Title
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Journal
Physics Letters B, 710(3)

ISSN
0370-2693

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Publication Date
2012-04-01

DOI
10.1016/j.physletb.2012.02.045

Physics Letters B 710 (2012) 363–382

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of the centrality dependence of the charged particle pseudorapidity distribution in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector ☆

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ARTICLE INFO

Article history:
Received 30 August 2011
Received in revised form 6 February 2012
Accepted 16 February 2012
Available online 21 February 2012
Editor: H. Weerts

ABSTRACT

The ATLAS experiment at the LHC has measured the centrality dependence of charged particle pseudorapidity distributions over $|\eta| < 2$ in lead–lead collisions at a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. In order to include particles with transverse momentum as low as 30 MeV, the data were recorded with the central solenoid magnet off. Charged particles were reconstructed with two algorithms (2-point "tracklets" and full tracks) using information from the pixel detector only. The lead–lead collision centrality was characterized by the total transverse energy in the forward calorimeter in the range $3.2 < |\eta| < 4.9$. Measurements are presented of the per-event charged particle pseudorapidity distribution, $dN_{ch}/d\eta$, and the average charged particle multiplicity in the pseudorapidity interval $|\eta| < 0.5$ in several intervals of collision centrality. The results are compared to previous mid-rapidity measurements at the LHC and RHIC. The variation of the mid-rapidity charged particle yield per colliding nucleon pair with the number of participants is consistent with lower $\sqrt{s_{NN}}$ results. The shape of the $dN_{ch}/d\eta$ distribution is found to be independent of centrality within the systematic uncertainties of the measurement.

1. Introduction

Collisions of lead (Pb) ions at the Large Hadron Collider provide an opportunity to study strongly interacting matter at the highest temperatures ever created in the laboratory [1]. Measurements of the centrality dependence of charged particle multiplicities and of charged particle pseudorapidity densities in such ultra-relativistic nucleus–nucleus (A + A) collisions provide essential information on the initial particle or entropy production and subsequent evolution in the created hot, dense matter. Results from the Relativistic Heavy Ion Collider (RHIC) over the centre-of-mass energy range from 19.6 to 200 GeV indicate that the multiplicity of charged particles per colliding nucleon pair has a mild dependence on the collision centrality and that the pseudorapidity dependence of the charged particle yield near mid-rapidity is essentially centrality independent [2]. The weak variation of the multiplicity per colliding nucleon pair with centrality at RHIC was initially found to be inconsistent with models such as HIJING [3] which includes a mixture of soft and hard scattering processes with a p_T cutoff on the hard scattering contribution at 2 GeV, or with a beam-energy-dependent cutoff in a more recent version [4]. In contrast, calculations based on parton saturation invoking k_T factorization were able to reproduce both the shape and centrality dependence of the RHIC charged particle pseudorapidity distributions [5,6]. However, more recent theoretical studies indicate that k_T factorization may not be applicable to nucleus–nucleus collisions, and improved soft + hard models may be able to describe RHIC multiplicity measurements. At the same time, older hydrodynamical models (e.g. Ref. [7]) have had some success describing the energy dependence of the total multiplicity as well as rapidity distributions of identified hadrons, although their domain of applicability is still not fully established.

Detailed measurements of the centrality dependence of charged particle multiplicities and pseudorapidity distributions at the LHC together with the earlier RHIC measurements could provide essential insight on the physics responsible for bulk particle production in ultra-relativistic nuclear collisions. Because hard scattering rates increase rapidly with centrality and $\sqrt{s_{NN}}$, the combined RHIC and LHC measurements should provide a strong constraint on the contribution of hard scattering processes to inclusive hadron production subject to uncertainties regarding the shadowing of nuclear parton distributions at low x. Measurements at the LHC can also provide a valuable test of recent parton saturation calculations that still claim to be able to describe inclusive particle production in ultra-relativistic nuclear collisions [5,6]. Previous measurements at the LHC [8,9] have already started addressing some of the physics raised above. In particular, those earlier measurements found a rapid rise in the particle multiplicity at the LHC compared to naive extrapolations of RHIC measurements and a variation of mid-rapidity charged particle multiplicity with centrality similar to that observed at RHIC.

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doi:10.1016/j.physletb.2012.02.045

This Letter presents the results of ATLAS [10] measurements of the per-event charged particle pseudorapidity distribution, $dN_{\mathrm{ch}}/d\eta$, in $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb + Pb collisions over $|\eta| < 2$ and as a function of collision centrality with the goal of testing and extending the results of the previous LHC measurements. In this Letter, N_{ch} denotes the per-event number of charged primary particles measured in an interval of η, which is the particle pseudorapidity.[1] The measurement was performed with the solenoid off, thereby allowing detection of charged particles down to very low transverse momenta ($p_{\mathrm{T}} \sim 30$ MeV).

2. Experimental setup and event selection

The measurements presented here were obtained using the ATLAS inner detector [11] which contains both silicon pixel and silicon strip detectors and the ATLAS forward calorimeters. The charged particle multiplicity is measured using the pixel detector [12] which consists of three layers of pixel staves in the barrel region, inclined at an angle of 20°, at radii of 50.5, 88.5, and 122.5 mm from the nominal beam axis. The typical pixel size is 50 µm × 400 µm in ϕ–z, and an average occupancy of about 0.5% is observed for the innermost pixel layer in central Pb + Pb collisions. To limit low-p_{T} multiple scattering losses in detector material, the measurement has been restricted to the barrel portion of the pixel detector, corresponding to pseudorapidity values in the range $|\eta| < 2$. Collision vertex positions were obtained by full reconstruction of nominally straight charged particle trajectories in the pixel and silicon strip detectors followed by reconstruction of a single collision vertex from the full set of particle trajectories. To maintain uniform acceptance of the pixel detector for the multiplicity measurement the vertex was required to lie within 50 mm of the nominal centre of the ATLAS detector in the longitudinal direction.

