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Medium-modified fragmentation of b-jets tagged by a leading muon in ultrarelativistic heavy ion collisions

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Abstract. The possibility to observe the medium-modified fragmentation of hard b quarks tagged by a leading muon in ultrarelativistic heavy ion collisions is analyzed. We have found that reasonable statistics, $\sim 10^4$ events per 1 month of LHC run with lead beams, can be expected for the realistic geometrical acceptance and kinematic cuts. The numerical estimates on the effect of the medium-induced softening b-jet fragmentation function are given.

1 Introduction

The experimental investigation of ultrarelativistic nuclear collisions offers a unique possibility of studying the properties of strongly interacting matter at a high energy density. In that regime the hadronic matter is expected to become deconfined and a gas of asymptotically free quarks and gluons is formed. This is a quark–gluon plasma (QGP), in which the color interactions between the partons are screened owing to collective effects [1]. One of the important tools to study QGP properties in heavy ion collisions is a QCD jet production. Medium-induced energy loss of energetic partons, the so-called jet quenching, has been proposed to be very different in cold nuclear matter and in QGP, resulting in many challenging observable phenomena [2]. Recent RHIC data on suppression of inclusive high-p_{T} charge and neutral hadron production from STAR [3], PHENIX [4], PHOBOS [5] and BRAHMS [6] are in agreement with the jet quenching hypothesis [7]. However direct event-by-event reconstruction of jets and their characteristics is not available in RHIC experiments at the moment, while the assumption that the integrated yield of all high-p_{T} particles originates only from the jet fragmentation is not obvious.

At LHC a new regime of heavy ion physics will be reached at $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$ where hard and semi-hard QCD multi-particle production can dominate over underlying soft events. The initial gluon densities in Pb–Pb reactions at LHC are expected to be significantly higher than at RHIC, implying a stronger partonic energy loss which can be observable in various new channels [8–10]. In particular, the influence of the medium-modified fragmentation of heavy quarks on dilepton spectra was analyzed in [11–13]. Since the estimated event rates for b quark production at LHC energies are expected to be high enough, in combination with high-p_{T} jet production by gluon and light quark fragmentation this can give important information about the medium-induced effects for both light and heavy partons in nucleus–nucleus interactions at the LHC.

In a previous paper [14] we analyzed the possibility to observe the medium-induced softening jet fragmentation function (JFF) of light partons tagged by a leading neutral or charged hadron in heavy ion collisions at the LHC. In this paper the possibility to measure the medium-modified b-JFF by a leading muon is suggested and analyzed for LHC conditions. In Sect. 2 we give the main definitions of JFF, calculate the cross section of $B(\to \text{leading } \mu)$ production at LHC energies with the PYTHIA generator and estimate the expected event rate for the realistic geometrical acceptance and kinematic cuts. Section 3 briefly describes a model of partonic energy loss in QGP used to evaluate the sensitivity of b-JFF to the jet quenching effect. A discussion of numerical results and a summary can be found in Sect. 4.

2 $B(\to$ leading $\mu)$ production at LHC

Let us recall that the jet fragmentation function $D(z)$ determines the probability for a final “jet-induced” particle to carry a fraction z of the jet transverse momentum $p_{\mathrm{T}}^{\mathrm{jet}}$. In nuclear AA interactions JFF for leading particles can be defined as [14]

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$$D(z) = \int\limits_{z\cdot p_{\mathrm{T\,min}}^{\mathrm{jet}}} \mathrm{d}(p_{\mathrm{T}}^{\mathrm{L}})^2 \mathrm{d}y \mathrm{d}z' \frac{\mathrm{d}N_{AA}^{\mathrm{h(k)}}}{\mathrm{d}(p_{\mathrm{T}}^{\mathrm{L}})^2 \mathrm{d}y \mathrm{d}z'} \delta\left(z - \frac{p_{\mathrm{T}}^{\mathrm{L}}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right) \Bigg/ \int\limits_{p_{\mathrm{T\,min}}^{\mathrm{jet}}} \mathrm{d}(p_{\mathrm{T}}^{\mathrm{jet}})^2 \mathrm{d}y \frac{\mathrm{d}N_{AA}^{\mathrm{jet(k)}}}{\mathrm{d}(p_{\mathrm{T}}^{\mathrm{jet}})^2 \mathrm{d}y} , \qquad (1)$$

