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# The Results of the Totem Experiment

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**Abstract.** The TOTEM experiment at the LHC has measured proton-proton elastic scattering in dedicated runs at $\sqrt{s} = 7$ and 8 TeV centre-of-mass LHC energies. The proton-proton total cross-section $\sigma_{\text{tot}}$ has been derived for both energies using a luminosity independent method. TOTEM has excluded a purely exponential differential cross-section for elastic proton-proton scattering with significance greater than $7\sigma$ in the $|t|$ range from 0.027 to 0.2 GeV$^2$ at $\sqrt{s} = 8$ TeV. The $\rho$ parameter has been measured at $\sqrt{s} = 8$ TeV via the Coulomb-nuclear interference, and was found to be $\rho = 0.12 \pm 0.03$.

## 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.

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].

## ELASTIC SCATTERING AND TOTAL CROSS-SECTION $\sigma_{\text{tot}}$ 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, see Figure 2 [5, 6, 7, 8, 9].

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

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

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].

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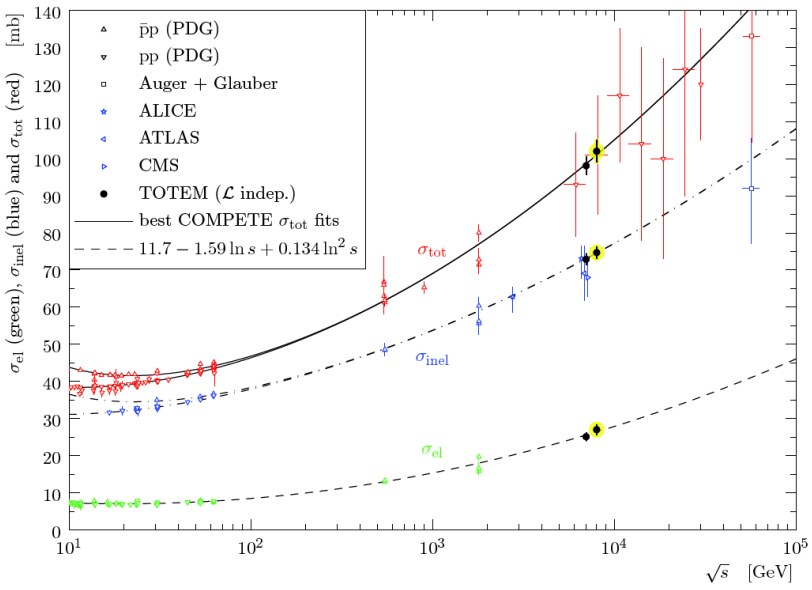


**FIGURE 1.** A compilation of total, inelastic and elastic pp cross-section measurements. The black points indicate the TOTEM measurements at $\sqrt{s}$ = 7 and 8 TeV using the luminosity independent method [10, 11, 12, 13, 14, 15].

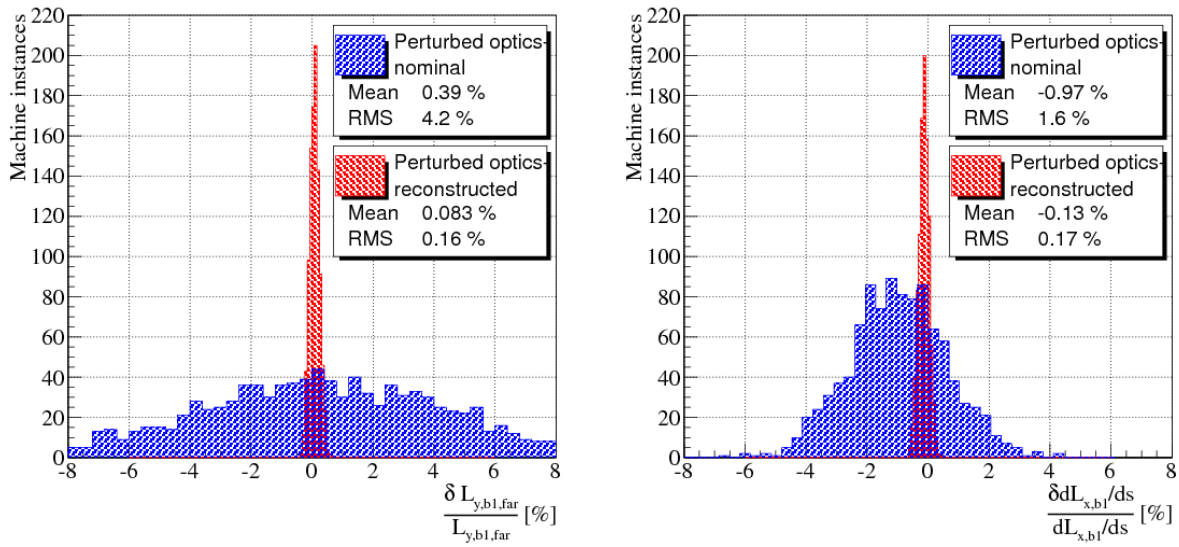


**FIGURE 2.** The MC error distribution of $\beta^*$ = 3.5 m optical functions $L_y$ and $dL_x/ds$ for Beam 1 at $\sqrt{s}$ = 7 TeV, before and after optics estimation.

