Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13$ TeV with the ATLAS Detector at the LHC

The ATLAS Collaboration

Abstract

This Letter presents a measurement of the inelastic proton-proton cross section using 60 \( \mu \text{b}^{-1} \) of \( pp \) collisions at a center-of-mass energy $\sqrt{s}$ of 13 TeV with the ATLAS detector at the LHC. Inelastic interactions are selected using highly efficient plastic scintillators in the forward region of the detector. A cross section of 68.2±1.5 mb is measured in the fiducial region $\xi = M_X^2/s > 10^{-6}$, where $M_X$ is the largest invariant mass of the two hadronic systems separated by the largest rapidity gap in the event. For diffractive events this corresponds to cases where at least one proton dissociates to a system of mass larger than 13 GeV. The measurement agrees with a range of theoretical predictions. When extrapolated to the full phase space, the result is consistent with an inelastic cross section increasing with center-of-mass energy, as observed at lower energies.
The rise of the total proton-proton (pp) cross section with center-of-mass energy \( \sqrt{s} \), first predicted by Heisenberg [1] and observed by experiments at the CERN Intersecting Storage Rings [2], provides a probe of the non-perturbative regime of quantum chromodynamics (QCD). General arguments based on unitarity, analyticity, and factorization imply an upper bound (the Froissart bound [3–5]) on the high-energy behavior of total hadronic cross sections that prevents them from rising more rapidly than \( \ln^2(s) \).

This Letter presents a measurement of the inelastic cross section \( \sigma_{\text{inel}} \) using pp collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector at the Large Hadron Collider (LHC). In inelastic interactions, one or both protons dissociate as a result of colored (non-diffractive) or colorless (diffractive) exchange. The fiducial region of this measurement excludes elastic pp scattering and diffractive dissociation processes in which neither proton is dissociated into a system of mass \( M_X > 13 \) GeV, or equivalently, \( \xi = M_X^2/s > 10^{-6} \). The measurement is reported for this fiducial region and after extrapolation to the total inelastic cross section using models of inelastic interactions. It is performed using two sets of scintillation counters in a dataset corresponding to an integrated luminosity of 60.1 \( \pm \) 1.1 \( \mu \)b\(^{-1} \) collected in June 2015. During this data-taking period, the mean number of pp collisions in the same LHC bunch crossing was 2.3 \( \times \) 10\(^{-3} \), and thus the contribution from multiple collisions is negligible.

Many experiments have measured \( \sigma_{\text{inel}} \) and found an increase with \( \sqrt{s} \) [6]. The previous measurement of \( \sigma_{\text{inel}} \) with the ATLAS detector at \( \sqrt{s} = 7 \) TeV [7] used the method employed in this letter in a fiducial region defined by \( \xi > 5 \times 10^{-6} \). The TOTEM and ATLAS collaborations also determined \( \sigma_{\text{inel}} \) at \( \sqrt{s} = 7 \) TeV using the optical theorem and a measurement of the elastic cross section with Roman pot detectors [8, 9]. The TOTEM Collaboration performed similar measurements at \( \sqrt{s} = 8 \) TeV [10, 11]. Using a variety of different techniques, the CMS, ALICE, and LHCb experiments have made measurements of \( \sigma_{\text{inel}} \) at \( \sqrt{s} = 7 \) TeV [12–14]. The ALICE Collaboration additionally measured it at \( \sqrt{s} = 2.76 \) TeV [13]. The Pierre Auger Collaboration measured the inelastic p-air cross section at \( \sqrt{s} = 57 \) TeV and extracted \( \sigma_{\text{inel}} \) using the Glauber model [15].

The ATLAS detector is a cylindrical particle detector\(^1\) composed of several subdetector layers [16]. The inner tracking detector (ID) comprises silicon pixel and strip detectors and a straw-tube tracker immersed in a 2 T magnetic field provided by a superconducting solenoid. Around the tracker there is a system of electromagnetic and hadronic calorimeters, which use liquid argon and lead, copper, or tungsten absorber for the electromagnetic and forward (|\( \eta \)| > 1.7) hadronic components of the detector, and scintillator-tile active material and steel absorber for the central (|\( \eta \)| < 1.7) hadronic component.

