Total and Elastic cross-sections

E. Radicioni - INFN
outline

• Experimental technique
• Results
  – Elastic scattering
  – Total cross-section
  – Interference region
• A short overview on future measurements
  – Upgraded detectors
  – Measurement programme
• Conclusions
TOTEM detectors

Silicon detectors in Roman Pots to tag elastic and diffractive protons

CMS detectors (in grey)

T1 and T2 gas detectors to measure particles from inelastic collisions

T1: $3.1 < \eta < 4.7$ ; T2: $5.3 < \eta < 6.5$

TOTEM T1 and T2 (in red)

All detectors symmetric w.r.t. IP, with trigger capability
TOTEM Roman Pot detectors

- a RP is a movable beam-pipe insertion device equipped with particle detectors
  - contains 5x2 back-to-back silicon strip detectors
  - retracted when beam unstable or unsuitable (or not in use)
  - close to beam for data taking
- each “station” = near+far units, 3 RPs per unit
  - top+bottom+horizontal in each unit
- edge-less silicon sensors
  - insensitive edge reduced to 50μm
  - 66μm pitch at 45° w.r.t. edge
Elastic scattering with ATLAS-ALFA

Roman Pot detectors at 240m from IP1 approaching the beam during special runs at high $\beta^*$. 

In October 2011 ALFA had the special run 191373 with $\beta^*=90\text{m}$ and recorded 800k good selected elastic events used for the analysis of the total cross section and the nuclear slope B.
The ALFA detector in a nutshell

ALFA is a scintillating fibre tracker, 10 double-sided modules with 64 fibres in uv-geometry. Resolution \(\sim 30\mu m\).

Special overlap detectors to measure the distance between upper and lower detectors \(\rightarrow\) alignment
relation between elastic, inelastic, total

elastic observables only:

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

q independent:

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

luminosity independent:

$$\sigma_{tot} = \frac{16\pi}{1 + \varrho^2} \frac{dN_{el}/dt}{N_{el} + N_{inel}} \bigg|_0$$

$$\mathcal{L} = \frac{1 + \varrho^2}{16\pi} \frac{(N_{el} + N_{inel})^2}{dN_{el}/dt} \bigg|_0$$

$N_{el}$ from RP; $N_{inel}$ from inel detectors; Lumi from ATL or CMS; $\varrho$ from data or COMPETE
measurement principle

from selection of topology ...

LHC magnet lattice ⇒ accelerator optics

... to understanding of transport properties ...

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

... to extraction of kinematical variables
\[
x(RP) = (\text{effective length } L_x) \cdot (\text{scattering angle } \Theta^*_x) + (\text{magnification } v_x) \cdot (\text{vertex } x^*) + (\text{dispersion } D_x) \cdot (\text{rel. momentum loss } \Delta p/p)
\]
optics

Optics is a product of lattice elements $T_i$ and imperfections $\Delta T_i$:

$$T_{IP5\to RP220} = \prod_{i=M}^{1} [T_i(k_i) + \Delta T_i]$$

Imperfections $\Delta T_i$

- Beam momentum offset ($\Delta p/p = 10^{-3}$)
- Magnet transfer function error, $I\to B$, ($\Delta B/B = 10^{-3}$)
- Magnet rotations and displacements ($\Delta \psi < 1 \text{ mrad}, \Delta x, \Delta y < 0.5 \text{ mm}$)
- Power converter errors, $k\to I$, ($\Delta I/I < 10^{-4}$)
- Magnet harmonics ($\Delta B/B = O(10^{-4})$)

Elastic scattering kinematics helps in constraining several parameters

Optics carefully optimized for special runs: hi $\beta^*$, low luminosity

Optics understanding is essential $\leftrightarrow$ measurements improve knowledge of optics
elastic scattering selection and analysis - I