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 $\sigma_{el}$ = 25.1 ± 1.1 mb and $\sigma_{inel}$ = 72.9 ± 1.5 mb.

The measurement was repeated at $\sqrt{s}$ = 8 TeV, yielding to $\sigma_{tot}$ = 101.7 ± 2.9 mb, $\sigma_{el}$ = 27.1 ± 1.4 mb and $\sigma_{inel}$ = 74.7 ± 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].

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

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

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 $7\sigma$ in the $|t|$ range from 0.027 to 0.2 GeV$^2$, see Figure 3. 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 TOTEM measurement. The TOTEM experiment performed its first measurement of elastic scattering in the

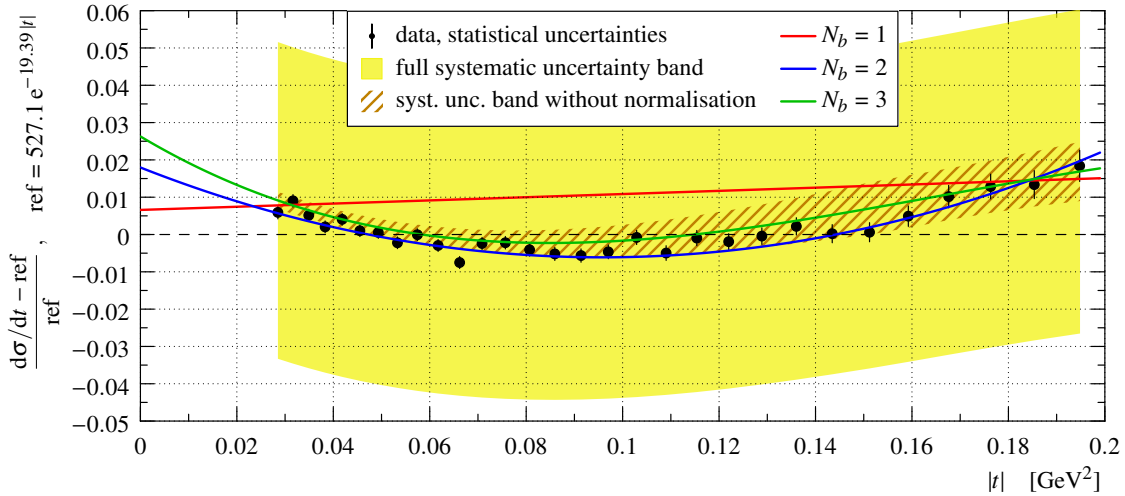


**FIGURE 3.** Differential cross-section measured at $\sqrt{s} = 8$ TeV LHC energy plotted as relative difference from a reference exponential. The black dots represent data points with statistical uncertainty bars [16].

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 $\rho$ parameter was for the first time at LHC extracted via the Coulomb-nuclear interference, and was found to be $\rho = 0.12 \pm 0.03$.

## FORWARD PHYSICS

### $dN_{ch}/d\eta$ Measured with the T2 Detector at $\sqrt{s} = 7$ and 8 TeV

The charged-particle pseudorapidity density $dN_{ch}/d\eta$ distribution in pp collisions was measured at 7 TeV in the very forward region with T2 [18]. The visible cross-section of the data was found to be around 94 % of the inelastic cross-section $\sigma_{\text{inel}}$. The main contributions to the systematical errors are the subtraction of secondary particles, the track efficiency and the misalignment uncertainties.

The TOTEM and CMS collaborations made a common measurement at 8 TeV collision energy [19], the measurement is shown in Figure 4. The TOTEM and CMS analysis were both obtained triggering with the T2 inelastic telescope on the same events, requiring at least one reconstructed track in one of the two inelastic telescopes of T2.

## DIFFRACTIVE PHYSICS

### Soft Single Diffractive Cross-section at $\sqrt{s}$ =7 TeV

The relevant data was taken at $\sqrt{s} = 7$ with $\beta^* = 90$ m optics. Single diffractive (SD) events were triggered with T2 and the RPs, where only one proton was required in the Pots.

