Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 7$ TeV with the ATLAS Detector

ATLAS Collaboration

Abstract

We present a first measurement of the inelastic cross section for proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV using the ATLAS detector at the Large Hadron Collider. Events are selected on the basis of scintillator counter signals in the forward region of the detector with a dataset corresponding to an integrated luminosity of 21 $\mu$b$^{-1}$. We measure $57.2 \pm 6.3$ mb for the inelastic cross section excluding diffractive contributions where both of the dissociation masses, $M_X$, satisfy $\xi = M_X^2/s < 10^{-5}$. 
1 Introduction

Since the earliest days of particle physics, measurements of the total $pp$ and $p\bar{p}$ cross-sections and their theoretical understanding have been topics of much interest [1, 2]. The cross-section can not yet be calculated by Quantum Chromo Dynamics (QCD), and many approaches have been used to describe the existing measurements [3]. Very general arguments based on unitarity, analyticity, and factorization imply a bound (the Froissart bound [4, 5]) on the high-energy behavior of total hadronic cross-sections that is independent of the details of the strong interaction dynamics and states that the total cross-section can not rise faster than $\ln^2(s)$, where $\sqrt{s}$ is the centre-of-mass energy. Recently this statement has been extended to the inelastic cross-section [6]. Experimental data so far show a rise in the hadronic cross-sections with $s$, but it is unclear whether the asymptotic behavior has already been reached. With the data presented in this Letter we shed further light on the high energy behavior of the inelastic cross-section.

The most commonly known models that describe the data up to $\sqrt{s} = 1.8$ TeV predict a rise of the cross-section with a simple power law ($s^{\alpha(0)-1}$ where $\alpha(0)$ denotes the pomeron intercept) [7, 8, 9] or logarithm [10, 11]. Others employ more complex models that use QCD for aspects of the calculation [12, 13]. However, while the phenomenological description of the existing data is largely adequate, there are large uncertainties on the extrapolation to higher energies, partly due to a long-standing 2.7 $\sigma$ discrepancy between the two highest energy collider measurements at CDF [14] and E811 [15].

In this Letter we present a measurement of the inelastic $pp$ cross-section using data taken by the ATLAS experiment [16] at the Large Hadron Collider (LHC) [17] at $\sqrt{s} = 7$ TeV. The data considered correspond to a single 8-hour fill1 beginning March 31st, 2010, corresponding to an integrated luminosity of $21.0 \pm 2.3 \mu$b$^{-1}$ and a peak instantaneous luminosity of $1.2 \times 10^{27}$ cm$^{-2}$s$^{-1}$. The analysis uses highly efficient scintillation counter detectors to detect inelastic collisions. They are insensitive to diffractive dissociation processes in which the dissociation systems have small invariant masses $M_{X}$. Their acceptance corresponds approximately to $\xi = M_{X}^2/s > 10^{-5}$, equivalent to $M_{X} > 22.1$ GeV for $\sqrt{s} = 7$ TeV. The cross-section measurement presented here is restricted to this kinematic range. However, in order to compare the data with previous measurements, we additionally extrapolate the cross-section to the full $\xi$ range, $\xi > m_{p}^2/s$ where $m_{p}$ is the proton mass.

2 The ATLAS Detector

The ATLAS detector is described in detail elsewhere [16]. The beam-line is surrounded by a tracking detector that uses silicon pixel, silicon strip, and straw tube technologies and is embedded in a 2 T magnetic field. The tracking system covers the pseudorapidity2 range $|\eta| < 2.5$. It is surrounded by electromagnetic and hadronic calorimeters covering $|\eta| < 3.2$ which are complemented by a forward hadronic calorimeter covering $3.1 < |\eta| < 4.9$. Minimum Bias Trigger Scintillator (MBTS) detectors, the primary detectors used in this measurement, are mounted in front of the endcap calorimeters on both sides of the interaction point at $z = \pm 3.56$ m and cover the range $2.09 < |\eta| < 3.84$. Each side consists of 16 independent counters divided into two rings; the inner 8 counters cover the rapidity range $2.83 < |\eta| < 3.84$ and the outer 8 counters cover the range $2.09 < |\eta| < 2.83$. Each individual counter subtends 45$^\circ$ of the azimuthal angle ($\phi$) and 31 out of 32 counters were operational. The luminosity is measured using a Cerenkov light detector, LUCID, which is located at $z = \pm 17$ m. The luminosity

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1The analysis has been repeated in a different fill and the result was in good agreement within the systematic uncertainties that are uncorrelated between different LHC fills.

2ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis coinciding with the axis of the beam pipe. The $x$-axis points from the IP to the centre 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 $\eta = -\ln(\tan(\theta/2))$.
calibration has been determined during dedicated van der Meer beam scans on April 26th and May 9th, 2010 [18, 19], to a precision of 11%.

3 Monte Carlo Models

Monte Carlo (MC) simulations are used to determine the acceptance of the event selection and to assess systematic uncertainties. The detector response to the generated events is simulated using the ATLAS simulation [20] based on GEANT4 [21], and the events are passed through the same reconstruction and analysis software as the data events. We use the PYTHIA6 [22], PYTHIA8 [23] and PHOJET [24] generators to give predictions for the properties of inelastic collisions. These generators distinguish between different processes that contribute to inelastic pp interactions: single dissociation (SD), pp → pX, processes in which one proton dissociates; double dissociation (DD), pp → XY, processes in which both protons dissociate with no net color flow between the two protons; and non-diffractive (ND) processes in which color flow is present between the two protons. The PYTHIA [25] model predicts individual cross-sections of 48.5 mb, 13.7 mb and 9.3 mb for the ND, SD and DD processes, respectively. Note that the cross-sections used by PYTHIA6 and PYTHIA8 are identical, but the two generators differ in the modeling of the hadronic final state. PHOJET predicts the corresponding cross-sections as 61.6 mb (ND), 10.7 mb (SD) and 3.9 mb (DD).³ PHOJET also includes central diffraction (CD), pp → ppX, a process wherein neither proton dissociates but the pomeron-trajectory exchange results in energy loss for the protons and the production of a central system of particles. The CD process has a cross-section of 1.1 mb, and is not present in PYTHIA. The MC generators define the inelastic cross-section as the sum of these contributions, and thus PYTHIA (PHOJET) predicts an inelastic cross-section of 71.5 mb (77.3 mb). Other recent predictions for this cross-section at \( \sqrt{s} = 7 \text{ TeV} \) are and 69 mb [11], 67 mb [12] and 68 mb [13].

We define \( \xi \) at the hadron level by dividing the final state particles into two systems, X and Y. The mean \( \eta \) of the two particles separated by the largest pseudorapidity gap in the event is used to assign all particles with greater pseudorapidity to one system and all particles with smaller pseudorapidity to the other [26]. We calculate the mass, \( M_{XY} \), of each system and define the higher mass system as X and the lower mass system as Y. The variable \( \xi \) is then given by \( \xi = M_{X}^{2}/s \) down to the elastic limit \( \xi > m_{p}^{2}/s \). Due to the limited MBTS detector acceptance, this measurement is restricted by an acceptance cut to the range \( \xi > 10^{-5} \); there is no restriction of the measurement in \( M_{Y} \). Within the restricted kinematic range \( \xi > 10^{-5} \), the predicted cross-section is 64.7 mb for PYTHIA and 73.5 mb for PHOJET.

4 Analysis Overview

Experimentally the cross-section is calculated using

\[
\sigma_{\text{inc}}(\xi > 10^{-5}) = \frac{(N - N_{BG})}{\epsilon_{\text{trig}} \times \int L \, dt} \times \frac{1 - f_{\xi < 10^{-5}}}{\epsilon_{\text{sel}}}
\]

where \( N \) is the number of selected events, \( N_{BG} \) is the number of background events, \( f_{\xi < 10^{-5}} \) is the fraction of events with \( \xi < 10^{-5} \) that pass the selection, \( \int L \, dt \) is the integrated luminosity, and \( \epsilon_{\text{trig}} \) and \( \epsilon_{\text{sel}} \) are the trigger and offline event selection efficiencies in the selected \( \xi \)-range. In this measurement we determine \( N_{BG} \) and \( \epsilon_{\text{trig}} \) directly from the data. We tune the MBTS individual counter efficiency in the MC to match the observed efficiency in data and then use the event level efficiency, \( \epsilon_{MBTS} \), from the tuned MC. We additionally take \( f_{\xi < 10^{-5}} \) from the tuned MC. In order to reduce the uncertainties in the factors taken from

