Intriguing similarities of high-p_T particle production between *pp* and *A-A* collisions

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In this paper we study the particle production at high transverse momentum ($p_T > 8\,\mathrm{GeV}/c$) in both *pp* and Pb-Pb collisions at LHC energies. The characterization of the spectra is done using a power-law function and the resulting power-law exponent (n) is studied as a function of x_T for minimum-bias *pp* collisions at different $\sqrt{s}$. The functional form of n as a function of x_T exhibits an approximate universal behavior. PYTHIA 8.212 reproduces the scaling properties and therefore, it is used to study the multiplicity-dependent particle production. Going from low to high multiplicities, the power-law exponent decreases. A similar behavior is also observed in heavy-ion collisions when one studies the centrality-dependent particle production. The interpretation of heavy-ion results requires the quantification of the impact of this correlation (multiplicity and high p_T) on jet-quenching observables.

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I. INTRODUCTION

The similarity between analogous observables in large (*A-A*) and small (*pp* and *p-A*) collisions systems was extensively studied by the heavy-ion community [1–5]. A vast number of quantities as a function of the charged-particle density ($dN_{\mathrm{ch}}/d\eta$) in small systems have been documented in recent works [6]. These observables (azimuthal anisotropies, radial flow, and strangeness enhancement [7–9]) have been measured in the low- and intermediate-transverse momentum regimes ($p_T < 8\,\mathrm{GeV}/c$). For higher transverse momenta, the traditional treatments intend to isolate the QGP effects using reference data where the formation of a medium is not expected. Minimum-bias proton-proton collisions have been used for this purpose. However, now this assumption is questionable [10,11].

The PHENIX collaboration has collected data of nucleus-nucleus collisions from $\sqrt{s_{\mathrm{NN}}} = 62.4$ up to 200 GeV, and the results were compared with those from Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$. Using the so-called fractional momentum loss, particle production at high p_T ($p_T > 8\,\mathrm{GeV}/c$) in *A-A* collisions was compared with the one in minimum-bias *pp* collisions at the corresponding center-of-mass energy. Surprisingly, this quantity was found to scale better with $\langle dN_{\mathrm{ch}}/d\eta\rangle$ and with the Bjorken energy density times the equilibration time ($\epsilon_{\mathrm{Bj}}\tau_0$) than with the number of participants obtained using the Glauber model [12]. These results motivated further studies which confirmed the scaling even at the top LHC energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [13]. Similarly, recent results of the ALICE collaboration show that the nuclear modification factors (R_{AA}) in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ and 5.02 TeV [14] and Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$ [15] scale with $\langle dN_{\mathrm{ch}}/d\eta\rangle$. This suggests that multiplicity (or energy density) may play an important role to describe the high-p_T particle production in heavy-nuclei collisions.

The correlation between particle production at high transverse momentum and the large underlying event activity was extensively documented for *pp* and *p*-Pb collisions [16–20]. Namely, for small systems the underlying event activity increases with increasing the leading particle transverse momentum. The production of high-momentum particles in Pb-Pb systems could also bias towards high-multiplicity nucleon-nucleon collisions. Therefore, it is important to perform a systematic study of the system-size dependence of particle production at high p_T. Moreover, the study of the transverse momentum spectra in a large momentum range is a very good laboratory to observe the successive dominance of the gluon and quark contributions [21].

In the present work we do a comprehensive study of the multiplicity dependence of particle production at high transverse momentum ($p_T > 8\,\mathrm{GeV}/c$) in *pp* collisions at LHC energies. The results are then compared with LHC *A-A* data. Although these kinds of studies are important to understand the propagation of a hard probe within the medium, they have not been reported so far. The message of the present paper is that the **shape** of R_{AA} for high-p_T particles is not fully attributed to the parton energy loss; because, as we will demonstrate, a similar shape is observed for the analogous ratios in *pp* collisions, i.e., high-multiplicity p_T spectra normalized to that for minimum-bias events.