where $p_{\mathrm{T}}^{\mathrm{L}} \equiv z p_{\mathrm{T}}^{\mathrm{jet}} = z' p_{\mathrm{T}}$ is the leading particle transverse momentum, z' is the momentum fraction relatively to p_{T} of the parent parton (of course, without energy loss $z = z'$ in the leading order of perturbative QCD), and $p_{\mathrm{T\,min}}^{\mathrm{jet}}$ is the minimum threshold for energy of observable jets. The rate of k-type jets in mid-rapidity with transverse momentum p_{T} in AA collisions at the given impact parameter b is estimated as

$$\frac{\mathrm{d}N_{AA}^{\mathrm{jet(k)}}}{\mathrm{d}(p_{\mathrm{T}}^{\mathrm{jet}})^2 \mathrm{d}y}(b) = \int\limits_0^{2\pi} \mathrm{d}\psi \int\limits_0^{r_{\max}} r \mathrm{d}r \times T_A(r_1) T_A(r_2) \frac{\mathrm{d}\sigma^{\mathrm{jet(k)}}(p_{\mathrm{T}}^{\mathrm{jet}} + \Delta p_{\mathrm{T}}^{\mathrm{jet}}(r,\psi,\theta_0))}{\mathrm{d}p_{\mathrm{T}}^2 \mathrm{d}y}, \qquad (2)$$

and is determined by the absolute value of partonic energy loss as well as by the angular radiation spectrum. Here $r_{1,2}(b,r,\psi)$ are the distances between the nucleus centers and the jet production vertex $V(r\cos\psi, r\sin\psi)$; $r_{\max}(b,\psi) \leq R_A$ is the maximum possible transverse distance r from the nuclear collision axis to the V; R_A is the radius of the nucleus A; $T_A(r_{1,2})$ is the nuclear thickness function (see [15] for detailed nuclear geometry explanations). The effective shift $\Delta p_{\mathrm{T}}^{\mathrm{jet}}(r,\psi,\theta_0)$ of the jet momentum spectrum depends on the jet angular cone size θ_0 (see Fig. 1). In the leading order of perturbative QCD the jet production cross section, $\mathrm{d}\sigma^{\mathrm{jet(k)}}/(\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y)$, is calculated in our case with PYTHIA6.2 [16]. The rate of high-p_{T} jet-induced hadrons is estimated as

$$\frac{\mathrm{d}N_{AA}^{\mathrm{h(k)}}}{\mathrm{d}(p_{\mathrm{T}}^{\mathrm{L}})^2 \mathrm{d}y \mathrm{d}z'}(b) = \int\limits_0^{2\pi} \mathrm{d}\psi \int\limits_0^{r_{\max}} r \mathrm{d}r \times T_A(r_1) T_A(r_2) \frac{\mathrm{d}\sigma^{\mathrm{jet(k)}}(p_{\mathrm{T}} + \Delta p_{\mathrm{T}}(r,\psi))}{\mathrm{d}p_{\mathrm{T}}^2 \mathrm{d}y} \frac{1}{z'^2} \times D_k^h(z', p_{\mathrm{T}}^2) , \qquad (3)$$

where the shift Δp_{T} of the hadron momentum distribution generally is not equal to the mean in-medium partonic energy loss due to the steep fall-off of the p_{T}-spectrum [17].

For jets initiated by light hadrons, the leading particles are the charged or neutral hadrons. However for heavy quark initiated jets there is the possibility to have a leading muon produced by semileptonic meson decays. Thus a jet tagged by a high-p_{T} muon can be identified as a heavy quark jet. Note that $\approx 20\%$ of the B-mesons and $\approx 12\%$ of the D-mesons decay to muons, about half of the muons from B-decays being produced through an intermediate D [18].

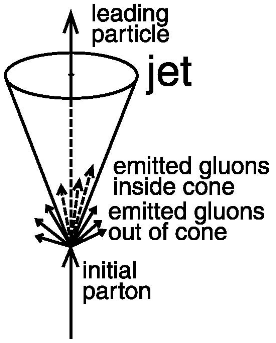

Fig. 1. The schematic view of a jet with gluons emitted inside and outside the jet cone

