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Pseudorapidity density of charged particles in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration*

Abstract

The charged-particle pseudorapidity density measured over 4 units of pseudorapidity in non-single-diffractive (NSD) p–Pb collisions at a centre-of-mass energy per nucleon pair $\sqrt{s_{NN}}$= 5.02 TeV is presented. The average value at midrapidity is measured to be 16.81 ± 0.71 (*syst.*), which corresponds to 2.14 ± 0.17 (*syst.*) per participating nucleon, calculated with the Glauber model. This is 16% lower than in NSD pp collisions interpolated to the same collision energy, and 84% higher than in d–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV. The measured pseudorapidity density in p–Pb collisions is compared to model predictions, and provides new constraints on the description of particle production in high-energy nuclear collisions.

*See Appendix A for the list of collaboration members

Particle production in proton–lead collisions, in contrast to pp, is expected to be sensitive to nuclear effects in the initial state. In particular, coherence effects in the nuclear wave function are expected to influence the initial parton flux, as well as the underlying description of particle production in the scattering processes. Therefore, measurements in p–Pb collisions at the Large Hadron Collider (LHC) at CERN provide an essential experimental tool to discriminate between the initial and final state effects, and allow one to attribute the latter to the formation of hot QCD matter in heavy-ion collisions [1]. Moreover, at LHC energies, the nuclear wave function is probed at small parton fractional momentum x. The growth of the parton densities with decreasing x must be limited to satisfy unitarity bounds. One of the mechanisms providing such a limitation is often referred to as gluon saturation. Its theoretical description varies between models of particle production resulting in significant differences in the predictions of the charged-particle pseudorapidity density. Thus, the measurements of particle production in p–Pb collisions constrain and potentially exclude certain models, and enhance the understanding of QCD at small x and the initial state.

In this letter, the measurement of the primary charged-particle pseudorapidity density in p–Pb collisions at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE detector [2] is reported. The primary charged-particle density, $dN_{\rm ch}/d\eta_{\rm lab}$, is measured in non single-diffractive (NSD) p–Pb collisions for $|\eta_{\rm lab}| < 2$, where $\eta_{\rm lab} = -\ln\tan(\theta/2)$ and θ is the polar angle between the charged-particle direction and the beam axis (z). Primary particles are defined as prompt particles produced in the collision, including decay products, except those from weak decays of strange particles. The data are compared to model predictions [3–7], and to measurements in proton–nucleus [8, 9], NSD [10–16], and inelastic [17–20] pp ($\mathrm{p\overline{p}}$), as well as central heavy-ion [20–31] collisions.

The p–Pb collisions were provided by the LHC during a short pilot run performed in September 2012 in preparation for the p–Pb physics run scheduled for the beginning of 2013. The two-in-one magnet design of the LHC imposes the same magnetic rigidity of the beams in the two rings. Beam 1 consisted of protons at 4 TeV energy circulating in the negative z-direction in the ALICE laboratory system, while beam 2 consisted of fully stripped $^{208}_{82}$Pb ions at 82×4 TeV energy circulating in the positive z-direction. This configuration resulted in collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in the nucleon–nucleon centre-of-mass system, which moves with a rapidity of $\Delta y_{\rm NN} = 0.465$ in the direction of the proton beam.

The main detector for the present analysis is the Silicon Pixel Detector (SPD), located in the inner barrel of the ALICE detector inside a solenoidal magnet providing a magnetic field of 0.5 T. The SPD consists of two cylindrical layers of hybrid silicon pixel assemblies covering $|\eta_{\rm lab}| < 2.0$ for the inner layer and $|\eta_{\rm lab}| < 1.4$ for the outer layer with respect to vertices at the nominal interaction point. A total of 9.8×10^6 pixels of size 50×425 μm^2 are read out, of which 93.5% were active during the run. The primary trigger signal was provided by the VZERO counters, two arrays of 32 scintillator tiles each covering the full azimuth within $2.8 < \eta_{\rm lab} < 5.1$ (VZERO-A) and $-3.7 < \eta_{\rm lab} < -1.7$ (VZERO-C). The signal amplitude and arrival time collected in each scintillator are recorded. The time resolution is better than 1 ns, allowing discrimination of beam–beam collisions from background events produced outside of the interaction region. Additionally, two neutron Zero Degree Calorimeters (ZDCs) are used, which are located at $+112.5$ m (ZNA) and -112.5 m (ZNC) from the interaction point. Their energy resolution is about 20% for single neutrons with a few TeV energy. Each ZDC also provided a trigger with high efficiency for single neutrons, which was used to collect a control sample of events for the estimation of the efficiency of the VZERO trigger.

