Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 967 (2017) 520–523

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

Measuring medium-induced gluons via jet grooming

Konrad Tywoniuk[a], Yacine Mehtar-Tani[b]

[a]*Theoretical Physics Department, CERN, 1211 Geneve 23, Switzerland*
[b]*Institute of Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*

Abstract

Jet substructure observables and applications of jet grooming techniques in heavy-ion collisions are still in its infancy and provide new alleys for studying medium modifications of perturbative degrees of freedom. We note that these measurements, given the right transverse momentum range, can be uniquely sensitive to rare medium-induced emissions inside of the jet cone. This corresponds to an infrared enhancement that would, for instance, affect the distribution of the groomed momentum-sharing variable z_g measured using the SoftDrop procedure.

Keywords: QCD jets, jet quenching, jet substructure

1. Introduction

Jet quenching currently refers to a wide spectrum of observables, spanning single-inclusive hadron production at high-p_{T} to modifications of inter-jet distributions in heavy-ion collisions. These modifications are expected to arise from a complex interplay of elastic and inelastic processes which alter the distribution within the jet cone and propagate a fraction of the total jet energy out of it. However, lacking a rigorous theoretical framework for jet evolution in matter, current, state-of-the-art models rely on various assumptions when interfacing medium effects with jet showering algorithms. Novel measurements of jet substructure observables prompt us to explore these issues from a new perspective. We argue below that a set of jet substructure observables that pin down details of the hard splitting, which will be defined shortly, provide a possibly more direct measurement of hard medium-induced radiation. This could provide a first observation of the generic mechanism that is expected to drive jet modifications and energy loss, codified through the medium parameter $\hat{q}$ and size L.

Jet grooming techniques provide useful tools for further quantifying QCD jet substructure, for reviews see [1, 2]. They are generally designed to single out perturbative radiation from soft, mostly non-perturbative components of the jet. In these proceedings, we report on work [3] that focussed on the "soft drop declustering" procedure [4, 5] which consists of sequentially declustering the jet constituents back to the first branching of a angular-ordered tree. The procedure terminates when the first pair of subjets that satisfy the grooming condition $\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})/(p_{\mathrm{T}1} + p_{\mathrm{T}2}) > z_{\mathrm{cut}}(\Delta R_{12}/R)^{\beta}$, is identified, where $p_{\mathrm{T}1}$ ($p_{\mathrm{T}2}$) are the two subjet transverse momenta and ΔR_{12} their angular separation (R being the jet radius), or if the angular separation is smaller than some minimal resolution angle R_0. The kinematics of that pair defines the jet groomed momentum $p_{\mathrm{Tg}} \equiv p_{\mathrm{T}1} + p_{\mathrm{T}2}$, which is smaller that the original jet p_{T}, the momentum sharing variable $z_g \equiv \min(p_{\mathrm{T}1}, p_{\mathrm{T}2})/p_{\mathrm{Tg}}$ and groomed jet radius $r_g \equiv \Delta R_{12}/R$ [5]. The normalised z_g-distribution

http://dx.doi.org/10.1016/j.nuclphysa.2017.05.067
0375-9474/

is referred to as the "splitting probability" and has been studied recently [6]. This observable has, for the first time, been successfully measured at the LHC for $\beta = 0$ [7]. 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.

2. The definition of the splitting probability in vacuum

The splitting probability of the longitudinal energy fraction z_g of a groomed jet in the vacuum [6], see also [5, 3], reads

$$p(z_g) = \int_{R_0}^{R} \mathrm{d}\theta\, \Delta(R,\theta)\mathcal{P}_{\rm vac}(z_g,\theta)\, \Theta_{\rm cut}\,(z,\theta) + \delta(1-z)\Delta(R,R_0)\,, \tag{1}$$

