TOTEM results on total, elastic, inelastic and diffractive scattering

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Overview

- TOTEM detector setup @ IP5 of LHC
- Elastic p-p scattering
- Inelastic and total p-p cross-sections
- Measurement in Coulomb (interference) region
- Diffractive cross-sections
- Summary
Roman Pots: elastic & diffractive protons close to outgoing beams → Proton Trigger

Inelastic Telescopes: charged particles in inelastic events:
T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV
T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV → Inelastic Trigger
Experimental Setup at IP5

Inelastic telescopes: rapidity gaps

Roman Pots: diffractive protons (di-proton trigger)

Si-det stack

Horizontal Pot  Vertical Pots  BPM

CASTOR (CMS)
Elastic and diffractive scattering: Pomeron exchange
Elastic pp Scattering: selection & data sets

Selected based on topology, low $|\xi|$, collinearity, & vertex

Data sets at different conditions to measure elastic scattering over wide $t$-range including very low $|t|

<table>
<thead>
<tr>
<th>E (TeV)</th>
<th>$\beta^*$ (m)</th>
<th>RP approach</th>
<th>$\mathcal{L}_{int}$ (μb⁻¹)</th>
<th>$t$ range (GeV²)</th>
<th>Elastic events</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>90</td>
<td>4.8-6.5$\sigma$</td>
<td>83</td>
<td>7·10⁻³ - 0.5</td>
<td>1M</td>
</tr>
<tr>
<td>90</td>
<td>10$\sigma$</td>
<td>1.7</td>
<td></td>
<td>0.02 - 0.4</td>
<td>14k</td>
</tr>
<tr>
<td>3.5</td>
<td>7$\sigma$</td>
<td>0.07</td>
<td></td>
<td>0.36 - 3</td>
<td>66k</td>
</tr>
<tr>
<td>3.5</td>
<td>18$\sigma$</td>
<td>2.3</td>
<td></td>
<td>2 - 3.5</td>
<td>10k</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>6-9$\sigma$</td>
<td>60</td>
<td>0.01 - 1</td>
<td>8M</td>
</tr>
<tr>
<td>1000</td>
<td>3$\sigma$</td>
<td>20</td>
<td></td>
<td>6·10⁻⁴ - 0.2</td>
<td>0.4M</td>
</tr>
<tr>
<td>2.76</td>
<td>11</td>
<td>5-13$\sigma$</td>
<td></td>
<td>0.05-0.6</td>
<td>45k</td>
</tr>
</tbody>
</table>

Key issues: RP alignment & optics

Show results from data sets indicated by arrows
TOTEM results:  
7 TeV \( \sigma_{el} = 25.4 \pm 1.0^{\text{lumi}} \pm 0.3^{\text{syst}} \pm 0.03^{\text{stat}} \text{ mb} \) (91% directly measured)  
7 TeV \( \sigma_{el} = 24.8 \pm 1.0^{\text{lumi}} \pm 0.7^{\text{syst}} \pm 0.2^{\text{stat}} \text{ mb} \) (67% directly measured)  
8 TeV \( \sigma_{el} = 27.1 \pm 1.2^{\text{syst+stat}} \text{ mb} \)  
ATLAS result:  
7 TeV \( \sigma_{el} = 24.00 \pm 0.57^{\text{syst}} \pm 0.19^{\text{stat}} \text{ mb} \) (90% directly measured)
Count events with charged particles in T1 & T2 (~95% of inelastic).

Trigger: at least one track in T2.

