# MEASUREMENT OF THE TOTAL PROTON–PROTON CROSS SECTION AT $\sqrt{s} = 7$ TeV WITH THE ATLAS DETECTOR AT THE LHC*

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*(Received May 4, 2015)*

The ATLAS measurement of the total proton–proton cross section at $\sqrt{s} = 7$ TeV is presented. The data used for the analysis were collected with the ALFA sub-detector of the ATLAS experiment. The measurement method is based on the optical theorem. The obtained cross section is $\sigma_{\rm tot} = 95.35 \pm 1.36$ mb. The measurement is compared to other published results on the total proton–proton cross section.

DOI:10.5506/APhysPolB.46.1319
PACS numbers: 13.85.Lg, 13.85.Dz

## 1. Introduction

Cross section is a physical quantity used in particle and nuclear physics to describe the probability of the interaction between particles. Presently, the calculation of total hadronic cross section based on quantum chromodynamics is an unsolved problem. Knowledge of the behaviour of the cross section with the increasing centre-of-mass energy is not only interesting from the theoretical point of view, but also desirable for the design of new colliders.

Measurement of the total proton–proton cross section at $\sqrt{s} = 7$ TeV was made by the ATLAS experiment at the LHC. The purpose of this proceedings is to describe this measurement. More details of the results presented in this paper are given in Ref. [1].

* Presented at the Cracow Epiphany Conference on the Future High Energy Colliders, Kraków, Poland, January 8–10, 2015.

## 2. Theoretical input

The measurement of the total cross section for proton–proton collisions is made based on the optical theorem. The optical theorem, one of the laws of scattering theory, relates the total cross section $\sigma_{\mathrm{tot}}$ to the forward elastic scattering amplitude

$$\sigma_{\mathrm{tot}} \propto \mathrm{Im}[f_{\mathrm{el}}(t \to 0)]\,, \tag{1}$$

where $t$ is the four-momentum transfer squared and $f_{\mathrm{el}}(t \to 0)$ is the elastic scattering amplitude extrapolated to the forward direction. By means of the optical theorem, the measurement of elastic scattering provides information about the total cross section.

The differential elastic cross section is related to the scattering amplitudes through the following formula

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_{\mathrm{N}}(t) + f_{\mathrm{C}}(t)e^{i\alpha\phi(t)}\right|^2\,, \tag{2}$$

where $f_{\mathrm{N}}$ is the amplitude for nuclear interaction, $f_{\mathrm{C}}$ is the amplitude for Coulomb interaction and $\phi$ is the phase induced by long-range Coulomb interactions. For the presented analysis, the Coulomb amplitude is much smaller than the nuclear one and can be neglected [1]. Then, relation (2) could be written as follows

$$\frac{d\sigma}{dt} = \sigma_{\mathrm{tot}}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \times e^{-B|t|}\,, \tag{3}$$

where $\rho = \frac{\mathrm{Re}(f_{\mathrm{el}})}{\mathrm{Im}(f_{\mathrm{el}})}$ and $B$ is the nuclear slope. Therefore, the total cross section $\sigma_{\mathrm{tot}}$ and the slope parameter $B$ can be found from a fit of the theoretical spectrum to the data, with the $\rho$ value taken from the theory.

## 3. Experimental setup — the ALFA detector

The data were collected with the ALFA detector [2]. ALFA (acronym for Absolute Luminosity For ATLAS) is one of the specialized ATLAS [3] detectors (besides ZDC and LUCID) which covers the measurement range in the forward region. The ALFA detector is sensitive to particles in the pseudorapidity range $|\eta| > 8.5$ and can be used to measure protons scattered elastically and diffractively at very small angles.

The ALFA detector position with respect to the ATLAS detector is presented in Fig. 1. The system, housing the Roman Pots, consists of two stations on each side (named A- and C-side) of the interaction point at distances of 238 and 241 meters. The Roman Pots can be moved close to the proton beams in the vertical plane. Between the ALFA stations and the interaction point the dipole magnets — D1 and D2 — and the quadrupole magnets — Q1 to Q6 — are placed. Each station consists of two detectors, lower and upper, marked in Fig. 1 as A1 to A8. These detectors are designed to track the scattered protons. An elastic event is recognized when the signal from the scattering proton is registered in detectors A1, A3, A6 and A8 (Arm 1) or in detectors A2, A4, A5 and A7 (Arm 2).

