TOTEM Physics Results

2 - 6 December 2013 | University of Antwerp, Belgium

MPI@LHC
Workshop on Multi-Parton Interactions at the LHC

Mario Deile
on behalf of the TOTEM Collaboration
Overview

- Charged Particle Pseudorapidity Density $dN / d\eta$
- pp Elastic Scattering (7 TeV, 8 TeV)
- Total pp Cross-Section (7 TeV, 8 TeV)
- Coulomb-Nuclear Interference (CNI), $\rho$ Parameter
- Diffractive Dissociation: Results and Analyses in Progress
- Outlook: Consolidation and Upgrade
Experimental Setup at IP5

[Ref.: JINST 3 (2008) S08007]

**Inelastic Telescopes:**
charged particles in inelastic events:
→ multiplicities, rapidity gaps

- **T1:** $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV
- **T2:** $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

→ **Inelastic Trigger**

**Roman Pots:** elastic & diffractive protons close to outgoing beams → **Proton Trigger**
dN\(\text{ch}/d\eta\): mean number of charged particles per event and per unit of pseudorapidity:

- **primary particles only**, i.e. lifetime > 30 ps (convention among LHC experiments)

  - probes hadronisation
  - constrains theoretical models
  - input for cosmic ray simulations

**7 TeV**

- TOTEM standalone (T2)

**8 TeV**

- CMS + TOTEM (T2)

→ Vardan Khachatryan (Wednesday)

**Corrections & correlated systematics between CMS & TOTEM** under study

- [EPL 98 (2012) 31002]
Proton Transport and Reconstruction via Beam Optics

(x*, y*): vertex position

(θx*, θy*): emission angle: \( t \approx -p^2 (\theta_{x*}^2 + \theta_{y*}^2) \)

ξ = Δp/p: momentum loss (elastic case: ξ = 0)

\[
\begin{pmatrix}
  x \\
  \Theta_x \\
  y \\
  \Theta_y \\
  \Delta p/p
\end{pmatrix}_{\text{RP}} = \begin{pmatrix}
  v_x & L_x & 0 & 0 & D_x \\
  v'_x & L'_x & 0 & 0 & D'_x \\
  0 & 0 & v_y & L_y & 0 \\
  0 & 0 & v'_y & L'_y & 0 \\
  0 & 0 & 0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
  x^* \\
  \Theta_x^* \\
  y^* \\
  \Theta_y^* \\
  \Delta p/p
\end{pmatrix}_{\text{IP5}}
\]

Product of all lattice element matrices

\( x_{\text{RP}} = L_x \Theta_x^* + v_x x^* + D_x \xi \)

\( y_{\text{RP}} = L_y \Theta_y^* + v_y y^* \)

Lx, Ly: effective lengths (sensitivity to scattering angle)

vx, vy: magnifications (sensitivity to vertex position)

Dx: dispersion (sensitivity to momentum loss); Dy ≈ 0

Reconstruction of proton kinematics = inversion of transport equation

Transport matrix elements depend on ξ ⇒ non-linear problem (except in elastic case!)

Excellent optics understanding needed.
LHC Optics and TOTEM Running Scenario

Acceptance of RP220 for diffractive protons:

\[ t \approx -p^2 \Theta^2 \]: four-momentum transfer squared; \( \xi = \Delta p/p \): fractional momentum loss

\[ \beta^* = 0.55 \text{ m} \]
\[ \beta^* = 90 \text{ m} \]
\[ \beta^* = 1000 \text{ m} \]

Diffraction:
\[ \xi > \sim 0.01 \]
low cross-section processes
(hard diffraction)

Elastic scattering: very low \(|t|\)
Coulomb-Nuclear Interference
Total Cross-Section

Diffraction:
all \( \xi \) if \(|t| > \sim 10^{-2} \text{ GeV}^2 \)
Elastic scattering: low to mid \(|t|\)
Total Cross-Section

\[ \mathcal{L} \propto \frac{1}{\beta^*} \]

