

FIRST MEASUREMENTS OF PROTON-PROTON ELASTIC SCATTERING AND TOTAL CROSS-SECTION AT THE LHC BY TOTEM

M. DEILE on behalf of the TOTEM Collaboration
CERN, 1211 Genève 23, Switzerland

The TOTEM experiment at the LHC has measured the differential cross-section for elastic proton-proton scattering at the energy of $\sqrt{s} = 7$ TeV in several dedicated runs, partly with a special high- β^* beam optics. The data published until now and presented here were collected with Roman Pot detectors placed as close as 7 times the transverse beam size from the outgoing beams at the interaction point 5. These data sets cover a range of squared four-momentum transfer $|t|$ from 0.02 to 2.5 GeV², exhibiting an approximately exponential behaviour for $|t| < 0.33$ GeV² with a slope $B = (20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}})$ GeV⁻², followed by a significant diffractive minimum at $|t| = (0.53 \pm 0.01^{\text{stat}} \pm 0.01^{\text{syst}})$ GeV². For $|t| > 1.5$ GeV², a power-law decrease with an exponent of $-7.8 \pm 0.3^{\text{stat}} \pm 0.1^{\text{syst}}$ was observed.

By extrapolation of the exponential part at low $|t|$ to $t = 0$, a total elastic cross-section of $(24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}})$ mb was obtained. Applying the optical theorem and using the luminosity measurement from CMS, a total cross-section of $(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}})$ mb was deduced. From the total and elastic cross-section measurements, an inelastic pp cross-section of $(73.5 \pm 0.6^{\text{stat}} \pm 1.3^{\text{syst}})$ mb was inferred.

1 Introduction

This article summarises the results of the measurements presented at the conference. For any details of experiment and analysis the reader is referred to the original publications^{1,2} and the references therein.

2 The Differential Cross-Section of Elastic pp Scattering

Proton-proton elastic scattering at $\sqrt{s} = 7$ TeV has been measured by the TOTEM experiment^{3,4} at the LHC with silicon strip detectors in Roman Pots placed as close as seven times the transverse beam size (σ_{beam}) from the outgoing beams. The results reported at EDS 2011 cover two overlapping ranges of squared four-momentum $|t|$:

- $0.36 \text{ GeV}^2 < |t| < 2.5 \text{ GeV}^2$ (¹) (Figure 1) measured in 2010 with the standard machine optics of that time ($\beta^* = 3.5$ m);
- $0.02 \text{ GeV}^2 < |t| < 0.4 \text{ GeV}^2$ (²) (Figure 2), measured in 2011 in a half-hour run with dedicated machine optics ($\beta^* = 90$ m); this data set was also used for determining the total cross-section via the optical theorem (Section 3).

The key observations are the following:

- In the low- $|t|$ range, $0.02 < |t| < 0.33 \text{ GeV}^2$, the data can be described by a single exponential fit ($\chi^2/\text{d.o.f.} = 0.8$) with an exponential slope $B = (20.1 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}}) \text{ GeV}^{-2}$. This value of B confirms the trend of a slope increase with \sqrt{s} observed by previous experiments (Figure 3).
- The overlap region between the two data sets ($0.35 \div 0.4 \text{ GeV}^2$) shows a good agreement within the uncertainties.
- Approaching the diffractive minimum (“dip”), the differential cross-section becomes steeper: from 0.36 to 0.47 GeV^2 it still shows approximately exponential behaviour, but with a slope of $(23.6 \pm 0.5_{\text{stat}} \pm 0.4_{\text{syst}}) \text{ GeV}^{-2}$.

