Recent results from the TOTEM and CMS experiments

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CERN*

ISMD 2023

MATE KRC, Gyöngyös, Hungary

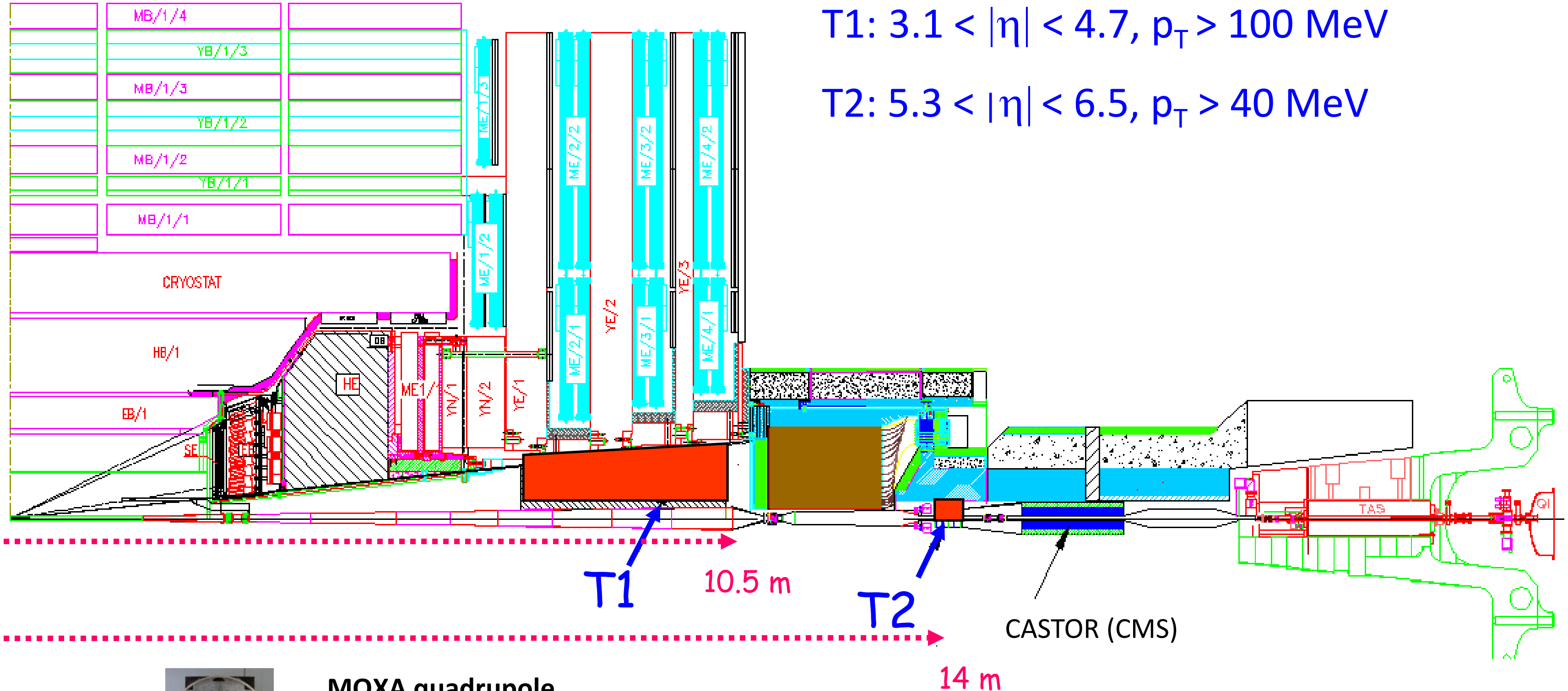
Aug. 21. – 26, 2023

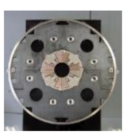
***Also at MATE, Gödöllő – Gyöngyös**
Wigner RCP, Budapest, Hungary

Experimental layout & LHC optics (LHC Run II)

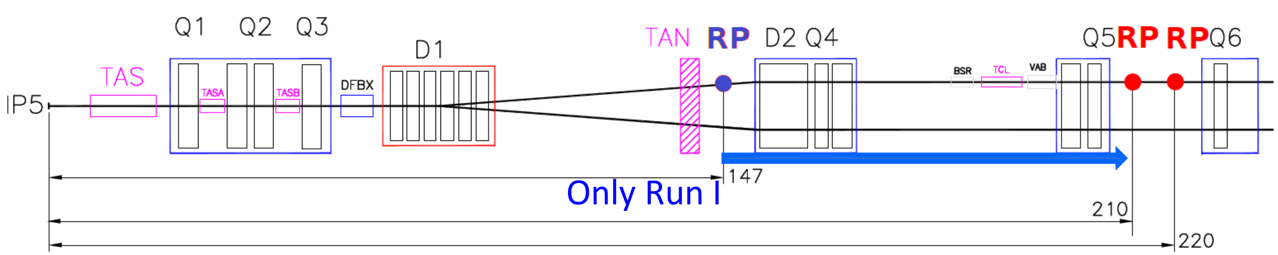
T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

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

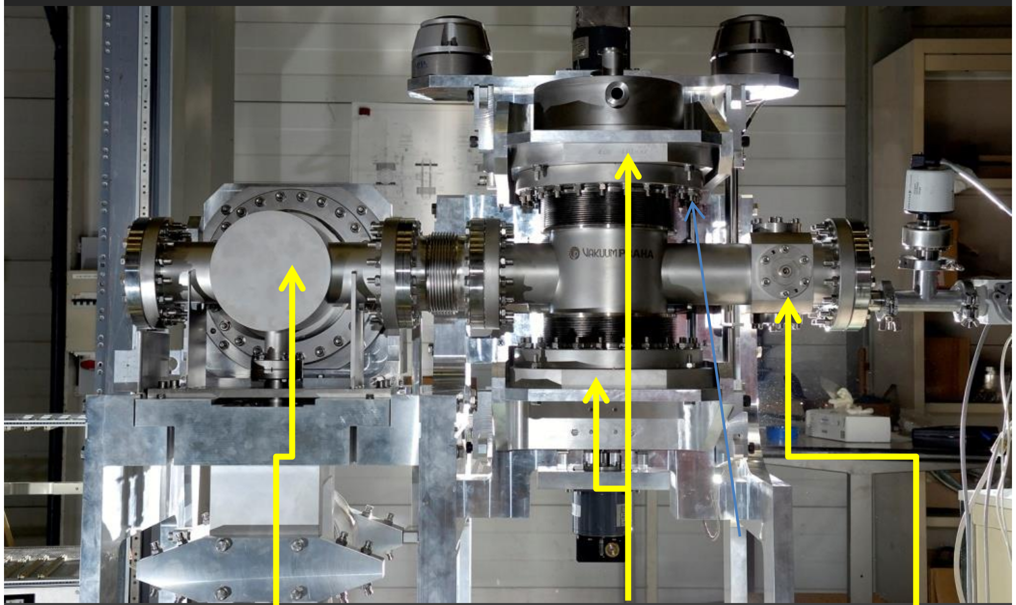
LHC optics (see backup sl.)

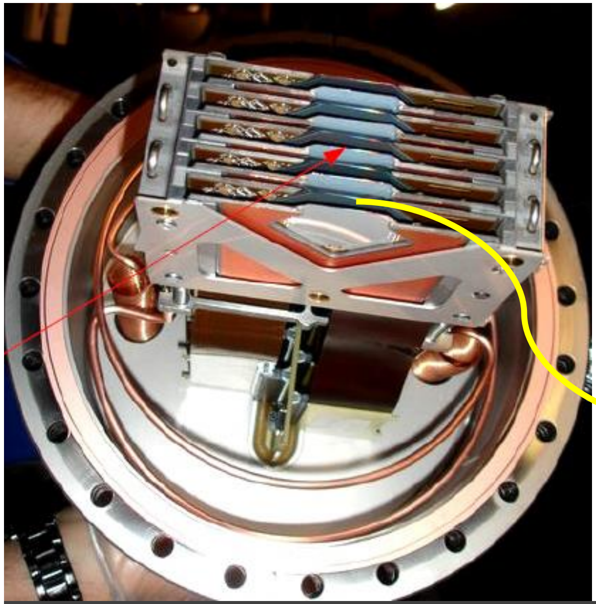
The Roman Pot (RP) stations of the TOTEM experiment

RP stations:

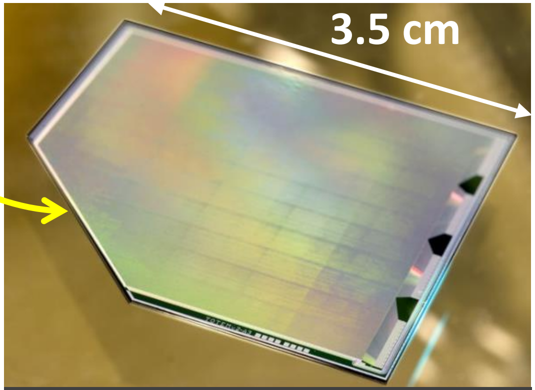
- 2 units (**N**ear, **F**ar) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few μrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 μm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

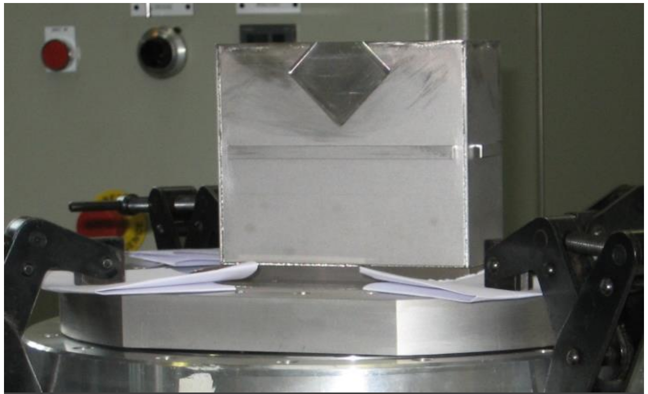




10 planes of edgeless detectors



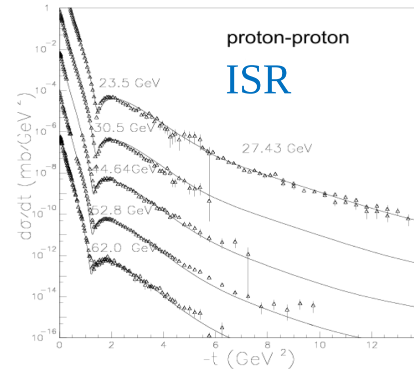
Si edgeless detector

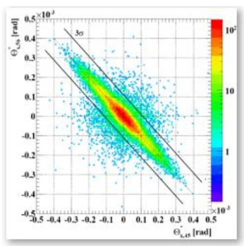


1 Roman Pot

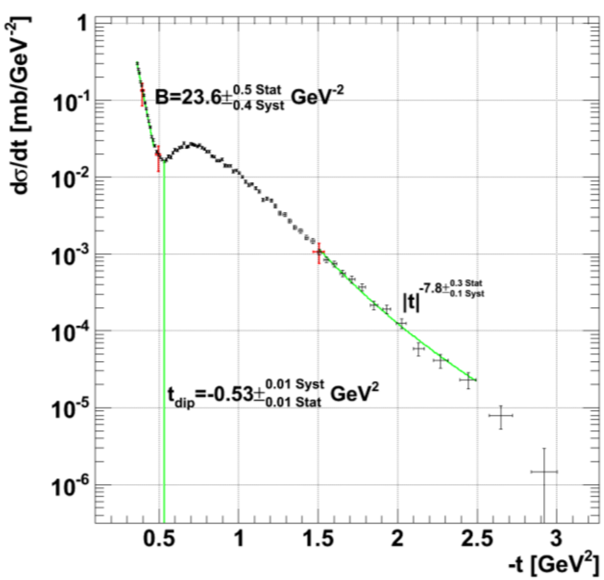
The elastic dσ/dt distribution at √s = 7 and 13 TeV

