Medium Modification of Photon-Tagged and Inclusive Jets in High-Multiplicity Proton-Proton Collisions

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We study modification of the photon-tagged and inclusive jets in pp collisions at $\sqrt{s} = 7$ TeV due to mini-quark-gluon plasma which can be produced in high multiplicity events. We show that for underlying events with $dN_{\rm ch}/d\eta \sim 20$–60 the medium effects lead to a considerable modification of the photon-tagged and inclusive jet fragmentation functions. For inclusive jets, the magnitude of the effect is surprisingly large. The effect is quite strong even for typical underlying events. We find that the spectrum of charged hadrons is suppressed by ~35%–40% at $p_T \sim 5$–10 GeV.

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The experiments at RHIC and LHC have provided strong evidence for the formation in AA collisions of a hot and dense QCD matter in the form of quark-gluon plasma (QGP). However, so far we have no compelling evidence for the formation of the QGP in pp collisions. It is widely believed that over the energy range covered by the accelerator experiments in the typical inelastic minimum bias pp collisions, the collectivity in the final states is unimportant due to small energy density. Nevertheless, in rare high-multiplicity (HM) pp events the energy density may be comparable to that in AA collisions at RHIC and LHC energies. And if the thermalization time, τ_0, is small enough, say $\tau_0 \lesssim 0.5$ fm, the QGP should be formed quite likely to AA collisions.

One can expect that collectivity in HM pp collisions may be observed via the hydrodynamic flow effects [1,2] similar to that in AA collisions. The hydrodynamical simulation of the flow effects in pp collisions with the initial conditions from the IP-Glasma model [3] has been performed in [4]. It was observed that for small-size QGP the theoretical uncertainties are large as compared to the QGP in AA collisions. This may make it difficult to extract information on the mini-QGP via measurements of the azimuthal flow coefficients.

Although today we do not have clear evidence for the formation of the QGP in pp collisions, there are some indications in its favor. It is possible that what was observed by the CMS collaboration ridge correlation structure in HM pp events [5] is due to the transverse flow of the mini-QGP. But an alternative explanation of this effect in the color glass condensate picture seems also possible [6]. In Ref. [7], employing van Hove's idea [8] that phase transition should lead to anomalous behavior of $\langle p_T\rangle$ as a function multiplicity, it has been argued that the pp data on $\langle p_T\rangle$ signal possible plasma formation in the domain $dN_{\rm ch}/d\eta \sim 6$–24.

An unambiguous proof of formation of a dense QCD matter in pp collisions would be observation of jet modification (quenching) similar to that observed in AA collisions. It is important that conditions for the QGP production are better in events with jets, because multiplicity of soft off-jet particles [so-called underlying events (UEs)] is enhanced by a factor of 2–3 [9]. In AA collisions jet quenching leads to suppression of high-p_T spectra characterized by the nuclear modification factor R_{AA} defined as the ratio of the particle yield in the AA collision to the binary-scaled yield in pp collisions. The latter provides the baseline which for now is assumed to be free of the final state medium effects. However, for pp collisions the medium modification factor, R_{pp}, is unobservable directly because we do not have the baseline spectra with the final state interactions in the QGP switched off. For observation of the medium effects in pp collisions, measurement of the jet fragmentation function (FF) in $\gamma +$ jet events seems to be promising, as was suggested in [10] for AA collisions. To understand the prospects of this method in this Letter we evaluate the medium modification of the γ-tagged FF at $\sqrt{s} = 7$ TeV in the midrapidity region near $y = 0$ for different multiplicities of the UE. We also give predictions for the medium modification of the FF for inclusive jets, which is closely related to R_{pp}. Although R_{pp} is unobservable directly, it is important for the nuclear modification factors R_{pA} and R_{AA}, which, in the presence of the mini-QGP, should be divided by R_{pp}. To illustrate the magnitude of the suppression effect in pp collisions, we present our preliminary results for R_{pp} of charged hadrons.

The jet quenching is dominated by radiative energy loss [11–15] with relatively small effect from the collisional mechanism [13,16,17]. We use the light-cone path integral (LCPI) approach [12,13] to induced gluon emission. We treat the effect of parton energy loss on the FFs within the scheme developed previously for AA collisions [18]. It takes into account both radiative and collisional energy loss. This approach was successful in explaining results for R_{AA} for light and heavy flavors in AA collisions [19–21]. We do not discuss the details of the model, and refer the reader to our above cited articles on jet quenching in AA collisions.