During the run, beams consisting of 13 bunches were circulating, with about 10^{10} protons and 6×10^7 Pb ions per bunch. In the ALICE interaction region, 8 pairs of bunches were colliding, leading to a luminosity of 8×10^{25} cm^{-2}s^{-1}. The luminous region had a r.m.s. width of 6.3 cm in the z-direction and about 60 μm in the transverse direction. The trigger was configured for high efficiency for hadronic events, requiring a signal in either VZERO-A or VZERO-C. This configuration led to an observed trigger rate of about 200 Hz with a hadronic collision rate of about 150 Hz. In the offline analysis, a signal is required in both VZERO-A and VZERO-C. Beam–gas and other machine-induced background triggers with deposited energy above the thresholds in the VZERO or ZDC detectors are suppressed by requiring the arrival time to be compatible with that of a nominal p–Pb interaction. The contamination from background is estimated from control triggers on non-colliding bunches, and found to be negligible.

In principle, the event sample obtained after these requirements consists of NSD collisions as well as single-diffractive (SD) and electromagnetic (EM) interactions. The efficiency of the trigger and event selection on the different processes is estimated using a combination (cocktail) of the following Monte Carlo (MC) event generators: a) DPMJET [32] for NSD p–Pb interactions, b) PHOJET [33] tuned to pp data at $\sqrt{s_{\rm NN}} = 2.76$ and 7 TeV [34] together with a Glauber model [35] for the contribution from SD interactions, and c) STARLIGHT [36] used together with PYTHIA [37] or PHOJET [33] for the proton excitation in the electromagnetic field of the ${}^{208}_{82}$Pb nucleus. The DPMJET [32] generator, which is based on the Gribov-Glauber approach and treats soft and hard scattering processes in an unified way, includes incoherent SD collisions of the projectile proton with target nucleons that are concentrated mainly on the surface of the nucleus. These are removed by requiring that at least one of the binary nucleon–nucleon interactions is NSD. The relative weight of the events in the cocktail is given by the cross sections of the corresponding processes, which are taken to be 2.0 b (0.1 b) for NSD (SD) collisions (estimated from the Glauber model), and 0.1–0.2 b for EM interactions (estimated from STARLIGHT calculations). The detector response to the cocktail is simulated using a model of the ALICE detector and the GEANT3 simulation tool [38]. An efficiency of 99.2% for NSD collisions and a negligible contamination from SD and EM interactions are obtained.

From the collected data sample used for the analysis, 0.8×10^6 events pass the selection criteria. Among the selected events, 98.5% are found to have a primary vertex. The corresponding fraction in DPMJET [32] for NSD collisions is 99.4% with the probability of selecting an event without a primary vertex of 41%. Taking into account the difference of the fraction of events without vertex in the data and the simulation results in an overall selection efficiency of 96.4% for NSD events entering the analysis.

The $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta_{\rm lab}$ analysis techniques employed are identical to those described in Ref. [29], where the similar measurement is reported for Pb–Pb collisions. Events are selected with a reconstructed vertex within $|z_{\rm vtx}| < 18$ cm, which results in a $|\eta_{\rm lab}| < 2$ coverage for the $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta_{\rm lab}$ measurement. Tracklet candidates are formed using the position of the primary vertex and two hits, one on each SPD layer. From these candidates, tracklets are selected by a requirement on the sum of the squares of the differences (residuals) in azimuthal and polar angles relative to the primary vertex for each hit, effectively selecting charged particles with transverse momentum ($p_{\rm T}$) above 50 MeV/c, while particles below 50 MeV/c are mostly absorbed by detector material. The charged-particle pseudorapidity density is then obtained from the measured distribution of tracklets $\mathrm{d}N_{\rm tracklets}/\mathrm{d}\eta_{\rm lab}$ as $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta_{\rm lab} = \alpha\,(1-\beta)\,\mathrm{d}N_{\rm tracklets}/\mathrm{d}\eta_{\rm lab}$. The correction α accounts for the acceptance and efficiency for a primary particle to produce a tracklet, while β is the contamination of reconstructed tracklets from combinations of hits not produced by the same primary particle. Both are determined as a function of the z-position of the primary vertex and the pseudorapidity of the tracklet from detector simulations using DPMJET [32] and GEANT3 [38], and found to be on average 1.2 and 0.01, respectively. Since the corrections applied in the analysis implicitly only account for the fraction of events without vertex given by the simulation, the $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta_{\rm lab}$ is further corrected by -2.2% for the difference of this fraction in the data and the simulation.

