Measurement of the forward charged particle pseudorapidity density in
pp collisions at $\sqrt{s} = 8$ TeV

The TOTEM Collaboration

Abstract

The TOTEM experiment has measured the pseudorapidity density of charged particles with transverse momentum above 40 MeV/c in pp collisions at $\sqrt{s} = 8$ TeV for $5.3 < |\eta| < 6.4$ in a low intensity run with common data taking with the CMS experiment. The measurement has been made for three different events categories: an inclusive one with at least one charged particle in either $-6.5 < \eta < -5.3$ or $5.3 < \eta < 6.5$, a non-single diffractive enhanced one with at least one charged particle in both $-6.5 < \eta < -5.3$ and $5.3 < \eta < 6.5$ and a single diffractive enhanced one with at least one charged particle in $-6.5 < \eta < -5.3$ and none in $5.3 < \eta < 6.5$ or vice-versa.
1 Introduction

The pseudorapidity density of charged particles produced in high energy proton-proton (pp) collisions reflects the strong interaction dynamics that can only partly be described by perturbative QCD. Non-perturbative models and parametrisation are used in Monte Carlo (MC) event generators to describe the hadronisation of the partonic final states and to model diffusive processes [1, 2]. In the forward region, where peripheral diffusive processes are important, the uncertainties are pronounced. A better understanding of these effects is also important for the interpretation of high energy showers recorded by cosmic ray experiments [3, 4, 5]. A direct measurement of the forward particle densities is, therefore, extremely valuable in constraining the theoretical models for particle production in pp interactions.

The measurement of the charged particle pseudorapidity density ($dN_{ch}/d\eta$) in the range $5.3 < |\eta| < 6.4$ with transverse momentum ($p_T$) above 40 MeV/$c$ at $\sqrt{s} = 8$ TeV is presented here. The measurement was done for three event categories: an inclusive one with at least one charged particle in either $-6.5 < \eta < -5.3$ or $5.3 < \eta < 6.5$ ("inclusive"), a non-single diffusive enhanced one with at least one charged particle in both $-6.5 < \eta < -5.3$ and $5.3 < \eta < 6.5$ ("double arm") and a single diffusive enhanced one with at least one charged particle in $-6.5 < \eta < -5.3$ and none in $5.3 < \eta < 6.5$ or vice-versa ("single arm"). Using the same data set and event categories, the $dN_{ch}/d\eta$ has been measured in the $-2.4 < \eta < 2.4$ range for the $p_T$ thresholds of 0.1, 0.5 and 1.0 GeV by the CMS experiment [6]. The present measurement follows closely the methods used for the TOTEM measurement of the $dN_{ch}/d\eta$ at $\sqrt{s} = 7$ TeV [7]. $dN_{ch}/d\eta$ is here defined as the mean number of charged particles per single pp collision and unit of pseudorapidity $\eta$, where $\eta \equiv -\ln[\tanh(\theta/2)]$, and $\theta$ is the polar angle of the direction of the particle with respect to the counterclockwise beam direction.

2 Experimental apparatus

TOTEM is a dedicated experiment to measure the total cross section, elastic scattering and diffusive processes at the LHC [8]. The experimental apparatus, composed of three subdetectors (Roman Pots (RP), T1 and T2 telescopes), is placed symmetrically on both sides of Interaction Point (IP) 5, shared with the CMS experiment. The present analysis is based on measurements with the T2 telescope. The T2, placed at about 14 m from the IP, detect charged particles produced in the range $5.3 < |\eta| < 6.5$. It is made of triple-GEM (Gas Electron Multipliers) chambers and consists of 2 quarters with 10 semicircular chambers each, on both sides of the IP. Each chamber provides two-dimensional information of the track position in an azimuthal coverage of $192^\circ$ 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 ($400 \mu m$ pitch, $80 \mu m$ width) for the measurement of the radial coordinate and a matrix of 1560 pads, each one covering $\Delta \eta \times \Delta \phi \simeq 0.06 \times 0.018$ rad, for the measurement of the azimuthal coordinate and for triggering. Radial and azimuthal coordinate resolution are about $110 \mu m$ and $1^\circ$, respectively [9]. The total material of 10 chambers amounts only to $\sim 0.05 X_0$ [10]. The read-out of all TOTEM detectors is based on the “VFAT” front-end ASIC, which provides as output a digital signal and trigger.

