Recent measurements from the TOTEM experiment at LHC

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on behalf of the TOTEM Collaboration

ŚRODOWISKOWE SEMINARIUM
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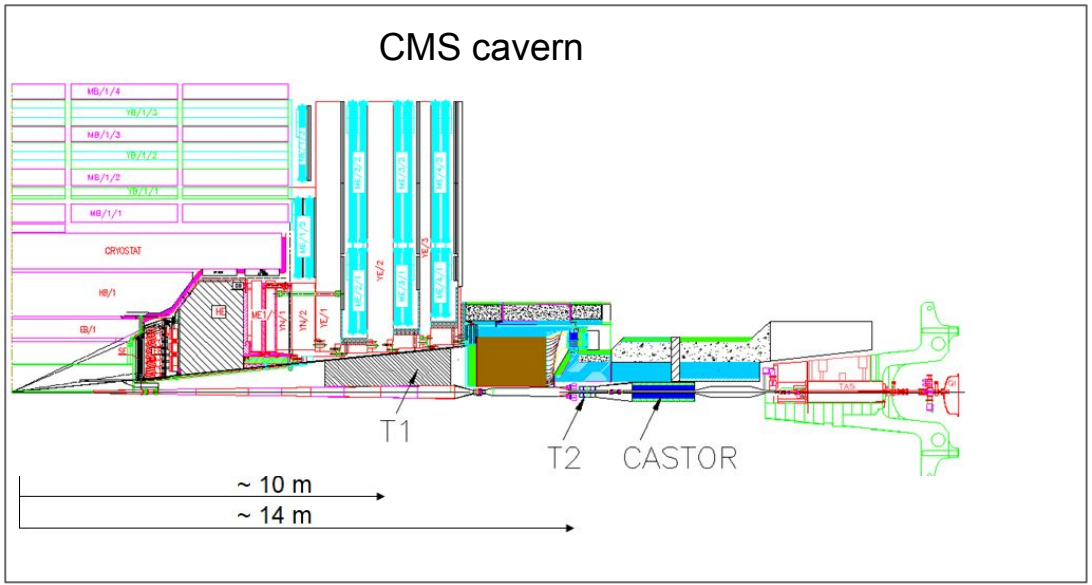
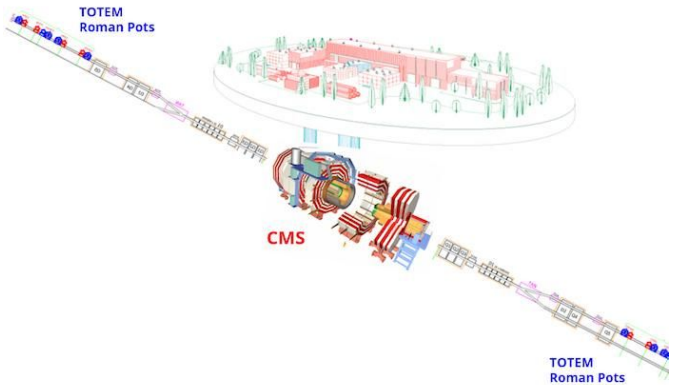
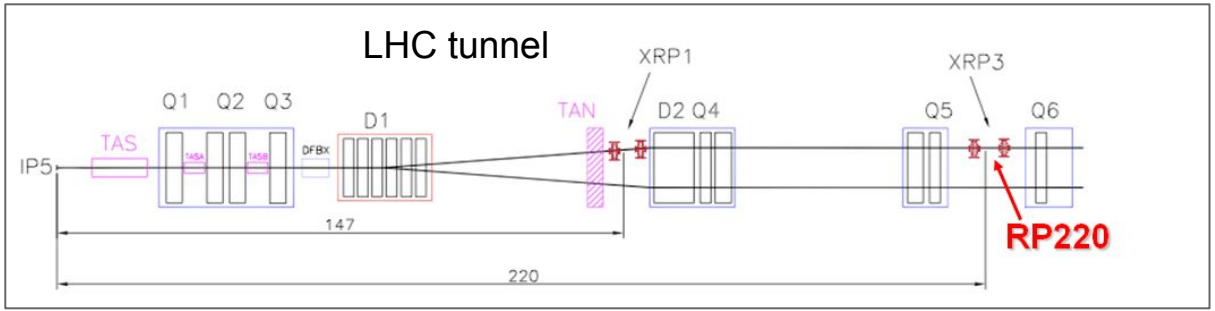
Outline

1. The TOTEM experiment detectors and its physics programme
2. Total p-p cross-section measurements
3. Differential p-p cross-section measurements
    a. Ruling out purely exponential approach in elastic scattering
    b. Coulomb-hadronic interpherence
    c. Search for t-channel colourless three-gluon exchange (or "Odderon")

