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# Measurements of elastic $pp$ interactions and exclusive production with the ATLAS detector

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The total proton–proton($pp$) cross section is a fundamental observable at the LHC. It can be derived from the measurement of the elastic cross section, using the optical theorem. Measurements of the elastic $pp$ cross section were performed at a center-of-mass energy of 8 TeV at various settings of the beam optics using the ALFA detector. Using a fit to the differential elastic cross section in the $-t$ range from 0.014 GeV$^2$ to 0.1 GeV$^2$ to extrapolate $t \to 0$, the total cross section, $\sigma_{\text{tot}}(pp \to X)$, is measured via the optical theorem. In addition, the slope of the exponential function describing the elastic cross section at small $t$ is determined. The production of exclusive $\gamma\gamma \to \mu^+\mu^-$ events in $pp$ collisions at a centre- of-mass energy of 13 TeV is measured with the ATLAS detector, using data corresponding to an integrated luminosity of 3.2 fb$^{-1}$. The measurement is performed for a dimuon invariant mass of 12 GeV $< m_{\mu^+\mu^-} <$ 70 GeV. The integrated cross section is determined within a fiducial acceptance region of the ATLAS detector and differential cross sections are measured as a function of the dimuon invariant mass. The results are compared to theoretical predictions both with and without corrections for absorptive effects.

ATL-PHYS-PROC-2018-172
01 December 2018

*The 39th International Conference on High Energy Physics (ICHEP2018)*
*4-11 July, 2018*
*Seoul, Korea*

[*]Speaker.

[†]This work was partly supported by the National Science Centre of Poland under grant number UMO-2015/19/B/ST2/00989, by the AGH UST statutory tasks No. 11.11.220.01/4 within subsidy of the Ministry of Science and Higher Education and by PL-GRID infrastructure.

## 1. Introduction

The total cross section for $pp$ interactions characterizes a fundamental process of the strong interaction. Its energy evolution has been studied at each new centre-of-mass energy available. Traditionally, the total cross section at hadron colliders has been measured via elastic scattering, $pp \to pp$, using the optical theorem. The optical theorem states: $\sigma_{\rm tot} \approx {\rm Im}[f_{\rm el}(t \to 0)]$, where $f_{\rm el}(t \to 0)$ 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:

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

where $\rho$ is the ratio of the real to imaginary part of the elastic scattering amplitude at $t \to 0$.

Central exclusive production (CEP), $pp \to pXp$, in which the protons remain intact and the system $X$ is produced with a rapidity gap on either side, proceeds via the exchange of colourless, neutral particles, either photons or combinations of gluons, for example Pomerons (see [1] and references therein). The dominant CEP mechanism at LHC energies is the Double Pomeron Exchange (DPE) - a fusion of two Pomerons. DPE allows the study of quantum chromodynamics (QCD) and the Pomeron. Typically rare photon-photon induced ($\gamma\gamma$) CEP occurs at perceptible rate and provide a unique opportunity to study high-energy electroweak processes. In order to reproduce the data, the calculations of CEP reactions need to take into account the proton absorptive effects [2]. They are mainly related to additional gluon interactions between the protons. These effects lead to the suppression of exclusive cross sections by producing extra hadronic activity in the event.

## 2. Experimental setup

ATLAS is a multi-purpose detector designed to study elementary processes in $pp$ interactions at the TeV energy scale. To improve the coverage in the forward direction two smaller detectors were installed at large distance from the nominal interaction point (IP) to measure protons produced at very small angles. The elastic-scattering data were recorded with the most forward ALFA subdetector (Absolute Luminosity For ATLAS) [3]. It consists of Roman Pot (RP) tracking- detector stations placed at distances of 237 m (inner station) and 241 m (outer station) on either side of the ATLAS IP. A detailed description of the ATLAS detector can be found in Ref. [4].

## 3. Elastic $pp$ cross section

ATLAS has reported measurements of the total cross section in $pp$ collisions at $\sqrt{s} = 7$ TeV [3] and at $\sqrt{s} = 8$ TeV [5]. The measurement methodology and analysis technique are very similar between the two measurements and the technical details are discussed thoroughly in Ref. [3]. Recent measurement at $\sqrt{s} = 8$ TeV is based on 500 $\mu$b$^{-1}$ of collision data collected in special $\beta^\star = 90$ m[1] run resulting in a small beam divergence.

[1]The $\beta-$function determines the variation of the beam envelope around the ring and depends on the focusing properties of the magnetic lattice; its value at the IP is denoted by $\beta^\star$.

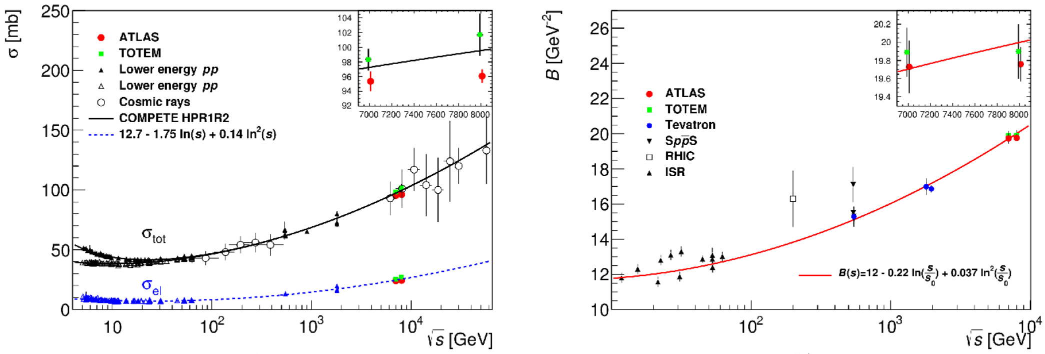


**Figure 1:** (left) Total and elastic cross section measurements with other published measurements and model predictions as a function of the centre-of-mass energy [5]. (right) Comparison of the measurement of the slope $B$ with other published measurements [5].

The following formulae are used to fit differential elastic cross section and extract $\sigma_{tot}$ and the nuclear slope $B$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{16\pi}|f_N(t) + f_C(t)e^{i\alpha\phi(t)}|^2,$$

$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}, \qquad f_N(t) = (\rho + i)\frac{\sigma_{\mathrm{tot}}}{\hbar c}e^{-B|t|/2}$$

where $G$ is the electric form factor of the proton, $f_C$ the Coulomb amplitude and $f_N$ the nuclear amplitude with $\phi$ being their relative phase shift. The total integrated elastic cross section, $\sigma_{\mathrm{el}}$ is obtained from the formula:

$$\sigma_{\mathrm{el}} = \frac{\sigma^2_{\mathrm{tot}}}{B}\frac{1+\rho^2}{16\pi(\hbar c)^2}$$

The TOTEM Collaboration exploited data from the same LHC fill for a measurement of $\sigma_{\mathrm{tot}}$ [6]. Their result is $1.9\sigma$ higher than the ATLAS measurement. Better agreement is observed in the nuclear slope measurement, which indicates that the difference is confined to the normalization. The measurements of ATLAS and TOTEM are compared to measurements at lower energy and to a global fit from Ref. [7] in Figure 1(left) for $\sigma_{\mathrm{tot}}(\sigma_{\mathrm{el}})$ and in Figure 1(right) for $B$.

Data in the Coulomb-Nuclear-Interference region at $-t \approx 10^{-3}$ GeV$^2$ allows a measurement of the $\rho$-parameter and better prediction of $\sigma_{\mathrm{tot}}$ at energies not accesible at LHC. Such measurement requires even higher value of $\beta^\star$ and measurements in wide range of c.m.s energies. ALFA collected data with $\beta^\star = 1$ km and $\beta^\star = 2.5$ km.

## 4. Exclusive production in $pp$ scattering

ATLAS has reported measurements of $pp(\gamma\gamma) \to l^+l^-pp$ production (referred to as exclusive $\gamma\gamma \to l^+l^-$) at $\sqrt{s} = 7$ TeV [8] and at $\sqrt{s} = 13$ TeV [9] for $\gamma\gamma \to \mu^+\mu^-$. Calculations of the cross section for exclusive $\gamma\gamma \to l^+l^-$ production in $pp$ collisions are based on the Equivalent Photon Approximation (EPA) [10]. Two models of absorptive corrections were used on top of EPA prediction. In the finite-size parameterisation approach [11], the absorptive effects are embedded in the evaluation of the $\gamma\gamma$ luminosity. In the approach implemented in the SuperChic2 event generator [12], the absorptive effects are included at the amplitude level differentially in the final-state momenta of scattered protons.

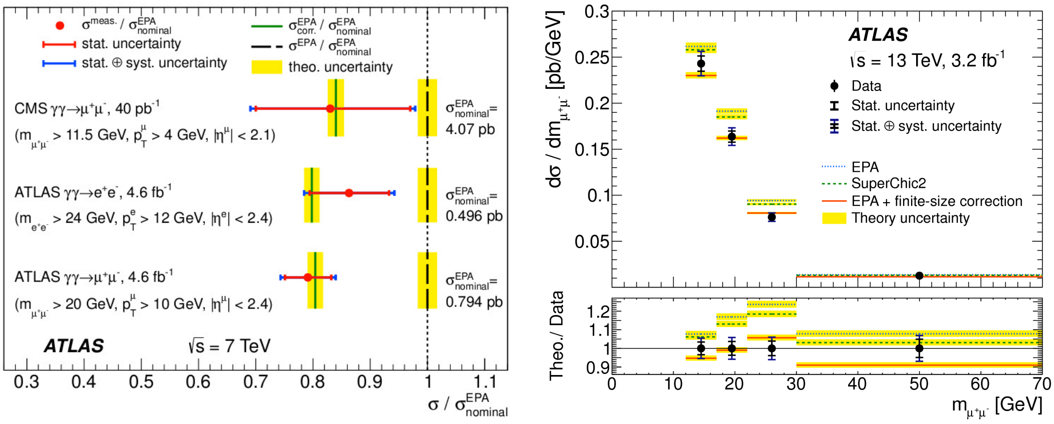


**Figure 2:** (left) The ratios of measured (red points) and predicted (solid green lines) exclusive $\gamma\gamma \to l^+l^-$ cross sections to the uncorrected EPA calculations (black dashed line) [8]. (right) The exclusive $\gamma\gamma \to \mu^+\mu^-$ differential fiducial cross section measurements as a function of dimuon invariant mass $m_{\mu^+\mu^-}$ [9].

Figure 2(left) shows the ratios of the measured cross sections to the EPA calculations and to the prediction with the inclusion of absorptive corrections. The measurements are in agreement with the predicted values corrected for proton absorptive effects. The figure includes a similar CMS cross section measurement [13]. The measured differential fiducial cross sections as a function of dimuon invariant mass is shown in 2(right), together with the theoretical predictions. The EPA predictions corrected for absorptive effects are in good agreement with data.

## 5. Summary

Measurement of the $\sigma_{\rm tot}$ was performed at $\sqrt{s} = 8$ TeV. New data are analized at various settings of the beam optics and energies using the ALFA detector. Exclusive processes are distinguished in the central part of the ATLAS detector requiring the absence of additional charged particles. A parameterisation of absorptive corrections provides a good description of the $\gamma\gamma \to \mu^+\mu^-$ data. New CEP results are expected with forward proton tagging detectors.

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