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Charged-particle multiplicities in pp interactions at $\sqrt{s} = 900$ GeV measured with the ATLAS detector at the LHC ☆,☆☆

ATLAS Collaboration

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The first measurements from proton–proton collisions recorded with the ATLAS detector at the LHC are presented. Data were collected in December 2009 using a minimum-bias trigger during collisions at a centre-of-mass energy of 900 GeV. The charged-particle multiplicity, its dependence on transverse momentum and pseudorapidity, and the relationship between mean transverse momentum and charged-particle multiplicity are measured for events with at least one charged particle in the kinematic range $|\eta| < 2.5$ and $p_T > 500$ MeV. The measurements are compared to Monte Carlo models of proton–proton collisions and to results from other experiments at the same centre-of-mass energy. The charged-particle multiplicity per event and unit of pseudorapidity at $\eta = 0$ is measured to be $1.333 \pm 0.003(\text{stat.}) \pm 0.040(\text{syst.})$, which is 5–15% higher than the Monte Carlo models predict.

1. Introduction

Inclusive charged-particle distributions have been measured in pp and $p\bar{p}$ collisions at a range of different centre-of-mass energies [1–13]. Many of these measurements have been used to constrain phenomenological models of soft-hadronic interactions and to predict properties at higher centre-of-mass energies. Most of the previous charged-particle multiplicity measurements were obtained by selecting data with a double-arm coincidence trigger, thus removing large fractions of diffractive events. The data were then further corrected to remove the remaining single-diffractive component. This selection is referred to as non-single-diffractive (NSD). In some cases, designated as inelastic non-diffractive, the residual double-diffractive component was also subtracted. The selection of NSD or inelastic non-diffractive charged-particle spectra involves model-dependent corrections for the diffractive components and for effects of the trigger selection on events with no charged particles within the acceptance of the detector. The measurement presented in this Letter implements a different strategy, which uses a single-arm trigger overlapping with the acceptance of the tracking volume. Results are presented as inclusive-inelastic distributions, with minimal model-dependence, by requiring one charged particle within the acceptance of the measurement.

This Letter reports on a measurement of primary charged particles with a momentum component transverse to the beam direction[1] $p_T >$ 500 MeV and in the pseudorapidity range $|\eta| < 2.5$. Primary charged particles are defined as charged particles with a mean lifetime $\tau > 0.3 \times 10^{-10}$ s directly produced in pp interactions or from subsequent decays of particles with a shorter lifetime. The distributions of tracks reconstructed in the ATLAS inner detector were corrected to obtain the particle-level distributions:

$$\frac{1}{N_{\text{ev}}} \cdot \frac{dN_{\text{ch}}}{d\eta}, \quad \frac{1}{N_{\text{ev}}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{\text{ch}}}{d\eta\, dp_T}, \quad \frac{1}{N_{\text{ev}}} \cdot \frac{dN_{\text{ev}}}{dn_{\text{ch}}} \quad \text{and} \quad \langle p_T \rangle \text{ vs. } n_{\text{ch}},$$

where N_{ev} is the number of events with at least one charged particle inside the selected kinematic range, N_{ch} is the total number of charged particles, n_{ch} is the number of charged particles in an event and $\langle p_T \rangle$ is the average p_T for a given number of charged particles.

☆☆ Date submitted: 2010-03-16T16:00:52Z.
E-mail address: atlas.secretariat@cern.ch.

[1] The ATLAS reference system is a Cartesian right-handed co-ordinate system, with the nominal collision point at the origin. The anti-clockwise beam direction defines the positive z-axis, while the positive x-axis is defined as pointing from the collision point to the centre of the LHC ring and the positive y-axis points upwards. The azimuthal angle ϕ is measured around the beam axis, and the polar angle θ is measured with respect to the z-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

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Comparisons are made to previous measurements of charged-particle multiplicities in pp and $p\bar{p}$ collisions at $\sqrt{s} = 900$ GeV centre-of-mass energies [1,5] and to Monte Carlo (MC) models.

2. The ATLAS detector

The ATLAS detector [14] at the Large Hadron Collider (LHC) [15] covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. It has been designed to study a wide range of physics topics at LHC energies. For the measurements presented in this Letter, the tracking devices and the trigger system were of particular importance.

The ATLAS inner detector has full coverage in ϕ and covers the pseudorapidity range $|\eta| < 2.5$. It consists of a silicon pixel detector (Pixel), a silicon microstrip detector (SCT) and a transition radiation tracker (TRT). These detectors cover a sensitive radial distance from the interaction point of 50.5–150 mm, 299–560 mm and 563–1066 mm, respectively, and are immersed in a 2 T axial magnetic field. The inner-detector barrel (end-cap) parts consist of 3 (2×3) Pixel layers, 4 (2×9) double-layers of single-sided silicon microstrips with a 40 mrad stereo angle, and 73 (2×160) layers of TRT straws. These detectors have position resolutions of typically 10, 17 and 130 μm for the R–ϕ co-ordinate and, in case of the Pixel and SCT, 115 and 580 μm for the second measured co-ordinate. A track from a particle traversing the barrel detector would typically have 11 silicon hits (3 pixel clusters and 8 strip clusters), and more than 30 straw hits.

The ATLAS detector has a three-level trigger system: Level 1 (L1), Level 2 (L2) and Event Filter (EF). For this measurement, the trigger relies on the L1 signals from the Beam Pickup Timing devices (BPTX) and the Minimum Bias Trigger Scintillators (MBTS). The BPTX are composed of beam pick-ups attached to the beam pipe ±175 m from the centre of the ATLAS detector. The MBTS are mounted at each end of the detector in front of the liquid-argon end-cap calorimeter cryostats at $z = \pm 3.56$ m and are segmented into eight sectors in azimuth and two rings in pseudorapidity ($2.09 < |\eta| < 2.82$ and $2.82 < |\eta| < 3.84$). Data were collected for this analysis using the MBTS trigger, formed from BPTX and MBTS trigger signals. The MBTS trigger was configured to require one hit above threshold from either side of the detector. The efficiency of this trigger was studied with a separate prescaled L1 BPTX trigger, filtered to obtain inelastic interactions by inner detector requirements at L2 and EF.

3. Monte Carlo simulation

Low-p_T scattering processes may be described by lowest-order perturbative Quantum Chromodynamics (QCD) two-to-two parton scatters, where the divergence of the cross section at $p_T = 0$ is regulated by phenomenological models. These models include multiple-parton scattering, partonic-matter distributions, scattering between the unresolved protons and colour reconnection [16]. The PYTHIA [17] MC event generator implements several of these models. The parameters of these models have been tuned to describe charged-hadron production and the underlying event in pp and $p\bar{p}$ data at centre-of-mass energies between 200 GeV and 1.96 TeV.

Samples of ten million MC events were produced for single-diffractive, double-diffractive and non-diffractive processes using the PYTHIA 6.4.21 generator. A specific set of optimised parameters, the ATLAS MC09 PYTHIA tune [18], which employs the MRST LO* parton density functions [19] and the p_T-ordered parton shower, is the reference tune throughout this Letter. These parameters were derived by tuning to underlying event and minimum-bias data from Tevatron at 630 GeV and 1.8 TeV. The MC samples generated with this tune were used to determine detector acceptances and efficiencies and to correct the data.

For the purpose of comparing the present measurement to different phenomenological models describing minimum-bias events, the following additional MC samples were generated: the ATLAS MC09c [18] PYTHIA tune, which is an extension of the ATLAS MC09 tune optimising the strength of the colour reconnection to describe the $\langle p_T \rangle$ distributions as a function of n_{ch}, as measured by CDF in $p\bar{p}$ collisions [3]; the Perugia0 [20] PYTHIA tune, in which the soft-QCD part is tuned using only minimum-bias data from the Tevatron and CERN $p\bar{p}$ colliders; the DW [21] PYTHIA tune, which uses the virtuality-ordered showers and was derived to describe the CDF Run II underlying event and Drell–Yan data. Finally, the PHOJET generator [22] was used as an alternative model. It describes low-p_T physics using the two-component Dual Parton Model [23,24], which includes soft hadronic processes described by Pomeron exchange and semi-hard processes described by perturbative parton scattering. PHOJET relies on PYTHIA for the fragmentation of partons. The versions[2] used for this study were shown to agree with previous measurements [3,5,6,9].

The non-diffractive, single-diffractive and double-diffractive contributions in the generated samples were mixed according to the generator cross sections to fully describe the inelastic scattering. All the events were processed through the ATLAS detector simulation program [25], which is based on Geant4 [26]. They were then reconstructed and analysed by the same program chain used for the data. Particular attention was devoted to the description in the simulation of the size and position of the collision beam spot and of the detailed detector conditions during data taking.

