The TOTEM Experiment

Jan Kašpar
on behalf of the TOTEM collaboration

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Outline

I) Physics programme
II) Detector apparatus
III) Analyses and results
IV) Upgrade plans
V) Summary
part I

Physics programme
TOTEM: forward hadronic phenomena at LHC

- LHC: \( \approx \frac{1}{3} \) of \( \sigma_{\text{tot}} \) flows more \textit{forward} than conventional experiments can detect.
- \textit{forward} \( \rightarrow \) \textit{low momentum transfer(s)} \( \rightarrow \) \textit{non-perturbative QCD} \( \rightarrow \) little explored/understood (\( \rightarrow \) interesting)
- \textit{diffractive processes} \( \Rightarrow \) non-suppressed \textit{rapidity gaps} \( \Leftarrow \) exchange of colourless objects.

\begin{align*}
\text{Non-diffractive} \\
\text{Colour exchange} \\
dN / d\Delta \eta = \exp(-\Delta \eta)
\end{align*}

\begin{align*}
\text{Diffractive} \\
\text{Colourless exchange with vacuum quantum numbers} \\
dN / d\Delta \eta = \text{const}
\end{align*}

\begin{center}
\textit{rapidity gap}
\end{center}

Incident hadrons retain their quantum numbers remaining colourless.
(Some) processes of interest

- **Elastic Scattering (ES),** $\approx 25$ mb

- **Single Diffraction (SD),** $\approx 10$ mb

- **Double Diffraction (DD),** $\approx 5$ mb

- **Central Diffraction (CD),** $\approx 1$ mb

$\leftarrow$ double line in diagrams: exchange of “Pomeron” – a colourless object with vacuum quantum numbers

\[\downarrow\]

consequence: rapidity gap

in contrast:

- **Non-Diffractive process (ND)**
part II

DETECTOR APPARATUS
TOTEM shares IP with CMS ⇒ collaboration possible
**TOTEM Detectors**

- Telescopes T1 and T2 charged particles from inelastic collisions
  - T1: $3.1 < |\eta| < 4.7$
  - T2: $5.3 < |\eta| < 6.5$

- Roman Pots at the LHC elastic and diffractive protons

- All detectors symmetrically on both sides of IP5
- All detectors trigger-capable
- All detectors radiation tolerant
Telescope T1

- installed inside CMS end-caps
- at 7.5 to 10.5 m from the IP
- one *telescope* on each side of IP
- each telescope consists of two *quarters*

- each quarter formed by 5 *planes* equally spaced along beam
- each plane consists of 3 trapezoidal *CSC detectors*, each covering 60° in azimuth
- Cathode Strip Chamber: gaseous detector with 3 read-out coordinates (at 60° wrt. each other)
Telescope T2

- installed inside CMS shielding between HF and Castor calorimeters
- centred about 13.5 m from the IP
- one telescope on each side of IP
- each telescope consists of two quarters

- each quarter formed by 10 semi-circular planes, assembled in 5 back-to-back mounted pairs
- each plane equipped with a Gas Electron Multiplier detector
  - gaseous detector, electron multiplication by 3 perforated foils (2 mm separation)
  - radial segmentation: strips (resolution \( \approx 0.15 \) mm)
  - coarse radial \( \times \) azimuthal segmentation: pads (for triggering, azimuthal resolution 0.8 \(^\circ\))
Roman Pots

- **stations** installed at ±220 m in the outgoing LHC beam-pipe
- each station has two **units**, separated by ≈ 5 m

- each unit contains 3 **Roman Pots**: top, bottom and horizontal
- Roman Pot = movable beam-pipe insertion
  - *beam unstable* ⇒ RPs retracted to safe position
  - *beam stable* ⇒ RPs as close to beam as reasonable
- typical approach: 10 \( \sigma_{\text{beam}} \) (record 3 \( \sigma_{\text{beam}} \))

- Roman Pot: container for sensors
• each RP contains a *package* of 10 silicon sensors
• 5 pairs of back-to-back mounted strip sensors

• custom developed *“edgeless” sensors*
  ⇒ *insensitive edge* \(\approx 50 \, \mu \text{m} \) (standard about 1 mm)
• single-sided p\(^+\)-n
• 512 strips at pitch of 66 \(\mu\)m, at 45 ° wrt. cut edge
• operated at \(\approx -20 \, ^\circ \text{C} \), bias voltage \(\approx 100 \, \text{V} \)
Proton measurement with Roman Pots

