Central charged-particle multiplicities in $pp$ interactions with $|\eta| < 0.8$ and $p_T > 0.5$ and 1 GeV measured with the ATLAS detector at the LHC

The ATLAS Collaboration

Abstract

This note presents the results of the analysis of charged-particle spectra from proton-proton collisions at $\sqrt{s} = 0.9$ TeV and 7 TeV in a restricted phase-space in order to be able to directly compare the measurements with the results from other LHC experiments. The analysis highlights charged-particle distributions in minimum bias events as function of the transverse momentum of the particle $p_T$, pseudorapidity $\eta$, particle multiplicity $n_{ch}$ and the average transverse momentum $\langle p_T \rangle$ as a function of $n_{ch}$. The measured distributions are corrected back to the hadron level, considering in the correction procedure inefficiencies of the trigger, vertex and track reconstruction. Two kinematical ranges are analysed on which ATLAS, CMS and ALICE agreed, defined by requiring at least one charged-particle with $|\eta| < 0.8$ and a minimum $p_T$ of 500 MeV and 1 GeV, respectively. Data taken at both energies $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV are analysed with these requirements and compared to predictions from Monte Carlo generators.
1 Introduction

The compilation of charged-particle spectra in a phase-space which is accessible to several LHC experiments allows a direct comparison of general properties in minimum bias events across the LHC experiments. Such measurements are important to improve soft QCD models for Monte-Carlo generators. Other physics analyses, which depend on a good model of pile-up and the underlying event, will also benefit. The analysis of properties of inelastic interactions in common detector regions aims at improving the analysis techniques and detector understanding at an LHC-wide scale. The kinematical cuts were chosen such that each experiment would be able to access this phase-space. This means in particular restricting the ATLAS analysis [1] to $|\eta| < 0.8$, to account for the geometrical acceptance of the ALICE tracker. The lowest $p_T$-cut was chosen to fully exploit the efficiency plateau of both ATLAS and CMS track reconstruction. ALICE, CMS and ATLAS agreed on two common phase-spaces, both going up to $|\eta| < 0.8$ with at least one primary track with minimum $p_T$ of 500 MeV and 1 GeV respectively.

The analysed datasets at $\sqrt{s} = 0.9$ and 7 TeV are exactly the same as used in Ref. [1], where differently motivated phase-spaces were analysed. They comprise $\sim 7 \, \mu b^{-1}$ of $pp$-collisions at $\sqrt{s} = 0.9$ TeV and $\sim 190 \, \mu b^{-1}$ of data recorded at 7 TeV. We refer thus to that paper for details of the analysis, since the same procedure and corrections for trigger, vertex and track reconstruction efficiencies were applied. In this note we present the results of the $\eta$-limited phase-space analyses and differences to [1].

2 Minimum Bias Distributions of Charged Particles

The distributions presented here are

$$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}, \quad \frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2N_{ch}}{dp_T^2}, \quad \frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$$

and $\langle p_T \rangle$ vs. $n_{ch}$,

where $p_T$ is the track momentum component transverse to the beam direction $^1$, $\eta$ is the track pseudo-rapidity, $n_{ch}$ is the number of charged particles in an event, $N_{ch}$ is the total number of charged particles in the data sample, $N_{ev}$ is the number of events with at least one charged particle within the selected kinematic range and $\langle p_T \rangle$ is the mean $p_T$ for a given number of charged particles $^2$. The charged-particle multiplicity results are compared to particle level Monte Carlo (MC) predictions from different tunes of PYTHIA6 (MC09 [2], DW [3] and the new tune AMBT1 [4]), PYTHIA8 [5] and PHOJET [6]. A modified binning relative to that used in Ref. [1] is used, again to facilitate comparison with the other experiments. Data distributions as a function of $n_{ch}$ and $p_T$ are truncated on the high end so that the statistical uncertainty does not exceed 30% in the final bin.

