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Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration[*]

Abstract

A measurement of the inelastic proton-proton cross section with the CMS detector at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ is presented. The analysis is based on events with energy deposits in the forward calorimeters, which cover pseudorapidities of $-6.6 < \eta < -3.0$ and $+3.0 < \eta < +5.2$. An inelastic cross section of $68.6 \pm 0.5\,\text{(syst)} \pm 1.6\,\text{(lumi)}\,\text{mb}$ is obtained for events with $M_\text{X} > 4.1\,\text{GeV}$ and/or $M_\text{Y} > 13\,\text{GeV}$, where M_X and M_Y are the masses of the diffractive dissociation systems at negative and positive pseudorapidities, respectively. The results are compared with those from other experiments as well as to predictions from high-energy hadron-hadron interaction models.

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[*] See Appendix A for the list of collaboration members

1 Introduction

Inclusive hadron-hadron cross sections are fundamental observables in high-energy particle, nuclear, and cosmic ray physics, and have been measured in experiments covering many orders of magnitude in center-of-mass energy, $\sqrt{s}$. The hadron-hadron cross section can be decomposed into elastic and inelastic contributions (including diffractive and nondiffractive topologies), each of which can be described by nonperturbative phenomenological models, based on general principles such as unitarity and analyticity [1]. These models have, however, large uncertainties when extrapolating existing data to higher center-of-mass energies [2–4], and need to be constrained by measurements.

Precise measurements of the proton-proton (pp) cross sections at CERN LHC energies provide valuable input for phenomenological hadronic interaction models, as well as for the tuning of Monte Carlo (MC) event generators used in collider [5–9] and cosmic ray physics [10]. The value of the inelastic pp cross section, σ_{inel}, is also used in the estimation of the number of simultaneous pp interactions occurring in the same beam-bunch crossing (henceforward referred to as "pileup") and is thus an important quantity to properly control the backgrounds in pp collision events measured at the LHC. It is also a crucial ingredient of Glauber models used to describe high-energy nuclear collisions [11].

At $\sqrt{s} = 7\,\text{TeV}$, there have been several pp cross section measurements at the LHC. The CMS Collaboration has measured an inelastic pp cross section of $60.2 \pm 0.2\,\text{(stat)} \pm 1.1\,\text{(syst)} \pm 2.4\,\text{(lumi)}\,\text{mb}$ in a phase space region that excludes elastic and diffractive proton dissociation events with very low invariant mass of the dissociation system [12], namely for $\xi = M^2/s > 5 \times 10^{-6}$, with M the invariant mass of the larger of the two diffractive dissociation systems (which corresponds to $M > 15.7\,\text{GeV}$). The ATLAS [13] and ALICE [14] Collaborations measured the inelastic pp cross section at $\sqrt{s} = 7\,\text{TeV}$ in the same phase space and reported consistent values. Several collaborations have extrapolated their measurements to the full inelastic phase space. The values reported for the total inelastic pp cross section at $\sqrt{s} = 7\,\text{TeV}$ range from 66.9 ± 5.3 to $73.7 \pm 3.4\,\text{mb}$[13–19]. The TOTEM Collaboration, in particular, derived the inelastic cross section by exploiting the optical theorem, thereby avoiding model-dependent extrapolations for the low-mass diffraction contribution. A value of $73.2 \pm 1.3\,\text{mb}$ was obtained [18].

At $\sqrt{s} = 8\,\text{TeV}$, the TOTEM Collaboration also measured the total, elastic, and inelastic pp cross sections [20], reporting a value of $\sigma_{\text{inel}} = 74.7 \pm 1.7\,\text{mb}$.

