TOTEM status and results

Fabrizio Ferro (INFN – Genova)
On behalf of the TOTEM Collaboration
TOTEM physics

Total p-p cross section

Elastic scattering

Forward particle production

Diffraction

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

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

Cosmic Rays

ISR

UA4

UA5

TEVATRON

LHC

\[ \sqrt{s} \text{ [GeV]} \]

\[ t_1 \]

\[ t_2 \]

\[ p \]

\[ p (\xi_1) \]

\[ P \]

\[ \Delta \eta \]

\[ M_{pp} \text{ at rap. } y_{pp} \]

\[ p \]

\[ p (\xi_2) \]
TOTEM detectors

Inelastic telescopes

T1: 3.1 < |\(\eta|\) < 4.7
T2: 5.3 < |\(\eta|\) < 6.5

Roman Pots
(inside LHC tunnel)

RP (147m)
RP (220m)
Inelastic telescopes

Inelastic event counting, charged multiplicity, rapidity gaps

T1

- 5 planes of Cathode Strip Chambers (CSC)
- 6 chambers per plane
- $3.1<|\eta|<4.7$
- $\Delta \phi = 2\pi$

T2

- 10 planes of Gas Electron Multipliers (GEM)
- $5.3<|\eta|<6.5$
- $\Delta \phi = 2\pi$
Roman pot detectors

Leading proton detection

- Roman pot stations in the LHC tunnel at 147m and 220m from IP (both sides)
- 10 edgeless (<50μm) Si micro strip detectors per pot
- Resolution ~15μm
Beam optics and proton transport

\[(x^*, y^*)\]: vertex position
\[(\theta_x^*, \theta_y^*)\]: emission angle: \[t = -p^2 (\theta_x^* + \theta_y^*)^2\]
\[\xi = \Delta p/p: \text{momentum loss (diffraction)}\]

\[y_{det} = L_y \theta_y^* + v_y y^*\]
\[\beta^* = 90 \text{ m}: L_y = 263 \text{ m}, v_y \approx 0\]
\[\beta^* = 3.5 \text{ m}: L_y \approx 20 \text{ m}, v_y = 4.3\]
→ Reconstruct via track positions

\[x_{det} = L_x \theta_x^* + v_x x^* + D\xi\]
Elastic: \[\xi = 0\]
\[\beta^* = 90 \text{ m}: L_x \approx 0, v_x = -1.9\]
\[\beta^* = 3.5 \text{ m}: L_x \approx 0, v_x = 3.1\]
→ Use derivative (reconstruct via local track angles):

\[
\frac{dx_{det}}{ds} = \frac{dL_x}{ds} \theta_x^* + \frac{dv_x}{ds} x^*
\]

| Beam width @ vertex | Angular beam divergence | Min. reachable \(|t|\) |
|---------------------|-------------------------|-----------------|
| \[\sigma_{x,y}^* = \frac{\varepsilon_p \beta^*}{\gamma}\] | \[\sigma_{x,y}^* = \frac{\varepsilon_p}{\beta^* \gamma}\] | \[|t_{min}| = \frac{n_p \rho \varepsilon_m m_F}{\beta^*}\] |

| Standard optics | \[\beta^* \approx 1-3.5 \text{ m}\] | \[\sigma_{x,y}^* \text{ small}\] | \[\sigma(\theta_{x,y}^*) \text{ large}\] | \[|t_{min}| \approx 0.3-1 \text{ GeV}^2\] |
| Special optics | \[\beta^* = 90 \text{ m}\] | \[\sigma_{x,y}^* \text{ large}\] | \[\sigma(\theta_{x,y}^*) \text{ small}\] | \[|t_{min}| \approx 10^{-2} \text{ GeV}^2\] |
Elastic scattering: proton tracks

\[ \beta^* = 3.5 \text{ m} \]
Roman pots at 7 \( \sigma_{\text{beam}} \)
\[ \hat{L} \sim 6.2 \text{ nb}^{-1} \]
\[ d\sigma/dt \text{ in } 0.36 < |t| < 2.5 \text{ GeV}^2 \]

\[ \beta^* = 90 \text{ m} \]
Roman pots at 10 \( \sigma_{\text{beam}} \)
\[ \hat{L} \sim 1.65 \mu\text{b}^{-1} \]
\[ d\sigma/dt \text{ for } |t| > 0.02 \text{ GeV}^2 \]

\[ \beta^* = 90 \text{ m} \]
Roman pots at 6.5, 5.5, 4.8 \( \sigma_{\text{beam}} \)
\[ \hat{L} \sim 83 \mu\text{b}^{-1} \]
\[ d\sigma/dt \text{ for } |t| > 7 \cdot 10^{-3} \text{ GeV}^2 \]

Several data sets with different running conditions:
* measurement of \( d\sigma/dt \) in a wide t range
* measurement of the elastic peak at very low t

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Elastic scattering analysis: an overview

Low $\xi$ selection: $|x|<3\sigma_x$ at $L_x=0$ ( $x=L_x\Theta_x+\xi D+v_x x^*$)

