TOTEM
PHYSICS PLANS

Mirko Berretti
Università degli studi di Siena & INFN-Pisa
(on behalf of the TOTEM Collaboration)

The 2009 Europhysics Conference
on High Energy Physics
17 July 2009, Krakow

OUTLOOK

- Totem Physics Programme
- The Totem Experiment at LHC
- Early measurements
TOTEM Physics Overview

**Total pp cross-section**

\[ \sigma_{pp} \text{ [mb]} \]

- best fit with stat. error band
- incl. both TEVATRON points
- total error band of best fit
- total error band from all models considered

Energy + Particle flow in the forward region
Low-x QCD
Hard diffraction

In cooperation with CMS

Central Exclusive diffractive production

**Elastic pp Scattering**

in the range

\[ 10^{-3} < |t| \sim (p\theta)^2 < 10 \text{ GeV}^2 \]

**Diffractive measurements**

SD, DPE (\(\xi, M, t\)) distributions
Forward Particle flow (validation/tuning of cosmic ray MC)
**TOTEM Experimental layout**

**RPs** at ±147 and ±220 m: measurement of elastic scattered and diffractive protons

**T1 & T2** inelastic telescopes: measurement of the forward charged particle flows and rapidity gaps

- **T1**: $3.1 < |\eta| < 4.7$
- **T2**: $5.3 < |\eta| < 6.5$

(detectors placed symmetrically on both sides of IP5)
**T1 - Two quarter per arm:**

- Each quarter: 5 planes, each formed by 3 CSC chambers.
- 3 coordinates/plane, hit spatial resolution: $\sigma_{xy} \sim 0.8$ mm
- L1 trigger capability (by anode wires), VFAT digital readout
- Successful ageing studies (at least 5y at $L = 10^{30}\, \text{cm}^{-2}\text{s}^{-1}$)
- Track $\sigma(\eta) \sim 0.02-0.2$ (E dependent)

**T2 - Two quarter per arm:**

- Each quarter: 10 (5×2 back-to-back mounted) GEM detectors
- Triple Gas Electron Multiplier detectors
- Hit spatial resolution: radial $\sim 0.1$ mm, azimuthal $\sim 1^\circ$
- L1 trigger capability (by pad), VFAT digital readout
- T2 Triple GEM technology adequate to work at least 1 yr at $\mathcal{L}=10^{33}\, \text{cm}^{-2}\text{s}^{-1}$
- Track $\sigma(\eta) \sim 0.04-0.1$ (E-\eta dependent)

**Installation status:**

- **T1:** 1 (maybe 2) arm in September 09
- **T2:** Both arms already installed

- **Primary Vtx reconstruction** to discriminate background (not beam-beam events) for the measurement of $N_{\text{inel}}$.
- **Multiplicity, correlation** measurements.
Each RP station has 2 units, each unit has 2 vertical insertions (‘pots’) + 1 horizontal

- Silicon detectors are placed inside a secondary vacuum vessel (called Pot). The Pot can be moved as close as possible to the beam.
- Protons at few \( \mu \text{rad} \) angles detected at \( 10\sigma + d \) from beam (\( \sigma_{\text{beam}} \sim 0.1–0.6 \text{ mm} \) - optics dep.)
- Use of ‘Edgeless’ detectors to minimize \( d \) (with current terminating structures: inefficient detector edge \( d= 50 \mu \text{m} \))

**RP-Si detectors features:**

- 512 strips at 45° orthogonal
- Pitch: 66 \( \mu \text{m} \)
- Resolution: \( \sigma \sim 20 \mu \text{m} \)
- Digital readout (VFAT): tracking and triggering (strips coincidence in a road)

**Installation status:**

RP 220m station, both arms, completed in July 09
**σ_{TOT} TOTEM Measurement**

- Current σ_{TOT} models predict at \( \sqrt{s} = 14 \text{ TeV}: \sigma_{pp} = 90 - 130 \text{ mb} \)

- TOTEM goal: absolute error \( \sim 1 \text{ mb} \)
  \( (\mathcal{L}_{\text{inst}} \sim 10^{28} \text{ cm}^{-2}\text{s}^{-1}) \)
  \Rightarrow \text{possibility to distinguish among different models}