The paper is organized as follows: Sec. II describes how the high-p_T production is characterized in terms of a power-law function as well as the description of the data which were used

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in this analysis. The results and discussions are displayed in Sec. III and final remarks are presented in Sec. IV.

II. PARTICLE PRODUCTION AT LARGE TRANSVERSE MOMENTA

In heavy-ion collisions particle production at high p_T is commonly used to study the opacity of the medium to the jets. Experimentally, the medium effects are extracted by means of the nuclear modification factor, R_{AA}, which is defined as

$$R_{AA} = \frac{d^2N_{AA}/dydp_T}{\langle N_{\rm coll}\rangle d^2N_{pp}/dydp_T}, \quad (1)$$

where $d^2N_{AA}/dydp_T$ and $d^2N_{pp}/dydp_T$ are the invariant yields measured in A-A and minimum-bias pp collisions, respectively. The ratio is scaled by the average number of binary nucleon-nucleon collisions ($N_{\rm coll}$) occurring within the same A-A interaction, which is usually obtained using Glauber simulations [22,23]. The resulting ratio is supposed to account (at least from 8 GeV/c onward) for the so-called jet quenching whereby the high-momentum partons would be "quenched" in the hot system created in the nuclei collisions.

The definition of R_{AA} involves two important aspects:

(1) The absolute normalization of the p_T spectra in minimum-bias pp collisions obtained from the Glauber model [22,23], means to represent the average number of minimum-bias pp collisions (binary collisions) that the colliding nucleons have suffered within the same heavy-ion collision.
(2) The shape of R_{AA} at high p_T is determined by the different probability for the occurrence of a hard scattering which is larger in heavy-ion collisions than in pp collisions and is proportional to the path length in the medium and its characteristic transport coefficient $\hat{q}$.

The rationale for the procedure is the following. The normalized ratio should give us the probability that partons normally produced in the multiple binary pp collision get degraded in the hot and dense system created in the heavy-ion collision, resulting in a suppression of the ratio ($R_{AA} < 1$). For instance, in the 0%–5% Pb-Pb collisions at the LHC energies the suppression is about 7–8 for p_T of around 6–7 GeV/c [14,24]. For higher p_T, R_{AA} exhibits a continuous rise and approaches unity [24]. As suggested by the p_T-differential baryon-to-meson ratio [25,26], for p_T larger than 8 GeV/c radial flow effects are negligible and therefore, the shape of R_{AA} is expected to be dominated by parton energy loss.

The underlying assumption to that paradigm is that the pp spectrum does not have a marked dependence on event multiplicity. However, this is not true as indicated by the sphericity analysis as a function of charged-particle multiplicity [27]. The results indicate that even at high multiplicity the abundance of jettylike events is not negligible, although its contribution is overestimated by the QCD-inspired Monte Carlo generators like PYTHIA 8.212 [28,29]. Based on models, in pp collisions the jet contribution increases with increasing multiplicity [30], this effect contributes to the increase of the particle production at high transverse momentum.

TABLE I. Event multiplicity classes based on the number of charged particles ($N_{\rm ch}$) within $|\eta| < 0.8$. Results are presented for pp collisions at $\sqrt{s} = 13$ TeV simulated with PYTHIA 8.212 (tune Monash 2013). The contributions to the inelastic cross section (fraction) are also displayed.

Class name	I	II	III	IV	V
$N_{\rm ch}$	0–5	6–10	11–15	16–20	21–25
fraction	10.45%	15.68%	14.79%	13.78%	12.34%
Class name	VI	VII	VIII	IX	X
$N_{\rm ch}$	26–30	31–35	36–40	41–50	⩾51
fraction	10.39%	8.08%	5.78%	6.09%	2.61%

In the present paper we study the shape of the p_T spectra of charged particles measured in heavy-ion and pp collisions separately. The aim is to discuss the origin of the rise of the R_{AA} for $p_T > 6$ GeV/c. Since PYTHIA 8.212 (tune Monash 2013 [31]) reproduces rather well many features of LHC data [32,33], we base our studies on PYTHIA 8.212 simulations of pp collisions for different multiplicity classes. The multiplicity classes are defined based on the number of primary charged particles within $|\eta| < 0.8$. Table I shows the different event classes and their corresponding contributions to the inelastic cross section for pp collisions at $\sqrt{s} = 13$ TeV.

