The CMS Collaboration

Abstract

The pseudorapidity and leading transverse momentum distributions of charged particles in proton-proton collisions at $\sqrt{s} = 8$ TeV are measured in the pseudorapidity range $|\eta| < 2.4$, by the CMS detector. The data correspond to an integrated luminosity of 17.4 nb$^{-1}$. Events were triggered by the TOTEM T2 telescopes that cover the pseudorapidity range $5.3 < |\eta| < 6.5$ for reconstructed tracks with $p_T > 40$ MeV. The measurement of the pseudorapidity distributions was performed for primary charged particles with $p_T > 0.1$ GeV and $p_T > 1$ GeV, for two different conditions: an inclusive sample obtained by requiring tracks reconstructed in the acceptance of the TOTEM T2 telescopes in either hemisphere, and a sample enhanced in non-single diffractive dissociation events by requiring tracks in T2 in both forward and backward hemispheres. The $p_T$ distribution of the leading tracks in the central region is also measured. The distribution integrated over the leading track transverse momentum, above a $p_{T,\text{min}}$ value, shows a transition from a steeply falling distribution at large $p_T$ (perturbative region) to a flat distribution at small $p_T$ (non-perturbative region) for $p_{T,\text{min}}$ of a few GeV. This region is not well described by current Monte Carlo event generators.
1 Introduction

Measurements of particle yields and kinematic distributions are essential in exploring the energy regimes of particle collisions at the Large Hadron Collider (LHC), contributing to a better understanding of the mechanisms of hadron production, and especially the relative roles of soft and hard scattering. Most of the particles produced in proton-proton (pp) collisions arise from semi-hard (multi)parton scatterings which are modeled phenomenologically, hence experimental results provide important input for tuning various models and event generators.

The results presented here are based on different requirements, dominated by different types of collisions and focus on the primary charged-particle multiplicity density \( dN_{ch}/d\eta \) and the transverse momentum of the highest-\( p_T \) track, hereafter called the leading track, in the pseudorapidity range \( |\eta| < 2.4 \). The pseudorapidity, \( \eta \), commonly used to characterize the direction of particle emission, is defined as \( -\ln[\tan(\theta/2)] \), where \( \theta \) is the polar angle of the particle with respect to the anticlockwise beam direction.

The pseudorapidity distributions are measured for different event topologies, either inclusive or dominated by non-single diffractive dissociation (NSD), for charged particles with \( p_T > 0.1 \) GeV and \( p_T > 1 \) GeV, allowing the study of both soft and hard scatterings. The integrated leading-track transverse momentum distribution, especially in the low \( p_T \) region, has been proposed as an observable sensitive to the unitarity bound set by the inelastic proton-proton cross section [1].

Inclusive measurements of the pseudorapidity and transverse momentum distributions of charged particles have been previously measured in pp and p\( \bar{p} \) collisions for different centre-of-mass energies and phase space regions [2–9].

2 The CMS & TOTEM detectors

A complete description of the CMS detector can be found in Ref. [10]. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the \( x \) axis pointing to the centre of the LHC ring, the \( y \) axis pointing up, and the \( z \) axis along the anticlockwise-beam direction. The azimuthal angle, \( \phi \), is measured in the \((x, y)\) plane, where \( \phi = 0 \) is the \(+x\) and \( \phi = \pi/2 \) is the \(+y\) direction.

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a uniform magnetic field of 3.8 T parallel to the beam axis. Inside the magnetic field are the pixel tracker, the silicon-strip tracker, the lead tungstate electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. In addition to the barrel and end-cap detectors, the steel/quartz fibre forward calorimeter (HF) covers the region of \( 2.9 < |\eta| < 5.2 \).