As in [18] we use the $1+1$D Bjorken's model of the QGP evolution, which gives $T_0^3\tau_0 = T^3\tau$, and take $\tau_0 = 0.5$ fm. For $\tau < \tau_0$ we take medium density $\propto \tau$. However, the effect of this region is relatively small. We neglect variation of the initial temperature T_0 with the transverse coordinates. To fix T_0 we use the entropy/multiplicity ratio $c = dS/dy/dN_{\rm ch}/d\eta \approx 7.67$ obtained in [22]. The initial entropy density can be written as

$$s_0 = \frac{c}{\tau_0 \pi R_f^2}\frac{dN_{\rm ch}}{d\eta}, \tag{1}$$

where R_f is the radius of the created fireball (we assume that the jet production is dominated by the head-on collisions and ignore azimuthal asymmetry of the QGP). One can expect that $R_f \sim R_p \sim 1$ fm (here R_p is the proton radius). It agrees qualitatively with R_f obtained for pp collisions at $\sqrt{s} = 7$ TeV in numerical simulations performed in [4] within the IP-Glasma model [3]. The R_f from [4] grows approximately as a linear function of $(dN_g/dy)^{1/3}$ and then flattens. We use the R_f from [4] parametrized in a convenient form via dN_g/dy in Ref. [23]. The values of the R_f and T_0 for different values of $dN_{\rm ch}/d\eta$ (we take $dN_g/dy \approx 2.13 dN_{\rm ch}/d\eta$) obtained using the ideal gas model with $N_f = 2.5$ are given in Table I. One sees that for $dN_{\rm ch}/d\eta \gtrsim 20$ (1) gives T_0 well above the deconfinement temperature $T_c \approx 170$ MeV. For $dN_{\rm ch}/d\eta = 40$ we have T_0 close to that for the central Au + Au collisions at $\sqrt{s} = 200$ GeV [21].

In γ + jet events the energy of the produced hard parton, E_T, in the direction opposite to the tagged direct photon is smeared around the photon energy, E_T^γ. The NLO calculations [24] show that for AA collisions at $E_T^\gamma \sim 8$ the smearing correction, $\Delta_{\rm sm}$, to the medium modification factor $I_{AA}(z)$ of the photon tagged FF blows up at $z \gtrsim 0.8$–0.9 (hereafter $z = p_T^h/E_T^\gamma$). One can show that $\Delta_{\rm sm} \approx F(z, E_T^\gamma) dI_{AA}/dz/{E_T^\gamma}^2$, where $F(z, E_T^\gamma)$ is a smooth function of E_T^γ. Using this formula and the results of [24] (shown in Fig. 2) one can show that for $E_T^\gamma \gtrsim 25$ GeV (which will be considered in our Letter) the effect of smearing should be very small at $z \lesssim 0.9$. To be conservative we will consider the region $z < 0.8$, where the effect of smearing is practically negligible and the LO relation $E_T = E_T^\gamma$ can be used. Then following [10] we can write the γ-tagged FF in pp collisions as a function of the UE multiplicity density $dN_{\rm ch}/d\eta$ (for clarity we denote it by m) as

$$D_h(z, E_T^\gamma, m) = \left\langle\left\langle \sum_i r_i(E_T^\gamma) D_{h/i}(z, E_T^\gamma, m) \right\rangle\right\rangle, \tag{2}$$

where $D_{h/i}$ is the medium modified FF for the $i \to h$ process, and r_i is the fraction of the $\gamma + i$ parton state in the γ + jet events, $\langle\langle \cdots \rangle\rangle$ means averaging over the transverse geometrical variables of pp collision and jet production, which includes averaging over the fast parton path length L in the QGP.

For not very high E_T^γ, the sum over all relevant types of partons on the right-hand side of (2) is dominated by gluon and light quarks. For all light quarks medium modification of the FFs are very similar, and we may consider one effective light quark state q with $r_q = 1 - r_g$. We use, for the r_i prediction of the ordinary LO, the pQCD formula, which gives $r_g \ll r_q$ at LHC energies. In principle, r_g/r_q may depend on m. However, there are no serious physical reasons for the strong multiplicity dependence of this ratio, because the UE activity is driven by fluctuations of soft gluons which should not strongly modify the hard cross sections. And since the dominating contribution to the γ-tagged jets comes from quark jets, the theoretical uncertainties due to modification of the r_g/r_q ratio should not be significant.

