Recent results at 2.76 TeV and 13 TeV p+p collisions from TOTEM

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CERN*

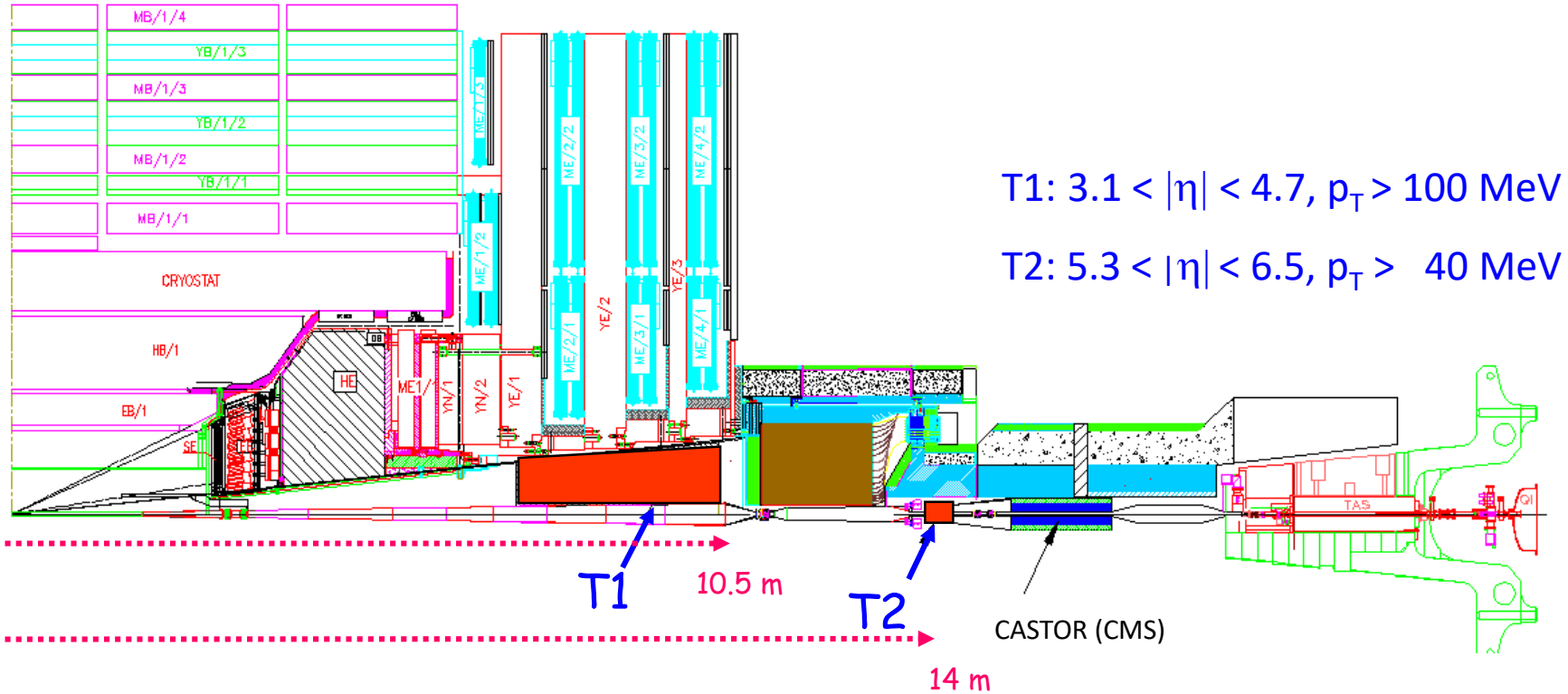
Zimányi School 2019

Budapest, Hungary

December 2 - 6, 2019

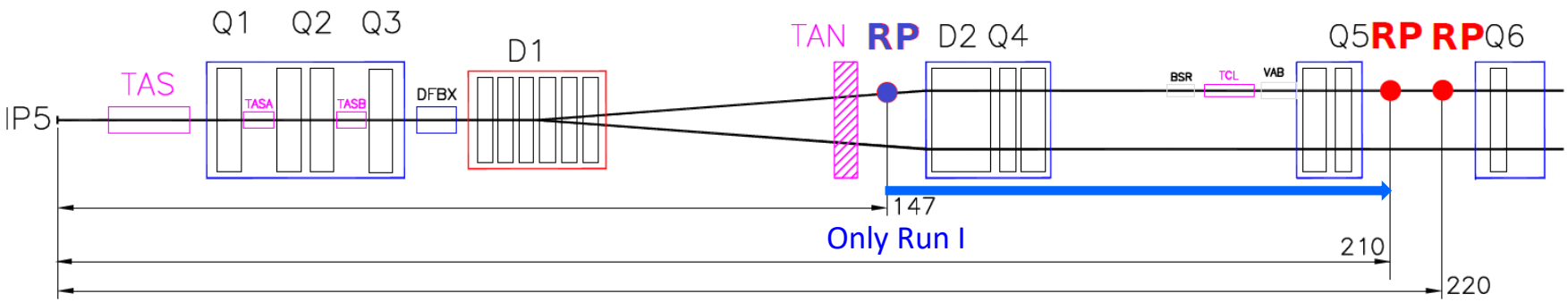
***Also at Wigner RCP, Budapest, Hungary**
Eszterházy Károly Egyetem, Eger

Experimental layout of the TOTEM experiment (LHC Run II)



T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

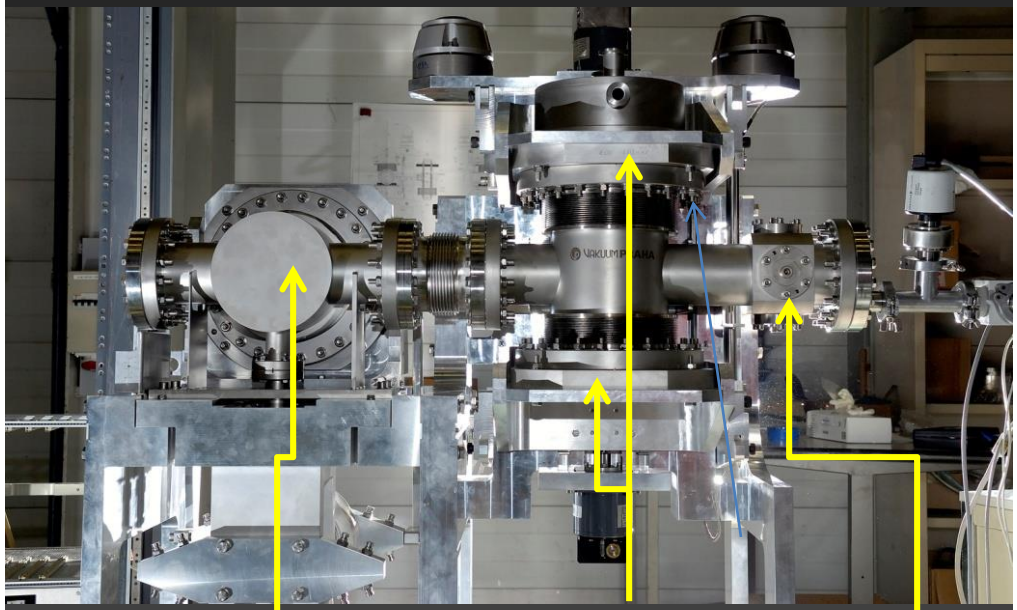


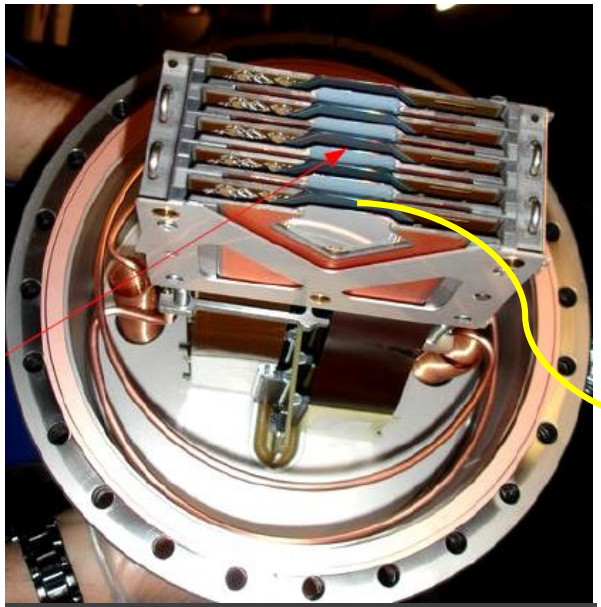
The Roman Pot (RP) stations of the TOTEM experiment

RP stations:

