The TOTEM experiment at the LHC and its physics results

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on behalf of the
TOTEM collaboration

http://totem.web.cern.ch/Totem/

ZIMÁNYI WINTER SCHOOL'15
2015, Dec 7 – 11, Budapest, Hungary

* Also at Wigner RCP
The TOTEM physics spectrum

Total cross-section

Diffraction: soft (and hard with CMS)

Elastic scattering

Forward physics
Experimental layout before LS1

T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$
The inelastic telescope T1

Properties:

- Inside CMS 7.5 - 10.5 m from IP5
- One telescope on each side of IP5
- Two quarters per telescope

- Quarters: 5 equally spaced planes
- Planes: 3 trapezoidal CSC detectors, 60° in azimuth
- Cathode Strip Chamber: gaseous detector with 3 read-out coordinates (at 60° w.r.t. each other)
The T2 inelastic telescope

Properties:

• Installed inside CMS shielding between HF and Castor calorimeters
• Centered around 13.5 m from IP5
• One telescope on each side of IP5
• Two quarters per telescope

• Each quarter formed by 10 semi-circular planes, assembled in 5 back-to-back mounted pairs
• Each plane equipped with a Gas Electron Multiplier detector
• Gaseous detector, electron multiplication by 3 perforated foils (2 mm separation)
• Radial segmentation: strips (resolution ≈ 0.15 mm)
Roman Pot stations

1 RP station:
- 2 units at about 5 m distance
- Measurement of very small proton scattering angles (few μrad)
- Vertical and horizontal pots mounted as close as possible to the beam
- BPM fixed to the structure gives precise position relative to the beam
- Overlapping detectors: relative alignment (10 μm inside unit between 3 RPs)
Essential for TOTEM physics!

- The relevant magnet lattice:

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, beam harmonics, ...

Measured RP

\[ \frac{d^2 x}{ds^2} - k(s)x = 0, \quad x = \sqrt{\varepsilon \beta(s) \cos[\phi(s) + \phi_0]} \rightarrow x', \quad (\ )' \equiv \frac{d}{ds} \]

\begin{equation}
\begin{pmatrix}
  x \\
  \Theta_x \\
  y \\
  \Theta_y \\
  \Delta p/p 
\end{pmatrix}_{RP} = \begin{pmatrix}
  v_x & L_x & 0 & 0 & D_x \\
  v_x' & L_x' & 0 & 0 & D_x' \\
  0 & 0 & v_y & L_y & 0 \\
  0 & 0 & v_y' & L_y' & 0 \\
  0 & 0 & 0 & 0 & 1 
\end{pmatrix}
\begin{pmatrix}
  x^* \\
  \Theta_x^* \\
  y^* \\
  \Theta_y^* \\
  \Delta p/p 
\end{pmatrix}_{IP5}
\end{equation}

\[ \Theta_y^* = \frac{y}{L_y} \]

\[ \Theta_x^* = \left( \frac{dL_x}{ds} \right)^{-1} \left( \Theta_x - \frac{dv_x}{ds}x^* \right) \]

and reconstructed IP5 proton kinematics

<table>
<thead>
<tr>
<th>Perturbed element</th>
<th>$\delta L_{y,b1}/L_{y,b1}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQXA.1R5</td>
<td>0.98</td>
</tr>
<tr>
<td>MQXB.A2R5</td>
<td>-2.24</td>
</tr>
</tbody>
</table>

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Optics optimization

Optics estimation based on:

- MAD-X based Monte-Carlo
- **Measured** optical function ratios from Roman Pots

MAD-X → Matching → Measurement

Optimized

Spread due to LHC imperfections

Novel method from TOTEM:

- Uses **measured** proton data from RPs
- [http://iopscience.iop.org/1367-2630/16/10/103041/](http://iopscience.iop.org/1367-2630/16/10/103041/)
Elastic scattering at $\sqrt{s} = 7$ TeV

Elastic tagging:
- $\beta^* = 3.5$ m
- Topology, collinearity cuts

Collinearity $\Theta_x$
Spread in agreement with beam divergence (17-18 μrad)