The data for the measurements presented here were collected with a minimum-bias trigger. This required a coincidence in either the two minimum-bias trigger scintillator (MBTS) detectors, located at ±3.56 m from the interaction centre and covering $2.1 < |\eta| < 3.9$, or two zero-degree calorimeters (ZDCs), located at ±140 m from the interaction centre and covering $|\eta| > 8.3$. The threshold on the analog energy sum in each ZDC was set below the single neutron peak. The offline analysis required the time difference between the two MBTS detectors to be $|\Delta t| < 3$ ns to eliminate upstream beam–gas interactions, a ZDC coincidence to efficiently reject photo-nuclear events [13], and a reconstructed vertex satisfying the selection described above. The measurements presented in this Letter were obtained from a 10 hour data-taking run corresponding to an integrated luminosity of approximately 480 mb^{-1}. A total of 1 631 525 events passed the trigger, vertex, and offline selections.

3. Centrality

In heavy ion collisions, "centrality" reflects the overlap volume of the two colliding nuclei, controlled by the classical impact parameter. That overlap volume is closely related to the number of "participants", the nucleons which scatter inelastically in each nuclear collision. While the number of participants, N_{part}, cannot be measured for a single collision, previous studies at RHIC and the SPS have demonstrated that the multiplicity and transverse energy of the produced particles are strongly correlated with N_{part}. Because of this, the average number of participants can be accurately estimated from a selected fraction of the multiplicity or transverse energy distribution [14]. In ATLAS, the Pb + Pb collision centrality is measured using the summed transverse energy ($\sum E_{\mathrm{T}}$) in the forward calorimeter (FCal) over the pseudorapidity range $3.2 < |\eta| < 4.9$, calibrated at the electromagnetic energy scale. An analysis of the FCal $\sum E_{\mathrm{T}}$ distribution after application of all trigger and selection requirements gives an estimate of the fraction of the sampled non-Coulomb inelastic cross section of $f = 98 \pm 2\%$. This estimate was derived from comparisons of the measured FCal $\sum E_{\mathrm{T}}$ distribution with a simulated $\sum E_{\mathrm{T}}$ distribution. The simulated distribution was obtained from a convolution of $\sqrt{s} = 2.76$ TeV proton–proton data with a Monte Carlo (MC) Glauber calculation [14,15] of the number of effective nucleon–nucleon collisions. This quantity was calculated as a linear combination of the number of participants and the number of binary collisions, similar to what was done in a previous analysis [16]. The value of f and its uncertainty was estimated by systematically varying the effect of trigger and event selection inefficiencies as well as backgrounds in the most peripheral $\sum E_{\mathrm{T}}$ interval. This was done by artificially injecting and removing counts in that interval in order to achieve the best agreement between the measured and simulated distributions. The estimate of f was made after removal of a 1% background contamination in the most peripheral events that was evaluated using comparisons of solenoid magnet-on and solenoid magnet-off data and which was attributed to photo-nuclear events.

For the results presented in this Letter, the minimum-bias FCal $\sum E_{\mathrm{T}}$ distribution was divided into centrality intervals according to the following percentiles: 10% intervals over 0–80%, 5% intervals over 20–80% and 2% intervals over 0–20%. By convention, the 0–10% centrality interval refers to the 10% most central events – the events with the highest $\sum E_{\mathrm{T}}$ values – and increasing percentiles refer to events with successively lower $\sum E_{\mathrm{T}}$. The average number of participants, $\langle N_{\mathrm{part}} \rangle$, was evaluated for each of the experimental centrality intervals by dividing the Glauber model $\sum E_{\mathrm{T}}$ distribution into the same percentile centrality intervals used for the data and evaluating the average number of participants of the Glauber MC events contributing to a given interval. This procedure incorporates more realistic fluctuations into the estimation of $\langle N_{\mathrm{part}} \rangle$ than would be achieved by binning in either N_{part} itself or in the classical impact parameter. The systematic errors on $\langle N_{\mathrm{part}} \rangle$ were evaluated from the quoted uncertainty on f and the known uncertainties in the nuclear density parameters as well as the assumed total inelastic nucleon–nucleon cross section of $\sigma_{\mathrm{NN}} = 64 \pm 5$ mb [17].

