Recent results from the TOTEM experiment

Frigyes Nemes on behalf of the D0 and TOTEM experiments
CERN*

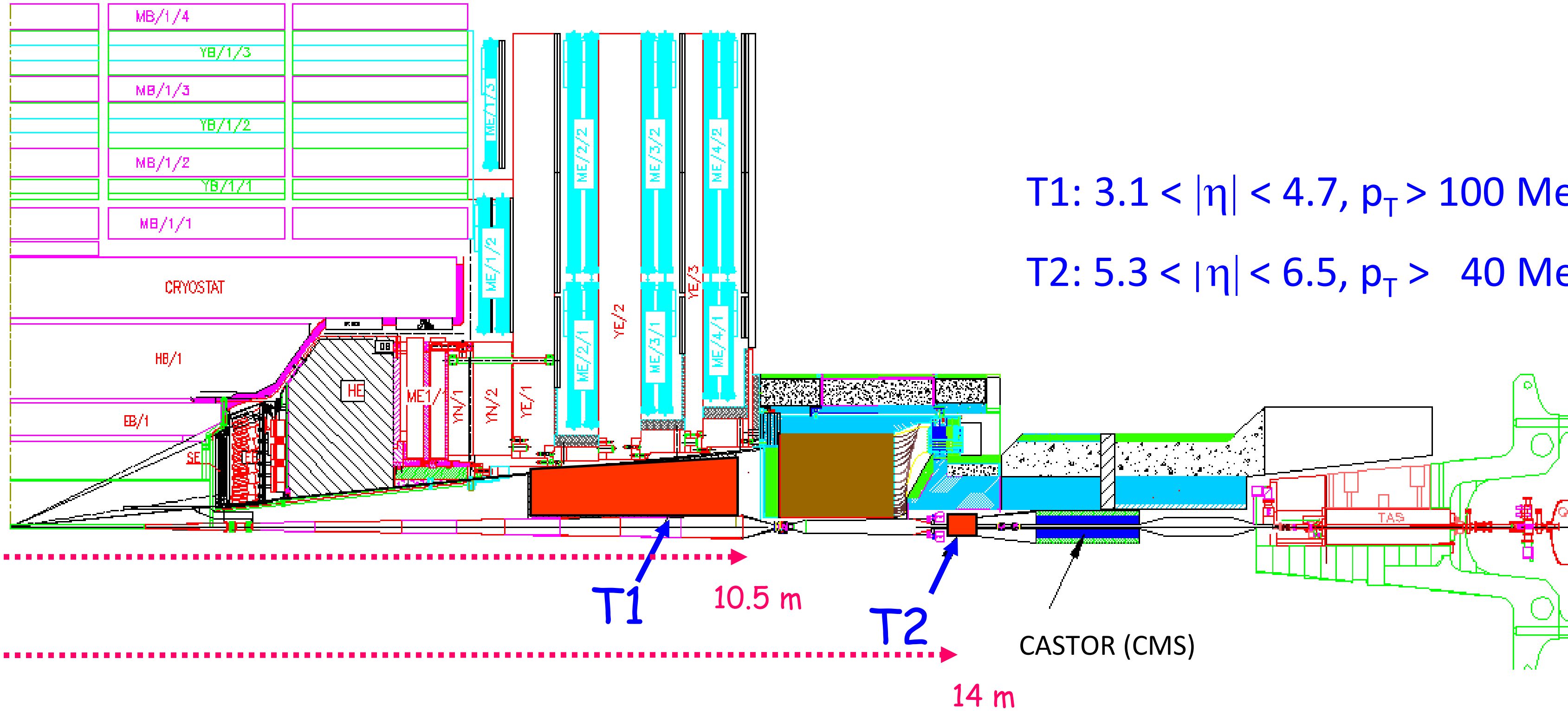
22nd Zimányi School 2022, Winter Workshop