Collinearity $\Theta_y$

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TOTEM first elastic $d\sigma/dt$ result at $\sqrt{s} = 7$ TeV

After acceptance corrections, unfolding, inefficiency corrections, luminosity:

- $|t|$ 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 - 2.0 GeV$^2$: power low behavior $|t|^{-n}$
Low-t measurement, cross-sections at $\sqrt{s} = 7$ TeV

**Properties:**

- $\beta^* = 90$ m

The exponential slope $B$ confirms that it increases with $\sqrt{s}$:

$$B = \left(20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}}\right) \text{ GeV}^{-2}$$

- Extrapolation to $t = 0$:

$$\frac{d\sigma}{dt}\bigg|_{t=0} = (503.7 \pm 1.5^{\text{stat}} \pm 26.7^{\text{syst}}) \text{ mb GeV}^{-2}$$

- Integral elastic cross-section:

$$\sigma_{el} = 8.3 \text{ mb}^{\text{extrapol.}} + 16.5 \text{ mb}^{\text{measured}} = 24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}} \text{ mb}$$

- Total cross-section (with optical theorem):

$$\sigma_{tot}^2 = \frac{16\pi(n^2)^2}{1 + \rho^2} \cdot \frac{d\sigma_{el}}{dt}\bigg|_{t=0} = 0.14^{+0.01}_{-0.08} \text{ mb}$$

$$\sigma_{tot} = \left(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}}\right) \text{ mb}$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left(73.5 \pm 0.6^{\text{stat}} \pm 1.8^{+1.3}_{-1.3}^{\text{syst}}\right) \text{ mb}$$

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

**References:**

- COMPETE
- EPL 96 (2011) 21002
\[ |t_{\text{min}}| = 5 \cdot 10^{-3} \text{ GeV}^2 \text{ reach at } 7 \text{ TeV} \]

- **Slope parameter:**
  \[ B = \left( 19.89 \pm 0.03_{\text{stat}} \pm 0.27_{\text{syst}} \right) \text{ GeV}^{-2} \]

- **Extrapolation:**
  \[ \left. \frac{d\sigma}{dt} \right|_{t=0} = (506.4 \pm 0.9_{\text{stat}} \pm 23_{\text{syst}}) \text{ mb GeV}^{-2} \]

- **Elastic cross section:**
  \[ \sigma_{el} = 25.43 \pm 0.03_{\text{stat}} \pm 1.07_{\text{syst}} \text{ mb} \]

- **91\% is measured**
- **EPL 101(2013) 21002**
- **Inelastic cross-section measurement**

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

At \( \sqrt{s} = 7 \) TeV:

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

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

   - Minimizes dependence on elastic efficiencies and **no dependence on \( \rho \)**
   \[\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}} \]
   \[\sigma_{\text{tot}} = 99.1 \pm 4.3 \text{ mb}\]

   - Eliminates dependence **on luminosity**
   \[
   \sigma_{\text{tot}} = \frac{16 \pi (\hbar c)^2}{1 + \rho^2} \left. \frac{dN_{\text{EL}}}{dt} \right|_{t=0} \frac{N_{\text{EL}} + N_{\text{INEL}}}{N_{\text{EL}} + N_{\text{INEL}}}
   \]
   \[\sigma_{\text{tot}} = 98.0 \pm 2.5 \text{ mb}\]
Luminosity independent cross-sections $\sqrt{s} = 8$ TeV

- $\beta^* = 90$ m
- Elastic, inelastic, total cross-sections

<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>101.7 $\pm$ 2.9</td>
<td>27.1 $\pm$ 1.4</td>
<td>74.7 $\pm$ 1.7</td>
</tr>
</tbody>
</table>
Evidence for non-exponential elastic $d\sigma/dt$ $\sqrt{s} = 8$ TeV

- High statistics data set ($\beta^* = 90$ m, 2012)
- 7 M elastic events
- $0.027 \text{ GeV}^2 < |t| < 0.2 \text{ GeV}^2$ dominated by hadronic interaction

