TOTEM @ LHC

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Introduction

When LHC meets CRs….

Cosmic ray connection

TOTEM measurements:
- multiplicities and energy fraction to the secondary particles
- related to the theoretical or phenomenological interaction models

....when CRs meet LHC

Experimental methods which are specific of an experiment installed in an accelerator beam line

TOTEM (beautiful) results related to the comprehension of proton interactions

Future prospects
TOTEM Physics Overview

Total cross-section

- best fit with stat. error band incl. both TEVATRON points
- total error band of best fit
- total error band from all models considered

- ISR
- UA4
- UA5
- TEVATRON
- LHC

Diffraction: soft and hard

Elastic Scattering

Forward physics
Extensive Air Shower characteristics ($\sim E_0$, mass)

$X_{\text{max}}$ & $N_e$: sensitive to cross-sections
$N_\mu$: depends on $N_{\text{ch}}$

$\Rightarrow$ Disentangle Energy, Mass, hadronic models

Measurement @LHC
of the forward energy flux including diffraction
of the total cross section are essential
(shower development, composition)

$10^4$ CR events / km$^2$ year $\Rightarrow$

$10^4$ events /s @ LHC ($L=10^{29}$ cm$^{-2}$ s$^{-1}$)
The evolution of air shower models

High multiplicity muons events at LEP and LHC

Are these excesses really explained by the post-LHC models?
TOTEM Experimental Setup

Inelastic Telescopes:
T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$

Roman Pot stations in the LHC tunnel
Telescopes:

**Inelastic telescopes:** charged particle & vertex reconstruction in inelastic events

*Roman Pot stations in the LHC tunnel*

**TOTEM Detectors**

- Cathode Strip Chambers
- Gas Electron Multiplier
TOTEM Detectors

Several Roman Pots (= movable beam-pipe insertion) host different sensors

- Vertical (Top, Bottom) RPs
- Edgeless Si-strips
- UltraFast Silicon (time measurement)

- Horizontal RPs
- Silicon Pixel
- Diamond (time measurement)
Cross section related measurements in Totem

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

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

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

- **2015**
  - $\rho$ measurement @ 8 TeV
    - EPJ C76-661
  - $\sigma_{tot}$ lumi independent @ 7 TeV

- **2016**
  - $d\sigma/dt$ elastic: non-exponential behaviour @ 8 TeV
    - NPB 899-527

- **2017**
  - $\sigma_{tot}$ lumi independent @ 8 TeV
    - PoS (DIS2017) 059
  - $\sigma_{tot}$ lumi independent @ 13 TeV
  - $\rho$ measurement @ 13 TeV
    - CERN-EP-2017-335

- **2018**
  - $d\sigma/dt$ elastic: DIP @ 13 TeV
  - Preliminary
  - $d\sigma/dt$ elastic: DIP @ 2.76 TeV
  - Preliminary

- **2019**
  - Schematic elastic cross-section

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<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>$\beta^*$ (m)</th>
<th>$\sigma_{tot}$ (σ)</th>
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</table>
| 13           | 2.5          | 3
| 8            | 1            | 3
| 2.76         | 11           | 5
| 7            | 90           | 10
| 7            | 90           | 5
| 8            | 90           | 6
| 7            | 3.5          | 7
| 13           | 90           | 5 - 10

---

**Raven I**

- 13 TeV: $\beta^* = 2.5$ km, 3σ
- 8 TeV: $\beta^* = 1$ km, 3σ
- 2.76 TeV: $\beta^* = 11$ m, 5σ
- 7 TeV: $\beta^* = 90$ m, 10σ
- 7 TeV: $\beta^* = 90$ m, 5σ
- 8 TeV: $\beta^* = 90$ m, 6σ
- 7 TeV: $\beta^* = 3.5$ m, 7σ
- 13 TeV: $\beta^* = 90$ m, 5 - 10σ
Cross section measurements

\[ \sigma_{\text{tot}} \text{ fits by COMPETI} \sim a + b \ln s + c \ln^2 s \]
(pre-LHC model $R_{\text{PP}} \ln L_{\text{PP}}$)