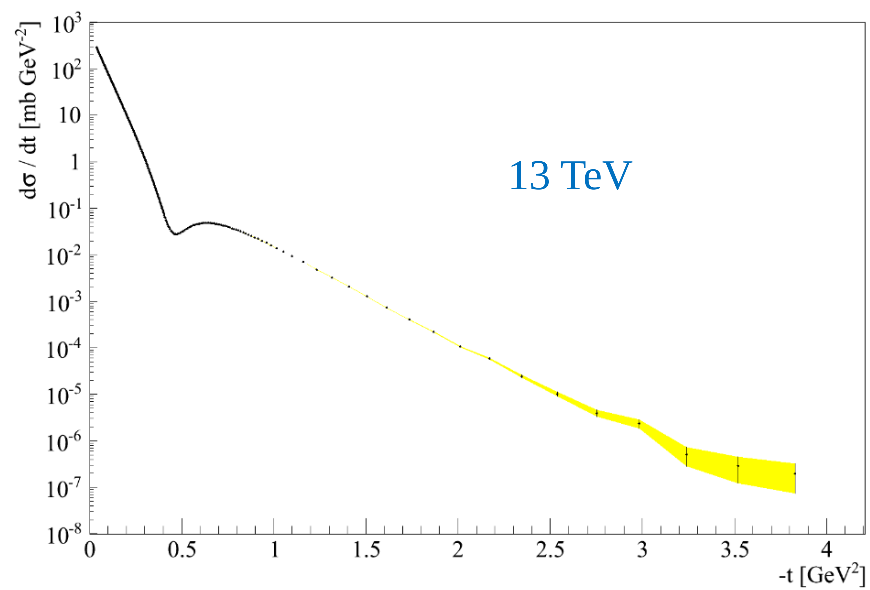
- Elastic |t| distribution over a wide |t| range (up to few GeV^2)
- Below dip exponential $e^{-B|t|}$ behavior
- Dip moves to lower |t| with increasing √s, proton becomes "larger"
- 1.5 - 2.5 GeV^2 power low behavior $|t|^{-n}$





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

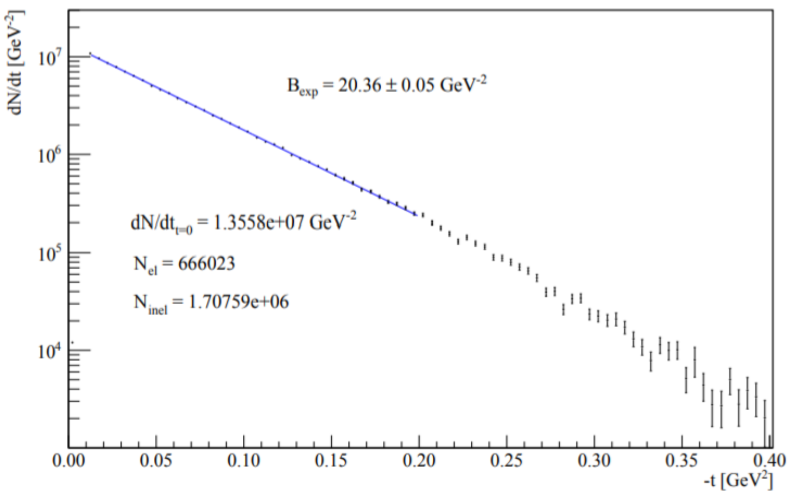




Luminosity independent measurement at 13 TeV

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)



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

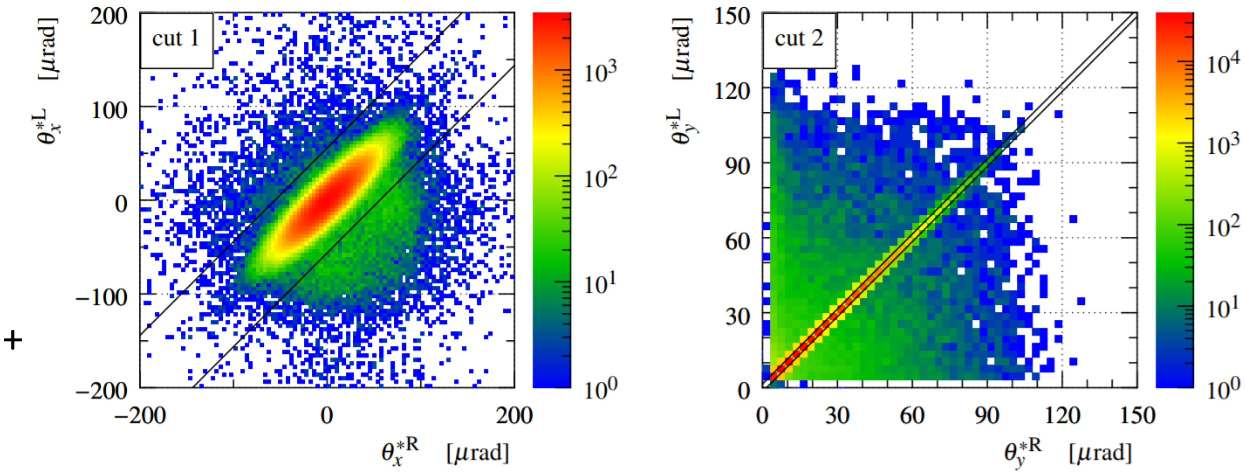
$$\rho = \left.\frac{\mathrm{Re}\, A^H}{\mathrm{Im}\, A^H}\right|_{t=0}$$

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

Coulomb-nuclear interference: the ρ parameter at 13 TeV

Basic properties of the data:

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



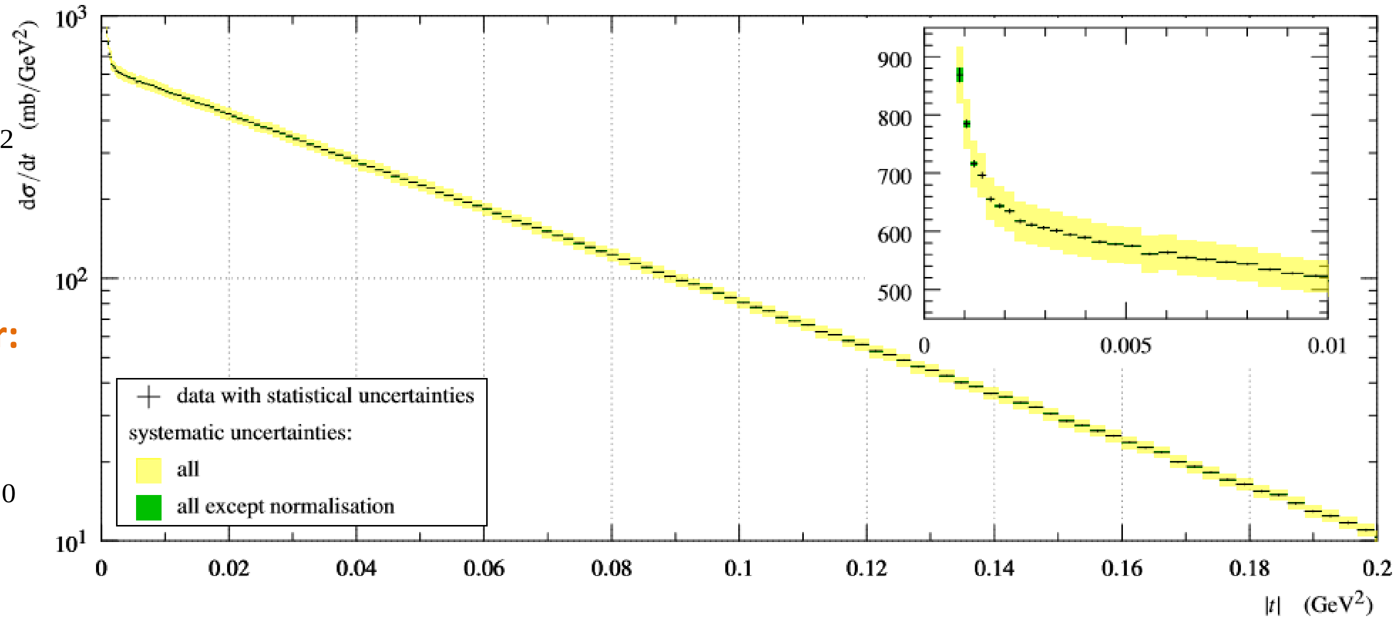
Analysis aims:

