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FIELDS, PARTICLES, AND NUCLEI

Jet Quenching in Mini-Quark–Gluon Plasma: Medium Modification Factor I_{pA} for Photon-Tagged Jets

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We calculate the medium modification factor I_{pA} for the photon-tagged jet fragmentation functions for scenario with the quark–gluon plasma formation in pA and pp collisions. We perform calculations of radiative and collisional parton energy loss in the quark–gluon plasma with running α_s which has a plateau around $Q \sim \kappa T$ with κ fitted to the LHC data on the heavy ion R_{AA}. We find that the theoretical predictions for I_{pA} in 5.02 TeV p + Pb collisions are within errors consistent with the data from ALICE [1]. However, a definite conclusion about the presence or absence of jet quenching in pA collisions cannot be drawn due to large experimental errors of the ALICE data [1]. Our calculations show that this requires a significantly more accurate measurement of I_{pA}.

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INTRODUCTION

Heavy ion collision experiments at RHIC and the LHC led to the discovery of the Quark–Gluon Plasma (QGP) formation in AA collisions. The most striking manifestations of the QGP formation in AA collisions are the transverse flow effects in the azimuthal correlations for soft hadrons and the strong suppression of high-p_T hadron spectra (jet quenching). Hydrodynamic analyses of soft hadron production in AA collisions show that the QCD matter produced in AA collisions flows almost as a perfect fluid (for reviews, see, e.g., [2, 3]). Jet quenching in AA collisions is due to radiative and collisional energy loss of fast partons in the hot QGP. The dominant contribution to the parton energy loss comes from the radiative mechanism due to induced gluon radiation [4–9]. The available data from RHIC and the LHC on the nuclear modification factor R_{AA} of hadron spectra in AA collisions can be described in the pQCD picture of parton energy loss for the QGP formation time $\tau_0 \sim 0.5$–1 fm (see, e.g., [10–12]) that is roughly consistent with the results of hydrodynamical analyses of experimental data on AA collisions [13].

In recent years, the azimuthal correlations in soft hadron production (the ridge effect), similar to that observed in AA collisions, have been observed in pp/pA collisions. The formation of a mini QGP (mQGP) fireball is the most popular explanation of the ridge/flow effects in pp/pA collisions (for a review, see [14]). There are several experimental evidences supporting the onset of the mQGP regime in pp/pA collisions at the charged hadron multiplicity density $dN_{ch}/d\eta \gtrsim 5$ [15, 16]. It is important that, from the point of view of the multiplicity density, conditions for the mQGP formation in pp/pA collisions are more favorable for events with jet production. Because in jet events the average multiplicity density of soft (underlying-event (UE)) hadrons is larger than the minimum-bias multiplicity by a factor of ~2—2.5 [17]. At the LHC energies in pp jet events we have $dN_{ch}^{ue}/d\eta \sim 10$–15 (and by a factor of ~2–3 larger values for pA collisions), that seems to be large enough to expect the mQGP formation (in the light of the results of [15, 16]). In the scenario with the mQGP formation in pp / pA collisions, the jet quenching effects must appear. Similarly to AA collisions, they should modify the jet fragmentation functions (FFs) and hadron spectra in pp/pA collisions as compared to predictions of the standard pQCD. The recent ALICE [18] measurement of the jet FF modification factor I_{pp} for the hadron-tagged jets in pp collisions at $\sqrt{s} =$ 5.02 TeV seems to confirm the scenario with the mQGP formation and jet quenching in pp collisions, since the data [18] show a monotonic decrease of I_{pp} with the UE multiplicity expected for the scenario with the mQGP formation [19]. The results of [18] agree within errors with calculations of [20] in the framework of the light-cone path integral (LCPI) approach to induced gluon emission [6].