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

Errors (TOTEM measurements)
- $\sigma_{\text{TOT}} \sim 2-3\%$
- $\sigma_{\text{INEL}} \sim 2\%$
- $\sigma_{\text{EL}} \sim 2-4\%$

New data available!
Measurement of the forward charged particle pseudorapidity density

Inclusive pp, $\sqrt{s} = 7$ TeV

$p_T > 40$ MeV/c

$N_{ch} \geq 1$ in $5.3 < |\eta| < 6.5$

Correlation of central and forward

$p_T > 0$ MeV/c

Measurement of the forward charged particle pseudorapidity density

Inclusive pp, $\sqrt{s} = 8$ TeV

$dN_{\text{ch}}/d\eta$

-7 < $\eta$ < -6

3.7 < $\eta$ < 4.8

11.25 m

TOTEM: $N_{\text{ch}} \geq 1$ in 3.7 < $\eta$ < 4.8 or -7.0 < $\eta$ < -6.0

CMS-TOTEM: $N_{\text{ch}} \geq 1$ in 5.3 < $\eta$ < 6.5 or -6.5 < $\eta$ < -5.3

Pythia8 4C (displaced IP), Pythia8 4C (nominal IP)
EPOS LHC (displaced IP), EPOS LHC (nominal IP)
QGSJetII-04 (displaced IP), QGSJetII-04 (nominal IP)
SIBYLL 2.1 (displaced IP), SIBYLL 2.1 (nominal IP)
Soft Single Diffraction (SD)

2 \cdot 10^{-7} < \xi < 1 \cdot 10^{-6}

M = 3.4 – 7 GeV

\Delta \eta = - \ln \frac{M^2}{s}

proton & opposite T2

1 \cdot 10^{-6} < \xi < 2.5 \cdot 10^{-3}

M = 7 – 350 GeV

proton & opposite T1 + T2

2.5 \cdot 10^{-3} < \xi < 2.5 \cdot 10^{-2}

M = 0.35 – 1.1 TeV

proton & opposite T2 (+ T1) & same side T1

\xi > 2.5 \cdot 10^{-2}

M > 1.1 TeV

proton & opposite T2 (+ T1) & same side T2 (+ T1)

Preliminary:

\sigma_{SD} = 6.5 \pm 1.3 \text{ mb}

(3.4 < M_{SD} < 1100 \text{ GeV})
One of the physics goal of TOTEM is to measure the (elastic, inelastic, total) cross sections at LHC.

- COMPETE Collaboration fits all available hadronic data and predicts at LHC: \( \sigma_{\text{tot}} = 111.5 \pm 1.2 + 4.1/-2.1 \) mb [PRL 89 201801 (2002)]
- Last pp data at the ISR; only ppbar at “high” energy
- Difference of \( \sigma_{pp} \) vs \( \sigma_{ppbar} \)?
- \( \sigma_{\text{TOT}}(s) \sim (\ln s)^\gamma \), \( \gamma = 2 \) ?
- \( \sigma_{\text{EL}} / \sigma_{\text{TOT}} \) 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 \( B(t) \)?

\[ \rho = \Re \left[ \frac{A^N}{\bar{A}^N} \right] \bigg|_{t=0} \]

- Foreseen to “decrease” at high energy: how fast?
- Test dispersion relation (mix real and imaginary part)
# Total Cross section: analysis methods

From Optical theorem

\[
\sigma_{tot}^2 \propto \left| \sum A_{el,N}(t=0) \right|^2 \propto \frac{1}{1+\rho^2} \left| A_{el,N}(t=0) \right|^2 = \frac{16\pi}{1+\rho^2} \left( \frac{d\sigma_{el}}{dt} \right)_{t=0}
\]

with \( \rho = \Re \frac{\sum A_{el,N}}{\sum A_{el,N}} \big|_{t=0} \)

\[
L \sigma_{tot} = N_{el} + N_{inel}
\]

\( \rho \) independent

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

\( \rho \) 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 tested to determine \( \rho \).

