First Measurements of Proton-Proton Elastic Scattering and Total Cross-Section at the LHC

EDS 2011
Qui Nhon, Vietnam

Mario Deile
on behalf of the TOTEM Collaboration
Roman Pots: measure elastic & diffractive protons close to outgoing beam

Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$
TOTEM Detectors

Package of 10 “edgeless” Si-detectors

RP Unit

Horizontal Pot  Vertical Pot  BPM

T1
(CSCs)

T2
(GEMs)
Presented here: data at $\sqrt{s} = 7$ TeV from 2010 and 2011

- Elastic scattering for $|t| \in [0.36; 2.5] \text{ GeV}^2$
  \[EPL \text{ 95 2011, 41001}\]

- Total pp cross-section measurement based on elastic scattering at $|t| \in [0.02; 0.4] \text{ GeV}^2$
  \[EPL \text{ 96 (2011) 21002}\]

Optical Theorem:
\[\sigma_{\text{TOT}}^2 = \frac{16\pi(hc)^2}{1 + \rho^2} \left| \frac{d\sigma_{\text{EL}}}{dt} \right|_{t=0}\]

Use $\rho$ from COMPETE fit:
\[\rho = 0.14^{+0.01}_{-0.08}\]

Normalisation with luminosity from CMS
\[\frac{d\sigma_{\text{EL}}}{dt} = \frac{1}{L} \frac{dN_{\text{EL}}}{dt}\]

Outlook:
- ongoing analyses of existing data
- plans for data taking in 2012 and beyond
(x*, y*): vertex position
(θx*, θy*): emission angle: \( t \approx -p^2 (θx*^2 + θy*^2) \)
ξ = Δp/p: momentum loss (diffraction)

\[ y_{det} = L_y θ_y^* + v_y y^* \]

\( β^* = 90 \text{ m}: L_y = 263 \text{ m}, v_y \approx 0 \)
\( β^* = 3.5 \text{ m}: L_y \approx 20 \text{ m}, v_y = 4.3 \)
→ Reconstruct via track positions

\[ x_{det} = L_x θ_x^* + v_x x^* + Dξ \]

Elastic: ξ = 0

\( β^* = 90 \text{ m}: L_x \approx 0, v_x = -1.9 \)
\( β^* = 3.5 \text{ m}: L_x \approx 0, v_x = 3.1 \)
→ Use derivative (reconstruct via local track angles):

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

| Beam width @ vertex | Angular beam divergence | Min. reachable |t|
|----------------------|-------------------------|---------------|
| \( σ_{x,y}^* \approx 1-3.5 \text{ m} \) | \( σ_{x,y}^* \) small | \( |t_{min}| \approx 0.3-1 \text{ GeV}^2 \) |
| \( β^* = 90 \text{ m} \) | \( σ_{x,y}^* \) large | \( σ(θ_{x,y}^*) \) large | \( |t_{min}| \approx 10^{-2} \text{ GeV}^2 \) |
Track distribution for an inclusive trigger (global “OR”)

\[ \xi = \frac{\Delta p}{p} \]
Proton tracks of a single diagonal (left-right coincidences)

Integrated luminosity: 6.2 nbarn$^{-1}$
Inelastic pile-up ~ 0.8 ev / bx

$\beta^*$ = 3.5 m, big bunches (7 x 10$^{10}$ p/b)
RPs at 7 $\sigma$ from beam centre

$\beta^*$ = 90 m, small bunches (1.5 x 10$^{10}$ p/b)
RPs at 10 $\sigma$ from beam centre

Integrated luminosity: 1.65 $\mu$barn$^{-1}$
Inelastic pile-up ~ 0.005 ev / bx
1. Low $|\xi|$ selection: $|x| < 3\sigma_x$ @ $L_x = 0$

$$x = L_x \Theta_x + \xi D + v_x x^*$$

2. Elastic collinearity:

<table>
<thead>
<tr>
<th>Total triggers</th>
<th>5.28M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructed tracks &amp; elastic topology</td>
<td>293k</td>
</tr>
<tr>
<td>Low $</td>
<td>\xi</td>
</tr>
<tr>
<td>Collinearity cuts</td>
<td>66.0k</td>
</tr>
</tbody>
</table>

