Recent Elastic and Total Cross-Section Measurements by TOTEM

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On behalf of the TOTEM Collaboration
TOTEM Detectors

Inelastic Telescopes:
T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$

Roman Pot stations in the LHC tunnel
One of the physics goals of TOTEM is to measure the (elastic, inelastic, total) cross sections at LHC.

- COMPETE Collaboration fits all available hadronic data and predicts at LHC: \( \sigma_{\text{tot}} = 111.5 \pm 1.2 + 4.1/-2.1 \) mb [PRL 89 201801 (2002)]
- Last pp data at the ISR; only ppbar at “high” energy
- Difference of \( \sigma_{pp} \) vs \( \sigma_{\bar{p}p} \)
- \( \sigma_{\text{TOT}}(s) \sim (\ln s)^\gamma \quad \gamma = 2 \)
- \( \sigma_{\text{EL}} / \sigma_{\text{TOT}} \) VS energy

Is the dip still present at high energy?
Is the position of the dip changing?
Large momentum transfer region: oscillations?
Any break in the elastic slope \( B(t) \)?

\[ \rho = \Re A^N/\Im A^N \big|_{t=0} \]
- Foreseen to “decrease” at high energy: how fast?
- Test dispersion relation (mix real and imaginary part)
Cross section related measurements in Totem

Run I
- Elastic scattering @ 7 TeV
  EPL 95-41001
- First $\sigma_{tot}$ @ 7 TeV
  EPL 96-21002
- $\sigma_{tot}$ lumi independent @ 7 TeV
  PRL 111-12001
- Elastic, inelastic cross section
- Elastic: full t-range
  EPL 101-21004/21003/21002

Run II
- $d\sigma/dt$ elastic: non-exponential behaviour @ 8 TeV
  NPB 899-527
- $\rho$ measurement @ 8 TeV
  EPJ C76-661
- $\sigma_{tot}$ lumi independent @ 8 TeV
  PoS (DIS2017) 059
- $\sigma_{tot}$ lumi independent @ 13 TeV
- $\rho$ measurement @ 13 TeV
  CERN-EP-2017-335
- $d\sigma/dt$ elastic: DIP @ 13 TeV Preliminary

2011
- Elastic scattering @ 7 TeV
  EPL 95-41001

2012
- $\sigma_{tot}$ lumi independent @ 7 TeV

2013
- $\sigma_{tot}$ lumi independent @ 7 TeV
- Elastic, inelastic cross section
- Elastic: full t-range
  EPL 101-21004/21003/21002

2014
- $\sigma_{tot}$ lumi independent @ 2.76 TeV
  PoS (DIS2017) 059

2015
- $\sigma_{tot}$ lumi independent @ 8 TeV
  EPJ C76-661
- $d\sigma/dt$ elastic: non-exponential behaviour @ 8 TeV
  NPB 899-527

2016
- $\rho$ measurement @ 8 TeV

2017
- $\sigma_{tot}$ lumi independent @ 13 TeV
- $\rho$ measurement @ 13 TeV
  CERN-EP-2017-335

2018
- $d\sigma/dt$ elastic: DIP @ 13 TeV Preliminary

Schematic elastic cross-section
Analysis methods

**Total cross section**: \( N_{\text{inel}} \) (from T1,T2 telescopes) \( N_{\text{el}} \) (from RomanPots detectors)

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{(dN_{\text{el}}/dt)_{t=0}}{(N_{\text{el}} + N_{\text{inel}})} \]

**L independent**

But also:

**L dependent/ Elastic Only**

\[ \sigma_{\text{tot}}^2 = \frac{16\pi}{1 + \rho^2} \frac{1}{\mathcal{L}} \left( \frac{dN_{\text{el}}}{dt} \right)_{t=0} \]

\[ \rho \text{ independent} \]

\[ \sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}} \]

\( \rho \text{ measurement} \): elastic scattering at very low-\( t \) (Coulomb-Nuclear Interference region)