- LHC lattice between IP5 and RPs at 220 m

- **proton transport**: described as in linear optics

\[
\begin{pmatrix}
  x \\
  \theta_x \\
  y \\
  \theta_y \\
  \zeta
\end{pmatrix}
_{\text{RP}}
= \begin{pmatrix}
  v_x & L_x & \cdot & \cdot & D_x \\
  \cdot & \cdot & \cdot & \cdot & \cdot \\
  v_y & L_y & \cdot & \cdot & D_y \\
  \cdot & \cdot & \cdot & \cdot & \cdot \\
  \cdot & \cdot & \cdot & 1
\end{pmatrix}
_{\text{effective length } L}

\begin{pmatrix}
  x^* \\
  \theta_x^* \\
  y^* \\
  \theta_y^* \\
  \zeta
\end{pmatrix}
_{\text{IP}}
\]

**optical functions:**
- effective length \( L \)
- magnification \( v \)
- dispersion \( D \)

\( \zeta = \Delta p/p: \) momentum loss

- **proton reconstruction**: inverted transport RPs \( \rightarrow \) IP
  - optical parameters functions of \( \zeta \Rightarrow \) reconstruction is non-linear problem
  - good knowledge of optics is crucial
**LHC optics**

- optics defines *what* and *how* can be observed – a CD sample seen with 2 different optics

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

\[
\begin{align*}
L_x & \approx 0, & L_y & \approx 260 \text{ m}, & D_x & \approx 4 \text{ cm} \\
\text{diffractive protons in vertical RPs}
\end{align*}
\]

\[
\begin{align*}
L_x & \approx 1.7 \text{ m}, & L_y & \approx 14 \text{ m}, & D_x & \approx 8 \text{ cm} \\
\text{diffractive protons in horizontal RPs}
\end{align*}
\]

- optics carefully optimised for TOTEM special runs

- optics typically “labelled” by \( \beta^* \equiv \text{betatron function at IP} \)
  - beam width: \( \sqrt{\epsilon \beta} \)
  - beam angular divergence: \( \sqrt{\epsilon / \beta} \) (\( \epsilon \): a measure of beam size/divergence)
  - luminosity \( \propto (\text{beam width at IP})^{-2} \propto 1/\beta^* \)
  - example: high \( \beta^* \) ⇒ reduced luminosity but protons “more parallel”
Run scenarios

\((t \approx -p^2 \vartheta^2): \text{four-momentum transfer squared; } \xi = \Delta p/p: \text{fractional momentum loss}\)

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### low **\(\beta^*\)**
- **\(\beta^* = 0.5 \text{ to } 3 \text{ m}\)**
- **\(\mathcal{L} \approx 10^{30} \text{ cm}^{-2}\text{s}^{-1}\)**
- Elastic data available
- \(0.4 \lesssim |t/\text{GeV}^2| \lesssim 3.5\)
- Resolution
  - \(\sigma(\vartheta^*) \approx 15 \mu\text{rad}\)
  - \(\sigma(\xi) \approx 0.2\%\)

- **diffraction, high \(|t|\) elastic scattering, low cross-section processes**

### medium **\(\beta^*\)**
- **\(\beta^* = 90 \text{ m}\)**
- **\(\mathcal{L} \approx 10^{28} \text{ cm}^{-2}\text{s}^{-1}\)**
- Elastic data available
- \(10^{-2} < |t/\text{GeV}^2| \lesssim 1.3\)
- Resolution
  - \(\sigma(\vartheta^*) \approx 1.7 \mu\text{rad}\)
  - \(\sigma(\xi) \approx 0.4 \text{ to } 0.6\%\)

- **diffraction, mid \(|t|\) elastic scattering, total cross section**

### high **\(\beta^*\)**
- **\(\beta^* \gtrsim 1000 \text{ m}\)**
- **\(\mathcal{L} \approx 10^{27} \text{ cm}^{-2}\text{s}^{-1}\)**
- Elastic data available
- \(6 \cdot 10^{-4} < |t/\text{GeV}^2| < 0.3\)
- Resolution
  - \(\sigma(\vartheta^*) \approx 0.4 \mu\text{rad}\)

- **total cross section, low \(|t|\) elastic scattering**

- **all \(\xi\) seen, universal optics**

- **all \(\xi\) seen**
Optics imperfections

good optics knowledge essential for reconstruction

- optics imperfection sources
  - power-converter error: $\Delta I/I \approx 10^{-4}$
  - magnet transfer function: $\Delta B/B \approx 10^{-3}$
  - magnet rotation ($\pm 1$ mrad) and displacements ($< 0.5$ mm)
  - magnet harmonics ($\Delta B \approx 10^{-4}$)
  - beam momentum offset: $\Delta p/p \approx 10^{-3}$
  - beam crossing-angle uncertainty

