# 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 ☆

ATLAS Collaboration *

## A R T I C L E   I N F O

## A B S T R A C T

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]. How-

ever, 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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This Letter presents the results of ATLAS [10] measurements of the per-event charged particle pseudorapidity distribution, $dN_{ch}/d\eta$, in $\sqrt{s_{NN}} = 2.76$ 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 $\eta$, 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 ($p_T \sim 30$ 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 $\phi$–$z$, 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 en-

ergy 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 ($\sum E_T$) 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 $\sum E_T$ 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 $\sum E_T$ distribution with a simulated $\sum E_T$ 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 $\sum E_T$ 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 $\sum E_T$ 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 $\sum E_T$ values – and increasing percentiles refer to events with successively lower $\sum E_T$. The average number of participants, $\langle N_{part} \rangle$, was evaluated for each of the experimental centrality intervals by dividing the Glauber model $\sum E_T$ 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 $\langle N_{part} \rangle$ than would be achieved by binning in either $N_{part}$ itself or in the classical impact parameter. The systematic errors on $\langle N_{part} \rangle$ 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 $\sigma_{NN} = 64 \pm 5$ 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

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

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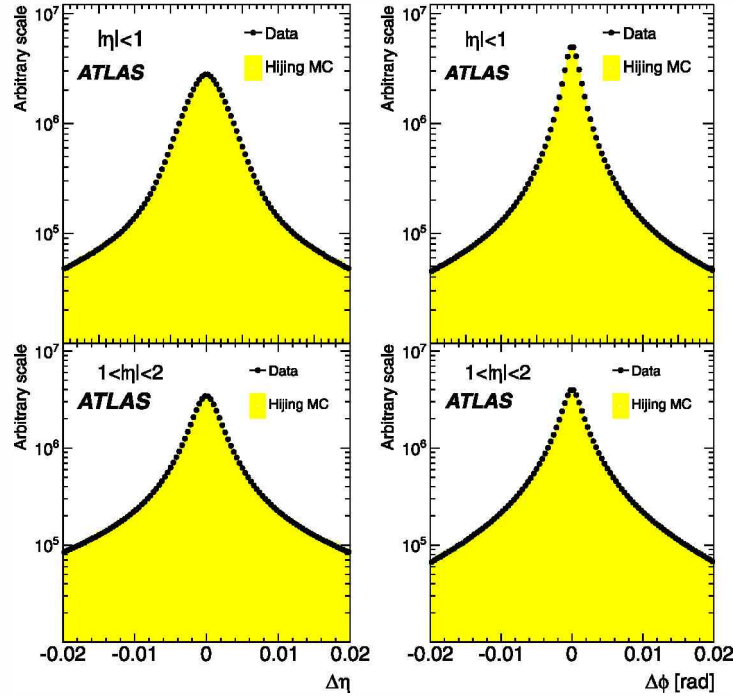
**Fig. 1.** Tracklet candidate $\Delta\eta$ (left) and $\Delta\phi$ (right) distributions from data (histogram) and reweighted MC (shaded region) for Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The top panels correspond to $|\eta| < 1$ and the bottom panels correspond to $1 < |\eta| < 2$. Data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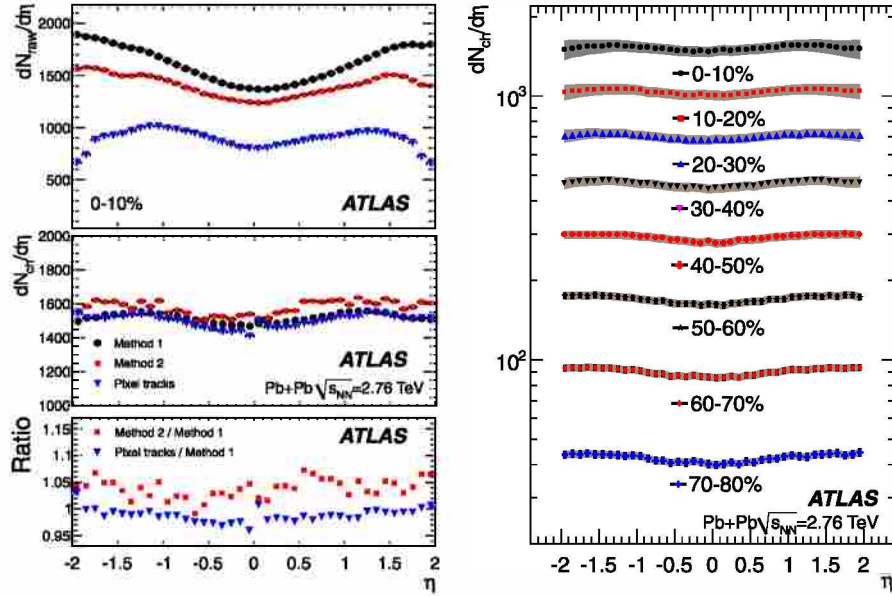


