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Probing jet decoherence in heavy ion collisions

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Abstract

We suggest to use the SofDrop jet grooming technique to investigate the sensitivity of jet substructure to color decoherence in heavy ion collisions. We propose in particular to analyze the two-prong probability angular distribution as a probe of the transition between the coherent and incoherent energy loss regimes. We predict an increasing suppression of two-prong substructures with angle as the medium resolves more jet substructure.

1. Introduction

Jet quenching phenomenon has been observed for the first time in heavy ion collisions at RHIC and confirmed at the LHC [1, 2]. The observed strong jet suppression is mainly attributed to medium-induced gluon radiation (see [3, 4] for instance and references therein). The details of jet energy loss mechanisms are however not completely understood. Indeed, the state of the art phenomenological models and their Monte-Carlo implementations [5, 6, 7, 8] are based on single parton energy loss [9, 10, 11] and thus, do not account for the fact that medium-induced radiation off a jet involves interferences between the multiple partons that form a jet. Recent works have emphasized the importance of color coherence for jets passing through QCD matter [12, 13, 14, 15]. The results show that jet energy loss is proportional to the number of subjets that the medium resolves. This motivated the recent interest for jet substructure observables which are expected to be more susceptible to those effects [16].

In vacuum jet fragmentation is characterized by color coherence, which leads to angular ordering of the parton shower. A simple setup that illustrates this mechanism is the antenna radiation pattern. Consider for instance a collimated high energy quark-anti-quark pair in a color singlet state, which is produced in a hard event after the decay of virtual photon (or a boosted W/Z boson). As a result of color coherence of the pair, gluons with transverse wavelength larger that the antenna separation *do not* resolve the individual color charges and hence are strongly suppressed. This corresponds to radiation at angles larger than the antenna opening angle. In the presence of a dense colored medium color coherence of the pair is altered due

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to rapid in-medium color randomization. For soft gluon radiation, that occurs at late times after medium interactions took place, the spectrum reads [13], $\omega \mathrm{d}I/\mathrm{d}\omega \mathrm{d}\theta \simeq \bar{\alpha}\ [\Theta(\theta_0 - \theta) + \Delta_{\rm med}(\theta_0)\,\Theta(\theta - \theta_0)]\,/\theta$, for the quark and similarly for the anti-quark. Here, θ_0 is the pair opening angle, $\bar{\alpha} \equiv \alpha_s C_F/\pi$ and, ω and θ are the gluon frequency and its radiation angle with respect to the quark momentum, respectively. The first term in the above equation corresponds the vacuum result with the constraint that only radiation at angle $\theta < \theta_0$ is permitted. The second term, which is the result of medium interactions that open up the phase space of large angle radiation, is proportional to the decoherence parameter:

$$\Delta_{\rm med}(\theta_0) \equiv 1 - \exp\left[-\frac{1}{12}\left(\frac{\theta_0}{\theta_c}\right)^2\right]. \tag{1}$$

At small opening angles compared to the medium characteristic angle $\theta_c = 1/\sqrt{\hat{q}L^3}$, $\theta_0 \ll \theta_c$ (where $\hat{q}$ is the jet-quenching parameter and L the medium length) the decoherence parameter vanishes: $\Delta_{\rm med} \to 0$. This reflects color transparency of the antenna that traverses the medium without being resolved and hence radiation intensity at large angles is proportional to the total charge of the antenna, which in the singlet case depicted above, vanishes. In the opposite situation, at large angles, $\theta_0 \gg \theta_c$, and $\Delta_{\rm med} \to 1$. In this case, the medium resolves the antenna inner structure, that is the two quark color charges, and as a result the angular constraint in the radiation intensity is removed opening phase space for large angle radiation that in vacuum is forbidden due to color coherence. Note that it is straightforward to generalize the above discussion to arbitrary color configurations. Although this example looks rather academic, it is nevertheless quite illuminating as to what to expect from the dependence of jet energy loss on the fluctuation of the jet substructure.

In the standard approach to jet quenching, a jet is assumed to be a single parton that loses energy via medium-induced radiation. In the approximation of multiple soft radiation and neglecting finite medium size effects parton energy loss probability reads [17]: $P(\epsilon) \simeq \sqrt{\frac{\omega_s}{\epsilon^3}}\exp\left(-\frac{\pi\omega_s}{\epsilon}\right)$, where $\omega_s \equiv \bar{\alpha}^2\hat{q}L^2$ is the characteristic medium-induced radiation frequency. It depends on the jet quenching parameter $\hat{q}$ that encodes medium properties and on the medium length L.