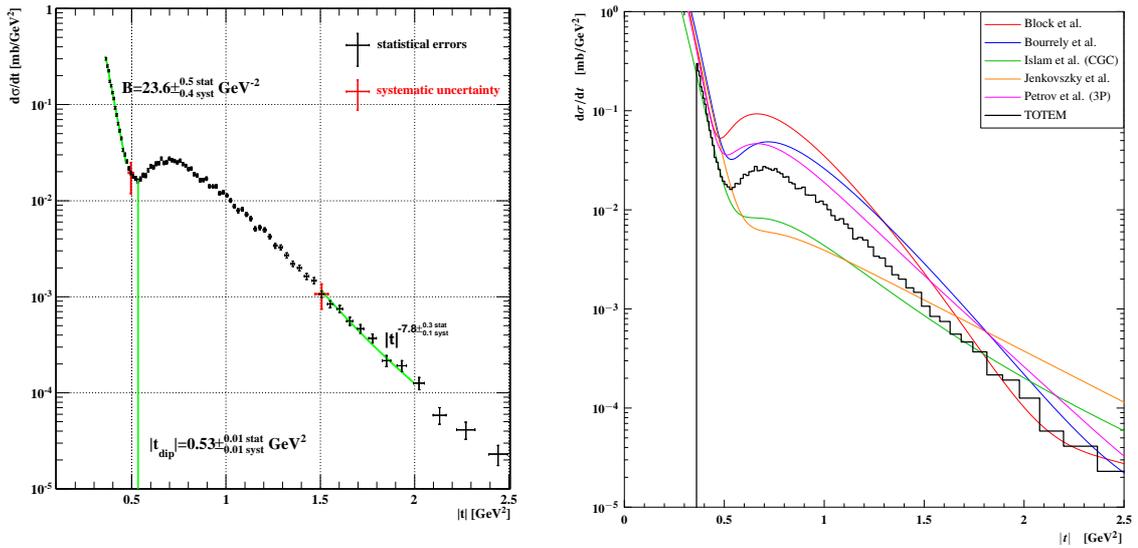


Figure 1: Left: the measured differential cross-section $d\sigma/dt$ with its statistical (for all points) and systematic (for two example points) error bars. Right: Comparison of the measurement with some theoretical models^{5,6,7,8,9}.

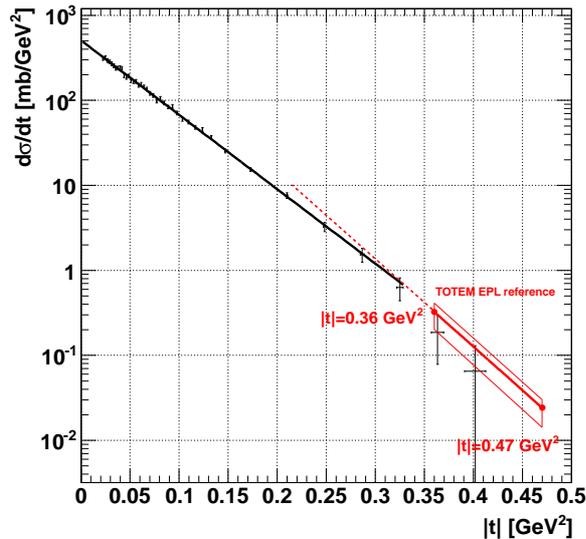


Figure 2: The measured pp elastic scattering differential cross-section $d\sigma/dt$ in the low- $|t|$ range with the exponential fit used for the extrapolation to the optical point $t = 0$. Between 0.35 and 0.4 GeV^2 the overlap with the data set from Figure 1 can be seen.

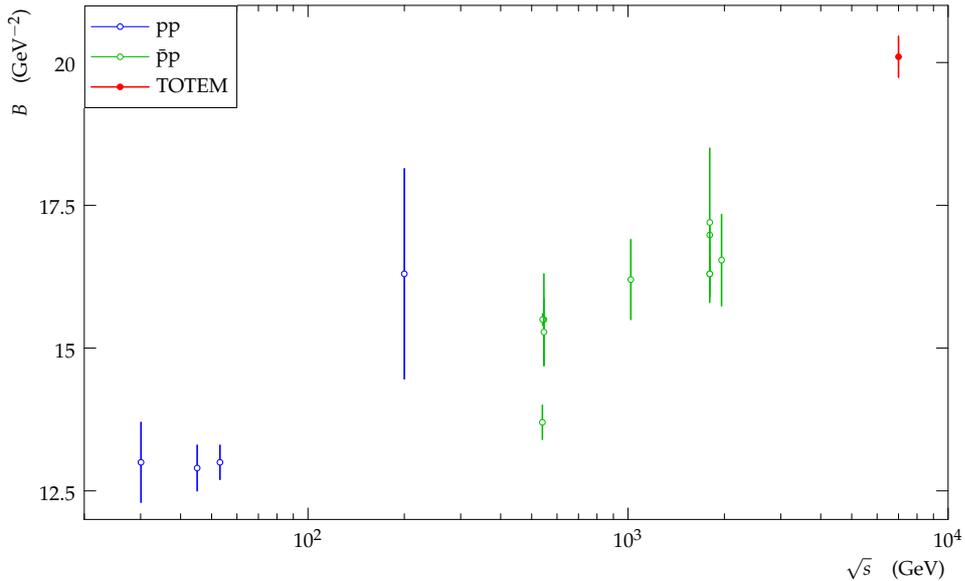


Figure 3: Compilation of measurements of B at different CM energies.