\( > 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)
\( \sim 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \)
Elastic pp Scattering: Event Topology and Hit Maps

Two diagonals analysed independently
Elastic Tagging

Selection cuts:

<table>
<thead>
<tr>
<th>number</th>
<th>cut</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>diagonal track reconstructed in all 4 diagonal RPs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$\theta_x^{sR} - \theta_x^{sL}$</td>
<td>9.2 $\mu$rad</td>
</tr>
<tr>
<td>2</td>
<td>$\theta_y^{sR} - \theta_y^{sL}$</td>
<td>3.5 $\mu$rad</td>
</tr>
<tr>
<td>3</td>
<td>$</td>
<td>x^{sR}</td>
</tr>
<tr>
<td>4</td>
<td>$</td>
<td>x^{sL}</td>
</tr>
<tr>
<td>5</td>
<td>$\alpha y^{R,N} - (y_{R,F}^{R,N} - y_{R,N}^{R,F})$</td>
<td>17 $\mu$m</td>
</tr>
<tr>
<td>6</td>
<td>$\alpha y^{L,N} - (y_{L,F}^{L,N} - y_{L,N}^{L,F})$</td>
<td>17 $\mu$m</td>
</tr>
<tr>
<td>7</td>
<td>$x^{sR} - x^{sL}$</td>
<td>9 $\mu$m</td>
</tr>
</tbody>
</table>

\{ collinearity \}
\{ low $|\xi|$ \}

Example: elastic collinearity: Scattering angle on one side versus the opposite side

Collinearity in $y$

Collinearity in $x$

Width of correlation band in agreement with beam divergence ($\sim 2.4$ $\mu$rad)
Elastic pp Scattering at 7 and 8 TeV: Differential Cross-Sections

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 8$ TeV

<table>
<thead>
<tr>
<th>E (TeV)</th>
<th>$\beta^*$ (m)</th>
<th>RP approach</th>
<th>$L_{int}$ (mb$^{-1}$)</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>$7\times10^{-3}$ - 0.5</td>
<td>1M</td>
</tr>
<tr>
<td>90</td>
<td>10$\sigma$</td>
<td>1.7</td>
<td>0.02 - 0.4</td>
<td></td>
<td>14k</td>
</tr>
<tr>
<td>3.5</td>
<td>7$\sigma$</td>
<td>0.07</td>
<td>0.36 - 3</td>
<td></td>
<td>66k</td>
</tr>
<tr>
<td>3.5</td>
<td>18$\sigma$</td>
<td>2.3</td>
<td>2 - 3.5</td>
<td></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>$6\times10^{-4}$ - 0.2</td>
<td></td>
<td>0.4M</td>
</tr>
<tr>
<td>2.76</td>
<td>11</td>
<td>5-13$\sigma$</td>
<td>0.05-0.6</td>
<td></td>
<td>45k</td>
</tr>
</tbody>
</table>
Some Lessons on Hadronic Elastic pp Scattering

At low |t|: nearly exponential decrease:

\[ B_{7\text{TeV}} = (19.89 \pm 0.27) \text{ GeV}^{-2} \]

\[ B_{8\text{TeV}} = (19.90 \pm 0.30) \text{ GeV}^{-2} \]

Old trends for increasing s are confirmed:

- “shrinkage of the forward peak”: minimum moves to lower |t|
- forward exponential slope B increases
Inelastic and Total pp Cross-Section Measurements

7 TeV
8 TeV

First measurements of the total proton-proton cross section at the LHC energy of $\sqrt{s} = 7\,\text{TeV}$ [EPL 96 (2011) 21002]

Measurement of proton-proton elastic scattering and total cross-section at $\sqrt{s} = 7\,\text{TeV}$ [EPL 101 (2013) 21002]

Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s} = 7\,\text{TeV}$ [EPL 101 (2013) 21003]

