# ELASTIC AND TOTAL CROSS-SECTION MEASUREMENTS BY TOTEM

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*Abstract.* The TOTEM experiment at the LHC has measured proton-proton (pp) elastic scattering in dedicated runs at $\sqrt{s} = 2.76,\ 7,\ 8$ and 13 TeV centre-of-mass energies. The total, elastic and inelastic pp cross-sections have been derived for each energy using the optical theorem and the luminosity independent method. At 13 TeV, the total pp cross-section has also been derived for the first time at LHC using the Coulomb amplitude for the normalization of the elastic $\mathrm{d}\sigma/\mathrm{d}t$. TOTEM has excluded using $\sqrt{s} = 8$ TeV data a purely exponential nuclear differential cross-section $\mathrm{d}\sigma/\mathrm{d}t$ at low $|t|$ for elastic pp scattering. The effect has been confirmed at $\sqrt{s} = 13$ TeV. The $\rho$ parameter, the real to imaginary ratio of the nuclear elastic scattering amplitude at $t = 0$, has been measured precisely at $\sqrt{s} = 13$ TeV using the Coulomb-nuclear interference region. To properly describe the measured $\rho$ value and all the TOTEM $\sigma_{\mathrm{tot}}$ measurements, in addition to the exchange of photons and colourless two-gluon compound states, the exchange of a colourless C-odd three-gluon compound state in the $t$-channel should be added for elastic pp scattering. At all LHC energies, TOTEM has observed a diffractive minimum ("dip") followed by a secondary maximum ("bump") in the elastic pp $\mathrm{d}\sigma/\mathrm{d}t$. In the measurement of the D0 experiment at $\sqrt{s} = 1.96$ TeV, no dip or bump can be observed in the elastic proton-antiproton $\mathrm{d}\sigma/\mathrm{d}t$. Under the assumption that possible effects due to the energy difference between the 2.76 TeV TOTEM and the 1.96 TeV D0 measurements can be neglected, the results provide evidence for the exchange of a colourless C-odd 3-gluon compound state in the $t$-channel of proton-(anti)proton elastic scattering.

## 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 Fig. 1.

The experimental apparatus of TOTEM is composed of three subdetectors: the Roman Pots (RP), the T1 and the 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.

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].

The T1 telescope is based on cathode strip chambers placed at ±9 m and covers the pseudorapidity range $3.1 \leq |\eta| \leq 4.7$; the T2 telescope is based on gas electron multiplier chambers placed at ±13.5 m and covers the pseudorapidity

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range $5.3 \le |\eta| \le 6.5$. The pseudorapidity coverage of the two telescopes at $\sqrt{s} = 2.76,\ 7,\ 8$ and 13 TeV allows the detection of about 96 %, 95 %, 94 % and 92 %, respectively, of the inelastic pp collisions, including collisions producing diffractive mass above about 2.1 GeV, 3.4 GeV, 3.6 GeV and 4.6 GeV, respectively [9, 11, 15].

Before the LHC long shutdown one (LS1) the RPs, used for the 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, newly designed horizontal RPs have been installed between the two units of the ±220 m station [3, 4].

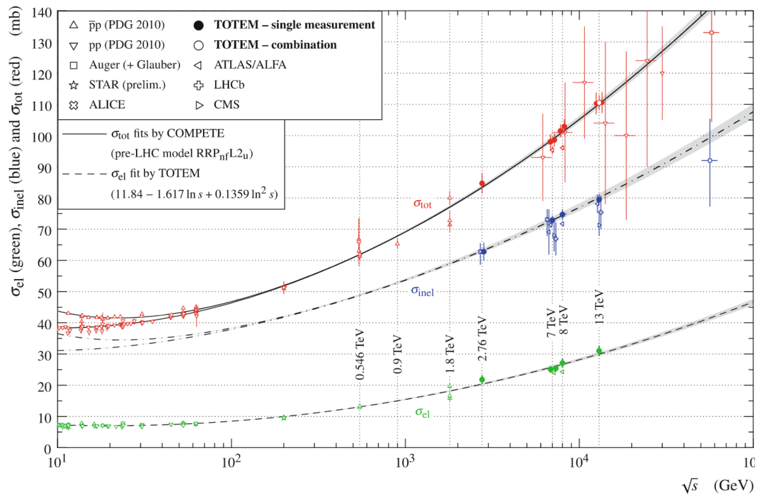


Figure 1: A compilation of total, inelastic and elastic pp cross-section measurements, see Ref. [12, 19] and references therein. The red points indicate the TOTEM total cross-section measurements at $\sqrt{s} = 2.76, 7, 8$ and 13 TeV using the luminosity independent method.

