Review of TOTEM results

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on behalf of the TOTEM collaboration

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30 Aug 2019
• selection of topics for this talk (all connected by optical theorem)
  o differential elastic cross-section
  o total cross-section
  o parameter $\rho \equiv \frac{\Re A_N}{\Im A_N} \bigg|_{t=0}$

• complete list of TOTEM results:
Detector apparatus

- **TOTEM**: LHC experiment at IP5 (together with CMS)
- **Inelastic telescopes T1 and T2**: charged particles from *inelastic* collisions
  - T1: $3.1 < |\eta| < 4.7$, $p_T > 100\,\text{MeV}$
  - T2: $5.3 < |\eta| < 6.5$, $p_T > 40\,\text{MeV}$
- **Roman Pots (RP)**: *forward protons* close to outgoing beam
  - station at 147m in Run I → station 210m in Run II

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Elastic scattering
Measurement of elastic scattering

- LHC as magnetic spectrometer
  \[ \theta_y^* = \frac{y}{L_y}, \quad t = -p^2 \sqrt{\theta_x^*^2 + \theta_y^*^2} \]

- 2 outgoing protons: anti-parallel, from the same vertex
  - strong tagging \rightarrow low background

- analysis almost fully data-driven \rightarrow confidence
Elastic scattering: *Data summary*

- (transition to) perturbative QCD
- "dip-bump": amplitude interference, Odderon effects
- "forward code": non-perturbative Pomeron(s)
- Coulomb-nuclear interference (CNI): phase determination ($\rho$)
Forward cone: Exponential slope

• at “low $|t|$”: $d\sigma/dt \propto e^{-B|t|}$

- up to $\sqrt{s} \approx 3$ TeV: linear in $\ln s$; agrees with simplistic Regge model:
  $$d\sigma/dt \propto s^{2(\alpha(t)-1)}$$
  $$\alpha(t) = \alpha_0 + \alpha' t \Rightarrow B = B_0 + 2\alpha' \ln s$$

- above $\sqrt{s} \approx 3$ TeV: change of regime? interpretation?

- or more general energy dependence: e.g. $B = a + b \ln^2 s$ due to multi-Pomeron exchanges [Ryskin and Schegelsky, PRD 85 (2012)]
deviations from the leading exponential behaviour:

\[
\frac{d\sigma/dt}{\text{ref. exp.}} \approx \frac{\text{ref. exp.} - 0.1}{\text{ref. exp.}}
\]

- |t| ≲ 0.2 GeV\(^2\): similar pattern at all energies
  - non-exponentiality evaluated at 8 TeV: 7.2 σ
- |t| ≳ 0.2 GeV\(^2\): rapid change of behaviour (faster decrease towards dip)

interpretation

  - why it is so close to an exponential?

could the non-exponentiality be due to CNI? see later...
• left pp from TOTEM, right from ISR

○ increasing $\sqrt{s} \Rightarrow$ dip at lower $|t|$

• interpretation
  ○ related to forward-cone shrinkage?
  ○ dynamical details?
• **pp**: always pronounced *dip* (ISR, LHC)

  ![Graph showing dip in proton-proton (pp) collisions for ISR, LHC data points]

  ![Graph showing dip in proton-antiproton (p̅p) collisions for ISR, LHC data points]

  ⇒ *recurrent difference between pp and p̅p*

• **pp**: always *shoulder* only (ISR, Sp̅pS, Tevatron)

  ![Graph showing shoulder in proton-antiproton (p̅p) collisions for ISR, LHC data points]

  ![Graph showing shoulder in proton-proton (pp) collisions for ISR, LHC data points]

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Dip: Shape - comparison at the same energy

- ISR, 53 GeV - the only comparison from same machine and same energy
  - low energy - interpretation complicated by secondary reggeons
- Tevatron (D0, $\sqrt{s} = 1.96$ TeV) - LHC (TOTEM, $\sqrt{s} = 2.76$ TeV, ...)