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

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

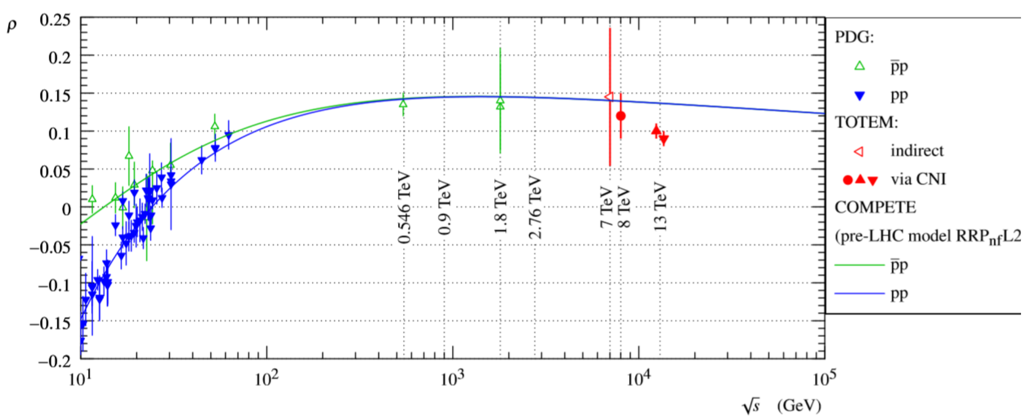
- **The ρ parameter:**

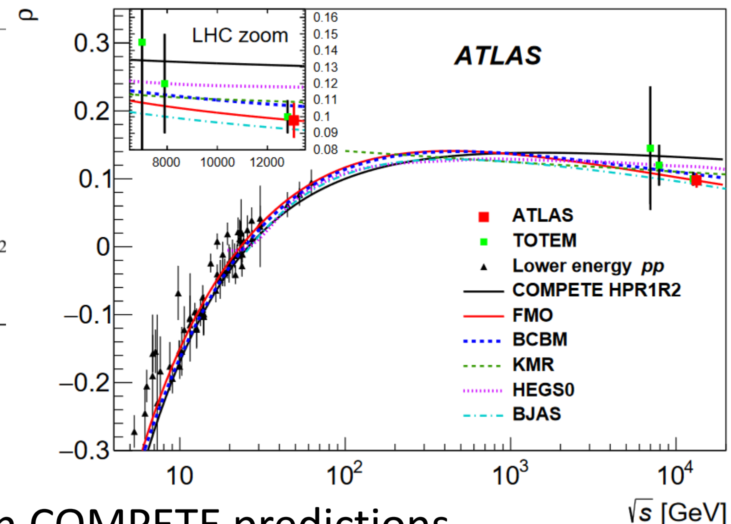
$$\rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$



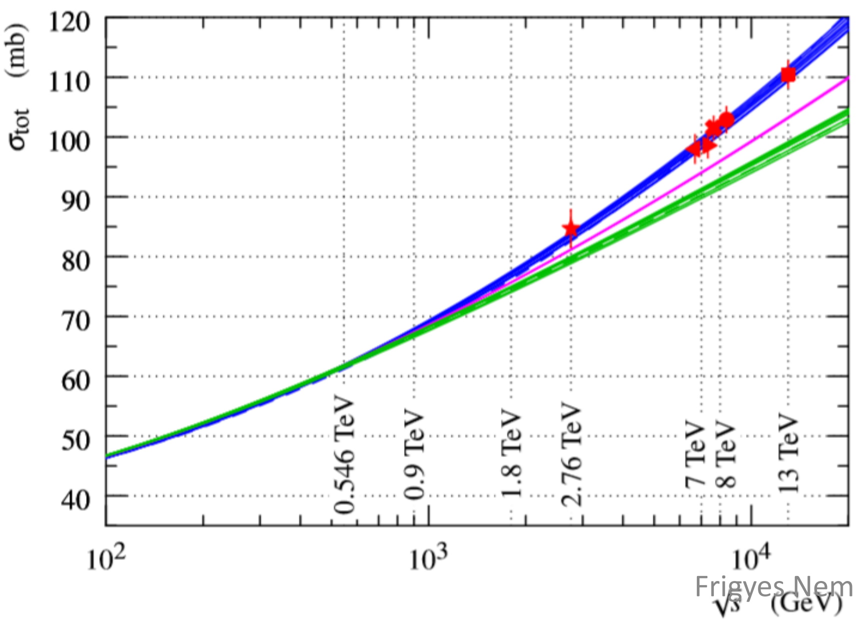
ρ as a function of √s: evidence for Odderon exhange

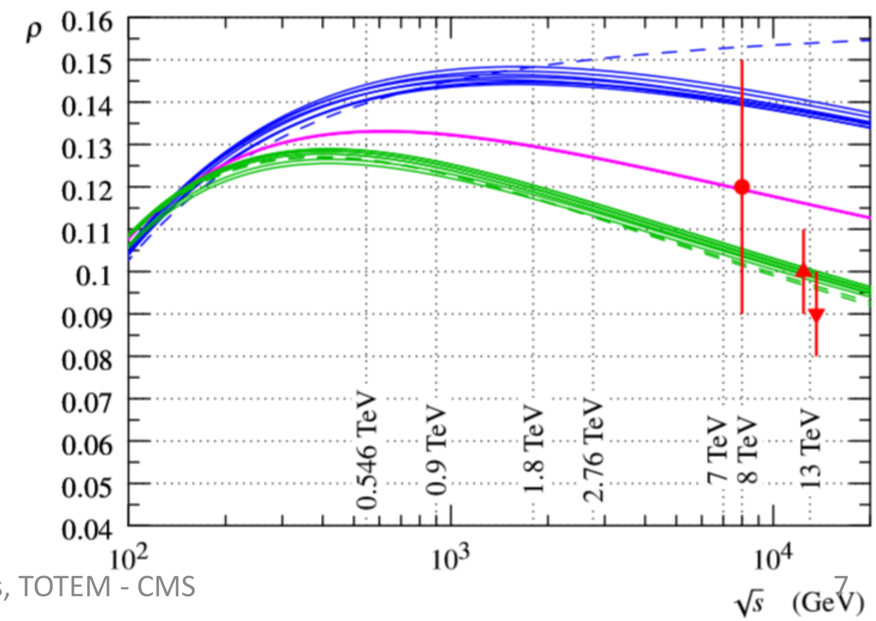
Latest TOTEM compilation together with more recent ATLAS compilation





Comparison of TOTEM σ_{tot} and ρ with COMPETE predictions

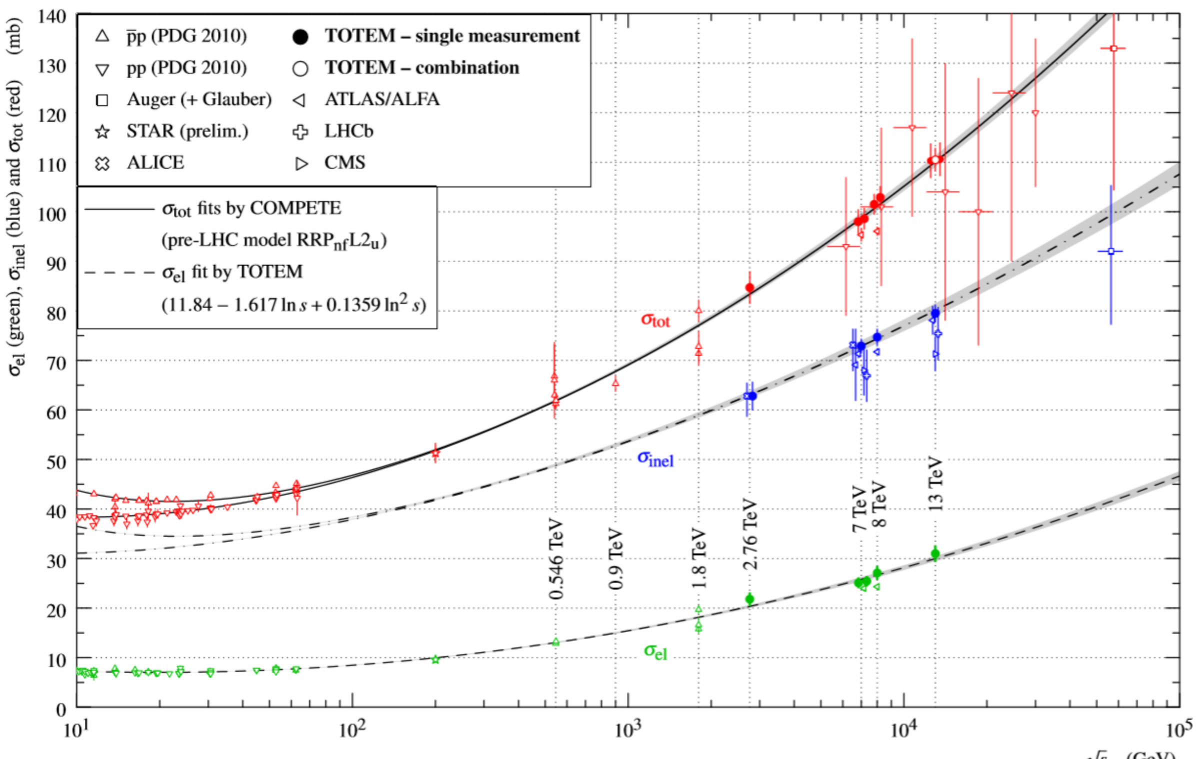


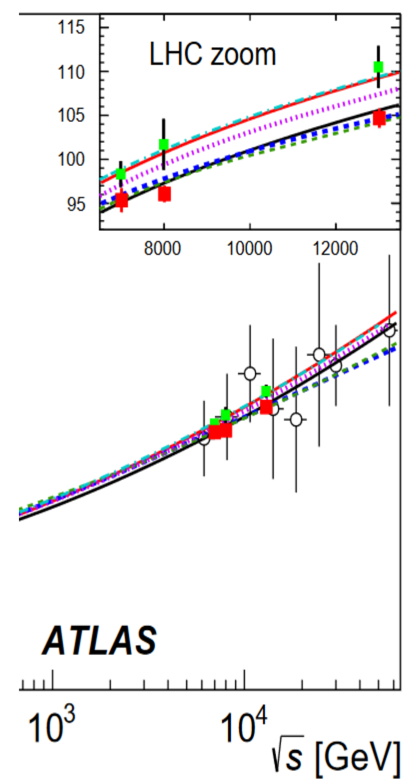


Total-cross sections & Coulomb normalization

Notes:

- Last TOTEM plot together with more recent ATLAS plot
- 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

