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Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

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Abstract

The pseudorapidity density of charged particles ($\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$) at mid-rapidity in Pb–Pb collisions has been measured at a center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. It increases with centrality and reaches a value of 1943 ± 54 in $|\eta| < 0.5$ for the 5% most central collisions. A rise in $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ as a function of $\sqrt{s_{\mathrm{NN}}}$ for the most central collisions is observed, steeper than that observed in proton–proton collisions and following the trend established by measurements at lower energy. The centrality dependence of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ as a function of the average number of participant nucleons, $\langle N_{\mathrm{part}} \rangle$, calculated in a Glauber model, is compared with the previous measurement at lower energy. A constant factor of about 1.2 describes the increase in $\frac{2}{\langle N_{\mathrm{part}} \rangle} \langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ from $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV to $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV for all centrality intervals, within the measured range of 0–80% centrality. The results are also compared to models based on different mechanisms for particle production in nuclear collisions.

*See Appendix A for the list of collaboration members

The theory describing the strong interaction, quantum chromodynamics (QCD), predicts the existence of a deconfined phase of matter, the quark-gluon plasma, at high temperature and energy density. Ultra-relativistic collisions of nuclei achieve the conditions necessary for the formation of this strongly interacting matter [1, 2].

The multiplicity of produced particles is an important property of the collisions related to the initial energy density and collision geometry. Its dependence on the impact parameter is sensitive to the interplay between particle production from hard and soft processes and coherence effects between individual nucleon–nucleon scatterings. With an increase in the collision energy, the role of hard processes i.e., parton scatterings with large momentum transfer, increases. The Large Hadron Collider (LHC) began operation at a higher energy producing Pb–Pb collisions at a center-of-mass energy of $\sqrt{s_{NN}}$ = 5.02 TeV. This is the highest energy achieved in the laboratory to date and offers the possibility to constrain particle production models by studying their $\sqrt{s_{NN}}$ dependence.

Collisions of extended objects such as nuclei can be classified according to their centrality which is related to the variation in the overlap area of the nuclei. This results in different numbers of nucleons participating in the collision. The number of these participants, N_{part}, can be calculated by a Monte Carlo sampling technique in the Glauber model [3]. The multiplicity can be quantified by the number of charged particles per unit of pseudorapidity, $\langle dN_{ch}/d\eta \rangle$ at mid-rapidity. The pseudorapidity is defined by $\eta \equiv -\ln\tan(\theta/2)$, with θ the emission angle of the particle relative to the beam axis. The primary charged particles are defined as prompt particles produced in the collision including all decay products, except products from weak decays of light flavor hadrons and of muons.

Previous measurements of $\langle dN_{ch}/d\eta \rangle$ for AA collisions were performed at the LHC by ALICE [4], ATLAS [5] and CMS [6] at $\sqrt{s_{NN}}$ = 2.76 TeV and at lower energies, in the range $\sqrt{s_{NN}}$ = 9 to 200 GeV with experiments at the Super Proton Synchrotron (SPS) and Relativistic Heavy Ion Collider (RHIC), e.g., [7–12]. They show that for Pb–Pb and Au–Au collisions $\langle dN_{ch}/d\eta \rangle$ per N_{part} pair increases more rapidly with the $\sqrt{s_{NN}}$ than for proton–proton collisions. As a function of centrality, $\frac{2}{\langle N_{part} \rangle}\langle dN_{ch}/d\eta \rangle$ in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV shows a relative rise with the number of participants which is very similar to the rise seen in $\sqrt{s_{NN}}$ = 200 GeV collisions at RHIC.