³Due to the different implementation of the interface between large \( \xi \) diffractive (SD and DD) processes and ND processes in PYTHIA and PHOJET the relative diffractive-dissociation cross-section is a model dependent quantity.
MC, we also constrain the relative diffractive dissociation cross-section, \( f_D = \frac{\sigma_{\text{DD}} + \sigma_{\text{CD}}}{\sigma_{\text{inel}}} \) for each generator. Each of these steps is described in detail below.

5 Event Selection

The MBTS functions as a trigger by determining the number of scintillation counters with a hit passing a leading-edge discriminator; in this analysis at least one trigger hit must be present. In the offline reconstruction, the MBTS signals are fitted to obtain the total charge and timing of the signal. The offline event selection requires at least two counters with a charge larger than 0.15 pC. This threshold is set to be above the noise, which is well described by a Gaussian centered at zero of width 0.02 pC. This inclusive sample contains 1,220,743 data events. In order to constrain the diffractive components we also select a subset of events, the single-sided sample, which contains only events that have at least two hits on one side of the detector and no hits on the opposing side (in \( z \)) of the detector. In the data we find 122,490 single-sided events.

6 Backgrounds

Backgrounds arise from beam related interactions, such as collisions of the beam with gas particles in the beam-pipe (beam-gas), collisions of the beam with material upstream from the detector and slowly-decaying, collision-induced radiation termed “afterglow” [19]. Additionally, instrumental noise and cosmic rays provide backgrounds which were studied and found to be negligible for this analysis. We determine the beam-related backgrounds using events collected in this fill when only one proton bunch was passing through ATLAS [27] and multiply the observed number of events by the ratio of the number of protons in the colliding to the non-colliding bunches. For the single-sided selection there are 422 background events and for the inclusive sample there are \( N_{BG} = 1,574 \) background events, corresponding to 0.34% and 0.13% of the total samples, respectively. This accounts for any beam-related backgrounds as well as afterglow from previous collisions. In addition, there is a background component due to the scattering of secondary low energy particles that arise from the same collision event. This could cause a migration of events from less than two hits to higher hit multiplicity, and thus allow the events to pass the selection. This contribution is evaluated to be at most 0.4% for both the inclusive and the single-sided samples by examining the asymmetry of the absolute timing measurement of the MBTS counters. We conservatively assume a 100% uncertainty on both background sources which covers any residual impact of the afterglow on the background subtraction, any uncertainty in the beam current measurements and the uncertainty on the background due to in-time hits caused by low energy particles from secondary scatters. The resulting overall uncertainty on the number of background events, \( N_{BG} \), is given by the quadratic sum of the two components and is 0.42%.

7 MBTS Efficiency

The trigger efficiency of the MBTS detector with respect to the offline requirement, \( \epsilon_{\text{trig}} \), is measured to be \( 99.98_{-0.02}^{+0.02} \% \) (statistical errors) using events triggered randomly on colliding beams. The systematic uncertainty on the trigger efficiency is determined using a second, independent trigger as reference. The difference between the two efficiency determinations leads to a 0.07% uncertainty on the cross-section measurement.

The data and MC agreement in the MBTS counter response is checked using other detector subsystems that cover the same \( \eta \) range: charged particles reconstructed by the tracking detector in the range \( 2.09 < |\eta| < 2.5 \), and calorimeter showers in the inner wheel of the electromagnetic calorimeter in the
range $2.5 < |\eta| < 3.2$ and in the forward calorimeter in the range $3.1 < |\eta| < 3.83$. The efficiency to have a signal above the 0.15 pC threshold in the outer (inner) counters is on average 98.5% (97.5%) for the data and a constant 99.4% (98.7%) in the MC. The individual counter efficiencies deviate by up to 2.0% (2.5%) from the average in the data. We correct the MC to match the data efficiency and consider as a systematic uncertainty the maximum variations in the individual MBTS counter responses. This results in a 0.09% uncertainty on the cross-section measurement.

