TOTEM results

Frigyes NEMES on behalf of the TOTEM experiment
CERN*

Low-x 2021

La Biodola, Isola d'Elba, Italy

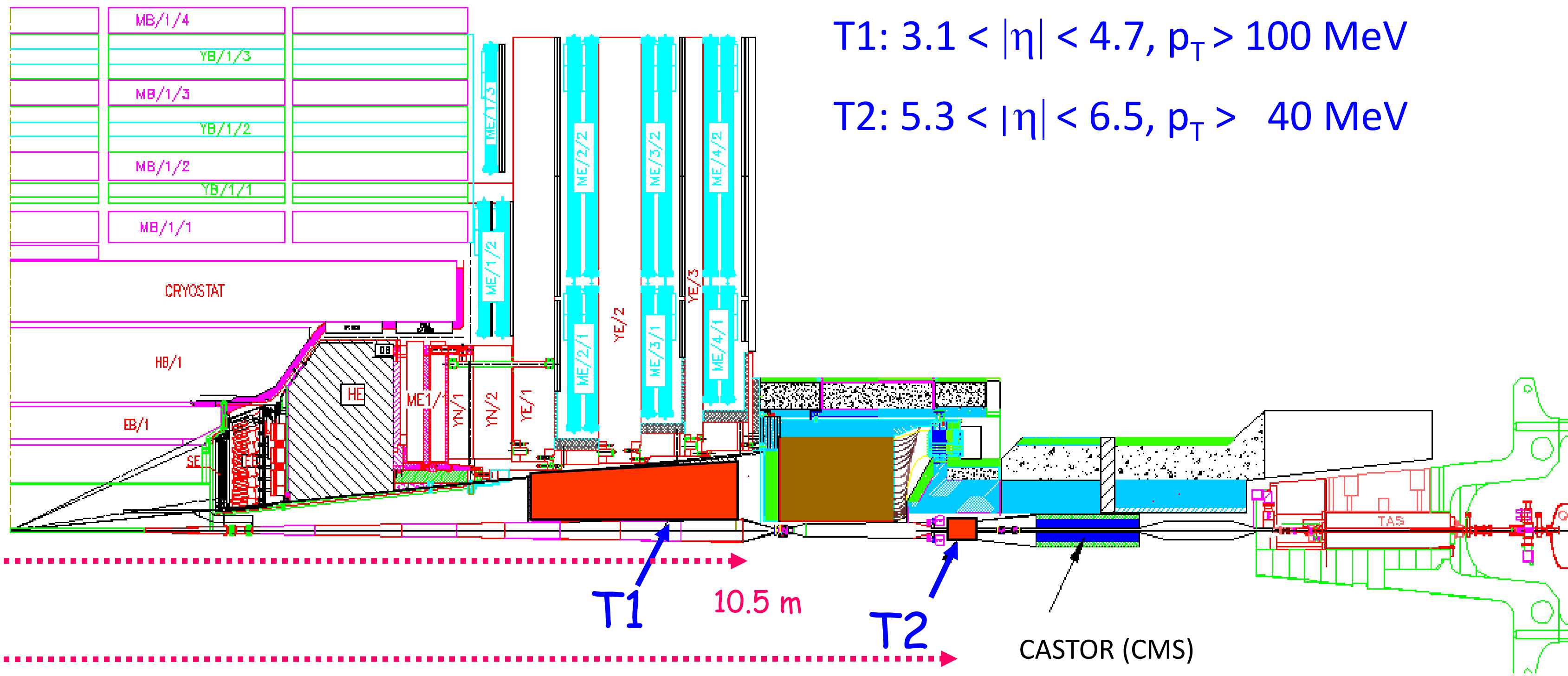
September 26. – October 1, 2021

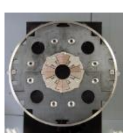
***Also at Wigner RCP, Budapest, Hungary**
MATE, Gödöllő - Gyöngyös

Experimental layout & LHC optics (LHC Run II)

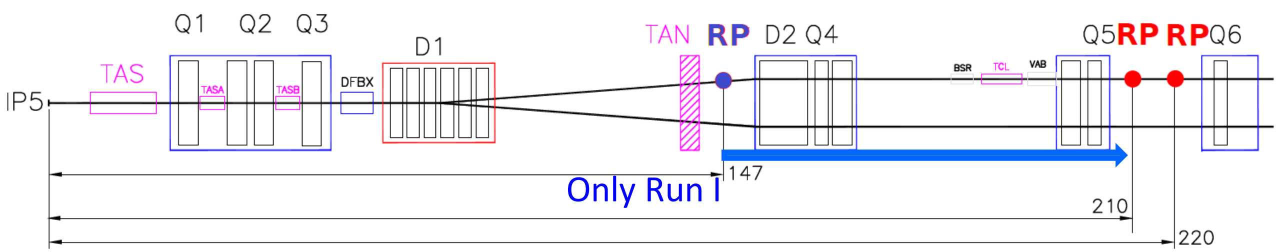
T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

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





MQXA quadrupole



Measured

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

Transport matrix

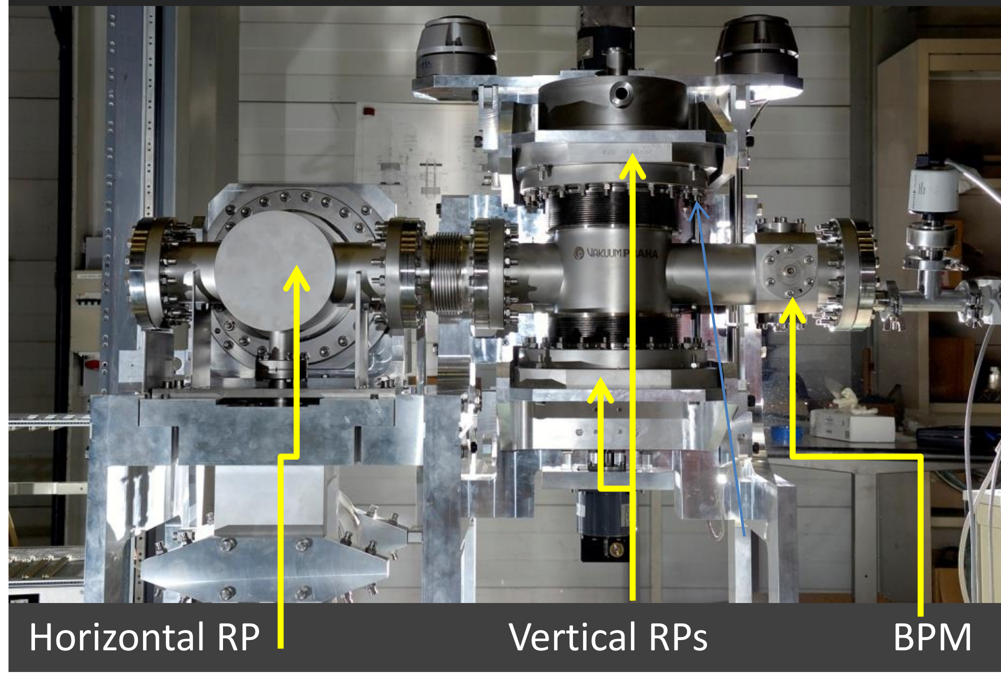
LHC optics (see backup sl.)

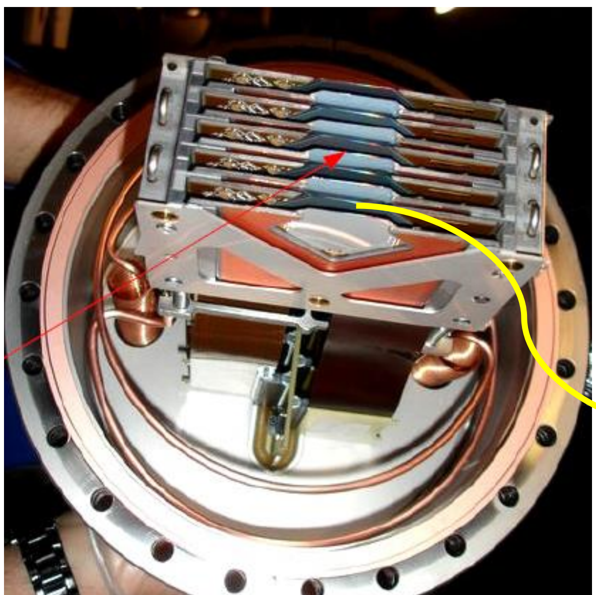
The Roman Pot (RP) stations of the TOTEM experiment

RP stations:

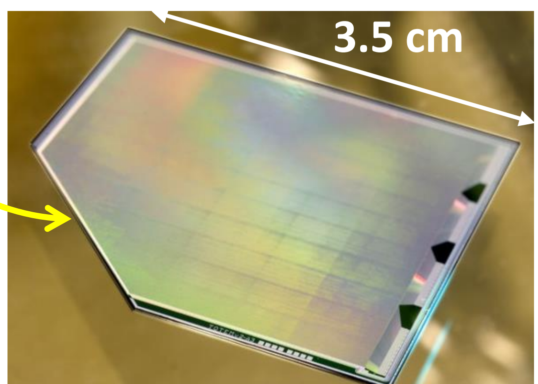
- 2 units (**N**ear, **F**ar) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few μrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 μm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