**Fig. 2.** Left: Top: uncorrected track/tracklet $dN_{raw}/d\eta$ distribution from tracklet Method 1 (points), tracklet Method 2 (squares) and pixel tracking (blue triangles) for 0–10% centrality events. Middle: corrected tracklet and track $dN_{ch}/d\eta$ distributions. Bottom: ratio of $dN_{ch}/d\eta$ 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 $\eta$-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

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

where $\Delta N^{raw}$ indicates either the number of reconstructed pixel tracklets or two-point tracklets and $C(\mathcal{O}, \eta)$ indicates the $\eta$-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 $\eta$ and $\phi$ distributions of clusters in each of the first two pixel layers between data and MC. The agreement between the $\eta$ and $\phi$ 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 $\eta = \pm2$. A centrality-dependent and $\eta$-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

**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 $\eta$-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 $K_s$, $\Lambda$ | 1% | 1% |
| HYDJET | 0.5–7.5% vs. $\eta$ | 0% |
| Analysis method | 3.5% | 1% |
| | | |
| Combined ($\eta = 0$) | 4% | 3% |
| Combined ($\eta = 2$) | 8.5% | 3% |

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.

## 6. Results

The measured charged particle $dN_{ch}/d\eta$ shown in Fig. 2, increases rapidly with collision centrality for all $\eta$. 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 proportionally 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 $8.8 \pm 0.1(\text{stat.}) \pm$
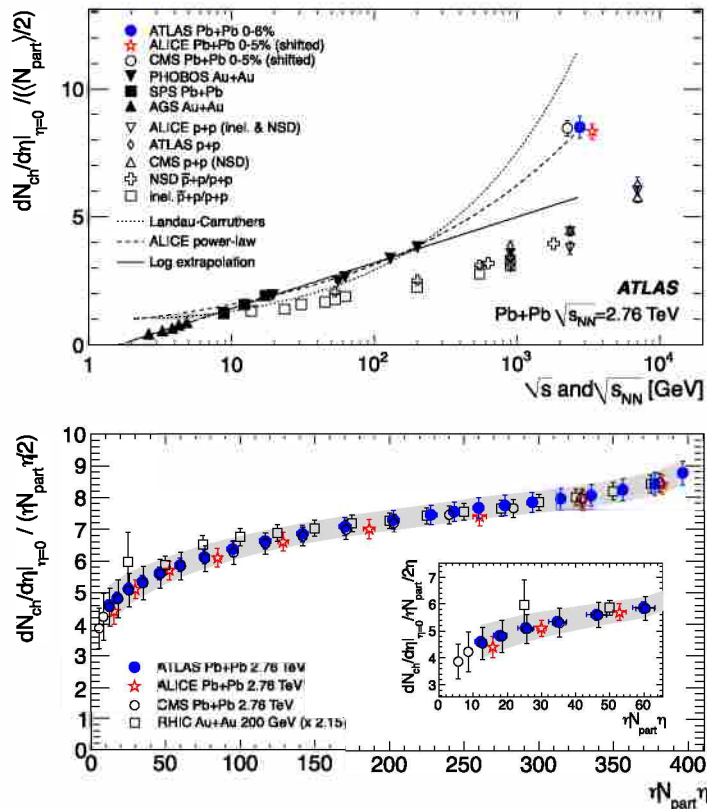
**Fig. 3.** Top: $\sqrt{s_{NN}}$ dependence of the charged particle $dN_{ch}/d\eta$ per colliding nucleon pair $dN_{ch}/d\eta|_{\eta=0}/(\langle N_{part}\rangle/2)$ from a variety of measurements in p+p and $\bar{p}$+p (inelastic and non-single diffractive results from [2] and references therein, as 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 | $\langle N_{part}\rangle$ | $dN_{ch}/d\eta|_{\eta=0}$ | $dN_{ch}/d\eta|_{\eta=0}/\langle N_{part}\rangle/2$ |
|---|---|---|---|
| 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
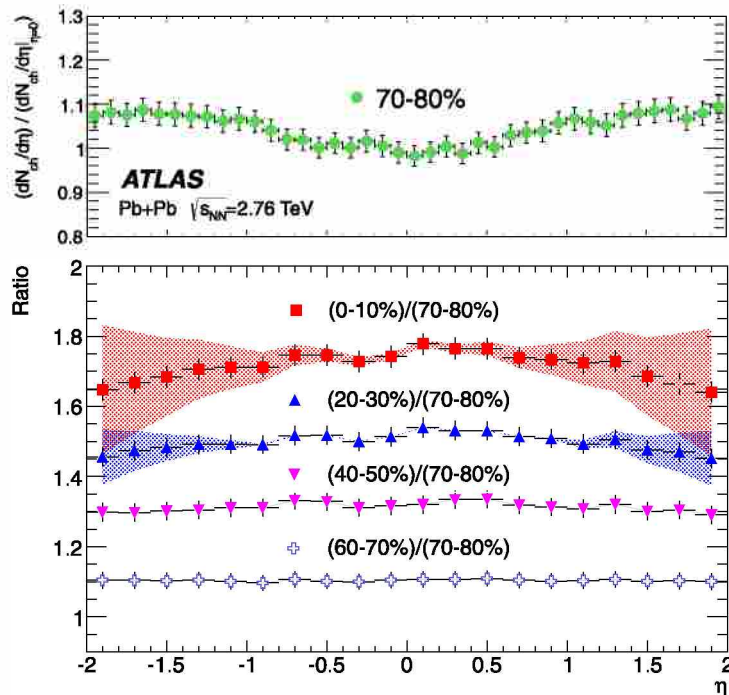
**Fig. 4.** Top: $dN_{ch}/d\eta$ distributions from tracklet Method 1, scaled by $dN_{ch}/d\eta|_{\eta=0}$, as a function of the pseudorapidity for the 70–80% centrality interval. The statistical errors are shown as error bars. Bottom: Ratio of $dN_{ch}/d\eta/(\langle N_{part}\rangle/2)$ measured in 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 $\eta$-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% ± 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.

