Title
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Pseudorapidity distributions of charged hadrons in xenon-xenon collisions at $\sqrt{s_{NN}} = 5.44$ TeV

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Measurements of the pseudorapidity distributions of charged hadrons produced in xenon-xenon collisions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 5.44$ TeV are presented. The measurements are based on data collected by the CMS experiment at the LHC. The yield of primary charged hadrons produced in xenon-xenon collisions in the pseudorapidity range $|\eta| < 3.2$ is determined using the silicon pixel detector in the CMS tracking system. For the 5% most central collisions, the charged-hadron pseudorapidity density in the midrapidity region $|\eta| < 0.5$ is found to be 1187 ± 36 (syst), with a negligible statistical uncertainty. The rapidity distribution of charged hadrons is also presented in the range $|y| < 3.2$ and is found to be independent of rapidity around $y = 0$. Existing Monte-Carlo event generators are unable to simultaneously describe both results. Comparisons of charged-hadron multiplicities between xenon-xenon and lead-lead collisions at similar collision energies show that particle production at midrapidity is strongly dependent on the collision geometry in addition to the system size and collision energy.

1. Introduction

Collisions between ultra-relativistic heavy ions are the only known way of experimentally studying quantum chromodynamics (QCD) matter at high temperatures and energy densities. The current understanding is that in such collisions, a state of matter known as the quark-gluon plasma (QGP) is formed shortly after the initial impact between the nuclei [1].

The multiplicity and pseudorapidity distributions of the produced charged particles are key observables that characterise the initial condition and subsequent hydrodynamic evolution of the QGP [2]. The dependence of the charged-particle multiplicity on the colliding system, centre-of-mass energy, and collision geometry can provide information about nuclear shadowing and gluon saturation effects [3], as well as the relative contributions to particle production from hard scattering and soft processes [4]. These observables also provide input for models of the particle production process [5], from which information about the formation and properties of the QGP can be extracted.

In October 2017, the CERN LHC collided xenon (Xe^{129}) ions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 5.44$ TeV, marking the first time ions other than protons and lead (Pb^{208}) have been circulated in the LHC. This new collision system provides a unique opportunity to study the dependence of the charged-particle multiplicity on the size of the matter produced at LHC energies. Previous measurements of charged-particle multiplicities in copper-copper (CuCu) and gold-gold (AuAu) collisions at RHIC have been observed to be sensitive to the collision geometry [6]. The XeXe collision data are thus important for determining if this feature is also present at higher energies. Comparisons of the data to predictions of models tuned to describe PbPb collision data [7–9] can also be used to test the extent to which these models are able to describe other collision systems.

In this Letter, measurements of the pseudorapidity density of primary charged hadrons, $dN_{ch}/d\eta$, in the range $|\eta| < 3.2$ are reported for XeXe collisions delivered by the LHC. Following earlier analyses in proton-proton collisions at 0.9–13 TeV [10–14], proton-lead collisions at 5.02 and 8.16 TeV [15], and PbPb collisions at 2.76 TeV [16], "primary" charged hadrons are defined as prompt charged hadrons and decay products of all particles with proper decay length $c\tau < 1$ cm, where c is the speed of light in vacuum and τ is the proper lifetime of the particle. Contributions from prompt leptons, decay products of longer-lived particles, and secondary interactions are excluded.

The results are compared to a measurement by the ALICE Collaboration [17] and to predictions from the EPOS LHC v3400 [8,18], HYDJET 1.9 [9], and AMPT 1.26t5 [19] event generators. The EPOS

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generator is based on Gribov–Regge theory [20,21] and includes the effect of collective hadronisation in hadron-hadron scattering. The HYDJET generator treats a heavy ion collision as a superposition of a hydrodynamically parametrised soft component and a hard component resulting from multi-parton fragmentation. The AMPT generator combines the HIJING event generator [22] with Zhang's parton cascade procedure [23] and the ART model [24] for the last stage of parton hadronisation.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker covering the range $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters (HF), made of steel and quartz-fibres and located on either side of the interaction point, extend the pseudorapidity coverage provided by the barrel and endcap detectors to $|\eta| < 5.2$. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid. The beam pickup timing for experiments (BPTX) devices are located around the beam pipe at a distance of 175 m from the interaction point on either side and provide precise information on the timing of the incoming beams. 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. [25].