• Alignment – I
  • beam scraping (collimator-like alignment)
• First selection: two diagonals, symmetric w.r.t. IP
• Alignment - II
  – residuals-based (relative between RPs) + absolute by exploiting the elastic scattering topology
• Reconstruction of kinematics
  – by using beam transport formulae
  – $\rightarrow$ minimize systematics by refining knowledge of optics by using actual data
• Tagging
  – Vertex and angles identical left/right (n.b. tolerance set by beam divergence $\rightarrow$ higher $\beta^*$ means cleaner sample)
  – proton $dp/p \approx 0$
• Bkg subtraction (typically needed for low-$\beta^*$ optics)
• Acceptance corrections
  – finite RP detector acceptance & finite LHC aperture
elastic scattering selection and analysis - II

- Resolution studies
  - angular resolution: comparison left-right
  - unfolding with Monte Carlo calculation

- Correct for inefficiencies
  - uncorrelated (per single pot)
  - correlated (due to showers within a group of RPs)
  - pile-up (elastic event + additional tracks)

- Inject luminosity info
  - from ATLAS or CMS
  - calculated from data

- Final $d\sigma/dt$, systematic uncertainties and $N_{el}$
elastic scattering results: $\sqrt{s} = 7$ TeV

ATLAS-ALPHA
$\beta^* = 90$ m

TOTEM
$\beta^* = 3.5$ m & 90 m
available data from TOTEM @ 7-8 TeV

<table>
<thead>
<tr>
<th>E (TeV)</th>
<th>$\beta^*$ (m)</th>
<th>RP approach</th>
<th>$L_{int}$ ($\mu$b$^{-1}$)</th>
<th>$t$ range (GeV$^2$)</th>
<th>Elastic events</th>
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<tbody>
<tr>
<td>7</td>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>6-9$\sigma$</td>
<td>60</td>
<td>$0.01 - 1$</td>
<td>0.6M</td>
</tr>
<tr>
<td>1000</td>
<td>3$\sigma$</td>
<td>20</td>
<td>$6 \cdot 10^{-4}$ - 0.2</td>
<td>0.4M</td>
<td></td>
</tr>
<tr>
<td>2.76</td>
<td>11</td>
<td>5-13$\sigma$</td>
<td>0.05-0.6</td>
<td>45k</td>
<td></td>
</tr>
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[EPL 101 (2013) 21002]
[EPL 96 (2011) 21002]
[EPL 95 (2011) 41001]
[PRL 111, 012001]
- Raw rate: event counting in inelastic detectors
  - corrections: trigger and detection efficiencies, beam-gas events, pile-up
- Visible rate
  - in TOTEM, cross-check T1 vs. T2 for recovery of events with no tracks in T2 (gap over T2, low-mass diffraction, ...)
- Physics rate: true rate $N_{\text{inel}}$ of inelastic events
- Note: only one relevant Monte Carlo correction (low mass diffraction)
  - it can be constrained from data $(\sigma_{\text{RP}}^{\text{tot}} - \sigma_{\text{RP}}^{\text{el}} - \sigma_{\text{T2}}^{\text{visible}})$
The table shows the measured cross sections with detailed uncertainty composition:

<table>
<thead>
<tr>
<th>√s [TeV]</th>
<th>method</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>elastic only</td>
<td>98.6±2.3 mb</td>
</tr>
<tr>
<td>7</td>
<td>ρ independent</td>
<td>99.1±4.4 mb</td>
</tr>
<tr>
<td>7</td>
<td>lumi independent</td>
<td>98.1±2.4 mb</td>
</tr>
<tr>
<td>8</td>
<td>lumi independent</td>
<td>101.7±2.9 mb</td>
</tr>
</tbody>
</table>

The systematic uncertainty is estimated to be 0.45% which corresponds to the maximal variation of the background that gives a probability of having a bunch crossing with uncertainty follows from the COMPETE preferred-model extrapolation error of 0.45% which corresponds approximately to diffractive masses of 0.07 mb.

The new data available at √s = 2.76 TeV.