A complete description of the CMS detector can be found in [11]. 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 along the beam axis. Immersed in the magnetic field are the tracking detectors and the electromagnetic and hadron calorimeters. The detector relevant for the analysis described here, the tracker, consists of 1440 silicon-pixel and 15148 silicon-strip detector modules. The barrel part consists of 3+10 layers around the interaction point at distances ranging from 4.4 cm to 1.1 m. Five out of the 10 strip layers are double sided and provide an additional measurement of the $z$-coordinate. The forward and backward endcaps consist of 2+12 disks that extend the pseudorapidity acceptance to $|\eta| = 2.5$. The tracker is designed to provide an impact-parameter resolution of about $100 \mu m$ and a transverse momentum resolution of about...
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0.7 % for 1 GeV/c charged particles at normal incidence. The standard track reconstruction algorithm of CMS is based on a combinatorial track finder which performs multiple iterations in an iterative tracking process [12].

3 Detector simulation

The TOTEM software [13] embeds the necessary interfaces to the GEANT4 simulation toolkit [14], the description of the material placed between the IP and T2 and the offline software used for the event reconstruction. The description of the T2 detector is implemented within this framework. The GEM signal digitisation has been parametrised using a dedicated model that, after proper tuning, reproduces well the measured cluster (a group of neighbouring strip or pad channels) size and reconstruction efficiency as a function of the ionisation energy released in the gas by the incident particle, diffusion coefficient of the fill gas, chamber gain and the VFAT thresholds [10, 15]. A special effort was devoted to understand and quantify secondary particles produced by the interaction of particles with the material in front of and around T2 and then seen in the detector. The simulation of the forward region, properly tuned with the data, showed that a large number of secondary particles is produced in the vacuum chamber walls in front of the detector, in the beam pipe conical section at $|\eta| = 5.53$ and at the lower edge of the CMS Hadron Forward (HF) calorimeter [16]. With respect to the measurement at $\sqrt{s} = 7$ TeV [7], the GEM chamber plane efficiency has been better reproduced in the MC using a finer granularity for the correction and the production of secondaries has been improved using an improved HF simulation. The simulated events were processed and reconstructed in the same manner as collision data.

4 Track reconstruction and alignment

The T2 track reconstruction [15] is based on a Kalman Filter-like algorithm that is simplified due to the small amount of material traversed by the particle crossing the 10 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. The reconstructed tracks have at least 4 hits (pad clusters with or without an overlapping strip cluster), of which at least three have a pad/strip cluster overlap. A $\chi^2$-probability greater than 1% is required for the straight line fit.

TOTEM uses a coordinate system with the origin located at the nominal collision point, the X axis pointing towards the centre of the LHC ring, the Y axis pointing upward (perpendicular to the LHC plane), and the Z axis along the counterclockwise beam direction. The ZImpact parameter (see fig. 1) is the Z coordinate of the intersection point between the track and a plane (“$\pi_2$”) containing the Z axis and orthogonal to the plane defined by the Z axis and the track entry point in T2 (“$\pi_1$”). Due to the short lever arm of the T2 detector (~40 cm) compared to the distance to the IP, the ZImpact resolution is of the order of 1 m.