The first calculations of the medium modification factor R_{pp} for pp collisions were performed in [19, 21] within the LCPI formalism for induced gluon emission [6]. These calculations (and the more recent and accurate analysis [12]) show that R_{pp} is close to unity. The R_{pp} does not admit a direct measurement, but it modifies a little theoretical predictions for R_{AA}. However, in [12] it was demonstrated that the available data on R_{AA} can be described fairly well both in the scenarios with and without the mQGP formation in pp collisions. It is believed that measurement of the nuclear modification factor R_{pA} for high-p_T hadrons in pA collisions is a promising method for observation of jet quenching caused by the mQGP formation. R_{pA} is defined as the ratio of the pA spectrum to the binary scaled pp one, and, contrary to R_{pp}, it is a measurable quantity ($R_{pA} \neq 1$ even without the final state interaction effects, due to the difference between the nuclear parton distribution functions (PDFs) and the proton PDFs (which we denote by R_{pA}^{PDF})). It is reasonable to expect that for the scenario with the mQGP formation both in pA and pp collisions, jet quenching should be stronger in pA collisions, as a result the experimental $R_{pA}^{\exp}$ should be smaller than R_{pA}^{PDF}. The available experimental data [22–24] on R_{pA} are controversial: there is a significant discrepancy between data from CMS [22] for 5.02 TeV p + Pb collisions ($R_{p\mathrm{Pb}} \sim 1.1$–$1.19$ at $p_T \gtrsim 10$ TeV) and data from ALICE [23, 24] for 5.02 and 8.16 TeV p + Pb collision ($R_{p\mathrm{Pb}} \sim 0.9$–$1.1$). Calculations of [12, 25] show that the data from CMS [22] are clearly inconsistent with the scenario with the mQGP formation, but the data on $R_{p\mathrm{Pb}}$ from ALICE [23, 24] may be consistent with the mQGP formation (both in pp and p + Pb collisions).

Another way to probe the jet quenching effects in pA collisions is measurement of the medium modification factor I_{pA} for the photon-tagged FFs for γ + jet events. In analogy with the medium modification factor I_{AA} in AA collisions (see, e.g., [26, 27]), I_{pA}, for a given photon transverse momentum p_T^γ, is defined as the ratio

$$I_{pA}(z_T, p_T^\gamma) = D_h^{pA}(z_T, p_T^\gamma)/D_h^{pp}(z_T, p_T^\gamma), \quad (1)$$

where $D_h^{pA,pp}$ are the photon-tagged FFs of the away-side hard partons to the associate charged hadron h for pA and pp collisions, $z_T = p_T^h/p_T^\gamma$, and p_T^h is the hadron transverse momentum. Experimentally, the photon-tagged FF D_h is the away-side associated hadron yield per trigger photon. In terms of the inclusive cross sections, D_h reads

$$D_h(z_T, p_T^\gamma) = \frac{p_T^\gamma d^3\sigma}{dp_T^h dp_T^\gamma dy^\gamma}\left(\frac{d^2\sigma}{dp_T^\gamma dy^\gamma}\right)^{-1}. \quad (2)$$

The advantage of I_{pA} is that experimental D_h do not suffer from the uncertainties of the yield normalizations in pA/pp collisions (since both the numerator and the denominator in (2) are hard cross sections, and the normalization uncertainties are largely canceled in D_h). For the same reason, the theoretical I_{pA}, contrary to R_{pA}, is insensitive to uncertainties in the nuclear and proton PDFs.

Recently, the midrapidity I_{pA} has been measured by the ALICE collaboration [1] for 5.02 TeV p + Pb collisions for the trigger photon momentum $12 < p_T^\gamma < 40$ GeV. The ALICE measurement gives $\langle I_{pA}\rangle \approx 0.84 \pm 0.11(\mathrm{stat}) \pm 0.19(\mathrm{sys})$. The z_T-dependence of I_{pA} obtained in [1] has some tendency of I_{pA} towards decrease with increasing z_T. This pattern, at least roughly, is what is expected in the scenario with the mQGP formation. Of course, to understand better whether the results of [1] are consistent with the scenario with the mQGP formation in pp/pA collisions, quantitative calculations of I_{pA} for this scenario are necessary. In this paper, we perform calculations of I_{pA} for conditions of the ALICE experiment [1]. We use the LCPI approach [6] to induced gluon emission with temperature dependent α_s [28], which has successfully been used in our recent analysis [12] of the available data on the nuclear modification factor R_{AA}.