The tracking detector consists of 1440 silicon-pixel and 15148 silicon-strip detector modules. The barrel consists of 3 pixel and 10 strip layers around the interaction point at distances ranging from 4.4 cm to 1.1 m. The forward and backward endcaps each consist of 2 pixel disks and 12 strip disks in up to 9 rings. Three of the strip rings and four of the barrel strip layers contain an additional plane, with a stereo angle of 100 mrad, to provide a measurement of the \( r \) coordinate and \( z \) coordinate, respectively. The tracker is designed to provide an impact-parameter resolution of about 100 \( \mu \)m and a transverse momentum resolution of about 0.7\% for 1 GeV charged particles at \( \eta = 0 \) [11]. The standard track reconstruction algorithm is based on a combinatorial track finder (CTF) [11]. The collection of reconstructed tracks is produced by multiple iterations of the CTF track reconstruction sequence, in a process called iterative tracking.
Minimum-bias events were triggered by the TOTEM [12] T2 telescopes. TOTEM is composed of three subdetectors: the Roman Pots and the T1 and T2 telescopes. They are placed symmetrically on both sides of the interaction point. The T2 telescopes, installed about 14 m from the interaction point, detect charged particles produced in the polar angular range of a few mrad to approximately 100 mrad. They cover the pseudorapidity range \(5.3 < |\eta| < 6.5\) and consist of triple-GEM (Gas Electron Multiplier) chambers. Each chamber provides two dimensional information on the track position in an azimuthal coverage of 192° with a small overlap region along the vertical axis between chambers of two neighbouring quarters. Every chamber has a double layered read-out board containing two columns of 256 concentric strips to measure the radial coordinate and a matrix of 1560 pads, each one covering \(\Delta \eta \times \Delta \phi \approx 0.06 \times 0.018\) rad, to measure the azimuthal coordinate and for triggering. The track reconstruction is based on a Kalman filter-like algorithm that is simplified due to the small amount of material traversed by the particle crossing the GEM planes and to the low local magnetic field in the T2 region. The particle trajectory can, therefore, be successfully reconstructed using a straight line fit. Charged particle tracks are reconstructed with a good efficiency for \(p_T > 40\) MeV, defining effectively the minimum \(p_T\) acceptance. The fraction of charged particles with \(p_T < 40\) MeV produced in the T2 acceptance is predicted to be very small (\(\sim 1\%\)).

The detailed Monte Carlo (MC) simulation of the CMS and TOTEM detectors is based on GEANT4 [13]. Simulated events were processed and reconstructed in the same manner as collision data.

### 3 Datasets and Trigger

The data were collected in July 2012 during a dedicated low pile up run with a non-standard \(\beta^* = 90\) m optics configuration and correspond to an integrated luminosity of \(\mathcal{L} = 17.4\) nb\(^{-1}\). A minimum bias trigger was provided by the TOTEM T2 telescopes and contributed to the CMS Global Trigger decision, which initiated simultaneous read out of both CMS and TOTEM detectors. The minimum-bias trigger was defined by the detection of at least one charged track, with \(p_T > 40\) MeV, in the acceptance of the T2 telescopes in either hemisphere, i.e. \(5.3 < \eta < 6.5\) or \(-6.5 < \eta < -5.3\). With the requirement of at least one reconstructed track in the T2 detector, the visible cross-section seen by T2 has been estimated to be about 95% of the total inelastic cross-section [14].

Due to a rate limitation in the TOTEM data-acquisition system, the total trigger rate was kept below 1 kHz. The CMS orbit-reset signal delivered to the TOTEM electronics at the start of the run assured the time synchronization of the two experiments. A zero bias data stream, defined as bunch-crossings, was also used to measure the trigger efficiency.

For the analysis, different Monte Carlo (MC) samples were used to determine the event selection efficiency and the tracking performance. The data corrections were based on the PYTHIA6 ZZ\(^*\) tune sample, and the uncertainty introduced by different physics generators was estimated by recalculating all corrections with an independent sample produced with the PYTHIA8 4C tune.

### 4 Event selection

The data are corrected to the stable particle level, defined to include charged particles with proper lifetime \((c\tau)\) larger than 1 cm that originate from the pp collision or are decay products of particles with \(c\tau < 1\) cm. An inclusive sample of events was selected by requiring at least
one primary charged particle with $p_T > 40$ MeV within the acceptance of T2 ($5.3 < \eta < 6.5$ or $-6.5 < \eta < -5.3$). In addition to this inclusive selection, a sample enhanced in non-single diffractive (NSD) events was defined by requiring at least one primary charged particle with $p_T > 40$ MeV within $5.3 < \eta < 6.5$ and $-6.5 < \eta < -5.3$.