At $\sqrt{s} = 13\,\text{TeV}$, the ATLAS Collaboration reported a measurement of the inelastic pp cross section of $68.1 \pm 0.6\,\text{(syst)} \pm 1.3\,\text{(lumi)}\,\text{mb}$ for $\xi > 10^{-6}$ (corresponding to $M > 13\,\text{GeV}$) [21]. This value has been extrapolated to the total inelastic phase space, yielding $\sigma_{\text{inel}} = 78.1 \pm 0.6\,\text{(syst)} \pm 1.3\,\text{(lumi)} \pm 2.6\,\text{(extr)}\,\text{mb}$, with the last number being the extrapolation uncertainty. Finally, the TOTEM Collaboration obtained a value for the inelastic cross section at $\sqrt{s} = 13\,\text{TeV}$ of $\sigma_{\text{inel}} = 79.5 \pm 1.8\,\text{(syst)}\,\text{mb}$ [22].

This paper presents a new measurement of the inelastic cross section in pp collisions at $\sqrt{s} = 13\,\text{TeV}$. Data collected with the CMS forward calorimeters HF and CASTOR, covering pseudorapidities $-6.6 < \eta < -3.0$ and $+3.0 < \eta < +5.2$, are analyzed. These detectors provide sensitivity to a large part of the total inelastic cross section, including diffractive events with dissociated protons that produce particles only at forward rapidity, with the exception of low-mass diffraction and events that happen to have rapidity gaps in the regions covered, including central exclusive production via double pomeron exchange. The fiducial cross section is therefore measured in a phase space region excluding fractional momentum losses of the scattered protons $\xi_X = M_X^2/s < 10^{-7}$ and $\xi_Y = M_Y^2/s < 10^{-6}$, corresponding to $M_X < 4.1\,\text{GeV}$ and $M_Y < 13\,\text{GeV}$, where M_X and M_Y are defined as the invariant masses of the dissociated proton systems with negative and positive pseudorapidities, respectively. The use of the CASTOR forward calorimeter allows the extension of this type of measurement to a low mass region so far unexplored.

2 The CMS detector

CMS uses a right-handed coordinate system, with the origin at the nominal interaction 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 central feature of the CMS apparatus [23] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of $B = 3.8\,\text{T}$ parallel to the beams. Within the solenoid volume are a silicon pixel and strip tracker (covering $|\eta| < 2.5$), a lead tungstate crystal electromagnetic calorimeter ($|\eta| < 3$) , and a brass and scintillator hadron calorimeter ($|\eta| < 3$), each composed of a barrel and two endcap sections.

Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The forward hadron (HF) calorimeters are located on each side of the detector, covering the range $3.0 < |\eta| < 5.2$, and are each composed of 18 steel azimuthal (ϕ) wedges, with embedded quartz fibers running parallel to the beam direction. Each wedge is subdivided into 13 segments in η, called towers. The very forward angles are covered at one end of CMS ($-6.6 < \eta < -5.2$) by the CASTOR calorimeter [24]. This detector, consisting of tungsten absorbers and quartz detection planes, is segmented in 16 ϕ-sectors and into 2 electromagnetic and 12 hadronic modules along the beam line, corresponding to a total of 224 cells. For operational reasons the CASTOR calorimeter was only partially included in the detector setup during the run periods considered in this analysis, and the data with CASTOR included were taken with the solenoid switched off ($B = 0\,\text{T}$).

A more detailed description of the CMS detector can be found in Ref. [23].

3 Physics models

Various Monte Carlo event generators are used to correct the measured cross section for acceptance and instrumental effects, as well as to compare the final results to different hadron-hadron interaction model predictions.

The PYTHIA MC generator [5, 6] uses the Donnachie–Landshoff (DL) parametrization [2] for the total hadron-hadron cross section, and provides different approaches to determine the elastic and diffractive contributions (unless stated otherwise, the default Schuler–Sjöstrand (SS) model [3, 4] is used). The difference between the total cross section and the sum of the elastic and diffractive cross sections is used to normalize the nondiffractive part, which is generated through a regularization of perturbative multi-parton interaction cross sections. Event samples are generated with different underlying event tunes: the Z2* [25] tune is used for the PYTHIA 6 (version 6.426) sample, while PYTHIA 8 (version 8.205) samples are generated with the Monash [26] and CUETP8M1 [27] tunes. These differ in the parameters used to describe initial- and final-state parton showers, multi-parton interactions, and hadronization. Samples are generated with the Monash DL (using the Donnachie–Landshoff diffraction model [28]) and Minimum–Bias–Rockefeller (MBR) [29] tunes. The MBR approach is based on a phenomenological renormalized Regge theory [30, 31].