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Siebel[174], F. Siegert[48], J. Siegrist[14], Dj. Sijacki[12a], O. Silbert[171], J. Silva[124a,b], Y. Silver[153], D. Silverstein[143], S.B. Silverstein[146a], V. Simak[127], O. Simard[136], Lj. Simic[12a], S. Simion[115], B. Simmons[77], M. Simonyan[35], P. Sinervo[158], N.B. Sinev[114], V. Sipica[141], G. Siragusa[173], A.N. Sisakyan[65], S.Yu. Sivoklokov[97], J. Sjölin[146a,146b], T.B. Sjursen[13], L.A. Skinnari[14], K. Skovpen[107], P. Skubic[111], N. Skvorodnev[22], M. Slater[17], T. Slavicek[127], K. Sliwa[161], T.J. Sloan[71], J. Sloper[29], V. Smakhtin[171], S.Yu. Smirnov[96], L.N. Smirnova[97], O. Smirnova[79], B.C. Smith[57], D. Smith[143], K.M. Smith[53], M. Smizanska[71], K. Smolek[127], A.A. Snesarev[94], S.W. Snow[82], J. Snow[111], J. Snuverink[105], S. Snyder[24], M. Soares[124a], R. Sobie[169,k], J. Sodomka[127], A. Soffer[153], C.A. Solans[167], M. Solar[127], J. Solc[127], E. Soldatov[96], U. Soldevila[167], E. Solfaroli Camillocci[132a,132b], A.A. Solodkov[128], O.V. Solovyanov[128], J. Sondericker[24], N. Soni[2], V. Sopko[127], B. Sopko[127], M. Sorbi[89a,89b], M. Sosebee[7], A. Soukharev[107], S. Spagnolo[72a,72b], F. Spanò[34], R. Spighi[19a], G. Spigo[29], F. Spila[132a,132b], E. Spiriti[134a], R. Spiwoks[29], M. Spousta[126], T. Spreitzer[158], B. Spurlock[7], R.D. St. Denis[53], T. Stahl[141], J. Stahlman[120], R. Stamen[58a], E. Stanecka[29], R.W. Stanek[5], C. Stanescu[134a], S. Stapnes[117], E.A. Starchenko[128], J. Stark[55], P. Staroba[125], P. Starovoitov[91], A. Staude[98], P. Stavina[144a], G. Stavropoulos[14], G. Steele[53], P. Steinbach[43], P. Steinberg[24], I. Stekl[127], B. Stelzer[142], H.J. Stelzer[88], O. Stelzer-Chilton[159a], H. Stenzel[52], K. Stevenson[75], G.A. Stewart[29], J.A. Stillings[20], T. Stockmanns[20], M.C. Stockton[29], K. Stoerig[48], G. Stoicea[25a], S. Stonjek[99], P. Strachota[126], A.R. Stradling[7], A. Straessner[43], J. Strandberg[147],

