PROCEEDINGS OF SCIENCE

TOTEM Physics Results

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The TOTEM experiment [1, 2] at the LHC is dedicated to the measurement of elastic and diffractive scattering, total cross-section and forward particle production. This contribution summarises the physics results and points to the respective publications.

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1. Elastic Scattering

At the centre-of-mass energy $\sqrt{s} = 7\,\text{TeV}$, the differential cross-section of elastic scattering, $d\sigma/dt$, has been measured in the squared four-momentum transfer range $0.005\,\text{GeV}^2 < |t| < 2.5\,\text{GeV}^2$ (Fig. 1), extending from the almost exponential forward peak ($\propto e^{-B|t|}$ with $B = (19.89 \pm 0.27)\,\text{GeV}^{-2}$) [3] through the dip-bump region (with the minimum observed at $0.53\,\text{GeV}^2$) to the large-$|t|$ domain exhibiting a power-law behaviour, $\propto |t|^{-7.8}$ [4]. The $|t|$-range analysed so far has been covered by two data sets and will be extended at its upper bound to about $3.5\,\text{GeV}^2$ with a third data set already under analysis.

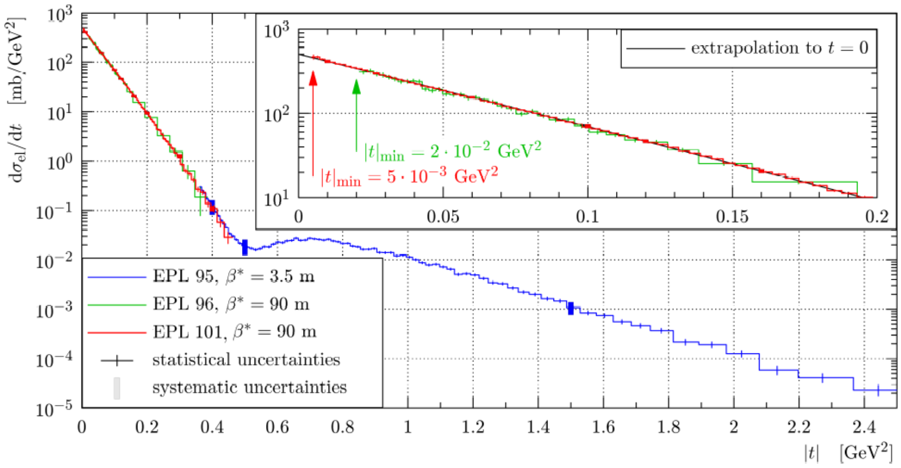

Figure 1: Differential cross-section of elastic scattering measured at $\sqrt{s} = 7\,\text{TeV}$.

At $\sqrt{s} = 8\,\text{TeV}$, analyses of data sets with two different machine optics are in progress.

- With the new $\beta^* = 1000\,\text{m}$ optics, $|t|$ values from $6 \times 10^{-4}\,\text{GeV}^2$ to $0.2\,\text{GeV}^2$ were reached, and the Coulomb-nuclear interference was observed for the first time at the LHC. This interference gives some sensitivity to the phase $\phi_N(t)$ of the nuclear scattering amplitude $A_N(t)$, mainly at $t = 0$. However, the precise functional form of the scattering amplitude in the interference region is not known from first principles and thus model dependent. There have been two approaches to derive interference formulas combining the Coulomb scattering amplitude $A_C(t)$ and the nuclear amplitude $A_N(t)$ to the total amplitude $A_{C+N}(t)$: (1) pursuing Feynman diagram techniques (best represented by the simplified formula by West and Yennie [5], SWY) and (2) using an eikonal description (most recently represented by Kundrát and Lokajíček [6], KL). The SWY formula is only consistent with a purely exponential nuclear amplitude and constant phase. The KL formula has no such limitations and was used in the analysis in conjunction with hadronic amplitude moduli of the form $a \exp(b_0 + b_1 t + \ldots)$ with $N_b = 1$ to 3 parameters b_i, and with constant or central or peripheral functional forms of the hadronic phase, all leading to different behaviours in the impact parameter space [6]. The preliminary results for $\rho = \cot\phi_N(0) = \mathscr{R}A_N(0)/\mathscr{I}A_N(0)$ (not yet reported in proceedings) are conditional to the functional form of modulus and phase of the nuclear amplitude, $\phi_N(t)$, and to the choice of the interference formula. In practice, for a given phase parameterisation only the value at $t = 0$ is kept free in the fits. The data cannot distinguish between constant and central phase. Also, for $N_b = 1$ no significant difference has been observed between the fits with SWY or KL interference formula. Hence there are 6 cases remaining: $[N_b = 1,2,3] \times$ [constant/central $\phi_N(t)$ or peripheral $\phi_N(t)$] $= 3 \times 2$.