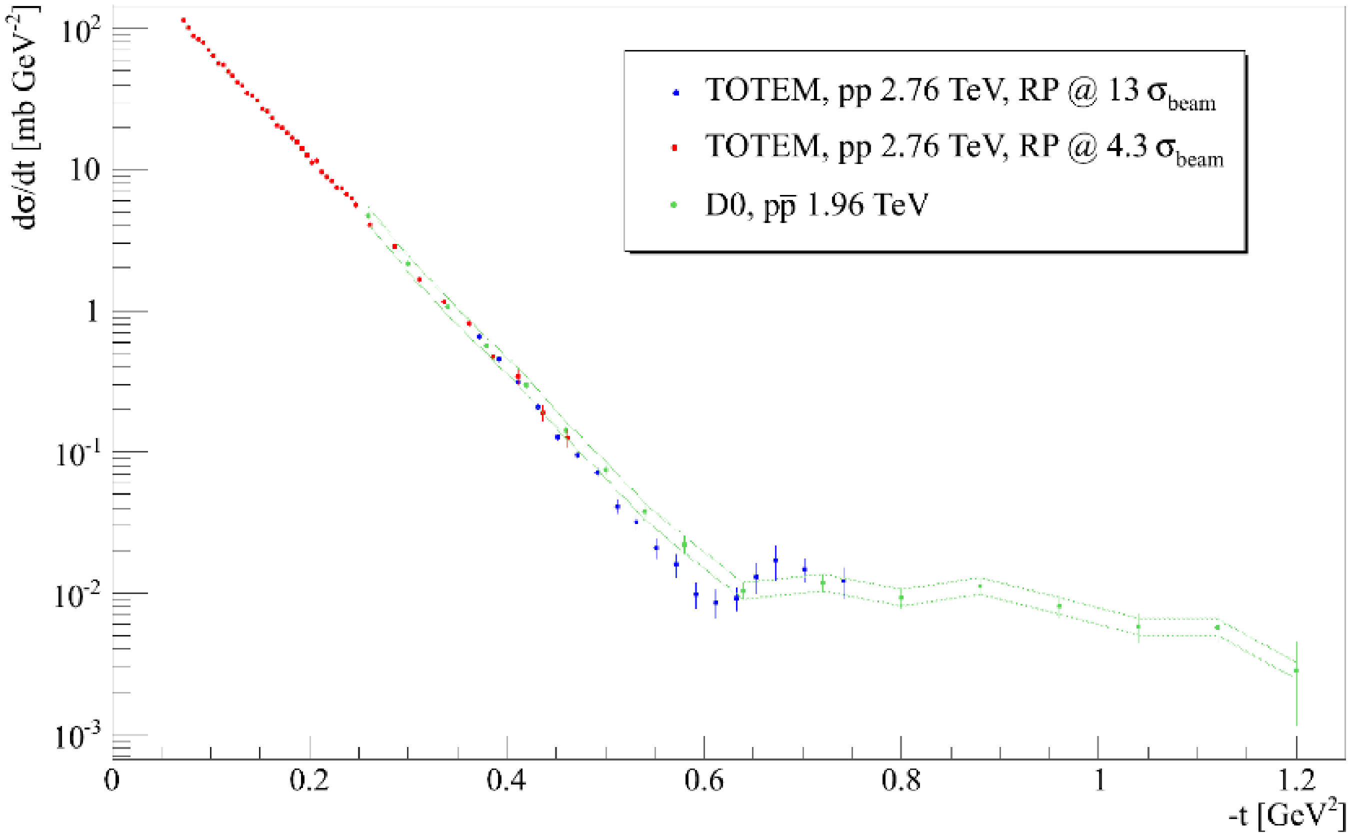




Comparison 2.76 TeV pp and D0 ppbar at 1.96 TeV

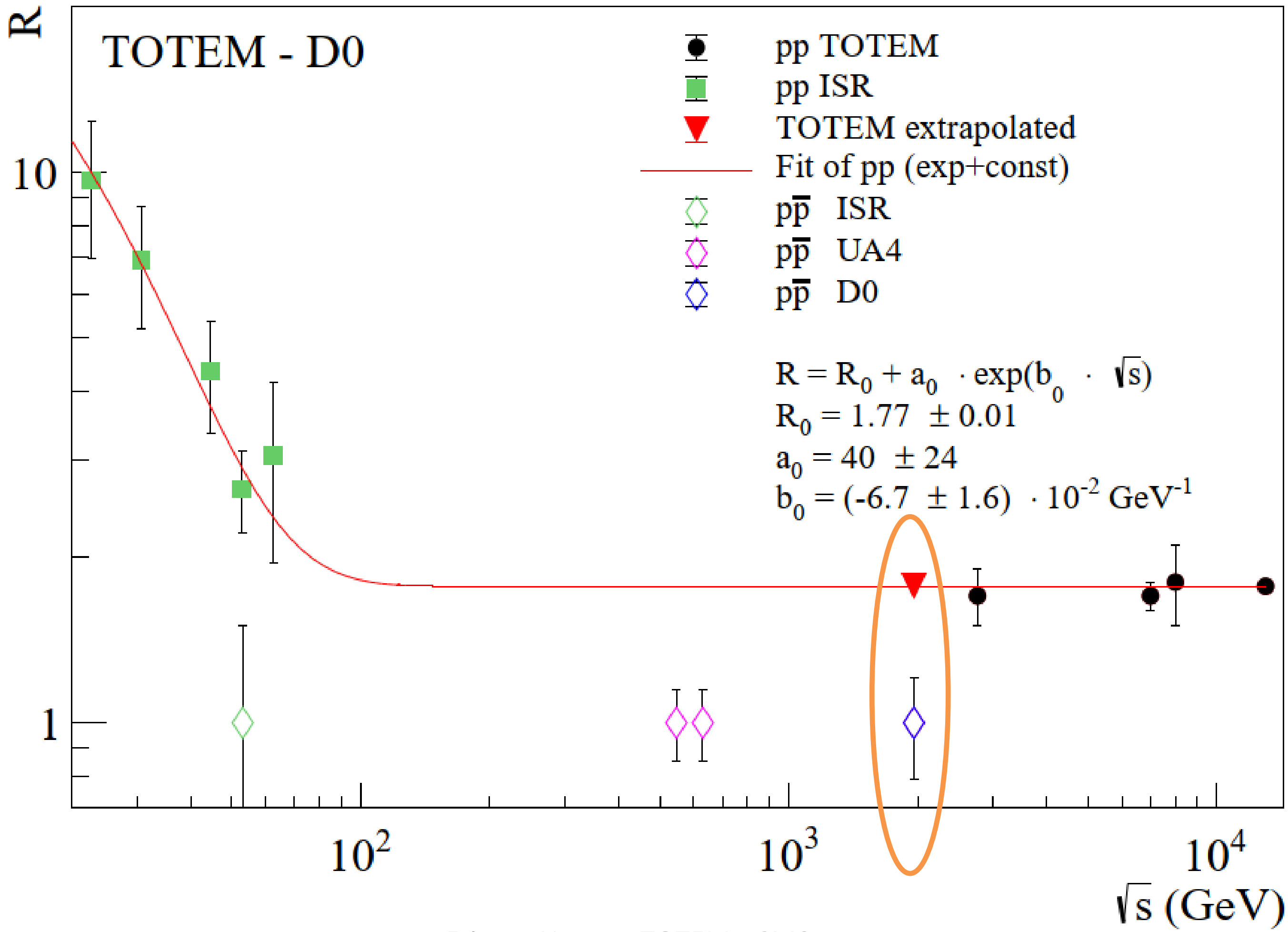
Note:

- "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"



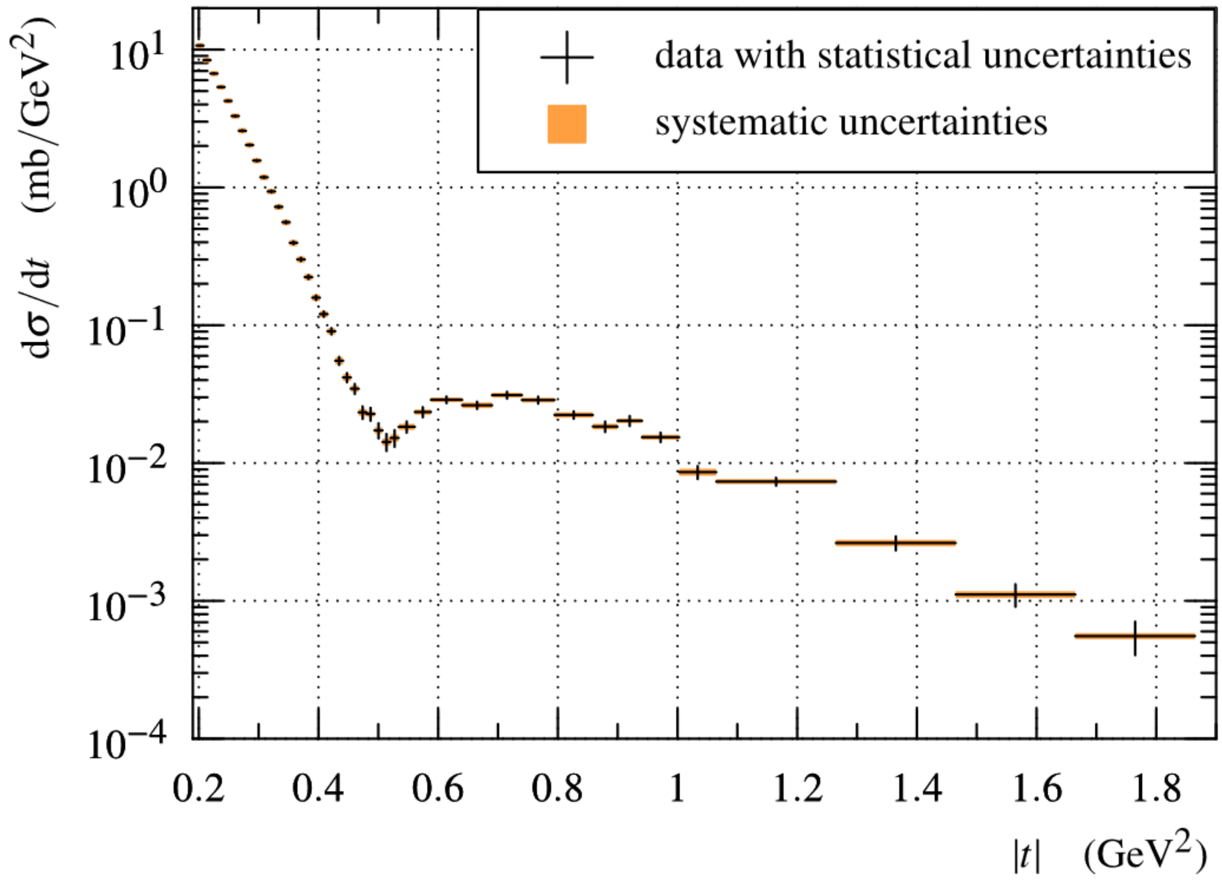
The bump over dip ratio R

- > 3σ difference between pp & $\bar{p}p$ @ s= 1.96 TeV (assuming flat behaviour above √s ~ 100 GeV)
- For $\bar{p}p$ R estimate, use $d\sigma/dt$ of t-bins close to expected pp bump & dip position



