The TOTEM experiment at the LHC and its physics results

Frigyes Nemes (Eötvös University) on behalf of the TOTEM collaboration

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

Hadron Structure'13
2013, 29 June – 4 July
TOTEM Physics

**Total cross-section**

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

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

- ISR
- UA1
- UA5
- TEVATRON
- LHC

**Elastic Scattering**

**Diffraction: soft (and hard with CMS)**

![Diagrams of elastic scattering](image)

- Elastic forward physics

**Forward physics**

![Graph showing forward physics](image)

- Hadron Structure'13 6/18/2013
- Frigyes Nemes, TOTEM
Experimental layout

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

CASTOR (CMS)
The inelastic telescope T1

Properties:

- installed inside CMS at 7.5 to 10.5 m from IP5
- there is one telescope on each side of IP5
- each telescope consists of two quarters

- the quarters are formed by 5 equally spaced planes
- the planes contain 3 trapezoidal CSC detectors, each covering 60° in azimuth
- Cathode Strip Chamber: gaseous detector with 3 read-out coordinates (at 60° wrt. each other)
The T2 inelastic telescope

Properties:

- installed inside CMS shielding between HF and Castor calorimeters
- centered around 13.5 m from IP5
- there is one telescope on each side of IP5
- each telescope contains 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 ≈ 0.15 mm)
Roman Pot stations

1 RP station:
- 2 units at about 5 m distance
- 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 relative to the beam
- overlapping detectors: relative alignment (10 µm inside unit between 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

Horizontal RP
Vertical RPs
BPM

10 planes of edgeless detectors
Si edgeless detector
1 Roman Pot
LHC Optics

Essential for TOTEM physics!

- The relevant magnet lattice:

Proton transport description IP5 → Roman Pots

- Proton position at a given RP \((x, y)\) is a function of \((x^*, y^*)\) and angle \((\Theta_x^*, \Theta_y^*)\) at IP5

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

Measured...

... and reconstructed proton kinematics

\[
\Theta_y^* = \frac{y}{L_y}
\]

\[
\Theta_x^* = \frac{dL_x}{ds}^{-1} \left( \Theta_x - \frac{d\nu_x}{ds} x^* \right)
\]

Machine imperfections alter the optics:

- Strength conversion error, \(\sigma(B)/B \approx 10^{-3}\)
- Beam momentum offset, \(\sigma(p)/p \approx 10^{-3}\)
- Magnet rotations, beam harmonics, ...

<table>
<thead>
<tr>
<th>Perturbed element</th>
<th>(\delta L_{y,b1}/L_{y,b1}) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQXA.1R5</td>
<td>0.98</td>
</tr>
<tr>
<td>MQXB.A2R5</td>
<td>-2.24</td>
</tr>
</tbody>
</table>

Frigyes Nemes, TOTEM
Optics optimization

Optics estimation based on:
- MAD-X based Monte-Carlo
- Measured optical function ratios from Roman Pots

F. Nemes, H. Niewiadomski, *LHC Optics Determination with Proton Tracks*
IPAC'12, Louisiana, USA, 20-25.05.2012

Spread due to imperfections

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Physics results
Elastic scattering

Elastic tagging:
- $\sqrt{s} = 7$ TeV, $\beta^* = 3.5$ m
- Topology, collinearity cuts

Collinearity $\Theta_x$
Spread in agreement with beam divergence (17-18 $\mu$rad)

Collinearity $\Theta_y$
TOTEM first elastic $\sigma/dt$ result

After acceptance corrections, unfolding, inefficiency corrections, luminosity:

- $|t|$ range spans from 0.36 to 2.5 GeV$^2$
- below $|t| = 0.47$ GeV$^2$ exponential $e^{-B|t|}$ behavior
- dip moves to lower $|t|$, proton becomes “larger”
- 1.5 - 2.0 GeV$^2$: power low behavior $|t|^{-n}$
Several model descriptions:

- the data show a strong discriminative power

Bourrely model & Petrov model:

- the slope $B_{|t|=0.4 \text{ GeV}^2}$, $t_{\text{dip}}$ and the exponent $n$ at large $|t|$ are consistent with the data
- not consistent with the cross-section $d\sigma/dt$ in the measured range
- other models are less consistent

