

# TOTEM status and results

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## 1 Introduction

The TOTEM experiment at the LHC is designed to measure the proton-proton elastic scattering, the inelastic and total cross-section and to study the diffractive physics in the forward region. This article summarizes the present status of the experiment and gives an overview of the latest results.

## 2 The experimental apparatus

The experimental apparatus [1], composed of three subdetectors (Roman Pots, T1 and T2 telescopes), is placed symmetrically on both sides of Interaction Point 5 (IP5), shared with the CMS experiment. All three subdetectors have trigger capability.

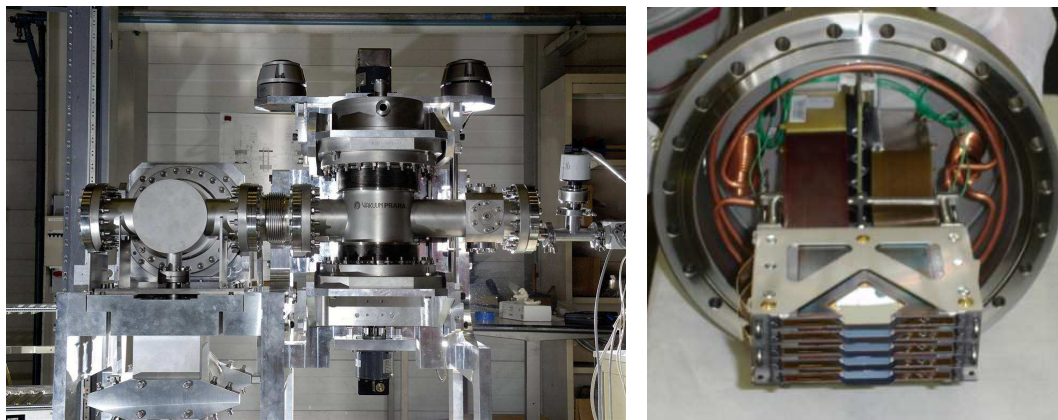


Figure 1: Left: a Roman Pot unit in the lab. Right: an array of 10 silicon detectors.

The Roman Pot stations, equipped with silicon detectors and placed at 147 and 220m from IP5, detect elastically and diffractively scattered protons with a small

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scattering angle down to a few  $\mu\text{rad}$ . They host silicon detectors which are moved very close to the beam when it is in stable conditions. Each RP station is composed of two units in order to have a lever arm for a better local track reconstruction and a higher efficiency of trigger selection by track angle. Each unit (Figure 1, left) consists of three pots, two vertical and one horizontal completing the acceptance for diffractively scattered protons. Each pot contains a stack of 10 planes of silicon strip detectors (Figure 1, right). Each plane has 512 strips (pitch of  $66\ \mu\text{m}$ ), oriented at  $+45^\circ$  (5 planes) or at  $-45^\circ$  (5 planes) w.r.t. the detector edge facing the beam, allowing a single hit resolution of  $\sim 20\ \mu\text{m}$ . As the detection of protons elastically scattered at angles down to few  $\mu\text{rads}$  requires a detector active area as close to the beam as  $\sim 1\text{mm}$ , a novel edgeless planar silicon detector technology has been developed in order to have an edge dead zone minimized to only  $\sim 50\ \mu\text{m}$ .

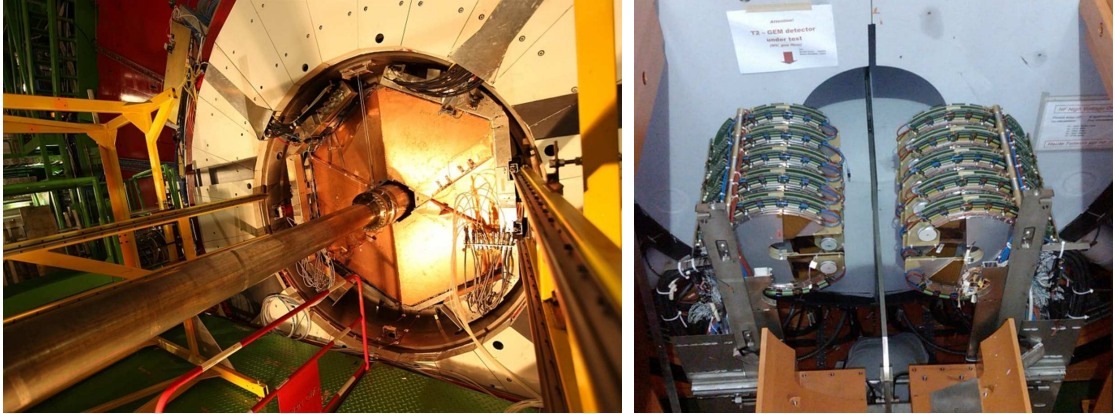


Figure 2: Left: T1 telescope installed in the CMS endcap. Right: T2 telescope during the installation inside the CMS rotating shield.