III. RESULTS AND DISCUSSION

Figure 1 shows the multiplicity-dependent p_T spectra for pp collisions at $\sqrt{s} = 13$ TeV. For $p_T > 8$ GeV/c the spectra become harder with increasing multiplicity. This is a

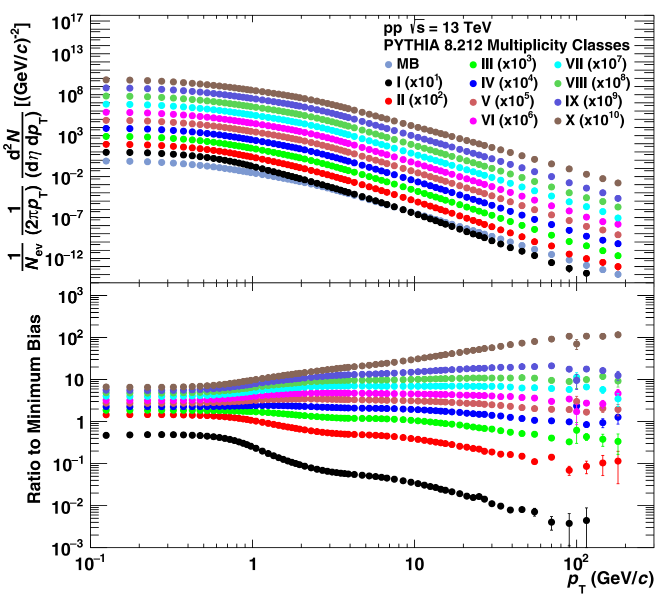

FIG. 1. Transverse-momentum distributions of charged particles for different multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV simulated with PYTHIA 8.212. The ratios of the multiplicity-dependent p_T spectra to the minimum-bias (MB) p_T spectrum are shown in the bottom panel. The spectra are scaled by different factors to improve the visibility.