- Luminosity independent method:

  **Optical theorem:**
  \[
  \sigma_{tot} = \frac{16\pi}{s} \mathcal{I}m F(s, t = 0)
  \]
  \[
  \mathcal{L} \sigma_{tot} = N_{el} + N_{inel}
  \]
  \[
  \rho = \left. \frac{\mathcal{R}e F(s, t)}{\mathcal{I}m F(s, t)} \right|_{t=0} \sim 0.136
  \]

  Example: best combined fit by COMPETE

  \[
  \sigma_{tot} = 111.5 \pm 1.2 \, \pm 4.1 \, -2.1 \, \text{mb}
  \]

---

To compute \( \sigma_{TOT} \) TOTEM needs to measure

- Elastic rate \( N_{el} \)
- Elastic scattering down to \( |t| \sim 10^{-3} \text{ GeV}^2 \)
  (extrapolation to the optical point \( t = 0 \))
- Inelastic rate \( N_{inel} \) (tracking in the fw region required)
LHC Optics

Totem plans/measurements strongly depend on LHC optics

Beam size $\sigma_{xy}$ & divergence $\sigma_\theta$ at IP5 & RP depends on beam emittance $\varepsilon$ & $\beta^*$ of optics

- High $\beta^*$ $\rightarrow$ small beam divergence (small $\sigma_\theta$ uncertainty)
  $\rightarrow$ access to elastic with small-$|t|$ @ RPs $\rightarrow$ necessary for extrapolation of $dN_{el}/dt$ to $t = 0$

- Proton position@RP $(x, y)$ (so acceptance) depends on IP position $(x^*, y^*)$, divergence $(\theta^*_x, \theta^*_y)$ & $\xi = \Delta p/p$

$y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta^*_y$

$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta^*_x + \xi \cdot D(s)$

$\sigma_x = \sqrt{\varepsilon \cdot \beta^*_x}$

$\sigma_\theta = \frac{\varepsilon}{\beta^*_x}$

$\beta^* = 1540 \text{ m}$

$\beta^* = 90 \text{ m}$

$\beta^* = 2 \text{ m}$

Proton acceptance determined by:
- optical functions, mainly $L_x, L_y, D_x$
- beam size $\sigma(x), \sigma(y)$ at RP
- internal LHC apertures

Elastic acceptance, optics dependence

Det. distance: 1.3 mm, 6 mm

$\log(-t / \text{GeV}^2)$
Elastic Scattering Measurements

**TOTEM Approach:**

- Measure the exp. slope $B$ in the $t$-range $0.002 - 0.2 \text{ GeV}^2$, extrapolate $d\sigma/dt$ to $t=0$
- Measure total elastic rates (test different models of central collisions at high-$|t|$)

**Target optics:**

1. $\beta^*=1540 \text{ m} \rightarrow |t| > 2 \cdot 10^{-3} \text{ GeV}^2$
   (difficult to have at the beginning – requires special injection optics)

2. $\beta^*=90 \text{ m} \rightarrow |t| > 3 \cdot 10^{-2} \text{ GeV}^2$
   (un-squeezing of existing injection optics)

**Early optics:**

- $\beta^*=1540 \text{ m}$
- $\beta^*=90 \text{ m}$

- *Coulomb int.: CKL formula*
- *Photon - Pomeron interference $\propto \rho$*
- *Multigluon ("Pomeron") exchange $\propto e^{-B|t|}$*

**Diffractive structure**

- *Multigluon ("Pomeron") exchange $\propto e^{-B|t|}$*
- *Coulomb int.: CKL formula*

- *N Events/GeV$^2$ (BSW)*

- *pQCD $\sim t^{-8}$*
### Inelastic Scattering Measurements

#### Inelastic Trigger

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>T1/T2</th>
<th>CMS</th>
<th>RP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Diffractive Trigger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Diffractive Trigger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Diffractive Trigger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Pomeron Trigger</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Cross-Section Measurements