Collinearity cuts

Background subtraction

Acceptance corrections
Elastic scattering: $d\sigma_{el}/dt$

$0.36 < |t| < 2.5$ GeV$^2$

$\sqrt{s} = 7$ TeV

$B = 23.6^{+0.5}_{-0.4}$ stat GeV$^{-2}$

Comparison with models

 ISR

$r_{dp} = 1.4$ GeV$^2$
Elastic scattering: $d\sigma_{el}/dt$

$0.02<|t|<0.33$ GeV$^2$

**Luminosity provided by CMS**

$$\frac{d\sigma_{el}}{dt} \propto e^{-B|t|}$$

$$B = 20.1 \pm 0.2^{(stat)} \pm 0.3^{(syst)} \text{ GeV}^{-2}$$

$$\left. \frac{d\sigma_{el}}{dt} \right|_{t=0} = 503.7 \pm 1.5^{(stat)} \pm 26.7^{(syst)} \text{ mb/GeV}^2$$

$$\sigma_{el} = 24.8 \pm 1.2 \text{ mb}$$

**October 2011 data sets at $\beta^*=90$ m**

| $t_{\text{min}}$ (GeV$^2$) | $B$ (GeV$^2$) | $\left. \frac{d\sigma_{el}}{dt} \right|_{t=0}$ (mb/GeV$^2$) | $\sigma_{el}$ |
|--------------------------|-------------|------------------------------------------|-------------|
| $10.5 \cdot 10^{-3}$    | $19.87 \pm 0.03^{(stat)}$ | $504.0 \pm 1.1^{(stat)}$ | $25.34$ |
| $9 \cdot 10^{-3}$       | $19.87 \pm 0.07^{(stat)}$ | $501.5 \pm 2.7^{(stat)}$ | $25.18$ |
| $7 \cdot 10^{-3}$       | $19.84 \pm 0.08^{(stat)}$ | $502.0 \pm 2.9^{(stat)}$ | $25.31$ |

**Systematics:**
- ~2% analysis
- ~4% luminosity
Inelastic cross section

Using T1 and T2 telescopes

Analysis

- Event classification (using T2)
  - tracks in both hemispheres (minimum bias + double diffraction)
  - tracks in one hemisphere only (mainly single diffraction with $M_x > 3.4$ GeV/c$^2$)

- Corrections to T2 visible events
  - reconstruction efficiency (from data tuned MC) ~1%
  - trigger efficiency (from BX triggered data) ~2.5%
  - beam-gas background (from non-colliding bunches data) ~0.85%
  - Pile-up ~1.5%

- From T2 visible cross section to Inelastic cross section
  - measuring T1 only events (from BX triggered data) ~2%
  - estimating low diffractive mass events (from MC) ~4%

Luminosity provided by CMS

$$\sigma_{inel} = 73.4 \pm 0.1^{(stat)} \pm 1.9^{(syst)} \pm 2.9^{(lumi)} \text{ mb}$$
Total cross section: the methods

Total cross section measurement: 4 methods

1. (low) Luminosity + Elastic scattering + Optical theorem
2. (high) Luminosity + Elastic scattering + Optical theorem
3. (high) Luminosity + Elastic scattering + Inelastic scattering
4. Elastic scattering + Inelastic scattering + Optical theorem

Optical theorem

\[ \sigma_{tot} = \left. \frac{8\pi}{k\sqrt{s}} \text{Im}\mathcal{F}_{el}(s, t) \right|_{t=0} \]

\[ q = \left. \frac{\text{Re}\mathcal{F}_{el}}{\text{Im}\mathcal{F}_{el}} \right|_{t=0} = 0.14^{+0.01}_{-0.08} \]

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

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

\[ \sigma_{tot} = \left. \frac{16\pi}{(1 + \rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el} + N_{inel})} \right|_{t=0} \]
Total cross section: results

Total cross section measurement: 4 methods

1. (low) Luminosity + Elastic scattering + Optical theorem
   \[ \sigma_{tot} = 98.3 \pm 2.2 \text{ mb} \]

2. (high) Luminosity + Elastic scattering + Optical theorem
   \[ \sigma_{tot} = 98.2 \pm 2.4 \text{ mb} \]

3. (high) Luminosity + Elastic scattering + Inelastic scattering
   \[ \sigma_{tot} = 98.7 \pm 4.4 \text{ mb} \]

4. Elastic scattering + Inelastic scattering + Optical theorem
   \[ \sigma_{tot} = 97.8 \pm 2.9 \text{ mb} \]
Cross sections

Total, elastic and inelastic cross sections well constrained by the 4 methods

TOTEM results in agreement with COMPETE predictions
Forward charged multiplicity

\( \frac{dN_{ch}}{d\eta} \) in the pseudorapidity range \( 5.3 < |\eta| < 6.5 \) using T2 telescope

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- Low luminosity/low pile up data sets
- Full control of primary-secondary particles separation
- Measurement done separately on the 4 T2 quarters and then combined

Data vs Monte Carlo comparison

ALICE, ATLAS, CMS, LHCb and TOTEM

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CMS + TOTEM

detector with the largest acceptance

- Successful common runs to prove trigger exchange and data combination
  - PbPb runs in 2011
  - p-p runs last April and May
- A common working group to share the effort of combining data
- Main physics goals
  - multiplicity distributions and correlations
  - rapidity gap studies
  - diffractive jet production (protons in RPs + jets in CMS)
- More common runs foreseen this year
Summary and outlook

- **TOTEM has measured:**
  - the total, elastic and inelastic p-p cross section at 7 TeV
  - the elastic differential cross section in the range 
    \[ 7 \cdot 10^{-3} < |t| < 2.5 \text{ GeV}^2 \]
  - the charged multiplicity in the range \( 5.3 < |\eta| < 6.5 \)

- **Newest results to be published soon**

- **More analyses ongoing** (e.g. charged multiplicity in T1, study of single, double, central diffractive processes,...)

