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Pseudorapidity distributions of charged hadrons in proton-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV

The CMS Collaboration*

Abstract

The pseudorapidity distributions of charged hadrons in proton-lead collisions at nucleon-nucleon center-of-mass energies $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV are presented. The measurements are based on data samples collected by the CMS experiment at the LHC. The number of primary charged hadrons produced in non-single-diffractive proton-lead collisions is determined in the pseudorapidity range $|\eta_{\mathrm{lab}}| < 2.4$. The charged-hadron multiplicity distributions are compared to the predictions from theoretical calculations and Monte Carlo event generators. In the center-of-mass pseudorapidity range $|\eta_{\mathrm{cm}}| < 0.5$, the average charged-hadron multiplicity densities $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{cm}} \rangle|_{|\eta_{\mathrm{cm}}|<0.5}$ are $17.31 \pm 0.01\,(\mathrm{stat}) \pm 0.59\,(\mathrm{syst})$ and $20.10 \pm 0.01\,(\mathrm{stat}) \pm 0.85\,(\mathrm{syst})$ at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV, respectively. The particle densities per participant nucleon are compared to similar measurements in proton-proton, proton-nucleus, and nucleus-nucleus collisions.

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*See Appendix A for the list of collaboration members

1 Introduction

Studies of charged-hadron yields have long been a key tool for exploring perturbative and nonperturbative quantum chromodynamics (QCD) phenomena in high-energy particle and nuclear collisions [1]. Measurements in proton-lead (pPb) collisions can shed light on initial-state nuclear effects in these interactions [2]. An example is the nuclear modification of parton distribution functions (PDFs) that can be observed in measurements of hadron [3–7] and jet [8–10] production. Such measurements also provide reference data for understanding the hot, dense medium produced in nucleus-nucleus (AA) collisions. At the CERN LHC energies, measurements of proton-nucleus (pA) collisions allow studies of the nuclear gluon distributions and parton shadowing effects at very small values (10^{-4}–10^{-6}) of the Bjorken x variable [2, 11]. This provides a crucial test of current theoretical approaches for high-energy QCD [11–13], and yields important constraints on phenomenological models and event generators [14–17].

The number of primary charged hadrons, N_{ch}, is commonly characterized by its pseudorapidity density, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. The pseudorapidity, η, is defined as $-\ln[\tan\theta/2]$, where θ is the polar angle of the particle with respect to the beam axis. The center-of-mass energy dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ constrains the theoretical modeling of particle production arising from hard and soft QCD processes in high-energy hadronic interactions. In the presence of the quark-gluon plasma (QGP), the hot medium produced in AA collisions, modifications of hadron production have been observed. Studying the energy dependence of the pseudorapidity density in different colliding systems (proton-proton (pp), pA, AA), for both total inelastic and non-single-diffractive (NSD) [18–20] collision processes, improves our understanding of these modifications in the AA case by identifying nuclear effects present in the initial state. Monte Carlo (MC) event generators, which reproduce the main characteristics of experimental results from hadronic collisions at lower energies, can provide predictions for the energy dependence of hadron production using different implementations of QCD effects [21].

