The proton-proton cross sections measured by TOTEM at LHC

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Abstract: The precise knowledge of the proton-proton cross section is extremely important to model the development, in the atmosphere, of the showers induced by the interaction of ultra high energy cosmic rays.
The TOTEM (TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC) experiment at LHC, has been designed to measure the total proton-proton cross-section with a luminosity independent method, based on the optical theorem, and study the elastic and diffractive scattering at the LHC energy. This method relies on the capability of the simultaneous measurements of inelastic and elastic rates; in the TOTEM experiment this is possible thanks to two forward inelastic telescopes, covering the pseudorapitidy range $3.1 < \|\eta\| < 6.5$, and Roman Pot detectors, that can be inserted down to few hundred microns to the beam centre.
Thanks to dedicated runs, taken between 2011 and 2012, with special beam optics, TOTEM experiment was able to measure the elastic, inelastic and total cross-section at $\sqrt{s} = 7$ *TeV* and 8 *TeV*, using the luminosity independent method.
In this contribution the TOTEM experiment will be described along with its performance and the latest proton-proton cross-section results.

Keywords: Total and inclusive cross-sections (including deep-inelastic processes).

1 Introduction

The LHC energy begins to overlap with the energy range where extreme energy cosmic-ray showers are studied. Investigations of proton-proton interactions at the LHC are therefore of high importance for the study of the development of cosmic-ray showers in the atmosphere and thus for the measurements of the high-energy cosmic-ray spectra and composition. One of the most important observable: the shower maximum (X_{max}), strongly depends on the inelastic proton-air cross-section and calculations of hadron-nucleus cross-sections in the Glauber-Gribov formalism require the knowledge of the inelastic pp cross-section along with the pp elastic scattering amplitude in the small $|t|$ range. The latest Auger measurement of the inelastic cross-section at $\sqrt{s}$ = 57TeV [2] used the TOTEM cross-section values as an input. In addition, all kinds of diffractive phenomena influence the development of the shower cascade and the multiplicity fluctuations of secondary hadrons [1]. Thus, the measurements of the pp cross-sections and the particle flow are of high importance for the interpretation of cosmic ray showers.

TOTEM measured the total pp cross-section at the energy of $\sqrt{s} = 7$ *TeV* and 8 *TeV* [6, 9], using a luminosity, $\mathscr{L}$, independent method and validating it by comparing several approaches to determine the total cross-sections [8, 7, 5, 4]. The total cross-section can be obtained via the optical theorem that combines the total inelastic rate N_{inel} and the total nuclear elastic rate N_{el} with its extrapolation to $t = 0$, $\mathrm{d}N_{el}/\mathrm{d}t|_{t=0}$.

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

where ρ is the ratio of the real to imaginary part of the hadronic scattering amplitute 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 T1 and T2 to detect charged particles produced in inelastic pp collisions, and Roman Pot stations to detect elastically scattered protons at very small angles.

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

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\frac{\mathrm{d}\sigma_{el}}{\mathrm{d}t}|_{t=0}, \;\; \sigma_{inel} = \sigma_{tot} - \sigma_{el}. \quad (2)$$

To access to the smaller $|t|$-value region, the colliding beams must have a beam divergence of not more than a few micro-radians. This can be obtained by either increasing the betatron value, β^*, or by reducing the beam emittance, ε (beam divergence = $\sqrt{\varepsilon/\beta^*}$). With a dedicated beam optics configuration (β^*= 90 m), TOTEM extended the measurement to $|t|$-values as low as 5×10^{-3} GeV^2, measuring the differential elastic cross-section over a wide range of t [4, 8]. This made the extrapolation of the differential cross-section to the optical point at $t = 0$ possible and enabled, for the first time at the LHC, the determination of the elastic scattering cross-section as well as the total cross-section via the optical theorem.