The following sources of systematic uncertainties have been considered. The uncertainty in detector acceptance is estimated to be 1.5% determined from the change of the multiplicity at a given $\eta_{\rm lab}$ by varying the range of the z-position of the vertex. The uncertainties resulting from the subtraction of the combinatorial background and from the contribution of weak decays are estimated to be 0.3% and 0.8%, respectively. They are determined from the comparison in data and simulation of the tracklet residual distributions, in which the tails are dominated by combinatorial background and secondaries. The uncertainty due to the particle composition is estimated to be 1%, which was determined by changing the relative abundances of pions, kaons and protons by a factor of 2 in the simulation. The uncertainty due to the correction down to zero $p_{\rm T}$ is estimated to be 1% by varying the amount of undetected particles at low $p_{\rm T}$ by 50%. The uncertainty related to the trigger and event selection efficiency for NSD collisions is estimated to be 3.1% using a small sample of events collected with the ZNA trigger with an offline selection on the deposited energy corresponding to approximately 12 neutrons from the Pb remnant. The value used for the threshold has been determined from DPMJET with associated nuclear fragment production [39], and was chosen to suppress the contamination of the EM and SD interactions. In total, a systematic uncertainty of about 3.8% is obtained by adding in quadrature all the contributions.

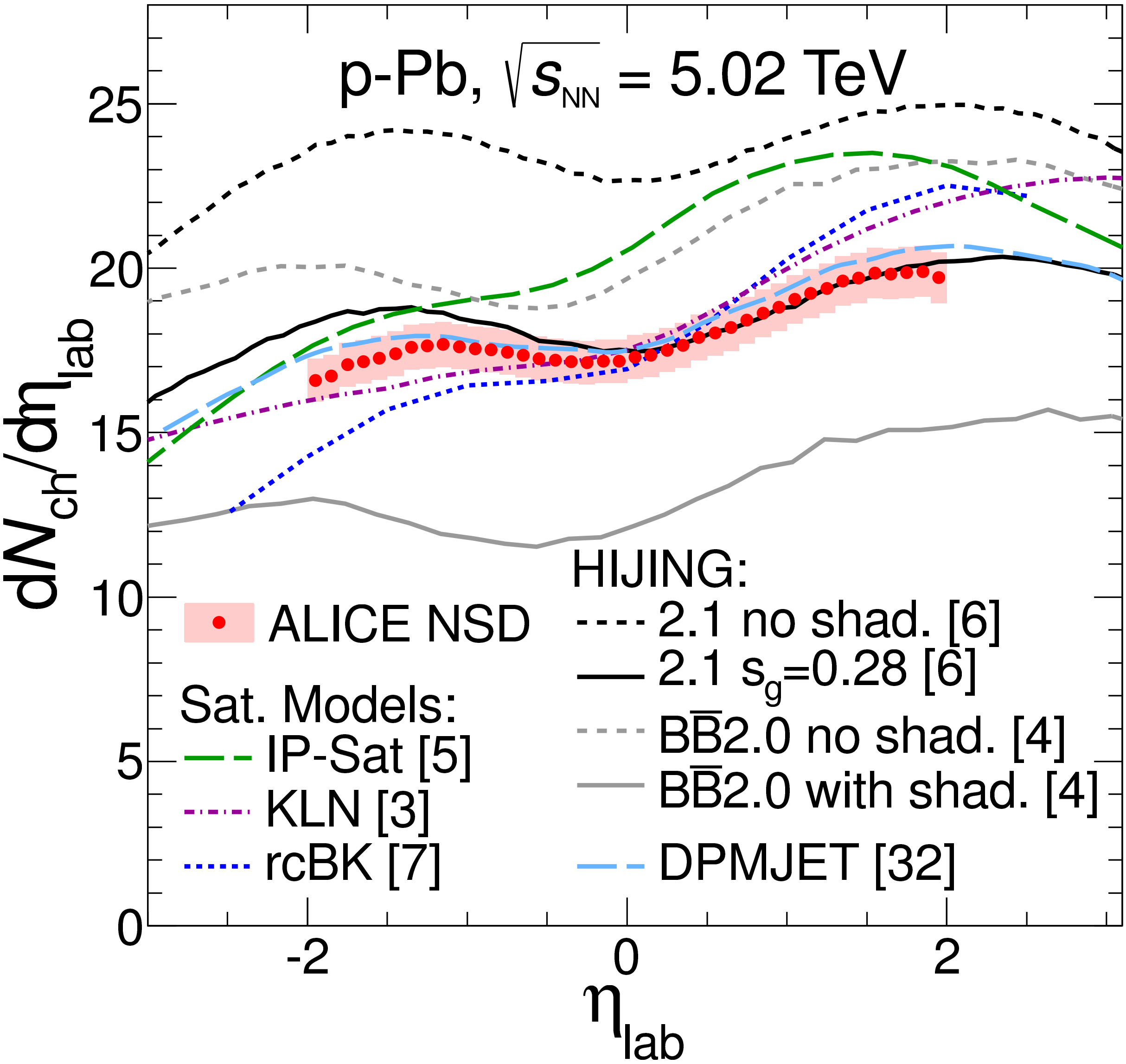

Fig. 1: Pseudorapidity density of charged particles measured in NSD p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV compared to theoretical predictions [3–7]. The calculations [4, 5] have been shifted to the laboratory system.

The resulting pseudorapidity density is presented in Fig. 1 for $|\eta_{\rm lab}| < 2$. A forward–backward asymmetry between the proton and lead hemispheres is clearly visible. The measurement is compared to particle production models [3–7] that describe similar measurements in other collision systems [9, 20–31]. The two-component models [4, 6] combine perturbative QCD processes with soft interactions, and include nuclear modification of the initial parton distributions. The saturation models [3, 5, 7] employ coher-

	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$			$\frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}\vert_{\eta_{\mathrm{lab}}=2.0}}{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}\vert_{\eta_{\mathrm{lab}}=-2.0}}$
	−2.0	0.0	2.0	
ALICE	16.65	17.24	19.81	1.19
	±0.65	±0.66	±0.78	±0.05
Saturation Models				
IP-Sat [5]	17.55	20.55	23.11	1.32
KLN [3]	15.96	17.51	22.02	1.38
rcBK [7]	14.27	16.94	22.51	1.58
HIJING				
2.1 no shad. [6]	23.58	22.67	24.96	1.06