S. Strandberg [146a,146b], A. Strandlie [117], M. Strang [109], E. Strauss [143], M. Strauss [111], P. Strizenec [144b], R. Ströhmer [173], D.M. Strom [114], J.A. Strong [76,*], R. Stroynowski [39], J. Strube [129], B. Stugu [13], I. Stumer [24,*], J. Stupak [148], P. Sturm [174], D.A. Soh [151,r], D. Su [143], HS. Subramania [2], A. Succurro [11], Y. Sugaya [116], T. Sugimoto [101], C. Suhr [106], K. Suita [67], M. Suk [126], V.V. Sulin [94], S. Sultansoy [3d], T. Sumida [29], X. Sun [55], J.E. Sundermann [48], K. Suruliz [139], S. Sushkov [11], G. Susinno [36a,36b], M.R. Sutton [149], Y. Suzuki [66], M. Svatos [125], Yu.M. Sviridov [128], S. Swedish [168], I. Sykora [144a], T. Sykora [126], B. Szeless [29], J. Sánchez [167], D. Ta [105], K. Tackmann [41], A. Taffard [163], R. Tafirout [159a], A. Taga [117], N. Taiblum [153], Y. Takahashi [101], H. Takai [24], R. Takashima [69], H. Takeda [67], T. Takeshita [140], M. Talby [83], A. Talyshev [107], M.C. Tamsett [24], J. Tanaka [155], R. Tanaka [115], S. Tanaka [131], S. Tanaka [66], Y. Tanaka [100], K. Tani [67], N. Tannoury [83], G.P. Tappern [29], S. Tapprogge [81], D. Tardif [158], S. Tarem [152], F. Tarrade [24], G.F. Tartarelli [89a], P. Tas [126], M. Tasevsky [125], E. Tassi [36a,36b], M. Tatarkhanov [14], Y. Tayalati [135d], C. Taylor [77], F.E. Taylor [92], G.N. Taylor [86], W. Taylor [159b], M. Teixeira Dias Castanheira [75], P. Teixeira-Dias [76], K.K. Temming [48], H. Ten Kate [29], P.K. Teng [151], S. Terada [66], K. Terashi [155], J. Terron [80], M. Terwort [41,p], M. Testa [47], R.J. Teuscher [158,k], J. Thadome [174], J. Therhaag [20], T. Theveneaux-Pelzer [78], M. Thioye [175], S. Thoma [48], J.P. Thomas [17], E.N. Thompson [84], P.D. Thompson [17], P.D. Thompson [158], A.S. Thompson [53], E. Thomson [120], M. Thomson [27], R.P. Thun [87], T. Tic [125], V.O. Tikhomirov [94], Y.A. Tikhonov [107], C.J.W.P. Timmermans [104], P. Tipton [175], F.J. Tique Aires Viegas [29], S. Tisserant [83], J. Tobias [48], B. Toczek [37], T. Todorov [4], S. Todorova-Nova [161], B. Toggerson [163], J. Tojo [66], S. Tokár [144a], K. Tokunaga [67], K. Tokushuku [66], K. Tollefson [88], M. Tomoto [101], L. Tompkins [14], K. Toms [103], G. Tong [32a], A. Tonoyan [13], C. Topfel [16], N.D. Topilin [65], I. Torchiani [29], E. Torrence [114], H. Torres [78], E. Torró Pastor [167], J. Toth [83,y], F. Touchard [83], D.R. Tovey [139], D. Traynor [75], T. Trefzger [173], L. Tremblet [29], A. Tricoli [29], I.M. Trigger [159a], S. Trincaz-Duvoid [78], T.N. Trinh [78], M.F. Tripiana [70], W. Trischuk [158], A. Trivedi [24,x], B. Trocmé [55], C. Troncon [89a], M. Trottier-McDonald [142], A. Trzupek [38], C. Tsarouchas [29], J.C.-L. Tseng [118], M. Tsiakiris [105], P.V. Tsiareshka [90], D. Tsionou [4], G. Tsipolitis [9], V. Tsiskaridze [48], E.G. Tskhadadze [51], I.I. Tsukerman [95], V. Tsulaia [14], J.-W. Tsung [20], S. Tsuno [66], D. Tsybychev [148], A. Tua [139], J.M. Tuggle [30], M. 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1 University at Albany, Albany, NY, United States
2 Department of Physics, University of Alberta, Edmonton, AB, Canada
3 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara; (d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
6 Department of Physics, University of Arizona, Tucson, AZ, United States
7 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18 (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
19 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston, MA, United States
22 Department of Physics, Brandeis University, Waltham, MA, United States
23 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
25 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa, ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
31 (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington, NY, United States
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas, TX, United States
40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

[43] Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany

[44] Department of Physics, Duke University, Durham, NC, United States

[45] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

[46] Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria

[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy

[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany

[49] Section de Physique, Université de Genève, Geneva, Switzerland

[50] [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy

[51] Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia

[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

[53] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

[56] Department of Physics, Hampton University, Hampton, VA, United States

[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States

[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

[59] Faculty of Science, Hiroshima University, Hiroshima, Japan

[60] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

[61] Department of Physics, Indiana University, Bloomington, IN, United States

[62] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

[63] University of Iowa, Iowa City, IA, United States

[64] Department of Physics and Astronomy, Iowa State University, Ames, IA, United States

[65] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

[66] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

[67] Graduate School of Science, Kobe University, Kobe, Japan

[68] Faculty of Science, Kyoto University, Kyoto, Japan

[69] Kyoto University of Education, Kyoto, Japan

[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

[71] Physics Department, Lancaster University, Lancaster, United Kingdom

[72] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Fisica, Università del Salento, Lecce, Italy

[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

[75] Department of Physics, Queen Mary University of London, London, United Kingdom

[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

[77] Department of Physics and Astronomy, University College London, London, United Kingdom

