Pseudorapidity and transverse-momentum distributions of charged particles in proton- proton collisions at √s = 13 TeV

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ABSTRACT

The pseudorapidity (η) and transverse-momentum (p_T) distributions of charged particles produced in proton–proton collisions are measured at the centre-of-mass energy $\sqrt{s} = 13$ TeV. The pseudorapidity distribution in $|\eta| < 1.8$ is reported for inelastic events and for events with at least one charged particle in $|\eta| < 1$. The pseudorapidity density of charged particles produced in the pseudorapidity region $|\eta| < 0.5$ is 5.31 ± 0.18 and 6.46 ± 0.19 for the two event classes, respectively. The transverse-momentum distribution of charged particles is measured in the range $0.15 < p_T < 20$ GeV/c and $|\eta| < 0.8$ for events with at least one charged particle in $|\eta| < 1$. The evolution of the transverse momentum spectra of charged particles is also investigated as a function of event multiplicity. The results are compared with calculations from PYTHIA and EPOS Monte Carlo generators.

1. Introduction

After a two-year long shutdown, the Large Hadron Collider (LHC) at CERN restarted its physics programme in June 2015 with proton–proton collisions at $\sqrt{s} = 13$ TeV, the highest centre-of-mass energy reached so far in laboratory. The measurement of the inclusive production of charged hadrons in high-energy proton–proton interactions is a key observable to characterise the global properties of the collision, in particular whenever the collision energy increases significantly. Particle production at collider energies originates from the interplay of perturbative (hard) and non-perturbative (soft) QCD processes. Soft scattering processes and parton hadronisation dominate the bulk of particle production at low transverse momenta and can only be modelled phenomenologically. Hence, these measurements provide constraints for a better tuning of models and event generators for hadron-collider and cosmic-ray physics [1].

We present the pseudorapidity (η) and transverse-momentum (p_T) distributions of primary charged particles measured in proton–proton collisions at the centre-of-mass energy $\sqrt{s} = 13$ TeV with the ALICE detector [2] at the LHC [3]. Primary particles are defined as prompt particles produced in the collisions, including all decay products, with the exception of those from weak decays of strange particles. Similar measurements have been performed by ALICE in proton–proton (pp), proton–lead (p–Pb) and lead–lead (Pb–Pb) collisions collected during the previous LHC run at lower energies [4–14]. The pseudorapidity distribution is measured at central rapidity in $|\eta| < 1.8$. The measurements reported here have been obtained for inelastic events (INEL) and events having at least one charged particle produced with $p_T > 0$ in the pseudorapidity interval $|\eta| < 1$ (INEL > 0). Similar results were recently published by the CMS Collaboration for INEL events [15]. The transverse-momentum distribution of charged particles is measured in the range $0.15 < p_T < 20$ GeV/c and $|\eta| < 0.8$ for INEL > 0 events. The evolution of the transverse momentum spectra of charged particles is also investigated as a function of event multiplicity. The data have been compared to calculations from models commonly used at the LHC.

2. The ALICE detector and data collection

A comprehensive description of the ALICE experimental setup can be found in [2,16]. The main detectors utilised for the analysis presented here are the Inner Tracking System (ITS), the Time-Projection Chamber (TPC), the V0 counters and the ALICE Diffractive (AD) detector. The ITS and TPC detectors, which are located inside a solenoidal magnet providing a magnetic field of 0.5 T, are used for primary-vertex and track reconstruction. The V0 counters and the AD detector are employed for triggering and for background suppression.

The ITS is composed of six cylindrical layers of high-resolution silicon tracking detectors. The innermost layers consist of two arrays of hybrid Silicon Pixel Detectors (SPD) located at radii 3.9 and 7.6 cm from the beam axis and covering respectively $|\eta| < 2.0$ and $|\eta| < 1.4$ for particles emerging from the nominal interac-

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tion point ($z = 0$ cm). The TPC is a large cylindrical drift detector of radial and longitudinal size of about $85 < r < 250$ cm and $-250 < z < 250$ cm, respectively. The active volume of nearly 90 m^3 is filled with an Ar–CO_2 (88–12%) gas mixture and is divided into two halves by a central high-voltage membrane maintained at -100 kV. The two end-caps are each equipped with 36 multi-wire proportional chambers with cathode pad readout, comprising a total of 558 000 readout channels. The V0 counters are two scintillator hodoscopes placed on either side of the interaction region at $z = 3.3$ m and $z = -0.9$ m, covering the pseudorapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The AD detector was integrated in ALICE during the LHC shutdown before Run 2 to enhance the capabilities of the experiment to tag diffractive processes and low p_T events [17]. It consists of two double layers of scintillation counters placed far from the interaction region, on both sides: one in the ALICE cavern at $z = 17.0$ m and one in the LHC tunnel at $z = -19.5$ m. The pseudorapidity coverage of the two AD arrays is $4.8 < \eta < 6.3$ and $-7.0 < \eta < -4.9$, respectively.