The relative position of the detector planes within a T2 quarter (internal alignment) and the overall alignment of all the detector planes with respect to their nominal position (global alignment) have been investigated in detail to define possible misalignment biases of the track measurements [15]. The most important internal alignment parameters which can be resolved within the T2 hit resolution are the shifts of the planes in the X and Y directions. Two different methods (iterative and MILLIPEDE) were used to correct for such displacements. Both gave consistent results, with an uncertainty on the transverse position of the plane of about 10 $\mu$m. The relative alignment between the two neighbouring quarters was obtained using tracks reconstructed in the overlap region.

The global alignment of the detector is of main importance for the present analysis. This was achieved by exploiting the symmetric distribution of the track parameters and the position of the “shadow” of the beam pipe, a circular shaped zone of the T2 planes characterised by a very low hit rate due to interactions
The combination of these methods gave, for each quarter, the X-Y shift with respect to the nominal position with a precision of $\sim 0.5$ mm and the tilts in the XZ and YZ planes with a precision of $\sim 0.3$ mrad. The alignment is more precise than what was achieved with the 7 TeV data [7].

After the local and global alignment parameters had been measured with the data, the corresponding misalignments were introduced into the GEANT4 simulation and the same algorithm for the correction of the hit positions was applied in the reconstruction of both simulation and data. In this way one can also take into account, in the simulation, the non-uniform effect that misalignment has on the reconstructed hit position, which depends on its X-Y coordinate in the GEM plane.

5 Data sample

The sample used for the present analysis consists of 500,000 pp collisions at $\sqrt{s} = 8$ TeV recorded during a dedicated run with low inelastic pile-up and non-standard $\beta^* = 90$ m optics configuration, in July 2012. The sample consists of events triggered on three bunches with an average luminosity per colliding bunch pair of about $8 \text{mb}^{-1} \text{s}^{-1}$ corresponding to an inelastic pile-up probability of between 3 and 5 % for individual bunches. The rate of beam gas interactions was estimated to be about 0.25 % of the inclusive sample per arm [17]. A minimum bias trigger was provided by the TOTEM T2 telescope and contributed to the CMS Global Trigger decision, which initiated simultaneous read out of both CMS and TOTEM detectors. The trigger required at least one trigger-road, defined as more than 3 “superpads” (3 radial and 5 azimuthal neighbouring pads) fired in the same r-$\phi$ sector of different planes of the same T2 quarter. This condition is satisfied if at least one charged particle traverses the T2 detector. Due to DAQ rate limitation, the total trigger rate was kept below 1 kHz by prescaling the minimum bias trigger with a factor 5. The CMS orbit reset signal delivered to the TOTEM DAQ at the start of the run assured the time synchronization of the two experiments. The event data from TOTEM and CMS were combined offline using the bunch and orbit number. A zero bias data stream, later used to measure the trigger efficiency, was also collected in a similar way.

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. This is based on the comparison of the direct measurement of the T2 visible inelastic cross section to the TOTEM inelastic
cross section measurement deduced from the difference between the total and elastic cross sections at \(\sqrt{s} = 7\) TeV [18]. The T2-triggered sample contains more than 99% of all non-diffractive events and all single and double diffractive events having at least one diffractive mass larger than \(\sim 3.6\) GeV/c^2.

The transverse momentum \((P_T)\) acceptance for single charged particles going into T2 is limited by the magnetic field and multiple scattering effects. Simulation studies have shown that the charged particle tracks are reconstructed, within the analysis cut utilised in this work, with a good efficiency for \(P_T \geq 40\) MeV/c, defining effectively the minimum \(P_T\) acceptance. The fraction of charged particles with \(P_T < 40\) MeV/c produced in the T2 acceptance is predicted to be small (\(\sim 2\%)\).

