Total, Elastic and Inelastic Cross-Section Measurements in TOTEM

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(on behalf of the TOTEM Collaboration)

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Cross-Section Measurements: from ISR to Tevatron

Importance of performing $\sigma_T$ and $d\sigma_{el}/dt$ measurements @ LHC with adequate resolution, allowing to distinguish among different models predictions and to check known features at higher energies.

COMPETE Coll. [PRL 89, 201801 (2002)],

- best fit with stat. error band
- total error band from all models considered
- total error band of best fit
- incl. both TEVATRON points
- $\sim \ln^2 s$
Three Methods for $\sigma_T$ Measurement

Optical Theorem: \[ \sigma_T = \frac{8\pi}{p\sqrt{s}} \text{Im} \ F(s,t)|_{t=0} \]

\[ \mathcal{L} \sigma_T^2 = \frac{16\pi}{1 + \rho^2} \left. \frac{dN_{el}}{dt} \right|_{t=0} \]

\[ \rho = \frac{\text{Re} \ F}{\text{Im} \ F} \bigg|_{t=0} \quad \rho = 0.140 \pm 0.007 \quad \text{(from Compete)} \]

1) Elastic Scattering + Inelastic Scattering + $\mathcal{L}$:

no dependence on $\rho$

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

2) Elastic Scattering + $\mathcal{L}$ + Optical Th.:

no dependence on $N_{inel}$

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

3) Elastic Scattering + Inelastic Scattering + Optical Th.:

$\mathcal{L}$-independent

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

Proper tracking acceptance in very forward region required: elastically scattered p detection mandatory
TOTEM Detector Setup @ IP5 of LHC

Detectors on both sides of IP5

TOTEM Inelastic Telescopes

T1: $3.1 < |\eta| < 4.7$ (18 – 90 mrad) \hspace{1cm} P_T > 100 \text{ MeV}

T2: $5.3 < |\eta| < 6.5$ (3 – 10 mrad) \hspace{1cm} P_T > 40 \text{ MeV}

⇒ \sim 92\% inelastic event acceptance

~14 m

TOTEM Elastic Detectors (RP)

Si strip detectors with active area up to \sim 50 \mu m from physical border, hosted in movable beam-pipe insertions (RP) approaching the LHC beam down to \sim 1 mm (\theta down to 5-10 \mu rad)

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Measurement of Inelastic Rate

- Trigger: from T2 (either arm); “Zero-Bias” (for calibration purposes)

- Experimental effects corrections (mostly data-driven):
  - beam-gas background, trigger and T2 reconstruction efficiency, pile-up, “T1-only” events

- Physical effects corrections (MC-driven):
  - accounting for events with no particles in T1/T2 region (central diffraction, rapidity gap over T2, low-mass diffraction);
  - → largest contribution from low-mass diffraction
    (Mx< 4.6 GeV for |η| > 6.5)

- $\sigma (N_{inel}) = 3.7\%$ (@ 13 TeV)
Trigger: from RP (double arm)

Very good knowledge of proton transport from IP5 to RP (via excellent determination of optical functions) → precise proton kinematics reconstruction

Two “anti-parallel” protons in final state (p tracks in opposite RP arms in diagonal topology) → very robust elastic pp event tagging

Selection cuts: left-right correlation in several kinematic variables

Differential rate corrections (mostly data-driven): acceptance, trigger/DAQ/reconstruction efficiencies, smearing in |t|

Integrated rate: from differential rate extrapolated to low-|t| region (unobserved)

\[ \sigma(N_{el}) = 2.3\%; \sigma(dN_{el}/dt)_{t=0} = 1.6\%, \text{ (at } 13 \text{ TeV, } \beta^* = 90 \text{ m)} \]
Overview on Cross-Section Measurements in TOTEM

Data taking in various LHC configurations and different RP detector approaches to the beam allowed the measurements of $\sigma_T$, $\sigma_{el}$, $\sigma_{inel}$ in a wide energy range (2.76 to 13 TeV) and of $d\sigma_{el}/dt$ in a wide $|t|$ range.

