



# Charged-particle multiplicity distributions over a wide pseudorapidity range in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

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**Abstract** This paper presents the primary charged-particle multiplicity distributions in proton–lead collisions at a centre-of-mass energy per nucleon–nucleon collision of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The distributions are reported for non-single diffractive collisions in different pseudorapidity ranges. The measurements are performed using the combined information from the Silicon Pixel Detector and the Forward Multiplicity Detector of ALICE. The multiplicity distributions are parametrised with a double negative binomial distribution function which provides satisfactory descriptions of the distributions for all the studied pseudorapidity intervals. The data are compared to models and analysed quantitatively, evaluating the first four moments (mean, standard deviation, skewness, and kurtosis). The shape evolution of the measured multiplicity distributions is studied in terms of KNO variables and it is found that none of the considered models reproduces the measurements. This paper also reports on the average charged-particle multiplicity, normalised by the average number of participating nucleon pairs, as a function of the collision energy. The multiplicity results are then compared to measurements made in proton–proton and nucleus–nucleus collisions across a wide range of collision energies.

## 1 Introduction

The multiplicity distribution of primary charged particles,  $P(N_{\text{ch}})$ , is one of the key observables that provides valuable insights into the particle production mechanisms in high-energy hadronic and nuclear collisions. The production of charged particles at current collider energies involves the interplay of perturbative and non-perturbative quantum chromodynamic (QCD) interactions and is sensitive to colliding particle species, centre-of-mass energy, and collision centrality. ALICE measurements of charged-particle multiplicities across different collision systems over a broad range of pseudorapidity allow us to perform comprehensive stud-

ies of particle production at Large Hadron Collider (LHC) energies [1–8].

Recent experimental findings in proton–lead (p–Pb) collisions have shown characteristics of collectivity and strangeness enhancement that are typically attributed in heavy-ion collisions to the creation of a quark–gluon plasma (QGP) [9–13]. The origin of these phenomena is not yet fully understood, and it is crucial to investigate and understand the global properties of the system formed in p–Pb collisions, which makes the measurement of multiplicity distributions important. Moreover, the study of p–Pb collisions aids in understanding cold nuclear matter effects [14, 15] on the final-state particle production.

Following earlier ALICE results in proton–proton (pp) collisions [4], this paper presents, for the first time in p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV, a comprehensive set of measurements of  $P(N_{\text{ch}})$  for the full phase space ( $-3.4 < \eta_{\text{lab}} < 5.0$ ) and for a set of symmetric pseudorapidity ranges:  $|\eta_{\text{lab}}| < 2.4$ ,  $|\eta_{\text{lab}}| < 3.0$ , and  $|\eta_{\text{lab}}| < 3.4$ . We also study the charged-particle production on both the p-fragmentation and the Pb-fragmentation sides in p–Pb collisions, covering pseudorapidity ranges:  $-3.4 < \eta_{\text{lab}} < -1.0$  and  $2.0 < \eta_{\text{lab}} < 5.0$ , respectively. The results are compared to model calculations from HIJING (v1.36) [16], DPMJET (v3.0-5) [17], PYTHIA 8.308/Angantyr [18], and QCD saturation-based IP-Glasma [19, 20]. From the multiplicity distributions, we calculate the mean ( $\langle N_{\text{ch}} \rangle$ ), standard deviation ( $\sigma$ ), skewness ( $S$ ), and kurtosis ( $\kappa$ ) and compare them to the same moments evaluated from the considered models. This approach allows for a quantitative comparison of the performance of these models and provides input for their improved tuning to accurately simulate the underlying physics processes involved in particle production. This paper also reports a description of multiplicity distributions in terms of a double negative binomial distribution (NBD) function.

This article is organised as follows: Sect. 2 describes the experimental conditions, data sample considered in the analysis, the selection of collisions, and the reconstruction of

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charged particles. Section 3 explains the correction procedure applied to the data. The estimates of systematic uncertainties from various sources are discussed in Sect. 4. Section 5 presents the results of this analysis, and, finally, the conclusions are summarised in Sect. 6.

## 2 Experimental details

The full description of the ALICE detectors and their performance can be found in dedicated publications [13, 21, 22]. The ALICE reference frame is defined with the  $z$  axis directed along the beam line and the nominal interaction point (IP) at  $z = 0$ . This analysis uses the data collected by ALICE in 2013 during the p–Pb collision run of the LHC. In these collisions, a proton beam with an energy of 4 TeV circulated towards the negative  $z$  direction ( $\eta_{\text{lab}} < 0$ ), while lead ions with an energy of 1.58 TeV per nucleon circulated in the opposite direction ( $\eta_{\text{lab}} > 0$ ). This configuration resulted in collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV in the nucleon–nucleon centre-of-mass frame which is shifted in rapidity by  $\Delta y = 0.465$  in the direction of the proton beam. In the following, the variable  $\eta_{\text{lab}}$  represents the pseudorapidity in the laboratory reference frame. The sub-detectors used in this analysis are briefly described below.

The V0 detector [23, 24] is made of two arrays of 32 scintillators: V0A, positioned at  $z = 330$  cm and covering the pseudorapidity interval  $2.8 < \eta_{\text{lab}} < 5.1$ , and V0C, at  $z = -90$  cm and covering  $-3.7 < \eta_{\text{lab}} < -1.7$ . Both the amplitude and the time of the signals produced by charged particles that hit each scintillator are recorded. The V0 detector is used for minimum-bias trigger selection and background rejection in this analysis.

The Silicon Pixel Detector (SPD) consists of the two innermost cylindrical layers of the ALICE Inner Tracking System (ITS) [22, 25] surrounding the central beryllium beam pipe. The SPD covers the pseudorapidity ranges  $|\eta_{\text{lab}}| < 2$  and  $|\eta_{\text{lab}}| < 1.4$  with full azimuthal coverage for the inner and outer layers, respectively. In this analysis, the SPD is used to determine the position of the interaction vertex and to estimate the charged-particle multiplicity around midrapidity ( $|\eta_{\text{lab}}| < 2$ ).

The Forward Multiplicity Detector (FMD) [4, 6, 23] is a silicon strip detector composed of three sub-detectors placed at  $z = 320$  cm (FMD1), 79 cm (FMD2), and  $-69$  cm (FMD3). The FMD has full azimuthal coverage in the pseudorapidity ranges  $-3.4 < \eta_{\text{lab}} < -1.7$  (FMD3) and  $1.7 < \eta_{\text{lab}} < 5.0$  (FMD1 and FMD2), and these extend the charged-particle detection acceptance beyond the reach of the central detectors in ALICE.

