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TOTEM, recent experimental review

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Abstract.
The TOTEM (TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC) experiment, located at the interaction point 5 of the LHC, has measured the total, elastic and inelastic proton-proton cross-sections, using a luminosity independent method, based on the optical theorem, in a center-of-mass energy range from 2.76 to 13 TeV. The elastic scattering was investigated in a wide range of the squared four-momentum transfer $|t|$ allowing study of the Coulomb-nuclear interference region down to $|t| \sim 8 \times 10^{-4}$ GeV^2. This made possible the first measurement of the ρ parameter at $\sqrt{s} = 13$ TeV, ρ being the ratio between the real and the imaginary part of the nuclear elastic scattering amplitude at $t = 0$. This measurement, combined with the total cross-section results, led to the exclusion of all the models classified and published by the COMPETE Collaboration. The results obtained by TOTEM are indeed compatible with predictions of a colourless 3-gluon bound state exchange in the t-channel of proton-proton elastic scattering, as postulated by alternative theoretical models both in the Regge-like framework and in the modern QCD framework. This result has been confirmed, with a significance of 5.4σ, also by the comparison with the $\bar{p}p$ data measured by the D0 collaboration at Fermilab. In this contribution the TOTEM experiment results will be described, along with the actual experiment status, the future physics program for the LHC Run 3.

1 Introduction

TOTEM measured the total pp cross-section at the energy of $\sqrt{s} = 2.76$, 7, 8 and 13 TeV [1–4], using a luminosity independent method and validating it by comparing several methods to determine the total cross-sections [5–10]. The total cross-section can be obtained via the optical theorem that combines the simultaneous measurements of the total inelastic rate, N_{inel}, and the total nuclear elastic rate, N_{el}, with its extrapolation to the optical point $t = 0$, $\mathrm{d}N_{el}/\mathrm{d}t|_{t=0}$:

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{(\mathrm{d}N_{el}/\mathrm{d}t)_{t=0}}{(N_{el}+N_{inel})} \tag{1}$$

where ρ is the ratio of the real to imaginary part of the hadronic scattering amplitude at $t = 0$. The method requires the simultaneous measurements of the inelastic and elastic rates, as well as the extrapolation of the latter in the invisible region down to $|t| = 0$. This is achieved with the experimental set-up of TOTEM, which consists of two inelastic telescopes, called T1 and

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T2, to detect charged particles produced in inelastic pp collisions, and Roman Pot stations to detect elastically scattered protons at very small angles [11]. The measured ratio of the elastic and inelastic rates N_{el}/N_{inel} allows for the determination of the elastic and inelastic cross-sections as well.

The optical theorem can be used also to derive the total and fully inclusive inelastic pp cross-section, from the measurement of the elastic scattering one:

$$\sigma^2_{tot} = \frac{16\pi}{1+\rho^2}\frac{d\sigma_{el}}{dt}|_{t=0}, \quad \sigma_{inel} = \sigma_{tot} - \sigma_{el}. \tag{2}$$

To access the smaller $|t|$-value region, the colliding beams must have a beam divergence of not more than a few micro-radians [12]. This can be obtained by either increasing the beta function value, β^*, or by reducing the beam emittance, ϵ (beam divergence = $\sqrt{\epsilon/\beta^*}$). With special runs having dedicated beam optics configurations, β^*= 90, 1000, 2500 m, TOTEM extended the measurement to $|t|$-values as low as 8×10^{-4} GeV^2, measuring the differential elastic cross-section over a wide range of t [5, 8, 10, 13]. This made the extrapolation of the differential cross-section to the optical point at $t = 0$ possible, allowing, for the first time at the LHC, the determination of the elastic scattering cross-section, the total cross-section via the optical theorem as well as the measurement of the ρ parameter [10].

To increase robustness and understanding of the systematic uncertainties, the TOTEM Collaboration, cross-checked the results of its measurements by comparing several independent approaches to determine the total cross-section, proving the reliability of the luminosity independent method. Measurements at 7 TeV, were double checked using different methods under the same beam conditions, while the ones at 8 and 13 TeV where checked leveraging different beam and optics conditions. Moreover, with the data collected by the very forward telescopes T1 and T2, during special runs at $\sqrt{s}$ = 7 TeV, also the double diffractive (DD) cross-section was measured in the pseudorapidity region $4.7 < |\eta_{min}| < 6.5$ [26].