In this Letter we present the centrality dependence of $\langle dN_{ch}/d\eta \rangle$ averaged in the interval $|\eta| < 0.5$. The data were recorded with the ALICE detector in November 2015 during the initial part of the Pb–Pb data-taking period, the first at $\sqrt{s_{NN}}$ = 5.02 TeV. Full details of the component detectors [13] and their operational performance [14] are given elsewhere. A brief description of the most relevant elements, along with the experimental conditions, follows. The observed interaction rate was around 300 Hz of which about 25 Hz were from hadronic interactions, the remainder being a background from electromagnetically induced processes. A total of about 10^5 hadronic events are used. The interaction probability per bunch-crossing (during which bunches of ions from each beam are arranged to be co-incident at the ALICE interaction point) was sufficiently small that the chance of two hadronic interactions occurring together, so-called pileup events, was negligible.

The measurement relies on the ALICE Inner Tracking System, the innermost two layers of which form the Silicon Pixel Detector (SPD). The SPD consists of arrays of pixel detectors, arranged with an approximate cylindrical geometry at radii of 3.9 and 7.6 cm covering intervals of $|\eta| < 2.0$ and $|\eta| < 1.4$ for the inner and outer layers respectively. The SPD is situated within a 0.5 T magnetic field which is parallel to the beamline. The interaction trigger is provided by two detectors, V0A and V0C, which consist of arrays of scintillators, covering the full azimuth and more than 4 units of pseudorapidity, in the ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ respectively. In all cases the η-coverage refers to collisions at the nominal interaction point. A signal must be present in both V0 detectors to trigger the recording of the interaction. The V0 detectors also provide a signal proportional to the number of charged particles striking them which is used to classify the events into centrality intervals, defined in terms of percentiles of the hadronic cross-section. In addition, an offline event selection employs the information from two Zero Degree Calorimeters (ZDC) positioned 112.5 m from the interaction point on either side. Beam background events are removed using the V0 and ZDC timing information.

The $\langle dN_{ch}/d\eta \rangle$ measurement is performed using short track segments, termed tracklets [15]. Tracklet candidates are formed using the position of the primary vertex and a pair of hits, one in each SPD layer. The primary vertex position is extracted by correlating hits in the two SPD layers. For each of the hits in the pair two angles are determined with respect to the reconstructed interaction vertex and the angular difference, $\Delta\varphi$ in the bending plane and $\Delta\theta$ in the polar direction is calculated. In order to reject candidates produced by the random combination of two hits, tracklets are selected by a cut on the sum of the squares, $\delta^2 = (\Delta\varphi/\sigma_\varphi)^2 + (\Delta\theta/\sigma_\theta)^2 < 1.5$ where $\sigma_\varphi = 60$ and $\sigma_\theta = 25 \sin^2\theta$ mrad. This selection excludes particles with very low momenta, below 30 MeV/c, which is below the cut-off due to absorption in the detector material of 50 MeV/c. The acceptance region in η depends on the position, z, of the interaction vertex along the beamline. Events with $|z| < 7$ cm are used, corresponding to a coverage of $|\eta| < 0.5$ with an approximately constant acceptance.

A correction is needed both for the combined acceptance and efficiency, including the extrapolation to zero p_T, and for the removal of combinatorial background tracklets. This is computed using simulated data from the HIJING event generator [16] transported through a GEANT3 [17] simulation of ALICE. A re-weighting of the generator output is performed to reproduce the p_T distributions of inclusive charged hadrons and the relative abundances of pions, protons, kaons and other strange particles as measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [18–21]. Using results from $\sqrt{s_{NN}}$ = 2.76 TeV is justified because the relative abundances change very little from those at $\sqrt{s_{NN}}$ = 200 GeV. Any variation with the increase in $\sqrt{s_{NN}}$ to 5.02 TeV will be much smaller than the differences between the default and re-weighted HIJING simulations, which lead to differences in the results within the systematic uncertainties estimated below.

The correction takes into account any inactive channels present at the time of data taking as well as losses due to physical processes like absorption and scattering which may result in a charged particle not creating a tracklet. The fraction of active pixels in the inner and outer SPD layers were about 85% and 97.5%, respectively. The estimated combinatorial background amounts to about 18% in the most central (0–2.5%) and 1% in the most peripheral (70–80%) centrality classes. A correction of about 2% for contamination by secondaries from weak decays is applied based on the same simulation.