We have performed averaging over L using the distribution of hard processes in the impact parameter plane obtained with the quark distribution from the MIT bag model. It is plausible for our preliminary study. In the MIT bag model, practically in the full range of the impact parameter, the distribution in L is sharply peaked around $L \approx \sqrt{S_{\rm ov}/\pi}$, where $S_{\rm ov}$ is the overlap area for two colliding bags. It means that the effective fireball radius R_f (which includes all centralities) at the same time gives the typical path length for fast partons. We have found that the effect of the L fluctuations is relatively small (as compared to $L = R_f$ they reduce the medium modification by $\sim$10%–15%).

As in Refs. [18–21], we evaluate radiative and collisional energy loss with running α_s frozen at some value $\alpha_s^{\rm fr}$ at low momenta. For gluon emission in vacuum, a reasonable choice is $\alpha_s^{\rm fr} \approx 0.7$ [25]. But in plasma, thermal effects can suppress $\alpha_s^{\rm fr}$. We observed previously [21] that data on R_{AA} are consistent with $\alpha_s^{\rm fr} \approx 0.5$ for RHIC and $\alpha_s^{\rm fr} \approx 0.4$ for LHC. The reduction of $\alpha_s^{\rm fr}$ from RHIC to LHC may be related to stronger thermal effects in the QGP due to higher initial temperature at LHC. As noted, for the mini-QGP produced in pp collisions the gluon formation length is of the order of or larger than the medium size. In this regime, in the LCPI treatment [12] a large contribution to the induced gluon spectrum comes from configurations with interference of the emission amplitude and the complex conjugate one when one of them typically has the gluon emission point outside the medium. For this reason for pp collisions, $\alpha_s^{\rm fr}$ may be somewhat larger than that obtained for AA collisions (for same T_0). We take

TABLE I. R_f and T_0 for different $dN_{\rm ch}/d\eta$.

$dN_{\rm ch}/d\eta$	3	6	20	40	60
R_f (fm)	1.046	1.27	1.538	1.538	1.538
T_0 (MeV)	177	196	258	325	372

$\alpha_s^{\rm fr} = 0.6$. The results are not very sensitive to variation of $\alpha_s^{\rm fr}$ in the physically reasonable domain $\alpha_s^{\rm fr} \sim 0.5$–0.7. The point is that for a small-size plasma the hardness Q of induced gluon emission can attain quite large values since $Q^2 \gtrsim 2\omega/L$ [16]. For he radiation of gluons with energy $\omega \sim 1$–3 GeV and $L \sim 1$ fm $Q \gtrsim 0.6$–1 GeV, where the freezing of α_s is not very important.

In Fig. 1 we present the results for the medium modification factor (for charged hadrons)

$$I_{pp}(z, E_T, m) = D_h(z, E_T, m)/D_h^{\rm vac}(z, E_T) \qquad (3)$$

for the γ-tagged (upper panels) and inclusive (lower panels) jets for $E_T = [25, 50, 100]$ GeV at $\sqrt{s} = 7$ TeV [as in (2) $m = dN_{\rm ch}/d\eta$]. We used the LO pQCD predictions: $r_g/r_q \approx [0.093, 0.12, 0.17]$ for γ-tagged jets and $r_g/r_q \approx [6.99, 5.68, 4.25]$ for inclusive jets for our set of E_T. The smearing effect is irrelevant to inclusive jets, and we show the results for the whole range of z since it is interesting in the context of the suppression factor of the high-p_T spectra. In principle, our treatment of multiple gluon emission, based on Landau's method [26], is not supposed to be valid at very small z, where cascading of the primary gluons radiated from the fast partons comes into play. We included the region of very small z just to illustrate the flow of jet energy into the soft region. For illustration of the difference between the medium effects in pp and AA collisions, we also present the curves for $\sqrt{s} = 2.76$ TeV for $L = 5$ fm and $T_0 = 420$ MeV that can be regarded as reasonable values for Pb + Pb collisions (we used $\alpha_s^{\rm fr} = 0.4$, which is favored by the data on $R_{AA}(p_T)$ at $p_T \gtrsim 20$ GeV). Figure 1 shows that there is a considerable quenching effect for $dN_{{\rm ch}/d\eta} \gtrsim 20$. The effect is stronger for inclusive jets since for the γ-tagged jets the dominating contribution comes from quarks and for inclusive ones from gluons. In practice, for the γ-tagged jets one should simply compare the FFs for different multiplicities (since the vacuum FF is unobservable). For illustration, we show the ratio of the FFs for $m = 40$ and $m = 3$ (for inclusive jets this ratio cannot be measured, we show it just to illustrate the difference between the γ-tagged and inclusive jets). One sees that for the observation of jet quenching at $E_T \sim 25$–50 GeV it is necessary to measure the γ-tagged FF with rather small errors, say, smaller than 10% for the UE with $dN_{\rm ch}/d\eta \sim 40$ at $z \sim 0.5$–0.8.

