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Multiplicity dependence of the average transverse momentum in pp, p–Pb, and Pb–Pb collisions at the LHC [☆]

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ABSTRACT

The average transverse momentum $\langle p_T \rangle$ versus the charged-particle multiplicity N_{ch} was measured in p–Pb collisions at a collision energy per nucleon–nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV and in pp collisions at collision energies of $\sqrt{s} = 0.9, 2.76,$ and 7 TeV in the kinematic range $0.15 < p_T < 10.0$ GeV/c and $|\eta| < 0.3$ with the ALICE apparatus at the LHC. These data are compared to results in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at similar charged-particle multiplicities. In pp and p–Pb collisions, a strong increase of $\langle p_T \rangle$ with N_{ch} is observed, which is much stronger than that measured in Pb–Pb collisions. For pp collisions, this could be attributed, within a model of hadronizing strings, to multiple-parton interactions and to a final-state color reconnection mechanism. The data in p–Pb and Pb–Pb collisions cannot be described by an incoherent superposition of nucleon–nucleon collisions and pose a challenge to most of the event generators.

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Measurements of particle production in proton–nucleus collisions at the Large Hadron Collider (LHC) energies allow the study of fundamental Quantum Chromodynamics (QCD) properties at low parton fractional momentum x and high gluon densities; see [1] for a recent review. Additionally, they provide an important reference measurement for studies of the properties of the QCD matter created in nucleus–nucleus collisions; see [2] for an overview of results at the LHC.

The first measurements of charged-particle production in p–Pb collisions at the LHC at a center-of-mass energy per nucleon–nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV [3,4] exhibited differences compared to pp collisions. These differences were mostly confined to low transverse momentum (p_T), leading to a slightly smaller average multiplicity per number of participating nucleons in p–Pb compared to pp collisions [3], while above a few GeV/c the p_T spectrum in p–Pb collisions exhibits binary collision scaling [4]. The measurements of particle correlations in azimuth and pseudorapidity [5–9] have raised the question whether collective effects in p–Pb collisions, as modeled for example in hydrodynamical approaches [10,11], are the origin of the observed correlations. Initial state effects, such as gluon saturation described by color glass condensate (CGC) models [12,13], reproduce the elliptic flow component, but the triangular flow remains a challenge within such models.

It remains questionable if the small system size created in pp or p–Pb collisions could exhibit collective, fluid-like, features due to early thermalization, as observed in Pb–Pb collisions [14]. A mean-

ingful way to address this issue is to investigate production mechanisms, correlations, and event shapes as a function of the particle multiplicity. Such studies were recently performed in pp collisions at the LHC, e.g. the ALICE measurements of two-pion Bose–Einstein correlations [15], event sphericity [16], J/ψ meson production [17], and anti-baryon to baryon ratios [18], or the measurements by CMS of long-range angular correlations [19] and of π , K , and p production [20].

The first moment of the charged-particle transverse momentum spectrum, $\langle p_T \rangle$, and its correlation with the charged-particle multiplicity N_{ch} , first observed at the Sp \bar{p} S collider [21], carries information about the underlying particle production mechanism. This has been studied by many experiments at hadron colliders in pp(\bar{p}) covering collision energies from $\sqrt{s} = 31$ GeV up to 7 TeV [22–29]. All experiments observed an increase of $\langle p_T \rangle$ with N_{ch} in the central rapidity region, a feature which could be reproduced in the PYTHIA event generator only if a mechanism of hadronization including color correlations (reconnections) is considered [30]. Although a good description of Tevatron data [26] was achieved within the PYTHIA 8 model [31], which also described the early LHC data [32], full consistency of the data description within models is yet to be achieved [33]. The LHC data highlighted the importance of color reconnections [34]; see also [33] and the discussion below. Data at LHC energies covering a large momentum range starting at low p_T provide additional input to these models.