Evidence for non-exponential elastic proton–proton differential cross-section at low $|t|$ and $\sqrt{s} = 8$ TeV by TOTEM

TOTEM Collaboration

Evidence for non-exponential elastic $d\sigma/dt$

$$B \to \sum_{i=1}^{N_b} b_i t^i$$

$N_b = 2$: $\sigma_{tot} = 101.5 \pm 2.1$ mb

$N_b = 3$: $\sigma_{tot} = 101.9 \pm 2.1$ mb

Relative deviation of $d\sigma/dt$ from exponential

Pure exponential form excluded at 7.2 $\sigma$ significance.
Coulomb-hadronic interference at $\sqrt{s} = 8$ TeV

Analysis aims:
- Measure $d\sigma_{el}/dt$ at the smallest possible proton $|t|$ (where the Coulomb interaction can be probed)
- $\beta^* = 1000$ m, RP at 3 $\sigma_{beam}$
- $\Rightarrow |t|_{\text{min}} = 6 \times 10^{-4}$ GeV$^2$
- $\Rightarrow$ Coulomb-hadronic interference

\[ F^{C+H} = F^C + F^H e^{i\rho} \]

- Determination of $\rho$:
\[ \rho = \frac{\text{Re} A^H}{\text{Im} A^H} \Bigg|_{t=0} \]

- Further improve the total cross-section $\sigma_{\text{tot}}$ measurement
“central phase”: profile function in impact parameter picture: Elastic scattering preferentially central (Bailly et al.)

\[ \text{arg} F(t) = \frac{\pi}{2} - \text{atan} \left( \frac{\cot p_0}{t} \right) \]

“peripheral phase”: profile function in impact parameter picture: Elastic scattering preferentially peripheral

\[ \text{arg} F(t) = p_0 + \zeta \left| \frac{t}{t_0} \right|^\kappa \text{exp}(\nu t), \quad t_0 = 1 \text{GeV}^2 \]

Constant phase:
also central behavior

\[ \text{arg} F(t) = p_0 \]

Result for

\[ \rho = \frac{\Re F_H(0)}{\Im F_H(0)} = \cot \text{ arg } F_H(0) = \cot p_0 \]

is model dependent
Coulomb-hadronic interference: results

Model descriptions:

- **Polynomial** exponential hadronic slope
- Both **central** and **peripheral** hadronic phase compatible with data
- Central (peripheral) had. phase + purely exponential hadronic slope excluded (disfavoured)
- In agreement with TOTEM non-exponential $d\sigma/dt$
# Measurement of $\rho$ at the LHC

## Results:

<table>
<thead>
<tr>
<th></th>
<th>KL, constant</th>
<th>KL, peripheral</th>
</tr>
</thead>
<tbody>
<tr>
<td>step 1: $\chi^2$/ndf</td>
<td>25.7/25 = 1.03</td>
<td>25.0/25 = 1.00</td>
</tr>
<tr>
<td>step 2: $\chi^2$/ndf</td>
<td>57.5/56 = 1.03</td>
<td>57.6/56 = 1.03</td>
</tr>
<tr>
<td>$a$ [mb/GeV$^2$]</td>
<td>549 $\pm$ 24</td>
<td>549 $\pm$ 24</td>
</tr>
<tr>
<td>$b_1$ [GeV$^{-2}$]</td>
<td>20.47 $\pm$ 0.14</td>
<td>19.56 $\pm$ 0.13</td>
</tr>
<tr>
<td>$b_2$ [GeV$^{-4}$]</td>
<td>8.8 $\pm$ 1.6</td>
<td>$-3.3 \pm 1.5$</td>
</tr>
<tr>
<td>$b_3$ [GeV$^{-6}$]</td>
<td>20 $\pm$ 6</td>
<td>$-13 \pm 5$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.12 $\pm$ 0.03</td>
<td>0.12 $\pm$ 0.03</td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}$ [mb]</td>
<td>102.9 $\pm$ 2.3</td>
<td>103.0 $\pm$ 2.3</td>
</tr>
</tbody>
</table>