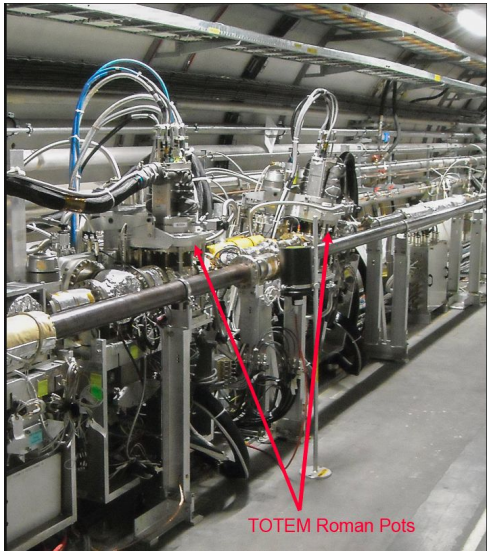
TOTEM experiment - detectors

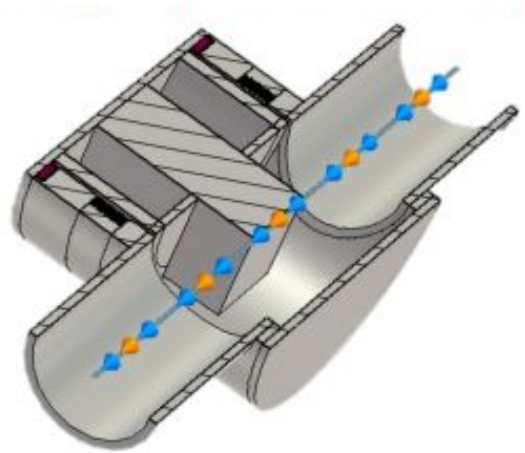


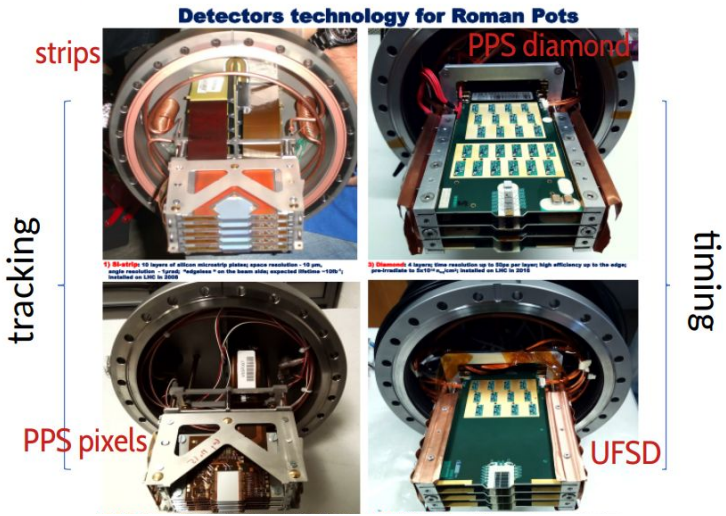




TOTEM experiment - Roman Pots



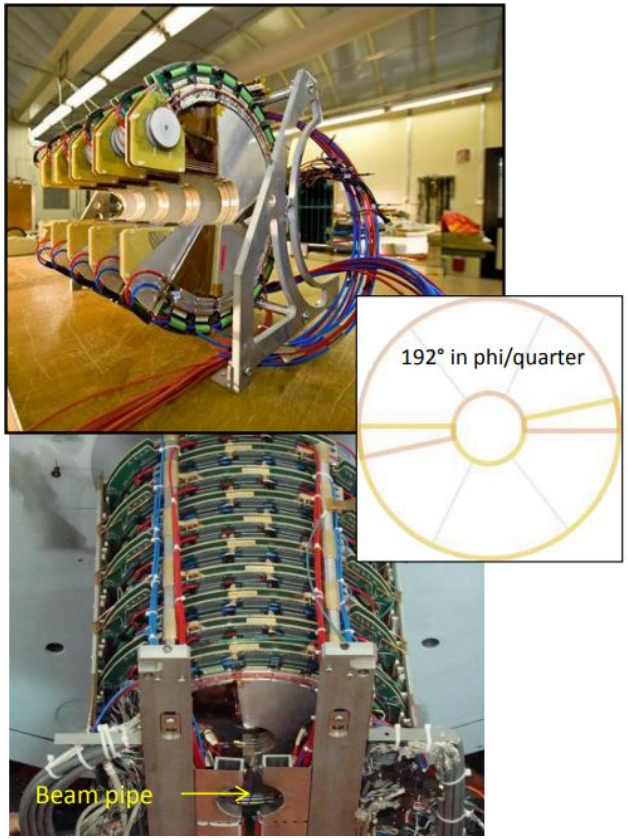




Roman Pots - movable beam-pipe insertions with different sensors

Detectors sensitive to scattered protons close to the beam

TOTEM experiment - T1 & T2 telescopes



T2 detector

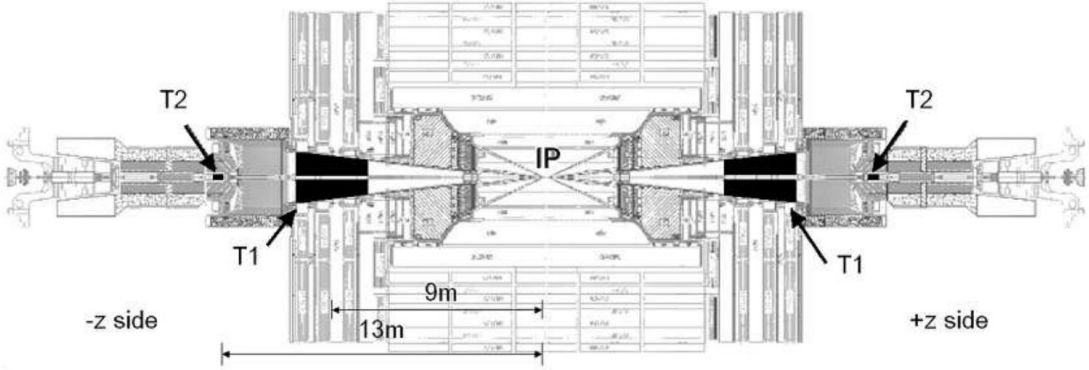
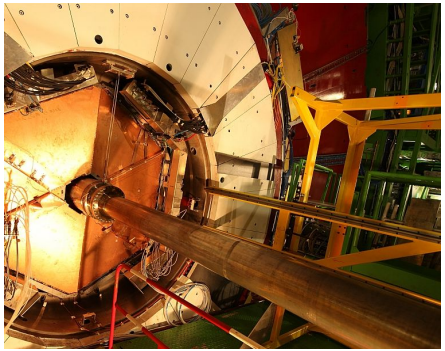


Figure 1.17: View of the inelastic forward trackers T1 and T2 inside the CMS detector.

T1 & T2 - inelastic triggers



T1 detector

TOTEM experiment - AGH IET contribution

Main research area - forward physics and computer science

Group has evolved from the TOTEM experiment at CERN and joined CMS via CTPPS project in 2017.

Main tasks of the group are: software development and support for data analysis groups by providing necessary computing tools.