In this Letter, we present a measurement of the average transverse momentum (p_T) versus the charged-particle multiplicity N_{ch} in p–Pb collisions at a collision energy per nucleon–nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV for primary particles in the kinematic range $|\eta| < 0.3$. These data are compared to results in pp interactions

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at collision energies of $\sqrt{s} = 0.9, 2.76,$ and 7 TeV and to results obtained in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The measurements are performed with the ALICE apparatus [35] at the LHC. The data in minimum-bias pp collisions were recorded in the years 2009–2011, details are given in [36]; the Pb–Pb data are from the 2010 run [37]. The p–Pb data were recorded during an LHC run of 4 weeks in January and February 2013 triggering on non-single-diffractive collisions [3]. The number of colliding bunches varied between 8 and 288. The proton and Pb bunch intensities ranged from 1.4×10^{10} to 1.9×10^{10} and from 0.8×10^{10} to 1.4×10^{10} particles, respectively. The luminosity at the ALICE interaction point was up to $5 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ resulting in a hadronic interaction rate of 10 kHz. The interaction region had an r.m.s. of 6.3 cm along the beam direction and about 60 μm transverse to the beam. The p–Pb minimum-bias events were triggered by requiring a signal in each of the VZERO detector arrays, VZERO-A located at $2.8 < \eta_{\text{lab}} < 5.1$ and VZERO-C at $-3.7 < \eta_{\text{lab}} < -1.7$, both covering full azimuth. The pseudorapidity of a charged particle in the detector reference-frame η_{lab} is defined as $\eta_{\text{lab}} = -\ln[\tan(\theta/2)]$, with θ the polar angle between the beam axis and the charged particle. The pp minimum-bias events were triggered requiring at least a hit in any of the VZERO detectors or in the silicon pixel detector covering $|\eta_{\text{lab}}| < 1.4$.

The offline event and track selection is identical to that used in the measurement of the charged-particle pseudorapidity density $dN_{\text{ch}}/d\eta_{\text{lab}}$ [3] and the p_{T} spectra in p–Pb [4] and Pb–Pb [37] collisions with ALICE. In total, 106 million events for p–Pb collisions, 7, 65, and 150 millions for pp collisions at $\sqrt{s} = 0.9, 2.76,$ and 7 TeV, respectively, and 15 millions for Pb–Pb collisions satisfy the trigger and offline event-selection criteria. Primary charged particles are defined as all prompt particles produced in the collision, including all decay products, except those from weak decays of strange hadrons. The efficiency and purity of the primary charged-particle selection are estimated from a Monte Carlo simulation using DPMJET [38] as an event generator with particle transport through the ALICE detector using GEANT3 [39].

Due to the asymmetric beam energies for the proton and lead beam, the nucleon–nucleon center-of-mass system is moving in the laboratory frame with a rapidity of $y_{\text{NN}} = -0.465$; the proton beam has negative rapidity. In order to ensure good detector acceptance around midrapidity, tracks are selected for this analysis in the pseudorapidity interval $|\eta| < 0.3$ in the nucleon–nucleon center-of-mass system. In the absence of information on the particle mass, the particle rapidity is unknown. Therefore, we calculate $\eta = \eta_{\text{lab}} - y_{\text{NN}}$, an approximation which is only accurate for massless particles or relativistic particles. The spectra are corrected based on our knowledge of the pion, kaon, and proton yields measured by ALICE [40]. The correction is below 2% for $p_{\text{T}} < 0.5$ GeV/c and below 1% for $p_{\text{T}} \geq 0.5$ GeV/c. The average transverse momentum $\langle p_{\text{T}} \rangle$ is then calculated from the corrected spectra as the arithmetic mean in the kinematic range $0.15 < p_{\text{T}} < 10.0$ GeV/c and $|\eta| < 0.3$. The number of accepted charged particles n_{acc} is the sum of all reconstructed charged particles in the same kinematic range. To extract the correlation between $\langle p_{\text{T}} \rangle$ and the number of primary charged particles N_{ch} , counting, for N_{ch} , all particles down to $p_{\text{T}} = 0$, a reweighting procedure is applied to account for the experimental resolution in the measured event multiplicity as described in [27]. This method employs a normalized response matrix from Monte Carlo simulations which contains the probability that an event with multiplicity N_{ch} is reconstructed with multiplicity n_{acc} .