## 2 ELASTIC SCATTERING AND TOTAL CROSS-SECTION $\sigma_{\rm tot}$ 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 $\beta^*$ [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].

The total inelastic rate $N_{\rm inel}$, measured by the T1 and T2 telescopes, and the total nuclear elastic rate $N_{\rm el}$ 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

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

The measured elastic $N_{\mathrm{el}}$ and inelastic rates $N_{\mathrm{inel}}$ allow for the determination of the elastic and inelastic cross-sections as well.

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 $\sigma_{\mathrm{el}} = (25.1 \pm 1.1)$ mb and $\sigma_{\mathrm{inel}} = (72.9 \pm 1.5)$ mb, respectively.

| Method | $\mathcal{L}$ independent [10] | [7] | [8] | [8] |
|---|---|---|---|---|
| $\sigma_{\mathrm{tot}}$ [mb] | 98.0 ± 2.5 | 98.3 ± 2.8 | 98.6 ± 2.2 | 99.1 ± 4.3 |

Table 1: The total cross-section $\sigma_{\mathrm{tot}}$ results measured by the TOTEM experiment at $\sqrt{s} = 7$ TeV with three different methods and two different data sets.

The luminosity-independent measurements were repeated at $\sqrt{s} = 2.76$, 8 and 13 TeV. At $\sqrt{s} = 2.76$ TeV, the total cross-section was found to be $\sigma_{\mathrm{tot}} = (84.7 \pm 3.3)$ mb, while the elastic and inelastic cross-section were $\sigma_{\mathrm{el}} = (21.8 \pm 1.4)$ mb and $\sigma_{\mathrm{inel}} = (62.8 \pm 2.9)$ mb, respectively [15]. At $\sqrt{s} = 8$ TeV, the total, elastic and inelastic cross-sections of $\sigma_{\mathrm{tot}} = (101.7 \pm 2.9)$ mb, $\sigma_{\mathrm{el}} = (27.1 \pm 1.4)$ mb and $\sigma_{\mathrm{inel}} = (74.7 \pm 1.7)$ mb, respectively, were obtained [11]. Finally at $\sqrt{s} = 13$ TeV, the total, elastic and inelastic cross-sections were found to be $\sigma_{\mathrm{tot}} = (110.6 \pm 3.4)$ mb, $\sigma_{\mathrm{el}} = (31.0 \pm 1.7)$ mb and $\sigma_{\mathrm{inel}} = (79.5 \pm 1.8)$ mb, respectively [15].

In 2016 TOTEM took data during a special run with $\beta^* = 2500$ m optics at 13 TeV collision energy, which allowed to probe sufficiently low $|t|$-values to be sensitive to the Coulomb amplitude allowing a first total pp cross section measurement at LHC with Climb normalization $\sigma_{\mathrm{tot}} = (110.3 \pm 3.5)$ mb [19]. Combining the two uncorrelated TOTEM measurement at 13 TeV, luminosity independent and Coulomb normalization, yields $\sigma_{\mathrm{tot}} = (110.5 \pm 2.4)$ mb. Fig. 1 shows a compilation of all the results together with other LHC measurements. The observed cross-sections are in agreement with the extrapolation of low-energy data to LHC and cosmic ray results as well.