The data were collected after the startup of LHC Run 2 in June 2015. Beams consisting of 39 bunches were circulating in the machine, with about 8×10^9 protons per bunch. In the ALICE interaction region, 15 pairs of bunches were colliding, leading to a luminosity of about 5×10^{27} cm^{-2} s^{-1}. This value corresponds to a rate of about 350 Hz for inelastic proton–proton collisions. The probability that a recorded event contains more than one collision was estimated to be around 10^{-3}, which is consistent with the fraction of events containing more than one distinct vertex and tagged as pileup. The luminous region had an RMS width of about 5 cm in the z direction and about 85 μm in the transverse direction. The data were collected using a minimum-bias trigger requiring a hit in either the V0 scintillators or in the AD arrays. The events were recorded in coincidence with the arrival of proton bunches from both directions. Control triggers taken for various combinations of beam and empty buckets were used to measure beam-induced and accidental backgrounds. The contamination from background events is removed offline by using the timing information from the V0 and the AD detectors, which have a time resolution better than 1 ns. Background events are also rejected by exploiting the correlation between the number of clusters of pixel hits and the number of tracklets (short track segments pointing to the primary vertex) in the SPD. From the analysis of control triggers it is estimated that the remaining background fraction in the sample is less than 10^{-4} and can be neglected.

3. Event selection and data analysis

About 1.5 million events pass the minimum-bias selection criteria. Events used for the data analysis are further required to have a valid reconstructed vertex within $|z| < 10$ cm. All corrections are calculated using a sample of about 4 million Monte Carlo events from the PYTHIA 6 [18] (Perugia-2011 [19]) event generator with particle transport performed via a GEANT3 [20] simulation of the ALICE detector.

The analysis technique employed for the measurement of the charged-particle pseudorapidity distribution is based on the reconstruction of tracklets, which are built using the position of the reconstructed primary vertex and two hits, one on each SPD layer. Details on the algorithm for tracklet reconstruction are described in [4]. This technique effectively allows to reconstruct charged particles with p_T above the 50 MeV/c cut-off determined by particle absorption in the material. The charged-particle pseudorapidity density is obtained from the measured distribution of tracklets $\mathrm{d}N_{\mathrm{tracklets}}/\mathrm{d}\eta$ as $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = \alpha(1-\beta)\mathrm{d}N_{\mathrm{tracklets}}/\mathrm{d}\eta$. The correction α accounts for the acceptance and efficiency for a primary particle to produce a tracklet, while β is the contamination of reconstructed tracklets from combinations of hits not produced by the same primary particle. Both correction factors are determined as a function of the z position of the primary vertex and the pseudorapidity of the tracklet from detector simulations and are found to be on average 1.5 and 0.01, respectively. The vertex position requirement results in an effective $|\eta| < 1.8$ coverage. Differences in strange-particle content between data and simulations, observed at lower beam energies [21,22], are taken into account by scaling the strangeness production in the Monte Carlo event sample by a factor 1.85 (strangeness correction), resulting in a further contamination correction of about 1%.

