CMS Physics Analysis Summary

Measurement of pp diffraction dissociation cross sections at $\sqrt{s} = 7$ TeV at the LHC

The CMS Collaboration

Abstract

Results are presented for the single- and double-diffractive cross sections in pp collisions at $\sqrt{s} = 7$ TeV at the LHC using the CMS detector. The differential SD cross section is measured as a function of $\xi$, the forward momentum loss of the incoming proton, for $-5.5 < \log_{10}(\xi) < -2.5$. The differential DD cross section is measured using events for which one hadronic system is detected in the central detector ($12 \lesssim M_X \lesssim 394$ GeV) and the other one in the CASTOR calorimeter ($3.2 \lesssim M_Y \lesssim 12$ GeV), as a function of $\xi_X = M_X^2/s$ for $-5.5 < \log_{10}(\xi_X) < -2.5$. The DD cross section is also measured differentially as a function of the width of the central pseudorapidity gap, $\Delta \eta$, for $\Delta \eta > 3$ and $M_X, M_Y > 10$ GeV. In addition, the inclusive differential cross section for events with a forward rapidity gap ($d\sigma / d\Delta \eta^F$) is measured over $\Delta \eta^F = 8.4$ units of pseudorapidity. Measurements are compared to results from other experiments and to theoretical predictions.
1 Introduction

Among the fundamental quantities studied in high energy physics are the total and total-inelastic cross sections of hadron-hadron collisions. A significant fraction ($\approx 25\%$) of the total inelastic proton-proton cross section at high energies can be attributed to diffractive interactions, characterized by the presence of at least one non-exponentially suppressed large rapidity gap (LRG) in the final state. Hadronic interactions with an LRG, defined as a region in pseudorapidity devoid of particles, are mediated by a color-singlet exchange carrying vacuum quantum numbers, commonly referred to as Pomeron ($P$) exchange. Figure 1 shows the main types of diffractive processes: single dissociation (SD), double dissociation (DD), and central diffraction (CD).

Inclusive diffractive interactions cannot be calculated within perturbative quantum chromodynamics (pQCD), and traditionally have been described by models based on Regge theory. The predictions of these models generally differ when extrapolated from pre-LHC center-of-mass energies ($\sqrt{s} \leq 1.96$ TeV) to 7 TeV at LHC. Therefore, measurements of diffractive cross sections at the LHC provide a valuable input for understanding diffraction and improve its modeling in current event generations. They are also crucial for the proper modeling of the final state of minimum-bias (MB) events, and can help improve the simulation of, e.g., the underlying event, pileup events, and the measurement of the machine luminosity at the LHC.

Existing measurements of diffractive cross sections at the LHC provide results either with a limited precision [1] or with no separation between SD and DD events [2]. This note presents the first Compact Muon Solenoid (CMS) measurement of inclusive diffractive cross sections at $\sqrt{s} = 7$ TeV, based on the presence of an LRG in pseudorapidity space. The SD and DD events are separated using the CASTOR calorimeter [3], which covers the very forward region of the experiment, $-6.6 < \eta < -5.2$. The measurement is based on the first CMS data, collected at $\sqrt{s} = 7$ TeV during the 2010 commissioning period, when the LHC was running in a low pileup scenario, most suitable for diffractive event selection using an LRG signature.

Figure 1: Schematic diagrams of (a) non-diffractive, $pp \rightarrow X$, and diffractive processes with (b) single-dissociation, $pp \rightarrow Xp$ or $pp \rightarrow pY$, (c) double-dissociation, $pp \rightarrow XY$, and (d) central diffraction, $pp \rightarrow pXp$. The $X(Y)$ represents a dissociated-proton or a centrally-produced hadronic system.
2 CMS detector

A detailed description of the CMS detector can be found in Ref. [4]. CMS uses a right-handed coordinate system, with the origin at the nominal collision point, the x-axis pointing to the center of the LHC, the y-axis pointing up (perpendicular to the LHC plane), and the z-axis along the anticlockwise-beam direction. The polar angle, $\theta$, is measured from the positive z-axis and the azimuthal angle, $\phi$, is measured in the x-y plane. The pseudorapidity is defined as $\eta = -\ln(|\tan(\theta/2)|)$. The central feature of the apparatus is a superconducting solenoid of 6 m internal diameter, providing a 3.8 T axial field. Within the field volume are located a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass-scintillator hadronic calorimeter (HCAL). Muons are measured in gaseous detectors embedded in an iron return yoke. The ECAL has an energy resolution of better than 0.5% above 100 GeV. The calorimeter cells are grouped in projective towers, of granularity $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$ at central rapidities and $0.175 \times 0.175$ at forward rapidities. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The forward component of the hadron calorimeter, HF ($2.9 < |\eta| < 5.2$), consists of steel absorbers with embedded radiation-hard quartz fibers, providing fast collection of Cherenkov light. The very forward angles are covered at one end of CMS ($-6.6 < \eta < -5.2$) by the CASTOR calorimeter [3]. CASTOR is made of quartz fibers/plates embedded in tungsten absorbers, segmented in 16 $\phi$-sectors and 14 $z$-modules.