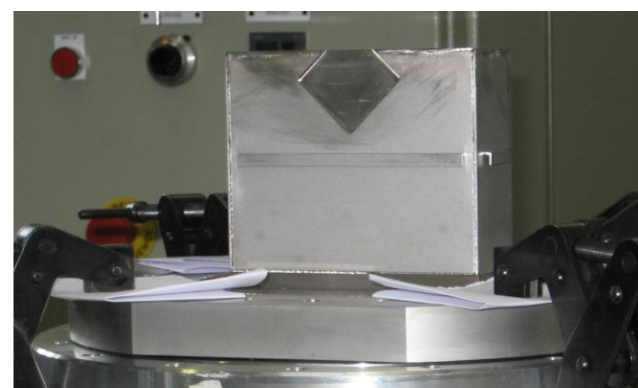




10 planes of edgeless detectors



Si edgeless detector



1 Roman Pot

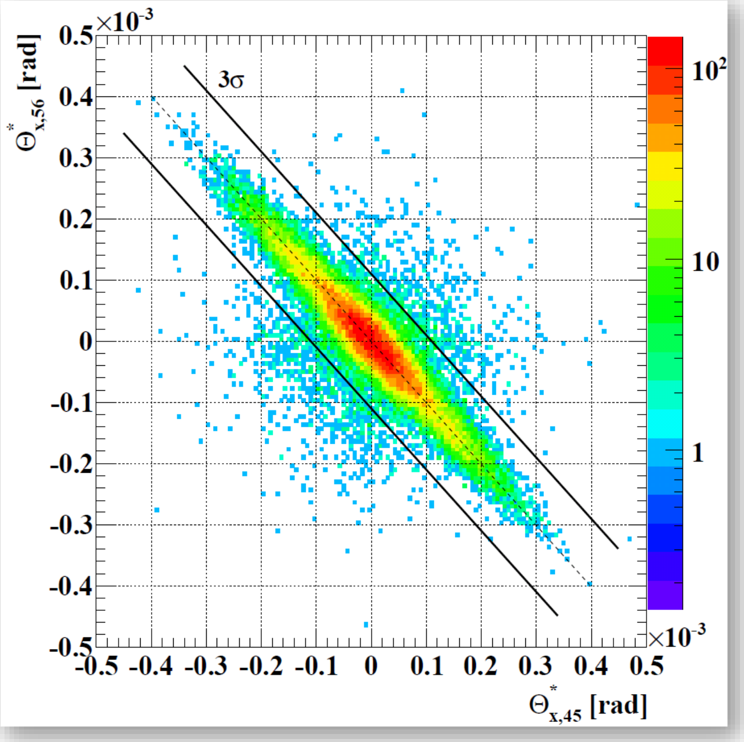
1^{st} TOTEM measurement at $\sqrt{s} = 7$ TeV

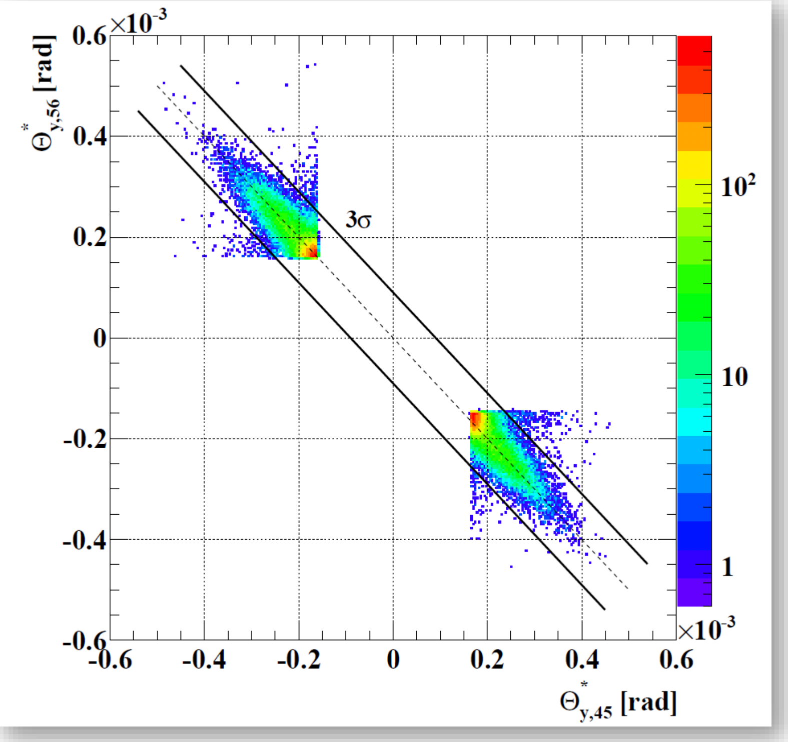
- **β* = 3.5 m LHC optics**
- **Horizontal and vertical scattering angles:**

$$\theta_x^* = \frac{1}{\frac{dL_x}{ds}} \left(\theta_x - \frac{dv_x}{ds} x^* \right), \; \theta_y^* = \frac{y}{L_y}$$

Momentum conservation is required in elastic events:

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

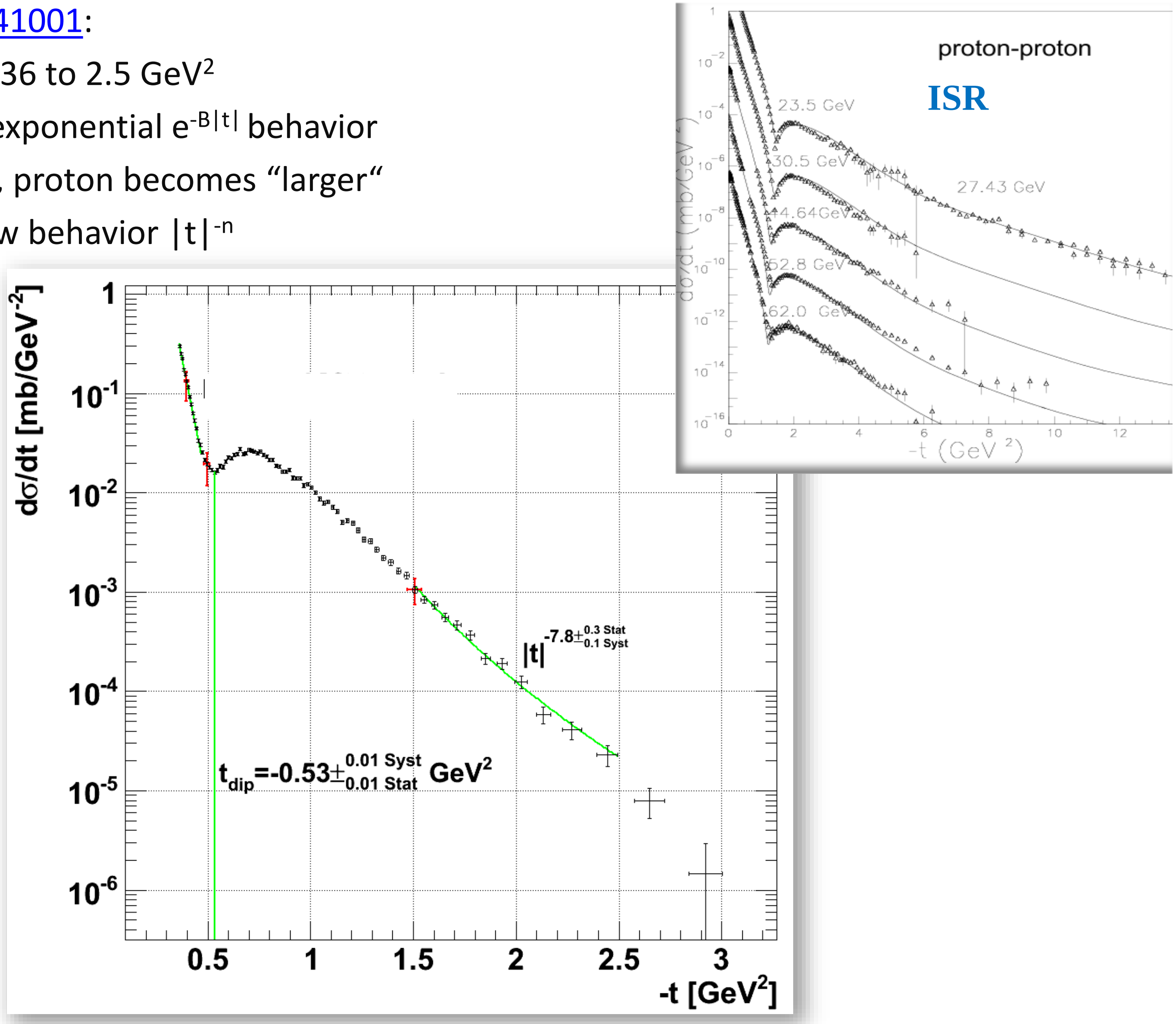




The elastic dσ/dt distribution at $\sqrt{s}$ = 7 TeV

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-sections measurement at $\sqrt{s}$ = 13 TeV