![Graph showing measurement of $\rho$ at the LHC](image-url)
Coulomb-hadronic interference

<table>
<thead>
<tr>
<th>Hadronic Slope</th>
<th>Constant Phase</th>
<th>Peripheral Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(representative for all central phases)</td>
<td></td>
</tr>
<tr>
<td>$N_B = 1$</td>
<td>Excluded</td>
<td>Disfavoured</td>
</tr>
<tr>
<td>(pure exponential)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_B = 3$</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>(parabolic exp. slope)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $\sqrt{|P|^2}_d = 0.88$ fm
- $\sqrt{|P|^2}_\text{had} = 1.38$ fm
- $\sqrt{|P|^2}_\text{tot} = 1.26$ fm

- $\sqrt{|P|^2}_d = 1.99$ fm
- $\sqrt{|P|^2}_\text{had} = 0.79$ fm
- $\sqrt{|P|^2}_\text{tot} = 1.23$ fm

Impact parameter picture: profile functions
2015: special $\beta^* = 90$ m run at 13 TeV

Integrated Luminosity

- LHC delivered: $0.74$ pb$^{-1}$
- CMS recorded: $\sim 0.68$ pb$^{-1}$
- TOTEM Trigger & CMS data: $0.55$ pb$^{-1}$
- CMS + TOTEM data: $\sim 0.4$ pb$^{-1}$

Details: TOTEM Status report 2015
2015 special run @13TeV : detector setup

After LS1:
Roman Pot stations in the LHC tunnel

Inserted RPs at $\beta^*=90\text{m}$
2015 special run @13TeV : trigger settings

- **TOTEM Triggers → CMS**
  - Roman Pots Double Arm & T2 Veto
  - Roman Pots Double Arm (TopTop/BottomBottom)
  - T2 Min Bias
  - Zero Bias

- **CMS Triggers → TOTEM**
  - Dijets ($p_T$ threshold 20, 32 GeV)
  - Dimuon
  - Single mu & HF Veto

- **CMS + TOTEM**
  - Independent DAQ
  - Level 1 Trigger exchange
  - TOTEM offline merging
  - LV1 Rate ~ **50 kHz** ! → recorded
    (x 50 wrt. Run-I, thanks to zero suppression)
  - ~ $3 \cdot 10^9$ events collected!
  - CMS HLT Rate ~ 10 kHz → recorded
elastic scattering $\sqrt{s} = 13$ TeV
all 10 $\sigma$ fills from October 2015
$\mathcal{O}(100 \%)$ statistics
reconstruction from 220N and 220F diagonals combined
conservative acceptance correction
no other corrections
Summary

**Total cross-section**

- Measured at 7 and 8 TeV
- Luminosity independent

**Elastic Scattering**

- Measured at 7 and 8 TeV Non-exponential CNI

**Diffraction: soft (and hard with CMS)**

- Preliminary results
- DD, CD, SD
- Many analysis in progress!

**Forward physics**

- Forward multiplicity distribution 7 and 8 TeV
Thank you for your attention!
Backup slides
Forward and diffractive physics
(Based on LHC Run I data)
Inelastic and Diffractive Processes

All the drawings show soft interactions. In case of hard interactions there should be jets, which fall in the same rapidity intervals.

Measure $\sigma(M, \xi, t)$

- Non-diffractive inelastic (ND) ~60 mb
- Elastic Scattering ~25 mb
- Single Diffraction ~10 mb
- Double Diffraction ~5 mb
- Double Pomeron Exchange ~1 mb
- Multi Pomeron Exchange << 1 mb
Very forward measurement with T2:

- Published EPL, 98 (2012) 31002
- Visible cross section measured on data: $\sim 94\% \sigma_{inel}$
- Diffractive mass $M_{diff} > 3.4$ GeV

Main contributions to the systematical error:
- Subtraction of secondary particles.
- Track efficiency
- Misalignment uncertainties