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Dip : *Shape - summary*

**experiment**
- difference between pp and p\(\bar{p}\) scattering
  - (indirectly) even at same energy
  - at high energies → cannot be attributed to C-odd reggeons
- high \(\sqrt{s}\), low \(|t|\): gluon-dominated, non-perturbative regime

**theory**
- Regge: Odderon as C-odd partner of Pomeron
- (perturbative) QCD: Odderon \(\sim C = -1\) state of mutually interacting gluons
- lattice calculations: vector glueballs firmly in predicted spectrum
- AdS/CFT: Odderon on same footing as Pomeron

matches
High $|t|$ structures

- $\sqrt{s} = 13$ TeV: very high statistics $\Rightarrow$ precise measurement to high $|t|$ model predictions:

- **no structures observed up to** $|t| \sim 3$ GeV
  - rules out many models, e.g. “optical” models (recurrent diffractive structures)
  - interpretation – transition to perturbative QCD? Already in many models, e.g. 3-gluon in Donnachie-Landshoff, hard Pomeron in Godizov, ...

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Total cross-section
3 ways to combine TOTEM observables:

**elastic observables only:**

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

\[\sigma_{\text{tot}}\]

- \(q\)-independent:
  \[
  \sigma_{\text{tot}} = \frac{1}{L} (N_{\text{el}} + N_{\text{inel}})
  \]

- luminosity-independent:
  \[
  \sigma_{\text{tot}} = \frac{16\pi}{1 + \varrho^2} \frac{dN_{\text{el}}/dt}{N_{\text{el}} + N_{\text{inel}}} \bigg|_0
  \]

- at 7 TeV: all applied, consistent results found
- \(N_{\text{el}}\): CNI may be explicitly subtracted
- \(dN_{\text{el}}/dt\): sensitive to “non-exponentiality”
- luminosity: from CMS or from CNI (“Coulomb normalisation”)

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Total cross-section : 13 TeV measurements

- 2 (complementary) datasets available
  - $\beta^* = 90$ m: inelastic data available, CNI region not covered
  - $\beta^* = 2500$ m: inelastic data not available, region CNI covered

- comparison

<table>
<thead>
<tr>
<th>data</th>
<th>method</th>
<th>$\rho$</th>
<th>$\sigma_{\text{tot}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^* = 90$ m</td>
<td>Ref. [6]</td>
<td>-</td>
<td>110.6 ± 3.4</td>
</tr>
<tr>
<td>$\beta^* = 2500$ m</td>
<td>approach 1</td>
<td>0.09 ± 0.01</td>
<td>111.8 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>approach 2</td>
<td>0.09 ± 0.01</td>
<td>111.3 ± 3.2</td>
</tr>
<tr>
<td></td>
<td>approach 3</td>
<td>0.08(5) ± 0.01</td>
<td>110.3 ± 3.5</td>
</tr>
<tr>
<td></td>
<td>approach 3 (single fit)</td>
<td>0.10 ± 0.01</td>
<td>109.3 ± 3.5</td>
</tr>
</tbody>
</table>

- $\beta^* = 90$ and $2500$ m
  - Ref. [6] $\oplus$ approach 3
  - $\sigma_{\text{tot}} = 110.5 ± 2.4$

- approach 1: normalisation from 90 m dataset
- approach 2: normalisation from 2500 m dataset within uncertainty of 90 m
- approach 3: normalisation from 2500 m – (partial) Coulomb normalisation
  - at lowest $|t|$: $dN/dt \approx \mathcal{L} d\sigma^{\text{QED}}/dt$
• selected TOTEM measurements (representing the full range)

- energy dependence: in general compatible with $\ln^2(s)$ at high energies
  - BTW: what about $s^\alpha$ dependence
- no sign of slow down
Ratio of elastic to total cross-section

\[
\frac{\sigma_{el}}{\sigma_{tot}} \, (\%)
\]

\[\sqrt{s} \, (\text{GeV}) \]

- relevance? interpretation? more figures of interest?
\( \rho \) parameter
\( \rho = \left. \frac{\Re A}{\Im A} \right|_{t=0} \)

- theory prediction
  - Pomeron: \( A(t = 0) \sim \) imaginary
  - Odderon: \( A(t = 0) \sim \) real \( \Rightarrow \rho \) sensitive to Odderon contributions

- dispersion relations: \( \rho \) related to \( \sigma_{\text{tot}} \) energy growth rate