Maciej Malawski

- TOTEM & CMS AGH Team Leader since 2017
- Assistant professor at AGH, Researcher at ACC Cyfronet
- Ph.D. in Computer Science (AGH), M.S. in CS (AGH)
- and Physics (UJ)
- Postdoc at University of Notre Dame, USA (2011-2012)
- Research interests: parallel, distributed, grid, cloud computing

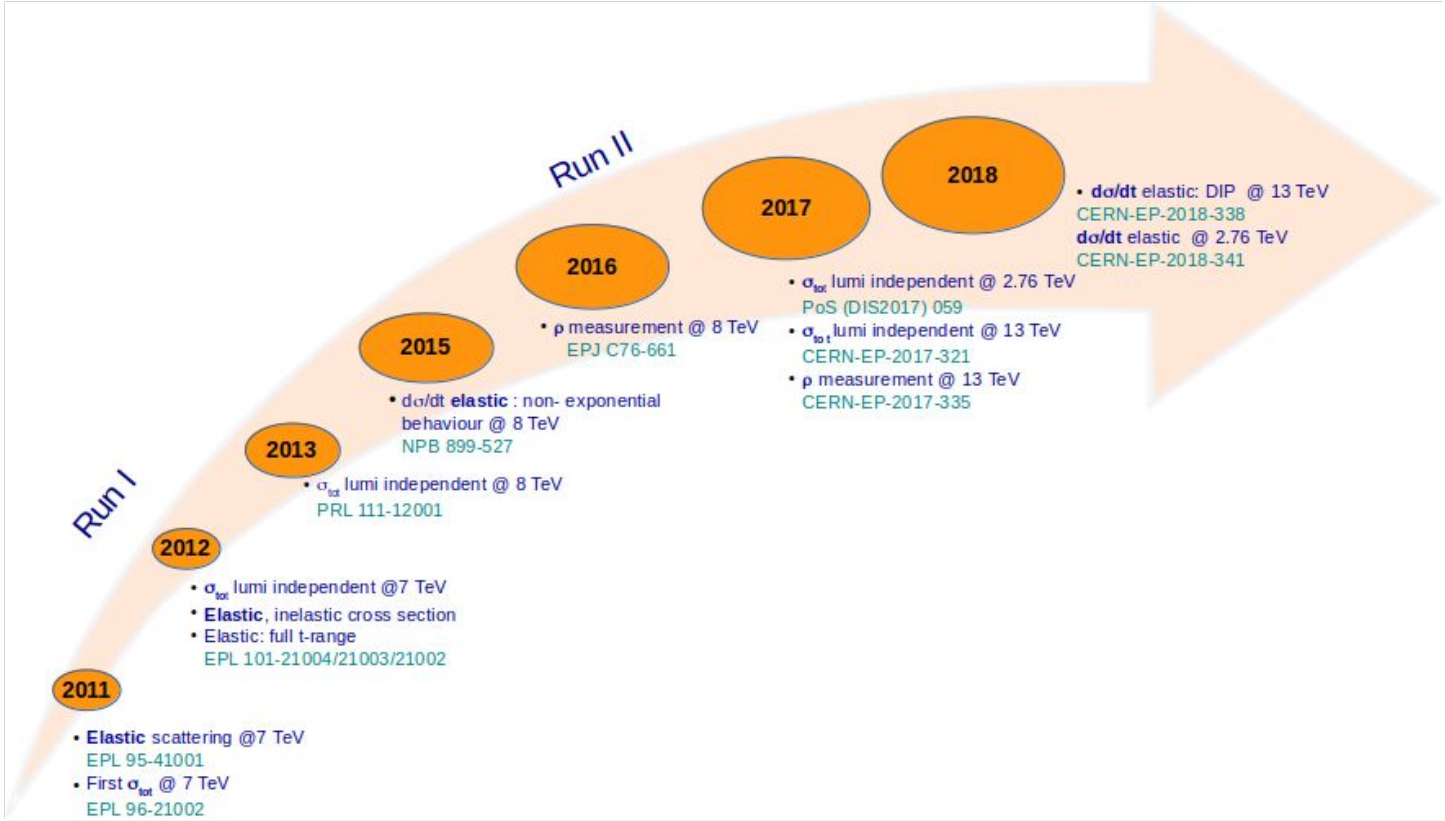
Leszek Grzanka

- TOTEM & CMS AGH Deputy Team Leader since 2017
- Coordinator of computing group in PPS project since 2018
- Assistant professor at AGH, Researcher at Institute of Nuclear Physics PAS
- Ph.D. in Physics (IFJ PAS), M.S. in Theoretical mathematics (UJ)
- Research interest: particle transport simulations, parallel computing, mathematical modelling
- Active participation in TOTEM experiment works since 2007

Valentina Avati

- PPS detector performance group convener
- Associated to AGH, researcher at CERN

Total cross-section measurements



Total cross-section measurements - methods

But also:

L dependent/ Elastic Only

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

r independent

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

Optical Theorem

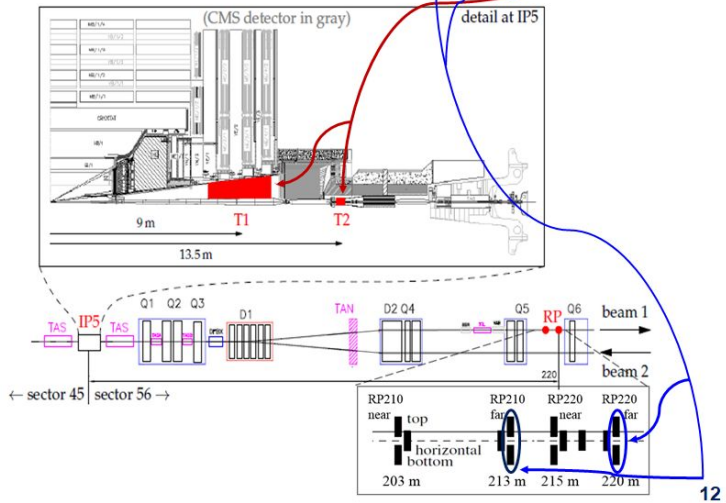
$$L\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \times \left.\frac{dN}{dt}\right|_{t=0}$$

$$L\sigma_{tot} = N_{elastic} + N_{inelastic}$$

t is the 4−momentum transfer squared (~ $p^2\,\theta^2$)

Luminosity independent method:

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

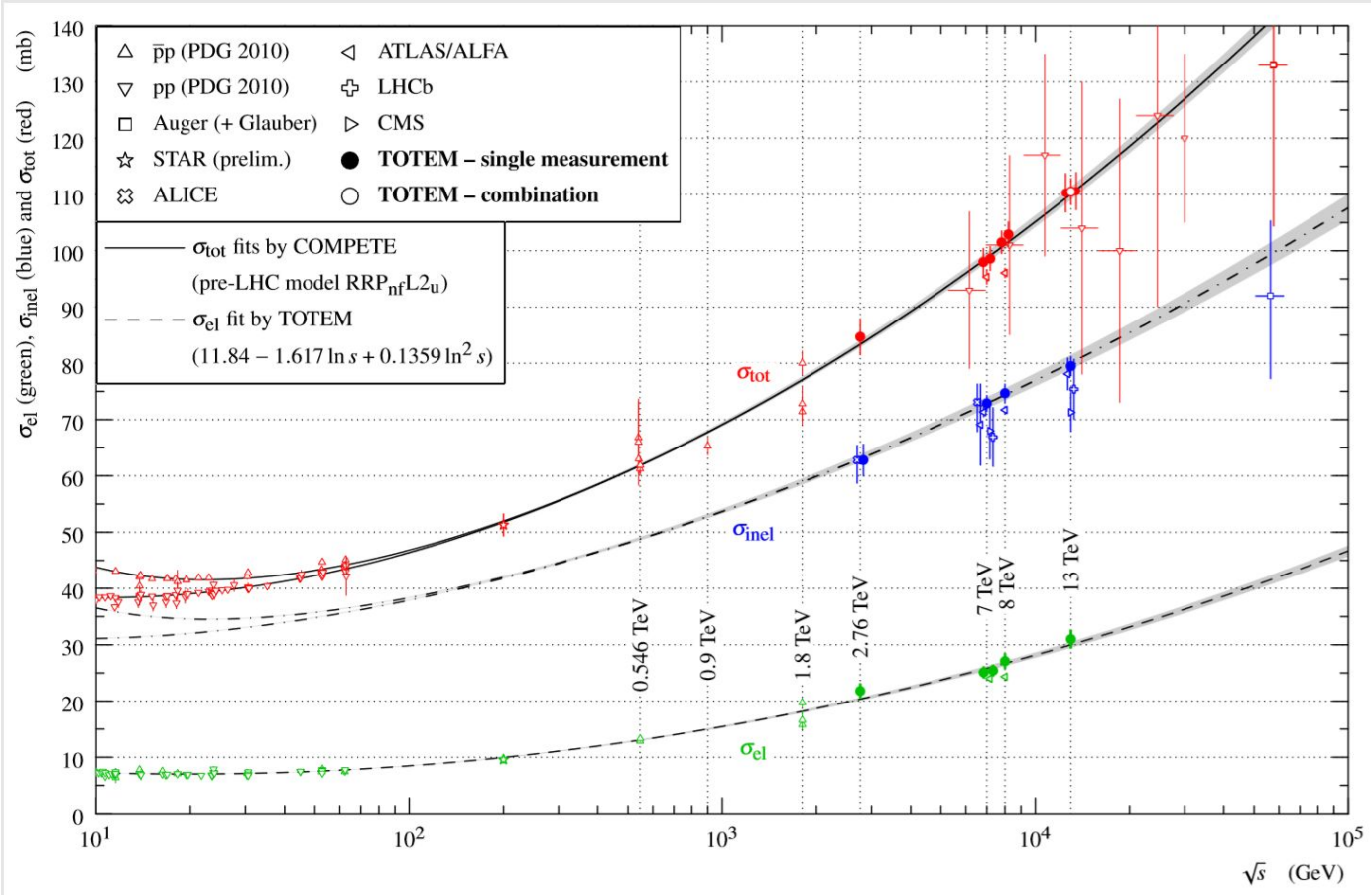


ρ - real-to-imaginary ratio of the forward hadronic amplitude

- Directly extracted from data in Coulomb-nuclear interface
- extrapolated from COMPETE models

$$\rho \equiv \cot \arg \mathscr{A}^N(0) = \frac{\Re \mathscr{A}^N(0)}{\Im \mathscr{A}^N(0)}$$

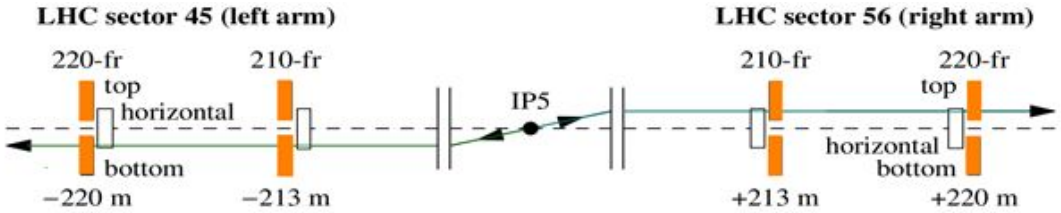
Total cross-section measurements



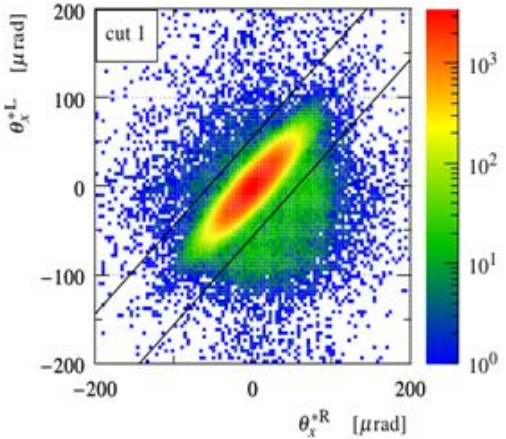
Compilation of the pp cross-section measurements:
total, elastic and inelastic scattering

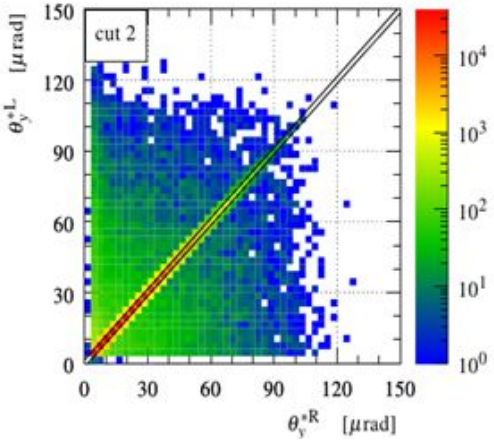
σ_{tot} ~110mb can be roughly associated to a sphere with a radius of ~2fm

