Status and Early Physics Program of TOTEM

Hubert Niewiadomski
Penn State University / CERN

on behalf of the

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

DIS 2009
28 April 2009
Physics programme

Elastically scattered protons measured
- Total pp cross section at 14TeV with a precision of 1-2%
- Elastic pp scattering, $10^{-3}$ GeV$^2 < -t < 10$ GeV$^2$
- Soft Single & Central Diffraction (SD, DPE)
- Leading particle & energy flow in forward direction

Inelastically scattered protons measured
- Semi–hard + hard Single & Central Diffraction: production of jets, W, heavy flavours...
- Exclusive particle production in Central Diffraction
- Low–x dynamics
- $\gamma\gamma$ & $\gamma p$ physics

Physics program for the LHC start
- Diffraction at low/medium luminosity: SD, DPE
- Total cross section with a precision of about 5%
- Multiplicity distributions
Leading Protons measured at -220m & -147m from the CMS

Experimental layout

Leading Protons measured at +147m & +220m from the CMS

Inelastic rates Telescopes
- Rapidity gaps
- Forward particle flows

28/04/2009 Hubert Niewiadomski, TOTEM
Experimental layout

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

Roman Pot 1 (147 m)  Roman Pot 3 (220 m)
**T1 Telescope**

- Cathode Strip Chambers (CSC)
- $3.1 < |\eta| < 4.7$
- 5 planes with measurement of three coordinates per plane, $\sigma \sim 1 \text{ mm}$
- Primary vertex reconstruction (beam-gas interaction removal)
- Trigger with anode wires
- Connected to VFAT chips
- Successful ageing studies
  (~ 5 years at $L_{\text{inst}}=10^{30} \text{ cm}^{-2}\text{s}^{-1}$)

**Installation as soon as possible**

*0.8 $\pm$ 1.1 m*

---

28/04/2009 Hubert Niewiadomski, TOTEM
T2 Telescope

- Gas Electron Multiplier (GEM)
- $5.3 < |\eta| < 6.5$
- 10 half-planes @ 13.5 m from IP5
- Half-plane:
  - 512 strips (width 80 µm, pitch of 400 µm), radial coordinate
  - $65 \times 24 = 1560$ pads (2x2 mm$^2$ -> 7x7 mm$^2$), radial and azimuth coord.
  - Resolution: $\sigma(R) \sim 100$ µm, $\sigma(\phi) \sim 1^\circ$
- Primary vertex reconstruction (beam-gas interaction removal)
- Trigger using (super) pads
- Detectors fully tested in a testbeam with VFAT chips
- Majority of T2 planes installed in LHC, fully done by May
Roman Pots

- 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 of the beam
- All RP stations installed in the LHC
- Leading proton detection at distances down to $10 \times \sigma(\text{beam}) + d$
- Need “edgeless” detectors that are efficient up to the physical edge to minimize “d”
- $\sigma(\text{beam}) \approx 0.1–0.6 \text{ mm (optics dep.)}$

| $\beta^*$ [m] | $t_{\text{min}}$ [GeV$^2$] | $|\Delta t/t_{\text{min}}|$ | $|\Delta t/t_{\text{min}}|$ |
|----------------|-----------------|-----------------|-----------------|
| 0.5            | 4.93            | 1.8 %           | 18.3 %          |
| 2              | 1.70            | 3.0 %           | 32.1 %          |
| 90             | $30.3 \cdot 10^{-3}$ | 1.5 % | 16.0 %          |
| 1535           | $0.69 \cdot 10^{-3}$ | 10.2 % | 124 %          |

28/04/2009  Hubert Niewiadomski, TOTEM
Si Edgeless Detectors for RP

- AC coupled microstrips made in planar technology with novel guard-ring design and biasing scheme
- Readout with VFAT chips
- Leakage current: 60 nA at 200 V (excellent)
- All produced
- Installation ongoing: RP220 (147) fully (partially) equipped by June

28/04/2009 Hubert Niewiadomski, TOTEM
Proton position at RP \((x^*, y^*)\) is a function of position \((x^*, y^*)\) and divergence \((\Theta_x^*, \Theta_y^*)\) at IP:

\[
y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* \\
x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \quad \xi = \Delta p/p - \text{momentum loss}
\]

Beam size and beam divergence at IP5 and at RP

\[
\sigma(x) = \sqrt{\varepsilon \beta_x} \quad \text{spread of the primary vertex, beam size at RP} \\
\sigma(\Theta_x) = \sqrt{\frac{\varepsilon}{\beta_x}} \quad \text{beam divergence at IP5 limits the angle measurement precision}
\]