Luminosity-independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s} = 7\,\text{TeV}$ [EPL 101 (2013) 21004]

A luminosity-independent measurement of the proton-proton total cross-section at $\sqrt{s} = 8\,\text{TeV}$ [Phys. Rev. Lett. 111, 012001 (2013)]
3 Ways to the Total Cross-Section

Optical Theorem: \[ \sigma_{\text{tot}}^2 \propto \left[ \Im F_{\text{el, had}} (t = 0) \right]^2 = \frac{1}{1 + \rho^2} \left| F_{\text{el, had}} (t = 0) \right|^2 \quad \text{with} \quad \rho = \frac{\Re F_{\text{el, had}}}{\Im F_{\text{el, had}}} \bigg|_{t=0} \]

\[ \sigma_{\text{tot}}^2 = \frac{16\pi}{1 + \rho^2} \frac{d}{dt} \left| \frac{\sigma_{\text{el}}}{dt} \right|_{t=0} \]

7 TeV

**elastic observables only:**

\[ \sigma_{\text{tot}}^2 = \frac{16\pi}{1 + \rho^2} \frac{1}{\mathcal{L}} \frac{dN_{\text{el}}}{dt} \bigg|_0 \]

(p=0.14 [COMPETE extrapol.])

**June 2011 (EPL96):** \( \sigma_{\text{tot}} = (98.3 \pm 2.8) \text{ mb} \)

**Oct. 2011 (EPL101):** \( \sigma_{\text{tot}} = (98.6 \pm 2.2) \text{ mb} \)

Different beam intensities!

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

\( \sigma_{\text{tot}} = (99.1 \pm 4.3) \text{ mb} \)

**luminosity independent:**

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{dN_{\text{el}}/dt|_0}{N_{\text{el}} + N_{\text{inel}}} \]

\( \sigma_{\text{tot}} = (98.0 \pm 2.5) \text{ mb} \)

Excellent agreement between cross-section measurements at 7 TeV using
- runs with different bunch intensities,
- different methods with different external inputs.
Inelastic Cross-Section Measurement (T1, T2)

T2 sees ~95 % of inelastic events (detection of 1 track is enough!)

Main correction and uncertainty: low-mass single diffraction

\[ \eta > 6.5 \text{ or } M < 3.4 \text{ GeV: outside T2 acceptance (too far forward)} \]

Correction based on QGSJET-II-3

Correction for the low mass diffractive cross-section:

\[ \sigma_{Mx < 3.4 \text{ GeV}} = 3.2 \pm 1.6 \text{ mb} \]

\[ \sigma_{\text{inelastic}} = 73.7 \pm 0.1^{\text{(stat)}} \pm 1.7^{\text{(syst)}} \pm 2.9^{\text{(lumi)}} \text{ mb} \]
Use the total cross-section determined from elastic observables, $L$ and $\rho$
(via the Optical Theorem)

$$
\sigma_{\text{tot}}^2 = \frac{16\pi}{1 + q^2} \frac{1}{L} \frac{dN_{\text{el}}}{dt} \bigg|_0 \quad \Rightarrow \quad \sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}} = 73.15 \pm 1.26 \text{ mb}
$$

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

$$
\sigma_{\text{inel}, |\eta| < 6.5} = 70.53 \pm 2.93 \text{ mb}
$$

to obtain the low-mass diffractive cross-section ($|\eta| > 6.5$ or $M < 3.4$ GeV):

$$
\sigma_{\text{inel}, |\eta| > 6.5} = \sigma_{\text{inel}} - \sigma_{\text{inel}, |\eta| < 6.5} = 2.62 \pm 2.17 \text{ mb} \quad \text{[MC: 3.2 mb]}
$$

$$
< 6.31 \text{ mb} \quad (95\% \text{ CL})
$$
7 TeV

- $\sigma_{\text{tot}}$
- $\sigma_{\text{inel}}$
- $\sigma_{\text{el}}$

8 TeV

- $\sigma_{\text{tot}}$
- $\sigma_{\text{inel}}$
- $\sigma_{\text{el}}$

New data available at $\sqrt{s} = 2.76$ TeV.
Elastic Scattering in the Coulomb-Nuclear Interference Region