The other important component of the measurement is the classification of events in centrality intervals. This is done by using the summed amplitudes of the signals in the V0A and V0C detectors, following the method developed previously [22, 23]. The multiplicity distribution is fitted with a two-component model assuming that the effective number of particle-producing sources is given by $f \times N_{part} + (1-f) \times N_{coll}$, where N_{part} is the number of participating nucleons, N_{coll} is the number of binary nucleon–nucleon collisions and $f \sim 0.8$ quantifies their relative contributions. The number of particles produced by each source is distributed according to a Negative Binomial Distribution (NBD), parametrised with μ and k, where μ is the mean multiplicity per source and k controls the contribution at high multiplicity. The two-component model provides a good description of the observed multiplicity distribution down to the point at which a further component from low multiplicity electromagnetic events becomes significant. This corresponds to the most peripheral 10% of the cross-section. In the Monte Carlo Glauber calculation, the nuclear density for ^{208}Pb is modeled by a Woods–Saxon distribution for a spherical nucleus with a radius of 6.62 ± 0.06 fm and a skin thickness of 0.546 ± 0.010 fm, based on data from low energy electron–nucleus scattering experiments [24], and a hard-sphere exclusion distance between nucleons of 0.4 ± 0.4 fm. For $\sqrt{s_{NN}}$ = 5.02 TeV collisions an inelastic nucleon–nucleon cross-section of 70 ± 5 mb, obtained by interpolation [25], is used. The calculations are repeated with the parameters varied by the quoted uncertainties, in order to estimate the uncertainty on the average N_{part} in each centrality range.

Centrality	$\langle dN_{ch}/d\eta \rangle$	$\langle N_{part} \rangle$	$\frac{2}{\langle N_{part} \rangle}\langle dN_{ch}/d\eta \rangle$
0–2.5%	2035 ± 52	398 ± 2	10.2 ± 0.3
2.5–5.0%	1850 ± 55	372 ± 3	9.9 ± 0.3
5.0–7.5%	1666 ± 48	346 ± 4	9.6 ± 0.3
7.5–10%	1505 ± 44	320 ± 4	9.4 ± 0.3
10–20%	1180 ± 31	263 ± 4	9.0 ± 0.3
20–30%	786 ± 20	188 ± 3	8.4 ± 0.3
30–40%	512 ± 15	131 ± 2	7.8 ± 0.3
40–50%	318 ± 12	86.3 ± 1.7	7.4 ± 0.3
50–60%	183 ± 8	53.6 ± 1.2	6.8 ± 0.3
60–70%	96.3 ± 5.8	30.4 ± 0.8	6.3 ± 0.4
70–80%	44.9 ± 3.4	15.6 ± 0.5	5.8 ± 0.5

Table 1: The $\langle dN_{ch}/d\eta \rangle$ and $\frac{2}{\langle N_{part} \rangle}\langle dN_{ch}/d\eta \rangle$ values measured in $|\eta| < 0.5$ for eleven centrality classes. The values of $\langle N_{part} \rangle$ obtained with the Glauber model are also given. The errors are total uncertainties, the statistical contribution being negligible.

Several sources of systematic uncertainty were investigated. The centrality determination introduces an uncertainty via the fitting of the V0 amplitude distribution to the hadronic cross-section, due to the contamination from electromagnetically induced reactions at small multiplicity. The fraction of the hadronic cross-section (10%), at lowest multiplicity, where the trigger and event selection are not fully efficient, and the contamination is non-negligible, was varied by an uncertainty of ±0.5%. This was estimated by varying fitting conditions and by fitting a different centrality estimator, based on the hits in the SPD. The uncertainty from the centrality estimation results in an uncertainty of 0.5% for central 0-2.5% collisions which increases going to more peripheral collision classes, reaching 7.5% for the 70–80% sample, where it is the largest contribution. Conversely, the uncertainty due to the subtraction of the background is largest for the central event sample where it is about 2% and becomes smaller as the collisions become more peripheral, amounting to only 0.2% for the 70–80% event class. It is estimated by using an alternative method where fake hits are injected into real events.

