The TOTEM Experiment: results and perspectives

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One of the physics goals of TOTEM was to measure the cross sections at LHC.

- COMPETE Collaboration fits all available hadronic data and predicts at LHC: $\sigma_{\text{tot}} = 111.5 \pm 1.2 + 4.1/-2.1 \text{ mb (14 TeV)}$
- Last pp data at the ISR; only ppbar at “high” energy
- Difference of $\sigma_{\text{pp}}$ vs $\sigma_{\text{pp}}$?
- $\sigma_{\text{TOT}}(s) \sim (\ln s)^\gamma \gamma = 2$?
- $\sigma_{\text{EL}} / \sigma_{\text{TOT}}$ 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 $B(t)$?

$\rho = \Re(\frac{A^N/A^N}{s})_{t=0}$
- Foreseen to “decrease” at high energy: how fast?
- Test dispersion relation (mix real and imaginary part)
Analysis methods

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

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

But also:

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

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

\( \rho \) 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 varied and allow to determine:

\[
\rho \equiv \cot \arg A^N(0) = \frac{\Re A^N(0)}{\Im A^N(0)}
\]
Cross section related measurements in Totem

Run II

- $\sigma_{\text{tot}}$ and $\rho$ measurement @ 14 TeV
- $\sigma_{\text{tot}}$ and $\rho$ measurement @ 900 GeV

2017

- $\sigma_{\text{tot}}$ lumi independent @ 2.76 TeV
- $\sigma_{\text{tot}}$ lumi independent @ 13 TeV
- $\rho$ measurement @ 13 TeV

Run I

- $\sigma_{\text{tot}}$ lumi independent @ 8 TeV

2016

- $\rho$ measurement @ 8 TeV
- d$\sigma$/dt elastic: non-exponential behaviour @ 8 TeV

2015

- $\sigma_{\text{tot}}$ lumi independent @ 8 TeV
- $\rho$ measurement @ 8 TeV

2013

- $\sigma_{\text{tot}}$ lumi independent @ 8 TeV
- Elastic scattering @ 8 TeV
- Elastic, inelastic cross section
- Elastic: full t-range

2012

- Elastic scattering @ 7 TeV
- First $\sigma_{\text{tot}}$ @ 7 TeV

2011

- Elastic scattering @ 7 TeV
- EPL 95-41001
- First $\sigma_{\text{tot}}$ @ 7 TeV
- EPL 96-21002
Total Cross section measurements

\[ \sigma_{\text{tot}} \text{ fits by COMPETE} \sim \ln^2 s \]

(pre-LHC model \(\text{RRP}_{\text{nf}}L_2u\))

\[ \sigma_{\text{el}} \text{ fit by TOTEM} \]

\( (11.84 - 1.617 \ln s + 0.1359 \ln^2 s) \)
Total Cross section measurements: methods

8 TeV: Luminosity independent
Elastic90 ($\beta^*=90m$ sample, exploiting non-exponentiality of elastic distribution)
Elastic1000 ($\beta^*=1Km$, measuring rho, test of different nuclear phases)

Several methods and different beam conditions

7 TeV: several methods
Same beam conditions
Ratio elastic – total cross section

The increase of $\sigma_{el}/\sigma_{TOT}$ with energy is confirmed also at LHC.
Elastic measurements: dip and structure at high-$t$

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

\[ \text{dip} = 0.53 \text{ GeV}^2 \]
\[ \text{bump/dip} \sim 1.7 \]

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

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \text{dip} = 0.47 \text{ GeV}^2 \]
\[ \text{bump/dip} \sim 1.8 \]

No structure seen at high-$t$
Elastic measurements: slope at low-$t$

The diffraction cone shrinkage speed up with the collision energy

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

The linear ($\ln s$) behavior changes for $\sqrt{s} > 3$ TeV
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-t

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

The non exponentiality is intrinsic in the nuclear amplitude
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:

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

Comparison with UA4/2 (same $t$-range)

The new measurement is clearly below the predictions
None of the models considered by COMPETE 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.

Odd-Component (Odderon) hint or first evidence of “slowing down” of $\sigma_{\text{TOT}}$ growth at higher energy?
No conclusions, rather some hints to trigger discussion………

Totem has made extensive measures related to $\sigma_{TOT}$ and elastic scattering
...many more than it was foreseen indeed

Some of the pre-LHC questions seems 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 of 3g-bound state:

✔ decrease of $\rho$ at high energies
✔ the growth rate of the total cross-section
✔ 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
✔ Precise measurement of $\sigma_{TOT}$ and $\rho$ at low energy (900 GeV) and 14 TeV
✔ Differences between the proton-proton and proton-antiproton scattering (“repeat” ISR)
✔ LHC in p-pbar?
✔ Exclusive vector meson production
✗ Observation in the s-channel (vector glueball) ?

Which could be the “three pieces of evidence” of the Odderon?
Once is happenstance. Twice is coincidence. Three times is enemy action.

Ian Fleming