- The position of the pronounced dip, $|t| = (0.53 \pm 0.01_{\text{stat}} \pm 0.01_{\text{syst}}) \text{ GeV}^2$, 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 the differential cross-section becomes less steep and can be described with a power law $|t|^n$ with an exponent $n = -7.8 \pm 0.3_{\text{stat}} \pm 0.1_{\text{syst}}$ for $|t|$ -values between 1.5 GeV^2 and 2.0 GeV^2 .
- Table 1 compares some characteristic features of the measured cross-section with the model predictions drawn in Figure 1 (right). Two models^{6,9} are consistent with the data for the slope parameter $B(|t| = 0.4 \text{ GeV}^2)$, the dip position, $|t_{\text{dip}}|$, and the exponent n at large $|t|$, but they both disagree with the cross-section in the measured range. The other three models^{7,5,8} are less consistent with the data presented here.

Table 1: The values of the elastic slope parameter $B(|t| = 0.4 \text{ GeV}^2)$, the $|t|$ -position of the diffractive minimum, $|t_{\text{dip}}|$, the exponent of the power law behaviour at large $|t|$, and the diffraction cross-section at $|t| = 0.7 \text{ GeV}^2$, as extracted from the prediction of several models and compared to the measured values.

Model	$B(t = 0.4 \text{ GeV}^2)$ [GeV^{-2}]	$ t_{\text{dip}} $ [GeV^2]	n in $ t ^n$ ($1.5 - 2 \text{ GeV}^2$)	$d\sigma/dt(t = 0.7 \text{ GeV}^2)$ [mb/GeV^2]
M.M. Block et al. ⁵	24.4	0.48	-10.4	$9.1 \cdot 10^{-2}$
C. Bourrely et al. ⁶	21.7	0.54	-8.4	$4.8 \cdot 10^{-2}$
M.M. Islam et al. ⁷	19.9	0.65	-5.0	$8.2 \cdot 10^{-3}$
L.L. Jenkovszky et al. ⁸	20.1	0.72	-4.2	$6.1 \cdot 10^{-3}$
V.A. Petrov et al. ⁹	22.7	0.52	-7.0	$4.6 \cdot 10^{-2}$
This measurement	23.6 $\pm 0.5^{\text{stat}} \pm 0.4^{\text{syst}}$	0.53 $\pm 0.01^{\text{stat}} \pm 0.01^{\text{syst}}$	-7.8 $\pm 0.3^{\text{stat}} \pm 0.1^{\text{syst}}$	2.7×10^{-2} $\pm 3.7\%^{\text{stat}} \pm 26\%^{\text{syst}}$ $-21\%^{\text{syst}}$

3 The Total pp Cross-Section

The elastic scattering data in the range $0.02 < |t| < 0.33 \text{ GeV}^2$ have been exploited to determine the total cross-section via the optical theorem

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

using the COMPETE prediction¹⁰ $\rho = 0.14_{-0.08}^{+0.01}$ as external input. The differential cross-section at the optical point was obtained by extrapolating $\frac{d\sigma_{\text{el}}}{dt}$ to $t = 0$ with a single exponential fit (see Section 2). The absolute normalisation was defined by the luminosity from CMS, measured with an uncertainty of 4%. Thus the total pp cross-section was determined to be

$$\sigma_{\text{tot}} = \left(98.3 \pm 0.2_{(\text{stat})} \begin{array}{l} +2.8 \\ -2.7 \end{array}_{(\text{syst})} \right) \text{ mb}. \quad (2)$$

The errors are dominated by the extrapolation to $t = 0$ and the luminosity uncertainty.