Experimentally, the inclusive sample consists of the minimum-bias events with at least one reconstructed track in any of the TOTEM T2 telescopes. The NSD-enhanced sample was defined by selecting a subset of events where there was a coincidence of at least one track in the acceptance of T2, in both forward and backward hemispheres. For both samples, primary reconstructed tracks in T2 were identified using an optimised track selection, significantly reducing the amount of secondary tracks, as described in Ref. [14].

The event and track selection aimed to reduce the effect of beam background events, to minimize the contribution from misidentified tracks and tracks with poor momentum resolution, and to reject non-primary tracks from weak decays and secondary interactions with the detector material. The following selection criteria were applied:

- Rejection of beam backgrounds was achieved by requiring at least one reconstructed primary vertex. The vertex, with at least two tracks, was required to be within $|z| < 15$ cm around the position of the nominal interaction point along the beamline. The transverse distance from the $z$-axis was required to be smaller than 0.2 cm.

- High purity tracks [15] were selected, with $p_T > 0.1$ GeV or $p_T > 1$ GeV and relative transverse momentum uncertainty less than 10%, within the pseudorapidity range $|\eta| < 2.4$.

- A track-vertex association was applied by requiring an impact parameter less than a cut with respect to the primary vertex position both in the transverse plane and along the $z$-axis. For the impact parameter with respect to the beam spot in the transverse plane, $d_{xy}$, we required $d_{xy}/\sigma_{xy} < 3$, while for the point of closest approach to the primary vertex, $d_z$, the requirement $d_z/\sigma_z < 3$ was applied, where $\sigma_{xy}$ and $\sigma_z$ denote the uncertainties in $d_{xy}$ and $d_z$, respectively.

The analysis was restricted to a fiducial acceptance for the tracking system ($|\eta| < 2.4$), in order to avoid effects from tracks very close to the geometric edge of the tracker. For the measurement of the leading-track $p_T$ distributions, the transverse momentum of the tracks was chosen to be $p_T > 0.4$ GeV and the distributions were normalised to the number of events with at least one selected track.

## 5 Monte Carlo models

In this section, the main features of Monte Carlo event generators used for correction and comparison of data are presented. PYTHIA6 (version 6.426) [16] with tune Z2* and PYTHIA8 (version 8.153) [17] with tune 4C were used, providing different descriptions of the non-diffractive component. Both use a new model [18] where multiple partonic interactions are interleaved with parton showering. The Z2* tune is derived from the Z1 tune [19] which uses the CTEQ5L parton distribution set, whereas Z2* is updated to CTEQ6L. PYTHIA8 tune 4C focuses on the description of early LHC data. Parton showers in PYTHIA are modelled according to the DGLAP prescription and hadronisation is based on the Lund string fragmentation model [20]. Diffractive cross sections are described by the Shuler-Sjöstrand model [21]. In PYTHIA6, particle production from a low mass state ($M_X < 1$ GeV) is treated as an isotropic two body decay, while from high mass states it is based on the string model. In PYTHIA8, the same model is used to
generate the cross section and the diffractive mass, however particle production differs. For low mass states, the string model is used, but for higher masses \( (M_X > 10 \text{ GeV}) \) a perturbative description of pomeron-proton scatterings is introduced, using diffractive parton distribution functions. The non-perturbative string model introduces a mass dependence on the relative probability of a pomeron coupling to a quark or a gluon. The addition of the perturbative treatment of pomeron-proton scattering results in harder \( p_T \) and multiplicity spectra for diffractive events generated with PYTHIA8 than for those obtained with PYTHIA6.

The HERWIG++ (version 2.5.0) [22] MC event generator, with a recent tune to LHC data (UE-EE-3C), is also used for comparison. It is based on matrix-element calculations similar to those used in PYTHIA. The evolution of the parton distribution functions with momentum scale is driven by the DGLAP equations. However, HERWIG++ features angular-ordered parton showers and uses cluster fragmentation for the hadronisation [23]. The description of diffractive processes also makes use of diffractive parton distribution functions.

