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Measurement of the inelastic proton–proton cross-section at $\sqrt{s} = 7$ TeV with the ATLAS detector

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The dependence of the rate of proton–proton interactions on the centre-of-mass collision energy, $\sqrt{s}$, is of fundamental importance for both hadron collider physics and particle astrophysics. The dependence cannot yet be calculated from first principles; therefore, experimental measurements are needed. Here we present the first measurement of the inelastic proton–proton interaction cross-section at a centre-of-mass energy, $\sqrt{s}$, of 7 TeV using the ATLAS detector at the Large Hadron Collider. Events are selected by requiring hits on scintillation counters mounted in the forward region of the detector. An inelastic cross-section of $60.3 \pm 2.1$ mb is measured for $\xi > 5 \times 10^{-6}$, where $\xi$ is calculated from the invariant mass, $M_X$, of hadrons selected using the largest rapidity gap in the event. For diffractive events, this corresponds to requiring at least one of the dissociation masses to be larger than 15.7 GeV.

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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. The cross-sections cannot yet be calculated by quantum chromodynamics, and many approaches have been used to describe the existing measurements. General arguments based on unitarity and analyticity imply a bound (the Froissart bound) on the high-energy behaviour of total hadronic cross-sections. This bound is independent of the details of the strong interaction dynamics and states that the total cross-section cannot rise faster than $\ln(s)$, where $s$ is the centre-of-mass energy. Recently, it has been extended to the inelastic cross-section. Existing experimental data show a rise in the hadronic cross-sections with $s$, but it is unclear whether the asymptotic behaviour has already been reached. In this letter, a direct measurement of the inelastic $pp$ cross-section at the highest energy collider to date is presented. Measurements of the inelastic $p$-air cross-section in the multi-TeV regime are available from cosmic-ray shower detection experiments, and have been used to infer the $pp$ cross-section albeit with significant uncertainties. The measurement presented here is of direct relevance for the modelling of high energy cosmic ray showers.

The most common models that describe the data up to $\sqrt{s} = 1.8$ TeV predict a rise of the total cross-section with a simple power law $\propto s^{\alpha}$, where $\alpha(0)$ denotes the Pomeron-trajectory intercept $3^{-9}$ or with a power law depending on $\ln(s)$ (refs 12–16). Others employ quantum chromodynamics for aspects of the calculation $17^{-20}$. However, although the phenomenological description of the existing data is largely adequate, there are significant uncertainties on the extrapolation to higher energies, partly due to a long-standing $2.7\sigma$ discrepancy between the two highest energy collider measurements of the total $\bar{p}p$ cross-section by CDF $^{21}$ and by E811 (ref. 22).

The inelastic $pp$ cross-section at $\sqrt{s} = 7$ TeV is measured with data taken by the ATLAS experiment $^{23}$ at the Large Hadron Collider (LHC) $^{24}$. The data considered were collected during a single 8-hour fill beginning 31 March 2010, corresponding to an integrated luminosity of $20.3\pm0.7 \mu b^{-1}$ and a peak instantaneous luminosity of $1.2\times10^{27}$ cm$^{-2}$ s$^{-1}$. The mean number of interactions per crossing in this fill is $0.01$. The analysis uses highly efficient scintillation counters, the minimum bias trigger scintillator (MBTS) detectors, to detect inelastic collisions. They are insensitive to dissociative interaction processes in which the dissociation systems have small invariant masses, $M_t$. Their acceptance corresponds approximately to $\xi = M_t/s > 5\times10^{-4}$, equivalent to $M_t > 15.7$ GeV for $\sqrt{s} = 7$ TeV. The cross-section measurement presented here is restricted to this kinematic range. However, to compare the data with previous measurements, an extrapolation of the cross-section is performed to the full $\xi$ range, $\xi > m_t/s$ where $m_t$ is the proton mass.