Subtracting the elastic scattering cross-section, we obtain the inelastic cross-section

$$\sigma_{\text{inel}} = \left(73.5 \pm 0.6_{(\text{stat})} \begin{array}{l} +1.8 \\ -1.3 \end{array}_{(\text{syst})} \right) \text{ mb}. \quad (3)$$

Within the quoted errors, this result is consistent with the measurements of the CMS¹², ATLAS¹³, and ALICE¹⁴ experiments, which took into account the uncertainties of the model predictions for the unobserved very-forward diffractive processes.

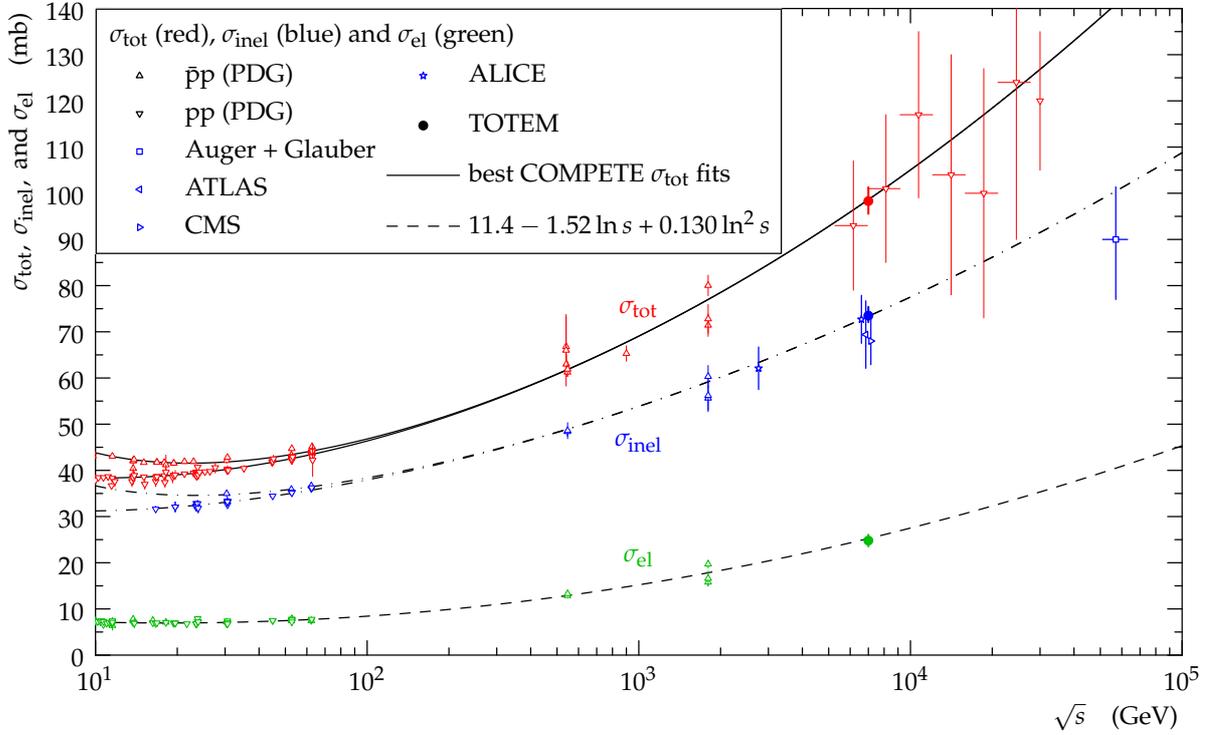


Figure 4: Compilation of measurements of σ_{tot} , σ_{inel} , and σ_{el} ^{10,11}.

4 Outlook

Additional elastic scattering data at $\sqrt{s} = 7$ TeV have already been collected, extending the $|t|$ -range on the lower and upper end to $(10^{-3} \div 3.5)$ GeV². For the total pp cross-section at the same CM energy there are now 3 more measurement results, obtained with different data sets or methods¹⁵:

- a measurement using the same technique as the one presented in this article (i.e. depending on the luminosity \mathcal{L} from CMS, on ρ from theory, and on the measured dN_{el}/dt), but based on a different data set;
- a direct measurement based on the identity $\sigma_{\text{tot}} = (N_{\text{el}} + N_{\text{inel}})/\mathcal{L}$, hence depending on the elastic and inelastic rates from TOTEM, on \mathcal{L} from CMS, but independent of ρ .
- a measurement with the luminosity-independent method, hence depending on ρ from theory, on N_{el} , dN_{el}/dt and N_{inel} from TOTEM, but independent of \mathcal{L} .