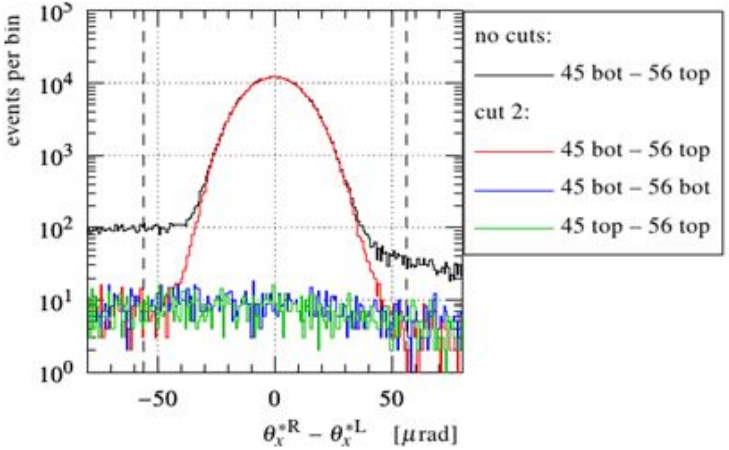
Elastic scattering - method



Example: b^*=2.5km, 13 TeV







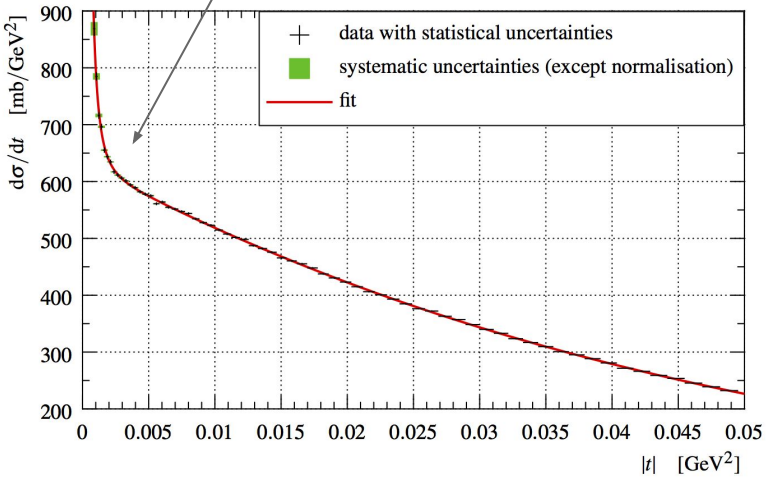
Selection cuts for elastic events - left-right correlation in kinematic variables
Trigger - protons in oposite (diagonal) RP arms