where R is the opening angle of the jet, R (R_0) is the jet opening (minimal resolution) angle and the Heaviside step function embodies the SoftDrop condition. At leading order, the splitting function is given by $\mathcal{P}_{\rm vac}(z,\theta) = \bar\alpha P(z)/\theta$, where $P(z)$ is the Altarelli-Parisi splitting function. For simplicity and without loss of generality, we shall restrict our discussion to the purely gluonic case, i.e., $P(z) \equiv P_{gg}(z) = (1-z(1-z))^2/(z(1-z))$ with $\bar\alpha = 2\alpha_s N_c/\pi$. In order to deal with the collinear ($\theta \to 0$) divergences, one has to resum multiple gluon emissions in the Sudakov form factor that corresponds to the probability not to measure a splitting that would fulfil the soft drop condition,

$$\Delta(R,\theta) = \exp\left[-\bar\alpha \int_\theta^R \frac{\mathrm{d}\theta'}{\theta'} \int_0^{1/2} \mathrm{d}z\, P(z)\, \Theta(z - z_{\rm cut}\theta'^{\beta})\right]. \tag{2}$$

The two terms in Eq. (1) correspond to the binary outcome of the SoftDrop procedure, the first term representing the term where two prong were identified. Hence the second term contains the probability of not finding a pair of sub-jets passing the cut, $\mathbb{P}_{\rm 1prong} = \Delta(R,R_0)$. Thus,

$$\mathbb{P}_{\rm 2prong} = \int_0^1 \mathrm{d}z_g\, p(z_g) = 1 - \Delta(R,R_0)\,, \tag{3}$$

so that the total probability is conserved.

3. The splitting probability in medium

The range of subjet energies explored in the CMS measurement [7], ensures that the primary splitting that created them occurs at very short time scales as compared to the time scale over which energy loss develops, which is typically of order of several fm's. Consider a sample of jets with $p_{\rm T} = 200$ GeV, within the range of measured momentum fractions $z \sim 0.1 - 0.5$ and jet resolution angles $R_0 \sim 0.1 - 0.4$, we thus get formation times within the range 10^{-2} fm $\lesssim t_{\rm f} \equiv 1/(z p_{\rm T} \Delta R_{12}^2) \lesssim 1$ fm, which is much smaller than the average medium length.

Let us list the main assumptions and caveats of our current setup. (i) We consider two radiative mechanisms that are assumed to be well separated in angles. On the one hand, hard and (quasi-)collinear splittings that remain within the jet cone. They can be vacuum or medium-induced splittings, where the latter are assumed to be rare emissions with large formation times, with energies $\alpha_s^2 \hat q L^2 \lesssim \omega \lesssim \hat q L^2$, and thus can be computed to leading order in the coupling constant. On the other hand, large-angle medium-induced soft radiation, $\omega \lesssim \alpha_s^2 \hat q L^2$. These gluons are not captured in the jet cone and are responsible for jet energy loss but not for particle number change. This separation presumes therefore that $\alpha_s^2 \hat q L^2 \lesssim z_{\rm cut} E$. (ii) We focus on a scenario where the jets are not resolved by the medium [8, 9]. The coherent energy loss picture matches closely the experimental SoftDrop procedure since the intra-jet structure is not modified. In addition to the energy loss suffered by the jet as a whole we include the emission of medium-induced radiation. If the jet transverse extension in the medium, $\sim RL$, is small compared to the medium resolution scale, $\sim (\hat q L)^{-1/2}$, it preserves its colour coherence and interacts with the medium as a single charge [10, 11]. (iii) We assume

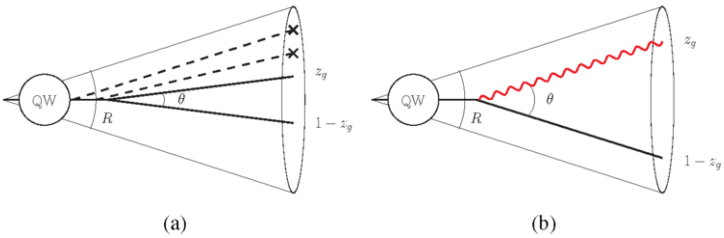

Fig. 1: (a) Vacuum radiation, including real, groomed emissions that are marked by a cross. (b) Hard, quasi-collinear medium-induced radiation (depicted by a red, wavy line) emitted inside the jet cone. The blob on the first propagator illustrates the coherent energy loss of the jet which does not affect the groomed jet structure. Its range extends however along the whole in-medium path length.

that the relevant part of the vacuum cascade occurs at short enough times scales such that one can ignore energy loss prior to the hard splittings. This is, of course, not applicable to medium-induced branchings which can be triggered anywhere along the in-medium jet path.