Charged hadrons are reconstructed using the silicon pixel detectors installed during the Phase 1 upgrade [26], which consist of four concentric cylindrical shells (layers) in the barrel region (BPIX) and three disks on both sides of the interaction point in the forward region (FPIX). The BPIX and FPIX consist of a total of 1184 and 672 modules, respectively, and provide excellent position resolution with their 100×150 μm pixels. In this Letter, the layers of the BPIX are denoted in increasing order of their radial distance from the beam axis, i.e. the layer closest to the beam axis is referred to as layer 1, the next closest layer is referred to as layer 2, and so on, while the disks of the FPIX are referred to in increasing order of their longitudinal distance from the nominal interaction point.

3. Event selection

This analysis is based on approximately 1.36 million events. The average interaction probability per bunch crossing was 1.8%. Events are selected in two stages: (i) online, a coincidence of signals from both BPTX devices and at least one energy deposit above 3 GeV on either side of the HF are required; (ii) offline, three energy deposits above 3 GeV on each side of the HF and at least one reconstructed vertex, according to the tracklet-based vertex reconstruction method described in Ref. [16], are required. A study of noncolliding ion bunches shows that the above requirements are sufficient to reject all backgrounds not originating from interactions between xenon ions. Consequently, the contribution of background events from beam, beam-halo, and cosmic ray sources to the observed yields is negligible.

Contamination from electromagnetic (EM) interactions between xenon ions is studied using simulated events generated by STARLIGHT 2.2 [27] interfaced with DPMJET-III 3.0-5 [28], and is estimated to be around 1%. The event selection efficiency is estimated by fitting the distribution of the total transverse energy in the HF calorimeter using a template extracted from simulated EPOS LHC events [16]. Variations in the fit parameters, as well as other observables correlated with event activity, are used to determine the uncertainty in this method. In combination with the contamination rate, an overall value of $95 \pm 3\%$ is quoted for the event selection efficiency.

Nuclei are extensive objects, and their collisions can be characterised by the centrality, which is related to the impact parameter of the collision. The centrality can be estimated from the sum of the transverse energy in the HF calorimeter [16,29]. The distribution of the total transverse energy, after correcting for the event selection efficiency, is divided into equal partitions and used to classify events into centralities. The centrality represents a percentile of the total nuclear interaction cross section [16]; the most central collisions, i.e. the collisions with the smallest impact parameter, are denoted by lower percentiles. To minimise the amount of EM contamination, which is concentrated in the 20% most peripheral events, the analysis is restricted to events with centrality in the 0–80% range, where the event selection is fully efficient.

The event centrality is also related to the number of participating nucleons N_{part}, which is determined from a Glauber model calculation [30,31]. For this calculation, the nucleon-nucleon inelastic cross section is taken to be 68.4 ± 0.5 mb [31], while the nuclear radius, skin depth, and deformation parameter β_2 of the xenon nucleus are set to 5.36 ± 0.1 fm, 0.59 ± 0.07 fm [32], and 0.18 ± 0.02 [17], respectively. Simulated EPOS LHC events are used to account for the energy resolution of the HF calorimeters and fluctuations in event activity, which smear the centrality distributions. The resulting values and associated uncertainties for N_{part} are listed in the supplemental material [URL will be inserted by publisher].

4. Analysis

The measurement of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ is performed using tracklets, which are pairs of pixel clusters from two different layers (disks) of the silicon pixel detector. Pairs of pixel clusters that are produced by the same charged particle have small differences in η and azimuthal angle ϕ with respect to the primary vertex. These correlations are exploited in the analysis to reconstruct tracklets that reflect the original distribution of primary charged hadrons. The vertex and tracklet reconstruction algorithms are described in Ref. [16].

Six possible types of tracklets can be formed from distinct combinations of the four layers of the BPIX. In addition, three types of tracklets can be formed from unique combinations of the three disks of the FPIX. The individual measurements from all nine combinations are averaged and symmetrised about $\eta = 0$ to obtain the final results. The different combinations are also useful for layer-by-layer systematic checks, as they have different sensitivities to the particle momentum spectrum. Particles with p_{T} above 40 MeV can be reconstructed using the two BPIX layers closest to the beam pipe.