Angular divergence @ IP: $\sigma_\theta = \sqrt{\varepsilon/\beta^*}$
Beam size @ IP: $\sigma^* = \sqrt{\varepsilon/\beta^*}$

Allowed $|t|$ range depends on beam optics (special high $\beta^*$– low $\mathcal{L}$ runs required for low $|t|$) and on proton detector approach to the beam.
Comparing Results from $\sigma_T$ Measurement Methods

Overview on $\mathcal{L}$-independent method results

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma_T$ (mb)</th>
<th>$\sigma_{\text{inel}}$ (mb)</th>
<th>$\sigma_{\text{el}}$ (mb)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.76</td>
<td>84.7 ± 3.3</td>
<td>62.8 ± 2.9</td>
<td>21.8 ± 1.4</td>
<td>PoS (DIS2017) 059</td>
</tr>
<tr>
<td>7</td>
<td>98.0 ± 2.5</td>
<td>72.9 ± 1.5</td>
<td>25.1 ± 1.1</td>
<td>EPL 101 (2013), 21004</td>
</tr>
<tr>
<td>8</td>
<td>101.7 ± 2.9</td>
<td>74.1 ± 1.7</td>
<td>27.1 ± 1.4</td>
<td>PRL 111 (2013) 012001</td>
</tr>
<tr>
<td>13</td>
<td>110.6 ± 3.4</td>
<td>79.5 ± 1.8</td>
<td>31.0 ± 1.7</td>
<td>CERN-EP-2017-321</td>
</tr>
</tbody>
</table>

- Measurement of $N_{\text{el}} / N_{\text{inel}} \rightarrow$ additional determination of $\sigma_{\text{el}}$ and $\sigma_{\text{inel}}$
- Very good agreement among different measurement methods and beam cond. (@ $\sqrt{s} = 7, 8$ TeV) → very good understanding of systematic uncertainties and correction procedures → proof of reliability of the $\mathcal{L}$-independent method
- Typical global uncertainty: $\sigma_T \sim 2-4\%$, $\sigma_{\text{inel}} \sim 2-4\%$, $\sigma_{\text{el}} \sim 4-5\%$
Summary of $\sigma_T$ Measurement Results

Latest results ($@ \sqrt{s} = 13$ TeV, $\mathcal{L}$-independent method assuming $\rho = 0.10$):

$\sigma_T = 110.6 \pm 3.4$ mb, $\sigma_{\text{inel}} = 79.5 \pm 1.8$ mb, $\sigma_{\text{el}} = 31.0 \pm 1.7$ mb

- $\sigma_T$ growth with energy compatible with COMPETE predictions (asymptotically with $\ln^2 s$)
- Fair agreement with other LHC experiments results
Highlights from $\sigma_T$ Measurements

- $\sigma_{el}/\sigma_T$ ratio increase with energy confirmed @ LHC
- Increase with $\sqrt{s}$

- For $\sqrt{s} > 3$ TeV: deviation of nuclear slope $B$ from the low energy linear (with ln $s$) extrapolation
- Diffraction cone shrinkage speeds up with energy
$d\sigma_{el}/d|t|$ at Low-|$t|$: Non-Exponential Behavior

- Confirmed @ LHC (already observed at ISR and SPS)
- First clear evidence with 8 TeV high statistics data sample: “purely” exponential slope excluded with a significance $> 7\sigma$
- Quadratic ($N_b = 2$) and cubic ($N_b = 3$) polynomials well describe data

Using the optimized parameterization for extrapolation to $t = 0$: new results for $\sigma_T$ are found in agreement with previous measurement

Non-exponential measurement in nuclear component at low-|$t$| → empirical guidance for hadronic modulus of $A^N$ determination in the Coulomb-nuclear interference region ($\rho$ measurement .... )
**Proper modeling of CNI**

\[ \frac{d\sigma}{dt} \sim |A_C + A_N(1-i\alpha G(t))|^2 \]

- sensitive to the phase of the nuclear amplitude \( A_N \)
- \(|t|\)-dependent modulus (constrained by hadronic region measurement) and phase of \( A_N \) can be derived to give:

\[ \rho = \text{Re}(A_N(0))/\text{Im}(A_N(0)) = \cot[\text{Arg} A_N(0)] \]

**CNI region reached @ \( \sqrt{s} = 13 \text{ TeV} \)**

(down to \(|t| \sim 8 \cdot 10^{-4} \text{ GeV}^2\):)

special high statistics run with \( \beta^* = 2500 \text{ m} \)
and RP approaching the beam centre @ \( \sim 3\sigma \)

**More details on our modeling:**

- “interference formula”: most general (Kundrát-Lokajíček) considered, also compared to others by Cahn and West-Yennie;
- phase of \( A_N \): assume slow variation with \(|t|\)
  (same assumption as in pre-LHC measurements) → fair comparison;
  more exploration in forthcoming studies …. 
@ $\sqrt{s} = 8 \text{ TeV} \ (\beta^* = 1000 \text{ m})$ – Eur. Phys. J. C76 (2016) 661

first LHC $\rho$ measurement from CNI; uncertainty too high due to low statistics: $\rho = 0.12 \pm 0.03$