4. Event selection

All data recorded during the stable LHC running periods between December 6 and 15, 2009, in which the inner detector was fully operational and the solenoid magnet was on, were used for this analysis. During this period the beams were colliding head-on in ATLAS. A total of 455,593 events were collected from colliding proton bunches in which the MBTS trigger recorded one or more counters above threshold on either side. In order to perform an inclusive-inelastic measurement, no further requirements beyond the MBTS trigger and inner detector information were applied in this event selection. The integrated luminosity for the final event sample, which is given here for reference only, was estimated using a sample of events with energy deposits in both sides of the forward and end-cap calorimeters. The MC-based efficiency and the PYTHIA default cross section of 52.5 mb were then used to determine the luminosity of the data sample to be approximately 9 μb^{-1}, while the maximum instantaneous luminosity was approximately 5×10^{26} $cm^{-2} s^{-1}$. The probability of additional interactions in the same bunch crossing was estimated to be less than 0.1%.

[2] PHOJET 1.12 with PYTHIA 6.4.21.

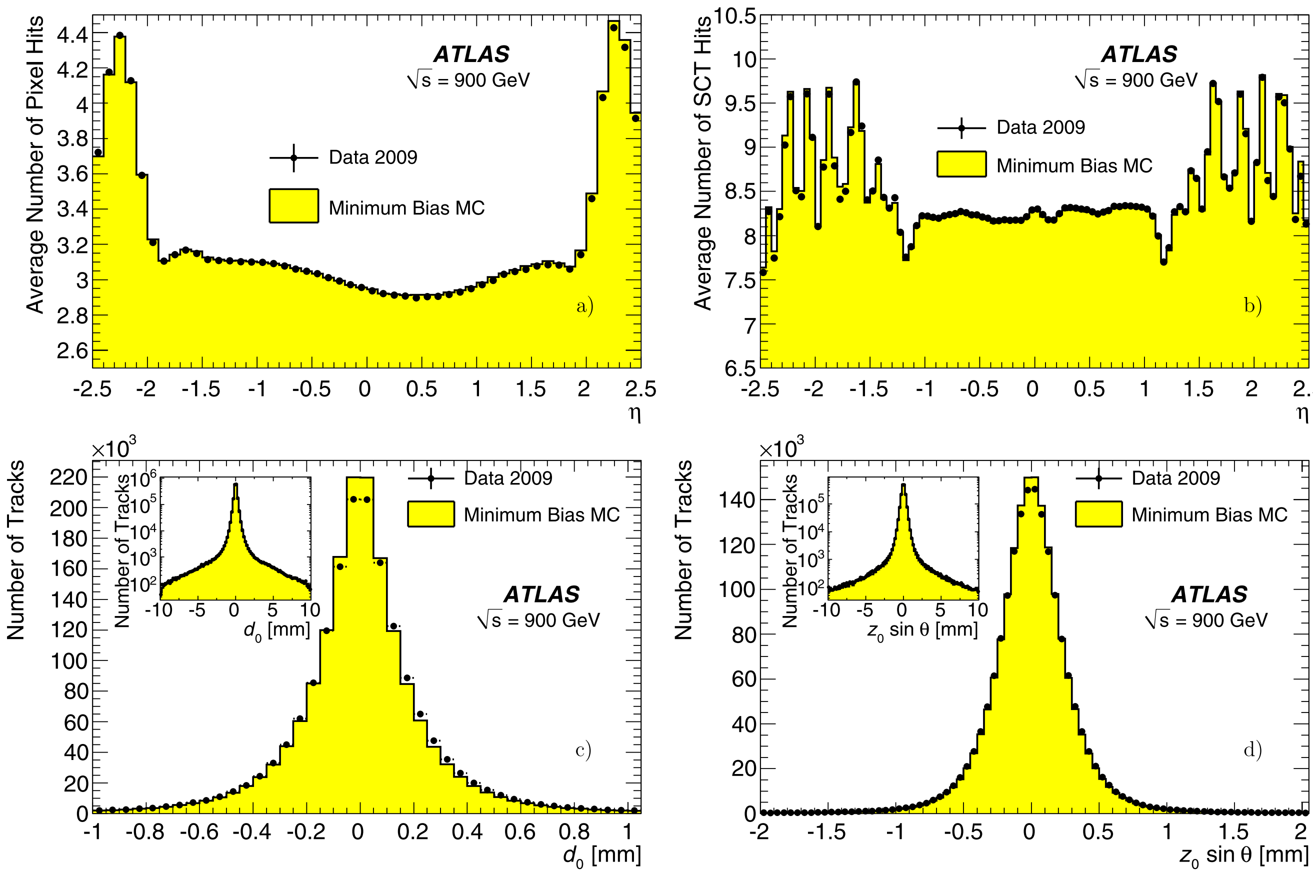

Fig. 1. Comparison between data (dots) and minimum-bias ATLAS MC09 simulation (histograms) for the average number of Pixel hits (a) and SCT hits (b) per track as a function of η, and the transverse (c) and longitudinal (d) impact parameter distributions of the reconstructed tracks. The MC distributions in (c) and (d) are normalised to the number of tracks in the data. The inserts in the lower panels show the distributions in logarithmic scale.

During this data-taking period, more than 96% of the Pixel detector, 99% of the SCT and 98% of the TRT were operational. Tracks were reconstructed offline within the full acceptance range $|\eta| < 2.5$ of the inner detector [27,28]. Track candidates were reconstructed by requiring seven or more silicon hits in total in the Pixel and SCT, and then extrapolated to include measurements in the TRT. Typically, 88% of tracks inside the TRT acceptance ($|\eta| < 2$) include a TRT extension, which significantly improves the momentum resolution.

This Letter reports results for charged particles with $p_T > 500$ MeV, which are less prone than lower-p_T particles to large inefficiencies and their associated systematic uncertainties resulting from interactions with material inside the tracking volume. To reduce the contribution from background events and non-primary tracks, as well as to minimise the systematic uncertainties, the following criteria were required:

- the presence of a primary vertex [29] reconstructed using at least three tracks, each with:
  - $p_T > 150$ MeV,
  - a transverse distance of closest approach with respect to the beam-spot position $|d_0^{BS}| < 4$ mm;
- at least one track with:
  - $p_T > 500$ MeV,
  - a minimum of one Pixel and six SCT hits,
  - transverse and longitudinal impact parameters calculated with respect to the event primary vertex $|d_0| < 1.5$ mm and $|z_0| \cdot \sin\theta < 1.5$ mm, respectively.

These latter tracks were used to produce the corrected distributions and will be referred to as selected tracks. The multiplicity of selected tracks within an event is denoted by n_{Sel}. In total 326,201 events were kept after this offline selection, which contained 1,863,622 selected tracks. The inner detector performance is illustrated in Fig. 1 using selected tracks and their MC simulation. The shapes from overlapping Pixel and SCT modules in the forward region and the inefficiency from a small number of disabled Pixel modules in the central region are well modelled by the simulation. The simulated impact-parameter distributions describe the data to better than 10%, including their tails as shown in the inserts of Fig. 1(c) and (d). The difference between data and MC observed in the central region of the d_0 distribution is due to small residual misalignments not simulated in the MC, which are found to be unimportant for this analysis.

Trigger and vertex-reconstruction efficiencies were parameterized as a function of the number of tracks passing all of the track selection requirements except for the constraints with respect to the primary vertex. Instead, the transverse impact parameter with respect to the beam spot was required to be less than 4 mm, which is the same requirement as that used in the primary vertex reconstruction preselection. The multiplicity of these tracks in an event is denoted by n_{Sel}^{BS}.

5. Background contribution

There are two possible sources of background events that can contaminate the selected sample: cosmic rays and beam-induced background. A limit on the fraction of cosmic-ray events recorded by the L1 MBTS trigger during data taking was determined from cosmic-ray studies, the maximum number of proton bunches, and the central trigger processor clock width of 25 ns, and was found to be smaller than 10^{-6}. Beam-induced background events can be produced by proton collisions with upstream collimators or with residual particles inside the beam pipe. The L1 MBTS trigger was used to select beam-induced background events from un-paired proton bunch-crossings. By applying the analysis selection criteria to these events, an upper limit of 10^{-4} was determined for the fraction of beam-induced background events within the selected sample. The requirement of a reconstructed primary vertex is particularly useful to suppress the beam-induced background.

Primary charged-particle multiplicities are measured from selected-track distributions after correcting for the fraction of secondary particles in the sample. The potential background from fake tracks is found to be less than 0.1% from simulation studies. Non-primary tracks are mostly due to hadronic interactions, photon conversions and decays of long-lived particles. Their contribution was estimated using the MC prediction of the shape of the d_0 distribution, after normalising to data for tracks within 2 mm $< |d_0| <$ 10 mm, i.e. outside the range used for selecting tracks. The simulation was found to reproduce the tails of the d_0 distribution of the data, as shown in Fig. 1(c), and the normalisation factor between data and MC was measured to be $1.00 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.})$. The MC was then used to estimate the fraction of secondaries in the selected-track sample to be $(2.20 \pm 0.05(\text{stat.}) \pm 0.11(\text{syst.}))$%. This fraction is independent of n_{Sel}, but shows a dependence on p_{T} and a small dependence on η. While the correction for secondaries was applied in bins of p_{T}, the dependence on η was incorporated into the systematic uncertainty.