Two elements of the CMS monitoring system, the Beam Scintillator Counters (BSC) and the Beam Pick-up Timing eXperiment (BPTX) devices, are used to trigger the CMS readout. The two BSC are located at a distance of $\pm 10.86$ m from the nominal interaction point (IP) and are sensitive in the $|\eta|$ range 3.23 - 4.65. Each BSC consists of 16 scintillator tiles. The BSC elements have a time resolution of 3 ns and an average minimum ionizing particle detection efficiency of 96.3%. They are designed to provide “hit” and coincidence rates. The two BPTX [4] devices, located around the beam pipe at a distance of 175 m from the IP on either side, are designed to provide precise information on the bunch structure and timing of the incoming beams, with better than 0.2 ns time resolution.

3 Monte Carlo simulation

A Monte Carlo (MC) simulation is used to correct the measured distributions for geometrical acceptance of the CMS detector, resolution of kinematic variables and their migrations from true to reconstructed values. The PYTHIA 8.165 [5, 6] generator is used to generate samples of total-inelastic events. We compare the data to the PYTHIA8-4C and PYTHIA8-MBR simulations and extract cross sections using PYTHIA8-MBR.

Diffractive events in the PYTHIA8-4C simulation [6] are generated according to the Schuler-Sjostrand model from PYTHIA6 [5]. The 4C tune includes an additional scaling of the SD and DD cross sections at $\sqrt{s} = 7$ TeV downwards by 10 and 12 %, respectively.

The PYTHIA8-MBR (Minimum Bias Rockefeller) simulation [7] is an event generator which predicts the energy dependence of the total, elastic, and total-inelastic $pp$ cross sections, and fully simulates the main diffractive components of the total-inelastic cross section: SD, DD and CD. The diffractive-event generation in MBR is based on a phenomenological renormalized-Regge-theory model [8], which is unitarized by interpreting the Pomeron flux as the probability for forming a diffractive rapidity gap. The MBR model was originally developed for the CDF experiment at the Tevatron, and successfully tested with CDF diffractive results. We find that the PYTHIA8-MBR simulation with an intercept for the Pomeron trajectory, $\alpha(t) = 1 + \epsilon + \alpha' t$, with
\[ \epsilon = 0.08 \] gives a good description of the data in this analysis. Additionally, a scaling of the DD cross section downwards by 15% improves the description of the DD-dominated data in a CASTOR-tag SD2-type and DD-type event samples, introduced in Sec. 5. The \textsc{pythia8-mbr} simulation with these modifications is used to extract the SD and DD cross sections.

The detailed MC simulation of the CMS detector response is based on \textsc{geant4} [9]. Simulated events are processed and reconstructed in the same manner as collision data.

4 Event selection

The present analysis is based on an event sample of pp collisions at \( \sqrt{s} = 7 \text{ TeV} \), collected during the 2010 commissioning period, when the LHC was operating in a low pileup scenario. Only data with information from the CASTOR calorimeter, corresponding to an integrated luminosity of 16.2 \( \mu \text{b}^{-1} \) and an average number of inelastic pp collisions per bunch crossing of \( \mu = 0.14 \), are included.

Events were selected online by requiring a signal in both BPTX detectors, in conjunction with a signal in any of the BSC scintillators. These conditions indicate a presence of both bunch crossings at the interaction point (IP) and an activity in the central CMS detector (minimum-bias (MB) trigger). Offline, the following standard cleaning cuts are applied:

- the fraction of high-quality tracks is required to be greater than 25% for events with at least 10 reconstructed tracks; this cut aims at rejecting beam-scraping events, in which long horizontal sections of the pixel tracker are hit;
- beam-halo event candidates are rejected; these events have hits in the BSC with timing consistent with that of a particle traversing horizontally the apparatus;
- events are rejected if large signals consistent with noise in HCAL are identified.

In addition, a minimal activity in the central CMS detectors is imposed by requiring at least two particle-flow (PF) object reconstructed in the geometrical acceptance of the BSC detectors \( (3.23 < |\eta| < 4.65) \). PF objects [10] are particle candidates obtained by combining the information from the tracking system and the calorimeters in an optimal way. The minimal energy required for each PF-object type is defined based on dedicated runs with an empty detector, and varies from zero for tracks to 4 GeV for towers in HF, depending on detector region and PF-object type. No vertex requirement is imposed on selected events. This retains high acceptance for diffractive events with a hadronic system outside the tracking acceptance (low or moderate diffractive masses, \( M_X \lesssim 100 \text{ GeV} \)).

