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

Frigyes Nemes on behalf of the TOTEM experiment
CERN*

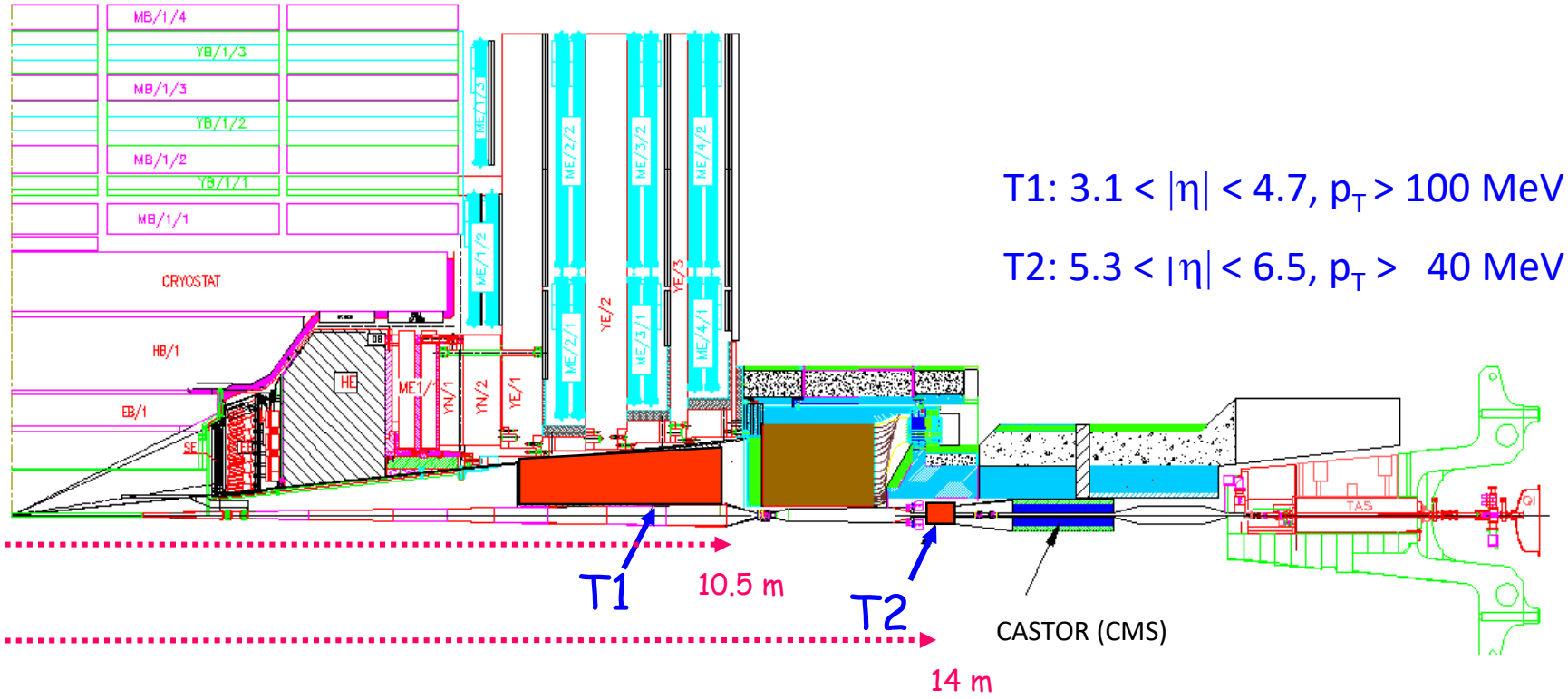
5th Day of Femtoscopy

Gyöngyös, Hungary

October 31, 2019

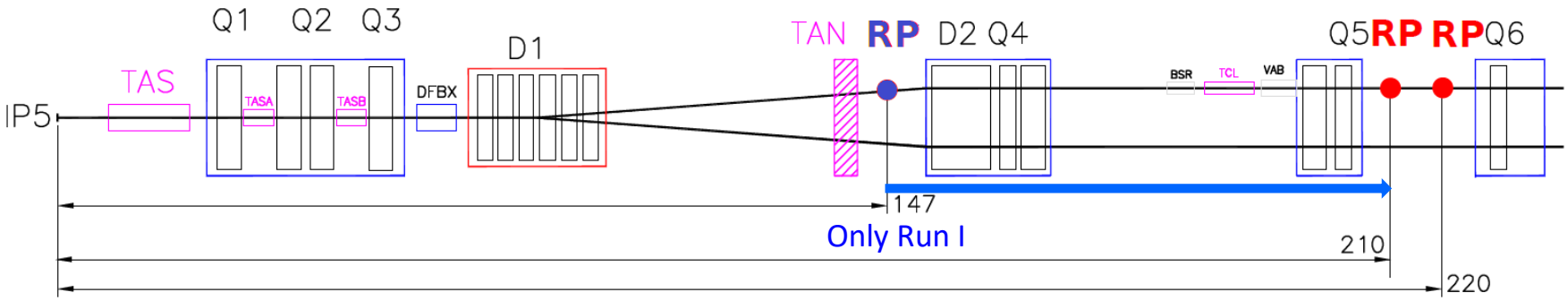
***Also at Wigner RCP, Budapest, Hungary**
Eszterházy Károly Egyetem, Eger

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

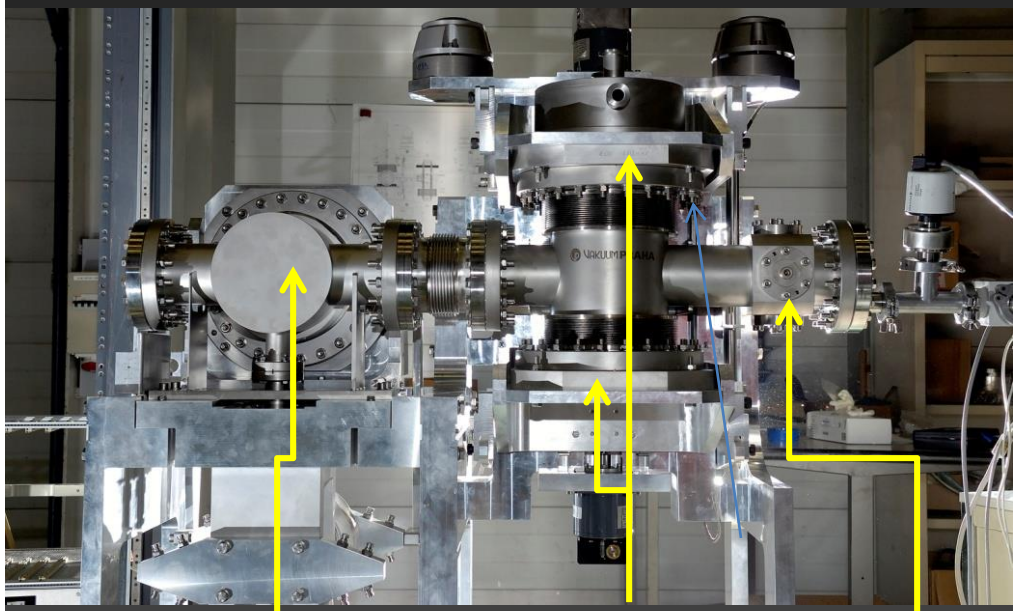


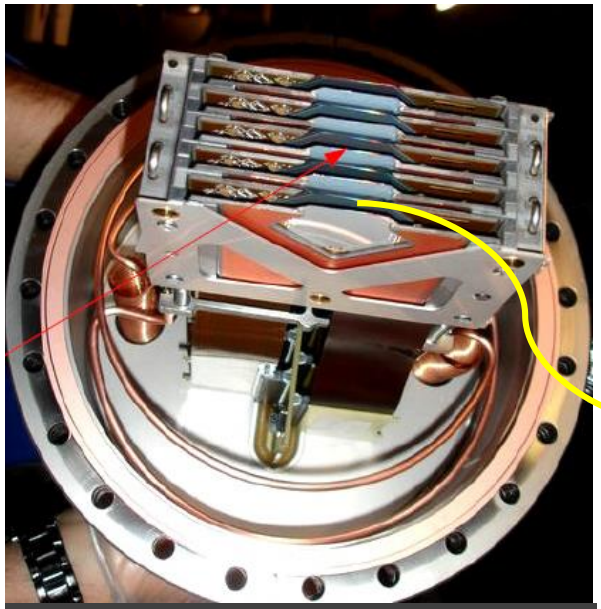
The Roman Pot (RP) stations of the TOTEM experiment