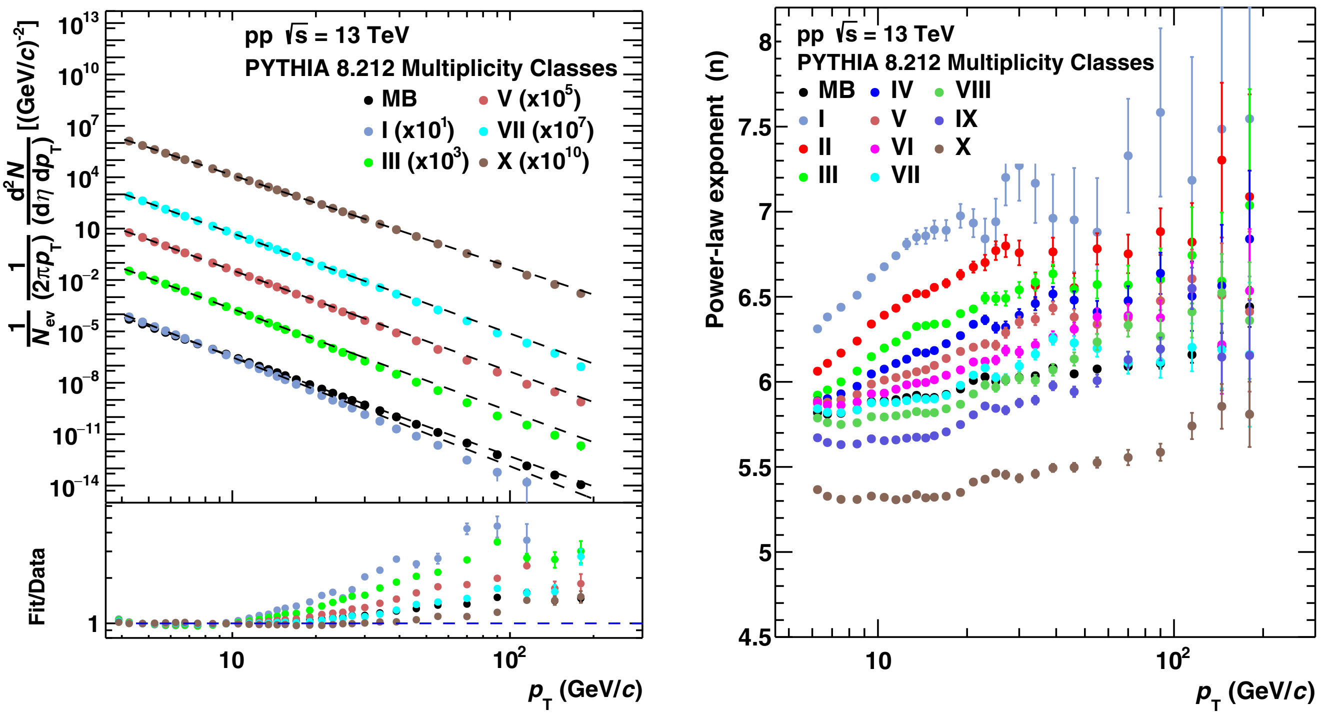

FIG. 2. (Left) Transverse momentum distributions of charged particles for minimum bias (MB) and different multiplicity classes in *pp* collisions at $\sqrt{s} = 13$ TeV simulated with PYTHIA 8.212. Power-law functions (dashed lines) are fitted to the p_T spectra for $p_T > 8$ GeV/c. (Right) The power-law exponents extracted from the fits are plotted as a function of transverse momentum.

consequence of the multiplicity selection bias towards hard processes which is induced when one determines the event multiplicity and the p_T spectrum within the same narrow pseudorapidity interval [29]. Figure 1 also shows the ratios of the p_T spectra for the different multiplicity classes divided by that for minimum-bias *pp* collisions. They exhibit an important increase with p_T, similar to the one observed in the R_{AA} measured in Pb-Pb collisions [24]. To characterize the changes with multiplicity we fitted a power-law function ($\propto p_T^{-n}$) to the p_T spectrum of a specific colliding system and for a given multiplicity class [40]. The power-law exponents allow us to investigate in a bias-free manner various systems, multiplicities, and energies.

Figure 2 displays the multiplicity-dependent transverse momentum spectra and their corresponding fitted power-law functions for *pp* collisions at $\sqrt{s} = 13$ TeV. To our surprise,