Thanks to a high statistics $\beta^* = 90$ m data set at $\sqrt{s} = 8$ TeV energy, the TOTEM experiment excluded a purely exponential elastic pp differential cross-section [13]. The significance of the exclusion is greater than $7\sigma$ in the $|t|$ range from 0.027 to 0.2 GeV$^2$. Using refined parametrizations for the extrapolation to the optical point, $t = 0$, yields total cross-section values $\sigma_{\mathrm{tot}} = (101.5 \pm 2.1)$ mb and $\sigma_{\mathrm{tot}} = (101.9 \pm 2.1)$ mb, compatible with the previous measurements. The deviation from the purely exponential elastic pp differential cross-section has been confirmed at 13 TeV [18].

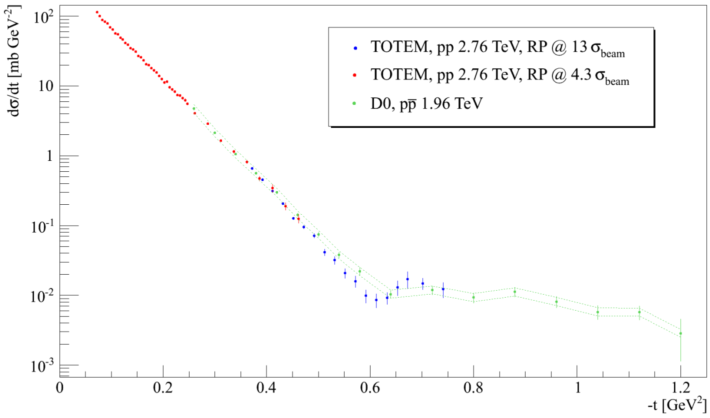


Figure 2: (color) The differential cross sections $d\sigma/dt$ at $\sqrt{s} = 2.76$ TeV measured by the TOTEM experiment and the elastic p$\bar{\text{p}}$ measurement of the D0 experiment at 1.96 TeV [17]. The green dashed line indicates the normalization uncertainty of the D0 measurement.

The TOTEM experiment performed its first measurement of elastic scattering in the Coulomb-nuclear interference (CNI) region [14]. The data have been collected at $\sqrt{s} = 8$ TeV with a special beam optics of $\beta^* = 1000$ m in 2012. The $\rho$ parameter was for the first time at LHC extracted via the Coulomb-nuclear interference, and was found to be $\rho = 0.12 \pm 0.03$. Taking the Coulomb-nuclear interference into account in the extrapolation to the optical point, $t = 0$, yields total cross-section values of $\sigma_{\text{tot}} = (102.9 \pm 2.3)$ mb and $\sigma_{\text{tot}} = (103.0 \pm 2.3)$ mb for central and peripheral phase descriptions, respectively, compatible with the previous measurements.

The special run with $\beta^* = 2500$ m optics at 13 TeV collision energy with higher statistics allowed also for a precise measurement of the $\rho$ yielding $\rho = 0.09 \pm 0.01$ and $\rho = 0.10 \pm 0.01$, depending on different physics assumptions and mathematical modelling. This $\rho$ result combined with all the TOTEM $\sigma_{\text{tot}}$ measurements indicate that it is not sufficient to include only photon and colourless 2-gluon compound state exchange, the so-called Pomeron, in the $t$-channel to properly describe elastic pp scattering. A significantly better description is obtained both in the Regge-like frameworks and QCD by adding colourless C-odd 3-gluon compound exchange in the $t$-channel [19], the so-called Odderon. On the contrary, if shown that the C-odd 3-gluon compound state $t$-channel exchange is not of importance for the description of elastic pp scattering at low $|t|$, the $\rho$ value determined by TOTEM would represent a first evidence of a slowing down of the total cross-section growth at higher energies.