The transverse-momentum distribution is measured from tracks reconstructed using the information from the ITS and TPC detectors. Candidate tracks are selected with cuts on the number of space points used for tracking and on the quality of the track fit, as well as on the distance of closest approach to the reconstructed vertex. Details on the track-reconstruction algorithm and quality cuts can be found in [10,11,14]. The requirements applied for track selection result in an effective $|\eta| < 0.8$ acceptance. The efficiency for track reconstruction and selection depends on the particle type and it is known that PYTHIA 6 does not reproduce correctly the particle fractions measured at $\sqrt{s} = 7$ TeV. A reweighting of the Monte Carlo efficiencies for each species with the relative abundances measured in minimum-bias pp collisions at $\sqrt{s} = 7$ TeV [21,22] is performed. The overall primary charged-particle reconstruction efficiency for $|\eta| < 0.8$ increases sharply from 34% at 150 MeV/c, reaches 73% at 0.8 GeV/c, decreases moderately to 67% for $p_T = 2$ GeV/c and rises again to reach a saturation value of 74% at 10 GeV/c. The minimum around 2 GeV/c arises due to the azimuthal segmentation of the TPC readout chambers. Tracks of moderate p_T, which may not have enough hits in adjacent azimuthal sectors, do not pass the selection criteria. Finally, the residual contamination from secondary particles is subtracted from the spectrum; this contamination, estimated from Monte Carlo simulations, is 7% for our lowest p_T bin and decreases below 1% for $p_T > 2$ GeV/c.

Table 1
Summary of the relative systematic uncertainties (expressed in %) contributing to the measurement of the charged-particle pseudorapidity and transverse-momentum distributions. The values for the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ analysis are reported separately for the INEL and INEL > 0 classes. For the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}p_T$ analysis the p_T dependence is summarised with the values at 0.15 and 20 GeV/c for the INEL > 0 class.

	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$		$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}p_T$	
	INEL	INEL > 0	0.15	20 GeV/c
Background events and pileup	Negligible		Negligible	
Normalisation	2.8	2.3	2.3	
Detector acceptance and efficiency	1.5		1.8	5.6
Material budget	0.1		1.5	0.2
Track(let) selection criteria	Negligible		1.5	3.0
Particle composition	0.2		0.3	2.4
Weak decays of strange hadrons	0.5		3.4	0.4
Zero-p_T extrapolation	1.0		Not applicable	
Total (η, p_T dependent)	1.9		4.4	6.8
Total	3.4	3.0	5.0	7.2

4. Systematic uncertainties

A summary of the contributions to the relative systematic uncertainties of the charged-particle pseudorapidity and transverse-momentum distributions is reported in Table 1.

One of the main contributions to the normalisation of the results comes from the limited knowledge of cross-sections and kinematics of diffractive processes. For proton–proton collisions at $\sqrt{s} = 13$ TeV there is not yet any experimental information available about diffractive processes, therefore trigger and event-selection efficiency corrections are solely based on previous experimental data at lower collision energies and simulations with Monte Carlo event generators. The corresponding systematic uncertainty has been evaluated by varying the fractions of single-diffractive (SD) and double-diffractive (DD) events produced by PYTHIA 6 (Perugia-2011) by ±50% of their nominal values at $\sqrt{s} = 13$ TeV. The resulting contribution to the systematic uncertainties for INEL and INEL > 0 events is estimated to be about 2% and 1.2%, respectively. To estimate systematic uncertainties associated to the model dependence of the normalisation correction we employed PYTHIA 8 [23] (Monash-2013 [24]), which shows large differences both in the multiplicity and transverse-momentum distributions of charged particles with respect to PYTHIA 6, especially in diffractive events [25]. A difference of about 0.4% and 2% is observed for INEL and INEL > 0 events, respectively. Finally, an uncertainty of 2% has been estimated by varying the offline event-selection criteria applied to the trigger detectors which only affects the normalisation of the INEL sample.

The systematic uncertainties for the transverse-momentum distribution analysis are evaluated in a similar way as in previous analyses of pp [9,10], p–Pb [11,12], and Pb–Pb [14] data. The dominant sources of uncertainty are the track selections, the efficiency corrections and, for low p_{T}, the contamination from weak decays of strange hadrons. The systematic uncertainties for the pseudorapidity distribution analysis are discussed in the following. The uncertainty in detector acceptance and efficiency is estimated to be about 1.5%, determined from the change of the multiplicity at a given η by varying the range of the z position of the vertex and performing the measurement in different runs. The material budget in the ALICE central barrel $|\eta| < 1$ is known with a precision of about 5% [16]. The corresponding systematic uncertainty, obtained by varying the material budget in the simulation, is estimated to be about 0.1% and is negligibly small compared to the other sources. The sensitivity to tracklet selection criteria was estimated varying the selection requirements and is negligible. The uncertainty due to the particle composition is estimated to be about 0.2% and was determined by changing the relative fractions of charged kaons and protons with respect to charged pions produced by the Monte Carlo generator by ±30%. The uncertainty resulting from the subtraction of the contamination from weak decays of strange hadrons is estimated to amount to about 0.5% by varying the strangeness correction by ±30%. The uncertainty due to the correction down to zero p_{T} is estimated to be about 1% by varying the amount of particles below the 50 MeV/c low-p_{T} cutoff by $^{+100}_{-50}$%.