**Results**

**Acceptance determination.** 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 $^{25}$ based on Geant4 (ref. 26), and both the simulated and data events are reconstructed and analysed with the same software. The Pythia 6 (ref. 27), Pythia8 (ref. 28) and PHOJET $^{29,30}$ generators are used to predict properties of inelastic collisions. These generators distinguish between different processes that contribute to inelastic $pp$ interactions: single dissociative (SD) processes, $pp\rightarrow pX$, in which one proton dissociates; double dissociative (DD) processes, $pp\rightarrow XY$, in which both protons dissociate with no net colour flow between the systems $X$ and $Y$; and non-dissociative (ND) processes in which colour flow is present between the two initial-state protons. The model by Schuler and Sjöstrand $^{31}$, used by Pythia6 and Pythia8, predicts cross-sections of $48.5, 13.7$ and $9.3$ mb for the ND, SD and DD processes, respectively. Whereas the cross-sections used by Pythia6 and Pythia8 are identical, they differ in the modelling 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). Because of differences in implementation of the interface between large $\xi$ diffractive (SD and DD) processes and ND processes in Pythia and PHOJET, the fractional contribution of these processes is a model-dependent quantity. PHOJET also includes a $1.1$ mb contribution from central diffraction (CD), $pp\rightarrow ppx$, a process not implemented in Pythia, 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 MC generators define the inelastic cross-section as the sum of these contributions, and thus Schuler and Sjöstrand (PHOJET) predicts an inelastic cross-section of $71.5$ mb (77.3 mb). Other recent predictions for this cross-section at $\sqrt{s} = 7$ TeV are $69$ mb (ref. 15), $65–67$ mb (ref. 17 and personal communication with the author), $68$ mb (refs 18,19) and $60–75$ mb (ref. 20).

Although the cross-section measured here is quoted for a restricted $\xi$ range, $\xi$ is not directly measured. However, the $\eta$ coverage of the MBTS implies a lower bound on the range of $\xi$ values for events that the detectors can observe. To study the acceptance as a function of $\xi$, MC generators are used. The variable $\xi$ is defined at the particle level by dividing the final state particles from the MC generators 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 $^{21}$. The mass, $M_{XY}$, of each system is calculated, and the higher mass system is defined as $X$ while the lower mass system is defined as $Y$. In the case of $SD$, $Y$ is the non-dissociated proton. The variable $\xi$ is then given by $\xi = M_{XY}/s$ and it is bounded by the elastic limit, satisfying $\xi > m_t/s$. As expected from kinematic considerations, a strong correlation is observed, independently of the MC model used to determine $\xi$, between $\xi$ and the pseudorapidity of the hadron from $X$ that is farthest from the initial-state proton pseudorapidity. Therefore, the upper limit of the MBTS detector acceptance of $|\eta| < 3.84$ (see Methods) can be translated into a limit on the $\xi$ of observed events. Thus the measurement is restricted in its $\xi$ range; there is no requirement on $M_t$. Several models are used for the dependence of the diffractive cross-sections on $\xi$. The Schuler and Sjöstrand model has a relatively flat dependence on $\xi$, whereas the PHOJET model predicts a slight decrease with decreasing $\xi$. Pythia8 has several extra predictions for the $\xi$-dependence of the diffractive cross-sections that are considered. In the low $\xi$ regime, Bruni and Ingelman $^{32}$ predict a flat $\xi$ dependence whereas Donnachie and Landshoff (DL) $^{34}$ and Berger $^{35}$ predict

$$\frac{d\sigma_{SD}}{d\xi} \propto \frac{1}{\xi^{\alpha}}$$

where $\alpha = (\alpha(0) - 1)$. Values of $\alpha$ between 0.06 and 0.10, and of $\alpha'$ between 0.10 and 0.40 GeV$^{-2}$ are considered for the DL model. $\alpha'$ is the slope of the Pomeron trajectory that is assumed to be linear such that $\alpha(t) = \alpha(0) + \alpha' t$. The DL model with $\alpha = 0.085$ and $\alpha' = 0.25$ GeV$^{-2}$ with Pythia8 fragmentation is the default model in this analysis, and the other models are used to assess uncertainties in the modelling of diffraction events.

**Cross-section calculation elements.** Experimentally the cross-section is calculated using

$$\sigma_{\text{inel}}(\xi > 5\times10^{-4}) = \frac{N_{\text{sel}} - N_{BG}}{\varepsilon_{\text{sel}}} \times \frac{1 - \int_{\xi < 5\times10^{-4}} f_{\xi} d\xi}{\varepsilon_{\text{inel}}}$$

where $N$ is the number of selected events, $N_{BG}$ is the number of background events, $f_{\xi} < 5\times10^{-4}$ is the fraction of events that pass the event.
selection but have $\xi < 5 \times 10^{-4}$, $\int L dt$ is the integrated luminosity, and $\varepsilon_{\text{trig}}$ and $\varepsilon_{\text{eff}}$ are the trigger and offline event selection efficiencies in the selected $\xi$-range. For $\xi = 5 \times 10^{-4}$, $\varepsilon_{\text{trig}}$ is 50%, rising to nearly 100% for $\xi > 1 \times 10^{-3}$. The dependence of the efficiency on $\xi$ is similar for the SD and DD processes and for different MC generators. The measurement is quoted for $\xi = 5 \times 10^{-4}$ that gives the smallest correction factor, $(1 - f_{\xi < 5 \times 10^{-4}})/\varepsilon_{\text{trig}}$, and thus yields the smallest systematic uncertainty on the measurement due to the underlying $\xi$-distribution.