8 TeV publication and results (update)

- Published in Eur. Phys. J. C (2022) 82: 263
- Precise measurement of the diffractive minimum and bump



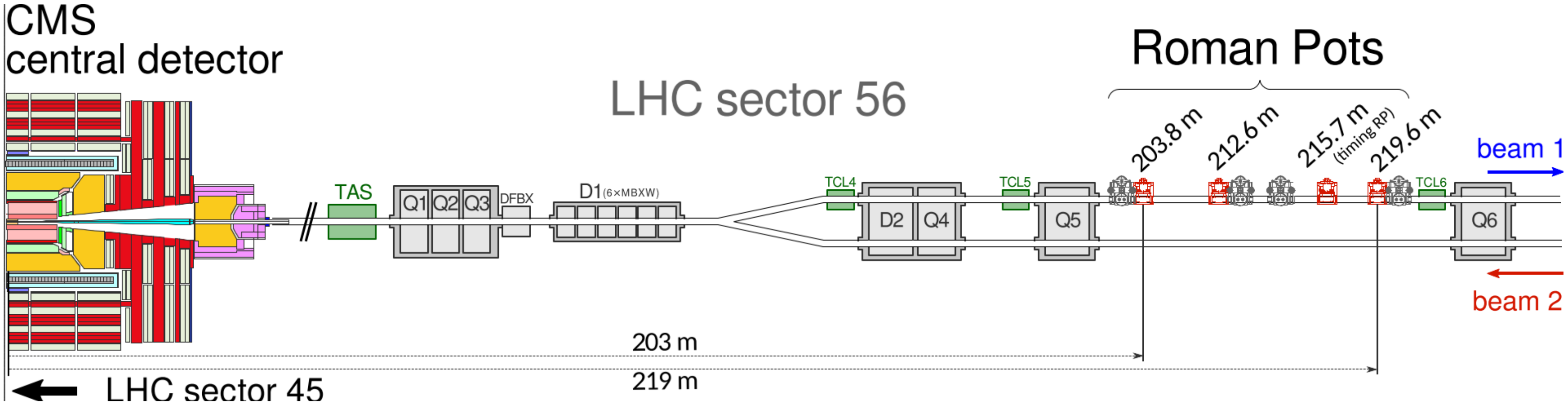
Nonresonant CEP of ππ at $\sqrt{s}$ = 13 TeV

PAS on CERN document server

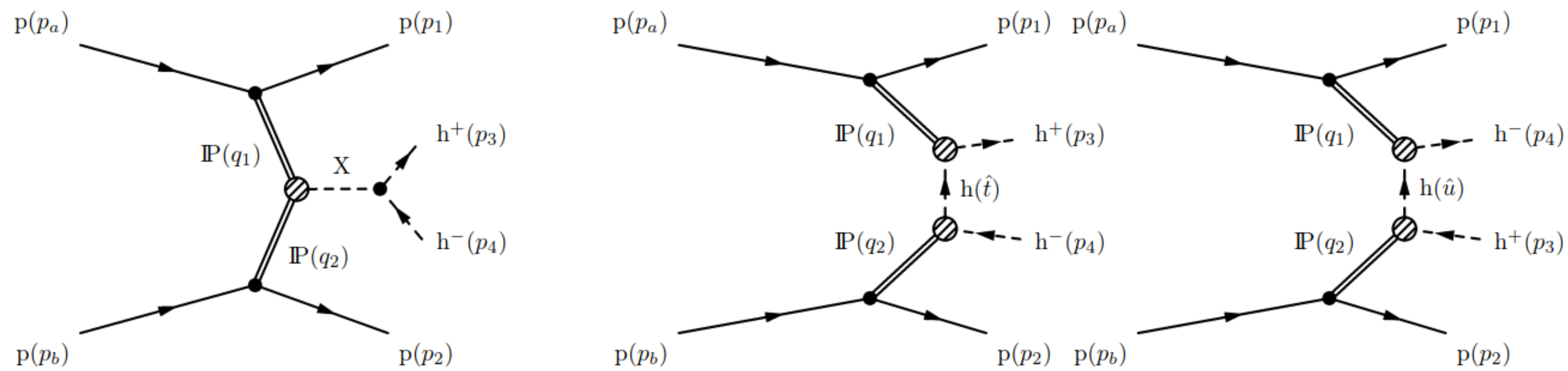
Presented at EPS-HEP 2023

Special CMS - TOTEM dataset

- CMS - TOTEM $\beta^* = 90$ m (2018)
- RP acceptance $|t_y| > 0.2$ GeV^2
- About 80 M events with two protons and two charged particles
- L1 trigger: double arm TOTEM RP, HLT: activity in CMS pixel detector
- Variables: proton pT's and phi (azimuthal angle diff.) and dipion inv. mass
- Central exclusive: particle – antiparticle, mostly $\pi^+\pi^-$, K^+K^-
- Focusing on non-resonant region: $0.35 < m_{\pi+\pi-} < 0.65$ GeV
- Effectively a Pomeron Pomeron collider → gluon-rich initial state



Theory – resonances vs background



resonant

nonresonant continuum

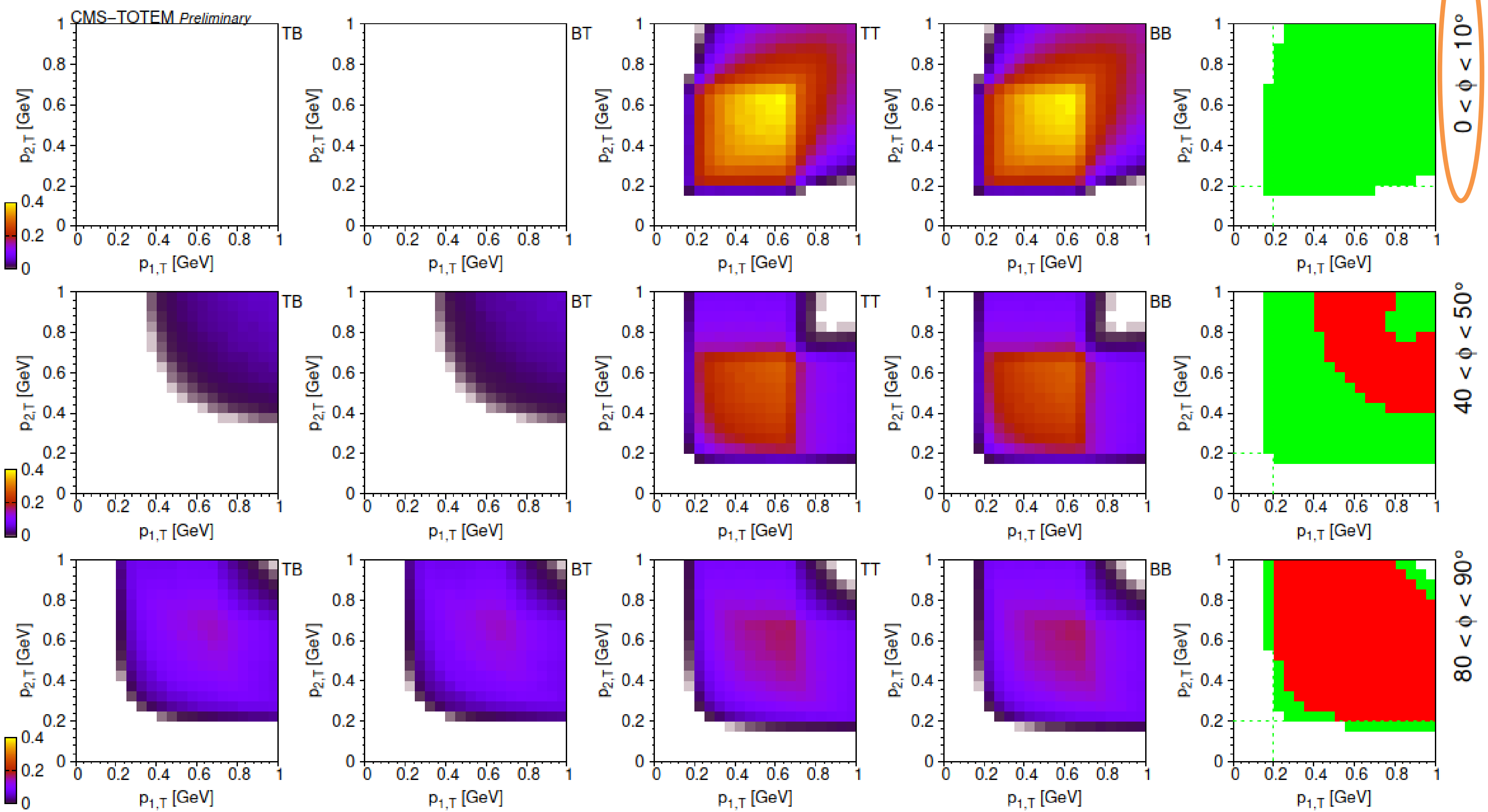
$$\mathcal{M} = M_{13}(t_1, s_{13}) \frac{F^2(\hat{t})}{\hat{t} - m^2} M_{24}(t_2, s_{24}) + M_{14}(t_1, s_{14}) \frac{F^2(\hat{u})}{\hat{u} - m^2} M_{23}(t_2, s_{23}),$$

- Matrix element M for nonresonant continuum process
- F(t) = meson-Pomeron form factor
- M_{ik} = “interaction” between Pomeron and created meson
- Meson propagator = $1/(\hat{t} - m^2)$
- At high energies Pomeron exchange dominates

$$M_{ik}(t_i, s_{ik}) = i s_{ik} C_{\mathbb{P}} \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_i)-1} \exp\left(\frac{B_{\mathbb{P}}}{2} t_i\right)$$