The systematic uncertainties of the charged-particle spectrum are evaluated in a similar way as in previous analyses of pp [27], Pb–Pb [37], and p–Pb [4] data and are propagated to $\langle p_{\text{T}} \rangle$. The main contributions and the total uncertainties are listed in Table 1.

Table 1

Relative systematic uncertainties on $\langle p_{\text{T}} \rangle$ in pp, p–Pb, and Pb–Pb collisions for $|\eta| < 0.3$ and $0.15 < p_{\text{T}} < 10.0$ GeV/c. The quoted ranges reflect the N_{ch} dependence and, for pp collisions, also some energy dependence.

Source	pp	p–Pb	Pb–Pb
Track selection	0.5–1.8%	0.8–1.0%	1.1–1.2%
Particle composition	0.2–0.4%	0.7–0.8%	0.2–0.3%
Tracking efficiency	0.1%	0.2%	0.1%
Monte Carlo generator	$\leq 0.2\%$	0.1–0.2%	0.2%
Reweighting procedure	2.3–4.1%	1.3–1.8%	0.5–1.2%
Total	2.4–4.5%	1.8–2.2%	1.2–3.0%

Table 2

Characteristics of pp, p–Pb, and Pb–Pb collisions for events with at least one charged particle with $p_{\text{T}} > 0.15$ GeV/c in $|\eta| < 0.3$. The average multiplicity (N_{ch}) is for $|\eta| < 0.3$ and extrapolating to $p_{\text{T}} = 0$. The average transverse momentum $\langle p_{\text{T}} \rangle$ is obtained in $|\eta| < 0.3$ and in the range $0.15 < p_{\text{T}} < 10.0$ GeV/c. The systematic uncertainties are reported; the statistical uncertainties are negligible. The uncertainties of $\langle N_{\text{ch}} \rangle$ are from the tracking efficiency.

Collision system	$\sqrt{s_{\text{NN}}}$ (TeV)	$\langle N_{\text{ch}} \rangle$	$\langle p_{\text{T}} \rangle$ (GeV/c)
pp	0.9	3.14 ± 0.16	0.540 ± 0.020
pp	2.76	3.82 ± 0.19	0.584 ± 0.020
pp	7	4.42 ± 0.22	0.622 ± 0.021
p–Pb	5.02	11.9 ± 0.5	0.696 ± 0.024
Pb–Pb	2.76	259.9 ± 5.9	0.678 ± 0.007

Other contributions investigated are material budget, trigger and event selection, and secondary particles from weak decays. The uncertainty from each of these contributions is below 0.1%, except the trigger and event selection, which amounts to 0.35% for $N_{\text{ch}} = 1$. For p–Pb collisions, the effect of the particle composition on the uncertainty from acceptance due to the shift in rapidity is included in Table 1. A comparison of the present measurement was performed for the centrality classes and the p_{T} range ($0.3 < p_{\text{T}} < 2$ GeV/c) of the data on pions, kaons and protons [40]. The agreement is within 0.5%, well within the estimated uncertainty quoted above. In Pb–Pb collisions, an additional source of uncertainty at low N_{ch} is electromagnetic (EM) processes. A correction of $\langle p_{\text{T}} \rangle$ of 2.7% for $N_{\text{ch}} = 1$ and less than 1% for $N_{\text{ch}} > 5$ was estimated based on a comparison to events in the centrality range 0–90%, where EM events are efficiently rejected [41]. A conservative systematic uncertainty equal to the correction was assigned to this correction and is included in the total uncertainty listed in Table 1.

The uncertainty from the reweighting method is extracted based on the Monte Carlo events. The reweighting procedure is performed using a response matrix generated with a second event generator and the outcome distribution $\langle p_{\text{T}} \rangle(N_{\text{ch}})$ is compared with the initial distribution. For pp collisions, PYTHIA6 (Perugia0) [34], PYTHIA8 [42] and PHOJET [43] event generators are used, while for p–Pb and Pb–Pb collisions we employ the DPMJET [38] and HIJING [44] event generators. This uncertainty dominates the overall uncertainty at low N_{ch} , and, in pp collisions, also at large N_{ch} . An alternative method, based on the integration and extrapolation of p_{T} spectra in n_{acc} bins, gives results well within the systematic uncertainties.

