Elastic and Total Cross-Section Measurements by TOTEM: Past and Future

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CERN*

DIS 2017
Birmingham, England

*Also at Wigner RCP, Budapest, Hungary
Experimental layout of the TOTEM experiment (LHC Run II)

T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

CASTOR (CMS)
The Roman Pot (RP) stations of the TOTEM experiment

RP stations:
- 2 units (Near, Far) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

- Horizontal RP
- Vertical RPs
- BPM

10 planes of edgeless detectors
Si edgeless detector
1 Roman Pot
LHC optics at IP5 briefly

Sketch of the LHC magnet lattice at IP5:

\[ k = \frac{1}{B \rho} \frac{dB_z}{dx} \]

MQXA quadrupole

\[ s: \text{distance from IP5 (} \ast \equiv \text{IP5)} \]

Measured

\[
\begin{pmatrix}
 x \\
 \Theta_x \\
 y \\
 \Theta_y \\
 \xi
\end{pmatrix}_{RP} =
\begin{pmatrix}
 v_x & L_x & m_{13} & m_{14} & D_x \\
 v'_x & L'_x & m_{23} & m_{24} & D'_x \\
 m_{31} & m_{32} & v_y & L_y & D_y \\
 m_{41} & m_{42} & v'_y & L'_y & D'_y \\
 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
 x^* \\
 \Theta^*_x \\
 y^* \\
 \Theta^*_y \\
 \xi^*
\end{pmatrix}
\]

\[ \sigma(\Theta) = \sqrt{\varepsilon / \beta_x(s)} \]

Determines angular resolution.
TOTEM cross-section measurements

$\sqrt{s} = 7 \text{ TeV}$

List of TOTEM publications

http://totem.web.cern.ch/Totem/publ_new.html
Momentum conservation is required in elastic events:

- Published in EPL 95 (2011) 41001

Horizontally...

...and vertically

Spread agrees with beam divergence (17-18 μrad)
The elastic $d\sigma/dt$ distribution at $\sqrt{s} = 7$ TeV ($\beta^* = 3.5$ m)

Published in EPL 95 (2011) 41001:

- $|t|$ range spans from 0.36 to 2.5 GeV$^2$
- Below $|t| = 0.47$ GeV$^2$ exponential $e^{-B|t|}$ behavior
- Dip moves to lower $|t|$, proton becomes "larger"
- $1.5 - 2.5$ GeV$^2$ power low behavior $|t|^{-n}$

The measured $d\sigma/dt$ compared with predictions of several models
Machine imperfections alter the optics:

- Strength conversion error, $\sigma(B)/B \approx 10^{-3}$
- Beam momentum offset, $\sigma(p)/p \approx 10^{-3}$
- Magnet rotations, $\sigma(\phi) \approx 1$ mrad
- Magnetic field harmonics, $\sigma(B)/B \approx 10^{-4}$
- Power converter errors, $\sigma(I)/I \approx 10^{-4}$
- Magnet positions $\Delta x, \Delta y \approx 100 \mu m$

$$t(v_x, L_x, L_y, ..., p) = -p^2 \cdot (\Theta_x^* + \Theta_y^*)$$

→ Precise model of the LHC optics is indispensable!

**Novel method from TOTEM:**

- Use measured proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- [http://iopscience.iop.org/1367-2630/16/10/103041/](http://iopscience.iop.org/1367-2630/16/10/103041/)
Low-t measurements with $\beta^* = 90 \text{ m at } \sqrt{s} = 7 \text{ TeV}$

Properties:

- $L_{Y,b1} = 264.1 \text{ m}$
- Slope $B$ confirms that it increases with $\sqrt{s}$
- Total cross-section with optical theorem
- $\rho$ value from COMPETE:

  $$\sigma_{\text{tot}}^2 = \frac{16\pi (\hbar c)^2}{1 + \rho^2} \cdot \frac{d\sigma_{\text{el}}}{dt} \bigg|_{t=0}$$

  $$\rho = \frac{\text{Re } A^H}{\text{Im } A^H} \bigg|_{t=0}$$

- Compatible results, published in:  
  