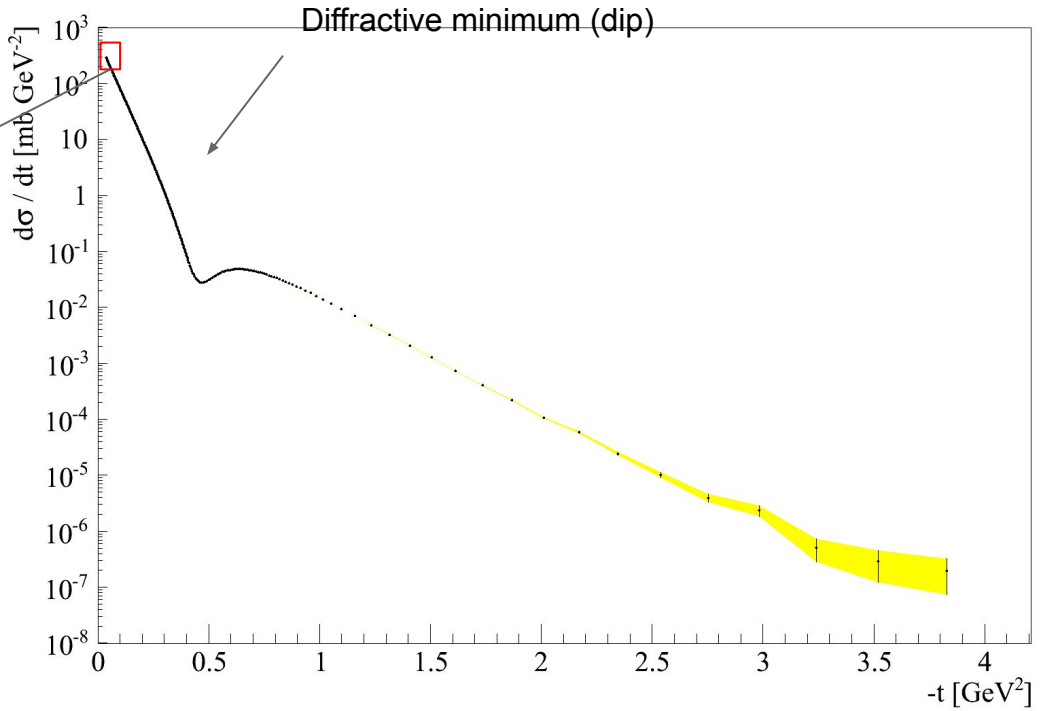
Differential cross-section measurements

√s = 13 TeV elastic differential cross-section

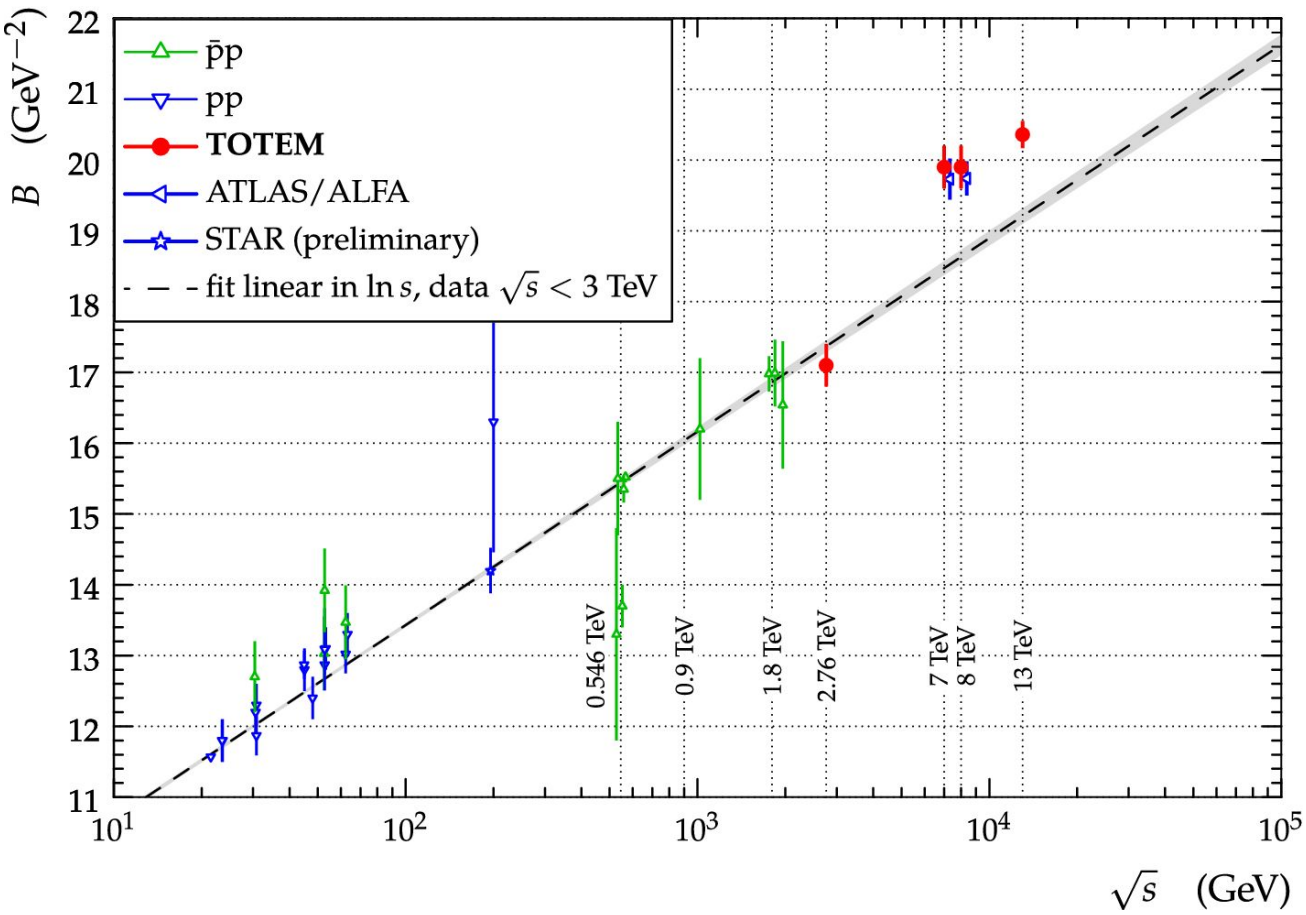
Diffractive minimum (dip)

Coulomb-nuclear interference region (CNI)





Diffraction cone shrinkage at LHC energies

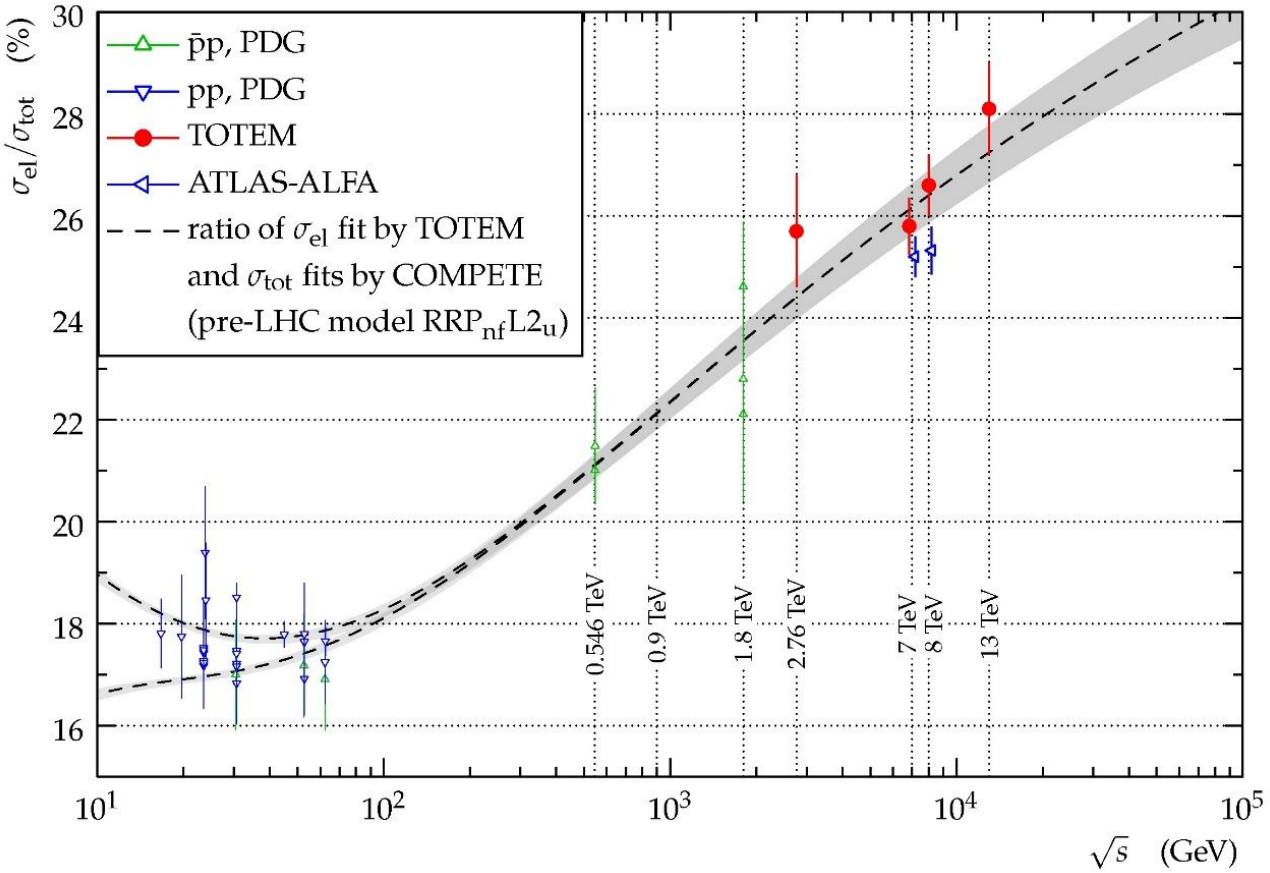


B=d/dn ln (ds/dt) | t=0
increase with √s

The linear (ln s) behaviour is compatible only
for √s < 3 TeV

Eur. Phys. J. C (2019) 79: 103

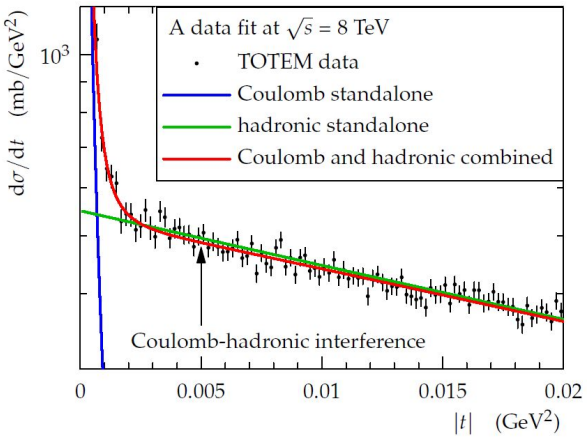
The elastic to total cross-section ratio



The Coulomb-nuclear interface

$F^{C+H} = F^{C} + F^{H} \exp(i\alpha\Psi)$
$|F^{H}|$ - constrained by measurement in nucl. region
$\arg(F^{H})$ - little guidance by data

In the CNI both modulus and phase of nuclear amplitude can be tested to determine ρ value.