4. Reconstruction of charged particle multiplicity

In the offline analysis, adjacent hits in the pixel modules were grouped into clusters using standard techniques. Two methods were, then, used to reconstruct charged particles from the pixel clusters. In one method, a Kalman Filter-based tracking algorithm, similar to that deployed in proton–proton collisions [18], was applied only to the pixel layers ("pixel tracks"). The other method, the "two-point tracklet" algorithm, used the reconstructed primary vertex and clusters on the first pixel layer to define a search region for clusters in the second layer consistent with a nominally straight track. Candidate tracklets were required to have deviations between projected and measured cluster positions in the second pixel layer in pseudorapidity and azimuth, $\Delta\eta$ and $\Delta\phi$, respectively, satisfying

$$\Delta\mathcal{R} \equiv \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\eta}{\sigma_\eta(\eta)}\right)^2 + \left(\frac{\Delta\phi}{\sigma_\phi(\eta)}\right)^2} < 3. \quad (1)$$

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

The widths of the $\Delta\eta$ and $\Delta\phi$ distributions characterized by the pseudorapidity-dependent resolutions $\sigma_\eta(\eta)$ and $\sigma_\phi(\eta)$ were obtained from the MC simulations described below. The η and ϕ values of the reconstructed tracklets were determined using the cluster position on the first layer and the primary vertex position. The two-point tracklet analysis excluded clusters with low energy deposits inconsistent with minimum-ionizing particles originating at the primary vertex. It also excluded duplicate clusters resulting from the overlap of the pixel modules in ϕ and from a small set of pixels at the centres of the pixel modules that share readout channels [12].

The high charged particle multiplicity in Pb + Pb collisions can generate misidentified tracks and/or two-point tracklets when only two or three measurements are made on each trajectory. The misidentified contributions have been evaluated using the MC studies described below, but to check the MC results, an independent, data-driven estimate of misidentified two-point tracklets was obtained using a variant of the two-point tracklet algorithm. In the default two-point tracklet analysis, referred to as "Method 1", at most one tracklet was reconstructed for a given cluster on the first pixel layer. If multiple clusters on the second pixel layer fell within the search region defined in Eq. (1), the closest cluster to the projected position was chosen. This method limits, but does not eliminate, the generation of misidentified tracklets. A second implementation of the two-point tracklet algorithm, referred to as "Method 2", produced tracklets for all combinations of clusters on the two layers consistent with the search region. Using Method 2, the rate of false tracklets resulting from random combinations of clusters was estimated by performing the same analysis but with the clusters on the second layer having their z positions inverted around the primary vertex and their azimuthal angles inverted, $\phi \to \pi - \phi$. The tracklet yield from this "flipped" analysis was then subtracted from the proper tracklet yield event-by-event to obtain the estimated yield of true tracklets,

$$N_{2p}(\eta) = N_{2p}^{ev}(\eta) - N_{2p}^{fl}(\eta), \tag{2}$$

where N_{2p}^{ev} represents the yield of two-point tracklets using Method 2 and N_{2p}^{fl} represents the yield obtained by flipping the clusters in the second pixel layer. For the 0–10% centrality interval, the flipped yield is about 50% of the unflipped yield in the $|\eta| < 0.5$ region.

The response of the detector to the charged particles produced in Pb + Pb collisions and the performance of the track and tracklet methods was evaluated by MC simulations of Pb + Pb collisions using the HIJING [3] event generator followed by GEANT4 [19] simulations of the detector response [20]. The resulting events were then reconstructed and analyzed using the full offline analysis chain that was applied to the experimental data. HIJING events were generated without jet quenching and with an unbiased impact parameter distribution. Impact parameter and p_T-dependent elliptic flow was imposed on the HIJING events after generation and prior to simulation. The GEANT4 detector geometry included a distribution of disabled pixel modules matching that in the experiment. The MC events were used to derive correction factors from reconstructed pixel tracks and two-point tracklets to the primary HIJING particles. Primary particles were defined to be either particles originating directly from the Pb + Pb collision or particles resulting from secondary decays of HIJING produced particles with lifetimes $c\tau < 1$ cm.

From the MC simulated events, correction factors accounting for particle detection efficiency, misidentified tracks or tracklets from unrelated clusters, and extra tracks or tracklets from secondary decays or from interactions in the detector were calculated. The correction factors were evaluated in 20 intervals of detector occupancy ($\mathcal{O}$) parameterized using the number of reconstructed clusters in the first pixel layer in the region $|\eta| < 1$. Different corrections were applied to the pixel track and both two-point tracklet measurements. For the pixel tracks, the efficiency, ε_{pt}, for reconstructing tracks associated with charged primary particles was obtained from

$$\varepsilon_{pt}(\mathcal{O}, \eta) \equiv \frac{N_{pr}^{match}(\mathcal{O}, \eta)}{N_{pr}(\mathcal{O}, \eta)}, \tag{3}$$

where N_{pr} represents the number of charged primary particles produced by HIJING within a given η interval, and N_{pr}^{match} represents the portion of those primary particles matched to reconstructed pixel tracks. The contributions to the number of reconstructed pixel tracks (N_{pt}) from "background" sources were separately evaluated to produce a "background" fraction

$$b_{pt}(\mathcal{O}, \eta) \equiv \frac{N_{pt}^{backg}(\mathcal{O}, \eta)}{N_{pt}(\mathcal{O}, \eta)}, \tag{4}$$

where N_{pt}^{backg} represents the number of tracklets from secondary interactions and decays, from particles initially produced outside the kinematic acceptance of the measurement but scattering into it, and from combinations of clusters not associated with any primary or secondary particle in the GEANT4 simulation. This factor was combined with $\varepsilon_{pt}(\mathcal{O}, \eta)$ to produce a correction factor

$$C_{pt}(\mathcal{O}, \eta) \equiv \frac{1}{\varepsilon_{pt}(\mathcal{O}, \eta)}\bigl(1 - b_{pt}(\mathcal{O}, \eta)\bigr). \tag{5}$$

For the 0–10% centrality interval, ε_{pt} is about 0.55 and b_{pt} is about 0.02 in the mid-rapidity region, giving a C_{pt} of about 1.8.