6. Selection efficiency

The data were corrected to obtain inclusive spectra for charged primary particles satisfying the event-level requirement of at least one primary charged particle within $p_{\text{T}} > 500$ MeV and $|\eta| < 2.5$. These corrections include inefficiencies due to trigger selection, vertex and track reconstruction. They also account for effects due to the momentum scale and resolution, and for the residual background from secondary tracks.

Trigger efficiency The trigger efficiency was measured from an independent data sample selected using the control trigger introduced in Section 2. This control trigger required more than 6 Pixel clusters and 6 SCT hits at L2, and one or more reconstructed tracks with $p_{\text{T}} > 200$ MeV at the EF. The vertex requirement for selected tracks was removed for this study, to avoid correlations between the trigger and vertex-reconstruction efficiencies for L1 MBTS triggered events. The trigger efficiency was determined by taking the ratio of events from the control trigger in which the L1 MBTS also accepted the event, over the total number of events in the control sample. The result is shown in Fig. 2(a) as a function of $n_{\text{Sel}}^{\text{BS}}$. The trigger efficiency is nearly 100% everywhere and the requirement of this trigger does not affect the p_{T} and η track distributions of the selected events.

Vertex-reconstruction efficiency The vertex-reconstruction efficiency was determined from the data, by taking the ratio of triggered events with a reconstructed vertex to the total number of triggered events. It is shown in Fig. 2(b) as a function of $n_{\text{Sel}}^{\text{BS}}$. The efficiency amounts to approximately 67% for the lowest bin and rapidly rises to 100% with higher multiplicities. The dependence of the vertex-reconstruction efficiency on the η and p_{T} of the selected tracks was studied. The η dependence was found to be approximately flat for $n_{\text{Sel}}^{\text{BS}} > 1$ and to decrease at larger η for events with $n_{\text{Sel}}^{\text{BS}} = 1$. This dependence was corrected for. No dependence on p_{T} was observed.

Track-reconstruction efficiency The track-reconstruction efficiency in each bin of the p_{T}–η acceptance was determined from MC. The comparison of the MC and data distributions shown in Fig. 1 highlights their agreement. The track-reconstruction efficiency was defined as:

$$\epsilon_{\text{bin}}(p_{\text{T}}, \eta) = \frac{N_{\text{rec}}^{\text{matched}}(p_{\text{T}}, \eta)}{N_{\text{gen}}(p_{\text{T}}, \eta)},$$

where p_{T} and η are generated quantities, and $N_{\text{rec}}^{\text{matched}}(p_{\text{T}}, \eta)$ and $N_{\text{gen}}(p_{\text{T}}, \eta)$ are the number of reconstructed tracks in a given bin matched to a generated charged particle and the number of generated charged particles in that bin, respectively. The matching between a generated particle and a reconstructed track was done using a cone-matching algorithm in the η–ϕ plane, associating the particle to the track with the smallest $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ within a cone of radius 0.05. The resulting reconstruction efficiency as a function of p_{T} integrated over η is shown in Fig. 2(c). The drop to ≈ 70% for $p_{\text{T}} < 600$ MeV is an artefact of the p_{T} cut at the pattern-recognition level and is discussed in Section 8. The reduced track-reconstruction efficiency in the region $|\eta| > 1$ (Fig. 2(d)) is mainly due to the presence of more material in this region. These inefficiencies include a 5% loss due to the track selection used in this analysis, approximately half of which is due to the silicon-hit requirements and half to the impact-parameter requirements.

7. Correction procedure

The effect of events lost due to the trigger and vertex requirements can be corrected for using an event-by-event weight:

$$w_{\text{ev}}(n_{\text{Sel}}^{\text{BS}}) = \frac{1}{\epsilon_{\text{trig}}(n_{\text{Sel}}^{\text{BS}})} \cdot \frac{1}{\epsilon_{\text{vtx}}(n_{\text{Sel}}^{\text{BS}})},$$

where $\epsilon_{\text{trig}}(n_{\text{Sel}}^{\text{BS}})$ and $\epsilon_{\text{vtx}}(n_{\text{Sel}}^{\text{BS}})$ are the trigger and vertex reconstruction efficiencies discussed in Section 6. The vertex-reconstruction efficiency for events with $n_{\text{Sel}}^{\text{BS}} = 1$ includes an η-dependent correction which was derived from the data.

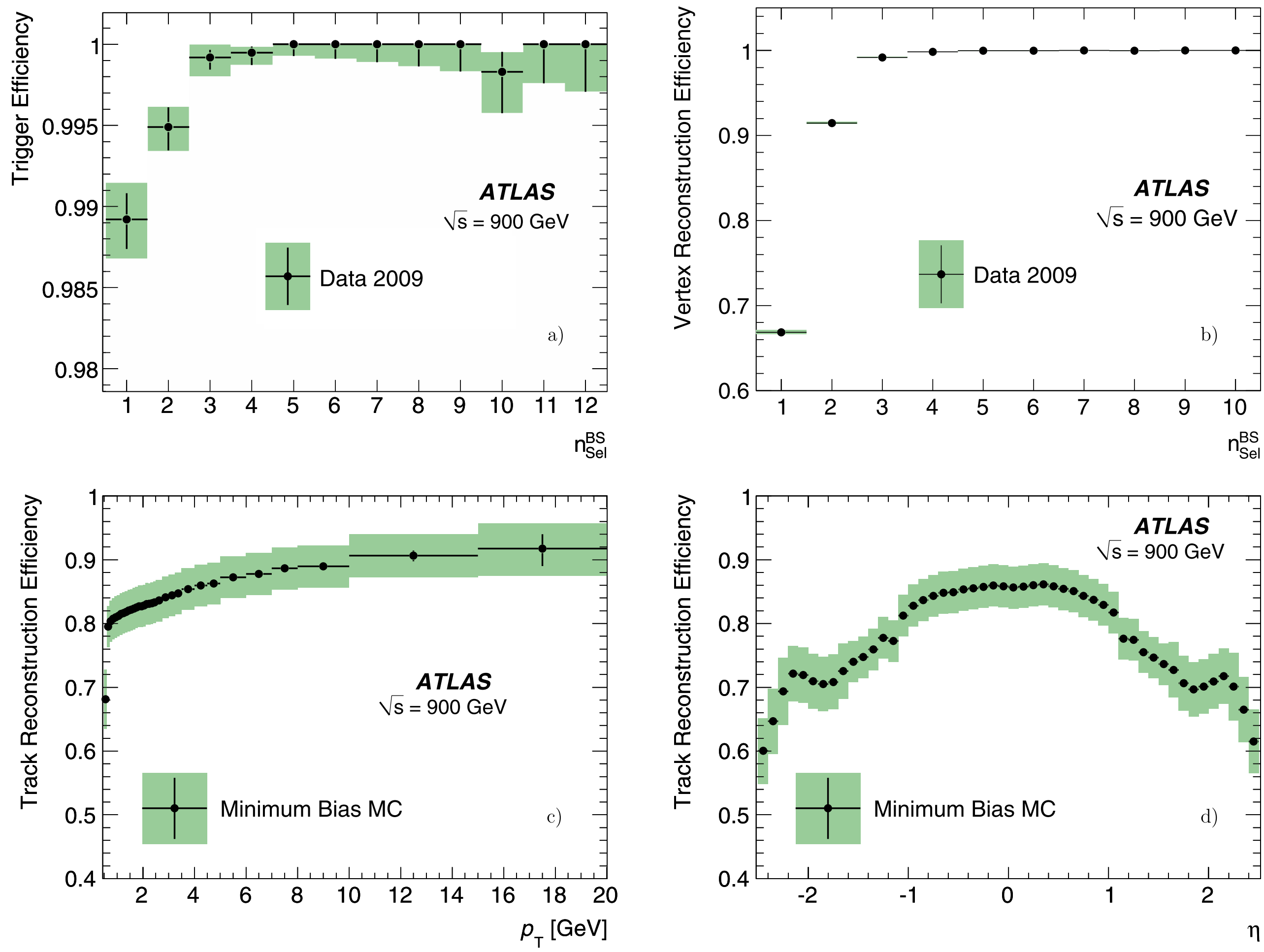

Fig. 2. Trigger (a) and vertex-reconstruction (b) efficiencies as a function of the variable $n_{\mathrm{Sel}}^{\mathrm{BS}}$ defined in Section 4; track-reconstruction efficiency as a function of p_{T} (c) and of η (d). The vertical bars represent the statistical uncertainty, while the shaded areas represent the statistical and systematic uncertainties added in quadrature. The two bottom panels were derived from the PYTHIA ATLAS MC09 sample.