6 Analysis procedure

Our pseudorapidity density measurement refers to charged particles with a lifetime longer than \(0.3 \times 10^{-10}\) s, and to the charged decay products of particles with shorter lifetime, which is consistent with the ATLAS [21], ALICE [22], CMS [23] and LHCb [24] definition of a primary charged particle. With this definition, decay products of the \(K_S^0\) and \(\Lambda\) hadrons are considered secondary particles, together with all of the charged particles generated by interactions with the material in front and around T2. The \(\eta\)-value of a track is defined here as the average pseudorapidity of the T2 track hits, calculated from the angle that the hit has with respect to the IP. This definition has been adopted on the basis of detailed MC simulation studies to find the optimal definition of the true \(\eta\) of a particle produced at the IP. The pseudorapidity density has been measured for each quarter independently, allowing an important consistency check among the four analysis results, as each quarter differs in its alignment and track reconstruction efficiency.

Since about 80% of the T2 reconstructed tracks are secondaries, it is important to have a procedure for the discrimination between them and primary charged particles. Based on detailed simulation studies, the most effective primary/secondary particle separation is achieved using the ZImpact track parameter [15]. This parameter is proven to be stable against misalignment errors and is well described by a double gaussian function for the primary particles and by an exponential function for the secondaries.

The mean, required to be the same for both gaussians, the standard deviation and the amplitude of the two gaussians for primaries as well as the mean and the amplitude of the exponential for secondaries have been left free in the fit. Since the fit results have been found to be \(\eta\)-dependent, the fit, performed on data, has been repeated for each \(\eta\)-bin of the pseudorapidity distribution giving standard deviations (amplitudes) of both gaussians that increases (decreases) with \(\eta\). The relative abundance of secondary particles has been found to be smaller for higher \(|\eta|\).

The primary tracks were selected using the ZImpact: ZImpact was required to be in the range for which the area covered by the double gaussian is 96% of the total. The fraction of primary tracks, among the ones passing the above selection criteria, was calculated for each \(\eta\)-bin as a function of the ZImpact-value using the double gaussian and exponential fits. This fraction, found to range from about 74% (lower \(|\eta|\) bins) to about 92% (higher \(|\eta|\) bins), allows each data track to be weighted by the probability for the track to be primary, according to its \(\eta\) and ZImpact-value.

Each track has then been weighted for the primary track efficiency according to its \(\eta\) and to the pad-cluster multiplicity in the corresponding quarter. This efficiency, evaluated by MC, is defined as the probability to successfully reconstruct a GEANT4 generated primary track that traverses the detector and yields a ZImpact parameter within the allowed region. The dependence of the efficiency from the pad-cluster multiplicity was included to make this correction independent from the tuning of the MC multiplicity. Once the ZImpact requirements were applied, a primary track efficiency that ranges from about 73% (lower \(|\eta|\) bins) to about 87% (higher \(|\eta|\) bins) was obtained.

A small contribution to the double gaussian peak is given by the decay products of strange particles and
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Fig. 2: ZImpact parameter distribution for the data tracks reconstructed in one T2 quarter in the $5.85 < \eta < 5.9$ range. The reported $\chi^2/\text{ndf}$ refers to the global (double gaussian + exponential) fit, performed in the range from -15 m up to 9 m. The blue-solid curve represents the exponential component due to secondaries, while the red-solid curve is the double gaussian component mainly related to primary tracks.

by conversion of photons from $\pi^0$ decays in the material near T2. The overall non-primary contribution to the central peak, to be subtracted, has been estimated as a function of $\eta$ using EPOS MC (LHC tune)[25] and found to range between 10% and 20%. For improving the description of the non-primary fraction of the tracks, the $\gamma \, dN/dE$ in the MC was normalised in order to reproduce, in its acceptance region, the measurement by LHCf[26].

MC studies also provided the correction due to the difference between the reconstructed $dN/d\eta$ for primary charged particles in events with at least one reconstructed charged particle satisfying the pointing condition in either ("inclusive"), both ("double arm") and only one ("single arm") T2 hemisphere(s) and the $dN/d\eta$ for primary charged particles for all events with at least one primary charged particle within the acceptance of the T2 hemisphere(s) in same configuration. The associated correction factor, in average $\sim 1.07$, $\sim 1.08$ and $\sim 0.98$ for the "inclusive", "double arm" and "single arm" sample, respectively, has been calculated for each $\eta$ bin in events with at least a charged particle in the $5.3 < |\eta| < 6.5$ range, by considering the number of primary GEANT4 tracks crossing the detector and the corresponding number of primary charged particles generated at the IP with $P_T > 40$ MeV/c.