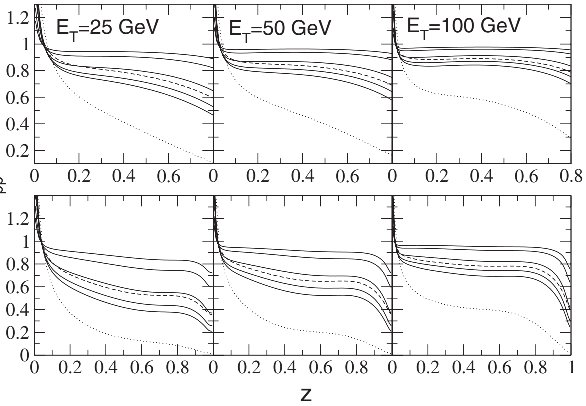

FIG. 1. I_{pp} for γ-tagged (upper panels) and inclusive (lower panels) jet FFs at $\sqrt{s} = 7$ TeV for $dN_{\rm ch}/d\eta = [3, 6, 20, 40, 60]$ (solid line). The order (top to bottom) of the curves at large z corresponds to increasing values of $dN_{\rm ch}/d\eta$. The dashed line shows the ratio of the FFs for $dN_{\rm ch}/d\eta = 40$ and 3. The dotted line shows the medium modification factor at $\sqrt{s} = 2.76$ TeV for the QGP with $T_0 = 420$ MeV and $L = 5$ fm for $\alpha_s^{\rm fr} = 0.4$.

To estimate the errors related to uncertainty in the fireball size we have performed the calculations for R_f increased by a factor of 1.3. We have found a very small variation of I_{pp}, typically $|\Delta I_{pp}/(1 - I_{pp})| \lesssim 0.01$–0.05. And even for R_f increased by a factor of 1.5 the variation remains approximately at the same level. This says that the I_{pp}, regarded as a functional of the density profile along the jet trajectory, is quite stable against variations of this profile (for a fixed initial entropy). This is due to a strong compensation between the enhancement of the energy loss caused by increase of the medium size and its suppression due to reduction of the medium density. This test also provides a strong argument that the transverse expansion, neglected in our analysis, should not dramatically modify our results. Indeed, from the point of view of the induced gluon emission there is nothing special in the variation of the density profile generated by the transverse expansion. And the magnitude of the hydrodynamic variation of the density profile is of the order of that in our test. For jet quenching in AA collisions the smallness of the hydrodynamical effects was demonstrated in [27]. In pp collisions their role should be reduced since the typical formation length for induced gluon emission is of the order of the medium size or larger. In this regime parton energy loss is mostly controlled by the mean amount of the matter traversed by fast partons, and the details of the density profile are not very important.

The observed strong quenching of inclusive jets is qualitatively supported by the preliminary data from ALICE [28] indicating that for the HM UE jets undergo a softer fragmentation. Note that even for typical UE when $dN_{\rm ch}/d\eta \sim 14$ [29] at $\sqrt{s} = 7$ TeV, at moderate z the suppression is ~20%–30%. It seems to be in contradiction with the jet FF measured in Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV [30] which gives I_{AA} close to unity. However, in Ref. [30] z is defined through the energy inside the jet cone, which should be smaller than the energy of the primary parton due to the energy of soft partons deposited in the plasma or outside the jet cone. The data on R_{AA} indicate that the real jet FF is strongly suppressed. At $\sqrt{s} = 2.76$ TeV the suppression should be like that shown by the dotted curve in Fig. 1.