All other sources of systematic uncertainty are independent of centrality. The uncertainty resulting from the subtraction of the contamination from weak decays of strange hadrons is estimated, from the tuned MC simulations, to amount to about 0.5% by varying the strangeness content by ±30%. The uncertainty due to the extrapolation down to zero p_T is estimated to be about 0.5% by varying the number of particles below the 50 MeV/c low-p_T cut-off by ±30%. An uncertainty of 1% for variations in detector acceptance and efficiency was evaluated by carrying out the analysis for different slices of the z-position of the interaction vertex distribution and with subsamples in azimuth.

Other effects due to particle composition, background events, pileup, material budget and tracklet selection criteria were found to be negligible. The final systematic uncertainties assigned to the measurements are the quadratic sums of the individual contributions, and range from 2.7% in central 0–2.5% collisions to 7.7% in 70–80% peripheral collisions, of which 2.1% and 7.5%, respectively, are centrality dependent and 1.2% are centrality independent.

The results for $\langle dN_{ch}/d\eta \rangle$ are shown in Table 1 along with the calculated values for $\langle N_{part} \rangle$. The rightmost column shows the $\langle dN_{ch}/d\eta \rangle$ values per participant pair for each centrality class. In order to compare with previous results an average value for the most central 5% collisions of 1943 ± 54 is produced, where the uncertainty is the total one, giving $\frac{2}{\langle N_{part} \rangle}\langle dN_{ch}/d\eta \rangle = 10.2 \pm 0.3$. Figure 1 shows this result with the existing data for central Pb–Pb and Au–Au collisions from experiments at LHC [4–6], RHIC [8–12] and SPS [7]. The data shown are for 0–5% except for the results from PHOBOS [11] and ATLAS [5] which are for 0–6%. The dependence of $\frac{2}{\langle N_{part} \rangle}\langle dN_{ch}/d\eta \rangle$ on the center-of-mass energy can be fitted with a power law of the form $a \cdot s^b$. This gives a value, under the assumption of uncorrelated uncertainties, of