For the two-point tracklet methods, a single multiplicative correction factor was obtained from the MC simulations,

$$C_{2p}(\mathcal{O}, \eta) \equiv \frac{N_{pr}(\mathcal{O}, \eta)}{N_{2p}(\mathcal{O}, \eta)}, \tag{6}$$

where $N_{2p}(\mathcal{O}, \eta)$ represents reconstructed tracklets. For the two-point tracklet Method 2, $N_{2p}(\mathcal{O}, \eta)$ was obtained from the MC events via Eq. (2) using the same flipping procedure as that applied in the data. For the 0–10% centrality interval, the correction factor is about 1.05 for Method 1 and 1.25 for Method 2 in the mid-rapidity region.

The Pb + Pb charged particle p_T spectrum measured at $\sqrt{s_{NN}} =$ 2.76 TeV [21] differs from the spectrum generated by HIJING at low and high p_T, with the generator exceeding the data by 20% at $p_T = 500$ MeV, and underpredicting the charged particle yield by a factor of about two at $p_T = 1.5$ GeV. Because the MC corrections are applied to the data in matching $\mathcal{O}$ intervals, the mismatch in the spectrum does not influence the corrections for misidentified tracks or occupancy-induced inefficiencies. However, if left uncorrected the mismatch could distort the p_T-weighted single track or tracklet efficiencies in the calculated correction factors. To avoid this distortion a p_T-dependent weight was applied to the generated particles and to tracklets or tracks that match generated particles in Eqs. (3)–(6). The p_T-dependent weights were obtained using an iterative procedure that, in each analyzed centrality interval, optimally matched the p_T spectrum of pixel tracks in Pb + Pb data with the solenoid magnet turned-on to the reweighted spectrum produced from a separate sample of HIJING + GEANT4 simulations also performed with the solenoid turned-on. Distributions of $\Delta\eta$ and $\Delta\phi$ for candidate tracklets are shown in Fig. 1 for two different pseudorapidity intervals, $|\eta| < 1$ and $1 < |\eta| < 2$. The corresponding distributions for the reweighted HIJING + GEANT4 events are also shown in the figure and compare well with the data. The max-

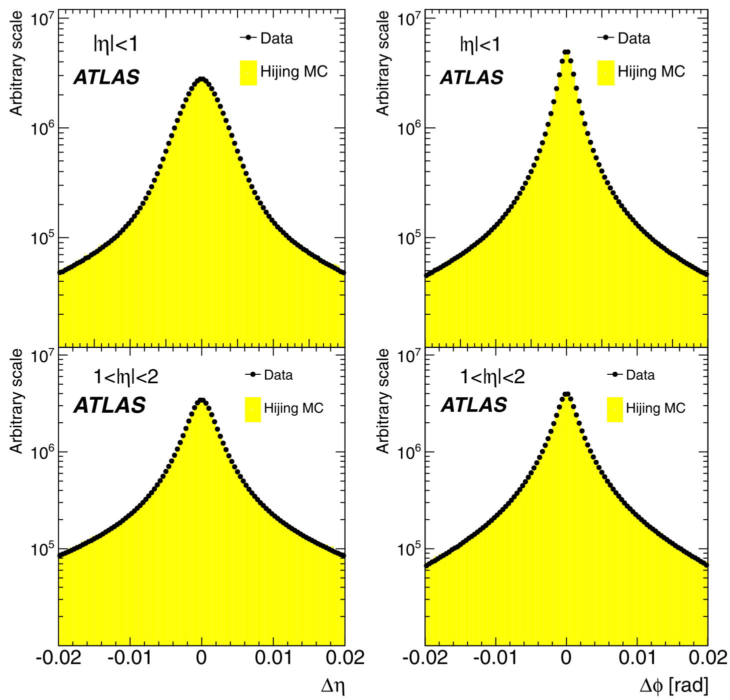

Fig. 1. Tracklet candidate $\Delta\eta$ (left) and $\Delta\phi$ (right) distributions from data (histogram) and reweighted MC (shaded region) for Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The top panels correspond to $|\eta| < 1$ and the bottom panels correspond to $1 < |\eta| < 2$. Data and MC distributions are normalized to the same area.