The TOTEM total cross-section as a function of √s is shown in the graph.
The ATLAS measurement is 3.2 mb lower than TOTEM, the difference corresponds to 1.3 σ, assuming uncorrelated uncertainties.
general observations

\[ \sqrt{s} = 7 \text{ TeV} \]

- \( |t|_{\text{dip}} = 0.53 \text{ GeV}^2 \)
- \( \sim |t|^{7.8} \)

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

\[ |t|_{\text{min}} = 2 \cdot 10^{-2} \text{ GeV}^2 \]

\[ |t|_{\text{min}} = 5 \cdot 10^{-3} \text{ GeV}^2 \]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ 23.5 \text{ GeV} \]

\[ 27.43 \text{ GeV} \]

\[ 30.5 \text{ GeV} \]

\[ 44.64 \text{ GeV} \]

\[ 62.0 \text{ GeV} \]

\[ \sim 1.4 \text{ GeV}^2 \]

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low-t elastic scattering

| $\beta^*$ | approach $\sigma$ | $|t|$ range GeV$^2$ | el events | pub          |
|---------|------------------|-----------------|------------|--------------|
| 1000m   | 3 or 10          | 0.0006 -> 0.2   | 352k       |              |
| 90m     | 6 -> 9.5         | 0.01 -> 0.3     | 0.68M      | PRL 111 (2013) |
| 90m     | 9.5              | 0.02 ->1.4      | 7.2M       |              |

- overlapping $|t|$ region between $\beta^*=90$m and $\beta^*=1000$m
- access to very low $|t|$ region and high statistics coverage of $|t| > 0.01$
reaching the interference region

\[ F^{C+H} = F^C + F^H e^{i\psi} \]

- Modulus constrained by measurement: \( \frac{d\sigma}{dt} \propto A e^{-B(t) |t|} \)
  - \( B(t) = b_0 + b_1 t + ... \)
- Phase \( \arg(F^H) \): guidance by data is difficult

Simplified West-Yennie (SWY):
- constant slope \( B(t) = b_0 \)
- constant hadronic phase \( \arg(F^H) = p_0 \)
- \( \psi(t) \) acts as real interference phase:

Kundrát-Lokajíček (KL) formula:
- any slope \( B(t) \)
- any hadronic phase \( \arg(F^H) \)
- complex \( \psi(t) \):

\[ \frac{d\sigma}{dt} \propto |F^{C+h}|^2 = \text{Coulomb} + \text{interference} + \text{hadronic} \]
preliminary indications

- high-statistics $\beta^* = 90\text{m}$ data can be used to compare $d\sigma/dt$ with a pure exponential form
- Present data exclude a simple exponential at $\sim 7\sigma$ significance
- $\rightarrow$ SWY model is ruled out

Fit $d\sigma/dt = A \exp(-B(t)|t|)$, with $B(t) = b_0$ or $B(t) = b_0 + b_1 t$ or $B(t) = b_0 + b_1 t + b_2 t$
## Status

<table>
<thead>
<tr>
<th>Coll energy</th>
<th>beta*</th>
<th>dataset</th>
<th>el X-sec</th>
<th>total X-sec</th>
<th>C-N interf</th>
</tr>
</thead>
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<tr>
<td>7 TeV</td>
<td>90m</td>
<td>medium</td>
<td>published</td>
<td>published</td>
<td>in progress</td>
</tr>
<tr>
<td></td>
<td>3.5m</td>
<td>high</td>
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<tr>
<td>8 TeV</td>
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<td>11m</td>
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### Future data sets:
- repeat same
  - with improved detectors
  - with higher precision CNI
- exploring the widest possible $|t|$ range
consolidation work towards RUN II

new ferrites for ALL RPs. Much higher:
• bake-out temperature: 1000 °C
• and Curie temperature: 375 °C

Rotated TOTEM RPs to add stereo angles

optimized placement of ATLAS RPs; relocation of TOTEM’s 147m RPs in 220m region → additional lever arm and bkg rejection
future data taking

• Running scenarios under discussion for RUN II include a wide range of $\beta^*$ values
  $\geq 1000m$ for high-precision low-$t$ elastic scattering analysis
  $= 90m$ with extended runs for high-statistics elastic & total cross-section studies

