Recent Elastic and Total Cross-Section Measurements by

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on behalf of the TOTEM Collaboration

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Elastic scattering – from ISR to Tevatron: Old Trends

- Dip vs. shoulder
- Dip position: shrinkage of forward peak
- Any further peaks at large $|t|$? Wide range of predictions.

- Evolutions $\sigma_{\text{tot}}(s)$, $\rho(s)$?
- No pp data after ISR
- $\sigma_{\text{el}} / \sigma_{\text{tot}}(s)$?

[Graphs and data points showing trends and comparisons across different energies and experiments.]
The TOTEM Experiment at the LHC

IP1: ATLAS, LHCf
IP2: ALICE
IP3: Momentum Cleaning
IP4: RF (Acceleration)
IP5: CMS, TOTEM
IP6: Beam Dump
IP7: Betatron Cleaning
IP8: LHCb, MoEDAL
Roman Pots: elastic & diffractive protons close to outgoing beams → Proton Trigger

Inelastic Telescopes: charged particles in inelastic events

T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV
T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

→ Inelastic Trigger

Experimental Setup at IP5 in Run 1

[Ref.: JINST 3 (2008) S08007]

Measurement and analysis techniques covered in past presentations and in the appendix (just ask!).
History of Elastic and Total Cross-Section Measurements

- **2011**
  - Elastic scattering @7 TeV
    EPL 95-41001
  - First $\sigma_{\text{tot}}$ @ 7 TeV
    EPL 96-21002

- **2012**
  - $\sigma_{\text{tot}}$ lumi-independent @7 TeV
  - Elastic, inelastic cross section
  - Elastic: full t-range
    EPL 101-21004/21003/21002

- **2013**
  - $\sigma_{\text{tot}}$ lumi independent @ 8 TeV
    PRL 111-12001

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

- **2016**
  - $d\sigma/dt$ measurement @ 8 TeV
  - EPJ C76-661

- **2017**
  - $\sigma_{\text{tot}}$ lumi independent @ 2.76 TeV
    PoS (DIS2017) 059
  - $\sigma_{\text{tot}}$ lumi independent @ 13 TeV

- **2018**
  - $d\sigma/dt$ elastic: dip @ 13 TeV
  - $d\sigma/dt$ elastic: dip @ 2.76 TeV
  - data taking at 900 GeV, CNI region
Elastic Cross-Section Measurements
Elastic Scattering Cross-Section Measurements

Data sets at different energies covering a wide $|t|$ range

Optics, XRP Approach distance

$(\beta_x^*, \beta_y^*) = (70 \text{ m}, 100 \text{ m}), \ 3 \, \sigma$

$\beta^* = 11 \text{ m}, \ 3 \, \sigma$

$\beta^* = 11 \text{ m}, \ 5 \, \sigma$

$\beta^* = 11 \text{ m}, \ 13 \, \sigma$

$\beta^* = 90 \text{ m}, \ 10 \, \sigma$

$\beta^* = 90 \text{ m}, \ 5 \, \sigma$

$\beta^* = 3.5 \text{ m}, \ 7 \, \sigma$

$\beta^* = 3.5 \text{ m}, \ 18 \, \sigma$

$\beta^* = 1 \text{ km}, \ 3 \, \sigma$

$\beta^* = 90 \text{ m}, \ 6 \, \sigma$

$\beta^* = 2.5 \text{ km}, \ 3 \, \sigma$

$\beta^* = 90 \text{ m}, \ 5 \, \sigma, 10 \, \sigma$

\[ |t| \text{ [GeV}^2] \]

perturbative QCD region: $> 1 \text{ GeV}^2$

Dip-bump region: $\sim 0.4 – 1 \text{ GeV}^2$

“Exponential” region (“Pomeron” exchange): $O(10^{-2} \text{ GeV}^2) – O(10^{-1} \text{ GeV}^2)$

Coulomb and CNI region: $< \sim 10^{-3} \text{ GeV}^2$
Elastic Scattering: Exponential Region

Coulomb and CNI region: $< \sim 10^{-3}$ GeV$^2$

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"Exponential" region ("Pomeron" exchange): $O(10^{-2}$ GeV$^2) – O(10^{-1}$ GeV$^2$)

perturbative QCD region: $> 1$ GeV$^2$
Elastic Scattering: The “Exponential” Region at low |t|