In this measurement, $N_{\text{off}}$ and $\varepsilon_{\text{trig}}$ are determined directly from the data. The MBTS individual counter efficiencies in the MC simulation are tuned to match the observed efficiencies in data. Then $\varepsilon_{\text{eff}}$ and $f_{\xi < 5 \times 10^{-4}}$ are taken from the tuned MC simulation. To reduce the uncertainties in the factors taken from MC simulation, the relative diffractive dissociation cross-section, $f_D = (\sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{trig}})/\sigma_{\text{trig}}$ for each generator is constrained. Each of these steps is described in detail below.

The MBTS functions as a trigger by determining the number of scintillation counters with a signal passing a leading-edge discriminator; in this analysis, at least one trigger signal must be present. In the offline reconstruction, the MBTS signals are fit 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 well above the noise level, which is well described by a Gaussian centred at zero with 0.02 pC. This inclusive sample contains 1,220,743 data events. To constrain the diffractive components, a subset of events that have at least two hits on one side of the MBTS detector and no hits on the opposing side (in $z$) are selected. In the data, 122,490 of these single-sided events are observed.

**Backgrounds.** Backgrounds arise from beam-related interactions, such as collisions of the beam with gas particles in the beam-pipe or with material upstream from the detector, and slowly-decaying, collision-induced radiation termed 'afterglow'. Additionally, instrumental noise and cosmic rays provide backgrounds that were studied and found to be negligible for this analysis. The beam-related backgrounds are determined using the number of selected events collected in this fill with the non-colliding bunches, that is, when only one proton bunch was passing through ATLAS. They are normalized by the ratio of the number of protons in the colliding to the non-colliding bunches. The single-sided selection contains 422$\pm$28 background events and the inclusive sample contains $N_{\text{BG}} = 1,574 \pm 54$ background events, corresponding to 0.3% and 0.1% of the total samples, respectively. In addition, there is an in-time afterglow component owing to the scattering of secondary low-energy particles produced in the single collision event that can give extra hits, causing low-activity events to migrate into the selected event sample. This contribution is evaluated to be at most 0.4% for the inclusive and 3.6% for 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 that covers any residual impact of the afterglow on the background subtraction, any uncertainty in the beam current measurements and the uncertainty due to in-time afterglow. The resulting overall uncertainty on the number of background events $N_{\text{BG}}$ is given by the quadratic sum of the two components and is 0.4%.

**Detector efficiency and modelling.** The trigger efficiency of the MBTS detector, with respect to the offline requirement, $\varepsilon_{\text{trig}}$ is measured to be 99.96$^{+0.05}_{-0.06}$ (statistical errors) using events triggered randomly on colliding beams. The systematic uncertainty on $\varepsilon_{\text{trig}}$ is determined using a second, independent trigger as reference. The difference between the two efficiency determinations leads to a 0.1% uncertainty on the cross-section measurement.

The data and MC simulation agreement in the MBTS counter response is checked using other detector subsystems with overlapping $\eta$ ranges: charged particles reconstructed by the tracking detector (2.09 < $|\eta|$ < 2.5), and calorimeter showers in the inner wheel of the electromagnetic calorimeter (2.5 < $|\eta|$ < 3.2) and in the forward calorimeter (3.1 < $|\eta|$ < 3.84). The efficiency with respect to a track (calorimeter energy deposit) 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 simulation. The individual counter efficiencies deviate by up to 2.0% (2.5%) from the average in the data. The MC simulation is corrected to match the data efficiency, and the maximum variations in the counter responses are considered as a systematic uncertainty. This results in a 0.1% uncertainty on the cross-section measurement.

The offline selection efficiency, $\varepsilon_{\text{trig}}$, depends on the amount of material traversed by particles before hitting the MBTS detector. The rate of photons (primarily from $\pi^0$ decays) converting to electrons that are subsequently detected by the MBTS increases with extra material, resulting in an increase of $\varepsilon_{\text{trig}}$. Second order effects arise from charged particles scattering out of the MBTS acceptance region (decreasing $\varepsilon_{\text{trig}}$), or charged particles scattering into the acceptance region (increasing $f_{\xi < 5 \times 10^{-4}}$). Within the tracking volume ($|\eta| < 2.5$), the material distribution has been studied using conversion electrons and $K_L^0 \rightarrow \pi^\pm \pi^\mp$ decays, and is known to better than $\pm 5\%$ in the central region of the detector and to $\pm 30\%$ for $2.2 < |\eta| < 2.5$ (ref. 38). In the region $|\eta| > 2.5$, the material is dominated by the cooling and electrical services to the silicon pixel detector, and an uncertainty of $\pm 40\%$ is assumed. This is validated in situ using the fraction of events wherein 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 0.2%.