During the special runs, TOTEM provides minimum and zero bias triggers to the CMS experiment [14], making also possible physics studies in common between the two experiments. The collaboration with CMS gave birth to a joint project: CMS-TOTEM Precision Proton Spectrometer (CT-PPS) [15], designed to take data during the LHC Run 2 standard run with high luminosity. The project collected slightly less than 100 fb^{-1}, in the last two years of Run 2 data taken, proving the feasibility of the project [16] that has been integrated into CMS as PPS subsystem, eventually.

In particular the direct measurement of forward pseudorapidity distributions, that are also valuable in constraining theoretical models and Monte Carlo programs of the high energy air showers initiated by cosmic rays, have been measured by both experiments [27] and by TOTEM standalone [28].

The results obtained by TOTEM are indeed compatible with predictions of a colourless 3-gluon bound state exchange in the t-channel of proton-proton elastic scattering, as postulated by alternative theoretical models both in the Regge-like framework and in the modern QCD framework. This result has been confirmed, with a significance of 5.4σ, also by the comparison with the $\bar{p}p$ data measured by the D0 collaboration at Fermilab.

2 The Totem Experiment

The TOTEM inelastic telescopes[11], T1 and T2, consist of two arms located symmetrically on both sides of the LHC interaction point 5 (IP5): the T1 telescope with cathode strip chambers (CSC), placed at a distance of 9 m from IP5, covers the pseudorapidity range $3.1 \leq |\eta| \leq 4.7$. The T2 telescope with gas electron multiplier (GEM) chambers, located at ±13.5 m from IP5, covers the pseudorapidity range $5.3 \leq |\eta| \leq 6.5$. The pseudorapidity coverage of the two telescopes allowed the detection of 95% of the inelastic events, including events with diffractive mass down to 3.6 GeV.

For the LHC Run 3, an upgrade of the T2 detector has been scheduled. The new T2 will fit in the reduced space left by the new LHC beamline configuration; it will be based on scintillator slabs read out by silicon photomultipliers (SiPM) [17].

Roman Pot (RP) stations are located symmetrically on both sides of the IP5. During the LHC Run 1, the Roman Pot stations were located at 147 m (RP147) and 220 m (RP220) along the LHC beam line. Each station is composed of two units (near and far, in the TOTEM jargon) separated by a distance of about 5 m. A unit consists of 3 RPs, two approaching the outgoing beam vertically, from the top and the bottom, and one horizontally. During LHC Run 1, each RP was equipped with a stack of 10 silicon strip detectors, designed with the specific objective of reducing the insensitive area at the edge facing the beam to only a few tens of micrometers. This edgelessness design permits to measure the proton distance from the beam center, in both coordinates perpendicular to the beam, with a resolution of about 11 μm [18]. The movement and the alignment of all pots are monitored with a precision better than 20 μm based on track reconstruction and external alignment tools. The long lever arm between the near and the far units allows the determination of the track angle in both projections with a precision of about 5 μrad. A more detailed description of the TOTEM detector and performance, in this configuration, can be found in [11, 19].

The RP layout for the LHC Run 2, has been modified. The stations previously installed at $\pm$147 m, from the interaction point, have been relocated at $\pm$210 m, with one of the two units, the far one, tilted around the beam axis by 8^o degree, to improve multi-track resolution[20]. Moreover, two newly designed horizontal RP, have been installed between the two units at $\pm$220 m. All RP have been refurbished and upgraded to stand the increase in luminosity foreseen. This new layout has been proposed to improve the apparatus performances, adding timing detectors, to resolve the pileup of multiple events in the same bunch crossing, and operate the experiment at higher luminosities. This has been fulfilled by TOTEM, for the special runs with low luminosity, installing new timing detectors in a vertical RP [21, 23, 24]. The RP upgrade was a feat that boosted the CT-PPS project. In fact the CT-PPS collaboration installed, in two horizontal RP, new tracking detectors, based on the silicon pixels developed for the CMS tracker upgrade [15], while the diamond timing detectors, developed for the TOTEM upgrade, were installed in the new horizontal ones [23]. At the end, CT-PPS was leveraging four different detector technologies: silicon strips and pixels, and diamond and Ultra Fast Silicon Detector (UFSD) [24], for tracking and timing respectively.

For the LHC Run 3, a consolidation and refurbishment of the mechanics and electronics of the station is in progress. Moreover a new diamond based timing detector package will be installed inside an horizontal RP.