- optics determination
  - direct measurement – difficult
  - indirect from TOTEM observables

- TOTEM optics determination – variation of magnet/beam parameters (within tolerances) to match TOTEM observables:
  - $L_y^L / L_y^R$
  - $dL_y / ds / L_y$
  - $s(L_x = 0)$
  - $xy$ coupling (tilts in $xy$ plane)
  - ...
Optics refinement with TOTEM data

example for $\beta^* = 3.5\, m$ optics

- optics uncertainty reduced:
  - $x$ projection: from 1.6% to 0.17%
  - $y$ projection: from 4.2% to 0.16%

[H. Niewiadomski, Roman Pots for beam diagnostic, OMCM, CERN, 20-23.06.2011]
[H. Niewiadomski, F. Nemes, LHC Optics Determination with Proton Tracks, IPAC’12, Louisiana, USA, 20-25.05.2012]
Alignment of Roman Pots

- RPs = movable insertions ⇒ each run at different positions
- required angular precision micro-radians ⇒ micro-metre alignment precision needed

- two types of alignment needed
  - alignment of mechanical RP edges → for machine protection
  - alignment of RP sensors → for physics
- need alignment *wrt. the beam*

↓

3-step alignment procedure

1) *Collimation alignment*: RP alignment *wrt. the beam*, rough sensor alignment

- standard procedure for LHC collimators
2) **Track-based alignment**: relative alignment among sensors
   - RP station: no magnetic field → straight tracks
   - misalignments → residuals
   - residual analysis → alignment corrections
   - overlap between horizontal and vertical RPs → relative alignment among all sensors
   - singular/weak modes: e.g. overall shift/rotation
     ⇒ need further alignment step

3) **Alignment with physics processes (elastic scattering)**: sensor alignment wrt. beam
part III

Analyses and results
Elastic scattering

\[ p \rightarrow \text{RP} \]

- interesting process on its own
- two anti-collinear protons ⇒ excellent tool for
  - alignment
  - understanding detector effects
  - optics tuning, etc.

- \( \theta \): scattering angle
- \( \phi \): azimuthal angle
- \( t \): four-momentum transfer squared
  \[ t \approx -p^2\theta^2 \]
Elastic scattering

Pre-TOTEM status

- theoretical/phenomenological models: very different predictions at larger $|t|$

- different $|t|$ regions: different scattering mechanisms/QCD regimes
Elastic scattering Analysis

entirely data-driven

1. Kinematics reconstruction
   - tracks in RPs \( \rightarrow \) kinematics at IP (\( \xi = 0 \) \( \Rightarrow \relatively easy \))
   - choice of formulae \( \rightarrow \) minimisation of systematics

2. Elastic tagging
   - angles left = angles right, vertex left = vertex right
   - protons \( \xi \approx 0 \) \( \Rightarrow \) correlation hit position vs. track angle at RPs

3. Background subtraction

4. Acceptance corrections
   - RP sensors have finite size, LHC apertures
   - azimuthal symmetry \( \Rightarrow \) geometrical correction (+ smearing around edges)

5. Unfolding of resolution effects
   - angular resolution: left-right proton comparison
   - Monte Carlo calculation \( \Rightarrow \) impact on \( t \)-distribution

6. Inefficiency corrections
   - 3-out-of-4 efficiency
   - near-far correlated RP inefficiencies
   - “pile-up” = elastic event + another track in a RP

7. Luminosity
   - from CMS (if available), uncertainty \( \approx 4\% \)
   - from TOTEM (details later on)
Elastic scattering

Results

building a puzzle from measurements with different $\beta^*$

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 8$ TeV

Elastic scattering

First conclusions

- no theoretical/phenomenological model describes completely TOTEM data
- at low $|t|$: nearly exponential decrease
  \[ \frac{d\sigma}{dt} \approx e^{-B|t|} \]

- previously observed trends confirmed: as $\sqrt{s}$ grows
  - “forward peak” shrinks
    ⇒ minimum moves to lower values
  - intercept at $t = 0$ increases
    ⇒ related to $\sigma_{\text{tot}}$ increase
  - forward slope $B$ increases
Elastic scattering

Very low $|t|$: Coulomb-hadronic interference

- $|t|$ as low as $6 \cdot 10^{-4}$ GeV$^2$ (i.e. $\vartheta \approx 6$ $\mu$rad) accessible thanks to
  - $\beta^* = 1000$ m optics: large effective lengths, low beam divergence ($\approx 0.5$ $\mu$rad)
  - RPs approach of $3 \sigma_{\text{beam}}$ from beam