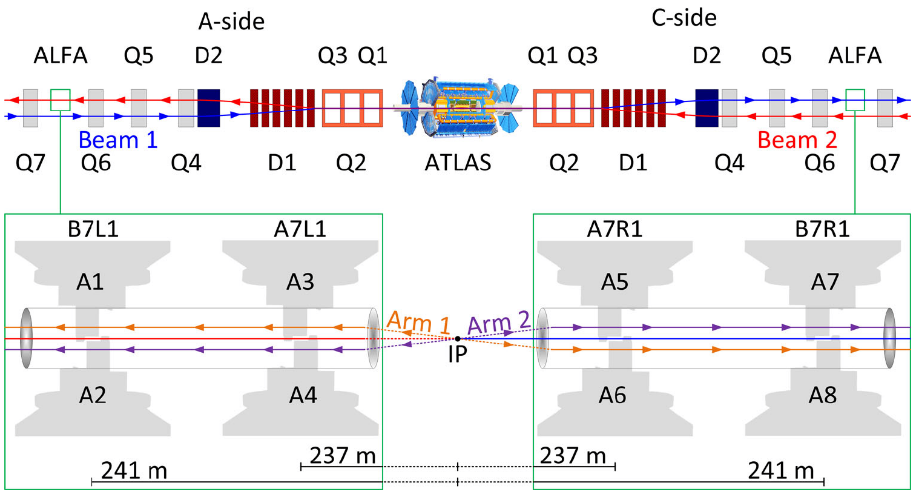


Fig. 1. Positions of the ALFA stations in the outgoing LHC beams. ALFA stations are described as B7L1, A7L1, A7R1, B7R1 [1].

Data for the presented measurement were collected during a special LHC run with the dedicated beam optics characterized by the betatron function value $\beta^*$ of 90 m at the interaction point. The run was characterized by the low luminosity of the order of $5 \times 10^{27}$ cm$^{-2}$s$^{-1}$. This luminosity was measured with the standard ATLAS methods based on the BCM and LUCID detectors [4]. In addition, a method of primary vertex counting was used. The methods were calibrated with the van der Meer scans [5]. The integrated luminosity for this run was $L_{\rm int} = 78.7 \pm 0.1(\text{stat.}) \pm 1.9(\text{syst.})$ $\mu$b.

Events for further analysis were required to pass the trigger conditions for elastic scattering events and have the reconstructed tracks in Arm 1 or Arm 2 (see Fig. 1). Figure 2 presents the correlation of the $y$ coordinate measured at the A- and C-side in the inner ALFA stations.

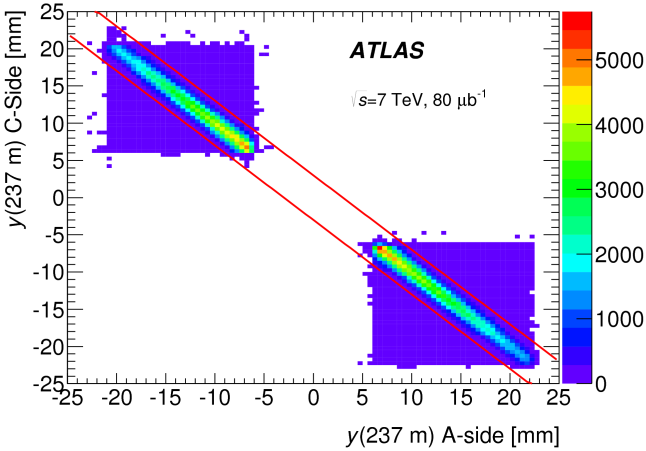


Fig. 2. The correlation of the $y$ coordinate measured between the A- and C-side for the stations closer to the interaction point. Candidates for the elastic scattering events (before acceptance and background rejection cuts) are between the black/red lines [1].