@ $\sqrt{s} = 13 \text{ TeV} \ (\beta^* = 2500 \text{ m})$ – CERN-EP-2017-335

$\rho$ measurement with unprecedented precision thanks to a very high statistics sample:

| $N_b$ | $|t|_{\text{max}} = 0.07 \text{ GeV}^2$ | $|t|_{\text{max}} = 0.15 \text{ GeV}^2$ |
|-------|---------------------------------|---------------------------------|
|       | $\chi^2/\text{ndf}$ | $\rho$ | $\chi^2/\text{ndf}$ | $\rho$ |
| 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 |

Red: important fit configurations
- $N_b = 3$, $|t|_{\text{max}} = 0.15 \text{ GeV}^2$: “our best“ determination
- $N_b = 1$, $|t|_{\text{max}} = 0.07 \text{ GeV}^2$: “most fair“ comparison to past measurements (same $|t|$-range of UA4/2)
COMPETE Collaboration: very comprehensive study of pre-LHC data [PRL 89 (2002) 201801]
- 256 models, based on various assumptions with crossing-even only asymptotic component
- 23 models found to reasonably describe data and give predictions which cluster in 3 bands

None of the COMPETE models is able to simultaneously describe the $\sigma_T$ and $\rho$ LHC measurements @ $\sqrt{s} = 13$ TeV

 Compatibility of TOTEM results with COMPETE models (p-value):

<table>
<thead>
<tr>
<th>$\sigma_{tot}$ (4 to 6 TOTEM measurements)</th>
<th>$\rho$ at 13 TeV (0.09 ± 0.01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>blue</td>
<td>0.990 to 0.995</td>
</tr>
<tr>
<td>magenta</td>
<td>$4 \cdot 10^{-3}$ to $7 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>green</td>
<td>$3 \cdot 10^{-9}$ to $2 \cdot 10^{-15}$</td>
</tr>
</tbody>
</table>
Alternative models (Nicolescu et al.; Durham Group):
- including a t-channel exchange of a crossing-odd (opposite sign for p-p and p-pbar) component
- agreement with TOTEM data

⇒ Crossing-odd component needed to describe TOTEM data: hint for the “Odderon”?
⇒ … or first indication of “slowing down” of $\sigma_T$ growth at higher energies, as predicted by dispersion relations when only crossing-even amplitude component considered?

Odderon:
- Originally introduced within axiomatic theory to account for differences between p-p and p-pbar data
- Studied in the framework of Regge theory as counterpart of crossing-even Pomeron
- Predicted in QCD as a colorless 3-gluons bound state with quantum numbers $J^{PC} = 1^{++}$
- Predicted in lattice-QCD (named “oddball” or “vector glueball”) with $M = 3$-$4$ GeV
Latest Results on $d\sigma_{el}/d|t|$ Measurements at High-$|t|$}

Other indications of Odderon exchange in $d\sigma_{el}/d|t|$
- Energy dependent difference in “deep” structure between p-p (pronounced also at LHC) and p-pbar (shallower)
- High-$|t|$ region power-low behavior without “oscillations”
- Low-$|t|$ deviation from pure exponential and not constant hadronic phase
- Deviation of elastic slope from a linear logs dependence

**TOTEM Results**
- Pronounced “deep/bump” structure in pp collisions confirmed at TeV scale (first seen @ $\sqrt{s} = 7$ TeV), with the deep position approaching $|t| = 0$ with increasing energies
- Comparison of results @ $\sqrt{s} = 2.76$ TeV with Tevatron data (@ $\sqrt{s} = 1.96$ TeV, shallower deep as expected) → first comparison of p-p and p-pbar results (at the TeV scale !) since ISR times ....
- Observed power-low behavior at high-$|t|$ without “oscillations”

**TOTEM**

$\sqrt{s} = 13$ TeV

$\sqrt{s} = 2.76$ TeV

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Extensive programme of $\sigma_T$, $\sigma_{el}$ and $\sigma_{inel}$ measurements in Run I and II

- $@ \sqrt{s} = 13$ TeV
  - $\rho$ measurement significantly below expectations from pre-LHC fits
  - none of the COMPETE “no-Odderon” models is able to simultaneously describe the $\sigma_T$ and $\rho$ measurements
  - alternative “Odderon” models are able to describe TOTEM data
    - inclusion of crossing-odd component (3-gluons bound state with $J^{PC} = 1^-$) essential
    - if crossing-odd component not important, current measurements give first indication (via dispersion relations) of slower rise of $\sigma_T$ at higher energies