5 Experimental topologies of diffractive events

Events satisfying the selection described in Sec. 4 comprise a minimum-bias sample corresponding to the total-inelastic cross section, limited to using only the central CMS detector \( (-4.7 \lesssim \eta \lesssim 4.7) \). They are dominated by non-diffractive (ND) events for which final-state particle production occurs in the entire \( \eta \) space available at \( \sqrt{s} = 7 \text{ TeV} \), \( |\eta| \lesssim \ln(\sqrt{s}/m_p) = 8.92 \), as shown schematically in Fig. 2a. In contrast, diffractive events are expected to have an LRG present in the final-state.

Experimentally, the following diffractive topologies may be defined, depending on the position of the LRG in the central detector:

- SD1, with the forward pseudorapidity gap reconstructed at the edge of the detector
Experimental topologies of diffractive events

Figure 2: Typical event topologies in the particle $\eta$ space for (a) non diffractive (ND), $pp \rightarrow X$, (b) SD, $pp \rightarrow Xp$, (d) SD, $pp \rightarrow pY$, and (c),(e),(f) DD, $pp \rightarrow XY$, events. The open box represents the central CMS detector, full boxes depict final-state hadronic systems (or a proton - thin box). The dotted opened box in sketches (c)-(d) represents the CASTOR calorimeter.

- SD2, with the forward pseudorapidity gap reconstructed at the edge of the detector on the negative $\eta$-side, as shown in Figs 2b-c;
- DD, with the central pseudorapidity gap reconstructed in the detector around $\eta = 0$, as shown in Fig. 2f.

For the experimental SD1 and SD2 topologies the pseudorapidity gap is related to the variables $\eta_{\text{max}}$ and $\eta_{\text{min}}$ (cf. Fig. 2). The $\eta_{\text{max}}$ ($\eta_{\text{min}}$) is defined as the highest (lowest) $\eta$ of the PF object reconstructed in the central detector. Then, for truly SD events, the width of the forward pseudorapidity gap is given by $\Delta \eta^F \approx 8.92 - \eta_{\text{max}}$ and $\Delta \eta^F \approx 8.92 + \eta_{\text{min}}$ for SD1 and SD2, respectively.

For the experimental DD topology the pseudorapidity gap can be expressed as $\Delta \eta^0 = \eta_{\text{max}}^0 - \eta_{\text{min}}^0$, with $\eta_{\text{max}}^0$ and $\eta_{\text{min}}^0$ defined as shown in Fig. 2. The $\eta_{\text{max}}^0$ ($\eta_{\text{min}}^0$) is the closest-to-zero $\eta$ value of the PF object reconstructed on the positive (negative) $\eta$-side of the central detector.

Figure 3 shows the distributions of $\eta_{\text{max}}$, $\eta_{\text{min}}$ and $\Delta \eta^0 = \eta_{\text{max}}^0 - \eta_{\text{min}}^0$ for the minimum-bias sample defined in Sec. 4, compared to MC predictions. For the $\Delta \eta^0$ selection, an additional requirement of the presence of activity on both $\eta$-sides of the central detector is imposed. The data are dominated by the contribution from ND events, for which rapidity gaps are exponentially suppressed (random multiplicity fluctuations). Diffractive events appear as a flattening of the exponential distributions, and dominate the regions of low $\eta_{\text{max}}$, high $\eta_{\text{min}}$, or high $\Delta \eta^0$.

In order to select the samples of SD1, SD2 and DD events with a central LRG signature (Fig. 2),...
the cuts $\eta_{\text{max}} < 1$, $\eta_{\text{min}} > -1$ and $\Delta \eta^0 > 3$ are imposed, respectively.

Figures 3a,b also show that approximately half of the sample defined experimentally as SD1 or SD2 originates from DD events. These events correspond to a topology in which one of the dissociated masses is low and escapes detection in the central detector, as depicted in Figs 2c,e. For the SD2 topology, CASTOR ($-6.6 < \eta < -5.2$) is used to select a diffractive event sample enhanced in DD events (Fig. 2e) and calculate DD and SD cross sections. The detection of the low-mass dissociated system in the enhanced DD sample is performed in terms of a CASTOR tag, defined as the presence of a signal above the energy threshold (1.48 GeV) in at least one of the 16 $\phi$-sectors summed over the first five CASTOR modules. Since no detector is available for tagging the low-mass dissociated system on the positive $\eta$-side, the SD1 sample is treated as a control sample in this analysis.