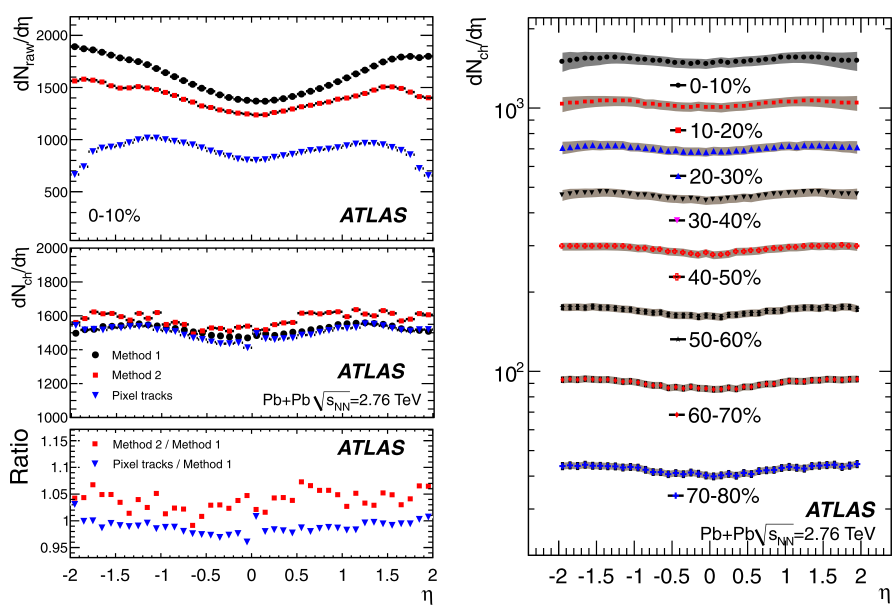

Fig. 2. Left: Top: uncorrected track/tracklet $dN_{raw}/d\eta$ distribution from tracklet Method 1 (points), tracklet Method 2 (squares) and pixel tracking (blue triangles) for 0–10% centrality events. Middle: corrected tracklet and track $dN_{ch}/d\eta$ distributions. Bottom: ratio of $dN_{ch}/d\eta$ from the tracklet Method 2 (squares) and pixel tracking (triangles) to tracklet Method 1. Right: $dN_{ch}/d\eta$ distributions from tracklet Method 1 for eight 10% centrality intervals. The statistical errors are shown as bars and the systematic errors are shown as shaded bands. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

imum difference between data and MC is less than 5%. It should be noted that the $\sigma_\eta(\eta)$ and $\sigma_\phi(\eta)$ mentioned above are evaluated using the unreweighted MC, but they are applied consistently to data and reweighted MC when calculating all η-dependent corrections.

Uncorrected pixel track and two-point tracklet pseudorapidity distributions for 0–10% centrality collisions are shown in the top left panel of Fig. 2. The corrections described above are applied to obtain corrected, per-event primary charged particle pseudorapidity distributions, averaged over the events in each centrality bin (c), according to

$$\left.\frac{dN_{ch}}{d\eta}\right|_c = \frac{1}{N_{evt}} \sum_{\text{events},c} \frac{\Delta N^{raw}}{\Delta\eta} C(\mathcal{O}, \eta), \tag{7}$$

where ΔN^{raw} indicates either the number of reconstructed pixel tracklets or two-point tracklets and $C(\mathcal{O}, \eta)$ indicates the η-dependent correction factors corresponding to the occupancy bin for each event. The corrected $dN_{ch}/d\eta$ distributions for the 0–10% centrality interval are shown in the middle left panel of Fig. 2. The bottom left panel of Fig. 2 shows the ratio of the pixel tracking and two-point tracklet Method 2 results to the two-point tracklet Method 1 results. In spite of the factor of ~ 2 differences between the raw yields for the three reconstruction methods, the corrected pseudorapidity distributions for central collisions agree within 5%. The measurements presented in the remainder of this Letter were obtained from tracklet Method 1, which has the highest reconstruction efficiency, only a moderate contribution of misidentified tracklets, and the smallest correction factors. The resulting corrected $dN_{ch}/d\eta$ distributions are shown for 8 centrality intervals in the right-hand panel of Fig. 2.

5. Systematic uncertainties

Various studies were performed to quantify the experimental uncertainties on the $dN_{ch}/d\eta$ measurement. To address inaccuracies in the MC description of bad channels, disabled sensors, or other small instrumental problems, a comparison was made of unit-normalized η and ϕ distributions of clusters in each of the first two pixel layers between data and MC. The agreement between the η and ϕ distributions was found to be better than 0.05% and 0.4% in the first and second layers, respectively. Therefore, a combined systematic uncertainty of 0.4% is assigned to account for potential MC inaccuracies. To evaluate the impact of inaccuracies in the description of the detector material in the GEANT4 simulation, a separate set of HIJING + GEANT4 simulations was performed with an artificial 10% increase in detector material and a 15–20% increase in material in various non-instrumented regions. The results obtained using correction factors from this "extra material" sample agree with those obtained using the default corrections to better than 2%. Furthermore, the analysis was repeated using a different $\Delta\mathcal{R}$ selection (see Eq. (1)), $\Delta\mathcal{R} < 1.5$, which should have a different sensitivity to multiple scattering, secondaries, and occupancy effects. The corrections for the $\Delta\mathcal{R} < 1.5$ selection differ from those of the default analysis in central (0–10%) collisions by 10% at $\eta = 0$ and 20% at $\eta = 2$. However, the corrected pseudorapidity distributions agree to 1% in all centrality intervals. To address differences between the HIJING description of particle production in Pb + Pb collisions and reality, the analysis was performed without the p_T spectrum re-weighting; the results agree with those obtained using the re-weighting within 0.5%. To address potential errors resulting from discrepancies in particle composition between data and MC, the changes in correction factors that would result from enhanced charged kaon and proton production as observed at RHIC [22] have been evaluated. From the impact of the modified corrections on the final result, a 1% systematic uncertainty due to incomplete knowledge of the hadron composition is assigned. To further test the sensitivity of the results to the use of the HIJING generator, a set of MC simulations using the HYDJET event generator [23] was produced, and a separate set of correction factors was obtained from this MC sample. HYDJET has a more complete description of soft particle production than HIJING, including a description of elliptic flow, and the version used here was tuned to have much lower multiplicities than found in HIJING. In central collisions, the results obtained using the HYDJET-based corrections agree with the HIJING-based results to better than 0.5% at mid-rapidity, but differ by as much as 7.5% at $\eta = \pm 2$. A centrality-dependent and η-dependent systematic error is assigned to account for this difference. To address the inaccuracies from the analysis procedure, a systematic uncertainty is assigned based on the differences between the results obtained from the three reconstruction methods described in this Letter. That uncertainty is centrality-dependent and maximal for the 0–10% centrality interval for which a 3.5% uncertainty on the overall scale of the pseudorapidity distribution is assigned based on the comparison of the three results in the left, bottom panel of Fig. 2. The systematic uncertainties described above are summarized in Table 1 for the most central (0–10%) and the most peripheral (70–80%) intervals. The total systematic uncertainties are shown as shaded bands in the right panel of Fig. 2.