Data outside the $3\sigma$ cuts used for background estimation
Optics Matching

• Optics defined by the magnetic lattice elements $T_i$ between IP5 and RP:

$$
\begin{pmatrix}
  x \\
  \Theta_x \\
  y \\
  \Theta_y
\end{pmatrix}_{\text{RP}} =
\begin{pmatrix}
  x^* \\
  \Theta_x^* \\
  y^* \\
  \Theta_y^*
\end{pmatrix}_{\text{IP5}}
= \prod_{i=M}^{1} [T_i(k_i) + \Delta T_i] = \begin{pmatrix}
  v_x & L_x & re_{13} & re_{14} \\
  \frac{dv_x}{ds} & \frac{dL_x}{ds} & re_{23} & re_{24} \\
  re_{31} & re_{32} & v_y & \left| L_y \right| \\
  \frac{dv_y}{ds} & \frac{dL_y}{ds}
\end{pmatrix}
\Delta T_i \quad \text{– magnet imperfections}

\begin{pmatrix}
  \frac{dL_x}{ds} \\
  \frac{dL_y}{ds}
\end{pmatrix} \quad \text{– values needed for proton reconstruction}

• $T_i$ determined by magnet currents

• Magnet currents continuously measured, but tolerances and imperfections leading to $\Delta T_i$:
  o Beam momentum offset ($\Delta p/p = 10^{-3}$)
  o Magnet transfer function error, $I \rightarrow B$, ($\Delta B/B = 10^{-3}$)
  o Magnet rotations and displacements ($\Delta \psi < 1\text{mrad}$, $\Delta x, \Delta y < 0.5\text{mm}$, WISE database)
  o Power converter errors, $k \rightarrow I$, ($\Delta I/I < 10^{-4}$)
  o Magnet harmonics ($\Delta B/B = O(10^{-4}) @ R_{\text{ref}} = 17\text{mm}$, WISE database)

  • The elements of $T$ are correlated and cannot take arbitrary values

• The TOTEM RP measurements provide additional constraints:
  o single beam constraints (position – angle correlations, x-y coupling)
  o two-beam constraints via elastic scattering ($\Theta_{\text{left}}^* \text{ vs. } \Theta_{\text{right}}^*$)

$\rightarrow$ Matching by a fit with 26 parameters (magnet strengths, rotations, beam energy) and 36 constraints.

$\rightarrow$ Error propagation to relevant optical functions $L_y (1\%)$ and $dL_x/ds (0.7\%)$
Acceptance

\[ |t| < 0.36 \text{GeV}^2 \text{ removed} \]

\[ \text{Total correction factor} \leq 10 \pm 0.1 \]
TOTEM: 2 “Experiments”

after resolution unfolding:

top 45 - bottom 56 ; bottom 45 - top 56

2 diagonals:

2 different experiments, but not 2 independent experiments

→ verification of alignment
TOTEM Result

\[ B = 23.6^{+0.5\text{ stat}}_{-0.4\text{ syst}} \text{ GeV}^2 \]

\[ t_{\text{dip}} = -0.53^{+0.01\text{ stat}}_{-0.01\text{ syst}} \text{ GeV}^2 \]