RP stations:

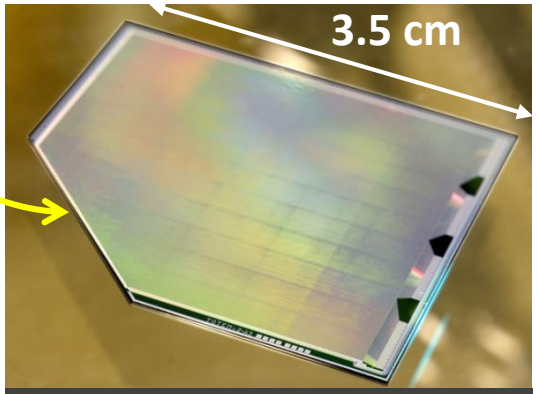
- 2 units (**N**ear, **F**ar) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

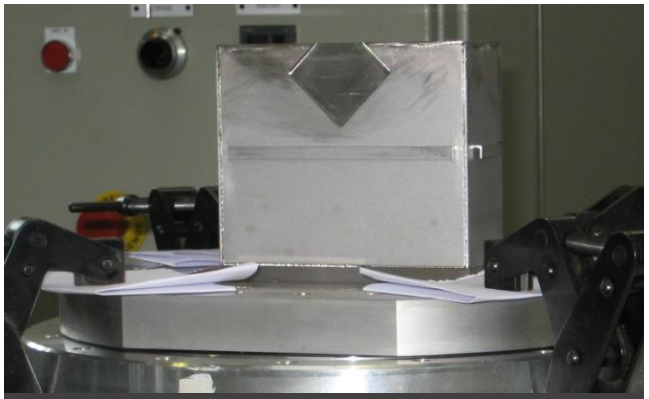




10 planes of edgeless detectors



Si edgeless detector



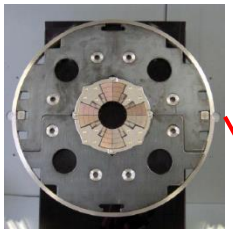
1 Roman Pot

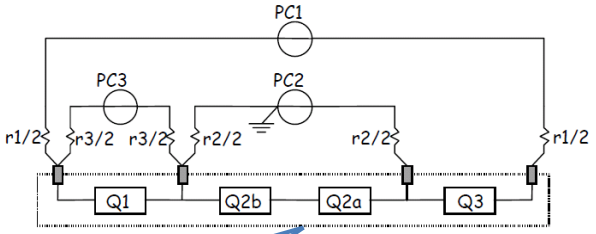
LHC optics at IP5 briefly

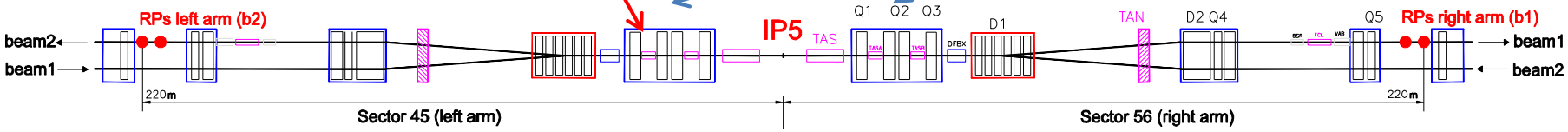
Sketch of the LHC magnet lattice at IP5:

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

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

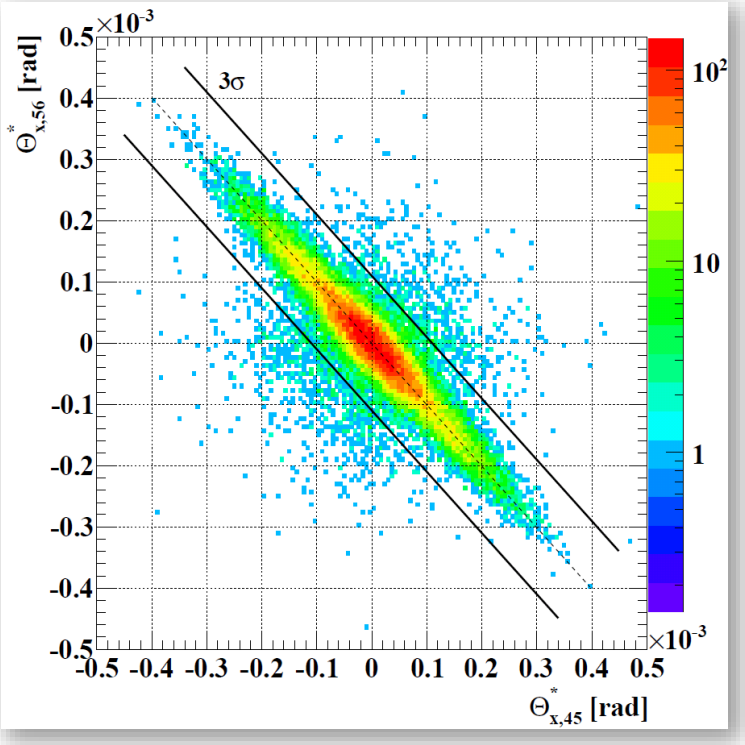
Reconstructed proton kinematics with β* = 3.5 m optics

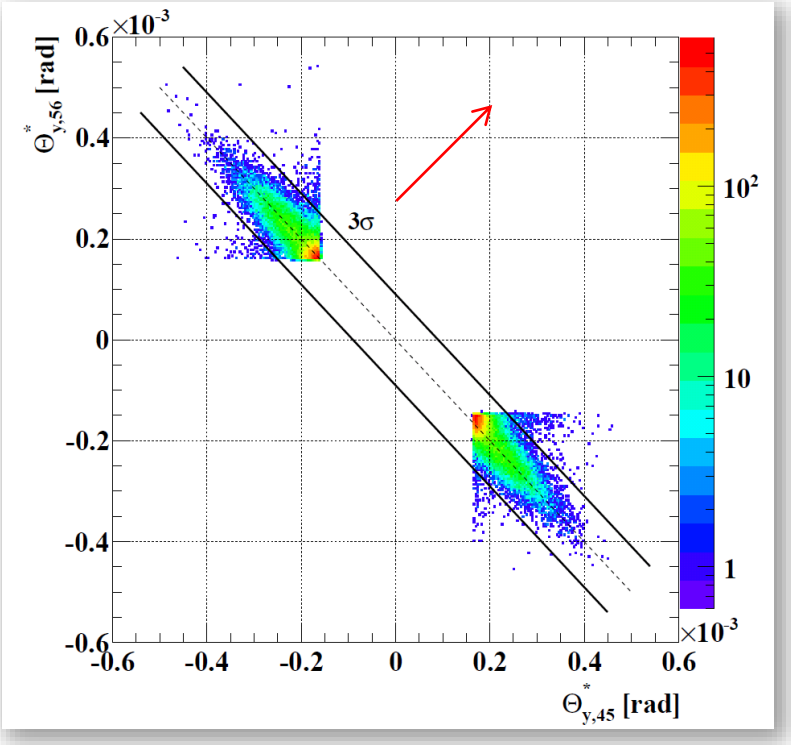
Reconstruction of kinematics:

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

Momentum conservation is required in elastic events:

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

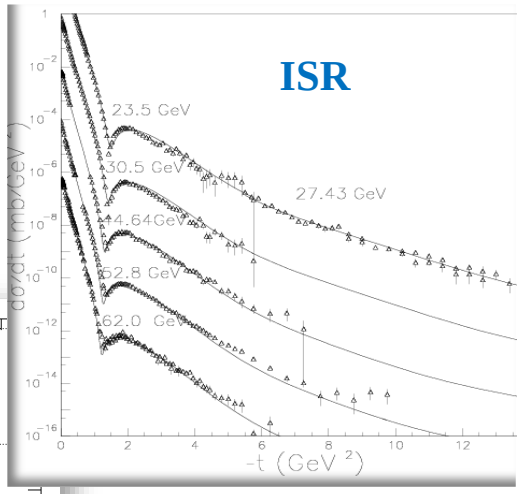


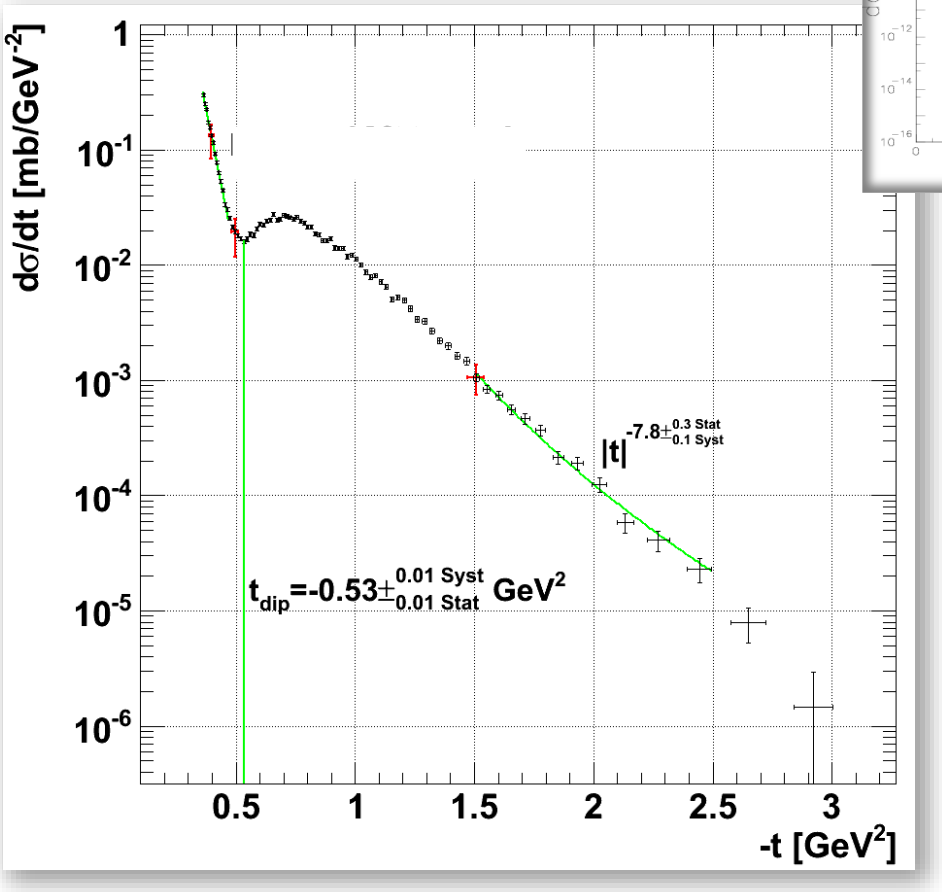


The elastic dσ/dt distribution at √s = 7 TeV (β* = 3.5 m)

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

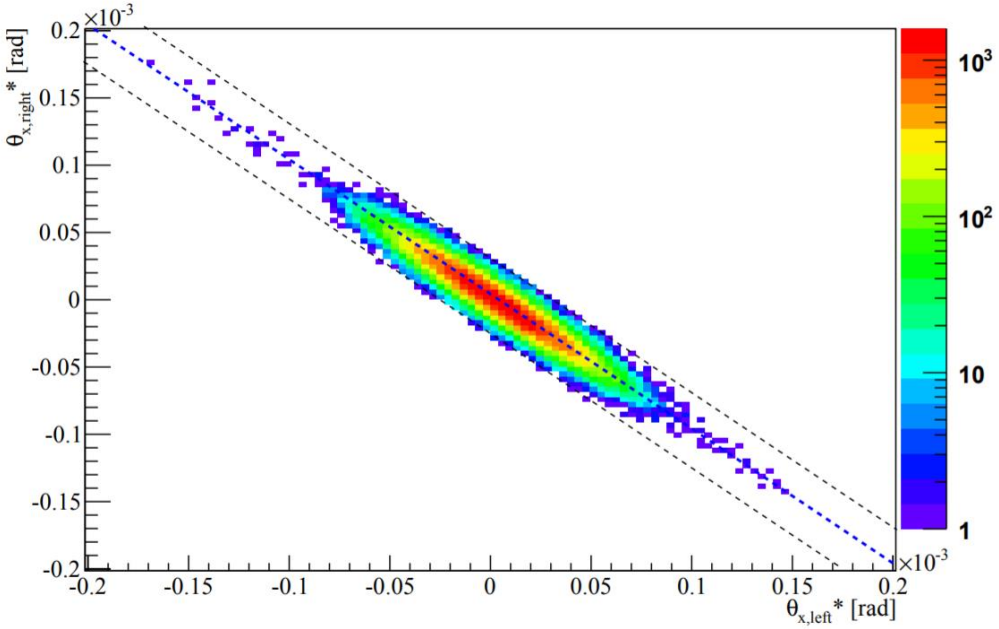
Published in Eur. Phys. J. C (2019) 79: 103)

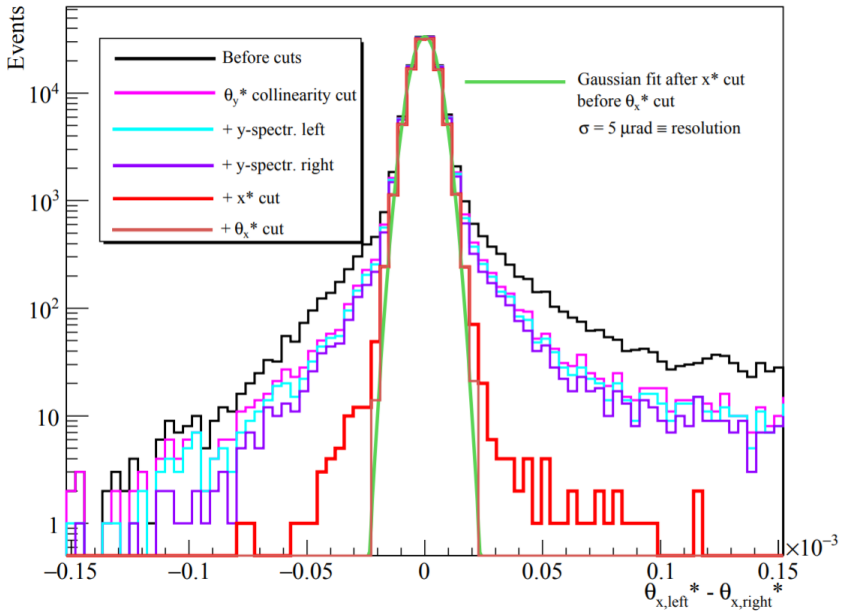
$\beta^* = 90$ m, $5\sigma_{RP}$ RP distance from beam

Signal selection at 13 TeV

Notes:

- Collinearity cut
- Signal selection



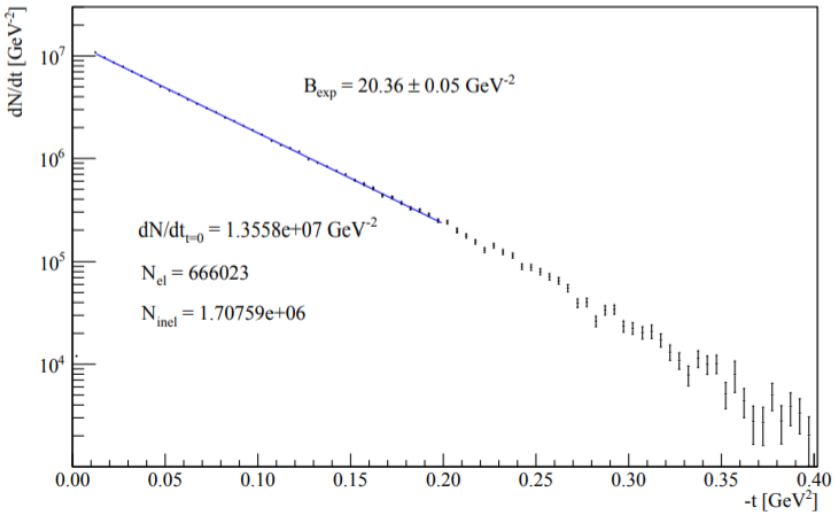


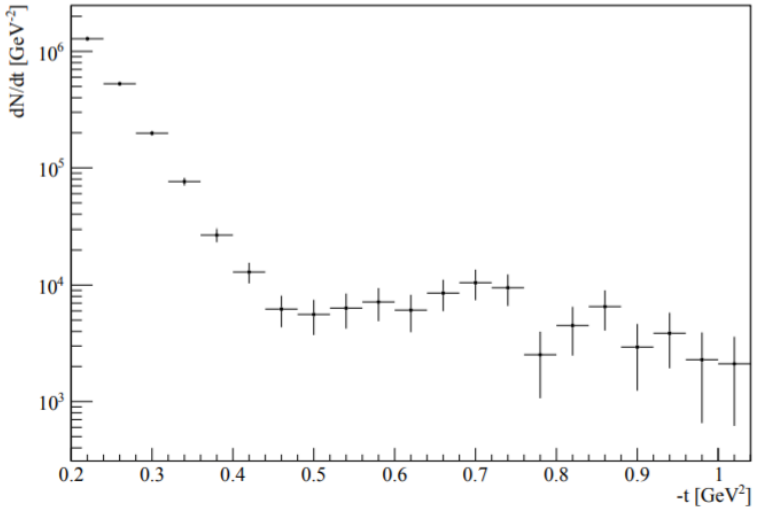
- Clean sample after usual elastic cuts
- Optics matching → kinematics reconstruction uncertainty ~ 2 permil

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)

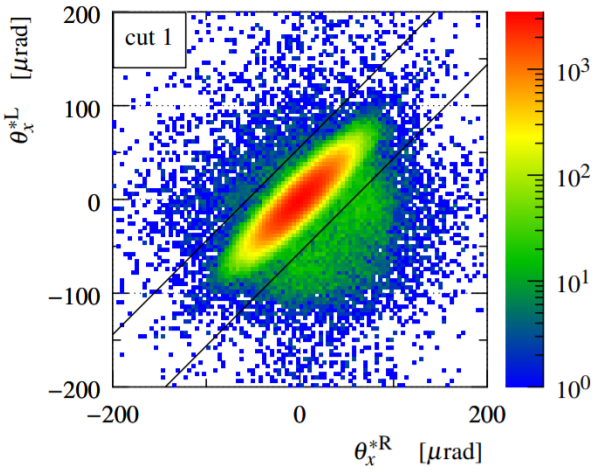
Published in Eur. Phys. J. C (2019)

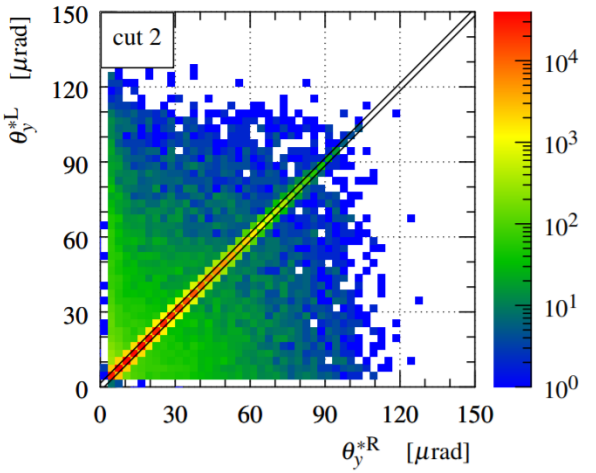
β* = 2500 m

Coulomb-nuclear interference: the ρ parameter

Basic properties of the data:

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





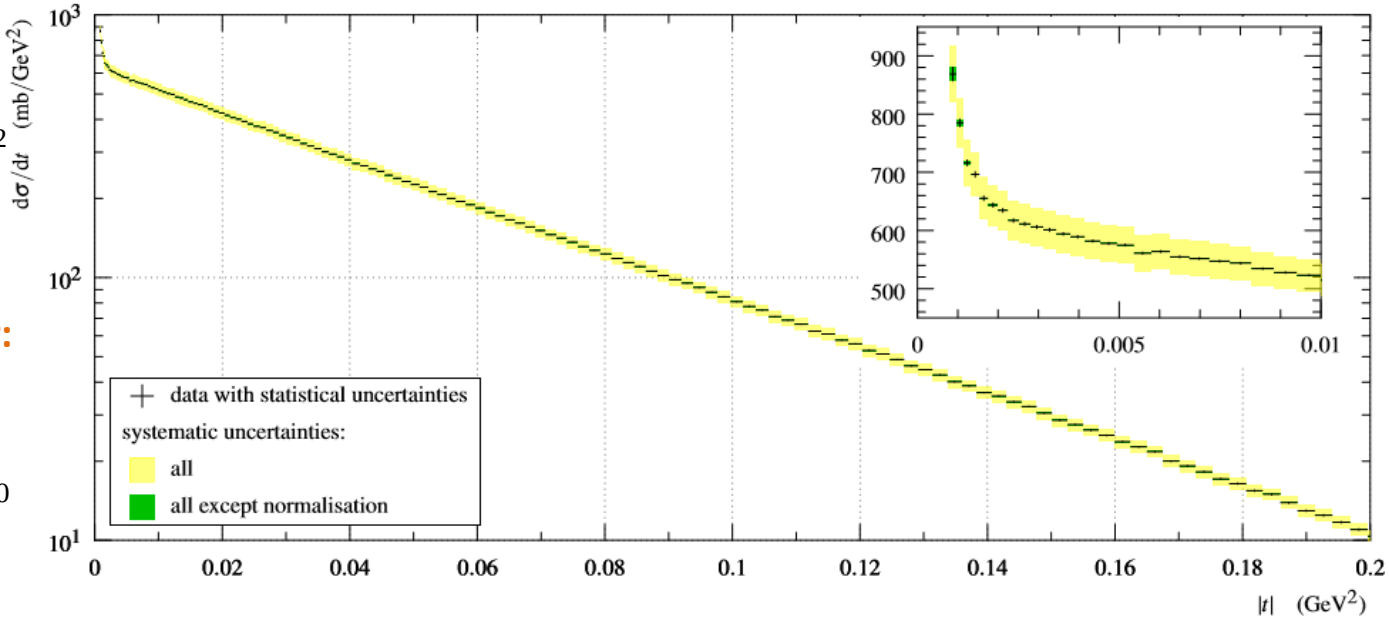
Analysis aims:

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

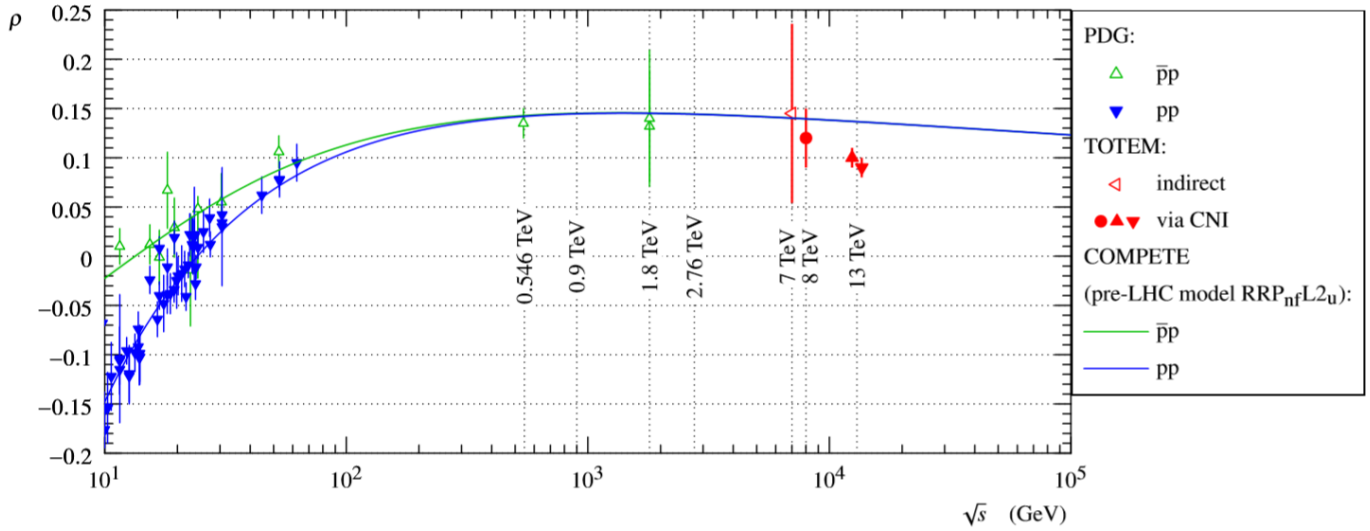
$$\frac{d\sigma}{dt} \propto \left|A_{C+H}\right|^2$$