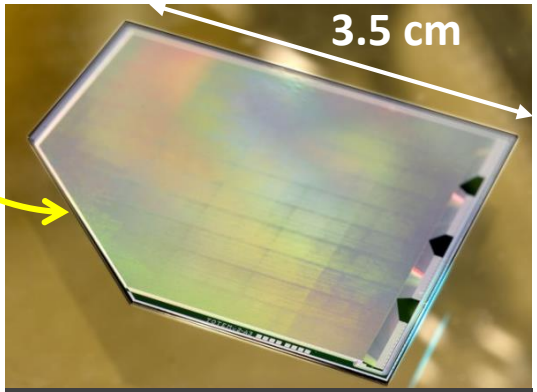
- 2 units (**N**ear, **F**ar) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

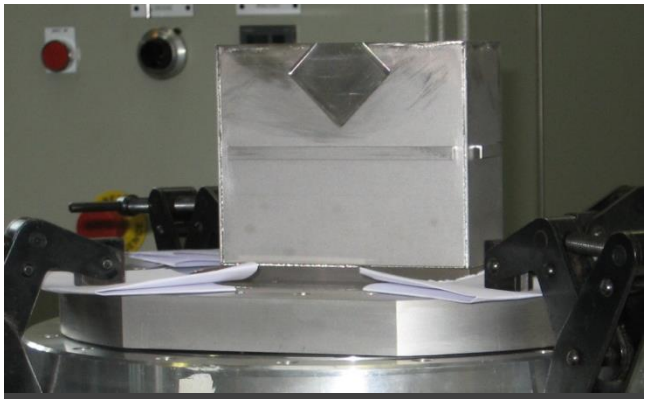




10 planes of edgeless detectors



Si edgeless detector



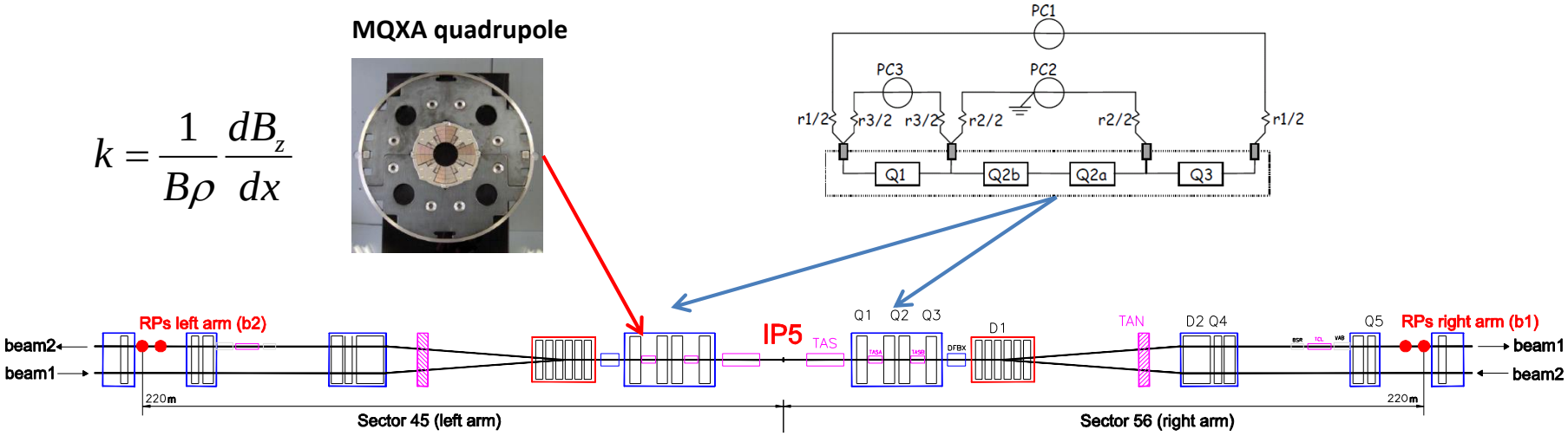
1 Roman Pot

LHC optics at IP5 briefly

Sketch of the LHC magnet lattice at IP5:

$$k = \frac{1}{B\rho}\frac{dB_z}{dx}$$

MQXA quadrupole



s: distance from IP5 (*≡IP5)

Measured

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \xi \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & m_{23} & m_{24} & D'_x \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \xi^* \end{pmatrix}$$

$$\sigma(\Theta) = \sqrt{\varepsilon / \beta_x(s)}$$

Determines angular resolution.

Introduction

List of TOTEM publications

http://totem.web.cern.ch/Totem/publ_new.html

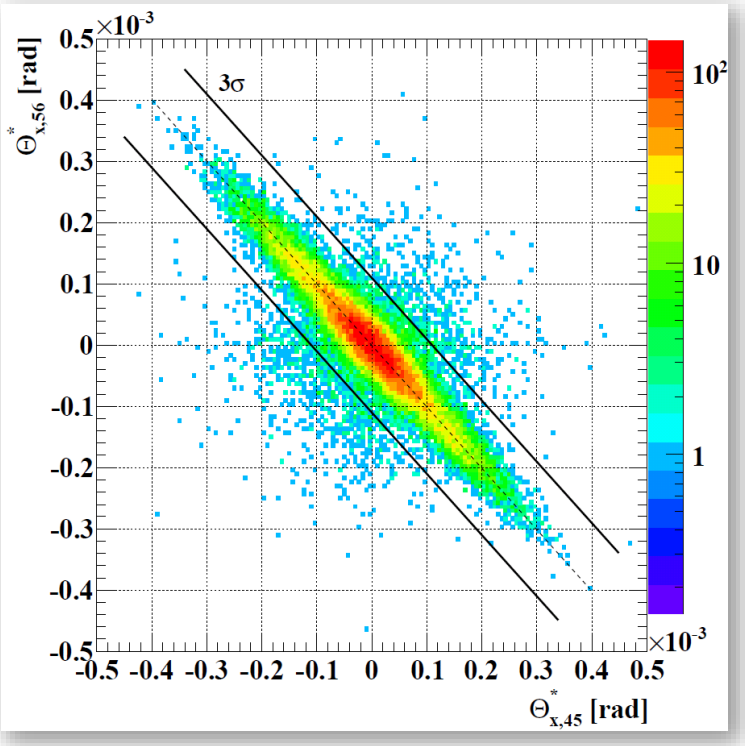
Reconstructed proton kinematics with β* = 3.5 m optics

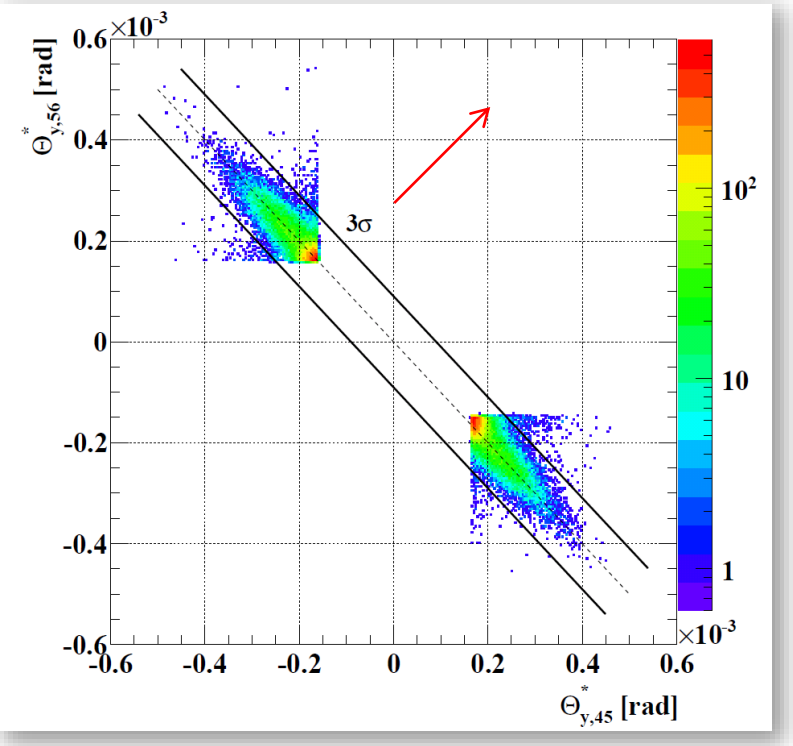
Reconstruction of kinematics:

$$\theta_x^* = \frac{1}{\frac{\mathrm{d}L_x}{\mathrm{d}s}}\left(\theta_x - \frac{\mathrm{d}v_x}{\mathrm{d}s}x^*\right), \theta_y^* = \frac{y}{L_y}$$

Momentum conservation is required in elastic events:

- Published in EPL **95** (2011) 41001

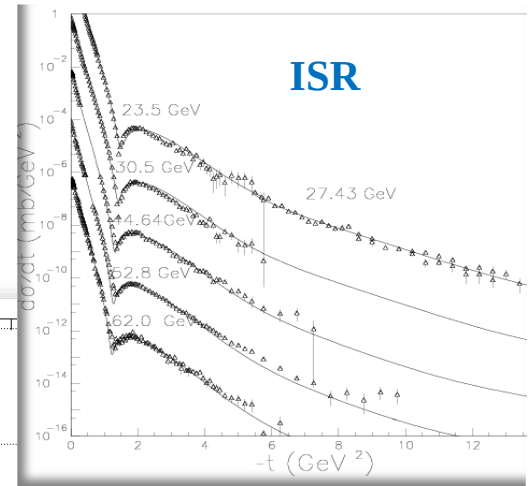


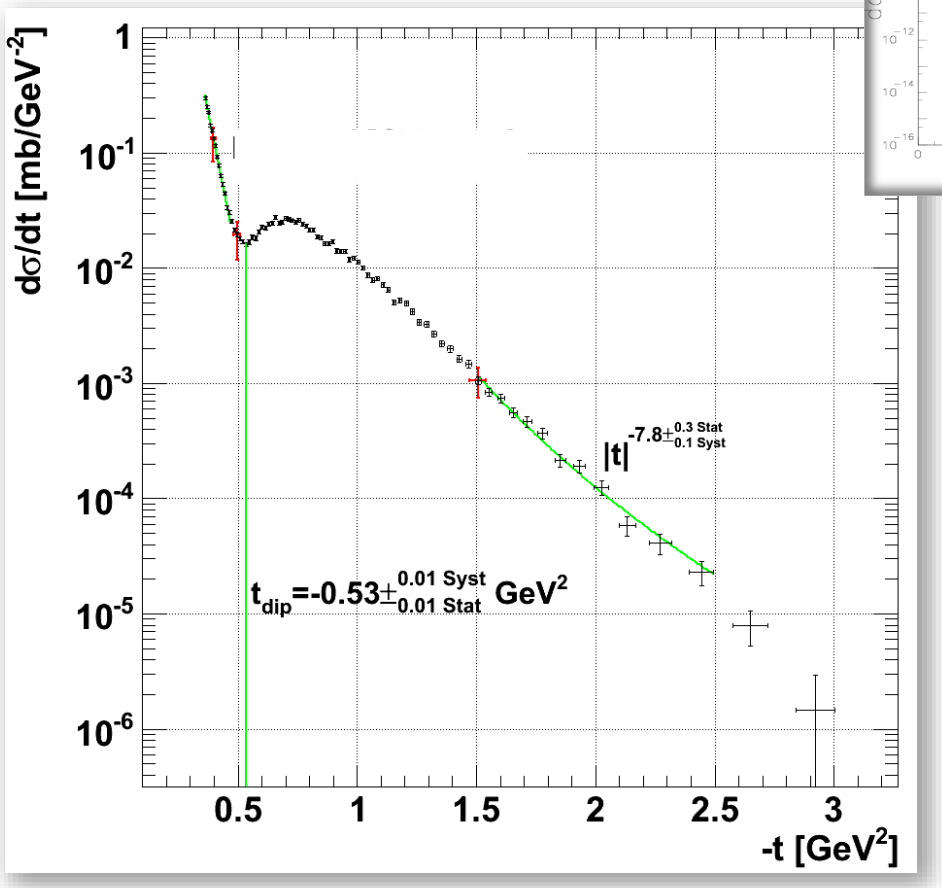


The elastic dσ/dt distribution at √s = 7 TeV (β* = 3.5 m)

Published in EPL **95** (2011) 41001:

- |t| range spans from 0.36 to 2.5 GeV^2
- Below |t| = 0.47 GeV^2 exponential $e^{-B|t|}$ behavior
- Dip moves to lower |t|, proton becomes "larger"
- 1.5 - 2.5 GeV^2 power low behavior $|t|^{-n}$





TOTEM cross-section measurement
√s = 13 TeV

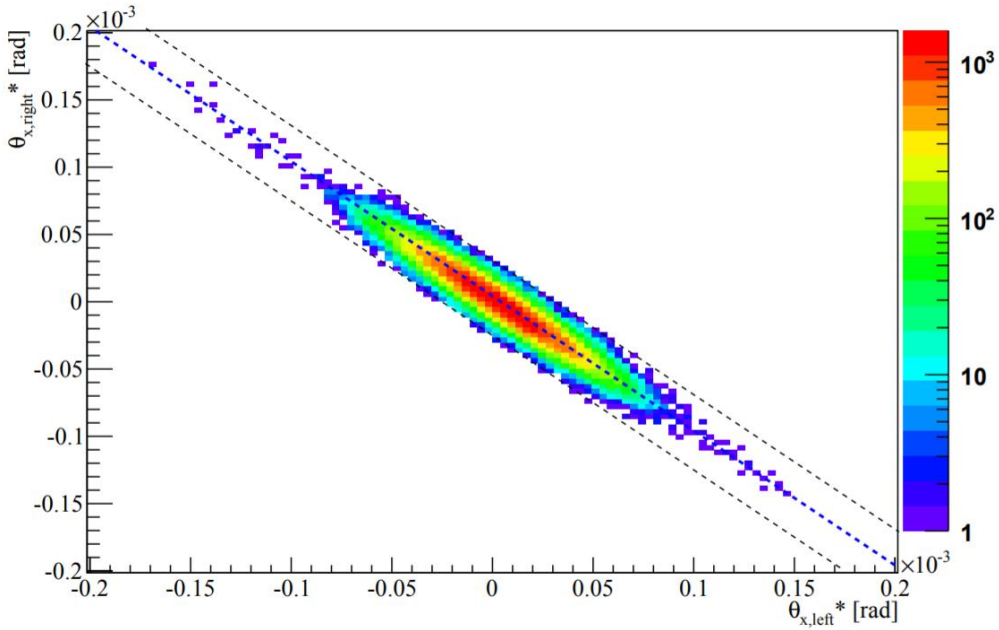
Published in Eur. Phys. J. C (2019) 79: 103)

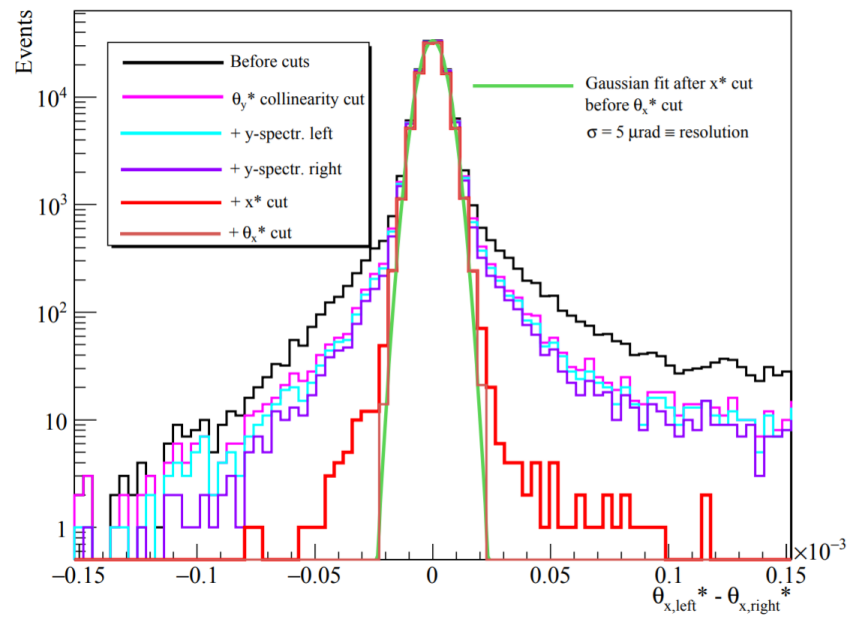
$\beta^* = 90$ m, $5\sigma_{RP}$ RP distance from beam

Signal selection at 13 TeV

Notes:

- Collinearity cut
- Signal selection



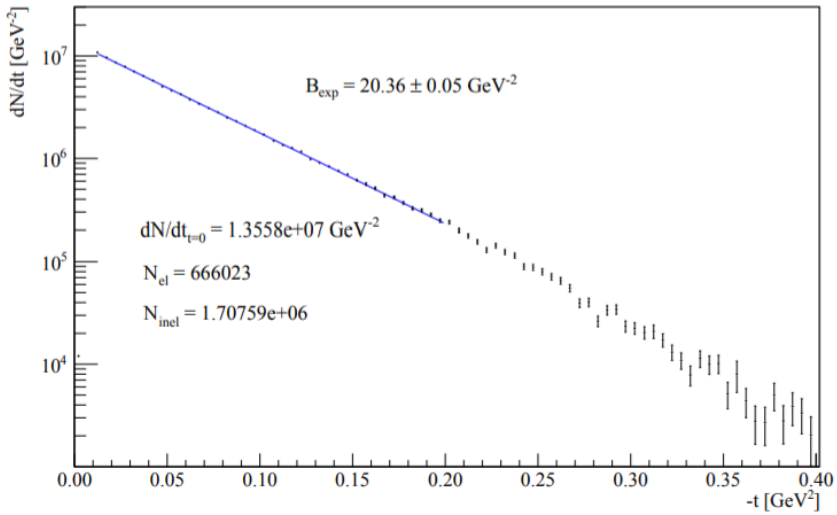


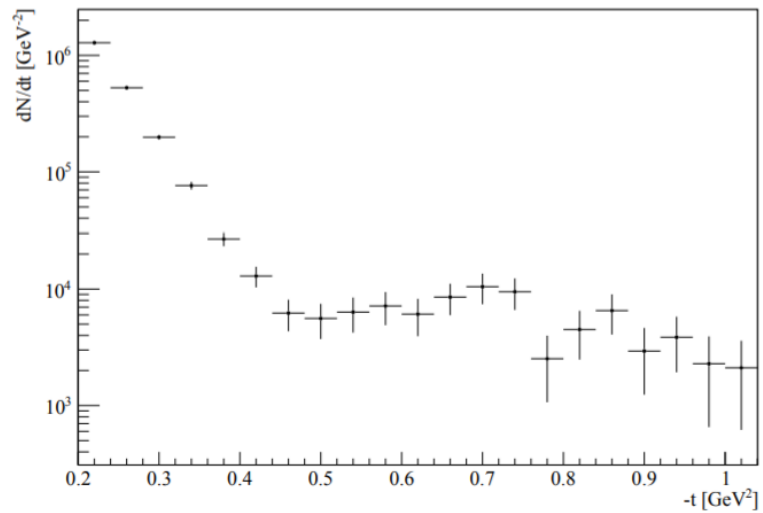
- Clean sample after usual elastic cuts
- Optics matching → kinematics reconstruction uncertainty ~ 2 permil

Main observables at 13 TeV

Note:

- $N_{inel,obs}$ is measured with the T2 inelastic telescope





- Cross-sections with ρ = 0.1

$$\sigma_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{el}}{dt}\right|_{t=0}}{N_{el}+N_{inel}} \qquad \rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$

σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
110.6 ± 3.4	31.0 ± 1.7	79.5 ± 1.8

ρ measurement at √s = 13 TeV

Probing the existence of a colourless C-odd three-gluon compound state (Odderon at t=0)

Published in Eur. Phys. J. C (2019)

$\beta^* = 2500$ m

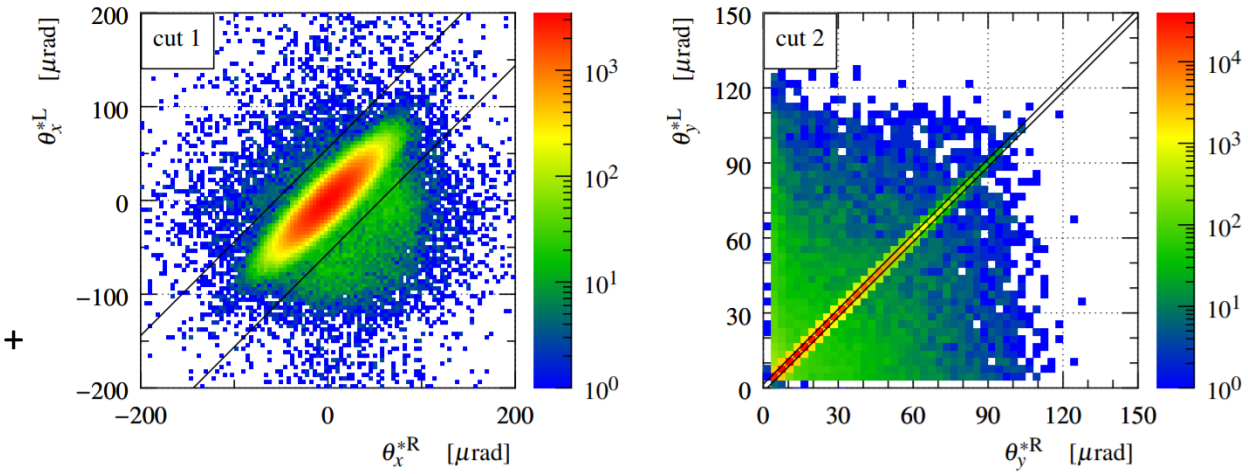
Coulomb-nuclear interference: the ρ parameter

Basic properties of the data:

- $|t|_{min} = 8 \times 10^{-4}$ GeV^2

Analysis aims:

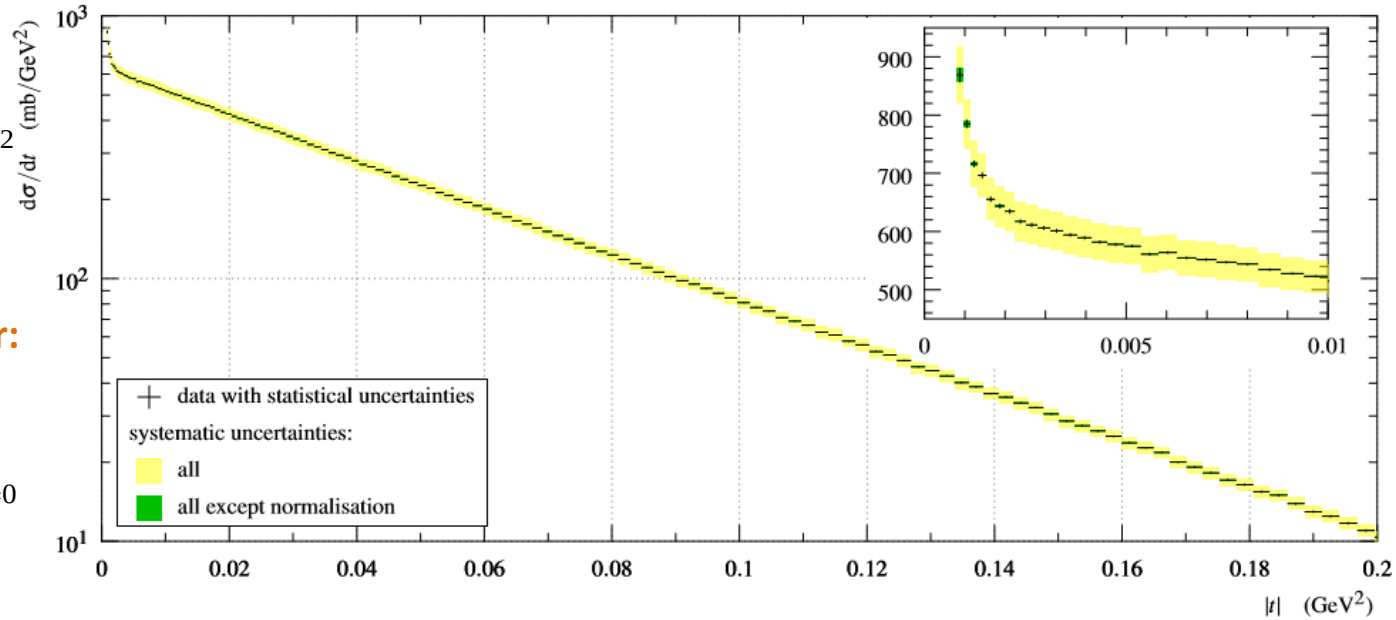
- Measure $d\sigma_{el}/dt$ at the smallest possible $|t|$
- A_{C+H}= Coulomb + Hadronic + Interference terms
- Interference: the **phase** of hadronic amplitude appears