The values of $\langle N_{\text{ch}} \rangle$ and $\langle p_{\text{T}} \rangle$ for events with at least one charged particle with $p_{\text{T}} > 0.15$ GeV/c in $|\eta| < 0.3$ for pp, p–Pb, and Pb–Pb collisions are presented in Table 2. A small increase in $\langle p_{\text{T}} \rangle$ is observed in pp collisions as a function of energy. An increase is seen from pp to p–Pb and to minimum-bias Pb–Pb collisions.

The average transverse momentum $\langle p_{\text{T}} \rangle$ of charged particles is shown in Fig. 1 as a function of the charged-particle multiplicity N_{ch} for pp collisions at $\sqrt{s} = 0.9, 2.76,$ and 7 TeV. The multiplicity distributions in pp collisions [45,46] fall off steeply for

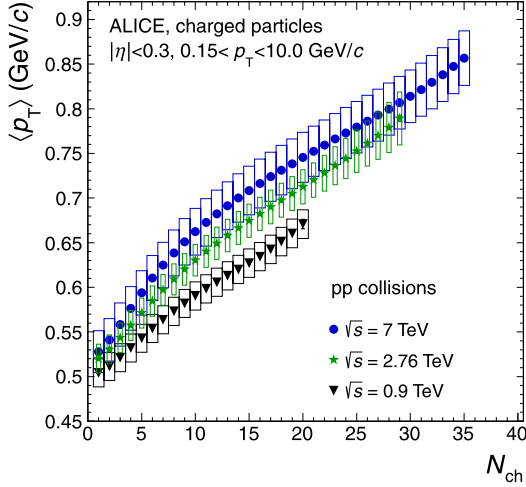


Fig. 1. Average transverse momentum $\langle p_T \rangle$ in the range $0.15 < p_T < 10.0$ GeV/c as a function of charged-particle multiplicity N_{ch} in pp collisions at $\sqrt{s} = 0.9, 2.76,$ and 7 TeV, for $|\eta| < 0.3$. The boxes represent the systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

large N_{ch} . The present measurement extends up to values of N_{ch} where statistical errors for $\langle p_T \rangle$ in the corresponding n_{acc} values are below 5%. An increase in $\langle p_T \rangle$ with N_{ch} is observed for all collision energies and also an increase with the collision energy at fixed values of N_{ch} , which agrees well with measurements reported by ATLAS [29,47] at $\sqrt{s} = 0.9$ and 7 TeV. We note a change in slope for all three collision energies at roughly the same value of $N_{ch} \approx 10$. This change in slope was also observed at Tevatron [24,26] and recently at the LHC [29,27].

In Monte Carlo event generators, high-multiplicity events are produced by multiple parton interactions. An incoherent superposition of such interactions would lead to a constant $\langle p_T \rangle$ at high multiplicities. The observed strong correlation of $\langle p_T \rangle$ with N_{ch} has been attributed, within PYTHIA models, to color reconnections (CR) between hadronizing strings [34]. In this mechanism, which can be interpreted as a collective final-state effect, strings from independent parton interactions do not hadronize independently, but fuse prior to hadronization. This leads to fewer hadrons, but more energetic. The CR strength is implemented as a probability parameter in the models. The CR mechanism bears similarity to the mechanism of string fusion [48] advocated early for nucleus–nucleus collisions. A model based on Pomeron exchange was shown to fit the pp data [49]. A mechanism of collective string hadronization is also used in the EPOS model, which was shown recently to describe a wealth of LHC data in pp, p–Pb, and Pb–Pb collisions [50].