- The very-low-$|t|$ data are complemented by – and overlapping with – two data sets recorded at $\beta^* = 90\,\mathrm{m}$:
  - The first set at $\beta^* = 90\,\mathrm{m}$ covers the range $0.01\,\mathrm{GeV}^2 < |t| < 1.4\,\mathrm{GeV}^2$ and includes inelastic rate measurements from T1 and T2. Therefore the extrapolation of the lower-$|t|$ region of the differential elastic rate, $\mathrm{dN_{el}/dt}$, has been used for the total cross-section determination with the luminosity-independent method (see Section 2).
  - The second set at $\beta^* = 90\,\mathrm{m}$ is characterised by very high statistics (8 M events) in the range $0.03\,\mathrm{GeV}^2 < |t| < 1.4\,\mathrm{GeV}^2$. It lacks inelastic information from T1 and T2 but can be normalised using the first set. Its strong statistical power enabled an in-depth analysis of the exponential slope $B(t)$. This analysis excluded a constant slope, i.e. a purely exponential form of $\mathrm{d}\sigma/\mathrm{dt}$, with about $7\,\sigma$ significance, whereas linear or quadratic parameterisations of $B(t)$ yield satisfactory fits. The consequence of this result is the data-based exclusion of the SWY interference formula which would require $N_b = 1$ and constant phase.

TOTEM also collected data at $\sqrt{s} = 2.76\,\mathrm{TeV}$ in an expected $|t|$-range from about 0.06 to about $0.4\,\mathrm{GeV}^2$, i.e. not covering the dip-bump structure. The analysis is ongoing.

2. Total and Inelastic pp Cross-Sections

At $\sqrt{s} = 7\,\mathrm{TeV}$, four articles on total and inelastic cross-section measurements were published.

- Refs. [7] and [3]: The pp elastic scattering differential cross-section $\mathrm{d}\sigma/\mathrm{d}t$ was normalised with the luminosity from CMS. After extrapolation to $t = 0$, the total pp cross-section was calculated using the optical theorem,

$$\sigma_{\mathrm{tot}}^2 = \frac{16\pi\,(\hbar c)^2}{1+\rho^2}\,\left.\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t}\right|_{t=0}, \tag{2.1}$$

  with $\rho = 0.141 \pm 0.007$ from the COMPETE [8] preferred-model extrapolation. Finally, the inelastic cross-section was obtained by subtraction: $\sigma_{\mathrm{inel}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}}$. The results reported in the two papers are based on independent data sets from different LHC fills with different beam intensities.

- Ref. [9]: The inelastic pp cross-section was directly measured with the forward trackers T1 and T2, using the luminosity from CMS for normalisation. Addition of the elastic cross-section from [3] yields a ρ-independent result for the total cross-section.

- Ref. [10]: The total cross-section and the integrated luminosity were simulaneously obtained from the elastic and inelastic event counts, applying the “luminosity-independent method”:

$$\sigma_{\mathrm{tot}} = \frac{16\pi\,(\hbar c)^2}{1+\rho^2}\,\frac{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_{t=0}}{N_{\mathrm{el}}+N_{\mathrm{inel}}}\,, \quad \mathscr{L}_{\mathrm{int}} = \frac{1+\rho^2}{16\pi\,(\hbar c)^2}\,\frac{(N_{\mathrm{el}}+N_{\mathrm{inel}})^2}{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_{t=0}}\,. \tag{2.2}$$

The luminosity result was found to confirm very well the CMS measurement. Also the four results for σ_{tot}, having very different systematic dependences, are in excellent agreement.