The range of the dissociated mass, $M_X$, for the truly SD process in the SD2 type sample after all selections is shown as a green histogram in Fig. 4 corresponding to $1.1 \lesssim \log_{10}(M_X/\text{GeV}) \lesssim 2.5$. Similar distributions are obtained for events in the SD1-type sample, in which the dissociated system originates from the proton on the other side of the detector. The range of disso-

Figure 4: The generator-level distributions of the dissociated mass, $M_X$, for the SD process in the SD1 sample at different selection stages for the PYTHIA8-MBR (left) and PYTHIA8-4C (right) MC samples.
Figure 5: The generator-level efficiency (PYTHIA8-MBR), in the $M_X$ and $M_Y$ plane, for selecting truly DD events after (a) the trigger selection and (b) the SD2 or (c) the DD selections (cf. Fig. 2).

6 SD and DD cross sections from SD2 event sample

The SD cross section is measured as a function of the variable $\xi$, which represents the fraction of the longitudinal momentum loss of the incoming proton. The $\xi$ is related to the mass of the dissociated system, $M_X$, by

$$\xi = \frac{M_X^2}{s},$$

where $s$ is the center-of-mass pp collision energy squared. The size of the pseudorapidity gap between the system $M_X$ and the surviving proton, $\Delta \eta^{SD}$, is given by $\Delta \eta^{SD} \approx -\log \xi$.

The DD cross section is measured as a function of the variable $\xi_X$, which is related to the mass of the dissociated system visible in the central detector, $M_X$, by Eq. (1). The mass of the hadronic system which escapes detection in the central detector, $M_Y$, is limited by the CASTOR acceptance to the range $0.5 < \log_{10}(M_Y/\text{GeV}) < 1.1$.

On the detector level, the variable $\xi$ is reconstructed as

$$\xi^\pm = \frac{\sum (E_i \mp p_i^z)}{\sqrt{s}},$$

where $i$ runs over all PF objects measured in the central detector, and $E_i$ and $p_i^z$ are the energy and the longitudinal momentum of the $i^{th}$ PF object, respectively. The superscript ($\pm$) in Eq. (2) denotes that the dissociated system occurs on the $\pm z$ side of the detector. For the SD2-type events under study, the $\xi$ and $\xi_X$ variables are approximated by $\xi^+ \approx \xi \approx \xi_X$.

Since part of the hadronic system $M_X$ escapes the detector through the forward beam hole, and since low-energy particles remain undetected (PF object thresholds), the reconstructed $\xi$
variable is expected to be underestimated. The correction factor, \( C(\xi) \), which brings the reconstructed values of \( \xi \) (Eq. (2)) to their true values (Eq. (1)) according to the formula \( \log_{10} \xi_{\text{corr}} = \log_{10} \xi + C(\xi) \) is evaluated from the MC simulation, by studying the \( \log_{10} \xi_{\text{true}} - \log_{10} \xi_{\text{corr}} \) relation in bins of \( \log_{10} \xi_{\text{corr}} \). The \( C(\xi) \) decreases from the value of 1.1 at \( \log_{10} \xi_{\text{corr}} \approx -6.5 \) to the value of 0.2 at \( \log_{10} \xi_{\text{corr}} \approx -2.5 \), with an uncertainty of 3 % estimated by comparing PYTHIA8-MBR and PYTHIA8-4C simulations.

Figure 6a presents the distribution of \( \log_{10} \xi \) for the SD2 sample, compared to predictions of the PYTHIA8-MBR MC. The separation of SD and DD processes (green and yellow histograms, respectively) using the CASTOR tag is clearly seen in Figs. 6b-c. The same distributions are compared to the PYTHIA8-4C simulation in Fig. 7. The PYTHIA8-MBR MC describes the shape of the data better and is used to calculate diffractive cross sections.

The differential SD cross section measured in bins of \( \xi \) is calculated using the formula:

\[
\frac{d\sigma^{SD}}{d \log_{10} \xi} = \frac{N_{\text{data, noCASTOR}}^{\text{data}} - (N_{\text{DD}} + N_{\text{CD}} + N_{\text{ND}})_{\text{MC}}}{\text{acc} \cdot \mathcal{L} \cdot (\Delta \log_{10} \xi)_{\text{bin}}},
\]

where \( N_{\text{data, noCASTOR}} \) is the number of events in the bin corresponding to the SD2 sample with no