[78] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

[79] Fysiska institutionen, Lunds universitet, Lund, Sweden

[80] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

[81] Institut für Physik, Universität Mainz, Mainz, Germany

[82] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

[83] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

[84] Department of Physics, University of Massachusetts, Amherst, MA, United States

[85] Department of Physics, McGill University, Montreal, QC, Canada

[86] School of Physics, University of Melbourne, Victoria, Australia

[87] Department of Physics, The University of Michigan, Ann Arbor, MI, United States

[88] Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States

[89] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano, Italy

[90] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus

[91] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus

[92] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States

[93] Group of Particle Physics, University of Montreal, Montreal, QC, Canada

[94] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

[95] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

[96] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

[97] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

[98] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

[99] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

[100] Nagasaki Institute of Applied Science, Nagasaki, Japan

[101] Graduate School of Science, Nagoya University, Nagoya, Japan

[102] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

[103] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States

[104] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

[105] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

[106] Department of Physics, Northern Illinois University, DeKalb, IL, United States

[107] Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

[108] Department of Physics, New York University, New York, NY, United States

[109] Ohio State University, Columbus, OH, United States

[110] Faculty of Science, Okayama University, Okayama, Japan

[111] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States

[112] Department of Physics, Oklahoma State University, Stillwater, OK, United States

[113] Palacký University, RCPTM, Olomouc, Czech Republic

[114] Center for High Energy Physics, University of Oregon, Eugene, OR, United States

[115] LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France

[116] Graduate School of Science, Osaka University, Osaka, Japan

[117] Department of Physics, University of Oslo, Oslo, Norway

[118] Department of Physics, Oxford University, Oxford, United Kingdom

[119] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy

[120] Department of Physics, University of Pennsylvania, Philadelphia, PA, United States

[121] Petersburg Nuclear Physics Institute, Gatchina, Russia
[122] (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[123] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
[124] (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[125] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[126] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[127] Czech Technical University in Prague, Praha, Czech Republic
[128] State Research Center Institute for High Energy Physics, Protvino, Russia
[129] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[130] Physics Department, University of Regina, Regina, SK, Canada
[131] Ritsumeikan University, Kusatsu, Shiga, Japan
[132] (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[133] (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134] (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[135] (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
[138] Department of Physics, University of Washington, Seattle, WA, United States
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby, BC, Canada
[143] SLAC National Accelerator Laboratory, Stanford, CA, United States
[144] (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145] (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146] (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
[147] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto, ON, Canada
[159] (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
[160] Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
[161] Science and Technology Center, Tufts University, Medford, MA, United States
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
[164] (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Fisica, Università di Udine, Udine, Italy
[165] Department of Physics, University of Illinois, Urbana, IL, United States
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver, BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
[170] Waseda University, Tokyo, Japan
[171] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[172] Department of Physics, University of Wisconsin, Madison, WI, United States
[173] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[174] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[175] Department of Physics, Yale University, New Haven, CT, United States
[176] Yerevan Physics Institute, Yerevan, Armenia
[177] Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[d] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[e] Also at TRIUMF, Vancouver, BC, Canada.
[f] Also at Department of Physics, California State University, Fresno, CA, United States.
[g] Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
[h] Also at Fermilab, Batavia, IL, United States.
[i] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[j] Also at Università di Napoli Parthenope, Napoli, Italy.
[k] Also at Institute of Particle Physics (IPP), Canada.
[l] Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[m] Also at Louisiana Tech University, Ruston, LA, United States.
[n] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.

[o] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[p] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[q] Also at Manhattan College, New York, NY, United States.
[r] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[s] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[t] Also at High Energy Physics Group, Shandong University, Shandong, China.
[u] Also at California Institute of Technology, Pasadena, CA, United States.
[v] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[w] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[x] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[y] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[z] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[aa] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ab] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[ac] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[ad] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.
[ae] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[af] Also at Department of Physics, Nanjing University, Jiangsu, China.
[*] Deceased.