Fig. 2 shows the average transverse momentum $\langle p_T \rangle$ of charged particles versus the charged-particle multiplicity N_{ch} as measured in pp collisions at $\sqrt{s} = 7$ TeV, in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, and in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In p–Pb collisions, we observe an increase of $\langle p_T \rangle$ with N_{ch} , with $\langle p_T \rangle$ values similar to the values in pp collisions up to $N_{ch} \approx 14$. At multiplicities above $N_{ch} \approx 14$, the measured $\langle p_T \rangle$ is lower in p–Pb collisions than in pp collisions; the difference is more pronounced with increasing N_{ch} . This difference cannot be attributed to the difference in collision energy, as the energy dependence of $\langle p_T \rangle$ is rather weak, see Fig. 1. In contrast, in Pb–Pb collisions, with increasing N_{ch} , there is only a moderate increase in $\langle p_T \rangle$ up to high charged-particle multiplicity with a maximum value of $\langle p_T \rangle = 0.685 \pm 0.016$ (syst.) GeV/c, which is substantially lower than the maximum value in pp. For pp and p–Pb, $N_{ch} > 14$ corresponds to about 10% and 50% of the cross section for events with at least one

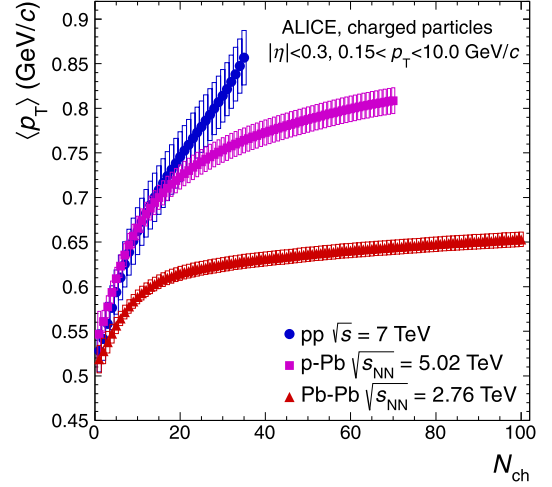


Fig. 2. Average transverse momentum $\langle p_T \rangle$ versus charged-particle multiplicity N_{ch} in pp, p–Pb, and Pb–Pb collisions for $|\eta| < 0.3$. The boxes represent the systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

charged particle with $p_T > 0.15$ GeV/c in $|\eta| < 0.3$, respectively, while for Pb–Pb collisions this fraction is about 82%; $N_{ch} > 40$ corresponds to the upper 1% of the cross section in p–Pb and to about 70% most central Pb–Pb collisions. This illustrates that the same N_{ch} value corresponds to a very different collision regime in the three systems.

In Pb–Pb collisions, substantial rescattering of constituents are thought to lead to a redistribution of the particle spectrum where most particles are part of a locally thermalized medium exhibiting collective, hydrodynamic-type, behavior. The moderate increase of $\langle p_T \rangle$ seen in Pb–Pb collisions (in Fig. 2, for $N_{ch} \gtrsim 10$) is thus usually attributed to collective flow [51]. The p–Pb data exhibit features of both pp and Pb–Pb collisions, at low and high multiplicities, respectively. However, the saturation trend of $\langle p_T \rangle$ versus N_{ch} is less pronounced in p–Pb than in Pb–Pb collisions and leads to a much higher value of $\langle p_T \rangle$ at high multiplicities than in Pb–Pb. An increase in $\langle p_T \rangle$ of a few percent is expected in Pb–Pb from $\sqrt{s_{NN}} = 2.76$ TeV to 5 TeV, but it appears unlikely that the p–Pb $\langle p_T \rangle$ values will match those in Pb–Pb at the same energy. While the p–Pb data cannot exclude collective hydrodynamic-type effects for high-multiplicity events, it is clear that such a conclusion requires stronger evidence. The features seen in Fig. 2 do not depend on the kinematic selection; similar trends are found for $|\eta| < 0.8$ ($|\eta_{lab}| < 0.8$, for p–Pb collisions) or for $p_T > 0.5$ GeV/c.