Budapest, Hungary

2022, December 5 – 9

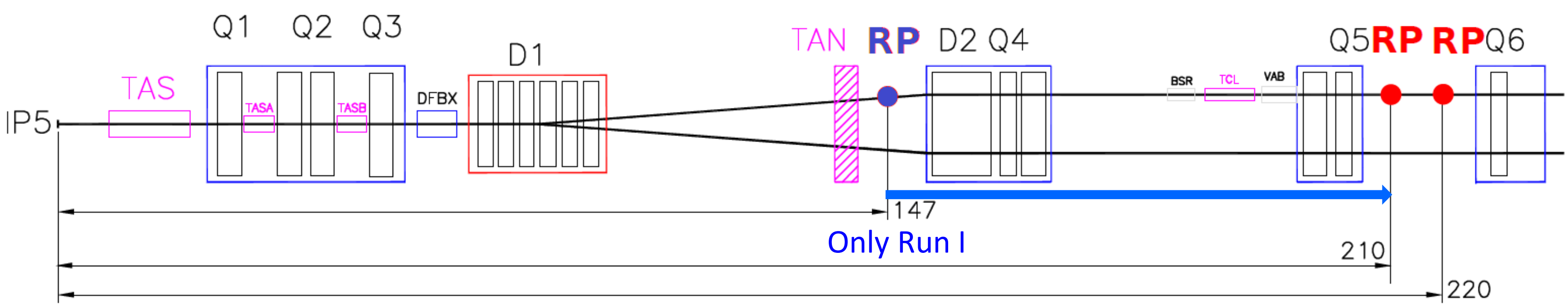
***Also at Wigner RCP, Budapest, Hungary**
MATE Institute of Technology, KRC, Gyöngyös, Hungary

Experimental layout of the TOTEM experiment (LHC Run II)



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

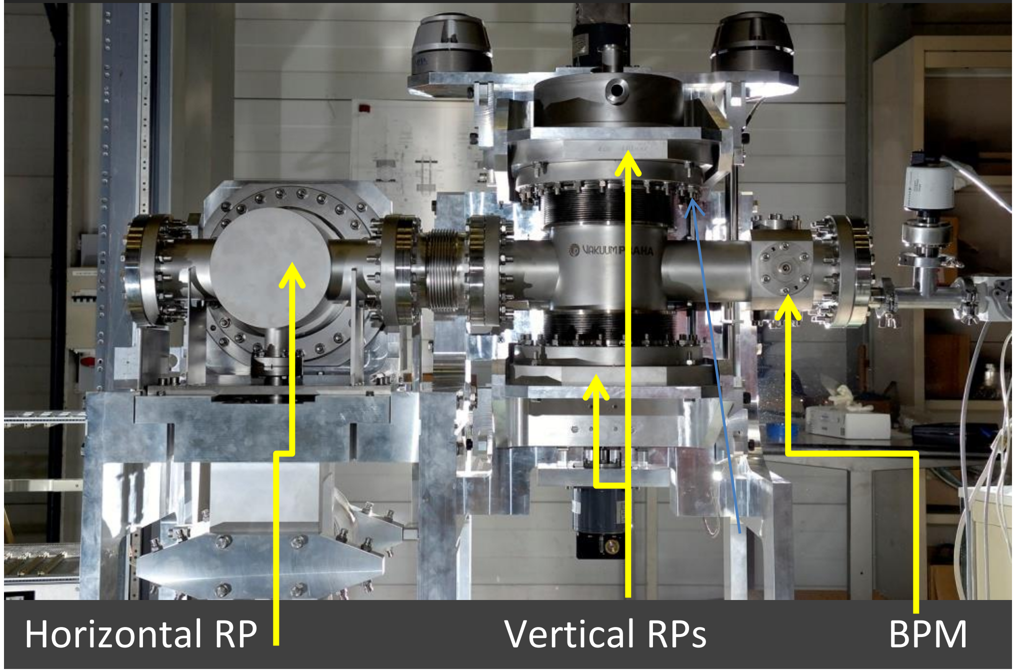
T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

