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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 $\sim 2{-}2.5$ [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, $\Delta E_r$, 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 $\Delta E_r$ for an expanding QGP remains approximately valid also for calculations with accurate treatment of the Coulomb effects with running $\alpha_s$ [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 $\alpha_s$ 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

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

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 $\phi$ and the transverse momentum which is bigger by a factor of $\sim 4.4$ 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 $\kappa$ 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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