Fig. 3 shows a comparison of the data to model predictions for $\langle p_T \rangle$ versus N_{ch} in pp collisions at $\sqrt{s} = 7$ TeV, p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For pp collisions, calculations using PYTHIA 8 with tune 4C are shown with and without the CR mechanism. As shown earlier [26,29], the model only gives a fair description of the data when the CR mechanism is included. Qualitatively, the difference between p–Pb and Pb–Pb collisions seen in Fig. 2 is similar to the difference seen in pp collisions between the cases with CR and without CR. The predictions using the EPOS model (1.99, v3400) describe the data well, as expected, given the recent tuning based on the LHC data [50]. In this model collective effects are introduced via parametrizations, for the sake of computation time; a full hydrodynamics treatment is available in other versions of this model, see [50]. In p–Pb collisions, none of the three models, DPMJET [38] (v3.0), HIJING [44] (v1.383), or AMPT [52] (v2.25, with the string melting option), describes the data. These models predict values of $\langle p_T \rangle$ significantly below the p–Pb data. The predictions of the EPOS model describe the magnitude of the data but show a different trend than data

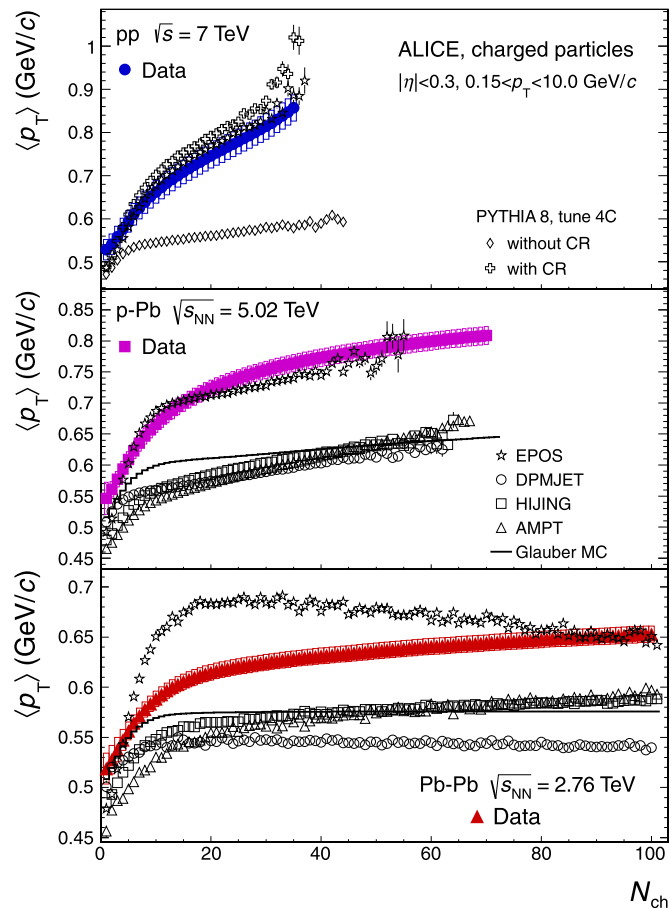


Fig. 3. Average transverse momentum $\langle p_T \rangle$ as a function of charged-particle multiplicity N_{ch} measured in pp (upper panel), p-Pb (middle panel), and Pb-Pb (lower panel) collisions in comparison to model calculations. The data are compared to calculations with the DPMJET, HIJING, AMPT, and EPOS Monte Carlo event generators. For pp collisions, calculations with PYTHIA 8 [42] with tune 4C are shown with and without the color reconnection (CR) mechanism. The lines show calculations in a Glauber Monte Carlo approach (see text).