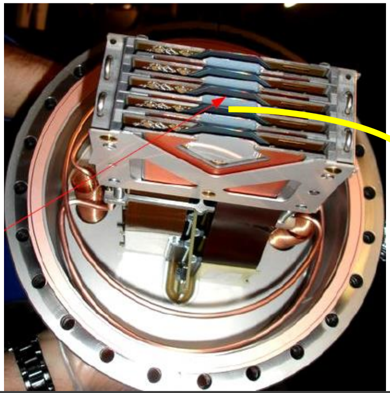


The Roman Pot (RP) stations of the TOTEM experiment

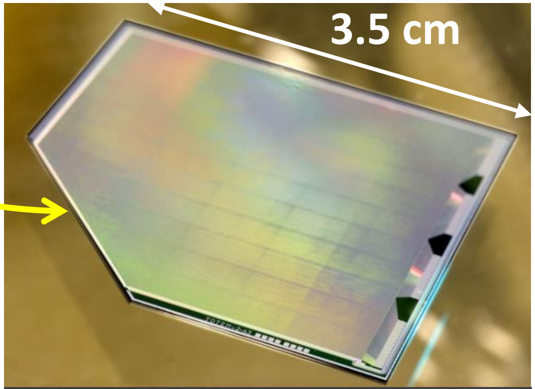
- Two RP stations at 210 and 220 m from the IP contain measuring planes separated by 10 and 5 m respectively
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position rel. to beam
- Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