5. Results

Fig. 1 shows the average charged-particle density distribution $\langle dN_{\mathrm{ch}}/d\eta\rangle$ measured in INEL and INEL > 0 events in the pseudorapidity range $|\eta| < 1.8$. The data points have been symmetrised averaging the results obtained in $\pm\eta$, which were consistent within statistical uncertainties. The corresponding pseudorapidity densities in $|\eta| < 0.5$ are 5.31 ± 0.18 and 6.46 ± 0.19, respectively. The pseudorapidity density for the INEL > 0 events is also measured in $|\eta| < 1$ for direct comparison with INEL > 0 results reported by ALICE at lower energies [5] and is 6.61 ± 0.20. Also shown in Fig. 1 are the results recently published by the CMS Collaboration for inelastic collisions [15], which agree, within the uncertainties, with the measurement presented here. We compared our measurement to Monte Carlo calculations performed with PYTHIA 6 [18] (Perugia-2011 [19]), PYTHIA 8 [26] (Monash-2013 [24]) and

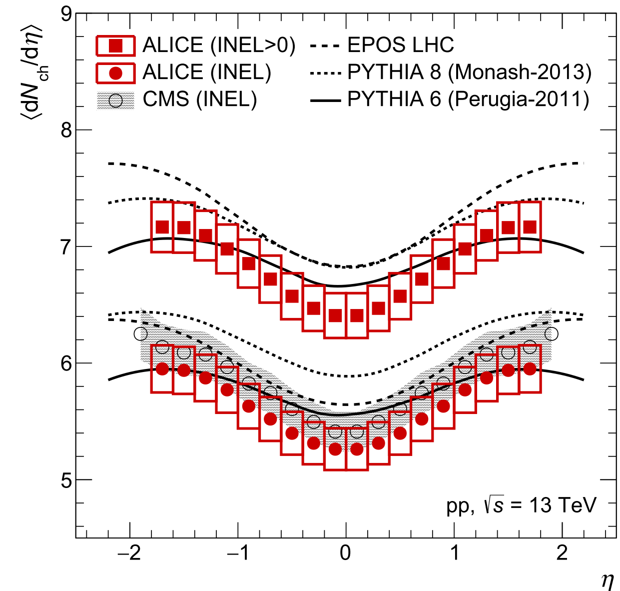

Fig. 1. Average pseudorapidity density of charged particles as a function of η produced in pp collisions at $\sqrt{s} = 13$ TeV. The ALICE results are shown in the normalisation classes INEL and INEL > 0 and compared to Monte Carlo calculations [18,19,24,26–28] and to the results from the CMS Collaboration [15]. The uncertainties are the quadratic sum of statistical and systematic contributions.

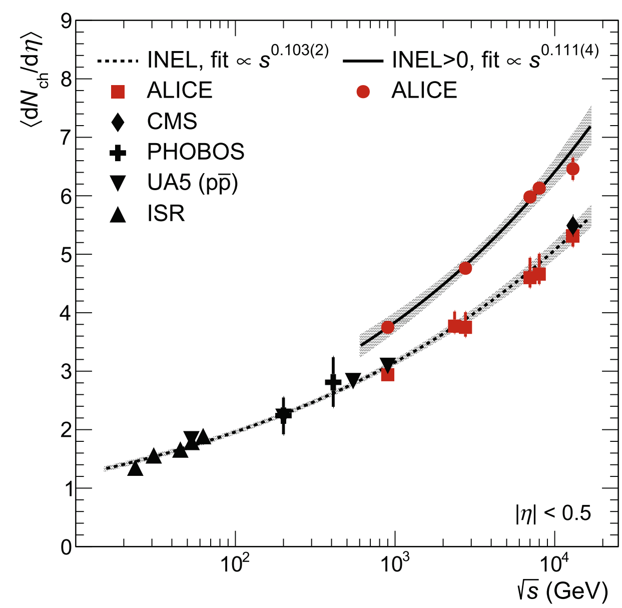

Fig. 2. Charged-particle pseudorapidity density measured in the central pseudorapidity region $|\eta| < 0.5$ for INEL and INEL > 0 events [4–6,15,29–33]. The uncertainties are the quadratic sum of statistical and systematic contributions. The lines are power-law fits of the energy dependence of the data and the grey bands represent the standard deviation of the fits.

