TOTEM Measurement of $\rho, \sigma_{\text{tot}}, \sigma_{\text{elastic}}$
at 13TeV at LHC

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The TOTEM experiment

T1&T2 Inelastic detectors

$T1: \ 3.1 < \eta < 4.7$

$T2: \ 5.3 < \eta < 6.5$

Roman Pots: edgeless silicon strip detectors, detecting scattered protons at ~220m from IP5 (CMS)
Detectors technology

Silicon Strips in secondary vacuum pots

Inelastic tracking detectors:
T1 (CSC)
T2 (triple GEM)
Cross section measurement

Luminosity independent method:

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

Optical theorem

\[ \rho = \mathcal{R} \left( F^H / \mathcal{F}^H \right)_{t=0} \]

special RP alignment fill October 2015, \( \beta^* = 90 \text{ m} \), \( \mu \sim 0.07 \), RPs at 5\( \sigma \)
In October we ran 5 days – 13Tev, $\beta^*=90m$, PU~0.7 ~13 billion elastics recorded.

No structure was observed at large $t$.

Soon more information on large $t$ analysis.
Differential Slope

\[ \frac{d\sigma}{dt} \approx A \exp(-B|t|) \]

- at low \(|t|\):

\[ \frac{dN}{dt}_{t=0, \text{exp}} = 1.3558 \times 10^7 \text{ GeV}^{-2} \]

\[ N_{\text{el}} = 666023 \]

\[ N_{\text{metastic}} = 1.70759 \times 10^6 \]

\[ B_{\text{exp}} = -20.36 \pm 0.05 \text{ GeV}^{-2} \]
Differential Slope

TOTEM @ $\sqrt{s} = 13$ TeV: $B = 20.36 \pm 0.25$ GeV$^{-2}$
\( \sigma_{\text{tot}}, \sigma_{\text{inel}} & \sigma_{\text{el}} \text{ vs } \sqrt{s} \)

TOTEM @ \( \sqrt{s} = 13 \text{ TeV} \) (\( \rho = 0.10 \)):

\[ \sigma_{\text{tot}} = 110.6 \pm 3.7 \text{ mb}, \quad \sigma_{\text{inel}} = 79.5 \pm 2.7 \text{ mb}, \quad \sigma_{\text{el}} = 31.0 \pm 2.1 \text{ mb} \]
\[ \frac{\sigma_{el}}{\sigma_{tot}} \text{ VS } \sqrt{s} \]

TOTEM @ $\sqrt{s} = 13$ TeV: $\frac{\sigma_{el}}{\sigma_{tot}} = 0.281 \pm 0.010$
\( \beta^* = 2.5 \text{ km data @ } \sqrt{s} = 13 \text{ TeV} \)

Elastic scattering in Coulomb-nuclear interference (CNI) region at very low \(|t|\):

\[ \rho = \Re \left( \frac{F^H}{\Im F^H} \right)_{t=0} \]

Special run September 2016, \( \beta^* = 2.5 \text{ km} \)

Vertical RPs @ \(3\sigma \Rightarrow |t|_{\text{min}} \approx 8 \cdot 10^{-4} \text{ GeV}^2\) \(L_{\text{int}} \approx 0.4 \text{ nb}^{-1} \Rightarrow \sim 7 \text{ M elastic}\)

Data taking: red RPs; optimize \(|t|\)-reach \(\Rightarrow\) analysis: only RP220 far

Reasonable background \(\Rightarrow\) regular beam cleaning procedure
Elastic selection in 2.5 km data

Horizontal scattering angle left vs right

Vertical scattering angle left vs right

Background: O(0.1 \%)
$\beta^* = 2.5\ \text{km low } |t|\ d\sigma_{el}/dt @ \sqrt{s} = 13\ \text{TeV}$

normalisation obtained from $\beta^* = 90\ \text{m } \sigma_{\text{tot}}$ analysis

Coulomb contribution clearly visible!
Interference region

- observed cross-section

\[
\frac{d\sigma}{dt} \propto F^H + \ldots + F^H + \ldots
\]