## 4. The measurement method

The four-momentum transfer squared $t$ is related to the elastic scattering angle by the formula

$$-t = (\theta^* \times p)^2 \,, \tag{4}$$

where $p$ is the beam momentum — 3.5 TeV for this run — and $\theta^*$ is the scattering angle at the interaction point.

The scattering angle is calculated based on the formalism of the transport matrices. A relation between the coordinates at the interaction point $(w^*, \theta^*_w)$ and the coordinates measured at a given ALFA station $(w, \theta_w)$ is given by the formula

$$\begin{pmatrix} w \\ \theta_w \end{pmatrix} = \boldsymbol{M} \begin{pmatrix} w^* \\ \theta^*_w \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} w^* \\ \theta^*_w \end{pmatrix} \,, \tag{5}$$

where $w \in \{x, y\}$. Transport matrices $\boldsymbol{M}$ depend on the magnetic lattice between the interaction point and ALFA detector. The beam optics with $\beta^* = 90$ m gives small divergence and provides parallel-to-point focusing in the vertical plane.

Several methods are used to reconstruct the scattering angles $\theta^*_x$ and $\theta^*_y$. The first one is the *subtraction* method where the scattering angle is calculated from the formula

$$\theta^*_w = \frac{w_{\rm A} - w_{\rm C}}{M_{12,{\rm A}} + M_{12,{\rm C}}} \,. \tag{6}$$

Another method is the *local angle* method with the formula

$$\theta^*_w = \frac{\theta_{w,\mathrm{A}} - \theta_{w,\mathrm{C}}}{M_{22,\mathrm{A}} + M_{22,\mathrm{C}}} \,. \tag{7}$$

The last one is called the *lattice* method and according to it, the scattering angle is calculated from

$$\begin{aligned} \begin{pmatrix} w^* \\ \theta^*_w \end{pmatrix} &= M^{-1} \begin{pmatrix} w \\ \theta_w \end{pmatrix} , \\ \theta^*_w &= M^{-1}_{12} \times w + M^{-1}_{22} \times \theta_w \,. \end{aligned} \tag{8}$$

Actually, $\theta^*_y$ is always reconstructed with the subtraction method. The other methods are used to reconstruct $\theta^*_x$. The results presented in this document are based on the subtraction method.

## 5. Differential and total cross sections

Figure 3 presents a comparison of the raw $t$ distribution obtained with different reconstruction methods (subtraction, local angle and lattice). Statistical uncertainties are represented by error bars.

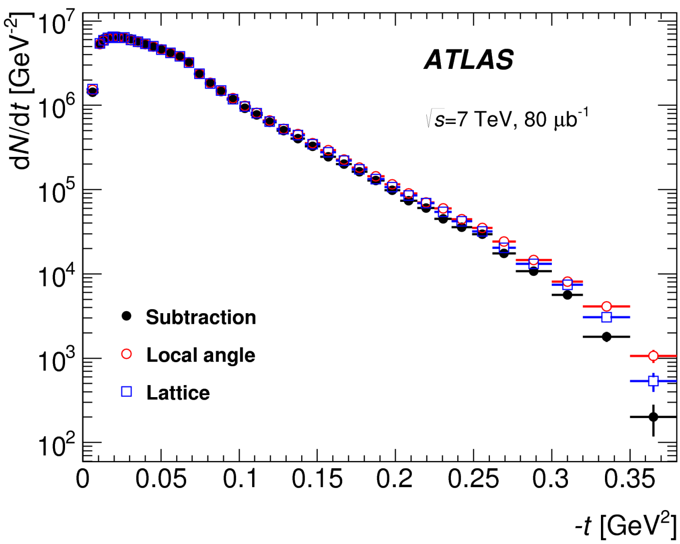


Fig. 3. Rate $\frac{dN}{dt}$ as a function of $t$ with statistical uncertainties. Three different methods of reconstruction are shown [1].