Finally, by combining the elastic and inelastic rate measurements with the CMS luminosity measurement, an estimate on ρ was obtained:

$$\rho^2 = 16\pi\,(\hbar c)^2\,\mathscr{L}_{\text{int}}\,\frac{\mathrm{d}N_{\text{el}}/\mathrm{d}t|_{t=0}}{(N_{\text{el}}+N_{\text{inel}})^2} - 1 = 0.009 \pm 0.056 \text{ or } |\rho| = 0.145 \pm 0.091. \tag{2.3}$$

At the energy of 8 TeV, the luminosity-independent results on elastic, inelastic and total cross-section were published [11]. Moreover, the ongoing analysis of the $\beta^* = 1000$ m data, allowing the separation of Coulomb and nuclear effects, will yield a methodically more accurate result for the total cross-section. A numerical overview of the cross-section results is given in Table 1.

At $\sqrt{s} = 2.76$ TeV TOTEM aims at applying all three total cross-section determination methods. The analysis is in progress.

Table 1: Cross-section summary. The errors represent the full systematic uncertainties; the statistical uncertainties are negligible and therefore omitted.

$\sqrt{s}$ [TeV]	Method	Data Set	σ_{tot} [mb]	σ_{inel} [mb]	σ_{el} [mb]
7	elastic only: Eq. (2.1)	June 2011 [7]	98.3 ± 2.8	73.5 ± 1.6	24.8 ± 1.2
7	elastic only: Eq. (2.1)	October 2011 [3]	98.6 ± 2.2	73.2 ± 1.3	25.4 ± 1.1
7	ρ-indep. (el. + inel.)	October 2011 [9]	99.1 ± 4.3	73.7 ± 3.4	25.4 ± 1.1
7	$\mathscr{L}_{\text{int}}$-indep.: Eq. (2.2)	October 2011 [10]	98.0 ± 2.5	72.9 ± 1.5	25.1 ± 1.1
8	$\mathscr{L}_{\text{int}}$-indep.: Eq. (2.2)	July 2012 [11]	101.7 ± 2.9	74.7 ± 1.7	27.1 ± 1.4

3. Forward Charged Particle Multiplicity

The Telescope T2 is an efficient tagger for an almost unbiassed sample of inelastic events due to its low p_T acceptance threshold ($\sim$40 MeV) and large acceptance to inelastic events ($>$ 90 %). Based on a special low-pileup run at $\sqrt{s} = 7$ TeV, the charged particle pseudorapidity density $\mathrm{d}N_{ch}/\mathrm{d}\eta$ for $5.3 < |\eta| < 6.4$ was determined in events with at least one charged particle with transverse momentum above 40 MeV [15]. This was the first measurement of $\mathrm{d}N_{ch}/\mathrm{d}\eta$ at such forward rapidities.

For $\sqrt{s} = 8$ TeV, TOTEM and CMS have performed a joint analysis of $\mathrm{d}N_{ch}/\mathrm{d}\eta$ on the same events both for the central tracker ($|\eta| < 2.3$) and for the very forward T2 ($5.3 < |\eta| < 6.4$), all triggered by T2 in a common low-pileup run. More details are given in another contribution to these proceedings [12] and in Ref. [13]. A recent TOTEM-standalone analysis profits from a short fill at $\sqrt{s} = 8$ TeV with a mistake in the bunch filling scheme creating an additional, "parasitical" interaction point shifted by 11 m relative to IP5. The resulting modified pseudorapidity acceptance of T2 covers the ranges $3.7 < \eta < 4.8$ and $6 < \eta < 7$. A preliminary result has been shown but cannot be included in proceedings yet.

4. Diffractive Scattering

Various studies of soft and hard diffractive scattering are in progress.

- Double diffractive (DD) cross-section:
  The DD cross-section in the forward region [14] was measured using a $\beta^* = 90\,\mathrm{m}$ run at 7 TeV with a low pileup probability (~0.05 inelastic events per bunch crossing). A forward DD sample was obtained by triggering with T2, requiring at least one charged particle in both T2 arms and no charged particles in T1. This strategy allows a very pure (~70%) DD sample to be selected, but only a few % of the total DD cross-section are kinematically covered. The measurement was corrected to be representative for DD events with a central rapidity gap from $\eta = -4.7$ to $\eta = +4.7$, corresponding approximately to events where both diffractive systems have masses between 3.4 and 8 GeV. The results – both for the total accessible η_{min} range on each side, and for a 2×2 matrix of subranges – are reported in Table 2 and compared with predictions of Monte Carlo models. Using data taken in common with CMS at $\sqrt{s} = 8\,\mathrm{TeV}$ in 2012, a much larger fraction of σ_{DD} can be measured with good purity.