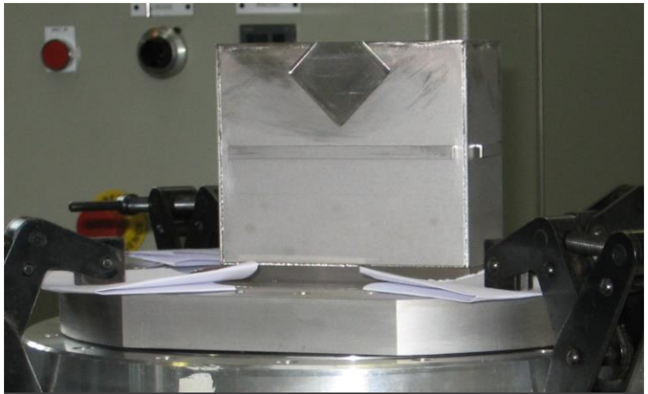




10 planes of edgeless detectors

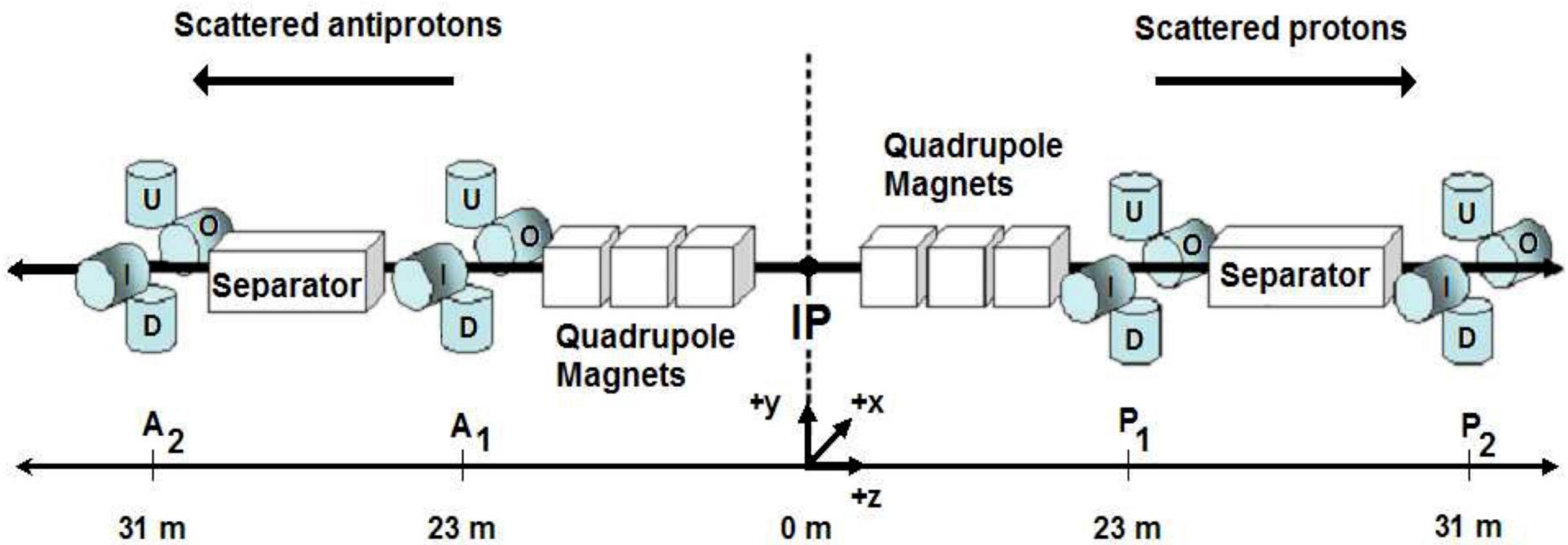


Si edgeless detector



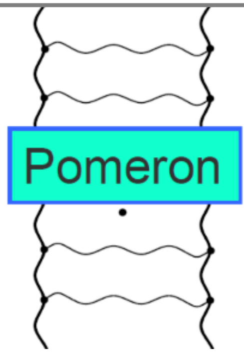
1 Roman Pot

Experimental layout of the D0 experiment (Tevatron, Fermilab)

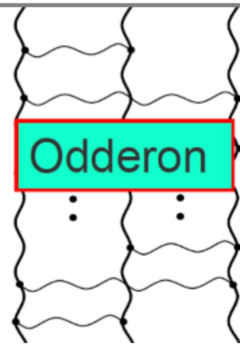


- Elastic $\bar{p}p\ d\sigma/dt$ measurements: measure both the intact $\bar{p}$ & p in D0 Roman Pots at 23 - 31 m from IP with scintillating fibre detectors
- Measurement at $\sqrt{s}$= 1.96 TeV: PRD 86 (2012) 012009.

Elastic scattering: multi-gluon exchanges



dominates at low-|t|
$\approx Im\,(A_{el}^{had})$
identical for pp & p$\bar{\text{p}}$



suppressed
mainly $Re(A_{el}^{had})$
different **sign** for pp & p$\bar{\text{p}}$

Elastic hadron-hadron scattering at very high-energies: **colourless** multi-gluon t-channel exchanges