Two models based on Regge–Gribov phenomenology [32, 33], including the Abramowski–Gribov–Kancheli cutting rules [34], are also used: EPOS [7] (version 1.99) with its LHC tune and QGSJET-II (version 04) [8, 9].

4 Event selection and reconstruction

4.1 Event selection

This analysis is based on pp collision data collected with the CMS detector in 2015 at $\sqrt{s} = 13\,\text{TeV}$, during several running periods with low pileup. Runs for which the solenoid was off ($B = 0\,\text{T}$), as well as runs with the solenoid at its nominal field strength ($B = 3.8\,\text{T}$) are analyzed. The former runs, with CASTOR included in the detector setup, are used because of its larger acceptance for inelastic collisions.

The total integrated luminosity recorded in these runs amounts to 40.8 (28.0) μb^{-1} for $B = 3.8\,\text{T}$ ($B = 0\,\text{T}$). The measurement of the integrated luminosity for the $B = 3.8\,\text{T}$ data is based on the pixel tracker, and has been calibrated by means of a dedicated analysis of van der Meer scans [35] with an accuracy of 2.3%. The integrated luminosity for the $B = 0\,\text{T}$ sample is obtained by normalizing the fiducial cross section found at $B = 3.8\,\text{T}$ to the one at $B = 0\,\text{T}$ in the same phase space.

The CMS data acquisition was triggered [36] by the presence of both beams in the interaction point ("zero bias"), signaled by beam pick-up monitors located at ±175 m from the interaction point. Additional triggers requiring the presence of only one beam ("single bunch") or no beams ("empty bunch") were used to study beam-gas, electronic noise, and other backgrounds. These triggers are 100% efficient for the event selection under consideration. A first sample of inelastic events is then selected offline by requiring an energy deposit above 5 GeV in either of the two HF calorimeters. This threshold was optimized by studying detector noise in events without beam. The rate of selected events from single bunches was found to be consistent with the one from empty bunches. This demonstrates that the presence of the beam on one side does not generate more background events compared to no beam, and that the total background contribution can be estimated from the empty bunch events alone.

The presence of the CASTOR calorimeter in the $B = 0\,\text{T}$ data sample allows a larger coverage of the phase space for inelastic pp collisions. In this case, inelastic events are selected offline by requiring either an energy deposit above 5 GeV in either of the two HF calorimeters, or an energy deposit above 5 GeV in CASTOR.

4.2 Correction for noise and pileup

The selected number of inelastic events is first corrected for the contribution of detector noise. The corrected number of interactions is obtained as

$$N_{\text{cor}} = N_{\text{ZB}}[(F_{\text{ZB}} - F_{\text{EB}}) + F_{\text{EB}}(F_{\text{ZB}} - F_{\text{EB}})], \tag{1}$$

where N_{ZB} is the number of events triggered by the zero bias trigger and F_{ZB} and F_{EB} are the fractions of events triggered by the zero bias and empty bunch triggers that are selected offline by requiring an energy deposit above threshold, respectively. In Eq. (1), the second term on the right-hand side is a first-order correction for genuine signal events (with occurrence approximated by $F_{\text{ZB}} - F_{\text{EB}}$) overlaid with noise (with occurrence F_{EB}). Corrections of higher order in F_{EB} are found to be negligible. Table 1 includes an overview of the noise-subtracted fraction of events ($N_{\text{cor}}/(N_{\text{ZB}}\,F_{\text{ZB}})$) found in the various runs.