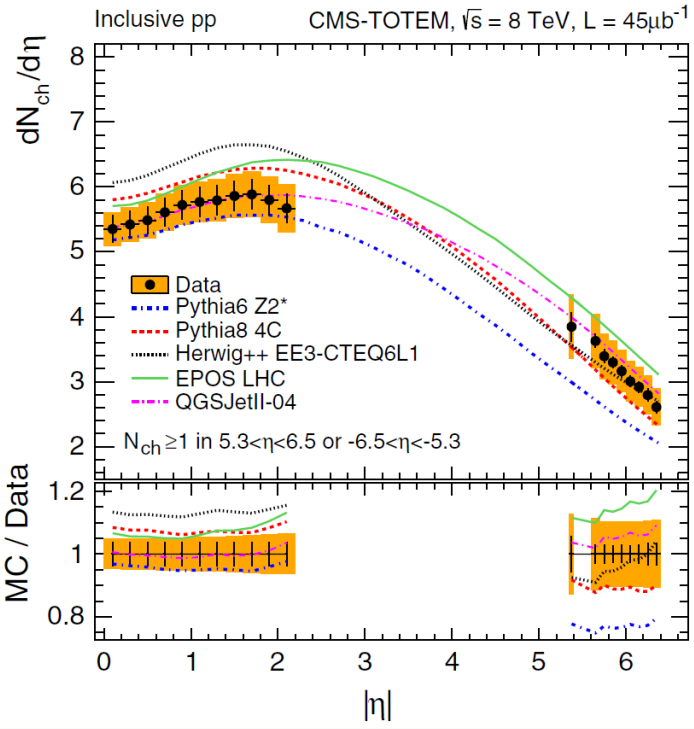


**FIGURE 4.** Common TOTEM-CMS measurement of the charged-particle pseudorapidity density $dN_{ch}/d\eta$ at $\sqrt{s}$ =8 TeV.

The detector configuration is such that the momentum loss of the proton $\xi$ can be calculated either by using the proton kinematics measured with the RPs, or by determining the rapidity gap, measured with the T1 or T2 inelastic telescopes. In the latter case the formula $\xi \approx e^{-\Delta\eta}$ is used to relate the proton fractional momentum loss and the width of the rapidity gap $\Delta\eta$. The mass of the diffractive system can be determined with formula $M_X \approx \sqrt{s\xi}$.

The preliminary TOTEM result is

$$\sigma_{SD(3.4<M_{SD}<1100\ \mathrm{GeV})} = 6.5 \pm 1.3\ \mathrm{mb}\,. \tag{2}$$

It must be emphasized that the contribution of diffractive masses below 3.4 GeV and of very-high diffractive masses is not included into this value. Together with the missing contributions the result is expected to be increased roughly by a factor of two.

## Soft Double Diffractive Cross-section at $\sqrt{s}$ = 7 TeV

The soft double diffractive cross-section at $\sqrt{s}$ = 7 TeV is an experimental challenge, since non-diffractive (ND) events and the pile-up from single diffraction create a large background. The measurement which is presented here requires at least one track in both T2 hemispheres while there is no track in T1 ("0T1+2T2 topology"). The result at $\sqrt{s}$ = 7 TeV was found to be

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 116 \pm 25\,\mu\mathrm{b}\,, \tag{3}$$

which covers only a limited rapidity $|\eta_{min}|$ range [20]. The obtained value can be further classified into pseudo-rapidity ranges, see Table 2. Improvement is expected in case of the recorded $\sqrt{s}$ =8 TeV TOTEM data, where also the CMS data is available.

## Central Diffraction TOTEM Alone

The available data for central diffractive (CD) analysis was taken at $\sqrt{s}$=7 TeV with $\beta^*$ = 90 m optics; the corresponding event topology is shown in Figure 5.

**TABLE 2.** Classification of the preliminary soft double diffractive cross-section at 7 TeV by pseudo-rapidity ranges.

| | $-4.7 > \eta_{\min} > -5.9$ | $-5.9 > \eta_{\min} > -6.5$ |
|---|---|---|
| $4.7 < \eta_{\min} < 5.9$ | $66 \pm 19\,\mu$b | $27 \pm 4\,\mu$b |
| $5.9 < \eta_{\min} < 6.5$ | $28 \pm 5\,\mu$b | $12 \pm 4\,\mu$b |