- **Plans for this year**
  - measure the total, elastic and inelastic cross section at 8 TeV using \( \beta^* = 90 \text{m} \) runs
  - carry on the common CMS-TOTEM physics program both in special and standard optics runs
  - measure very low-\( t \) elastic scattering and determine \( \rho \) if \( \beta^* \sim 500 \text{m} \) optics available (necessary to have access to the Coulomb-Nuclear interference region)
Back up slides
Results:

Elastic cross-section
Inelastic cross-section

Total cross-section via elastic & Optical Point (ref. LHCC method 2)
Total cross-section via sum elastic + inelastic (ref. LHCC method 3)
Total cross-section via $\mathcal{L}$-independent method (ref. LHCC method 4)

Elastic cross-section $\mathcal{L}$-independent
Inelastic cross-section $\mathcal{L}$-independent
Ratio elastic / inelastic $\mathcal{L}$-independent and $\rho$-independent

Luminosity calibration June runs
Luminosity calibration October runs

Upper limit of inclusive low mass diffraction for $\eta > 6.5$ ($M_x < \sim 3\text{GeV}$)
\( \rho \)

\( \sim 10-15\% \) measurement of \( \rho \) with \( \beta^* \approx 500 \text{ m} \), RP@5\( \sigma \) at \( \sqrt{s} = 8 \text{ TeV} \)
Analysis procedure: primary track selection.

- A cut on the Zimpact parameter has been used to select primary tracks.

- We know from MC and data comparison, the shape of the primary and secondary track Zimpact distribution (double-gaussian for primaries, exponential for secondaries).

- A large part of the secondary can be therefore extracted from the primary region by fitting the track-ZImpact distribution. The fit is repeated for each \( \eta \) bin.
# Elastic scattering systematics

<table>
<thead>
<tr>
<th>Correction</th>
<th>Effect on</th>
<th>Functional form</th>
<th>Total values or integral</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recorded Luminosity</td>
<td>$d\sigma/dt$</td>
<td>const($t$)</td>
<td>Efficiency-corrected int. Luminosity</td>
<td>Int. Luminosity $(6.1 \pm 0.2)\text{nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mult. factor</td>
<td>$(6.03 \pm 0.36)\text{nb}^{-1}$</td>
<td>Trigger eff. $(99 \pm 1)%$</td>
</tr>
<tr>
<td>Inefficiency</td>
<td>$d\sigma/dt$</td>
<td>Ineff. = const($t$)</td>
<td>Tot. ineff. = $(30 \pm 10)%$</td>
<td>DAQ eff. $(99 \pm 1)%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mult. corr. factor = $(1 + \text{ineff.})$</td>
<td></td>
<td>Detector 1%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>$d\sigma/dt$</td>
<td>Hyperbola function: $f_A \approx 1.3 + \frac{0.3}{(</td>
<td>t</td>
<td>- 0.3)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mult. corr. factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>$d\sigma/dt$</td>
<td>Parameterisation $bkg. = 1.16e^{-6.0</td>
<td>t</td>
<td>}$</td>
</tr>
<tr>
<td>Resolution unfolding</td>
<td>$s \rightarrow d\sigma/dt$</td>
<td>$f_u = \frac{\text{measured}}{\text{total}}$</td>
<td>$\text{bkg}_{\text{total}} = \left{ \begin{array}{c} (11 \pm 2)%</td>
<td>t</td>
</tr>
<tr>
<td>Alignment</td>
<td>$t$</td>
<td>$\delta t = 2p/(\Delta s , dL_\text{u} / ds) \sqrt{</td>
<td>s</td>
<td>} , \delta x$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta t = 2p/L_s \sqrt{</td>
<td>s</td>
<td>} , \delta y$</td>
</tr>
<tr>
<td>Optics</td>
<td>$t$</td>
<td>$t_\varepsilon = f(k, \Psi, p)$; $t_x = f(k, \Psi, p)$</td>
<td>$\delta (dL_x / ds) / dL_x = 1%$</td>
<td>$\frac{\delta t}{t} = 0.1%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k$: magnet strength</td>
<td>$\delta L_x / L_x = 1.5%$</td>
<td>$\delta \varepsilon = 1\text{rad}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Psi$: magnet rotation</td>
<td>$\delta t / t = 2%$</td>
<td>$\delta p / p = 10^{-3}$</td>
</tr>
</tbody>
</table>