**Table:**

| \( |t| \) in GeV\(^2\) | \( \delta t \) on single \( t \) meas. | \( \delta t = \delta t^{\text{stat}}(t) \oplus \delta t^{\text{syst}}(t) \) | \( \delta (d\sigma/dt) = \delta (d\sigma/dt)^{\text{stat}}(t) \oplus \delta (d\sigma/dt)^{\text{syst}}(t) \) |
|---------------|----------------|-------------------------------------------------|-------------------------------------------------|
| 0.4 GeV\(^2\) | 13 % (from beam div.) | \( \delta t = \pm 0.5\%^{\text{stat}} \pm 2.6\%^{\text{syst}} \) | \( \delta (d\sigma/dt) = \pm 2.6\%^{\text{stat}} \pm 25 \%^{\text{syst}} \) |
| 0.5 GeV\(^2\) | 12 % (from beam div.) | \( \delta t = \pm 0.7\%^{\text{stat}} \pm 2.5\%^{\text{syst}} \) | \( \delta (d\sigma/dt) = \pm 4.4\%^{\text{stat}} \pm 28 \%^{\text{syst}} \) |
| 1.5 GeV\(^2\) | 7 % (from beam div.) | \( \delta t = \pm 0.8\%^{\text{stat}} \pm 2.3\%^{\text{syst}} \) | \( \delta (d\sigma/dt) = \pm 8.2\%^{\text{stat}} \pm 27 \%^{\text{syst}} \) |
# 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>$\text{const}(r)$</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>$\text{mult. factor}$</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>$\text{Ineff.} = \text{const}(r)$</td>
<td>Tot. ineff. = $(30 \pm 10)%$</td>
<td>Detector 1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{mult. corr. factor} = (1 + \text{ineff.})$</td>
<td></td>
<td>Event reconstruction $(29 \pm 10)%$</td>
</tr>
<tr>
<td>Acceptance</td>
<td>$d\sigma/dt$</td>
<td>$\text{Hyperbola function:}$</td>
<td>$f_A = \begin{cases} 4.96 \pm 0.05 &amp;</td>
<td>r</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{mult. corr. factor}$</td>
<td>$1.5</td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>$d\sigma/dt$</td>
<td>$\text{Parameterisation}$</td>
<td>$\frac{f_{bkg,dr}}{f_{\text{total}}} = (8 \pm 1)%$</td>
<td>$19 \pm 3)%</td>
</tr>
<tr>
<td>Resolution</td>
<td>$t \rightarrow d\sigma/dt$</td>
<td>$f_u(\Theta^*) = \frac{\text{unsmeared}}{\text{measured}}$</td>
<td>$f_u = \begin{cases} 0.55 \pm 0.02 &amp;</td>
<td>r</td>
</tr>
<tr>
<td>Unfolding</td>
<td></td>
<td>$\delta t/t = 0.6%</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Alignment</td>
<td>$t$</td>
<td>$\delta t_x = 2p/\sqrt{</td>
<td>t_x</td>
<td>} \delta x$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta t_y = 2p/\sqrt{</td>
<td>t_y</td>
<td>} \delta y$</td>
</tr>
<tr>
<td>Optics</td>
<td>$t$</td>
<td>$t_x = f(k, \psi, p); t_y = f(k, \psi, p)$</td>
<td>$\delta p_f = 1%$</td>
<td>$\delta k_f = 0.1%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k$: magnet strength \text{ } \psi$: magnet rotation \text{ } \text{ } p$: LHC beam momentum</td>
<td>$\delta \psi = 1 \text{mrad}$</td>
<td>$\delta p = 10^{-3}$</td>
</tr>
</tbody>
</table>
Comparison to Some Models

<table>
<thead>
<tr>
<th>Model</th>
<th>$B$ (t=−0.4 GeV$^2$)</th>
<th>$t_{DIP}$</th>
<th>n in t$^n$ [1.5–2.5 GeV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block et al.</td>
<td>24.4</td>
<td>0.48</td>
<td>10.4</td>
</tr>
<tr>
<td>Bourrely et al.</td>
<td><strong>21.7</strong></td>
<td>0.54</td>
<td><strong>8.4</strong></td>
</tr>
<tr>
<td>Islam et al. (CGC)</td>
<td><strong>19.9</strong></td>
<td>0.65</td>
<td><strong>5.0</strong></td>
</tr>
<tr>
<td>Jenkovszky et al.</td>
<td>20.1</td>
<td>0.72</td>
<td>4.2</td>
</tr>
<tr>
<td>Petrov et al. (3P)</td>
<td>22.7</td>
<td>0.52</td>
<td>7.0</td>
</tr>
<tr>
<td>TOTEM</td>
<td><strong>23.6</strong></td>
<td><strong>0.53</strong></td>
<td><strong>7.8</strong></td>
</tr>
</tbody>
</table>

| Errors                        | ±0.5±0.4               | ±0.01±0.01 | ±0.3±0.3                     |
Total Cross-Section Measurement

