

Elastic and Total Cross-Section Measurements by TOTEM: Past and Future

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The TOTEM experiment at the LHC has measured proton-proton elastic scattering in dedicated runs at $\sqrt{s} = 7, 8$ and 2.76 TeV centre-of-mass LHC energies. The proton-proton total cross-section σ_{tot} has been derived for each energies using a luminosity independent method. TOTEM has excluded a purely exponential differential cross-section for elastic proton-proton scattering with significance greater than 7σ in the $|t|$ range from 0.027 to 0.2 GeV² at $\sqrt{s} = 8$ TeV. The ρ parameter has been measured at $\sqrt{s} = 8$ TeV via the Coulomb-nuclear interference, and was found to be $\rho = 0.12 \pm 0.03$.

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1. INTRODUCTION

The TOTEM (TOTAL cross section, Elastic scattering and diffraction dissociation Measurement at the LHC) experiment has been designed to measure the total proton-proton (pp) cross-section, elastic scattering and diffractive processes at the LHC [1], see Figure 1.

The experimental apparatus of TOTEM is composed of three subdetectors: the Roman Pots (RP) and the T1, T2 inelastic forward telescopes. The detectors are placed symmetrically on both sides of the Interaction Point 5 (IP5), which is shared with the CMS experiment.

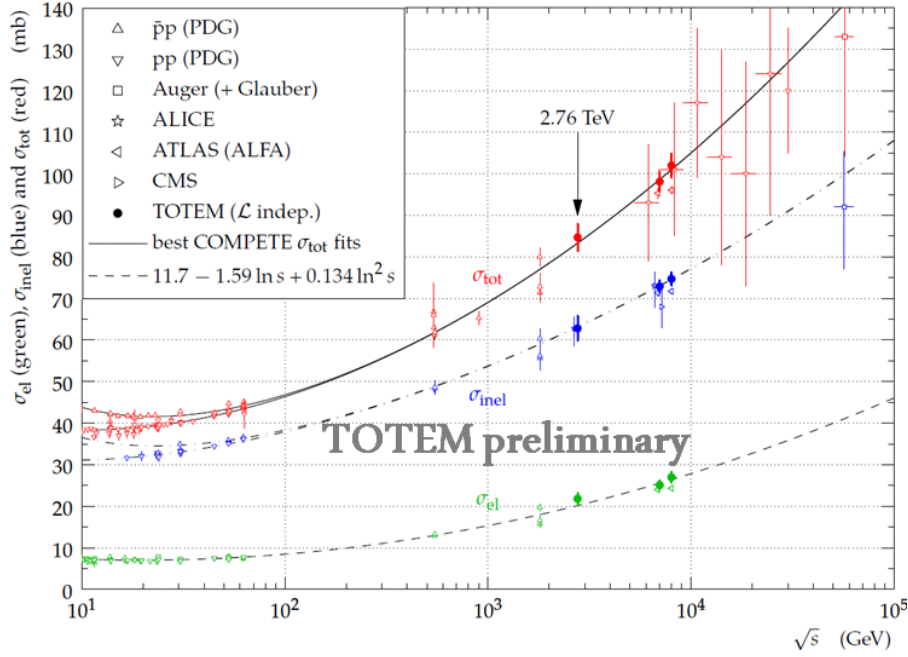


Figure 1: A compilation of total, inelastic and elastic pp cross-section measurements. The red points indicate the TOTEM total cross-section measurements at $\sqrt{s} = 7, 8$ and 2.76 TeV using the luminosity independent method [10, 11, 12, 13, 14, 15].

The RPs are moveable beam-pipe insertions, hosting edgeless silicon detectors to detect leading protons scattered at very small angles. In order to maximize the acceptance of the experiment for elastically scattered protons, the RPs are able to approach the beam center to a transverse distance as small as 1 mm. The alignment of the RPs is optimized by reconstructing common tracks going through the overlap between the vertical and horizontal RPs [1, 2].

Before the LHC long shutdown one (LS1) the RPs, used for measurements, were located at distances of 215–220 m from IP5 [1]. The actual layout, i.e., after the LHC LS1, is different in RP location and quantity. The RP stations previously installed at ± 147 m, from IP5, have been relocated to ± 210 m. Moreover, two newly designed horizontal RPs have been installed between the two units of the ± 220 m station [3, 4].

2. ELASTIC SCATTERING AND TOTAL CROSS-SECTION σ_{tot} MEASUREMENTS

For each tagged elastic event the four-momentum transfer squared t is reconstructed using the LHC optical functions, characterized with the so-called betatron amplitude at IP5 β^* [1]. The TOTEM experiment developed a novel experimental method to estimate the optical functions at the RP locations, using the measured elastically scattered protons [5, 6, 7, 8, 9].

The total inelastic rate N_{inel} , measured by the T1 and T2 telescopes, and the total nuclear elastic rate N_{el} with its extrapolation to zero four-momentum transfer squared $t = 0$ are combined with the optical theorem to obtain the total cross-section in a luminosity, \mathcal{L} , independent way

$$\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \cdot \left. \frac{dN_{\text{el}}}{dt} \right|_{t=0} \cdot (N_{\text{el}} + N_{\text{inel}})^{-1}. \quad (2.1)$$

The measured ratio of the elastic and inelastic rates $N_{\text{el}}/N_{\text{inel}}$ allows for the determination of the elastic and inelastic cross-sections as well [1, 9].

The TOTEM experiment determined the total pp cross-section at $\sqrt{s} = 7$ TeV using the luminosity independent method [10], which was shown to be consistent with the total cross-sections measured in independent ways, see Table 1. The elastic and inelastic cross-sections were found to be $\sigma_{\text{el}} = 25.1 \pm 1.1$ mb and $\sigma_{\text{inel}} = 72.9 \pm 1.5$ mb.

The measurement was repeated at $\sqrt{s} = 8$ TeV, yielding to $\sigma_{\text{tot}} = 101.7 \pm 2.9$ mb, $\sigma_{\text{el}} = 27.1 \pm 1.4$ mb and $\sigma_{\text{inel}} = 74.7 \pm 1.7$ mb [11]. A compilation of the results is shown in Figure 1, which also demonstrates that the observed cross-sections are in agreement with low-energy data and cosmic ray results as well [12, 13, 14, 15].

Method	\mathcal{L} independent [10]	[7]	[8]	[8]
σ_{tot} [mb]	98.0 ± 2.5	98.3 ± 2.8	98.6 ± 2.2	99.1 ± 4.3

Table 1: The total cross-section σ_{tot} results measured by the TOTEM experiment at $\sqrt{s} = 7$ TeV with four different methods.

Thanks to a very-high statistics $\beta^* = 90$ m data set at $\sqrt{s} = 8$ TeV energy, the TOTEM experiment has excluded a purely exponential elastic pp differential cross-section [16]. The exclusion's significance is greater than 7σ in the $|t|$ range from 0.027 to 0.2 GeV², see Figure 2. Using refined parametrizations for the extrapolation to the optical point, $t = 0$, yields total cross-section values $\sigma_{\text{tot}} = 101.5 \pm 2.1$ mb and $\sigma_{\text{tot}} = 101.9 \pm 2.1$ mb, compatible with the previous

The TOTEM experiment performed its first measurement of elastic scattering in the Coulomb-nuclear interference (CNI) region [17]. The data have been collected at $\sqrt{s} = 8$ TeV with a special beam optics of $\beta^* = 1000$ m. The ρ parameter was for the first time at LHC extracted via the Coulomb-nuclear interference, and was found to be $\rho = 0.12 \pm 0.03$.

Using the luminosity independent method TOTEM achieved a preliminary measurement of the pp cross-sections at $\sqrt{s} = 2.76$ TeV, see Figure 1. The total cross-section was found to be $\sigma_{\text{tot}} = 84.7 \pm 3.3$ mb, while the elastic and inelastic cross-section are $\sigma_{\text{el}} = 21.8 \pm 1.4$ mb and $\sigma_{\text{inel}} = 62.8 \pm 2.9$ mb, respectively.

In 2016 TOTEM took data during a special run with $\beta^* = 2500$ m optics at 13 TeV collision energy, in order to make Odderon searches via CNI; the analysis is currently ongoing.

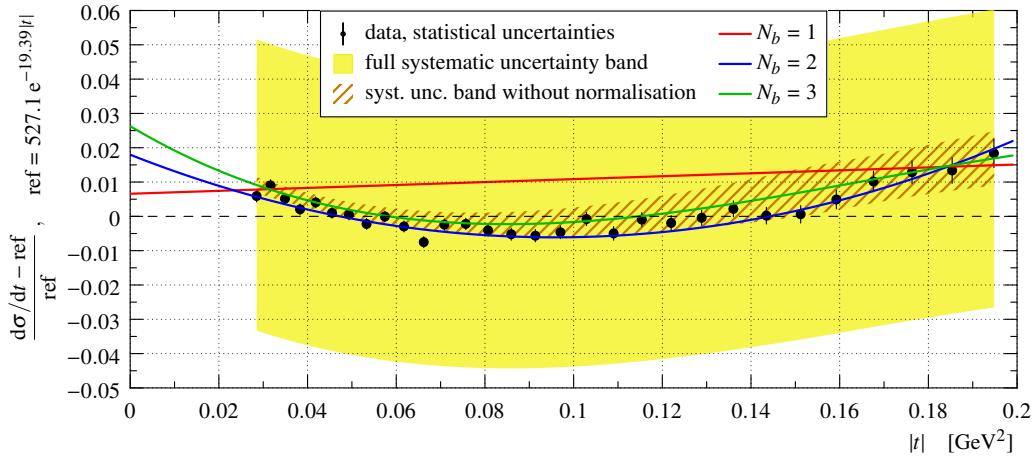


Figure 2: Differential cross-section measured at $\sqrt{s} = 8$ TeV LHC energy plotted as relative difference from a reference exponential. The black dots represent data points with statistical uncertainty bars [16].

3. CONCLUSIONS

The TOTEM experiment has measured elastic pp scattering at $\sqrt{s} = 7, 8$ and 2.76 TeV. The total, elastic and inelastic cross-sections have been derived for all energies using a luminosity independent method, at 2.76 TeV the result is preliminary. TOTEM has excluded a purely exponential differential cross-section for elastic pp scattering with significance greater than 7σ in the $|t|$ range from 0.027 to 0.2 GeV^2 at $\sqrt{s} = 8$ TeV. Using $\beta^* = 1000$ m optics at $\sqrt{s} = 8$ TeV energy the ρ parameter was for the first time at LHC extracted via the Coulomb-nuclear interference.

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