Recent results from TOTEM at the LHC

Christophe Royon
University of Kansas, Lawrence, USA
Forward Physics Workshop, Guanajuato, Mexico

November 21 2019

Contents

- Soft Diffraction at the LHC
- Elastic cross section
- rho measurement and the Odderon
What do we want to measure? Diffractive events!

- Protons remain intact after interactions $pp \rightarrow pXp$ (central diffraction or double omen exchange) or $pp \rightarrow pXY$ (single diffraction)

- Non-diffractive interactions represent 60 $mb$ out of 100 $mb$ at LHC

- Intact protons can be detected using dedicated detectors

- Elastic interactions: $pp \rightarrow pp$

Recent results from TOTEM at the LHC
How do diffractive events look like in our detector?

Recent results from TOTEM at the LHC
Elastic cross section measurements: detecting protons!

- Measurement of $pp \rightarrow pp$ elastic cross section by detecting intact protons and vetoing on activity in the main CMS detector

- TOTEM installed vertical roman pot detectors at 220 m from CMS; Additional horizontal detectors for hard diffraction and photon exchange measurements

- Trigger for elastics using proton in opposite configurations: Up (Down) on one side, Down (Up) on the other side

Recent results from TOTEM at the LHC
Forward coverage in CMS-TOTEM

**Inelastic Telescopes:**
charged particles in inelastic events:
\[ \Rightarrow \text{ multiplicities, rapidity gaps} \]
- **T1:** \( 3.1 < |\eta| < 4.7 \), \( p_T > 100 \text{ MeV} \)
- **T2:** \( 5.3 < |\eta| < 6.5 \), \( p_T > 40 \text{ MeV} \)
\[ \Rightarrow \text{ Inelastic Trigger} \]

**Roman Pots:**
elastic & diffractive protons close to outgoing beams
\[ \Rightarrow \text{ Proton Trigger} \]

Roman Pot stations in the LHC tunnel (before LS1)

RP (147 m)  RP (220 m)
Variety of models especially at high $t$

Possible structures at high $|t|$?

Regions in $|t|$ at the LHC sensitive to different kinds of physics: Diffraction/Pomeron exchange at low $|t|$, diffractive structures at medium $|t|$ and parton scattering/QCD at higher $|t|$
Elastic scattering

- Study of elastic $pp \to pp$ reaction: exchange of momentum between the two protons which remain intact
- Measurement of total cross section via $dN/dt$
- From the fit of the number of events at a function of $|t|$ (quadric-momentum transferred squared at the proton vertex), we get $\sigma_{tot}$, $\rho$, $b$ and $L$
Elastic scattering in the Coulomb region: how technically?

- Goal: Measurement of $dN/dt$ with a precision better than 2-3%
- Measure elastic rate $dN/dt$ in the Coulomb interference region: Necessity to go down to $t \sim 6.5 \times 10^{-4}$ GeV$^2$, or $\theta \sim 3.5 \, \mu$rad (when the strong amplitude equals the electromagnetic one)

This requires:
- Special high $\beta^*$ beam optics
- Detectors at $\sim 1.5$ mm from LHC beam axis
- Spatial resolution well below 100 $\mu$m
- No significant inactive edge ($< 100 $\mu$m)

Installation of two sets of roman pots at 220-240 m from the main TOTEM/ATLAS detector
Different beam optics at the LHC: what is $\beta^*$?

- $\beta^*$ is a beam parameter that is related to the beam size ($\sigma$) at the interaction point
- Low $\beta^*$: beams well focused, high luminosity, high pile up
- High $\beta^*$: beam not well focused, low luminosity, low pile up, can approach closer to the beam center in terms of $\sigma$

Recent results from TOTEM at the LHC
Recent results from TOTEM at the LHC
$d\sigma/dt$ measurements in TOTEM

- Elastic measurements: Use double arm roman pots (2.76/7/13 TeV)

- Inelastic measurements: Use $T_2$ as a trigger ($N_{inel}$ gives a signal in $T_1$ and/or $T_2$ for 92% of events)
Analysis methods in TOTEM: total cross section

- \( N_{inel} \) measured using \( T_1 \) and \( T_2 \) telescopes, and \( N_{el} \) from the roman pots
- Known equations (Optical theorem) (\( \rho \): ratio of real/Imaginary part of cross section)

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

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

- Different methods to measure the total cross section
  - Lumi independent measurement
    \[
    \sigma_{tot} = \frac{16\pi}{(1 + \rho^2)} \left( \frac{dN_{el}/dt}{t=0} \right) (N_{el} + N_{inel})
    \]
  - Lumi dependent measurement (elastic only)
    \[
    \sigma_{tot}^2 = \frac{16\pi}{(1 + \rho^2)} \frac{1}{L} \left( \frac{dN_{el}/dt}{t=0} \right)
    \]
  - \( \rho \) independent measurement \( \sigma_{tot} = \sigma_{el} + \sigma_{inel} \)
Analysis methods in TOTEM: $\rho$ measurement

- Measure elastic scattering at very low $t$: Coulomb-Nuclear interference region

$$\frac{d\sigma}{dt} \sim |A^C + A^N(1 - \alpha G(t))|^2$$

- The differential cross section is sensitive to the phase of the nuclear amplitude.