Proton acceptance is determined by

- optical functions, mainly \(L_x, L_y, D_x\)
- beam size \(\sigma_x, \sigma_y\) at RP
- internal LHC apertures

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

Disagreement E811–CDF: 2.6 σ

Best combined fit by COMPETE:

\[ \sigma_{\text{tot}} = 111.5 \pm 1.2 \pm 1.2 \text{ mb} \]

Models vary within (at least) \(+10\% \text{ \, } -20\%\)

**Luminosity independent method:**

\[ \sigma_T = \frac{8 \pi}{p \sqrt{s}} \text{Im} F(s,t)|_{t=0} \]

\[ L \sigma_T = \frac{16 \pi}{1 + \rho^2} \frac{dN_{el}}{dt} \bigg|_{t=0}, \quad \rho = \frac{\text{Re} F}{\text{Im} F}|_{t=0} \]

\[ L \sigma_T = N_{el} + N_{inel} \]

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

\[ t \approx -p^2 \Theta^2 \]

\[ \rho = 0.1361 \pm 0.0015 \pm 0.0058 \text{ \, } -0.0025 \]

28/04/2009 Hubert Niewiadomski, TOTEM
Elastic scattering, exponential part

High $\beta^*$ optics needed to measure the total pp cross-section

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

**Target optics:**
$\beta^* = 1540$ m (difficult to have at the beginning – requires special injection optics)
acceptance at very low $|t| > 2 \cdot 10^{-3}$ GeV$^2$

28/04/2009          Hubert Niewiadomski, TOTEM

---

BSW

$\beta^* = 90$ m

$\beta^* = 11$ m

$\beta^* = 2$ m
Elastic rate measurement ($\beta^* = 90$ m optics)

- Earliest possible high $\beta^*$ optics
- $|t|$-acceptance down to 0.03 GeV$^2$, covering well the exponential region of $d\sigma/dt$;
- Typical luminosity $L \sim 10^{28} - 10^{29}$ cm$^{-2}$ s$^{-1}$
- parallel–to–point focusing only in vertical plane @ 220 m
- no emmission-angle dependence in horizontal displacement
- Thick beam useful for commissioning of RP detectors

Elastically scattered protons @ RP 220, $\beta^* = 90$

\[
y(220) = L_y \cdot \Theta_y^* \\
x(220) = v_x(s) \cdot x^*
\]

Usefull for BPMs calibration

28/04/2009 Hubert Niewiadomski, TOTEM
Inelastic event rate $N_{\text{inel}}$

T1&T2 + RP provide fully inclusive trigger:

primary vertex reconstruction to discriminate against beam-gas interactions

TOTEM Trigger efficiency:
SD: 82 %,
NSD > 99 % !

Extrapolation of SD cross-section to large $1/M^2$ using $d\sigma/dM^2 \sim 1/M^2$.

Loss at low masses

Acceptance single diffraction

simulated

detected

extrapolated
Combined uncertainty in $\sigma_{\text{tot}}$

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

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

- Extrapolation of elastic cross-section to $t = 0$:
  (Smearing effects due to beam divergence, statistical errors, uncertainty of effective length $L_{\text{eff}}$, RP alignment, model dependent deviations)

- Total elastic rate (strongly correlated with extrapolation): $\pm 2 \% \quad \pm 0.1 \%$

- Total inelastic rate:
  (error dominated by Single Diffractive trigger losses)

- Error contribution from $(1 + \rho^2)$: $\pm 1.2 \%$

Total uncertainty in $\sigma_{\text{tot}}$:
$\pm 5\% \quad \pm 1\div2 \%$

Total uncertainty in $L$:
$\pm 7\% \quad \pm 2\%$

$\beta^* = 90 \text{ m} \text{ required for early } \sigma_{\text{tot}} \text{ measurement during the first year of LHC running at 10 TeV}$

28/04/2009

Hubert Niewiadomski, TOTEM
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 the horizontal direction

Diffractive protons : hit distribution @ RP220

Low \( \beta^* \): 0.5 – 2 m

\[ y \sim \Theta_y^{\text{scatt}} \sim |t_y|^{1/2} \]
\[ x \sim \xi = \Delta p/p \]

- For low-\( \beta^* \) optics \( L_x, L_y \) are low
- \( v_x, v_y \) are not critical because of small IP beam size

\( \beta^* = 90 \text{ m} \)

- \( L_x = 0, L_y \) is high
- beam \( \sigma = 212 \mu \text{m} \) → \( v_x, v_y \) important
  (deterioration of rec. resolution)