\[
L \text{ independent}
\]

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<tr>
<th>( L )</th>
<th>( \sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \left( \frac{dN_{el}}{dt} \right)<em>{t=0} (N</em>{el} + N_{inel}) )</th>
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<td>( L ) dependent Elastic Only</td>
<td>( \rho ) independent</td>
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Total Cross section measurements: methods

7 TeV, several methods
Same beam conditions

8 TeV, several methods
Different beam conditions

13 TeV
90m: lumi independent
2500m: \( \rho \) measurement
Different beam conditions
The diffraction cone shrinkage speed up with the collision energy

The linear (ln s) behaviour is compatible for $\sqrt{s} \leq 3$ TeV

$B = \frac{d}{dn} \ln (ds/dt) \big|_{t=0}$ increases with $\sqrt{s}$
Measurement of Forward Protons: the principle

Diffractive protons: hit distribution @ RP220

Low $\beta^* \sim 0.25 - 3$ m

High $\beta^* \sim 50 - 2500$ m

Detect the proton via:

- its momentum loss (low $\beta$)
- its transverse momentum (high $\beta$)

$t = -p^2 \theta^2$

$\xi = \Delta p/p$

$y \sim \Theta_y^{\text{scatt}}$

$x \sim \xi = \Delta p/p$

Detector edges

Beam envelope
Measurement of Forward Protons: the principle

Low $\beta^* \sim 0.25 - 3$ m

$\sigma_x \sim 10-20 \mu m$

$\sigma_\theta \sim 20-30 \mu rad$

Optimized for high luminosity

High $\beta^* \sim 50 - 2500$ m

$\sigma_x \sim 1$ mm

$\sigma_\theta < 1 \mu rad$

Choice: parallel to point focusing

Optimized for elastic scattering measurement (very low angle)
Measurement of Forward Protons: the principle

\[(x', y') \quad \text{vertex position}\]

\[(\theta_x^*, \theta_y^*) \quad \text{emission angle}\]

Measured in RP

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

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

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

Product of all lattice element matrices

\[\xi = \Delta p/p: \text{momentum loss}\]

\[\sqrt{\beta \beta^* \sin (\Delta \mu)} \quad \Delta \mu = \pi/2\]

If point to parallel focusing

\[\sqrt{\beta / \beta^* \cos (\Delta \mu)}\]

\[\text{L}_{x,y} \text{ effective length} \sim \quad \text{magnification} \quad \text{dispersion (sensitivity to momentum loss)}\]
**Measurement of Forward Protons: the principle**

(x', y') vertex position

(θ_x*, θ_y*) emission angle

LHC magnet lattice $\Rightarrow$ accelerator optics

RP station

$s \equiv$ beam axis

$\xi = \Delta p/p$: momentum loss

Product of all lattice element matrices

Measured in RP

$\frac{\Delta p}{p}$

Values at IP5 to be reconstructed


- Magnet currents measurements $\rightarrow$ MADX optics model
- Selection of elastic protons
- Determination of the optics parameters constraints with proton tracks
  - $\Theta_*^{\text{left}} = \Theta_*^{\text{right}}$ (proton pair collinearity)
  - Proton position $\leftrightarrow$ angle correlations
  - $L_x = 0$ determination, coupling corrections
- Matching of the optics (transport matrix) $\Rightarrow \delta L'_x/L'_x < 1\%$ and $\delta L'_y/L_y < 1\%$
Elastic measurement: method

**Collinearity cut (left-right)**

\[ \theta^*_{x,45} \leftrightarrow \theta^*_{x,56} \]

\[ \theta^*_{y,45} \leftrightarrow \theta^*_{y,56} \]

*Background subtraction*

*Trigger: double-arm RP*

*RP tracks in opposite arm in diagonal topology*

*Cuts: left-right correlation in several kinematics variables*
Elastic measurement: method

Corrections to differential rate (mostly data-driven):

- acceptance, efficiencies (trigger, DAQ, reconstruction), smearing in |t|

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

\[ \sigma(\frac{dN_{el}}{d|t|_{t=0}}) \sim 1.6 \% \]
\[ \sigma(N_{el}) \sim 2.3 \% \]
No structure seen at high-$t$
Dip present at all energies