Measure elastic scattering at $|t|$ as low as $6 \times 10^{-4}$ GeV$^2$:

- $\beta^* = 1000$ m optics: large effective lengths $L_x$ and $L_y$, small beam divergence
- RP approach to $3 \sigma$ from the beam centre

$$\frac{d\sigma}{dt} \propto |F_{C+h}|^2 = \text{Coulomb + interference + hadronic}$$
Elastic Scattering in the Coulomb-Nuclear Interference Region

Simplified West-Yennie formula:
- constant slope \( B(t) = b_0 \)
- constant hadronic phase \( \arg(F^H) = p_0 \)
- \( \Psi(t) \) acts as real interference phase: \( \Psi(t) = \ln \frac{B(t)}{2} + \gamma_{\text{Euler}} \)

Kundrát-Lokajíček formula:
- any slope \( B(t) \)
- any hadronic phase \( \arg(F^H) \)
- complex \( \Psi(t) \):
  \[
  \Psi(t) = \pm \int_{t_{\text{min}}}^{0} \int_{t_{\text{min}}}^{t'} \ln \frac{t'}{t} \frac{d}{dt'} F^2(t') + \int_{t_{\text{min}}}^{0} \int_{t_{\text{min}}}^{t'} \left( \frac{F^H(t')}{F^H(t)} - 1 \right) \frac{I(t, t')}{2\pi} dt'
  \]
  \[
  I(t, t') = \int_0^{2\pi} d\varphi \frac{F^2(t'')}{t''}, \quad t'' = t + t' + 2\sqrt{tt'} \cos \varphi
  \]

Modulus constrained by measurement:
\[
\frac{d\sigma}{dt} \cong A e^{-B(t) |t|}
\]
\[
B(t) = b_0 + b_1 t + \ldots
\]

Phase \( \arg(F^H) \): very little guidance by data
Elastic Scattering in the Coulomb-Nuclear Interference Region

Only 1 free parameter: $p_0 \Rightarrow \rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0) = \cot p_0$

“central phase”:
$$\arg F(t) = \frac{\pi}{2} - \cot p_0 \frac{\cot t}{t} \frac{1}{1 - \frac{t}{t_d}}$$

constant phase:
$$\arg F(t) = p_0$$

“peripheral phase”:
$$\arg F(t) = p_0 + p_A \exp \left[ \kappa \left( \ln \frac{t}{t_m} - \frac{t}{t_m} + 1 \right) \right]$$

data sensitivity region
Preliminary Result for $\rho$

Put unknown elements of the functional form into the systematic uncertainty.

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

luminosity independent

[PRL 111 (2013) 012001]
Synopsis of $\rho$ Measurements

COMPETE: preferred model and band from all models

TOTEM: red = fit uncertainty, cyan = band from varying peripheral phase

model: Block et al.
model: Bourrely et al.
model: Petrov et al. (3P)
model: Petrov et al. (2P)
model: Islam et al.

details at $\sqrt{s} = 8$ TeV

From optical theorem:

$$\rho^2 = 16\pi L_{\text{int}} \frac{dN_{\text{el}}}{dt} \bigg|_{t=0} \frac{1}{(N_{\text{el}} + N_{\text{incl}})^2} - 1 = 0.009 \pm 0.056 \quad \Rightarrow |\rho| = 0.145 \pm 0.091$$

Indirect crude measurement at 7 TeV:

$|\rho| = 0.145 \pm 0.091$
Measure topologies and $\sigma (M, \xi, t)$
Soft Single Diffraction (SD)