In this paper, measurements of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$ (where the pseudorapidity is measured in the laboratory frame) in the range $|\eta_{\mathrm{lab}}| < 2.4$ are reported for NSD events in pPb collisions delivered by the LHC in 2016 at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ and 8.16 TeV. Following earlier analyses in pp collisions at $\sqrt{s} = 0.9$–13 TeV [22–25] and in lead-lead collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 2.76$ TeV [26], N_{ch} is restricted to "primary" charged hadrons, defined to include prompt hadrons as well as decay products of all particles with proper decay length $c\tau < 1$ cm, where τ is the proper lifetime of the particle and c is the velocity of light in vacuum. Contributions from prompt leptons and decay products of longer-lived particles and secondary interactions are excluded. For $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ (8.16) TeV, the beam energies per nucleon were 4 (6.5) TeV and 1.58 (2.56) TeV for the proton and lead nucleus, respectively. Because the beam energies were asymmetric and the proton was going in the positive η_{lab} direction, massless particles emitted at midrapidity in the nucleon-nucleon center-of-mass, $\eta_{\mathrm{cm}} = 0$, will be detected at $\eta_{\mathrm{lab}} = 0.465$. Results are compared to predictions from the KLN model [11], as well as the EPOS LHC (v3400) [17, 27], HIJING [14] (versions 1.3 [15] and 2.1 [12]), and DPMJET-III [16] MC event generators. The $\sqrt{s_{_{\mathrm{NN}}}}$ dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{cm}}$ in the region $\eta_{\mathrm{cm}} \approx 0$ is also presented.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The silicon tracker measures charged particles within the range $|\eta_{\mathrm{lab}}| < 2.5$. It consists of 1440 silicon pixel detector modules. The barrel region of the pixel detector consists of three layers, which are very close to the beam line. They are located at average radii of 4.3, 7.2, and 11.0 cm, and provide excellent position resolution with their $150 \times 100\,\mu$m pixels. The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. It consists of two halves, each located 11.2 m from the interaction region, and together they provide coverage in the range $3.0 < |\eta_{\mathrm{lab}}| < 5.2$. The beam pickup for timing (BPTX) devices were used to trigger the detector readout. They are located around the beam pipe at a distance of 175 m on either side of the interaction point (IP) and are designed to provide precise information on the LHC bunch structure and the timing of the incoming beams. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [28].

3 Event selection

The data used in this analysis were taken with the beam configuration in which the proton beam traveled in the negative pseudorapidity direction, and selected to contain collision events recorded during low-intensity beam configurations, with 0.3–0.6% proton-lead interaction probability per bunch crossing. The collision events are selected online by requiring a coincidence of signals from both BPTX devices, indicating the presence of both proton and lead ion bunches crossing the IP, and at least one energy deposit above the readout threshold of 3 GeV on either side of the HF. The offline selection of NSD events is accomplished by requiring that at least one energy deposit greater than 3 GeV is found on each of the two sides of the HF and at least one reconstructed interaction vertex is found. A study of noncolliding bunches shows that these requirements are also sufficient to reject all backgrounds not originating from pPb collisions. The probability to select events in the presence of a single (noncolliding) beam is found to be around 2×10^{-5} per bunch crossing, to be compared to the average number of collisions per bunch crossing of 4.5×10^{-3}. Consequently, the contribution of background events from beam, beam halo, and cosmic ray sources to the observed yields is negligible. The total number of pPb collision events passing the selection criteria is approximately 420 thousand and 3 million at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ and 8.16 TeV, respectively.

The corrections from the detector-level offline event selection to the hadron-level event definition are derived from MC simulations with the EPOS generator. The MC simulations are produced with the same vertex distribution along the interaction region as observed in data. The detector response is simulated with GEANT4 [29] and processed through the same event reconstruction chain as the collision data.

4 Data analysis

In the presence of a magnetic field, charged particles follow curved trajectories, perturbed mostly by multiple Coulomb scattering. The reconstructed pixel clusters (or "hits") alone are sufficient to reconstruct vertices and tracks with high precision and purity. The analysis technique is based on tracklets, pairs of hits from two different layers, and relies on the fact that for a primary charged hadron, the differences in pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) between the two hits are small. This method is sensitive to charged hadrons with transverse momenta p_{T} as low as 40 MeV/c.

The primary vertex reconstruction is based on pixel hits in the first two layers of the detector, as in Ref. [26]. In the first step, a hit from the first layer is selected and a matching hit from the second layer is sought. If the $|\Delta\phi|$ of the hits is smaller than 0.05 (optimized to maximize the vertex reconstruction efficiency), the z positions of the hits (with the z axis defined to be parallel to the beam axis) are extrapolated linearly and projected onto the beam axis. This procedure is repeated for every hit in the first layer, and the projected z positions are saved as vertex candidates. The primary vertex is determined in a second step. If the magnitude of the difference between the z positions of any two vertex candidates is smaller than 0.12 cm, they are combined into a vertex cluster. The vertex cluster with the highest number of associated vertex candidates is selected as the primary vertex, and the final vertex z position, z_v, is given by the average z position of the associated vertex candidates. The typical resolution of z_v is 0.02–0.04 cm, depending on the number of pixel hits. The vertex reconstruction efficiency is found to be high even for low-multiplicity events with few pixel hits, with around 90 (100)% efficiency for events with 4 (10) hits in the first layer.