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

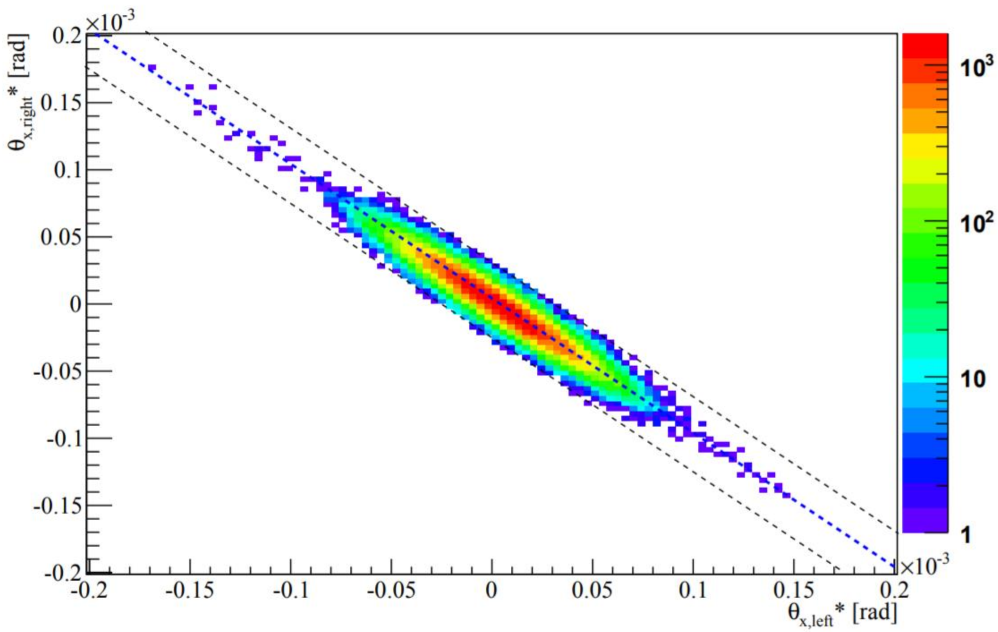
β^* = 90 m, 5σ_{RP} RP distance from beam

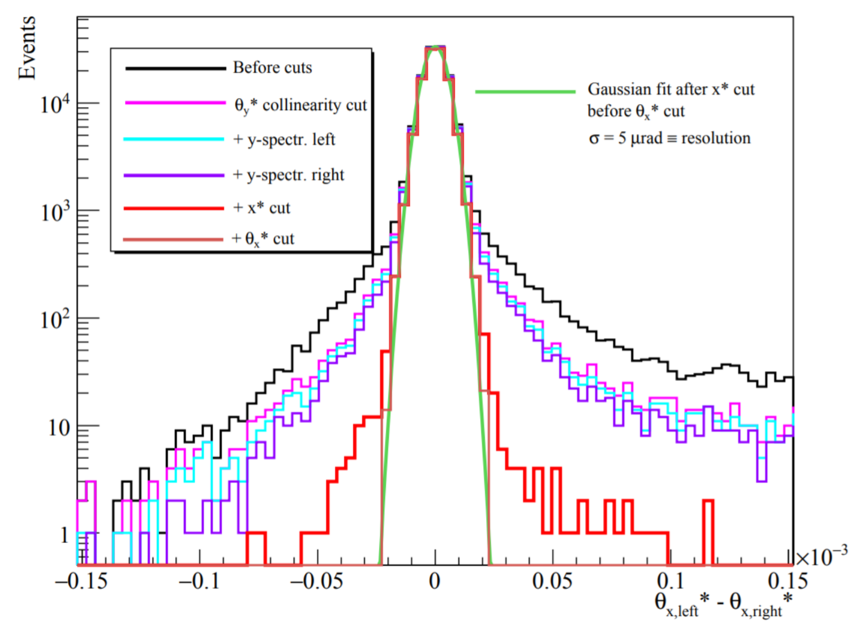
List of TOTEM publications

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

Elastic signal selection at 13 TeV

- Collinearity cut in the horizontal plane
- Optics matching → kinematics reconstruction uncertainty ~ 2 permil
- Elastic signal selection: clean sample after coll., spectrometer and vertex cuts
- Discriminator: compatibility with beam divergence required

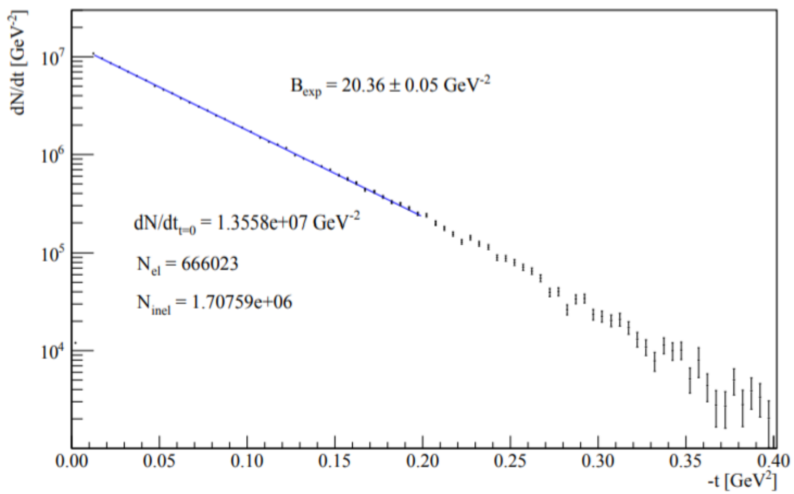




Luminosity independent measurement at 13 TeV

Ingredients:

- Elastic rate as a function of |t| to determine the optical point OP
- N_{inel} is measured with the T2 inelastic telescope
- Cross-sections with ρ = 0.1 from TOTEM ρ measurement (see upcoming slides)



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

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

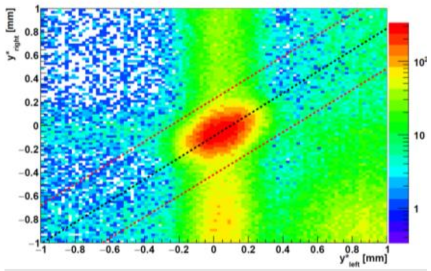
σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
110.6 ± 3.4	31.0 ± 1.7	79.5 ± 1.8

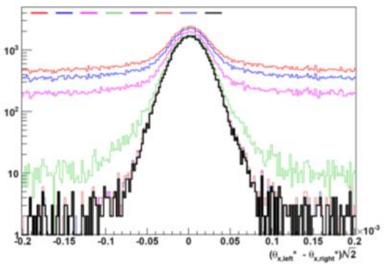
Cross-section measurement at $\sqrt{s}$ = 2.76 TeV

Manuscript in preparation

β^* = 11 m, 4.3 σ_{RP} RP distance from beam

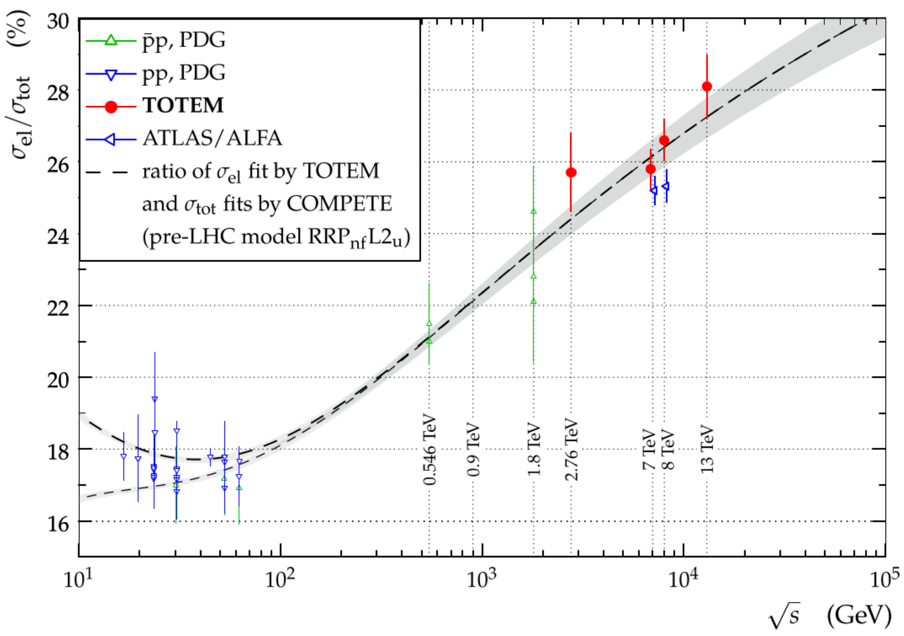
2.76 TeV luminosity independent cross-sections (β* = 11 m optics)

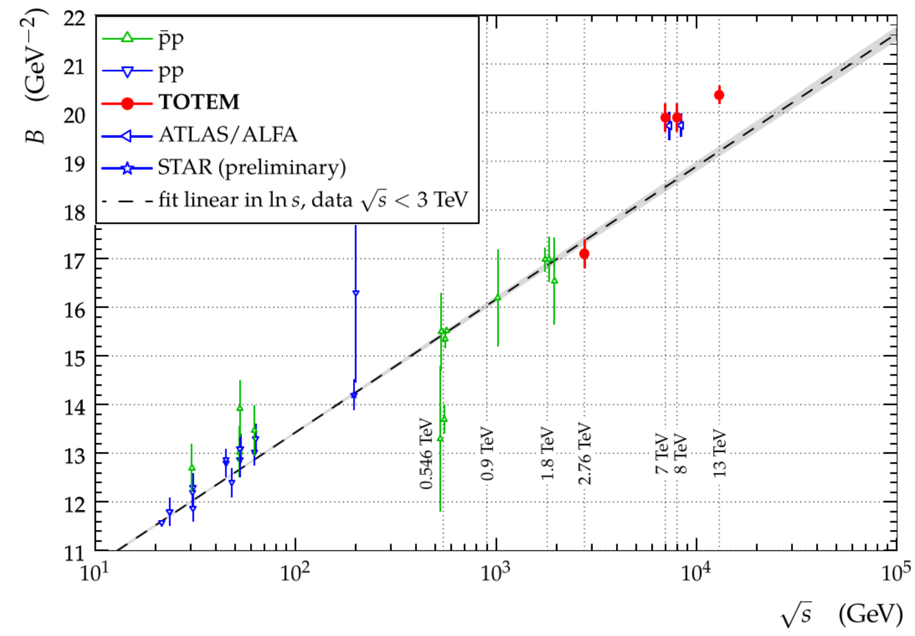




σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
84.7 ± 3.3	21.8 ± 1.4	62.8 ± 2.9