- 1 proton breaks up \( \rightarrow \) diffractive mass \( M \)
- 1 proton survives with momentum loss \( \xi \)
- rapidity gap \( \Delta \eta \) between proton and \( M \)

\[
\Delta \eta = -\ln \xi, \quad M^2 = \xi s
\]

2 ways for measuring \( \xi \):

1. via the proton trajectory (RP): \[ x_{RP} = \frac{L_x}{\theta_x} + v^*_{x} x^* + D_x x^* \xi \]

   resolution at \( \beta^* = 90 \text{m} \): \( \delta \xi \sim 0.004 - 0.01 \)
   (dependent on \( t, \xi \))

2. via the rapidity gap (T1, T2)
   Note: \( \eta_{\text{max},\text{T2}} = 6.5 \iff M_{\text{min}} = 3.4 \text{ GeV} \)

Full differential cross-section: \[ \frac{d^2 \sigma}{d \xi \, dt} \]
## SD Topologies for Different Mass Ranges

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Condition</th>
<th>Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 3.4 - 7\text{ GeV}$</td>
<td>$2 \times 10^{-7} &lt; \xi &lt; 1 \times 10^{-6}$</td>
<td>proton &amp; opposite T2</td>
</tr>
<tr>
<td>$M = 7 - 350\text{ GeV}$</td>
<td>$1 \times 10^{-6} &lt; \xi &lt; 2.5 \times 10^{-3}$</td>
<td>proton &amp; opposite T1 + T2</td>
</tr>
<tr>
<td>$M = 0.35 - 1.1\text{ TeV}$</td>
<td>$2.5 \times 10^{-3} &lt; \xi &lt; 2.5 \times 10^{-2}$</td>
<td>proton &amp; opposite T2 (+ T1) &amp; same side T1</td>
</tr>
<tr>
<td>$M &gt; 1.1\text{ TeV}$</td>
<td>$\xi &gt; 2.5 \times 10^{-2}$</td>
<td>proton &amp; opposite T2 (+ T1) &amp; same side T2 (+ T1)</td>
</tr>
</tbody>
</table>

$$\Delta \eta = -\ln \frac{M^2}{s}$$
### SD for Different Mass Ranges (7 TeV Data)

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Condition</th>
<th>Differential Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 3.4 - 7 \text{ GeV}$</td>
<td>$2 \times 10^{-7} &lt; \xi &lt; 1 \times 10^{-6}$</td>
<td>$d\sigma/dt \sim A \cdot e^{-B</td>
</tr>
<tr>
<td>$M = 7 - 350 \text{ GeV}$</td>
<td>$1 \times 10^{-6} &lt; \xi &lt; 2.5 \times 10^{-3}$</td>
<td>$B_{SD} = 10.1 \text{ GeV}^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx \frac{1}{2} B_{el}$ !</td>
</tr>
<tr>
<td>$M = 0.35 - 1.1 \text{ TeV}$</td>
<td>$2.5 \times 10^{-3} &lt; \xi &lt; 2.5 \times 10^{-2}$</td>
<td>$B_{SD} = 8.5 \text{ GeV}^{-2}$</td>
</tr>
<tr>
<td>$M &gt; 1.1 \text{ TeV}$</td>
<td>$\xi &gt; 2.5 \times 10^{-2}$</td>
<td>in progress</td>
</tr>
</tbody>
</table>

- Estimated uncertainty: $\delta B/B \approx 15\%$
- Work in progress!
- Some corrections still missing!