Optical Theorem:

\[ \sigma^2_{TOT} = \frac{16\pi \left(\frac{\hbar c}{\rho}\right)^2 \cdot \frac{d\sigma_{EL}}{dt}}{1 + \rho^2} \bigg|_{t=0} \]

Use \( \rho \) from COMPETE fit:

\[ \rho = 0.14^{+0.01}_{-0.08} \]

Normalisation with luminosity from CMS

\[ \frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt} \]

Uncertainty \( \pm 4\% \)

[Not yet done with luminosity-independent method; coming soon.]

\[ \rightarrow \text{Measure } d\sigma_{el} / dt \text{ at lowest possible } |t| \]
First run with the $\beta^* = 90$ m optics and RP insertion

- Two bunches with $1$ and $2 \times 10^{10}$ protons / bunch
- Instantaneous luminosity: $8 \times 10^{26}$ cm$^{-2}$ s$^{-1}$
- Integrated luminosity: $1.7 \mu$b$^{-1}$
- Estimated pile-up: $\sim 0.5$ %
- Vertical Roman Pots at $10 \sigma$ from beam center
- Trigger rate: $\sim 50$ Hz
- Recorded events in vertical Roman Pots: 66950 in $\frac{1}{2}$ hour.
Angular Correlations between outgoing protons

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

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

\[ L_y \sim 260 \text{ m} \]

\[ L_x \sim 0 - 3 \text{ m} \]

- Background negligible < 1%
- Width of correlation band in agreement with beam divergence (~ 2.4 µrad)
Optics, t-Scale and Acceptance

- Perturbations: optics very robust ($L_\gamma \sim s_{RP}$):
  - $\delta \Theta_x^* / \Theta_x^* = 1.3\%_{\text{syst}}$
  - $\delta \Theta_y^* / \Theta_y^* = 0.4\%_{\text{syst}}$
- $t$ systematics: $\delta t / t = 0.8\%$ (low $t$) up to 2.6\% (large $|t|$)
- Acceptance correction factor $< 3$ at low $|t|$, based on $\phi$ symmetry
Raw t-Distributions

Comparison of the two diagonals

Acceptance corrected

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_top45_bot56</td>
<td>7315</td>
<td>0.07117</td>
<td>0.04268</td>
</tr>
<tr>
<td>t_top56_bot45</td>
<td>7370</td>
<td>0.07192</td>
<td>0.04444</td>
</tr>
</tbody>
</table>
Final Differential Cross-Section for $t > 2 \times 10^{-2}$ GeV$^2$
(Data taking: June 2011 for 30 min.)

Good agreement with the measurement at $|t| > 0.36$ GeV$^2$
[EPL 95 (2011) 41001]

Total elastic cross-section:

$$\sigma_{EL} = 8.3 \text{ mb}^{(\text{extrapol.})} + 16.5 \text{ mb}^{(\text{measured})} = 24.8 \text{ mb}$$

**Extrapolation to $t = 0$:**

$$\left. \frac{d\sigma}{dt} \right|_{t=0} = 5.037 \times 10^2 \text{ mb / GeV}^2$$

**Exponential slope**

$$B|_{t=0} = 20.1 \text{ GeV}^{-2}$$

Extract total cross-section

Optical Theorem:

$$\sigma_{TOT}^2 = \frac{16\pi(hc)^2}{1 + \rho^2} \cdot \left. \frac{d\sigma_{EL}}{dt} \right|_{t=0}$$

$$\rho = 0.14^{+0.01}_{-0.08}$$ from Compete Coll.