\( (d\sigma/dt) \sim |A^C + A^N (1-\alpha G(t))|^2 \)

The differential cross section is sensitive to the phase of the nuclear amplitude

In the CNI both modulus (constrained by measurement in the hadronic \( t \)-region) and phase (\( t \)-dependent) of nuclear amplitude can be tested to determine:

\[ \rho \equiv \cot \arg \mathcal{A}^N(0) = \frac{\Re \mathcal{A}^N(0)}{\Im \mathcal{A}^N(0)} \]
Elastic measurement: method

Example: $\beta^*=2.5\text{km}, 13\text{ TeV}$

Trigger: double-arm RP
RP tracks in opposite arm in diagonal topology
Cuts: left-right correlation in several kinematic variables

Corrections to differential rate (mostly data-driven): acceptance, efficiencies (trigger, DAQ, reconstruction), smearing in $|t|$
Integrated rate: differential rate extrapolated to low $|t|$ (unobserved)

\[
\sigma(dN_{el}/d|t|_{t=0}) \sim 1.6 \%
\]
\[
\sigma(N_{el}) \sim 2.3 \%
\]

@ $13\text{ TeV}$
Inelastic measurement : method

Trigger: activity in T2 either arm

$N_{\text{ev \ in \ T1+T2}} \sim 92\%$ of the inelastic rate

Experimental corrections (mostly data-driven): beam-gas background, trigger efficiency, pileup, T2 reconstruction efficiency, T1-only events

Corrections for final state particles outside T1/T2 acceptance (Monte-Carlo): central diffraction, rapidity gap over T2, low-mass diffraction

Largest contribution from low-mass diffraction ($M< 4.6$ GeV, $|\eta| > 6.5$)

$\sigma(N_{\text{inel}}): 3.7\% \ [\text{at } 13 \text{ TeV}].$
Total Cross section measurements: methods

7 TeV, several methods 
Same beam conditions

8 TeV, several methods 
Different beam conditions

13 TeV
90m: lumi independent
2500m: $\rho$ measurement
Different beam conditions
Total Cross section measurements

\[ \sigma_{\text{TOT}} \sim 2-3\% \]
\[ \sigma_{\text{INEL}} \sim 2\% \]
\[ \sigma_{\text{EL}} \sim 2-4\% \]

\( \sigma_{\text{tot}} \) fits by COMPETE 
\( \sim a + b \ln s + c \ln^2 s \) 
(pre-LHC model RRP\(_{nfL2u}\))

\( \sigma_{\text{el}} \) fit by TOTEM 
\( 11.84 - 1.617 \ln s + 0.1359 \ln^2 s \)
The diffraction cone shrinkage speed up with the collision energy

The increase of $\sigma_{el}/\sigma_{TOT}$ with energy is confirmed also at LHC

\[ B = \frac{d}{dn} \ln \left( \frac{ds}{dt} \right) \bigg|_{t=0} \] increase with $\sqrt{s}$

The linear (ln s) behavior is compatible for $\sqrt{s} \leq 3$ TeV
Elastic measurements: dip @ 13 TeV

dip position in |t| decreases with increasing \( \sqrt{s} \)

\[ \sqrt{s} = 13 \text{ TeV} \quad \beta^* = 2500 \text{ m} \]

dip = 0.47 GeV\(^2\)  
bump/dip ~ 1.8

\[ \sqrt{s} = 7 \text{ TeV} \quad \beta^* = 90 \text{ m} \]

dip = 0.53 ± 0.01 GeV\(^2\)  
bump/dip ~ 1.7 ± 0.1

\[ \sqrt{s} = 13 \text{ TeV} \quad \beta^* = 90 \text{ m} \]

dip = 0.47 GeV\(^2\)  
bump/dip ~ 1.77 ± 0.01

Dip is missing in pp
Elastic measurements: dip and structure at high-\(t\)

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<tr>
<th>(t)</th>
<th>(-7.8 \pm 0.3 \pm 0.1)</th>
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<td>(t)</td>
<td>(-10.95 \pm 0.6)</td>
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No structure seen at high-\(t\)