The angular distance between the two clusters that make up a tracklet is defined as

$$\Delta r = \sqrt{\left(\eta_i - \eta_j\right)^2 + \left(\phi_i - \phi_j\right)^2}, \quad (1)$$

where $\eta_{i(j)}$ is the pseudorapidity of the pixel cluster position in the $i(j)$th layer or disk, calculated with respect to the primary vertex position, and $\phi_{i(j)}$ is defined similarly for the azimuthal angle. The Δr distribution for tracklets reconstructed from layers 1 and 2 of the BPIX is shown in Fig. 1. The spectrum is compared to fully simulated events generated by EPOS LHC, HYDJET, and AMPT.

Tracklets with $\Delta r < 0.5$ are selected for analysis. This selection criterion suppresses the combinatorial background from uncorrelated background clusters and low transverse momentum (p_{T}) particles that loop around in the high magnetic field and leave

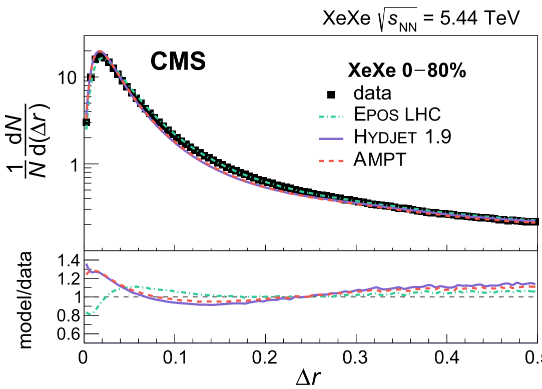

Fig. 1. The Δr distributions for tracklets reconstructed from the two layers of the BPIX closest to the beam pipe. The distributions are normalised by the number of tracklets. The spectrum in collision data (black squares) is compared to the spectra obtained from fully simulated events generated with EPOS LHC v3400 [8,18], HYDJET 1.9 [9], and AMPT 1.26t5 [19]. The ratio of the distributions in simulation to data is shown in the bottom panel. The statistical uncertainties are smaller than the marker sizes for all distributions shown.

multiple charge deposits per layer of the pixel detector. The reconstructed tracklet spectrum is then corrected to the hadron-level event definition by applying a number of correction factors accounting for the geometric acceptance, reconstruction efficiency, and event selection efficiency. These correction factors are derived from MC simulations generated with the aforementioned event generators. The detector response is simulated with GEANT4 [33] and processed through the same event reconstruction chain as the collision data. All simulations are produced with the same vertex distribution along the interaction region as is observed in data.

Simulations generated with EPOS LHC are used as the primary reference for the derivation of these correction factors because the Δr spectrum obtained from these simulated events most closely resembles the corresponding spectrum in data at large Δr, where the combinatorial background is dominant. The other event generators are used in the study of systematic uncertainties. The correction factors are calculated as functions of the primary vertex position, pseudorapidity, and tracklet multiplicity. Typical values of these correction factors at $|\eta| = 0$ (1.6) range from 1.12 (0.95) at low multiplicities to 1.01 (0.85) at high multiplicities.

The Jacobian transformation from η to rapidity, y, can also be derived from simulations by relating the rapidity density of charged hadrons to the corresponding pseudorapidity density in each η interval [34,35]. The particle composition in data is assumed to fall within the range of particle compositions predicted by the various event generators. The final transformation factors applied are the mean values of the factors derived from each event generator.

The sum of transverse energy in the HF, on which the event selection is based, is correlated with the charged-hadron multiplicity in the region around $\eta = 0$ where the measurement is made. Hence, the event selection criteria are susceptible to multiplicity fluctuations and may lead to a nonnegligible bias in the results [36]. The magnitude of this bias is studied using various MC event generators by comparing the average $dN_{ch}/d\eta$ at midrapidity, defined as $|\eta| < 0.5$, for two sets of generated events: (i) events selected based on the transverse energy sum in the HF, and (ii) events selected based on N_{part}, weighted to have the same distribution of N_{part} as the former selection. This provides a comparison of results with and without the selection bias while also accounting for detector effects that smear the N_{part} distribution of selected events. The bias caused by the event selection criteria is found to be negligible in the centrality interval used in this analysis.