A bin migration correction accounting for all smearing effects on the reconstructed track $\eta$ was also derived. The track distribution was then normalised to the full acceptance in azimuthal angle. Events with more than one reconstructed vertex using the CMS tracker were discarded. This allowed to reduce the incidence from pile-up to about 0.5%.

Events characterised by a high hit multiplicity, typically due to showers generated in interactions with the material, were not included in the analysis. These events, where track reconstruction capability is limited, constitute $\sim 13.5\%$, $\sim 16.5\%$ and $\sim 7.5\%$ for the "inclusive", "double arm" and "single arm" sample respectively, and have an average pad cluster multiplicity per plane larger than 60. The effect of not considering these events has been evaluated in a MC study, giving an overall correction factor on the measurement of $\sim 1.05$, $\sim 1.04$ and $\sim 1.05$ for the "inclusive", "double arm" and "single arm" sample respectively.
Eq. (1) was used for the $dN_{ch}/d\eta$ determination: $\eta_0$ is the $\eta$-value of the bin centre, $S$ is the sample of tracks with $\eta_0 - \Delta \eta/2 < \eta < \eta_0 + \Delta \eta/2$ satisfying the selection criteria above, $\Delta \eta = 0.05$ is the bin width, $N_{Ev}$ is the number of events in the data sample, $W$ is the probability for a track to be primary, $\varepsilon$ is the primary track efficiency (where $m$ indicates the event pad-cluster multiplicity), $B_j$ is the bin migration correction associated with the $j$th bin, $G$ is the unfolding factor to go from the $dN/d\eta$ of the events selected by the pointing requirement to the $dN/d\eta$ of all events in the category, $S_p$ is the correction factor for the non-primary contribution to the double gaussian peak, $\phi/2\pi$ is the azimuthal acceptance, $H$ is the correction factor taking into account the effect of the exclusion of the events with high secondary multiplicity and $P$ is the pile-up correction factor.

$$\frac{dN}{d\eta} \bigg|_{\eta=\eta_0} = \frac{1}{\Delta \eta} \sum_{\text{Evts}} \varepsilon_{\text{Trig}}(N_{\text{Trk}}) \sum_{\text{Trk}} \frac{W(\eta_0, \text{ZImpact}) \sum_j B_j(\eta_0)}{\varepsilon(\eta_0, m) \varepsilon_{\text{Trig}}^{-1}(N_{\text{Trk}})} G(\eta_0) S_p(\eta_0) \frac{2\pi}{\phi} H(\eta_0) P \quad (1)$$

7 Systematic uncertainties

The systematic uncertainty on the $W$ function, found to be in the range of 3-5%, has been evaluated by including 3 effects: the one on the misalignment corrections, by reconstructing and analysing the data for different misalignment corrections (varied within their systematic uncertainty) and re-evaluating both the $W$ function and the primary particle $dN_{ch}/d\eta$; the one related to the fitting range of the ZImpact parameter, by varying it by 1 m to 2 m depending on the $\eta$ bin; the one on the fitting procedure, by evaluating the difference between the integral of the global fit function and the experimental ZImpact distribution.

The systematic uncertainty associated with the primary track efficiency has been evaluated in studies where tracks were reconstructed using a set of 5 detector planes (out of the total of 10) in a single T2 quarter. The track reconstruction efficiency was determined using the other set of 5 detector planes in the same quarter. The associated systematic uncertainty, estimated with this procedure, was defined as the difference between the result obtained using the above data driven method, and the MC analysis using the same definitions. This uncertainty, computed as a function of the pad-cluster multiplicity and of the track $\eta$, has been found to give a relative contribution from 3 to 5%.