2.1 $s_g = 0.28$ [6]	18.30	17.49	20.21	1.10
B$\bar{\mathrm{B}}$2.0 no shad. [4]	20.03	19.68	23.24	1.16
B$\bar{\mathrm{B}}$2.0 with shad. [4]	12.97	12.09	15.16	1.17
DPMJET [32]	17.50	17.61	20.67	1.18

Table 1: Comparison of the pseudorapidity distribution between data and the models at $\eta_{\mathrm{lab}} = -2$, 0 and 2 (integrated in 0.2 units of pseudorapidity) as well as the ratio of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$ at $\eta_{\mathrm{lab}} = 2$ to that at $\eta_{\mathrm{lab}} = -2$. The uncertainty introduced by taking the ratio neglecting the Jacobian amounts to about 2 and 6% estimated for the saturation and HIJING models, respectively.

ence effects to reduce the number of soft gluons available for particle production below a given energy scale. The calculations [3, 6, 7] at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV were provided by the authors in the laboratory system. The calculations that were performed in the centre-of-mass system [4, 5] have been shifted by Δy_{NN} into the ALICE laboratory system. For low-p_{T} particles, this is only an approximation of a Lorentz transformation. In the η_{lab}-range of our measurement, the error on the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$ density induced by this procedure is estimated using the HIJING model [40], and found to be below 6%. It is worth noting that the HIJING calculations include single-diffraction, which from the HIJING generator [40] is estimated to be about 4%. A comparison of the model calculations with the data shows that most of the models that include shadowing [6] or saturation [3, 7] predict the measured multiplicity values to within 20% (see also Tab. 1). The HIJING/B$\bar{\mathrm{B}}$2.0 [4] model, which uses an energy and nuclear thickness dependent string tension to mimic the effect of strong longitudinal color fields, predicts values below the data when including shadowing, and above the data when excluding shadowing. DPMJET [32] (normalized to NSD) and HIJING 2.1 [6], where the gluon shadowing parameter $s_g = 0.28$ was tuned to describe experimental data on rapidity distributions in d–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 0.2$ TeV (RHIC) [9, 20], give values that are closest to the data. Both also describe the pseudorapidity shape relatively well, whereas the saturation models [3, 5, 7] exhibit a steeper η_{lab} dependence than the data. This can also be seen in Tab. 1 by quantifying the density at midrapidity, near the proton and lead peak regions, as well as the ratio of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$ at $\eta_{\mathrm{lab}} = 2$ to that at $\eta_{\mathrm{lab}} = -2$, for the data (integrated in 0.2 units of pseudorapidity) and the models. The error introduced by taking the ratio amounts to about 2 and 6% for the saturation and HIJING models.