**TOTEM Preliminary**
Soft Double Diffraction

- Both protons break up $\rightarrow$ 2 diffractive masses $M_1$, $M_2$
- Central rapidity gap

Ultimate goal: 2-dim. cross-section

$$\frac{d^2\sigma}{d M_1 \, d M_2}$$

or

$$\frac{d^2\sigma}{d |\eta|_{\text{min,1}} \, d |\eta|_{\text{min,2}}}$$

Difficulties:
- no leading protons to tag
- for large masses ($\rightarrow$ small central gap) not easy to separate from non-diffractive events

First step: sub-range with particles triggering both T2 hemispheres, veto on T1:

$$4.7 < |\xi|_{\text{min,1/2}} < 6.5 \quad \text{or} \quad 3.4 \text{ GeV} < M_{1/2} < 8 \text{ GeV}$$
Double Diffraction: Results at 7 TeV

Partial 2-dim. cross-section in 2 x 2 bins:

<table>
<thead>
<tr>
<th></th>
<th>-4.7 &lt; $\eta_{\text{min}}$ ≤ -5.9</th>
<th>-5.9 &lt; $\eta_{\text{min}}$ ≤ -6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7 &lt; $\eta_{\text{min}}$ ≤ 5.9</td>
<td>65±20 µb</td>
<td>26±5 µb</td>
</tr>
<tr>
<td>5.9 &lt; $\eta_{\text{min}}$ ≤ 6.5</td>
<td>27±5 µb</td>
<td>12±5 µb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{DD}(4.7 &lt; \eta_{\text{min}} &lt; 6.5)} = 116 \pm 25$ µb</td>
</tr>
</tbody>
</table>

Leading systematics:

- DD events with $\eta_{\text{min}}$ outside T1/T2 acceptance
- backgrounds from non-diffractive, single diffractive, central diffractive events

So far, only a small part of DD measured: 116 µb out of ~5 mb, but:

benchmark for Monte Carlos:

- Pythia 8: $\sigma_{\text{DD}(4.7 < \eta_{\text{min}} < 6.5)} = 159$ µb
- Phojet: $\sigma_{\text{DD}(4.7 < \eta_{\text{min}} < 6.5)} = 101$ µb

Improvement expected with 8 TeV data: also CMS detector information available (joint run).
Central Diffraction ("Double Pomeron Exchange")

- both protons survive with momentum losses $\xi_1, \xi_2$
- diffractive mass $M$ in the centre
- 2 rapidity gaps $\Delta \eta_1, \Delta \eta_2$

$$\Delta \eta_{1,2} = -\ln \xi_{1,2}, \quad M^2 = \xi_1 \xi_2 s$$

Joint data taking CMS + TOTEM:
kinematic redundancy between protons and central diffractive system

$$M_{CMS} = M_{TOTEM}(pp) \, ?$$
Central Diffraction ("Double Pomeron Exchange")

Soft DPE: study differential cross-section with correlations:

\[ \left( \text{in progress: } \frac{d\sigma}{dM}, \quad d\sigma \, dt_1 \right) \]

\[ \frac{d^5 \sigma}{d \xi_1 \, d \xi_2 \, d t_1 \, d t_2 \, d \Delta \Phi} \]

Single arm CD event rate (integrated $\xi$, acceptance corrected)

Estimate on the integral:

$\sigma_{CD} \sim 1 \text{ mb}$
Central Production of Particles or Di-Jets

**Exclusive Particle Production:**

\[ p_1 (\xi_1) \]

\[ X \text{ at rapidity } y_X \]

\[ p_2 (\xi_2) \]

exchange of colour singlets with vacuum quantum numbers

⇒ Selection rules for system X: \( J^{PC} = 0^{++} \) (mainly) \( X = \chi_{c0}, \chi_{b0}, H, \text{glueballs?} \)

**(Exclusive) Dijet Production:**

\[ \xi_1 = \frac{1}{\sqrt{s}} \sum_i E_{T,i} e^{+\eta_i} \]

\[ \xi_2 = \frac{1}{\sqrt{s}} \sum_i E_{T,i} e^{-\eta_i} \]

Joint analysis of special run at 8 TeV, \( \beta^* = 90 \text{ m} \) together with CMS in progress
CMS + TOTEM 90 m $\beta'$
Run/Event 198903/3478279
Jets $E_T = 65, 45, 27$ GeV