We used PYTHIA6.2 [16] with CTEQ5L pdf parameterization to calculate the cross section of b-jet production and the corresponding spectra at $\sqrt{s_{\mathrm{pp}}} = 5.5\,\mathrm{TeV}$ and to estimate the expected event rate for the realistic geometrical acceptance and kinematic cuts. To be specific, the geometry of Compact Muon Solenoid (CMS) detector is considered [19,20]: the pseudo-rapidity coverage $\mid \eta \mid < 3$ for jets and $\mid \eta \mid < 2.4$ for muons. We define the muon as a leading particle if it belongs to a hard jet and carries more than 20% of the jet transverse momentum. To be specific, the jet energy is determined here as the total transverse energy of the final particles collected around the direction of a leading particle inside the cone $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} = 0.5$, where η and φ are the pseudo-rapidity and the azimuthal angle respectively. Extra cuts $p_{\mathrm{T}}^{\mu} > 5\,\mathrm{GeV}/c$ and $E_{\mathrm{T}}^{\mathrm{jet}} > 50\,\mathrm{GeV}$ were applied. Then the corresponding pp cross section for $B(\rightarrow$ leading $\mu)$ production is $\approx 0.7\,\mathrm{pb}$, and the Pb–Pb cross section is estimated as $0.7\,\mathrm{pb} \times (207)^2 \approx 0.03\,\mathrm{mb}$. The corresponding event rate in a 1 month Pb–Pb run (assuming 15 days of data taking), $H = 1.3 \times 10^6\,\mathrm{s}$, with luminosity $L = 5 \times 10^{26}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, is $N_{\mathrm{ev}} = H\sigma_{\mathrm{PbPb}}L \approx 2 \times 10^4$ in this case. Increasing the minimal jet energy results in reducing the expected statistics, e.g. for $E_{\mathrm{T}}^{\mathrm{jet}} > 100\,\mathrm{GeV}$ the estimated rate is only $\sim 10^3$ events.

3 The model for simulation of jet quenching

In order to test the sensitivity of b-JFF to the jet quenching, the following event-by-event Monte Carlo simulation procedure was applied (see [15,21] for details of the model).

- Generation of the initial parton spectra with PYTHIA (fragmentation *off*).
- Generation of the jet production vertex at the impact parameter b according to the distribution

$$\frac{\mathrm{d}N^{\mathrm{jet}}}{\mathrm{d}\psi \mathrm{d}r}(b) = \frac{T_A(r_1)T_A(r_2)}{\int\limits_0^{2\pi} \mathrm{d}\psi \int\limits_0^{r_{\max}} r\mathrm{d}r T_A(r_1)T_A(r_2)} . \qquad (4)$$

- Calculation of the cross section $\sigma = \int \mathrm{d}t \mathrm{d}\sigma/\mathrm{d}t$ for scattering of a parton with energy E off the "thermal" partons with energy (or effective mass) $m_0 \sim 3T \ll E$ (T is the medium temperature) and generation of the transverse momentum transfer t_i according to the distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \cong C \frac{2\pi\alpha_{\mathrm{s}}^2(t)}{t^2} \frac{E^2}{E^2 - m_q^2} \ ,$$
$$\alpha_{\mathrm{s}} = \frac{12\pi}{(33 - 2N_f)\ln(t/\Lambda_{\mathrm{QCD}}^2)} \ . \tag{5}$$

  Here $C = 9/4, 1, 4/9$ for gg, gq and qq scatterings respectively, α_{s} is the QCD running coupling constant for N_f active quark flavors, and Λ_{QCD} is the QCD scale parameter which is of the order of the critical temperature, $\Lambda_{\mathrm{QCD}} \simeq T_{\mathrm{c}} \simeq 200\,\mathrm{MeV}$. The integrated cross section σ is regularized by the Debye screening mass squared $\mu_D^2(T) \simeq 4\pi\alpha_{\mathrm{s}}T^2(1 + N_f/6)$. The maximum momentum transfer $t_{\max} = [s - (m_q + m_0)^2][s - (m_q - m_0)^2]/s$, where $s = 2m_0E + m_0^2 + m_q^2$, and m_q is the hard parton mass.
- Generation of the transverse distance between scatterings, $l_i = (\tau_{i+1} - \tau_i)p_{\mathrm{T}}/E$:

$$\frac{\mathrm{d}P}{\mathrm{d}l_i} = \lambda^{-1}(\tau_{i+1}) \exp\left(-\int_0^{l_i} \lambda^{-1}(\tau_i + s)\mathrm{d}s\right) \ ,$$
$$\lambda^{-1}(\tau) = \sigma(\tau)\rho(\tau) \ , \tag{6}$$

  where τ is the proper time, λ is the in-medium mean free path, and $\rho \propto T^3$ is the medium density.
- Reducing the parton energy by collisional and radiative loss per scattering i:

$$\Delta E_{\mathrm{tot},i} = \Delta E_{\mathrm{col},i} + \Delta E_{\mathrm{rad},i} \ , \tag{7}$$

  where the collisional part is calculated in the high-momentum transfer approximation,

$$\Delta E_{\mathrm{col},i} = \frac{t_i}{2m_0} \ , \tag{8}$$

  and the radiative part is generated according to the energy spectrum $\mathrm{d}I/\mathrm{d}\omega$ obtained in the frame of BDMS model [22] generalized to the case of heavy quarks – the "dead cone" approximation [23] (but note there are more recent developments on heavy quark energy loss in the literature [24,25]):

$$\left.\frac{\mathrm{d}I}{\mathrm{d}\omega}\right|_{m_q \neq 0} = \frac{1}{(1 + (l\omega)^{3/2})^2} \left.\frac{\mathrm{d}I}{\mathrm{d}\omega}\right|_{m_q = 0} \ ,$$
$$l = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3} \left(\frac{m_q}{E}\right)^{4/3} \ , \tag{9}$$

$$\left.\frac{\mathrm{d}I}{\mathrm{d}\omega}\right|_{m_q = 0} = \frac{2\alpha_{\mathrm{s}}(\mu_D^2)\lambda C_R}{\pi L\omega} \left[1 - y + \frac{y^2}{2}\right] \times \ln\left|\cos(\omega_1\tau_1)\right| \ , \tag{10}$$

$$\omega_1 = \sqrt{\mathrm{i}\left(1 - y + \frac{C_R}{3}y^2\right)\bar{\kappa}\ln\frac{16}{\bar{\kappa}}} \quad \text{with} \quad \bar{\kappa} = \frac{\mu_D^2\lambda_g}{\omega(1 - y)} \ , \tag{11}$$

  where $\tau_1 = L/(2\lambda_g)$, $y = \omega/E$ is the fraction of the hard parton energy carried by the radiated gluon, and $C_R = 4/3$ is the quark color factor. A similar expression for the gluon jet can be obtained by substituting $C_R = 3$ and a proper change of the factor in the square bracket in (10); see [22]. The allowed range of values $\omega_i = \Delta E_{\mathrm{rad},i}$ in (10) is from $\omega_{\min} = E_{\mathrm{LPM}} = \mu_D^2\lambda_g$, the minimal radiated gluon energy in the coherent LPM regime, to the initial jet energy E.
- Calculation of the parton transverse momentum kick due to elastic scattering i:

$$\Delta k_{t,i}^2 = \left(E - \frac{t_i}{2m_{0i}}\right)^2 - \left(p - \frac{E}{p}\frac{t_i}{2m_{0i}} - \frac{t_i}{2p}\right)^2 - m_q^2. \tag{12}$$

- Formation of the additional (in-medium emitted) gluon with the energy $\omega_i = \Delta E_{\mathrm{rad},i}$ and the direction relatively to the parent parton determined according to one of two possible simple parameterizations for the emission angle θ: the "small-angular" parameterization,

$$\frac{\mathrm{d}N^g}{\mathrm{d}\theta} \propto \sin\theta \exp\left(-\frac{(\theta - \theta_0)^2}{2\theta_0^2}\right) \ , \tag{13}$$

  where $\theta_0 \sim 5^0$ is the typical angle of the coherent gluon radiation estimated in [26]; or the "wide-angular" parameterization,

$$\frac{\mathrm{d}N^g}{\mathrm{d}\theta} \propto \frac{1}{\theta} \ . \tag{14}$$

- Halting the parton rescattering if (1) a parton escapes from the dense zone, or (2) QGP cools down to $T_{\mathrm{c}} = 200\,\mathrm{MeV}$, or (3) a parton loses so much energy that its $p_{\mathrm{T}}(\tau)$ drops below $2T(\tau)$.
- In the end of each event adding new (in-medium emitted) gluons into the PYTHIA parton list and rearrangements of partons to update string formation are performed.
- Formation of the final particles by PYTHIA (fragmentation *on*).