- TOTEM observations of pronounced “dip/bump” structures in $p-p$ $d\sigma_{el}/d|t|$ at the TeV scale represent another independent indication for Odderon
  - confirmed by comparisons to Tevatron (D0) results on $p-pbar$ $@ \sqrt{s} = 1.96$ TeV
    (shallower dip structure, as expected)

- Other TOTEM observations consistent with “Odderon” models:
  - deviation from pure exponentially in the elastic slope (B) and not constant hadronic phase at low-$|t|$; deviation of B from a linear $\log(s)$ dependence; power-low behavior at high-$|t|$ in $d\sigma_{el}/d|t|$ without “oscillations”; growth rate of $\sigma_T$ as a function of $\sqrt{s}$

- Next: analysis of new data $@ \sqrt{s} = 900$ GeV and ...
  - looking forward for new data taking $@ \sqrt{s} = 14$ TeV from LHC Run III
Backup Slides
Roman Pots (II)

Each Pot:
- **10 planes** of Si detectors
- 512 strips at 45° orthogonal
- Pitch: 66 µm
- Total ~ 5.1K channels
- Digital readout (VFAT): trigger/tracking
- Hit Resolution: $\sigma \sim 10$ µm

Integration of traditional **Voltage Terminating Structure** with the **Current Terminating Structure**

Detectors expected to work up to $\mathcal{L}_{\text{int}} \sim 1$ fb$^{-1}$
(no loss of performance during Run I)

Edgeless Si detector:
50 µm of dead area
Proton Transport from IP5 to RP Location

Optical functions:
- \( L \) (effective length), \( v \) (magnification), \( D \) (machine dispersion)
- Describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP
- Define \( t \) and \( \xi \)-range (acceptance)
- Depend on LHC machine optics configuration

With:
\[
\xi = \Delta p/p; \quad t = t_x + t_y; \quad t_i = -(p\theta_i^*)^2
\]

\((x, y)\): vertex position at RP location (s)
\((x', y')\): vertex position at IP
\((\theta_x^*, \theta_y^*)\): emission angle at IP

→ Elastic proton kinematics reconstruction \((\theta_x^*, \theta_y^*)\)
(for \(\beta^* = 90\, \text{m} @ \text{RP220m:}\)
\(L_y = 263\, \text{m}, v_y \approx 0, L_x \approx 0, v_x = -1.9\):)

\[
\begin{align*}
\Theta_x^* &\approx \left(\Theta_x - \frac{dv_x}{ds} x^*\right) \frac{dL_x}{ds}, \quad \frac{\Delta p}{p} = 0 \\
\Theta_y^* &\approx y / L_y
\end{align*}
\]

Excellent optics determination (~ 0.25% using constraints from proton tracks in RPs, TOTEM: *New J. Phys.* 16 (2014) 103041) and detector alignment
→ precise proton reconstruction
Critical procedures (fill-based): movable devices, beam optics variations

- **Pot position wrt LHC beam center:**
  
  alignment wrt collimaters by approaching the beam “cut edge” (~ 20 µm)

- **Internal alignment of components within detector assembly:**
  
  metrology, local tracks (few µm)

- **Relative alignment of the pots in a station:**
  
  tracks in overlapping regions (Millepede algorithm, few µm)

- **Global alignment:**
  
  track based exploiting symmetries (co-linearity) of hit profiles for elastically scattered protons, also allows “left-right” constraints (< 10 µm in x, ~ 20 µm in y)

**Final precision achieved:**

~ 10(50) µm in x(y) → δt/t ~ 0.3-0.6%
Proton selection cuts
- collinearity cuts (left-right):
  \[ \Theta^*_{x,45} \leftrightarrow \Theta^*_{x,56} \]
  \[ \Theta^*_{y,45} \leftrightarrow \Theta^*_{y,56} \]
  (width in agreement with beam divergence)
- low \( \xi \) cuts: \( |x^*| < 0.6 \text{ mm} \) and \( 2\sigma \) cut in \( \Delta \theta^*_{y} \)
- vertex cuts (beam halo): \( |x^*_{45} - x^*_{56}| < 27 \ \mu\text{m} \)
- optics related cuts

Background subtraction
- interpolating the background tails (> 3 \( \sigma \))
  into the signal region (< 3 \( \sigma \))

Acceptance correction
- assuming azimuthal symmetry
- correcting for smearing around limitation edges
Unfolding of resolution effects:
MC based iterative procedure

Normalization (reconstruction efficiencies):