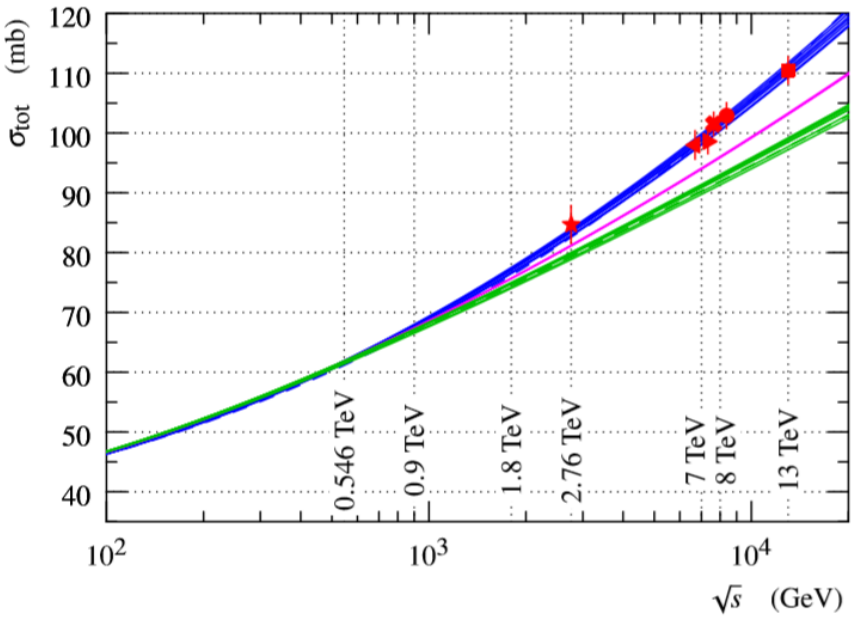
- **The ρ parameter:**

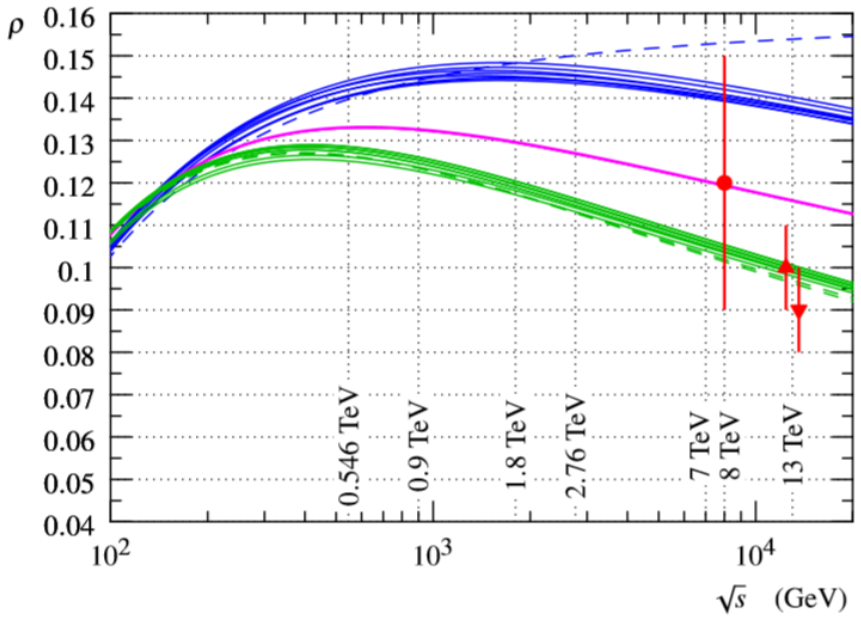
$$\rho = \left.\frac{\mathrm{Re}\, A^H}{\mathrm{Im}\, A^H}\right|_{t=0}$$



ρ as a function of √s

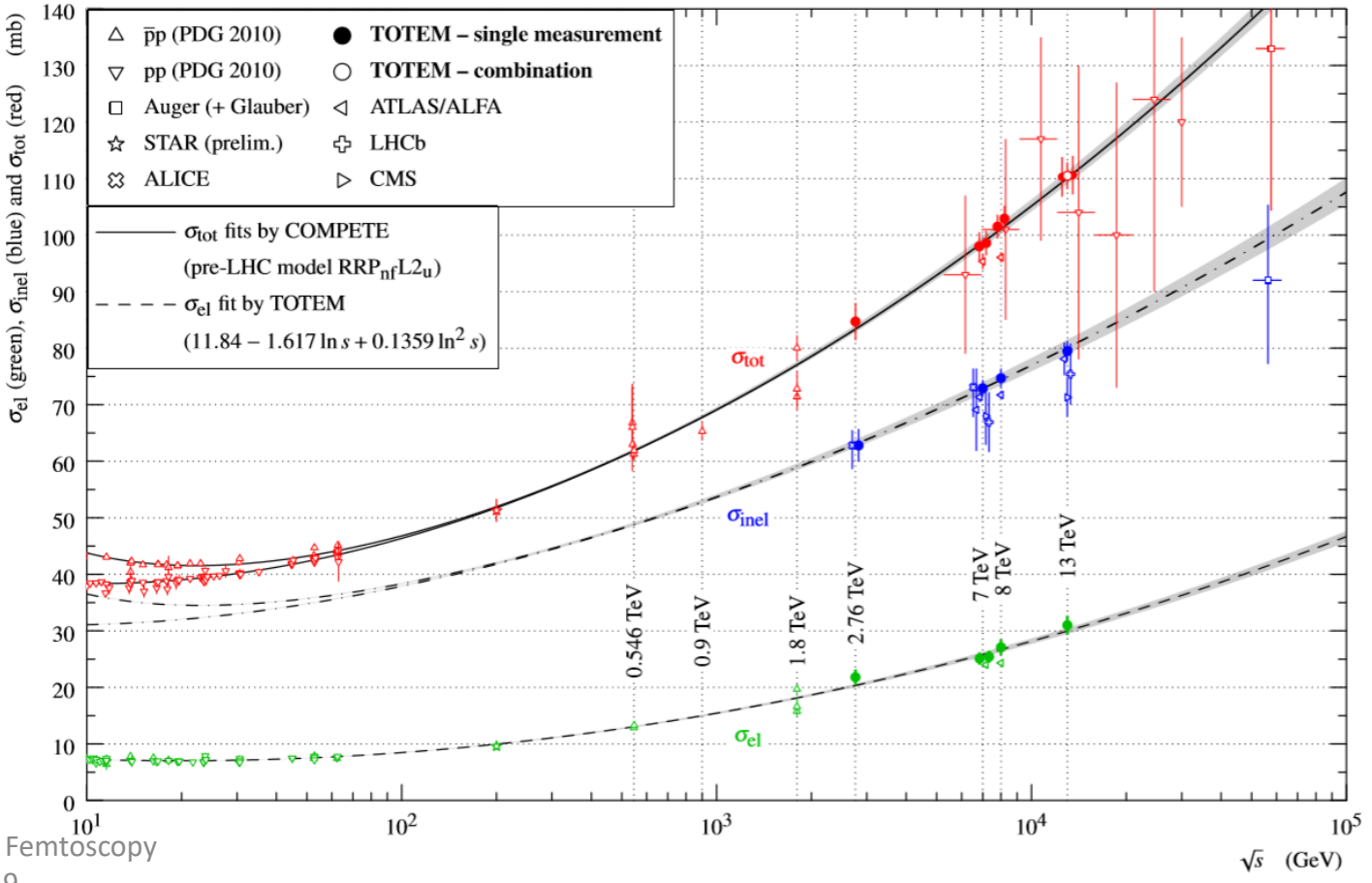






Total-cross section with Coulomb normalization

data	method	ρ	σ_{tot} [mb]
$\beta^* = 90\,m$	Ref. [6]	-	110.6 ± 3.4
$\beta^* = 2500\,m$	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 $2500\,m$	Ref. [6] $\oplus$ approach 3		110.5 ± 2.4