Table 1: Overview of the noise-subtracted fraction of events ($N_\text{cor}/(N_\text{ZB}\,F_\text{ZB})$), average pileup ($\lambda$), and fiducial cross section (with the statistical uncertainty) for all runs used in this analysis. The uncertainties in the noise-subtracted fraction of events and pileup (not shown) have a negligible contribution to the uncertainty in the fiducial cross section.

Runs $B = 3.8\,\text{T}$	$N_\text{cor}/(N_\text{ZB}\,F_\text{ZB})$ (%)	λ	Fiducial cross section (mb) $\xi > 10^{-6}$
254989	98.5	0.52	67.35 ± 0.05
255019	99.9	0.54	67.66 ± 0.04
255029	99.3	0.54	67.50 ± 0.04

Runs $B = 0\,\text{T}$	$N_\text{cor}/(N_\text{ZB}\,F_\text{ZB})$ (%)	λ	Fiducial cross section (mb) $\xi_\text{X} > 10^{-7}$ or $\xi_\text{Y} > 10^{-6}$
247324	98.5	0.05	68.88 ± 0.49
247920	98.9	0.34	68.63 ± 0.08
247934	98.8	0.32	68.63 ± 0.09

The number of events is further corrected for the effect of pileup. The observed number of pp collisions per bunch crossing, n, follows a Poisson distribution, $P(n, \lambda)$, with average value λ. As the probability to find an interaction in a crossing with filled bunches is given by N_cor/N_ZB, the probability to have no interaction can be obtained as $P(0, \lambda) \equiv \exp(-\lambda) = 1 - N_\text{cor}/N_\text{ZB}$, which allows λ to be determined from the data. With this information it is possible to correct the inelastic event count using the pileup correction factor:

$$f_\text{PU} = \frac{\sum_{n=0}^{\infty} nP(n,\lambda)}{\sum_{n=1}^{\infty} P(n,\lambda)} = \frac{\lambda}{1 - P(0,\lambda)}. \tag{2}$$

The values of λ in the studied runs range from 0.05 to 0.54 and are given in Table 1. As the beam intensity may vary from one proton bunch to another, the actual pileup correction is applied bunch-by-bunch. The total reconstructed number of interactions, corrected for the contributions of noise and pileup, is then given by

$$N_\text{int} = \sum_\text{bunches} N_\text{cor}^\text{b}\, f_\text{PU}^\text{b}, \tag{3}$$

with the number of noise-corrected events N_cor^b (Eq. (1)) and pileup correction factors f_PU^b (Eq. (2)) calculated for individual bunches.

5 Extraction of the fiducial inelastic cross section

Before comparison to theoretical predictions, the experimental results need to be corrected for various detector effects, including the event selection efficiency and the resolution in the energy measurement. Corrected results are obtained by means of a simulation of the CMS detector based on GEANT4 [37–39].

The event selection criteria at the detector level are optimized in order to obtain a sample of inelastic events in the largest possible phase space. Low-mass diffractive dissociation events will, however, escape the detector. Central exclusive production is found to be negligible with respect to the experimental uncertainty, both from model predictions and from counting events in the data with activity in the central detectors but without any energy deposited in the forward calorimeters. Adapting the particle-level phase space to the detector acceptance results in a smaller correction of the results, and thus also in a smaller model dependence of the correction factors. A precise definition of the phase space at the level of generated stable particles, for which corrected results are presented, is obtained as follows.

The collection of stable final-state particles (with proper lifetime $c\tau > 1\,\mathrm{cm}$) is divided into two systems, X and Y, based on the mean rapidity of the two particles separated by the largest rapidity gap in the event. All particles on the negative (positive) side of the largest gap are assigned to the system X (Y). The invariant masses, M_{X} and M_{Y}, of each system are calculated from the four-momenta of the individual particles, and are used to obtain the squared ratios of the mass over the center-of-mass energy, ξ_{X} and ξ_{Y}. For convenience, ξ can be defined by $\xi = \max(\xi_{\mathrm{X}}, \xi_{\mathrm{Y}})$. These Lorentz-invariant variables are well defined for any type of events (diffractive and nondiffractive) and are related to the size of the largest rapidity gap [1].