Data are also compared to predictions obtained from pp Monte Carlo event generators used in cosmic-ray physics [24]. EPOS [25] LHC tune (based on EPOS 1.99) and QGSJETII-04 [26] were considered. Both models take into consideration contributions from both soft- and hard-parton dynamics. The soft component is described in terms of the exchange of virtual quasi-particle states, as in Gribov’s Reggeon field theory [27], with multi-pomeron exchanges accounting for underlying event effects. At higher energies and scales, the interaction is described using the same degrees of freedom but generalized to include hard processes via “cut (hard) Pomeron” diagrams, which are equivalent to a leading-order perturbative QCD approach with DGLAP evolution. These models were tuned to a variety of LHC data, including charged-particle pseudorapidity and transverse momentum distributions.

### 6 Charged-particle pseudorapidity distributions

The measured charged particle pseudorapidity distributions were calculated from the raw distributions of charged tracks after applying a number of corrections according to the formula:

\[
\frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{d\eta} = C_{T2} \sum_M \sum_{p_T} N_{\text{tracks}}(M, p_T, \eta) \frac{\omega_{\text{track}}(M, p_T, \eta) \omega_{\text{event}}(M, n_{T2})}{\Delta\eta \sum_M N_{\text{evt}}(M) \omega_{\text{event}}(M, n_{T2})}
\]

where \( N_{\text{tracks}} \) is the number of tracks that pass the selection criteria for a given bin in pseudorapidity, \( \eta \), transverse momentum, \( p_T \), and track multiplicity, \( M \), \( N_{\text{evt}} \) is the number of triggered events in the corresponding track multiplicity bin, \( \omega_{\text{event}} \) is an event correction factor accounting for the trigger efficiency and the vertex reconstruction, \( \omega_{\text{track}} \) is a correction for the tracking efficiency and non primary tracks and \( C_{T2} \) accounts for the track reconstruction efficiency of T2. The number of tracks is normalised to the bin width, \( \Delta\eta = 0.4 \).

The event correction, \( \omega_{\text{event}} \), depends on the track multiplicity in T2, \( n_{T2} \), as well as on the multiplicity in the CMS tracker due to the minimum number of tracks required in the vertex reconstruction. It is given by:

\[
\omega_{\text{event}}(M, n_{T2}) = \frac{1}{\epsilon_{\text{trig}}(n_{T2}) \epsilon_p(M)}
\]

where \( \epsilon_{\text{trig}} \) is the efficiency of the trigger provided by T2, which depends on the number of tracks in T2, and \( \epsilon_p \) accounts for the primary vertex reconstruction and selection efficiency.

The trigger efficiency was determined from a zero-bias event sample, as a function of the T2 track multiplicity, separately for three event samples: single-sided events with tracks in only
The tracking efficiency, \( \omega_{\text{track}}(M, p_T, \eta) \), is defined as:

\[
\omega_{\text{track}}(M, p_T, \eta) = \frac{1 - f_{np}(M, p_T, \eta)}{\epsilon_{\text{track}}(M, p_T, \eta) \left(1 + f_m(M, p_T, \eta)\right)},
\]

where \( \epsilon_{\text{track}} \) accounts for the geometric detector acceptance and the algorithmic tracking efficiency for particles in a given \( M, p_T, \eta \) bin. The correction factor \( f_{np} \) accounts for the fraction of non-primary tracks, i.e. secondary and misidentified tracks. The overall correction is compensated for a small fraction of tracks that may correspond to a single generated charged particle that was reconstructed multiple times, \( f_m \).

The efficiency \( \epsilon_{\text{track}} \) was calculated from a detector simulation in bins of \( M, p_T \) and \( \eta \). The effect of bin migrations was estimated to be negligible. Reconstructed events were required to have a well defined primary vertex and the generated particles were matched to the reconstructed tracks using spacial and momentum information. The angular separation between reconstructed tracks and generated particles in a \( \Delta R(\eta, \phi) \) cone was required to be smaller than 0.04. The relative momentum difference \( \delta p_T / p_T \) was required to be smaller than 5%, 6% and 7% according to the pseudorapidity of the generated particle (\( |\eta| < 0.9, 0.9 < \eta < 1.5 \) and \( 1.5 < |\eta| < 2.4 \), respectively), thus accounting for the detector resolution in different pseudorapidity regions. The tracking and matching efficiency, \( \epsilon_{\text{track}} \), was determined from the ratio of the number of all reconstructed matched good tracks in a \( M, p_T, \eta \) bin to the number of
Figure 2: Left: Average tracking efficiency as a function of pseudorapidity for tracks with $p_T > 0.1$ GeV. Right: Average tracking efficiency as a function of transverse momentum for tracks in $|\eta| < 2.4$.