Combined with other LHC exp.
Diffractive physics
Soft Single Diffractive cross-section 7 TeV

Low mass diffraction \((2 \cdot 10^{-7} < \xi < 10^{-6})\)

- Tracks in the T2 hemisphere opposite to the proton

\[ \xi = \Delta p/p \]

\[ \Delta \eta = -\ln \xi \]

Very high mass \((\xi > 2.5 \%)\)

- SD events are triggered with T2, only 1 proton required in RP
- \(M\) obtained from the rapidity gap estimation based on charged track \(\eta\) in T1 and T2

\[ \Delta \eta = -\ln(M^2/s) \]

This allows a better \(\xi\) resolution \((\sigma(\xi)/\xi \sim 1)\) for low medium mass

<table>
<thead>
<tr>
<th>SD class</th>
<th>Inelastic telescopes configuration</th>
<th>Mass</th>
<th>(\xi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Mass</td>
<td>(p + T2) opposite only (no T1)</td>
<td>3.4 - 7 GeV</td>
<td>(2 \cdot 10^{-7} &lt; \xi &lt; 10^{-6})</td>
</tr>
<tr>
<td>Medium Mass</td>
<td>(p + T2) opposite + T1 opposite</td>
<td>7 - 350 GeV</td>
<td>(10^{-6} &lt; \xi &lt; 0.25%)</td>
</tr>
<tr>
<td>High Mass</td>
<td>(p + T2) opposite + T1 same</td>
<td>0.35 - 1.1 TeV</td>
<td>(0.25% &lt; \xi &lt; 2.5%)</td>
</tr>
<tr>
<td>Very High Mass</td>
<td>(p +) both T2 arms</td>
<td>&gt; 1.1 TeV</td>
<td>&gt; 2.5%</td>
</tr>
</tbody>
</table>
Soft Single Diffractive cross-section 7 TeV

\[ \frac{d\sigma}{dt} \propto C \cdot e^{-B \cdot t} \]

Corrections included:
- Trigger efficiency
- Reconstruction efficiency
- Proton acceptance
- Background subtraction
- Extrapolation to \( t = 0 \)

Missing corrections:
- \( \xi \) – resolution
- Beam divergence effects

Estimated uncertainty:
- \( B \sim 15 \% \), \( \sigma \sim 20 \% \)

Very preliminary result:
- \( \sigma_{SD} = 6.5 \pm 1.3 \) mb
- \( 3.4 < M_{SD} < 1100 \) GeV
- Very-high masses: ongoing

\( B = 10.1 \) GeV\(^2\)
\( B = 8.5 \) GeV\(^2\)
\( B = 6.8 \) GeV\(^2\)
ty-acceptance corrections

Correction error (ty):
0.31 GeV² : 30%
0.33 GeV² : 11%
0.35 GeV² : 2%
0.4 GeV² : 0.8%
0.5 GeV² : 0.1%

Missing acceptance in θy due to beam divergence
φ-acceptance corrections

Critical at low t-acceptance limit

Total φ-acceptance correction

<table>
<thead>
<tr>
<th>No.</th>
<th>t [GeV²]</th>
<th>Θ* [rad]</th>
<th>Accepted φ (2 diag.) [°]</th>
<th>φ accept. correct. factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.33</td>
<td>1.65E-04</td>
<td>38.6</td>
<td>9.3±4.7%</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>1.71E-04</td>
<td>76.4</td>
<td>4.7±1.8%</td>
</tr>
<tr>
<td>3</td>
<td>0.60</td>
<td>2.21E-04</td>
<td>162.5</td>
<td>2.2±0.3%</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>2.86E-04</td>
<td>209.8</td>
<td>1.7±0.1%</td>
</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>3.83E-04</td>
<td>246.3</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>3.00</td>
<td>4.95E-04</td>
<td>269.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

| | t | [GeV²] | φ acceptance correction factor |
| |   |        |                               |
| | <0.36 | excluded | from analysis |

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