A sample of non-single diffractive (NSD) collisions is selected using a minimum-bias (MB) trigger condition, which requires a coincidence between V0A and V0C time

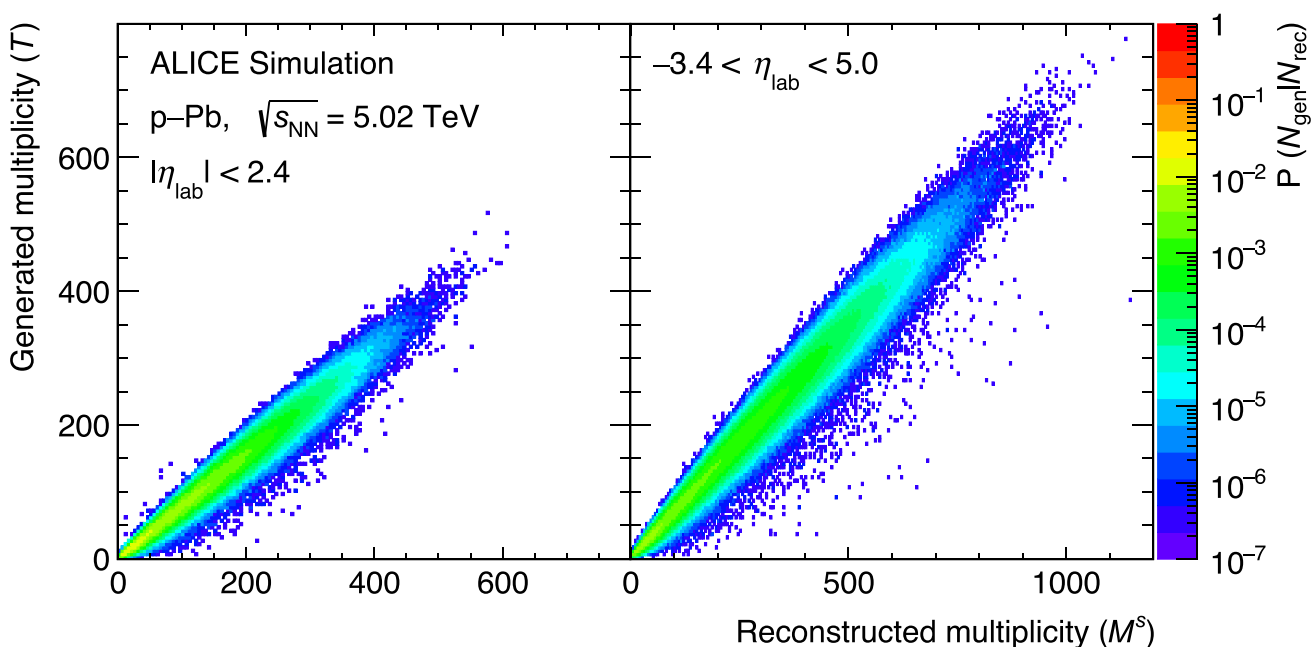
signals. The standard ALICE collision selection criteria [26] is used in this analysis, which includes: rejection of background collisions such as beam–gas or beam–halo interactions that occur outside the interaction region, exclusion of pile-up collisions, and selection of the reconstructed primary vertex position ( $z_{\text{vtx}}$ ) along  $z$  axis. However, in this analysis, the position of  $z_{\text{vtx}}$  is further restricted to be within  $\pm 4$  cm from the nominal IP to minimise the acceptance gaps in the pseudorapidity coverage of the SPD and FMD [4]. After applying all selection criteria, approximately 9 million p–Pb collisions are considered in this analysis.

The measurements of multiplicity at mid and forward rapidity are provided by the SPD and FMD, respectively. This analysis is focused on primary charged-particle measurements. Primary charged particles are defined as charged particles with a mean proper lifetime  $\tau$  larger than  $1 \text{ cm}/c$ , which are either a) produced directly in the collision, or b) from decays of particles with  $\tau$  smaller than  $1 \text{ cm}/c$ , excluding particles produced in interactions with material [27]. In the midrapidity region ( $|\eta_{\text{lab}}| < 2$ ), charged particles can deposit energy and produce signals in more than one pixel of the SPD. The offline reconstruction combines such adjacent pixel signals into a single cluster. The clusters from the two layers of SPD, together with the primary vertex, are combined to form tracklets. The charged-particle multiplicity is then determined by counting the number of tracklets [28]. In the forward regions ( $-3.4 < \eta_{\text{lab}} < -1.7$  and  $1.7 < \eta_{\text{lab}} < 5.0$ ), the FMD records the energy deposited by charged particles that traverse each silicon strip. The number of charged particles per strip is then calculated using a statistical approach as described in Ref. [5]. When there is an overlap in the acceptance ( $1.7 < |\eta_{\text{lab}}| < 2$ ) of the SPD and FMD, the multiplicity is determined by averaging the two measurements.

## 3 Correction procedure

As reported earlier, the main challenge in measuring the charged-particle multiplicity at forward rapidity is the significant background of secondary particles produced in interactions with the beam pipe and the material that exists in front of the FMD [4–6]. There are also other instrumental effects, such as detector acceptance and collision selection inefficiencies. A set of correction techniques is considered to account for these effects.

The main ingredients necessary to extract the primary charged-particle multiplicity distributions are the raw, uncorrected measured multiplicity distributions and a response matrix  $R$ . The matrix  $R$  is constructed via simulations where the known primary generated charged-particle multiplicity  $T$  is correlated with the simulated detector response  $M^s$ . Figure 1 shows a graphical representation of response matrix



**Fig. 1** Graphical representation of the detector response matrices obtained with the HIJING event generator for two pseudorapidity coverages:  $|\eta_{\text{lab}}| < 2.4$  (left) and  $-3.4 < \eta_{\text{lab}} < 5.0$  (right) in p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV

ces obtained with the HIJING event generator for the two pseudorapidity coverages:  $|\eta_{\text{lab}}| < 2.4$  (left) and  $-3.4 < \eta_{\text{lab}} < 5.0$  (right). The simulated detector response takes into account known conditions at the time of the data-taking, including inefficiencies, acceptance, electronic noise, and other smearing effects. Thus, one can write  $M^S \approx RT$ . The matrix element  $R_{mt}$  represents the conditional probability that an event with true multiplicity  $t$  is measured as an event with multiplicity  $m$ .

Experimentally, one needs to determine  $T$  for a given measured charged-particle distribution  $M$ . This can be symbolically written as

$$T = R^{-1}M. \tag{1}$$

However, the matrix  $R$  may be singular and cannot always be inverted analytically. Furthermore, even if  $R$  can be inverted, the results obtained with Eq. (1) contain oscillations mainly because of finite statistics in the response matrix. A regularised unfolding method based on Bayes’ theorem [29] using the RooUnfold software package [30] is used to overcome this problem.