1.1 The TOTEM experiment

The TOTEM experiment layout is shown in Figure 1 along with the position of the inelastic telescopes and Roman Pot stations. The two inelastic telescopes consists of two arms located symmetrically on both sides of the LHC interaction point 5 (IP5): the T1 telescope is based on cathode strip chambers (CSC) placed at a distance of 9 m from IP5 and covers the pseudorapidity range $3.1 \leq \eta \leq 4.7$. The T2

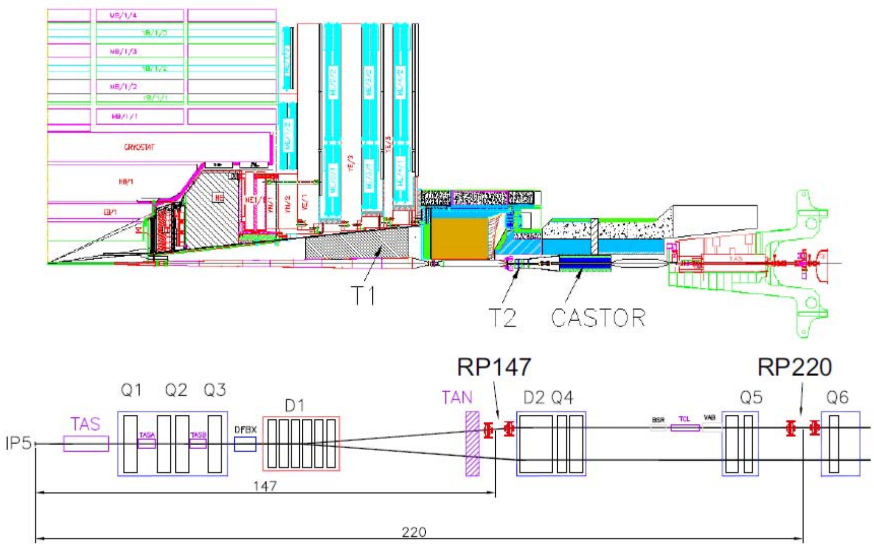

Figure 1: The TOTEM experiment layout. The position of the inelastic telescopes: T1 and T2, in the CMS experiment (top), and of the Roman Pots, along the LHC beam line, at 147 m (RP147) and 220 m (RP220) (bottom).

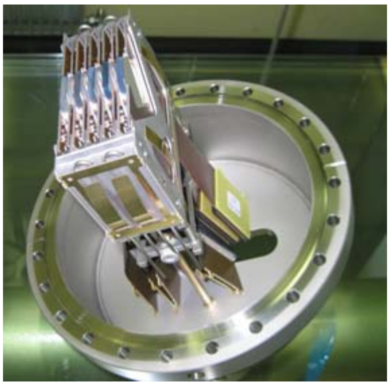

Figure 2: The silicon detector stack of a Roman Pot, as seen from the bottom cover.

telescope is based on gas electron multiplier (GEM) chambers and located at ± 13.5 m from IP5 and covers the pseudorapidity range $5.3 \leq \eta \leq 6.5$. The pseudorapidity coverage of the two telescopes allows the detection of 95% of the inelastic events, including events with difractive mass down to 3.6 GeV. Both T1 and T2 telescopes are shown in Figure 3.

Also the Roman Pot (RP) stations, used for these measurements, are located symmetrically on either side of the IP5 at distances of 215-220 m from it. Each station is composed of two units (near and far) 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. Each RP is 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 design permits to measure the proton distance from the beam center, in both coordinates perpendicular to the beam, with a precision of about 11 μm. 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.

Figure 3: One arm of the T2 GEM based inelastic telescope during the installation in IP5 (top). Half arm of the T1 CSC based telescope before the installation (bottom).

The large 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. The silicon detector stack of one RP is shown in Figure 2.

A more detailed description of the TOTEM detector can be found in [3].

1.2 Data set

In this contributions are reported the results of the analysis of two data samples recorded in October 2011, at $\sqrt{s} = 7$ TeV, and July 2012, at $\sqrt{s} = 8$ TeV. In both cases data

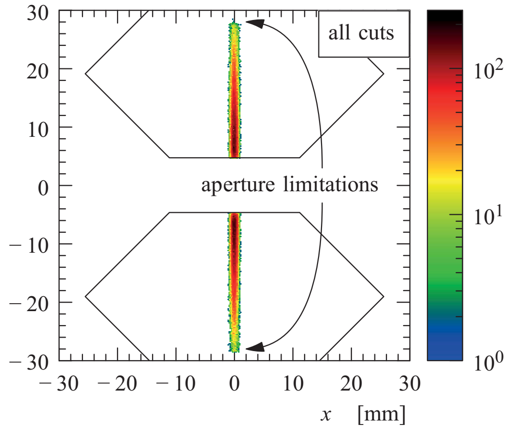

Figure 4: Hit distributions after the selection cuts for elastic scattered events; it has been obtained for a 7 TeV data set in the far unit of the 220m station, right arm. The the sharp cuts of the hit distribution at about $|y| = 29$ mm, is due to the LHC aperture limitations.

have been recorded during special LHC fills with β^*= 90 m.