8 Material and Alignment Effects

The offline selection efficiency $\epsilon_{sel}$ depends on the amount of material traversed by particles before hitting the MBTS detector. The dominant effect arises from photons (primarily from $\pi^0$ decays) converting to electrons which are subsequently detected by the MBTS. Thus the efficiency for an event to pass the selection increases with increasing material. A second order effect arises from charged particles scattering out of the MBTS acceptance region (decreasing $\epsilon_{sel}$), or charged particles scattering into the acceptance region (increasing $f_{\xi<10^{-5}}$). Within the tracking volume ($|\eta| < 2.5$) the material distribution has been studied using conversion electrons and $K^0_s \rightarrow \pi^+\pi^-$ decays and is known to better than ±30% [27]. In the region $|\eta| > 2.5$ the material is dominated by the cooling and electrical services to the silicon pixel detector, and we estimate an uncertainty of ±40%. This is validated in-situ using the fraction of events where we observe significant energy in the forward calorimeters but no signal (above noise) in the MBTS detector. The resulting systematic uncertainty on the cross-section is 0.20%.

A misalignment of the MBTS detector with respect to the nominal center of the detector could change the efficiency of the event selection for a particular value of $\xi$. Possible misalignments of up to 10 mm were considered and found to have a negligible impact. The value of 10 mm is conservative compared to the survey precision and any known misalignments within the ATLAS experiment [16].

9 Relative Diffractive Cross Section

The fractional contribution of diffractive events, $f_D$, is constrained by the ratio of single-sided to inclusive events, $R_{ss}$. РТНГА8, РНОЕТ and РТНГА6 predict for the ND process that 0.2%, 0.7% and 1.0% pass the single-sided event selection, respectively, while it is roughly 30% for all generators for the SD and DD processes when considering the full $\xi$ range. РТНГА8 (РНОЕТ) predicts 1% (8%) of the events in the single-sided sample to be non-diffractive while for the inclusive sample this component accounts for 74% (84%). The corresponding РТНГА6 values are 7% and 74%, respectively. Thus the ratio of single-sided to inclusive events is sensitive to the relative fraction of diffractive events. We measure $R_{ss}$ in the data as $R_{ss} = [10.02 \pm 0.03(\text{stat.}) \pm 0.17(\text{syst.})]\%$.

Fig. 1 compares the observed value for $R_{ss}$ to the predictions of the different MC generators as a function of $f_D$. It is seen that all generators predict a similar dependence of $R_{ss}$ on $f_D$. We use the intersection of the $R_{ss}$ value measured in data with the prediction of РТНГА8 for the central value of $f_D$. The systematic uncertainty on $f_D$ is determined by the maximum and minimum values consistent with the 1σ uncertainty on the data when varying the double- to single-dissociation event ratio between 0 and 1. The resulting value using the РТНГА8 acceptance model is $f_D = 29.8^{+1.6}_{-0.7}$. For РТНГА6 and РНОЕТ, the values are $f_D = 30.0\%$ and $f_D = 29.8\%$, respectively. These values are in fair agreement with the prediction by the РТНГА generator of 32.2% while they differ significantly from the РНОЕТ prediction of 20.3%. The uncertainty on $f_D$ results in a 0.13% uncertainty on the cross-section measurement.
Figure 1: $R_{ss}$ versus $f_D$. The data value for $R_{ss}$ is shown as the horizontal line with its systematic uncertainties (gray band). Also shown are the predictions from Pythia6 with the MC09 tune [28], Pythia8 and Phojet as a function of an assumed value of $f_D$. The default $f_D$ value of Pythia6 and Pythia8 is 32.2% and 20.3% for Phojet, as indicated by the filled circles.