The Bayesian unfolding technique is an iterative method in which the number of iterations serves as a regularisation parameter. Given an initial hypothesis (a prior),  $P_t$ , with  $t = 1, \dots, n$ , for the true distributions, Bayes’ theorem provides an estimation of the inverse matrix elements,  $\tilde{R}_{tm}$ ,

$$\tilde{R}_{tm} = \frac{R_{mt}P_t}{\sum_{t'} R_{mt'}P_{t'}}.$$

The unfolded distribution,  $U_t$ , is then obtained from

$$U_t = \sum_m \tilde{R}_{tm}M_m.$$

The obtained  $U_t$  is used as the prior distribution for the next iteration. After each iteration, the iterative process makes the unfolded distribution closer to the true one. In order to optimise the number of iterations, the  $\chi^2/\text{ndf}$  between the unfolded and the true distribution is computed and then studied as a function of the number of iterations using MC simulations. The number of iterations is then set to the number for which the  $\chi^2/\text{ndf}$  becomes minimum. The optimised number of iterations is found to be from 2 to 3 for the different pseudorapidity ranges. These number of iterations are used to unfold the experimental data to obtain the corrected multiplicity distributions.

The unfolded distributions are corrected further for the collision selection efficiency ( $\epsilon$ ), estimated via simulations as:

$$\epsilon = \frac{N_{\text{detected}}}{N_{\text{simulated}}},$$

where  $N_{\text{detected}}$  is the number of collisions detected by the simulated detector using NSD trigger condition with  $|z_{\text{vtx}}| < 4$  cm and  $N_{\text{simulated}}$  is the number of simulated NSD collisions with  $|z_{\text{vtx}}| < 4$  cm. There is a dependence in the  $z_{\text{vtx}}$  distribution and selecting  $z_{\text{vtx}}$  introduces a bias in the efficiency. The effect is visible only for narrow vertex selections, and it is not relevant for  $|z_{\text{vtx}}| < 4$  cm [4]. The values of  $\epsilon$  are estimated as



**Table 2** Contributions to systematic uncertainties (in percent) in the measurements of multiplicity distributions of primary charged particles on the p-fragmentation and the Pb-fragmentation sides in p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. Numbers are given at three characteristic

multiplicity values of 2, the mean  $\langle N_{ch} \rangle$ , and the value for which  $P(N_{ch}) = 10^{-3}$ . Where the uncertainty is less than 0.1%, it is specified as ‘negl.’ in the table

| Sources                               | $-3.4 < \eta_{lab} < -1.0$ (p-fragmentation side) |                                   |                       | $2.0 < \eta_{lab} < 5.0$ (Pb-fragmentation side) |                                   |                       |
|---------------------------------------|---|-----------------------------------|-----------------------|--|-----------------------------------|-----------------------|
|                                       | $N_{ch} = 2$                                      | $N_{ch} = \langle N_{ch} \rangle$ | $P(N_{ch}) = 10^{-3}$ | $N_{ch} = 2$                                     | $N_{ch} = \langle N_{ch} \rangle$ | $P(N_{ch}) = 10^{-3}$ |
| Upstream material                     | 1.5   | 1.1                               | 7.5                   | 3.4  | 1.0                               | 9.2                   |
| Event generator dependence            | 4.9   | 0.4                               | 1.3                   | 4.2  | 0.4                               | 3.5                   |
| Unfolding parameters                  | 1.7   | negl.                             | 0.2                   | 2.7  | 0.1                               | 0.1                   |
| Collision selection efficiency        | 1.0   | negl.                             | negl.                 | 8.9  | negl.                             | negl.                 |
| Charged-particle detection thresholds | 1.7   | 0.3                               | 1.4                   | 2.2  | 1.2                               | 3.7                   |
| Total                                 | 5.7   | 1.0                               | 7.7                   | 11.0   | 1.6                               | 10.5                  |

unknown distribution and assign that as a systematic uncertainty due to the imprecise knowledge of the material in front of the detectors.

To determine the systematic uncertainty due to the event generator’s dependence on the unfolding procedure, the measured distributions in data are unfolded using two separate response matrices built using HIJING and DPMJET. The average of these two unfolded distributions is used as our final measurement. The resulting difference between the average value and the unfolded distributions obtained using HIJING and DPMJET is assigned as the systematic uncertainty. As described in Sect. 3, the unfolding of measured distributions is sensitive to the choice of the number of iterations in the Bayesian unfolding procedure. To account for this, unfolded distributions are obtained by varying the number of iterations by  $\pm 1$  around the optimised values. The deviations of these modified unfolded results from the nominal ones are considered as the systematic uncertainty.