The p_{T} and η distributions of selected tracks were corrected on a track-by-track basis using the weight:

$$w_{\mathrm{trk}}(p_{\mathrm{T}},\eta) = \frac{1}{\epsilon_{\mathrm{bin}}(p_{\mathrm{T}},\eta)} \cdot \big(1 - f_{\mathrm{sec}}(p_{\mathrm{T}})\big) \cdot \big(1 - f_{\mathrm{okr}}(p_{\mathrm{T}},\eta)\big),$$

where ϵ_{bin} is the track-reconstruction efficiency described in Section 6 and $f_{\mathrm{sec}}(p_{\mathrm{T}})$ is the fraction of secondaries determined as described in Section 5. The fraction of selected tracks for which the corresponding primary particles are outside the kinematic range, $f_{\mathrm{okr}}(p_{\mathrm{T}},\eta)$, originates from resolution effects and has been estimated from MC. Bin migrations were found to be due solely to reconstructed track momentum resolution and were corrected by using the resolution function taken from MC.

In the case of the distributions versus n_{ch}, a track-level correction was applied by using Bayesian unfolding [30] to correct back to the number of charged particles. A matrix $M_{\mathrm{ch,Sel}}$, which expresses the probability that a multiplicity of selected tracks n_{Sel} is due to n_{ch} particles, was populated using MC and applied to obtain the n_{ch} distribution from the data. The resulting distribution was then used to re-populate the matrix and the correction was re-applied. This procedure was repeated without a regularisation term and converged after four iterations, when the change in the distribution between iterations was found to be less than 1%. It should be noted that the matrix cannot correct for events which are lost due to track-reconstruction inefficiency. To correct for these missing events, a correction factor $1/(1-(1-\epsilon(n_{\mathrm{ch}}))^{n_{\mathrm{ch}}})$ was applied, where $\epsilon(n_{\mathrm{ch}})$ is the average track-reconstruction efficiency.

In the case of the $\langle p_{\mathrm{T}}\rangle$ versus n_{ch} distribution, each event was weighted by $w_{\mathrm{ev}}(n_{\mathrm{Sel}}^{\mathrm{BS}})$. For each n_{Sel} a MC-based correction was applied to convert the reconstructed average p_{T} to the average p_{T} of primary charged particles. Then the matrix $M_{\mathrm{ch,Sel}}$ was applied as described above.

8. Systematic uncertainties

Numerous detailed studies have been performed to understand possible sources of systematic uncertainties. The main contributions are discussed below.

Trigger The trigger selection dependence on the p_T and η distributions of reconstructed tracks was found to be flat within the statistical uncertainties of the data recorded with the control trigger. The statistical uncertainty on this result was taken as a systematic uncertainty of 0.1% on the overall trigger efficiency.

Since there is no vertex requirement in the data sample used to measure the trigger efficiency, it is not possible to make the same impact-parameter cuts as are made on the final selected tracks. Therefore the trigger efficiency was measured using impact-parameter constraints with respect to the primary vertex or the beam spot and compared to that obtained without such a requirement. The difference was taken as a systematic uncertainty of 0.1% for $n_{\mathrm{Sel}}^{\mathrm{BS}} \leqslant 3$.

The correlation of the MBTS trigger with the control trigger used to select the data sample for the trigger-efficiency determination was studied using the simulation. The resulting systematic uncertainty was found to affect only the case $n_{\mathrm{Sel}}^{\mathrm{BS}} = 1$ and amounts to 0.2%.

Vertex reconstruction The run-to-run variation of the vertex-reconstruction efficiency was found to be within the statistical uncertainty. The contribution of beam-related backgrounds to the sample selected without a vertex requirement was estimated by using non-colliding bunches. It was found to be 0.3% for $n_{\mathrm{Sel}}^{\mathrm{BS}} = 1$ and smaller than 0.1% for higher multiplicities, and was assigned as a systematic uncertainty. This background contribution is larger than that given in Section 5, since a reconstructed primary vertex was not required for these events.

Track reconstruction and selection Since the track-reconstruction efficiency is determined from MC, the main systematic uncertainty results from the level of disagreement between data and MC.

Three different techniques to associate generated particles to reconstructed tracks were studied: a cone-matching algorithm, an evaluation of the fraction of simulated hits associated to a reconstructed track and an inclusive technique using a correction for secondary particles. A systematic uncertainty of 0.5% was assigned from the difference between the cone-matching and the hit-association methods.

A detailed comparison of track properties in data and simulation was performed by varying the track-selection criteria. The largest deviations between data and MC were observed by varying the $z_0 \cdot \sin\theta$ selection requirement, and by varying the constraint on the number of SCT hits. These deviations are generally smaller than 1% and rise to 3% at the edges of the η range.

The systematic effects of misalignment were studied by smearing simulation samples by the expected residual misalignment and by comparing the performance of two alignment algorithms on tracks reconstructed from the data. Under these conditions the number of reconstructed tracks was measured and the systematic uncertainty on the track reconstruction efficiency due to the residual misalignment was estimated to be less than 1%.

To test the influence of an imperfect description of the detector material in the simulation, two additional MC samples with approximately 10% and 20% increase in radiation lengths of the material in the Pixel and SCT active volume were used. The impact of excess material in the tracking detectors was studied using the tails of the impact-parameter distribution, the length of tracks, and the change in the reconstructed K_S^0 mass as a function of the decay radius, the direction and the momentum of the K_S^0. The MC with nominal material was found to describe the data best. The data were found to be consistent with a 10% material increase in some regions, whereas the 20% increase was excluded in all cases. The efficiency of matching full tracks to track segments reconstructed in the Pixel detector was also studied. The comparison between data and simulation was found to have good agreement across most of the kinematic range. Some discrepancies found for $|\eta| > 1.6$ were included in the systematic uncertainties. From all these studies a systematic uncertainty on the track reconstruction efficiency of 3.7%, 5.5% and 8% was assigned to the pseudorapidity regions $|\eta| < 1.6$, $1.6 < |\eta| < 2.3$ and $|\eta| > 2.3$, respectively.

The track-reconstruction efficiency shown in Fig. 2(c) rises sharply in the region $500 < p_T < 600$ MeV. The observed turn-on curve is produced by the initial pattern recognition step of track reconstruction and its associated p_T resolution, which is considerably worse than the final p_T resolution. The consequence is that some particles which are simulated with $p_T > 500$ MeV are reconstructed with momenta below the selection requirement. This effect reduces the number of selected tracks. The shape of the threshold was studied in data and simulation and a systematic uncertainty of 5% was assigned to the first p_T bin.

In conclusion, an overall relative systematic uncertainty of 4.0% was assigned to the track reconstruction efficiency for most of the kinematic range of this measurement, while 8.5% and 6.9% were assigned to the highest $|\eta|$ and to the lowest p_T bins, respectively.

Momentum scale and resolution To obtain corrected distributions of charged particles, the scale and resolution uncertainties in the reconstructed p_T and η of the selected tracks have to be taken into account. Whereas the uncertainties for the η measurement were found to be negligible, those for the p_T measurement are in general more important. The inner detector momentum resolution was taken from MC as a function of p_T and η. It was found to vary between 1.5% and 5% in the range relevant to this analysis. The uncertainty was estimated by comparing with MC samples with a uniform scaling of 10% additional material at low p_T and with large misalignments at higher p_T. Studies of the width of the mass peak for reconstructed K_S^0 candidates in the data show that these assumptions are conservative. The reconstructed momentum scale was checked by comparing the measured value of the K_S^0 mass to the MC. The systematic uncertainties from both the momentum resolution and scale were found to have no significant effect on the final results.

Fraction of secondaries The fraction of secondaries was determined as discussed in Section 5. The associated systematic uncertainty was estimated by varying the range of the impact parameter distribution that was used to normalise the MC, and by fitting separate distributions for weak decays and material interactions. The systematic uncertainty includes a small contribution due to the η dependence of this correction. The total uncertainty is 0.1%.

Correction procedure Several independent tests were made to assess the model dependence of the correction matrix $M_{\mathrm{ch,Sel}}$ and the resulting systematic uncertainty. In order to determine the sensitivity to the p_T and η distributions, the matrix was re-populated using the other MC parameterizations described in Section 3 and by varying the track-reconstruction efficiency by ±5%. The correction factor for events lost due to the track-reconstruction inefficiency was varied by the same amount and treated as fully correlated. For the overall normalisation, this leads to an uncertainty of 0.4% due to the model dependence and of 1.1% due to the track-reconstruction efficiency. The size of the systematic uncertainties on n_{ch} increases with the multiplicity.

Table 1
Summary of systematic uncertainties on the number of events, N_{ev}, and on the charged-particle density $(1/N_{\text{ev}}) \cdot (\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta)$ at $\eta = 0$. The uncertainty on N_{ev} is anti-correlated with $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$. All other sources are assumed to be uncorrelated.