  EPL 96 (2011) 21002  
  EPL 101 (2013) 21002

<table>
<thead>
<tr>
<th>RP distance</th>
<th>$\sigma_{\text{beam}}$</th>
<th>10</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>GeV$^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{d\sigma}{dt}$</td>
<td>mb GeV$^{-2}$</td>
<td>503.7 ± 1.5$^{\text{stat}}$ ± 26.7$^{\text{syst}}$</td>
<td>506.4 ± 0.9$^{\text{stat}}$ ± 23$^{\text{syst}}$</td>
</tr>
<tr>
<td>$\sigma_{\text{el}}$</td>
<td>mb</td>
<td>24.8 ± 0.2$^{\text{stat}}$ ± 1.2$^{\text{syst}}$</td>
<td>25.43 ± 0.03$^{\text{stat}}$ ± 1.07$^{\text{syst}}$</td>
</tr>
<tr>
<td>$\sigma_{\text{inel}}$</td>
<td>mb</td>
<td>73.5 ± 0.6$^{\text{stat}}$ $^{+1.8}_{-1.3}$ $^{\text{syst}}$</td>
<td>73.15 ± 1.26$^{\text{full}}$</td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}$</td>
<td>mb</td>
<td>98.3 ± 0.2$^{\text{stat}}$ ± 2.8$^{\text{syst}}$</td>
<td>98.6 ± 2.2$^{\text{full}}$</td>
</tr>
<tr>
<td>$t_{\text{min}}$</td>
<td>GeV$^{2}$</td>
<td>$2 \times 10^{-2}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

DIS2017 3-7/04/2017  
Frigyes Nemes, TOTEM
$\sqrt{s} = 7$ TeV: combined elastic $d\sigma/dt$ results

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Graph showing the combined elastic $d\sigma/dt$ results for different $\beta^*$ values.}
\end{figure}

- EPL 95 (2011) 41001 ($\beta^* = 3.5$ m)
- EPL 96 (2011) 21002 ($\beta^* = 90$ m)
- EPL 101 (2013) 2100 ($\beta^* = 90$ m)

- extrapolation to $t = 0$

$|t|_{\text{min}} = 5 \cdot 10^{-3}$ GeV$^2$ (RP @ 6.5, 5.5, 4.8 $\sigma_{\text{beam size}}$@RP)

$|t|_{\text{min}} = 2 \cdot 10^{-2}$ GeV$^2$

EPL 96 (2011) 21002 ($\beta^* = 90$ m)
**Inelastic cross-section measurement**

**Trigger:** at least one track in T2
- 95% of inelastic events

1. **Raw rate:** event counting with T2

   Experimental corrections: trigger and reconstruction inefficiencies, beam-gas event suppression, pile-up

2. **Visible rate:** visible with T2 in perfect conditions

   Estimation of events with no tracks in T2: T1-only events, events with gap over T2, low-mass diffraction

3. **Physics rate:** true rate of inelastic events
   - Only one major Monte-Carlo-based correction: low-mass diffraction (which can be constrained from data, 6.31 mb upper limit for $M_x < 3.4$ GeV)

4. **Cross-section:** uses CMS luminosity measurement

\[
\sigma_{\text{inel}} = 73.7 \pm 3.4 \text{ mb}
\]
\( \sigma_{\text{tot}} \) with 4 methods at \( \sqrt{s} = 7 \text{ TeV} \)

Results:

1. Low luminosity (CMS) + Elastic \( d\sigma/dt \) + Optical th. \( \text{(EPL 96(2011) 21002)} \)
   - depends on CMS luminosity for low-L bunches, elastic efficiencies and on \( \rho \)
   
   \[
   \sigma_{\text{tot}}^2 = \frac{16\pi(hc)^2}{1 + \rho^2} \cdot \left. \frac{d\sigma_{\text{el}}}{dt} \right|_{t=0}
   \]
   \[\sigma_{\text{tot}} = 98.3 \pm 2.8 \text{ mb}\]

2. High luminosity (CMS) + Elastic + Optical theorem \( \text{(EPL 101 (2013) 21002)} \)
   \[\sigma_{\text{tot}} = 98.6 \pm 2.2 \text{ mb}\]

3. High luminosity (CMS) + Elastic + Inelastic \( \text{(EPL, 101 (2013) 21004)} \)
   - minimizes dependence on elastic efficiencies and no dependence on \( \rho \)
   
   \[\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}\]
   \[\sigma_{\text{tot}} = 99.1 \pm 4.3 \text{ mb}\]

