Recent cross section, diffractive and forward multiplicity measurements with TOTEM

K. Österberg,
Department of Physics,
University of Helsinki & Helsinki
Institute of Physics
on behalf of
TOTEM collaboration

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- Introduction
- Elastic, inelastic & total pp cross-section
- Forward multiplicity in pp (w/o CMS)
- Soft (& hard) diffraction in pp (w/o CMS)
TOTEM physics menu

**Total pp cross-section**

- **Elastic pp scattering**
  - Ultimately ~1-2% precision

**Forward particle production**

- **Cosmic ray connection**

**Diffraction: soft and hard**

- **Proton**
  - Over a wide $|t|$ range

**Elastic pp scattering**

- Understand QCD nature

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**TOTEM physics menu**

- **Total pp cross-section**
- **Forward particle production**
- **Diffraction: soft and hard**
- **Elastic pp scattering**
Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$ (inelastic trigger)

$P_T$ threshold: 40 MeV (T2) & 100 MeV (T1)

Roman Pots: elastic & diffractive protons (di-proton trigger)
Experimental setup @ IP5

Inelastic telescopes: rapidity gaps

Roman Pots: diffractive protons (di-proton trigger)
Soft pp processes

- Elastic Scattering
- Single Diffraction (SD)
- Double Diffraction (DD)
- Central Diffraction (CD)
- Non-diffractive minimum bias (MB)

Diffraction: a large fraction of total pp cross-section!!

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

- $\sigma @ LHC$
  - $\sim 25 \text{ mb}$
  - $\sim 10 \text{ mb}$
  - $\sim 5 \text{ mb}$
  - $\sim 1 \text{ mb}$
  - $\sim 60 \text{ mb}$
Elastic pp scattering: selection & data sets

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

Key issues:
RP alignment & optics

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

<table>
<thead>
<tr>
<th>$E$ (TeV)</th>
<th>$\beta^*$ (m)</th>
<th>RP approach</th>
<th>$L_{int}$ ($\mu$b$^{-1}$)</th>
<th>$t$ range (GeV$^2$)</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>0.6M</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>
Elastic pp scattering: cross-section @ 7 TeV

Extrapolation to $t = 0$: $\frac{d\sigma}{dt} = A e^{-Bt}$

A (mb/GeV$^2$) = $506 \pm 23^{\text{syst}} \pm 0.9^{\text{stat}}$
503 $\pm 27^{\text{syst}} \pm 1.5^{\text{stat}}$

B (GeV$^{-2}$) = $19.89 \pm 0.27^{\text{syst}} \pm 0.03^{\text{stat}}$
(fit range: $5\cdot10^{-3} < |t| < 0.2$ GeV$^2$)
20.1 $\pm 0.3^{\text{syst}} \pm 0.2^{\text{stat}}$
(fit range: $2\cdot10^{-2} < |t| < 0.33$ GeV$^2$)

Elastic cross section $\sigma_{\text{elastic}}$
25.43 $\pm 1.07^{\text{syst}} \pm 0.03^{\text{stat}}$ mb (91% measured)
24.8 $\pm 1.2^{\text{syst}} \pm 0.2^{\text{stat}}$ mb (67% measured)
Elastic pp scattering: implications

\[ \frac{d\sigma}{dt} \sim e^{-B|t|} \]

Increase of B slope with collision energy

\[ B_{7\text{TeV}} = (19.89 \pm 0.27) \text{ GeV}^{-2} \]
\[ B_{8\text{TeV}} = (19.90 \pm 0.30) \text{ GeV}^{-2} \]
Elastic pp scattering: $\sigma$ & very low-$|t|$ @ 8 TeV

$\beta^* = 90$ m:

$\sigma_{\text{elastic}} = 27.1 \pm 1.4$ mb

Luminosity-independent

*PRL 111 (2013) 012001*

$\sqrt{s} = 8$ TeV,

$\beta^* = 1$ km, $3\sigma$

$|t|_{\text{min}} = 6 \times 10^{-4}$ GeV$^2$

Coulomb hadronic

$\beta^* = 1$ km:

Access to Coulomb-hadronic interference term $\Rightarrow \rho \left(= \Re \frac{F_h}{\bar{F}_h} F_h^0\right)$

& $\sigma_{\text{total}}$ measurements
Elastic pp: Coulomb-hadronic interference

\[ \frac{d\sigma}{dt} \propto |F^{C+h}|^2 = \text{Coulomb} + \text{“interference”} + \text{hadronic} \]

from theory

Modulus constrained by measurement \( e^{-B(t)} \)

\( B(t) \) described by \( n > 1 \) parameters

Key elements considered:

- number of parameters to describe \( B(t) \)
- \( \psi \) phase of hadronic amplitude (t dependence not constrained by measurements): central or peripheral

\[ \rho = \frac{1}{\tan(\psi|_0)} \]

Example: \( \chi^2 \) fit with Kundrát-Lokajícek formula

\[ B(t) \sim b_0 + b_1 t + b_2 t^2 \]

Central hadronic phase

All errors included

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Elastic pp scattering: $\rho$ measurement

$$q = \left. \frac{\Re F^H}{\Im F^H} \right|_0$$

Method: $\chi^2$ fit
KL formula

$B(t)$ parameters:
- 2: central
- 3: central, periph.
- 2: periph.
- 3: periph.

Phase:
- central
- central, periph.
- periph.

$$\rho = 0.107 \pm 0.027^{\text{(stat)}} \pm 0.010^{\text{(syst)}} +0.009 -0.009^{\text{(model)}}$$

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{(1 + \rho^2)} \frac{1}{\mathcal{L}} \left( \frac{dN_{e\text{l}}}{dt} \right)_{t=0}^{\text{had}}$$

$\sigma_{\text{total}} = 101.7 \pm 2.9 \text{ mb}$

luminosity independent

*PRL111(2013)012001*
Inelastic pp cross-section

- Count events with charged particles in T1 & T2 (~ 95 % of inelastic).
- Trigger: at least one track in T2.

- Corrections:
  - beam-gas background (non-colliding bunches)
  - trigger efficiency, pile-up, T1 only events (zero-bias)
  - central diffraction unseen (PHOJET & MBR)
  - Low mass diffraction $M_{\text{diff}} < 3.4$-$3.6$ GeV (tuned QGSJETII-03 to observed $1hemi$ fraction)

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam gas</td>
<td>0.45 %</td>
<td>0.45 %</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>1.2 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>Pile up</td>
<td>2.8 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>T2 reconstruction</td>
<td>0.35 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>“T1 only”</td>
<td>0.8 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Internal Gap covering T2</td>
<td>0.4 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Central diffraction</td>
<td>-</td>
<td>0.35 %</td>
</tr>
<tr>
<td>Low mass diffraction (seen)</td>
<td>0.4 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Low mass diffraction</td>
<td>4.8 %</td>
<td>2.4 %</td>
</tr>
</tbody>
</table>

**σ_{inel} (mb)**

- **Direct**
  - $73.7 \pm 3.4$
  - *EPL 101 (2013) 21003*

- **Indirect**
  - $73.15 \pm 1.26$
  - *EPL 101 (2013) 21002*

- **$L$ independent**
  - $72.9 \pm 1.5$
  - *EPL 101 (2013) 21004*
  - $74.7 \pm 1.7$
  - *PRL 111 (2013) 012001*
Total pp cross-section: methods & results

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

based on elastic scattering \(\Rightarrow\) low mass diffraction independent

\[ \sigma_{tot} = \sigma_{el} + \sigma_{inel} \]

optical theorem & \(\rho\) independent

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

\(L\) independent

\[ \sigma_{total} = 98.3 \text{ mb} \pm 2.0 \text{ mb} \]