The charged-particle pseudorapidity density at midrapidity in the laboratory system ($|\eta_{\mathrm{lab}}| < 0.5$) is $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}} = 17.35 \pm 0.01$ (*stat.*) $\pm$ 0.67 (*syst.*). The statistical uncertainty is neglected in the following. To obtain the pseudorapidity density in the centre-of-mass system, the data is integrated in the range $-0.965 < \eta_{\mathrm{lab}} < 0.035$, and corrected for the effect of the Δy shift. The correction is estimated from the HIJING model [40] to be 3%, with an uncertainty of 1.5%, added in quadrature to the systematic uncertainty. The resulting pseudorapidity density in the nucleon–nucleon centre-of-mass system is $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{cms}} = 16.81 \pm 0.71$ (*syst.*).

In order to compare bulk particle production in different collision systems, the charged particle density is scaled by the number of participating nucleons, determined using the Glauber model [35] with a nuclear

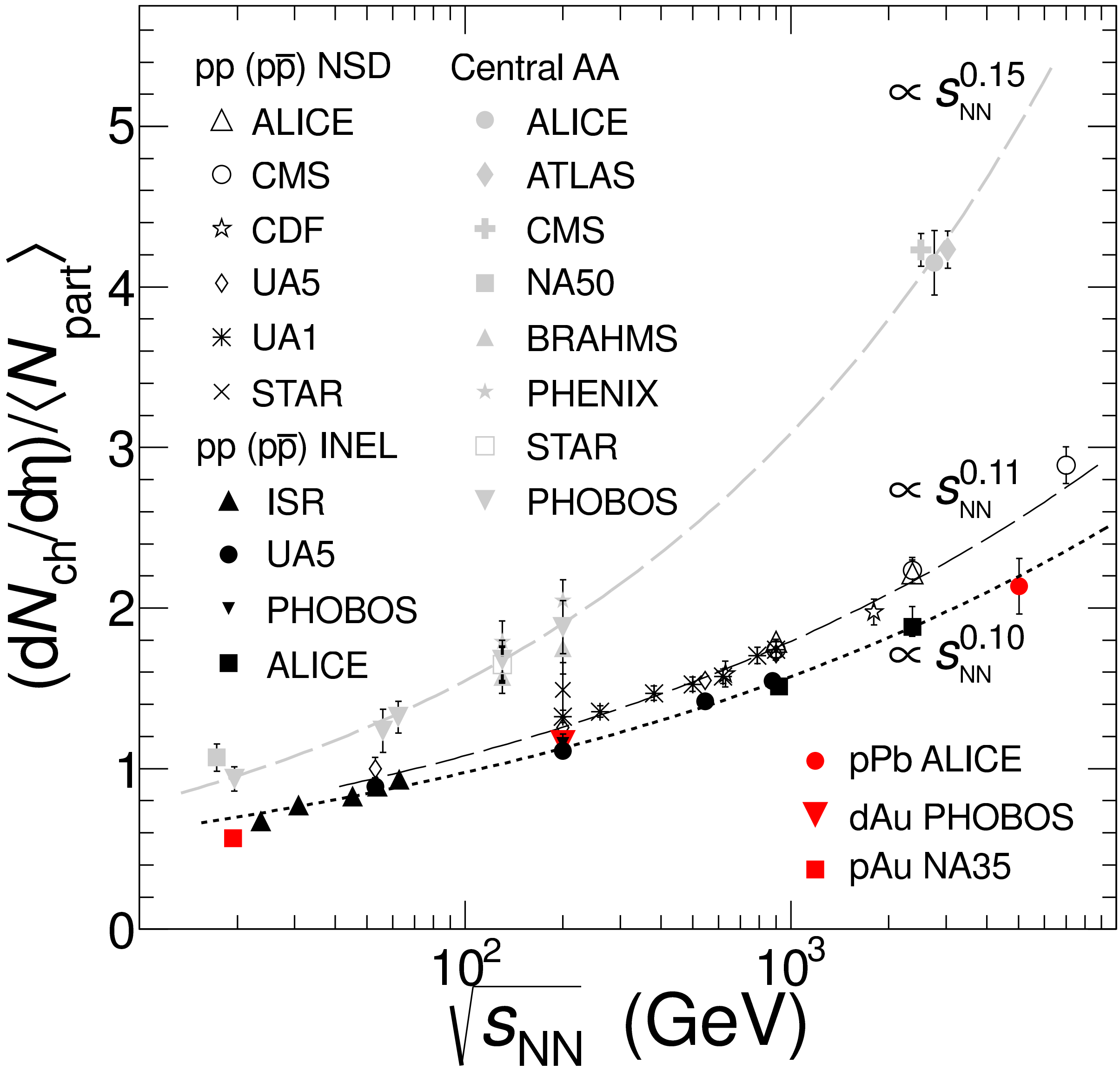

Fig. 2: Charged-particle pseudorapidity density at midrapidity normalized to the number of participants, calculated with the Glauber model, for p–Pb, p–Au and d–Au [8, 9] collisions as a function of $\sqrt{s_{NN}}$, compared to NSD [10–16], and inelastic [17–20] pp (p$\bar{\text{p}}$) collisions, as well as central heavy-ion [20–31] collisions. The curves $\propto s_{NN}^{0.11}$ and $s_{NN}^{0.15}$ (from [29]) are superimposed on the NSD pp (p$\bar{\text{p}}$) and central heavy-ion data, respectively, while $\propto s_{NN}^{0.10}$ (from [19]) on the inelastic pp (p$\bar{\text{p}}$) data.

radius of 6.62 ± 0.06 fm and a skin depth of 0.546 ± 0.010 fm, a hard-sphere exclusion distance of 0.4 ± 0.4 fm for the lead nucleus, a radius of 0.6 ± 0.2 fm for the proton, and an inelastic nucleon–nucleon cross section of 70 ± 5 mb. The latter is obtained by interpolating data at different centre-of-mass energies [41] including measurements