OUTLINE OF THE JET QUENCHING SCHEME FOR FRAGMENTATION FUNCTIONS

We treat the γ + jet process in leading order (LO) pQCD. In this approximation the transverse momentum of the hard parton, produced in the direction opposite to the direct photon, equals the photon transverse momentum. The higher order effects lead to fluctuation of the away side parton transverse momentum around p_T^γ. In [29], using the results of the NLO pQCD analysis of the direct photon production of [30], it was demonstrated that for the trigger photon momentum $p_T^\gamma \gtrsim 12$ GeV the smearing correction to the medium modification factor I_{AA} (which is $\propto dI_{AA}/dz/p_T^{\gamma 2}$) is very small at $z_T \lesssim 0.85$–0.9. Since the magnitude of the jet modification for pA collisions is considerably smaller than that in AA collisions, the effect of smearing on I_{pA} should also be smaller. This allows us to ignore the smearing correction to I_{pA} (except for z_T very close to unity).

In the LO pQCD, when the photon transverse momentum coincides with that for the away side parton, the photon-tagged jet FFs defined by (2) can be decomposed as

$$D_h(z_T, p_T^\gamma) = \sum_i r_i(p_T^\gamma) D_{h/i}(z_T, p_T^i), \quad (3)$$

where $D_{h/i}(z_T, p_T^i)$ is the FF for transition of the initial parton i with momentum $p_T^i = p_T^\gamma$ into the final hadron h, and r_i is the relative weight of the $\gamma + i$ state in the jet production. For scenario without the mQGP formation, $D_{h/i}$ in (3) is the ordinary vacuum FF, $D_{h/i}^v$, and for scenario with the mQGP formation $D_{h/i}$ is the medium modified FF, $D_{h/i}^m$ (averaged over the jet path length L in the mQGP). We calculate the hard parton cross sections with the CTEQ6 [31] PDFs (with the EPS09 correction [32] for the nuclear PDFs). For 5.02 TeV p + Pb collisions with the trigger conditions of the ALICE experiment [1] ($12 < p_T^\gamma < 40$ GeV), the dominating contribution to the pp and pA photon-tagged FFs given by (3) comes from the quark jets ($r_q/r_g \sim 20$).

As in [12], we calculate the medium-modified FFs $D_{h/i}^m$ using the triple z-convolution formula

$$D_{h/i}^m(Q) \approx D_{h/j}(Q_0) \otimes D_{j/k}^{\text{in}} \otimes D_{k/i}^{\text{DGLAP}}(Q), \quad (4)$$

where $D_{k/i}^{\text{DGLAP}}$ is the DGLAP FF for $i \to k$ transition, $D_{j/k}^{\text{in}}$ is the in-medium $j \to k$ FF, and $D_{h/j}$ describes vacuum hadronization transition of the parton j to hadron h. We calculate the vacuum FFs $D_{h/i}^v(z,Q)$ using (4) with dropped $D_{j/k}^{\text{in}}$. We use the KKP [33] parametrization for $D_{h/j}$ with $Q_0 = 2$ GeV. We calculate the DGLAP FFs $D_{k/i}^{\text{DGLAP}}$ using the PYTHIA event generator [34]. The medium dependence of $D_{h/i}^m$ given by (4) comes only from the in-medium FFs $D_{j/k}^{\text{in}}$. We calculate them from the one gluon spectrum in the approximation of the independent gluon emission [35]. As in [12], we account for collisional energy loss (which is relatively small [36]), by treating it as a perturbation to the radiative mechanism with the help of a renormalization of the mQGP temperature in calculating $D_{j/k}^{\text{in}}$. As in [12], we calculate $D_{j/k}^{\text{in}}$ for an effective symmetrical fireball with a uniform entropy/density distribution in the transverse plane. We have checked that for a small size QGP this approximation has a very good accuracy. In calculating $D_{j/k}^{\text{in}}$, the averaging over the jet production points (which corresponds to accounting for fluctuations of the parton path length L in the fireball) has been performed for the Gaussian parton distribution in the transverse plane. However, we have found that the L-fluctuations (and the shape of the distribution of the jet production points in the transverse plane) are unimportant. This occurs because for the expanding QGP the radiative energy loss to good accuracy $\propto L$ [21]. As a results, the predictions for I_{pA} turn out to be close to that obtained with the pA/pp FFs $D_{h/i}^m$ for the average jet path lengths $\langle L \rangle$ (which are close to the values of R_f). We refer the interested reader for details of the numerical calculations of $D_{h/i}^{m,v}$ to [12].