10 Modeling Uncertainties

The acceptance calculation relies on the MC generators to provide an adequate description of the particle multiplicity in the acceptance region. We assess the validity of the MC description by examining the hit multiplicity in the MBTS detector in the inclusive and single-sided event samples as shown in Fig. 2. While none of the generators gives a perfect description, the data lie between the three generators in the low multiplicity region which is most important for the measurement. We use Pythia8 for the central value but take the variation when using Pythia6 as the uncertainty due to the fragmentation model and the difference with respect to Phojet as the uncertainty due to the $\xi$ distribution in the vicinity of the $\xi$ cut. Adding both contributions in quadrature a symmetric uncertainty of 0.35% on the cross-section is obtained.

11 Results

The final result for the measured inelastic cross-section is calculated using $f_D = 30.0\%$, $\epsilon_{\text{sel}} = 99.81\%$, $\epsilon_{\text{trig}} = 99.98\%$, $f_{\xi<10^{-5}} = 1.47\%$, $N = 1,220,743$, $N_{BG} = 1,574$ and $\int L dt = 21.0 \mu b^{-1}$, resulting in

\[ \sigma_{\text{inel}}(\xi > 10^{-5}) = 57.2 \pm 0.1(\text{stat}) \pm 0.4(\text{syst}) \pm 6.3(\text{lumi}) \text{mb}. \]

The systematic uncertainty includes all contributions discussed above as summarized in Table 1. The luminosity uncertainty is quoted separately. The prediction by Pythia (64.7 mb) agrees with the measured cross section, while that of Phojet (73.5 mb) is 16.3 mb (2.4$\sigma$) higher.

Assuming an overall acceptance of the $\xi > 10^{-5}$ cut of 90.6% (95.2%) as predicted by Pythia\(^4\) (Phojet) this results in a total inelastic cross-section of 63.2 $\pm$ 7.0 mb (60.1 $\pm$ 6.6 mb). The result obtained using the Pythia-based extrapolation is shown in Fig. 3, where it is compared to the theoretical predictions and a variety of data at lower $\sqrt{s}$. The measurement agrees with the predictions from Pythia,

\(^4\)The acceptance value is the same for Pythia6 and Pythia8.
Figure 2: The MBTS multiplicity distribution in the data (closed circles) compared with MC expectations for the inclusive (a) and single-sided (b) samples for the different MC models (histograms). The band around the data indicates the systematic uncertainty due to the MBTS detector response and the amount of material in front of the MBTS detector.

which uses a power law dependence on $\sqrt{s}$, and Block [11], which has a logarithmic dependence, and is also in agreement with other recent theoretical predictions that vary between 67 and 70 mb [12, 13]. It should be noted that this extrapolation relies on the generator prediction of the $\xi$-dependence of the cross-section and we have not attempted to quantify the uncertainty on this extrapolation.

12 Conclusions

We have presented the first measurement of the inelastic cross-section in $pp$ collisions at $\sqrt{s} = 7$ TeV, in the range $\xi > 10^{-5}$, to be $57.2 \pm 0.1\text{(stat)} \pm 0.4\text{(syst)} \pm 6.3\text{(lumi)}$ mb. Theoretical predictions for both a power law dependence and a logarithmic rise of the cross-section with energy within the Froissart bound extended to the inelastic cross-section are consistent with the measurement. The measurement is already dominated by the systematic uncertainties and will directly benefit from a further reduction of the dominant luminosity uncertainty.
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Table 1: Relative uncertainty on the cross section due to the various sources of systematic uncertainties. The total systematic uncertainty is the quadratic sum of the individual uncertainties. In addition to the sources listed here, an 11% uncertainty on the cross section measurement arises from the uncertainty on the luminosity measurement.

References


Figure 3: The inelastic cross-section versus $\sqrt{s}$. The ATLAS measurement for $\xi > 10^{-5}$ is shown as the red triangle and compared with the Pythia prediction (dashed red line) for the same phase space. Data (closed circles for $pp$ data and open circles for $p\bar{p}$ data) from several experiments are compared with the predictions of the $pp$ inelastic cross-section from Schuler and Sjöstrand [25] (as used by Pythia) and by Block [11]. An extrapolation from the measured range of $\xi > 10^{-5}$ to the full inelastic cross-section using the Pythia acceptance of 90.6% is also shown (blue filled circle). It is artificially shifted to a slightly larger $\sqrt{s}$ value for display purposes.