The medium was treated as a boost-invariant longitudinally expanding quark–gluon fluid, and partons as being produced on a hyper-surface of equal proper times τ [27]. In order to simplify numerical calculations in the original version of the model we omit the transverse expansion and viscosity of the fluid using the well-known scaling solution due to Bjorken [27] for a temperature and density of QGP at $T > T_{\mathrm{c}} \simeq 200$ MeV:

$$\varepsilon(\tau)\tau^{4/3} = \varepsilon_0\tau_0^{4/3},$$
$$T(\tau)\tau^{1/3} = T_0\tau_0^{1/3},$$
$$\rho(\tau)\tau = \rho_0\tau_0. \tag{15}$$

For certainty we used the initial conditions for the gluon-dominated plasma formation expected for central Pb–Pb collisions at LHC [28]:

$$\tau_0 \simeq 0.1\,\mathrm{fm}/c, \quad T_0 \simeq 1\,\mathrm{GeV}, \quad \rho_g \approx 1.95T^3 \ .$$

4 Numerical results and conclusions

Figure 2 shows the b-JFF (1) of leading muons for the cases without and with medium-induced energy loss in central Pb–Pb collisions with the two parameterizations of the distribution on the gluon emission angles (13) and (14); the same geometrical acceptance and kinematic cuts as described in Sect. 2 were used. One can see the softening b-JFF due to partonic energy loss at $z \gtrsim 0.4$. The effect enhances with z decreasing (see Fig. 3) and is more pronounced for the small-angular radiation. The reason for the latter fact is the following. The contribution of the small-angular radiation to the total jet energy loss (due to "out-of-cone" partonic energy loss) is much less as compared with the broad-angular radiation. The former does not disappear totally mostly because not only the leading (parent) parton, but all partons of a jet pass through the dense medium and emit gluons under the angles θ relatively to their proper directions, which in general may not coincide with the jet axis (determined by the direction of a leading particle) and sometimes be even at the jet periphery. The broad-angular radiation increases the "out-of-cone" part of partonic energy loss and thus decreases the final jet transverse momentum $p_{\mathrm{T}}^{\mathrm{jet}}$ (which is the denominator in the definition of $z \equiv p_{\mathrm{T}}^{\mathrm{L}}/p_{\mathrm{T}}^{\mathrm{jet}}$ in JFF; see (1)) without any influence on the numerator of z and, as a consequence, in reducing effect on JFF softening.

Note that in the real experimental situation the jet observables will be sensitive to the accuracy of the jet energy reconstruction in a high multiplicity environment, in particular, to the systematic jet energy loss. However, since the average reconstructed jet energy in Pb–Pb collisions is expected to be the same as in pp interactions (see the section "Jet detection at CMS" in [8]), the short measure of the jet energy will be the well-controlled systematic error for heavy ion as well for pp collisions, and it can be taken into account using the standard calibration procedure.

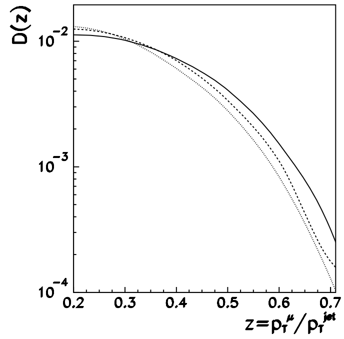

Fig. 2. B-jet fragmentation function for leading muons without (solid curve) and with medium-induced partonic energy loss for the "small-angular" (13) (dotted curve) and the "broad-angular" (14) (dashed curve) parameterizations of emitted gluon spectrum in central Pb–Pb collisions. Applied kinematic cuts are described in the text

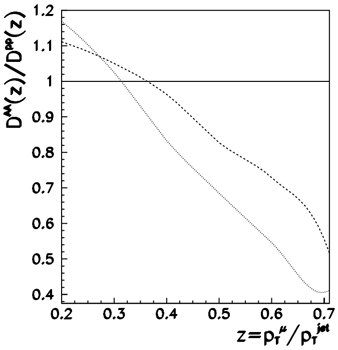

Fig. 3. The ratio of B-jet fragmentation function for leading muons with energy loss to one without energy loss in central Pb–Pb collisions. The dotted curve is the result for the "small-angular" radiation, the dashed curve is for the "broad-angular" radiation. Applied kinematics cuts are described in the text

In summary, the channel with the muon tagged b-jet production in ultrarelativistic heavy ion collisions was first analyzed. Reasonable statistics, $\sim 10^4$ events per 1 month of LHC run with lead beams, can be expected for the realistic geometrical acceptance and kinematic cuts. The effect on the medium-modified b-jet fragmentation was numerically studied for Pb–Pb collisions at the LHC. A significant softening b-jet fragmentation function determined by the absolute value of partonic energy loss and the angular radiation spectrum is predicted.

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