The induced gluon spectrum and the collisional energy loss have been calculated with running α_s. As in [12, 28], we use the parametrization (motivated by the lattice results of [37])

$$\alpha_s(Q,T) = \begin{cases} \dfrac{4\pi}{9\log\left(\dfrac{Q^2}{\Lambda_{\text{QCD}}^2}\right)} & \text{if} \quad Q > Q_{fr}(T), \\ \alpha_s^{fr}(T) & \text{if} \quad Q_{fr}(T) \geq Q \geq cQ_{fr}(T), \\ \dfrac{Q\alpha_s^{fr}(T)}{cQ_{fr}(T)} & \text{if} \quad Q < cQ_{fr}(T), \end{cases} \quad (5)$$

with $c = 0.8$, $Q_{fr}(T) = \Lambda_{\text{QCD}} \exp\left\{2\pi/9\alpha_s^{fr}(T)\right\}$ (we take $\Lambda_{\text{QCD}} = 200$ MeV) and $Q_{fr} = \kappa T$. We use $\kappa = 2.55$, obtained in [12] for scenario with the mQGP formation in pp collisions by fitting of the LHC data on R_{AA} for 2.76 and 5.02 TeV Pb + Pb, and 5.44 TeV Xe + Xe collisions.

MODEL OF THE MINI-QUARK–GLUON-PLASMA FIREBALL IN *pp* AND *pA* COLLISIONS

We assume that in the midrapidity region the QGP evolution may be described by Bjorken's model [38] with 1 + 1D isentropic longitudinal expansion. This gives the QGP entropy density $s = s_0(\tau_0/\tau)$ at $\tau > \tau_0$ (τ_0 is the QGP formation proper time, as in [12], we take $\tau_0 = 0.5$ fm), and use a linear parametrization $s = s_0(\tau/\tau_0)$ for $\tau < \tau_0$.

We perform calculations of jet modification in pp/pA collisions for symmetric fireballs. This seems to be reasonable, since the azimuthal asymmetry is irrelevant for the azimuthally averaged FFs that we need. In Bjorken's model [38], with isentropic evolution of the fireball, the initial entropy density s_0 can be expressed as

$$s_0 = \frac{C}{\tau_0 \pi R_f^2} \frac{dN_{ch}^f}{d\eta}, \quad (6)$$

where R_f is the fireball radius, $dN^f_{ch}/d\eta$ is the charged hadron multiplicity pseudorapidity density generated after hadronization of the QGP fireball, and $C = dS/dy/dN_{ch}/d\eta \approx 7.67$ is the entropy/multiplicity ratio [39]. We assume that in *pp* collisions the whole multiparticle production goes through hadronization of the isentropically expanding mQGP fireball, and consequently $dN^f_{ch}(pp)/d\eta = dN^{ue}_{ch}(pp)/d\eta$. This seems to be reasonable, since for *pp* collisions the initial entropy deposition distribution should be more or less uniform due to a small size of the interaction region (of the order of the proton size, since *pp* jet events are dominated by nearly central *pp* collisions). By interpolating the ATLAS data [40] for $dN^{ue}_{ch}(pp)/d\eta$ at $\sqrt{s} = 0.9$ and 7 TeV (assuming that $dN^{ue}_{ch}(pp)/d\eta \propto s^{\delta}$) we obtain $dN^{ue}_{ch}(pp)/d\eta \approx 12.5$ for 5.02 TeV *pp* collisions. Using, as in [12, 20], the predictions for the multiplicity dependence of $R_f(pp)$ obtained in the Color Glass Condensate (CGC) model [41, 42], we obtain $R_f(pp) \approx 1.49$ fm. This leads to the initial fireball temperature $T_0(pp) \approx 225$ MeV for the ideal gas model entropy density, and $T_0(pp) \approx 256$ MeV for the lattice entropy density [43].

One can expect that for *pA* jet events $dN^f_{ch}(pA)/d\eta$ should be somewhat smaller than the experimentally observed UE multiplicity density $dN^{ue}_{ch}(pA)/d\eta$. Indeed, in *pA* collisions the typical UE in jet production includes one hard *pN* interaction with jet production (as for *pp* collisions it should be dominated by nearly central *pN* collisions) and several additional soft interactions with "spectator" nucleons that are not involved in the jet production. To understand the relative contribution to $dN^{ue}_{ch}(pA)/d\eta$ in *pA* jet events of hadrons that are not related to the mQGP fireball, we have performed simulation of the entropy deposition for *pA* jet events within the Monte Carlo wounded nucleon Glauber model [44–47]. We used the form of the Monte Carlo Glauber model suggested in [48]. In [49, 50], this model was successfully used for description of a large amount of experimental data on *AA* and *pA* collisions from RHIC and the LHC.