At \( z = \pm 3.6 \) m, thin plastic scintillation counters, named the minimum-bias trigger scintillators (MBTS), are installed on the front face of each endcap calorimeter. These detectors cover the region \( 2.07 < |\eta| < 3.86 \). They are similar to those described in Ref. [16] but were rebuilt during 2014, when the coverage was slightly extended from \( 2.08 < |\eta| < 3.75 \) after the previous run at \( \sqrt{s} = 7 \) TeV. The MBTS are divided into inner (149 < \( r < 445 \) mm) and outer (444.5 < \( r < 895 \) mm) octagonal rings, with 8 counters in the inner ring and 4 counters in the outer ring.

The ATLAS experiment uses a hardware-based first-level trigger to select events at about 75 kHz and a software-based high-level trigger to record events at about 1 kHz for offline analysis. Three trigger configurations were used to collect data for this analysis. The primary triggers use the MBTS detector and constant-fraction discriminators to select events when two proton bunches collide in the detector. To

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\(^1\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the \( z \)-axis along the beam pipe. The \( x \)-axis points from the IP to the center of the LHC ring, and the \( y \)-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \).
facilitate background studies, data were also collected with the same selection when no proton bunch ("empty") or a single proton bunch from only one of the two beams ("single beam") was passing through the center of ATLAS. All these triggers require at least one MBTS hit above threshold. Two additional triggers were used to collect data to determine the efficiency of the MBTS trigger, requiring either hits in a forward (5.6 < |η| < 5.9) Cerenkov detector (LUCID) or a far forward (|η| > 8.4) tungsten-scintillator calorimeter detector (LHCf [17]) located at z = ±17 m and ±140 m, respectively. The LHCf detector is an independent detector, but for the runs considered in this analysis, its trigger signals were incorporated into the ATLAS readout.

Several Monte Carlo (MC) simulation samples were produced to correct the fiducial measurement and to compare to the data. The detector response is modeled using a simulation based on Geant4 [18–20]. The data and MC simulated events are passed through the same reconstruction and analysis software.

The primary MC samples are based on the Pythia8 generator [21, 22] either with the A2 [23] set of tuned underlying-event parameters and the MSTW 2008 LO PDF set [24] or with the Monash [25] set of tuned underlying-event parameters and the NNPDF 2.3 LO PDF set [26]. The samples are divided into four components: single-dissociation (SD, pp → pX), double-dissociation (DD, pp → XY), central-dissociation (CD, pp → pXp), all of which involve colorless exchange, and non-diffractive dissociation (ND) wherein color flow is present between the two colliding protons. For all dissociation event types, the Monash tune is used by default.

Pythia8 uses a pomeron-based diffraction model [27] to describe colorless exchanges between two protons. The default model has a pomeron flux model by Schuler and Sjöstrand (SS) [28, 29]. Alternative MC samples are generated with the pomeron flux model of Donnachie and Landshoff (DL) [30] and with the minimum-bias Rockefeller (MBR) simulation of pp interactions [31]. In the DL model, the pomeron Regge trajectory is given by \( \alpha(t) = 1 + \varepsilon + \alpha' t \), where \( \varepsilon \) and \( \alpha' \) are free parameters. In most of the samples used for this analysis, the value of \( \alpha' \) is 0.25, the Pythia8 default. The \( \varepsilon \) parameter is varied from 0.06 to 0.10 (the Pythia8 default is 0.085). An additional sample produced with \( \alpha' = 0.35 \) is found to be statistically consistent with the \( \alpha' = 0.25 \) default samples in each aspect of this analysis. The ranges of \( \varepsilon \) and \( \alpha' \) considered are motivated by previous total, inelastic, elastic, and diffractive cross-section measurements, including measurements of low-mass diffraction by the ATLAS and CMS collaborations [32, 33]. For the DL and SS models the CD component is neglected. The MBR model is tuned to data as described in Ref. [31], and unlike the other models of diffraction, includes a small CD component.