Systematic uncertainty on the number of events, N_{ev}	
Trigger efficiency	< 0.1%
Vertex-reconstruction efficiency	< 0.1%
Track-reconstruction efficiency	1.1%
Different MC tunes	0.4%
Total uncertainty on N_{ev}	1.2%
Systematic uncertainty on $(1/N_{\text{ev}}) \cdot (\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta)$ at $\eta = 0$	
Track-reconstruction efficiency	4.0%
Trigger and vertex efficiency	< 0.1%
Secondary fraction	0.1%
Total uncertainty on N_{ev}	−1.2%
Total uncertainty on $(1/N_{\text{ev}}) \cdot (\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta)$ at $\eta = 0$	2.8%

The correction for the $\langle p_T \rangle$ was also studied using the different PYTHIA tunes and PHOJET. The change was found to be less than 2% over the whole sample.

As the track-reconstruction efficiency depends on the particle type, the uncertainty in the composition of the charged particles in the minimum-bias MC sample was studied. The relative yields of pions, kaons and protons in the simulation were separately varied by ±10%. These variations, combined with changing the fraction of electrons and muons by a factor of three, resulted in a systematic uncertainty of 0.2%.

The systematic uncertainty on the normalisation and on the number of charged particles were treated separately. In each of these two groups the systematic uncertainties were added in quadrature. These were then combined taking into account their anti-correlation and were propagated to the final distributions. Table 1 summarises the various contributions to the systematic uncertainties on the charged-particle density at $\eta = 0$.

9. Results

The corrected distributions for primary charged particles for events with $n_{\text{ch}} \geqslant 1$ in the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ are shown in Fig. 3, where they are compared to predictions of models tuned to a wide range of measurements. The data are presented as inclusive-inelastic distributions with minimal model-dependent corrections to facilitate the comparison with models.

The charged-particle pseudorapidity density is shown in Fig. 3(a). It is measured to be approximately flat in the range $|\eta| < 1.5$, with an average value of $1.333 \pm 0.003(\text{stat.}) \pm 0.040(\text{syst.})$ charged particles per event and unit of pseudorapidity in the range $|\eta| < 0.2$. The particle density is found to drop at higher values of $|\eta|$. All MC tunes discussed in this Letter are lower than the data by 5–15%, corresponding to approximately 1–4 standard deviations. The shapes of the models are approximately consistent with the data with the exception of PYTHIA DW.

The N_{ch} distribution in bins of p_T is shown in Fig. 3(b) and is constructed by weighting each entry by $1/p_T$. The MC models do not reproduce the data for $p_T > 0.7$ GeV. The most significant difference is seen for the PHOJET generator.

The multiplicity distribution as a function of n_{ch} is shown in Fig. 3(c). The PYTHIA models show an excess of events with $n_{\text{ch}} = 1$ with respect to the data, while the fraction of events with $n_{\text{ch}} \gtrsim 10$ is consistently lower than the data. The net effect is that the integral number of charged particles predicted by the models are below that of the data (Fig. 3(a) and (b)). The PHOJET generator successfully models the number of events with $n_{\text{ch}} = 1$, while it deviates from the data distributions at higher values of n_{ch}.

The average p_T as a function of n_{ch} is illustrated in Fig. 3(d). It is found to increase with increasing n_{ch} and a change of slope is observed around $n_{\text{ch}} = 10$. This behaviour was already observed by the CDF experiment in $p\bar{p}$ collisions at 1.96 TeV [3]. The Perugia0 parameterization, which was tuned using CDF minimum-bias data at 1.96 TeV, describes the data well. The other models fail to describe the data below $n_{\text{ch}} \approx 25$, with the exception of the PYTHIA-MC09c tune.

The N_{ch} distribution as a function of p_T in the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ is shown in Fig. 4. The CMS [1] results at the same centre-of-mass energy are superimposed. The number of charged particles in the CMS data is consistently lower than the data presented in this Letter. This offset is expected from the CMS measurement definition of NSD events, where events with $n_{\text{ch}} = 0$ enter the normalisation and the number of lower transverse momentum particles are reduced by the subtraction of the PYTHIA single diffractive component. The UA1 [5] results, normalised by their associated cross section measurement, are also overlaid. They are approximately 20% higher than the present data. A shift in this direction is expected from the double-arm scintillator trigger requirement used to collect the UA1 data, which rejected events with low charged-particle multiplicities.

To compare more directly the present data with results from CMS, the mean charged-particle density was calculated in the range $|\eta| < 2.4$ and a model dependent correction was applied to form an NSD particle density. For the calculation of the NSD value the PYTHIA DW tune was selected due to its similarity with the tune used in the CMS analysis. This generator set-up was used to produce a correction for the removal of the fraction of single diffractive events, the removal of electrons from π^0 Dalitz decays and the addition of non-single diffractive events with no charged particles within the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$. The net effect of the correction is to reduce the charged-particle multiplicity. The resulting value $1.240 \pm 0.040(\text{syst.})$ is consistent with the CMS measurement of $1.202 \pm 0.043(\text{syst.})$ in the kinematic range of $p_T > 500$ MeV and $|\eta| < 2.4$.

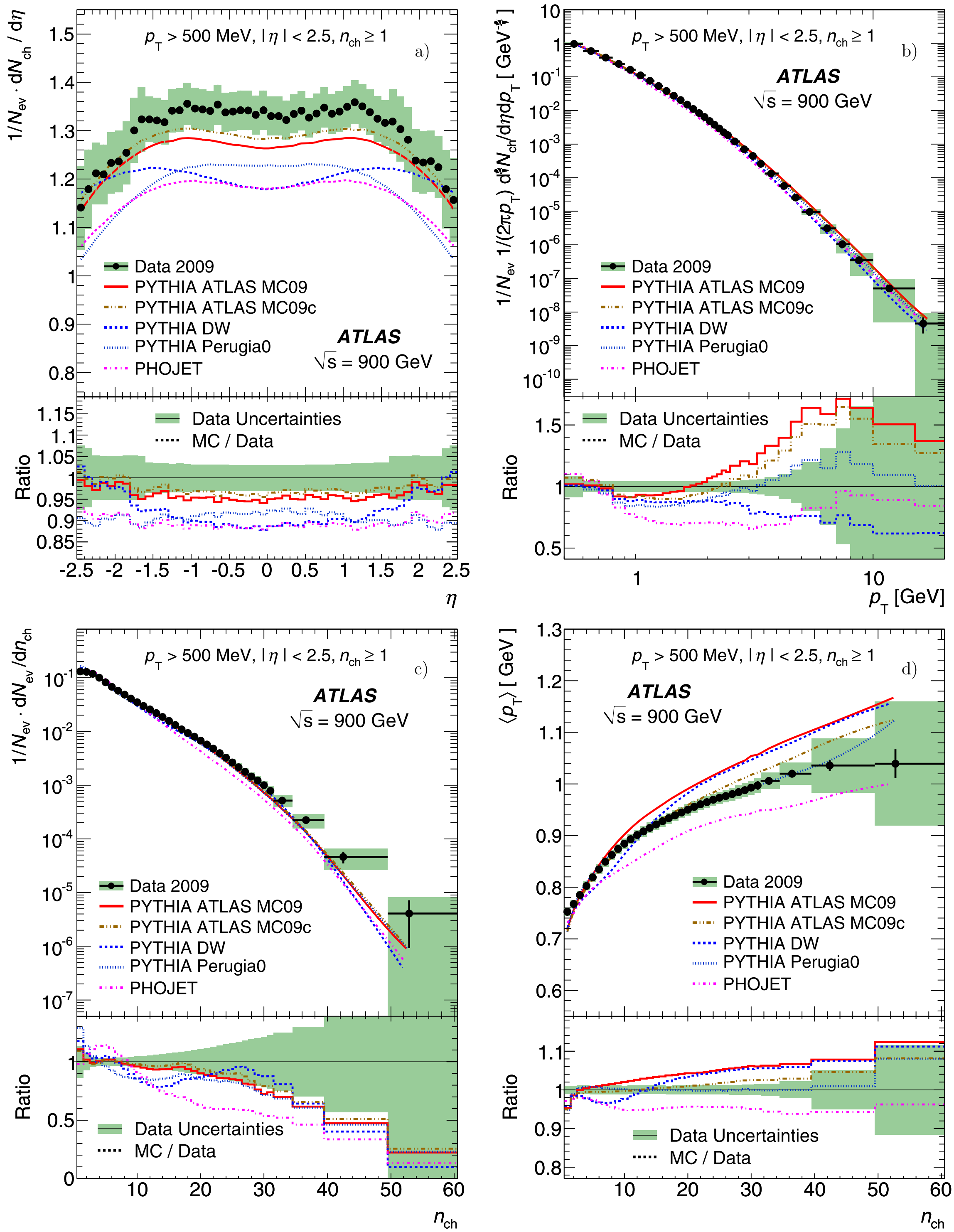

Fig. 3. Charged-particle multiplicities for events with $n_{ch} \geqslant 1$ within the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$. The panels show the charged-particle multiplicity as a function of pseudorapidity (a) and of the transverse momentum (b), the charged-particle multiplicity (c), and the average transverse momentum as a function of the number of charged particles in the event (d). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The values of the ratio histograms refer to the bin centroids.