generated primary charged particles in that bin:

$$\epsilon_{\text{track}}(M, p_T, \eta) = \frac{N_{\text{matched track}}(M, p_T, \eta)}{N_{\text{all primary}}(M, p_T, \eta)}$$

The correction factor $\epsilon_{\text{track}}$ is shown in Fig. 2 as a function of pseudorapidity and transverse momentum. For $p_T > 0.1$ GeV, the efficiency as a function of pseudorapidity and integrated in $p_T$ is about 60%. The tracking efficiency improves for tracks with higher transverse momentum, and for $p_T > 500$ MeV it exceeds 80%.

The correction for non-primary tracks, $f_{\text{np}}$, was estimated from the ratio of the number of reconstructed tracks not matched to a generated primary particle in a $M, p_T, \eta$ bin to all reconstructed tracks in that bin:

$$f_{\text{np}} = \frac{N_{\text{not matched tracks}}(M, p_T, \eta)}{N_{\text{all track candidates}}(M, p_T, \eta)}.$$  (5)

As shown in Fig. 3, the correction varies as a function of the pseudorapidity and the transverse momentum of the tracks, taking its lowest values of about 2% and 5% for $|\eta| < 1.5$ and $p_T > 500$ MeV, respectively. It reaches values as large as 15% at very low transverse momentum ($p_T < 200$ MeV) and/or large pseudorapidity ($|\eta| > 1.5$).

The correction factor for multiply reconstructed particles was estimated from the ratio of the number of generated primary charged particles that are associated to multiple reconstructed tracks in a given multiplicity, $p_T$ and $\eta$ bin to the number of all generated charged particles in that bin. It was found to be below 1%.

The model dependence of the corrections was determined by using two different event generators, PYTHIA6 tune Z2* and PYTHIA8 tune 4C. The corrected data, using correction factors derived from each generator independently, were found to differ by 0.1-1.5% per pseudorapidity bin, which was taken as systematic uncertainty.

An additional correction factor, $C_{T2}$, was applied in order to correct the data for triggered events without a charged primary particle in T2. This was evaluated from a detector simulation of T2.
Figure 3: Correction factor accounting for non-primary tracks as a function of pseudorapidity for tracks with $p_T > 0.1$ GeV (left) and as a function of the transverse momentum for tracks in $|\eta| < 2.4$ (right).

Table 1: Most significant systematic and statistical uncertainties. The values in parentheses apply to the leading-track $dN_{ch}/dp_T$ measurement.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inclusive</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>4.0 (4.0)</td>
</tr>
<tr>
<td>Model dependence</td>
<td>1.0 (2.3)</td>
</tr>
<tr>
<td>T2 correction</td>
<td>1.5 (0.7)</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.1 (0.3–14.6)</td>
</tr>
<tr>
<td>Total</td>
<td>4.4 (4.7–15.3)</td>
</tr>
</tbody>
</table>

using two different event generators, EPOS LHC and PYTHIA8. The correction was found to be smaller than 4% (5%) and 8% (10%) for the inclusive and NSD-enhanced sample, respectively, for $p_T > 0.1$ GeV ($p_T > 1$ GeV). For each event sample, the correction factors are independent of the pseudorapidity. The average correction factor, obtained from EPOS LHC and PYTHIA8, was applied by multiplying the data, while the relative difference between the two generators was assigned as an additional systematic uncertainty.

A summary of the most significant systematic uncertainties, averaged over $\eta$, is given in Table 1. The dominant systematic uncertainty is due to the uncertainty on the tracking efficiency [28]. The uncertainties related to the primary vertex selection, the trigger efficiency and pile up events were also estimated and found to be negligible, at the level of 0.1%.