- our modelling (assumptions)
  - “interference” formula: Kundrát-Lokajíček
  - Coulomb amplitude: QED + experimental form factors
  - hadronic modulus: empirical guidance, at low \(|t|\):
    \[
    a \exp \left( \sum_{n=1}^{N_b} b_n t^n \right)
    \]
  - hadronic phase: slowly varying (central behaviour), as in pre-LHC determinations
\( N_b = 1, |t|_{\text{max}} = 0.07 \text{ GeV}^2 \)

\[ \rho \equiv \Re \frac{F^H}{\Im F^H} \bigg|_{t=0} \]

\( |t| \) ranges:
- \( |t| < 0.015 \text{ GeV}^2 \): \( N_b = 3 \), for higher \( t \), fast decrease due to the dip
- \( |t| < 0.07 \text{ GeV}^2 \): \( N_b = 1 \) expected sufficient, equivalent to UA4

\( \rho \) extraction

\( \rho \equiv \Re \frac{F^H}{\Im F^H} \bigg|_{t=0} \)
Data incompatible with purely-exponential hadronic component
- \( \rho \) constrained in a narrow range
- one of the most precise \( \rho \) determinations in history
- important fit configurations (red)
  - \( Nb = 3, |t|_{\text{max}} = 0.15 \text{ GeV}^2 \): “our best“ determination
  - \( Nb = 1, |t|_{\text{max}} = 0.07 \text{ GeV}^2 \): “most fair“ comparison to past measurements
Observe significant decrease of $\rho$ at larger $\sqrt{s}$. 

PDG:
- $\Delta$ for $pp$
- $\mathbf{p}$ for $pp$

TOTEM:
- $\circ$ for indirect
- $\mathbf{r}$ for via CNI

COMPETE
(pre-LHC model RRP_{nf,1,2u}):
- $\mathbf{g}$ for $pp$
- $\mathbf{p}$ for $pp$
Models compatibility

Comparison with COMPETE model predictions:


Compatibility with COMPETE models (P-value):

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{tot}}$ (6 points)</th>
<th>$\rho$ at 13 TeV ($0.098 \pm 0.01$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>blue</td>
<td>0.99</td>
<td>$2 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>magenta</td>
<td>$4 \cdot 10^{-5}$</td>
<td>0.11</td>
</tr>
<tr>
<td>green</td>
<td>$2 \cdot 10^{-16}$</td>
<td>0.84</td>
</tr>
</tbody>
</table>
Physics interpretation

• $t$-channel exchange of a colourless 3-gluon bound state ($JPC = 1--$) could decrease $\rho$ in pp collisions at large $\sqrt{s}$
  – originally predicted as “Odderon” in axiomatic theory [Lukaszuk, Nicolescu]
  – confirmed in QCD [Vacca, Braun, Lipatov et al.]: colourless 3-gluon bound state with stronger internal coupling than external
  – “vector glueball” in lattice calculations [Luscher, Morningstar et al.]
• other manifestations
  – difference of depth of “diffractive dip” between p-p and p-p$_{\text{bar}}$ collisions
  – faster increase of $\sigma_{\text{tot}}$ with $\sqrt{s}$
  – non-constant hadronic phase and low-|$t$| deviation from pure exponential
  – no oscillatory effects at large |$t$|
• 2 models in agreement with TOTEM data [Nicolescu, Durham]
  – agreement improved when included exchange of 3-gluon bound state
Conclusions

- Totem experiment made a precise measurement of the proton-proton cross section at $\sqrt{s}=13\text{TeV}$.
- In a special run with $\beta^*=2500\text{m}$, could reach the Coulomb-Nuclear Interference zone and measure the $\rho$ parameter with unprecedented precision.
- Both measurement seems incompatible with COMPETE calculations.
- The presence of a bound 3 gluon state $JPC=1^-$ can explain such behavior.
- New data are foreseen at 14TeV after LHC Long Shutdown 2 in 2021.