4. Elastic ratios + Inelastic ratios (T1, T2) + Optical theorem \( \text{(EPL, 101 (2013) 21004)} \)
   - Eliminates dependence on luminosity
   
   \[
   \sigma_{\text{tot}} = \frac{16\pi(hc)^2}{1 + \rho^2} \cdot \left. \frac{dN_{\text{el}}}{dt} \right|_{t=0} \cdot \frac{N_{\text{el}}}{N_{\text{el}} + N_{\text{inel}}}
   \]
   \[\sigma_{\text{tot}} = 98.0 \pm 2.5 \text{ mb}\]
TOTEM cross-section measurements at $\sqrt{s} = 8$ TeV
Read more:
- EPL 101 (2013) 21004
- Evidence for non-exponentiality

The observed differential cross-section w.r.t. reference exponential:
- Fits with different assumptions on hadronic component
  \[ A^N = a \cdot \exp(b_1t) \quad \rightarrow \quad A^N = a \cdot \exp(b_1t + b_2t^2 + b_3t^3) \]
- Pure exponential excluded with more than 7σ significance!

<table>
<thead>
<tr>
<th>( N_b )</th>
<th>( \sigma_{\text{tot}} ) [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>101.5 ± 2.1</td>
</tr>
<tr>
<td>3</td>
<td>101.9 ± 2.1</td>
</tr>
</tbody>
</table>

\[ \sigma_{\text{tot}} \equiv \sigma_{\text{el}} + \sigma_{\text{inel}} \]

\[ \sigma_{\text{el}} = 27.1 \pm 1.4 \quad \sigma_{\text{inel}} = 74.7 \pm 1.7 \]
Basic properties of the data:

- RP detectors at about $3 \times \sigma_{\text{beam}}$
- $|t|_{\text{min}} = 6 \times 10^{-4} \text{ GeV}^2$

Analysis aims:

- Measure $d\sigma_{\text{el}}/dt$ at the smallest possible $|t|$
- $A_{C+H}=\text{Coulomb} + \text{Hadronic} + \text{Interference terms}$
- Interference: the phase of hadronic amplitude appears in

$$\frac{d\sigma}{dt} \propto |A_{C+H}|^2$$

- **Determination of $\rho$ became possible:**

$$\rho = \left. \frac{\text{Re} A^H}{\text{Im} A^H} \right|_{t=0}$$

- Further improve the total cross-section $\sigma_{\text{tot}}$ measurement

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**Hadronic-Coulomb interference with $\beta^* = 1000$ m optics at 8 TeV**
Purely exponential hadronic amplitude:
- Constant phase: excluded
- Peripheral phase: disfavored

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

<table>
<thead>
<tr>
<th>Hadronic phase</th>
<th>$\sigma_{\text{tot}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>$102.9 \pm 2.3$</td>
</tr>
<tr>
<td>Peripheral</td>
<td>$103.0 \pm 2.3$</td>
</tr>
</tbody>
</table>
TOTEM elastic scattering measurement at $\sqrt{s} = 2.76$ TeV
RP can resolve uniquely single tracks
If cannot be resolved: array of multitrack candidates per RP
Elastic cuts defined with unique tracks
*Every* combination of the 4 RPs of a diagonal
*One* combination is selected with elastic cuts (+physics oriented topology studies)

**Unique tracks to define cuts**

... to select elastic candidates from multitracks

Progressive selection of elastic candidates cut by cut
Horizontal RPs were not inserted:
• No track based top-bottom RP alignment
• Horizontal and relative near-far alignment is done
• New methods to find absolute y-alignment of the 2 diagonals
• 2 diagonals: 2 constraints from elastic scattering symmetries

1st constraint: alignment of $\theta_y^*$ barycenter to 0

2nd constraint: alignment of $\theta_y^*$ to $\theta_x^*$

Optics calibration done in the usual way (alignment independent procedure)
Careful measurement of optics estimators:
2.76 TeV luminosity independent cross-sections ($\beta^* = 11$ m optics)

<table>
<thead>
<tr>
<th>$\sigma_{\text{tot}}$ [mb]</th>
<th>$\sigma_{\text{el}}$ [mb]</th>
<th>$\sigma_{\text{inel}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>84.7 ± 3.3</td>
<td>21.8 ± 1.4</td>
<td>62.8 ± 2.9</td>
</tr>
</tbody>
</table>

TOTEM preliminary
The nuclear slope $B$ and the $\sigma_{el}/\sigma_{tot}$ ratio at $\sqrt{s} = 2.76$ TeV