- Elastic to total cross-section ratio
- The nuclear slope as a function of √s
- The deviation for √s > 3 TeV from the linear extrapolation is highly significant





ρ measurement at $\sqrt{s}$ = 13 TeV

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

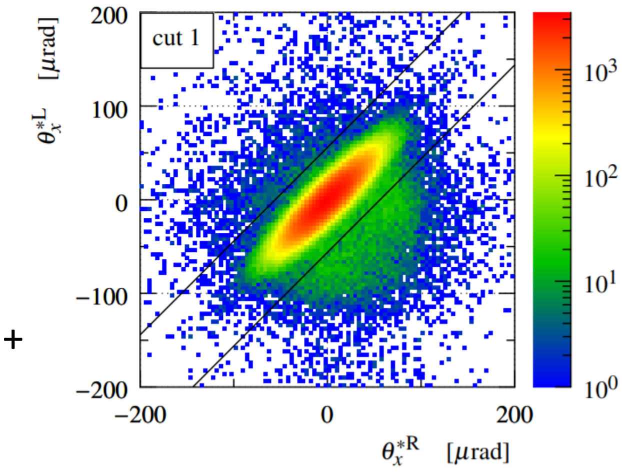
[Published in Eur. Phys. J. C (2019)]

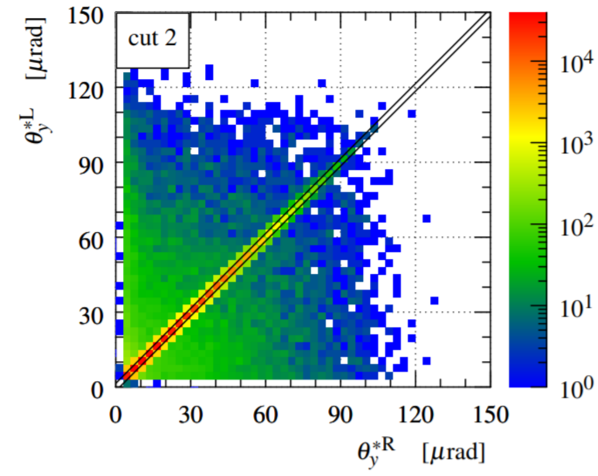
β^* = 2500 m

Coulomb-nuclear interference: the ρ parameter

Basic properties of the data:

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





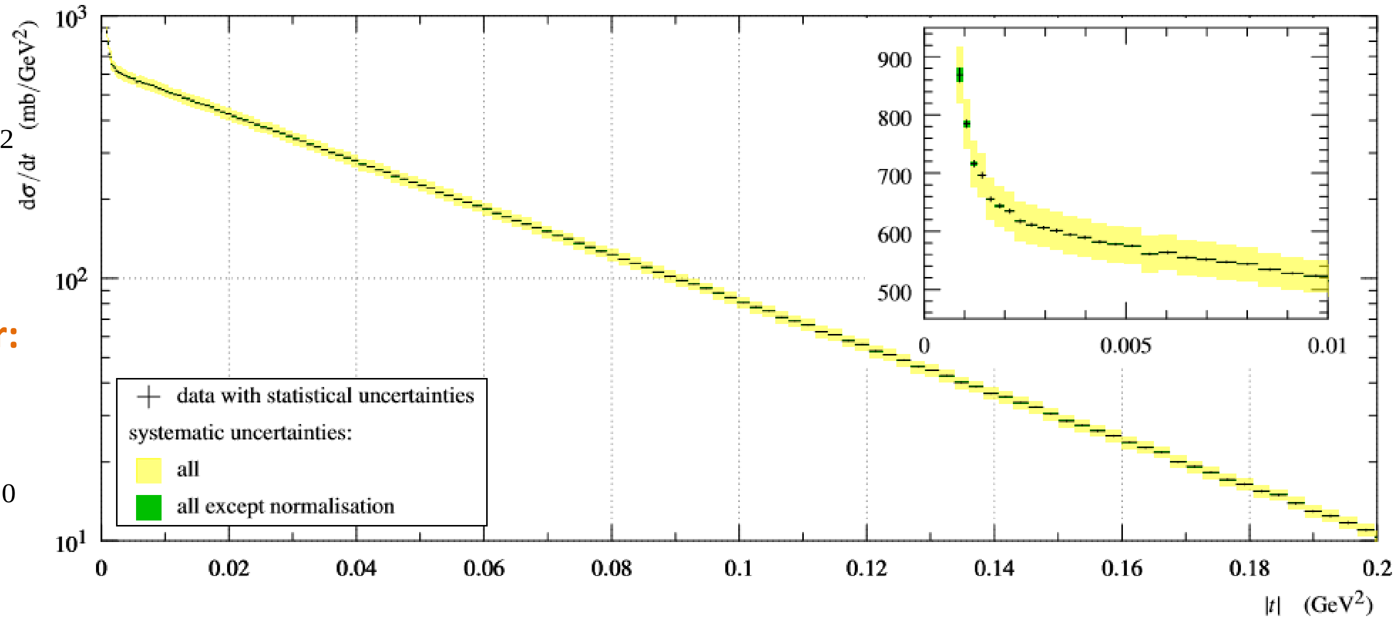
Analysis aims:

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

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

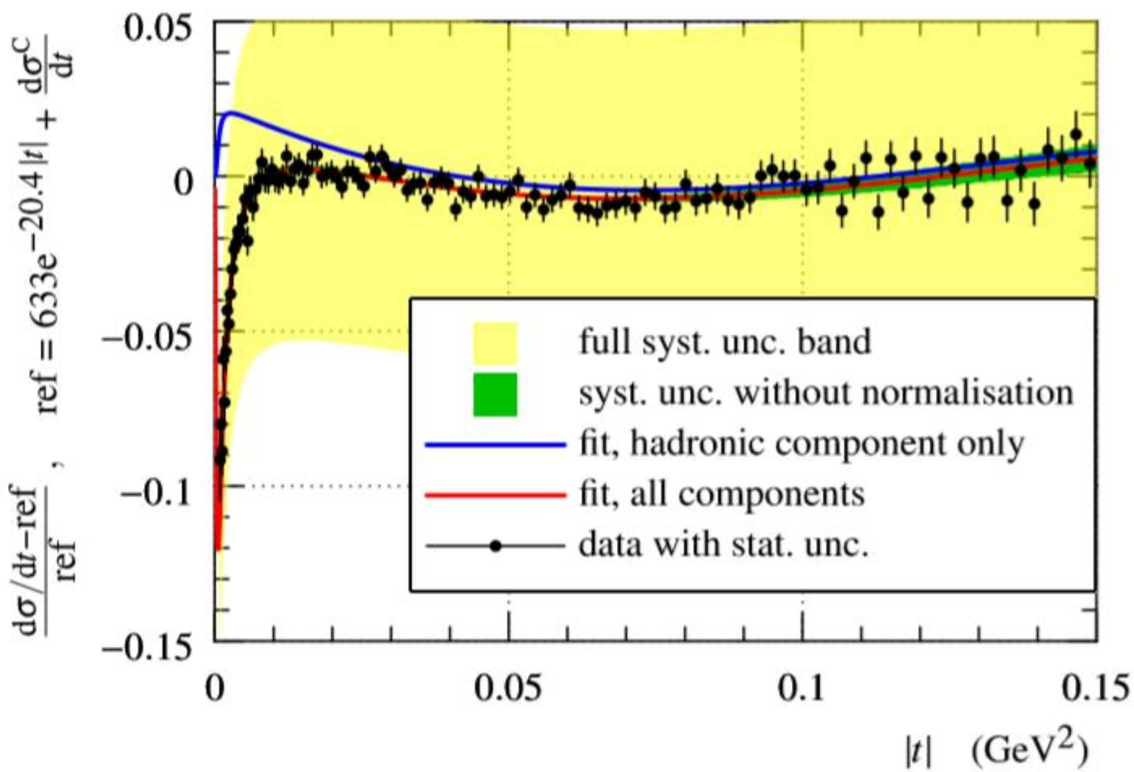
- **The ρ parameter:**

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

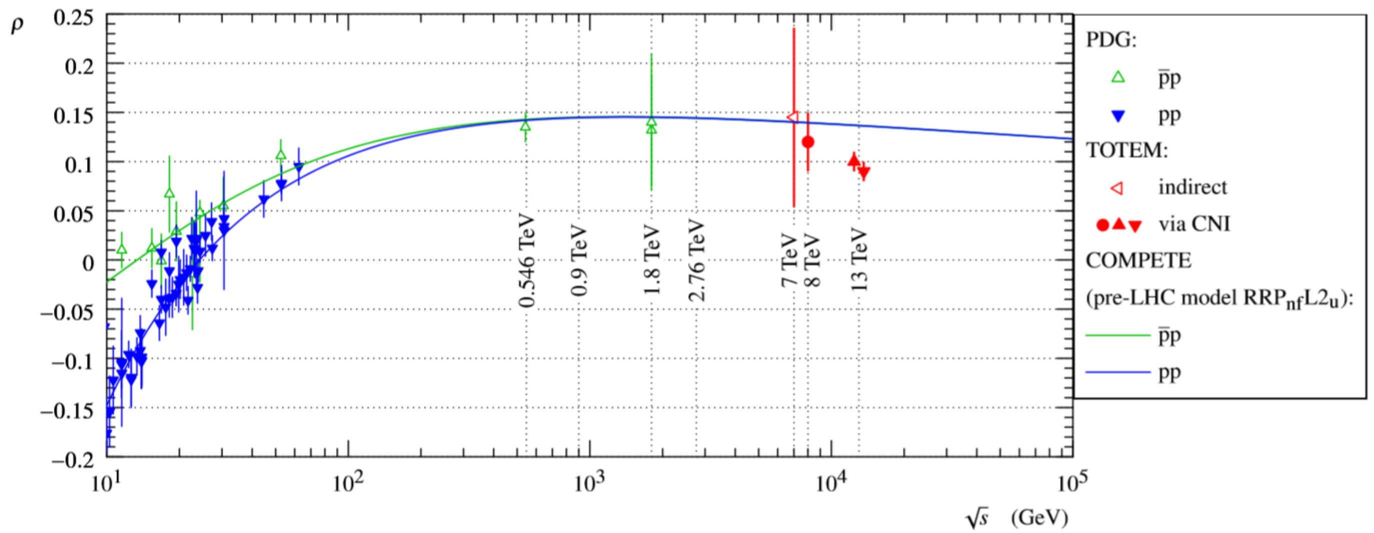


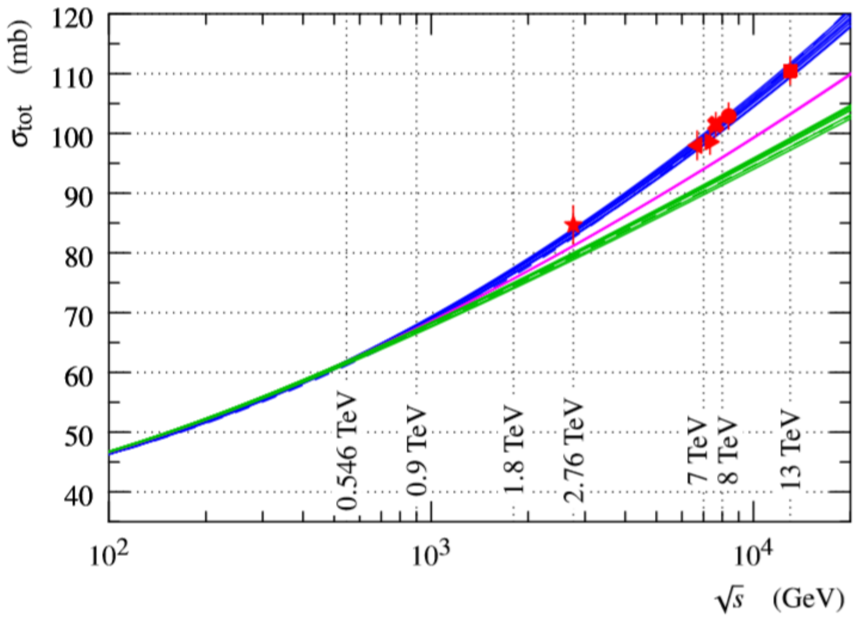
Interference in details and ρ measurements

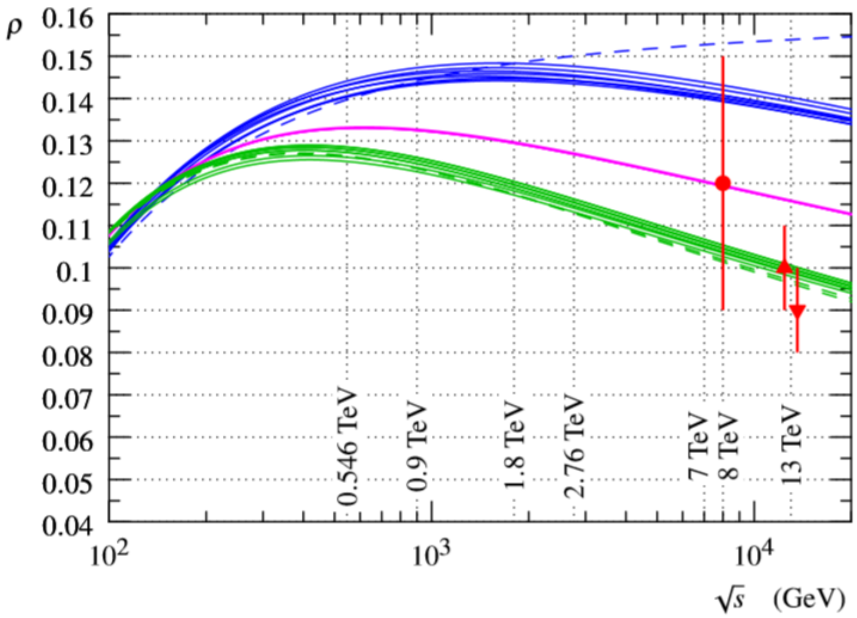
N_b	χ^2/ndf ($\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$)	ρ ($\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$)	σ_{tot} [mb] ($\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$)	χ^2/ndf ($\lvert t\rvert_{max} = 0.15\,\mathrm{GeV}^2$)	ρ ($\lvert t\rvert_{max} = 0.15\,\mathrm{GeV}^2$)	σ_{tot} [mb] ($\lvert t\rvert_{max} = 0.15\,\mathrm{GeV}^2$)
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



ρ as a function of √s: evidence for Odderon exhange



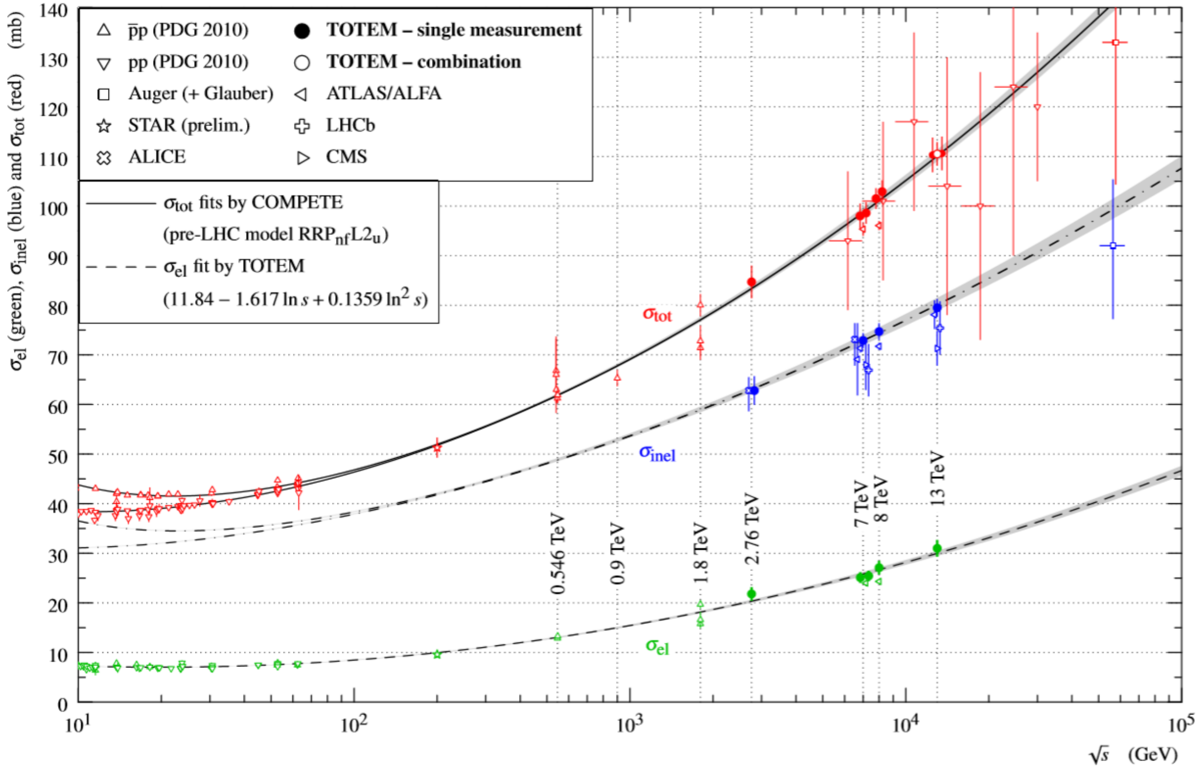




Total-cross sections & Coulomb normalization

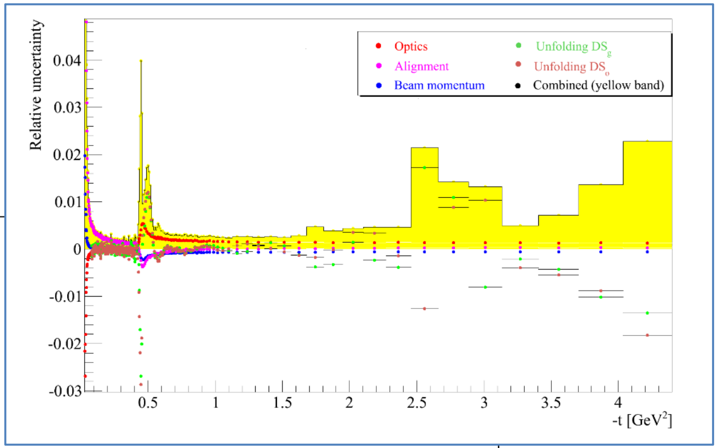
Notes:

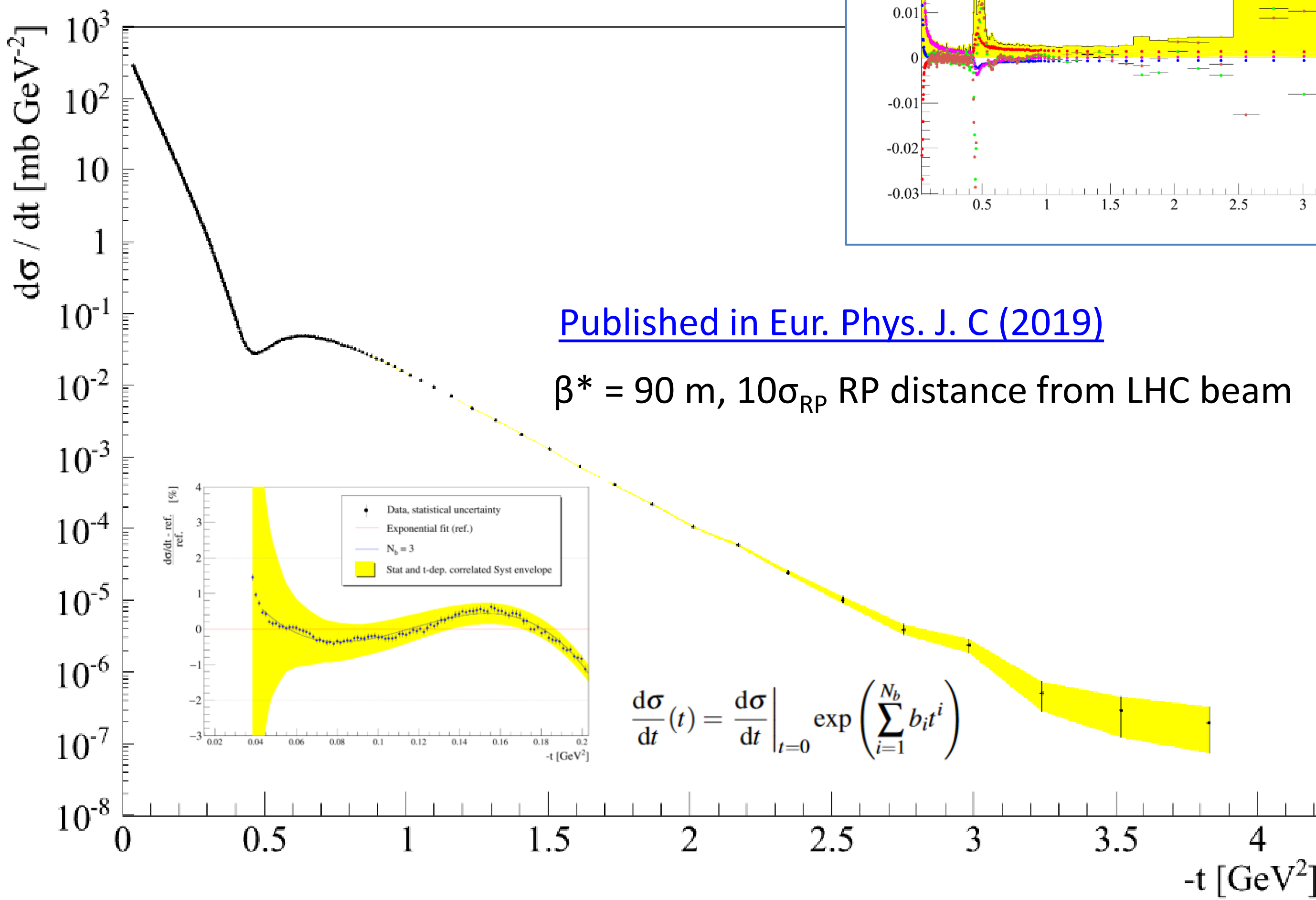
- Lumi-independent σ_{tot} from β^* = 90 m: 110. 6 ± 3.4 mb
- ρ from β^* = 2.5 km, lumi-independent normalization: 0.09 ± 0.01
- ρ from β^* = 2.5 km, Coulomb normalization: 0.08(5) ± 0.01
- σ_{tot} from β^* = 2.5 km, Coulomb normalization: 110.3 ± 3.5 mb
- Combined lumi-independent and Coulomb normalization σ_{tot}: 110.5 ± 2.4 mb



Note: Differential cross-section measurement at 13 TeV

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



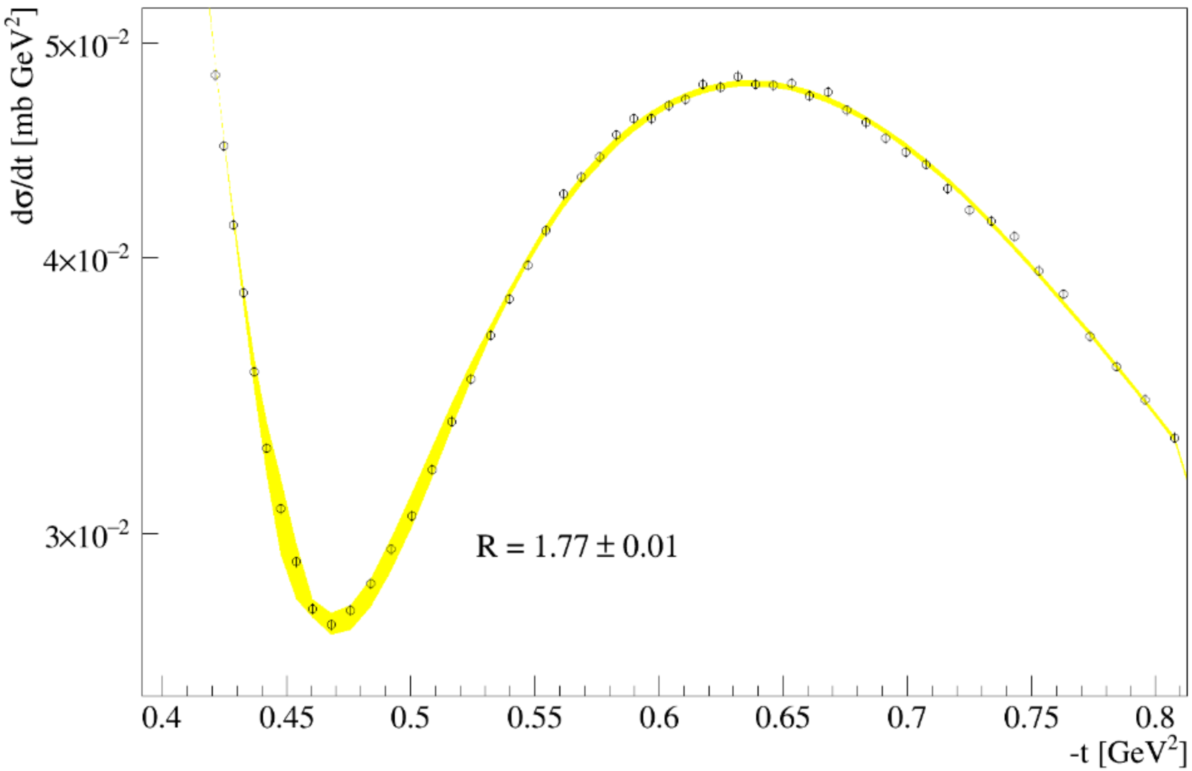


[Published in Eur. Phys. J. C (2019)]

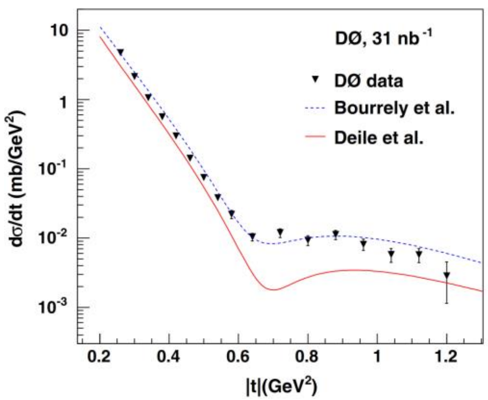
β^* = 90 m, $10\sigma_{RP}$ RP distance from LHC beam

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

The diffractive minimum at 13 TeV in details



ppbar √s = 1.96 TeV



- Result confirms with unprecedented precision at the TeV scale the dip structure (**R = max / dip**)
- Hadronic elastic @ TeV sqrt(s) dominated by t-channel exchange of colourless gluon states
- 2 (or even) gluon exchange (C = +): "Pomeron" (~ mostly imaginary) ⟹ pp vs ppbar invariance
- 3 (or odd) gluon exchange (C = -): "Odderon" (expected ~ real) ⟹ different sign for pp and ppbar
- 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