The systematic uncertainty associated with the fraction of the non-primary contribution to the central peak, $S_p$, has been evaluated by considering the variation in the predictions obtained using the EPOS MC with its default settings and with a version properly tuned in order to reproduce the $\gamma$ spectrum measured by the LHCf experiment (0.71 rescaling factor). It has been found to be 5%.

The primary track efficiency variation due to magnetic field effects and to the uncertainty on the energy spectrum resulted in an error of about 2%.

The uncertainty on the correction accounting for the exclusion of events with high multiplicity of secondary particles ($H$) and the correction accounting for the tracks not reaching the T2 ($G$), was studied considering the difference between Pythia8 and EPOS MC predictions, has been found to be $\sim 3\%$, $\sim 3\%$ and $\sim 10\%$, respectively for the ‘inclusive”, “double arm” and “single arm” subsamples. This uncertainty is in particular pronounced in the “single arm” subsample, where there is a strongest model dependence of the $G(\eta_0)$ function.

The $B_j$ functions have been found to have a negligible variation. The effect of the track quality criterion requirement, $\chi^2$-probability $> 1\%$, has been estimated to be around 1% by evaluating the data/MC discrepancy observed with and without using this requirement. The effect of the trigger bias in our measurement has been conservatively evaluated to be of the same size as the correction due to trigger inefficiency estimated from pure bunch crossing trigger with the sample triggered with T2, i.e. 0.5%. The pile-up probability systematic uncertainty has been estimated to be 0.3%.
Table 1 shows the uncertainties, for each analysed subsample, of a typical bin in one of the four T2 quarters. The double dashed line separates the quarter dependent contributions (top) from the ones in common for all the quarters (bottom). The total systematic uncertainty has been computed by first

<table>
<thead>
<tr>
<th>dN_{ch}/d\eta error summary</th>
<th>“inclusive”</th>
<th>“double arm”</th>
<th>“single arm”</th>
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<tr>
<td>1. Primary track efficiency data-MC discrepancy</td>
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<td>3-5%</td>
<td>3-5%</td>
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<tr>
<td>2. Primary selection (including alignment)</td>
<td>3-5%</td>
<td>3-5%</td>
<td>3-5%</td>
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<tr>
<td>3. Non-primaries in the central peak</td>
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<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>4. High-multiplicity events and charged particles not in T2</td>
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<td>3%</td>
<td>10%</td>
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<td>5. Uncertainty on material</td>
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<td>6. Primary track efficiency MC and B-field dependence</td>
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<td>7. Track quality criterion</td>
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<td>8. Trigger bias</td>
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<td>9. Pile-up probability</td>
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<tr>
<td>10. Statistical</td>
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<td>0.7%</td>
<td>0.7%</td>
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<tr>
<td>Total (after averaging quarters)</td>
<td>11-12%</td>
<td>11-12%</td>
<td>15%</td>
</tr>
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</table>

linearly adding the global alignment and track efficiency systematics to take into account misalignment effects on the primary track efficiency estimation, then this result has been added in quadrature to the uncertainty contributions from 4) to 10) of table 1 and finally the uncertainty associated with the non-primary contribution to the central peak has been added linearly. To obtain the total uncertainty of the single quarter measurement, the statistical error is then added in quadrature.

8 Results

The dN_{ch}/d\eta measurements obtained for the different T2 quarters are compatible within the quarter-dependent systematic uncertainties. For each \eta-bin, the measurements for the four quarters have been combined with a weighted average using only the quarter-dependent uncertainties. A conservative approach has been adopted for the combination of the quarter-dependent systematic uncertainties: an error propagation on the weighted averages has been applied, considering the measurements completely and positively correlated. The resulting error has then been combined with the systematic contributions that are common to all quarters and with the statistical one, as in the case of the single quarter measurement.