at 2.76 and 7 TeV [34, 42]. The number of participants for minimum-bias events is found to be distributed with an average $\langle N_{part} \rangle = 7.9 \pm 0.6$ and an r.m.s. width of 5.1. The uncertainty of 7.6% on $\langle N_{part} \rangle$ is obtained by varying the parameters of the Glauber calculation within the ranges mentioned above (as explained in Ref. [43]). Note that the number of participants would increase by only 2.5% if normalized to NSD events in the Glauber calculation. Normalizing to the number of participants gives $(dN_{ch}/d\eta_{cms})/\langle N_{part} \rangle = 2.14 \pm 0.17$ (*syst.*). In Fig. 2, this value is compared to measurements in p–Au and d–Au [8, 9] collisions, NSD [10–16], and inelastic [17–20] pp ($p\overline{p}$), as well as central heavy-ion [20–31] collisions, over a wide range of collision energies. (Data for d–Au at $\sqrt{s_{NN}} = 200$ GeV from [44, 45] are consistent with that from [9] and not shown in the figure.) The $(\mathrm{d}N_{ch}/\mathrm{d}\eta_{cms})/\langle N_{part}\rangle$ at $\sqrt{s_{NN}} = 5.02$ TeV is found to be 16% lower than in NSD pp and consistent with inelastic pp collisions interpolated to $\sqrt{s_{NN}} = 5.02$ TeV, and 84% higher than in d–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV.

In summary, the charged-particle pseudorapidity density in $|\eta_{lab}| < 2$ in non-single-diffractive p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented. At midrapidity, $\mathrm{d}N_{ch}/\mathrm{d}\eta_{cms} = 16.81 \pm 0.71$ (*syst.*) is measured, corresponding to 2.14 ± 0.17 (*syst.*) charged particles per unit pseudorapidity per participant, where the number of participants are calculated with the Glauber model. The new measurement extends the study of charged-particle densities in proton–nucleus collisions into the TeV scale, and provides new constraints on the description of particle production in high-energy nuclear collisions.

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