Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 982 (2019) 583–586

www.elsevier.com/locate/nuclphysa

Probing jet splitting and energy loss via groomed jets in relativistic heavy-ion collisions

Ning-Bo Chang[a,c], Shanshan Cao[b], Guang-You Qin[c]

[a] *Institute of Theoretical Physics, Xinyang Normal University, Xinyang, Henan 464000, China*
[b] *Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA*
[c] *Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China*

Abstract

The nuclear modification of groomed jet splitting in relativistic heavy-ion collisions at RHIC and the LHC is studied based on higher twist jet energy loss formalism. Assuming coherent energy loss for two subjets, we find a non-monotonic dependence on jet energy for the nuclear modification of jet splitting function, which provides a good description of CMS and STAR groomed jet measurements. In contrast, the assumption of independent energy loss for two subjets cannot explain the observed nuclear modification pattern for groomed jet splitting.

Keywords: Jet quenching, jet energy loss, parton splitting function, jet grooming, medium-induced emission, subjet

1. Introduction

Jet quenching provides one of the most important tools for studying the quark-gluon plasma (QGP) in high-energy nucleus-nucleus collisions at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC) [1]. Medium-induced emission or parton splitting function is one central input for understanding the evolution and energy loss of jets and partons [2, 3], and the modifications of jet internal structure [4, 5], in hot and dense nuclear matter. However, in most jet quenching observables, such as the nuclear modification factors R_{AA} for high transverse momentum ($p_{\rm T}$) hadrons and jets, various components of the complex heavy-ion collisions are involved, which makes it extremely difficult to directly extract the informatin about medium-induced splitting process via the model-to-data comparisons.

Recently, jet grooming measurements using the soft-drop procedure have attracted quite a lot of interest [6, 7, 8, 9, 10, 11]. Essentially, one declusters full jets by dropping the softer branches until finding two hard subjets satisfying the condition: $\frac{\min(p_{\rm T1},p_{\rm T2})}{p_{\rm T1}+p_{\rm T2}} \equiv z_g > z_{\rm cut}\left(\frac{\Delta R}{R}\right)^{\beta}$, where R is jet size parameter, p_{T1} and p_{T2} are transverse momenta of two subjets, z_g is the momentum fraction shared by the lower p_T subjet, $\Delta R = \sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$ is the angular separation between subjets, the threshold $z_{\rm cut}$ and power index β are two parameters of the soft-drop jet grooming algorithm (they are taken as $z_{\rm cut} = 0.1$ and $\beta = 0$ in this work). The groomed jet momentum sharing distribution $p(z_g)$ provides a unique opportunity to directly probe the splitting process of hard jet partons in vacuum and in hot and dense nuclear matter. In this work [12], we study the nuclear modification of groomed jet z_g distribution in relativistic heavy-ion collisions.

https://doi.org/10.1016/j.nuclphysa.2018.09.013

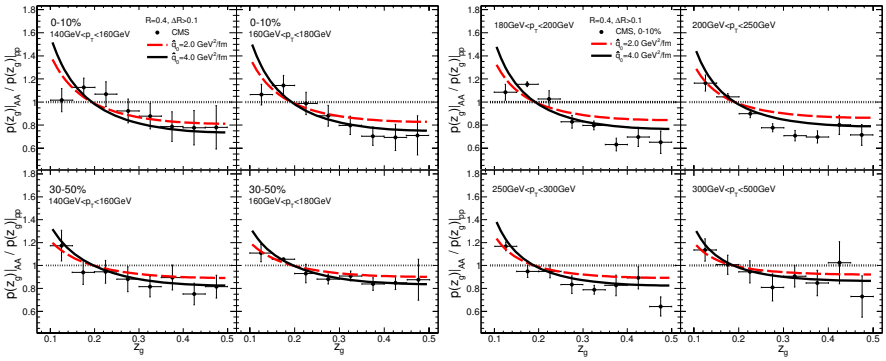

Fig. 1. (Color online) Left: $R_{p(z_g)}$ in central (0-10%) and mid-central (30-50%) Pb+Pb collisions for two different jet p_{T} values: 140-160 GeV and 160-180 GeV. Right: $R_{p(z_g)}$ in central (0-10%) Pb+Pb collisions for four different jet p_{T} values: 180-200 GeV, 200-250 GeV, 250-300 GeV and >300 GeV.