The measured $d\sigma/dt$ compared with predictions of several models

| Model          | $B_{|t|=-0.4 \text{ GeV}^2}$ [GeV$^{-2}$] | $t_{\text{dip}}$ [GeV$^2$] | $t^{-N}$ [1.5–2.0 GeV$^2$] [N] |
|----------------|------------------------------------------|---------------------------|---------------------------------|
| Islam          | 19.9                                     | 0.65                      | 5.0                             |
| Jenkovsky      | 20.1                                     | 0.72                      | 4.2                             |
| Petrov         | 22.7                                     | 0.52                      | 7.0                             |
| Bourrely       | 21.7                                     | 0.54                      | 8.4                             |
| Block          | 24.4                                     | 0.48                      | 10.4                            |
| TOTEM          | $23.6 \pm 0.5 \pm 0.4$                   | $0.53 \pm 0.01 \pm 0.01$  | $7.8 \pm 0.3 \pm 0.1$           |
Low-t measurement, cross-sections

Properties:

- $\beta^* = 90\,\text{m}$
- Excellent agreement between the two measurements with different optics
- The exponential slope $B$ confirms that it increases with $\sqrt{s}$:

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

- Extrapolation to $t = 0$:

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

- Integral elastic cross-section:

$$\sigma_{el} = 8.3\,\text{mb}^{\text{extrapol.}} + 16.5\,\text{mb}^{\text{measured}} = 24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}}\,\text{mb}$$

- Total cross-section (with optical theorem):

$$\sigma_{tot} = \left(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}}\right)\,\text{mb}$$
$|t_{\text{min}}| = 5 \cdot 10^{-3} \text{ GeV}^2$ at 7 TeV
Extrapolation to \( t = 0 \)

- **Slope parameter:**

\[
B = \left(19.89 \pm 0.03_{\text{stat}} \pm 0.27_{\text{syst}} \right) \text{GeV}^{-2}
\]

- **Extrapolation:**

\[
\left. \frac{d\sigma}{dt} \right|_{t=0} = (506.4 \pm 0.9_{\text{stat}} \pm 23_{\text{syst}}) \text{mb GeV}^{-2}
\]

- **Elastic cross section:**

\[
\sigma_{el} = 25.43 \pm 0.03_{\text{stat}} \pm 1.07_{\text{syst}} \text{mb}
\]

- **91\% is measured**
- **EPL 101(2013) 21002**
Inelastic cross-section measurement

Trigger: at least one track in T2
• 95 % of inelastic events

1. **Raw rate**: event counting with T2

   Experimental corrections: trigger and reconstruction inefficiencies, beam-gas event suppression, pile-up

2. **Visible rate**: visible with T2 in perfect conditions

   Estimation of events with no tracks in T2: 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 (which can be constrained from data)

\[ \sigma_{inel} = 73.7 \pm 3.4 \text{ mb} \]
σ\text{tot} with 4 methods

At \sqrt{s}=7 \text{ TeV}:

   - depends on CMS luminosity for low-L bunches, elastic efficiencies and on ρ
     \[
     \sigma_{\text{tot}}^2 = \frac{16\pi(hc)^2}{1 + \rho^2} \cdot \frac{d\sigma_{\text{el}}}{dt} \bigg|_{t=0}
     \]
     \[
     \sigma_{\text{tot}} = 98.3 \pm 2.8 \text{ mb}
     \]

   \[
   \sigma_{\text{tot}} = 98.6 \pm 2.2 \text{ mb}
   \]

   - minimizes dependence on elastic efficiencies and no dependence on ρ
     \[
     \sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}
     \]
     \[
     \sigma_{\text{tot}} = 99.1 \pm 4.3 \text{ mb}
     \]

   - Eliminates dependence on luminosity
     \[
     \sigma_{\text{tot}} = \frac{16\pi(hc)^2}{1 + \rho^2} \cdot \left( \frac{dN_{EL}}{dt} \bigg|_{t=0} \right) \frac{N_{EL} + N_{INEL}}{N_{EL} + N_{INEL}}
     \]
     \[
     \sigma_{\text{tot}} = 98.0 \pm 2.5 \text{ mb}
     \]
Luminosity independent cross-sections $\sqrt{s}=8$ TeV

- $\beta^* = 90$ m
- Accepted by PRL
- Elastic, inelastic, total cross-sections

<table>
<thead>
<tr>
<th>$\sigma_{\text{tot}}$ [mb]</th>
<th>$\sigma_{\text{el}}$ [mb]</th>
<th>$\sigma_{\text{inel}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$101.7 \pm 2.9$</td>
<td>$27.1 \pm 1.4$</td>
<td>$74.7 \pm 1.7$</td>
</tr>
</tbody>
</table>