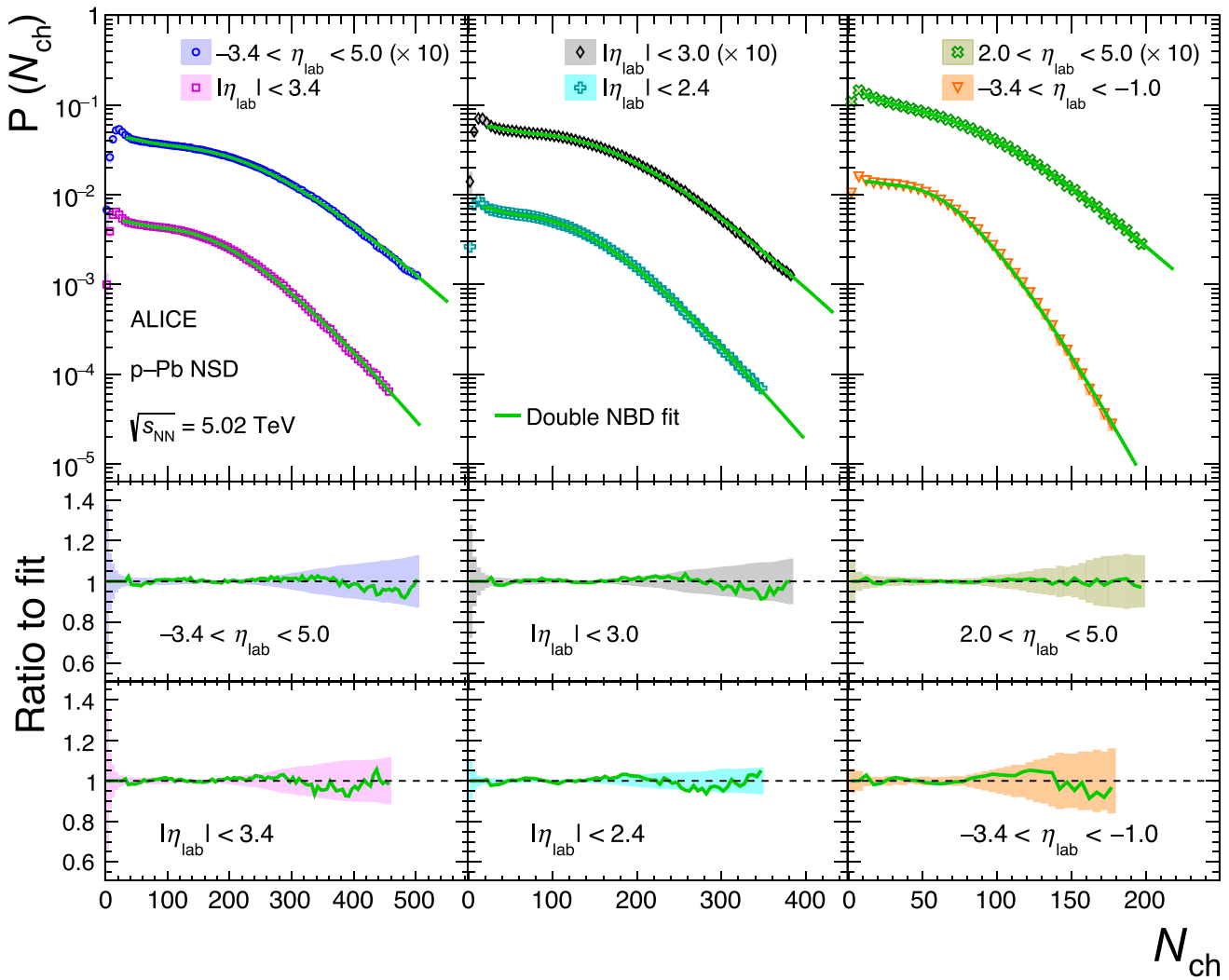
The systematic uncertainty associated with the correction for the collision selection efficiency is evaluated by determining the efficiency values using two different event generators, HIJING and DPMJET. This uncertainty is largest at low multiplicity values and reduces significantly at larger  $N_{ch}$  because contributions from diffractive processes become smaller when going to higher multiplicity [1, 3, 4].

Depending on the incident angle, a charged particle may deposit energy in more than one FMD strip [5]. Signals shared in the neighbouring strips are then merged based on specific thresholds: a lower threshold ( $T_{low}$ ) for accepting a signal and an upper threshold ( $T_{high}$ ) to consider a signal as isolated, i.e. all energy is deposited in a single strip. The lower threshold is defined by the noise level ( $n$ ) in the detector as  $T_{low} = xn$ , where the factor  $x$  is typically varied by one unit to estimate the one sigma variance in  $N_{ch}$ . The upper threshold is set such that the probability of energy loss ( $\Delta$ ) exceeding  $T_{high}$  for a single minimum ionizing particle (1

MIP) is greater than 99% ( $P(\Delta > T_{high}|1MIP) > 99\%$ ). This threshold is varied so that the probability increases or decreases by one standard deviation, thus estimating the variance of  $N_{ch}$ . In order to calculate the number of charged particles using a Poisson statistical approach, the strips in the FMD are divided into regions, and the number of empty strips is compared to the total number of strips in a given region. Strips with a signal below a given threshold are considered empty. This threshold is varied within the boundaries of fits to the energy loss spectra to evaluate the systematic uncertainty.

## 5 Results and discussion

The primary charged-particle multiplicity distributions are measured for NSD p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in six bins of pseudorapidities:  $-3.4 < \eta_{lab} < 5.0$ ,  $|\eta_{lab}| < 3.4$ ,  $|\eta_{lab}| < 3.0$ ,  $|\eta_{lab}| < 2.4$ ,  $-3.4 < \eta_{lab} < -1.0$ , and  $2.0 < \eta_{lab} < 5.0$ . The results are presented in Fig. 2. In the widest pseudorapidity range, the multiplicity distribution reaches a maximum around  $N_{ch} \approx 22$ , while for  $|\eta_{lab}| < 2.4$ , the maximum occurs around  $N_{ch} \approx 12$ . Beyond the maxima, the distributions fall steeply over several orders of magnitude. The coloured bands represent the systematic uncertainties, and the statistical uncertainties are smaller than the marker size. The multiplicity distributions  $P(N_{ch})$  are found to broaden as the  $\eta_{lab}$  range increases. These measurements extend the high-multiplicity reach with respect to the previous ALICE results of pp collisions both in the central [1–3] and forward rapidity [4] regions. The distributions for  $-3.4 < \eta_{lab} < 5.0$ ,  $|\eta_{lab}| < 3.0$ , and  $2.0 < \eta_{lab} < 5.0$  are scaled by a factor of 10 for clarity. The green lines show fits using a double Negative Binomial Distribution (NBD) function to the data, as discussed in the next subsection.



**Fig. 2** Charged-particle multiplicity distributions for different pseudorapidity intervals measured in p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV for NSD collisions. The green lines show fits of a double NBD function to the data. The ratios of the data to the fits are shown in the bottom panels

### 5.1 Parametrisation of multiplicity distributions with double NBDs

Experimental measurements in pp ( $p\bar{p}$ ) collisions at  $\sqrt{s} \leq 2.36$  TeV for charged particles at midrapidity ( $|\eta| < 1.5$ ) [1, 32, 33] have shown that the multiplicity distributions can be described by a single NBD given by the probability density function (p.d.f.)

$$f_{\text{NBD}}(n; \langle n \rangle, k) = \frac{\Gamma(n+k)}{\Gamma(k)\Gamma(n+1)} \frac{(\langle n \rangle/k)^n}{(1 + \langle n \rangle/k)^{n+k}}.$$

Here,  $\langle n \rangle$  denotes the mean multiplicity and the parameter  $k$  is related to the standard deviation ( $\sigma$ ) of the distribution by  $\sigma/\langle n \rangle = \sqrt{1/\langle n \rangle + 1/k}$ . However, at higher collision energies ( $\sqrt{s} \geq 2.76$  TeV) and wider pseudorapidity intervals ( $-3.4 < \eta < 5.0$ ), such a description is not adequate [2–4, 33]. Instead, those measurements are better captured by a