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

**Fractional diffractive event contribution.** The fractional contribution of diffractive events, $f_D$, is constrained by the ratio of single-sided to inclusive events, $R_{f_D}$. The MC generators predict that less than 1% of the ND process pass the single-sided event selection, whereas 27–41% of the SD and DD processes pass the single-sided selection. For all models, the inclusive sample is dominated by ND events; therefore, the ratio of single-sided to inclusive events is sensitive to the relative fraction of diffractive events.

The measured $R_{f_D}$ in the data is $R_{f_D} = [10.02 \pm 0.03 \text{ (stat.)} ^{+0.21}_{-0.10} \text{ (syst.)} ] \%$, where the systematic error includes the uncertainties on the backgrounds, the MBTS response and the material.

Figure 1 compares the observed value of $R_{f_D}$ to the predictions of several models as a function of $f_D$. The intersection of the $R_{f_D}$ value measured in data with the prediction is used as the central value of $f_D$ for each model. 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 default DL model is $f_D = 26.9^{+2.5}_{-1.5}\%$.

**Uncertainty on acceptance.** The acceptance calculation relies on the MC generators to provide an adequate description of the particle multiplicity in the acceptance region. The validity of the MC description is assessed by examining the hit multiplicity in the MBTS detector in the inclusive and single-sided event samples as shown in Figure 2. Whereas none of the generators gives a perfect
The final result for the measured inelastic cross-section is calculated using the default DL model of $\varepsilon=0.085$ and $\alpha'=0.25$, which yields $f_D=26.9\%$, $\varepsilon_{\text{rel}}=98.77\%$, and $f_{\text{rel}}=0.968\%$. Together with $\varepsilon_{\text{rel}}=99.98\%$, $N=1,220,743$, $N_{\text{MBTS}}=1,574$, and $L_{\text{int}}=20.25\mu\text{b}^{-1}$ this results in $\sigma_{\text{inel}}(\xi>5\times10^{-6}) = 60.3\pm0.05(\text{stat.})\pm2.1(\text{lumi.})\text{ mb}$.

The systematic uncertainty includes all contributions discussed above and listed in Table 1. The dominant uncertainty arises from the luminosity calibration and is quoted separately.

**Discussion**

The measurement is compared with the predictions in Figure 3 and Table 2. The predictions by the Schuler–Sjöstrand model (66.4 mb) and the Phojet model (74.2 mb) are both higher than the data. The prediction of 51.8–56.2 mb by Ryskin et al. and personal communication, is slightly lower than the data.

To compare with previous measurements and analytic models, the fractional contribution to the inelastic cross-section of events passing the $\xi>5\times10^{-6}$ cut is determined from the models and used to extrapolate the measurement to the full inelastic cross-section. This fraction is 87.3% for the default model of DL with $\varepsilon=0.085$ and $\alpha'=0.25$. The other models considered give fractions ranging from 96% (Phojet) to 86% (DL with $\varepsilon=0.10$). Recent calculations also yield values between 79 and 84% (ref. 17). Thus
The pseudorapidity is defined in terms of the polar angle as 
\[
\eta = -\ln \tan\left(\frac{\theta}{2}\right),
\]
with \(\theta\) being the azimuthal angle around the beam pipe. The pseudorapidity is represented in terms of the polar angle \(\theta\) as \(\eta = \ln \tan(\theta/2)\).

At the interaction point, the beam-line is surrounded by a tracking detector, which uses silicon pixel, silicon strip, and straw tube technologies, and is embedded in a 2-T magnetic field. The tracking system covers the pseudorapidity range \(|\eta| < 2.5\). It is surrounded by electromagnetic and hadronic calorimeters which are divided into two rings; the inner 8 counters cover the rapidity range 2.83 < |\(\eta\)| < 3.84 and the outer 8 counters cover the rapidity range 2.09 < |\(\eta\)| < 2.83. Each individual counter spans 45° of the azimuthal angle (\(\phi\)), and 31 out of 32 counters were operational. The luminosity is measured using a Cherenkov light detector, LUCID, which is located at \(z = \pm 17\) m. The luminosity calibration has been determined during dedicated van der Meer beam scans to a precision of 3.4% using the technique described in ref. 36.

### References


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Author contributions
All authors have contributed to the publication, being variously involved in designing and building the detector, writing offline software, operating and calibrating the detector and analysing the processed data.

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