Two other event generators, Eros LHC and QGSJet-II, are also used to simulate pp collisions. The Eros LHC event generator [34] uses a “cut pomeron” model for diffraction and differs significantly from Pythia8 in its modeling of hadronization and the underlying event. The QGSJet-II event generator [35, 36] uses Reggeon field theory to describe pomeron-pomeron interactions. Both Eros LHC and QGSJet-II have been developed primarily to model cosmic-ray showering in the atmosphere.

The fiducial region of the measurement is determined from MC simulation. In each generated event, the largest rapidity gap between any two final-state hadrons is used to define the boundary between two collections of hadrons. These collections define the dissociation systems in a generalized manner applicable to any event sample. The invariant mass of each collection is calculated, and the larger of the two masses, denoted \( M_X \), is used to define \( \xi = M_X^2/s \). The variable \( \xi \) is constrained to be \( > 6 \times 10^{-9} \) by the elastic limit of \( m_p^2/s \) where \( m_p \) is the mass of the proton. This measurement is restricted to \( \xi > 10^{-6} \), the region in which the event selection efficiency exceeds 50%.

Two samples of data events passing the MBTS trigger requirements are selected: an inclusive sample and a single-sided sample. The inclusive selection requires at least two MBTS counters with a charge...
above a threshold of 0.15 pC ($n_{MBTS} \geq 2$). This threshold is chosen to be well above the electronic noise level of the counters. Requiring two hits rather than one hit substantially reduces background due to collision-induced radiation and activation. To constrain the diffractive component of the cross section and to reduce the uncertainty in extrapolation to $\sigma_{inel}$, an additional single-sided selection is defined, requiring hits above threshold in at least two counters on one side of the detector and no hits on the other. In the data, 4,159,074 events pass the inclusive selection and 442,192 events pass the single-sided selection.

The fiducial cross section is determined by

$$\sigma_{fid}^{inel}(\xi > 10^{-6}) = \frac{N - N_{BG}}{\epsilon_{trig} \times L} \times \frac{1 - f_{\xi<10^{-6}}}{\epsilon_{sel}},$$

where $N$ is the number of observed events passing the inclusive selection, $N_{BG}$ is the number of background events, $\epsilon_{trig}$ and $\epsilon_{sel}$ are factors accounting for the trigger and event selection efficiencies, $1 - f_{\xi<10^{-6}}$ accounts for the migration of events with $\xi < 10^{-6}$ into the fiducial region, and $L$ is the integrated luminosity of the sample.

There are several sources of background, including interactions between the beam and residual gas in the beam pipe (beam-gas interactions), interactions between the beam and collimators upstream of the detector, which can send charged particles through the detector parallel to the beam (beam-halo events), collision-induced radiation, and activation backgrounds. Backgrounds from cosmic rays and instrumental noise are negligible. The beam-related background components are extracted from single-beam events and dominate the total background. They are normalized by scaling the number of selected single-beam events by a factor of $37^4 \times 2$, accounting for the 37 colliding pairs of bunches and 4 bunches producing the single-beam data in this run. The factor of 2 accounts for the presence of two colliding bunches. The number of protons per bunch producing these single-beam events agrees with that in the colliding bunches to within 10%. The radiation and activation-induced backgrounds are implicitly part of this background estimate. Double-counting of these components is removed using estimates from events read out when no bunches were passing through the center of the detector. The total background contributions to the inclusive and single-sided data samples are determined to be 1.2% and 5.8% respectively. The classification of single-sided events as double-sided due to noise and other backgrounds is estimated to be below 0.1%. A systematic uncertainty of 50% is assigned to the background based on studies of the background composition and the relative contributions of the beam-gas, beam-halo, and radiation and activation components. This uncertainty is treated as fully correlated between the single-sided and inclusive selections.