The differential elastic cross section is calculated in a given bin $t_i$ by the formula

$$\frac{d\sigma}{dt_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times e^{\mathrm{reco}} \times e^{\mathrm{trig}} \times e^{\mathrm{DAQ}} \times L_{\mathrm{int}}} \,, \tag{9}$$

where $\Delta t_i$ is the bin width, $\mathcal{M}^{-1}$ — unfolding procedure applied to the background-subtracted number of events $N_i - B_i$, $A_i$ — acceptance, $e^{\rm reco}$ — event reconstruction efficiency, $e^{\rm trig}$ — trigger efficiency, $e^{\rm DAQ}$ — data acquisition dead-time correction and $L_{\rm int}$ — the integrated luminosity. Figure 4 shows the corrected $t$ distribution for the subtraction reconstruction method with statistical and systematic uncertainties.

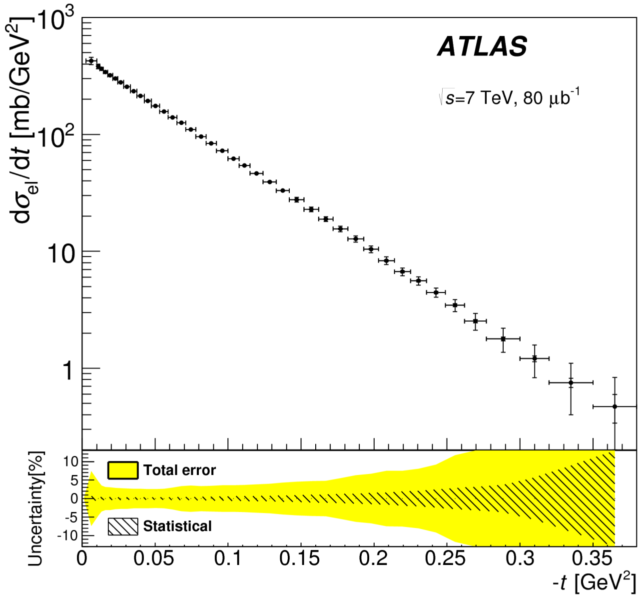


Fig. 4. Differential elastic cross section reconstructed with the subtraction method. Two type of error bars are marked: the internal ones describe statistical uncertainty, external ones — experimental uncertainty [1].

Fitting of the theoretical spectrum (3) provides the total cross section and the slope parameter $B$ values. This fit is presented in Fig. 5. The fit range is chosen from $t = -0.01$ GeV$^2$ to $t = -0.1$ GeV$^2$. The lower limit was chosen to be as close as possible to $t = 0$ to reduce the extrapolation uncertainty, but keeping the acceptance above 10%. The upper limit was chosen so that the fit is not extended into the region where deviations from the exponential function are expected.

The obtained value of the total cross section from the subtraction reconstruction method is

$$\sigma_{\rm tot} = 95.35 \pm 0.38({\rm stat.}) \pm 1.25({\rm exp.}) \pm 0.37({\rm extr.})\ {\rm mb}\,, \qquad (10)$$

where the first error is statistical, the second denotes the total experimental uncertainty and the last one accounts for the uncertainty in the extrapolation