3 Results

The distributions of charged-particle multiplicities, after the full correction procedure, are shown for the different phase-spaces and energies in the low $n_{ch}$-region, Fig. 1, and on logarithmic scales, Fig. 2 - 3. The charged-particle $\eta$ distributions are depicted in Fig. 4. The $p_T$-spectra are shown in Fig. 5 for the lower $p_T$-region and in Fig. 6 - 7 in logarithmic scales. $\langle p_T \rangle$ versus $n_{ch}$ is plotted in Fig. 8.

$^1$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 center of the LHC ring and the positive $y$-axis points upwards. The azimuthal angle $\phi$ is measured around the beam axis, and the polar angle $\theta$ is measured with respect to the $z$-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

$^2$The factor $2\pi p_T$ in the $p_T$ spectrum comes from the Lorentz invariant definition of the cross section $d^3\sigma/dp^3$, having approximated the rapidity $y = 1/2 \cdot \ln((E + p_L)/(E - p_L))$ with the pseudorapidity $\eta$. 

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As a result of considering only tracks from the central barrel region, we obtain smaller systematic uncertainties compared to Ref. [1] in the higher \( p_T \)-bins due to fewer poorly measured tracks and the fact that the alignment is better known in the central detector. See Table 1 for a comparison.

| \( p_T \) [GeV] | \( |\eta| < 0.8 \) | \( \sqrt{s} = 0.9 \text{ TeV} \) | \( \sqrt{s} = 7 \text{ TeV} \) | \( |\eta| < 2.5 \) | \( \sqrt{s} = 0.9 \text{ TeV} \) | \( \sqrt{s} = 7 \text{ TeV} \) |
|-----------------|----------------|-----------------|----------------|----------------|----------------|----------------|
| 10 - 20         | -8 %           | -6 %            | -20 %          | -10 %          |                 |                 |
| 20 - 30         | n/a            | -6 %            | n/a            | -20 %          |                 |                 |

Table 1: Comparisons of one component of the systematic uncertainties due to the estimate of high-\( p_T \) tracks for the \( \eta \)-limited phase-space, i.e. \( |\eta| < 0.8 \), and the full \( \eta \) analysis, i.e. \( |\eta| < 2.5 \), at both energies. The percentage refers to the nominal bin content. The negative sign indicates the uncertainties are considered as downwards fluctuations only.

The opposite effect is observed for the uncertainties of the high \( n_{ch} \)-bins, in particular when comparing the \( n_{ch} \)-spectrum of the limited-\( \eta \) (Fig. 2(b)) and full-\( \eta \) range (Fig. 9(c) of Ref. [1]). At a given high \( n_{ch} \)-bin the total relative uncertainty is significantly larger in the limited-\( \eta \) case. The last \( n_{ch} \)-bin from 42 to 50 \( n_{ch} \) has a total uncertainty of roughly +22 % and −18 %, while the same bin in the full-\( \eta \) analysis has ± 6 % uncertainty. The much more restricted \( \eta \) acceptance results here in a much more steeply falling \( n_{ch} \) distribution than for the full \( \eta \) acceptance. This gives rise to an increased fractional systematic error from the tracking efficiency uncertainty as it causes migration between \( n_{ch} \) bins.

### 3.1 Charged-particle density at \( \eta = 0 \)

The charged-particle density at \( \eta = 0 \), calculated by taking the average of the bins from -0.2 and 0.2, are shown, per phase-space and center-of-mass energy, in Table 2.

| phase-space | \( \sqrt{s} \) | \( 1/N_{ev} \cdot dN_{ch}/d\eta|\eta|=0 \) |
|-------------|-----------|-----------------------------|
|              | 0.9 TeV   | 1.809 ± 0.006(stat) ± 0.030(syst) |
|              | 7 TeV     | 2.983 ± 0.001(stat) ± 0.054(syst) |
|              |           | 1.661 ± 0.001(stat) ± 0.024(syst) |

Table 2: Charged-particle density at \( \eta = 0 \), denoted as \( 1/N_{ev} \cdot dN_{ch}/d\eta|\eta|=0 \), for both phase-spaces and energies. The systematic uncertainty is the result of different contributions with a major part coming from the track reconstruction uncertainty.