The trigger efficiency for events passing the inclusive selection, $\epsilon_{trig}$, is measured with respect to events selected with the LUCID and LHCf detectors after subtracting the background as a function of the number of MBTS hits above threshold. A trigger efficiency of 99.7% is measured for the inclusive event sample, and 97.4% for the single-sided sample. In both cases the statistical uncertainty is below 0.1%. The measurements based on the LUCID and LHCf detectors agree within ±0.3%, and this difference is taken as a systematic uncertainty.

The ratio of the number of events passing the single-sided event selection to the number passing the inclusive selection ($R_{SS}$) is used to adjust, for each model separately, the fractional contribution of the single- and double-diffractive dissociative cross section ($\sigma_{SD}$ + $\sigma_{DD}$) to the inelastic cross section, $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel}$ [7].
The measured value is $R_{SS} = 10.4\%$ with a total uncertainty of $\pm 0.4\%$. The dominant systematic uncertainty arises from the background subtraction in the single-sided sample. For each MC model, $f_D$ is varied until it matches the observed $R_{SS}$ value in data. The data uncertainty is used to set the error in the constrained $f_D$ for each model. An additional uncertainty in the ratio of single- to double-diffractive events is determined by taking the diffractive events to be entirely SD or to be evenly divided between SD and DD.

Using this method, the fitted $f_D$ in the Pythia8 samples is between 25% and 31%, depending on the model (the default value is 28%). For the QGSJet-II (Epos LHC) model the fitted $f_D$ is 35% (37%), and differs significantly from the default value of 21% (28%). The observed $R_{SS}$, with the MC predictions of its dependence on $f_D$, are shown in Figure 1. The adjusted $f_D$ is used when determining the acceptance corrections $\epsilon_{sel}$ and $f_{\xi<10^{-6}}$.

![Figure 1: The ratio of the number of single-sided to inclusive events ($R_{SS}$) as a function of the fraction of the cross section that is diffractive according to each model ($f_D$). The default value of $f_D$ in each generator is shown with a marker along each MC simulation line.](image)

The $n_{MBTS}$ distributions in data are compared to the predictions from MC simulation in Figure 2 for both the inclusive and single-sided selections. The estimated background is subtracted from the measured distribution, and the trigger efficiency measured in data is applied to the simulated samples. The data distributions and MC simulation are peaked at high multiplicity values. In the single-sided case, $n_{MBTS} = 12$ corresponds to hits in all counters on one side of the detector. The data agree best with the DL models, particularly in the low-$n_{MBTS}$ range. The MBR-based distribution provides a slightly worse description of the data. The Pythia8 sample using the SS model does not provide a good description of the data in the low-multiplicity region. Epos LHC and QGSJet-II also do not describe the data well, particularly in the single-sided hit multiplicity distribution. Therefore, the Pythia8 DL model with $\epsilon = 0.085$ is chosen as the nominal MC model for the $\epsilon_{sel}$ and $f_{\xi<10^{-6}}$ corrections, and only the DL and MBR models are considered for systematic uncertainties related to the MC corrections.

The efficiency of the event selection, $\epsilon_{sel}$, depends upon the sensitivity of the MBTS counters. This
Figure 2: The background-subtracted distribution of the number of MBTS counters ($n_{MBTS}$) above a threshold of 0.15 pC in data and MC simulation for (top) the inclusive selection and (bottom) the single-sided selection. The ratio of the MC models to the data is also shown. The experimental uncertainty, including uncertainties in the MBTS counter efficiency, trigger efficiency, detector material and backgrounds, is shown as a shaded band around the data points. The models shown here use the $f_D$ value determined from the $R_{SS}$ measurement.
sensitivity is tested using isolated charged particles, reconstructed as ID tracks in the region $2.07 < |\eta| < 2.5$ where the coverages of the MBTS and ID overlap. Over the full coverage of the MBTS counters, the calorimeter is used to measure the counter efficiency with respect to particles that deposit sufficient energy in the calorimeter to seed a topological energy cluster [37]. Differences between the efficiencies in data and MC simulation are accounted for by adjusting the MBTS charge threshold in MC simulation until the simulated efficiencies match those observed in the data. The residual uncertainty in the counter efficiency after these corrections is determined to be ±0.5% for the outer and ±1.0% for the inner counters. Additionally, an uncertainty arises from the knowledge of the material in front of the MBTS detector. It is estimated using additional MC samples with an increased amount of material in front of the MBTS. Based on the MC samples, the uncertainty in the efficiency measurement due to modeling of hadronization and the underlying event is estimated to be negligible.