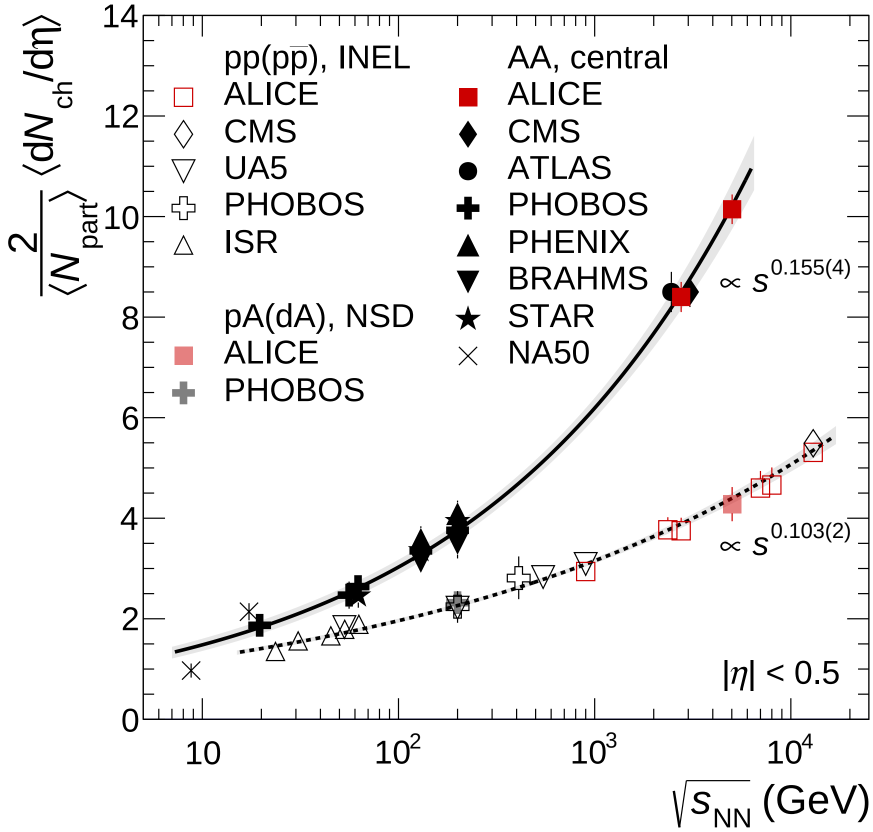

Fig. 1: Values of $\frac{2}{\langle N_{part}\rangle}\langle dN_{ch}/d\eta\rangle$ for central Pb–Pb [4–7] and Au–Au [8–12] collisions (see text) as a function of $\sqrt{s_{NN}}$. Measurements for inelastic pp collisions and p$\bar{p}$ collisions as a function of $\sqrt{s}$ are also shown [26–28] along with those from non-single diffractive p–A and d–A collisions [29, 30]. The s-dependence, proportional to $s_{NN}^{0.155}$ for AA collisions is indicated by a solid line: similarly a dashed line shows an $s_{NN}^{0.103}$ dependence in pp collisions. The shaded bands show the uncertainties on the extracted power-law dependencies. The central Pb–Pb measurements from CMS and ATLAS at 2.76 TeV have been shifted horizontally for clarity.

$b = 0.155 \pm 0.004$. It is a much stronger s-dependence than for proton–proton collisions, where a value of $b = 0.103 \pm 0.002$ is obtained from a fit to the same function [28]. The fit results are plotted with their uncertainties shown as shaded bands. The result at $\sqrt{s_{NN}}$ = 5.02 TeV confirms the trend established by lower energy data since b is not significantly different when the new point is excluded from the fit. It can also be seen in the figure that the values of $\frac{2}{\langle N_{part}\rangle}\langle dN_{ch}/d\eta\rangle$ measured by ALICE for p–Pb [25] and PHOBOS for d–Au [11] collisions fall on the curve for proton–proton collisions, indicating that the strong rise in AA is not solely related to the multiple collisions undergone by the participants since the proton in p–A collisions also encounters multiple nucleons.

The centrality dependence of $\frac{2}{\langle N_{part}\rangle}\langle dN_{ch}/d\eta\rangle$ is shown in Figure 2. The point-to-point centrality-dependent uncertaintes are indicated by error bars whereas the shaded bands show the correlated contributions. The statistical uncertainties are negligible. The data are plotted as a function of $\langle N_{part}\rangle$ and a strong dependence is observed, with $\frac{2}{\langle N_{part}\rangle}\langle dN_{ch}/d\eta\rangle$ decreasing by a factor 1.8 from the most central collisions, large $\langle N_{part}\rangle$, to the most peripheral, small $\langle N_{part}\rangle$. There appears to be a smooth trend towards the value measured in minimum bias p–Pb collisions [25]. The data measured at $\sqrt{s_{NN}}$ = 2.76 TeV [4, 26] are also shown, scaled by a factor 1.2, which is calculated from the observed $s^{0.155}$ dependence of the results in the most central collisions, and which describes well the increase for all centralities. Given