New measurement at 13 TeV confirms:

Steepling increase of nuclear elastic slope B with $\sqrt{s}$:

$$\left|\frac{d\sigma}{dt}\right| = e^{-B|t|}$$

Up to $\sim 3$ TeV: compatible with simple Regge model:

$$\frac{d\sigma}{dt} \propto s^{2[\alpha(t)-1]}, \quad \alpha(t) = \alpha_0 + \alpha' t \quad \Rightarrow B = B_0 + 2\alpha' \ln s$$

Around 3 TeV: B(s) trend changes: threshold to new effects?

E.g. multi-Pomeron exchanges: \( B \propto \ln s \rightarrow (\ln s)^2 \)  

Elastic Scattering: The “Exponential” Region at low $|t|$

Is it really exponential?

Data set with 7 M events ($\sqrt{s} = 8$ TeV, $\beta^* = 90$ m):

$0.027 \text{ GeV}^2 < |t| < 0.2 \text{ GeV}^2$, i.e. Coulomb effects negligible

Quite exponential at the first glance, but a closer look reveals …

Relative deviation from exponential:

$$\frac{d\sigma/dt - \text{ref}}{\text{ref}}$$

Pure exponential form ($N_b = 1$) excluded at 7.2 $\sigma$ significance.

[NPB 899 (2015) 527]

... a percent-level deviation only visible with very high statistics.
Elastic Scattering: The “Exponential” Region at low $|t|$

Non-exponentiality at $|t| < 0.2$ GeV$^2$: similar pattern observed also at $\sqrt{s} = 7$ and 13 TeV

$$\frac{d\sigma}{dt} - \text{ref}$$

where ref = fixed exponential function

$$A e^{-B|t|}$$

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 8$ TeV

Can this be due to CNI effects?

(although fit region strongly dominated by nuclear amplitude)

$\Rightarrow$ Include region at even lower $|t|$!

$\text{NEW}$
Elastic Scattering: Coulomb and CNI Region

Coulomb and CNI region: $< \sim 10^{-3}$ GeV

“Exponential” region (“Pomeron” exchange): $O(10^{-2}$ GeV$^2) - O(10^{-1}$ GeV$^2)$

Dip-bump region: $\sim 0.4 - 1$ GeV$^2$

perturbative QCD region: $> 1$ GeV$^2$
Measure elastic scattering at $|t|$ as low as $6 \times 10^{-4}$ GeV$^2$ (8 TeV) and $8 \times 10^{-4}$ GeV$^2$ (13 TeV)

- optics specially developed for measurements at very low $|t|$ ($\beta^* = 1 - 2.5$ km)
- RP approach to $3 \sigma$ from the beam centre

$\sqrt{s} = 8$ TeV, $\beta^* = 1000$ m

$\sqrt{s} = 13$ TeV, $\beta^* = 2500$ m
Elastic Scattering: Coulomb-Nuclear Interference Region

Simplified West-Yennie (SWY) formula (standard in the past):
- constant slope $B(t) = b_0$  $\rightarrow$ already excluded by 90m data at higher $|t|$  $\rightarrow$ SWY incompatible with data!
- constant hadronic phase $\arg(F^H) = p_0$
- $\Psi(t)$ acts as real interference phase

Cahn or Kundrát-Lokajiček (KL) formula:
- any slope $B(t)$
- any hadronic phase $\arg(F^H)$: to be chosen as input
- complex $\Psi(t)$!

- Modulus constrained by measurement in nucl. region: $\frac{d\sigma}{dt} \simeq A \ e^{-B(t) |t|}$

- Phase $\arg(F^H)$: very little guidance by data

Interference region: sensitivity to $\arg(F^H)(t=0)$:

$$F^{C+H} = F^C + F^H e^{i\alpha\Psi}$$

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

Choice of hadronic phase $\arg F^H(t)$ controls the behaviour in impact-parameter space ($b$):
- elastic scattering preferentially central or peripheral.
Elastic Scattering: Coulomb-Nuclear Interference Region