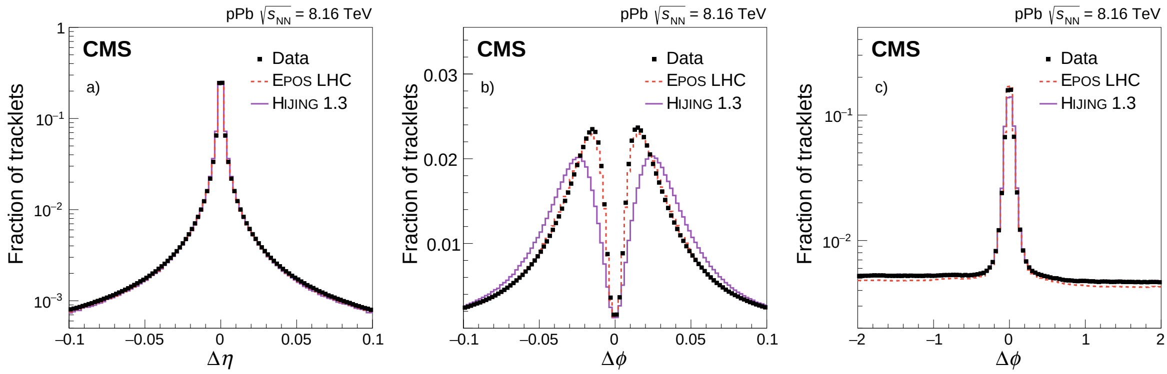

Figure 1: The $\Delta\eta$ (a) and $\Delta\phi$ (b, c) distributions of hit pairs for tracklets in pPb collisions at 8.16 TeV (squares) and from MC simulations with the EPOS and HIJING 1.3 generators (solid lines). The statistical uncertainties are smaller than the marker sizes for all distributions shown.

The tracklet reconstruction follows a separate algorithm from the vertex reconstruction. There is no requirement on the $\Delta\phi$ of the hits. Instead, a hit on a given layer is paired with the hit on another layer which is closest in η (where η is measured with respect to the primary vertex) and these two hits form a tracklet. No hit can be used more than once. No selection is applied on the hit quality or charge, such that the analysis is rather insensitive to the accuracy of the simulation of pixel cluster charge. Three different types of tracklets can be reconstructed, corresponding to different combinations of the three pixel detector layers: 1+2, 1+3, and 2+3. The reconstruction efficiency, acceptance, fraction of background hits, and sensitivity to particle p_T is different for each type of tracklet. This serves as a consistency check for the analysis, and reduces systematic biases in the measurement.

Figures 1(a) and (b) show the $\Delta\eta$ and $\Delta\phi$ distributions of reconstructed hit pairs for tracklets in data and simulation. To suppress the combinatorial background, while still including most particles in the analysis, only tracklets with $|\Delta\eta| < 0.1$ are considered "signal". In this kinematic region, there is good agreement between data and simulations with the EPOS generator, indicating that the p_T distributions of both hard and soft particles in data are described well by this MC generator. The HIJING generator, used in this analysis for systematic studies, gives a poorer description of the distributions, especially for $\Delta\phi$. Tracklets corresponding to charged hadrons that originate from the primary vertex have small but nonzero $\Delta\phi$ due to the magnetic field in the detector, while background tracklets from uncorrelated pixel hits form a roughly flat $\Delta\phi$ spectrum over the entire $\Delta\phi$ range, as shown in Fig. 1(c), where the abscissa is extended to $|\Delta\phi| < 2$. Hence, a sideband region defined by $1 < |\Delta\phi| < 2$ is used to estimate the background fraction, which is then subtracted from the signal region ($|\Delta\phi| < 1$) to obtain the uncorrected $dN_{ch}/d\eta_{lab}$ [26]. The background estimation and subtraction is performed as a function of η_{lab}, z_v, and tracklet multiplicity. Typical values of the estimated background fraction in the signal region in data increase with $|\eta_{lab}|$ from 10 – 25%. The η_{lab} range is restricted to $|\eta_{lab}| < 2.4$ to avoid a large acceptance correction.

