PROCEEDINGS OF SCIENCE

Probing medium-induced jet splitting in heavy-ion collisions

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We study the nuclear modification of the splitting function of groomed jets in relativistic heavy-ion collisions within the higher twist formalism. With the assumption of coherent energy loss of the two prongs, we find a non-monotonic dependence on jet energy for the nuclear modification of the jet splitting function, and provide a simultaneous description of the experimental data at RHIC and the LHC. On the contrary, the same experiment data cannot be explained within the picture of independent energy loss of the two prongs within the groomed jet.

International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
30 September - 5 October 2018
Aix-Les-Bains, Savoie, France

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PoS(HardProbes2018)076

1. Introduction

The medium-induced parton splitting process is crucial for the energy loss of leading partons and full jets as well as the nuclear modification of jet structures [1, 2, 3, 4]. However, few jet quenching observables are able to provide direct constraints on the medium-induced parton splitting functions because of the complexity of physical systems in heavy-ion collisions. With the introduction of the soft drop jet grooming algorithm [5], one is now able to identify a hard splitting within a groomed jet and thus conduct a direct investigation on the parton splitting function [6, 7].

In theory, one may relate $p(z_g)$, the distribution of the transverse momentum fraction z_g in a hard splitting, to the normalized parton splitting function that satisfies a given soft drop condition [8, 6]: $p_i(z_g) = \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \overline{P}_i(z_g, k_\perp^2) \big/ \int_{z_{\rm cut}}^{1/2} dx \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \overline{P}_i(x, k_\perp^2)$, where i denotes the jet flavor, and $k_\perp = 2p_{\rm T}x(1-x)\tan(\theta/2)$ represents the transverse momentum of the daughter partons with respect to the parent parton with k_Δ and k_R being its lower and upper limits. Since the measured $p(z_g)$ does not identify the flavor of the two prongs, the parton splitting function in theoretical calculations should be symmetrized: $\overline{P}_i(x, k_\perp^2) = \sum_{j,l} \left[P_{i\to j,l}(x, k_\perp^2) + P_{i\to j,l}(1-x, k_\perp^2)\right]$.

In nucleus-nucleus (AA) collisions, we consider the parton splitting functions contributed by both the vacuum part and the medium induced part, $P_i(x, k_\perp^2) = P_i^{\rm vac}(x, k_\perp^2) + P_i^{\rm med}(x, k_\perp^2)$, the latter of which is taken from the higher-twist energy loss formalism [9] in our work:

$$P_i^{\rm med}(x, k_\perp^2) = \frac{2\alpha_s}{\pi k_\perp^4} P_i^{\rm vac}(x) \int d\tau \hat{q}(\tau) \sin^2\left(\frac{\tau}{2\tau_f}\right). \tag{1.1}$$

Here, τ represents the accumulated time of parton-medium interaction, $\tau_f = 2Ex(1-x)/k_\perp^2$ is the formation time of the emitted gluon, $\hat{q}$ is the jet transport coefficient. In this work, we calculate $\hat{q}$ via $\hat{q}(\tau, \vec{r}) = \hat{q}_0 \left[T^3(\tau, \vec{r})/T_0^3(\tau_0, \vec{0})\right] \left[p \cdot u(\tau, \vec{r})/p^0\right]$, where the local temperature T and 4-velocity u of the medium are provided by the hydrodynamical simulation [10]. Note that $\hat{q}_0$ is our model parameter and is fixed at the highest (central) initial temperature T_0 in a given collision system.

To compare to experimental data measured in a given final $p_{\rm T}$ range, the jet splitting function at a fixed $p_{\rm T}$ is convoluted with the jet cross section. In the case of AA collisions, the nuclear geometry and the effect of jet energy loss are taken into account as follows:

$$p^{\rm obs}(z_g) = \frac{1}{\sigma_{\rm total}} \sum_{j=q,g} \int d^2X \mathscr{P}(\vec{X}) \times \int_{p_{\rm T,1}^{\rm ini}=p_{\rm T,1}^{\rm obs}+\Delta E_1}^{p_{\rm T,2}^{\rm ini}=p_{\rm T,2}^{\rm obs}+\Delta E_2} dp_{\rm T}^{\rm ini} \frac{d\sigma_j}{dp_{\rm T}^{\rm ini}} p_j(z_g|p_{\rm T}^{\rm ini}). \tag{1.2}$$

In this work, we first investigate the $p_{\rm T}$ dependence of the nuclear modification of the jet splitting function in Sec. 2 with the assumption that the two prongs within a groomed jet lose energy coherently inside the medium and the energy loss is contributed by medium-induced gluon radiation out of the jet cone [11]. In Sec. 3, we discuss the effects of incoherent energy loss for the two prongs.