The medium modification factor for hadron spectra can be written through the medium modified FFs in the form

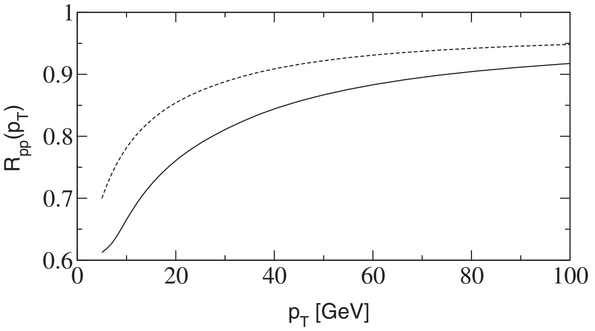

FIG. 2. R_{pp} of charged hadrons at $\sqrt{s}=7$ TeV for the parameters of the fireball obtained with the UE (solid line) and minimum bias (dashed line) $dN_{\rm ch}/d\eta$.

$$R_{pp}(p_T)=\frac{\sum_i\int_0^1\frac{dz}{z^2}D_{h/i}(z,p_T^i)\frac{d\sigma(pp\to iX)}{d\mathbf{p}_T^i dy}}{\sum_i\int_0^1\frac{dz}{z^2}D_{h/i}^{\rm vac}(z,p_T^i)\frac{d\sigma(pp\to iX)}{d\mathbf{p}_T^i dy}}, \qquad (4)$$

where $d\sigma(pp\to iX)/d\mathbf{p}_T^i dy$ is the ordinary hard cross section, $\mathbf{p}_T^i=\mathbf{p}_T/z$ is the parton transverse momentum. In Eq. (4) it is implicit that $D_{h/i}$ is averaged over the jet production point, the impact parameter of pp collision and the UE multiplicity. Equation (4) can be thought of as an analogue of the formula for R_{AA} in the whole impact parameter range. Presently we do not have information about the UE activity for each impact parameter and transverse position of the jet production. We evaluated the medium modified FFs $D_{h/i}$ averaging over L but using simply the average UE multiplicity measured by ATLAS [29]. The $dN_{\rm ch}/d\eta$ from Ref. [29] grows with the momentum of the leading charged jet hadron at $p_T^l \lesssim 3$–5 GeV and then flattens at $dN_{\rm ch}/d\eta\approx 13.9$ (it corresponds to $R_f\approx 1.51$ fm and $T_0\approx 232$ MeV). Simulation with PYTHIA [31] shows that for jets with energy $E\lesssim 15$ GeV, that can feel the jet energy dependence of the UE multiplicity, one can simply take $p_T^l=\eta p_T$, where p_T is the hadron momentum in Eq. (4) and $\eta\sim 1.9$ for LHC energies. Figure 2 shows R_{pp} at $\sqrt{s}=7$ TeV obtained with $\alpha_s^{\rm fr}=0.6$. The suppression is quite strong: ∼35%–40% at $p_T\sim 5$–10 GeV. We also show R_{pp} for the minimum bias multiplicity $dN_{\rm ch}^{\rm mb}/d\eta=6.01$ [32]. Even in this case the effect is significant. The medium suppression should be important for pA collisions as well. The data on R_{pPb} at $\sqrt{s}=5.02$ TeV from ALICE [33] show a small deviation from unity at $p_T\gtrsim 10$ GeV, where the Cronin effect is weak. In light of the strong medium suppression for pp collisions, this may be consistent with the scenario with the mini-QGP only if the UE multiplicities for pp and pPb collisions are close to each other. The detailed results on the R_{pp} and its effect on R_{AA} and R_{pA} will be presented elsewhere.

In summary, assuming that a mini-QGP fireball may be created in pp collisions, we have evaluated the medium modification factors for the γ-tagged and inclusive jet FFs for $\sqrt{s}=7$ TeV. We show that in pp collisions with UE multiplicity density $dN_{\rm ch}/d\eta\sim 20$–40 the mini-QGP can suppress the γ-tagged FF at $E_T\sim 25-100$ GeV and $z\sim 0.5$–0.8 by ∼10%–40%, and for inclusive jets the effect is even stronger. The formation of the mini-QGP also leads to a sizeable suppression of the high-p_T spectra in pp collisions $R_{pp}\sim 0.6$–0.65 at $p_T\sim 5$–10 GeV for $\sqrt{s}=7$ TeV. The deviation of R_{pp} from unity will increase the theoretical predictions for the R_{AA} and R_{pA}. Because of a smaller suppression of the heavy flavors the effect of the mini-QGP in pp collisions may be important for the jet flavor tomography of AA [21,34].