5. Systematic uncertainties

The uncertainties resulting from various systematic effects affecting the measurement are evaluated. The sources of these systematic uncertainties include differences between data and simulation for effects such as the probability of pixel cluster splitting, pixel cluster reconstruction efficiency, and the fraction of uncorrelated pixel clusters, as well as the uncertainties in the alignment of pixel detector modules, tracklet selection criteria, parametrisation of correction factors, consistency between different tracklet combinations, and model dependence of the correction factors. Additionally, the uncertainty in the event selection is taken into account as an independent, fully correlated uncertainty. The individual contributions are then summed in quadrature to give the total systematic uncertainty.

Pixel cluster splitting refers to when the charge deposit from a single charged particle is reconstructed as two pixel clusters in close proximity. The difference in the relative fraction of split clusters between data and simulation can be estimated by artificially splitting the pixel clusters in simulation and comparing the resulting modified Δr distribution of cluster pairs in simulation to that in data. This difference is found to be no more than 2%, which results in a variation of 1.8–2.0% in the $dN_{ch}/d\eta$ results. The pixel cluster reconstruction efficiency can be estimated by studying the fraction of tracklets reconstructed from pixel clusters from the first and third layers that have a matching pixel cluster in the second layer. The ratio of this efficiency in data and simulation shows a relative difference of 0.5%, which has an effect of 0.5% when propagated to the final results. The pixel cluster positions are smeared by the uncertainty in the alignment of the pixel detector modules, and the effect on the final results is found to be <0.1%. The difference in the number of uncorrelated pixel clusters in data and simulation is estimated by comparing the tracklet Δr distributions in the region $\Delta r > 0.3$, where tracklets reconstructed from two uncorrelated clusters are dominant. Additional pixel clusters (on the order of 1–4%) were randomly added to the simulated events such that the tracklet Δr distributions at large Δr match those in data. A difference of 0.5% in the final results is observed at $\eta = 0$, which increases monotonically with $|\eta|$ to 2.4% at $|\eta| = 3.2$.

The tracklet selection criteria affect the minimum p_T and signal-to-background ratio of reconstructed tracklets. The sensitivity of the correction factors to these effects is checked by varying the nominal selection criterion on Δr by ± 0.1. The effect of such variations on the final results is found to be about 0.2%. The multiplicity variable used in the parametrisation of the correction factors can be changed to be the number of pixel clusters, which is independent of the tracklet reconstruction efficiency. The effects of such a change are negligible. In any given η range, measurements can be made using multiple tracklet combinations. The maximum deviation of the measurements obtained using each tracklet combination from the final averaged and symmetrised result, which ranges from 1.0 to 2.1% within $|\eta| < 1.4$ and up to 5.0% at larger values of $|\eta|$, is quoted as a systematic uncertainty. The model dependence of the correction factors is studied by using different sets of correction factors derived from HYDJET and AMPT, which have different descriptions of the particle production mechanisms. The predicted particle spectra and composition can differ significantly among the event generators, which affect the correction for leptons and the extrapolation of the measured tracklet spectra to $p_T = 0$. The maximum deviation from the nominal results is quoted as an uncertainty, and ranges from 2.0–2.2% within $|\eta| < 1.0$ to a maximum of 5.0% around $|\eta| = 2.0$. The model dependence of the Jacobian transformation from η to rapidity is also evaluated in a similar manner, and the maximum deviation, which ranges from

Table 1
Sources of systematic uncertainty affecting the measurement of charged hadron multiplicities and $\langle N_{\text{part}}\rangle$ in XeXe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV.