![Graph showing data fit at $\sqrt{s} = 8$ TeV with Coulomb, hadronic, and combined interference]

- interesting aspects
  - Coulomb-hadronic interference $\Rightarrow$ determination of phase of hadronic amplitude
  - Coulomb/hadronic separation $\Rightarrow$ hadronic extrapolation to $t = 0$
    $\Rightarrow$ total-cross section implications via optical theorem

\[ \sigma_{\text{tot}} \propto \Im A_{\text{el}}(t = 0) \]
Elastic scattering

**Hadronic phase: first results**

### Theory

\[ \frac{d\sigma}{dt} \propto |A^{C+H}|^2 \]

\[ A^{C+H} = \text{COMBINATION}(A^C, A^H) \]

- **COMBINATION**: 2 theoretical alternatives
- \( A^C \): well known
- \( A^H \)
  - *modulus*: constrained by TOTEM data \( \Rightarrow \) parametrised \( \exp(Bt + \ldots) \)
  - *phase*: test a range of theoretical predictions

### Fits

- various fit metrics: generalised \( \chi^2 \), Kolmogorov-like
- combination of above choices: little impact on the fit
- very PRELIMINARY result

\[ \varrho = \left. \frac{\Re A^H}{\Im A^H} \right|_{t=0} = 0.110 \pm 0.027^{(\text{stat})} \pm 0.010^{(\text{syst})} + 0.013^{(\text{model})} - 0.012 \]
Total cross-section
Total cross-section
**Pre-TOTEM status**

Various $\sigma_{\text{tot}}$ fits by COMPETE

- Various models/theories:
  \[
  \sigma_{\text{tot}} \sim \ln s, \quad \sigma_{\text{tot}} \sim \ln^2 s, \quad \sigma_{\text{tot}} \sim s^{\alpha-1}
  \]

- Predictions for $\sqrt{s} = 14$ TeV
  \[
  90 \text{ mb} < \sigma_{\text{tot}} < 130 \text{ mb} \Rightarrow 40 \% \text{ uncertainty}
  \]

- Available data not decisive (incompatible Tevatron measurements)
Total cross-section

**Methods**

- consequence of optical theorem

\[
\sigma_{tot}^2 \propto [\Im A_{el}(t = 0)]^2 = \frac{1}{1 + \varrho^2} |A_{el}(t = 0)|^2 \propto \frac{1}{1 + \varrho^2} \frac{d\sigma_{el}}{dt} \bigg|_{t=0}
\]

- 3 methods available

**elastic observables only:**

\[
\sigma_{tot}^2 = \frac{16\pi}{1 + \varrho^2} \frac{1}{\mathcal{L}} \frac{dN_{el}}{dt} \bigg|_{0}
\]

**\(\varrho\)-independent:**

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

**luminosity-independent:**

\[
\sigma_{tot} = \frac{16\pi}{1 + \varrho^2} \frac{dN_{el}/dt|_{0}}{N_{el} + N_{inel}}
\]

- \(\varrho\) value from TOTEM or from an external source, e.g. COMPETE
  - enters as \(1 + \varrho^2\) \(\Rightarrow\) limited impact

- by-product: by method combination luminosity \(\mathcal{L}\) can be determined
• T2 sees $\approx 95\%$ of inelastic events (enough to detect 1 track!)

1) **Raw rate**: event counting with T2
   \[ \downarrow \text{experimental corrections}: \text{trigger and reconstruction inefficiencies, beam-gas event suppression, pile-up consideration} \]

2) **Visible rate**: visible with T2 in perfect conditions
   \[ \downarrow \text{recovery of events with no tracks in T2}: \text{T1-only events, events with gap over T2, low-mass diffraction} \]

3) **Physics rate**: true rate of inelastic events

• only one major Monte-Carlo-based correction: *low-mass diffraction*
  \[ \Rightarrow \text{but can be constrained from data} \]
### Total cross-section

#### Results

<table>
<thead>
<tr>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
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</table>

**elastic observables only:**

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

\[
\sigma_{tot} = (98.6 \pm 2.3) \text{ mb}
\]

- **$\varrho$-independent:** \[\sigma_{tot} = \frac{1}{L} (N_{el} + N_{inel})\]

\[
\sigma_{tot} = (99.1 \pm 4.4) \text{ mb}
\]

- **luminosity-independent:** \[\sigma_{tot} = \frac{16\pi}{1 + \varrho^2} \frac{1}{N_{el} + N_{inel}} \frac{dN_{el}}{dt} \bigg|_0\]

\[
\sigma_{tot} = (98.1 \pm 2.4) \text{ mb}
\]

