Elastic scattering at the LHC

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Elastic scattering: From ISR to Tevatron
Elastic scattering: From ISR to Tevatron

\[ \frac{d\sigma}{dt} \text{(mb/GeV}^2) \]

- UA4 × 100 (0.546 TeV)
- CDF (1.800 TeV)
- E710 (1.800 TeV)
- DØ (1.960 TeV)
Elastic scattering at the LHC: variety of predictions

- Variety of models especially at high $|t|$
- Regions in $|t|$ at the LHC sensitive to different kinds of physics:
  - Diffraction/Pomeron exchange at low $|t|$, diffractive structures at medium $|t|$ and parton scattering/QCD at higher $|t|$
**ATLAS/ALFA and TOTEM Roman pot detectors**

- For elastic measurements, TOTEM installed vertical roman pot detectors at 220 m from CMS.
- ATLAS-ALFA installed similar roman pots at 240 m.
- Trigger for elastics using proton in opposite configurations: Up (Down) on one side, Down (Up) on the other side.
Forward coverage in CMS-TOTEM

Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

$T_1$: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV
$T_2$: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV
→ Inelastic Trigger

Roman Pots: elastic & diffractive protons close to outgoing beams → Proton Trigger

Roman Pot stations in the LHC tunnel (before LS1)

RP (147 m)  RP (220 m)
ALFA and TOTEM detectors

TOTEM

Planar silicon detectors
Stack of 10
Insensitive region < 60-70\(\mu\)m
Space resolution 11\(\mu\)m per stack

ATLAS/ALFA

Scintillating fibres
10 staggered planes
Insensitive region < 20-30\(\mu\)m
Space resolution 35 \(\mu\)m
Similarities between ALFA and TOTEM

- Divergence smaller than angles to be measured $\Rightarrow \sqrt{\varepsilon}/\beta^*$ small
  $\Rightarrow$ large $\beta^*$; ATLAS/TOTEM used $\beta^*=90\text{m}$

- "parallel to point" in at least one plane
  ATLAS/TOTEM in vertical plane

- Large effective lever arm in at least one plane for good $t$-resolution
  $\theta_y = y/L_y^{\text{eff}}$  ATLAS/TOTEM vertical plane

- Different methods used to reconstruct $t$ (differences in horizontal lever arm)
- Different methods used to extract the elastic and total cross sections
- ATLAS claims smaller uncertainties due to luminosity measurement
**pp scattering at 7 TeV (ATLAS)**

- Coverage in $t$: $0.006 < |t| < 0.38$ GeV$^2$
- Simple exponential fit to data ($\frac{d\sigma}{dt} = A \exp(-B|t|)$) leads to
  - $A = 474 \pm 13(syst) \pm 4(stat)$, and
  - $B = 19.73 \pm 0.26(syst) \pm 0.14(stat)$,
  - $\sigma_{el} = 24.00 \pm 0.57(syst) \pm 0.19(stat)\text{ mb}$
**pp scattering at 7 TeV (TOTEM)**

- Wide range of measurement in $t$: $0.005 < |t| < 0.2$ GeV$^2$, results in red, $0.002 < |t| < 0.33$ GeV$^2$, results in green

- Simple exponential fit: $A = 506.4 \pm 23 \text{(stat)} \pm 0.9 \text{(syst)}$, $A = 503.0 \pm 26.7 \text{(syst)} \pm 1.5 \text{(stat)}$; $B = 19.89 \pm 0.27 \text{(syst)} \pm 0.03 \text{(stat)}$, $B = 20.1 \pm 0.3 \text{(syst)} \pm 0.2 \text{(stat)}$
$pp$ scattering at 8 TeV (TOTEM)

- High statistics data set ($\beta^* = 90\text{m}$, 7 million elastic events, $0.027 < |t| < 0.2 \text{ GeV}^2$)
- $\sigma_{el} = 27.1 \pm 1.4 \text{ mb}$
\textit{pp scattering at 8 TeV (TOTEM)}

- **Exponential fit:** \( \frac{d\sigma}{dt} = A \exp(-B(t)|t|) \)
- **Pure exponential form \((N_b = 1)\) excluded at 7.2 \(\sigma\)
  - \(N_b = 1\) \(B = b_1\), reference
  - \(N_b = 2\), \(B = b_1 + b_2t\)
  - \(N_b = 3\), \(B = b_1 + b_2t + b_3t^2\)
Total cross section measurement (7 TeV)
Elastic scattering in the Coulomb-Nuclear interference region

\[ F_{C+H} = F_C + F_H e^{i\alpha\Psi} \]