2. Theoretical framework

At leading order, the distribution $p(z_g)$ for soft-drop groomed jets can be obtained as follows [8, 11]:

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

where the index i denotes jet flavor, $k_\perp = 2p_{\mathrm{T}}x(1-x)\tan(\theta/2)$ is the transverse momentum of the daughter parton with k_Δ (k_R) the lower (upper) limit, and $\overline{P}(x, k_\perp^2)$ is the symmetrized parton splitting function: $\overline{P}_i(x, k_\perp^2) = \sum_{j,l}\left[P_{i\to j,l}(x, k_\perp^2) + P_{i\to j,l}(1-x, k_\perp^2)\right]$.

In the presence of nuclear medium, the parton splitting function should include both vacuum and medium-induced contributions:

$$P_i(x, k_\perp^2) = P_i^{\mathrm{vac}}(x, k_\perp^2) + P_i^{\mathrm{med}}(x, k_\perp^2). \tag{2}$$

In this work, medium-induced splitting functions are taken from higher twist energy loss formalism [13],

$$P_i^{\mathrm{med}}(x, k_\perp^2) = \frac{2\alpha_s}{\pi k_\perp^4} P_i^{\mathrm{vac}}(x) \int d\tau \hat{q}(\tau) \sin^2\left(\frac{\tau}{2\tau_f}\right), \tag{3}$$

where $\tau_f = 2Ex(1-x)/k_\perp^2$ is the formation time, and $\hat{q}$ is jet transport coefficient. Here, we relate $\hat{q}$ to the local temperature T and flow four-velocity u of the QGP as: $\hat{q}(\tau, \vec{r}) = \hat{q}_0 \frac{T^3(\tau,\vec{r})}{T_0^3(\tau_0,\vec{0})} \frac{p\cdot u(\tau,\vec{r})}{p^0}$. The dynamical evolution of the QGP is simulated via a (3+1)-dimensional ideal hydrodynamics model [14].

In heavy-ion collisions, we also need to take into account the effect of energy loss experienced by jets:

$$p^{\mathrm{obs}}(z_g) = \frac{1}{\sigma_{\mathrm{total}}} \sum_{j=q,g} \int d^2X \mathcal{P}(\vec{X}) \times \int_{p_{\mathrm{T},1}^{\mathrm{ini}}=p_{\mathrm{T},1}^{\mathrm{obs}}+\Delta E_1}^{p_{\mathrm{T},2}^{\mathrm{ini}}=p_{\mathrm{T},2}^{\mathrm{obs}}+\Delta E_2} dp_{\mathrm{T}}^{\mathrm{ini}} \frac{d\sigma_j}{dp_{\mathrm{T}}^{\mathrm{ini}}} p_j(z_g|p_{\mathrm{T}}^{\mathrm{ini}}), \tag{4}$$

where $\mathcal{P}(\vec{X})$ denotes the probability density for jet production at point $\vec{X}$. Here we only consider the energy loss out of the jet cone via medium-induced radiation, which is calculated via a Boltzmann transport model [2]. In this formula, it is assumed that two subjets lose energy coherently as a single parent jet. We will also explore the effect of independent energy loss of two subjets on the nuclear modification of z_g distribution.

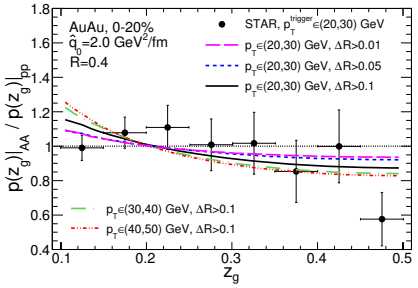

Fig. 2. (Color online) $R_{p(z_g)}$ for central 0-20% Au+Au collisions at 200A GeV.

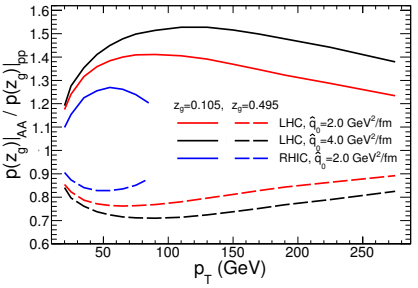

Fig. 3. (Color online) Jet p_T dependence of $R_{p(z_g)}$ at $z_g = 0.105$ and $z_g = 0.495$ for RHIC and the LHC.