7 Leading charged particle transverse momentum distributions

For the measurement of the leading-track transverse momentum distribution, $dN_{ch}/dp_{T,\text{leading}}$, charged-particle tracks with $p_T$ in excess of 0.4 GeV were selected and the inclusive event sample requiring a reconstructed track in T2 in either hemisphere was used. All relevant control plots for the leading track are well described by PYTHIA6 Z2* and PYTHIA8 4C. To improve the
determination of the detector corrections, the distribution of the transverse momentum of the leading track was reweighted to the data.

The measured charged particle $p_T$ distribution was calculated from the raw distribution after applying a number of corrections according to the formula:

$$\frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{dp_{\text{T,leading}}} = \frac{\sum \eta N_{\text{tracks}}(\eta, p_{\text{T,leading}}) \cdot C(p_{\text{T,leading}}) \cdot C_{T2}(p_{\text{T,leading}})}{N_{\text{events}} \cdot \Delta p_{\text{T,leading}}},$$

where $N_{\text{events}}$ is the number of selected events, $N_{\text{tracks}}$ is the number of tracks that pass the selection criteria and $\Delta p_{\text{T,leading}}$ is the $p_T$ bin width. The events were corrected for the trigger efficiency as described in Section 6 for the measurement of the pseudorapidity distributions. The correction to stable particle level, $C$, was calculated for each $p_T$ bin from the ratio of the number of generated stable charged particles to the number of reconstructed tracks:

$$C(p_{\text{T,leading}}) = \left(\frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{dp_{\text{T,leading}}}\right)_{\text{gen}} / \left(\frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{dp_{\text{T,leading}}}\right)_{\text{reco}},$$

where reconstructed tracks were not matched to generated particles and all generated events were selected without any requirement on a reconstructed track or primary vertex. The bin widths were chosen in such way that a purity of more than 80% was ensured for all bins, hence reducing the amount of bin migrations from inside or outside the $p_T$ range of the measurement. The correction factor $C$ was taken as the average of the factors estimated by PYTHIA6 Z2* and PYTHIA8 4C. It increases up to 20% for small $p_{\text{T,leading}}$, while for $p_{\text{T,leading}} > 0.8$ GeV it is below 10%. As for the measurement of the pseudorapidity distributions, an additional correction factor, $C_{T2}$, was applied to correct the data for triggered events without a charged primary particle in T2, using PYTHIA8 4C and EPOS LHC. The correction was found to be smaller than 7% for $p_{\text{T,leading}} < 0.8$ GeV and smaller than 4% for higher values of the transverse momentum. Due to the rise of both correction factors in the range $p_{\text{T,leading}} < 0.8$ GeV and the large systematic uncertainty arising from the model dependence in this region, the results are shown for $p_{\text{T,leading}} > 0.8$ GeV.

The systematic uncertainty arising from the model dependence of the corrections was taken as half the difference of the correction factors estimated by the different event generators used. For the correction to stable particle level, it varies bin-by-bin between 0.6% and 2.3% and it is 1.7% on average. For the correction factor $C_{T2}$, the systematic uncertainty was estimated to be 0.7% on average. The 4% uncertainty associated with the track reconstruction efficiency was applied as a systematic uncertainty on every data point. A summary of the systematic uncertainties, averaged in $p_T$, is given in parentheses in Table 1. The dominant systematic uncertainty is attributed to the efficiency of the track reconstruction. The statistical error varies between 0.3% and 14.6% and it is dominant for the highest $p_T$ bins.

From the normalised $dN_{\text{ch}}/dp_{\text{T,leading}}$ spectrum, the integrated leading track $p_T$ distribution was calculated as a function of the minimum transverse momentum of the leading track, defined as:

$$D(p_{\text{T,min}}) = \frac{1}{N_{\text{events}}} \sum_{p_{\text{T,leading}} > p_{\text{T,min}}} \Delta p_{\text{T,leading}} \left(\frac{dN_{\text{ch}}}{dp_{\text{T,leading}}}\right)$$

8 Results

The fully corrected pseudorapidity distributions of charged particles are presented in Figs. 4 and 5 for different event samples for tracks in $|\eta| < 2.4$ with transverse momentum $p_T > 0.1$
GeV and 1 GeV, respectively. Data are compared to predictions obtained from various MC event generators. In general we observe that the model predictions vary within 10-20% for both measurements.