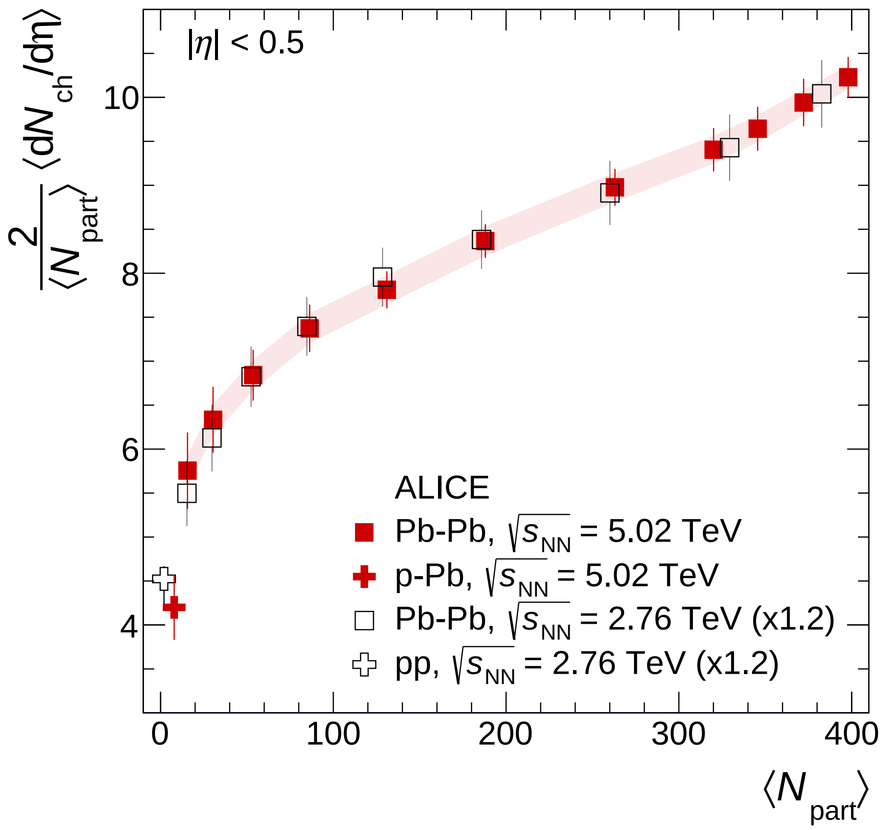

Fig. 2: The $\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$ for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the centrality range 0–80%, as a function of $\langle N_{part} \rangle$ in each centrality class. The error bars indicate the point-to-point centrality-dependent uncertainties whereas the shaded band shows the correlated contributions. Also shown is the result from non-single diffractive p–Pb collisions at the same $\sqrt{s_{NN}}$ [25]. Data from lower energy (2.76 TeV) Pb–Pb and pp collisions [4, 26], scaled by a factor of 1.2, are shown for comparison. The error bars for p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV and lower energy Pb–Pb and pp collisions indicate the total uncertainty.

that the uncertainties at the two energies are largely uncorrelated, the ratio between the data from these collision energies is consistent with being constant [22].

Figure 3 shows a comparison of the data to some of the models which were compared to the measurements at lower energy. The curves shown are predictions of the models, without any retuning of the parameters based on the new data presented here.

The two-component model (EKRT [31, 32]) combines perturbative-QCD (pQCD) processes with soft interactions, tuned to $\sqrt{s} = 7$ TeV pp and lower energy Pb–Pb data. It includes a strong impact parameter dependence of parton shadowing, the depletion of the parton distribution function at Bjorken-x smaller than about 0.1 [40]. The dependence for quarks is fixed by the experimental data on deep inelastic scattering and that for gluons determined by the centrality dependence of multiplicity in heavy-ion collisions, which limits the rise of particle production with centrality. They can broadly describe both the shape and the overall magnitude of the dependence of multiplicity on centrality.