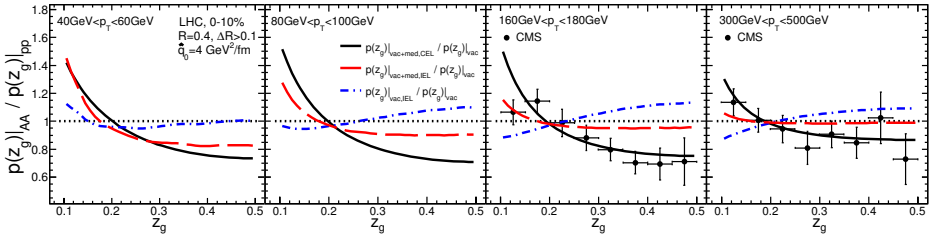

Fig. 4. (Color online) $R_{p(z_g)}$ for three scenarios: medium-modified splitting with coherent energy loss (CEL) of subjets (solid), medium-modified splitting with independent energy loss (IEL) of subjets (dashed), and vacuum splitting with IEL of subjets (dash-dotted).

3. Numerical results: $R_{p(z_g)}$ at RHIC and the LHC

Figure 1 shows the nuclear modification factor $R_{p(z_g)} = \frac{p(z_g)|_{AA}}{p(z_g)|_{pp}}$ in Pb+Pb collisions at 5.02A TeV. The left shows $R_{p(z_g)}$ in central and mid-central collisions for two jet p_T values: 140-160 GeV and 160-180 GeV. The right shows $R_{p(z_g)}$ in central Pb+Pb collisions for four jet p_T values: 180-200 GeV, 200-250 GeV, 250-300 GeV and >300 GeV. With $\hat{q}_0 = 4\ GeV^2/fm$, our calculation provides a good description of CMS data for both central and non-central collisions, and for various jet p_T ranges. One interesting observation is that the nuclear modification for groomed jet z_g distribution tends to diminish with increasing jet p_T.

The result for $R_{p(z_g)}$ for Au+Au collisions at 200A GeV is shown in Figure 2. With $\hat{q}_0 = 2\ GeV^2/fm$ at RHIC, STAR data can be described. One finds that the nuclear modification of groomed jet z_g distribution is quite modest at RHIC (smaller modification for smaller ΔR). Also shown is the jet p_T dependence for $R_{p(z_g)}$ at RHIC, and it is interesting that the modification of z_g distribution decreases with decreasing jet p_T, which is opposite to CMS results in Figure 1. This implies a non-monotonic dependence on jet p_T for the nuclear modification factor $R_{p(z_g)}$. Such effect is illustrated in Figure 3, where $R_{p(z_g)}$ values at $z_g = 0.105$ and $z_g = 0.495$ are plotted as a function of jet p_T at both RHIC and the LHC. One can see that the nuclear modification of z_g distribution reaches maximum at $p_T \sim 50$ GeV at RHIC and at $p_T \sim 100$ GeV at the LHC, and decreases with increasing and decreasing jet p_T. The non-monotonic dependence on jet p_T can be traced back to the interplay of two competing factors. One is the relative contribution of medium-induced splitting to total medium-modified splitting: it decreases with increasing jet p_T (thus the modification of $p(z_g)$ decreases for large jet p_T). The other is the x behavior of medium-induced splitting function, which goes as $\sim 1/x^3$ for large jet p_T limit and $\sim 1/x$ for small jet p_T limit. Thus for small jet p_T, even though the relative contribution from medium-induced splitting becomes large, the x behavior is actually more like vacuum splitting function ($\sim 1/x$), which explains small modification of $p(z_g)$ for small jet p_T.

In the above results, it is assumed that two subjets lose energy coherently like a single parent jet, i.e., they

are not resolved by medium. If the transverse separation between two subjets (e.g., ΔR) is large compared to the medium resolution scale, then they may be resolved by the medium [15]. In this case, they interact with the medium constituents and lose energy independently. The effect of independent energy loss (IEL) of subjets is illustrated in Figure 4, where $R_{p(z_g)}$ is shown for three different scenarios: solid for medium-modified splitting and coherent energy loss (CEL) of subjets, dashed for medium-modified splitting and IEL of subjets, and dash-dotted for vacuum splitting and IEL of subjets. We can see that the use of IEL for subjets cannot explain the CMS data. One may understand this as follows. While IEL for subjets tends to shift z_g to smaller values, the soft-drop condition removes the events with $z_g < z_{cut} = 0.1$, and the resulting normalized $p(z_g)$ is actually flattened. More details on the pattern of $p(z_g)$ modification depends on the interplay between the slope of z_g distribution and the details of z_g shift caused by IEL of subjets [12].

4. Summary

We study the nuclear modification of jet splitting process in relativistic heavy-ion collisions at RHIC and the LHC. It is found that the nuclear modification of groomed jet momentum sharing z_g distribution exhibits a non-monotonic dependence on jet p_T. Our calculation can describe both CMS and STAR groomed jet measurements; the data favors the picture of coherent energy loss of two subjets. Further measurements with wider jet p_T range at RHIC and the LHC and with varying jet cone size and angular separation will provide more stringent test of our understanding of jet splitting process in hot and dense nuclear matter.