Normalisation with luminosity from CMS

Uncertainty $\pm 4\%$
Comparison of Total, Inelastic and Elastic Cross-Section Measurements

### Comparison of Cross-Sections

- **Total Cross-Section** ($\sigma_{\text{tot}}$)
- **Inelastic Cross-Section** ($\sigma_{\text{inel}}$)
- **Elastic Cross-Section** ($\sigma_{\text{el}}$)

#### Data Points
- **pp (PDG)**
- **Auger + Glauber**
- **ALICE**
- **TOTEM**
- **ATLAS**
- **CMS**

#### Best Fit Functions
- **COMPETE Fit**
- **Best COMPETE $\sigma_{\text{tot}}$ fits**
- **11.4 - 1.52 ln s + 0.130 ln^2 s**

#### Mathematical Expressions

\[
\sigma_T = \left( 98.3 \pm 0.2^{\text{stat}} \pm 2.7^{\text{syst}} \left[ +0.8 \, -0.2 \right]^{\text{syst from } \rho} \right) \text{ mb}
\]

\[
\sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}} = \left( 73.5 \pm 0.6^{\text{stat}} \left[ +1.8 \, -1.3 \right]^{\text{syst}} \right) \text{ mb}
\]
# Systematics and Statistics

<table>
<thead>
<tr>
<th></th>
<th>Statistical uncertainties</th>
<th>Systematic uncertainties</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t )</td>
<td>( \pm [3.4 \div 11.9] % ) single measurement(*)</td>
<td>( \pm [0.6 \div 1.8] %\text{optics} \pm &lt; 1%\text{alignment} )</td>
<td></td>
</tr>
<tr>
<td>( \frac{d\sigma}{dt} )</td>
<td>5% / bin</td>
<td>( \pm 4%\text{luminosity} \pm 1%\text{analysis} \pm 0.7%\text{unfolding} )</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>( \pm 1% )</td>
<td>( \pm 1%\text{scale} \pm 0.7%\text{unfolding} )</td>
<td>( (20.1 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}}) \text{ GeV}^{-2} )</td>
</tr>
<tr>
<td>( \frac{d\sigma}{dt} \big</td>
<td>_{t=0} )</td>
<td>( \pm 0.3% )</td>
<td>( \pm 0.3%\text{optics} \pm 4%\text{luminosity} \pm 1%\text{analysis} )</td>
</tr>
<tr>
<td>( \int \frac{d\sigma}{dt} , dt )</td>
<td>( \pm 0.8%\text{extrapolation} )</td>
<td>( \pm 4%\text{luminosity} \pm 1%\text{analysis} )</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{\text{tot}} )</td>
<td>( \pm 0.2% )</td>
<td>( (\pm 0.8%_{-0.2%}^{+0.2%}) \text{(p)} \pm 2.7%)</td>
<td>( (98.3 \pm 0.2_{\text{stat}} \pm 2.8_{\text{syst}}) \text{ mb} )</td>
</tr>
<tr>
<td>( \sigma_{\text{cl}} = \int \frac{d\sigma}{dt} , dt )</td>
<td>( \pm 0.8% )</td>
<td>( \pm 5% )</td>
<td>( (24.8 \pm 0.2_{\text{stat}} \pm 1.2_{\text{syst}}) \text{ mb} )</td>
</tr>
<tr>
<td>( \sigma_{\text{inel}} )</td>
<td>( \pm 0.8% )</td>
<td>( (\pm 2.4%_{-1.8%}^{+2.4%}) )</td>
<td>( (73.5 \pm 0.6_{\text{stat}} \pm 1.8_{\text{syst}}) \text{ mb} )</td>
</tr>
<tr>
<td>( \sigma_{\text{inel}} ) (CMS)</td>
<td>( \pm 0.8% )</td>
<td>( (68.0 \pm 2.0_{\text{syst}} \pm 2.4_{\text{lumi}} \pm 4_{\text{extrap}}) \text{ mb} )</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{\text{inel}} ) (ATLAS)</td>
<td>( \pm 0.8% )</td>
<td>( (69.4 \pm 2.4_{\text{exp}} \pm 6.9_{\text{extrap}}) \text{ mb} )</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{\text{inel}} ) (ALICE)</td>
<td>( \pm 0.8% )</td>
<td>( (72.7 \pm 1.1_{\text{model}} \pm 5.1_{\text{lumi}}) \text{ mb} )</td>
<td></td>
</tr>
</tbody>
</table>