The final results need to be corrected for contributions from decaying particles with $c\tau > 1$ cm, particles created in secondary interactions, and prompt leptons. The contribution of these particles to $dN_{ch}/d\eta_{lab}$ is removed using a correction factor found using MC simulations. In addition, corrections are needed to account for the selection, efficiency, and acceptance of reconstructed tracklets, as well as trigger and vertexing efficiencies. The acceptance factor includes the extrapolation down to $p_T = 0\,\text{GeV}/c$. Correction factors (with a typical total of <15%) are derived using the EPOS event generator as a reference and are calculated as a function of η_{lab}, z_v, and tracklet multiplicity, as was done in Ref. [26].

To account for the differences between data and MC in the pixel detector geometry and its alignment conditions, an additional correction is applied as a function of η_{lab} and z_v. This correction is obtained by taking the ratio between data and simulation of the geometrical distribution of tracklets in (η_{lab}, z_v) intervals. The size of this correction ranges from 0 to 5%, where the largest correction factors are associated with the presence of inactive tracker modules.

4.1 Systematic uncertainties

The systematic uncertainties in the final results arise from several sources: detector misalignment, pixel hit reconstruction inefficiency, pixel cluster splitting, background modeling, selection of signal and sideband regions, parametrization of the correction factors, and the NSD event selection. For each source of uncertainty, that part of the analysis procedure is varied independently and the change is propagated to the final results. The individual contributions are then summed in quadrature to give the total systematic uncertainty.

To estimate the uncertainty from detector misalignment, each pixel hit is offset by a small distance corresponding to the uncertainty in the alignment of the pixel detectors. The effects of pixel hit reconstruction inefficiency are studied by randomly excluding 0.5% of the pixel hits from the analysis. The 0.5% inefficiency value is determined by studying tracklets reconstructed from pixel hits in layers 1 and 3, and taking the double ratio in data and simulation of the fraction of tracklets that have no corresponding hit in layer 2. Pixel cluster splitting refers to the situation where the charge deposit in the pixel detector from a single charged particle is reconstructed as two separate pixel clusters. Its effect on the measurement is estimated by randomly splitting pixel clusters with a probability of 1.2%, as determined by previous studies [22]. The contributions from the above three sources are all below 1%.

The remaining uncertainties are associated with the MC correction factors. Additional pixel hits, randomly sampled from the hit distributions in data, are added such that the $\Delta\phi$ sidebands match between data and MC. The percentage of additional pixel hits needed is less than 5%. The variations observed compared to the nominal results are around 1.5–2.5%. The signal and sideband regions are also varied to $|\Delta\phi| < 1.5$ and $1.5 < |\Delta\phi| < 3.0$, respectively. A variation of 0.6–1.5% is found as compared to the nominal setting, which is propagated as a systematic uncertainty. Different multiplicity variables are used to parametrize the correction factors, in addition to the background-subtracted tracklets variable used for the nominal results: number of tracklets (before background subtraction), number of pixel hits in the first pixel layer used (layer 1 for tracklet type 1+2 and 1+3, and layer 2 for tracklet type 2+3). The maximum deviation in each η_{lab} interval, 1.5–2.5%, is quoted as an uncertainty. An uncertainty is assigned for the selection of NSD events. The fraction of the single-diffractive events removed by the event selection, as determined from the EPOS generator, is 16% when the tracklet multiplicity in the event is less than 10, and falls quickly to 0% with increasing tracklet multiplicity. This fraction is varied from 0% to twice the nominal value, and the maximum deviation from the final results, 1.2%, is quoted as the uncertainty. A summary of the systematic uncertainties for the measurements at 5.02 and 8.16 TeV is shown in Table 1.

Table 1: Summary of the systematic uncertainties from various sources, for pPb collisions at 5.02 and 8.16 TeV. The range of values indicates the minimum and maximum uncertainties across the η_{lab} range.