• Proton tagging will also allow additional physics output at medium (90m) and low (0.5m) $\beta^*$
  – wide range of masses in central diffraction
  – forward particle production
  – soft and hard diffraction
conclusions

• During Run I the total, elastic and inelastic cross-sections have been measured at √S=7 and 8 TeV.
• The elastic scattering has been studied in a wide t range.
  – Measurements at very low t excluded a purely exponential behavior of the forward peak and allow first studies of the Coulomb-Nuclear interference region.
• An extensive consolidation and upgrade activity is being finalized to ensure a rich physics programme during RUN II.
backup
**TOTEM operations**

![Graph showing TOTEM operations](image)

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- EPL 101 (2013) 21002
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Notes:
- $\beta^* = 1$ km, $3\sigma$, $8$ TeV
- $\beta^* = 90$ m, $10\sigma$, $7$ TeV
- $\beta^* = 90$ m, $5\sigma$, $7$ TeV
- $\beta^* = 90$ m, $6\sigma$, $8$ TeV
- $\beta^* = 3.5$ m, $7\sigma$, $7$ TeV
- $\beta^* = 3.5$ m, $18\sigma$, $7$ TeV
- $\beta^* = 11$m, $5$-$13\sigma$, $2.76$ TeV
effect of CNI (explorative simulations)

Low $|t|$: sensitivity to $\rho$

Higher $|t|$: sensitivity to $|t|$ behaviour of nuclear phases
determination of $\rho$

<table>
<thead>
<tr>
<th>B(t)</th>
<th>1 par.</th>
<th>2 par.</th>
<th>3 par.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>central or constant</td>
<td>peripheral</td>
<td></td>
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$\rho$ from fits with different B(t) and Phase(t)

COMPETE: preferred model and band from all models

TOTEM: red = fit uncertainty, cyan = band from varying peripheral phase

- model: Block et al.
- model: Bourrely et al.
- model: Petrov et al. (3P)
- model: Petrov et al. (2P)
- model: Islam et al.

details at $\sqrt{s} = 8$ TeV

TOTEM mean:
$\varepsilon = 0.104 \pm 0.027^{\text{stat}} \pm 0.010^{\text{syst}} + 0.012^{\text{(model)}} - 0.006$

From optical theorem:
Indirect measurement at 7 TeV:
$\rho_{\text{PDG}} = 0.145 \pm 0.091$

Mario Deile – 15
possible running conditions

<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>cr. angle [µrad]</th>
<th>$\varepsilon_N$ [µm rad]</th>
<th>$N$ [10^{11} p/b.]</th>
<th>$k$ bunches</th>
<th>$\mu$ [cm^{-2} s^{-1}]</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>0</td>
<td>2</td>
<td>0.7 $\div$ 1.5</td>
<td>2</td>
<td>0.004 $\div$ 0.02</td>
<td>$(1.2 \div 5.6) \times 10^{27}$ = $(0.1 \div 0.5)$ nb^{-1}/24h</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>2</td>
<td>0.5 $\div$ 1.5</td>
<td>156</td>
<td>0.06 $\div$ 0.5</td>
<td>$(1.3 \div 12) \times 10^{30}$ = $(0.1 \div 1)$ pb^{-1}/24h</td>
</tr>
<tr>
<td>90</td>
<td>100</td>
<td>2</td>
<td>0.5 $\div$ 1.5</td>
<td>1000</td>
<td>0.06 $\div$ 0.5</td>
<td>$(0.9 \div 7.7) \times 10^{31}$ = $(0.8 \div 7)$ pb^{-1}/24h</td>
</tr>
<tr>
<td>0.5</td>
<td>310 $\div$ 390</td>
<td>1.9 $\div$ 3.75</td>
<td>1.15</td>
<td>2520 $\div$ 2760 (\Delta t = 25 \text{ ns})</td>
<td>19 $\div$ 34</td>
<td>$(0.8 \div 1.3) \times 10^{34}$ = $(0.7 \div 1.1)$ fb^{-1}/24h</td>
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