(*) corrected after unfolding

(analysis) includes tagging, acceptance, efficiency, background
Energy dependence of the exponential slope $B$
Data already available and being analysed:

- $\beta^* = 3.5 \text{ m}$: Elastic scattering extended to larger $|t|$: up to $3.5 \text{ GeV}^2$
- $\beta^* = 90 \text{ m}$:
  - Elastic scattering extended to smaller $|t|$: down to $6 \times 10^{-3} \text{ GeV}^2$
  - + inelastic triggers (T1, T2, zero bias)
  - $\rightarrow$ total cross-section with the luminosity independent method

- Central Diffraction (DPE): $t$-spectrum, later mass spectrum
- Single Diffraction: $t$-spectrum
- $dN / d\eta$ from T2, later also T1
Data October 2011: Elastic Differential Cross-Section

Raw distribution
(to be corrected for acceptance, ...)

$6 \times 10^{-3}$
Data October 2011: DPE Cross-Section

DPE RP candidates t-distribution
B=10 GeV$^{-2}$

Raw distribution
(to be corrected for acceptance, ...)

~8 \times 10^{-3} \text{ GeV}^2

Distribution integrated over $\xi$
Data October 2011: SD Cross-Section

\[ d\sigma_{SD}/dt \ & \ \sigma_{SD} \]

Rapidity Gap
\[ \Delta \eta = -\ln \zeta \]

\[ M_{x^2} = \xi s \]

Single proton with T2 tracks on opposite side
\[ \beta^* = 90 \text{ m}, \ RP@6.5\sigma \ - \ Oct \ 11 \]

Raw distribution
(to be corrected for acceptance, ...)

Analysis in progress

Preliminary
7 TeV $dN/d\eta$ analysis @ LHC

dN/d\eta from ALICE, ATLAS, CMS, LHCb & TOTEM-T2

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, at least 1 Track in $5.3<|\eta|<6.5$, $p_T > 30$ MeV/c

LHCb

T1 coming soon
2012:
- Try to measure elastic scattering down into the Coulomb region ($|t| \sim 5 \times 10^{-4}$ GeV$^2$) after development of an optics with $\beta^* \sim 800 – 1000$ m.
  \[\rightarrow \rho\]

- If LHC runs at a new energy ($\sqrt{s} = 8$ TeV), measure large $|t|$ elastic scattering
- Trigger exchange between TOTEM and CMS being commissioned
  \[\rightarrow \text{common data taking (diffraction, total cross-section with optimal coverage)}\]

Later (after long shutdown):
- Repeat all measurements at $\sqrt{s} = 14$ TeV
- Intensify cooperation with CMS on diffraction
Backup
Beam-Based Roman Pot Alignment (Scraping)

A primary collimator cuts a sharp edge into the beam, symmetrical to the centre

The top RP approaches the beam until it touches the edge

The last 10 µm step produces a spike in a Beam Loss Monitor downstream of the RP

When both top and bottom pots are touching the beam edge:

• they are at the same number of sigmas from the beam centre as the collimator
• the beam centre is exactly in the middle between top and bottom pot

➔ Alignment of the RP windows relative to the beam (~ 20 µm)
Software Alignment

Track-Based Alignment

Residual-based alignment technique (similar to MILLEPEDE): shifts and rotations within a RP unit

Alignment Exploiting Symmetries of Physics Processes

Fine vertical alignment: about 20 µm precision

Map of all track intercepts after elastic selection

Slope mainly caused by optics (less by detector rotation!)