EPOS LHC[1] [27,28] in both the INEL and INEL > 0 event classes. PYTHIA 6 calculations are in better agreement with the data than PYTHIA 8 in both classes, with PYTHIA 8 being higher than the data by about 12% (7%) in INEL events and about 7% (3%) in INEL > 0 events at $\eta \sim 0$ ($\eta \sim 1.5$). EPOS LHC calculations are about 7% (4%) and about 7% (5%) higher than the data in INEL and INEL > 0 events, respectively, at $\eta \sim 0$ ($\eta \sim 1.5$). In Fig. 2 we show

[1] Calculations performed with CRMC package version 1.5.3.

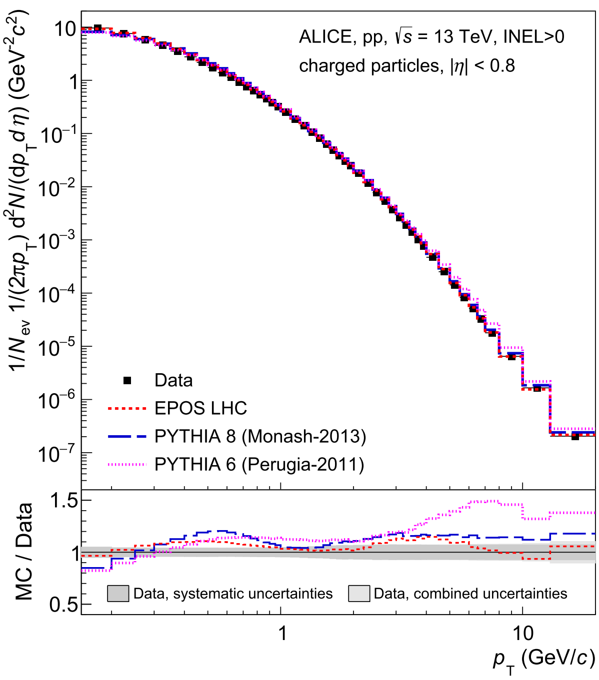

Fig. 3. Invariant charged-particle yield as a function of p_T normalised to INEL > 0 events. The data are compared to Monte Carlo calculations [18,19,24,26–28]. For the ratio of models (MC) and data (lower panel) the systematic and total uncertainties of the data are shown as grey bands.

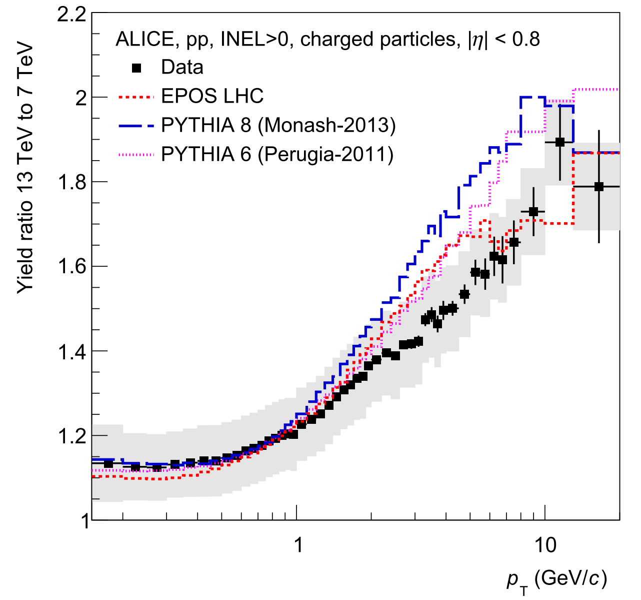

Fig. 4. Ratio of transverse-momentum spectra in INEL > 0 events at $\sqrt{s}$ = 13 and 7 TeV. The boxes represent the systematic uncertainties. The data are compared to Monte Carlo calculations [18,19,24,26–28].

a compilation of results on pseudorapidity density of charged particles measured in $|\eta| < 0.5$ for the INEL and INEL > 0 results at different proton–proton collider energies [4–6,15,29–33]. The energy dependence of $\langle dN_{ch}/d\eta\rangle$ is parametrised by the power law as^b fitted to data, where a and b are free parameters. By combining the data at lower energies with ALICE and CMS results at $\sqrt{s} = 13$ TeV, we obtain $b = 0.103 \pm 0.002$ and $b = 0.111 \pm 0.004$ for INEL and INEL > 0 event classes, respectively. Notice that the fit results assume that uncertainties at different centre-of-mass energies are independent, which is not strictly the case.

