Status and Plans of the TOTEM Experiment

LHCC Open Session
26 September 2012

Mario Deile
on behalf of the TOTEM Collaboration
**Experimental Setup @ IP5**

**Inelastic telescopes:** charged particle & vertex reconstruction in inelastic events

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

**Roman Pots:** measure elastic & diffractive protons close to outgoing beam
Recent and Upcoming Publications

- Measurement of the forward charged particle pseudorapidity density in pp collisions at $\sqrt{s} = 7$ TeV with the TOTEM experiment
  [EPL 98 (2012) 31002]

- Measurement of proton-proton elastic scattering and total cross-section at $\sqrt{s} = 7$ TeV
  [CERN-PH-EP-2012-239, to be submitted to journal]

- Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s} = 7$ TeV
  [final draft, to be submitted to journal]

- Luminosity independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s} = 7$ TeV
  [draft in progress, to be submitted to journal]
Charged Particle Pseudorapidity Density $dN / d\eta$

Analyses in progress:

- **T1** measurement at 7 TeV ($3.1 < |\eta| < 4.7$)
- **NEW**: combined analysis CMS + TOTEM ($0 < |\eta| < 6.5$) on low-pileup run of 1st May 2012 (8 TeV): common trigger (T2, bunch crossings), both experiments read out

- **NEW**: parasitical collision at $\beta^* = 90$ m (7 July 2012) → vertex at ~11 m → shifted $\eta$ acceptance:
Elastic pp Scattering at 7 TeV: Differential Cross-Section

Integrated elastic cross-section:

- $25.4 \pm 1.0_{\text{lumi}} \pm 0.3_{\text{syst}} \pm 0.03_{\text{stat}}$ mb (90% measured)
- $24.8 \pm 1.0_{\text{lumi}} \pm 0.2_{\text{syst}} \pm 0.2_{\text{stat}}$ mb (50% measured)
Elastic pp Scattering at 7 TeV: Differential Cross-Section

\[ d\sigma_{el}/dt = A e^{-B|t|} \]

\[ A = 506 \pm 22.7^{\text{syst}} \pm 1.0^{\text{stat}} \text{mb/GeV}^2 \]
\[ 503 \pm 26.7^{\text{syst}} \pm 1.5^{\text{stat}} \text{mb/GeV}^2 \]
\[ B = 19.9 \pm 0.26^{\text{syst}} \pm 0.04^{\text{stat}} \text{GeV}^{-2} \]

\[ |t|_{\text{dip}} = 0.53 \text{ GeV}^2 \]

Additional data set under analysis:
\[ 2 \text{ GeV}^2 < |t| < 3.5 \text{ GeV}^2 \]
3 Ways to the Total Cross-Section

elastic observables only:

\[ \sigma_{\text{tot}}^2 = \left. \frac{16\pi}{1 + \varrho^2} \frac{1}{\mathcal{L}} \frac{dN_{\text{el}}}{dt} \right|_0 \]

\( \varrho \) independent:

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

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

\( \rho \) independent:

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

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

Excellent agreement between cross-section measurements at 7 TeV using
- runs with different bunch intensities,
- different methods.
Absolute Luminosity Measurement

The “luminosity-independent method” also yields the luminosity:

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

June 2011: \( L_{int} = (1.65 \pm 0.07) \, \mu b^{-1} \) \[ CMS: (1.65 \pm 0.07) \, \mu b^{-1} \]
October 2011: \( L_{int} = (83.7 \pm 3.2) \, \mu b^{-1} \) \[ CMS: (82.0 \pm 3.3) \, \mu b^{-1} \]

Excellent agreement with CMS luminosity measurement.

Absolute luminosity calibration for T2
Cross-Section Measurements

\[ \sigma_{\text{tot}}, \sigma_{\text{inel}}, \text{and } \sigma_{\text{el}} \text{ (mb)} \]

- \( \Lambda \) (PDG)
- \( \Lambda \) (PDG)
- TOTEM (\( \mathcal{L} \) indep.)
- Auger + Glauber
- ATLAS
- CMS

\[ \sigma_{\text{tot}} = 11.4 - 1.52 \ln s + 0.130 \ln^2 s \]

\[ \sigma_{\text{tot}} \text{ (mb)} \]

\[ \sigma_{\text{inel}} \text{ (mb)} \]

\[ \sigma_{\text{el}} \text{ (mb)} \]

\( \sqrt{s} \) (GeV)