The fiducial phase space can then be quantified at the stable-particle level by appropriate limits on ξ_{X} and ξ_{Y}. These acceptance limits are obtained from a dedicated study based on the hadron-hadron interaction models mentioned in Section 3 using fully simulated events, and are chosen such that the factors required to correct the data to stable-particle level are close to unity, thereby minimizing the model dependence of the correction. An inelastic event is selected at the stable-particle level if $\xi > 10^{-6}$ for the selection based on the HF calorimeter alone, and, because the CASTOR calorimeter allows a lower ξ limit on one side, if $\xi_{\mathrm{X}} > 10^{-7}$ or $\xi_{\mathrm{Y}} > 10^{-6}$ when the HF and CASTOR calorimeters are combined.

The relationship between the stable-particle level phase space definition and the detector-level offline selection can be quantified through efficiency and contamination factors. The efficiency, ϵ_{ξ}, is defined as the fraction of selected stable-particle level events that fulfill the detector-level offline selection criteria, while the contamination, b_{ξ}, is defined as the fraction of detector-level offline selected events that are not part of the considered stable-particle level phase space. The efficiency and contamination factors are calculated as the average over MC models and are found to be equal to 97.6% and 0.6% (98.6% and 0.6%) for the HF (HF+CASTOR) fiducial region, respectively.

Finally, the fiducial cross section is calculated as

$$\sigma = \frac{N_{\mathrm{int}}(1 - b_{\xi})}{\epsilon_{\xi}\,\mathcal{L}}, \tag{4}$$

and is given in Table 1 for all runs used in the analysis. The integrated luminosity, $\mathcal{L}$, of the $B = 0\,\mathrm{T}$ runs has been rescaled in order to yield the same cross section for $\xi > 10^{-6}$ as measured in the $B = 3.8\,\mathrm{T}$ runs, thus exploiting the more accurate luminosity determination in the latter runs.

6 Systematic uncertainties

The following sources of systematic bias are investigated and the corresponding uncertainties are evaluated.

- **Model dependence.** The efficiency and contamination factors are obtained from MC simulation. Although the phase space domains are chosen so as to minimize extrapolations, there is a remaining model dependence due to the matching of stable-particle level and detector-level selections. This uncertainty is taken as the standard

Table 2: Overview of systematic uncertainties from various sources that contribute to the cross section uncertainty in the two phase space regions considered in this analysis.

	$\sigma(\xi > 10^{-6})$ (mb)	$\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6})$ (mb)
Model dependence	0.68	0.39
HF energy scale uncertainty	0.35	0.14
CASTOR energy scale uncertainty	—	0.04
Run-to-run variation	0.15	0.14
Total	0.78	0.45
Integrated luminosity uncertainty	1.55	1.58

deviation of the correction factors obtained from all the models discussed in Section 3.

- **HF and CASTOR energy scale uncertainties.** The energy scales for the HF and CASTOR calorimeters have been estimated with an accuracy of 10% [40] and 15% [41, 42], respectively. The systematic uncertainties are estimated as the change in the fiducial cross section after varying the reconstructed energy in HF and CASTOR by the energy scale uncertainty upwards and downwards.
- **Run-to-run variation.** The cross sections are obtained from various runs and the run-to-run variation is taken as an additional source of systematic uncertainty, estimated as the standard deviation of the cross section distribution.
- **Integrated luminosity.** The integrated luminosity of the runs at $B = 3.8\,\mathrm{T}$ is determined with an accuracy of 2.3% [35]. The integrated luminosity of the $B = 0\,\mathrm{T}$ runs is rescaled using the ratio of the cross sections for $\xi > 10^{-6}$ at $B = 0\,\mathrm{T}$ and $B = 3.8\,\mathrm{T}$. This procedure has a negligible effect on the accuracy of integrated luminosity at $B = 0\,\mathrm{T}$ because the energy scale and model uncertainties are fully correlated between the $B = 0\,\mathrm{T}$ and $B = 3.8\,\mathrm{T}$ samples. Hence, the same accuracy of 2.3% is used to determine the systematic uncertainty due to the integrated luminosity determination at $B = 0\,\mathrm{T}$.