- **low mass diffraction**

\[
\sigma_{inel}^{|\eta| > 6.5} = \sigma_{tot}^{EOO} - \sigma_{el}^{EOO} - \sigma_{inel}^{\text{visible}} = (2.6 \pm 2.2) \text{ mb}
\]

(greyed: CMS luminosity unavailable)
**Total cross-section**

**Results in context**

![Graph showing total cross-section results](image)

- \( \sigma_{\text{tot}} \), \( \sigma_{\text{inel}} \), and \( \sigma_{\text{el}} \) (mb)
- \( \sqrt{s} \) (GeV)

**Measurements at \( \sqrt{s} = 7 \text{ TeV} \)**

- \( \sigma_{\text{tot}} \)
- \( \sigma_{\text{inel}} \)
- \( \sigma_{\text{el}} \)

- ALICE
- ATLAS
- CMS

- Auger + Glauber
- TOTEM (\( L \)-independent)

- best COMPETE \( \sigma_{\text{tot}} \) fits

- \( 11.4 - 1.52 \ln s + 0.130 \ln^2 s \)

Data available here
Intermezzo: Optics for diffractive studies

\[ x_{\text{RP}} = v_x x^* + L_x \theta_x^* + \xi D_x, \quad \xi = \Delta p/p_0 \]

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

- optical functions at RP 220:
  - \( L_x \approx 0 \), \( L_y \approx 260 \text{ m} \), \( D_x \approx 4 \text{ cm} \)
  - diffractive protons in **vertical RPs**
    (a CD sample)

- \(|\xi|_{\text{min}} = 0\% \Rightarrow \text{low masses}\)
- \(\xi\)-resolution
  - RPs only: (0.4 to 1)\% (\(t\)-dependent)
  - with CMS vertex: \(\approx 2 \times\) better

- \(\beta^*\) (0.7 m here)

- optical functions at RP 220:
  - \( L_x \approx 1.7 \text{ m} \), \( L_y \approx 14 \text{ m} \), \( D_x \approx 8 \text{ cm} \)
  - diffractive protons in **horizontal RPs**
    (a CD sample)

- \(|\xi|_{\text{min}} = 2.8\% \Rightarrow \text{higher masses}\)
- \(\xi\)-resolution
  - RPs only: \(\approx 0.2\%\)
  
  *used so far*

  *planned after long shutdown*
Single diffraction

- kinematics: $\zeta \approx e^{-\Delta \eta}$
  - double “determination” of $\zeta$
    - from proton (Roman Pots)
    - from rapidity gap (T1/2)

- mass of diffractive system $X$
  $m_X \approx \sqrt{s\zeta}$

- minimal mass visible (T2 acceptance):
  $m_X \geq 3.4$ GeV
Single diffraction

Topologies / diffractive-mass classes

- **T2 opposite arm**: $m_X \approx 3.4$ to 7 GeV, $2 \cdot 10^{-7} < \zeta < 1 \cdot 10^{-6}$

- **T1 opposite arm**: $m_X \approx 7$ to 350 GeV, $1 \cdot 10^{-6} < \zeta < 2.5 \cdot 10^{-3}$

- **T1 same arm**: $m_X \approx 350$ to 1100 GeV, $2.5 \cdot 10^{-3} < \zeta < 2.5 \cdot 10^{-2}$

- **T2 same arm**: $m_X \gtrsim 1100$ GeV, $\zeta > 2.5 \cdot 10^{-2}$
Single diffraction

Analysis I

- available data: $\sqrt{s} = 7$ and 8 TeV, $\beta^* = 90$ m (proton in vertical RPs)
  - 7 TeV analysis used here for illustration
  - 8 TeV data: also CMS data available
- trigger: RP & T2
- four RP combinations (left/right × top/bottom) ⇒ each analysed separately ⇒ confidence
- background – pile-up:
  - beam halo (RP) + inelastic (T1/2) or SD/DPE (RP) + inelastic (T1/2)
  ⇒ proton and inelastic products independent
  ⇒ background estimation: events with proton on the “wrong” side

- complicated for class T2 same arm
**Single diffraction**

**Analysis II**

- **corrections**
  - *RP proton acceptance*

- **grey regions = sensors → protons detected**

- **$L_x$ (ellipse width) strongly dependent on $\xi$**

- **$L_y$ (ellipse width) weakly dependent on $\xi$**

- **ellipse centre moves right with $|\xi|$ (dispersion $D_x$)**

- **efficiencies (trigger, reconstruction, ...)**

- **smearing in $t$ and $\xi$ (yet to be applied)**

- **experimental $\xi$ resolution from RPs**

  - **class: T2 opposite arm**
    \[ 2 \cdot 10^{-7} < \xi < 1 \cdot 10^{-6} \]