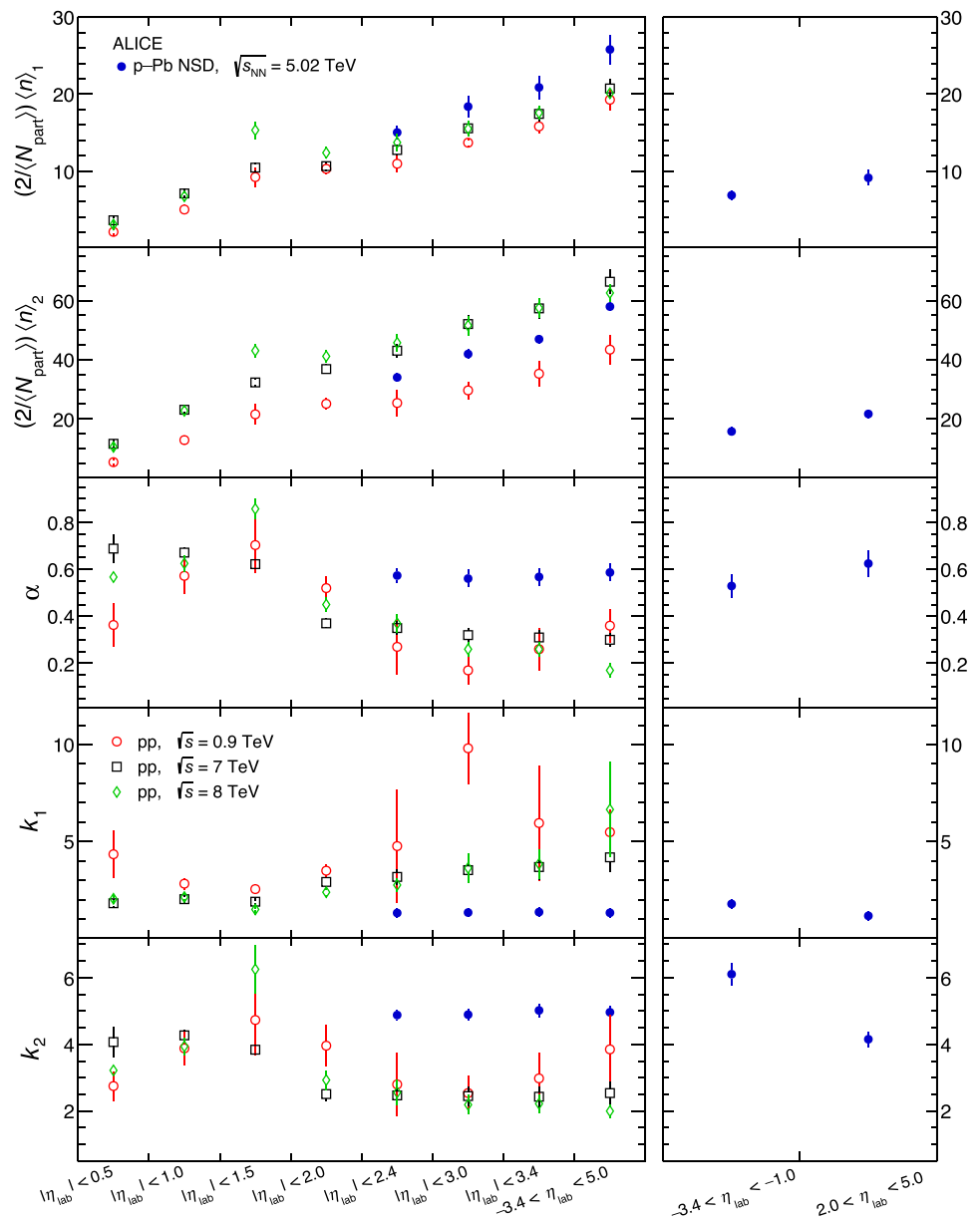
double NBD p.d.f. [3, 4, 33] given by

$$g(n; \langle n \rangle_1, k_1, \langle n \rangle_2, k_2, \lambda, \alpha) = \lambda[\alpha f_{\text{NBD}}(n; \langle n \rangle_1, k_1) + (1 - \alpha) f_{\text{NBD}}(n; \langle n \rangle_2, k_2)]. \quad (2)$$

In Eq. (2),  $\langle n \rangle_1$  and  $\langle n \rangle_2$  are the mean multiplicities of the first and second components (often interpreted as corresponding to soft and semihard processes), respectively, and the parameter  $\alpha$  reflects the fraction of the first component [33–35]. The parameters  $k_1$  and  $k_2$  are related to the standard deviations of the distributions associated with the first and second components, respectively.

In this work, the double NBD p.d.f. (given by Eq. (2)) is fitted to the measured multiplicity distributions. The first few bins ( $N_{\text{ch}} \approx 10$  to 30 depending on  $\eta$  window) of the multiplicity distributions are excluded from the fit and a free normalisation factor  $\lambda$  is introduced to account for this. This cut-off is chosen, primarily, to avoid the low-multiplicity

**Fig. 3** The pseudorapidity dependence of the double NBD parameters:  $\langle n \rangle_1$ ,  $\langle n \rangle_2$ ,  $k_1$ , and  $k_2$  in p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in comparison with pp measurements at  $\sqrt{s} = 0.9, 7,$  and  $8$  TeV [3,4]. For p–Pb collisions, the  $\langle n \rangle_1$  and  $\langle n \rangle_2$  values are scaled by the  $\langle N_{part} \rangle / 2$