Fig. 3 presents the measured p_T spectrum and its comparison with calculations with PYTHIA 6 (Perugia-2011), PYTHIA 8 (Monash-2013) and EPOS LHC. For bulk particle production, the mechanism of colour reconnection is an important one in the PYTHIA models (see discussion below and in Ref. [34]). EPOS is a model based on the Gribov–Regge theory at parton level [27]. Collective (flow-like) effects are incorporated in the EPOS3 version [35] and treated via parametrisations in the EPOS LHC version [28]. These event generators, benefitting from the tuning performed on the LHC data in Run 1, describe the p_T spectrum reasonably well, although not in detail. It is interesting to note that both PYTHIA 8 and EPOS LHC models show a similar pattern in the ratio to data with discrepancies up to 20% and that PYTHIA 6 overestimates particle production at high p_T.

Fig. 4 shows the ratio of transverse-momentum spectra of charged particles at $\sqrt{s} = 13$ TeV and 7 TeV. The published data at $\sqrt{s} = 7$ TeV [10] were for INEL events. We have recalculated the normalisation of the spectrum to correspond to INEL > 0 events in a similar manner as done for $\sqrt{s} = 13$ TeV. The trigger and event-selection efficiency for INEL > 0 events at $\sqrt{s} = 7$ TeV was estimated using the same Monte Carlo simulations used for the publication [10]. The systematic uncertainties of the ratio are the quadratic sum of uncertainties at the two energies. As expected, the spectrum is significantly harder at $\sqrt{s} = 13$ TeV than at $\sqrt{s} = 7$ TeV. PYTHIA 6, PYTHIA 8 and EPOS LHC reproduce the trend observed in the data, but exhibit a slightly more pronounced hardening with energy in the transverse momentum region of a few GeV/c. The effect appears to be more significant in PYTHIA 8 than in PYTHIA 6 and EPOS LHC.

The correlation of the particle mean transverse momentum ($\langle p_T\rangle$) with the multiplicity of the event (N_{ch}) first observed at the Sp$\bar{p}$S collider [36] has been studied by many experiments at hadron colliders in pp($\bar{p}$) covering collision energies from $\sqrt{s}$ = 31 GeV up to 7 TeV [9,37–44]. The increase of $\langle p_T\rangle$ with N_{ch} in the central rapidity region observed in all experiments could be reproduced in the PYTHIA event generator only if a mechanism of hadronisation with colour reconnections (CR) is considered [34, 45–47]. A connection between CR and features of collective flow has been conjectured in [48]. In heavy-ion collisions, collective flow is established as a genuine space–time evolution of a fireball, while CR in PYTHIA is a mechanism invoked for hadronisation. The relevance of the CR-flow conjecture is currently investigated further [49]. A mechanism involving collective string hadronisation is also used in the EPOS model [28].

Fig. 5 shows the ratio of spectra measured in three intervals of multiplicity to the inclusive (INEL > 0) spectrum. For this ratio, the spectra were normalised by the integral prior to dividing. The selection is performed on the multiplicity measured in the same kinematic region as the spectrum, $|\eta| < 0.8$ and $0.15 < p_T < 20$ GeV/c, using the measured track multiplicity N_{ch}^{acc} for data and the true value of N_{ch} known in Monte Carlo events. For INEL > 0 events, $\langle N_{ch}^{acc}\rangle = 6.73$ (and, from the spectrum in Fig. 3, $\langle N_{ch}\rangle = 9.41 \pm 0.38$) for data and $\langle N_{ch}\rangle = 10.13$ for PYTHIA 8 and $\langle N_{ch}\rangle = 9.97$ for EPOS LHC events. The low-multiplicity interval corresponds to N_{ch} (N_{ch}^{acc}) smaller than the average value in INEL > 0 events, $\langle N_{ch}\rangle$ ($\langle N_{ch}^{acc}\rangle$), the medium-multiplicity interval covers between $\langle N_{ch}\rangle$ ($\langle N_{ch}^{acc}\rangle$) and twice $\langle N_{ch}\rangle$ ($\langle N_{ch}^{acc}\rangle$), while the high-multiplicity interval includes all events with N_{ch} (N_{ch}^{acc}) $\geq 2\langle N_{ch}\rangle$ ($\langle N_{ch}^{acc}\rangle$). Given that the measurement efficiency of the p_T spectrum for INEL > 0 events with $N_{ch} = 1$ is about 50%, the data is slightly biased for the lowest multiplicity interval. This leads to a slight hardening of the measured spectrum, but the magnitude of the spectral shape change, of a few percent, is clearly smaller than the observed difference between data and models. The systematic