The T1 and T2 telescopes, placed at about 8 and 14m from IP5 respectively, detect charged particles produced in the polar angular range of a few mrad to  $\sim 100$  mrad. The T1 telescope ( $3.1 < |\eta| < 4.7$ ) consists of five planes formed by six trapezoidal Cathode Strip Chambers (CSC, Figure 2, left). These CSCs, with 10 mm thick gas gap and a gas mixture of  $\text{Ar}/\text{CO}_2/\text{CF}_4$  (40%/50%/10%), give three measurements of the charged particle coordinates with a spatial resolution of  $\sim 1\text{mm}$ : anode wires (pitch of 3mm) are parallel to the trapezoid base; cathode strips (pitch of 5mm) are rotated by  $\pm 60^\circ$  with respect to the wires. The T2 telescope ( $5.3 < |\eta| < 6.5$ ) is made of triple-GEM (Gas Electron Multipliers) chambers. Each half-arm, located at  $\sim 13.5\text{m}$  from IP5, is made by the combination of ten aligned detector planes having an almost semicircular shape (Figure 2, right). The T2 GEMs are characterized by a triple-GEM structure and a gas mixture of  $\text{Ar}/\text{CO}_2$  (70%/30%). The read-out board has two separate layers with different patterns: one with  $256 \times 2$  concentric circular

strips ( $80\mu\text{m}$  wide, pitch of  $400\mu\text{m}$ ), allowing track radial coordinate reconstruction with a resolution of  $\sim 100\mu\text{m}$ ; the other with a matrix of  $24 \times 65$  pads (from  $2 \times 2\text{mm}^2$  to  $7 \times 7\text{mm}^2$  in size) providing level-1 trigger information and track azimuthal coordinate reconstruction.

### 3 LHC special optics

The detection of elastically and diffractively scattered protons in the RP detectors is strongly dependent on the accelerator optics used during the runs. After an elastic interaction in IP5 with the transverse vertex position  $(x^*; y^*)$  and with scattering angle projections  $(\Theta_x^*; \Theta_y^*)$ , the displacement  $(x; y)$  of the proton trajectory from the beam centre at the RP position is given by  $x = L_x \Theta_x^* + v_x x^*$  and  $y = L_y \Theta_y^* + v_y y^*$  with  $L_{x,y}$  and  $v_{x,y}$  depending on the optics. A special  $\beta^*=90\text{m}$  optics has been developed and used during dedicated runs. This optics is characterized by  $v_y \sim 0$  and  $L_x \sim 0$ , which allows the reconstruction of the vertical scattering angle  $\Theta_y^*$  from the proton track position  $y$  and of the horizontal angle  $\Theta_x^*$  from the track angle  $\Theta_x = dx/ds$  at the RP:  $\Theta_y^* = y/L_y$  and  $\Theta_x^* = (\frac{dL_x}{ds})^{-1} \cdot (\Theta_x - \frac{dv_x}{ds} x^*)$ , where  $s$  denotes the distance from the interaction point and  $x^* = x/v_x$  since  $L_x \sim 0$ .

### 4 Data taking and analysis

Data presented here have been taken at  $\sqrt{s} = 7\text{TeV}$  during runs in 2010 and in 2011. An integrated luminosity of  $6.1\text{nb}^{-1}$  was collected in runs with the standard  $\beta^* = 3.5\text{m}$  optics, with the RP detectors approaching the beam to a distance as small as 7 times the transverse beam size  $\sigma_{beam}$ . With the special  $\beta^* = 90\text{m}$  optics more than  $84\mu\text{b}^{-1}$  were collected with different RP approaches to the beam (10, 6.5, 5.5 and  $4.8 \cdot \sigma_{beam}$ ).

For a detailed description of the event selection, background estimation, corrections, statistical and systematic errors, the reader is referred to the original TOTEM publications [2, 3, 4, 5, 6, 7].

### 5 Results

At the LHC energy of  $\sqrt{s} = 7\text{TeV}$ , under various beam and background conditions, luminosities, and Roman Pot positions, TOTEM has measured the differential cross-section for proton-proton elastic scattering as a function of the four-momentum transfer squared  $t$ , the inelastic and the total cross-section.