10. Conclusions

Charged-particle multiplicity measurements with the ATLAS detector using the first collisions delivered by the LHC during 2009 are presented. Based on over three hundred thousand proton–proton inelastic interactions, the properties of events with at least one primary charged particle produced within the kinematic range $|\eta| < 2.5$ and $p_T > 500$ MeV were studied. The data were corrected with minimal model dependence to obtain inclusive distributions. The charged-particle multiplicity per event and unit of pseudorapidity at $\eta = 0$ is

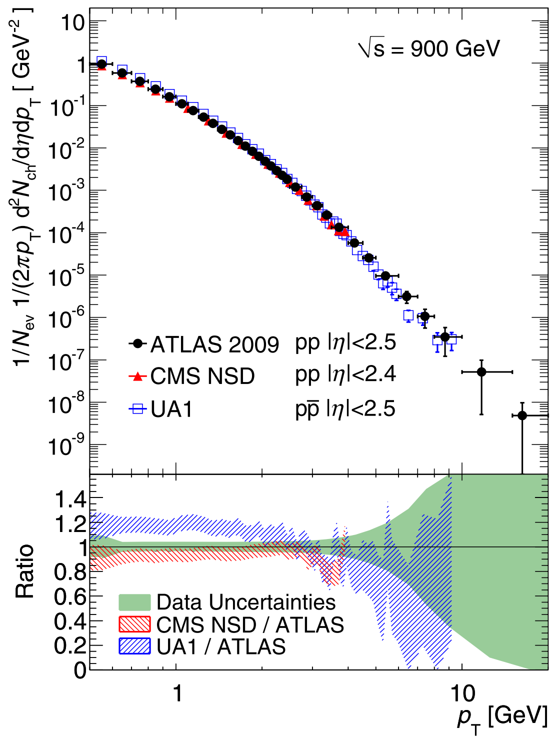

Fig. 4. The measured p_T spectrum of charged-particle multiplicities. The ATLAS pp data (black dots) are compared to the UA1 $p\bar{p}$ data (blue open squares) and CMS NSD pp data (red triangles) at the same centre-of-mass energy.

measured to be $1.333 \pm 0.003(\text{stat.}) \pm 0.040(\text{syst.})$, which is 5–15% higher than the Monte Carlo model predictions. The selected kinematic range and the precision of this analysis highlight clear differences between Monte Carlo models and the measured distributions.

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Voss [167], R. Voss [29], T.T. Voss [172], J.H. Vossebeld [73], A.S. Vovenko [127], N. Vranjes [12a], M. Vranjes Milosavljevic [12a], V. Vrba [124], M. Vreeswijk [105], T. Vu Anh [81], B. Vuaridel [49], D. Vudragovic [12a], R. Vuillermet [29], I. Vukotic [114], A. Waananen [35], P. Wagner [119], H. Wahlen [172], J. Walbersloh [42], J. Walder [71], R. Walker [98], W. Walkowiak [140], R. Wall [173], S. Walsh [138], C. Wang [44], H. Wang [170], J. Wang [55], J.C. Wang [137], M.W. Wang [129], S.M. Wang [149], F. Wappler [1], A. Warburton [85], C.P. Ward [27], M. Warsinsky [48], R. Wastie [117], P.M. Watkins [17], A.T. Watson [17], M.F. Watson [17], G. Watts [137], S. Watts [82], A.T. Waugh [148], B.M. Waugh [77], M. Webel [48], G. Weber [81], J. Weber [42], M.D. Weber [16], M. Weber [128], M.S. Weber [16], P. Weber [58a], A.R. Weidberg [117], J. Weingarten [54], C. Weiser [48], H. Wellenstein [22], H.P. Wellisch [157a], P.S. Wells [29], M. Wen [47], T. Wenaus [24], S. Wendler [122], T. 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Wunstorf [42], B.M. Wynne [45], L. Xaplanteris [9], S. Xella [35], S. Xie [48], Y. Xie [32a], D. Xu [138], G. Xu [32a], N. Xu [170], M. Yamada [158], A. Yamamoto [66], K. Yamamoto [64], S. Yamamoto [153], T. Yamamura [153], J. Yamaoka [44], T. Yamazaki [153], Y. Yamazaki [67], Z. Yan [21], H. Yang [87], S. Yang [117], U.K. Yang [82], Y. Yang [32a], Z. Yang [144a,144b], W.-M. Yao [14], Y. Yao [14], K. Yarradoddi [24,g], Y. Yasu [66], J. Ye [39], S. Ye [24], M. Yilmaz [3c], R. Yoosoofmiya [122], K. Yorita [168], H. Yoshida [66,y], R. Yoshida [5], C. Young [142], S.P. Youssef [21], D. Yu [24], J. Yu [7], J. Yuan [99], L. Yuan [78], A. Yurkewicz [146], V.G. Zaets [127], R. Zaidan [63], A.M. Zaitsev [127], Z. Zajacova [29], Yo.K. Zalite [120], V. Zambrano [47], L. Zanello [131a,131b], P. Zarzhitsky [39], A. Zaytsev [106], M. Zdrazil [14], C. Zeitnitz [172], M. Zeller [173], P.F. Zema [29], A. Zemla [38], C. Zendler [20], A.V. Zenin [127], O. Zenin [127], T. Zenis [143a], Z. Zenonos [121a,121b], S. Zenz [14], D. Zerwas [114], G. Zevi della Porta [57], Z. Zhan [32d], H. Zhang [83], J. Zhang [5], Q. Zhang [5], X. Zhang [32d], L. Zhao [107], T. Zhao [137],

Z. Zhao [32b], A. Zhemchugov [65], S. Zheng [32a], J. Zhong [149,z], B. Zhou [87], N. Zhou [34], Y. Zhou [149], C.G. Zhu [32d], H. Zhu [41], Y. Zhu [170], X. Zhuang [98], V. Zhuravlov [99], B. Zilka [143a], R. Zimmermann [20], S. Zimmermann [20], S. Zimmermann [48], M. Ziolkowski [140], R. Zitoun [4], L. Živković [34], V.V. Zmouchko [127,*], G. Zobernig [170], A. Zoccoli [19a,19b], Y. Zolnierowski [4], A. Zsenei [29], M. zur Nedden [15], V. Zutshi [5]