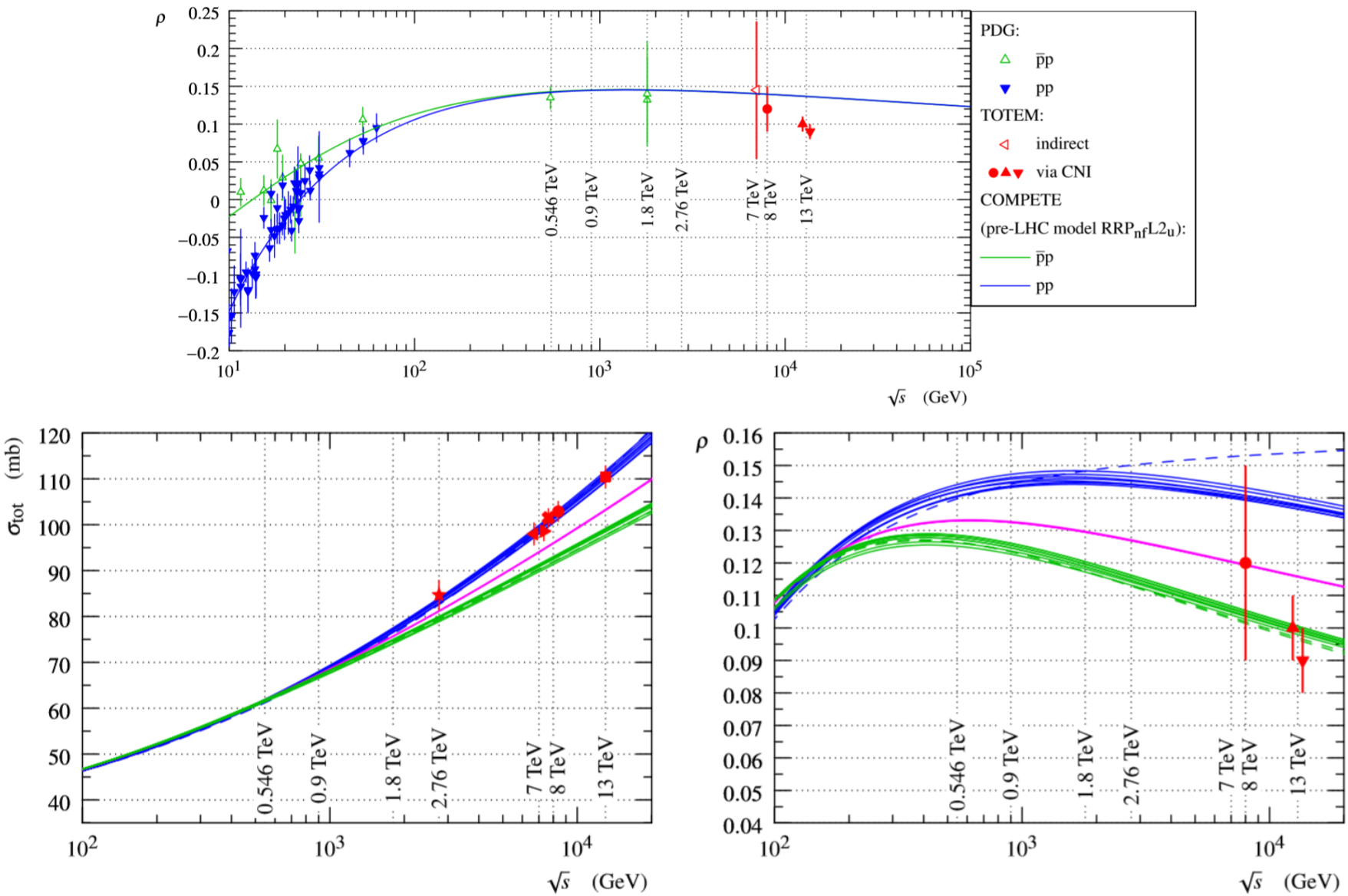
$$\frac{d\sigma}{dt} \propto \left|A_{C+H}\right|^2$$

- **The ρ parameter:**

$$\rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$

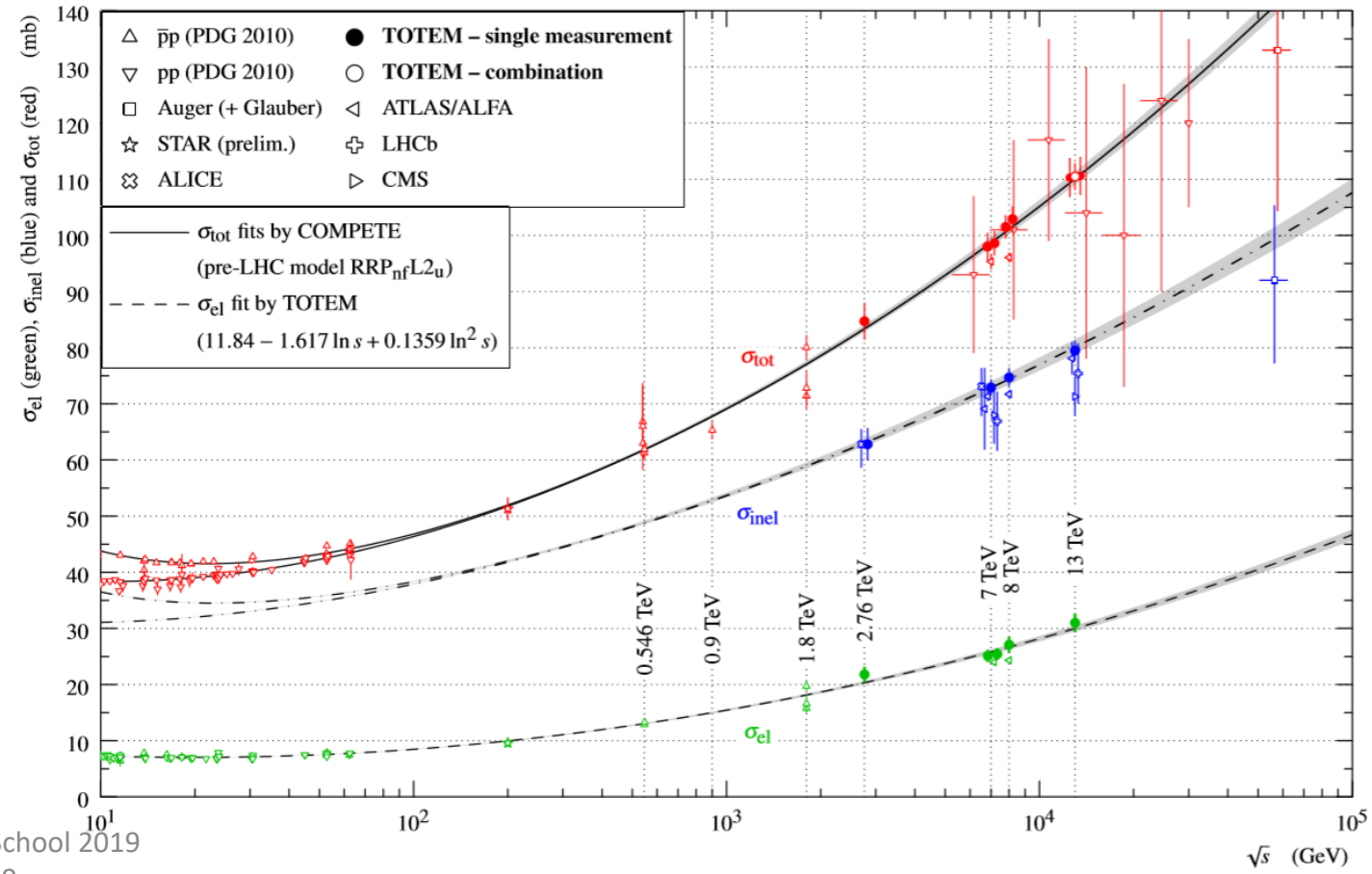


ρ as a function of √s

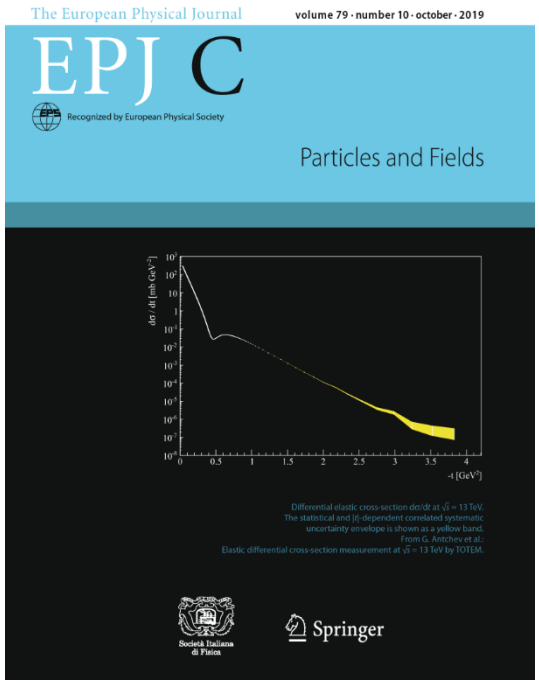


Total-cross section with Coulomb normalization

data	method	ρ	σ_{tot} [mb]
$\beta^* = 90\,\mathrm{m}$	Ref. [6]	-	110.6 ± 3.4
$\beta^* = 2500\,\mathrm{m}$	approach 1	0.09 ± 0.01	111.8 ± 3.1
	approach 2	0.09 ± 0.01	111.3 ± 3.2
	approach 3	$0.08(5) \pm 0.01$	110.3 ± 3.5
	approach 3 (single fit)	0.10 ± 0.01	109.3 ± 3.5
$\beta^* = 90$ and $2500\,\mathrm{m}$	Ref. [6] $\oplus$ approach 3		110.5 ± 2.4