Table 1
Summary of the various sources of systematic uncertainties and their estimated impact on the $dN_{ch}/d\eta$ measurement in central (0–10%) and peripheral (70–80%) Pb + Pb collisions. Only the uncertainty due to the choice of the event generator is η-dependent.

Source	Uncertainty (0–10%)	(70–80%)
MC detector description	0.4%	0.4%
Extra material	2%	2%
$\Delta\mathcal{R}$ cut	1%	1%
p_T re-weighting	0.5%	0.5%
Hadron composition	1%	1%
Enhanced K_s, Λ	1%	1%
HYDJET	0.5–7.5% vs. η	0%
Analysis method	3.5%	1%
Combined ($\eta = 0$)	4%	3%
Combined ($\eta = 2$)	8.5%	3%

6. Results

The measured charged particle $dN_{ch}/d\eta$ shown in Fig. 2, increases rapidly with collision centrality for all η. It is conventional to characterize particle production in nucleus–nucleus collisions by the mid-rapidity $dN_{ch}/d\eta$, $dN_{ch}/d\eta|_{\eta=0}$, which here is defined to be $dN_{ch}/d\eta$ averaged over $|\eta| < 0.5$. The analysis presented in this Letter yields $dN_{ch}/d\eta|_{\eta=0}$ values in central collisions of $1479 \pm 10(\text{stat.}) \pm 63(\text{syst.})$, $1598 \pm 11(\text{stat.}) \pm 68(\text{syst.})$, and $1738 \pm 12(\text{stat.}) \pm 75(\text{syst.})$ for the 0–10%, 0–6%, and 0–2% centrality intervals, respectively. Table 2 provides results of the $dN_{ch}/d\eta|_{\eta=0}$ measurements for all centrality bins.

The top panel of Fig. 3 compares the ATLAS measurement to the previously reported ALICE [8] and CMS [9] results for $|\eta| < 0.5$ for the 0–5% centrality interval in terms of $dN_{ch}/d\eta|_{\eta=0}$ per colliding nucleon pair, $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$, and to other A + A measurements at different $\sqrt{s_{NN}}$ (see [2], which includes data from Refs. [24–29]). The ALICE and CMS 0–5% centrality measurements agree with the result reported here for the 0–6% centrality interval, $8.5 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.})$, within the quoted errors. The LHC results show that the multiplicity in central A + A collisions rises rapidly with $\sqrt{s_{NN}}$ above the RHIC top energy of $\sqrt{s_{NN}} = 200$ GeV. The three curves shown in Fig. 3 indicate possible variations of $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ with $\sqrt{s_{NN}}$. The dotted curve describes a $\sqrt{s_{NN}}$ dependence expected from Landau hydrodynamics [7]. It is clearly inconsistent with the data. The dot-dashed curve represents a logarithmic extrapolation of RHIC and SPS data [30] that is also excluded by the measurement presented in this Letter and by the ALICE and CMS measurements. The dashed curve shows an $s^{0.15}$ dependence suggested by ALICE [8] that is consistent with the ATLAS measurement. Also shown in the top panel in Fig. 3 are results from p + p and $\bar{p}$ + p measurements at different $\sqrt{s}$ ([2] and references therein, as well as [31–35]). The excess of $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ in A+A collisions over p+p collisions observed at RHIC persists and is proportionately larger at the higher $\sqrt{s_{NN}}$ values of the LHC.

The bottom panel of Fig. 3 shows $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ as a function of $\langle N_{part}\rangle$ for 2% centrality intervals over 0–20%, and 5% centrality intervals over 20–80%. The values are also reported in Table 2. A moderate variation of $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ with $\langle N_{part}\rangle$ is observed, from a value of $4.6 \pm 0.1(\text{stat.}) \pm 0.6(\text{syst.})$ at $\langle N_{part}\rangle = 12.3$ (centrality 75–80%) to $8.8 \pm 0.1(\text{stat.}) \pm$