In the wounded nucleon Glauber model, we have for the average midrapidity multiplicity density in *pA* minimum-bias events (we use the form without the binary collision term, since it gives the best fit to the experimental midrapidity multiplicity in 5.02 TeV *p* + Pb collisions)

$$\frac{dN^{mb}_{ch}(pA)}{d\eta} = \frac{dN^{mb}_{ch}(pp)}{d\eta} + \frac{(N^A_w - 1)}{2}\frac{dN^{mb}_{ch}(pp)}{d\eta}, \quad (7)$$

where $dN^{mb}_{ch}(pp)/d\eta$ is the *pp* minimum-bias multiplicity density (as usual [44], the contribution of each wounded nucleon equals $(1/2)dN^{mb}_{ch}(pp)/d\eta$), and N^A_w is the number of the wounded nucleons in the nucleus. Our Monte Carlo simulation gives $N^A_w \approx 5.64$ for the minimum-bias 5.02 TeV *p* + Pb collisions. With $dN^{mb}_{ch}(pp)/d\eta \approx 5.32$ for 5.02 TeV *pp* collisions (obtained with the help of the power law interpolation of the ALICE data [51] on the charged multiplicity in NSD *pp* events at $\sqrt{s} = 2.76$ and 7 TeV) formula (7) gives $dN^{mb}_{ch}(pPb)/d\eta \approx 17.7$, which agrees well with the experimental value $dN^{mb}_{ch}(pPb)/d\eta \approx 17.8$ from the ALICE measurement [52].

The UEs for jet events differ from the minimum-bias *pA* collisions, since for each UE we always have (at least) one hard *pN* interaction, which gives the multiplicity density $dN^{ue}_{ch}(pp)/d\eta$ (instead of the first term $dN^{mb}_{ch}(pp)/d\eta$ on the right hand side of (7) for minimum-bias *pA* collisions). Then, it is natural to write the generalization of (7) to the UEs in *pA* collisions with jet production as

$$\frac{dN^{ue}_{ch}(pA)}{d\eta} = \frac{dN^{ue}_{ch}(pp)}{d\eta} + \frac{(N^A_w - 1)}{2}\frac{dN^{mb}_{ch}(pp)}{d\eta}. \quad (8)$$

For jet events N^A_w is larger than for the minimum-bias events, since jet events are biased to more-central *pA* collisions. Our Monte Carlo Glauber simulation of jet events in 5.02 TeV *p* + Pb collisions gives $N^A_w \approx 9$. With this value of N^A_w, (8) gives $dN^{ue}_{ch}(pPb)/d\eta \approx 34.3$, which agrees well with the average UE charged multiplicity density for jet events found by ALICE [1] in 5.02 TeV *p* + Pb collisions. The Monte Carlo simulation shows that in the *b*-plane the fireball has a well pronounced peak at $r \lesssim 1$ fm (due to the UE multiplicity for the hard *pN* collision with jet production, which also leads to the $dN^{ue}_{ch}(pp)/d\eta$ in (8)), and a broad corona region at $r \gtrsim 1$–1.5 fm formed by the spectator wounded nucleons (each of them gives the multiplicity $0.5dN^{mb}_{ch}(pp)/d\eta \sim 2.65$). At $r \sim 1.5$–2 fm the ideal gas QGP temperature falls to ~130–200 MeV (and falls steeply with rising *r*). The entropy/multiplicity density in the corona region is close to or smaller than that for *pp* minimum-bias events at $\sqrt{s} \sim 0.2$ TeV ($dN^{mb}_{ch}(pp)/d\eta \sim 2.65$ [53]), for which the probability of the QGP formation is expected to be small [15, 16]. For this reason, it is reasonable to assume that, only the core region is occupied by the mQGP fireball, and the corona wounded nucleons produce hadrons in a nearly free-streaming regime. Note that excluding the region with the energy density corresponding to $T \lesssim 130$–200 MeV from the mQGP fireball is similar to the prescription of [41] used for calculation of the mQGP fireball size within the CGC model. To exclude the corona contribution to the mQGP fireball entropy we write the charged hadron multiplicity associated with the mQGP fireball hadronization as

$$\frac{dN_{ch}^{f}(pA)}{d\eta} = \frac{dN_{ch}^{ue}(pp)}{d\eta} + \xi\frac{(N_w^A - 1)}{2}\frac{dN_{ch}^{mb}(pp)}{d\eta}. \quad (9)$$