Differential cross-section measurement at √s = 13 TeV



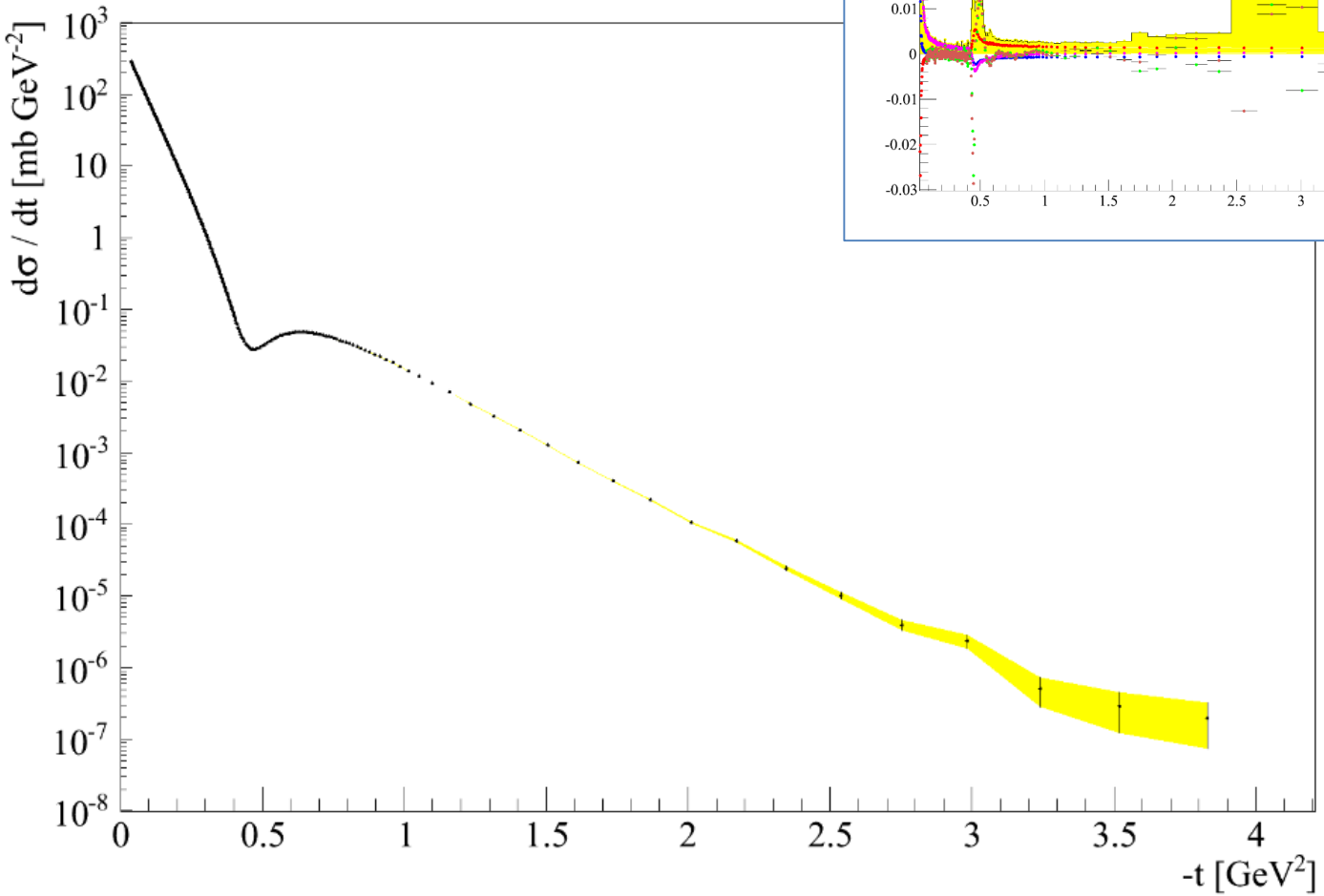
[Published in Eur. Phys. J. C (2019)]

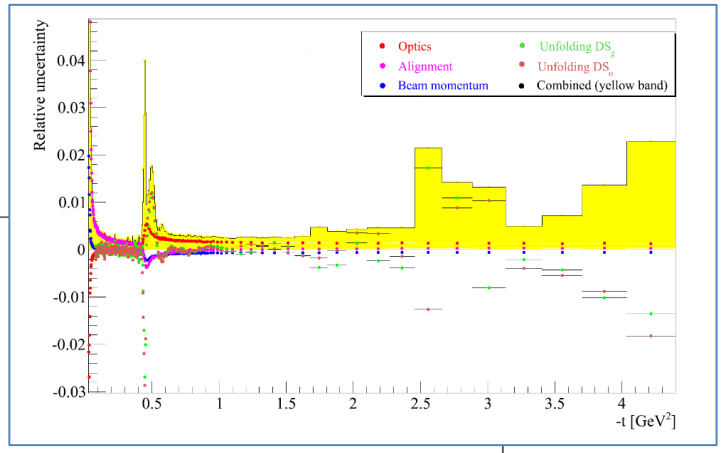
$\beta^* = 90$ m, $10\sigma_{RP}$ RP distance from LHC beam

Elastic differential cross-section

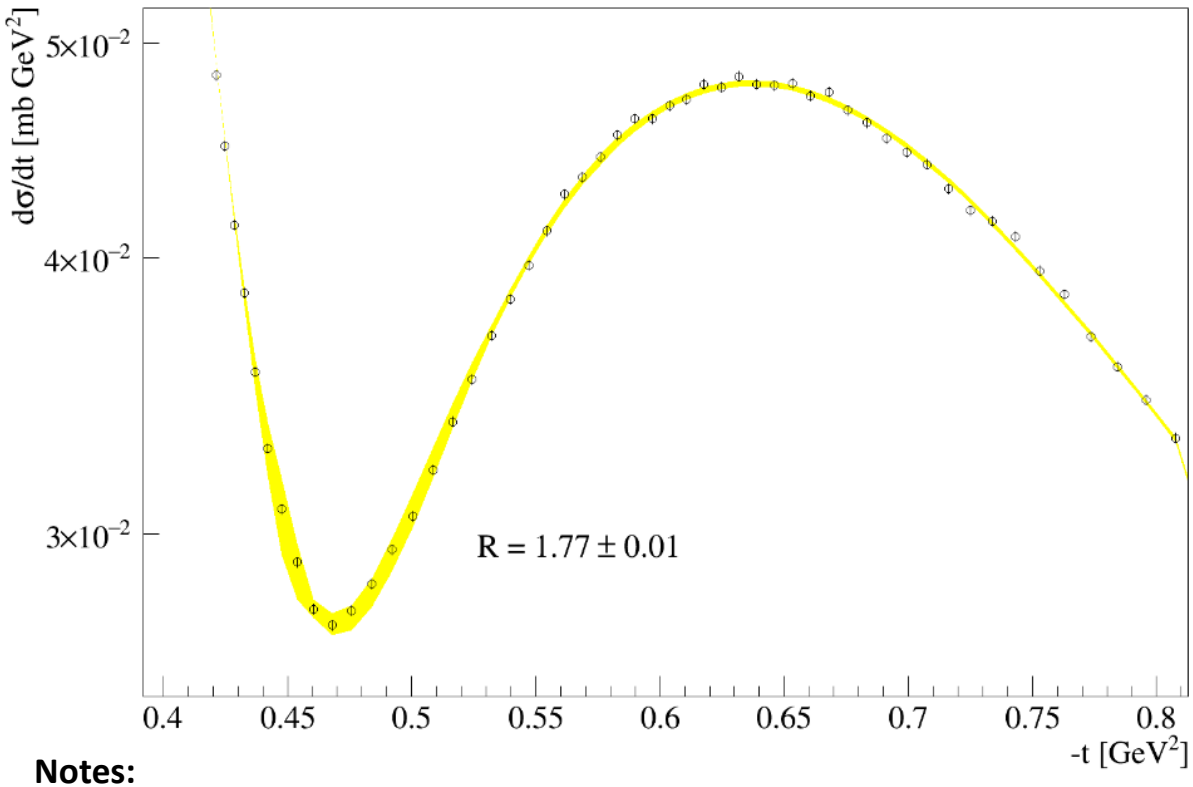
Note:

- O(10^9) observed elastic events (trigger rate **50 ×** Run I)
- Acceptance and beam divergence corrected
- 3/4 correction, matched optics
- Unfolded