**Impact of Low-Mass diffraction:**

- Extrapolation to low $M_X$ region: main source of systematic uncertainty on $\sigma_{inel}$
- Minimal $M_X$ depends on maximal $|\eta|$ coverage: lower $M_X$ reachable $\rightarrow$ minimal model dependence on corrections for low mass diffraction
- TOTEM ($T1 + T2$: $3.1 < |\eta| < 6.5$) gives an unique forward charged particle coverage @ LHC $\rightarrow$ direct measurement of $\sigma_{inel}$ with lower sys. unc.
- Low mass diffraction @ $M_{diff} < 3.4$-$3.6$ GeV (tuned QGSJETII-03 to observed 1hemi fraction)

### $\sigma_{inelastic}$ Measurement

<table>
<thead>
<tr>
<th>@ 7 TeV</th>
<th>@ 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct</strong></td>
<td>$73.7 \pm 3.4$ mb</td>
</tr>
<tr>
<td><strong>Indirect</strong></td>
<td>$73.15 \pm 1.26$ mb</td>
</tr>
<tr>
<td>$\mathcal{L}$ independent</td>
<td>$72.9 \pm 1.5$ mb</td>
</tr>
</tbody>
</table>

**References:**

- EPL 101 (2013) 21003
- EPL 101 (2013) 21002
- EPL 101 (2013) 21004
- PRL 111 (2013) 012001
Constraint on low mass diffraction cross-section from TOTEM data:

Use total cross-section determined from elastic observables (via the Optical Theorem)
→ no assumption on low mass diffraction

\[ \sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}} = 73.2 \pm 1.3 \text{ mb} \]

and the measured “visible” inelastic cross-section for \(|\eta| < 6.5\) (T1, T2)

\[ \sigma_{\text{inel}, |\eta| < 6.5} = 70.5 \pm 2.9 \text{ mb} \]

to obtain the low-mass diffractive cross-section

\(|\eta| > 6.5 \text{ or } M_X < 3.4 \text{ GeV/c}^2\)

\[ \sigma_{\text{inel}, |\eta| > 6.5} = \sigma_{\text{inel}} - \sigma_{\text{inel}, |\eta| < 6.5} = 2.6 \pm 2.2 \text{ mb} \]

(or \(< 6.3 \text{ mb @ 95\% CL}\) [MC: 3.1 \pm 1.5 \text{ mb}]
Total Cross Section Measurements @ 7 TeV

1) Elastic Scatt. + Inelastic Scatt. + \( \mathcal{L} \)
(no dependence on \( \rho \))
\[ \sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}} \]

2) Elastic Scatt. + \( \mathcal{L} \) + Optical Th.
(no assumption on low mass diffr.)
\[ \sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}} \]

(no dependence on \( \mathcal{L} \))
\[ \sigma_{\text{el}} \text{ and } \sigma_{\text{inel}} \text{ : from } \sigma_{\text{tot}} \text{ and } N_{\text{el}} / N_{\text{inel}} \]

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

\[ \sigma_{\text{tot}}^2 = \frac{16\pi}{(1 + \rho^2)} \frac{1}{\mathcal{L}} \left( \frac{dN_{\text{el}}}{dt} \right)_{t=0} \]

\[ \sigma_{\text{tot}} = \frac{16\pi}{(1 + \rho^2)} \left( \frac{dN_{\text{el}}}{dt} \right)_{t=0} \cdot \left( N_{\text{el}} + N_{\text{inel}} \right) \]

<table>
<thead>
<tr>
<th>Method</th>
<th>( \sigma_{\text{tot}} ) (mb)</th>
<th>( \sigma_{\text{inel}} ) (mb)</th>
<th>( \sigma_{\text{el}} ) (mb)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.1 ± 4.3</td>
<td>73.7 ± 3.4</td>
<td>25.4 ± 1.1</td>
<td>EPL 101 (2013), 21002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EPL 101 (2013), 21003</td>
</tr>
<tr>
<td>2</td>
<td>98.3 ± 2.8</td>
<td>73.5 ± 1.6</td>
<td>24.8 ± 1.2</td>
<td>EPL 96 (2011), 21002</td>
</tr>
<tr>
<td>2</td>
<td>98.6 ± 2.2</td>
<td>73.2 ± 1.3</td>
<td>25.4 ± 1.1</td>
<td>EPL 101(2013), 21002</td>
</tr>
<tr>
<td>3</td>
<td>98.0 ± 2.5</td>
<td>72.9 ± 1.5</td>
<td>25.1 ± 1.1</td>
<td>EPL 101 (2013), 21004</td>
</tr>
<tr>
<td>2</td>
<td>95.35 ± 1.36</td>
<td>71.3 ± 0.9</td>
<td>24.0 ± 0.6</td>
<td>ATLAS / Nucl. Phys. B 889 (2014)</td>
</tr>
</tbody>
</table>