The differential elastic cross-section  $d\sigma_{el}/dt$  was measured in the range  $5 \cdot 10^{-3} < |t| < 2.5\text{GeV}^2$ . In the low  $|t|$  range ( $5 \cdot 10^{-3} < |t| < 0.2\text{GeV}^2$ ) the data can be

described by a single exponential fit with a slope  $B = (19.9 \pm 0.3)\text{GeV}^2$  [5], which confirms the trend of a slope increase with  $\sqrt{s}$  observed by previous experiments; this value is compatible with the fit performed with a different data set in the range  $0.02 < |t| < 0.33\text{GeV}^2$  [2]. The position of the pronounced dip,  $|t| = (0.53 \pm 0.01^{stat} \pm 0.01^{syst})\text{GeV}^2$ , confirms the *shrinkage* of the forward elastic peak with  $\sqrt{s}$ , a trend already observed in elastic pp scattering at lower energies. Above the dip structure  $d\sigma_{el}/dt$  becomes less steep and can be described with a power law  $|t|^n$  with an exponent  $n = -7.8 \pm 0.3^{stat} \pm 0.1^{syst}$  for  $|t|$  values between  $1.5\text{GeV}^2$  and  $2.0\text{GeV}^2$ .

The small error on the slope parameter  $B$  allowed a precise extrapolation over the 9% non-visible elastic cross-section to  $t = 0$  (optical point). With the luminosity from CMS, known with a  $\sim 4\%$  uncertainty, the elastic cross-section was determined to be  $(25.4 \pm 1.1)\text{mb}$  [5].

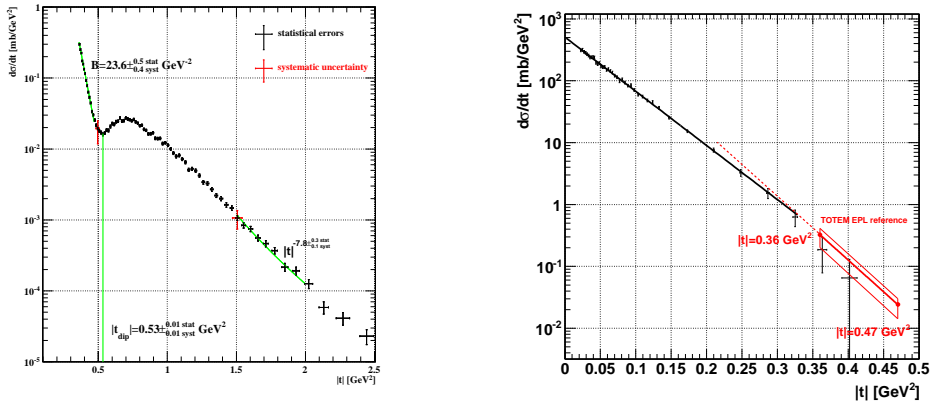


Figure 3: Left: the measured differential cross-section  $d\sigma_{el}/dt$  with its statistical (for all points) and systematic (for two example points) error bars [3]. Right: The measured pp elastic scattering differential cross-section  $d\sigma_{el}/dt$  in the low  $|t|$  range with the exponential fit. Between  $0.35$  and  $0.4\text{GeV}^2$  the overlap between data sets of [2] and [3] can be seen.

The inelastic cross-section has been directly measured by TOTEM using the inelastic telescopes and the luminosity from CMS. The preliminary value of this measurement is  $\sigma_{inel} = (73.7 \pm 0.1^{stat} \pm 1.7^{syst} \pm 2.9^{lumi})\text{mb}$  [10].

The measurement of the total cross-section has been done by TOTEM in different ways (the still preliminary values are taken from [10]):

- using the optical theorem, depending on the measurement of the elastic scattering and on its extrapolation to the optical point, on  $\rho$  from theory<sup>2</sup> and on

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<sup>2</sup> $\rho = 0.141 \pm 0.007$ [8]

the luminosity from CMS

$$\sigma_{tot}^2 = \frac{16\pi}{1 + \rho^2} \frac{1}{\mathcal{L}} \frac{dN_{el}}{dt} \Big|_{t=0}$$

The measured value is  $\sigma_{tot} = (98.6 \pm 2.2)\text{mb}$ . Moreover, in this case, the inelastic cross-section can be obtained by  $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ ;

- using the separate measurement of the elastic and inelastic cross-section ( $\sigma_{tot} = \sigma_{el} + \sigma_{inel}$ ), depending on the luminosity from CMS. The measured value is  $\sigma_{tot} = (99.1 \pm 4.3)\text{mb}$ ;
- using the optical theorem, depending on the measurement of the elastic and inelastic rate, on the measurement of the elastic scattering extrapolation to the optical point, on  $\rho$  from theory and luminosity independent

$$\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \frac{dN_{el}/dt|_{t=0}}{N_{el} + N_{inel}}$$

The measured value is  $\sigma_{tot} = (98.0 \pm 2.5)\text{mb}$ .

