent with the preliminary data within the experimental uncertainties. An exploratory calculation with $g = 2.5$ is shown in the upper panel of Fig. 1 to assess the effect of a larger coupling, which might effectively arise from multiple induced gluon emissions [47,57]. Still, the red band corresponds to the theoretical calculation with the strongest current constraints from hadron production [50].

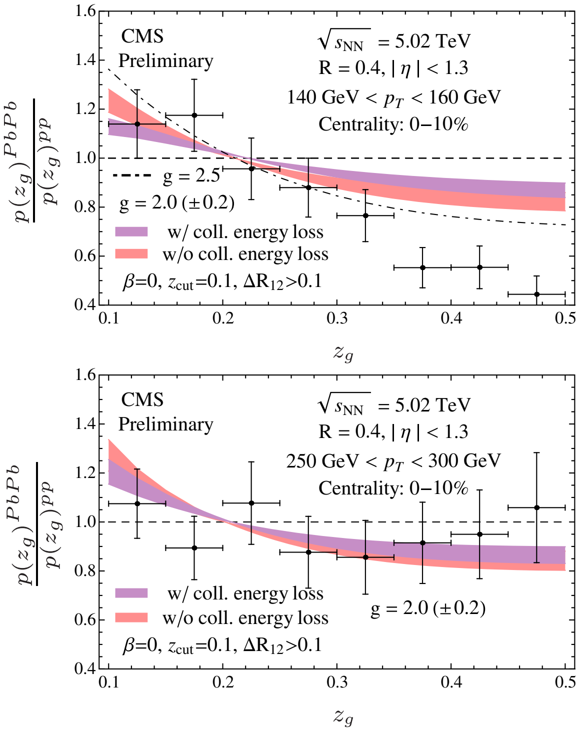

FIG. 1. Comparison of theoretical calculations and preliminary CMS data for the ratio of momentum sharing distributions of inclusive anti-k_T $R = 0.4$ jets in central Pb + Pb and $p + p$ collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Jets are soft dropped with $\beta = 0$, $z_{\rm cut} = 0.1$, and $\Delta R_{12} > 0.1$. The bands correspond to the theoretical uncertainty estimated by varying the jet-medium coupling ($g = 2.0 \pm 0.2$). The purple (red) bands correspond to calculations with (without) the implementation of collisional energy loss. Upper panel: modification for jets with $140 < p_T < 160$ GeV and $|\eta| < 1.3$. The exploratory calculation with $g = 2.5$ is also shown. Lower panel: modification for jets with $250 < p_T < 300$ GeV and $|\eta| < 1.3$.

Figure 2 shows the modification of the momentum sharing distribution for inclusive jets in midperipheral lead-lead collisions with centrality 30%–50% at $\sqrt{s_{\rm NN}} = 5.02$ TeV. We examine jets in the $140 < p_T < 160$ GeV bin since the modification is larger for lower p_T jets. Both the CMS preliminary data and our calculation show moderate modifications of the z_g distributions, and the two are consistent with each other. The medium modification of the z_g distribution decreases with collision centrality.

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 are shown in Fig. 3. We consider the p_T bins $60 < p_T < 80$ GeV (red band) and $250 < p_T < 300$ GeV (blue band). However, whereas in the CMS preliminary measurements the cut $\Delta R_{12} > 0.1$ is

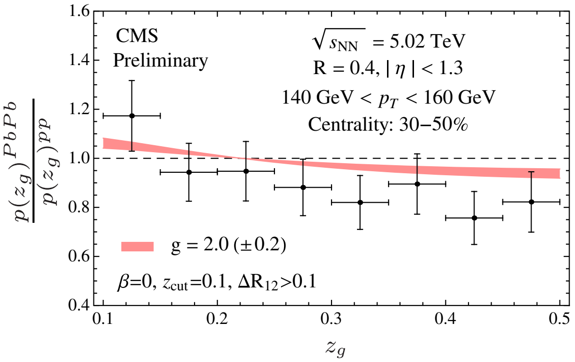

FIG. 2. Comparison of theoretical calculations and preliminary CMS data for the momentum sharing modification of inclusive jets in proton-proton and lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Anti-k_T $R = 0.4$ jets with $140 < p_T < 160$ GeV and $|\eta| < 1.3$ in midperipheral collisions are considered and the same soft-drop parameters as in Fig. 1 are used to groom the jets.

imposed in the jet selection, here we present the theoretical calculations with a more stringent cut $\Delta R_{12} > 0.2$ to study the z_g distribution with wider splitting angles. We find that the modification increases (decreases) for the new ΔR_{12} choice for low (high) p_T jets, rendering a stronger p_T dependence in the modification pattern. This suggests that additional information on the medium induced parton shower can be obtained by examining the groomed jet radius r_g.