![Graph showing cross-sections](#)
Hadronic-Coulomb interference at 8 TeV

Analysis aim:
• Measure $d\sigma_{el}/dt$ at the smallest possible proton $|t|$ (where the Coulomb interaction can be probed):

$$\frac{d\sigma}{dt} \propto |A_{C+H}|^2$$

• Coulomb + Hadronic + Interference
• Determination of $\rho$:

$$\rho = \left. \frac{\text{Re} A^H}{\text{Im} A^H} \right|_{t=0}$$

• Further improve the total cross-section $\sigma_{tot}$ measurement

The relevant data set:
• $\sqrt{s} = 8$ TeV, $\beta^* = 1000$ m
• RP at $3 \times \sigma_{\text{beam}}$
• $|t|_{\text{min}} = 6 \times 10^{-4}$ GeV^2
Hadronic-Coulomb interference at 8 TeV

Extraction of $\rho$ and $\sigma_{\text{tot}}$ by fitting the Hadronic-Coulomb interference region:

Error bars include:

- Fit statistical uncertainty
- The effect induced on the fit by the relevant experimental uncertainties (misalignment, normalization,..)

$$\rho = 0.107 \pm 0.027_{\text{stat}} \pm 0.010_{\text{syst}} \left[ + 0.009 - 0.009 \right]$$

Green line + band: 8 TeV $\sigma_{\text{tot}}$ measurement ($\beta^* =90\text{m}$, luminosity independent):
Forward and diffractive physics
Inelastic and Diffractive Processes

All the drawings show soft interactions. In case of hard interactions there should be jets, which fall in the same rapidity intervals.

Non-diffractive inelastic (ND) ~60 mb

Elastic Scattering ~25 mb

Single Diffraction ~10 mb

Double Diffraction ~5 mb

Double Pomeron Exchange ~1 mb

Multi Pomeron Exchange << 1 mb

Measure $\sigma (M,\xi,t)$
$dN_{ch}/d\eta$ measured with T2, $\sqrt{s}=7$ TeV

**Very forward measurement with T2:**
- Published *EPL, 98 (2012) 31002*
- Visible cross section measured on data: $\sim 94\% \sigma_{\text{inel}}$
- Diffractive mass $M_{\text{diff}} > 3.4$ GeV

- **Main contributions to the systematical error:**
  - Subtraction of secondary particles.
  - Track efficiency
  - Misalignment uncertainties

---

**Combined with other LHC exp.**
- ALICE Data. Inelastic, Nch $> 0$ in $|\eta| < 1$
- ATLAS Data. Inelastic, Nch $> 2$ in $|\eta| < 2.5, p_T > 0.1$ GeV/c
- CMS Data (NSD)
- TOTEM-T2 Data. Inelastic, Nch $> 0$ in $5.2 < |\eta| < 8.5, p_T > 40$ MeV/c
- LHCb Data, Nch $> 0$ in $2.0 < |\eta| < 4.5$

**Models and Data Points:**
- Pythia 8.108 (Default-Tune)
- Sherpa 1.3.0 (Default-Tune)
- Pythia 6.42 D6T
- PhoJet 1.12
- TOTEM Data
CMS+TOTEM common $dN_{\text{ch}}/d\eta$ @ 8 TeV

Very forward measurement with T2:

- CMS vertex information is used to reduce the pile-up correction
- Both CMS and TOTEM analysis obtained triggering with T2, on the same events
- Same CMS-TOTEM event selection (at least a track reconstructed in T2)
- Measurements are representative for an inelastic event sample with at least a primary charged particle with $p_t > 40$ MeV/c produced in the range $5.3 < |\eta| < 6.5$
Diffractive physics
Soft Single Diffractive cross-section 7 TeV

**Low mass diffraction** ( $2 \cdot 10^{-7} < \xi < 10^{-6}$ )

- Tracks in the T2 hemisphere opposite to the proton

**Very high mass** ( $\xi > 2.5\%$ )

- SD events are triggered with T2, only 1 proton required in RP
- $M$ obtained from the rapidity gap estimation based on charged track $\eta$ in T1 and T2

$\Delta \eta = -\ln \xi$

<table>
<thead>
<tr>
<th>SD class</th>
<th>Inelastic telescopes configuration</th>
<th>Mass</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Mass</td>
<td>$p + T2$ opposite only (no T1)</td>
<td>3.4 - 7 GeV</td>
<td>$2 \cdot 10^{-7} &lt; \xi &lt; 10^{-6}$</td>
</tr>
<tr>
<td>Medium Mass</td>
<td>$p + T2$ opposite + T1 opposite</td>
<td>7 - 350 GeV</td>
<td>$10^{-6} &lt; \xi &lt; 0.25%$</td>
</tr>
<tr>
<td>High Mass</td>
<td>$p + T2$ opposite + T1 same</td>
<td>0.35 - 1.1 TeV</td>
<td>$0.25% &lt; \xi &lt; 2.5%$</td>
</tr>
<tr>
<td>Very High Mass</td>
<td>$p +$ both T2 arms</td>
<td>$&gt; 1.1$ TeV</td>
<td>$&gt; 2.5%$</td>
</tr>
</tbody>
</table>
Soft Single Diffractive cross-section 7 TeV

\[ \frac{d\sigma}{dt} \propto C \cdot e^{-B \cdot t} \]