[1] University at Albany, 1400 Washington Ave, Albany, NY 12222, United States
[2] University of Alberta, Department of Physics, Centre for Particle Physics, Edmonton, AB T6G 2G7, Canada
[3] Ankara University[(a)], Faculty of Sciences, Department of Physics, TR 061000 Tandogan, Ankara; Dumlupinar University[(b)], Faculty of Arts and Sciences, Department of Physics, Kutahya; Gazi University[(c)], Faculty of Arts and Sciences, Department of Physics, 06500 Teknikokullar, Ankara; TOBB University of Economics and Technology[(d)], Faculty of Arts and Sciences, Division of Physics, 06560 Sogutozu, Ankara; Turkish Atomic Energy Authority[(e)], 06530 Lodumlu, Ankara, Turkey
[4] LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France
[5] Argonne National Laboratory, High Energy Physics Division, 9700 S. Cass Avenue, Argonne, IL 60439, United States
[6] University of Arizona, Department of Physics, Tucson, AZ 85721, United States
[7] The University of Texas at Arlington, Department of Physics, P.O. Box 19059, Arlington, TX 76019, United States
[8] University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopouli, Zografou, GR 15771, Athens, Greece
[9] National Technical University of Athens, Physics Department, 9-Iroon Polytechniou, GR 15780, Zografou, Greece
[10] Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan
[11] Institut de Física d'Altes Energies, IFAE, Edifici Cn, Universitat Autònoma de Barcelona, ES-08193 Bellaterra (Barcelona), Spain
[12] University of Belgrade[(a)], Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences[(b)], Mihajla Petrovica Alasa 12-14, 11001 Belgrade, Serbia
[13] University of Bergen, Department for Physics and Technology, Allegaten 55, NO-5007 Bergen, Norway
[14] Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, United States
[15] Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany
[16] University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[17] University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom
[18] Bogazici University[(a)], Faculty of Sciences, Department of Physics, TR-80815 Bebek-Istanbul; Dogus University[(b)], Faculty of Arts and Sciences, Department of Physics, 34722 Kadikoy, Istanbul; Gaziantep University[(c)], Faculty of Engineering, Department of Physics Engineering, 27310 Sehitkamil, Gaziantep; Istanbul Technical University[(d)], Faculty of Arts and Sciences, Department of Physics, 34469 Maslak, Istanbul, Turkey
[19] INFN Sezione di Bologna[(a)]; Università di Bologna, Dipartimento di Fisica[(a)], viale C. Berti Pichat, 6/2, IT-40127 Bologna, Italy
[20] University of Bonn, Physikalisches Institut, Nussallee 12, D-53115 Bonn, Germany
[21] Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States
[22] Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States
[23] Universidade Federal do Rio De Janeiro, COPPE/EE/IF[(a)], Caixa Postal 68528, Ilha do Fundao, BR-21945-970 Rio de Janeiro; Universidade de Sao Paulo[(b)], Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo, SP 05508-900, Brazil
[24] Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States
[25] National Institute of Physics and Nuclear Engineering[(a)], Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125; University Politehnica Bucharest[(b)], Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University[(c)] in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania
[26] Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina
[27] University of Cambridge, Cavendish Laboratory, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom
[28] Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada
[29] CERN, CH-1211 Geneva 23, Switzerland
[30] University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States
[31] Pontificia Universidad Católica de Chile, Facultad de Fisica, Departamento de Fisica[(a)], Avda. Vicuna Mackenna 4860, San Joaquin, Santiago; Universidad Técnica Federico Santa María, Departamento de Física[(b)], Avda. Espãna 1680, Casilla 110-V, Valparaíso, Chile
[32] Institute of High Energy Physics, Chinese Academy of Sciences[(a)], P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics[(b)], Hefei, CN - Anhui 230026; Nanjing University, Department of Physics[(c)], 22 Hankou Road, Nanjing 210093; Shandong University, High Energy Physics Group[(d)], Jinan, CN - Shandong 250100, China
[33] Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR-63177 Aubiere Cedex, France
[34] Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States
[35] University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Kobenhavn 0, Denmark
[36] INFN Gruppo Collegato di Cosenza[(a)]; Università della Calabria, Dipartimento di Fisica[(b)], IT-87036 Arcavacata di Rende, Italy
[37] Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland
[38] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL-31342 Krakow, Poland
[39] Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States
[40] University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States
[41] DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany
[42] TU Dortmund, Experimentelle Physik IV, D-44221 Dortmund, Germany
[43] Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany
[44] Duke University, Department of Physics, Durham, NC 27708, United States
[45] University of Edinburgh, School of Physics & Astronomy, James Clerk Maxwell Building, The Kings Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom
[46] Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, AT-2700 Wiener Neustadt, Austria
[47] INFN Laboratori Nazionali di Frascati, via Enrico Fermi 40, IT-00044 Frascati, Italy
[48] Albert-Ludwigs-Universität, Fakultät für Mathematik und Physik, Hermann-Herder Str. 3, D-79104 Freiburg i.Br., Germany
[49] Université de Genève, Section de Physique, 24 rue Ernest Ansermet, CH-1211 Geneve 4, Switzerland
[50] INFN Sezione di Genova[(a)]; Università di Genova, Dipartimento di Fisica[(b)], via Dodecaneso 33, IT-16146 Genova, Italy
[51] Institute of Physics of the Georgian Academy of Sciences, 6 Tamarashvili St., GE-380077 Tbilisi; Tbilisi State University, HEP Institute, University St. 9, GE-380086 Tbilisi, Georgia
[52] Justus-Liebig-Universität Giessen, II Physikalisches Institut, Heinrich-Buff Ring 16, D-35392 Giessen, Germany
[53] University of Glasgow, Department of Physics and Astronomy, Glasgow G12 8QQ, United Kingdom
[54] Georg-August-Universität, II. Physikalisches Institut, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3, Université Joseph Fourier, INPG, 53 avenue des Martyrs, FR-38026 Grenoble Cedex, France
[56] Hampton University, Department of Physics, Hampton, VA 23668, United States
[57] Harvard University, Laboratory for Particle Physics and Cosmology, 18 Hammond Street, Cambridge, MA 02138, United States
[58] Ruprecht-Karls-Universität Heidelberg: Kirchhoff-Institut für Physik[(a)], Im Neuenheimer Feld 227, D-69120 Heidelberg; Physikalisches Institut[(b)], Philosophenweg 12, D-69120 Heidelberg; ZITI Ruprecht-Karls-University Heidelberg[(c)], Lehrstuhl für Informatik V, B6, 23-29, D-68131 Mannheim, Germany
[59] Hiroshima University, Faculty of Science, 1-3-1 Kagamiyama, Higashihiroshima-shi, JP - Hiroshima 739-8526, Japan
[60] Hiroshima Institute of Technology, Faculty of Applied Information Science, 2-1-1 Miyake Saeki-ku, Hiroshima-shi, JP - Hiroshima 731-5193, Japan
[61] Indiana University, Department of Physics, Swain Hall West 117, Bloomington, IN 47405-7105, United States
[62] Institut für Astro- und Teilchenphysik, Technikerstrasse 25, A-6020 Innsbruck, Austria

[63] University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242-1479, United States
[64] Iowa State University, Department of Physics and Astronomy, Ames High Energy Physics Group, Ames, IA 50011-3160, United States
[65] Joint Institute for Nuclear Research, JINR Dubna, RU-141 980 Moscow Region, Russia
[66] KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan
[67] Kobe University, Graduate School of Science, 1-1 Rokkodai-cho, Nada-ku, JP - Kobe 657-8501, Japan
[68] Kyoto University, Faculty of Science, Oiwake-cho, Kitashirakawa, Sakyou-ku, Kyoto-shi, JP - Kyoto 606-8502, Japan
[69] Kyoto University of Education, 1 Fukakusa, Fujimori, fushimi-ku, Kyoto-shi, JP - Kyoto 612-8522, Japan
[70] Universidad Nacional de La Plata, FCE, Departamento de Física, IFLP (CONICET-UNLP), C.C. 67, 1900 La Plata, Argentina
[71] Lancaster University, Physics Department, Lancaster LA1 4YB, United Kingdom
[72] INFN Sezione di Lecce[(a)]; Università del Salento, Dipartimento di Fisica[(b)], Via Arnesano, IT-73100 Lecce, Italy
[73] University of Liverpool, Oliver Lodge Laboratory, P.O. Box 147, Oxford Street, Liverpool L69 3BX, United Kingdom
[74] Jožef Stefan Institute and University of Ljubljana, Department of Physics, SI-1000 Ljubljana, Slovenia
[75] Queen Mary University of London, Department of Physics, Mile End Road, London E1 4NS, United Kingdom
[76] Royal Holloway, University of London, Department of Physics, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom
[77] University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, United Kingdom
[78] Laboratoire de Physique Nucléaire et de Hautes Energies, Université Pierre et Marie Curie (Paris 6), Université Denis Diderot (Paris-7), CNRS/IN2P3, Tour 33, 4 place Jussieu, FR-75252 Paris Cedex 05, France
[79] Lunds Universitet, Naturvetenskapliga Fakulteten, Fysiska Institutionen, P.O. Box 118, SE-221 00 Lund, Sweden
[80] Universidad Autonoma de Madrid, Facultad de Ciencias, Departamento de Fisica Teorica, ES-28049 Madrid, Spain
[81] Universität Mainz, Institut für Physik, Staudinger Weg 7, D-55099 Mainz, Germany
[82] University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom
[83] CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[84] University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, MA 01003, United States
[85] McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada
[86] University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia
[87] The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States
[88] Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States
[89] INFN Sezione di Milano[(a)]; Università di Milano, Dipartimento di Fisica[(b)], via Celoria 16, IT-20133 Milano, Italy
[90] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus
[91] National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus
[92] Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, MA 02139, United States
[93] University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
[94] P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU-117 924 Moscow, Russia
[95] Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU-117 218 Moscow, Russia
[96] Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU-115409 Moscow, Russia
[97] Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1(2), Leninskie gory, GSP-1, Moscow 119991, Russia
[98] Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, D-85748 Garching, Germany
[99] Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, Föhringer Ring 6, 80805 München, Germany
[100] Nagasaki Institute of Applied Science, 536 Aba-machi, JP - Nagasaki 851-0193, Japan
[101] Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya 464-8602, Japan
[102] INFN Sezione di Napoli[(a)]; Università di Napoli, Dipartimento di Scienze Fisiche[(b)], Complesso Universitario di Monte Sant'Angelo, via Cinthia, IT-80126 Napoli, Italy
[103] University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131, United States
[104] Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands
[105] Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands
[106] Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia
[107] New York University, Department of Physics, 4 Washington Place, New York, NY 10003, United States
[108] Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States
[109] Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan
[110] University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy, 440 West Brooks, Room 100, Norman, OK 73019-0225, United States
[111] Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, OK 74078-3072, United States
[112] Palacký University, 17.listopadu 50a, 772 07 Olomouc, Czech Republic
[113] University of Oregon, Center for High Energy Physics, Eugene, OR 97403-1274, United States
[114] LAL, Univ. Paris-Sud, IN2P3/CNRS, Orsay, France
[115] Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan
[116] University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO-0316 Oslo 3, Norway
[117] Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
[118] INFN Sezione di Pavia[(a)]; Università di Pavia, Dipartimento di Fisica Nucleare e Teorica[(b)], Via Bassi 6, IT-27100 Pavia, Italy
[119] University of Pennsylvania, Department of Physics, High Energy Physics Group, 209 S. 33rd Street, Philadelphia, PA 19104, United States
[120] Petersburg Nuclear Physics Institute, RU-188 300 Gatchina, Russia
[121] INFN Sezione di Pisa[(a)]; Università di Pisa, Dipartimento di Fisica E. Fermi[(b)], Largo B. Pontecorvo 3, IT-56127 Pisa, Italy
[122] University of Pittsburgh, Department of Physics and Astronomy, 3941 O'Hara Street, Pittsburgh, PA 15260, United States
[123] Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP[(a)], Avenida Elias Garcia 14-1, PT 1000-149 Lisboa; Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE[(b)], E-18071 Granada, Spain
[124] Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ-18221 Praha 8, Czech Republic
[125] Charles University in Prague, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holesovickach 2, CZ-18000 Praha 8, Czech Republic
[126] Czech Technical University in Prague, Zikova 4, CZ-166 35 Praha 6, Czech Republic
[127] State Research Center Institute for High Energy Physics, Pobeda street 1, 142281 Protvino, Moscow Region, Russia
[128] Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom
[129] University of Regina, Physics Department, Canada
[130] Ritsumeikan University, Noji Higashi 1 chome 1-1, JP - Kusatsu, Shiga 525-8577, Japan
[131] INFN Sezione di Roma I[(a)]; Università La Sapienza, Dipartimento di Fisica[(b)], Piazzale A. Moro 2, IT-00185 Roma, Italy
[132] INFN Sezione di Roma Tor Vergata[(a)]; Università di Roma Tor Vergata, Dipartimento di Fisica[(b)], via della Ricerca Scientifica, IT-00133 Roma, Italy
[133] INFN Sezione di Roma Tre[(a)]; Università Roma Tre, Dipartimento di Fisica[(b)], via della Vasca Navale 84, IT-00146 Roma, Italy
[134] Réseau Universitaire de Physique des Hautes Energies (RUPHE): Université Hassan II, Faculté des Sciences Ain Chock[(a)], B.P. 5366, MA - Casablanca; Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN)[(b)], B.P. 1382 R.P. 10001 Rabat 10001; Université Mohamed Premier[(c)], LPTPM, Faculté des Sciences, B.P.717. Bd. Mohamed VI, 60000 Oujda; Université Mohammed V, Faculté des Sciences[(d)], 4 Avenue Ibn Battouta, BP 1014 RP, 10000 Rabat, Morocco
[135] CEA, DSM/IRFU, Centre d'Etudes de Saclay, FR-91191 Gif-sur-Yvette, France
[136] University of California Santa Cruz, Santa Cruz Institute for Particle Physics (SCIPP), Santa Cruz, CA 95064, United States
[137] University of Washington, Seattle, Department of Physics, P.O. Box 351560, Seattle, WA 98195-1560, United States