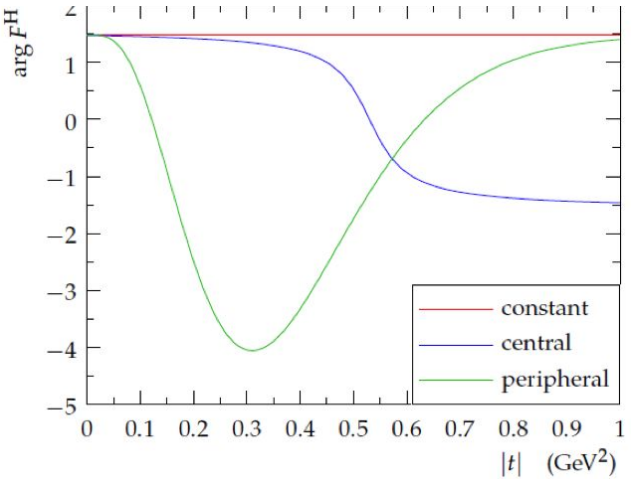


Measuring elastic scattering at |t| down to $6*10^{-4}$ GeV^2 to investigate Coulomb-nuclear interference

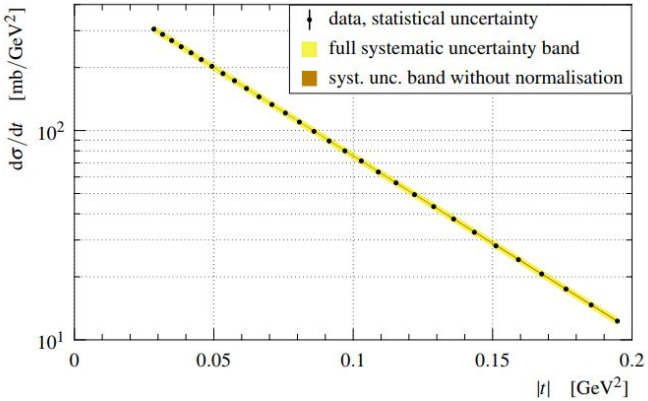
Different nuclear phase models:

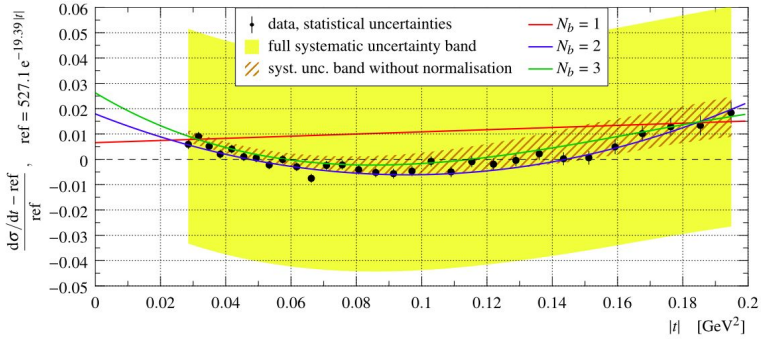
- constant phase
  - $arg\ F^{H}(t) = p_0$
- central phase
  - $arg\ F^{H}(t) = \pi/2 - atan\ (cotp_0 / (1 - t/t_d))$
- peripheral phase
  - $arg\ F^{H}(t) = p_0 + \xi_1 |t/t_0|^{\kappa} exp(vt)$

$\rho = cot\ arg\ F^{H}(0)$ - model dependent



Ruling-out purely exponential approach





Differential cross-section as a relative difference from reference exponential. *Nucl. Phys. B (2015) 527-546*

√s = 8 TeV elastic differential cross-section
nuclear component region

$d\sigma / dt = A \exp(-B(t) |t|)$
N_b=1: $B(t) = b_0$
N_b=2: $B(t) = b_0 + b_1 t$
N_b=3: $B(t) = b_0 + b_1 t + b_2 t^2$

N_b	χ^2/ndf	p-value	significance
1	$117.5/28 = 4.20$	$6.1 \cdot 10^{-13}$	$7.2\,\sigma$
2	$29.3/27 = 1.09$	0.35	$0.94\,\sigma$
3	$25.5/26 = 0.98$	0.49	$0.69\,\sigma$

Purely exponential form excluded at 7.2 σ significance.