After having adjusted the counter charge threshold, $\epsilon_{\text{sel}}$ is determined from the nominal Pythia8 DL MC, using the fitted $f_D$ corresponding to this model, to be 99.34% with a statistical uncertainty of ±0.03%. The uncertainty in the efficiencies of the MBTS counters results in only a ±0.1% uncertainty in the overall event selection efficiency, because many counters are hit in typical events. In addition, an uncertainty of ±0.2% in $\epsilon_{\text{sel}}$ arises from the knowledge of the material in front of the MBTS.

The fraction of events passing the inclusive selection that have $\xi < 10^{-6}$ represents an additional background component in the fiducial cross-section measurement. It is determined using the same Pythia8 DL MC to be $f_{\xi<10^{-6}} = (1.37 ± 0.05)\%$, where the uncertainty is statistical.

Because the efficiency and migration corrections are correlated, they are combined in a single correction factor, $C_{\text{MC}} = (1 - f_{\xi<10^{-6}})/\epsilon_{\text{sel}}$, for which systematic uncertainties are assessed. The systematic uncertainties include the variations of the counter efficiencies, the impact of the material uncertainty, the uncertainty in the fitted value of $f_D$, and the variation in $C_{\text{MC}}$ found by comparing the Pythia8 DL and MBR models. Of these sources of uncertainty, the last is most important at ±0.5%. The value of $C_{\text{MC}}$ used is (99.3 ± 0.5)%. The uncertainty also implicitly contains an uncertainty due to the CD contribution, since this is included in some of the models but not in others.

The uncertainty in the integrated luminosity is ±1.9%. It is derived, following a methodology similar to that detailed in Refs. [38, 39], from a calibration of the luminosity scale using $x$–$y$ beam-separation scans performed in August 2015.

The individual components necessary for the fiducial cross-section calculation [Eq. (1)] are shown in Table 1 with their systematic uncertainties. The statistical uncertainties are negligible. The measured fiducial cross section is determined to be

$$\sigma_{\text{fid}}^{\text{inel}} = 68.2 ± 0.8 \, (\text{exp.}) ± 1.3 \, (\text{lum.}) \, \text{mb},$$

where the first uncertainty refers to all experimental uncertainties apart from the luminosity and the second refers to the luminosity only.

The Pythia8 DL model predicts values of 71.0 mb, 69.1 mb and 68.1 mb for $\epsilon = 0.06$, 0.085 and 0.10 respectively, and is compatible with the measurement for all these values of $\epsilon$. The Pythia8 MBR model predicts 70.1 mb, also in agreement with the measurement. The Eros LHC (71.2 mb) and QGSJet-II (72.7 mb) predictions exceed the data by 2–3$\sigma$. The Pythia8 SS model predicts 74.4 mb, and thus exceeds the measured value by $\sim 4\sigma$.
Table 1: Values used for the calculation of the measured cross section, along with their systematic uncertainties.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
<th>Rel. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events passing the inclusive selection ((N))</td>
<td>4159074</td>
<td>–</td>
</tr>
<tr>
<td>Number of background events ((N_{BG}))</td>
<td>51187</td>
<td>±50%</td>
</tr>
<tr>
<td>Integrated luminosity ([\mu b^{-1}] (L))</td>
<td>60.1</td>
<td>±1.9%</td>
</tr>
<tr>
<td>Trigger efficiency ((\epsilon_{\text{trig}}))</td>
<td>99.7%</td>
<td>±0.3%</td>
</tr>
<tr>
<td>MC correction factor ((C_{MC}))</td>
<td>99.3%</td>
<td>±0.5%</td>
</tr>
</tbody>
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The extrapolation to \(\sigma_{\text{inel}}\) uses constraints from previous ATLAS measurements to minimize the model dependence of the component that falls outside the fiducial region. That is, \(\sigma_{\text{inel}}\) can be written as