Figure 7: The detector-level distributions of the reconstructed and corrected \( \xi \) for (a) the entire SD2 sample, and the SD2 subsamples with (b) no CASTOR tag and (c) a CASTOR tag. The data are compared to predictions of the PYTHIA8-4C simulation normalized to the luminosity of the data. Contributions for each one of the generated processes are shown separately.
CASTOR tag. The factor $acc$ is the acceptance, defined as the number of events reconstructed to the number of events generated in that bin, taking into account the pileup correction. The acceptance is evaluated with the PYTHIA8-MBR MC. The symbol $\mathcal{L}$ is the integrated luminosity and $(\Delta \log_{10} \xi_{X})_{\text{bin}}$ is the bin width. The term $(N_{\text{DD}} + N_{\text{SD}} + N_{\text{ND}})_{\text{MC}}$ accounts for the number of DD, CD or ND background events and is taken from the MBR MC prediction. The dominant background originates from DD events, while ND events are negligible (cf. Fig. 6b). We emphasize, however, that DD events are measured using the CASTOR-tag events (subject to the uncertainty in the ND contribution to DD-like events, estimated at $\sim 10 - 20\%$ by the simulation), and therefore only the uncertainty in the difference between DD data and DD MC, amounting to a few $\%$, contributes to the error in the DD subtraction from the no-CASTOR-tag events to obtain the SD events. The resulting SD cross section is presented in Fig. 8 (left).

The differential DD cross section measured in bins of $\xi_{X}$, for $0.5 < \log_{10} (M_{Y}/\text{GeV}) < 1.1$, is calculated according to the formula

$$\frac{d\sigma^{DD}}{d \log_{10} \xi_{X}} = \frac{N_{\text{data CASTOR}} - (N_{\text{ND}} + N_{\text{SD}} + N_{\text{CD}})_{\text{MC}}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10} \xi_{X})_{\text{bin}}}$$

where $N_{\text{data CASTOR}}$ is the number of events in the bin corresponding to the SD2 sample with a CASTOR tag. The factors $acc$, $\mathcal{L}$ and $(\Delta \log_{10} \xi_{X})_{\text{bin}}$ are defined as above. The factor $(N_{\text{ND}} + N_{\text{SD}} + N_{\text{CD}})_{\text{MC}}$ corresponds to the number of ND, SD or CD background events taken from the PYTHIA8-MBR MC prediction. The dominant background originates from ND events, while CD and SD events are negligible (cf. Fig. 6c). The resulting DD cross section is presented in Fig. 8 (right).

Figure 8 presents also a comparison of the measured cross sections with predictions of theoretical models used in the PYTHIA8-MBR, PYTHIA8-4C, and PYTHIA6 MC simulations. The predictions of PYTHIA8-MBR are shown for two values of the $\epsilon$ parameter of the Pomeron trajectory, $a(t) = 1 + \epsilon + a' t$. Both values, $\epsilon = 0.08$ and $\epsilon = 0.104$, describe the measured SD cross section within uncertainties. The DD data favor the smaller value of $\epsilon$, in particular in the region of lower-$\xi_{X}$, corresponding to the topology in which both dissociated masses are low (low $M_{X}$ and $M_{Y} < 10\text{ GeV}$). Predictions of the Schuler-Sjostrand model, used in the PYTHIA8-

Figure 8: The SD (left) and DD (right) cross sections as a function of $\xi$ compared to PYTHIA6, PYTHIA8-4C and PYTHIA8-MBR MC predictions. Error bars are dominated by systematic uncertainties, discussed in Sec. 8.
4C and PYTHIA6 simulations, describe well the measured DD cross section. However, they are higher than the SD data at high $\log_{10} \xi$, and fail to describe the falling behavior of the data in the region of $-5.5 < \log_{10} \xi < -2.5$.

The total SD cross section at $\sqrt{s} = 7$ TeV integrated over $-5.5 < \log_{10} \xi < -2.5$ is also measured. A value of $4.27 \pm 0.04_{\text{stat.}}^{+0.65}_{-0.58_{\text{syst.}}}$ mb is extracted from the data, after multiplying by a factor of 2 to account for both the $pp \rightarrow Xp$ and $pp \rightarrow pY$ processes.

7 DD cross section from DD event sample

The DD cross section is measured as a function of the variable $\Delta \eta$, defined as $\Delta \eta = -\log \xi$, where $\xi = M_X^2 \cdot M_Y^2 / (s \cdot m_p^2)$, with $s$ being the center-of-mass energy squared and $m_p$ the proton mass. The position of the gap center is related to the dissociated masses by $\xi_c = \log(M_Y/M_X)$.