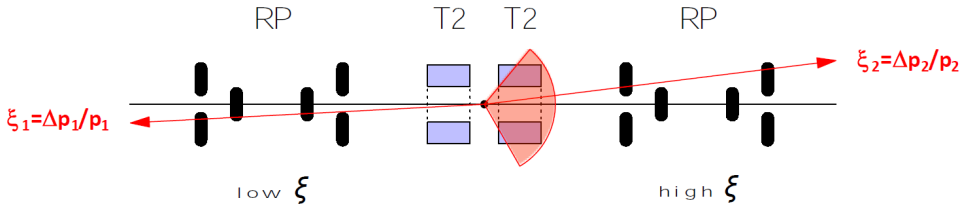


**FIGURE 5.** Topology of central diffractive event selection in the TOTEM standalone analysis.

The background for central diffraction consists of elastic events, beam-halo and inelastic events. The elastic background can be removed with "anti-elastic" cuts or with event topologies which are forbidden for elastic events (top-top Roman Pot configuration or bottom-bottom). With the $\beta^* = 90$ m optics all protons with $|t| > 0.02$ GeV$^2$ are accepted independently of their momentum loss $\xi$.

## Combined TOTEM and CMS Central Diffraction

The TOTEM and CMS experiments are independent, they exchange their triggers during measurement; the data is merged offline. The combined TOTEM and CMS detector system has an unprecedented coverage, see Figure 6. The CMS tracker and calorimeters cover the $|\eta| < 5.5$, while the TOTEM T1 and T2 the $3.1 < |\eta| < 4.7$ and $5.3 < |\eta| < 6.5$ rapidity ranges, respectively. The CMS FSC completes the acceptance with its $6 < |\eta| < 8$ coverage [21].

The mass of the diffractive system $m_X$ is double determined. It is reconstructed by CMS and it can be derived by TOTEM using $M_x = \sqrt{s\xi_1\xi_2}$, where $\xi_1$ and $\xi_2$ are the fractional momentum losses of the two protons.

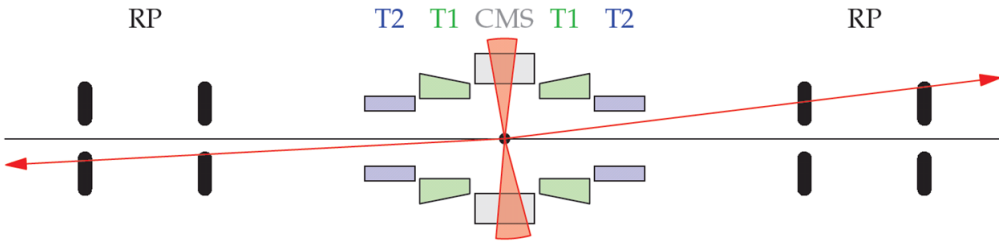


**FIGURE 6.** The event topology of the TOTEM-CMS common central diffraction measurement.

The common TOTEM-CMS data was taken at $\sqrt{s} = 8$ TeV with $\beta^* = 90$ m optics. There are two direction of studies. Soft central diffraction, with inclusive diffractive system X, as in the TOTEM standalone case. The other opportunity is hard central diffraction, where the diffractive system can contain jets and other objects. In this case an interesting interplay between soft/non-perturbative and hard/perturbative QCD effects can be explored.

## Glueball Searches

The collected $\mathcal{L} = 1$ nb$^{-1}$ data of 2012 with $\beta^* = 90$ m optics provided the proof of principle for the glueball search. The data taken at $\sqrt{s} = 13$ TeV (Oct 2015) collected $\mathcal{L} = 0.4$ pb$^{-1}$ which should allow full production and decay characterisation. The CMS + TOTEM trigger required RP double arm, T2 veto, at least one track in CMS. The analysis strategy is based on the following glueball conditions: search for resonance enhancement with increasing

collision energy, final states branching ratio to $\pi\pi$, KK, ..., with equi-flavour partitioning selection rules (or with proportionality of gluon coupling to quarks), suppression of photon-photon channel (in production and final state).

## CONCLUSIONS

The TOTEM experiment has measured elastic pp scattering at $\sqrt{s}$ =7 and 8 TeV. The total, elastic and inelastic cross-sections have been derived for both energies using a luminosity independent method. TOTEM has excluded a purely exponential differential cross-section for elastic pp scattering with significance greater than $7\sigma$ 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 $\rho$ parameter was for the first time at LHC extracted via the Coulomb-nuclear interference.

The charged-particle pseudorapidity density $dN_{ch}/d\eta$ distribution has been measured at $\sqrt{s}$ =7 TeV. The measurement has been repeated by the TOTEM and CMS collaborations at 8 TeV. TOTEM has its first preliminary results on single, double and central diffraction. The data analysis is still in progress, also with emphasis on the combined TOTEM-CMS data.

In 2016 TOTEM is looking forward to a special run with $\beta^*$ = 2500 m optics at 13 TeV collision energy, in order to make Odderon searches via CNI.

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