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[1] P. Bozek, Acta Phys. Pol. B **41**, 837 (2010).
[2] J. Casalderrey-Solana and U. A. Wiedemann, Phys. Rev. Lett. **104**, 102301 (2010).
[3] B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. **108**, 252301 (2012).
[4] A. Bzdak, B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. C **87**, 064906 (2013).
[5] V. Khachatryan *et al.* (CMS Collaboration), J. High Energy Phys. 09 (**2010**) 091.
[6] K. Dusling and R. Venugopalan, Phys. Rev. D **87**, 094034 (2013).
[7] R. Campanini, G. Ferri, and G. Ferri, Phys. Lett. B **703**, 237 (2011).
[8] L. van Hove, Phys. Lett. **118B**, 138 (1982).
[9] A. A. Affolder *et al.* (CDF Collaboration), Phys. Rev. D **65**, 092002 (2002).
[10] X.-N. Wang, Z. Huang, and I. Sarcevic, Phys. Rev. Lett. **77**, 231 (1996); X.-N. Wang and Z. Huang, Phys. Rev. C **55**, 3047 (1997).
[11] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigné, and D. Schiff, Nucl. Phys. **B483**, 291 (1997); Nucl. Phys. **B484**, 265 (1997).
[12] B. G. Zakharov, JETP Lett. **63**, 952 (1996); JETP Lett. **65**, 615 (1997); JETP Lett. **70**, 176 (1999); Phys. At. Nucl. **61**, 838 (1998).
[13] R. Baier, D. Schiff, and B. G. Zakharov, Annu. Rev. Nucl. Part. Sci. **50**, 37 (2000).
[14] M. Gyulassy, P. Lévai, and I. Vitev, Nucl. Phys. **B594**, 371 (2001).
[15] P. Arnold, G. D. Moore, and L. G. Yaffe, J. High Energy Phys. 06 (**2002**) 030.
[16] B. G. Zakharov, JETP Lett. **86**, 444 (2007).
[17] G.-Y. Qin, J. Ruppert, C. Gale, S. Jeon, G. Moore, and M. Mustafa, Phys. Rev. Lett. **100**, 072301 2008).
[18] B. G. Zakharov, JETP Lett. **88**, 781 (2008).
[19] B. G. Zakharov, JETP Lett. **93**, 683 (2011).
[20] B. G. Zakharov, JETP Lett. **96**, 616 (2013).
[21] B. G. Zakharov, J. Phys. G **40**, 085003 (2013).
[22] B. Müller and K. Rajagopal, Eur. Phys. J. C **43**, 15 (2005).

[23] L. McLerran, M. Praszalowicz, and B. Schenke, Nucl. Phys. **A916**, 210 (2013).

[24] H. Zhang, J. F. Owens, E. Wang, and X.-N. Wang, Phys. Rev. Lett. **103**, 032302 (2009).

[25] N. N. Nikolaev and B. G. Zakharov, Phys. Lett. B **327**, 149 (1994).

[26] R. Baier, Yu. L. Dokshitzer, A. H. Mueller, and D. Schiff, J. High Energy Phys. 09 (**2001**) 033.

[27] R. Baier, A. H. Mueller, and D. Schiff, Phys. Lett. B **649**, 147 (2007).

[28] H. L. Vargas, for the ALICE Collaboration, J. Phys. Conf. Ser. **389**, 012004 (2012).

[29] G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. D **83**, 112001 (2011).

[30] S. Chatrchyan *et al.* (CMS Collaboration), J. High Energy Phys. 10 (**2012**) 087.

[31] T. Sjostrand, L. Lonnblad, S. Mrenna, and P. Skands, arXiv: hep-ph/0308153.

[32] E. Abbas *et al.* (ALICE Collaboration), Eur. Phys. J. C **73**, 2496 (2013).

[33] B. Abelev *et al.* (ALICE Collaboration), Phys. Rev. Lett. **110**, 082302 (2013).

[34] A. Buzzatti and M. Gyulassy, Phys. Rev. Lett. **108**, 022301 (2012).