\( \rho = 0.140 ± 0.007 \)
(from Compete)

Proper tracking acceptance in very forward region required: elastically scattered p detection mandatory
TOTEM $\sigma_{\text{tot}}$ Measurement @ 8 TeV & Summary

Analysis in progress at $\sqrt{s} = 2.76$ TeV

$\sigma_{\text{tot}}$ from $\mathcal{L}$–independent Method

<table>
<thead>
<tr>
<th>quantity</th>
<th>value</th>
<th>systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>el. t-dep</td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}$ [mb]</td>
<td>101.7</td>
<td>±1.8</td>
</tr>
<tr>
<td>$\sigma_{\text{inel}}$ [mb]</td>
<td>74.1</td>
<td>±1.2</td>
</tr>
<tr>
<td>$\sigma_{\text{el}}$ [mb]</td>
<td>27.1</td>
<td>±0.5</td>
</tr>
</tbody>
</table>

TOTEM @ 8 TeV
PRL 111 (2013) 012001
High statistic data sample allows a precise $d\sigma_{el}/dt$ measurement (for $0.027 < |t| < 0.2$ GeV$^2$)

“Purely” exponential slope excluded with a significance $> 7 \sigma$

$\leftarrow d\sigma_{el}/dt = Ae^{-B(t)|t|}$

Plotting relative deviation from exponential and fitting

$\frac{d\sigma}{dt} = A e^{-B(t)|t|}$,

with $B(t) = b_1$ (N$_b$ = 1)

or $B(t) = b_1 + b_2 t$ (N$_b$ = 2)

or $B(t) = b_1 + b_2 t + b_3 t^2$ (N$_b$ = 3)

**Quadratic and cubic polynomials in the exponent well describe data**

**Using the new parametrisations for extrapolation to $t = 0$ and applying the optical theorem, new results for $\sigma_{tot}$ are found in agreement with previous measurement:**

$N_b = 2$ (quadratic polynomial)  $\rightarrow$  $\sigma_{tot} = 101.5 \pm 2.1$ mb

$N_b = 3$ (cubic polynomial)  $\rightarrow$  $\sigma_{tot} = 101.9 \pm 2.1$ mb
Measurement of $\rho$ by studying the CNI down to $|t| \sim 6 \cdot 10^{-4} \text{GeV}^2$

Reached @ $\sqrt{s} = 8 \text{ TeV}$, with $\beta^* = 1000 \text{ m}$ and RP approaching the beam centre @ $\sim 3\sigma$
\[ d\sigma/dt \propto |F^{C+H}|^2 = \text{Coulomb} + \text{“interference”} + \text{hadronic} \]

\[ \psi \text{ (phase of } F^H) \text{ accessible via interference with } F^C \text{ (known)}! \]

- **Interference formulae:**
  - **Simplified West-Yennie (SWY) [1]:** past “standard”, only compatible with pure exponential hadronic amplitude with constant phase
  - **Kundrát-Lokajícek (KL) [2]:** no limitations on hadronic amplitude
  - **phase of } F^H: central or peripheral } \leftrightarrow b = \text{impact parameter of elastic pp collisions}

\[ \rho \equiv \text{Re } F^H/ \text{Im } F^H|_{t=0} = 1/ \tan(\psi|_{t=0}) \]

Best fit method retained: 2-stage fit:
- Fit 1: only } b^* = 1\text{km data (very low } |t|): all parameters free → determines } \rho
- Fit 2: combined } b^* = 1\text{km and 90m data with fixed } \rho