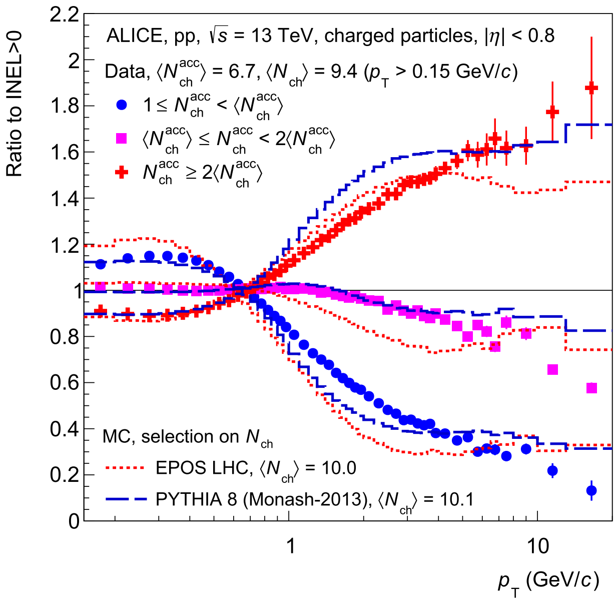

Fig. 5. Ratios of transverse-momentum distributions of charged particles in three intervals of multiplicities to the respective one for inclusive (INEL > 0) collisions. The spectra were normalised by the integral prior to division. The data are compared to Monte Carlo calculations [24,26–28].

uncertainties of the measured spectra cancel out completely in the ratios. A residual contribution, not estimated at this stage, is that of the contamination from strange-particle decays.

It is known that the increase of $\langle p_T \rangle$ as a function of multiplicity is moderate [44]. The data in Fig. 5 show that the correlation of the spectrum with multiplicity is prominent for the whole p_T range and in particular that it is stronger at high p_T. In first order, this correlation arises naturally from jets, giving the leading high-p_T hadron and a significant contribution to multiplicity. The general features seen in the data, which are similar to those first seen at $\sqrt{s} = 0.9$ TeV [9], are reproduced by PYTHIA 8 and EPOS LHC fairly well, but some disagreements are noticeable too, in particular in the p_T region of a few GeV/c. This is more prominent for EPOS LHC. It was shown earlier [44] that both EPOS LHC and PYTHIA 8 reproduce well, although slightly overpredicting, the correlation of $\langle p_T \rangle$ with N_{ch}. The present data on spectral shape highlight some deficiencies in both models concerning the description of spectral shapes as a function of multiplicity.

6. Conclusions

We have reported the measurement of the pseudorapidity and transverse-momentum distributions of charged particles produced in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ALICE detector at LHC. The pseudorapidity distribution is measured for two normalisation classes: inelastic events (INEL) and events having at least one charged particle in the pseudorapidity interval $|\eta| < 1$ (INEL > 0). The charged-particle densities in $|\eta| < 0.5$ are 5.31 ± 0.18 and 6.46 ± 0.19, respectively. The transverse-momentum distribution is measured in the range $0.15 < p_T < 20$ GeV/c and $|\eta| < 0.8$ for INEL > 0 events. The spectrum is significantly harder than at $\sqrt{s} = 7$ TeV and shows rich features when correlated with the charged-particle multiplicity measured in the same kinematic region. The results are found to be in fair agreement with the expectations from lower energy extrapolations and with the calculations from PYTHIA and EPOS Monte Carlo generators, but not in all details. Both models exhibit a slightly more pronounced hardening of the p_T distributions with collision energy than the data for transverse momenta above a few GeV/c.

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