	Source	Uncertainty [%]	
		5.02 TeV	8.16 TeV
Data and simulation	Detector misalignment	0.2 – 1.0	0.2 – 1.0
	Pixel hit reconstruction inefficiency	1.0	1.0
	Pixel cluster splitting	0.3 – 0.8	0.3 – 0.6
MC corrections	Background modeling	1.3 – 3.2	1.5 – 2.5
	Signal and sideband region selection	0.5 – 1.5	0.6 – 1.5
	Choice of parametrization variable	1.6 – 2.5	1.5 – 3.5
	NSD selection	1.2	1.2
	Total uncertainty	3.0 – 4.3	3.7 – 4.6

5 Results

Pseudorapidity density distributions of charged hadrons in the region $|\eta_{\mathrm{lab}}| < 2.4$ for NSD pPb collisions are shown in Fig. 2. The distributions shown are the average of the measured distributions from the three types of tracklets (1+2, 1+3, and 2+3), which are consistent with each other within 3%. A clear difference in the particle densities between the lead ion ($\eta_{\mathrm{lab}} < 0$) and the proton ($\eta_{\mathrm{lab}} > 0$) beam directions is observed. The measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$ distribution at 5.02 TeV agrees with the measurement by the ALICE Collaboration [30]. The multiplicities at 8.16 TeV are significantly higher than those at 5.02 TeV.

Figure 3 shows a comparison between the measurement at 8.16 TeV and theoretical calculations from the HIJING (versions 1.3 and 2.1), EPOS LHC (v3400), and DPMJET-III MC generators, and the KLN model. The HIJING and EPOS generators were tuned to data from RHIC and the LHC, respectively. Calculations from HIJING 2.1, a two-component model that combines perturbative QCD descriptions of hard parton scatterings with a string excitation model for soft interactions, agree with the experimental data in the region $-0.5 < \eta_{\mathrm{lab}} < 1.5$ when the nuclear modification of the initial parton distributions (shadowing) is included in the calculation. The HIJING 1.3 calculation overpredicts the particle density because it has an older implementation of the gluon shadowing effects. The importance of shadowing can be assessed using the comparison of HIJING 2.1 simulations generated with and without this physics process included. The results are significantly higher than the data when shadowing is disabled. The KLN parton saturation model combines Glauber modeling of the collision geometry with a simple model for the unintegrated parton distributions that accounts for the existence of a saturation momentum scale [31, 32]. It describes the particle density accurately for $|\eta_{\mathrm{lab}}| < 1$ but overall shows a steeper increase of density versus η_{lab} than observed in the data, similar to what was observed in the comparisons to the PHOBOS deuteron-gold (dAu) data at 200 GeV [33] and ALICE data at 5.02 TeV [30]. The DPMJET-III generator, commonly used in the description of

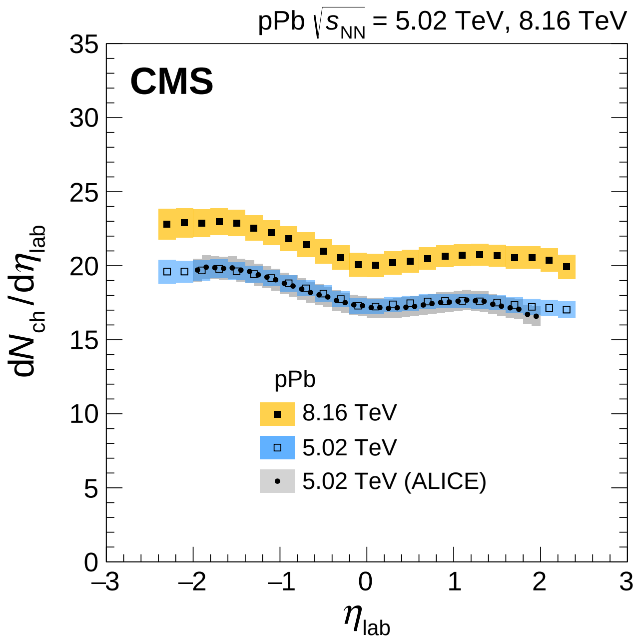

Figure 2: Distributions of the pseudorapidity density of charged hadrons in the region $|\eta_{lab}| < 2.4$ in NSD pPb collisions at $\sqrt{s_{NN}} = 5.02$ (open squares) and 8.16 TeV (full squares). The measurement at 5.02 TeV by the ALICE Collaboration [30] is shown as filled circles. The shaded boxes indicate the systematic uncertainties which, in the case of the CMS data, are correlated between the two beam energies. The proton beam goes in the positive η_{lab} direction.

cosmic ray, nucleon-nucleon, and nucleon-nucleus interactions, is based on the dual parton model [34], which generates soft hadronic interactions by considering the expansion of non-perturbative QCD in the limit where the number of color and flavor states are large [35]. This generator is found to predict both a steeper increase versus η_{lab} and a higher particle density over the measured η_{lab} interval. The EPOS generator, which is based on the Gribov–Regge theory and includes the effect of collective hadronization in hadron-hadron scattering, was found to describe pp data up to 13 TeV [25], but underpredicts the observed $dN_{ch}/d\eta_{lab}$ by a roughly constant factor over the entire measured range for pPb at 8.16 TeV.