*EPL 96 (2011) 21002*

\[ \sigma_{total} = 98.6 \text{ mb} \pm 2.3 \text{ mb} \]

*EPL 101 (2013) 21002*

\[ \sigma_{total} = 99.1 \text{ mb} \pm 4.3 \text{ mb} \]

*EPL 101 (2013) 21004*

\[ \sigma_{total} = 98.1 \text{ mb} \pm 2.4 \text{ mb} \]

*EPL 101 (2013) 21004*

\[ \sigma_{total} = 101.7 \text{ mb} \pm 2.9 \text{ mb} \]

*PRL 111(2013) 012001*
pp cross-section: summary

7 TeV

7 & 8 TeV
pp cross-section: implications

Luminosity & $\rho$ independent ratios:

\[
\begin{align*}
\frac{\sigma_{\text{elastic}}}{\sigma_{\text{total}}} &= 0.257 \pm 0.005 ; 0.266 \pm 0.006 \\
\frac{\sigma_{\text{elastic}}}{\sigma_{\text{inelastic}}} &= 0.354 \pm 0.009 ; 0.362 \pm 0.011
\end{align*}
\]

SD acceptance for T1+T2

Low mass diffraction (7 TeV):

\[
\begin{align*}
\sigma_{\text{inelastic, } |\eta| > 6.5} &= \\
\sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{inelastic, } |\eta| < 6.5} &= 2.62 \pm 2.17 \text{ mb}
\end{align*}
\]

\[
\sigma_{\text{inelastic, } |\eta| > 6.5} \leq 6.3 \text{ mb @ 95% CL}
\]
Very forward $dN_{\text{ch}}/d\eta$ @ 7 TeV

Measured with T2 on T2 triggered events (EPL 98 (2012) 31002)
Visible inelastic cross-section ~ 93 %, diffractive events with $M_{\text{diff}} > 3.4$ GeV

At least 1 primary charged particle with $p_T > 40$ MeV in T2

Main contributions to systematic error ~10%:
- Subtraction of large secondary contribution
- Track efficiency & misalignment uncertainties ($\theta < 10$ mrad!)
Very forward $dN_{ch}/d\eta$ @ 8 TeV (with CMS!)

TOTEM analysis similar to 7 TeV one (EPL 98 (2012) 31002):

- Improved simulation of T2 response, secondary particles production, event selection strategy & alignment procedures.
- Uses of vertex information from CMS to reduce pile-up correction
- Better MC tuning to LHC measurements (important for estimation of secondaries)

- CMS & TOTEM analysis on same events trigger by T2 (~ 93 % of inelastic)
- Same CMS-TOTEM event selection (at least a “pointing” track in T2)
- For inelastic events with at least 1 primary charged particle with $p_T > 40$ MeV/c in $5.3 < |\eta| < 6.5$. 

Corrections & correlated systematics between CMS & TOTEM under study
“Non-Single diffractive enhanced”: primary tracks in both T2 hemispheres
“Single diffractive enhanced”: primary tracks in only one T2 hemispheres

**NSD-enhanced**

At least 1 charged particle with $p_T > 40$ MeV in only one T2 hemisphere

**SD-enhanced**

Corrections & correlated systematics between CMS & TOTEM under study

Updated analysis with a common $p_T = 0$ thresholds ongoing in both CMS & TOTEM!
Soft single diffraction @ 7 TeV

Low & medium mass SD:
Tracks in T2 hemisphere opposite to proton \((2 \times 10^{-7} < \xi < 0.025)\)

Very high mass SD:
Tracks also in same T2 hemisphere as proton \((\xi > 2.5\%)\)

- SD events triggered with T2, only 1 proton required in RP
- \(M_{\text{diff}}\) from rapidity gap based on charged particles in T1 & T2: \(M_{\text{diff}} = \sqrt{s} \cdot e^{-\Delta\eta}\) allows better \(\xi\) resolution \((\delta(\xi)/\xi \approx 1)\) for low & medium \(M_{\text{diff}}\)
- SD events classified into 4 classes, based on rapidity gap:

<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 - 8 GeV</td>
<td>(2 \times 10^{-7} &lt; \xi &lt; 10^{-6})</td>
</tr>
<tr>
<td>Medium Mass</td>
<td>p + T2 opposite + T1 opposite</td>
<td>8 - 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 diffraction @ 7 TeV**

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

- 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:
  - \( B \approx 15\% \); \( \sigma \approx 20\% \)

\[ \sigma_{SD}, \text{low } M_{\text{diff}} \approx 1.8 \text{ mb} \]
\[ \sigma_{SD}, \text{medium } M_{\text{diff}} \approx 3.3 \text{ mb} \]
\[ \sigma_{SD}, \text{high } M_{\text{diff}} \approx 1.4 \text{ mb} \]

\[ d\sigma/dt \sim A \cdot e^{-Bt} \]

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

\[ \sigma_{SD}, \text{low } M_{\text{diff}} \approx 1.8 \text{ mb} \]
\[ \sigma_{SD}, \text{medium } M_{\text{diff}} \approx 3.3 \text{ mb} \]
\[ \sigma_{SD}, \text{high } M_{\text{diff}} \approx 1.4 \text{ mb} \]

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

- Analysis of very high mass events ongoing
- 8 TeV SD analysis started

\[ \sigma_{SD} = 6.5 \pm 1.3 \text{ mb} \]
(3.4 < \( M_{\text{diff}} \) < 1100 GeV)
Soft double diffraction @ 7 TeV

Measurement of soft DD cross section with only particles visible in T2 (4.7 < |ξ|_{min} < 6.5)

\[ \sigma_{DD}(|ξ|_{min}) \text{ for } 3.4 < M_{\text{diff}} < 8 \text{ GeV} \]

Event selection: Trigger with T2, at least one track in both T2 hemispheres, no tracks in T1 “(0T1+2T2) topology”.

- ND background estimated scaling MC prediction using a control sample from data dominated by ND (2T1+2T2 events)
- SD background estimated completely from data using a SD-dominated control sample (0T1+1T2) with protons in RP
Soft double diffraction @ 7 TeV

\[ \sigma_{DD}(4.7 < |\eta_{\text{min}}| < 6.5) = 120 \pm 25 \mu b \]

|       | -4.7 > |\eta_{\text{min}}| > -5.9 | -5.9 > |\eta_{\text{min}}| > -6.5 |
|-------|--------|-----------------|-----------------|
| 4.7 < |\eta_{\text{min}}| < 5.9  | 66 \pm 19 \mu b | 27 \pm 5 \mu b |
| 5.9 < |\eta_{\text{min}}| < 6.5  | 28 \pm 5 \mu b | 12 \pm 4 \mu b |

- \sigma_{DD} uncertainty dominated by:

"Internal migration": real DD events that have a |\eta|_{\text{min}} smaller than T1 but with no tracks in T1 \( \eta \)-range

Pythia 8
(\sigma_{DD} = 8.1 \text{ mb})

|       | -4.7 > |\eta_{\text{min}}| > -5.9 | -5.9 > |\eta_{\text{min}}| > -6.5 |
|-------|--------|-----------------|-----------------|
| 4.7 < |\eta_{\text{min}}| < 5.9  | 70 \mu b       | 36 \mu b       |
| 5.9 < |\eta_{\text{min}}| < 6.5  | 36 \mu b       | 17 \mu b       |

Phojet
(\sigma_{DD} = 3.9 \text{ mb})

|       | -4.7 > |\eta_{\text{min}}| > -5.9 | -5.9 > |\eta_{\text{min}}| > -6.5 |
|-------|--------|-----------------|-----------------|
| 4.7 < |\eta_{\text{min}}| < 5.9  | 44 \mu b       | 23 \mu b       |
| 5.9 < |\eta_{\text{min}}| < 6.5  | 23 \mu b       | 12 \mu b       |

Improvement expected with 8 TeV data sample that includes also CMS detector information.
Double-arm proton detection

Prediction of mass to be seen in CMS from reconstructed protons: \( M^2 = s \xi_1 \xi_2 \)

Initial vs. final state comparison: \( M_{\text{TOTEM}} (pp) =? M_{\text{CMS}} \)

Prediction of central particle flow topology from proton \( \xi \)'s (rapidity gaps): \( \Delta \eta_{1,2} = -\ln \xi_{1,2} \)

Masses up to 1.8 TeV with pp survival!