\[
\sigma_{\text{inel}} = \sigma_{\text{inel}}^{\text{fid}} + \sigma_{\text{7 TeV}}^{\text{MC}}(\xi < 5 \times 10^{-6}) \times \frac{\sigma_{\text{MC}}^{\text{MC}}(\xi < 10^{-6})}{\sigma_{\text{7 TeV}, \text{MC}}^{\text{MC}}(\xi < 5 \times 10^{-6})},
\]

where \(\sigma_{\text{MC}}^{\text{MC}}(\xi < 10^{-6})\) is the MC-predicted cross section outside the fiducial range at 13 TeV and \(\sigma_{\text{7 TeV}, \text{MC}}^{\text{MC}}(\xi < 5 \times 10^{-6})\) is the MC predicted cross section outside the fiducial range of the 7 TeV measurement. The term \(\sigma_{\text{7 TeV}}^{\text{MC}}(\xi < 5 \times 10^{-6}) = \sigma_{\text{7 TeV}}^{\text{MC}}(\xi > 5 \times 10^{-6}) = 11.0 \pm 2.3\) mb is the difference between \(\sigma_{\text{inel}}\) measured at 7 TeV using the ALFA detector [9], \(\sigma_{\text{7 TeV}}^{\text{MC}}\), and \(\sigma_{\text{inel}}\) measured at 7 TeV for \(\xi > 5 \times 10^{-6}\) using the MBTS [7]. The uncertainties of the two measurements are uncorrelated.

The Pythia8 DL and Pythia8 MBR MC samples are used to assess the systematic uncertainty in the MC-derived ratio of cross sections in Eq. (2), which is determined to be 1.015 ± 0.081. These models also agree with the measurement of \(\sigma_{\text{7 TeV}}^{\text{MC}}(\xi < 5 \times 10^{-6})\) to within 2\(\sigma\).

The measured value for \(\sigma_{\text{inel}}\) is

\[
\sigma_{\text{inel}} = 79.3 \pm 0.8 \text{ (exp.)} \pm 1.3 \text{ (lum.)} \pm 2.5 \text{ (extrap.)} \text{ mb}.
\]

This measurement and other inelastic cross-section measurements are compared to several Monte Carlo models in Figure 3. Additional predictions range between 76.6 and 81.6 mb [40–44]. Compared to the measurement with the ALFA detector at \(\sqrt{s} = 7\text{ TeV}\) the cross section is higher by (11 ± 4)%.

In summary, a measurement of the inelastic cross section in 60 \(\mu b^{-1}\) of proton-proton collision data at \(\sqrt{s} = 13\text{ TeV}\) collected with the ATLAS detector at the LHC is presented. The measurement is performed in a fiducial region \(\xi > 10^{-6}\), and the result is extrapolated to the inelastic cross section using measurements at \(\sqrt{s} = 7\text{ TeV}\). The measured cross section agrees well with a variety of theoretical predictions and is consistent with the inelastic cross section increasing with center-of-mass energy, as observed at lower energies.
Figure 3: The inelastic proton-proton cross section versus $\sqrt{s}$. Measurements from other hadron collider experiments [6, 8, 10, 13, 14] and the Pierre Auger experiment [15] are also shown. Some of the LHC data points have been slightly shifted in the horizontal position for display purposes. The data are compared to the Pythia 8, EPOS LHC and QGSJet-II MC generator predictions. The uncertainty in the ATLAS ALFA measurement is smaller than the size of the marker.

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