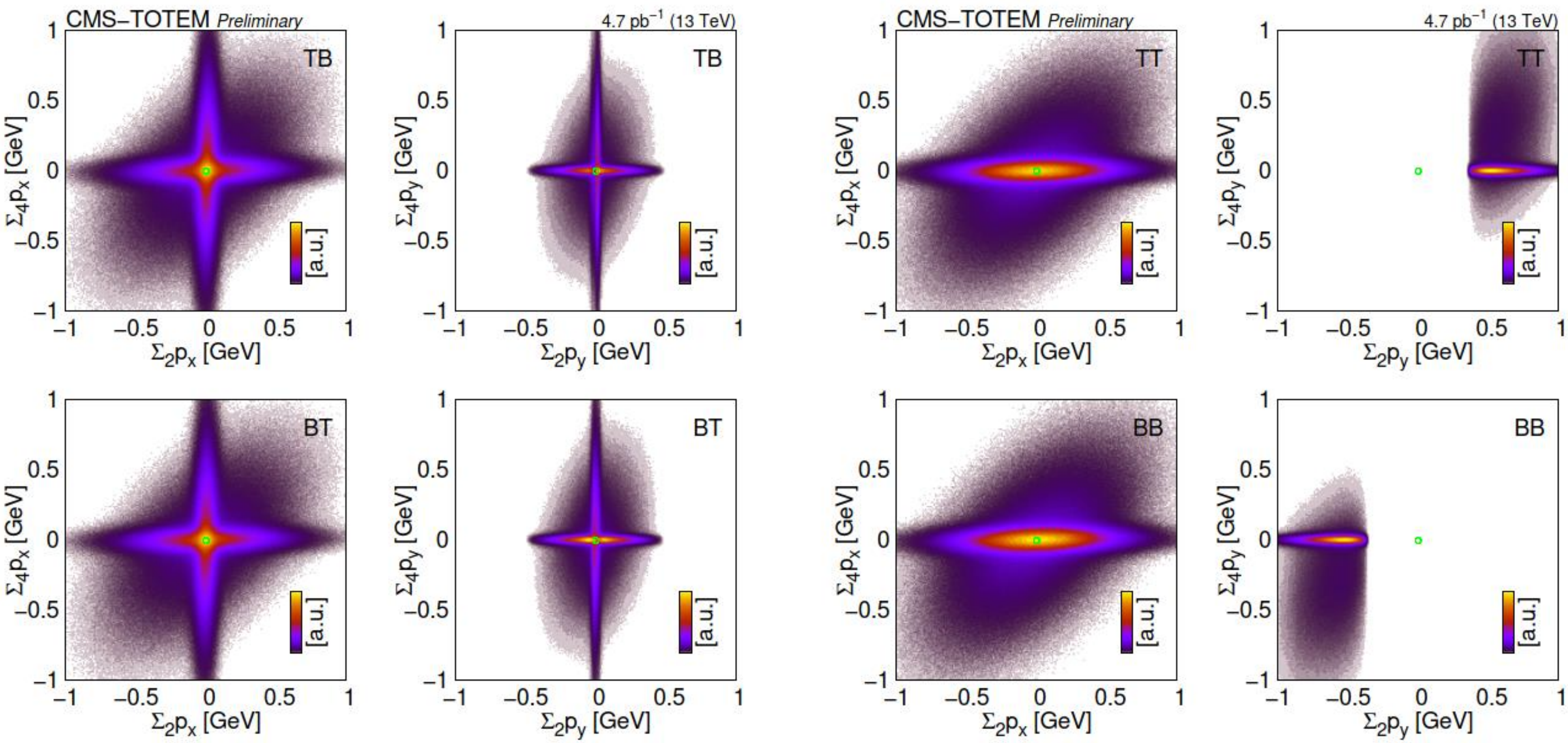
RP acceptance vs azimuthal angle diff. Φ

- Calculated detection efficiencies for the pair of scattered protons as a function of their transverse momenta ($p^{1,T}$, $p^{2,T}$)



Event selection

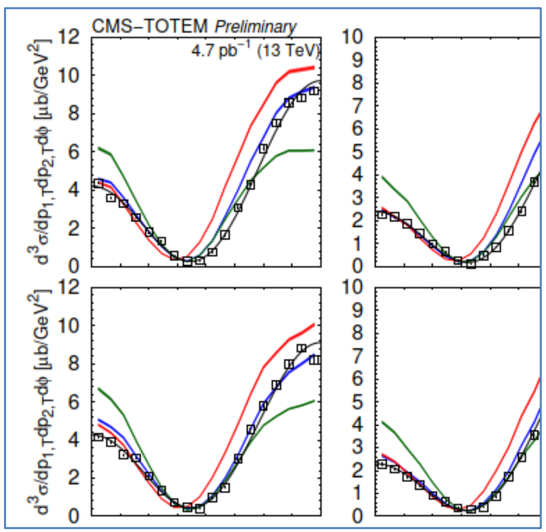
- Momentum conservation in the transverse momentum plane
- Scattered proton momenta (horizontal axis)
- Scattered proton AND central hadrons (vertical axis)
- Pile-up from elastic: vertical band in TB and BT configurations

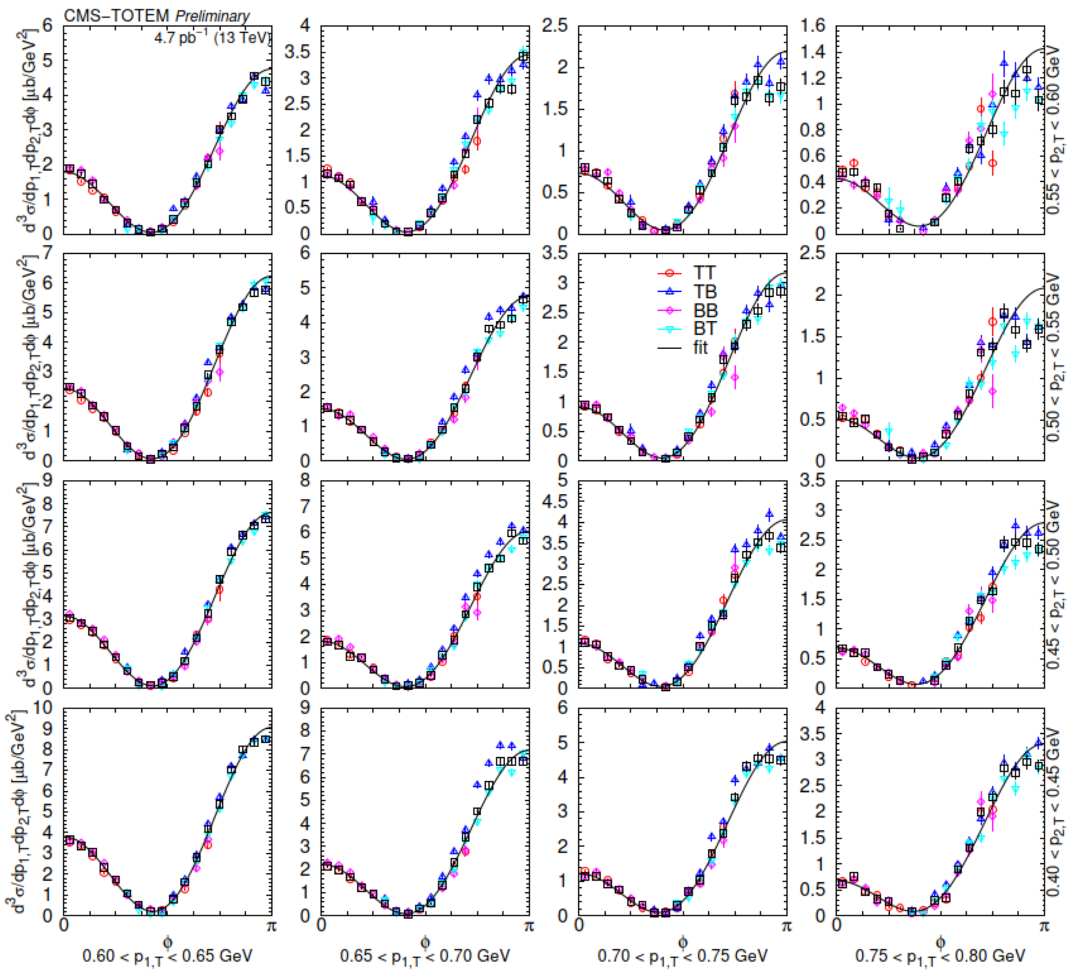


Dip in the diproton opening angle differential distribution

- 1st observation of parabolic minimum in the proton azimuthal angle difference
- Except at very low and high $-(t_1 + t_2)$

$$\frac{d^3\sigma}{\mathrm{d}p_{1,\mathrm{T}}\mathrm{d}p_{2,\mathrm{T}}\mathrm{d}\phi} = [A(R - \cos\phi)]^2 + c^2$$





Model fit results

Form factors

- Pomeron – meson coupling
- Proton - Pomeron

$$F(\hat{t}) = \begin{cases} \exp(b_{\text{exp}}(\hat{t} - m^2)) & \text{(exponential)}, \\ \exp(b_{\text{ore}}[a_{\text{ore}} - \sqrt{a_{\text{ore}}^2 - (\hat{t} - m^2)}]) & \text{(Orear-like)}, \\ 1/(1 - b_{\text{pow}}(\hat{t} - m^2)), & \text{(power-law)}. \end{cases}$$

Models

- Empirical
- One-channel (proton in ground state)
- Two-channel (p + N*, two diff. eigenstates of the proton)
- Remarkable agreement with DIME ("soft model 1"), although with unexpected eigenstate-pomeron coupling ($\gamma_1 \approx \gamma_2$)

Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
empirical model				
a_{ore}[GeV]	—	0.735 ± 0.015	—	
$b_{\text{exp/ore/pow}}$[GeV^{-2} or $^{-1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{\mathbb{P}}$ [GeV^{-2}]	3.757 ± 0.033	3.934 ± 0.027	4.159 ± 0.019	
χ^2/dof	9470/5796	10059/5795	11409/5796	
one-channel model				
σ_0[mb]	34.99 ± 0.79	27.98 ± 0.40	26.87 ± 0.30	
$\alpha_P - 1$	0.129 ± 0.002	0.127 ± 0.001	0.134 ± 0.001	
α'_P [GeV^{-2}]	0.084 ± 0.005	0.034 ± 0.002	0.037 ± 0.002	
a_{ore}[GeV]	—	0.578 ± 0.022	—	
$b_{\text{exp/ore/pow}}$[GeV^{-2} or $^{-1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{\mathbb{P}}$ [GeV^{-2}]	2.745 ± 0.046	4.271 ± 0.021	4.072 ± 0.017	
χ^2/dof	7356/5793	7448/5792	8339/5793	
two-channel model				
σ_0[mb]	20.97 ± 0.48	22.89 ± 0.17	23.02 ± 0.23	23 / 33
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001	0.13 / 0.115
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001	0.08 / 0.11
a_{ore}[GeV]	—	0.718 ± 0.012	—	
$b_{\text{exp/ore/pow}}$[GeV^{-2} or $^{-1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\|a\|^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011	−0.04 / −0.25
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023	0.55 / 0.4
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040	8.5 / 8.0
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006	0.18 / 0.18
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003	0.45 / 0.63
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060	4.5 / 6.0
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006	0.58 / 0.58
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004	0.45 / 0.47
χ^2/dof	5741/5786	6415/5785	7879/5786	

Summary & Outlook

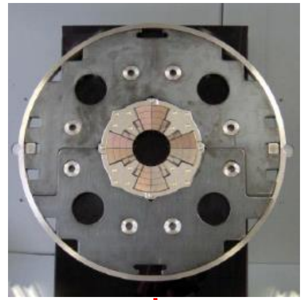
- TOTEM elastic measurements at LHC at 2.76, 7, 8 and 13 TeV!
  (with 0.9 and 13.6 TeV measurements in the pipeline)
- 13 TeV ρ measurement
  - Coulomb normalization leading to independent total cross-section measurement
  - **Evidence** for t-channel exchange of colourless C-odd 3g compound (odderon)
- 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)
- 8 TeV, differential cross-section measurement
- 13 TeV, detailed study of non-resonant CEP of hadron pairs
  (central exclusive $\pi^+\pi^-$, K^+K^- **resonance** study will be published soon)

Thank you for your attention !