The reconstruction of the variable $\Delta \eta^0$ on the detector level was introduced in Sec. 5. The central-gap width is defined as the difference $\Delta \eta^0 = \eta^0_{\text{max}} - \eta^0_{\text{min}}$, where $\eta^0_{\text{max}}$ and $\eta^0_{\text{min}}$ are the closest-to-zero $\eta$ values of the PF object reconstructed on the positive (negative) $\eta$-side of the central detector. The distribution of $\Delta \eta^0$ was presented in Fig. 3c. The correction factor, $C$, bringing the reconstructed values of $\Delta \eta^0$ to their true values according to the formula $\Delta \eta^0_{\text{corr}} = \Delta \eta^0_{\text{rec}} - C$, is extracted from the PYTHIA8-MBR MC and amounts to $C = 2.15 \pm 0.25$. Figure 9 presents the distribution of $\Delta \eta^0$ for the DD sample along with simulated distributions using PYTHIA8-MBR and PYTHIA8-4C. In PYTHIA8-MBR, the DD events are scaled downwards by 15 %, as in Fig. 6.

The differential DD cross section, measured in bins of $\Delta \eta$ for $\Delta \eta > 3$, $M_X > 10$ GeV and $M_Y > 10$ GeV, is calculated according to the formula

$$\frac{d\sigma^{DD}}{d\Delta \eta} = \frac{N_{\text{data}} - (N_{\text{ND}} + N_{\text{SD}} + N_{\text{CD}})_{\text{MC}}}{\text{acc} \cdot L \cdot (\Delta \eta)_{\text{bin}}}$$

where $N_{\text{data}}$ is the number of events in the bin. The factor $\text{acc}$ is the acceptance, defined as

![Figure 9: The detector-level distributions of the reconstructed and corrected $\Delta \eta^0$ for the DD sample with central LRG. The data are compared to predictions of the PYTHIA8-MBR (left) and PYTHIA8-4C (right) simulations normalized to the luminosity of the data. Contributions for each one of the generated processes are shown separately. The DD events in PYTHIA8-MBR sample are scaled downwards by 15 %.

(CMS Preliminary) $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$](image-url)
the number of events reconstructed in the bin to the number of events generated. It contains the pileup correction and the $\Delta \eta^0 > 3$ to $\Delta \eta > 3$ extrapolation, evaluated with the Pythia8-MBR MC. The symbol $L$ is the integrated luminosity and $<(\Delta \eta)_{\text{bin}}$ is the bin width. The factor $(N_{\text{ND}} + N_{\text{SD}} + N_{\text{CD}})^{\text{MC}}$ corresponds to the number of ND, SD and CD background events evaluated from the MC prediction. The dominant background originates from ND events (cf. Fig. 9a). The resulting DD cross section is shown in Fig. 10, where it is compared to predictions of theoretical models used in the Pythia8-MBR, Pythia8-4C and Pythia6 MC simulations. The predictions are in agreement with the data.

The total DD cross section integrated over the region $\Delta \eta > 3, M_X > 10$ GeV and $M_Y > 10$ GeV is also measured. The value of $\sigma^{DD} = 0.93 \pm 0.01(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$ mb is extracted from the data.

8 Systematic uncertainties in SD and DD cross sections

Systematic uncertainties are estimated by varying the cuts and modifying the analysis procedure. The following sources of systematic uncertainties are taken into account:

- HF energy scale: varied in MC by $\pm 10\%$.
- PF energy thresholds: raised by $10\%$.
- CASTOR energy scale: changed in MC by $\pm 20\%$.
- CASTOR energy threshold in each sector: changed from 4 $\sigma$ to 3.5 $\sigma$ and 4 $\sigma$ to 5 $\sigma$, where $\sigma$ is the pedestal width;
- CASTOR alignment uncertainty: systematic uncertainties of 8% and 2% are added to the measurements of the DD and SD cross sections with and without a CASTOR tag, respectively.
- trigger efficiency uncertainty: estimated from a comparison of the efficiency curves between data (measured using the Zero-Bias sample) and MC.
hadronization and diffraction model: the hadronization parameters in the nominal PYTHIA8-MBR MC sample are tuned to describe the multiplicity and $p_T$ spectra of diffractive systems [11]. The uncertainty in hadronization is evaluated by comparing with the PYTHIA8-4C simulation and symmetrizing the differences with respect to the nominal analysis. This procedure takes also into account the difference between diffraction models of PYTHIA8-MBR and PYTHIA8-4C.

- background subtraction: backgrounds from DD and ND in SD and from ND and SD in DD events are obtained from the PYTHIA8-MBR predictions (cf. Figs. 6 and 9), with the uncertainty estimated by varying their relative contributions by -10 % and +10 % (average normalization uncertainty of the model). Contribution from CD in SD and DD are negligible.