The results of these 3 new analyses agree well with the one presented in this contribution and will be published in the near future.

Other ongoing TOTEM analyses address the t - and mass spectra of Single and Central Diffraction, and the charged particle pseudorapidity density in the range $5.3 < |\eta| < 6.4$ (¹⁶).

The highlight of TOTEM's physics programme in the year 2012 will be the first common runs with CMS aiming at hard diffractive phenomena like diffractive dijet production. Furthermore, measurements of elastic scattering and total cross-section at the new CM energy of 8 TeV are foreseen. After the commissioning of a new beam optics ($\beta^* \sim 500$ m), the first measurement of ρ will be attempted.

References

1. G. Antchev et al. (TOTEM Collaboration): "Proton-proton elastic scattering at the LHC energy of $\sqrt{s} = 7$ TeV", EPL **95** (2011) 41001.
2. G. Antchev et al. (TOTEM Collaboration): "First measurements of the total proton-proton cross section at the LHC energy of $\sqrt{s} = 7$ TeV", EPL **96** (2011) 21002.
3. V. Berardi et al. (TOTEM Collaboration), CERN-LHCC-2004-002; addendum CERN-LHCC-2004-020 (2004).
4. G. Anelli et al.: "The TOTEM Experiment at the CERN Large Hadron Collider", JINST **3** (2008) S08007.
5. M. M. Block, F. Halzen: "Forward hadronic scattering at 7 TeV: predictions for the LHC: an update", Phys.Rev. D **83** (2011) 077901.
6. C. Bourrely, J. Soffer, T. T. Wu: "Impact picture phenomenology for $\pi^+ - p$, $K^+ - p$ and pp , $\bar{p}p$ elastic scattering at high-energies", Eur.Phys.J. C **28** (2003) 97-105.
7. M. Islam, J. Kašpar, R. Luddy: "Deep-elastic pp scattering at LHC from low-x gluons", Mod.Phys.Lett. A **24** (2009) 485-496.
8. L. Jenkovszky, A. Lengyel, D. Lontkovskiy: "The Pomeron and Odderon in elastic, inelastic and total cross sections at the LHC", Int J. Mod Phys A in press, arXiv 1105.1202 (2011).
9. V. Petrov, E. Predazzi, A. Prokudin: "Coulomb interference in high-energy pp and $\bar{p}p$ scattering", Eur.Phys.J. C **28** (2003) 525-533.
10. J.R. Cudell et al.: "Benchmarks for the Forward Observables at RHIC, the Tevatron-Run II, and the LHC", Phys.Rev.Lett. **89** (2002) 201801.
11. K. Nakamura et al. (Particle Data Group), J. Phys. G **37** (2010) 075021.
12. CMS-Collaboration: "Inelastic pp cross section at 7 TeV", Performance Analysis Note CMS-PAS-FWD-11-001, 2011.

13. G. Aad et al. (ATLAS Collaboration): “Measurement of the Inelastic Proton-Proton Cross-Section at $\sqrt{s} = 7$ TeV with the ATLAS Detector”, arXiv:1104.0326 (hep-ex), 2011.
14. M.G. Poghosyan for the ALICE Collaboration: “Diffraction dissociation in proton-proton collisions at $\sqrt{s} = 0.9$ TeV, 2.76 TeV and 7 TeV with ALICE at the LHC”, arXiv:1109.4510 (hep-ex), 2011.
15. V. Avati for the TOTEM Collaboration: “TOTEM Status Report”, LHCC Open Session, 21 March 2012,
[https://indico.cern.ch/materialDisplay.py
?contribId=5&materialId=slides&confId=179702](https://indico.cern.ch/materialDisplay.py?contribId=5&materialId=slides&confId=179702)
16. G. Antchev et al. (TOTEM Collaboration): “Measurement of the forward charged particle pseudorapidity density in pp collisions at $\sqrt{s} = 7$ TeV with the TOTEM experiment”, CERN-PH-EP-2012-106, EPL **98** (2012) 31002.