Differential cross-section measurement at $\sqrt{s}$ = 13 TeV

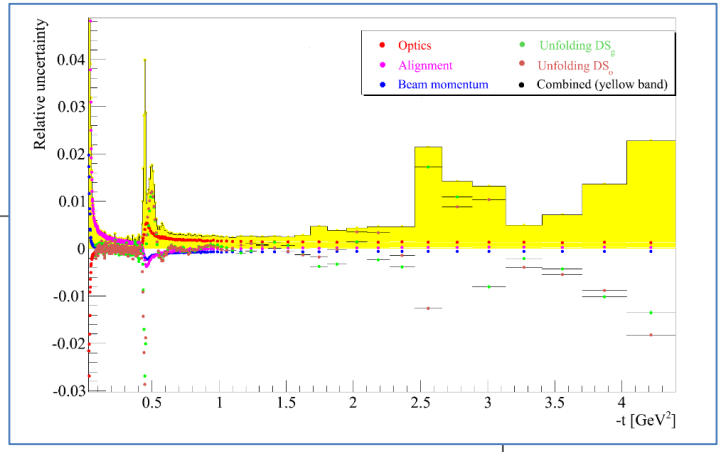
Published in Eur. Phys. J. C (2019)

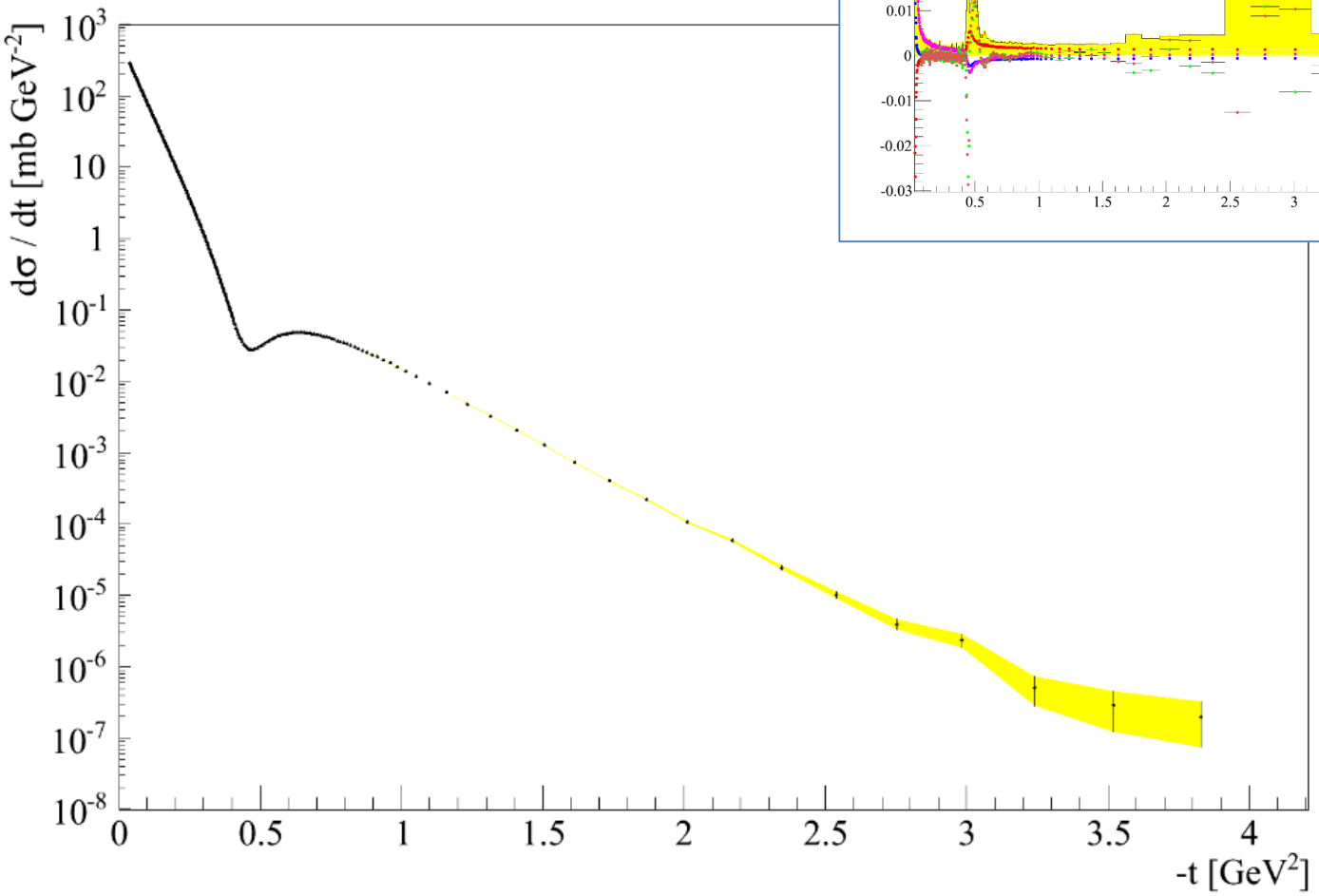
$\beta^* = 90$ m, $10\sigma_{RP}$ RP distance from LHC beam

Elastic differential cross-section

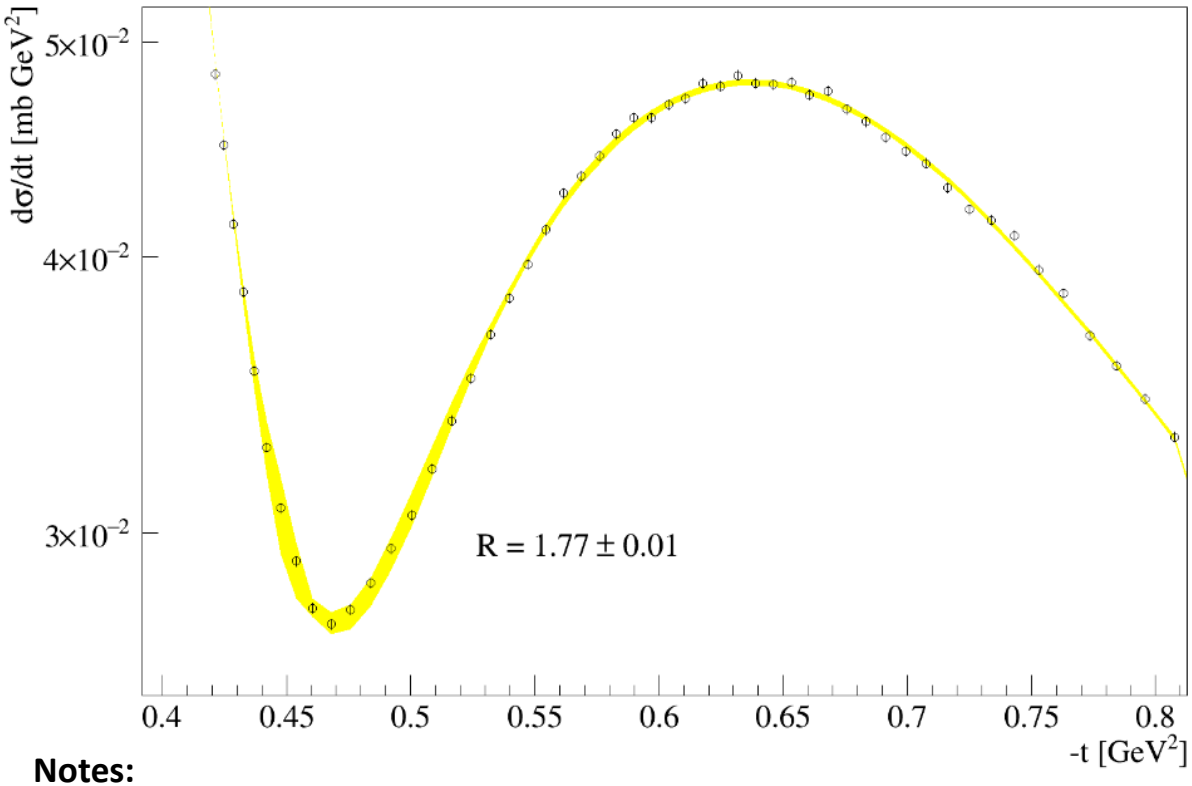
Note:

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

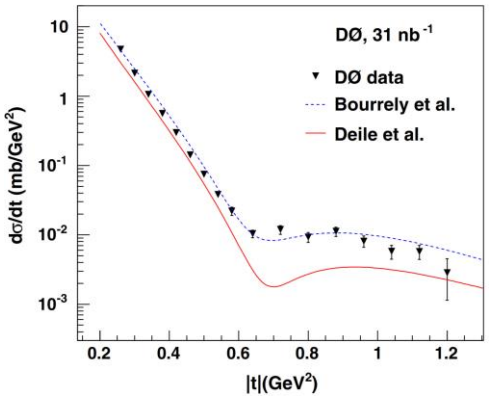




The diffractive minimum



ppbar $\sqrt{s}$ = 1.96 TeV

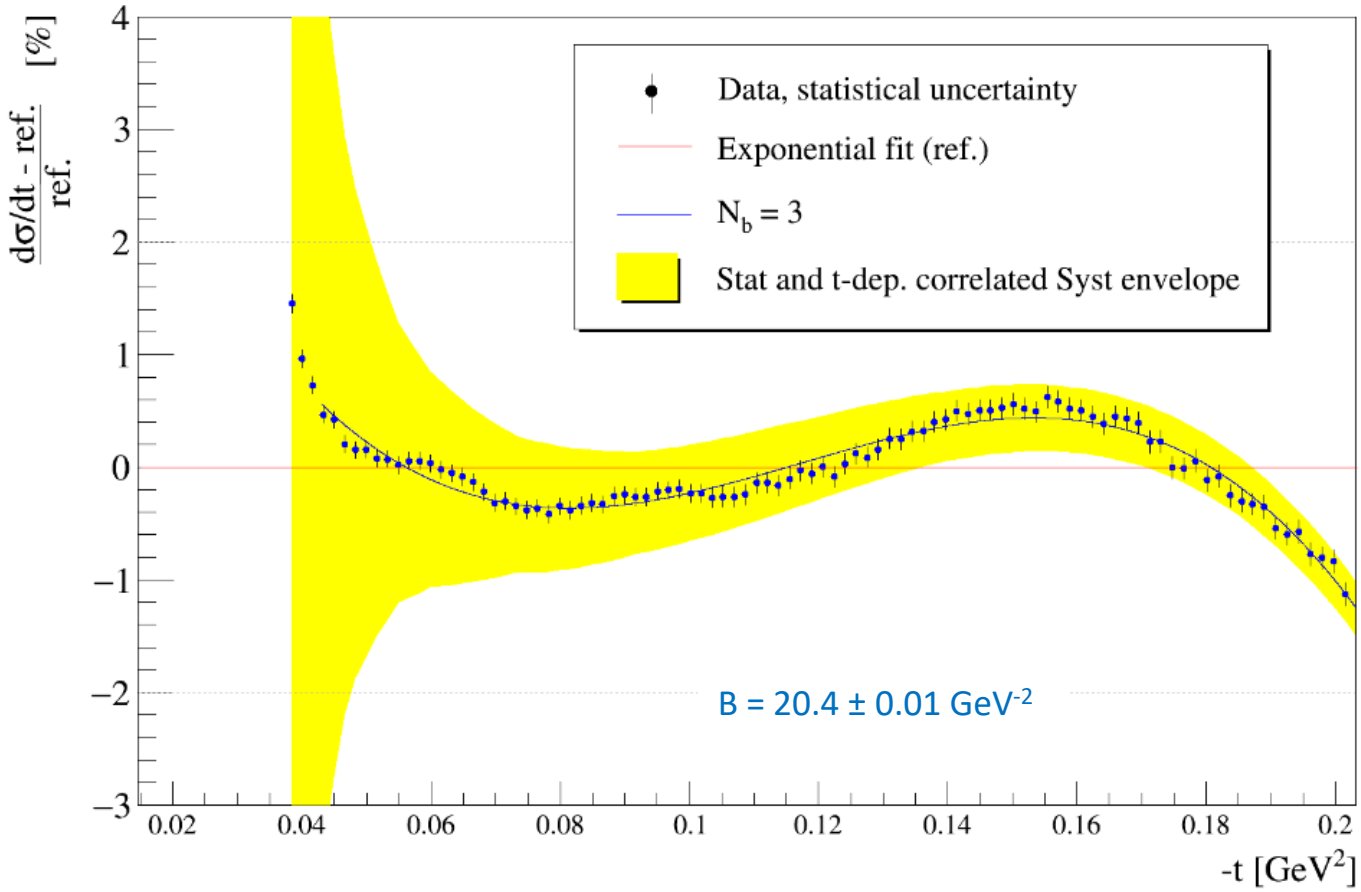


Notes:

- 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

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



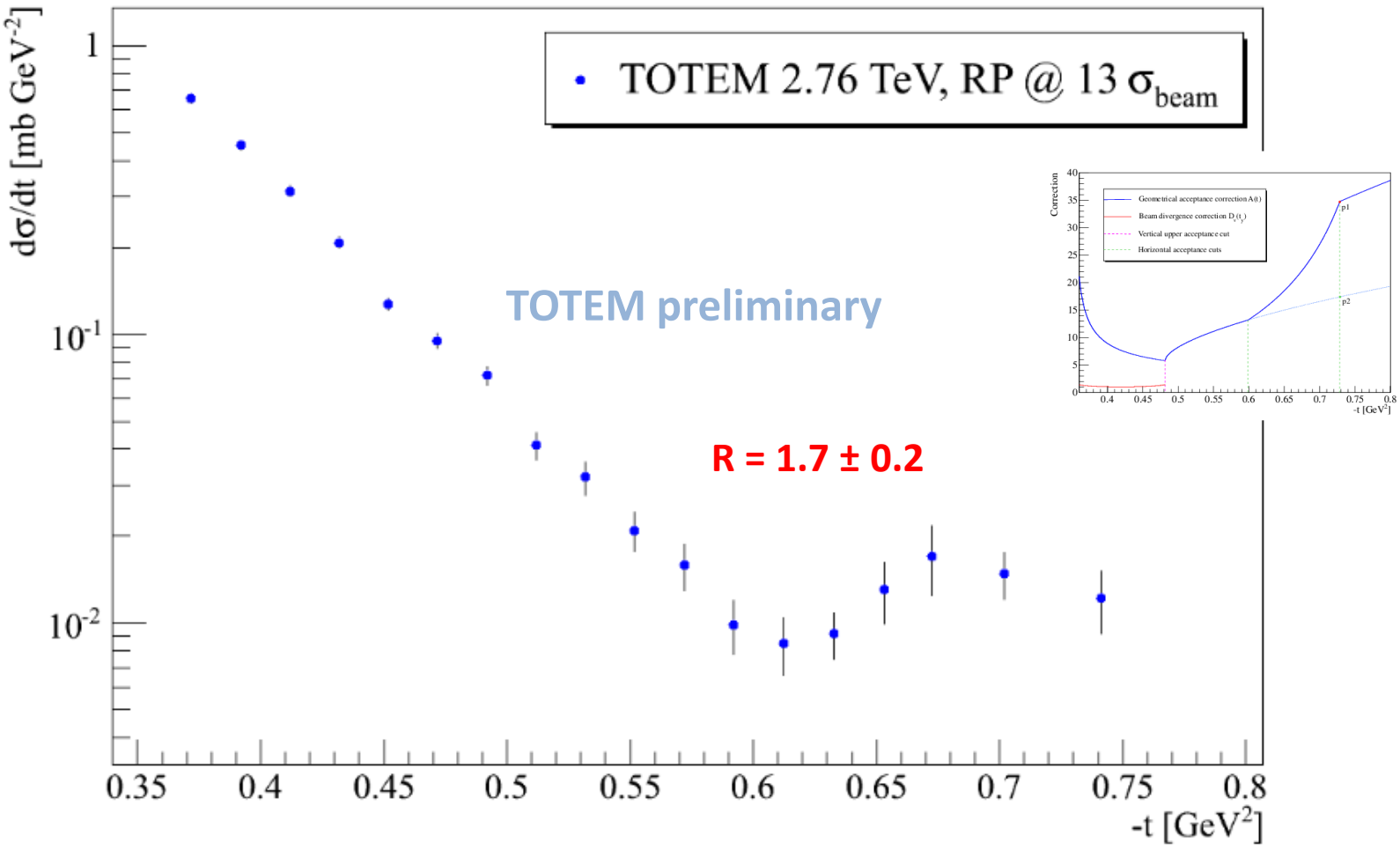
Dip measurement √s = 2.76 TeV

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

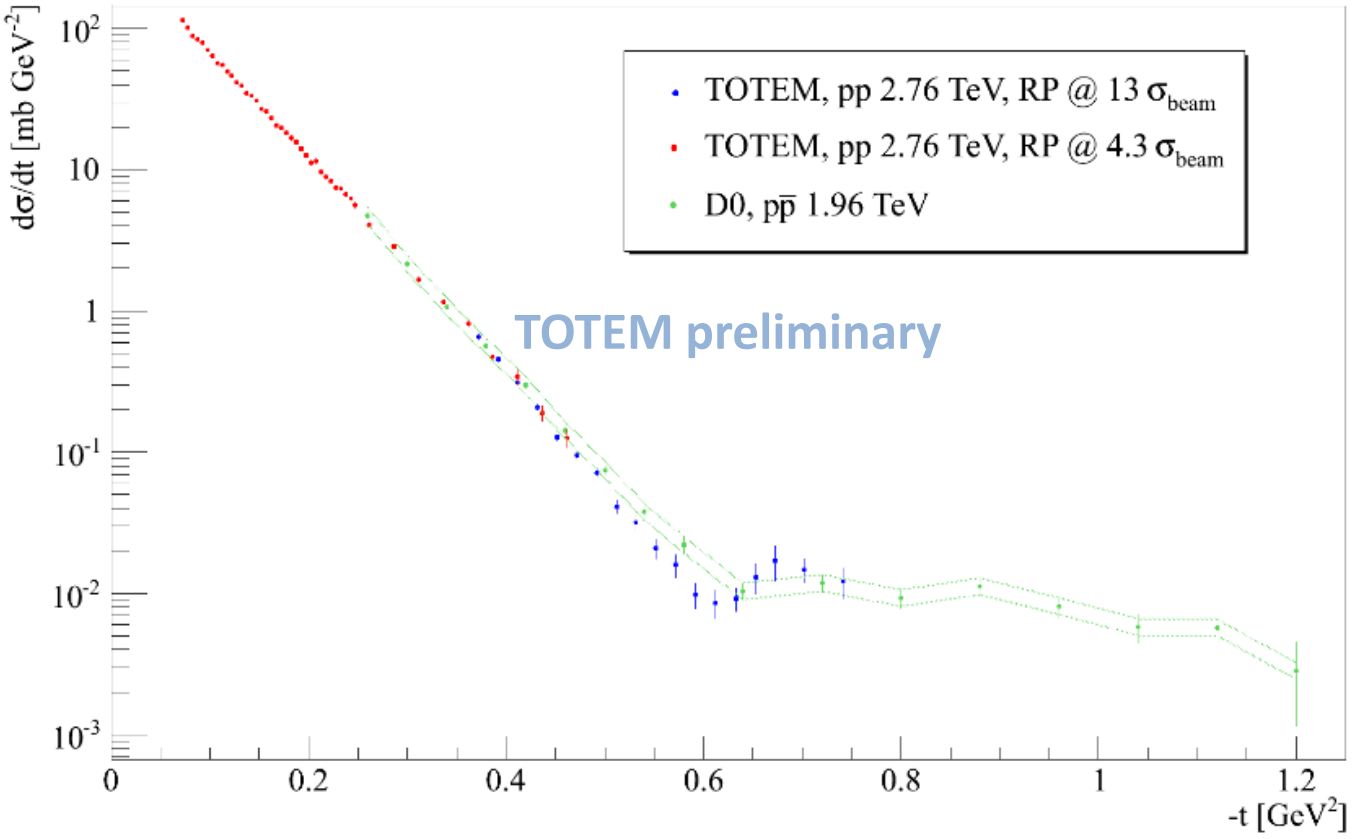
The diffractive minimum at √s = 2.76 TeV



Comparison 2.76 TeV pp and D0 ppbar at 1.96 TeV

Note:

- "Neglecting the small energy difference in √s between the measurements of the TOTEM and D0 collaborations, the results provide evidence for a colourless C-odd 3-gluon compound state exchange in the t-channel of proton-proton elastic scattering"

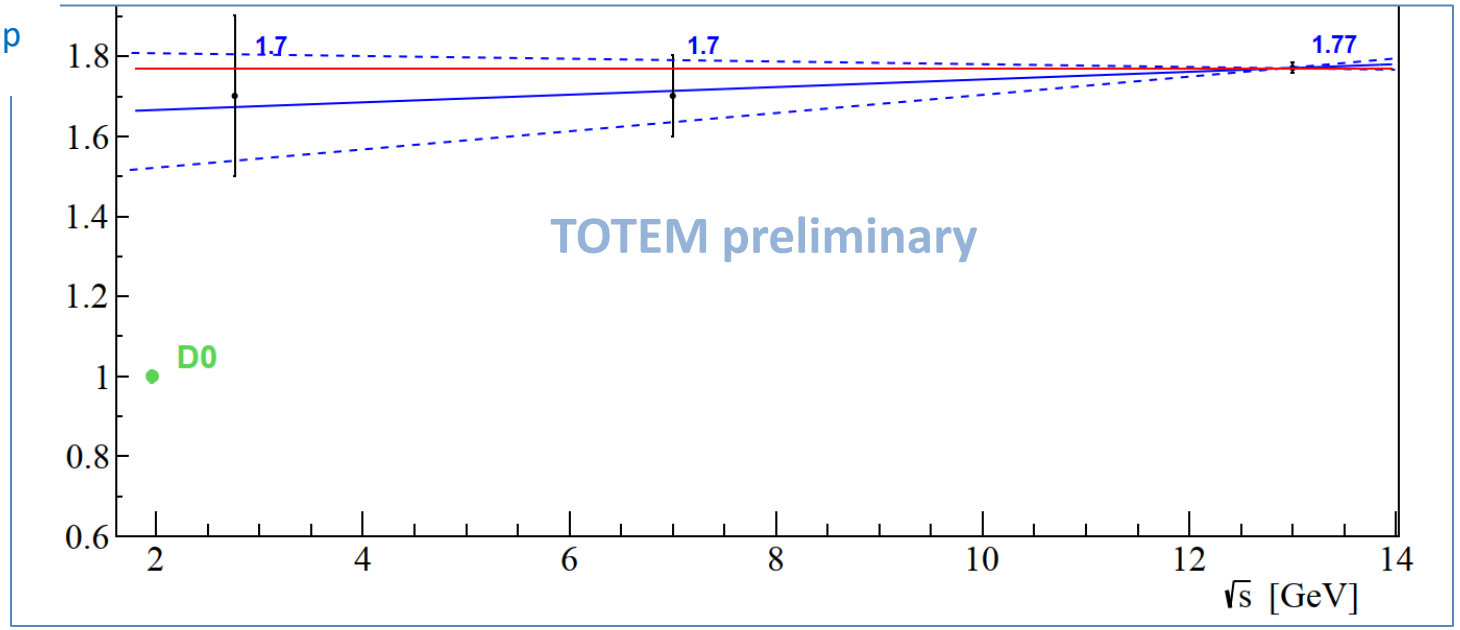


Comparison 2.76 TeV pp and D0 ppbar at 1.96 TeV

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)
- Neglecting the small energy difference in √s between the measurements of the TOTEM and D0 collaborations, the results provide evidence for a colourless C-odd 3-gluon compound state exchange in the t-channel of proton-proton elastic scattering

R = max / dip



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 !