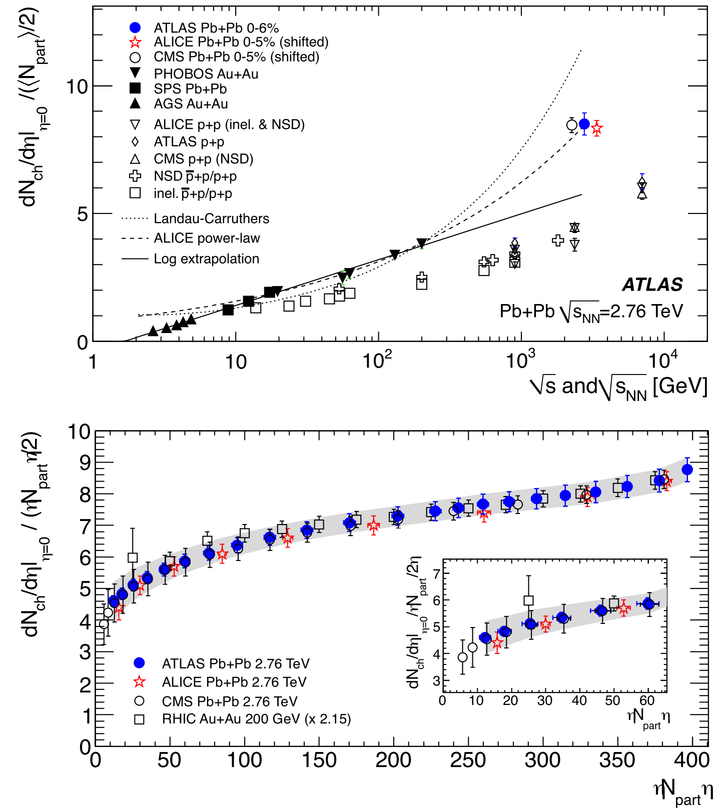

Fig. 3. Top: $\sqrt{s_{NN}}$ dependence of the charged particle $dN_{ch}/d\eta$ per colliding nucleon pair $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ from a variety of measurements in p+p and $\bar{p}$+p (inelastic and non-single diffractive results from [2] and references therein, as well as [31–35]) and central A + A collisions, including the ATLAS 0–6% centrality measurement reported here for $|\eta| < 0.5$ and the previous 0–5% centrality ALICE [8] and CMS [9] measurements (points shifted horizontally for clarity). The curves show different expectations for the $\sqrt{s_{NN}}$ dependence in A + A collisions: results of a Landau hydrodynamics calculation [7] (dotted line), an $s^{0.15}$ extrapolation of RHIC and SPS data proposed by ALICE [8] (dashed line), a logarithmic extrapolation of RHIC and SPS data from [30] (solid line). Bottom: $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ vs $\langle N_{part}\rangle$ for 2% centrality intervals over 0–20% and 5% centrality intervals over 20–80%. Error bars represent combined statistical and systematic uncertainties on the $dN_{ch}/d\eta|_{\eta=0}$ measurements, whereas the shaded band indicates the total systematic uncertainty including $\langle N_{part}\rangle$ uncertainties. The RHIC measurements (see text) have been multiplied by 2.15 to allow comparison with the $\sqrt{s_{NN}} = 2.76$ TeV results. The inset shows the $\langle N_{part}\rangle < 60$ region in more detail.

Table 2
Tabulation of measurements of $dN_{ch}/d\eta|_{\eta=0}$ evaluated over $|\eta| < 0.5$ and $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ for the full set of centrality bins considered in the analysis and shown in Fig. 3. The uncertainties on $dN_{ch}/d\eta|_{\eta=0}$ include statistical and systematic errors on the multiplicity measurement. The errors reported for $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ also include systematic uncertainties on the centrality selection and $\langle N_{part}\rangle$ determination.

Centrality	$\langle N_{part}\rangle$	$dN_{ch}/d\eta\vert_{\eta=0}$	$dN_{ch}/d\eta\vert_{\eta=0}/\langle N_{part}\rangle/2$
0–2%	396 ± 2	1738 ± 76	8.8 ± 0.4
2–4%	378 ± 2	1591 ± 67	8.4 ± 0.4
4–6%	356 ± 3	1467 ± 63	8.2 ± 0.4
6–8%	335 ± 3	1350 ± 57	8.1 ± 0.4
8–10%	315 ± 3	1250 ± 53	8.0 ± 0.3
10–12%	296 ± 3	1159 ± 48	7.8 ± 0.3
12–14%	277 ± 4	1074 ± 44	7.8 ± 0.3
14–16%	260 ± 4	996 ± 41	7.7 ± 0.3
16–18%	243 ± 4	918 ± 37	7.6 ± 0.3
18–20%	228 ± 4	849 ± 34	7.5 ± 0.3
20–25%	203 ± 4	739 ± 29	7.3 ± 0.3
25–30%	170 ± 4	603 ± 24	7.1 ± 0.3
30–35%	142 ± 4	486 ± 19	6.9 ± 0.3
35–40%	117 ± 4	387 ± 15	6.6 ± 0.3
40–45%	95.0 ± 3.7	303 ± 11	6.4 ± 0.3
45–50%	76.1 ± 3.5	233 ± 9	6.1 ± 0.4
50–55%	59.9 ± 3.3	176 ± 6	5.9 ± 0.4
55–60%	46.1 ± 3.0	129 ± 5	5.7 ± 0.4
60–65%	34.7 ± 2.7	93 ± 3	5.3 ± 0.5
65–70%	25.4 ± 2.3	65 ± 2	5.1 ± 0.5
70–75%	18.0 ± 2.0	43 ± 2	4.8 ± 0.6
75–80%	12.3 ± 1.6	28 ± 1	4.6 ± 0.6

0.4(syst.) at $\langle N_{part}\rangle = 396$ (centrality 0–2%). The increase of $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ with $\langle N_{part}\rangle$ is monotonic up to the most central interval (0–2%). This demonstrates that, even for the most central collisions, variations in centrality – as characterized by transverse energy depositions well outside the acceptance used for the multiplicity measurement – yield significant changes in the measured final state multiplicity.