  - **plotted $\xi$ from RP reconstruction**

  - **Gaussian fit: $\sigma(\xi) = 0.008$**
Single diffraction
First results

• $|t|$-distributions (unfolding not yet applied) fitted with $\frac{d\sigma}{dt} = Ce^{-Bt}$

• cross-section per class, including the invisible low-$|t|$ contribution (exploiting the fit above)

<table>
<thead>
<tr>
<th>Topology</th>
<th>Mass Range</th>
<th>Slope $B$</th>
<th>Extrapolated Cross-section</th>
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<tbody>
<tr>
<td>T2 Opposite</td>
<td>3.4 to 7 GeV</td>
<td>10.1 GeV$^{-2}$</td>
<td>1.8 mb</td>
</tr>
<tr>
<td>T1 Opposite</td>
<td>7 to 350 GeV</td>
<td>8.5 GeV$^{-2}$</td>
<td>3.3 mb</td>
</tr>
<tr>
<td>T1 Same</td>
<td>350 to 1100 GeV</td>
<td>6.8 GeV$^{-2}$</td>
<td>1.4 mb</td>
</tr>
<tr>
<td>T2 Same</td>
<td>above 1100 GeV</td>
<td></td>
<td>effort ongoing ...</td>
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</table>

– already for both proton sides
– PRELIMINARY

• very preliminary

$\sigma_{SD}(3.4 < m_X < 1100 \text{ GeV}) = (6.5 \pm 1.3) \text{ mb}$, \hspace{1cm} $\sigma_{SD}(m_X < 3.4 \text{ GeV}) = \mathcal{O}(2.5 \text{ mb})$

• final goal: $\xi$ and $t$ double-differential distribution
Double diffraction

\[ p \rightarrow X \rightarrow T_1/T_2 \]

\[ p \rightarrow X \rightarrow T_1/T_2 \]
Double diffraction

Method

- Method

\[ \sigma_{DD} = \frac{(\text{experimental corrections}) \cdot (\text{raw data}) - (\text{background})}{L} \]

- Experimental challenge: background (non-diffractive, SD pile-up)

  
  \begin{align*}
  \text{non-diffractive background} & \quad \text{based on control sample } 2 \times T2 + 2 \times T1 \\
  & \quad \text{transferred to } 2 \times T2 + 0 \times T1 \text{ using Monte-Carlo} \\
  \text{SD background} & \quad \text{based on control sample } 1 \times T2 + 0 \times T1 \\
  & \quad \text{transferred to } 2 \times T2 + 0 \times T1 \text{ using the measured SD distributions} \\
  \text{outputs} & \quad \text{integral visible cross-section} \\
  & \quad \text{cross-section as function of } \eta_{\text{min}} \text{ on both sides } \Rightarrow \text{ challenge:} \\
  & \quad \text{reconstructed } \eta_{\text{min}} \rightarrow \text{true/generator } \eta_{\text{min}} \quad \text{(bin migration } \Rightarrow \text{ limited number of bins)}
  \end{align*}

sub-sample with signal \( \gg \) background \( \Rightarrow 2 \times T2 \) and T1 veto
Double diffraction

Results

7 TeV results

• measurement

\[ \sigma_{DD}(4.7 < |\eta_{\text{min}}| < 6.5) = 120 \pm 25 \mu b \]

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<thead>
<tr>
<th></th>
<th>-4.7 &lt; \eta_{\text{min}} &lt; -5.9</th>
<th>-5.9 &lt; \eta_{\text{min}} &lt; -6.5</th>
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<tbody>
<tr>
<td>4.7 &lt; \eta_{\text{min}} &lt; 5.9</td>
<td>66 \pm 19 \mu b</td>
<td>27 \pm 4 \mu b</td>
</tr>
<tr>
<td>5.9 &lt; \eta_{\text{min}} &lt; 6.5</td>
<td>28 \pm 5 \mu b</td>
<td>12 \pm 4 \mu b</td>
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(T1: 3.1 < \eta < 4.7, T2: 5.3 < \eta < 6.5)

• comparison to Monte Carlos

\[ \sigma_{DD}(4.7 < |\eta_{\text{min}}| < 6.5) = 159 \mu b \]

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<tr>
<td>4.7 &lt; \eta_{\text{min}} &lt; 5.9</td>
<td>70 \mu b</td>
<td>37 \mu b</td>
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<tr>
<td>5.9 &lt; \eta_{\text{min}} &lt; 6.5</td>
<td>35 \mu b</td>
<td>17 \mu b</td>
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\[ \sigma_{DD}(4.7 < |\eta_{\text{min}}| < 6.5) = 101 \mu b \]