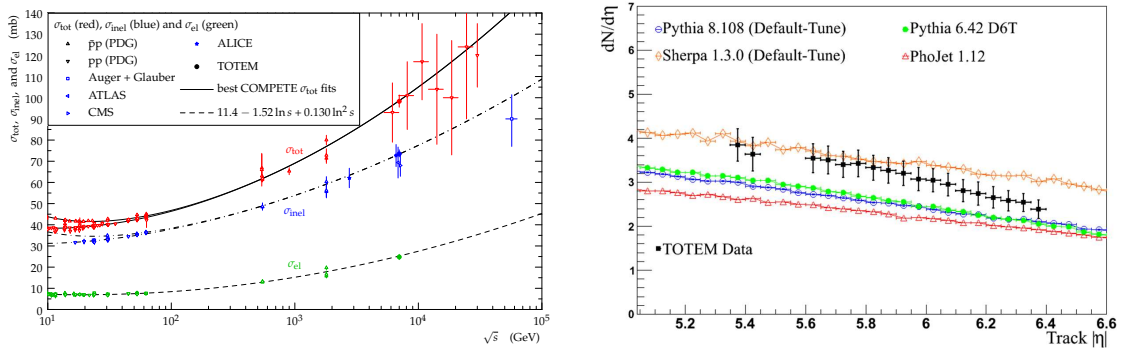


Figure 4: Left: Compilation of measurements of  $\sigma_{tot}$ ,  $\sigma_{inel}$ , and  $\sigma_{el}$  [8, 9]. Right: Charged particle pseudorapidity density distribution in the  $5.3 < |\eta| < 6.5$  range.

TOTEM has also measured the charged particle pseudorapidity density  $dN_{ch}/d\eta$  for  $5.3 < |\eta| < 6.4$  in events with at least one charged particle with  $p_T > 40\text{MeV}/c$  in this pseudorapidity range, extending the measurements performed by the other LHC experiments [4] into the forward region.

The measurement refers to more than 99% of non-diffractive events and to single and double diffractive events with diffractive masses above  $\sim 3.4\text{GeV}/c^2$ , corresponding to about 95% of the total inelastic cross-section. Several MC generators have been compared to data; none of them has been found to fully describe the measurement (see Figure 4, right).

## 6 Summary

The TOTEM experiment at the LHC has measured the total, inelastic and differential elastic cross-section at the energy of  $\sqrt{s} = 7$  TeV. The data were collected with the two inelastic telescopes and the Roman Pot detectors during several dedicated runs, partly with a special  $\beta^* = 90$ m beam optics. The elastic scattering measurements cover a range of squared four momentum transfer  $|t|$  from 0.005 to 2.5 GeV<sup>2</sup> and exhibit an approximately exponential behaviour for  $|t| < 0.33$  GeV<sup>2</sup>, followed by a significant diffractive minimum at  $|t| = (0.53 \pm 0.01^{\text{stat}} \pm 0.01^{\text{syst}})$  GeV<sup>2</sup>. For  $|t| > 1.5$  GeV<sup>2</sup>, a power-law decrease with an exponent of  $-7.8 \pm 0.3^{\text{stat}} \pm 0.1^{\text{syst}}$  has been observed. The inelastic cross-section has been measured both directly and indirectly. The total cross-section has been measured with different methods providing consistent results. Furthermore, the charged particle pseudorapidity density  $dN_{ch}/d\eta$  has been measured in the range  $5.3 < |\eta| < 6.5$ .

## References

- [1] V. Berardi et al. (TOTEM Collaboration), CERN-LHCC-2004-002; addendum: CERN-LHCC-2004-020 (2004).
- [2] G. Antchev et al. (TOTEM Collaboration), Europhys. Lett., **96**, 21002 (2011).
- [3] G. Antchev et al. (TOTEM Collaboration), Europhys. Lett., **95**, 41001 (2011).
- [4] G. Antchev et al. (TOTEM Collaboration), Europhys. Lett., **98**, 31002 (2012).
- [5] G. Antchev et al. (TOTEM Collaboration), CERN-PH-EP-2012-239.
- [6] Totem Collaboration, Measurement of pp elastic scattering and total cross section at  $\sqrt{s} = 7$ TeV, to be published.
- [7] Totem Collaboration, Measurement of pp inelastic scattering cross section at  $\sqrt{s} = 7$ TeV, to be published.
- [8] J.R. Cudell et al., Benchmarks for the Forward Observables at RHIC, the Tevatron-Run II, and the LHC, Phys.Rev.Lett. **89**, 201801 (2002).
- [9] K. Nakamura et al. (Particle Data Group), J. Phys. **G 37**, 075021 (2010).
- [10] J. Kaspar for the TOTEM Collaboration, TOTEM status report, CERN LHCC Open Session, 13 June 2012.