Backup slides

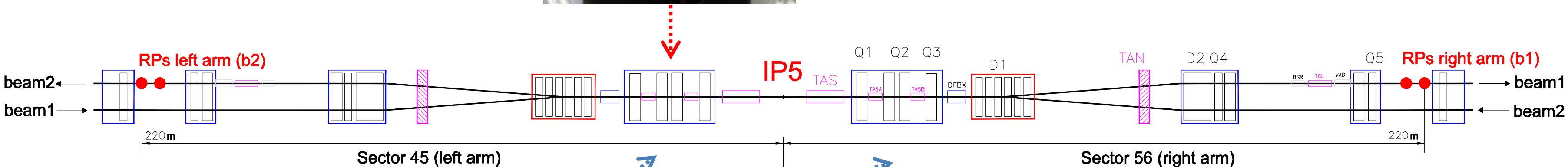
LHC optics around IP5

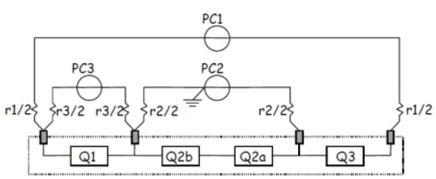
Schematic layout of the magnet lattice at IP5:



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.

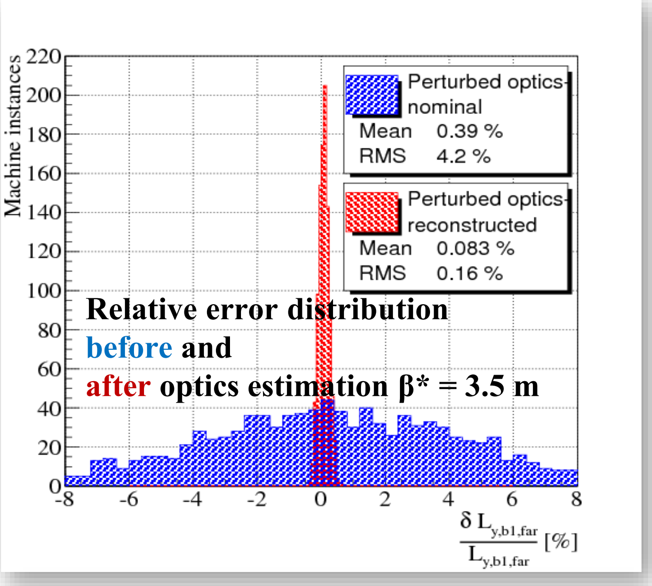
Note on proton kinematics reconstruction & optics imperfections

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

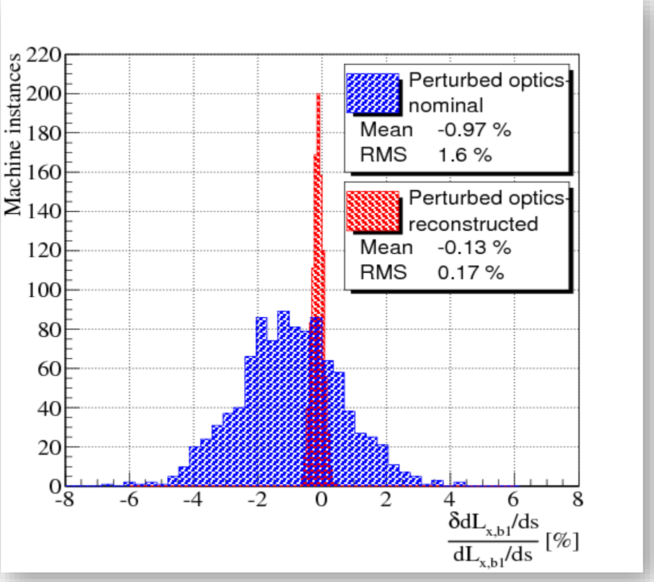
$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ **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	

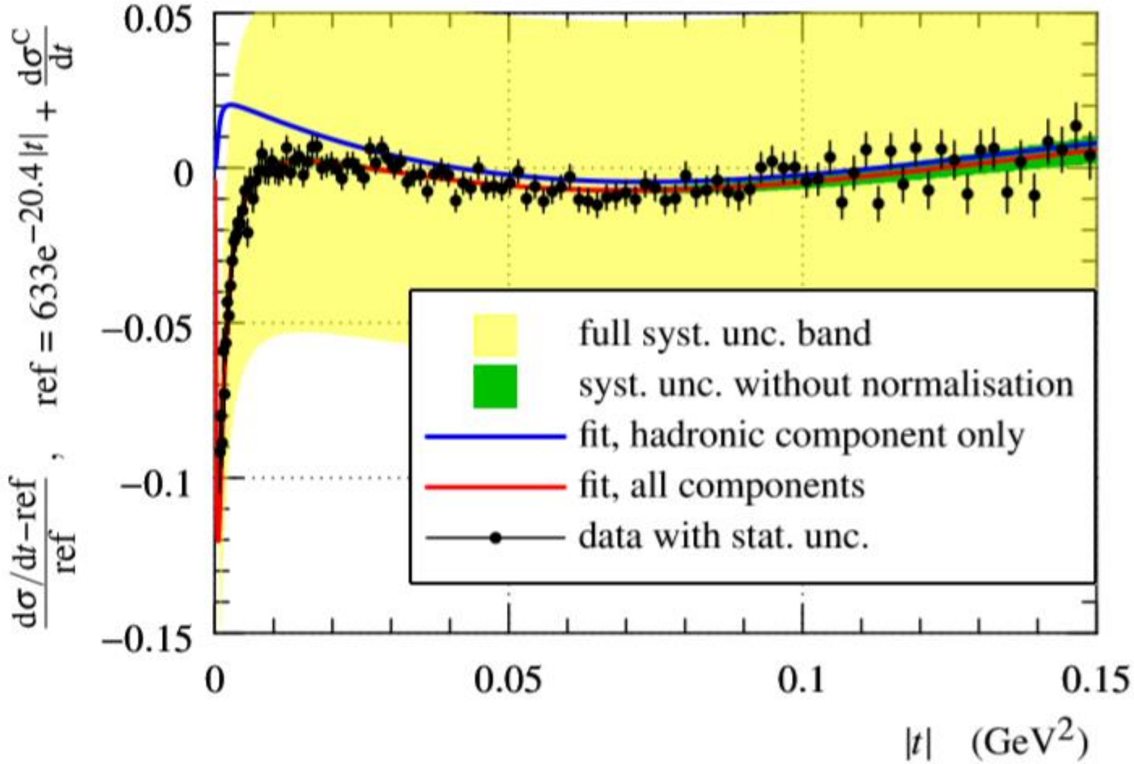
- Total correction per event:

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

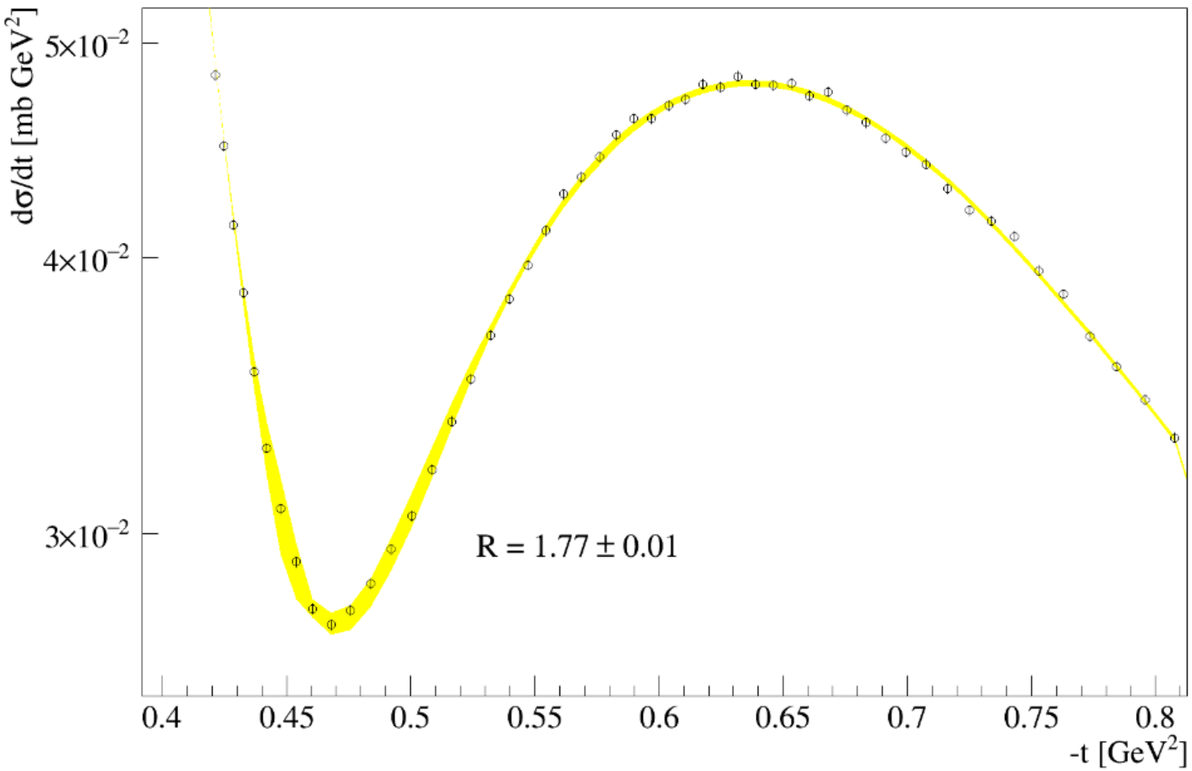
$$\mathcal{I} = \mathcal{I}_{3/4}(\theta_y^*) + \mathcal{I}_{2/4} + \mathcal{I}_{2/4\,\mathrm{diff}}$$