Source	[%]
Pixel cluster splitting	1.8–2.0
Pixel cluster reconstruction efficiency	0.5
Alignment uncertainty	<0.1
Uncorrelated pixel clusters	0.5–2.4
Tracklet selection	0.2
Tracklet reconstruction efficiency	<0.05
Consistency between tracklet combinations	1.0–5.0
Model dependence	2.0–5.0
Model dependence (Jacobian transformation)	0.5–2.5
Event selection efficiency (0–5% to 75–80%)	0.4–25.7
Glauber model calculation	0.7–8.9

0.5% around $|\eta| = 1.4$ to 2.1% (2.5%) around $|\eta| = 0$ (3.2), is quoted as an additional uncertainty for the $\mathrm{d}N_{\text{ch}}/\mathrm{d}y$ results.

The determination of event centrality depends on the hadronic event selection efficiency, as well as the amount of contamination from EM processes. Since the inefficiency is limited to the most peripheral collisions, the effect of the uncertainty in the event selection efficiency is to shift the events into other centrality intervals. Hence, to evaluate the uncertainty in the final results, different sets of centrality calibrations, derived after varying the event selection efficiency by its uncertainty, are used to categorise the data. This leads to a difference of 0.4–25.7% in the final results, largest in the 75–80% centrality interval and decreasing towards more central collisions, which is fully correlated across different centrality intervals and η values. The uncertainties in the N_{part} values are determined by propagating the uncertainties in the parameters of the Glauber model, which are listed in Section 3, and which range from 0.7 to 8.9%.

A summary of the systematic uncertainties is given in Table 1. With the exception of the uncertainties in the event selection efficiency and the N_{part} values, the systematic uncertainties are largely independent of centrality and highly correlated point-to-point in the region $|\eta| < 1.4$, where only combinations of BPIX layers contribute to the result.

6. Results

The pseudorapidity distributions of charged hadrons for $|\eta| < 3.2$ are shown in Fig. 2 (upper) for events in the 0–80% centrality interval, and in Fig. 2 (lower) for events in the 0–5% and 50–55% centrality intervals. The bottom panel in Fig. 2 (lower) shows the ratios of the $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions for events in the 0–5% centrality interval to those in the 50–55% centrality interval, normalised to unity at midrapidity. There is a hint of a centrality dependence in the shape of the $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distribution, in that the distribution in peripheral collisions is flatter than that in central collisions.

None of the event generators are able to fully describe the $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions in the three centrality intervals shown, in particular the $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ at midrapidity. However, the shapes of the distributions, where the overall normalisations are factored out, are consistent with those predicted by the Epos LHC event generator within the total systematic uncertainties. The centrality dependence of the shape of the $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions is described well by Epos LHC but not by the other event generators, as shown in the bottom panel of Fig. 2 (lower).

The rapidity distribution of charged hadrons in XeXe collisions with 0–80% centrality is shown in Fig. 3. The $\mathrm{d}N_{\text{ch}}/\mathrm{d}y$ distribution in data is observed to be consistent with a rapidity plateau in the region $|y| < 1$. The $\mathrm{d}N_{\text{ch}}/\mathrm{d}y$ distributions obtained from the Epos LHC, Hydjet, and Ampt event generators are also shown for comparison. None of the event generators describe the plateau around $y = 0$.

Fig. 4 (upper) shows the charged-hadron $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ at midrapidity as a function of centrality. For events in the 0–5% centrality