At 13 TeV the differential cross-section has been measured in the [0.04; 4] GeV$^2$ range of $t$ using a very-high statistics sample (more than $10^9$) of elastic events taken in 2015 using a dedicated data acquisition system allowing an increased data taking rate by an order of magnitude. This sample allowed for a precise measurement of the non-exponential part that contains a diffractive minimum "dip" and a secondary maximum "bump", see Fig. 3 [18]. The dip position at 13 TeV was found to be $|t_{\rm dip}| = (0.47 \pm 0.004^{\rm stat} \pm 0.01^{\rm syst})$ GeV$^2$ and the ratio of the d$\sigma$/d$t$ at the bump and at the dip $1.77 \pm 0.01$. Using $\beta^*$ = 11 m optics data taken in 2013, also the dip and bump at $\sqrt{s} =$ 2.76 TeV could be observed; the position of the dip is $|t_{\rm dip}| = (0.61 \pm 0.03)$ GeV$^2$ and the bump-dip cross-section ratio $1.7 \pm 0.2$, as shown in Fig. 2 [16]. These new results confirm the d$\sigma$/d$t$ feature of dip and bump at TeV scale already observed at 7 TeV with a dip position of $|t_{\rm dip}| = (0.53 \pm 0.01^{\rm stat} \pm 0.01^{\rm syst})$ GeV$^2$ and a bump-dip cross-section ratio of $1.7 \pm 0.1$ [2, 19]. The series of TOTEM elastic pp measurements show that the dip is a permanent feature of the pp differential cross-section at TeV scale.

When the 2.76 TeV d$\sigma$/d$t$ measurement of TOTEM is compared to the proton-antiproton (p$\bar{\rm p}$) measurement of the D0 experiment at $\sqrt{s} = 1.96$ TeV, a significant difference can be observed, see Fig. 2. Under the assumption that possible effects due to the energy difference between TOTEM and D0 can be neglected, the result provides evidence for a colourless C-odd 3-gluon compound state exchange in the $t$-channel of pp and p$\bar{\rm p}$ elastic scattering.

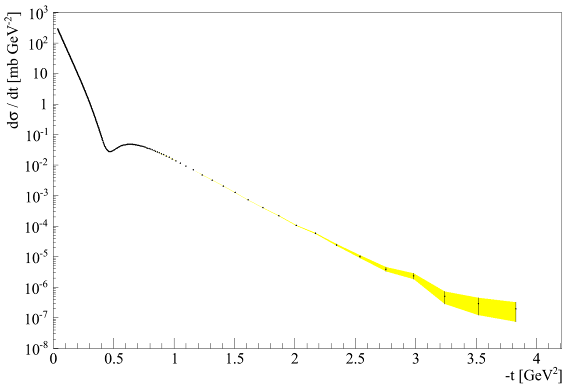


Figure 3: (color) Differential elastic cross-section d$\sigma$/d$t$ at $\sqrt{s} = 13$ TeV. The statistical and $|t|$-dependent correlated systematic uncertainty envelope is shown as a yellow band.

## 3 CONCLUSIONS

The TOTEM experiment has measured elastic pp scattering at $\sqrt{s} = 2.76, 7, 8$ and 13 TeV. The total, elastic and inelastic pp cross-sections have been derived for all energies using the luminosity independent method and the optical theorem. At $\sqrt{s} = 8$ TeV, TOTEM has also excluded a purely exponential nuclear pp differential cross-section at low $|t|$. This deviation has been confirmed at 13 TeV. At 13 TeV, the $\rho$ parameter has been precisely measured and the total pp cross-section using the Coulomb amplitude has been derived for the first time at the LHC. The $\rho$ measurement combined with all the TOTEM $\sigma_{\rm tot}$ measurements indicate the necessity to add the exchange of a colourless C-odd 3-gluon compound state in the $t$-channel of elastic pp scattering.

At $\sqrt{s} = 2.76$ TeV, a diffractive minimum "dip" and a secondary maximum "bump" has been observed; when compared to the $\mathrm{p\bar{p}}$ measurement of the D0 experiment at $\sqrt{s} = 1.96$ TeV, a significant difference can be observed. Under the assumption that possible effects due to the energy difference between TOTEM and D0 can be neglected, the result provides evidence for the exchange of a colourless C-odd 3-gluon bound state in the $t$-channel of pp and $\mathrm{p\bar{p}}$ elastic scattering. At 13 TeV, the differential cross-section has been measured in the [0.04 GeV$^2$; 4 GeV$^2$] $|t|$-range allowing for the precise measurement of the dip. The series of TOTEM elastic pp measurements show that the dip is a permanent feature of the pp differential cross-section at the TeV scale.

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