2. Energy dependence of the nuclear modification of jet splitting function

Within the framework discussed in Sec. 1 we first calculate the jet splitting function in vacuum and verify that our results are consistent with the experimental data in proton-proton (pp) collisions [7]. With the reliable pp baseline, we continue calculating its nuclear modification factor

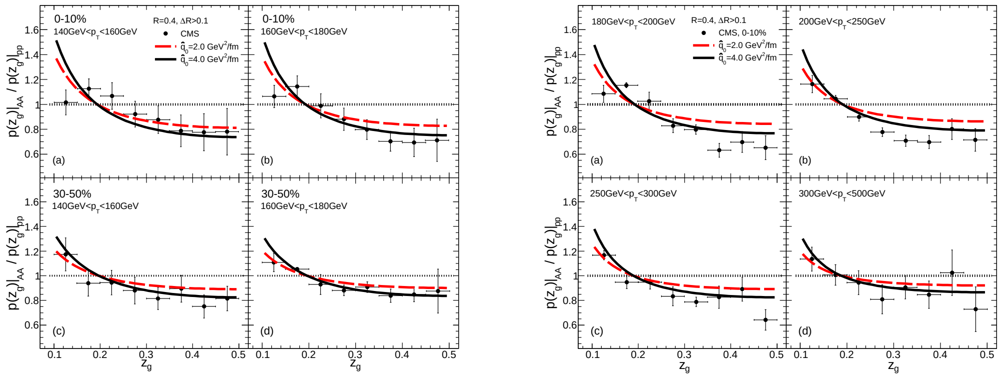

Figure 1: (Color online) Nuclear modification factor of jet splitting function in 5.02 ATeV Pb+Pb collisions [7] – left for the centrality dependence and right for the jet p_{T} dependence.

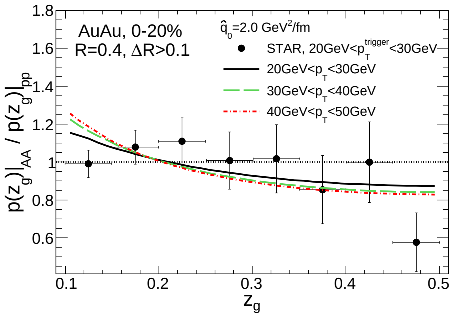

Figure 2: (Color online) $R_{p(z_g)}$ in 200 AGeV Au-Au collisions [7].

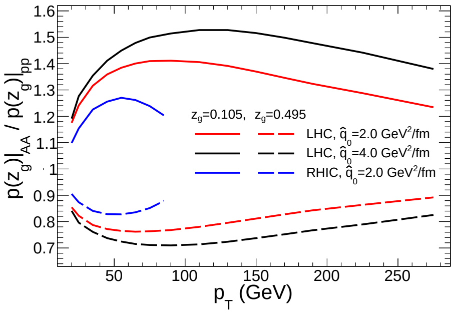

Figure 3: (Color online) $R_{p(z_g)}$ vs. p_{T} at $z_g = 0.105$ and 0.495 [7].

$R_{p(z_g)}$ in heavy-ion collisions. In Fig. 1, we present our results for 5.02 ATeV Pb-Pb collisions. The left panel of Fig. 1 shows the results in 0-10% and 30-50% centralities for two jet p_{T} bins. With $\hat{q}_0 = 4$ GeV^2/fm, our results are consistent with the CMS data [12]. In the right panel, we investigate the jet p_{T} dependence of $R_{p(z_g)}$ within the 0-10% centrality bin. Our results and experimental data indicate a decrease of the nuclear modification as the jet p_{T} increases. Following this p_{T} dependence, one would expect an even stronger nuclear modification effect at RHIC at low p_{T}. However, as shown in Fig. 2, both our calculation and the STAR data [13] show little nuclear modification of the jet splitting function at RHIC. Note that the value of $\hat{q}_0$ at RHIC is half of that at the LHC due to the lower initial temperature at RHIC than that that at the LHC. We explore the effects of the ΔR cut on $R_{p(z_g)}$ in Fig. 2, where one can observe that as ΔR decreases, our result provides a better description of the STAR data [13] in which no ΔR cut is implemented.

Figures 1 and 2 imply that there exists a non-monotonic p_{T} dependence of the nuclear modification of the jet splitting function. To have a clearer illustration of this non-monotonic behavior, we present $R_{p(z_g)}$ in Fig. 3 as a function of p_{T} at the two end points of those curves in Figs. 1 and 2 – $z_g = 0.105$ and $z_g = 0.495$. One clearly sees that the nuclear modification on the jet splitting function first increases and then decreases as the jet p_{T} increases.