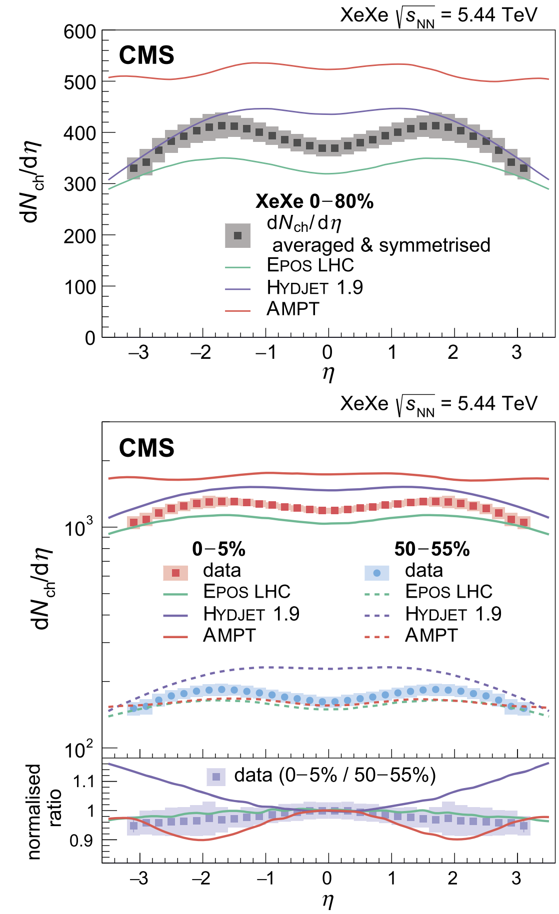

Fig. 2. Averaged and symmetrised $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions in XeXe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV (grey squares), for events in the 0–80% centrality interval (upper), as well as the 0–5% (red squares) and 50–55% (blue circles) centrality intervals (lower). Predictions from the Epos LHC v3400 [8,18], Hydjet 1.9 [9], and Ampt 1.26t5 [19] event generators are also shown for comparison. The ratios of the $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions for events in the 0–5% to those in the 50–55% centrality interval, normalised to unity at midrapidity, are shown in the bottom panel. The bands around the data points denote the total systematic uncertainties, while the statistical uncertainties are negligible.

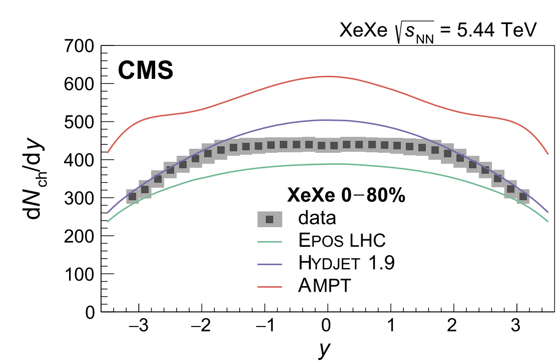

Fig. 3. Averaged and symmetrised charged-hadron $\mathrm{d}N_{\text{ch}}/\mathrm{d}y$ distribution in XeXe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV for events with 0–80% centrality (grey squares). The band around the data points denotes the total systematic uncertainties, while the statistical uncertainties are negligible. Predictions from the Epos LHC v3400 [8,18], Hydjet 1.9 [9], and Ampt 1.26t5 [19] event generators are also shown in comparison.

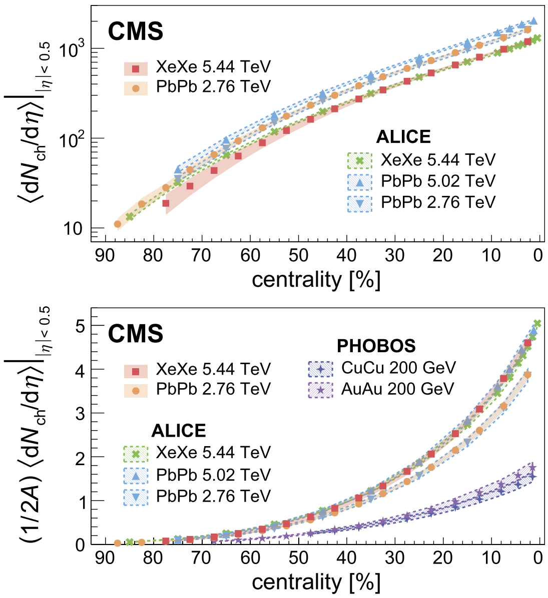

Fig. 4. Charged-hadron $dN_{ch}/d\eta$ in XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV at midrapidity as a function of event centrality, shown as is (upper) and normalised by $2A$ (lower), where A is the atomic number of the nuclei. The results are compared to measurements in PbPb and XeXe collisions by the CMS [16] and ALICE [17,37,38] Collaborations, and to measurements in CuCu and AuAu collisions by the PHOBOS Collaboration [39]. The bands around the data points denote the total systematic uncertainties, while the statistical uncertainties are negligible.

interval, $dN_{ch}/d\eta$ is found to be 1187 ± 36(syst) at midrapidity. This is nearly a factor of two greater than the interpolated $dN_{ch}/d\eta$ in proton-proton collisions at the same energy [11] after scaling by A, the atomic number of the nuclei. The results are compared to a measurement at the same energy for charged particles by the ALICE Collaboration [17], which includes leptons in the analysis. Within the total uncertainties, the measurements are consistent in the 0–60% centrality interval, although the ALICE Collaboration reports a slightly higher $dN_{ch}/d\eta$ for more peripheral collisions.

