

## Elastic Scattering and Total Cross-Section in p+p Reactions

— As Measured by the LHC Experiment TOTEM at  $\sqrt{s} = 7 \text{ TeV}$  —

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Proton-proton elastic scattering has been measured by the TOTEM experiment at the CERN Large Hadron Collider at  $\sqrt{s} = 7$  TeV in special runs with the Roman Pot detectors placed as close to the outgoing beam as seven times the transverse beam size. The differential cross-section measurements are reported in the  $|t|$ -range of 0.36 to 2.5 GeV<sup>2</sup>. Extending the range of data to low  $t$  values from 0.02 to 0.33 GeV<sup>2</sup>, and utilizing the luminosity measurements of CMS, the total proton-proton cross section at  $\sqrt{s} = 7$  TeV is measured to be  $(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}})$  mb.

## §1. Introduction

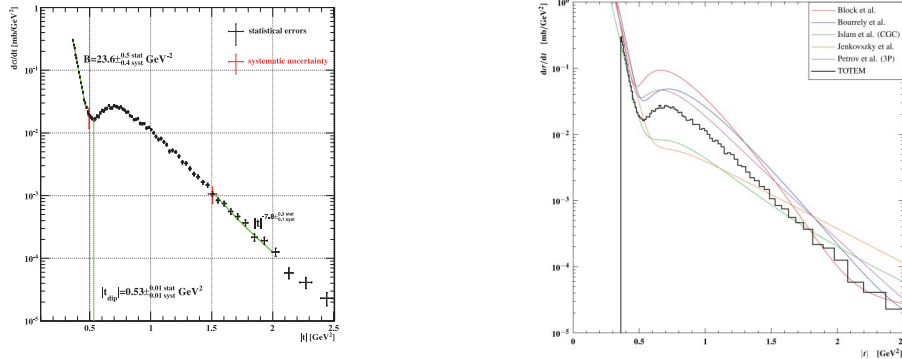
TOTEM is one of the special purpose experiments at CERN Large Hadron Collider (LHC), dedicated to make precision measurements of p+p scattering in the forward direction. TOTEM stands for TOTAL and Elastic scattering cross-section Measurement. The experiment is located at Interaction Point 5 at the LHC, shared with CMS, which is one of the general purpose LHC experiments.

TOTEM consists of two inelastic telescope subsystems T1 and T2, located at approximately 10 and 14 meters from the collision point, and two Roman Pot (RP) detector stations, located approximately 147 and 220 m away from the collision point IP5, on its both sides in the LHC tunnel. A detailed description of TOTEM is published in Ref. 1), while the great physics potential of this specialized LHC experiment was highlighted in Ref. 2). In this report, we review the results of the first two physics papers from TOTEM, based on Refs. 3)–5).

## §2. Differential cross-section of elastic p+p scattering

TOTEM is optimised for measuring elastic p+p scattering over a large four momentum transfer  $|t|$ -interval, ranging ultimately from 10<sup>-3</sup> to 10 GeV<sup>2</sup>, using specialized LHC runs. The first TOTEM measurements of elastic pp scattering were reported in the  $|t|$ -range from 0.36 to 2.5 GeV<sup>2</sup> in Ref. 3). The data were taken using the standard 2010 LHC beam optics with  $\beta^* = 3.5$  m, during a TOTEM dedicated run with four proton bunches of  $7 \times 10^{10}$  p/bunch per beam with a total integrated luminosity of 6.1 nb<sup>-1</sup>. This low-luminosity configuration allowed the Roman Pot detectors to approach the beams to a distance as small as 7 times the transverse beam size  $\sigma_{\text{beam}}$ .

A reconstructed track in both projections in the near and in the far vertical RP unit is required on each side of the IP. The two diagonals *top left of IP – bottom right of IP* and *bottom left of IP – top right of IP*, tagging possible elastic candidates, are used as almost independent experiments with slightly different optics corrections, yet constrained by the alignment of the RPs. Collinearity cuts, acceptance, background and inefficiency corrections, resolution and bin migration effects, alignment and relevant LHC magnet dependent optics uncertainties are detailed in Ref. 3). The systematic uncertainty in  $t$ , the square of the four-momentum transferred in the elastic scattering, was found to be dominated by optics and alignment. The systematic uncertainties in  $d\sigma/dt$  were dominated by the uncertainty on the efficiency correction ( $t$ -independent) and on the resolution unfolding, which depends on the  $t$  measurement errors and hence on the uncertainty on the beam divergence. The



(a) The first TOTEM data on differential cross-section of elastic p+p scattering at  $\sqrt{s} = 7$  TeV, measured in the momentum transfer range of  $0.36 \leq |t| \leq 2.5$  GeV<sup>2</sup>.