$\sqrt{s} = 7$ TeV
- $\beta^* = 3.5$ m
  - EPL 95 (2011) 31002
- $\beta^* = 90$ m
  - EPL 101 (2013) 21002

$\sqrt{s} = 8$ TeV (scaled 10x)
- $\beta^* = 90$ m
  - PRL 111-12001
- $\beta^* = 1000$ m
  - NPB 899-527

$\sqrt{s} = 13$ TeV (scaled 1000x)
- $\beta^* = 90$ m
- $\beta^* = 2500$ m
  - CERN-EP-2017-335
Elastic measurements: dip @ 13 TeV

dip position in |t| decreases with increasing √s

√s = 13 TeV
β* = 2500 m

dip = 0.47 GeV²
bump/dip ~ 1.8

dip = 0.47 GeV²
bump/dip ~ 1.77 ± 0.01

√s = 7 TeV

dip = 0.53 ± 0.01 GeV²
bump/dip ~ 1.7 ± 0.1

√s = 1.96 TeV

Dip is missing in pp

DIP is visible also at √s = 2.76 TeV!
Elastic Scattering: Coulomb interference and $\rho$ parameter

First LHC determination from Coulomb-hadronic interference at 8TeV: $\rho = 0.12 \pm 0.03$

Uncertainty still too high (low statistics)

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

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

Modulus nuclear amplitude (low-|t|) ~ $a \exp \left( \sum_{n=1}^{N_b} b_n t^n \right)$

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

Comparison with UA4/2 (same t-range)

The new measurement is clearly below the predictions
**σ_{TOT}** and **ρ** parameter: possible interpretation?

T-channel exchange of a colourless **3-gluon bound state** (J^{PC} = 1^{−}) could decrease ρ in pp collisions at high energy.

“Odderon” hint or first evidence of “slowing down” of σ_{TOT} growth at higher energy?
σ_{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 high energy.

Other observations:

- diffractive dip in the proton-proton elastic t-distribution
- the deviation of the elastic differential cross-section at low-\(|t|\) from a pure exponential
- no oscillations of the elastic differential cross-section at large-\(|t|\)
Extended Physics programme: CMS + TOTEM

Combine central detector with forward protons measurement in Roman Pot

Joint data taking started already in Run-I
Now all RP detectors are integrated in CMS DAQ

1) Low luminosity/pileup: collected ~40/nb @8 TeV, ~5.4/pb @ 13 TeV,
Acceptance: low and moderate diffractive mass $M_x$
Low-mass resonances in Central Exclusive Production, Diffraction with proton tag

- Measurement of dijet production with a leading proton in pp collisions at $\sqrt{s} = 8$ TeV
[CMS-PAS-FSQ-12-033,TOTEM-NOTE-2018-001]

Ongoing analyses:
- Jet-Gap-Jet with proton tag (ongoing)
- Study of resonances in the $M_x<4$ GeV mass range.
Search for scalar ($0^{++}$) and tensor ($2^{++}$) glueball candidates and their decays: $\pi\pi$, $KK$, $\rho\rho$, ...
Potentially wide possibility for measurements of inclusive and exclusive diffraction with proton(s) tag

2) High luminosity/pileup : since 2016 , collected ~ 100/fb
Acceptance : $M_x>400$ GeV (Central Exclusive Production, 2 tagged protons)
High-mass/low cross section BSM, electroweak, and QCD & top physics with forward protons: gauge boson pair production ($WW$, $ZZ$, $Z\gamma$, $\gamma\gamma$), searches for anomalous couplings, new resonances,...

Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV [JHEP 07 (2018) 153]
Summary

Totem has made extensive measurements related to pp cross sections and elastic scattering
Some of the pre-LHC questions are 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)

Several measurements related to the Cosmic Ray domain have been performed and more results are expected in the future

The extended programme with CMS has excellent prospects to study exclusive production, photon-photon physics and new physics searches