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,

$$p_i(r_g) = \frac{\int_{z_{\rm cut}}^{1/2} dx\, p_T x(1-x)\bar{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{\rm cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \bar{\mathcal{P}}_i(x, k_\perp)}, \tag{9}$$

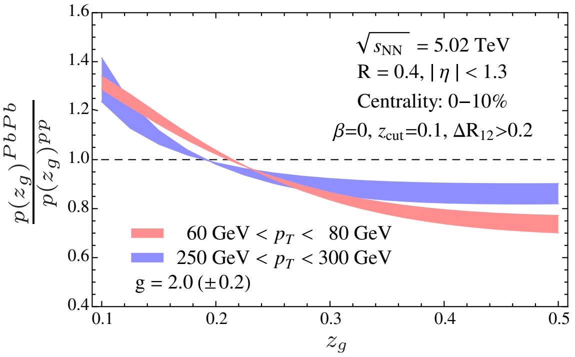

FIG. 3. Theoretical calculations for the momentum sharing distribution ratio of inclusive jets in central lead-lead and proton-proton collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Jets are soft dropped with $\beta = 0$, $z_{\rm cut} = 0.1$, and $\Delta R_{12} > 0.2$. We study its jet p_T dependence and provide results for $60 < p_T < 80$ GeV (red band) and $250 < p_T < 300$ GeV (blue band).

and $k_\perp(r_g, x) = \omega x(1-x)\tan(r_g/2)$. The power of this observable is that it is sensitive to the angular medium modification of the hardest branching inside jets, rather than the soft radiation that can be transported to larger angles through different mechanisms, e.g., QGP excitation. In Fig. 4 we predict the angular separation modification for the leading subjets in the 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 angles 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 the most significant.

To conclude, we presented the first calculation of the momentum sharing distribution in heavy ion collisions. This observable is sensitive to the hard branching within jets and is a new powerful way to investigate the jet formation mechanism. In heavy ion collisions, the momentum sharing distribution of the two leading subjets in a reconstructed jet allows us to probe many-body quantum coherence effects in the early stages of the QGP evolution. We found that the z_g distribution is significantly modified in the medium, as shown in our theory calculation and the preliminary CMS data. We also examined the effect from collisional energy loss and found that jet quenching effects acting independently on the subjets alone cannot cause the observed z_g modification. This suggests that the hard branching of jets itself has been modified in the QGP. We also proposed a new measurement of the angular separation distribution between the leading subjets inside a groomed jet and present theoretical predictions for its behavior. This new observable will, for the first time, directly test the angular characteristics of hard

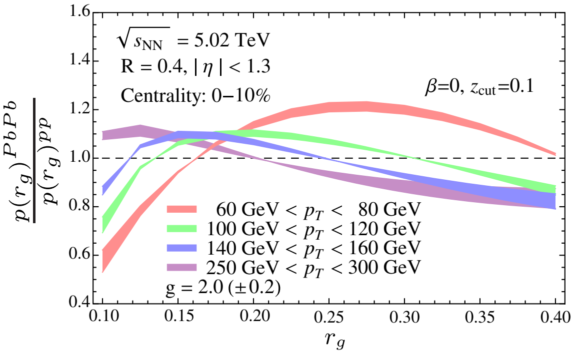

FIG. 4. Theoretical calculations for the groomed jet radius modification of inclusive jets in proton-proton and central lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The soft drop parameters $\beta = 0$, $z_{\rm cut} = 0.1$, and $\Delta R_{12} > 0.1$ are used. Shown are results for four p_T bins with $60 < p_T < 80$ GeV (red band), $100 < p_T < 120$ GeV (green band), $140 < p_T < 160$ GeV (blue band), and $250 < p_T < 300$ GeV (purple band).

bremsstrahlung due to strong in-medium interactions. Future studies of jet substructure observables that are more sensitive to the soft radiation, for example, the jet mass [58–62], will allow us to map out the whole jet formation history.

Y.-T. C. would like to thank Y. Chen, P. Harris, A. Larkoski, Y.-J. Lee, S. Marzani, Y. Mehtar-Tani, G.-Y. Qin, F. Ringer, J. Thaler, and M. Verweij for very helpful discussions and comments, and the ESI at Universität Wien for hospitality and support. This research was supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC52-06NA25396, the DOE Early Career Program, and the LHC Theory Initiative Postdoctoral Fellowship under National Science Foundation Grant No. PHY-1419008.

Note added.—Recently, the CMS collaboration updated its preliminary subjet momentum sharing distribution analysis. As a result, the three data points near $z_g \sim 0.4$ in the upper panel of Fig. 1 have moved up considerably, eliminating what might have been a discrepancy between the measurement and the theoretical predictions presented here

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