The average multiplicity, per unit of pseudorapidity, for tracks with $p_T > 0.1$ GeV was found to be $5.4 \pm 0.2$ for the most inclusive selection and $6.2 \pm 0.3$ for the NSD-enhanced sample. For tracks with $p_T > 1$ GeV the average multiplicity is $0.78 \pm 0.03$ for the most inclusive selection and $0.93 \pm 0.04$ for the NSD-enhanced sample.

When applying the lowest transverse momentum threshold, the data are well described by Pythia6 Z2*, Pythia8 4C, Epos LHC and QGSJetII-04 for the inclusive selection. All models overestimate the data by up to 20% for the NSD-enhanced sample. Increasing the transverse momentum threshold to 1 GeV, the level of agreement of the models with the data changes. For the inclusive measurement Pythia6 Z2*, Pythia8 4C, Epos LHC and QGSJetII-04 are within the systematic uncertainties for most pseudorapidity bins, while Herwig++ EE3C underestimates the data. All models fail to describe the data well for the sample enhanced in non-single diffractive events, with the exception of EPOS LHC for $|\eta| < 1.5$.

![Figure 4: Charged particle pseudorapidity distributions at $\sqrt{s} = 8$ TeV for tracks in $|\eta| < 2.4$ with $p_T > 0.1$ GeV. Results are shown for an inclusive sample obtained by requiring tracks in the range of any of the TOTEM T2 telescopes in either hemisphere (left) and a sample enhanced in non-single diffractive events requiring tracks in the range of TOTEM T2 in both forward and backward hemispheres (right). The data are compared to different model predictions and their ratio is shown in the lower panels. The error bands show the total systematic uncertainty.](image)

The centre-of-mass energy dependence of the pseudorapidity distribution at $\eta = 0$ is shown in Fig. 6, which includes data from various other experiments obtained for NSD events in pp and p$\bar{p}$ collisions. Previous CMS measurements were performed by extrapolating to $p_T = 0$ and the fraction of charged particles with $p_T < 0.1$ GeV was estimated to be 5%. For the purposes of the comparison, the present measurement at $\sqrt{s} = 8$ TeV was scaled upwards by the same amount. Particle production at midrapidity is expected to follow a power-law centre-of-mass energy dependence, $dN_{ch}/d\eta \mid \eta = 0 \propto s^{\epsilon}$, with exponent in the range $\epsilon \approx 0.14-0.24$ [24]. Figure 6 shows the result of a fit with such an expected $s$-dependence to the high-energy pp and p$\bar{p}$ central pseudorapidity particle densities. We find $\epsilon \approx 0.23$. 
Figure 5: Charged particle pseudorapidity distributions at $\sqrt{s} = 8$ TeV for tracks in $|\eta| < 2.4$ with $p_T > 1$ GeV. Results are shown for an inclusive sample obtained by requiring tracks in the range of any of the TOTEM T2 telescopes in either hemisphere (left) and a sample enhanced in non-single diffractive events requiring tracks in the range of TOTEM T2 in both forward and backward hemispheres (right). The data are compared to different model predictions and their ratio is shown in the lower panels. The error bands show the total systematic uncertainty.

Figure 6: Average value of $dN_{ch}/d\eta$ in the central region as a function of the centre-of-mass energy in pp and $p\bar{p}$ collisions. Shown are measurements performed with different NSD event selections from UA1 [8], UA5 [9], CDF [6, 7], ALICE [5] and CMS [3]. The dashed line is a power-law fit to the data.

The leading-track $p_T$ distribution is shown in Figs. 7 and 8 (left) and the integrated distribution, $D(p_{T,min})$, is presented in the right panels of Figs. 7 and 8. In Fig. 7, predictions from PYTHIA8 4C, PYTHIA6 Z2*, PYTHIA6 D6T and PYTHIA6 default tune with or without multi-parton in-
In Fig. 8, the data are compared to predictions obtained from different event generators: PYTHIA8 4C, PYTHIA6 Z2*, HERWIG++ EE3C, EPOS LHC and QGSJETII-04. We observe that EPOS LHC is in better agreement with the measurement and best describes the shape of the distributions. HERWIG++ EE3C describes the data relatively well only for low $p_T$, while QGSJETII-04 fails to describe them.