### 4 Discussion and Conclusion

It it important to compare independent measurements, with different systematic uncertainties, between the different LHC experiments. The LHC-wide coordinated working-group, the MB & UE WG, have therefore agreed on the first LHC combined analysis, for which this note is the ATLAS input. In addition to the inclusive minimum bias measurements, two more phase-spaces were analysed restricted in pseudorapidity, using the same analysis techniques and the same sources of systematic uncertainties for the corresponding \( \eta \)-range. The main differences to the analysis, which considers the full \( \eta \)-range
(but keeps the same $p_T$ and $n_{ch}$ requirements), concern the systematic uncertainties being smaller in the high-$p_T$ regions and larger for the high-$n_{ch}$ bins.

The comparison of the data with different predictions from MC models and tunes from Sec. 3 shows that the central charged-particle production, just like the more inclusive charged-particle production, lacks a good soft QCD model able to describe various characteristic spectra of inelastic $pp$ interactions.

At $\sqrt{s} = 0.9$ TeV the ATLAS tune of PYTHIA6, AMBT1, describes most of the distributions best, with the exception of the high-$p_T$ tail, where PHOJET fits better. At $\sqrt{s} = 7$ TeV PYTHIA8 and AMBT1 both provide a better description, with PYTHIA8 describing the $p_T$ distribution best. No tune can reproduce the high-$n_{ch}$ tails seen in the data in the $p_T > 500$ MeV phase-space, although AMBT1 comes closest.

In conclusion, these and other related measurements [1,7] suggest that only tuning of MC models may not be enough to describe soft parton interactions, in particular in the LHC environment. Nevertheless, this is an important step towards the understanding of such processes.
Figure 1: Primary charged-particle multiplicity distributions for low $n_{ch}$ values for events with $n_{ch} \geq 1$, $p_T > 500$ MeV (a,b) and 1 GeV (c,d) and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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 bottom inserts show the ratio of the MC over the data. The values of the ratio histograms refer to the bin centroids.
Figure 2: Primary charged-particle multiplicity distributions for events with $n_{\text{ch}} \geq 1$, $p_T > 500$ MeV and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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 bottom inserts show the ratio of the MC over the data. The values of the ratio histograms refer to the bin centroids.
Figure 3: Primary charged-particle multiplicity distributions for events with $n_{\text{ch}} \geq 1$, $p_T > 1$ GeV and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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 bottom inserts show the ratio of the MC over the data. The values of the ratio histograms refer to the bin centroids.
Figure 4: Primary charged-particle $\eta$ distributions for events with $n_{ch} \geq 1$, $|\eta| < 0.8$, $p_T > 500$ MeV (a,b) and 1 GeV (c,d) at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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.
Figure 5: Primary charged-particle multiplicity distributions as a function of $p_T$ in the lower $p_T$ region for events with $n_{ch} \geq 1, p_T > 500$ MeV (a,b) and 1 GeV (c,d) and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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 bottom inserts show the ratio of the MC over the data. The values of the ratio histograms refer to the bin centroids.
Figure 6: $p_T$-spectra of charged primary particles for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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 bottom inserts show the ratio of the MC over the data. The values of the ratio histograms refer to the bin centroids.
Figure 7: $p_T$-spectra of charged primary particles for events with $n_{ch} \geq 1$, $p_T > 1$ GeV and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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 bottom inserts show the ratio of the MC over the data. The values of the ratio histograms refer to the bin centroids.
Figure 8: $<p_T>$ distribution of charged particles as a function of $n_{ch}$ for events with $n_{ch} \geq 1$, $p_T > 500$ MeV (a,b) and 1 GeV (c,d) and $|\eta| < 0.8$ at $\sqrt{s} = 0.9$ TeV (a,c) and $\sqrt{s} = 7$ TeV (b,d). The points 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.
References


[4] ATLAS Collaboration, Charged-particle multiplicities in pp interactions at $\sqrt{s} = 0.9$ TeV and 7 TeV in a diffractive limited phase space measured with the ATLAS detector at the LHC and a new pythia6 tune, ATLAS-CONF-2010-031, June, 2010.