Table 2 gives an overview of the systematic uncertainties.

7 Results

The fully corrected cross sections in phase space domains corresponding to the specific detector acceptances (fiducial cross sections) are given in Table 1. The weighted average of the results at $B = 3.8\,\mathrm{T}$ obtained with the HF calorimeters only is

$$\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8\,(\mathrm{syst}) \pm 1.6\,(\mathrm{lumi})\,\mathrm{mb}, \tag{5}$$

with negligible statistical uncertainty. This can be compared to the cross section reported by ATLAS for inelastic pp collisions at 13 TeV with $\xi > 10^{-6}$ of $68.1 \pm 0.6\,(\mathrm{syst}) \pm 1.3\,(\mathrm{lumi})\,\mathrm{mb}$ [21].

Averaging the cross sections obtained from runs with the HF and CASTOR calorimeters in the extended phase space yields

$$\sigma(\xi_X > 10^{-7}\,\mathrm{or}\,\xi_Y > 10^{-6}) = 68.6 \pm 0.5\,(\mathrm{syst}) \pm 1.6\,(\mathrm{lumi})\,\mathrm{mb}, \tag{6}$$

also with negligible statistical uncertainty.

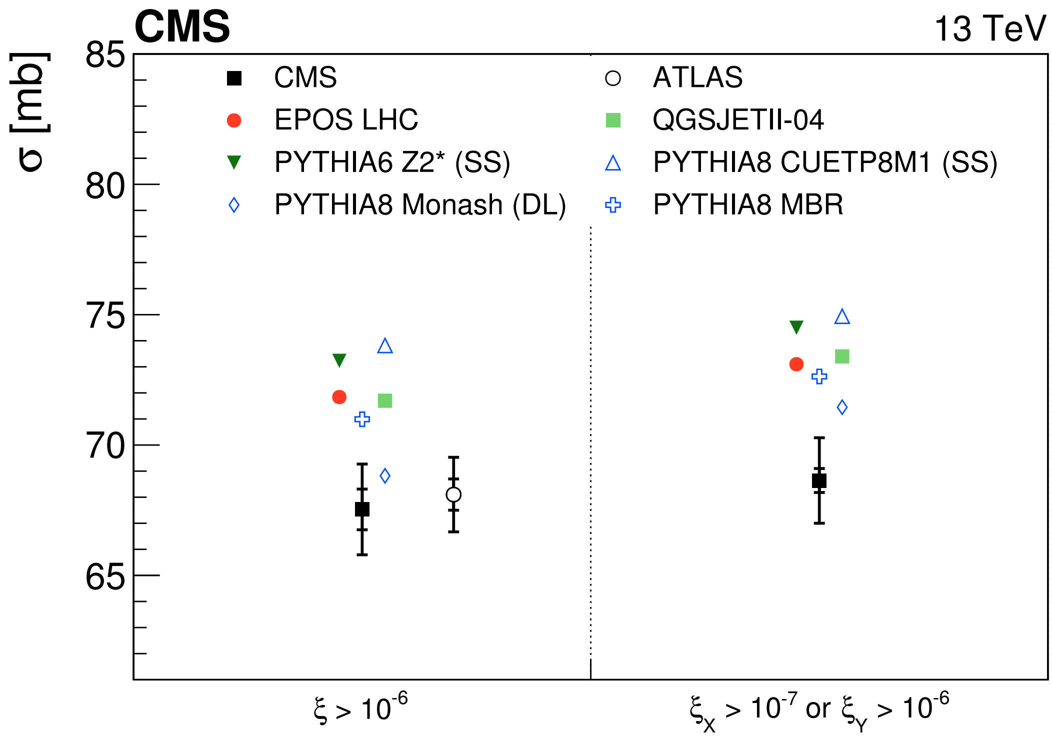

Figure 1: Proton-proton inelastic cross section at $\sqrt{s} = 13\,\text{TeV}$ in two phase space regions, where $\xi = M^2/s$, compared to different models and to the ATLAS result. The inner error bar on the CMS and ATLAS data points indicates the systematic uncertainty only, while the full error bar reflects the total (including the integrated luminosity) uncertainty. The horizontal placement of the points within each phase space bin is arbitrary.

Figure 1 shows the inelastic cross sections in the two phase space domains compared to the predictions of the various models used in this analysis. Table 3 shows the increase in the cross section from $\xi > 10^{-6}$ to $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$ for the data and the various models. The variation between model predictions is mainly due to different descriptions of the diffractive contribution to the cross section. This can be concluded from the fact that models with the same approach to diffraction predict very similar cross sections (EPOS LHC and QGSETII-04, versus PYTHIA 6 Z2* (SS) and PYTHIA 8 CUETP8M1 (SS), respectively). Most models describe reasonably well the small, but significant, relative increase in the inelastic cross section, but in general overpredict their value in both ξ ranges. The PYTHIA 8 Monash (DL) model describes data fairly well for $\xi > 10^{-6}$, but predicts a too steep increase for $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$. Moreover, a comparison of the same models to fiducial and total inelastic cross