- an uncertainty in luminosity measurement of ±4 % [12, 13] is taken into account.

All individual uncertainties are added in quadrature, separately for the positive and negative deviations from the nominal cross section values, to obtain the total systematic uncertainty. Systematic uncertainties are significantly larger than the statistical ones, with the dominant source being due to the HF energy scale uncertainty. The uncertainty from the hadronization and diffraction modeling are also significant in some bins.

### 9 Rapidity gap cross section

Since it is not possible to measure the whole mass of the diffractively dissociated system due to the limited coverage in the forward region of the detector, one can alternatively measure the size of the corresponding pseudorapidity gap [14]. In each reconstructed event, the size of the gap between each edge of the detector at $\eta = +4.7$ and $\eta = -4.7$ and the position in $\eta$ of the first particle found in moving away from the edge is designated as the largest forward rapidity gap, $\Delta\eta^F$. The uncorrected distribution of the forward rapidity gap size is shown in Fig. 11, along with the predictions of various MC models.

![Figure 11: Comparison of measured uncorrected forward-gap-size distribution, $\Delta\eta^F$ (black points), along with the MC predictions.](image-url)
9.1 Corrections for experimental effects

The differential cross section of forward rapidity gaps is determined in bins of $\Delta \eta^F$ with the formula

$$\frac{d\sigma(\Delta \eta^F)}{d\Delta \eta^F} = \frac{A(\Delta \eta^F) N(\Delta \eta^F) - N_{BG}(\Delta \eta^F)}{\epsilon(\Delta \eta^F) \times L},$$

where $A(\Delta \eta^F)$ is the correction factor for the migration between bins, $\Delta \eta_{\text{bin}}$ is the bin width, $N(\Delta \eta^F)$ is the number of minimum bias events, and $N_{BG}(\Delta \eta^F)$ is the number of background events obtained from circulating beams. The $\epsilon(\Delta \eta^F)$ is the trigger efficiency of a single-side BSC trigger with at least two offline hits, and $L$ is the total integrated luminosity. The data used for the signal extraction correspond to an integrated luminosity of 20.3 $\mu b^{-1}$ with an average pile-up of 0.0066.

The background from circulating beams, given in Fig. 12, is estimated from unpaired bunches using a zero-bias dataset, and scaled by 0.5 considering the number of satellite bunches, which is twice larger than the number of collision bunches. The background is numerically subtracted from each measured $\Delta \eta^F$ bin. The overall background is found to be $\approx 0.7\%$.

The single-side BSC trigger efficiency, obtained from zero-bias data for events with at least two offline hits in either side of the BSC, is shown in Fig. 13. The trigger efficiency correction factors are obtained from a fit to the data. The discrepancy between the fit and the data-points has a small effect on the results and is covered by the systematics.

The migration matrix between the truth and reconstructed $\Delta \eta^F$ according to PYTHIA8-MBR ($\epsilon = 0.08$) is given in Fig. 14. A better correlation is observed with a $p_T > 200$ MeV cut at truth level. The corresponding hadron-level definition of the analysis considers all stable final-state particles with $p_T > 200$ MeV in $|\eta| < 4.7$. The Bayesian unfolding method is used to correct the data for the migration between bins, and the effect of the fake (measured events with no corresponding truth) and miss (unmeasured) events is also taken into account.

![Figure 12: Beam background from unpaired bunches.](image-url)
9.1 Corrections for experimental effects

Figure 13: The single-side BSC trigger efficiency for at least two hits (offline) in either side of the BSC. The trigger efficiency correction factors are obtained from a fit to the data. The discrepancy between the fit and the data-points has a small effect on the results and is covered by the systematics.

Figure 14: Migration matrix between the truth and reconstructed $\Delta \eta^F$ according to PYTHIA8-MBR ($\epsilon = 0.08$) for stable final-state particles with $p_T > 200$ MeV in $|\eta| < 4.7$. The plot is normalized to unity in each column.
9.2 Systematic uncertainties

The following uncertainties are taken into account and summed in quadrature to estimate the final systematic error on the measurement.

- HF energy-scale uncertainty,
- PF energy-thresholds uncertainty,
- Modeling uncertainty,
- Unfolding-technique uncertainty,
- Luminosity uncertainty.