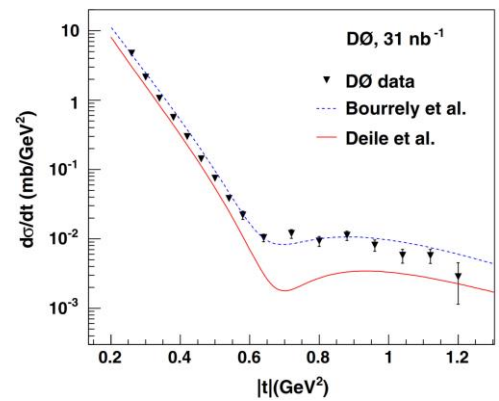




The diffractive minimum



ppbar √s = 1.96 TeV

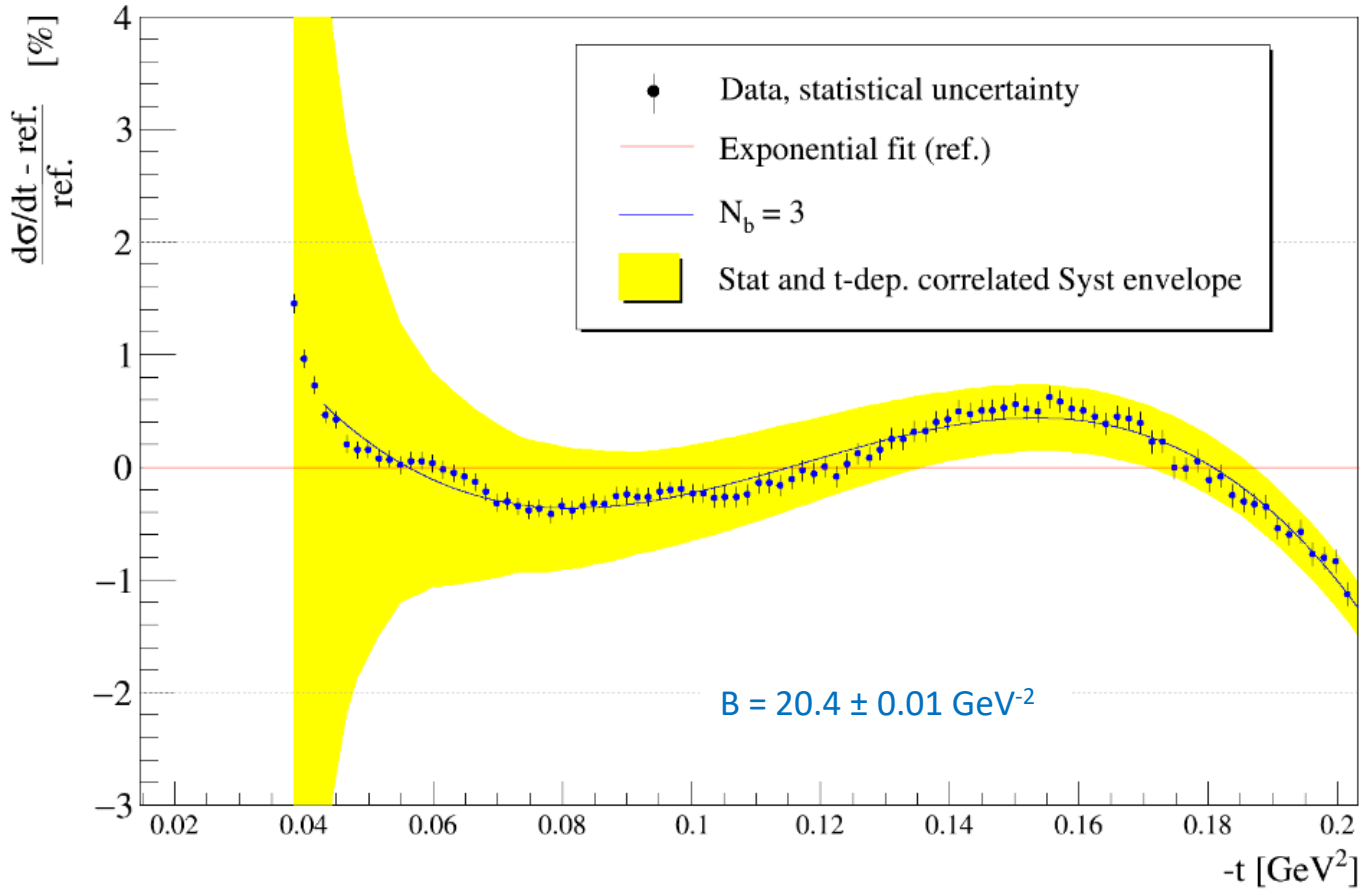


Notes:

- Result confirms with unprecedented precision at the TeV scale the dip structure in elastic pp scattering
- Hadronic elastic @ TeV sqrt(s) dominated by t-channel exchange of colourless gluon states
- 2 (or even) gluon exchange (PC = ++): "Pomeron" (~ mostly imaginary) ⟹ pp vs ppbar invariance
- 3 (or odd) gluon exchange (PC = - -): "Odderon" (expected ~ real) ⟹ no pp vs ppbar invariance
- How observe indications of 3-gluon exchange?
- At low t: by measuring rho = real/imaginary amplitude Coulomb-nuclear interference
- At dip: 2g exchange (~ imaginary) suppressed ⟹ 3g exchange (~ real) observable

Low-t, normalization and non-exponential part

$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i t^i\right)$$



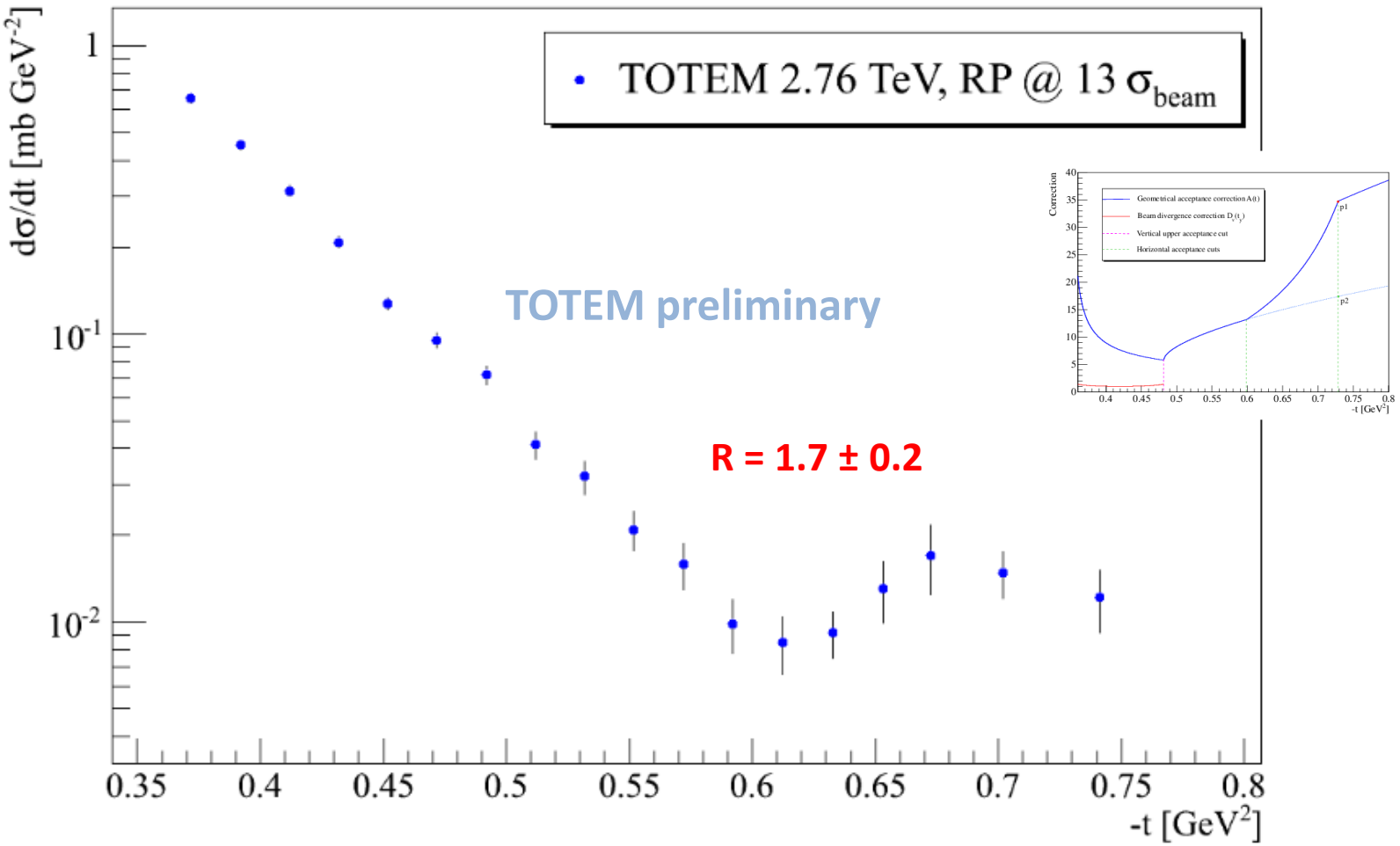
Dip measurement √s = 2.76 TeV

Implication on the existence of a colourless C-odd 3-gluon compound state (Odderon at t ≠ 0)