(b) When compared to predictions of different models, the TOTEM elastic scattering  $d\sigma/dt$  data show a strong discriminative power.<sup>3)</sup>

Fig. 1. (color online) TOTEM elastic scattering  $d\sigma/dt$  data measurements at  $\sqrt{s} = 7$  TeV.

uncertainty of  $|t|$  has been found to be  $\delta|t| = 0.1 \text{ GeV} \sqrt{|t|}$ .<sup>3)</sup>

The time dependent instantaneous luminosity was taken from CMS measurements,<sup>6),7)</sup> with uncertainty of 4%. The recorded luminosity is derived by integrating the luminosity, the trigger efficiency and the DAQ efficiency over all the different runs taken.

The differential cross-section  $d\sigma/dt$  for elastic p+p scattering at  $\sqrt{s} = 7$  TeV is shown on the left panel of in Fig. 1. Its comparison to model predictions is shown on the right panel of the same figure, indicating the precision and the high selectivity of the first TOTEM measurement. For a more detailed discussion, see Ref. 3).

For further understanding of pp elastic scattering the  $|t|$ -range has to be considerably extended. The development of the approximately exponential behaviour at low  $|t|$  is fundamental for the extrapolation to the optical point at  $t = 0$  and hence for the measurement of the elastic scattering and the total cross-section. The first TOTEM result on this topic is the subject of the next section.

### §3. Measurement of the total cross-section of p+p scattering

TOTEM has also measured<sup>4)</sup> the differential cross-section for elastic proton-proton scattering at  $\sqrt{s} = 7$  TeV, analysing data from a short run with a dedicated LHC optics of  $\beta^* = 90$  m. This optics made it possible to measure the differential cross-section  $d\sigma/dt$  of the elastic p+p scattering in the  $|t|$  range of  $(0.02 \div 0.33)$  GeV<sup>2</sup>. In this range, a single exponential fit with a slope  $B = (20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}})$  GeV<sup>-2</sup> describes the differential cross-section. (Note that in the  $|t|$  range of 0.36 to 2.5 GeV<sup>2</sup> the slope is slightly different,  $B = (23.6 \pm 0.5^{\text{stat}} \pm 0.4^{\text{syst}})$  GeV<sup>-2</sup>, see Fig. 1.) After the extrapolation of the data in the low  $|t|$  range to  $|t| = 0$ , a total elastic scattering cross-section of  $(24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}})$  mb was obtained. Applying the

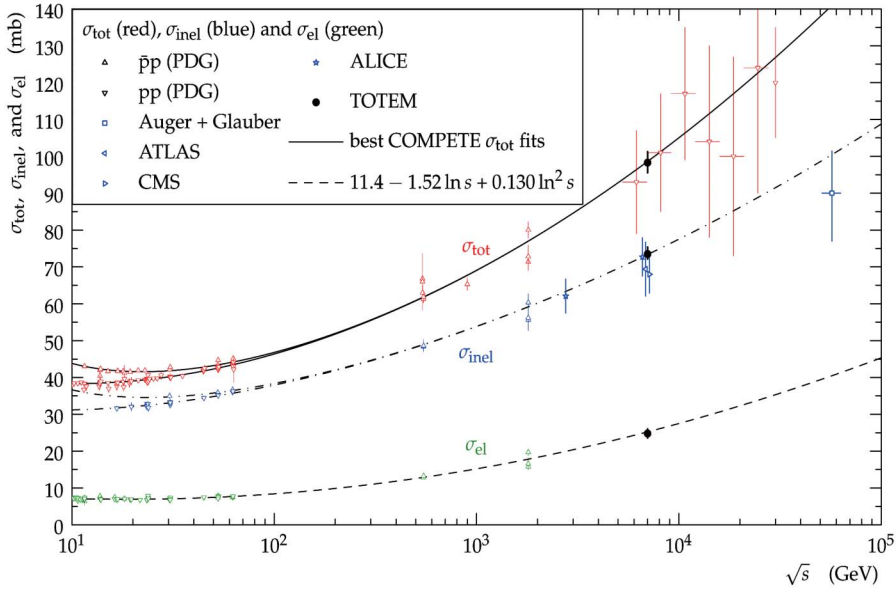


Fig. 2. (color online) The new TOTEM data demonstrate the continuation of the trends from earlier measurements, and indicate the high precision of the TOTEM experiment.<sup>4)</sup>

optical theorem and using the luminosity measurement from CMS, and taking the COMPETE prediction as detailed in Ref. 4) for the parameter  $\rho = 0.14^{+0.01}_{-0.08}$  a total proton-proton cross-section of  $(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}})$  mb was deduced. From the total and elastic pp cross-section measurements, an inelastic pp cross-section of  $(73.5 \pm 0.6^{\text{stat}} \pm 1.8^{\text{syst}}_{-1.3})$  mb was also inferred.

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