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>( \sigma ) [mb]</th>
<th>Trigger Loss [mb]</th>
<th>Systematic Error after Extrapolations [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-diffractive inelastic</td>
<td>58 [~60]</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Single diffractive</td>
<td>14 [10:16]</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Double diffractive</td>
<td>7 [4:14]</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Double Pomeron</td>
<td>1 [0.2:1.5]</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>80 [3.6]</td>
<td></td>
<td>0.8</td>
</tr>
</tbody>
</table>

Example: extrapolation of SD cross-section to large \( 1/M^2 \) using \( d\sigma/dM^2 \approx 1/M^2 \):

#### Loss at low masses

- **(diffractive system below T2 acceptance)**

#### Difference between simulated and extrapolated number of events used to evaluate the systematic error.
Combined Uncertainty in $\sigma_{TOT}$

$$\sigma_{tot} = \frac{16 \pi}{1 + \rho^2} \frac{dN_{el} / dt|_{t=0}}{N_{el} + N_{inel}}$$

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

Relative errors:

- Extrapolation of elastic cross-section to $t = 0$: $\beta^* = 90\,\text{m}$ $\beta^* = 1540\,\text{m}$ $\pm 4\%$ $\pm 0.2\%$
- Total elastic rate (strongly correlated with extrapolation): $\pm 2\%$ $\pm 0.1\%$
- Total inelastic rate:
  (error dominated by Single Diffractive trigger losses) $\pm 1\%$ $\pm 0.8\%$
- Error contribution from $(1+\rho^2)$
  using full COMPETE error band $\mathrm{d}\rho/\rho = 33\%$ $\pm 1.2\%$

Total uncertainty in $\sigma_{TOT}$ (including correlations in the error propagation):

- $\beta^* = 90\,\text{m}$: $\pm 5\%$
- $\beta^* = 1540\,\text{m}$: $\pm (1 \div 2)\%$

Slightly worse in $\mathcal{L}$ ($\sim$ total rate squared!): $\pm 7\%$ ($\pm 2\%$).

Note: precise Measurement with $\beta^* = 1540\,\text{m}$ requires:
improved knowledge of optical functions alignment precision $< 50\,\mu\text{m}$
**TOTEM Early Physics (1)**

- **LHC 2009-2010 main run:** $\sqrt{s} = 10$ TeV, $\beta^* = 3m$ & $\mathcal{L} = \begin{cases} 10^{28} \to 10^{29} \text{ (days)} \\ 10^{30} \to 10^{31} \text{ (weeks)} \\ 10^{31} \to 10^{32} \text{ (months)} \end{cases}$

**RP220 Physics**

- **Diffractive physics:** high mass single & central diffraction (DPE)
  
  (RP acceptance $0.02 < \xi < 0.18$, resolution: $\sigma(\xi) < 6 \cdot 10^{-3}$)

### Diffractive proton acceptance

- Protons seen for $\xi > 2\%$

### Single Diffraction

- $\Phi$, $\Phi$

### Double Pomeron Exchange (DPE)

- $\Phi$, $\Phi$

**DPE - M acceptance**

- $\beta^* = 0.5 - 3$
  - $\beta^* = 1540$
  - $\beta^* = 90$

**T1/T2 Physics**

- Charged multiplicity studies (min. bias and cosmic ray MC generators tuning/val.)
- Rapidity gap studies (topologies of diffractive events)

- Large $|t|$ elastic scattering, (RP acceptance $2 < |t| < 10$ GeV$^2$)

**Possible short runs (2010) with $\beta^* = 90$ m**

$\rightarrow 1^{st} \sigma_{TOT}$ measurement (precision $\sim 5\%$)
TOTEM Early Physics (2)

Diffractive mass distributions: RPs (+ T1 & T2)

\( p = 5 \text{ TeV}, \beta^* = 3m \)

Acceptance: \(0.02 < -\xi < 0.18\), \(\xi = \Delta p/p\)

Resolution: \(\sigma(\xi) \sim 1 - 6 \cdot 10^{-3}\), \(\sigma(\Theta^*) \sim 15 \mu \text{rad}\)