Preprint: CERN-EP-2018-341

$\beta^* = 11$ m, 13 σ_{RP} RP distance from beam

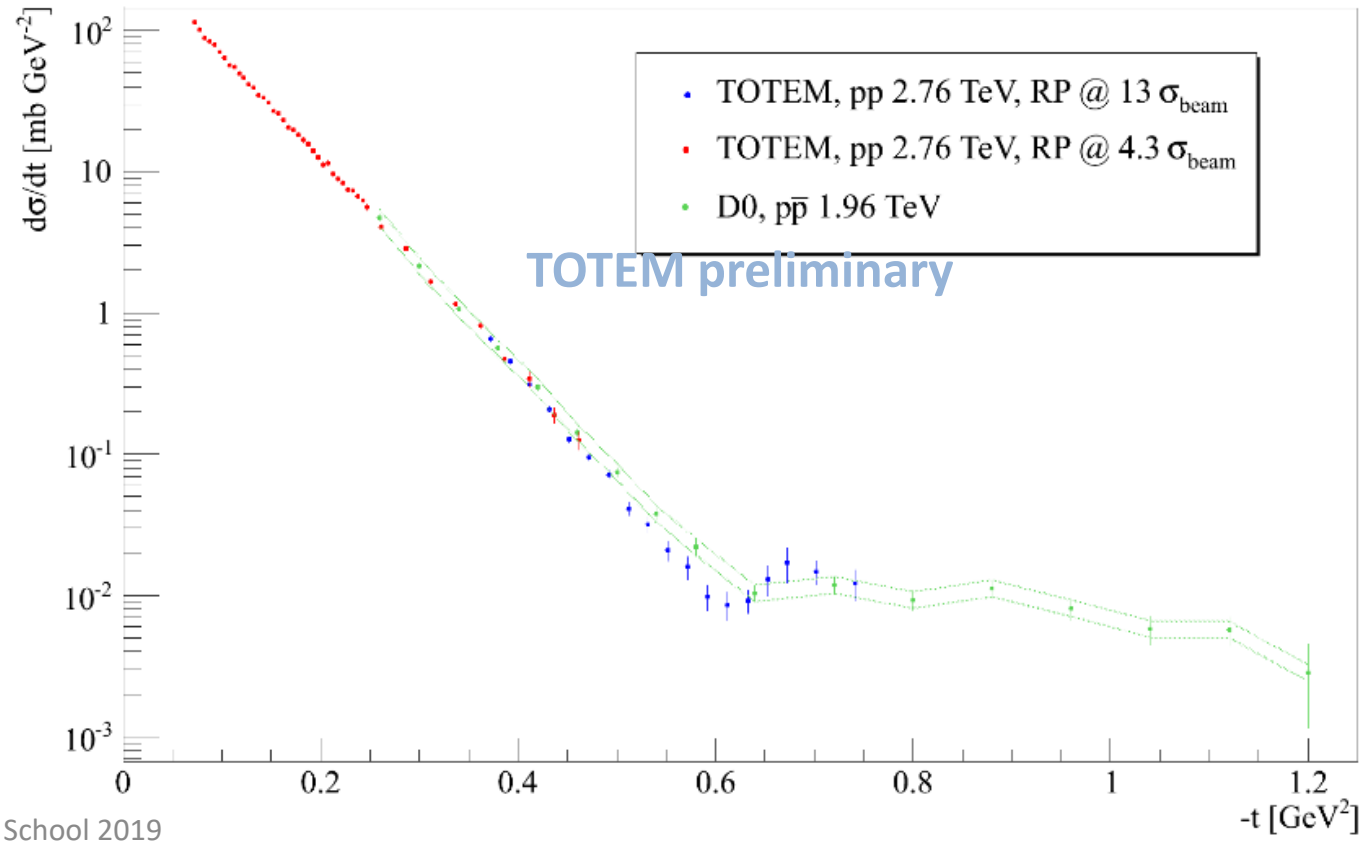
The diffractive minimum at √s = 2.76 TeV



Comparison 2.76 TeV pp and D0 ppbar at 1.96 TeV

Note:

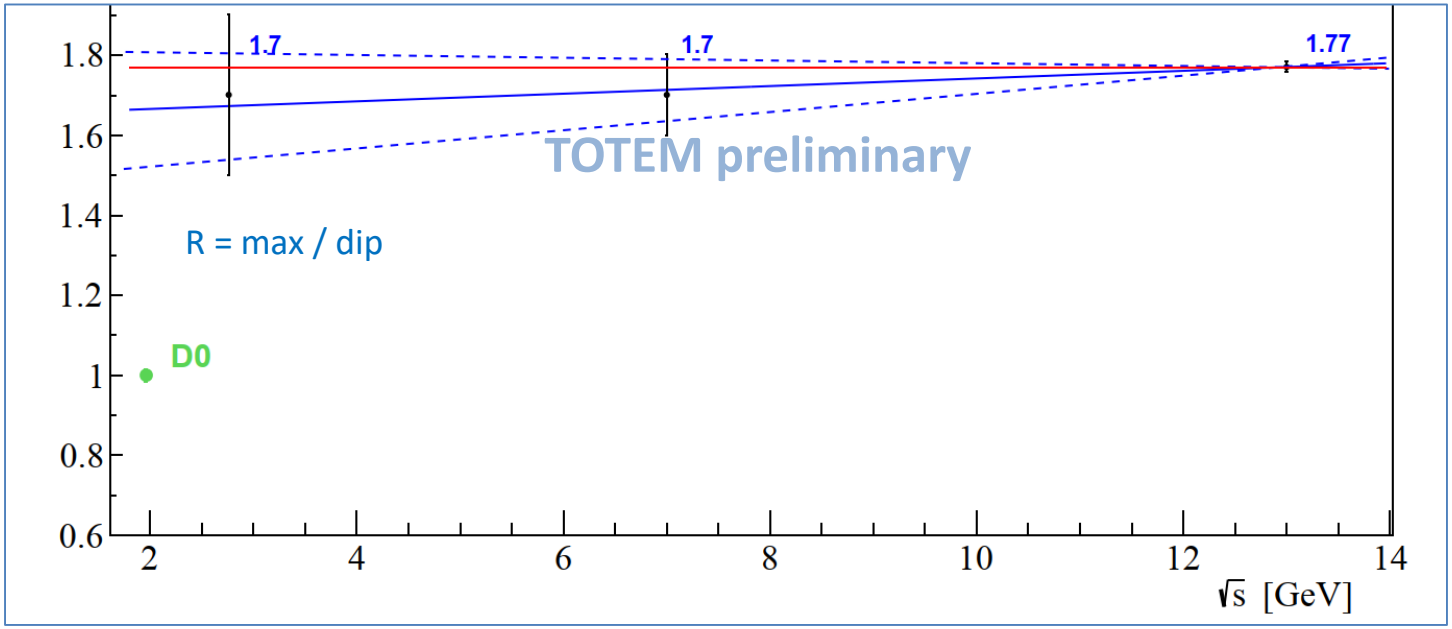
- "In case the 800 GeV energy difference (between this TOTEM measurement and the D0 measurement) is not responsible for the observed difference between them, as indicated by the broad energy range of pp and ppbar measurements from 500 GeV to 13 TeV, the results provide evidence for a colourless C-odd 3-gluon compound state exchange in the t-channel of the proton-proton and proton-antiproton elastic scattering."



Comparison 2.76 TeV pp and D0 ppbar at 1.96 TeV

Note:

- Persistency of diffractive dip in pp, absence of diffractive dip in ppbar
- R = max / dip approximately constant in pp and significantly larger than in ppbar
- Significance being evaluated in close collaboration with D0 to appear in joint paper)
- "In case the 800 GeV energy difference (between this TOTEM measurement and the D0 measurement) is not responsible for the observed difference between them, as indicated by the broad energy range of pp and ppbar measurements from 500 GeV to 13 TeV, the results provide evidence for a colourless C-odd 3-gluon compound state exchange in the t-channel of the proton-proton and proton-antiproton elastic scattering."



Summary

- 13 TeV total cross-section measurement
- 13 TeV ρ measurement
  - Coulomb normalization
  - Data compatible with t-channel exchange of a colourless QCD 3 gluon C-odd compound state
- 13 TeV differential cross-section measurement
  - Confirms with unprecedented precision the dip structure in pp scattering at TeV scale
- 2.76 TeV, total cross-section measurement
  - Total, elastic and inelastic cross-section measurement (published in)
  - Change of √s behaviour of slope parameter B at around 3 TeV
- 2.76 TeV, differential cross-section measurement
  - Provides Odderon **evidence** (joint TOTEM – D0 analysis to determine significance)

Thank you for your attention !