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<th>-4.7 &lt; \eta_{\text{min}} &lt; -5.9</th>
<th>-5.9 &lt; \eta_{\text{min}} &lt; -6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7 &lt; \eta_{\text{min}} &lt; 5.9</td>
<td>44 \mu b</td>
<td>23 \mu b</td>
</tr>
<tr>
<td>5.9 &lt; \eta_{\text{min}} &lt; 6.5</td>
<td>23 \mu b</td>
<td>12 \mu b</td>
</tr>
</tbody>
</table>

8 TeV results

• similar analysis to be repeated
• improvement expected: data from CMS available
Central diffraction – TOTEM alone

- both protons detected (unprecedented)
- mass of diffractive system $X$
  $$m_X \approx \sqrt{s \xi_1 \xi_2}$$
Central diffraction – TOTEM alone

First results

- available data: $\sqrt{s} = 7$ TeV, $\beta^* = 90$ m
  $\Rightarrow$ almost complete $\xi$ acceptance, but resolution sufficient only $\xi \gtrsim 0.03$
- trigger/event selection: $2 \times$ RP
- background: ES + inelastic, beam halo + inelastic
  - ES: anti-elastic cuts or use forbidden topologies only (top-top, bottom-bottom)
  - beam-halo: cut $|y| > 11 \sigma_{\text{beam}} \Rightarrow$ halo negligible
- $|t_y|$ distribution: all $\xi$ values, only acceptance correction
- estimate of $\sigma_{\text{CD}}$

$$\frac{d^2 \sigma_{\text{CD}}}{dt_1 dt_2} = Ce^{-Bt_1} e^{-Bt_2}$$

$$\sigma_{\text{CD}} = \int_{-\infty}^{0} dt_1 \int_{-\infty}^{0} dt_2 Ce^{-Bt_1} e^{-Bt_2} \approx 1 \text{ mb}$$

- final goal: $\frac{d^4 \sigma_{\text{CD}}}{dt_1 dt_2 d\xi_1 d\xi_2}$

![Graph showing data and MC comparison with fitted function and LHC aperture limit.](image)
Central diffraction – TOTEM + CMS

- both protons detected (unprecedented)
- mass of diffractive system $X$ – double determination (unprecedented)
  - by TOTEM RPs
  - by CMS

\[ m_X \approx \sqrt{s \xi_1 \xi_2} \]
Central diffraction – TOTEM + CMS

Combined TOTEM+CMS analyses

- TOTEM and CMS independent experiments – common runs need:
  - exchange of triggers (TOTEM developed a faster electrical trigger)
  - offline data merging (based on BunchCrossing and Orbit counters)

- TOTEM + CMS = unprecedented rapidity coverage
  - CMS tracker: $|\eta| < 2.5$
  - CMS calorimeters: $|\eta| < 5.5$
  - TOTEM-T1: $3.1 < |\eta| < 4.7$
  - TOTEM-T2: $5.3 < |\eta| < 6.5$
  - CMS-FSC: $6 < |\eta| < 8$

- data available: $\sqrt{s} = 8$ TeV, $\beta^* = 90$ m

- two direction of studies
  - soft CD: inclusive $X$
    ⇒ analysis as with TOTEM alone
  - hard CD: $X = \text{jets} + \ldots$
    ⇒ interesting interplay between soft/non-perturbative and hard/perturbative QCD effects
Central diffraction – TOTEM + CMS

Hard CD

- low cross-section processes
  - background critical (typically pile-up)
  - more data needed
    ⇒ 90 m optics with more bunches or low-$\beta^*$ optics

- pile-up removal:
  - 0 or 1 vertex in CMS
  - RP near edge area removed (1 elastic proton + beam halo or SD)
  - $\xi > 1.5 \%$ (far enough from resolution effects)
  - RP $\xi$ predict event topology in central detectors
  - FSC empty: QCD background protection
  - $M_X^{CMS} < M_X^{TOTEM RPs}$
Forward charged-particle multiplicities

- $dN_{\text{ch}}/d\eta$: mean number of charged particles per event and per unit of pseudorapidity
- probes (non-)perturbative strong interactions and hadronisation
- primary particles only: primary = lifetime $> 30$ ps (definition consistent with other LHC experiments)
- T1 and T2 extend $\eta$ range to forward directions
  - T1 analyses yet in early phase
- measurement based on T2 only
  - still $\approx 95\%$ of inelastic events seen
  - almost all non-diffractive events visible
  - almost all diffraction with $m_X \gtrsim 3.4$ GeV detected
Forward charged-particle multiplicities