\( 10^1 \) to \( 10^5 \)
Elastic Scattering and Total Cross-Section at 8 TeV

July 2012: runs at $\beta^* = 90$ m

| dataset | date           | bunches | RPs | $|t|_{\text{min}}$ (GeV$^2$) | $\mathcal{L}$ (mb$^{-1}$) |
|---------|----------------|---------|-----|-----------------------------|--------------------------|
| 1       | 7 July, 1st fill | 1       | $3\sigma$ | $4 \cdot 10^{-3}$ | -- |
| 2       | 7 July, 2nd fill | 1       | $6\sigma$ | $7 \cdot 10^{-3}$ | $\approx 40$ |
| 3a      | 12–13 July      | 1       | $9.5\sigma$ | $15 \cdot 10^{-3}$ | $\approx 30$ |
| 3b      | 12–13 July      | 2 or 3  | $9.5\sigma$ | $15 \cdot 10^{-3}$ | $\approx 820$ |

only RP alignment, RPs moving

collinearity, low $\xi$, common vertex

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Elastic Scattering and Total Cross-Section at 8 TeV

July 2012: runs at $\beta^* = 90$ m

| dataset | date                  | bunches | RPs | $|t|_{\text{min}}$ (GeV$^2$) | $\mathcal{L}$ (mb$^{-1}$) |
|---------|-----------------------|---------|-----|-----------------------------|-----------------------------|
| 1       | 7 July, 1st fill      | 1       | $3\sigma$ | $4 \cdot 10^{-3}$           | $-$                         |
| 2       | 7 July, 2nd fill      | 1       | $6\sigma$ | $7 \cdot 10^{-3}$           | $\approx 40$                |
| 3a      | 12–13 July            | 1       | $9.5\sigma$ | $15 \cdot 10^{-3}$         | $\approx 30$                |
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*only RP alignment, RPs moving*

Preliminary t-distributions (unnormalised)

To be normalised via: CMS, T2, “luminosity-independent method”

→ total and inelastic pp cross-sections at 8 TeV

Coming Soon
Elastic Scattering and Total Cross-Section at 8 TeV

July 2012: runs at $\beta^* = 90$ m

| dataset | date            | bunches | RPs | $|t|_{\text{min}}$ (GeV$^2$) | $\mathcal{L}$ (mb$^{-1}$) |
|---------|-----------------|---------|-----|-----------------------------|--------------------------|
| 1       | 7 July, 1st fill| 1       | $3\sigma$ | $4 \times 10^{-3}$ | --                      |
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Preliminary $t$-distributions (unnormalised)

down to $|t| \sim 6 \times 10^{-4}$; foreseen at $\beta^* = 1$ km

larger $|t|$:  
- possible at $\beta^* = 0.6$m  
- difficult due to 2xSD and other background

only RP alignment, RPs moving
A First, Very Crude $\rho$ Estimate at 7 TeV

$$\rho = \frac{\text{Re} T(t = 0)}{\text{Im} T(t = 0)}$$

From optical theorem:

$$\rho^2 = 16\pi \mathcal{L}_{\text{int}} \frac{\left.\frac{dN_{\text{el}}}{dt}\right|_{r=0}}{(N_{\text{el}} + N_{\text{inel}})^2} - 1 = 0.009 \pm 0.056$$

$\rho < 0.32$ (95% CL),
or, using Bayes’ approach (with uniform prior $|\rho|$ distribution):

$|\rho| = 0.145 \pm 0.091$ [COMPETE extrapolation: $\rho = 0.141 \pm 0.007$]

Not so exciting, but …
**Measurement: Elastic Scattering at Low |t|**

**Optical Theorem:** \( \sigma_{\text{tot}} = \frac{4\pi}{s} \Im \left( T_{\text{elastic, nuclear}}(t = 0) \right) \)

\[
\frac{d\sigma}{dt} = \frac{4\pi\alpha^2 (\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha (\rho - \alpha\phi) \sigma_{\text{tot}}^2 G^2(t)}{|t|} e^{-B|t|/2} + \frac{\sigma_{\text{tot}}^2 (1 + \rho^2)}{16\pi (\hbar c)^2} e^{-B|t|}
\]

- \( \alpha \) = fine structure constant
- \( \phi \) = relative Coulomb-nuclear phase
- \( G(t) = \) nucleon el.-mag. form factor = \((1 + |t|/0.71)^{-2}\)
- \( \rho = R/\Im [T_{\text{elastic, nuclear}}(t = 0)] \)

Measurement of \( \rho \) by studying the Coulomb – Nuclear interference region down to

\[ |t| \sim 6 \times 10^{-4} \text{ GeV}^2 \]

Reachable with \( \beta^* \sim 1000 \text{ m} \) still in 2012 if RPs can approach beam centre to \( \sim 4\sigma \)
How to reach the Coulomb-Nuclear Interference Region?