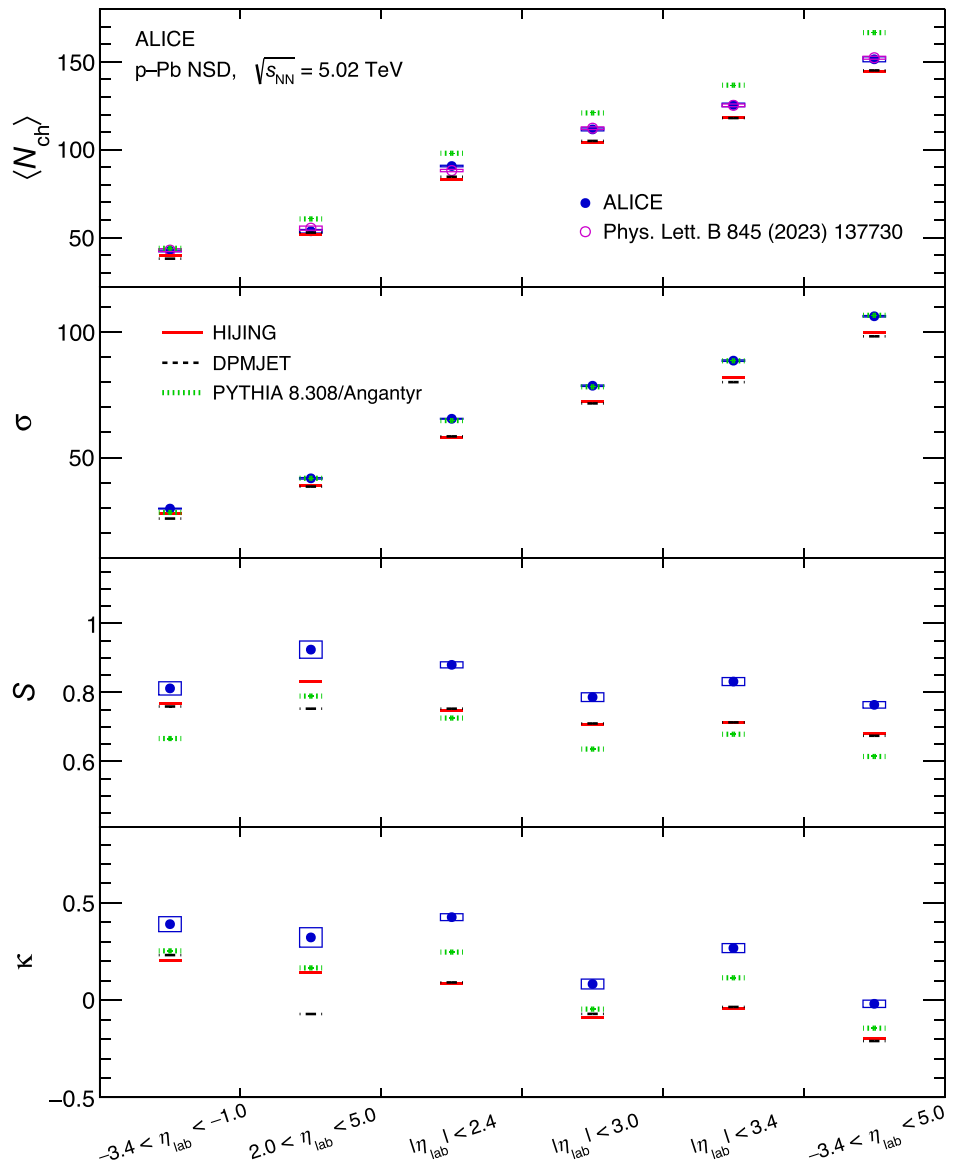


shape that is known to be not compatible with double NBD p.d.f. [3,4]. Coincidentally, diffractive contribution is only present at low multiplicities, however, there are no specific measurements available to estimate the importance of its effect on the shape of the multiplicity distribution. Nevertheless, it is expected that this contribution is well below the chosen cut-off as high-mass diffractive events that contribute to central multiplicity are quite rare. The fits are plotted together with the measured distributions in Fig. 2. The double NBD function reasonably describes the data within the uncertainties.

The obtained parameters from the fit to the data for different pseudorapidity intervals are shown in Fig. 3. The fit parameters obtained in p–Pb collisions are compared with the available pp measurements [3,4]. In p–Pb collisions, val-

ues of  $\langle n \rangle_1$  and  $\langle n \rangle_2$  are normalised by the average number of participating nucleon pairs ( $\langle N_{part} \rangle / 2$ ). Both  $\langle n \rangle_1$  and  $\langle n \rangle_2$  increase with the increase in  $\eta_{lab}$ . It is found that  $\langle n \rangle_2 \simeq 3\langle n \rangle_1$  for pp collisions at  $\sqrt{s} = 7$  and  $8$  TeV whereas  $\langle n \rangle_2 \simeq 2.4\langle n \rangle_1$  for pp collisions at  $\sqrt{s} = 0.9$  TeV and p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. This observation suggests a relationship between the two components of the multiplicity distribution, which may reflect the relative contributions from soft and semihard processes. In the left panels of Fig. 3, one can notice that for increasing pseudorapidity ranges starting at  $|\eta_{lab}| < 2.4$ , the normalised  $\langle n \rangle_1^{p-Pb} \gtrsim \langle n \rangle_1^{pp}$  whereas the normalised  $\langle n \rangle_2^{p-Pb}$  lies between the values observed at 0.9 and 7, 8 TeV for pp collisions. This suggests that the average multiplicity of the first (soft) component is nearly identical for both pp and p–Pb collisions, whereas the second

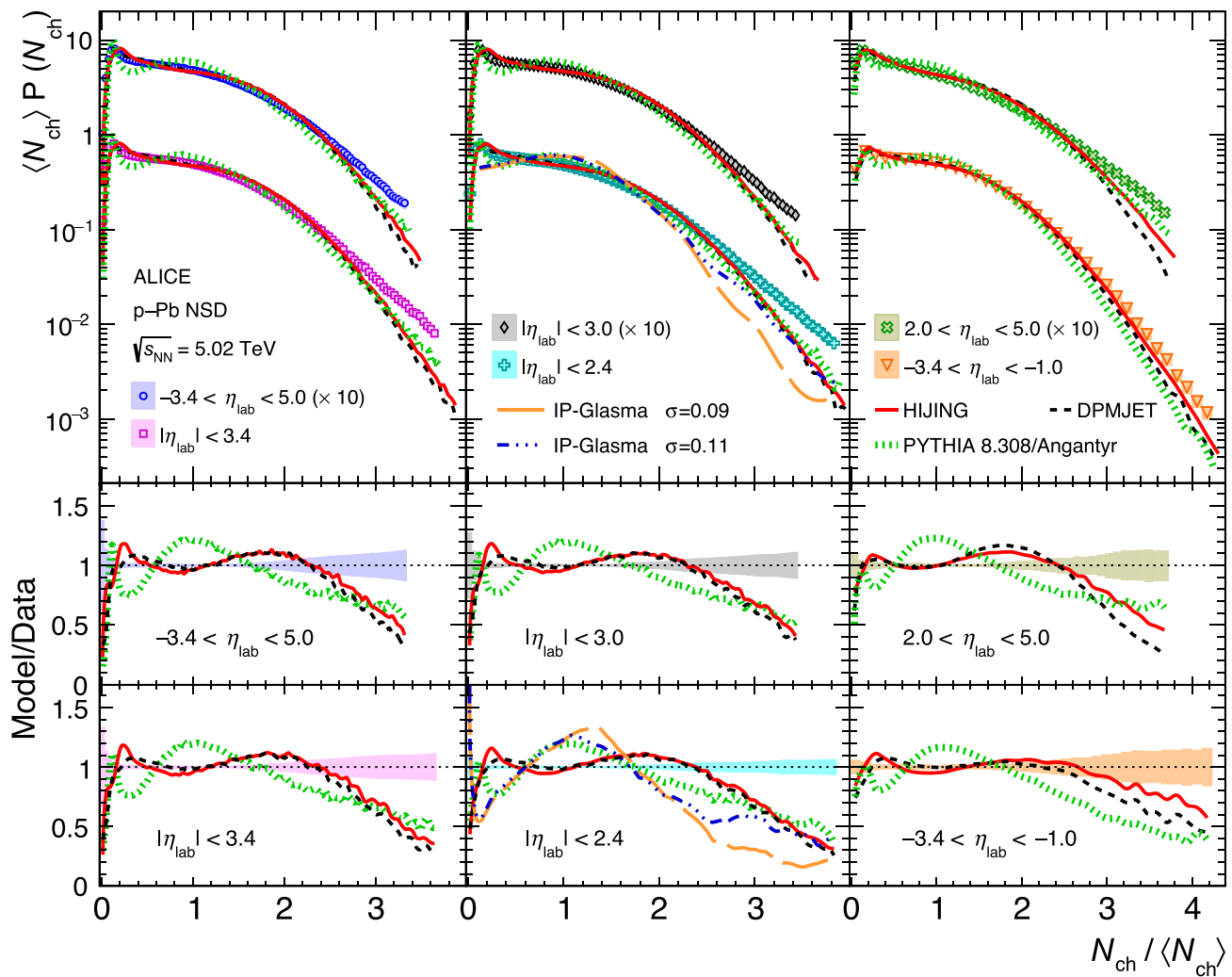
**Fig. 4** Four moments:  $\langle N_{\text{ch}} \rangle$ ,  $\sigma$ ,  $S$ , and  $\kappa$  of charged-particle multiplicity distributions for different pseudorapidity intervals in p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. Both skewness and kurtosis are plotted on two different ordinate scales to better visualize their respective variations. Predictions from the HIJING, DPMJET, and PYTHIA 8/Angantyr event generators are superimposed