- Single Diffraction (SD), horizontal RPs:
  \(d\sigma^{SD}/dM\) at high masses,
  \(1.4 < M < 4.2 \text{ TeV}\), \(\sigma(M)/M = 2 - 4\%\)

- Double Pomeron Exchange (DPE), horizontal RPs:
  \(d\sigma^{DPE}/dM\) at high masses,
  \(0.2 < M < 1.8 \text{ TeV}\), \(\sigma(M)/M < 2 - 4\%\)

- Elastic Scattering, vertical RPs:
  \(d\sigma^{ES}/dt\) for \(2 < |t| < 10 \text{ GeV}^2\), \(\sigma(t)/t \sim 0.2/\sqrt{|t|}\)

\[
\left( \frac{d\sigma}{d\Delta\eta} \right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}
\]

- Measure \(\xi\)
- Compare with rap. gap \(\Delta\eta = -\ln\xi\)
- Cross-section \(\sigma(\xi, t)\)
Measure charged multiplicity & correlations for different processes

Also important for interpretation of cosmic ray air shower data & MC tuning

Large uncertainties in predictions of forward particle multiplicity at LHC energies especially for diffractive events

• TOTEM acceptance:
  \(3.1 < |\eta| < 4.7\) (T1)
  \(5.3 < |\eta| < 6.5\) (T2)
  \(\sigma(\eta) = 0.04 \text{ – } 0.2\), No mom. info

• CMS fwd calorimeter acceptance:
  \(3 < |\eta| < 5\) (HF)
  \(5.3 < |\eta| < 6.6\) (CASTOR)

CR connection

\(1.4 \text{ TeV} \Rightarrow 10^{17} \text{ eV}\)

\(10^4 \text{ CR events/km}^2/\text{yr} \Rightarrow 10^4 \text{ events/s } @\text{LHC}\)

\(L = 10^{29} \text{ cm}^{-2} \text{ s}^{-1}\)
Summary & Conclusion

- **TOTEM ready** at the LHC restart will run under all beam conditions. Will need high $\beta^*$ optics for total pp cross-section measurements.

- **Early measurements**
  - low $\beta^*$:
    - study of SD and DPE at high masses
    - elastic scattering at high $|t|$
    - measurement of forward charged multiplicity
  - $\beta^* = 90$ m:
    - first measurement of $\sigma_{\text{tot}}$ (and $L$) with a precision of $\sim 5\%$ ($\sim 7\%$)
    - elastic scattering in a wide $|t|$ range
    - inclusive studies of diffractive processes
    - measurement of forward charged multiplicity

- **Later**
  - Measurement of $\sigma_{\text{tot}}$ (and $L$) with a precision of $1\pm2\%$ ($2\%$) with $\beta^* = 1540$ m (dedicated short runs).
  - Measurement of elastic scattering in the range $10^{-3} < |t| < 10$ GeV$^2$
  - An extensive CMS/TOTEM Physics Programme
Thanks for your attention
Determination of $d\sigma/dt$ at $t=0$

Model dependent uncertainty due to Coulomb interferences

$$d\sigma/dt = \frac{4\pi\alpha^2(hc)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho - \alpha\phi)\sigma_{tot} G^2(t)}{|t|} e^{-B|t|/2} + \frac{\sigma_{tot}^2 (1 + \rho^2)}{16\pi(hc)^2} e^{-B'|t|}$$

Very approximate formula: West and Yenneie model for Coulomb-Nuclear interference ($\rho(t) = \text{const}$)

$\alpha$ = fine structure constant
$\phi$ = relative Coulomb-nuclear phase
$G(t) =$ nucleon em form factor $= (1 + |t|/0.71)^{-2}$
$\rho$ = Re/Im $f(p\rightarrow p)$

Measurement of the exponential slope $B$ in the $t$-range $0.002 - 0.2$ GeV$^2$ needs beams with tiny angular spread $\Rightarrow$ large $\beta^*$
Leading proton acceptance (RP220)