Our Monte Carlo simulation shows that the number of the corona nucleons may be as large as $\sim 0.5(N_w^A - 1)$ (i.e., $\xi \sim 0.5$ in (9)). For $\xi = 0.5$ formula (9) gives $dN_{ch}^f(pPb)/d\eta \approx 23.4$. Of course, this value of $dN_{ch}^f(pPb)/d\eta$ is only a rough estimate. Nevertheless, there is no reason to doubt that a sizeable fraction of the UE hadron multiplicity in 5.02 TeV p + Pb collisions may not be related to the mQGP hadronization. Since the dynamics of the non mQGP hadrons should be close to the free-streaming regime, their effect on jet quenching should be small.

Our model neglects the size and density fluctuations for the mQGP fireballs produced in pp and pA collisions. In [20] it has been argued that for a small size QGP this approximation is quite reasonable, since due to the dominance of the $N = 1$ rescattering contribution to induced gluon emission, which has approximately linear dependence on L and density, the effect of the fireball size and density fluctuations should be small.

NUMERICAL RESULTS

In the absence of accurate calculations of the mQGP fireball parameters for pA collisions, we perform numerical calculations of I_{pA} for several values of $dN_{ch}^f(pA)/d\eta$ between the pp and pA UE charged multiplicity density corresponding to $\xi = 0, 1/3, 2/3$, and 1 in (9). This set of ξ leads to $dN_{ch}^f(pA)/d\eta \approx 12.5$, 19.8, 27.1, and 34.3. We determine R_f for pA collisions using the multiplicity dependence of R_f obtained in the CGC numerical simulations performed in [41]. For our set of values of $\xi/dN_{ch}^f(pA)/d\eta$ we obtain

$$R_f(pA)[\xi = 0, 1/3, 2/3, 1] \approx [1.62, 1.85, 2.03, 2.16] \text{ fm}. \quad (10)$$

Then, using the Bjorken relation (6), we obtain for the initial temperature defined via the ideal gas entropy and via the lattice entropy [43] (numbers in brackets)

$$T_0(pA)[\xi = 0, 1/3, 2/3, 1] \approx [214(244), 228(257), 237(267), 246(275)] \text{ MeV}. \quad (11)$$

In Fig. 1 we plot the z_T-dependence of I_{pA} for $\xi = 0, 1/3, 2/3$, and 1. To illustrate the effect of jet quenching in pp collisions on I_{pA}, in Fig. 1 we show the results both for the scenarios with (solid) and without (dotted) the mQGP formation in pp collisions. The area between the solid lines for $\xi = 1/3$ and 2/3 can be thought as a reasonable theoretical uncertainty band for I_{pA} in the scenario with the mQGP formation in pA and pp collisions due to uncertainties in the corona contribution to the UE multiplicity in p + Pb collisions. The solid curve for $\xi = 0$ in Fig. 1 corresponds to the mQGP entropy in p + Pb collisions the same as that in pp collisions. The equality of the pA and pp fireball entropies results in the same degree of medium suppression for the pA and pp photon-tagged FFs. For this reason, for $\xi = 0$ we have $I_{pA} \approx 1$ (the effect of the difference in the nuclear PDFs and the proton PDFs, that can affect the weight factors r_i in (3) and lead to a deviation of I_{pA} from unity, turns out to be negligible). As can be seen from Fig. 1, I_{pA} decreases with z_T. For $\xi \sim 0.5$ we have $(1 - I_{pA}) \sim 0.1(0.2)$ at $z_T \sim 0.5$ and $(1 - I_{pA}) \sim 0.2(0.45)$ at $z_T \sim 0.9$ for scenario with(without) the mQGP formation in pp collisions. The ALICE data [1] also show the tendency of I_{pA} to decrease with increasing z_T. However, the experimental errors are large ($\sim\pm 0.5$ at $z_T \sim 0.5$), this fact does not allow to validate or rule out the scenario with the mQGP formation. From the results shown in Fig. 1 one can conclude that the use of the γ + jet process as a probe for jet quenching in pA and pp collisions requires high accuracy data on I_{pA} (with errors $\lesssim 0.1$–0.2).