Total cross-section and rho measurements

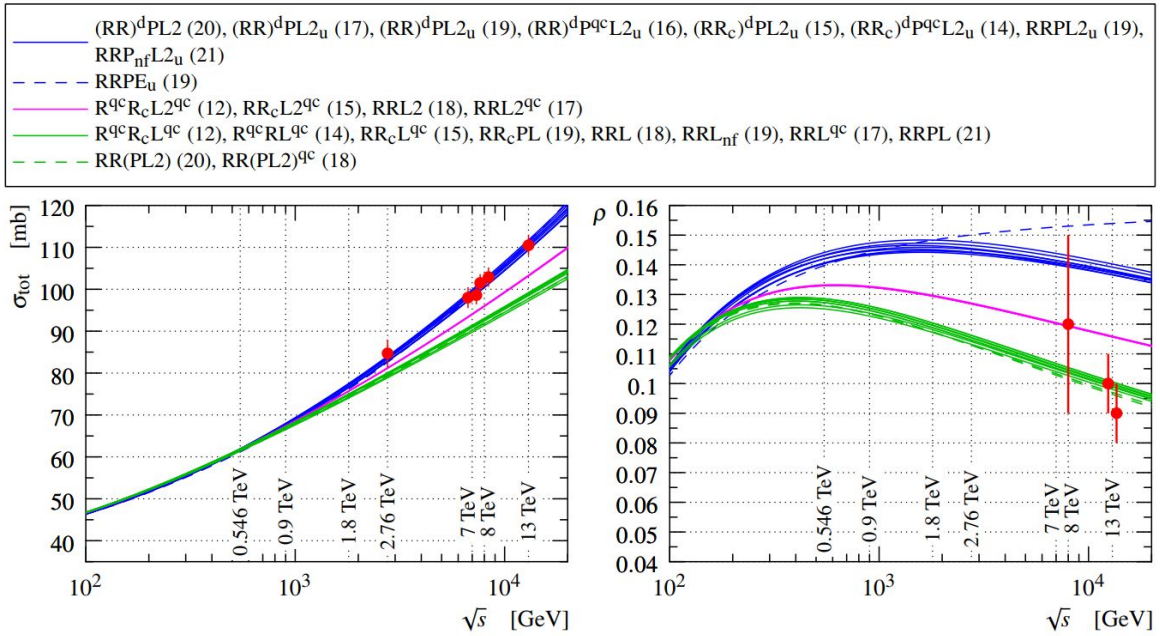


Fig. 19: Predictions of COMPETE models [39] for pp interactions. Each model is represented by one line (see legend). The red points represent the reference TOTEM measurements. The σ_{tot} point at 13 TeV corresponds to the weighted average in Eq. (21). The two ρ points at 13 TeV correspond to the two cases discussed in Section 6.2: the left point to the fit with $N_b = 3$ and $|t|_{max} = 0.15\,\mathrm{GeV}^2$, the right point to $N_b = 1$ and $|t|_{max} = 0.07\,\mathrm{GeV}^2$.

No conventional COMPETE models properly describe both TOTEM total cross-section and ρ measurments.

Adding 3-gluon exchange improves model predictions

arXiv:1812.04732 (submitted to EPJC)

13TeV, various assumptions on nuclear amplitude model:

	$\|t\|_{max} = 0.07\,\mathrm{GeV}^2$			$\|t\|_{max} = 0.15\,\mathrm{GeV}^2$		
N_b	χ^2/ndf	ρ	σ_{tot} [mb]	χ^2/ndf	ρ	σ_{tot} [mb]
1	0.9	0.09 ± 0.01	111.8 ± 3.1	2.1	-	-
2	0.9	0.10 ± 0.01	111.9 ± 3.1	1.0	0.09 ± 0.01	111.9 ± 3.1
3	0.9	0.09 ± 0.01	111.9 ± 3.0	0.9	0.10 ± 0.01	112.1 ± 3.1

Elastic measurements and diffractive dip

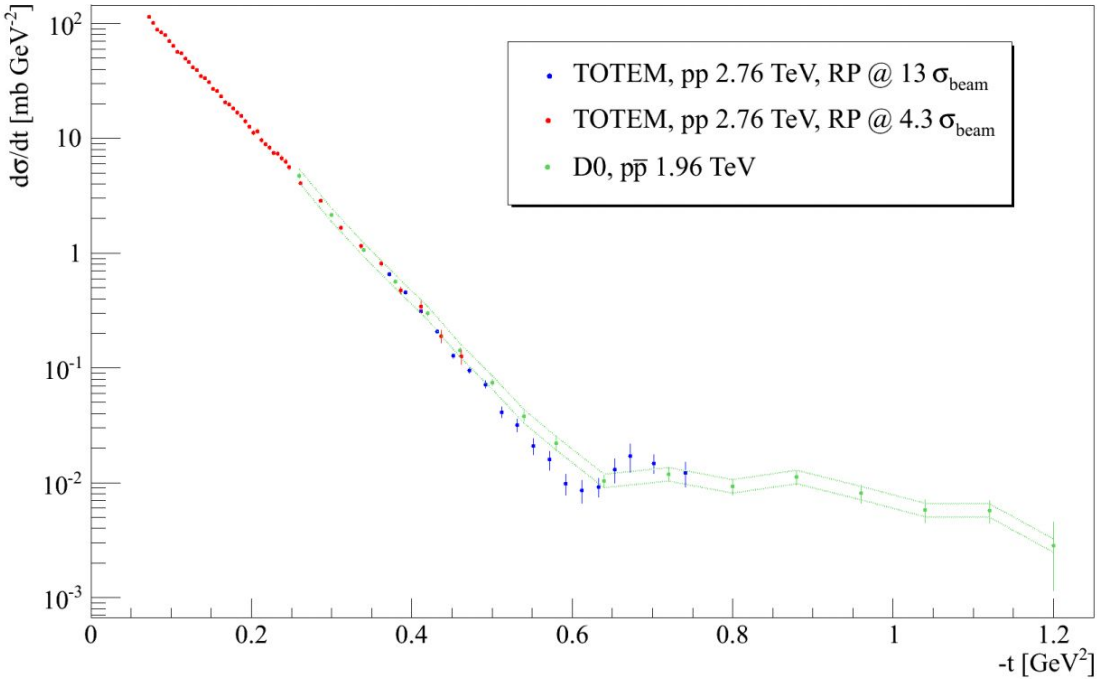


Fig. 9: (color) The differential cross sections $d\sigma/dt$ at $\sqrt{s} = 2.76$ TeV measured by the TOTEM experiment and the elastic $p\bar{p}$ measurement of the D0 experiment at 1.96 TeV [21]. The green dashed line indicates the normalization uncertainty of the D0 measurement.

Diffractive dip visible for all energies in TOTEM measurements

Dip is missing in ppbar data from D0 experiment

V. Khoze "any significant difference in $d\sigma_{el}/dt$ between pp and ppbar @ $\sqrt{s}$ > 0.5-1 TeV would be evidence of the odd signature term - the Odderon contribution"

CERN-PH-EP-2018-341

Summary and future prospects

TOTEM has made extensive measures related to total pp cross-section and elastic scattering

TOTEM experimental predictions cover:

- decrease of ρ at high enegies
- diffractive dip in the proton-proton elastic t-distribution
- the deviation of the elastic differential cross-section from a pure exponential
- the deviation of the elastic diffractive slope, B, from a linear log(s) dependence
- the variation of the nuclear phase as a function of t
- the large-|t| power-law behaviour of the elastic t -distribution with no oscillatory behaviour
- the growth rate of the total cross-section

Plans:

- Precise measurment of ρ and σ_{tot} at low energy (900 GeV)
- Analysis of proton-proton and proton-antiproton elastic scattering with D0 experiment.
- Total cross-section measurements at 14 TeV

Acknowledgements

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