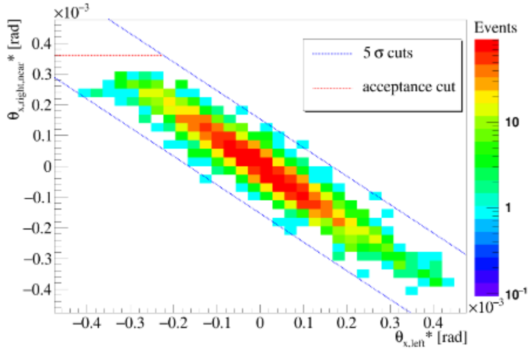
Differential cross –section measurement at √s = 2.76 TeV

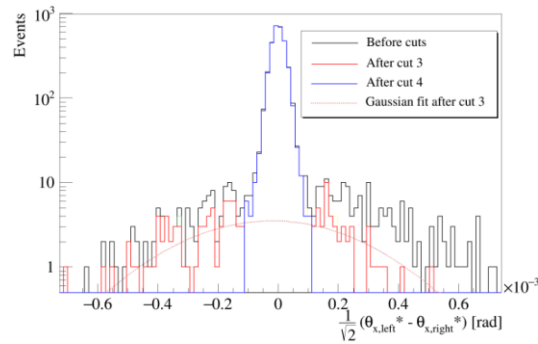
Implication on the existence of a colourless C-odd 3-gluon compound (Odderon at $t \neq 0$)

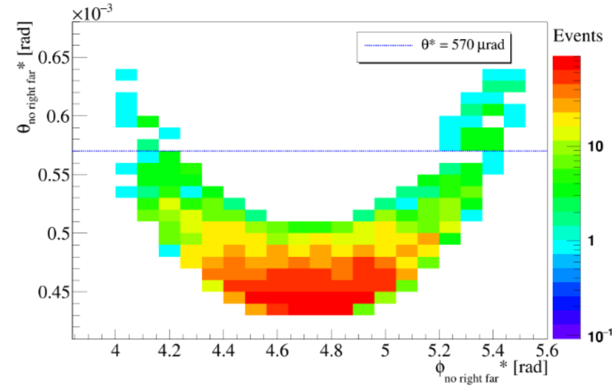
Published in Eur. Phys. J. C (2020)

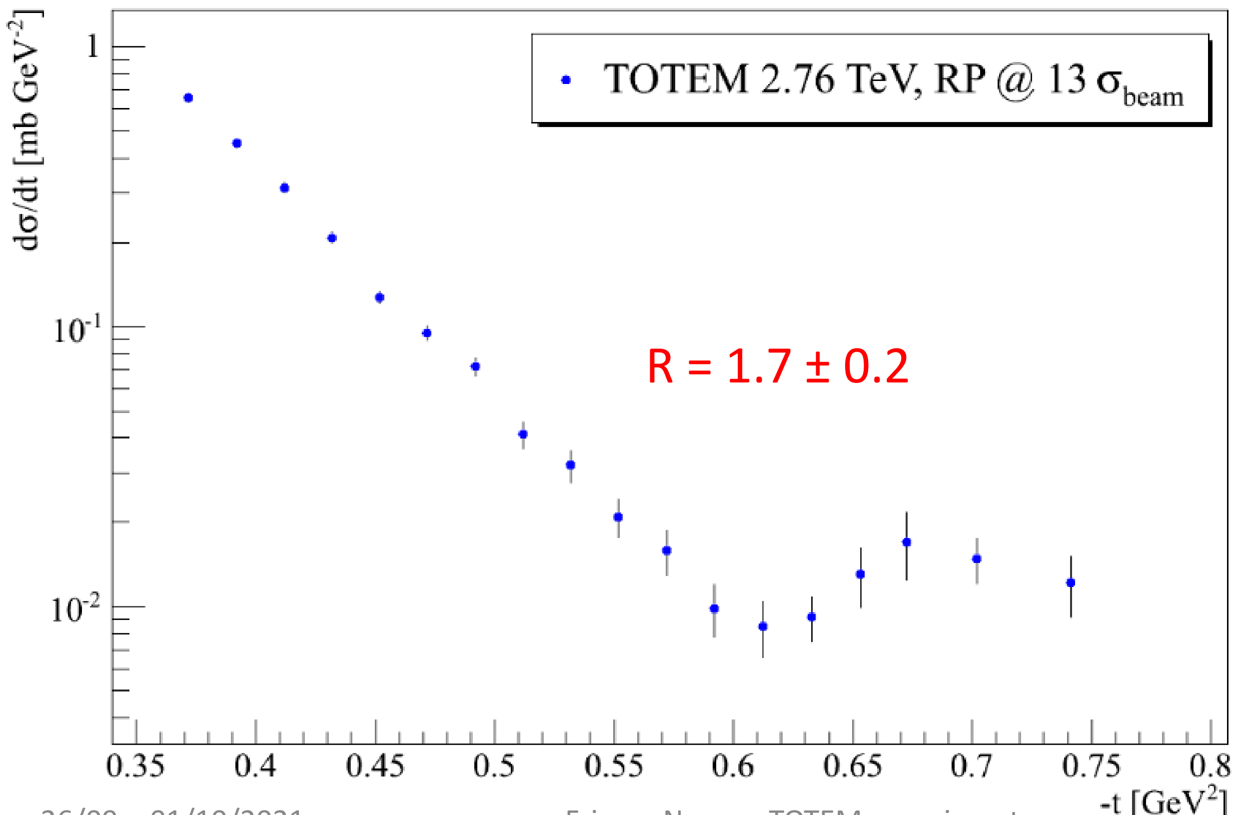
β^* = 11 m, 13 σ_{RP} RP distance from beam

The diffractive minimum at $\sqrt{s}$ = 2.76 TeV

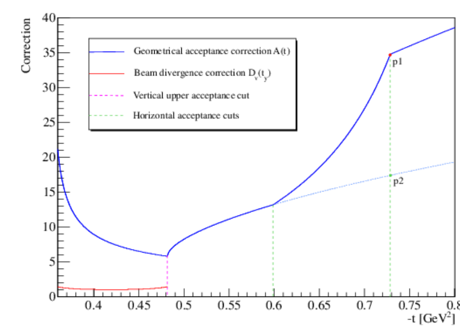








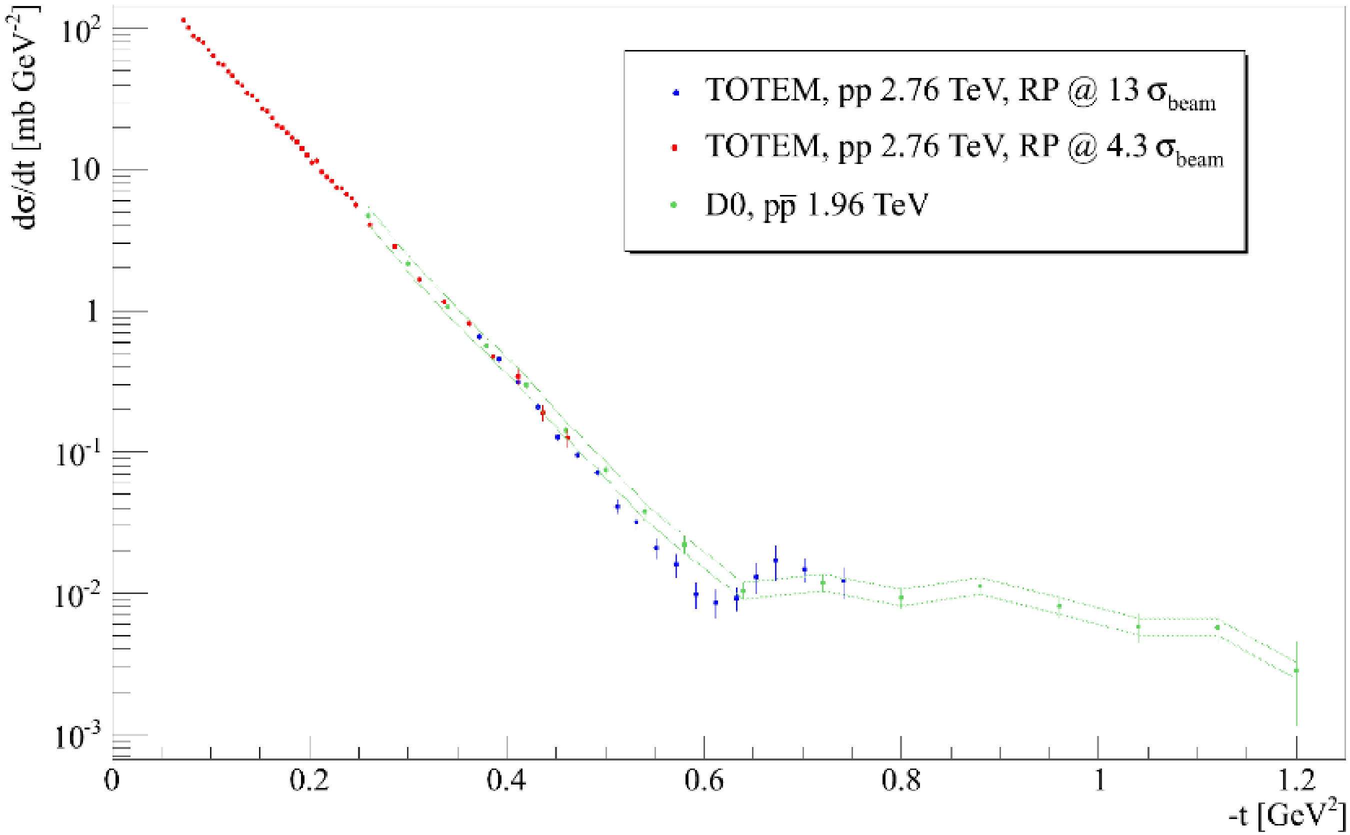
Acceptance correction



Comparison 2.76 TeV pp and D0 ppbar at 1.96 TeV

Note:

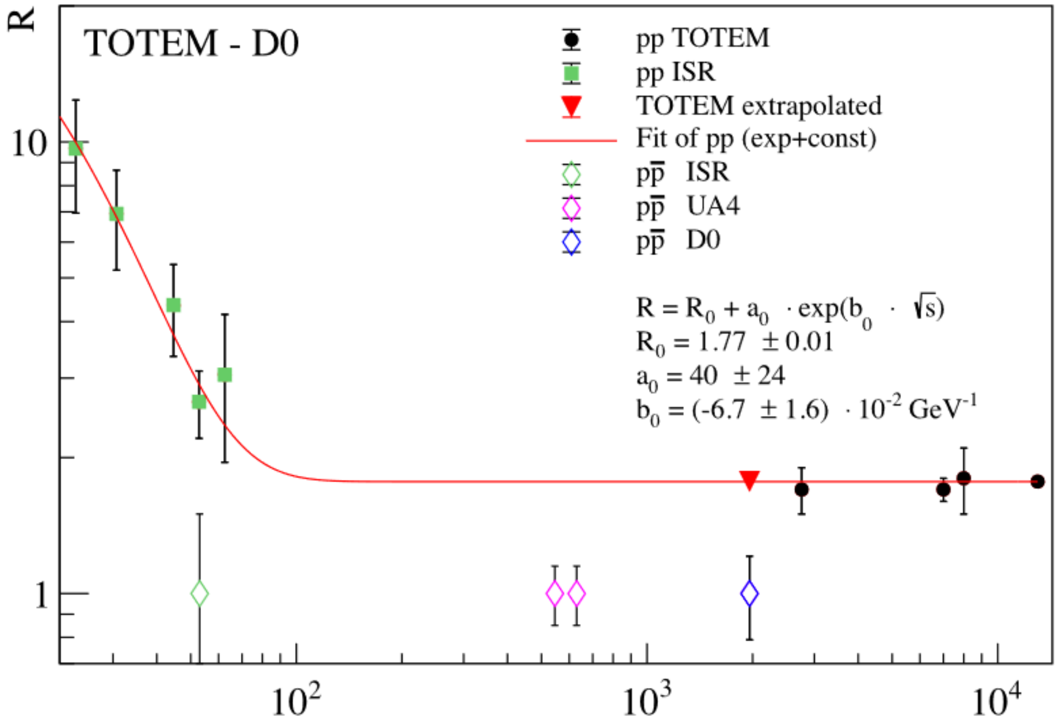
- "Neglecting the small energy difference in √s between the measurements of the TOTEM and D0 collaborations, the results provide evidence for a colourless C-odd 3-gluon compound exchange in the t-channel of proton-proton elastic scattering"



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** have been evaluated in close collaboration with D0: paper is published, see presentation from D0 and TOTEM



Summary & Outlook

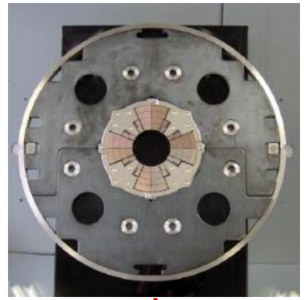
- 7 TeV first measurement of dip in pp at TeV scale
- 13 TeV total cross-section measurement
- 13 TeV ρ measurement
  - Coulomb normalization leading to independent total cross-section measurement
  - **Evidence** for t-channel exchange of colourless C-odd 3g compound (odderon)
- 13 TeV differential 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 (manuscript in preparation)
  - Change of $\sqrt{s}$ behaviour of slope parameter B at around 3 TeV
- 2.76 TeV, differential cross-section measurement
  - Confirming the dip in pp close in energy to the D0 ppbar data without dip
  - Neglecting energy difference, provides **evidence** for colourless C-odd 3g compound (odderon)

Thank you for your attention !

Backup slides

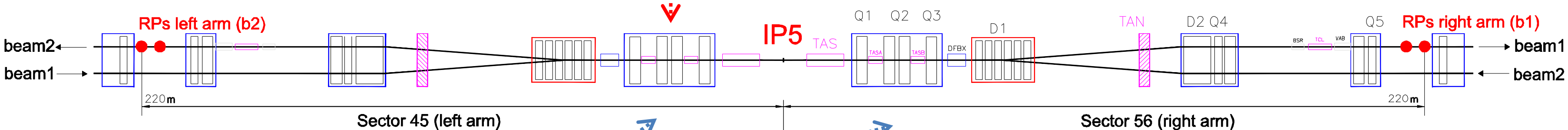
LHC optics around IP5

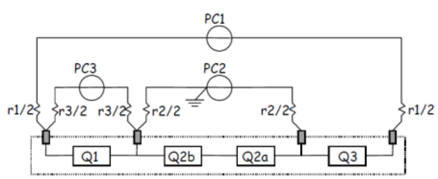
Schematic layout of the magnet lattice at IP5:



MQXA quadrupole

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





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.

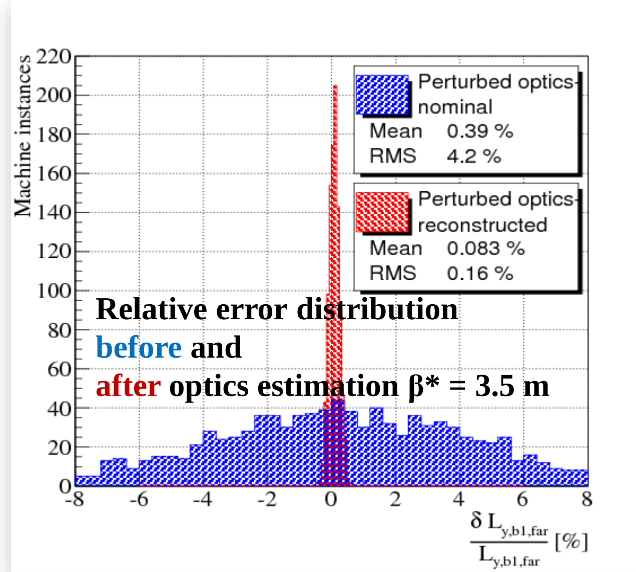
Note on proton kinematics reconstruction & optics imperfections

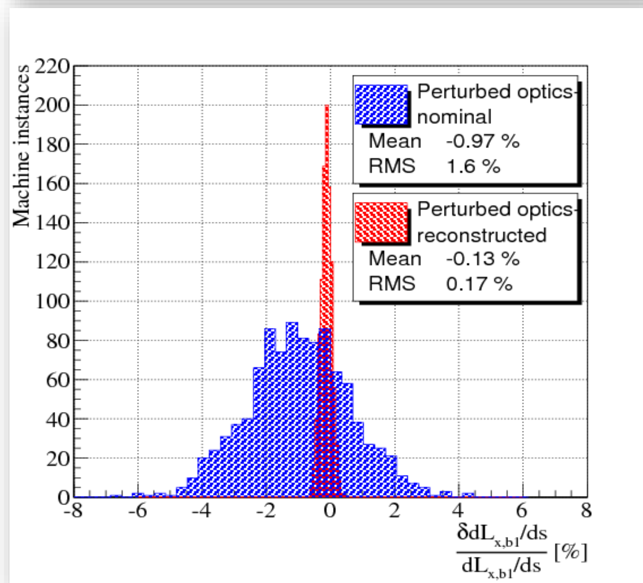
Machine imperfections alter the optics:

- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Magnetic field harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 µm

$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ Precise model of the LHC optics is indispensable!





Novel method from TOTEM:

- Use **measured** proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- http://iopscience.iop.org/1367-2630/16/10/103041/

Inefficiencies and corresponding physics corrections

- Large O(20 %) but well measurable, inefficiencies
- Two data sets DS1 and DS2
- Compatibility per diagonal per data set within uncertainties required

Correction [%]	DS1		DS2	
	Diag. 1	Diag. 2	Diag. 1	Diag. 2
$\mathcal{I}_{3/4}$	25.86 ± 0.2	22.04 ± 0.2	20.34 ± 0.1	21.37 ± 0.1
$\mathcal{I}_{2/4}$	19.91 ± 0.2	16.16 ± 0.2	16.09 ± 0.2	17.11 ± 0.2
$\mathcal{I}_{2/4\,\mathrm{diff.}}$	2.38 ± 0.05	1.61 ± 0.04	1.33 ± 0.02	1.5 ± 0.02
η_{d}	80.93 ± 0.01		99.95 ± 0.01	
η_{tr}	99.9 ± 0.1		99.9 ± 0.1	

- Total correction per event:

$$f(\theta^*, \theta_y^*) = \frac{1}{\eta_{\mathrm{d}} \eta_{\mathrm{tr}}} \cdot \frac{\mathcal{C}(\theta^*, \theta_y^*)}{1 - \mathcal{I}} \cdot \frac{1}{\Delta t}$$

$$\mathcal{I} = \mathcal{I}_{3/4}(\theta_y^*) + \mathcal{I}_{2/4} + \mathcal{I}_{2/4\,\mathrm{diff}}$$