→ Fine horizontal alignment: precision better than 10 µm
Background Subtraction, Resolution Determination

Signal to background normalisation

\[ \sigma^* \rightarrow t\text{-reconstruction resolution:} \]

\[ \frac{\sigma(t)}{t} = \frac{\sqrt{2} p \sigma^*}{\sqrt{t}} : \]

\begin{align*}
0.4 \text{ GeV}^2 & : 14\% \\
1 \text{ GeV}^2 & : 8.8\% \\
3 \text{ GeV}^2 & : 5.1\%
\end{align*}

Signal vs. background (t)

\begin{align*}
|t| = 0.4\text{GeV}^2 & : B/S = (11 \pm 2)\% \\
|t| = 0.5\text{GeV}^2 & : B/S = (19 \pm 3)\% \\
|t| = 1.5\text{GeV}^2 & : B/S = (0.8 \pm 0.3)\%
\end{align*}
Resolution Unfolding

data fit

- corrected data
- fit

\[ \text{correction} = \frac{\text{unsmear}}{\text{fit}} \]

MC smearing of result

- corrected data
- result re-smear

additional smearing steps

“learning” correction trend and backward application

method comparison
Resolution Unfolding

\[ t \rightarrow \theta \rightarrow \theta' \rightarrow t' \]

\[ \sigma_0 = \text{const}(\theta) \]

Data parameterization

Extrapolation below acceptance cut

Analytical deconvolution

Consistency checked with random generator smearing and unsmearing

Consistency checked with golden sample selected within 0.5\( \sigma \) of resolution
Data transformations (after selection cuts)

Diagonal top 45 - bottom 56 alone

1 – raw data (signal + background)
2 – estimated background
3 – estimated background acceptance corrected
4 – raw data acceptance corrected
5 – raw data acceptance corrected - background
6 – final unfolded distribution
Elastic scattering – from ISR to Tevatron

Diffractive minimum: analogous to Fraunhofer diffraction: \(|t| \sim p^2 \theta^2\)

- exponential slope B at low \(|t|\) increases
- minimum moves to lower \(|t|\) with increasing s
  → interaction region grows (as also seen from \(\sigma_{\text{tot}}\))
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, p\(\bar{p}\)p
  → different mix of processes

\[\sim 1.4 \text{ GeV}^2\]
90 m: Angular difference between the two outgoing protons

\[
\frac{[\Theta_y^* (\text{proton1}) - \Theta_y^* (\text{proton2})]}{\sqrt{2}}
\]

beam divergence \(\sigma_{\Theta^*}\)

\[
\sigma_{\Theta^*} = \sqrt{\frac{\varepsilon}{\gamma \beta^*}} = 2.4 \mu\text{rad}
\]
90 m: Efficiency Correction and Resolution Unfolding

Trigger efficiency ~ 99.9 %
Reconstruction efficiency ~ 91 %

\[
\sigma(\Theta_x^*) = \sqrt{1.7^2 \text{(from beam div.)} + 4^2 \text{(det. res.)}} = 4.4 \mu\text{rad}
\]

\[
\sigma(\Theta_y^*) = 1.7 \mu\text{rad (from beam div.)}
\]

Unfolding correction

Effect on slope: \(\Delta B = 0.11 \text{ GeV}^{-2}\)
Elastic Scattering: $\rho = \Re f(0) / \Im f(0)$

COMPETE [PRL 89 201801 (2002)]

$E710/E811$: $\rho = 0.135 \pm 0.044$

7 TeV
Example of DPE Mass Reconstruction

\[ \xi_1 < 1.5\%; \quad \xi_2 > 5.0\% \]

Low-\( \beta \)
RP vertical
RP horizontal
T2
How to reach the Coulomb Region?

At 8 TeV the pots have to move by $\sim 1\sigma$ closer to reach the same $t$ as at 7 TeV.

$\Rightarrow$ Challenging but possible