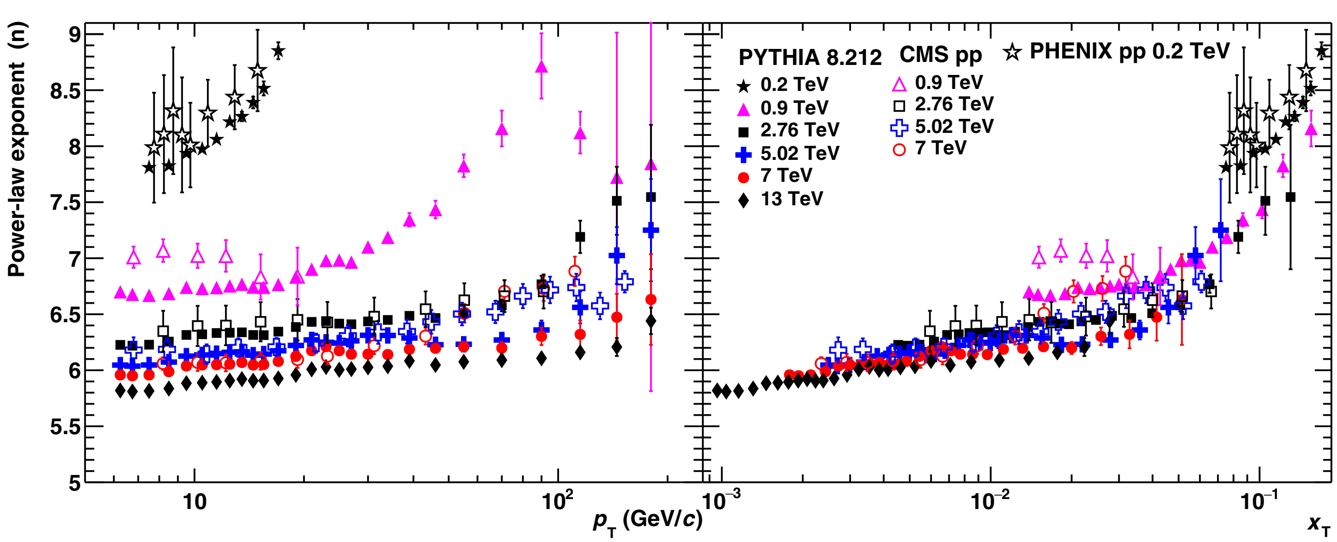

FIG. 3. Power-law exponent as a function of transverse momentum (right) and x_T (left) for minimum-bias *pp* collisions at different energies. The data have been taken from [24,34–38]. Results are compared with PYTHIA 8.212 predictions.

