Latest results of the TOTEM experiment at LHC

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On behalf of the TOTEM Collaboration

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Outline

- TOTEM experiment at LHC
- Total cross-section
- Elastic scattering
- Diffraction dissociation

TOTal cross-section, Elastic scattering and diffraction dissociation Measurement the LHC
The TOTEM detector at the LHC

The TOTEM experimental apparatus was designed to measure the Total Cross Section and to study Elastic Scattering and Diffraction Dissociation at the LHC.

T1 and T2 are used to detect charged particle in inelastic events.

Roman Pots detect elastic and diffractive protons close to outgoing beam.

$10 \leq |\eta| \leq 12$
The TOTEM Roman Pot system

A Roman Pot is a movable section of the beam pipe that allows the insertion of a detector at few millimeters from the beam.

- 16 Vertical RPs
- 4 Shielded RPs for high-luminosity operation
- 4 Horizontal RPs
- 2 Cylindrical RPs for time-of-flight detector

High intensity runs:
- 4 Vertical RPs (per arm)
- 2 Shielded RPs
- Cylindrical RP

Dedicated runs:
- 6 Vertical RPs
- 2 Horizontal RPs
- 1 Shielded RP

\[ \beta^* = 90 \text{ m, 1 km, 2.5 km} \]

*: Si strip removed, waiting for timing detectors...
**Total cross-section**

Optical Theorem, Elastic $\frac{d\sigma}{dt}$ extrapolated to $t = 0$

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

Explicit dependency on $\mathcal{L}$:

$$\sigma_{tot}^2 = \frac{16 \pi}{1 + \rho^2} \left. \frac{dN_{el}}{dt} \right|_{t=0}$$

Elastic + Inelastic measurement: no dependency on $\rho$

$$\sigma_{tot} = \left( \frac{1}{\mathcal{L}} (N_{el} + N_{inel}) \right)$$

Elastic + Inelastic measurement: no dependency on $\mathcal{L}$

$$\sigma_{tot} = \frac{16 \pi}{1 + \rho^2} \left. \frac{dN_{el}/dt}{N_{el} + N_{inel}} \right|_{t=0}$$

Measured using Roman Pots

$\sigma_{tot} = 98.3 \pm 2.8 \text{ mb}$ EPL 96(2011) 21002

$\sigma_{tot} = 98.6 \pm 2.2 \text{ mb}$ EPL 101(2013) 21002

Measured using T1 and T2

$\sigma_{tot} = 99.1 \pm 4.3 \text{ mb}$ EPL 101(2013) 21004

$\sigma_{tot} = 98.0 \pm 2.5 \text{ mb}$ EPL 101(2013) 21004
Dependences of total, inelastic and elastic cross-sections on the scattering energy $\sqrt{s}$

**Total cross-section**

EPL 101 (2013) 21004 - 7 TeV

$\sigma_{el} = 25.1 \pm 1.1$ mb

$\sigma_{inel} = 72.9 \pm 1.5$ mb

$\sigma_{tot} = 98.0 \pm 2.5$ mb
(luminosity independent)

PRL 111 (2013) 012001 - 8 TeV

$\sigma_{el} = 27.1 \pm 1.4$ mb

$\sigma_{inel} = 74.7 \pm 1.7$ mb

$\sigma_{tot} = 101.7 \pm 2.9$ mb
(luminosity independent)
Elastic scattering at $\sqrt{s} = 7 \text{ TeV}$, $\beta^* = 3.5 \text{ m}$ (First measurement)

0.36 $< |t| < 2.5 \text{ GeV}^2$

Exponential behavior $e^{-B|t|}$ for $|t| < 0.47 \text{ GeV}^2$

Dip moves to lower $|t|$: proton becomes “larger”

Power low behavior $|t|^{-n}$ for $1.5 < |t| < 2.5 \text{ GeV}^2$

EPL 95 (2011) 41001
Elastic scattering at $\sqrt{s} = 7\, TeV$, $\beta^* = 3.5\, m$

Selected reconstructed tracks in a RP transverse to the beam at 220 m.

Correlation between the reconstructed proton scattering angles

Horizontal...

... and vertical

on both sides of the IP.

The observed spread is due to the beam divergence.

Published in EPL 95 (2011) 41001
Elastic scattering at $\sqrt{s} = 7\, \text{TeV}, \beta^* = 90\, \text{m}$

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Published in
EPL 96 (2011) 21002
EPL 101(2013) 21002
Elastic scattering at $\sqrt{s} = 7$ TeV, $\beta^* = 90$ m

$$\sigma_{el} = \int \frac{d\sigma}{dt} dt = (24.8 \pm 0.2^{stat} \pm 1.2^{syst}) \text{ mb}$$

EPL, 96 (2011) 21002

$$\sigma_{el} = (25.43 \pm 0.03^{stat} \pm 1.07^{syst}) \text{ mb}$$

EPL, 101 (2013) 21002
Elastic scattering: non-exponentiality at low $|t|$
Elastic scattering: Coulomb interference

\[ \sqrt{s} = 8 \text{ TeV}, \beta^* = 1000 \text{ m} \]
Roman Pots at \( \sim 3 \sigma \)
\(|t|_{\text{min}} \sim 6 \times 10^{-4} \text{ GeV}^2 \)

- TOTEM data
- Coulomb standalone
- Hadronic standalone
- Coulomb and hadronic combined

Coulomb-hadronic interference

\[
\frac{d\sigma}{dt} \propto \left( 1 + \cdots + \psi^4 + \cdots \right)
\]