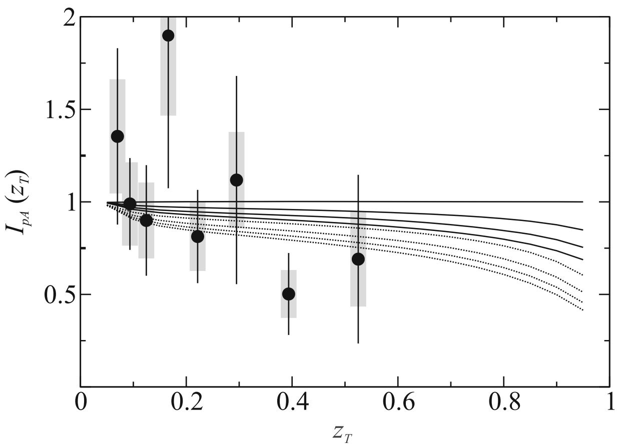

Fig. 1. Medium modification factor I_{pA} of the photon-tagged FFs for 5.02 TeV p + Pb collisions vs. $z_T = p_T^h/p_T^\gamma$ for the trigger photon momentum window $12 < p_T^\gamma < 40$ GeV. Solid and dashed lines show the results of our calculations with and without the mQGP formation, respectively, in pp collisions for ξ = (from top to bottom) 0, 1/3, 2/3, and 1 in Eq. (9). Data points are from ALICE [1].

From the results presented in Fig. 1 one can see that for the scenario without the mQGP formation in

pp collisions $(1 - I_{pA})$ is larger than that for the scenario with the mQGP formation both in pA and pp collisions by a factor of 2. This says that the effect of the medium modification of the reference pp FF D_h^{pp} in the denominator of (1) is very important. By itself the scenario with the mQGP formation only in pA collisions seems to be unrealistic, since this scenario is clearly inconsistent with data on the nuclear modification factor R_{pA} [25].

To test the stability of the results with respect to variation of τ_0, we also performed calculations for $\tau_0 = 0.8$ fm. Calculations with the same α_s (i.e., for $\kappa = 2.55$) as for $\tau_0 = 0.5$ fm, show very small variation of I_{pA}: e.g. for $z_T \sim 0.5$ the value of $(1 - I_{pA})$ is suppressed by ~1(5)% for version with(without) the mQGP formation in pp collisions for $\xi = 1$ (for which the changes in I_{pA} are maximal). Calculations with $\kappa \approx 2.43$, which corresponds to the optimal χ^2 fit of the LHC heavy ion data on R_{AA} for $\tau_0 = 0.8$ fm [12], lead to nearly the same results for I_{pA} as shown in Fig. 1. Note also that for a given $dN_{ch}^f(pA)/d\eta$ we found very little sensitivity of I_{pA} to the fireball radius R_f (which we determined from the IP-Glasma model calculations [41, 42]). This is due to a compensation of the variations of parton energy loss arising from the increase/decrease of the parton path length and from the decrease/increase of the mQGP density. The low sensitivity of the jet quenching effects to the mQGP fireball size was previously found for R_{pp} [12].

SUMMARY

We have calculated the medium modification factor I_{pA} for the photon-tagged jets in 5.02 TeV p + Pb collisions for the conditions of the ALICE experiment [1] in the scenario with the mQGP formation. Radiative and collisional energy losses of fast partons in the QGP have been evaluated with running $\alpha_s(Q,T)$ that has a plateau around $Q \sim \kappa T$. We perform calculations using $\kappa = 2.55$ fitted to the LHC heavy ion data on the nuclear modification factor R_{AA}. Our calculations show that jet quenching can lead to a deviation of I_{pA} from unity by ~0.1–0.2 for $z_T \sim 0.5$–0.8 for the scenario with the mQGP formation both in p + Pb and pp collisions. This, within errors, is consistent with the data from ALICE [1]. However, a definite conclusion about the presence or absence of jet quenching in pA collisions cannot be drawn due to large experimental errors of the ALICE data [1]. Our results demonstrate that this requires a significantly more accurate measurement of I_{pA} (with errors $\lesssim$0.1–0.2).

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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