In these special runs, the Roman Pots, were put very close to the beam center; the actual distances depend on the transverse beam size value, σ_{beam}. This was possible since the beams were scraped by the LHC collimators at a distance equal to 4 times the σ_{beam}. In this configuration TOTEM took data in very clean conditions with only a few colliding bunch pairs and reached $|t|$-values down to 5×10^3 GeV^2, enabling the observation of 91% of the elastic cross-section.

Moreover triggers from the forward inelastic telescopes, were used during these runs, making possible the direct measurement of the inelastic cross-secion [7].

The RP first-level trigger benefits from the 20 possible hits (10 planes in both near and far RP) per proton track and is based on a track segment in the near or the far unit. A coincidence between a proton on the left and the right side of the interaction point was requested in the elastic double-arm signature, in the vertical RP detectors, in either ot the two diagonals (left top right bottom or left bottom right top). The RP detector was designed to leverage the characteristics of a beam optics with large β^*. This optics configuration force most of the elastically scattered protons into the vertical RPs. Elastically scattered protons impinge on the RP detectors close to the vertical plane ($x = 0$ in Figure 4, while diffrative protons are deviated to positive x-values in the vertical detectors (positive x value in Figure 4). In this way the β^*= 90m optics force most of the elastically scattered protons into the vertical RPs, defining a nice topological criterion for selecting elastic candidate events. In Figure 4 the hit distributions of the elastic scattered events, during a special run, is reported for a RP station.

2 Results

Taking maximum advantage from the possibility of measuring elastic and inelastic rates, it was possible to perform completely different estimation of the inelastic, elastic and total cross-sections, comparing all the results for better understanding of the systematic uncertainties and double checks.

By extrapolating the differential elastic cross-section to the optical point $|t| = 0$ and using the optical theorem, the total and inelastic cross-sections were also derived [8, 6]. 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 [7].

In this way, leveraging the advantage of two measurements and the special run conditions, it was possible to extract a wealth of informations from the data, like:

- luminosity-independent cross-sections,
- luminosity determination,
- ρ-independent cross-sections,
- luminosity and ρ-independent cross-section ratios,
- ρ constraints.

	$\mathscr{L}$ independent at $\sqrt{s} = 7$ TeV, eq. 1	$\mathscr{L}$ independent at $\sqrt{s} = 8$ TeV, eq. 1
σ_{tot} (mb)	98.0 ± 2.5	101.7 ± 2.9
σ_{inel} (mb)	72.9 ± 1.5	74.7 ± 1.7
σ_{el} (mb)	25.1 ± 1.1	27.1 ± 1.4

Table 1: Summary of the measured cross-sections using a luminosity, $\mathscr{L}$, independent method. The full systematic uncertainty is reported for each measurements, see [6, 9] for a detailed description of the systematic uncertainty.

The cross-sections obtained using the luminosity independet method of eq. 1, during the special run with β^*=90 m, are reported in Table 1. In the same table the 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 for these measurements see [4, 6, 9] and references therein. For the ρ parameter value the COMPETE [14] preferred-model extrapolation of 0.141 ± 0.007 was chosen.

In Figure 5 results of Table 1 are shown along the ones obtained by other experiments at LHC [11, 13, 12] and by the AUGER Collaboration [2]. The good agreement between TOTEM measurements and the COMPETE fit, extrapolating from lower energies [14], can be noted.

3 Conclusions

TOTEM has measured, for the first time at the LHC, the total proton-proton cross section at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, using a luminosity independent method. The method was validated comparing the elastic and inelastic cross sections measured in independent ways.