Predictions from commonly used Monte Carlo generators, HIJING [33] and EPOS LHC [39], are shown. The data at $\sqrt{s_{NN}} = 2.76$ TeV were previously compared to HIJING using gluon shadowing parameter, s_g, values of 0.20 and 0.23 [4]. The higher value gave a better estimate of the overall normalization, the lower one a better agreement with the shape. At $\sqrt{s_{NN}} = 5.02$ TeV a larger s_g value of

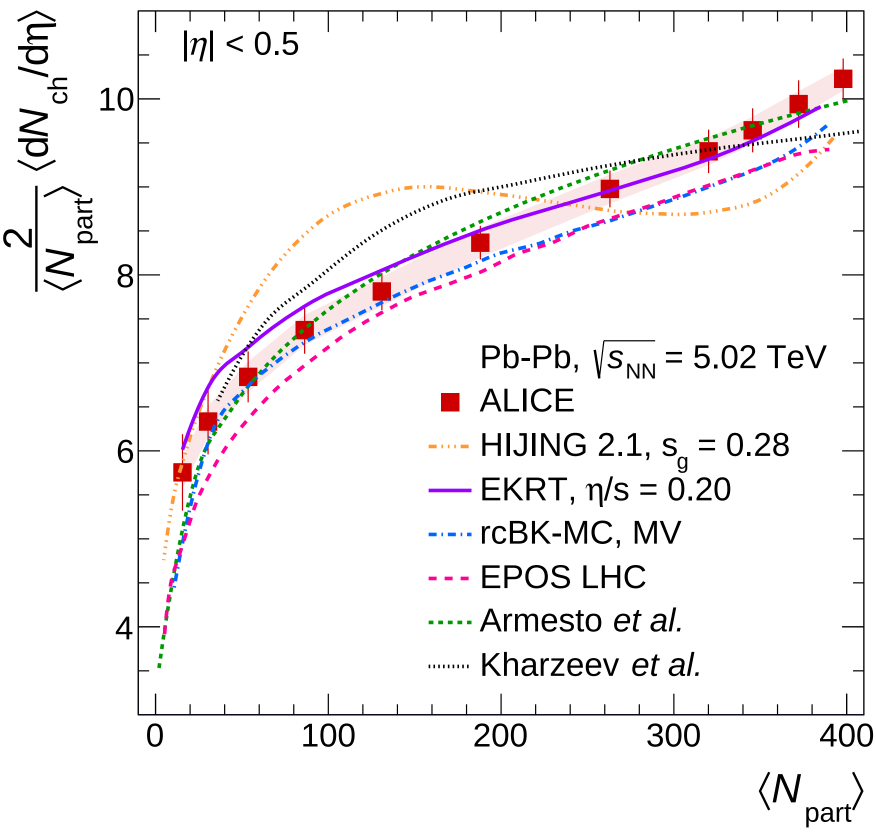

Fig. 3: The $\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$ for Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in the centrality range 0-80%, as function a of $\langle N_{part} \rangle$ in each centrality class, compared to model predictions [31–39].

0.28, is required to limit the multiplicity per participant, leading to a centrality dependence which does not reproduce the data.

Saturation-inspired models (rcBK-MC [35, 36], Kharzeev *et al.* [38] and Armesto *et al.* [37]) rely on pQCD and use an initial-state gluon density to fix an energy-dependent scale at which the quark and gluon densities saturate thereby limiting the number of produced partons and, in turn, of particles. This results in a factorization of the energy and centrality dependences of the multiplicity in the models, as observed in the experimental data. The rcBK-MC and Armesto *et al.* models provide a better agreement, in particular of the shape, with the data than the Kharzeev *et al.* model. In general, theoretical models need some sort of mechanism to limit the growth of multiplicity in order to describe the centrality and energy evolution of the multiplicity.

In summary, we have measured the multiplicity per participant pair in Pb–Pb collisions at the highest available center-of-mass energy and observe a 20% increase with respect to similar measurements at 2.76 TeV, in agreement with the previously established power-law dependence of this quantity. The centrality dependence of the charged-particle multiplicity density is very similar to that previously measured in lower energy AA collisions, with a factor of 1.8 increase from peripheral to central collisions. Those models which were able to reproduce the data at $\sqrt{s_{NN}}$ = 2.76 TeV are able to describe the data at $\sqrt{s_{NN}}$ = 5.02 TeV. Our results provide essential constraints for models describing high-energy heavy-ion collisions.

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