- tool: Coulomb-nuclear interference \( \rightarrow \) phase exposed in \( d\sigma/dt \)
  - determine nuclear phase wrt. known QED amplitude
Coulomb-nuclear interference

- observed cross-section

\[
\frac{d\sigma}{dt} \propto \left| + \cdots + A^N + \cdots \right|^2
\]

- Coulomb amplitude
- nuclear amplitude
- “mixed” terms

- our modelling
  - "interference formula" = summation for practical applications
    - considered: West-Yennie, Cahn and Kundrát-Lokajíček
  - Coulomb amplitude: QED + experimental form factors
  - modulus of $A^N$: empirical guidance $\Rightarrow$ at low $|t|$: $a \exp \left( \sum_{n=1}^{N_b} b_n t^n \right)$
  - phase of $A^N$
    - little/no experimental guidance $\Rightarrow$ theory suggestions welcome!
    - different assumptions $\Rightarrow$ different behaviour in $b$ space
    - fair comparison with pre-LHC data $\Rightarrow$ assume slow variation with $|t|$
CNI exploration at 8 TeV

- test of assumptions on nuclear modulus and phase
- choice of phase

- data fit quality
  - \( B = \text{const}, \) constant phase: excluded
  - \( B = \text{const}, \) peripheral phase: not excluded, but disfavoured
  - \( B \neq \text{const}, \) both phases compatible with data

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• **8 TeV** – uncertainty dominated by statistics

• **13 TeV** – two points plotted
  
  ○ represent the range of numerical results
  
  ○ represent the range of concepts
  
  ○ the lower point – most similar conditions to the UA4/2 measurement

  \[\Rightarrow 13 \text{ TeV measurement significantly lower than extrapolations (more than 4 } \sigma \text{ effect)}\]
Comparison to COMPETE

- comprehensive study of pre-LHC data by COMPETE
  - 256 models considered to describe \( \sigma_{\text{tot}} \) and \( \rho \) data in \( pp, p\pi, pK, \ldots \)
    - various assumptions on energy dependence, reaction dependence
    - asymptotic component: only crossing-even
  - 23 models (shown above) found to give reasonable description
    - predictions cluster in 3 bands

- red: selection of TOTEM measurements

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• simple version of derivative dispersion relation for crossing-even amplitude

\[
\rho \approx \frac{\pi}{2\sigma_{\text{tot}}} \frac{d\sigma_{\text{tot}}}{d \ln s}
\]

- faster $\sigma_{\text{tot}}$ rise $\Rightarrow$ higher value of $\rho$
- TOTEM data show the opposite $\Rightarrow$ model-independent argument for crossing-odd component

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Models compatible with TOTEM data

- Nicolescu et al. (updated version of original model)
  - crossing-odd effect: strong energy dependence, increase with energy
  - TOTEM’s $\rho$ measurement at $\sqrt{s} = 13$ TeV correctly predicted long before LHC
  - considered as first experimental evidence for “Odderon”

- Durham group (model enhanced with crossing-odd contribution)
  - crossing-odd effect: mild energy dependence, decrease with energy

$\Rightarrow$ crossing-odd component needed to describe data
Summary and outlook

• measurements
  ○ elastic scattering and total cross-section: 2.76, 7, 8 and 13 TeV
  ○ $\rho$ parameter: 8 and 13 TeV

• observation/confirmation of trends
  ○ forward-cone shrinkage, but change of regime?
  ○ non-exponentiality at low $|t|$
  ○ dip moves to lower $|t|$ with increasing $s$
  ○ cross-sections: sustained growth

• evidence for Odderon
  ○ at $t \neq 0$: dip in pp, shoulder in p$\bar{p}$
  ○ at $t = 0$: low value of $\rho$, high value of $\sigma_{\text{tot}}$

• outlook
  ○ $\sqrt{s} = 900$ GeV elastic, $\sigma_{\text{tot}}$ and $\rho$ analysis in progress
  ○ plans for Run III: elastic, $\sigma_{\text{tot}}$ and $\rho$ measurement at 14 TeV
Thank you for your attention!

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Backup
Effect of $\rho$ on differential cross-section

- simulation (with realistic nuclear component):

- TOTEM data, $\sqrt{s} = 13$ TeV, $\beta^* = 2500$ m: