PROCEEDINGS OF SCIENCE

Measurement of the total cross section in proton proton collisions at $\sqrt{s} = 7$ TeV with the ALFA sub-detector of ATLAS

Leszek ADAMCZYK[*†] **on behalf of the ATLAS Collaboration**
AGH University of Science and Technology (PL)
E-mail: `leszek.adamczyk@agh.edu.pl`

A measurement of the total pp cross section at the LHC at $\sqrt{s} = 7$ TeV by the ATLAS experiment is presented. In a special run with high-β^* beam optics, an integrated luminosity of 80 μb^{-1} was accumulated in order to measure the differential elastic cross section as a function of the Mandelstam momentum transfer variable t. The measurement is performed with the ALFA sub-detector of ATLAS. Using a fit to the differential elastic cross section in the $|t|$ range from 0.01 GeV^2 to 0.1 GeV^2 to extrapolate to $|t| \rightarrow 0$, the total cross section, $\sigma_{tot}(pp \rightarrow X)$, is measured via the optical theorem to be: $\sigma_{tot}(pp \rightarrow X) = 95.35 \pm 0.38$ (stat.) ± 1.25 (exp.) ± 0.37 (extr.) mb , where the first error is statistical, the second accounts for all experimental systematic uncertainties and the last is related to uncertainties in the extrapolation to $|t| \rightarrow 0$. In addition, the slope of the elastic cross section at small t is determined to be $B = 19.73 \pm 0.14$ (stat.) ± 0.26 (syst.) GeV^2.

ATL-PHYS-PROC-2015-125
27 October 2015

XXIII International Workshop on Deep-Inelastic Scattering
27 April - May 1 2015
Dallas, Texas

[*]Speaker.
[†]This work was partly supported by the Polish NCN grant nr UMO-2012/05/B/ST2/02480

PoS(DIS2015)061

1. Introduction

The total hadronic cross section is a fundamental parameter of strong interactions, setting the scale of the size of the interaction region at a given energy. A calculation of the total hadronic cross section from first principles, based upon perturbative quantum chromodynamics (pQCD), is currently not possible. Large distances are involved in the collision process and thus perturbation theory is not applicable. Traditionally, the total cross section at hadron colliders has been measured via elastic scattering using the optical theorem. This paper presents a measurement by the ATLAS experiment [1] at the LHC in pp collisions at $\sqrt{s} = 7$ TeV using this approach. The optical theorem states:

$$\sigma_{tot} \approx \mathrm{Im}[f_{el}(t \to 0)]$$

where $f_{el}(t \to 0)$ is the elastic-scattering amplitude extrapolated to the forward direction, i.e. at $|t| \to 0$, t being the four-momentum transfer. Thus, a measurement of elastic scattering in the very forward direction gives information on the total cross section. An extrapolation of the differential cross section to $|t| \to 0$ gives the total cross section through the formula:

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{\mathrm{d}\sigma_{el}}{\mathrm{d}t}\right|_{t\to 0},$$

where ρ represents a small correction arising from the ratio of the real to imaginary part of the elastic scattering amplitude in the forward direction and is taken from theory. More details on the results presented in this paper are given in Ref. [2].

2. Experimental setup

ATLAS is a multi-purpose detector designed to study elementary processes in proton–proton interactions at the TeV energy scale. To improve the coverage in the forward direction three smaller detectors with specialized tasks are installed at large distance from the interaction point. The most forward detector, ALFA, is sensitive to particles in the range $|\eta| > 8.5$.[1] A detailed description of the ATLAS detector can be found in Ref. [1].

The ALFA detector (Absolute Luminosity For ATLAS) is designed to measure small-angle proton scattering. Two tracking stations are placed on each side of the central ATLAS detector at distances of 238 m and 241 m from the interaction point. The tracking detectors are housed in so-called Roman Pots (RPs) which can be moved close to the circulating proton beams. Combined with special beam optics allows the detection of protons at scattering angles down to 10 μrad. Each station carries an upper and lower RP connected by flexible bellows to the primary LHC vacuum. Elastically scattered protons are detected in the main detectors (MDs) while dedicated overlap detectors (ODs) measure the distance between upper and lower MDs. The arrangement of the upper and lower MDs and ODs with respect to the beam is illustrated in Fig. 1.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the interaction point to the centre of the LHC ring and the y-axis points upwards. The pseudorapidity η is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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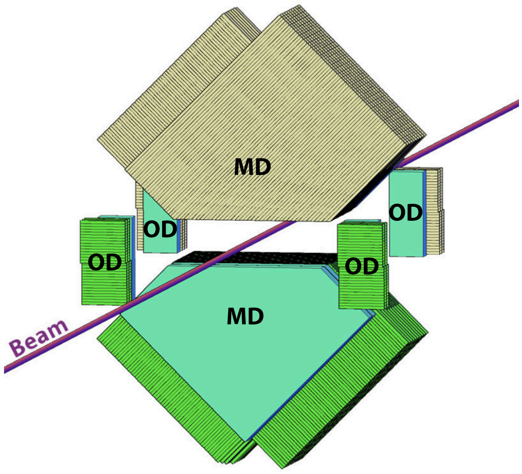

Figure 1: A schematic view of a pair of ALFA tracking detectors in the upper and lower RPs[2].

Each MD consists of 2 times 10 layers of 64 square scintillating fibres with 0.5 mm side length glued on titanium plates. The fibres on the front and back sides of each titanium plate are orthogonally arranged at angles of ±45° with respect to the *y*-axis. The overlap detectors consist of three layers of 30 scintillating fibres per layer measuring the vertical coordinate of traversing beam-halo particles or shower fragments. Two independent ODs are attached at each side of both MDs, as sketched in Fig. 1.Both tracking detectors are completed by trigger counters which consist of 3 mm thick scintillator plates covering the active areas of MDs and ODs.

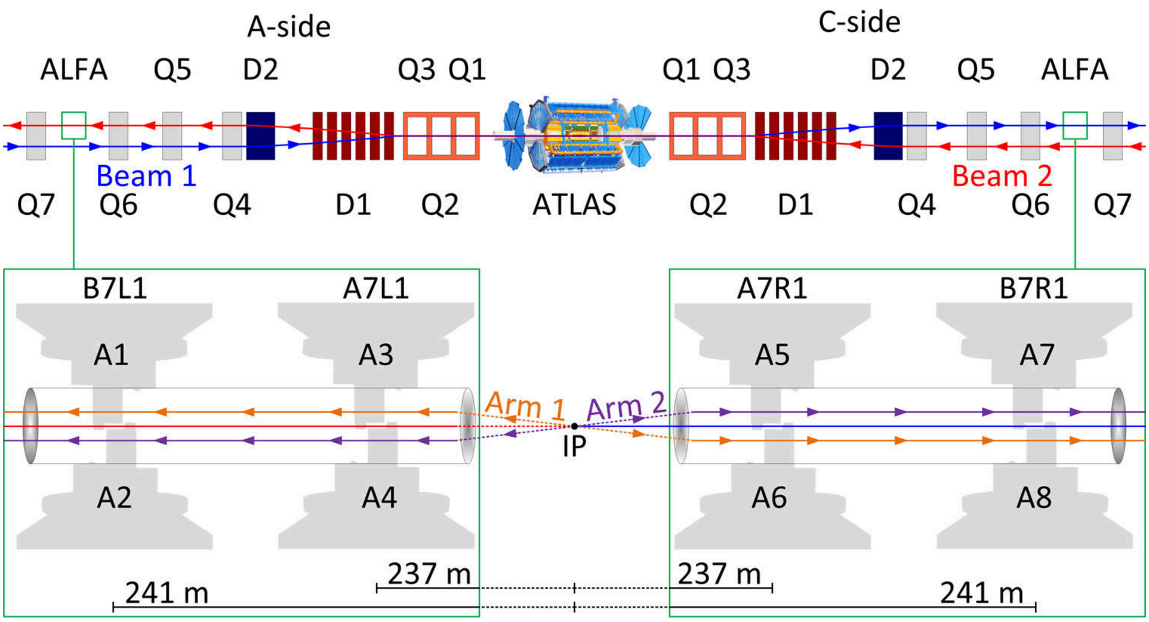

Figure 2: A sketch of the experimental set-up, not to scale, showing the positions of the ALFA Roman Pot stations in the outgoing LHC beams, and the quadrupole (Q1–Q6) and dipole (D1–D2) magnets situated between the interaction point and ALFA [2].

The station and detector naming scheme is depicted in Fig. 2. The stations A7R1 and B7R1 are positioned at $z = -237.4$ m and $z = -241.5$ m respectively in the outgoing beam 1 (C side), while the stations A7L1 and B7L1 are situated symmetrically in the outgoing beam 2 (A side). The data were recorded in a dedicated low-luminosity run using special beam optics. The duration of this run was four hours. For elastic-scattering events, the main pair of colliding bunches was used, which contained around 7×10^{10} protons per bunch. Several pairs of pilot bunches with lower intensity and unpaired bunches were used for the studies of systematic uncertainties. To trigger on elastic-scattering events, two main triggers were used. The triggers required a coincidence of the main detector trigger scintillators between either of the two upper (lower) detectors on side A and either of the two lower (upper) detectors on side C. The elastic-scattering rate was typically 50 Hz in each arm. The trigger efficiency for elastic-scattering events was determined from a data stream in which all events with a hit in any one of the ALFA trigger counters were recorded. In the geometrical acceptance of the detectors, the efficiency of the trigger used to record elastic-scattering events is $99.96 \pm 0.01\%$.

3. Measurement method

The data were recorded with special beam optics characterized by a $\beta^\star = 90$ m at the interaction point resulting in a small divergence and providing parallel-to-point focusing in the vertical plane.[2] In parallel-to-point beam optics the betatron oscillation has a phase advance Ψ of 90° between the interaction point and the RPs, such that all particles scattered at the same angle are focused at the same position at the detector, independent of their production vertex position. This focusing is only achieved in the vertical plane.

The beam optics parameters are needed for the reconstruction of the scattering angle $\theta^\star$ at the interaction point. The four-momentum transfer t is calculated from $\theta^\star$; in elastic scattering at high energies this is given by:

$$-t = (\theta^\star \times p)^2 \ ,$$

where p is the nominal beam momentum of the LHC of 3.5 TeV and $\theta^\star$ is measured from the proton trajectories in ALFA. A formalism based on transport matrices allows positions and angles of particles at two different points of the magnetic lattice to be related.

The trajectory $(w(z),\ \theta_w(z))$, where $w \in \{x, y\}$ is the transverse position with respect to the nominal orbit at a distance z from the interaction point and θ_w is the angle between w and z, is given by the transport matrix $\mathbf{M}$ and the coordinates at the interaction point ($w^\star$, $\theta_w^\star$):

$$\begin{pmatrix} w(z) \\ \theta_w(z) \end{pmatrix} = \mathbf{M} \begin{pmatrix} w^\star \\ \theta_w^\star \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} w^\star \\ \theta_w^\star \end{pmatrix} \ ,$$

where the elements of the transport matrix can be calculated from the optical function β and its derivative with respect to z and Ψ. The transport matrix $\mathbf{M}$ must be calculated separately in x and y and depends on the longitudinal position z; the corresponding indices have been dropped for clarity. While the focusing properties of the beam optics in the vertical plane enable a reconstruction of the scattering angle using only M_{12} with good precision, the phase advance in the horizontal plane is close to 180° and different reconstruction methods are investigated.

The ALFA detector was designed to use the "subtraction" method, exploiting the fact that for elastic scattering the particles are back-to-back, that the scattering angle at the A- and C-sides are the same in magnitude and opposite in sign, and that the protons originate from the same vertex.

[2]The β-function determines the variation of the beam envelope around the ring and depends on the focusing properties of the magnetic lattice.

The positions measured with ALFA at the A- and C-side of ATLAS are roughly of the same size but opposite sign and in the subtraction method the scattering angle is calculated according to:

$$\theta_w^\star = \frac{w_\mathrm{A} - w_\mathrm{C}}{M_{12,\mathrm{A}} + M_{12,\mathrm{C}}}.$$

This is the nominal method in both planes and yields the best t-resolution. An alternative methods “local angle” and “lattice” [2] were also used. For all methods t is calculated from the scattering angles as follows:

$$-t = \left((\theta_x^\star)^2 + (\theta_y^\star)^2\right) p^2$$

4. Data analysis

Events are required to pass the trigger conditions for elastic-scattering events and have a reconstructed track in all four detectors of the arm which fired the trigger. Events with additional tracks in detectors of the other arm arise from the overlap of halo protons with elastically scattered protons and are retained. Further geometrical cuts on the left-right acollinearity are applied, exploiting the back-to-back topology of elastic-scattering events. The position difference between the left and the right sides is required to be within 3.5σ of its resolution determined from simulation. An efficient cut against non-elastic background is obtained from the correlation of the local angle between two stations and the position in the horizontal plane. Finally, fiducial cuts to ensure a good containment inside the detection area are applied to the vertical coordinate. At the end of the selection procedure 805 428 events survive all cuts.

The measured t-spectrum in each arm, after background subtraction, is corrected for migration effects using an iterative, dynamically stabilized unfolding method [4]. Monte Carlo simulation is used to obtain the migration matrix used in the unfolding. The results are cross-checked using an unfolding based on the singular value decomposition method [5].

The luminosity is determined using the BCM (beam conditions monitor), as in Ref. [3], and other detectors and algorithms are used to assess the systematic uncertainty. The total systematic uncertainty on the integrated luminosity L_int during the high-$\beta^\star$ run is computed as the sum in quadrature of the scale uncertainty, the overall calibration-transfer uncertainty and the background uncertainty and it amounts to 2.3%. The final integrated luminosity for the selected running period is:

$$L_\mathrm{int} = 78.7 \pm 0.1\,(\mathrm{stat.}) \pm 1.9\,(\mathrm{syst.})\ \mu\mathrm{b}^{-1}\ .$$

5. Results

In order to calculate the differential elastic cross section, several corrections are applied. The corrections are done individually per detector arm and the corrected spectra from the two arms are combined. In a given bin t_i the cross section is calculated according to the following formula:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t_i} = \frac{1}{\Delta t_i} \times \frac{\mathscr{M}^{-1}[N_i - B_i]}{A_i \times \varepsilon^\mathrm{reco} \times \varepsilon^\mathrm{trig} \times \varepsilon^\mathrm{DAQ} \times L_\mathrm{int}}\ ,$$

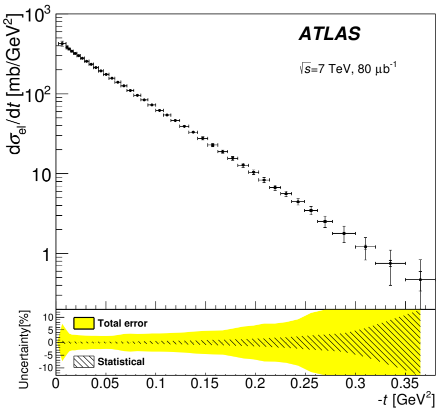

Figure 3: The differential elastic cross section measured using the subtraction method [2].

where Δt_i is the bin width, $\mathscr{M}^{-1}$ represents the unfolding procedure applied to the background-subtracted number of events $N_i - B_i$, A_i is the acceptance, $\varepsilon^{\rm reco}$ is the event reconstruction efficiency, $\varepsilon^{\rm trig}$ is the trigger efficiency, $\varepsilon^{\rm DAQ}$ is the dead-time correction and $L_{\rm int}$ is the integrated luminosity used for this analysis. The resulting differential elastic cross section using the subtraction method is shown in Fig. 3 with statistical and systematic uncertainties.

Traditionally, the nuclear amplitude at small $|t|$ is parameterized by a single exponential function where slope parameter B can be related via a Fourier transform to the impact parameter and therefore to the effective interaction radius. The total cross section and the slope parameter B are obtained from a fit of the theoretical spectrum

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}t} &= \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2}\times G^4(t)\\ &- \sigma_{tot}\times\frac{\alpha G^2(t)}{|t|}\left[\sin\left(\alpha\phi(t)\right)+\rho\cos\left(\alpha\phi(t)\right)\right]\times\exp\frac{-B|t|}{2}\\ &+ \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\times\exp\left(-B|t|\right)\ ,\end{aligned}$$

where G is the electric form factor of the proton [6], ϕ is the Coulomb phase [7, 8]. The value of ρ is extracted from global fits performed by the COMPETE Collaboration to lower-energy elastic-scattering data comprising results from a variety of initial states [9, 10]. Both the statistical and systematic uncertainties as well as their correlations are taken into account in the fit. The fit yields:

$$\sigma_{tot} = 95.35 \pm 1.30 \text{ mb}\ , \qquad B = 19.73 \pm 0.24\text{GeV}^{-2}\ ,$$

The total elastic cross section is derived from the nuclear scattering term under the assumption that the slope B remains constant over the full t-range. The Coulomb and interference terms are not taken into account. With this approximation the differential elastic cross section is reduced to the exponential form:

$$\frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}t} = \left.\frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}t}\right|_{t=0}\exp(-B|t|) \qquad \text{with} \qquad \left.\frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}t}\right|_{t=0} = \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\,.$$

Integrating the parameterized form of the differential cross section over the full t-range yields the total elastic cross section:

$$\sigma_{\rm el} = 24.00 \pm 0.19\ (\text{stat.}) \pm 0.57\ (\text{syst.})\text{ mb},$$

6. Discussion

The result for the total hadronic cross section presented here, $\sigma_{tot} = 95.35 \pm 1.36$ mb, can be compared to the most precise value measured by TOTEM, in the same LHC fill using a luminosity-dependent analysis, $\sigma_{tot} = 98.6 \pm 2.2$ mb [11]. Assuming the uncertainties are uncorrelated, the difference between the ATLAS and TOTEM values corresponds to 1.3σ. The uncertainty on the TOTEM result is dominated by the luminosity uncertainty of $\pm 4\%$, giving a ± 2 mb contribution to σ_{tot} through the square root dependence of σ_{tot} on luminosity. The measurement reported here profits from a smaller luminosity uncertainty of only $\pm 2.3\%$.

The value of the nuclear slope parameter $B = 19.73 \pm 0.29$ GeV^{-2} reported here is in good agreement with the TOTEM measurement of 19.89 ± 0.27 GeV^{-2} [11]. These large values of the B-parameter confirm that elastically scattered protons continue to be confined to a gradually narrowing cone as the energy increases.

The elastic cross section is measured to be 24.0 ± 0.6 mb. This is in agreement with the TOTEM result of 25.4 ± 1.1 mb within 1.1σ. The ratio of the elastic cross section to the total cross section is often taken as a measure of the opacity of the proton. Measurements shed light on whether the black disc limit of a ratio of 0.5 is being approached. It is interesting to note that although there are some small differences between ATLAS and TOTEM for the total and elastic cross sections, the ratio $\sigma_{\rm el}/\sigma_{\rm tot}$ is very similar. The TOTEM value is $\sigma_{\rm el}/\sigma_{tot} = 0.257 \pm 0.005$ [12, 13], while the measurement reported here gives $\sigma_{\rm el}/\sigma_{tot} = 0.252 \pm 0.004$. All derived measurements depend on σ_{tot} and B and are therefore highly correlated.

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