9 Conclusions

Measurements of charged-particle densities are presented for pp collisions at a centre-of-mass energy of 8 TeV, using data recorded in common by the CMS and TOTEM detectors. The pseudorapidity distribution of charged particles in $|\eta| < 2.4$ was measured for an inclusive minimum-bias sample, obtained by requiring tracks in the acceptance of any of the TOTEM T2 telescopes in either hemisphere, and a sample enhanced in non-single diffractive events requiring tracks in T2 in both forward and backward hemispheres. Results are shown for charged particles with $p_T > 0.1$ GeV and $p_T > 1$ GeV. For $p_T > 0.1$ GeV, the average multiplicity per unit of pseudorapidity was found to be $5.4 \pm 0.2$ for the inclusive selection and $6.2 \pm 0.3$ for the NSD-enhanced sample, while for $p_T > 1$ GeV it was found to be $0.78 \pm 0.03$ and $0.93 \pm 0.04$, respectively. Theoretical predictions obtained with different MC event generators and tunes do not fully describe the data. For $p_T > 0.1$ GeV, the inclusive measurement is well described by...
Figure 8: Normalised $p_T$-distribution (left) and normalised integrated $p_T$-distribution (right) of the leading charged particle in $|\eta| < 2.4$. Data are compared to predictions by different event generators. The error bars indicate the statistical uncertainty and the shaded area the systematic uncertainty.

$\text{PYTHIA6 } Z2^*$ and $\text{QGSJETII-04}$, while all models overestimate the data for the NSD-enhanced event sample. For $p_T > 1$ GeV, the inclusive measurement is best described by $\text{PYTHIA6 } Z2^*$ and EPOS LHC while none of the models considered succeeds to describe the data for the NSD-enhanced sample. At $\sqrt{s} = 8$ TeV, the average value of $dN_{ch}/d\eta|_{\eta=0}$ for the NSD-enhanced sample was found to follow the power-like centre-of-mass energy dependence indicated by previous NSD measurements at different energies. The measured charged-particle distributions can help constrain the modeling of semi-hard (multi)parton scatterings in pp collisions at the LHC over a large phase space in $p_T$ and $\eta$.

The distribution of the leading $p_T$ of charged particles is also presented for $p_T > 0.8$ GeV. The same distribution integrated over the leading charged particle transverse momentum, above a $p_{T,\text{min}}$ value, shows a transition from a steeply falling distribution at large $p_T$ (perturbative region) to a flat distribution at small $p_T$ (non-perturbative region) in the range of $p_{T,\text{min}}$ of a few GeV. This region is not well described by theoretical predictions obtained from various Monte Carlo event generators. The shape of the measured integrated $p_T$ distribution is best described by EPOS LHC.

References


A Combined CMS and TOTEM results

The charged particle pseudorapidity distributions, \(dN_{ch}/d|\eta|\), are shown in Fig. 9 combined with the measurement performed by the TOTEM collaboration with T2 [14]. The data, as function of \(|\eta|\), were derived by averaging the data points in the corresponding \(\pm \eta\) bins.

![Figure 9: Charged particle pseudorapidity distributions, \(dN_{ch}/d|\eta|\), in \(|\eta| < 2.4\) for \(p_T > 100\) MeV and in \(5.3 < |\eta| < 6.5\) for \(p_T > 40\) MeV, as measured by CMS and TOTEM, respectively. Results are shown for an inclusive sample obtained by requiring tracks in the range of any of the TOTEM T2 telescopes in either hemisphere (left) and a sample enhanced in NSD events requiring tracks in the range of TOTEM T2 in both forward and backward hemispheres (right). The data are compared to various model predictions and their ratio is shown in the lower panels. The error bars indicate the statistical uncertainty and the shaded area the correlated systematic uncertainty.](image-url)