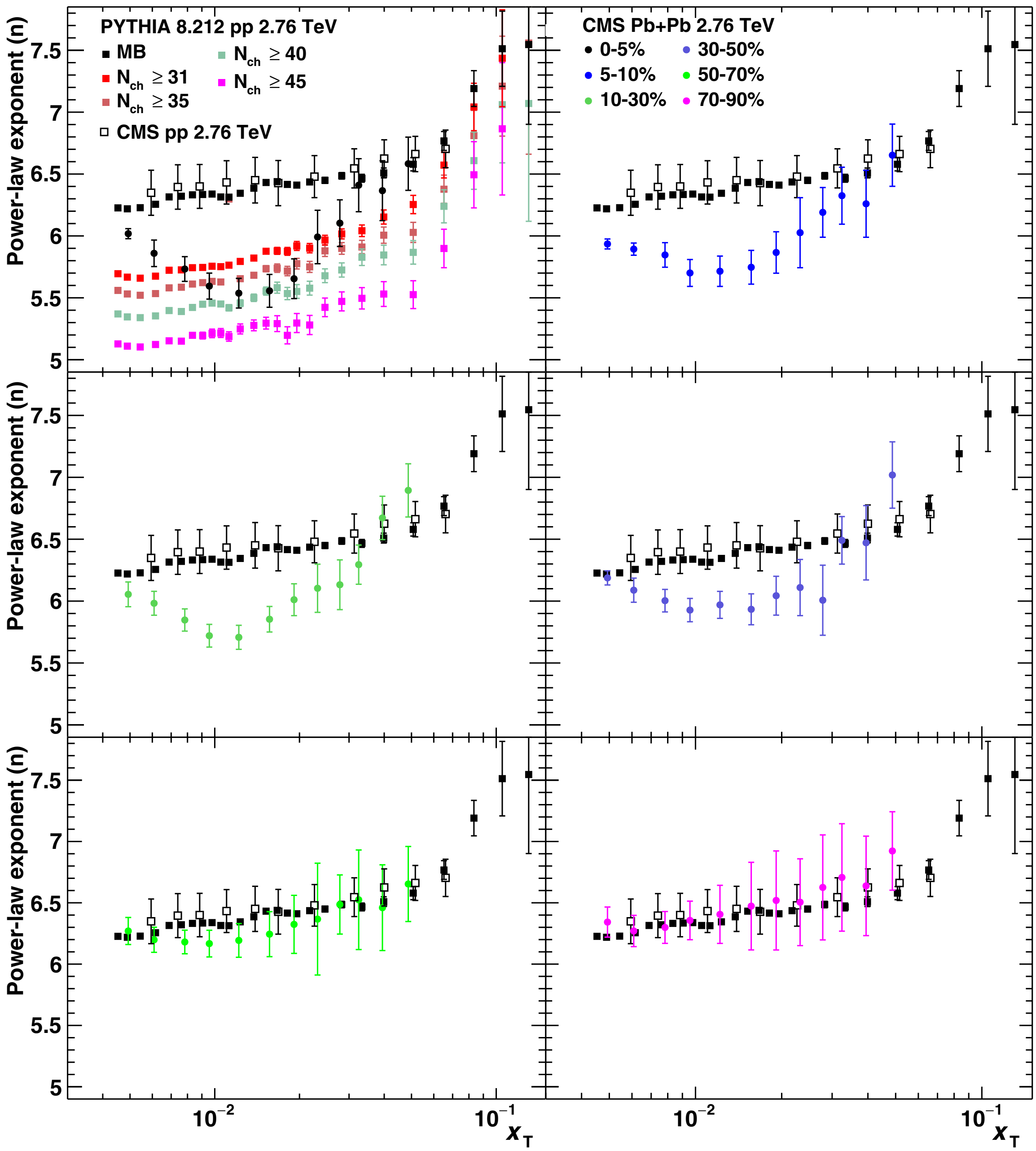

FIG. 4. (Upper left) Power-law exponent as a function of x_T for central Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. Heavy-ion data [39] are compared with minimum-bias (MB) CMS data for pp collisions [35] and high-multiplicity ($|\eta| < 0.8$) pp collisions at $\sqrt{s} = 2.76$ TeV simulated with PYTHIA 8.212. Other panels show the centrality-dependent power-law exponents of Pb-Pb collisions as a function of x_T compared with results from MB pp collisions.

we observed that it is not possible to describe the full p_T (8–300 GeV/c) interval assuming the same power-law exponent. For instance, for p_T larger than 20 GeV/c the ratios go beyond 20%. To check this, we have performed the fit considering subintervals of p_T . This allows the extraction of local power-law exponents for different p_T subintervals. The results indicate that the exponent has an important dependence on p_T . This is shown in the right-hand side of Fig. 2 where the multiplicity dependence of n as a function of p_T is shown. The exponents have a very specific behavior with multiplicity. At low multiplicities the exponents rise more rapidly than the minimum-bias ones. At $\sqrt{s} = 13$ TeV one observes a behavior of exponents below the minimum-bias ones until quite sizable multiplicities of 25 are reached. Above, the spectra tend to have exponents that are smaller than observed for minimum bias. We observe that for all multiplicity classes there is a trend to have smaller exponents (softening of the spectra) at higher momenta, the tendency getting smaller for high multiplicities. Theoretically p_T can range from 0 to half of the center-of-mass energy $\sqrt{s}/2$ of the collision. Therefore, the