28/04/2009    Hubert Niewiadomski, TOTEM
TOTEM diffractive protons’ acceptance

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

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

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

low $\beta^*$

$\beta^*$ : 0.5 – 2 m, $L \approx 10^{33}$ cm$^{-2}$s$^{-1}$

early running: $E = 5$ TeV, $\beta^* = 3$ m

elastic acceptance

$2$ GeV$^2 < -t < 10$ GeV$^2$

resolution

$\sigma(\Theta) = 16 – 30$ µrad

$\sigma(\zeta) = 1 – 6 \cdot 10^{-3}$

$\zeta > 2\%$ seen

(hard) diffraction, high $|t|$ elastic scattering

$\beta^* = 90$ m

$L \approx 10^{30}$ cm$^{-2}$s$^{-1}$

elastic acceptance

$3 \cdot 10^{-2}$ GeV$^2 < -t_y < 10$ GeV$^2$

resolution

$\sigma(\Theta) = 1.7$ µrad

$\sigma(\zeta) = 6 – 15 \cdot 10^{-3}$

all $\zeta$ seen, universal optics

diffraction, mid $|t|$ elastic scattering

total cross-section, low $|t|$ elastic scattering

$\beta^* = 1535$ m

$L \approx 10^{28}$ – $10^{29}$ cm$^{-2}$s$^{-1}$

elastic acceptance

$2 \cdot 10^{-3}$ GeV$^2 < -t_y < 0.5$ GeV$^2$

resolution

$\sigma(\Theta) = 0.3$ µrad

$\sigma(\zeta) = 2 – 10 \cdot 10^{-3}$

all $\zeta$ seen

total cross-section, low $|t|$ elastic scattering

28/04/2009

Hubert Niewiadomski, TOTEM
Early measurements with 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,
  \( 1.4 < M < 4.2 \, \text{TeV}, \quad \sigma(M)/M = 2 - 4 \% \)

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

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

\[ 28/04/2009 \quad \text{Hubert Niewiadomski, TOTEM} \]
Early measurements T1 & T2

- Rapidity gap studies (topologies of diffractive events)
- Charged multiplicity studies (essential for minimum bias and cosmic ray MC generators tuning / validation)
Outlook: Detection of Diffractive Protons in IR3

Good acceptance and momentum resolution for diffractive protons needs:
large dispersion $D$ (few m) ($x = \xi \cdot D$)
small beam width $\sigma (<1$ mm)

Available in Momentum Cleaning Region IR3!

A combined collimator-detector device can be placed there.

**Advantage for machine protection:**
- collimator downstream of detectors absorbs possible showers
- Warm region!
- Detect diffractive protons from all interaction points.
- $\sim 3$MHz diffractive proton rate hitting Q6 magnet found ($\sim 5$MHz quench limit)
  - magnet protection possibly needed at $L=10^{34}$

28/04/2009 Hubert Niewiadomski, TOTEM
Proton Acceptance of a “Combined IP3 + RP220 TOTEM” Experiment

ξ-acceptance, $\beta^*=0.5$ m, $p=7$ TeV

DPE Mass Spectrum with Detector Acceptance

$\xi_1 \xi_2$ s

$M_{PP}^2 = \xi_1 \xi_2$ s

- Nearly full $M_{DPE}$-range available at low $\beta^*$ and high $\mathcal{L}$
- Luminosity calibration for all LHC experiments:
  - After absolute $\sigma_{tot}$ & $\mathcal{L}$ measurements with TOTEM
  - Use low-mass DPE with both protons detected in IR3 as a “standard candle”
  - Identify interaction point by time difference between the 2 protons
Summary

- **TOTEM** will be ready for data taking at the LHC restart and will run under all beam conditions.
- Measurement of **total pp cross-section** (and L) with a precision of 1-2% (2%) with $\beta^* = 1540$ m (dedicated runs).
- Measurement of **elastic scattering** in the range $10^{-3} < |t| < 10$ GeV$^2$
- 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 $\sigma_{tot}$ (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: common CMS/TOTEM Physics Programme
largest acceptance detector ever built at a hadron collider

90% (65%) of all diffractive protons are detected for $\beta^* = 1540$ (90) m

$\eta = -\ln \tan \theta/2$

28/04/2009  Hubert Niewiadomski, TOTEM
CMS + TOTEM running scenarios

**Cross section**

<table>
<thead>
<tr>
<th>β (m)</th>
<th>1540</th>
<th>90</th>
<th>2</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (cm⁻² s⁻¹)</td>
<td>$10^{29}$</td>
<td>$10^{30}$</td>
<td>$10^{32}$</td>
<td>$10^{34}$</td>
</tr>
</tbody>
</table>