- **Trigger Efficiency** (from zero-bias data stream) > 99.8% (68% CL)
- **DAQ Efficiency** 98.142 ± 0.001 %
- **Reconstruction Efficiency**
  - intrinsic detector inefficiency: 1.5 – 3 % / pot
  - elastic proton lost due to interaction: 1.5% / pot
  - event lost due to overlap with beam halo
    (depends on RP position wrt beam and diagonals): 4 – 8% (β*=90m); 30% (β*=3.5m)

Luminosity from CMS: systematic error of 4%

Systematic uncertainties: dominated by \( \mathcal{L} \) and by analysis t-dependent effects
(misalignments, optics imperfections, energy offset, acceptance correction and un-smearing correction)
Elastic Scattering in the Coulomb-Nuclear Interference Region

Experimental data → Physics parameters (ρ, …) → Theoretical/phenomenological models

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

\[ F_C = \frac{\alpha s}{t} \mathcal{F}^2(t) \]

• Modulus constrained by measurement: \( \frac{d\sigma}{dt} \equiv A e^{-B(t) |t|} \)
  \[ B(t) = b_0 + b_1 t + \ldots \]

• Phase \( \arg F^H \) (interference term): very little guidance by data

Simplified West-Yennie formula:
• constant slope \( B(t) = b_0 \)
• constant hadronic phase \( \arg(F^H) = p_0 \) (“constant phase”)
• \( \Psi(t) \) acts as real interference phase:
  \[ \Psi(t) = \ln \frac{B(t)}{2} + \gamma_{\text{Euler}} \]

General Kundrát-Lokajíček formula:
• any slope \( B(t) \)
• any hadronic phase:
  - if \( \arg F^H(t) \rightarrow \) “peripheral phase”
  - if \( \arg F^H \sim \cos t \rightarrow \) “central phase”
• complex \( \Psi(t) \):
  \[ \Psi(t) = \pm \int_{t_{\text{min}}}^{0} dt' \ln \frac{t'}{t} \frac{d}{dt'} \mathcal{F}^2(t') \pm \int_{t_{\text{min}}}^{0} dt' \left( \frac{F^H(t')}{F^H(t)} - 1 \right) \frac{I(t, t')}{2\pi} \]
  \[ I(t, t') = \int_{0}^{2\pi} d\varphi \frac{\mathcal{F}^2(t'')}{t''} , \quad t'' = t + t' + 2\sqrt{tt'} \cos \varphi \]
Elastic Scattering in the Coulomb-Nuclear Interference Region

data sensitivity region

“central phase”:
\[ \arg F^H(t) = \frac{\pi}{2} - \arctan \frac{\cot p_0}{1 - \frac{t}{t_d}} \]

“constant phase”:
\[ \arg F^H(t) = p_0 \]

“peripheral phase”:
\[ \arg F^H(t) = p_0 + p_A \exp \left[ \kappa \left( \ln \frac{t}{t_m} - \frac{t}{t_m} + 1 \right) \right] \]

Only 1 free parameter: \( p_0 = \psi(0) \)

Most recent details on:
- Jiri Prochazka (jiri.prochazka@cern.ch) PhD thesis: “Elastic proton-proton collisions at high energies”, Prague 2018 - Charles University
Direct $\sigma_{\text{inel}}$ Measurement @ 7 TeV

Impact of Low-Mass diffraction:

- Extrapolation to low $M_X$ region: main source of systematic uncertainty on $\sigma_{\text{inel}}$
- Minimal $M_X$ depends on maximal $|\eta|$ coverage: lower $M_X$ reachable $\rightarrow$ minimal model dependence on corrections for low mass diffraction
- TOTEM (T1+T2: $3.1 < |\eta| < 6.5$) gives an unique forward charged particle coverage @ LHC $\rightarrow$ direct measurement of $\sigma_{\text{inel}}$ with lower sys. unc.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma_{\text{inel}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>$73.2^{+2.0}_{-4.6}$ (model) $\pm$ 2.6 (exp)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$69.1 \pm 6.9$ (model) $\pm$ 2.4 (exp)</td>
</tr>
<tr>
<td>CMS</td>
<td>$68.0 \pm 4.0$ (model) $\pm$ 3.1 (exp)</td>
</tr>
<tr>
<td>LHCb</td>
<td>$66.9 \pm 4.4$ (model) $\pm$ 2.9 (exp)</td>
</tr>
<tr>
<td>TOTEM</td>
<td>$73.7 \pm 1.5$ (model) $\pm$ 2.9 (exp)</td>
</tr>
</tbody>
</table>