However, as alluded to above, this approach misses the fact that a jet fragments into many partons and this fragmentation pattern fluctuates from an event to another. In order to investigate the dependence of energy loss on the fluctuation of the jet substructure, we propose to use the SoftDrop jet substructure technique to single out the primary hard splitting in the parton shower history and investigate the energy loss of the two subjets as a function of their angular separation. As a direct measurement of color (de)coherence, in this work we argue that wide-angle structures should be strongly suppressed compared to narrow ones [18].

2. Two-prong nuclear modification factor

In order to better understand the mechanisms of jet energy loss in the quark-gluon plasma, many observables have been investigated in the past few years by the LHC collaborations. Only recently, however, jet substructure techniques are being investigated in the context of heavy ion collisions. These "grooming" techniques (such as "trimming" and "pruning") have been developed for proton-proton collisions to reduce the soft contamination from underlying events and pileup, to identify boosted W, Z and Higgs events from the QCD background. They proved to be useful tools for investigating QCD jet substructure (for reviews see [19, 20]).

We focus in this exploratory work on the SoftDrop declustering procedure[1] [22] which consists of sequentially declustering the jet constituents using the Cambridge-Aachen algorithm (C/A) back to the first hard branching. The procedure ends when the first pair of subjets satisfying the condition, $z_g = \min(p_{T1}, p_{T2})/(p_{T1} + p_{T2}) > z_{\rm cut}\,(\Delta R_{12}/R)^\beta$, is identified, where p_{T1} (p_{T2}) are the two subjet transverse momenta and ΔR_{12} their angular separation (R being the jet radius). In effect, the declustering procedure retains

[1]Note that SoftDrop with $\beta = 0$ reduces to the modified mass-drop tagger [21].

the two substructures that pass the condition at the largest angular separation $\Delta R_{12} \equiv r_g$ [22, 23]. This observable has been measured for the first time at the LHC for $\beta = 0$ and $z_{\rm cut} = 0.1$, with the implementation of a minimal resolution angle $\Delta R_{12} \geq 0.1$ to account for detector resolution effects [16]. The z_g-distribution appears to be steeper in heavy-ion collisions than in proton-proton collisions and the effect seems to decrease with increasing jet energy. It was argued that this medium modification might be a signature of hard medium-induced gluon radiation [24] (see also [25]). For jet $p_T > 200$ GeV, the ratio of the self-normalized z_g distributions in PbPb and pp collisions is consistent with one. This, however, does not indicate, the absence of medium-modification. We argue in the present work that while the z_g distribution is unmodified the yield of two-prong substructures might be strongly sensitive to medium effects even at very high p_T in the same way as the jet nuclear modification factor.

In order to investigate the dependence of energy loss upon the fluctuations of the jet substructure and the resolution of the medium, we introduce the two-prong nuclear modification factor:

$$R^{2-\rm prong} \equiv \frac{p_{_{AA}}(r_g)}{p_{_{pp}}(r_g)}. \tag{2}$$

where $p_{_{AA}}(r_g)$ and $p_{_{pp}}(r_g)$ are the angular probability distribution of two prong substructures as defined by the SoftDrop procedure in nucleus-nucleus and proton-proton collisions, respectively. Probability conservation implies $\mathbb{P}_{\rm 1prong} + \mathbb{P}_{\rm 2prong} = 1$ where $\mathbb{P}_{\rm 2prong} = \int_{R_0}^{R} {\rm d}r_g p(r_g)$. R_0 stands for the experimental angular resolution. To provide a qualitative prediction for the two prong nuclear modification factor (2), we consider for simplicity the leading order (LO) process in vacuum, $p_{_{pp}}(r_g) = \frac{\bar\alpha}{r_g} \int_{z_{\rm cut}}^{1/2} {\rm d}z_g\, P(z_g)$, where $P(z_g)$ is the QCD splitting function. Thus, we neglect the effect of multiple splittings that should be resumed in a Sudakov Form Factor. At very high jet energy we expect the z_g distribution not to be strongly modified by energy loss as confirmed by the CMS data for $p_T > 300$ GeV. Furthermore, if $z_{\rm cut} p_T > \omega_c = \hat{q} L^2$, the contribution of medium-induced hard gluon radiation is negligible due to LPM suppression. In this situation, the two-prong substructures will form via hard vacuum splitting at very short times compared to the length of the medium and their yield will depend on the opening angle of the pair: when $r_g \ll \theta_c$, the unresolved pair loses energy as a single parton, conversely, at large angle $r_g \gg \theta_c$, the two color charges are resolved by the medium and hence lose energy independently, as a result, the two-prong probability is more suppressed. We interpolate between the two limiting cases with the help of the decoherence parameter (1) (for simplicity we only consider $g \to gg$ splitting),