$B = 17.1 \pm 0.26$ GeV$^{-2}$

$\sigma_{el}/\sigma_{tot} = 25.7 \pm 1.1\%$

TOTEM preliminary
TOTEM elastic scattering measurement at $\sqrt{s} = 13$ TeV
\( \sqrt{s} = 13 \text{ TeV}, \ \beta^* = 90 \text{ m optics: preliminary elastic } \frac{d\sigma}{dt} \)

Note:

- Large amount of data (trigger rate 50× w.r.t. Run I)

No structures at high-\(|t|\): rules out several models
\( \sqrt{s} = 13 \text{ TeV}, \ \beta^* = 2500 \text{ m}, \) first analysis cycle completed
Summary of elastic cross-sections

- Published proton-proton elastic analysis results at \( \sqrt{s} = 7 \) TeV and 8 TeV
  - \( \beta^* = 3.5 \) m, 90 m, 1000 m

- Total cross-section measurements at \( \sqrt{s} = 7 \) TeV, 8 TeV and 2.76 TeV
  - Luminosity independent method

- Non-exponentiality of the differential cross-section at low-\(|t|\) at 8 TeV and 13 TeV
  - \( \beta^* = 90 \) m, 1000 m

- Hadronic-Coulomb interference at 8 TeV with \( \beta^* = 1000 \) m optics
  - 1\(^{st}\) determination of the \( \rho \) parameter at the LHC with CNI

- \( \sqrt{s} = 2.76 \) TeV preprint in progress
- Ongoing analyses at \( \sqrt{s} = 13 \) TeV (\( \beta^* = 90 \) m, 2500 m)
TOTEM measurements of cross-sections at the LHC

Thank you for your attention!
Backup slides
On the basis of constraints $R_{1}-R_{10}$ the optics can be estimated:

$$\chi^2 = \sum_{i=1}^{10} \left( \frac{(R_i, \text{measured} - R_i, \text{calculated})}{\sigma(R_i)} \right)^2 + \chi^2_{\text{LHC Design}}$$

Refine machine settings
- 2x6 quad. magnet strength
- 2x6 quad. rotation
- Momentum of 2 beams

Calculated ratios $R_{1} - R_{10}$

Comparison

Measured ratios $R_{1} - R_{10}$

$$R_2 \equiv \frac{y_{b1,RP}}{y_{b2,RP}} \approx \frac{L_{y,b1,RP}}{L_{y,b2,RP}}$$

$$R_7 \equiv \frac{x_{b1,RP}}{y_{b1,RP}} \approx \frac{m_{14,b1,\text{near pots}}}{L_{y,b1,\text{near pots}}}$$

$$R_3 \equiv \frac{\Theta_{y,b1,RP}}{y_{b1,RP}} \approx \frac{dL_{y,b1,RP}}{ds}$$

$$R_5 \equiv \frac{x_{b1,RP}}{\Theta_{x,b1,RP}} \approx \frac{L_{x,b1,RP}}{dL_{x,b1,RP}/ds}$$

$$R_3 \equiv \frac{\Theta_{y,b1,RP}}{y_{b1,RP}} \approx \frac{dL_{y,b1,RP}}{ds}$$

$$R_5 \equiv \frac{x_{b1,RP}}{\Theta_{x,b1,RP}} \approx \frac{L_{x,b1,RP}}{dL_{x,b1,RP}/ds}$$

$$\beta^* = 3.5 \text{ m optics estimation}$$
Reconstructed kinematics ($\beta^* = 90$ m optics)

Symmetries of the tagged particles’ reconstructed kinematics:

- High statistics
- Rotational symmetry
- Left-right arm symmetry

Left-right symmetry (in background estimation)
Central and peripheral phases

Different formulations of the interference phenomenon:

- Simplified West-Yennie (SWY)
  - Based on QFT
  - Simplifications: constant slope and constant hadronic phase
- Cahn or Kundrát-Lokajicek (KL) model
  - Eikonal framework
  - No explicit simplifications

The t-dependence of the two considered hadronic phase model families:

![Graph showing the t-dependence of the two considered hadronic phase model families.](image)
Physics corrections

- So-called 3 and 2/4 inefficiencies:
  - Several topology recovered by multitracking
  - Empty pot inefficiencies
  - Frequent showers (regulation)
  - Usual acceptance corrections (beam div., unfolding, geometrical accep. corr.)

- dN/dt histogram after physics corrections
- Fit for t=0 point measurement

Regulation of showery events with cluster cut

TOTEM preliminary