The HF energy-scale uncertainty is estimated by varying the energy of PF HF objects in MC by ±10%. The noise thresholds of PF objects are raised by 10% to determine the systematic uncertainty of the PF-object thresholds. The model dependence of hadronization is estimated using \textsc{pythia} 8 and \textsc{pythia} 6, where both models are evolved separately and the average of the differences with the default unfolded data is taken as the uncertainty. This is the dominant source of the uncertainty, particularly in the $1 < \Delta \eta^F < 3$ region. Differences due to parametrization of diffractive modeling are accounted for by using a \textsc{pythia} 8-MBR sample generated with $\epsilon = 0.104$. The systematic uncertainty on the unfolding technique is studied by switching between the default Bayesian method and the bin-by-bin method. In addition, a ±4% normalization uncertainty is added due to the uncertainty on the integrated luminosity measurement \cite{12, 13}. All above uncertainties are summed in quadrature, and the total uncertainty is applied symmetrically upwards and downwards. Finally, the region of $\Delta \eta^F > 8.4$ is removed due to the very large uncertainty and the trigger inefficiency in that region.

9.3 Corrected results

The unfolded and fully corrected differential cross section of the forward rapidity gap size, $d\sigma/d\Delta \eta^F$, for particles with $p_T > 200$ MeV in $|\eta| < 4.7$ is given in Fig. 15, along with the hadron-level predictions of \textsc{pythia} 8-MBR ($\epsilon = 0.08$ and 0.104), \textsc{pythia} 8 tune 4C, and \textsc{pythia} 6 tune Z2star. The total systematic uncertainty of the measurement, which is $\lesssim 20 \%$, is shown with a green band. The results show that in the limited pseudo-rapidity coverage of the detector, $|\eta| < 4.7$, a large fraction of non-diffractive events can be suppressed by a $\Delta \eta^F > 3$ cut.

\textsc{atlas} previously measured the pseudorapidity gap cross section in $|\eta| < 4.9$ using all stable final-state particles with $p_T > 200$ MeV. Although the hadron-level definition is not quite the same (CMS gaps start at $|\eta| = \pm 4.7$), a comparison of the CMS result with the \textsc{atlas} measurement is given in Fig. 16. The green band represents the total systematic uncertainty of the CMS measurement, while the \textsc{atlas} measurement is incorporated in the error bars of the \textsc{atlas} points. The CMS result extends the \textsc{atlas} measurement by 0.4 unit of gap size.
Figure 15: Unfolded and fully corrected differential cross section of the forward rapidity gap size \( \frac{d\sigma}{d\Delta\eta^F} \) for stable particles with \( p_T > 200 \text{ MeV} \) in \( |\eta| < 4.7 \) are compared with the hadron-level predictions of (a) PYTHIA8-MBR \((\epsilon = 0.08)\), (b) PYTHIA8-MBR \((\epsilon = 0.104)\), (c) PYTHIA8 tune 4C and PYTHIA6 tune Z2star. The green band represents the total systematic uncertainty on the measurement which is obtained as the quadrature sum of the different uncertainty sources.
Figure 16: Comparison of CMS measurement (black points) with ATLAS result (blue points). The green band represents the total systematic uncertainty of the CMS measurement, while the total uncertainty of ATLAS measurement is shown by the error bars on the ATLAS points. The hadron-level definitions of the two measurements are not the same. CMS measures the forward rapidity gap size in \( \eta \) starting from \( \eta = \pm 4.7 \), whereas the ATLAS limit is \( \eta = \pm 4.9 \).

10 Summary

Results are reported for the single- and double-diffractive cross sections in pp collisions at \( \sqrt{s} = 7 \) TeV at the LHC using the CMS detector.

The differential SD cross section is measured as a function of \( \xi \), the forward momentum loss of the incoming proton, for \( -5.5 < \log_{10} \xi < -2.5 \). In this region, the total measured SD cross section is \( 4.27 \pm 0.04 \) (stat.) \( +0.65^{+0.55}_{-0.58} \) (syst.) mb.

The differential DD cross section is measured using events for which one hadronic system is detected in the central detector (12 \( \lesssim M_X \lesssim 394 \) GeV) and the other one in the CASTOR calorimeter (3.2 \( \lesssim M_Y \lesssim 12 \) GeV), as a function of \( \xi_X = M_X^2/s \) for \( -5.5 < \log_{10} \xi_X < -2.5 \). The DD cross section is also measured differentially as a function of the width of the central pseudorapidity gap, \( \Delta \eta \), for \( \Delta \eta > 3 \) and \( M_X, M_Y > 10 \) GeV. The total DD cross section integrated over this region is \( 0.93 \pm 0.01 \) (stat.) \( +0.26^{+0.26}_{-0.22} \) (syst.) mb.

In addition, the inclusive differential cross section for events with a forward rapidity gap \( (d\sigma/d\Delta \eta^F) \) is measured over \( \Delta \eta^F = 8.4 \) units of pseudorapidity. The result extends the ATLAS measurement by 0.4 unit of gap size.

Measurements are compared to results from other experiments and to theoretical predictions.

References