Interference in details and ρ measurements

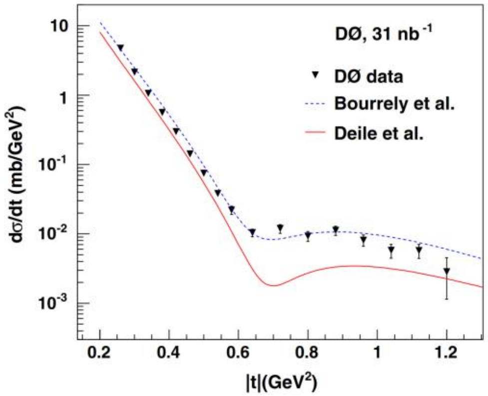
N_b	χ^2/ndf ($\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$)	ρ ($\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$)	σ_{tot} [mb] ($\lvert t\rvert_{max} = 0.07\,\mathrm{GeV}^2$)	χ^2/ndf ($\lvert t\rvert_{max} = 0.15\,\mathrm{GeV}^2$)	ρ ($\lvert t\rvert_{max} = 0.15\,\mathrm{GeV}^2$)	σ_{tot} [mb] ($\lvert t\rvert_{max}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



The diffractive minimum at 13 TeV in details



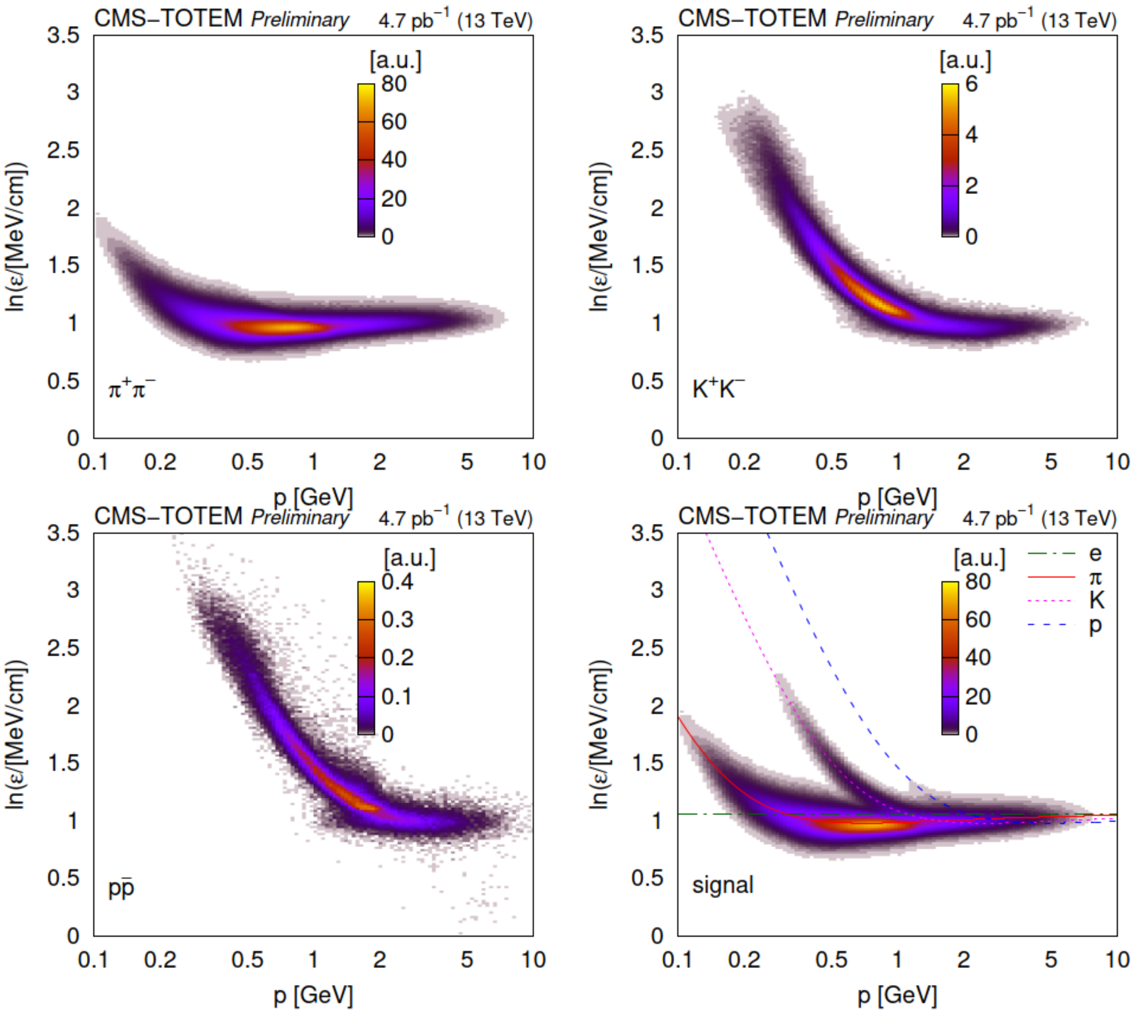
ppbar √s = 1.96 TeV



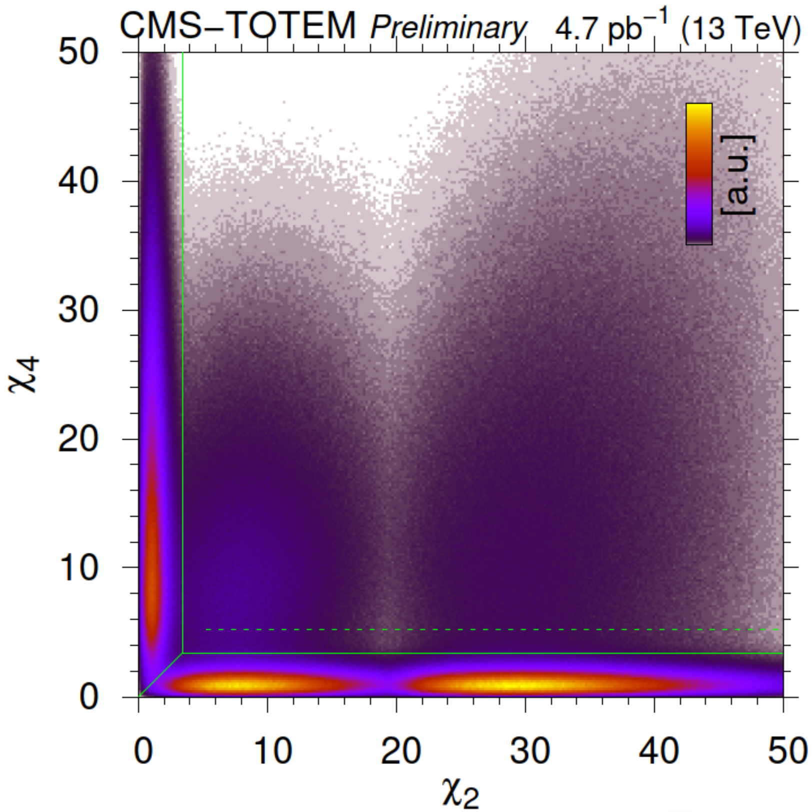
- Result confirms with unprecedented precision at the TeV scale the dip structure (**R = max / dip**)
- Hadronic elastic @ TeV sqrt(s) dominated by t-channel exchange of colourless gluon states
- 2 (or even) gluon exchange (C = +): "Pomeron" (~ mostly imaginary) ⟹ pp vs ppbar invariance
- 3 (or odd)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

Particle identification with dE/dx

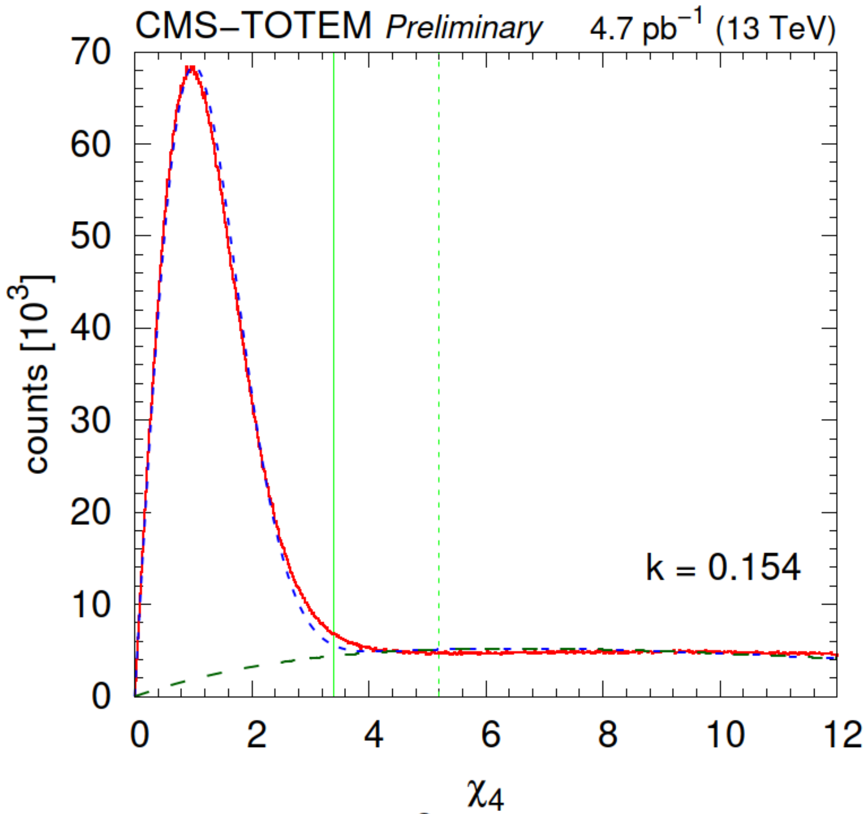
- Energy loss measurement with CMS tracker
- Identification of $\pi^+\pi^-$, K^+K^- (and $\bar{p}p$)



Event selection - χ_4 - signal and sideband



Mahalanobis distance $\chi(\mathbf{s}) = (\mathbf{s}^T V^{-1} \mathbf{s})^{1/2}$



$A\chi \exp(-\chi^2/2) + B\chi \exp(-k\chi)$