[138] University of Sheffield, Department of Physics & Astronomy, Hounsfield Road, Sheffield S3 7RH, United Kingdom
[139] Shinshu University, Department of Physics, Faculty of Science, 3-1-1 Asahi, Matsumoto-shi, JP - Nagano 390-8621, Japan
[140] Universität Siegen, Fachbereich Physik, D-57068 Siegen, Germany
[141] Simon Fraser University, Department of Physics, 8888 University Drive, CA - Burnaby, BC V5A 1S6, Canada
[142] SLAC National Accelerator Laboratory, Stanford, CA 94309, United States
[143] Comenius University, Faculty of Mathematics, Physics & Informatics[(a)], Mlynska dolina F2, SK-84248 Bratislava; Institute of Experimental Physics of the Slovak Academy of Sciences, Dept. of Subnuclear Physics[(b)], Watsonova 47, SK-04353 Kosice, Slovak Republic
[144] Stockholm University, Department of Physics[(a)]; The Oskar Klein Centre[(b)], AlbaNova, SE-106 91 Stockholm, Sweden
[145] Royal Institute of Technology (KTH), Physics Department, SE-106 91 Stockholm, Sweden
[146] Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800, United States
[147] University of Sussex, Department of Physics and Astronomy, Pevensey 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
[148] University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
[149] Insitute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
[150] Technion, Israel Inst. of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
[151] Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv 69978, Israel
[152] Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR-54124 Thessaloniki, Greece
[153] The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1 Hongo, Bunkyo-ku, JP - Tokyo 113-0033, Japan
[154] Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
[155] Tokyo Institute of Technology, 2-12-1-H-34 O-Okayama, Meguro, Tokyo 152-8551, Japan
[156] University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
[157] TRIUMF[(a)], 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3; York University[(b)], Department of Physics and Astronomy, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada
[158] University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki 305-8571, Japan
[159] Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States
[160] Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
[161] University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States
[162] INFN Gruppo Collegato di Udine[(a)]; ICTP[(b)], Strada Costiera 11, IT-34014 Trieste; Università di Udine, Dipartimento di Fisica[(c)], via delle Scienze 208, IT-33100 Udine, Italy
[163] University of Illinois, Department of Physics, 1110 West Green Street, Urbana, IL 61801, United States
[164] University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE-751 20 Uppsala, Sweden
[165] Instituto de Física Corpuscular (IFIC), Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear, Univ. of Valencia, and Instituto de Microelectrónica de Barcelona (IMB-CNM-CSIC), 08193 Bellaterra Barcelona, Spain
[166] University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1, Canada
[167] University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada
[168] Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
[169] The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL 76100, Rehovot, Israel
[170] University of Wisconsin, Department of Physics, 1150 University Avenue, Madison, WI 53706, United States
[171] Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany
[172] Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D-42097 Wuppertal, Germany
[173] Yale University, Department of Physics, P.O. Box 208121, New Haven, CT 06520-8121, United States
[174] Yerevan Physics Institute, Alikhanian Brothers Street 2, AM-375036 Yerevan, Armenia
[175] ATLAS-Canada Tier-1 Data Centre 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada
[176] GridKA Tier-1 FZK, Forschungszentrum Karlsruhe GmbH, Steinbuch Centre for Computing (SCC), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[177] Port d'Informacio Cientifica (PIC), Universitat Autonoma de Barcelona (UAB), Edifici D, E-08193 Bellaterra, Spain
[178] Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France
[179] INFN-CNAF, Viale Berti Pichat 6/2, 40127 Bologna, Italy
[180] Nordic Data Grid Facility, NORDUnet A/S, Kastruplundgade 22, 1, DK-2770 Kastrup, Denmark
[181] SARA Reken- en Netwerkdiensten, Science Park 121, 1098 XG Amsterdam, Netherlands
[182] Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, No.128, Sec. 2, Academia Rd., Nankang, Taipei, Taiwan 11529, Taiwan
[183] UK-T1-RAL Tier-1, Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom
[184] RHIC and ATLAS Computing Facility, Physics Department, Building 510, Brookhaven National Laboratory, Upton, NY 11973, United States

[a] Present address FermiLab, United States.
[b] Also at CPPM, Marseille, France.
[c] Also at TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada.
[d] Also at Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland.
[e] Also at Università di Napoli Parthenope, via A. Acton 38, IT-80133 Napoli, Italy.
[f] Also at Institute of Particle Physics (IPP), Canada.
[g] Louisiana Tech University, 305 Wisteria Street, P.O. Box 3178, Ruston, LA 71272, United States.
[h] At Department of Physics, California State University, Fresno, 2345 E. San Ramon Avenue, Fresno, CA 93740-8031, United States.
[i] Currently at Istituto Universitario di Studi Superiori IUSS, V.le Lungo Ticino Sforza 56, 27100 Pavia, Italy.
[j] Also at California Institute of Technology, Physics Department, Pasadena, CA 91125, United States.
[k] Also at University of Montreal, Canada.
[l] Also at Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany.
[m] Now at Chonnam National University, Chonnam 500-757, South Korea.
[n] Also at Petersburg Nuclear Physics Institute, RU-188 300 Gatchina, Russia.
[o] Also at School of Physics and Engineering, Sun Yat-sen University, Taiwan.
[p] Also at School of Physics, Shandong University, Jinan, China.
[q] Also at Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11, United Kingdom.
[r] Also at School of Physics, Shandong University, Jinan, China.
[s] Also at Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom.
[t] University of South Carolina, Dept. of Physics and Astronomy, 700 S. Main St, Columbia, SC 29208, United States.
[u] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[v] Also at Institute of Physics, Jagiellonian University, Cracow, Poland.
[w] University of Rochester, Rochester, NY 14627, United States.
[x] Transfer to LHCb 31.01.2010.
[y] Naruto University of Education, Takashima, JP - Tokushima 772, Japan.
[z] Also at Dept. of Physics, Nanjing University, China.
* Deceased.