$$\frac{{\rm d}N_{2-\rm prong}}{{\rm d}p_T^2 {\rm d}r_g} \simeq \left[1 - \Delta_{\rm med}(r_g)\right] \frac{{\rm d}N_{\rm coh}}{{\rm d}p_T^2 {\rm d}r_g} + \Delta_{\rm med}(r_g) \frac{{\rm d}N_{\rm incoh}}{{\rm d}p_T^2 {\rm d}r_g}, \tag{3}$$

with ${\rm d}N_{\rm coh}/{\rm d}p_T^2{\rm d}r_g \simeq p_{_{pp}}(r_g)\, Q_1(p_T)$ and ${\rm d}N_{\rm incoh}/{\rm d}p_T^2{\rm d}r_g \simeq p_{_{pp}}(r_g)\, Q_2(p_T)$, where Q_1 and Q_2 are, respectively, the quenching factors for a single (coherent) and two (incoherent) color charges. They are related to the jet spectrum as follows $Q_1(p_T) \equiv \int_0^\infty {\rm d}\epsilon\, P(\epsilon)\, {\rm d}N_{\rm jet}(p_T + \epsilon)/{\rm d}p_T^2$ and $Q_2(p_T) \equiv \int_0^\infty {\rm d}\epsilon_1 \int_0^\infty {\rm d}\epsilon_2\, P(\epsilon_1)\, P(\epsilon_2)\, {\rm d}N_{\rm jet}(p_T + \epsilon_1 + \epsilon_2)/{\rm d}p_T^2$. Here we assumed that energy loss does not affect the hard splitting (z_g, r_g) distribution. The implementation of a more complete formula is postpone to a future work. Note that it is evident that the yield of 2-prong structures in the incoherent case Q_2 is smaller that the coherent one Q_1 due to the presence of two energy loss probabilities $P(\epsilon_1)$ and $P(\epsilon_2)$ in the former. Finally, inserting the LO two-prong probability distribution $p_{_{AA}}(r_g) \simeq Q_1^{-1}(p_T)\, {\rm d}N_{2-\rm prong}/({\rm d}p_T^2 {\rm d}r_g)$ in Eq. (2), the two prong nuclear modification factor takes the following simple form $R^{2-\rm prong} \simeq 1 + \left(Q_2(p_T)/Q_1(p_T) - 1\right) \Delta_{\rm med}(r_g)$. The evaluation of the above expression is shown in Fig. 2 were the transition between the coherent regime at small angle, $R^{2-\rm prong} \simeq 1$ to the decoherence regime where $R^{2-\rm prong} \simeq Q_2/Q_1 \ll 1$ is controled by the characteristic angle θ_c.

Many inclusive jet observables turned out to have limited discriminating power as many jet quenching models, with rather different physical contents, have been successful in describing the data. We expect that the study of jet substructure observables will put new constraints on theoretical uncertainties. To that aim, we propose to use the SofDrop declusturing technique to investigate the angular and energy distribution of the first hard splitting as a probe of in-medium color decoherence. To explore the sensitivity of this observable to

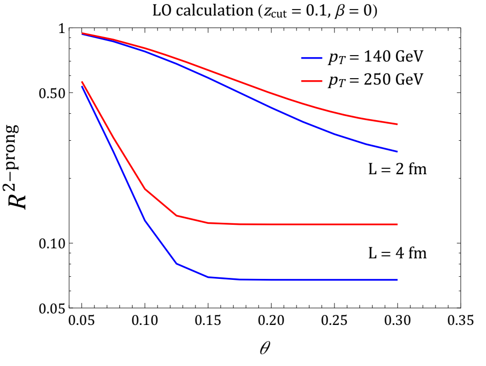

Fig. 1. The two prong nuclear modification factor as a function of the groomed angle $\theta \equiv r_g$ at leading order (LO) for $\hat{q}$ = 2 GeV^2/fm. By varying the angle of the two prong substructure one can investigate the transition between the coherence and decoherence regimes of jet energy loss.

the color coherence we have performed a simple interpolation between the two limiting scenarios: coherent and incoherent energy loss of the jet substructure. We find that the two-prong nuclear modification factor defined in Eq. (2) decreases with increasing groomed angle.

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