Coulomb amplitude
Hadronic amplitude
“interference” terms

Purely exponential hadronic amplitude:
Constant phase excluded with both Simplified West-Yennie and Kundrát-Lokajicek models

Non-exponential hadronic amplitude:
Both peripheral and constant phase compatible with data
Preliminary results

Different physics regimes are accessible thanks to different LHC configurations

Hints:

non-exponentiability confirmed at 13 TeV
\( \sqrt{s} = 7 \rightarrow 13 \text{ TeV}: \) dip moves to lower |t|

Forward slope \( B = \frac{d}{dt} \ln(\frac{d\sigma}{dt} |_{t=0}) \)
increase wrt previous experiments

No structures at high-|t|
(rules out the “optical” models)
Outlook: Odderon searches

- Odderon = (hypothetical) cross-odd partner of Pomeron
- overview of past Odderon searches
  - comparison pp vs. anti-pp (dip): not applicable at LHC
  - spin analyses: not applicable at LHC
  - structures in $d\sigma/dt$: where Pomeron contribution small
    - high-$|t|$: disfavoured by 13 TeV measurements
    - low-$|t|$: shifts of $\rho$ value $\Rightarrow$ within reach of TOTEM
- Coulomb-nuclear interference at $\sqrt{s} = 13$ TeV
  - needs special optics: $\beta^* = 2500$ m
  - $|t| = 6 \cdot 10^{-4}$ GeV$^2$ reachable
  - $\sim 1$ week data-taking time approved in 2016
Single diffraction: Preliminary results at $\sqrt{s} = 7$ TeV

Corrections included:
- Trigger efficiency
- Proton acceptance & reconstruction efficiency
- Background subtraction
- Extrapolation to $t = 0$

Missing corrections:
- Class migration
- $\xi$ resolution & beam divergence effects

Estimated uncertainties:
$B \sim 15\%$; $\sigma \sim 20\%$

**TOTEM preliminary:**

$\sigma_{SD} = 6.5 \pm 1.3$ mb

3.4 GeV < $M_{diff}$ < 1.1 TeV

Analysis of very high mass $SD$ events ongoing

courtesy of H. Saarikko
Summary

- Total cross-section measurements at $\sqrt{s} = 7$ TeV and 8 TeV with a luminosity independent method.
- Published proton-proton elastic analysis results at $\sqrt{s} = 7$ TeV and 8 TeV with $\beta* = 3.5$ m, 90 m, 1000 m.
- Non-exponentiality of the differential cross-section at low- |t| at $\sqrt{s} = 8$ TeV and 13 TeV ($\beta* = 90$ m, 1000 m).
- Hadronic-Coulomb interference at $\sqrt{s} = 8$ TeV with $\beta* = 1000$ m optics.
- 1st determination of the $\rho$ parameter at the LHC with CNI.
- Ongoing analyses at $\sqrt{s}=2.76$ TeV and $\sqrt{s} = 13$ TeV data.
- About 1 week data taking time foreseen in 2016 at 13 TeV with $\beta* = 2500$ m.

References:

F. Nemes, TOTEM measurements of cross-sections at LHC, 3rd Elba Workshop on Forward Physics @ LHC Energy, May 2016
J. Kaspar, TOTEM, QCD at Cosmic Energies – VII, May 2016
Backup slides
Tricks to obtain lower $|t|$
Elastic scattering: Coulomb interference - Fits

\[ R^{*} = 1000 \text{ m}; \quad R^{*} = 90 \text{ m}; \]

- data with stat. unc.
- full syst. unc.
- syst. unc. w/o norm.

\[ \text{fits:} \quad \text{SWY, constant} \quad \text{Cahn/KL, constant} \quad \text{Cahn/KL, peripheral} \]

\( \leftarrow \) purely-exponential hadronic amplitude

- constant phase excluded (with both SWY and KL formulae) \( \Rightarrow \) application of SWY formula excluded too
- peripheral phase not excluded by data, but disfavoured
  - \( \rho \) value outside a consistent pattern of other fits and theoretical predictions
  - number of theoretical reasons for non-exponential hadronic amplitude

\( \leftarrow \) non-exponential hadronic amplitude

- both constant and peripheral phases compatible with data \( \Rightarrow \) centrality not necessity
TOTEM & CMS

TOTEM
LHC experiment dedicated to measurement of:
*total cross-section, elastic scattering and diffractive processes*
Designed to study rapidity gaps, particles in very forward region, surviving protons

TOTEM + CMS
both experiments at LHC Interaction Point 5
excellent pseudorapidity coverage: optimal for hard diffraction studies
cooperation mode: independent experiments and DAQ, exchange of triggers for off-line synchronization

CT-PPS (CMS-TOTEM Precision Proton Spectrometer)
all sub-detectors fully integrated under CMS
Infrastructure for high luminosity and high-pileup configurations of the LHC: RF optimized RP, timing and pixel detectors
Diamond timing detector for Cylindrical RP
Roman Pot insertion in 2016

Roman Pot insertion allowed at $15 \sigma$ from June 2016!

Before:
2 hours after declaration of stable beam the RPs could be inserted at $15 \sigma + 0.5$ mm.

The second fill of each intensity step the 0.5 mm margin was removed and then subsequent insertions were possible.

Successful insertion with 2244 bunches (max in 2015)
Temperature of the Cylindrical Roman Pot

Timeseries Chart between 2016-05-20 00:06:00.000 and 2016-05-21 23:10:32.191 (LOCAL_TIME)