TOTEM will finish the cross section measurement campaign, during the LHC Run 3, when the machine will reach the maximum energy of $\sqrt{s} = 14\ TeV$. For this measurement an upgrade of the T2 detector has been scheduled. The new T2 will fit in the reduced space left by the new LHC beamline configuration; it will be based on scintillator slabs readout by silicon photomultipliers (SiPM).

3 The Cross Sections and ρ Measurements

The cross-sections obtained using the luminosity independent method of eq. 1, measured by TOTEM, are reported in Table 1 and shown in Figure 1, along with the ones obtained by other experiments at LHC and using cosmic ray measurements (see [4] and references therein). The

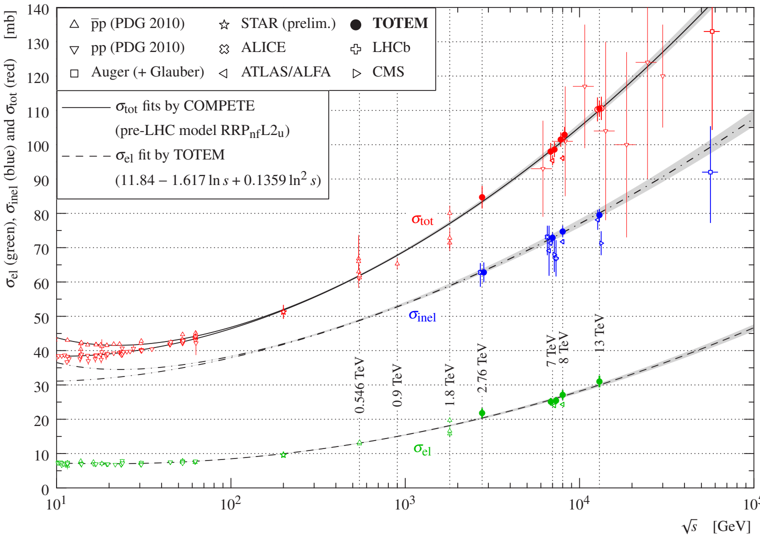

Figure 1. A compilation (see [4] and references therewith, of pp and $\bar{p}p$ total (σ_{tot}), inelastic (σ_{inel}) and elastic (σ_{el}) cross-sections measurements as a function of $\sqrt{s}$. The TOTEM measurements using the luminosity independent method are reported using full circle. The continuous lines (lower, for pp, upper for $\bar{p}p$) represent the best fits of the total cross-section data by the COMPETE collaboration [32]. The dashed line results from a fit of the elastic cross-section data. The dash-dotted lines refer to the inelastic cross-section and are obtained as the difference between the continuous and dashed fits.

total systematic uncertainty has been reported, obtained combining in quadrature all the systematic uncertainties, taking into account the correlations between contributions. For a more detailed description and discussion of the systematic uncertainties see [2–4, 8] and references therein. For the ρ parameter value the COMPETE [32] preferred-model extrapolation of 0.141 ± 0.007 was chosen.

Given the various methods of measuring elastic and inelastic rates, it was possible to perform completely different measurement of the three cross-section types, comparing the results for a better understanding of the systematic uncertainties and a double check of the results.

In particular at $\sqrt{s} = 7\ TeV$ the luminosity independent result [2] was shown to be consistent with the total cross section calculated by extrapolating the differential elastic cross-section to the optical point $|t| = 0$, using Equation 2 [5, 8], as well as with a luminosity dependent method [7]. While from the direct measurement of the inelastic rates the inelastic cross-section was determined and compared with the one deduced from the difference between the total and the elastic cross section [6].

Also results at $\sqrt{s} = 8\ TeV$ [3], has been double checked using the extrapolation of the differential elastic cross-section. This time, thanks to a very-high statistics collected at β^*= 90 m, the TOTEM experiment was able to exclude a pure exponential behavior of the elastic differential cross-section [13], so refined parametrizations have been used for the extrapolation to the optical point. The significance of the exclusion is greater than 7σ in the $|t|$ range from 0.027 to 0.2 GeV^2.

Thanks to the data collected at this energy, $\sqrt{s} = 8\ TeV$, with β^*= 1000 m, it was possible to explore the elastic scattering in the Coulomb Nuclear Interference (CNI) region. For the

Table 1. Summary of the cross-sections measured using a luminosity ($\mathcal{L}$) independent method. The full systematic uncertainty is reported for each measurements, see [2–4, 8] for a detailed description of this uncertainties.