Study of non-exponentiality with Coulomb terms included

**Purely exponential hadronic amplitude**
- excluded assuming a central (e.g. constant) phase
- not explicitly excluded by data if peripheral phase

**Non-exponential hadronic amplitude**
Both central & peripheral phase compatible with data

| Same result $\rho = 0.12 \pm 0.03$ for central and peripheral phase |

| $|t|_{\text{max}} = 0.07 \text{ GeV}^2$ | $|t|_{\text{max}} = 0.15 \text{ GeV}^2$ |
|---|---|
| $N_b$ | $\chi^2/\text{ndf}$ | $\rho$ | $\chi^2/\text{ndf}$ | $\rho$ |
| 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 | $0.10 \pm 0.01$ |

|$|t|_{\text{max}} = 0.07 \text{ GeV}^2$ |

Discussion of $\rho(s)$ after $\sigma_{\text{tot}}$

NEW

[radiation]

**8 TeV**

**13 TeV**

So far only central phases studied:
non-exponentiality confirmed.

$\chi^2/\text{ndf}$ comparison with UA4/2 (same range)
Elastic Scattering: The Dip and Beyond

- **Coulomb and CNI region:** $< \sim 10^{-3}$ GeV
- **“Exponential” region ("Pomeron" exchange):** $O(10^{-2}$ GeV$^2) - O(10^{-1}$ GeV$^2)$
- **Dip-bump region:** $\sim 0.4 - 1$ GeV$^2$
- **Perturbative QCD region:** $> 1$ GeV$^2$
Elastic Scattering: The Dip and Beyond

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

\[ |t|_{\text{dip}} = 0.53 \text{ GeV}^2 \]

\[ |t|_{\text{dip}} = 0.47 \text{ GeV}^2 \]

\[ |t|_{\text{dip}} = 0.61 \text{ GeV}^2 \]

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

\[ O(10^9) \text{ elastic events!} \]

\[ \sqrt{s} = 2.76 \text{ TeV} \]

No structure at high \(|t|\) beyond the dip/bump!
Elastic Scattering: The Dip and Beyond

**Focus on the Dip; Comparison pp – p pbar**

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

\[ R = \frac{\frac{d\sigma}{dt} (\text{bump})}{\frac{d\sigma}{dt} (\text{dip})} \]

\[ R = 1.77 \pm 0.01 \]

Joint D0 – TOTEM analysis in progress to quantify dip / shoulder difference:

- Persistence of dip+bump in pp at TeV scale: \( R \sim 1.7 \sim \text{constant} \)
- Absence of dip in ppbar \( R \sim 1 \)

\[ \rightarrow \text{Evidence for exchange of colourless C-odd three-gluon compound state ("Odderon")} \]
Total pp Cross-Section
Total Cross-Section: Methods and Results

7 TeV

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{1}{\mathcal{L}} \left. \frac{dN_{\text{el}}}{dt} \right|_0 \]

\( (\rho=0.14 \text{ [COMPETE extrapolation]} ) \)

June 2011: \( \sigma_{\text{tot}} = (98.3 \pm 2.8) \text{ mb} \) [EPL 96 (2011) 21002]
Oct. 2011: \( \sigma_{\text{tot}} = (98.6 \pm 2.2) \text{ mb} \) [EPL 101 (2013) 21002]

Different beam intensities!

Different beam intensities!

8 TeV

Luminosity-independent (\( \beta^* = 90 \text{ m} \)): \( \sigma_{\text{tot}} = (101.7 \pm 2.9) \text{ mb} \) [PRL 111(2013) 012001]

... improved with non-exponentiality (\( N_b = 3 \)): \( \sigma_{\text{tot}} = (101.9 \pm 2.1) \text{ mb} \) [NPB 899 (2015) 527]

Combining \( \beta^* = 90 \text{ m} \) & 1 km data: Improved extrapolation of hadronic amplitude to \( t = 0 \) using CNI fit:

\( \sigma_{\text{tot}} = (102.9 \pm 2.3) \text{ mb} \) (assuming central hadronic phase)
\( \sigma_{\text{tot}} = (103.0 \pm 2.3) \text{ mb} \) (assuming peripheral hadronic phase)

[EPJC 76 (2016) 661]

2.76 TeV

Luminosity-independent: \( \sigma_{\text{tot}} = (84.7 \pm 3.3) \text{ mb} \) using \( \rho = 0.145 \) [COMPETE]
Total Cross-Section: Methods and Results

13 TeV

2 Data Sets

β* = 90 m
|t| ∈ [0.01; 3.75] GeV²
CNI not covered, with inelastic data

β* = 2500 m
|t| ∈ [0.0008; 0.2] GeV²
CNI covered, no inelastic data

Lumi-independent method

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

\[ \sigma_{tot} = (110.6 \pm 3.4) \text{ mb} \]

First normalisation via Coulomb!