- In the CNI region, both the modulus and the phase of the nuclear amplitude can be used to determine $\rho = \frac{\text{Re}(A^N(0))}{\text{Im}(A^N(0))}$ where the modulus is constrained by the measurement in the hadronic region and the phase by the $t$ dependence.
Elastic, Inelastic and Total cross section at 7 and 8 TeV

- Independent methods with different precision/systematics lead to similar results on elastic, inelastic and total cross sections.

- In addition, at 13 TeV, total cross section using lumi independent method for $\beta^* = 90m$.

- $\rho$ measurement using $\beta^* = 2500m$ data.
High precision measurement of elastic, inelastic and total cross sections: new measurement by LHCb

Measurements in agreement with cosmic-ray data (large error bars though)

ATLAS 1.9 $\sigma$ lower than TOTEM at 8 TeV
Implication of elastic cross section measurements: $B$ slope at 13 TeV

- $B$ slope of $d\sigma/dt$: larger slope at 13 TeV
- Linear behavior ($lns$) compatible for $\sqrt{s} < 3$ TeV, incompatible at higher energy
- The increase of $\sigma_{el}/\sigma_{tot}$ with energy is confirmed at LHC

Recent results from TOTEM at the LHC
Implication of total cross section measurements: no structure at high $|t|$

- No structure seen at high $|t|$, compatible with a flat behavior
- Differences with respect to many pre-TOTEM models
Non-exponential dependence of TOTEM elastic data

- Attempt of a usual simple exponential fit to $d\sigma/dt$ at low $t$
- Exponential fit: $d\sigma/dt = A \exp(-B(t)|t|)$
- Different polynomial fits of $B(t)$:
  - $N_b = 1$, $B = b_1$, reference
  - $N_b = 2$, $B = b_1 + b_2 t$
  - $N_b = 3$, $B = b_1 + b_2 t + b_3 t^2$
- Pure simple exponential form ($N_b = 1$, $B = cte$) excluded at 7.2 $\sigma$ with 8 TeV data, similar results using 13 TeV data
Using low $|t|$ data, measurement of $\rho$ at 13 TeV: $\rho = 0.09 \pm 0.01$

- High precision measurements at 13 TeV using low $\beta^*$ data
- $\rho$ value at 13 TeV clearly below expectations (COMPETE fits as an example)
$\rho$ measurement at 13 TeV

- $\rho$ is the ratio of the imaginary and real part of the total cross section
- Using low $|t|$ data, measurement of $\rho$ at 13 TeV: $\rho = 0.09 \pm 0.01$
- $\rho$ value at 13 TeV clearly below expectations (COMPETE fits as an example)
- This result can be explained by the exchange of the Odderon in addition to the Pomeron, or saturation effects of $\sigma_{tot}$ at high energies
Very recent measurement of $d\sigma/dt$ at 2.76 TeV
Dip and bump also observed at 2.76 TeV, what about $p\bar{p}$ interactions?
Implication of elastic cross section measurements dip position

- Dip position in $|t|$ decreases with increasing $\sqrt{s}$
- Differences between $pp$ and $p\bar{p}$ data: Dip missing in $p\bar{p}$?
If the odderon exists, it should show up as a difference between $pp$ and $p\bar{p}$ total cross sections.

No dip/maximum for $p\bar{p}$ cross sections (D0 at 1.96 TeV) whereas the dip/max is observed in TOTEM data at 2.76 TeV: quantitative studies in progress (D0/TOTEM).

Clear signal of Odderon?
Conclusion

- Measurements of elastic, inelastic and total cross sections at different center-of-mass energies: unprecedented precision
- $B$ slope of $d\sigma/dt$ is larger at 13 TeV
- Dip position in $d\sigma/dt$ decreases with $\sqrt{s}$, and no structure is found at high $|t|$
- Pure exponential form of $d\sigma/dt$ is excluded
- $\rho$ and $d\sigma/dt$ cannot be described within the same model (COMPETE): sign of Odderon or slowing down of $\sigma_{tot}$ at high energy?
- Comparison between $pp$ and $p\bar{p}$ data (TOTEM/D0) in progress