The pots have to approach the beam to a distance $\sim 4 \sigma$

Beam emittance $\varepsilon_n < 2 \mu m \text{ rad}$

$\rightarrow$ Challenging but possible
The $\beta^* = 1000$ m Optics

MD in June: first unsqueeze to 1km achieved

14 September:

- special beam optics with $\beta^* = 1000$ m fully commissioned
- collisions in IP1 and IP5 found
- vertical emittances $\varepsilon_n \sim 2$ $\mu$m rad
- 4 vertical TOTEM RPs (out of 8) aligned at $\sim 4$ $\sigma$
- time slot ended $\Rightarrow$ no physics data taken yet, diagnostic data on halo background being analysed

Physics run scheduled for October 2012
After LS1: Low-|t| Elastic Scattering at 13 TeV

- To reach CNI region, push $\beta^*$ to $> 2000$ m
- At 13 TeV: good t-resolution needs parallel-to-point focussing in both x and y (phase advance $\pi/2$)

$\Rightarrow$ Additional magnet cables needed. To be installed during LS1.
Diffractive Analyses Ongoing

Based on $\beta^* = 90\ m\ (7\ TeV)$ run in Oct. 2011 (RP @ $4.8\sigma - 6.5\sigma$):

- **Central Diffraction**
  \[
  \frac{d^2\sigma_{DPE}}{dt_1\ dt_2},\ \sigma_{DPE}
  \]

- **Single Diffraction**
  \[
  \frac{d\sigma_{SD}}{dt},\ \frac{d\sigma_{SD}}{d\xi},\ \sigma_{SD}
  \]

- **Double Diffraction**
  Select diff. masses $3.4\ GeV < M < 10\ GeV$
  requiring tracks in both T2s, veto on T1s

→ Extend studies over full $\eta$ range with CMS (2012 data)
Realisation of common running much earlier than ever anticipated

1. **Hardware**: electrical from RP220 to CMS → trigger within CMS latency
2. **Trigger**: bi-directional level-1 exchange → same events taken
3. **Synchronisation**: orbit number and bunch number in data streams
4. **Offline**:
   - common repository for independently reconstructed data
   - merging procedure → common n-tuples
Joint Data Taking with CMS

May 2012: low pileup run: $\beta^* = 0.6$ m, $\sqrt{s} = 8$ TeV, T1 & T2 & CMS read out

<table>
<thead>
<tr>
<th>Date</th>
<th>Trigger</th>
<th>Inelastic events</th>
<th>RP position</th>
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<tbody>
<tr>
<td>May 1</td>
<td>T2</td>
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<td>BX</td>
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July 2012: $\beta^* = 90$ m, $\sqrt{s} = 8$ TeV, RP & T1 & T2 & CMS read out

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Abundant material for analysis activities throughout LS1

Analyses starting:
- hard diffraction: $p +$ dijets (90m runs)
- combined $dN_{ch} / d\eta$ and multiplicity correlations
**Runs Planned for 2012 / 2013**

- $\beta^* = 1000 \text{ m}$: scheduled for 24 October
  → study CNI region, attempt to measure $\rho$

- RP insertions in normal physics runs ($\beta^* = 0.6 \text{ m}$)
  - hard diffraction together with CMS (high diffractive masses reachable)
  - study of closest possible approach of the horizontal RPs (i.e. acceptable beam losses)
  → essential for all near-beam detector programmes at high luminosity after LS1

- request a low-pileup run ($\mu \sim 5 \%$) with RPs at $\beta^* = 0.6 \text{ m}$ (in May RPs were not aligned)
  → study soft central diffraction final states
    with 2 leading protons defining Pomeron-Pomeron mass $M^2 = \xi_1 \xi_2 s$
    (good $\xi$ resolution at $\beta^* = 0.6 \text{ m}$ → $\sigma(M) \sim 5 \text{ GeV}$)