This non-monotonic behavior stems from two competing factors of the medium-induced parton splitting function: the relative contribution from medium-induced vs. vacuum parts, and the x dependence of its medium-induced vs. vacuum parts. As shown in Eq. (1.1), the medium-induced

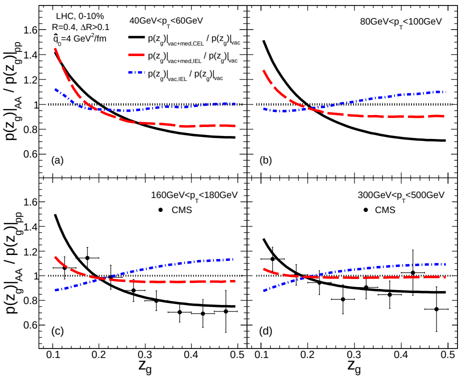

Figure 4: (Color online) $R_{p(z_g)}$ for three different scenarios: solid for medium-modified splitting with coherent energy loss (CEL) of subjets, dashed for medium-modified splitting with independent energy loss (IEL), and dash-dotted for vacuum splitting with IEL [7].

splitting function within the higher-twist formalism has a $1/k_\perp^4$ dependence. Compared to the vacuum splitting function that depends on $1/k_\perp^2$, the medium-induced vs. vacuum contribution is suppressed by $1/k_\perp^2$. With a fixed cone size, this transverse momentum broadening $k_\perp$ is proportional to the jet p_T. Consequently, as p_T increases, the medium-induced part contributes less to the jet splitting function, leading to a weaker nuclear modification effect. On the other hand, in the small jet p_T limit, the medium-induced splitting function Eq. (1.1) shows a $1/x$ dependence, different from its $1/x^3$ dependence at the large p_T limit. Since the vacuum splitting function always has the $1/x$ dependence, as p_T decreases, the medium-induced part becomes more similar to the vacuum part, and can be hardly reflected in the nuclear modification factor of the self-normalized $p(z_g)$ despite its large contribution. These two competing factors are crucial in understanding the non-monotonic p_T dependence of $R_{p(z_g)}$ observed at RHIC and the LHC.

3. Coherent vs. incoherent energy loss of subjets

Calculations in the previous section are based on the assumption that the two prongs within the groomed jet lose energy coherently. Whether the two prongs can be resolved by the medium depends on the relation between the transverse separation between the two prongs and the medium resolution scale [14]. If the two prongs lose energy independently, the momentum fraction z_g will be shifted to a smaller value because jets with larger energy usually lose less fractional energy in most theories. Thus, one may expect an enhancement of $p(z_g)$ at small z_g. However, since the measured $p(z_g)$ is always normalized between $z_\mathrm{cut} = 0.1$ and $z_g = 0.5$, whether the shape of the normalized $p(z_g)$ is steepened or flattened after the independent energy loss of the two prongs depends on the slope of the initial z_g distribution and the amount of the z_g shift due to energy loss. Assuming the initial z_g distribution obeys $p^\mathrm{ini}(z_g) = 1/z_g^\alpha$ and $\Delta z_g = z_g^\mathrm{ini} - z_g^\mathrm{fin}$, we have the final distribution as $p^\mathrm{fin}(z_g^\mathrm{fin}) \approx \left(1 - \alpha\Delta z_g/z_g^\mathrm{fin}\right)\left(1 + d\Delta z_g/dz_g^\mathrm{ini}\right)/(z_g^\mathrm{fin})^\alpha$ [7]. The term in first parentheses flattens $p^\mathrm{ini}(z_g)$ while the term in second parentheses steepens $p^\mathrm{ini}(z_g)$. For most realistic cases, the first term dominates.

In Fig. 4 we compare the nuclear modification of the groomed jet splitting function for three different scenarios in four different p_T ranges. The black solid lines represent the results that was described in the previous section where we assume medium-modified splitting together with coherent energy loss of subjects. The blue dash-dotted lines represent the results assuming no medium-induced splitting (i.e., vacuum splitting only) together with independent energy loss of subjets through the medium after the splitting, from which one can observe that such independent energy loss of energy loss indeed flattens the z_g distribution, leading to an enhancement of $p(z_g)$ at large z_g. In the end, the red dashed lines represent the results assuming the medium-induced jet splitting together with independent energy loss of subjets, from which we see the medium effect still steepens the z_g distribution, but cannot quantitatively describe the data. By comparing these three scenarios, we find that the experimental data with the current kinematic cuts favor the picture that the two prongs evolve coherently within the groomed jet.

4. Summary

We have studied the nuclear modification of the groomed jet splitting function in high-energy nuclear collisions. We found a non-monotonic p_T dependence of its nuclear modification, which is crucial for a simultaneous description of data at RHIC and the LHC. Data within current kinematic cuts prefer the picture of coherent energy loss of the two prongs within the groomed jet. Our findings can be tested by future measurements that cover wider ranges of the jet p_T and cone size.

Acknowledgments. This work is supported in part by the Natural Science Foundation of China (NSFC) under Grant Nos. 11775095, 11890711 and 11375072. 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.

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