The results are also compared to previous measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV by the CMS [16] and ALICE [37,38] Collaborations. As one would expect, for the same centrality, $dN_{ch}/d\eta$ increases with energy and system size. It is interesting to note that for different colliding nuclei at the same energy, $dN_{ch}/d\eta$ is proportional to $2A$. This is evident from Fig. 4 (lower), where $(dN_{ch}/d\eta)/2A$ is shown as functions of centrality for a variety of colliding nuclei and energies. These results show that the feature observed at lower energies, that the geometry of the colliding systems plays an important role in determining the production of particles [6], is also present at the much higher LHC energies.

To study the relevance for particle production of the number of participating nucleons, $(dN_{ch}/d\eta)/\langle N_{part}\rangle$ is shown as a function of $\langle N_{part}\rangle$ in Fig. 5 (upper). The results are compared to a measurement at the same energy by the ALICE Collaboration and to previous measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. As can be seen, the per-participant multiplicity for XeXe and PbPb collisions with similar $\langle N_{part}\rangle$, but corresponding to different centrality classes in the two collision systems, are inconsistent. This is most apparent when nearly completely overlapping XeXe collisions (0–5% centrality or $\langle N_{part}\rangle \approx 236$) are compared to PbPb collisions with similar $\langle N_{part}\rangle$, for which the corresponding centrality is approximately 15–20%. However, as shown in Fig. 5 (lower), where $\langle N_{part}\rangle/2A$ is used as a proxy for centrality (the correspondence between centrality and $\langle N_{part}\rangle/2A$ is tabulated in the supplemental material [URL will be inserted by publisher]), the per-participant

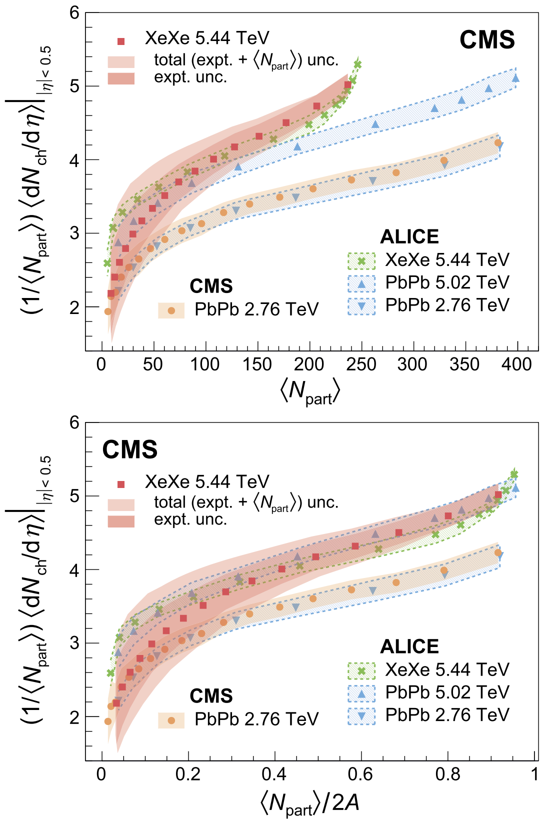

Fig. 5. Average $dN_{ch}/d\eta$ at midrapidity normalised by $\langle N_{part}\rangle$, shown as a function of $\langle N_{part}\rangle$ (upper) and $\langle N_{part}\rangle/2A$ (lower), where A is the atomic number of the nuclei. The results are compared to measurements in PbPb and XeXe collisions by the CMS [16] and ALICE [17,37,38] Collaborations. The bands around the data points denote the systematic uncertainties, while the statistical uncertainties are negligible.