CNI Fit (for \( N_b = 1 \))

\[ \sigma_{tot} = (111.8 \pm 3.2) \text{ mb}, \ \rho = 0.09 \pm 0.01 \]

\[ \sigma_{tot} = (111.3 \pm 3.2) \text{ mb}, \ \rho = 0.09 \pm 0.01 \]

2 variants:

\[ \sigma_{tot} = (110.3 \pm 3.5) \text{ mb}, \ \rho = 0.08(5) \pm 0.01 \]

\[ \sigma_{tot} = (109.3 \pm 3.5) \text{ mb}, \ \rho = 0.10 \pm 0.01 \]

fully independent \( \rightarrow \) weighted average

\[ \sigma_{tot} = (110.5 \pm 2.4) \text{ mb} \]
pp Cross-Section Measurements

900 GeV: data taken in 2018
analysis in progress

14 TeV: planned for LHC Run 3

Increase of $\sigma_{el} / \sigma_{tot}$ continues.

$\sigma_{tot}$ fits by COMPETE
(pre-LHC model $R_{PbL2u}$)

$\sigma_{el}$ fit by TOTEM
(11.84 - 1.617 ln s + 0.1359 ln^2 s)

$\sigma_{el}$ (green), $\sigma_{inel}$ (red) (mb)

$\sigma_{tot}$ (black)
$\sqrt{s}$ Trends of $\rho$ and Total Cross-Section

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

from CNI analysis (see earlier).

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

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

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

The 13 TeV measurement (for both fit range choices) lies significantly ($4 - 4.7 \sigma$) below the prediction.
None of COMPETE models (all without Odderon!) is able to describe simultaneously $\sigma_{\text{tot}}$ and $\rho$. 
Exchange of a colourless 3-gluon CP-odd compound state ("Odderon") in the t-channel could decrease \( \rho \) in pp collisions at large energy:

... or is it a hint at a slower growth of \( \sigma_{\text{tot}}(\sqrt{s}) \) at higher \( \sqrt{s} \)? (dispersion relations!)
Summary & Outlook

New measurements:
- 13 TeV: $\sigma_{\text{tot}}$, $d\sigma_{\text{el}}/dt$ from $8 \times 10^{-4}$ to 3.8 GeV$^2$, $\rho$
- 2.76 TeV: $d\sigma_{\text{el}}/dt$ up to dip/bump region

Lessons:
- Two pieces of evidence for “Odderon”:
  - dip/bump in pp vs. shoulder in ppbar
  - decrease of $\rho(\sqrt{s})$ at $\sqrt{s} > 8$ TeV
  - still missing: glueball in s-channel
- Steepening of $B(\sqrt{s})$ confirmed at 13 TeV
- Low $|t|$: non-exponential structure of $d\sigma_{\text{el}}/dt$ confirmed at 13 TeV
- High $|t|$: no further structure beyond first dip/bump

Outlook:
- Data at $\sqrt{s}=900$ GeV taken in 2018:
  Analysis of $\sigma_{\text{tot}}$, $d\sigma_{\text{el}}/dt$, $\rho$ started
- Plans for LHC Run 3 @ 14 TeV:
  - $\beta^* \sim 90$ m run for $\sigma_{\text{tot}}$ (lumi-independent with new T2 detector)
  - $\beta^* \sim 5 – 6$ km run for CNI analysis
The End
Proton Transport and Reconstruction via Beam Optics