One of the main goals of the heavy ion studies is to understand hadron production in the extremely dense medium formed in AA collisions. One way to approach this goal is to consider a direct comparison between the charged-hadron multiplicity density in minimum bias pp and pA collisions, reference systems for particle production in the absence of a QGP, and central AA collisions (the most extreme type of collisions with the highest particle multiplicities). The comparison is made by dividing $dN_{ch}/d\eta_{cm}$ by the number of participating nucleons, N_{part}, determined by a Glauber model calculation [4, 36]. This normalization is the one assumed in two-component models (e.g. HIJING) for the bulk of the particle production.

In order to compare particle production in pPb collisions to that in symmetric collision systems such as pp or AA, the rapidity shift due to the asymmetric beam energies must be taken into account. The average charged-hadron multiplicity density at midrapidity in the center-of-mass frame, $\langle dN_{ch}/d\eta_{cm}\rangle|_{|\eta_{cm}|<0.5}$, in pPb collisions is calculated by integrating the data in the interval $-0.035 < \eta_{lab} < 0.965$, corresponding to $|\eta_{cm}| < 0.5$ for massless particles. A correction is applied to account for the massless assumption entering the calculation of the pseudorapidity shift: 0.1 and 0.2% for the 5.02 TeV and 8.16 TeV analyses, respectively, as obtained from the EPOS generator. The 1% variation in the results, obtained when this correction is evaluated

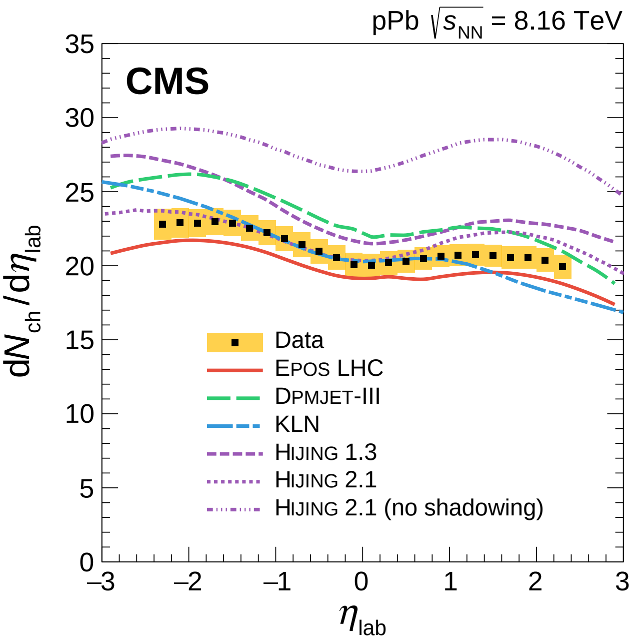

Figure 3: Distributions of the pseudorapidity density of charged hadrons in the region $|\eta_{lab}| < 2.4$ for NSD pPb collisions at 8.16 TeV (squares) compared to predictions from the MC event generators EPOS LHC [17, 27] (v3400), HIJING [14] (versions 1.3 [15] and 2.1 [12]), and DPMJET-III [16], as well as from the KLN model [11]. The shaded boxes around the data points indicate their systematic uncertainties. The proton beam goes in the positive η_{lab} direction.

from HIJING, is quoted as an additional uncertainty for the $\langle dN_{ch}/d\eta_{cm}\rangle|_{|\eta_{cm}|<0.5}$ results. In the range $|\eta_{cm}| < 0.5$, values of $17.31 \pm 0.01\,(stat) \pm 0.59\,(syst)$ and $20.10 \pm 0.01\,(stat) \pm 0.85\,(syst)$ are obtained for pPb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV, respectively.

