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Medium effects for hadron-tagged jets in proton-proton collisions

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The observations at RHIC and the LHC in AA collisions of the transverse flow effects and the strong suppression of high-p_T hadron spectra (jet quenching) give evidence of the quark-gluon plasma (QGP) formation in AA collisions (for reviews see, e.g., [1–3]). The results of hydrodynamic analyses of the flow effects support that the QGP is formed at the proper time $\tau_0 \sim 0.5 - 1\,\mathrm{fm}$ [1, 2]. The observation of the ridge effect [4, 5] in pp collisions at the LHC energies, suggests that a mini QGP (mQGP) can be created in pp collisions as well. This is also supported by the steep growth of the midrapidity strange particle production at charged multiplicity $dN_{ch}/d\eta \sim 5$ [6]. This agrees with the onset of the QGP regime at $dN_{ch}/d\eta \sim 6$, found in [7] from behavior of $\langle p_T \rangle$ as a function of multiplicity, employing van Hove's arguments that the phase transition should lead to an anomalous multiplicity dependence of $\langle p_T \rangle$. These estimates of the critical multiplicity density for the onset of the mQGP formation regime are smaller than the typical midrapidity charged multiplicity of the soft (underlying-event (UE)) hadrons for jet events in pp collisions at the LHC energies – $dN_{ch}/d\eta \sim 10$–15 (it is bigger than the ordinary minimum bias multiplicity by a factor of ~ 2–2.5 [8]).

The mQGP formation in pp collisions should lead to some jet modification. However, one can expect that the quenching effects in pp collisions should be significantly smaller than in heavy ion collisions due to lower temperature of the mQGP and due to strong reduction of the induced gluon emission for a small size fireball. The latter is closely related to the anomalously strong L-dependence of the radiative parton energy loss, ΔE_r, in a finite-size QCD matter [9] (as compared to predictions of the Bethe–Heitler formula). Fixed coupling calculations without the Coulomb effects within the BDMPS approach [9] give $\Delta E_r \propto L^2$ for a static QGP, and $\Delta E_r \propto L$ [10] for an expanding QGP with entropy density $s \propto 1/\tau$ (as in the Bjorken model with purely longitudinal expansion of the QGP). The linear L-dependence of ΔE_r for an expanding QGP remains approximately valid also for calculations with accurate treatment of the Coulomb effects with running α_s [11]. Calculations of the medium modification factor R_{pp} (which is not directly observable quantity) within the light-cone path integral (LCPI) approach [12] with accurate treatment of the Coulomb effects and running α_s give a small deviation of R_{pp} from unity at the LHC energies [13] ($R_{pp} \sim 0.8$ at $p_T \sim 10\,\mathrm{GeV}$). For this reason observation of jet quenching in pp collisions via a weak modification of the p_T-dependence of hadron spectra is practically impossible. A promising observable for quenching effects in pp collisions is the variation with the UE activity of the medium modification factor I_{pp} for the photon-tagged jet fragmentation functions (FFs) [14]. However, this measurement requires high statistics due to a very small cross section. This problem is absent for the modification factor I_{pp} for the hadron-tagged jets. The medium modification factor I_{pp} for the di-hadron production in pp collisions can be written similarly to AA collisions [15]

$$I_{pp}(p_T^a, p_T^t, y^a, y^t) = \frac{Y_m^{pp}(p_T^a, p_T^t, y^a, y^t)}{Y_v^{pp}(p_T^a, p_T^t, y^a, y^t)}\,, \qquad (1)$$

where $p_T^{a,t}$ and $y^{a,t}$ are the transverse momenta and rapidities of the trigger (h^t) and the associated (h^a) hadrons, Y_m^{pp} is the per-trigger yield accounting the medium effects, and Y_v^{pp} is the per-trigger yield calculated ignoring the medium effects. The per-trigger yields (similarly to AA collisions [15]) can be written in terms of the di-hadron (back-to-back) and one-hadron inclusive cross sections as

$$Y_{m,v}^{pp}(p_T^a, p_T^t, y^a, y^t) = \frac{d^4\sigma_{m,v}}{dp_T^a dp_T^t dy^a dy^t} \Big/ \frac{d^2\sigma_{m,v}}{dp_T^t dy^t}\,. \qquad (2)$$

Of course, the denominator in (1) is unobservable. But one can study the UE multiplicity dependence of I_{pp}, say, by using the ratio of the per-trigger yield to its minimum bias value. Because we can reasonably expect that the UE multiplicity dependence of the numerator

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and the denominator of (2) for Y_v^{pp} is very similar, and consequently $Y_v^{pp}/\langle Y_v^{pp}\rangle \approx 1$. Then we have

$$\frac{I_{pp}(p_T^a, p_T^t, y^a, y^t)}{\langle I_{pp}(p_T^a, p_T^t, y^a, y^t)\rangle} \approx \frac{Y_m^{pp}(p_T^a, p_T^t, y^a, y^t)}{\langle Y_m^{pp}(p_T^a, p_T^t, y^a, y^t)\rangle}\,. \qquad (3)$$

This relation allows one to study the multiplicity dependence of I_{pp} by measuring the per-trigger yield (which corresponds to the theoretical Y_m^{pp}). Recently, this method has been used by ALICE [16] in the first measurement of the variation of I_{pp} with the UE multiplicity for the hadron-tagged jets for 5.02 TeV pp collisions (for the trigger hadron momentum $8 < p_T^t < 15$ GeV, and the associated away side hadron momentum $4 < p_T^a < 6$ GeV). It was found that I_{pp} decreases monotonically by about 15 % with increase of the UE activity in the range $5 \lesssim dN_{ch}/d\eta \lesssim 20$ (we use $dN_{ch}/d\eta$ for the whole range of the azimuthal angle ϕ and the transverse momentum which is bigger by a factor of ~ 4.4 than the transverse side charged multiplicity N_{ch}^{TS} of [16] for the kinematic region $\pi/3 \le |\phi| \le 2\pi/3$, $|\eta| < 0.8$, and $p_T > 0.5$ GeV). Such a decrease of I_{pp} agrees qualitatively with the quenching effect obtained in [14] for the jet energy $E = 25$ GeV (which is of the order of the jet energy for the ALICE trigger particle momentum region [16]). For drawing a more definitive conclusion on whether the ALICE data [16] on I_{pp} may be consistent with jet quenching in the mQGP, it is of course highly desirable to perform calculations of I_{pp} for hadron-tagged jets accounting for the jet energy fluctuations and the quenching effects for both the back-to-back jets. In the present paper, we carry out such calculations of I_{pp} for hadron-tagged jets for conditions of the ALICE experiment [16] within the LCPI approach [12] to the induced gluon emission. We use the parametrization of the running QCD coupling $\alpha_s(Q,T)$ which has a plateau around $Q \sim \kappa T$ (motivated by the lattice calculations of the effective QCD coupling in the QGP [17]). We use the value of κ fitted in [13] to the LHC heavy ion data on the nuclear modification factor R_{AA}. We find that the theoretical predictions with no free parameters for the multiplicity dependence of the ratio $I_{pp}/\langle I_{pp}\rangle$ for 5.02 TeV pp collisions are in reasonable agreement with the recent preliminary data from ALICE [16]. The description of the data becomes better for the scenario with an incomplete thermalization of the matter at $dN_{ch}/d\eta \lesssim 10$. Our results show that the drop of the ratio $I_{pp}/\langle I_{pp}\rangle$ with the UE multiplicity, if confirmed by further measurements, may be viewed as the first direct evidence for the jet quenching in pp collisions.

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