Results coming soon

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High mass
\( M_{\text{diff}} = 0.35 - 1.1 \) TeV

Medium mass
\( M_{\text{diff}} = 8 - 350 \) GeV

Low mass
\( M_{\text{diff}} = 3.4 - 8 \) GeV

\( \frac{d\sigma}{dt} \sim A \cdot e^{-Bt} \)

\( \sigma_{SD, \text{low}} \sim 1.8 \) mb

\( B = 10.1 \) GeV\(^{-2}\)

\( \sigma_{SD, \text{medium}} \sim 3.3 \) mb

\( B = 8.5 \) GeV\(^{-2}\)

\( \sigma_{SD, \text{high}} \sim 1.4 \) mb

\( B = 6.8 \) GeV\(^{-2}\)

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

Missing corrections:
- Class migration
- \( \zeta \) 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 < \( M_{\text{diff}} \) < \( 1.1 \) TeV

Analysis of very high mass SD events ongoing
Both protons break up
\[ \Rightarrow 2 \text{ diffractive masses } M_{\text{diff1}}, M_{\text{diff2}} \]

Central rapidity gap
\[ |\eta|_{\text{min,1}} - |\eta|_{\text{min,2}} \]

For large masses (→ small central gap) not easy to separate from ND events

Select: sub-range with particles in both T2 hemispheres, veto on both T1 ("0T1+2T2")

\[
4.7 < |\eta|_{\text{min,1/2}} < 6.5 \quad \text{or} \quad 3.4 \text{ GeV} < M_{\text{diff1/2}} < 8 \text{ GeV}
\]

Event selection with high DD purity (≈ 70%)

SD & DD results combined seems to indicate factorisation breaking since

\[
\sigma_{\text{DD}} (4.7 \leq |\eta_{\text{min}}| \leq 6.5) \gg \\
\sigma_{\text{SD}} (-4.7 \geq \eta_{\text{min}} \geq -6.5) \times \sigma_{\text{SD}} (4.7 \leq \eta_{\text{min}} \leq 6.5) / \sigma_{\text{elastic}}
\]

\[
\sigma_{DD(4.7<|\eta_{\text{min}}|<6.5)} = 116\pm25 \text{ \(\mu b\)}
\]

<table>
<thead>
<tr>
<th>(4.7&lt;\eta_{\text{min}}&lt;5.9)</th>
<th>(-5.9&gt;\eta_{\text{min}}&gt;-6.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>66±19 (\mu b)</td>
<td>27±4 (\mu b)</td>
</tr>
</tbody>
</table>

\[ \sigma_{SD} (-4.7 \geq \eta_{\text{min}} \geq -6.5) \times \sigma_{SD} (4.7 \leq \eta_{\text{min}} \leq 6.5) / \sigma_{\text{elastic}} \]
Extensive programme of $\sigma_{\text{tot}}$, $\sigma_{\text{el}}$, $\sigma_{\text{inel}}$ and diffractive scattering measurements @ LHC in Run I

@ $\sqrt{s} = 7$ TeV collision data taken in special runs with different beam conditions ($\beta^* = 3.5$ m, 90 m) allowed measurements of:

- elastic scattering in a wide $|t|$ range ($5 \cdot 10^{-3} < |t| < 3.5$ GeV$^2$)
- elastic, inelastic and total p-p cross-section
  (very good agreement among results from different experiments)
- soft single and double diffraction

@ $\sqrt{s} = 8$ TeV collision data taken in special runs with different beam conditions ($\beta^* = 90$ m, 1000 m) and high statistics gave measurements of:

- elastic scattering down to very low $|t|$ ($6 \cdot 10^{-4} < |t| < 0.2$ GeV$^2$)
  → evidence for non-exponential slope
  → study of Coulomb-Nuclear interference feasible, more to come soon …
- elastic, inelastic and total p-p cross-section ($\mathcal{L}$-independent only)

Looking forward for new data during LHC Run II, so to perform new measurements at higher $\sqrt{s}$ ....