Table 2: The forward double diffractive (DD) cross-section measurements and their MC predictions. $|\eta^+|_{\mathrm{min}}$ ($|\eta^-|_{\mathrm{min}}$) refers to the primary particle with smallest $|\eta|$ in the positive (negative) hemisphere. The Pythia and Phojet estimates for the total σ_{DD} are 8.1 mb and 3.9 mb, respectively.

$\lvert\eta^+\rvert_{\mathrm{min}}$	$\lvert\eta^-\rvert_{\mathrm{min}}$	TOTEM [μb]	Pythia 8.108 [μb]	Phojet 1.12 [μb]
[4.7,5.9]	[4.7,5.9]	65 ± 20	70	44
[4.7,5.9]	[5.9,6.5]	26 ± 5	36	23
[5.9,6.5]	[4.7,5.9]	27 ± 5	36	23
[5.9,6.5]	[5.9,6.5]	12 ± 5	17	12
[4.7,6.5]	[4.7,6.5]	116 ± 25	159	101

- Single diffractive (SD) cross-section:
  A study of SD events at 7 TeV is performed on a data set triggered with T2. SD-like events (proton + gap + diffractive system) are selected requiring only one proton in the Roman Pots, charged particles in the T2 arm opposite to the proton and none in the other arm. The events are classified according to their diffractive mass, M_{diff}, based on the charged particle configuration in T1 and T2 (Table 3). Here the relation $M^2_{\mathrm{diff}} = s e^{-\Delta\eta}$ is used, where $\Delta\eta$ is the rapidity gap between the very forward proton and the charged particle in T1 and T2 closest in η to the proton.

  The aim of the study is to determine $\mathrm{d}\sigma_{SD}/\mathrm{d}t$ and its integral over t for each class separately.

Table 3: Classification of the single diffractive events into different ranges of the diffractive mass M_{diff} and proton momentum loss ξ. The “opposite” and “same” side of the IP are defined relative to the proton detected in the Roman Pot.

M_{diff} [GeV]	ξ	Event signature
$3.4 \div 8$	$2 \times 10^{-7} \div 10^{-6}$	p + opposite T2, no T1
$8 \div 350$	$10^{-6} \div 0.0025$	p + opposite T2 + opposite T1
$350 \div 1100$	$0.0025 \div 0.025$	p + opposite T2 + same side T1

- Central Diffraction (CD):
  A CD data set has been collected in a 12 hour run together with CMS at 7 TeV with the $\beta^* = 90\,\mathrm{m}$ optics. In addition to the TOTEM-standalone analysis of the differential cross-

section in $t_{1,2}$ and $\xi_{1,2}$, a joint CMS+TOTEM analysis of exclusive central production of low-mass resonances is in progress. Furthermore, central diffractive jet production is studied. An example event with 3 central jets and both leading protons reconstructed in the Roman Pots has been shown at the conference.

5. Outlook and the TOTEM Upgrade Programme

In addition to measurements of elastic scattering and total cross-section at the final LHC energy of 13 or 14 TeV, TOTEM will put emphasis on studying central exclusive production with strongly increased statistics. Potential candidates for new states within reach are e.g. glue balls. To be able to perform leading proton measurements at substantial levels of event pileup, TOTEM has submitted in 2013 an upgrade proposal [16] which is now being further elaborated in two technical design reports, both aiming at pileup resolution via timing detectors in the Roman Pots measuring the longitudinal vertex position. For special runs at $\beta^* = 90\,\mathrm{m}$ with acceptance for diffractive masses down to 0, some vertical Roman Pots will be equipped with timing detectors in a TOTEM-standalone initiative [17]. The complementary CMS-TOTEM Precision Proton Spectrometer (CT-PPS) project [18] for hard diffractive processes with masses above $\sim 300\,\mathrm{GeV}$ in standard low-β^* LHC fills foresees timing detectors in horizontal Roman Pots.

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