**Method**

\[
\frac{\Delta N_{ch}}{\Delta \eta} \bigg|_{\eta=\eta_0} = \frac{1}{N_{ev}} \sum_{\text{events}} \sum_{\text{tracks in bin } \eta_0} \frac{\text{corrections}}{\Delta \eta}
\]

\[
\text{corrections} = \frac{W(\eta_0, z_{\text{impact}})}{\varepsilon(\eta_0, m)} \sum_j B_j(\eta_0) G(\eta_0) S_p(\eta_0) \frac{2\pi}{\Phi} H P
\]

- \(W(\eta_0, z_{\text{impact}})\): probability of a track to be primary
- \(\varepsilon(\eta_0, m)\): primary-track efficiency, function of pad multiplicity \(m\); value: 0.7 to 0.9
- \(B_j(\eta_0)\): bin migration (MC based)
- \(G(\eta_0)\): primary particles not reaching T2 (MC based); value \(\approx 1.05\)
- \(S_p(\eta_0)\): impurity of primary selection, mainly due to \(K_S^0\) and \(\pi^0 \rightarrow \gamma\)'s; MC based; value 0.8 to 0.9
- \(2\pi/\Phi\): geometrical acceptance of 1 quarter; analyses performed per quarter \(\Rightarrow\) confidence
- \(H\): correction for large-shower events discarded in the analysis (MC based); value \(\approx 1.08\)
- \(P\): pile-up correction (estimated from zero-bias data stream); value \(\approx 1.03\)
Forward charged-particle multiplicities

7 TeV Results

main contributions to systematic uncertainty (≈ 10 %)
– subtraction of a large fraction of secondaries (about 80 % of all T2 tracks)
– track efficiency and misalignment uncertainties

gap LHCb – TOTEM T2 will be filled
– analysis of T1 data in progress
– data with shifted IP by 11 m ⇒ shift of T2 acceptance: 6.0 < \eta < 7.3 or 3.8 < \eta < 4.8
Forward charged-particle multiplicities

8 TeV: combined analysis TOTEM + CMS

- combined TOTEM + CMS analysis
  - the same T2-triggered data sample
  - unified track selection

- number of improvements wrt. 7 TeV analysis
  - improved simulation of T2 detector response
  - vertex information from CMS reduces pile-up correction
  - MC better tuned to reproduce LHC data

PRELIMINARY RESULT:
corrections and correlated systematics between CMS and TOTEM under study
• TOTEM stand-alone analysis performed also for different event classes:
  – inclusive: as before
  – non-single-diffractive enhanced: requiring both hemispheres of T2 on
  – single-diffractive enhanced: requiring only one hemisphere of T2 on

• in future: also correlations left/centre/right
**Upgrade plans**

- now: LHC in Long Shutdown 1
  - restart 2015: $\sqrt{s} = 14$ TeV, possibly even higher luminosities
    $\Rightarrow$ higher pile-up

- TOTEM: interest in lower-cross-section processes $\Rightarrow$ higher luminosity needed
  $\Rightarrow$ higher pile-up

Two aspects of coping with pile-up

- *RP detectors resolve multiple tracks*
  - two new units will be installed – hosting pixel or rotated-strip detectors

- *association of RP and central detector (CMS) tracks* $\Rightarrow$ tracks with common vertex
  - current RPs: with certain optics, transverse vertex component(s) determinable $\Rightarrow$ insufficient
  - two new units with timing detectors, resolution $\lesssim 30$ ps
Summary

Number of results published
- elastic differential cross-section ($\sqrt{s} = 7$ TeV)
- total, elastic and inelastic cross-section ($\sqrt{s} = 7$ and 8 TeV)
- forward charged-particle pseudorapidity density ($\sqrt{s} = 7$ TeV)

Number of analyses in progress, some of them combined with CMS
- double diffraction ($\sqrt{s} = 7$ and 8 TeV)
- low-|t| elastic cross-section and Coulomb-interference ($\sqrt{s} = 8$ TeV)
- elastic differential cross-section ($\sqrt{s} = 8$ TeV)
- forward charged-particle pseudorapidity density ($\sqrt{s} = 8$ TeV), with CMS
- single diffraction ($\sqrt{s} = 7$ and 8 TeV)
- central diffraction, soft and hard ($\sqrt{s} = 7$ and 8 TeV), some with CMS

More data available
- p + p data at $\sqrt{s} = 2.76$ TeV
- p + A data

Roman Pot upgrade ongoing
- preparation for higher luminosities (higher pile-up)