Corrections included:
- Trigger efficiency
- Reconstruction efficiency
- Proton acceptance
- Background subtraction
- Extrapolation to \( t = 0 \)

Missing corrections:
- \( \xi \) – resolution
- Beam divergence effects

Estimated uncertainty:
- \( B \sim 15\% \), \( \sigma \sim 20\% \)

Very preliminary result:
- \( \sigma_{SD} = 6.5 \pm 1.3 \) mb
- \( 3.4 < M_{SD} < 1100 \) GeV
- Very-high masses: ongoing

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Soft Double Diffractive cross-section at 7 TeV

**Event selection:**
- Trigger with T2, at least one track in both T2 hemispheres, no tracks in T1
- “(0T1+2T2) topology”

**Aim:**
- Measurement of soft double diffractive cross-section with particle $\eta_{\text{min}}$ visible to TOTEM T2 ($4.7 < |\eta_{\text{min}}| < 6.5 \equiv 3.4 < M_{\text{diff}} < 8 \text{ GeV}$)
- ND background estimated scaling the MC prediction using a control sample from data dominated by ND (2T1+2T2 events)
- SD background estimated completely from data using a SD-dominated control sample (0T1+1T2) with protons in the RP

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Soft Double Diffractive cross-section at 7 TeV

Results from 7 TeV data:
• Preliminary
• the $\sigma_{DD}$ uncertainty is dominated by events with $|\eta_{\text{min}}|$ outside detector acceptance

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

<table>
<thead>
<tr>
<th>$\eta_{\text{min}}$ range</th>
<th>$\sigma$ (Pythia 8)</th>
<th>$\sigma$ (Phojet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.7 $&lt; \eta_{\text{min}} &lt;$ -5.9</td>
<td>66±19 $\mu$b</td>
<td>50 $\mu$b</td>
</tr>
<tr>
<td>-5.9 $&lt; \eta_{\text{min}} &lt;$ -6.5</td>
<td>27±4 $\mu$b</td>
<td>37 $\mu$b</td>
</tr>
<tr>
<td>4.7 $&lt; \eta_{\text{min}} &lt;$ 5.9</td>
<td>60 $\mu$b</td>
<td>44 $\mu$b</td>
</tr>
<tr>
<td>5.9 $&lt; \eta_{\text{min}} &lt;$ 6.5</td>
<td>28±5 $\mu$b</td>
<td>23 $\mu$b</td>
</tr>
</tbody>
</table>

MC comparisons:
• Improvement expected with the 8 TeV data, including also the CMS information

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

$\sigma_{DD}(4.7<|\eta_{\text{min}}|<6.5) = 101 \, \mu\text{b}$
Central Diffraction (or DPE) TOTEM alone

Correlation between leading protons and forward detector T2:

\[ \xi_1 = \Delta p_1/p_1 \]

\[ \xi_2 = \Delta p_2/p_2 \]

run: 37220007, event: 9904

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Central Diffraction TOTEM alone

Available data $\sqrt{s}=7\text{ TeV}$ and $\beta^*=90\text{m}$ optics:

- trigger selection: $2 \times \text{RP}$
- nearly complete $\xi$-acceptance
- background: elastic, beam-halo + inelastic
- elastic: anti-elastic cuts, or use forbidden topologies (top-top, bottom-bottom)
- beam-halo: $|y| > 11 \times \sigma_{\text{beam}} \rightarrow$ halo is negligible

**$\sigma_{\text{CD}}$ estimation:**

$$
\frac{d^2\sigma_{\text{CD}}}{dt_1 dt_2} = C(\Delta \varphi_{1,2}) e^{-B_{t_1}} e^{-B_{t_2}}
$$

$$
\sigma_{\text{CD}} = \int_0^\infty \int_0^\infty \frac{d^2\sigma_{\text{CD}}}{dt_1 dt_2} \approx 1\text{ mb}
$$

Single arm CD event rate in RP integrated $\xi$, acceptance corrected
Unprecedented properties:

- Mass of diffractive system X is double determined
  - By TOTEM Roman Pots $M_X = \sqrt{s} \xi_1 \xi_2$
  - By CMS
- Double arm proton detection
Central Diffraction TOTEM+CMS

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 : $6 < |\eta| < 8$

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

- CMS and TOTEM is consistent within resolution
- $M_{CMS}(\text{particle flow}) = M_{TOTEM}$
- $p_{CMS}(\text{particle flow}) = p_{TOTEM}$

Low cross-section processes:

- Background critical (pile-up)
- More data needed

Pile-up removal

- 0 or 1 vertex in CMS
- RP near edge area removed (1 elastic proton + beam halo or SD)
- $\xi > 1.5\%$
- RP $\xi$ predicts event topology in central detectors
- FSC empty: QCD background protection
- $M_{X,CMS} < M_{X,RP}$
Central Diffraction TOTEM+CMS

Run / Event: 198903 / 3478279
- $\beta^* = 90$ m
- Jets $E_T = 65, 45, 27$ GeV
- $\sum p_T$ (CMS) = 3.4 GeV
- FSC empty both sides
- $\xi^- = -0.1, \xi^+ = -0.01$
- $M(pp) = 244$ GeV
- $M_{CMS} = 219$ GeV
Summary

Total cross-section

Measured at 7 and 8 TeV

Elastic Scattering

Measured at 7 and 8 TeV

Forward physics

Forward multiplicity distribution 7 and 8 TeV

Diffraction: soft (and hard with CMS)

Preliminary results
• DD, CD, SD
• Many analysis in progress!

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TOTEM Consolidation & Upgrade program

**Present : LHC in LS1**
- Restart: 2015 at $\sqrt{s}=7$ TeV → even higher luminosities → higher pile-up
- TOTEM interest to lower cross-section processes → higher lumi. → pile-up

**How to deal with pile-up?**
- two units will be replaced hosting rotated (or pixel) detectors → multiple tracks can be resolved
- association of TOTEM and CMS tracks: two new units hosting timing detectors

**RP147:**
- relocated to 203-213 m → longer arm → better angular resolution
- 1 unit rotated by 8 degrees

**Other upgrade activities:**
- RP impedance optimization → reduce heating → reduce feedback on beam
- Secondary particle / shower production studies
Thank you for your attention!
Backup slides
Missing acceptance in $\theta_y^*$ due to beam divergence

Correction error ($t_y$):
- $0.31 \text{ GeV}^2$: 30%
- $0.33 \text{ GeV}^2$: 11%
- $0.35 \text{ GeV}^2$: 2%
- $0.4 \text{ GeV}^2$: 0.8%
- $0.5 \text{ GeV}^2$: 0.1%

$|t| < 0.36 \text{ GeV}^2$ excluded from analysis
φ-acceptance corrections

Critical at low $t$-acceptance limit

### Total φ-acceptance correction

<table>
<thead>
<tr>
<th>No.</th>
<th>$t$ [GeV$^2$]</th>
<th>$\Theta^*$ [rad]</th>
<th>Accepted $\phi$ (2 diag.) [$^\circ$]</th>
<th>φ accept. correct. factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.33</td>
<td>1.65E-04</td>
<td>38.6</td>
<td>9.3 ± 4.7%</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>1.71E-04</td>
<td>76.4</td>
<td>4.7 ± 1.8%</td>
</tr>
<tr>
<td>3</td>
<td>0.60</td>
<td>2.21E-04</td>
<td>162.5</td>
<td>2.2 ± 0.3%</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>2.86E-04</td>
<td>209.8</td>
<td>1.7 ± 0.1%</td>
</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>3.83E-04</td>
<td>246.3</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>3.00</td>
<td>4.95E-04</td>
<td>269.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

| $|t| < 0.36$GeV$^2$ excluded from analysis |
Differential DPE distributions (uncorrected)

RP reconstruction alone

\[ \xi \text{-distribution} \]

\[ \frac{dN}{d\xi_{1,2}} \text{ Uncorrected} \]

- proton 45
- proton 56

\[ \xi_{1,2} > 3\% \]

- acceptance loss

\[ t \text{-distribution} \]

\[ \frac{dN}{dt} \text{ Uncorrected} \]

- all \( \xi_{1,2} \)

- acceptance difference

\[ M \text{-distribution} \]

\[ \frac{dN}{dM} \text{ Uncorrected} \]

- proton 45
- proton 56

\[ M = \sqrt{E_1 + E_2} \text{ [GeV]} \]

\[ \xi_{1,2} > 3\% \]