(semihard) component follows an energy-dependent trend, increasing with energy. The parameters  $\alpha$ ,  $k_1$ , and  $k_2$  are independent of the width of the measured pseudorapidity interval for p–Pb collisions unlike in pp where they are found to have a mild dependence on the width of  $\eta_{\text{lab}}$  range. We observe clear differences in the NBD parameters of the multiplicity distributions between the p-fragmentation and the Pb-fragmentation sides (right panels of Fig. 3) in p–Pb collisions. The Pb-fragmentation side exhibits higher values of  $\langle n \rangle_1$  and  $\langle n \rangle_2$ , likely due to increased particle production relative to the p-fragmentation side. In addition, both  $\langle k \rangle_1$  and  $\langle k \rangle_2$  are found to decrease from the p-fragmentation to the Pb-fragmentation side, while the parameter  $\alpha$  is approximately similar for both sides.

### 5.2 Moments of the multiplicity distributions

To study multiplicity distributions and their shape, the first four moments ( $\langle N_{\text{ch}} \rangle$ ,  $\sigma$ ,  $S$ , and  $\kappa$ ) are calculated. The obtained values of  $\langle N_{\text{ch}} \rangle$ ,  $\sigma$ ,  $S$ , and  $\kappa$  of the measured multiplicity distributions at different pseudorapidity intervals are shown in Fig. 4. The open boxes represent the systematic uncertainty and the statistical errors are smaller than the symbols. The values of  $\langle N_{\text{ch}} \rangle$  and  $\sigma$  rise with the increasing width of the pseudorapidity interval. The expectation values of  $N_{\text{ch}}$  are also compared to those derived from previous ALICE  $dN_{\text{ch}}/d\eta$  measurements [8] (open circles), which differ in methodology, and, consequently, have different uncertainties, albeit with some overlap. Both measurements are found to be consistent and have uncertainties of less than 1%, and overlapping uncertainties contribute no more than half of that



**Fig. 5** KNO-scaled multiplicity distribution versus the KNO variable  $N_{ch}/\langle N_{ch} \rangle$  in NSD p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV for various pseudorapidity intervals. Comparison with predictions from HIJING,

DPMJET, PYTHIA 8/Angantyr, and the IP-Glasma model are shown. The ratios between models and data are calculated using a linear interpolation between adjacent points

uncertainty. The skewness is positive, showing only a modest variation of approximately 0.2 across the studied  $\eta_{lab}$  intervals, while the kurtosis exhibits a weakly decreasing trend with increasing  $\eta_{lab}$  interval, changing by about 0.5. The different lines in Fig. 4 are predictions from the HIJING, DPMJET, and PYTHIA 8/Angantyr (default tune) event generators. The models follow the general trend of the data points; however, they show significant deviations from the data. The moments of the HIJING and DPMJET distributions are similar except the  $S$  and  $\kappa$  on the Pb-fragmentation side. The  $\langle N_{ch} \rangle$  of the HIJING and DPMJET distributions are close to the data, but for the higher moments, they describe the data poorly, implying that the shape of their distributions is different from the data. On the other hand, PYTHIA 8/Angantyr reproduces the  $\sigma$  of the measured distributions but cannot

explain the rest of the moments (except the  $\langle N_{ch} \rangle$  of the data on the p-fragmentation side).

### 5.3 KNO scaling in the multiplicity distributions

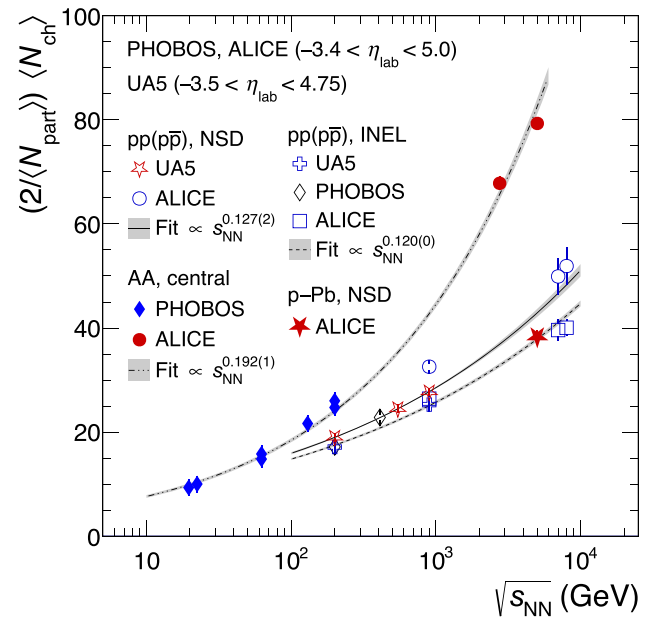
Koba, Nielsen and Olesen (KNO) found that for lower energy collisions, all moments of the multiplicity distribution scale with the first moment, i.e.,  $\langle N_{ch}^n \rangle \propto \langle N_{ch} \rangle^n$  [36]. Thus, a way to investigate properties of the multiplicity distributions is to plot these scaled by the mean multiplicity using the so-called KNO variable  $N_{ch}/\langle N_{ch} \rangle$ . This also has the added benefit that models that may differ in the mean of the distribution can still be compared to the empirical data. Figure 5 presents the data after scaling the probability density and the charged-particle multiplicity with the average number of charged particles  $\langle N_{ch} \rangle$ . The distributions for  $-3.4 < \eta_{lab} < 5.0$ ,  $|\eta_{lab}| < 3.0$ ,