$M(pp) = 244$ GeV; $M(CMS) = 219$ GeV
$\sum p_T(CMS) = 3.4$ GeV
FSC empty both sides

$M(pp) = 244$ GeV
$\xi^- = 0.1; \; \xi^+ = 0.01$
TOTEM Consolidation and Upgrade Programme

In 2012: successful data taking together with CMS in special runs
→ first studies of central production, diffractive dijets, other hard diffractive processes

Problems: limited statistics, pileup
→ upgrade RP system for operation at higher luminosities
→ resolve event pileup: timing measurement, multi-track resolution

New collimator to protect Q6

2 new horizontal pots

Allow insertion of pots at high beam intensity

Long lever arm (~15m) improves angular resolution
1 unit tilted 8° around beam axis to allow multitrack event reconstruction (beam halo pileup, background)

Later: pixel detectors

RP147 relocated to 203-213m

existing RP220

4 RP units:
Different LHC Optics

Hit maps of simulated diffractive events for 2 optics configurations (labelled by $\beta^*=\text{betatron function at the interaction point}$)

$\beta^*=0.55\text{ m} $ (low $\beta^*=\text{standard at LHC}$) $\beta^*=90\text{ m} $ (special development for RP runs)

$L_x=1.7\text{ m}, L_y=14\text{ m}, D_x=8\text{ cm}$

- diffractive protons: mainly in horizontal RP
- elastic protons: in vertical RP near $x\sim0$
- sensitivity only for large scattering angles

$L_x=0, L_y=260\text{ m}, v_y=0, D_x=4\text{ cm}$

- diffractive protons: mainly in vertical RP
- elastic protons: in narrow band at $x\cong0$
- sensitivity for small vertical scattering angles

| $\beta^*$ | Beam width @ vertex | Angular beam divergence | Min. reachable $|t|$ |
|-----------|----------------------|-------------------------|------------------|
| $0.5-3.5\text{ m}$ | small | $\sigma(\Theta_{x,y}^*)=\sqrt{\frac{\varepsilon_n}{\beta^*\gamma}}$ large | $|t_{\text{min}}|=\frac{n^2 p \varepsilon_n m_p}{\beta^*} \sim 0.3-1\text{ GeV}^2$ |
| $90\text{ m}$ | large | $\sigma(\Theta_{x,y}^*)=\sqrt{\frac{\varepsilon_n}{\beta^*\gamma}}$ small | $10^{-2}\text{ GeV}^2$ |
Absolute Luminosity Calibration

\[ \mathcal{L} = \frac{(1 + \rho^2)}{16\pi} \frac{(N_{el} + N_{inel})^2}{(dN_{el}/dt)_{t=0}} \]

7 TeV

June 2011: \[ L_{int} = (1.65 \pm 0.07) \mu b^{-1} \quad [\text{CMS: (1.65 \pm 0.07) \mu b^{-1}}] \]

October 2011: \[ L_{int} = (83.7 \pm 3.2) \mu b^{-1} \quad [\text{CMS: (82.0 \pm 3.3) \mu b^{-1}}] \]

Excellent agreement with CMS luminosity measurement.

Absolute luminosity calibration for T2
Charged Particle Pseudorapidity Density \( \frac{dN}{d\eta} \)

Analyses in progress:
- T1 measurement at 7 TeV \( (3.1 < |\eta| < 4.7) \)
- Parasitical collision at \( \beta^* = 90 \) m \( (7 \) July 2012)  
  → vertex at \( \sim 11 \) m → shifted \( \eta \) acceptance:
"Non-Single diffractive enhanced": primary tracks in both T2 hemispheres

"Single diffractive enhanced": primary tracks in only one T2 hemispheres

**NSD-enhanced**

- Corrections & correlated systematics between CMS & TOTEM under study

**SD-enhanced**

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

Updated analysis with a common $p_T = 0$ threshold ongoing in both CMS & TOTEM!