Acknowledgements: This work is supported in part by the Natural Science Foundation of China (NSFC) under Grant Nos. 11775095, 11375072 and 11647066. N.-B. C. is supported by Nanhu Scholar Program for Young Scholars of XYNU and the CCNU-QLPL Innovation Fund (Grant No. QLPL2016P01). S. C. is supported by U.S. Department of Energy under Contract No. DE-SC0013460.

References

[1] G.-Y. Qin, X.-N. Wang, Jet quenching in high-energy heavy-ion collisions, Int. J. Mod. Phys. E24 (11) (2015) 1530014. arXiv:1511.00790, doi:10.1142/S0218301315300143.
[2] S. Cao, T. Luo, G.-Y. Qin, X.-N. Wang, Heavy and light flavor jet quenching at RHIC and LHC energies, Phys. Lett. B777 (2018) 255–259. arXiv:1703.00822, doi:10.1016/j.physletb.2017.12.023.
[3] G.-Y. Qin, B. Muller, Explanation of Di-jet asymmetry in Pb+Pb collisions at the Large Hadron Collider, Phys. Rev. Lett. 106 (2011) 162302, [Erratum: Phys. Rev. Lett.108,189904(2012)]. arXiv:1012.5280, doi:10.1103/PhysRevLett.108.189904, 10.1103/PhysRevLett.106.162302.
[4] N.-B. Chang, G.-Y. Qin, Full jet evolution in quark-gluon plasma and nuclear modification of jet production and jet shape in Pb+Pb collisions at 2.76ATeV at the CERN Large Hadron Collider, Phys. Rev. C94 (2) (2016) 024902. arXiv:1603.01920, doi:10.1103/PhysRevC.94.024902.
[5] Y. Tachibana, N.-B. Chang, G.-Y. Qin, Full jet in quark-gluon plasma with hydrodynamic medium response, Phys. Rev. C95 (4) (2017) 044909. arXiv:1701.07951, doi:10.1103/PhysRevC.95.044909.
[6] M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, Towards an understanding of jet substructure, JHEP 09 (2013) 029. arXiv:1307.0007, doi:10.1007/JHEP09(2013)029.
[7] A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft Drop, JHEP 05 (2014) 146. arXiv:1402.2657, doi:10.1007/JHEP05(2014)146.
[8] A. J. Larkoski, S. Marzani, J. Thaler, Sudakov Safety in Perturbative QCD, Phys. Rev. D91 (11) (2015) 111501. arXiv:1502.01719, doi:10.1103/PhysRevD.91.111501.
[9] A. M. Sirunyan, et al., Measurement of the Splitting Function in pp and Pb-Pb Collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, Phys. Rev. Lett. 120 (14) (2018) 142302. arXiv:1708.09429, doi:10.1103/PhysRevLett.120.142302.
[10] K. Kauder, Measurement of the Shared Momentum Fraction z_g using Jet Reconstruction in p+p and Au+Au Collisions with STAR, Nucl. Part. Phys. Proc. 289-290 (2017) 137–140. arXiv:1703.10933, doi:10.1016/j.nuclphysbps.2017.05.028.
[11] Y.-T. Chien, I. Vitev, Probing the Hardest Branching within Jets in Heavy-Ion Collisions, Phys. Rev. Lett. 119 (11) (2017) 112301. arXiv:1608.07283, doi:10.1103/PhysRevLett.119.112301.
[12] N.-B. Chang, S. Cao, G.-Y. Qin, Probing medium-induced jet splitting and energy loss in heavy-ion collisions, Phys. Lett. B781 (2018) 423–432. arXiv:1707.03767, doi:10.1016/j.physletb.2018.04.019.
[13] X.-N. Wang, X.-F. Guo, Multiple parton scattering in nuclei: Parton energy loss, Nucl. Phys. A696 (2001) 788–832. arXiv:hep-ph/0102230, doi:10.1016/S0375-9474(01)01130-7.
[14] L. Pang, Q. Wang, X.-N. Wang, Effects of initial flow velocity fluctuation in event-by-event (3+1)D hydrodynamics, Phys. Rev. C86 (2012) 024911. arXiv:1205.5019, doi:10.1103/PhysRevC.86.024911.
[15] J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, New picture of jet quenching dictated by color coherence, Phys. Lett. B725 (2013) 357–360. arXiv:1210.7765, doi:10.1016/j.physletb.2013.07.046.