- participation in the p-Pb runs with insertions of the RPs on the proton side
  → study diffractive/electromagnetic and quasi-elastic p-Pb scattering
  p-Pb test run in September with CMS was successful (T2 trigger given to CMS)
Backup
Upgrade of RP detector system at 220 m

For diffractive physics at high-luminosity (high pileup):
- Installation of additional RPs (horizontal)
- Integration of timing and pixel detectors in horizontal RPs

Guideline:
- The present 220m stations must not be affected (touched) by any upgrade activity, until the high beta special runs after LS1 are finished.
- The new horizontal RPs could be installed during LS1 and equipped successively with new tracking & timing detectors.
- Preparation of engineering change request for TCL6 collimator installation started (CMS+TOTEM)
Detectors

- RP 147
- Package of 10 “edgeless” Si-detectors
- T1 (CSCs)
- T2 (GEMs)
After LS1: Elastic Scattering and Total Cross-Section at lower $E$

- $\sqrt{s} = 900$ GeV: compare with $S\bar{p}pS$
- $\sqrt{s} = 1.8$ TeV: compare with Tevatron, help resolving the $\sigma_{\text{tot}}$ ambiguity
- compare $d\sigma_{\text{elastic}}/dt$ for $pp$ and $\bar{p}p$ (dip vs. shoulder)

- $\rho$ measurement more precise due to access deep into the Coulomb region:
Charged particle acceptance (together with CMS): $|\eta| \leq 6.5$

Trigger: one T2 track(?)

$\frac{dN}{d\eta_{pPb}}$ using T1 & T2 (vs centrality from CMS)

Forward-backward multiplicity correlations?

Central-forward multiplicity correlations?

Energy flow & small $x$: T1+HF, T2+Castor

Pattern recognition at high multiplicity to be optimized

[K. Oesterberg, pA @ LHC workshop, June 2012]
Cross-sections

Test of dynamics:

- **knockout**: $p \, \text{Pb} \rightarrow p + d + (A-2)^*$

  - measure both $p$ & $d$ (= "$p$ with $\Delta p/p = -0.21$") + veto hadron activity.
  - Need large $t$ for $p$ or significant $\Delta p/p$. Study $\Delta p/p$ & $t$ dependence.

- **quasielastic**: $p \, \text{Pb} \rightarrow p \, \text{Pb}^*$
  - dominates at large $t$
  - measure $x_i$ & $t$ of $p$ + only $\gamma$ on opposite side (veto hadrons)

**Diffraction & $\gamma\gamma$**

- very large Pomeron & $\gamma$ fluxes but nothing measured in RP on outgoing Pb side (rate problem?)
- $p$ with significant $\Delta p/p$ (or large $t$) + central object (jets, $J/\Psi$, $Y$ etc.)

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[K. Oesterberg, pA @ LHC workshop, June 2012]
Assumption: $\beta^* = 0.6 \text{ m}$, $\varepsilon_n = 2.5 \mu\text{m rad}$, x-angle = $142.5 \mu\text{rad}$,
$L_{y,\text{RP220}} = 13.07 \text{ m}$, $D_{x,\text{RP220}} = 0.08 \text{ m}$

Diffractive protons: $0.026 < \xi < 0.25$ (horizontal RPs @ 14 $\sigma$)

Quasi-elastic protons: $|t| > 3.7 \text{ GeV}^2$ (vertical RPs @ 12 $\sigma$)

Beam-based alignment for Roman Pots needed.
Elastic Scattering @ 8 TeV, β*=90m: Analysis

- **Optics @8 TeV basically the same as @7 TeV (in terms of optical functions)**
  - follow the same analysis steps

- **Alignment**:
  - RPs aligned wrt collimators; tracks-based alignment; alignment with physics tracks

- **Kinematics reconstruction**:
  - $\Theta^*_{x,y}$ and $x^*$

- **Elastic Tagging**: collinearity, low $\zeta$, vertex

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**Elastic Scattering @ 8 TeV, \(\beta^*=90\text{m}:\) Analysis**

- Optics @8 TeV basically the same as @7 TeV (in terms of optical functions)
  - follow the same analysis steps

- Alignment : RPs aligned wrt collimators; tracks-based alignment; alignment with physics tracks

- Kinematics reconstruction: \(\Theta_{x,y}^*\) and \(x^*\)

- Elastic Tagging: collinearity, low \(\zeta\), vertex

- Acceptance Correction

- Resolution Unfolding

- Normalization: Background Efficiency Luminosity

- Systematics uncertainty determination