and  $2.0 < \eta_{\text{lab}} < 5.0$  are scaled by a factor of 10 for clarity. The data are compared with predictions from the HIJING, DPMJET, and PYTHIA 8/Angantyr event generators. The models underestimate the data both at low and high multiplicities, indicating that they give narrower distributions than the data. The HIJING and DPMJET distributions are close to one another and compatible with the data (within 10%) for  $0.2 < N_{\text{ch}}/\langle N_{\text{ch}} \rangle < 2.5$ . This indicates that HIJING and DPMJET provide similar  $\langle N_{\text{ch}} \rangle$  values relative to data (also evident in the top panel of Fig. 4). On the other hand, PYTHIA 8/Angantyr gives the poorest description of the data in the intermediate multiplicities than the other two MC models. More specifically, PYTHIA 8/Angantyr is lower than the data for  $0.2 < N_{\text{ch}}/\langle N_{\text{ch}} \rangle < 0.6$  while higher than the data for  $0.6 < N_{\text{ch}}/\langle N_{\text{ch}} \rangle < 1.7$ .

The measurement in  $|\eta_{\text{lab}}| < 2.4$  is also compared to the prediction from the IP-Glasma model [37] based on the Color Glass Condensate (CGC) framework [38]. The IP-Glasma model incorporates fluctuations in the density of colour charges. In Fig. 5, the orange and blue distributions are generated with fluctuations of the colour charge density around the mean following a Gaussian distribution with width  $\sigma = 0.09$  and  $0.11$ , respectively. The IP-Glasma model, irrespective of the size of the fluctuations, largely overestimates the data at very low multiplicities ( $N_{\text{ch}}/\langle N_{\text{ch}} \rangle < 0.1$ ) and underestimates the same at high multiplicities ( $N_{\text{ch}}/\langle N_{\text{ch}} \rangle > 2$ ).

#### 5.4 System-size and energy dependence of $\langle N_{\text{ch}} \rangle$

In order to understand and compare the evolution of bulk particle production with collision energy and system-size, the mean charged-particle multiplicity is normalised by the  $\langle N_{\text{part}} \rangle$  pairs and then presented as a function of  $\sqrt{s_{\text{NN}}}$  in Fig. 6 for different collision systems. The  $\langle N_{\text{ch}} \rangle$  is measured over a range more than eight units in pseudorapidity and the  $\langle N_{\text{part}} \rangle$  is estimated using Glauber model calculations [7, 39–41]. Data from inelastic (INEL) and non-single diffractive pp ( $p\bar{p}$ ) collisions [4, 39, 42] and central heavy-ion collisions [5–7] are shown for comparison. A power-law ( $\alpha \cdot s_{\text{NN}}^\beta$ ) is fitted to the  $\langle N_{\text{ch}} \rangle$  as a function of centre-of-mass energy. Best-fit parameter values are  $\beta = 0.120 \pm 0.0001$ ,  $0.127 \pm 0.002$ , and  $0.192 \pm 0.001$  for INEL pp ( $p\bar{p}$ ), NSD pp ( $p\bar{p}$ ), and central AA collisions, respectively. The fit results are presented with their uncertainties shown by shaded bands. The results clearly show that the normalised  $\langle N_{\text{ch}} \rangle$  increases faster with energy in central AA collisions than in pp collisions. The value of  $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$  measured in p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV is half the magnitude of that in Pb–Pb collisions at the same energy, and falls on the INEL pp curve. A similar observation was also reported for charged-particle multiplicity measurements at midrapid-



**Fig. 6** Values of  $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$  for minimum-bias pp [4, 39],  $p\bar{p}$  [42], p–Pb and central AA [5–7] collisions as a function of  $\sqrt{s_{\text{NN}}}$  are shown. The  $s_{\text{NN}}$ -dependencies of INEL pp ( $p\bar{p}$ ) and NSD pp ( $p\bar{p}$ ) collisions are proportional to  $s_{\text{NN}}^{0.120}$  and  $s_{\text{NN}}^{0.127}$  respectively. The results from central AA collisions are proportional to  $s_{\text{NN}}^{0.192}$ . The bands represent the uncertainties on the extracted power-law dependencies

ity ( $|\eta_{\text{lab}}| < 0.5$ ) [26, 43, 44]. The similarity between the NSD p–Pb and the INEL pp data is yet to be understood.

## 6 Summary

The multiplicity distributions of primary charged particles have been measured in non-single diffractive p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV using the ALICE detector at the LHC. The measurements were performed over a wide pseudorapidity range ( $-3.4 < \eta_{\text{lab}} < 5.0$ ), the widest possible among the four large LHC experiments. The multiplicity distributions are parametrised with a double Negative Binomial Distribution function, which describes the data well within the measurement uncertainties. The first four moments (mean, standard deviation, skewness, and kurtosis) of the multiplicity distributions are determined and compared with predictions from the HIJING, DPMJET, and PYTHIA 8/Angantyr MC event generators. HIJING and DPMJET describe the mean of the distribution within  $\sim 5\%$  but cannot explain the higher moments of the data. On the other hand, PYTHIA 8/Angantyr reproduces only the second moment of the measured distributions but cannot describe the rest of the moments.

The multiplicity distributions are also presented as a function of the KNO variable and compared with predictions from HIJING, DPMJET, PYTHIA 8/Angantyr, and the CGC-based IP-Glasma model. None of the models can reproduce

the data in the reported multiplicity range. HIJING and DPMJET explain the data better than PYTHIA 8/Angantyr in the intermediate multiplicities. However, all MC predictions largely underestimate the multiplicity distributions at low and high multiplicities. The CGC-based IP-Glasma model disagrees with the measurements, irrespective of the level of colour charge fluctuations introduced into that model.

Finally, the dependence of  $\frac{2}{\langle N_{\text{part}} \rangle} \langle N_{\text{ch}} \rangle$  on the centre-of-mass energy is parametrised by a power-law function, which shows that the multiplicity in p–Pb collisions coincides with the trend observed in inelastic pp collisions.

The measurements reported in this paper provide valuable information for better understanding particle production mechanisms in p–Pb collisions and offer valuable input for developing theoretical models and Monte Carlo event generators.

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**Code Availability Statement** This manuscript has associated code/software. [Authors’ comment: The code/software used for the analysis is publicly available on the github repository, at the links <https://github.com/alisw/AlIRoot> and <https://github.com/alisw/AlIPhysics>.]

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












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