Furthermore, successful measurements with larger betatron values, like $\beta^*$of 1000 m , have been done and data analisys is in progress. Such an optics will allow the study of the Coulomb-hadronic interference, pushing the mini-

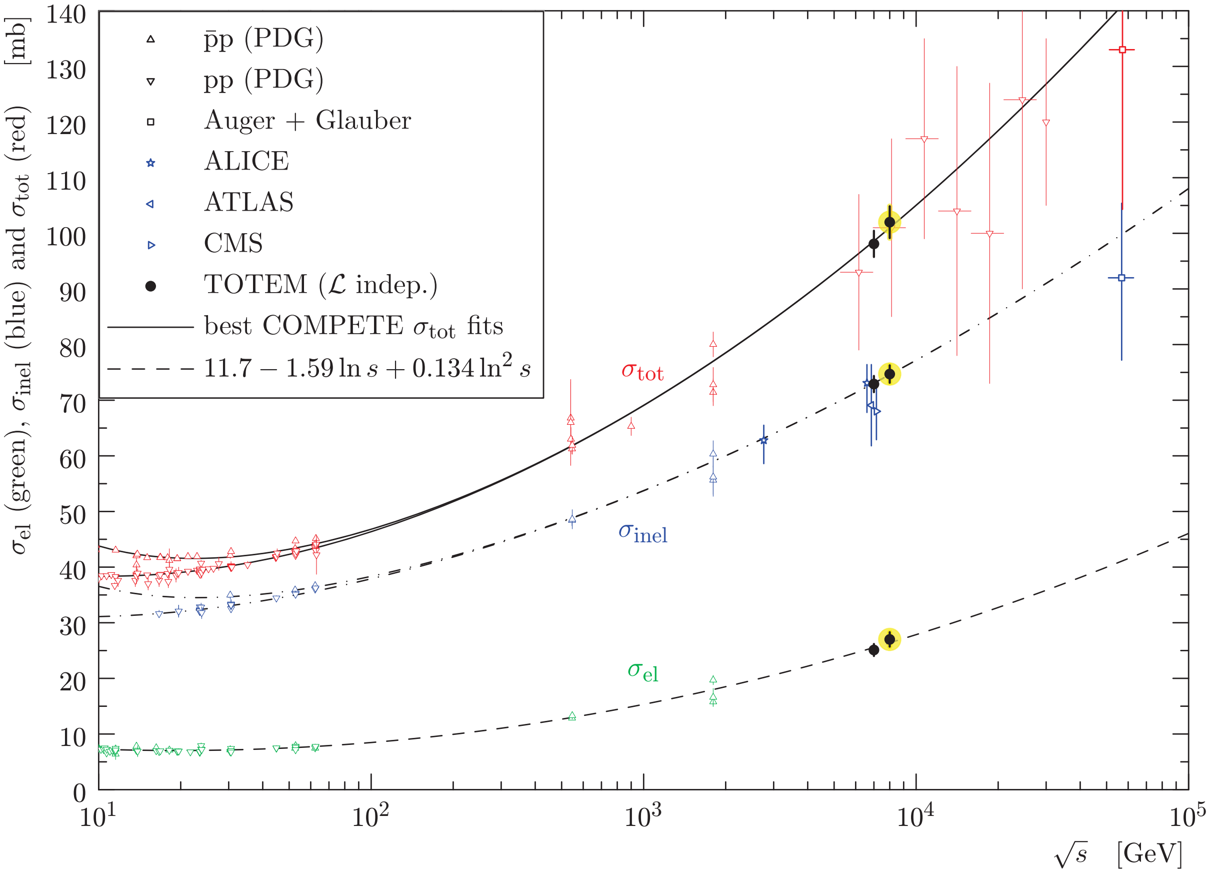

Figure 5: A compilation of [6, 11, 13, 12, 10] the total (σ_{tot}), inelastic (σ_{inel}) and elastic (σ_{el}) cross-sections measurements: the TOTEM measurements using the luminosity independent method are the black points. The continuous black lines (lower for pp, upper for $\bar{p}p$) represent the best fits of the total cross-section data by the COMPETE collaboration [14]. TOTEM results at $\sqrt{s} = 8$ TeV are highlighted. The dashed line results from a fit of the elastic scattering data. The dash-dotted lines refer to the inelastic cross-section and are obtained as the difference between the continuous and dashed fits.

mum reachable $|t|$ value down to 5×10^{-4} GeV, allowing us to determine the ρ parameter.

Acknowledgment: We are grateful to the beam optics development team for the design and the successful commissioning of the high β^* optics and to the LHC machine coordinators for scheduling the dedicated fills.

This work was supported by the institutions listed on the front page and partially also by NSF (US), the Magnus Ehrnrooth foundation (Finland), the Waldemar von Frenckell foundation (Finland), the Academy of Finland, the Finnish Academy of Science and Letters (The Vilho, Yrjö and Kalle Väisälä Fund),the OTKA grant NK 73143 (Hungary) and by the NKTH-OTKA grant 74458 (Hungary).

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