The pseudorapidity density measurement is shown as black, red and blue squares for the "inclusive", "double arm" and "single arm" sample, respectively, in fig. 3, where the error bars represent the total uncertainty including the statistical error.

9 Conclusions

The TOTEM experiment has measured the charged particle pseudorapidity density (dN_{ch}/d\eta) in pp collisions at \sqrt{s} = 8 TeV for 5.3 < |\eta| < 6.4 in events with at least one reconstructed track in this range. This represents the extension of an analogous measurement already performed at \sqrt{s} = 7 TeV. The measurement refers to charged particles with P_T > 40 MeV/c and with a mean lifetime \tau > 0.3 \times 10^{-10} s, directly produced in pp interactions or in subsequent decays of particles having a shorter lifetime. The
Fig. 3: Charged particle pseudorapidity density distribution for the "inclusive" (one charged particle with $p_T$ larger than 40 MeV/c in either $-6.5 < \eta < -5.3$ or $5.3 < \eta < 6.5$), "double arm" (one charged particle with $p_T$ larger than 40 MeV/c in both $-6.5 < \eta < -5.3$ and $5.3 < \eta < 6.5$) and "single arm" (one charged particle with $p_T$ larger than 40 MeV/c in either $-6.5 < \eta < -5.3$ only or $5.3 < \eta < 6.5$ only) sample shown with black, red and blue squares, respectively. The points represent the average of the four T2 quarters, with the error bars including both statistical and systematic error.

The visible cross section for events triggered by T2 has been estimated to be about 95% of the total inelastic cross section: more than 99% of all non-diffractive events and all single and double diffractive events having at least one diffractive mass larger than $\sim 3.6$ GeV/c$^2$.

The measurement reported here was done for three event categories into which the full dataset has been subdivided: an inclusive one with at least one charged particle in one of the T2 arms ("inclusive" sample), a non-single diffractive enhanced one with at least one charged particle in both T2 arms ("double arm" sample) and a single diffractive enhanced one with at least one charged particle in one of the T2 arms and none in the other ("single arm" sample). Using the same data set and event categories, the $dN/d\eta$ has also been measured in the $-2.4 < \eta < 2.4$ range for the $p_T$ thresholds of 0.1, 0.5 and 1.0 GeV by the CMS experiment [6], see Appendix A. The combination of the two analyses allowed a joint measurement over an unprecedented covered $\eta$ range.

Acknowledgements

We thank M. Ferro-Luzzi and the LHC machine coordinators for scheduling and providing us the dedicated TOTEM runs. We are very grateful to the CMS collaboration for the common data taking as well as providing us the software framework where all the toolkits used for the analysis reported here have
been developed.

References

Appendix A: Combined CMS-TOTEM $dN/d\eta$ plots

The $dN/d\eta$ measurement on events triggered by the T2 both with the CMS tracker and the TOTEM T2 for $p_T > 100$ MeV/c and $p_T > 40$ MeV/c, respectively, in two event samples, “inclusive” shown in fig. 4 (left) and ”non-single diffractive enhanced” or ”double arm” shown in fig.4 (right).

Fig. 4: Charged particle pseudorapidity density distribution as measured by the CMS tracker in the central region and TOTEM T2 in the forward region for the same events with one charged particle with transverse momentum ($p_T$) larger than 40 MeV/c in either $-6.5 < \eta < -5.3$ or $5.3 < \eta < 6.5$ (“inclusive sample”, left) and in both $-6.5 < \eta < -5.3$ and $5.3 < \eta < 6.5$ (“non-single diffractively enhanced” or ”double arm” sample, right). The measurements are compared to Pythia6 Z2* tune [19], Pythia8 4C tune [20], Herwig++ EE3C tune [27], EPOS LHC tune [25] and QGSJETII-04 [28] with the appropriate $p_T$ threshold applied in corresponding $\eta$ regions.