The two contributions are illustrated in Fig. 1. All in-cone emission, including early emissions that fail to pass the grooming condition, marked with an "×" in Fig. 1a, are emitted coherently. It follows that any collinear splitting would appear as if it occurred after the energy was lost and therefore we have $\mathcal{P}^{\rm coh}_{\rm vac}(z,\theta) = \mathcal{P}_{\rm vac}(z,\theta)$, that is the splitting of energy between the two subjets matches the vacuum. This is a manifestation of the fact that coherent energy loss does not resolve nor modify the inter-jet structure [8]. The number of measured jets is suppressed, as confirmed by experiment, however this falls out in the *normalised* definition Eq. (1).

Figure 1b depicts medium-induced radiation that is emitted inside the jet cone. Even though these emissions are rare, $O(\alpha_s)$, their energies are in the relevant range for the measurement since $\hat{q}L^2 \sim 100$ GeV. Taking into account the constraint on a minimal resolution angle, $R_0 \geq 0.1$ one should be sensitive to these emissions in jets with $p_{\rm T} \sim 100 - 200$ GeV. The medium-induced splitting function is given by $\mathcal{P}_{\rm med}(z_g,\theta) = 2\theta\, P_{\rm br}(\theta)\, {\rm d}I_{\rm med}/{\rm d}z_g$, where, as for the vacuum splitting, we have assumed that energy loss is coherent and therefore does not affect the observables. The spectrum ${\rm d}I_{\rm med}/{\rm d}z$ is the spectrum of medium-induced emissions [12, 13] and the factor $P_{\rm br}(\theta)$ accounts for their diffusive broadening, see [3] for details. The medium-induced emission are infrared enhanced, for instance ${\rm d}I_{\rm med}/{\rm d}z \propto z^{-3/2}$ for the BDMPS-Z spectrum, compared to the vacuum.

However, because of the collinear safety of the BDMPS-Z spectrum no Sudakov form factor is to be associated with it in the collinear limit. Thus, to derive the formula for the splitting probability, we start out with the leading order formula that corresponds to the incoherent sum of the vacuum and BDMSP-Z splitting functions. While the BDMPS-Z spectrum at small angles is regular, the vacuum part contains a collinear singularity that requires the resummation of large collinear logs leading to a Sudakov form factor. The final formula for the splitting probability ($z_g < 1/2$) for coherent jets in heavy-ion collisions then reads

$$p(z_g) = \int_0^R {\rm d}\theta\, \Delta(R,\theta)\mathcal{P}_{\rm vac}(z_g,\theta)\Theta\left(z_g - z_{\rm cut}\theta^\beta\right)\left[1 - \int_0^R {\rm d}\theta \int_{z_{\rm cut}\theta^\beta}^{1/2} {\rm d}z\, \mathcal{P}_{\rm med}(z,\theta)\right] + \int_0^R {\rm d}\theta\, \mathcal{P}_{\rm med}(z_g,\theta)\Theta\left(z_g - z_{\rm cut}\theta^\beta\right), \quad (4)$$

where $R_0 \to 0$ to increase the readability of the formula. Corrections to Eq. (4) are sub-leading in the leading-log approximation. A few remarks are in order. The first and second terms correspond to the the probability for the two subjets to be formed by a vacuum or a medium-induced splitting, respectively. Now, in order for the measured hard splitting to be vacuum-like, one has to ensure that no rare medium-induced splitting had occurred earlier. This is accounted for by the suppression factor in the square-brackets in the first term that corresponds to the probability of no medium-induced radiation at leading order. As a result, the medium-modified splitting function $p(z_g)$, given by Eq. (4), is properly normalised as a probability.