Figure 4 shows the dependence of normalized $dN_{ch}/d\eta_{cm}$ on the collision energy for various collision systems and event selections. The NSD pA results are found to be lower than those from central AA collisions [26, 37–50] ($s_{NN}^{0.158}$ dependence) and NSD pp collisions ($s_{NN}^{0.110}$ dependence) at similar center-of-mass energies, but coincide with the trend observed in inelastic pp collisions ($s_{NN}^{0.103}$ dependence). While the difference between the NSD pp and pA results could be attributed to non-QGP nuclear effects, the similarity between the NSD pA and total inelastic pp is yet to be understood.

6 Summary

The pseudorapidity distributions of primary charged hadrons have been measured by the CMS experiment at the LHC in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV. Based on pairs of pixel clusters from two different layers of the barrel region of the CMS pixel detector, the distributions have been obtained for NSD pPb events at both collision energies. The measured $dN_{ch}/d\eta_{lab}$ distribution at 5.02 TeV is consistent with published results by the ALICE Collaboration. At 8.16 TeV, the measured $dN_{ch}/d\eta_{lab}$ distribution is higher than the predictions of EPOS LHC, but significantly lower than the predictions from the HIJING 1.3 and DPMJET-III event generators. At $\eta_{lab} \approx 0$, the measured distributions are in good agreement with calculations from the KLN gluon saturation model and predictions from the HIJING 2.1 event generator with the effects of gluon shadowing included. The charged-hadron multiplicity densities in the nucleon-nucleon center-of-mass frame, $\langle dN_{ch}/d\eta_{cm}\rangle|_{|\eta_{cm}|<0.5}$, are $17.31 \pm 0.01\,(stat) \pm 0.59\,(syst)$ and $20.10 \pm 0.01\,(stat) \pm 0.85\,(syst)$ at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV, respectively. When comparing

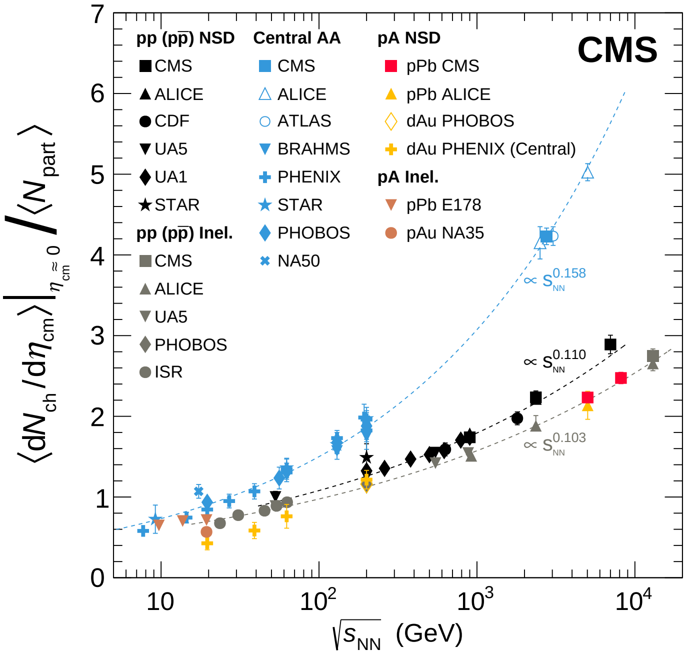

Figure 4: Comparison of the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{cm}}$ at midrapidity, scaled by the number of participating nucleons (N_{part}) in pPb [30, 51], pAu [52], dAu [33, 48, 53] and central heavy ion collisions [26, 37–50], as well as NSD [22, 23, 50, 54–57] and inelastic [25, 37, 56, 58, 59] pp collisions. The AA data points at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV have been shifted horizontally for visibility. The dashed curves, included to guide the eye, correspond to a fit to the data points using the same functional form as in Refs. [46, 59].

the average charged-particle density per participant nucleon for pp, pA, and AA collisions as a function of collision energy, the pA results are found to be below those in central AA collisions and NSD pp collisions, but coincide with the trend seen in inelastic pp collisions. These results represent the first measurement of hadron production at this new center-of-mass energy frontier in nuclear collisions, and provide constraints for the understanding of nonperturbative QCD effects in high-energy nuclear collisions.

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