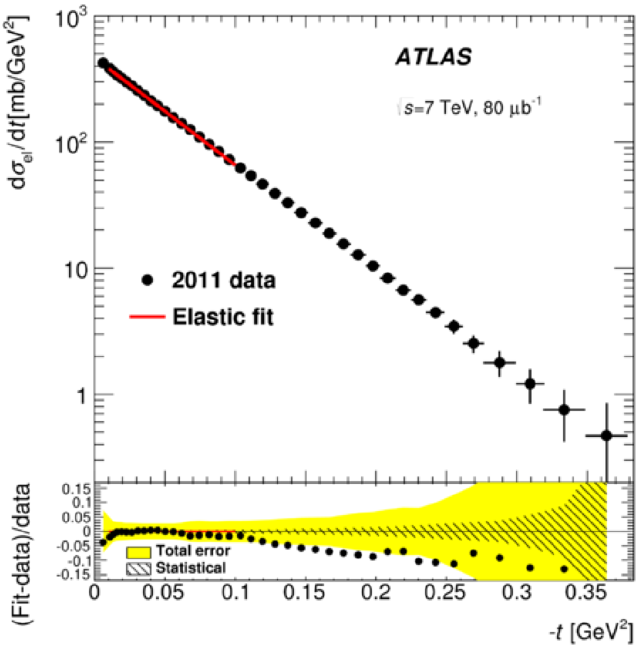


Fig. 5. Differential elastic cross section reconstructed with the subtraction method. The fit of the theoretical spectrum (3) is represented by the black/red line. The bottom plot shows statistical and total errors and the normalized difference between data and the fit [1].

to $t = 0$. The obtained value of the nuclear slope $B$ from the subtraction reconstruction method is

$$B = 19.73 \pm 0.14(\text{stat.}) \pm 0.19(\text{exp.}) \pm 0.17(\text{extr.})\ \text{GeV}^{-2}\,. \tag{11}$$

The dominant sources of experimental systematic uncertainty for $\sigma_{\text{tot}}$ are the luminosity, nominal beam energy and reconstruction efficiency uncertainties. For $B$ slope, the main contribution to the experimental systematic uncertainty is the nominal beam energy uncertainty. The fit-range dependence is the dominant source of the uncertainty on the extrapolation.

## 6. Conclusions

A measurement of the hadronic total cross section was performed at the LHC also by the TOTEM experiment [6]. The results obtained by TOTEM are: $\sigma_{\text{tot}} = 98.6 \pm 2.2$ mb and $B = 19.89 \pm 0.27$ GeV$^{-2}$ [6]. Corresponding results presented in this document with their total errors are $\sigma_{\rm tot} = 95.35 \pm 1.36$ mb and $B = 19.73 \pm 0.29$ GeV$^{-2}$. The ALFA and TOTEM measurement results are consistent.

Figure 6 presents the total cross section measured as a function of the centre-of-mass energy for ALFA, TOTEM and other published measurements (*e.g.* cosmic ray experiments [7–11] and experiments at lower energy [12]). Measurements are compared with the best fit to the energy evolution of the total cross section from the COMPETE Collaboration [13].

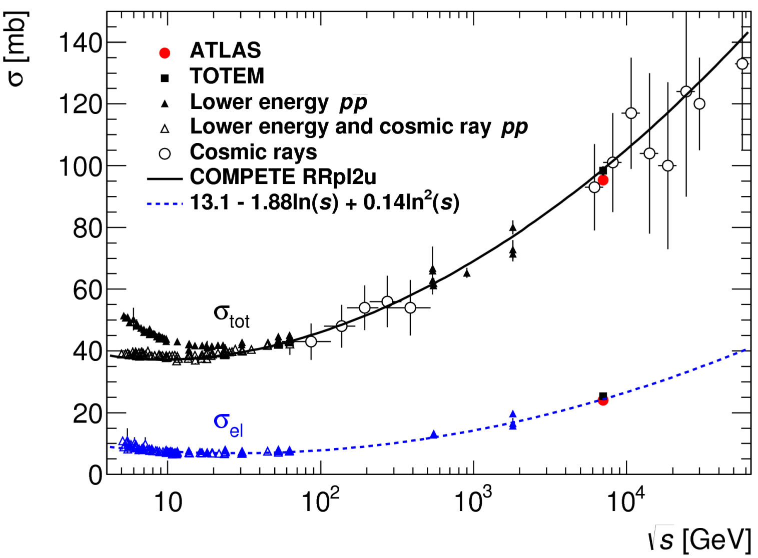


Fig. 6. Theoretical predictions and the measurements of the total and elastic hadronic cross section as a function of centre-of-mass energy $\sqrt{s}$. The measurements made by ATLAS and TOTEM are indicated [1].

This work was supported in part by the Polish National Science Centre grant: DEC-2013/08/M/ST2/00320.

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