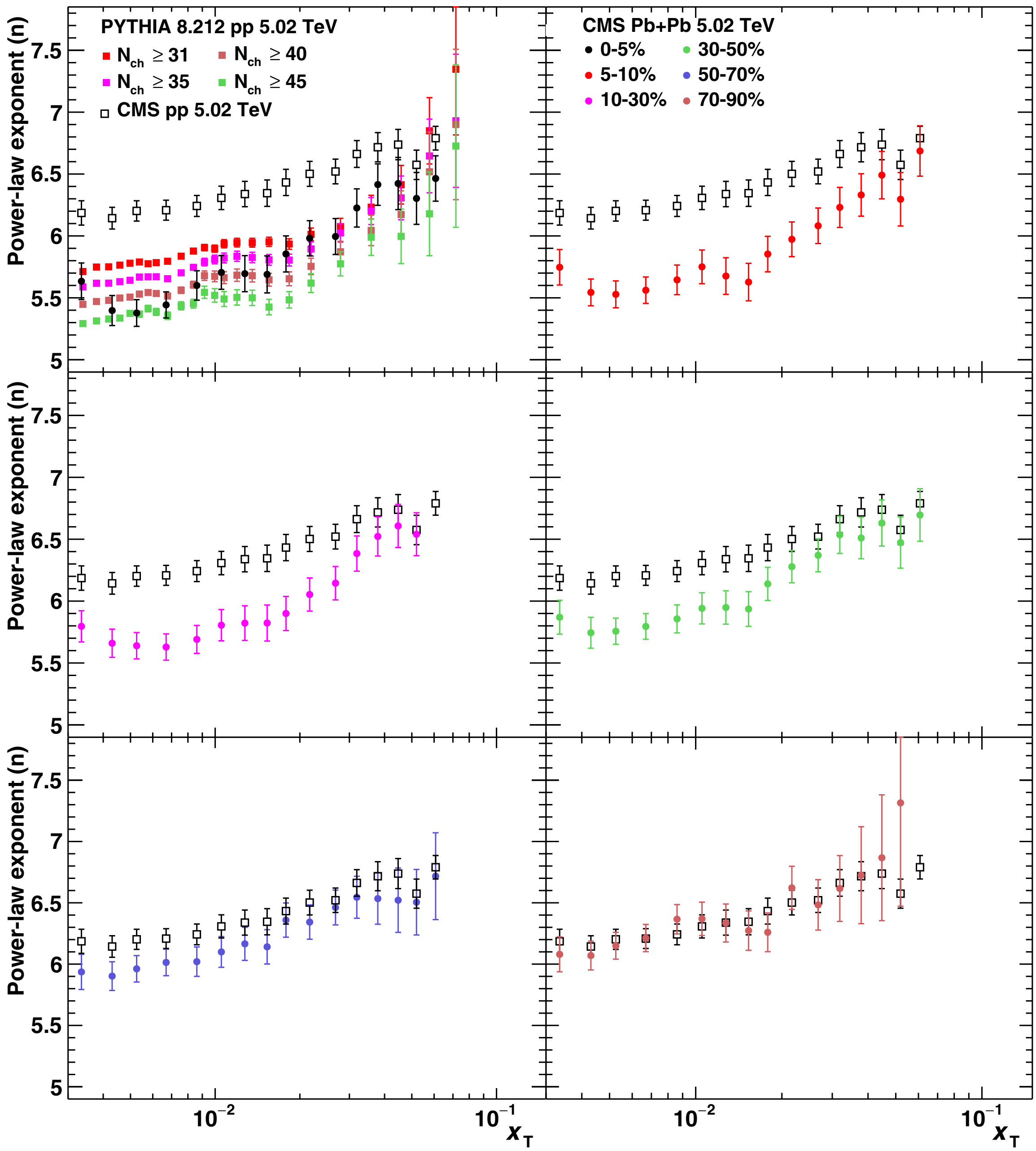

FIG. 5. (Upper left) Power-law exponent as a function of x_T for central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Heavy-ion data [24] are compared with minimum-bias and high-multiplicity ($|\eta| < 0.8$) pp collisions at $\sqrt{s} = 5.02$ TeV simulated with PYTHIA 8.212. Other panels show the centrality-dependent power-law exponents of Pb-Pb collisions as a function of x_T compared with results from MB pp collisions.

distribution can also be presented as a function of the dimensionless variable $x_T = 2p_T/\sqrt{s}$ [41], which varies between 0 and 1.