The bottom panel of Fig. 3 also shows ALICE and CMS measurements of $dN_{ch}/d\eta|_{\eta=0}$ as a function of $\langle N_{part}\rangle$ that agree with the results presented here for all centrality intervals. Also shown are results from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV obtained from an average of measurements from the four RHIC Collaborations [36–40]. Similar to the approach used in Ref. [8], the 200 GeV Au + Au results have been scaled by a factor of 2.15 to allow comparison with the $\sqrt{s_{NN}} = 2.76$ TeV data. This factor was obtained by matching the most central 200 GeV Au + Au $dN_{ch}/d\eta$ measurement at $\eta = 0$ to the $dN_{ch}/d\eta$ measurement from this Letter at $\eta = 0$ in the 2–4% centrality interval, the interval that has the closest value of $\langle N_{part}\rangle$ to the most central 200 GeV measurement. After re-scaling, the trend of the 200 GeV data is in good agreement with the 2.76 TeV measurements for all reported centrality intervals. Similar observations have been made previously in comparisons of top energy RHIC data to much lower energies [2]. Therefore, this scaling behavior appears to be a robust feature of particle production in heavy ion collisions.

To evaluate the shapes of the measured charged particle $dN_{ch}/d\eta$ distributions Fig. 4 (top) shows the $dN_{ch}/d\eta$ distribution

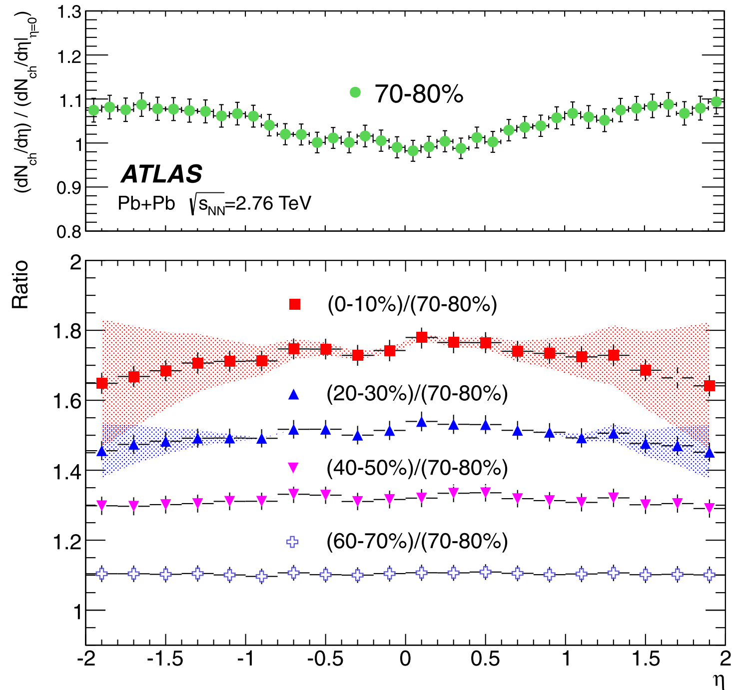

Fig. 4. Top: $dN_{ch}/d\eta$ distributions from tracklet Method 1, scaled by $dN_{ch}/d\eta|_{\eta=0}$, as a function of the pseudorapidity for the 70–80% centrality interval. The statistical errors are shown as error bars. Bottom: Ratio of $dN_{ch}/d\eta/(\langle N_{part}\rangle/2)$ measured in different centrality intervals: 0–10% (squares), 20–30% (triangles), 40–50% (inverted triangles) and 60–70% (crosses) to that measured in peripheral collisions (70–80%). Statistical uncertainties are shown as bars while η-dependent systematic uncertainties are shown as shaded bands.

divided by $dN_{ch}/d\eta|_{\eta=0}$ for the 70–80% centrality interval. For this centrality interval, the $dN_{ch}/d\eta$ increases by $7\% \pm 1\%$ from $\eta = 0$ to $|\eta| > 1$. The bottom panel shows ratios of $dN_{ch}/d\eta/(\langle N_{part}\rangle/2)$ for several other 10% centrality intervals to the same quantity in the 70–80% interval. No significant variation of the shape of $dN_{ch}/d\eta$ with centrality is observed within the systematic uncertainties.

7. Conclusions

This Letter presents results on the measurement of charged particle pseudorapidity distributions over $|\eta| < 2$ as a function of collision centrality in a sample of $\sqrt{s_{NN}} = 2.76$ TeV lead–lead collisions recorded with the ATLAS detector at the LHC. Three different analysis methods are used, based on the pixel detector and using events with the solenoid magnet turned off in order to measure particles with transverse momenta as low as 30 MeV. The charged particle mid-rapidity $dN_{ch}/d\eta$, normalized by $\langle N_{part}\rangle/2$, is found to increase significantly with beam energy by about a factor of two relative to earlier RHIC data, and is substantially larger than $p + p$ data at the same energy. The relative centrality dependence of $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ agrees well with that observed at RHIC. These results agree well with previous mid-rapidity measurements from ALICE and CMS. Furthermore, the peripheral (70–80%) $dN_{ch}/d\eta$ distribution shows a significant rise with increasing $|\eta|$ away from $\eta = 0$. No variation of the shape of the $dN_{ch}/d\eta$ distribution with centrality outside the reported systematic uncertainties is observed.

Acknowledgements

We thank CERN for the efficient commissioning and operation of the LHC during this initial heavy ion data taking period as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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