TOTEM LHC runs

Standard LHC runs

**Luminosity**

Accessible physics depends on luminosity & $\beta^*$

Prospects for Diffractive and Forward Physics at the LHC, CERN/LHCC 2006-039/G-124
Differential mass distribution in DPE

- Study of mass distributions via the 2 protons
  - Trigger with 2p+T1/T2: rate ~200Hz @ $\beta^*=90m$, $L=10^{30}\text{cm}^{-2}\text{s}^{-1}$
  - TOTEM trigger rate limit ~2kHz

- $\xi$ measured directly (TOTEM) or
  - With rapidity gap $\Delta\eta=-\ln \xi$
  - With calorimeters $\xi = \sum_i E_i e^{\pm \eta_i / \sqrt{s}}$ (TOTEM+CMS)

Differential mass distribution (acceptance corrected)
Pseudorapidity Distributions for SD

\[ \xi = \frac{\Delta p}{p} \]

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

\[ (M_x^2 = \xi \text{ s}) \]

\( \xi < 5 \times 10^{-7} \)

\( M_{SD} < 9.9 \text{ GeV} \)

\( dN_{\text{ch part}}/d\eta \)

\( 5 \times 10^{-7} < \xi < 2 \times 10^{-5} \)

\( 9.9 < M_{SD} < 63 \text{ GeV} \)

\( 1.0 \times 10^{-5} \)

\( 1.0 \times 10^{-5} \)

\( 1.0 \times 10^{-5} \)

\( 1.0 \times 10^{-5} \)

\( 0.5 \times 10^{-5} \)

\( 0.5 \times 10^{-5} \)

\( 0.5 \times 10^{-5} \)

\( 0.5 \times 10^{-5} \)

\( 2 \times 10^{-3} < \xi < 0.02 \)

\( 0.63 < M_{SD} < 2.0 \text{ TeV} \)

\( dN_{\text{ch part}}/d\eta \)

\( 0.02 < \xi < 0.2 \)

\( 2.0 < M_{SD} < 6.3 \text{ TeV} \)

\( dN_{\text{ch part}}/d\eta \)

\( 2.0 \times 10^{-3} < \xi < 2 \times 10^{-3} \)

\( 63 < M_{SD} < 630 \text{ GeV} \)

\( dN_{\text{ch part}}/d\eta \)
# Running Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Physics:</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>low</td>
<td>low/large</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td></td>
<td>elastic</td>
<td>elastic</td>
<td>elastic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma_{\text{tot}}$ (@ ~1%), MB, soft diffr.</td>
<td>$\sigma_{\text{tot}}$ (@ ~5%), MB, soft/semi-h. diffr.</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>1540</td>
<td>90</td>
<td>2 \pm 0.5</td>
<td></td>
</tr>
<tr>
<td>N of bunches</td>
<td>43 \div 156</td>
<td>156</td>
<td>936 \div 2808</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>2025 \div 525</td>
<td>525</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>N of part. per bunch</td>
<td>(0.6 \pm 1.15) \times 10^{11}</td>
<td>1.15 \times 10^{11}</td>
<td>1.15 \times 10^{11}</td>
<td></td>
</tr>
<tr>
<td>Half crossing angle [\mu rad]</td>
<td>0</td>
<td>0</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Transv. norm. emitt. $\varepsilon_n$ [\mu m rad]</td>
<td>1</td>
<td>3.75</td>
<td>3.75</td>
<td></td>
</tr>
<tr>
<td>RMS beam size at IP [\mu m]</td>
<td>450</td>
<td>213</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>RMS beam diverg. at IP [\mu rad]</td>
<td>0.3</td>
<td>2.3</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Peak Luminosity [cm$^{-2}$ s$^{-1}$]</td>
<td>$10^{28}$ \div 2 \times 10^{29}</td>
<td>3 \times 10^{30}</td>
<td>$10^{33}$</td>
<td></td>
</tr>
</tbody>
</table>

Cross section 
Luminosity

| $\beta^*$ (m) | 1540 | 90 | 2 | 0.5 |
| L (cm$^{-2}$ s$^{-1}$) | $10^{29}$ | $10^{30}$ | $10^{32}$ | $10^{33}$ |

**Cross section**

- Beam ang. spread at IP: $\sigma_{\theta^*} = \sqrt{\varepsilon / \beta^*}$
- Beam size at IP: $\sigma^* = \sqrt{\varepsilon \beta^*}$

- **Optimal $\beta^* = 1540$m optics requires special injection optics: probably NOT available at the beginning of LHC**
- **Early $\beta^* = 90$m optics achievable using the standard LHC injection optics**

Accessible physics depends on luminosity & $\beta^*$