In Fig. 3 we show n as a function of p_T for minimum-bias pp data at different $\sqrt{s}$ (0.2, 0.9, 2.76, 5.02, 7, and 13 TeV [24,34–38]). The results are compared with PYTHIA 8.212 [29] (tune Monash 2013 [31]) simulations. Going from low to high energies the power-law exponent decreases in both data and PYTHIA 8.212. This is expected because at higher energies the production cross sections of hard processes increase resulting in a change in the slope of the spectra at large transverse momenta. A different representation is shown in the right-hand-side plot, where the power-law exponent is presented as a function of x_T. Within 10% the data, that were before distinctly different, fall now approximately on a universal curve. Prominent in this respect is the case of the $\sqrt{s} = 0.2$ TeV data. The approximate scaling property is well reproduced by PYTHIA 8.212.

Applying now the same treatment to the Pb-Pb data we observe that the exponents as a function of x_T and centrality behave very similar to those for pp collisions simulated with PYTHIA 8.212. The comparison in shown in Fig. 4 for pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Going from 70%–90% peripheral to 0%–5% central Pb-Pb collisions the exponent exhibits an overall decrease for x_T below 0.02. This is consistent with the hardening of the p_T spectra going from peripheral to central Pb-Pb collisions. For higher x_T (>0.02) the exponents gradually rise towards the minimum-bias value at $x_T \approx 0.04$. This behavior is consistent with the approaching to unity of R_{AA} at very high p_T [23]. The multiplicity dependence of n vs x_T in pp collisions simulated with PYTHIA 8.212 is qualitatively similar to that observed in heavy-ion data. The same behavior is also observed at higher energies; in particular Fig. 5 shows results for Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The observed behavior invites one interesting consequence. The accepted view which entirely attributes the rise in R_{AA} to the decrease of the parton energy loss should be revised. It is well known that the mean p_T continues rising with multiplicity both in pp and in heavy-ion collisions, implying that high multiplicity, which is proportional to the energy density, is correlated with the high-momentum particle production.

IV. CONCLUSION

We have studied the high-p_T ($p_T > 8$ GeV/c) charged-particle production in both pp and Pb-Pb collisions. Considering different p_T subintervals, power-law functions were fitted to the transverse momentum distributions of minimum-bias pp collisions measured by experiments at the RHIC and LHC. The local exponents of the power-law fits were compared to those obtained from Pb-Pb data. Using PYTHIA 8 simulations, we also studied the charged-particle multiplicity dependence of the exponent in pp collisions. With respect to minimum-bias pp collisions, we have determined the following.

(1) The high-p_T part of the p_T spectra cannot be described by a single power-law function (same exponent value) within a wide p_T interval (8–100 GeV/c).

(2) The minimum-bias p_T spectra, when represented in terms of the local exponent as a function of the Bjorken variable x_T, obey an approximate scaling behavior over a wide range of center-of-mass energy, $\sqrt{s} =$ 0.2–13 TeV.

(3) The p_T spectral shape (characterized by local exponents) as a function of multiplicity exhibits a specific behavior. For $8 < p_T < 30$ GeV/c the local exponents are smaller than those for minimum-bias events, i.e., the p_T spectra are harder for high-multiplicity events than that for minimum-bias pp collisions. At higher p_T (30–100 GeV/c) the exponents gradually increase to reach the values which describe the minimum-bias p_T spectra.

(4) For heavy-ion collisions the evolution of the local exponent as a function of x_T and collision centrality is qualitatively similar to that for pp collisions. The only specific difference is that the heavy-ion data show a particular shape of the exponent evolution with a downward trend for lower values of x_T (p_T). This is not observed in pp collision, but one has to consider that PYTHIA 8 does not necessarily describe the multiplicity-dependent pp data. Unfortunately at the present, pp data for different multiplicity classes and wide p_T intervals are not available.

It would be very important to produce experimental results on high-multiplicity pp collisions over a wide p_T interval to be able to assess in details the source of the apparent similarity between pp and A-A data.

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