- \(\sqrt{s} = 7\) TeV
- \(\sqrt{s} = 8\) TeV (scaled 10\(\times\))
- \(\sqrt{s} = 13\) TeV (scaled 1000\(\times\))

Totem Preliminary

\(d\sigma/dt\) (mb/GeV\(^2\))
Elastic Scattering: Non-exponential behavior at low-\( t \)

Already observed at ISR and SPS: confirmed at LHC energies
Change of slope \( \sim 0.1 \text{ GeV}^2 \), faster decrease \(|t| > 0.2 \text{ GeV}^2\)

Pure exponential excluded \( \sim 7\sigma \) significance

Non-exponentiality measured in the nuclear component: contribution of the Coulomb scattering or else?
Elastic Scattering: Non-exponential behavior at low-

Explore in very low-t region the contribution of the interference coulomb-nuclear term and of the nuclear phase

→ the pure exponential behavior of nuclear amplitude is excluded (constant phase excluded, peripheral phase disfavored)
→ Non exponential (n=3) with both constant and peripheral phase is compatible with data
Elastic Scattering : Coulomb interference and $\rho$ parameter

First LHC determination from Coulomb-hadronic interference at 8TeV : $\rho=0.12\pm0.03$
Uncertainty still too high (low statistics)

At 13 TeV : sample with very high statistics allows an unprecedented precision:

| $N_b$ | $|t|_{\text{max}} = 0.07 \text{ GeV}^2$ | $|t|_{\text{max}} = 0.15 \text{ GeV}^2$ |
|------|----------------|----------------|
|      | $\chi^2$/ndf | $\rho$   | $\chi^2$/ndf | $\rho$   |
| 1    | 0.7           | 0.09 ± 0.01 | 2.6           |   -       |
| 2    | 0.6           | 0.10 ± 0.01 | 1.0           | 0.09 ± 0.01 |
| 3    | 0.6           | 0.09 ± 0.01 | 0.9           | 0.10 ± 0.01 |

$|t|_{\text{max}} = 0.07 \text{ GeV}^2$
Comparison with UA4/2 (same t-range)

The new measurement is clearly below the predictions
None of COMPETE models is able to describe simultaneously $\sigma_{\text{TOT}}$ and $\rho$
$\sigma_{\text{TOT}}$ and $\rho$ parameter: possible interpretation?

T-channel exchange of a colourless 3-gluon bound state ($J^{PC} = 1^{--}$) could decrease $\rho$ in pp collisions at large energy. Odderon hint or first evidence of "slowing down" of $\sigma_{\text{TOT}}$ growth at higher energy?
Summary

- Totem has made extensive measures related to $\sigma_{TOT}$ and elastic scattering
- Some of the pre-LHC questions are nevertheless still open

- The (experimental) hints of odd-state seems confined in the sensitivity in the t-channel, although several theories predict the existence of such object (Odderon, 3g-bound state, vector glueball)

TOTEM contributions (observed/confirmed) to the predictions:

✔ decrease of $\rho$ at high energies
✔ diffractive dip in the proton-proton elastic t-distribution
✔ the deviation of the elastic differential cross-section from a pure exponential
✔ the deviation of the elastic diffractive slope, B, from a linear log(s) dependence
✔ the variation of the nuclear phase as a function of t
✔ the large-$|t|$ power-law behavior of the elastic t-distribution with no oscillatory behavior
✔ the growth rate of the total cross-section

What next:

✔ Precise measurement of $\rho$ at low energy (900 GeV)
✔ $\sigma_{TOT}$ at 14 TeV

Beyond Totem:

✔ Differences between the proton-proton and proton-antiproton scattering (ISR)
  LHC in p-pbar?
✗ Observation of 3g-bound state in the s-channel?
Which could be the “three pieces of evidence”?

Once is happenstance. Twice is coincidence. Three times is enemy action.

Ian Fleming

Thanks for your attention!

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