section measurements at $\sqrt{s} = 7$ and $13\,\text{TeV}$ [12–18, 21, 22] indicates that, while the total inelastic cross section is reasonably well described, the cross section for diffractive dissociation events escaping detection, at masses even lower than those considered here, is substantially underestimated by the models, leading to an overestimation of the fiducial cross sections. One may therefore conclude that a model-based extrapolation of the fiducial cross section to the total inelastic phase space would yield a value that is too low for most models.

Table 3: Relative increase in the cross section from the $\xi > 10^{-6}$ to the $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$ fiducial region. The uncertainty in the cross section ratio in data is obtained using systematic uncertainties only, varying each uncertainty source simultaneously for both phase space regions and obtaining the total uncertainty from the variation of the ratio (thus assuming full correlation between both measurements).

	Relative cross section increase in %
Data	1.64 ± 0.53
EPOS LHC	1.76
QGSJETII-04	2.36
PYTHIA 6 Z2* (SS)	1.74
PYTHIA 8 CUETP8M1 (SS)	1.52
PYTHIA 8 Monash (DL)	3.83
PYTHIA 8 MBR	2.32

8 Summary

A measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13\,\text{TeV}$ with the CMS detector at the LHC has been presented. An inelastic cross section of $67.5 \pm 0.8\,(\text{syst}) \pm 1.6\,(\text{lumi})$ mb is obtained for $\xi = M^2/s > 10^{-6}$ (corresponding to $M > 13\,\text{GeV}$), with M the larger of M_X and M_Y, where M_X and M_Y are the masses of the diffractive dissociation systems with negative and positive pseudorapidities, respectively, consistent with a previous measurement in the same phase space [21]. In addition, an inelastic cross section of $68.6 \pm 0.5\,(\text{syst}) \pm 1.6\,(\text{lumi})$ mb is obtained in the enlarged phase space $\xi_X > 10^{-7}$ and/or $\xi_Y > 10^{-6}$ (corresponding to $M_X > 4.1\,\text{GeV}$ and/or $M_Y > 13\,\text{GeV}$). The measured cross sections are smaller than those predicted by the majority of models for hadron-hadron scattering. In contrast, the same models generally describe reasonably well the measurements of the total inelastic cross section at $\sqrt{s} = 13\,\text{TeV}$ [21, 22]. Given that the difference between the two sets of measurements is dominated by the contribution from low-mass diffractive processes, the data-model discrepancies observed here suggest a theoretical underestimation of the cross section for such events.

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