at moderate multiplicities ($N_{ch} < 20$). In addition to predictions from event generators, results of a calculation in a Glauber approach are shown. In this approach, p-Pb collisions are assumed to be a superposition of independent nucleon-nucleon collisions, each characterized in terms of measured multiplicity distributions in pp collisions [45,46] and the $\langle p_T \rangle$ values as a function of N_{ch} for $\sqrt{s} = 7$ TeV shown in Fig. 1 (for a similar approach, see [53]). This calculation (continuous line in Fig. 3) underpredicts the data, producing, interestingly, results similar to those of event generators. The conclusion that $\langle p_T \rangle$ in p-Pb collisions is not a consequence of an incoherent superposition of nucleon-nucleon collisions invites an analogy to the observation that $\langle p_T \rangle$ in pp collisions cannot be described by an incoherent superposition of multiple parton interactions. Whether initial state effects, as considered for the measurement of the nuclear modification factor of charged-particle production [4], or final-state effects analogous to the CR mechanism are responsible for this observation, remains to be further studied. In Pb-Pb collisions, the DPMJET, HIJING, and AMPT models fail to describe the data, predicting, as in p-Pb collisions, lower values of $\langle p_T \rangle$ than the measurement. The EPOS model overpredicts the data and shows an opposite trend versus N_{ch} ; note, however, that the present model [50] includes collective flow via parametrizations and not a full hydrodynamic treatment. Also the Glauber MC model with inputs from $\langle p_T \rangle$ data at $\sqrt{s} = 2.76$ TeV

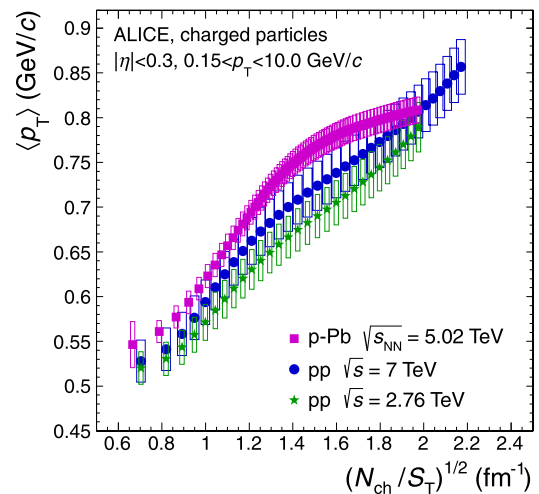


Fig. 4. Average transverse momentum $\langle p_T \rangle$ as a function of the scaled charged-particle multiplicity in p-Pb and pp collisions for $|\eta| < 0.3$. The boxes represent the systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

and the measured multiplicity distribution at $\sqrt{s} = 2.36$ TeV [45] fails to describe the data.

The data are compared to the geometrical scaling recently proposed in [54] (and references therein) within the color glass condensate model [55]. In this picture, the $\langle p_T \rangle$ is a universal function of the ratio of the multiplicity density and the transverse area of the collision, S_T , calculated within the color-glass model [14]. A reasonable agreement was found between this model and CMS data [56]. Employing the parametrizations of S_T for pp and p-Pb proposed in [54], the scaling plot in Fig. 4 is obtained. The ALICE pp data as well as the p-Pb data at low and intermediate multiplicities are compatible with the proposed scaling. As already noted above while discussing Fig. 2 and Fig. 3, the behavior of p-Pb data at high multiplicities, $N_{ch} \gtrsim 14$, shows a departure from the pp values and cannot be described by a binary collision superposition of pp data. The deviation from scaling visible in Fig. 4 for $(N_{ch}/S_T)^{1/2} \gtrsim 1.2$ is related to these observations.

In summary, we have presented the average transverse momentum $\langle p_T \rangle$ in dependence of the charged-particle multiplicity N_{ch} measured in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, in pp collisions at collision energies of $\sqrt{s} = 0.9, 2.76,$ and 7 TeV and in peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the kinematic range $0.15 < p_T < 10.0$ GeV/c and $|\eta| < 0.3$. In pp and p-Pb collisions, a strong increase of $\langle p_T \rangle$ with N_{ch} is observed, which is understood, in models of pp collisions, as an effect of color reconnections between strings produced in multiple parton interactions. Whether the same mechanism is at work in p-Pb collisions, in particular for incoherent proton-nucleon interactions, is an open question. The EPOS model describes the p-Pb data assuming collective flow; it remains to be further studied if initial state effects are compatible with the data. The $\langle p_T \rangle$ values in Pb-Pb collisions, instead, indicate a softer spectrum and with a much weaker dependence on multiplicity. These data pose a challenge to most of the existing models and are an essential input to improve our understanding of particle production as well as the role of initial and final-state effects in these systems.

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