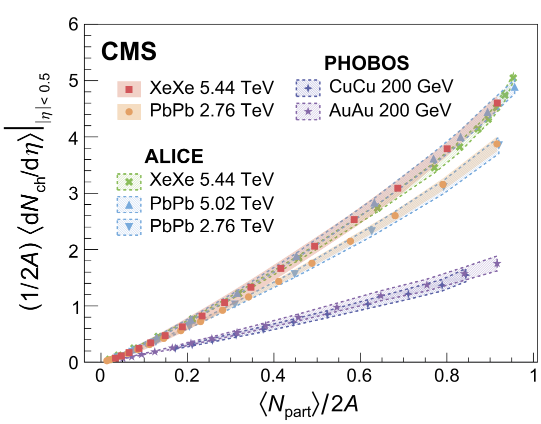

Fig. 6. Average $dN_{ch}/d\eta$ at midrapidity normalised by $2A$, shown as a function of $\langle N_{part}\rangle/2A$, where A is the atomic number of the nuclei. The results are compared to measurements in PbPb and XeXe collisions by the CMS [16] and ALICE [17,37,38] Collaborations, and to measurements in CuCu and AuAu collisions by the PHOBOS Collaboration [39]. The bands around the data points denote the systematic uncertainties, while the statistical uncertainties are negligible.

charged-hadron multiplicity for different colliding nuclei are equal within uncertainties when the geometry (centrality) and energy of the compared systems are the same.

An equivalent representation of Fig. 5 (lower) is shown in Fig. 6, where $(dN_{ch}/d\eta)/2A$ is shown as a function of $\langle N_{part}\rangle/2A$. In this form, it is clear that multiparticle production scales as $2A$ times a function of $\langle N_{part}\rangle/2A$, indicating a dependence on both the system size (given by $2A$) and the geometry of the colliding system (represented by $\langle N_{\text{part}}\rangle/2A$). Considering that multiparticle production processes in heavy ion collisions are highly complex—starting with the initial impact of the two nuclei, through the creation and evolution of a relativistic fluid, and followed by a hadronisation and scattering phase—it is not surprising that the result depends on both the colliding system and energy, in a non-trivial way.

7. Summary

The pseudorapidity distributions of charged hadrons in xenon-xenon collisions at a centre-of-mass energy of 5.44 TeV per nucleon pair are reported. Using data taken with the upgraded 4-layer silicon pixel detectors, the charged-hadron pseudorapidity densities, $dN_{\text{ch}}/d\eta$, are measured to an extended η range of $|\eta| < 3.2$. For events in the 0–5% centrality interval, the $dN_{\text{ch}}/d\eta$ at midrapidity is measured to be 1187 ± 36 (syst), with a negligible statistical uncertainty. The results are found to be consistent with the ALICE Collaboration's measurement. The charged-hadron rapidity density is also presented, and is found to be consistent with a rapidity plateau in the region $|y| < 1$. The results are compared to predictions from the Epos LHC v3400, Hydjet 1.9, and Ampt 1.26t5 event generators. None of the event generators are able to fully describe the measurements in terms of the magnitude, pseudorapidity dependence, and centrality dependence of the $dN_{\text{ch}}/d\eta$ distributions, although Epos LHC describes the shape well. The per-participant $dN_{\text{ch}}/d\eta$ at midrapidity in XeXe collisions is observed to rise faster with N_{part} than in PbPb collisions. However, when comparing events with similar fractional overlap, the per-participant $dN_{\text{ch}}/d\eta$ is consistent between the two collision systems. The results also show that the $dN_{\text{ch}}/d\eta$ at midrapidity is a function of the collision geometry after normalising by $2A$, where A, is the atomic number of the nuclei. This is observed for a variety of collision systems and energies, both at RHIC and the LHC, demonstrating that final-state charged-hadron multiplicities are strongly dependent on the collision geometry. These results provide important constraints on models and generators which describe multiparticle production in heavy ion collisions at high energies. They may also help in the characterisation of the initial conditions of the quark gluon plasma, which is needed for the understanding of its subsequent hydrodynamic evolution, as well as the properties of this fluid.

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Appendix A. Supplementary material

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