\( (x^*, y^*)\): vertex position
\( (\theta_x^*, \theta_y^*)\): emission angle: \( t \approx -p^2 (\theta_x^*^2 + \theta_y^*^2) \)
\( \xi = \Delta p/p\): momentum loss (elastic case: \( \xi = 0 \))

\[
\begin{pmatrix}
  x \\
  \Theta_x \\
  y \\
  \Theta_y \\
  \Delta p/p
\end{pmatrix}_{\text{RP}} = 
\begin{pmatrix}
  v_x & L_x & 0 & 0 & D_x \\
  v_x' & L_x' & 0 & 0 & D_x' \\
  0 & 0 & v_y & L_y & 0 \\
  0 & 0 & v_y' & L_y' & 0 \\
  0 & 0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  x^* \\
  \Theta_x^* \\
  y^* \\
  \Theta_y^* \\
  \Delta p/p
\end{pmatrix}_{\text{IP5}}
\]

Product of all lattice element matrices

\[
x_{\text{RP}} = L_x \Theta_x^* + v_x x^* + D_x \xi
\]

\[
y_{\text{RP}} = L_y \Theta_y^* + v_y y^*
\]

Reconstruction of proton kinematics = inversion of transport equation

Excellent beam optics understanding needed.

Elastic Measurement Method

**Trigger:** double arm in XRP

**Cuts:** collinearity, common vertex, position-angle correlation, low $\xi$

**Collinearity of left and right proton in x and y** (Example for 13 TeV)

**Corrections:** acceptance, efficiency (trigger, DAQ, reconstruction), smearing in t

**Extrapolation to t=0** (for $\sigma_{_{\text{tot}}}$ with opt. theorem):

\[
\frac{\sigma(dN_{_{\text{el}}}/d|t|_{t=0})}{\sigma(N_{_{\text{el}}})} \sim 1.6 \% \quad \sigma(N_{_{\text{el}}}) \sim 2.3 \% \quad \text{@ 13 TeV}
\]
Inelastic Measurement Method

**Trigger:** activity in T2 (either arm)

T1+T2 Acceptance $\sim 92\%$ of the inelastic rate

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

**MC corrections for event classes invisible to T1/T2:**
central diffraction, rapidity gap over T2, low-mass diffraction ($M < 4.6$ GeV, $|\eta| > 6.5$)

$\sigma(N_{\text{inel}}) = 3.7\%$ @ 13 TeV
Choice of hadronic phase $\arg F^H(t)$ controls the behaviour in impact-parameter space ($b$)

**Phase examples:**

- **constant (central):**
  
  \[ \arg F(t) = p_0 \]

- **peripheral:**
  \[ \arg F(t) = p_0 + \frac{t}{t_0} \exp(\nu t) \quad (t_0 = 1 \text{ GeV}^2) \]

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

in both cases.

**Impact parameter distributions:**

- constant (central): most commonly used:
  
  \[ \langle |b| \rangle_{\text{el}} < \langle |b| \rangle_{\text{inel}} \]

- peripheral:
  \[ \langle |b| \rangle_{\text{el}} > \langle |b| \rangle_{\text{inel}} \]

**TOTEM 8 TeV data compatible with both phases** (same result for $\rho$: $0.12 \pm 0.03$)

\[ \Rightarrow \text{elastic pp scattering not necessarily central} \]
The 7 TeV Measurements

(3 data sets at different optics and RP distances to cover max. t-range)

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

\[ |t|_{\text{dip}} = 0.53 \text{ GeV}^2 \]

\[ \sim |t|^{-7.8} \]

Comparison with 7 TeV Predictions

At the time of the first publication:
No model described the TOTEM data.

pQCD (e.g. Donnachie-Landshoff): \( \sim |t|^{-8} \)
The 13 TeV Measurement

Data: no structure at large $|t|$ → rules out most models
Dip position: moves to lower $|t|$ with increasing energy

New measurement @ 2.76 TeV, $\beta^* = 11m$:
very limited $t$-range (0.08 – 0.4 GeV$^2$) $\Rightarrow$ dip not reached
Elastic Scattering: the Dip and beyond (A4)

\[ R = \frac{\frac{d\sigma}{dt} (\text{bump})}{\frac{d\sigma}{dt} (\text{dip})} \]
pp Cross-Section Measurements: TOTEM vs. ALFA

8 TeV: tension with ATLAS-ALFA due to normalisation (elastic slopes compatible)