	$\mathcal{L}$ independent using eq. 1			
	$\sqrt{2.76}\ TeV$ [1]	$\sqrt{7}\ TeV$ [2]	$\sqrt{8}\ TeV$ [3]	$\sqrt{13}\ TeV$ [4]
σ_{tot} (mb)	84.7 ± 3.3	98.0 ± 2.5	101.7 ± 2.9	110.6 ± 3.4
σ_{inel} (mb)	62.8 ± 2.9	72.9 ± 1.5	74.7 ± 1.7	79.5 ± 1.8
σ_{el} (mb)	21.8 ± 1.4	25.1 ± 1.1	27.1 ± 1.4	31.0 ± 1.7

first time at LHC, the ρ parameter was measured, via the CNI, and was found to be $\rho = 0.12 \pm 0.03$ [25]. The ρ parameter has been measured also at $\sqrt{s}$ = 13 TeV, thanks to the data collected in a special run with β^*= 2500 m. The values obtained are: $\rho = 0.09 \pm 0.01$ and $\rho = 0.10 \pm 0.01$, depending on different physics assumptions and mathematical modelling [10]. This time the CNI region has been used to estimate the σ_{tot} using three different and independent approaches. This novel "Coulomb normalization" technique was applied for the first time to LHC data, finding a result of $\sigma_{tot} = 110.3 \pm 3.5$ mb, that, combined with the luminosity independent method calculation, yields $\sigma_{tot} = 110.5 \pm 2.4$ mb. A summary of this results is shown in Table 2.

Table 2. Summary of ρ and total cross-section results.

data	method	ρ	σ_{tot} [mb]
$\beta^* = 90$ m	Ref. [22]	-	110.6 ± 3.4
$\beta^* = 2500$ m	approach 1	0.09 ± 0.01	111.8 ± 3.2
	approach 2	0.09 ± 0.01	111.3 ± 3.2
	approach 3	0.08(5) ± 0.01	110.3 ± 3.5
	approach 3 (single fit)	0.10 ± 0.01	109.3 ± 3.5
$\beta^* = 90$ and 2500 m	Ref. [22] ⊕ approach 3		110.5 ± 2.4

The unprecedented precision of the ρ measurement, shown in Figure 2, combined with the TOTEM total cross-section measurements in an energy range from 2.76 to 13 TeV, has implied the exclusion of all the models classified and published by the COMPETE Collaboration [32]. The ρ results obtained by TOTEM are compatible with the predictions, from alternative theoretical models both in the Regge-like framework and in the QCD framework, of a colourless 3-gluon bound state exchange in the t-channel of the proton-proton elastic scattering.

4 Comparison between TOTEM and D0 results

At high energies, the scattering amplitudes of both pp and $\bar{p}p$ elastic collisions are dominated by t-channel exchanges that carry the quantum numbers of the vacuum. Out of these amplitudes, a subdominant crossing- odd combination can be formed and contribute to the elastic collision at the TeV energy scale. The differences between these cross sections are due to physics that couples differently to particles and their charge conjugates that result from the exchange of the so called *odderon*, in QCD, a colourless three-gluon state at leading order [33–35]. A quantitative analysis has been carried out to compare the $\bar{p}p$ elastic cross section as measured by the D0 collaboration at a center-of-mass energy of 1.96 TeV