- \( F^C = \alpha_S/t^2(t) \)
- \( F^H \): Modulus constrained by measurement in hadronic \( t \)-region \( (d\sigma/dt = A \exp(-B(t)|t|)) \) and \( B(t) = b_0 + b_1 t \); Hadronic phase \( \arg(F^H(t)) \): very little guidance by data
- Interference formula for \( \exp i\alpha\Psi \) term:
- Simplified West-Yennie formula:
  - Constant slope \( B(t) = b_0 \), already excluded by data
  - Constant hadronic phase \( \arg(F^H) = p_0 \)
  - \( \Psi(t) \) acts as real interference phase
- Kundrat-Lokajicek formula:
  - Any slope \( B(t) \)
  - Any hadronic phase \( \arg(F^H) = p_0 \)
  - Complex \( \Psi(t) \)
Different options for the unknown nuclear phase

“central phase”: profile function in impact parameter picture: Elastic scattering preferentially central

\[
\arg F(t) = \frac{\pi}{2} - \tan \frac{p_0}{1 - \frac{t}{t_d}}
\]

constant phase: also central behaviour

\[
\arg F(t) = p_0
\]

Result for

\[
\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0) = \cot p_0
\]

“peripheral phase”: profile function in impact parameter picture: Elastic scattering preferentially peripheral

\[
\arg F(t) = p_0 + \alpha \exp \left[ \kappa \left( \ln \frac{t}{t_m} - \frac{t}{t_m} + 1 \right) \right]
\]

is model dependent
Elastic scattering in the Coulomb-Nuclear interference region

- Measure elastic scattering at $|t|$ as low as $6 \times 10^{-4}$ GeV$^2$ using high $\beta^* = 1000$ m optics
- Detectors approach the beam at $3\sigma$ from the beam center
- Measurement of $\rho$ expected soon!
More data available: Stay tuned!

| Experiment | $\sqrt{s}$ (TeV) | $\beta'(m)$ | RP approach (beam $\sigma$) | $|t|$- range (GeV$^2$) | Elastic events | Reference |
|------------|------------------|-------------|-----------------------------|-----------------------|---------------|-----------|
| ATLAS      | 7                | 90          | 6.5                         | 0.01–0.38             | 805K          | Nucl. Phys. B 889 (2014), 486 |
|            | 8                | 90          | 6-10                        |                       |               | In progress |
|            | 8                | 1000        | 3-10                        |                       |               | In progress |
| TOTEM      | 7                | 90          | 4.8 – 6.5                   | 5 · $10^3$ – 0.4      | 1M            | EPL 101 (2013), 21002 |
|            | 7                | 90          | 10                          | 0.02 – 0.33           | 15K           | EPL 96 (2011), 21002 |
|            | 7                | 3.5         | 7                           | 0.36 – 2.5            | 66K           | EPL 95 (2011), 41001 |
|            | 7                | 3.5         | 18                          | 2 – 3.5               | 10K           | In progress |
|            | 8                | 90          | 6 – 9.5                     | 0.01 – 0.3            | 0.65M         | PRL 111, 012001 (2013) |
|            | 8                | 90          | 9.5                         | 0.03 – 1.4            | 7.2M          | ArXiv:1503.08111 Submit Nucl. Phys. B |
|            | 8                | 1000        | 3 – 10                      | 6 · $10^4$ – 0.2      |               | In progress |
|            | 2.76             | 11          | 5 – 13                      | 0.06 – 0.5            | 45K           | In progress |
The future: roman pot system now!

- **New collimator TCL6**
- **Intercept showers from RP insertions at high beam intensity**
- **existing RP220**
- **new horizontal RP for future timing detectors**

**RP147 relocated to 203-214m**
- 214m unit tilted 8° around beam axis
  - multitrack event reconstruction
- RF shields in horizontal RPs
  - impedance reduction
The future: upgrades for AFP CMS-TOTEM and CT-PPS

- Finalise measurements at 8 TeV: measurement of $\rho$ parameter, hard diffraction (jets, $Z$...) with CMS
- Elastic and total cross section measurements at 13 TeV using TOTEM and ALFA
- Special high $\beta^*$ =2.5 km runs in order to access the Coulomb interference region foreseen in 2016
- In parallel, measurements of low and medium mass diffraction using high $\beta^*$ runs in CMS-TOTEM: glueballs, jets, $W$ bosons, vector mesons in SD and DPE, exclusive events...
- High mass diffraction using CT-PPS and AFP: sensitivity to new physics via anomalous couplings
Conclusion - Opening for discussion

- What impact have LHC results on Models? Islam et al., Maor at al., Soffer et al. revisited and refined their models

- Non exponential form of $d\sigma/dt$

- Could new measurements in the pipeline ($\rho...$) already lead to a better understanding?

- Which additional measurements should be performed at the LHC to have a better understanding of the elastic scattering mechanism?

- Broad diffractive program at the LHC for the future