Analysis on going.
Good statistics for soft central diffraction; limited for hard central diffraction

Good statistics for hard single diffraction, SD dijet analysis ongoing!
Summary

Total pp cross-section

- **Measured at 7 & 8 TeV**

Forward particle production

- **Forward charged multiplicity**
  - measured at 7 & 8 TeV
  - Started with CMS to explore capability of the large combined $\eta$ coverage!

Diffraction: soft and hard

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

Elastic pp scattering

- Measured at 7 & 8 TeV
- $6 \cdot 10^{-4} < |t| < 2.5$ GeV$^2$
The End
Elastic pp scattering: $\rho$ measurement

Comparison of $\rho$ with models and measurements at lower energy

$$\rho = 0.107 \pm 0.027^{\text{(stat)}} \pm 0.010^{\text{(syst)}} +0.009\text{ (model)} -0.009$$
SD cross-section comparison

NB! TOTEM measures "p+rap gap + diffractive system", ALICE & CMS "rap gap + diffractive system"
M(pp) = 244 GeV
ξ+ = -0.1  ξ- = -0.01
Central diffraction: TOTEM + CMS

Categories of events:

- CMS and TOTEM consistent (within resolution)
  \[ M_{CMS}(\text{Particle Flow}) = M_{TOTEM}(pp) \]
  \[ p_{CMS}(\text{Particle Flow}) = p_{TOTEM}(pp) \]
  → Many candidates in the soft sample
  Few candidates in the dijet sample; none exclusive!

- Missing “tracks” in CMS
  \[ M_{CMS}(\text{Particle Flow} + \text{missing momentum}) \leq M_{TOTEM}(pp) \]

- Additional tracks indeed observed in forward detectors where allowed by x-predicted gaps
  → Large fraction of soft events
  Several candidates in the dijet sample

- Secondary particles violating rapidity gaps
  → No candidates in the dijet sample;
  Background issue in the soft sample

- Escaping-mass candidates
  Additional tracks NOT observed in forward detectors where allowed by x-predicted gaps
  → few candidates with \( \Delta M \geq 400 \text{ GeV} \)

  Additional tracks NOT observed in forward detectors forbidden by x-predicted gaps
  → no candidates

Cuts:
- Vertex \leq 1
- RP near edge area removed (background suppression)
- RP top-top/bot-bot topology
- \( \xi > 1.5\% \), better resolution
- FSC empty (background suppression)
RP system: LHCC endorsed program

- Installation of a collimator to protect Q6
- Infrastructure to install 2 new horizontal pots
- RP147 (fully equipped) relocated at 203-213m
  1 unit rotated by 8 degrees
- Long lever arm (~15m) improves angular resolution (until beam divergence limit)
- Si-strip detectors rotated to improve multitrack event reconstruction (beam halo pileup, background)
- On going studies to implement high beta optics with 1000 bunches
  Pileup ≈ 0.09 ; L ≈ 10^{31} \text{ cm}^2 \text{ s}^{-1} → 1 \text{ pb}^{-1}/\text{day}

- Forward proton detector system will consist of 4 units/arm, each with 2 vert. and 1 horiz., pot equipped with 10 planes Si-strip detectors, with full trigger capability
- Extreme flexibility in using 4 units according to running scenario; possibility to dedicate pots to new **Si-pixel detectors** as well as to timing detectors with low material budget