5 TeV, $\beta^* = 3$ m

- **Low $\beta^*$**
  - Elastic acceptance: $2 \text{ GeV}^2 < -t < 10 \text{ GeV}^2$
  - Diffractive acceptance: $0.02 < \xi < 0.18$
  - Resolution:
    - $\sigma(\Theta) = 16 - 30 \text{ µrad}$
    - $\sigma(\xi) = 1 - 6 \cdot 10^{-3}$

- High $|t|$ elastic scattering, high mass diffraction

7 TeV, $\beta^* = 90$ m

- **$\beta^* = 90$ m**
  - Elastic acceptance: $0.03 \text{ GeV}^2 < -t_y < 10 \text{ GeV}^2$
  - Diffractive acceptance: all $\xi$ seen (condition on $-t_y$)
  - Resolution:
    - $\sigma(\Theta) = 1.7 \text{ µrad}$
    - $\sigma(\xi) = 6 - 15 \cdot 10^{-3}$

- Total pp cross-section, soft diffraction, elastic scattering

7 TeV, $\beta^* = 1535$ m

- **$\beta^* = 1535$ m**
  - Elastic acceptance: $2 \cdot 10^{-3} \text{ GeV}^2 < -t < 0.5 \text{ GeV}^2$
  - Diffractive acceptance: all $\xi$ seen (condition on $-t$)
  - Resolution:
    - $\sigma(\Theta) = 0.3 \text{ µrad}$
    - $\sigma(\xi) = 2 - 10 \cdot 10^{-3}$

- Total pp cross-section, low $|t|$ elastic scattering
Optical Functions ($\beta^* = 90$ m)

\[ L = (\beta \beta^*)^{1/2} \sin(\mu(s)) \]

Idea:
- $L_y$ large, $L_x = 0$
- $v_y = 0$
- $\mu_y(220) = \pi/2$, $\mu_x(220) = \pi$

(parallel-to-point focussing on $y$)

\[ v = (\beta/\beta^*)^{1/2} \cos(\mu(s)) \]

$x = L_x \theta_x^* + v_x x^* + \xi$

$y = L_y \theta_y^* + v_y y^*$

$\xi = \Delta p/p$

$(x^*, y^*)$: vertex position at IP

$(\theta_x^*, \theta_y^*)$: emission angle at IP

$t = t_x + t_y$

$t_i \sim -(p \theta_i^*)^2$

Optical functions:
- $L$ (effective length)
- $v$ (magnification)
- $\theta_x$ (betatron function)
- $\mu$ (phase advance)
- $D$ (machine dispersion)

⇒ describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP
Diffractive forward protons @ RPs

\[ y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* \]
\[ x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \]

Dispersion shifts diffractive protons in horizontal direction

Diffractive protons : hit distribution @ RP220m

For low-\( \beta^* \) \( L_x \) & \( L_y \) low

\( v_x \) & \( v_y \) not relevant since IP beam size small

- \( L_x = 0 \), \( L_y \) high
- beam \( \sigma = 212 \mu m \rightarrow v_x, v_y \) important
Soft diffraction at $\beta^* = 90$ m

$\beta^* = 90$ m: 65% of all diffractive protons are detected, independently on their $\xi$
$\beta^* = 1540$ m: 95% detected, independently on their $\xi$

Reconstruction of $\xi$ via protons or rapidity gap ($\Delta \eta = -\ln \xi$):
$\beta^* = 90$ m: $\sigma_p(\xi) = 6 \times 10^{-3}$ (without CMS vertex info)
$\beta^* = 1540$ m: $\sigma_p(\xi) \leq 9 \times 10^{-3}$
$\sigma(\Delta \eta) = 0.8 - 1 \Rightarrow \sigma_{\Delta \eta}(\xi) = (0.8 - 1) \xi$

Example: single diffraction $pp \rightarrow p + X$

$M_{SD} < 0.6$ TeV

0.6 < $M_{SD} < 1.3$ TeV

1.3 < $M_{SD} < 3.6$ TeV
Expected Radiation Dose in CMS/TOTEM

In 1 year @

\( \mathcal{L}_{\text{inst}} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

At RPs locations