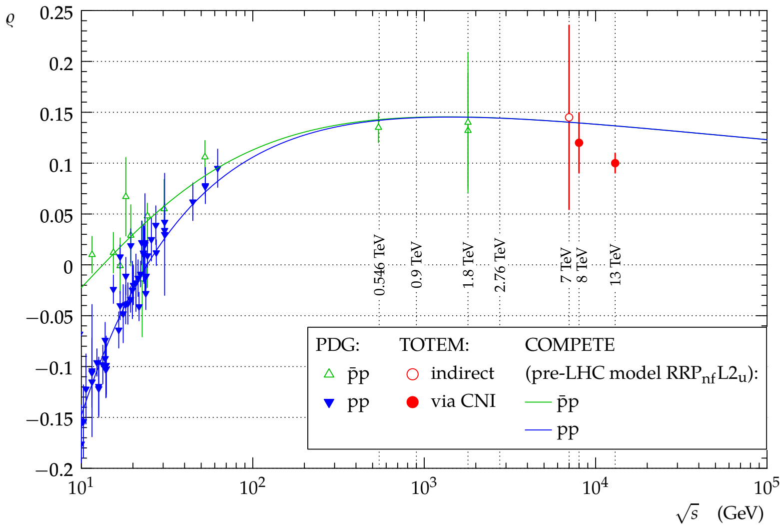

Figure 2. Dependence of the ρ parameter on $\sqrt{s}$. The pp (blue) and $p\bar{p}$ (green) data are taken from PDG [31], TOTEM measurements [10, 25] are marked in red. The continuous lines (lower, in blue,for pp, upper, in red, for $\bar{p}p$) represent the best fits of the total cross-section data by the COMPETE collaboration [32]. The dashed line.

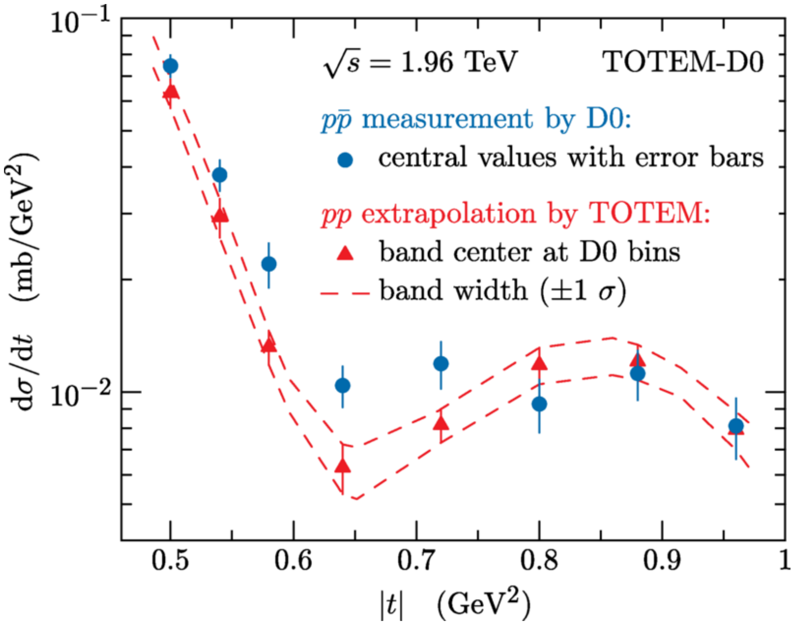

Figure 3. Comparison between the D0 $\bar{p}p$ measurement at 1.96 TeV and the extrapolated TOTEM pp cross section, rescaled to match the optical point ($d\sigma/dt|_{t=0}$) of the D0 measurement. The dashed lines show the 1σ uncertainty band on the extrapolated pp cross section.

to that in pp collisions as measured by the TOTEM collaboration at 2.76, 7, 8, and 13 TeV using a model-independent approach. The TOTEM cross sections have been extrapolated to a center-of-mass energy of 1.96 TeV and compared with the D0 measurement in the region of the diffractive minimum and second maximum of the pp cross section. The two data sets disagree with a significance os 3.4σ and thus provide a further evidence that an exchange of an *odderon* is needed to descibe elastic scattering at high energies. When combined with the result of [10], the significance is in the range 5.2 to 5.7σ and thus constitutes the first experimental observation of the *odderon*.

5 Conclusions

TOTEM has measured, for the first time at the LHC, the total, inelastic and elastic proton-proton cross sections at $\sqrt{s} = 2.76, 7, 8$ and 13 TeV using a luminosity independent method. The method was validated comparing the elastic and inelastic cross sections measured in independent ways and using a novel "Coulomb normalization" technique based on QED data. Furthermore, for the first time at LHC, the ρ parameter has been estimated studying the CNI region.

This measurement, combined with the total cross-section results, led to the exclusion of all the models published by the COMPETE Collaboration, and shows compatibility with predictions of a colourless 3-gluon bound state exchange in the t-channel of proton-proton elastic scattering.

The evidence for an *odderon* exchange is further confirmed by the comparison of the pp and $\bar{p}p$ cross secionts as measured by TOTEM and D0. The combined significance of the differences between the two measurement, is larger than 5σ and is interpreted as the first observation of the exchange of a colorless, C-odd gluonic compound: the *odderon*.

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