We have plotted the ratio of the *normalised* medium-modified splitting function (4) to the vacuum one

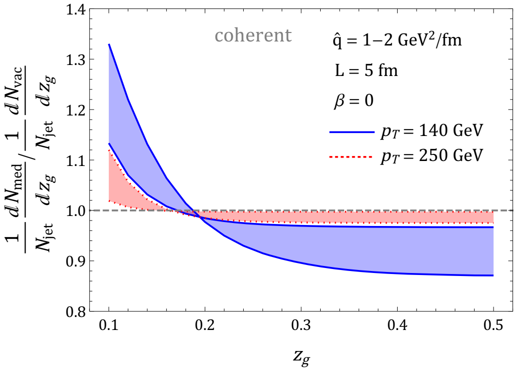

Fig. 2: (Color online) The ratio of normalised z_g-distributions in Pb-Pb and pp collisions for $p_{\rm T} = 140$ GeV (full lines) and $p_{\rm T} = 250$ GeV (dashed lines). The shaded area between the pairs of curves accounts for the variation of $\hat{q}$.

(1) in Fig. 2 (normalisation to the number of jets). We have considered a static medium of length $L = 5$ fm, which is close to the average path-length of jets traversing the medium at LHC, and characterised by a constant transport parameter in the range $\hat{q} = 1 - 2$ GeV^2/fm, that gauges the uncertainty on the medium parameter, and used $\alpha_s = 0.3$. Finally, we set $R = 0.3$ and replace $R_0 = 0.1$ as in the experimental data. Note that one-pronged jets are discarded in the experimental procedure, hence the distribution in Fig. 2 is self-normalised. We observe an enhancement for small-z_g for intermediate-$p_{\rm T}$ jets. These additional emissions would also lead to a modest enhancement of the two-prong probability, cf. Eq. (3) [3]. It is also interesting to consider effects of energy-loss beyond the coherent scenario considered here, which lead to strong suppression of two-pronged structures and could modify the splitting. This indicates that jet substructure measurements are potentially sensitive to medium-modifications.

Acknowledgements: KT has been supported by a Marie Skłodowska-Curie Individual Fellowship of the European Commission's Horizon 2020 Programme under contract number 655279 ResolvedJetsHIC.

References

[1] G. P. Salam, Towards Jetography, Eur.Phys.J. C67 (2010) 637–686. arXiv:0906.1833, doi:10.1140/epjc/s10052-010-1314-6.
[2] S. Sapeta, QCD and Jets at Hadron Colliders, Prog. Part. Nucl. Phys. 89 (2016) 1–55. arXiv:1511.09336, doi:10.1016/j.ppnp.2016.02.002.
[3] Y. Mehtar-Tani, K. Tywoniuk, Groomed jets in heavy-ion collisions: sensitivity to medium-induced bremsstrahlungarXiv:1610.08930.
[4] 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.
[5] A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft Drop, JHEP 05 (2014) 146. arXiv:1402.2657, doi:10.1007/JHEP05(2014)146.
[6] 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.
[7] C. Collaboration, Splitting function in pp and PbPb collisions at 5.02 TeV.
[8] 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.
[9] J. Casalderrey-Solana, D. Pablos, K. Tywoniuk, Two-gluon emission and interference in a thin QCD medium: insights into jet formation, JHEP 11 (2016) 174. arXiv:1512.07561, doi:10.1007/JHEP11(2016)174.
[10] Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Anti-angular ordering of gluon radiation in QCD media, Phys.Rev.Lett. 106 (2011) 122002. doi:10.1103/PhysRevLett.106.122002.
[11] Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Jets in QCD Media: From Color Coherence to Decoherence, Phys.Lett. B707 (2012) 156–159. doi:10.1016/j.physletb.2011.12.042.
[12] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, D. Schiff, Radiative energy loss of high-energy quarks and gluons in a finite volume quark - gluon plasma, Nucl.Phys. B483 (1997) 291–320. doi:10.1016/S0550-3213(96)00553-6.
[13] B. Zakharov, Fully quantum treatment of the Landau-Pomeranchuk-Migdal effect in QED and QCD, JETP Lett. 63 (1996) 952–957. doi:10.1134/1.567126.