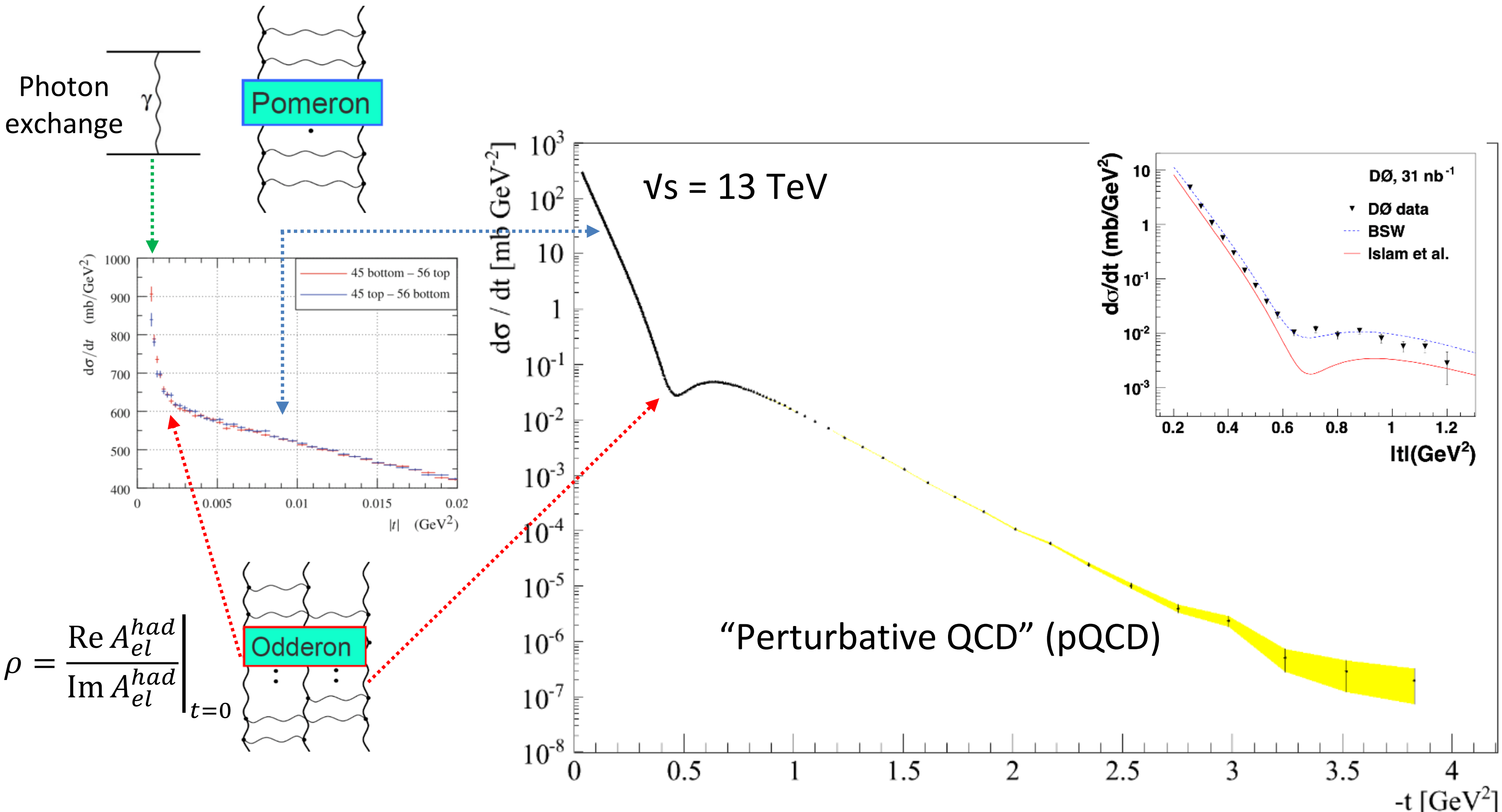
- @ TeV-scale: gluon exchanges dominate ⇒ pp and p$\bar{\text{p}}$ difference due to C-odd exchange
- gluonic compounds: colourless gluon combinations bound sufficiently strongly not to interact with individual p/$\bar{\text{p}}$ partons

Odderon / C-odd gluon compound:

- C-odd exchange contribution predicted in Regge-theory *L. Lukaszuk & B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405*
- Confirmed in QCD as C-odd exchange of 3 (or odd #) gluons at leading order *J. Bartels, Nucl. Phys. B 175 (1980) 365; J. Kwiecinski & M. Praszlowics Phys. Lett. B 94 (1980) 413.*
- Searched for last 50 years, experimental evidence so far missing

Sensitive to C-odd exchange:

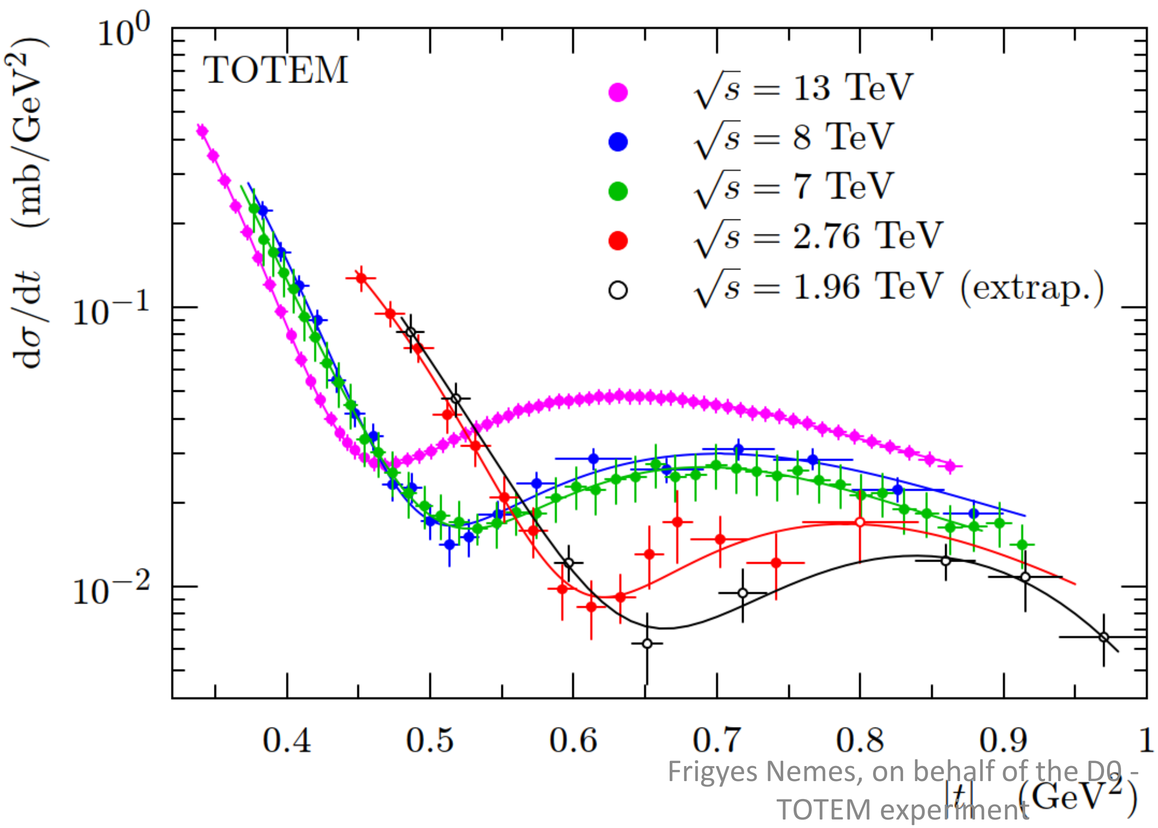
- “Coulomb-nuclear interference” (CNI) region ρ
- Diffractive minimum (“dip”): $Im\ (A_{el}^{had})$ suppressed w.r.t. $Re(A_{el}^{had})$!

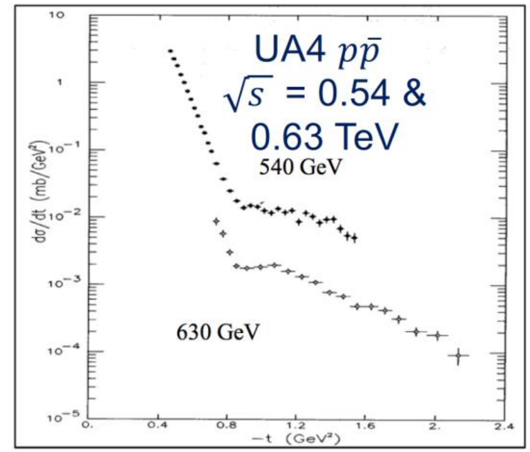


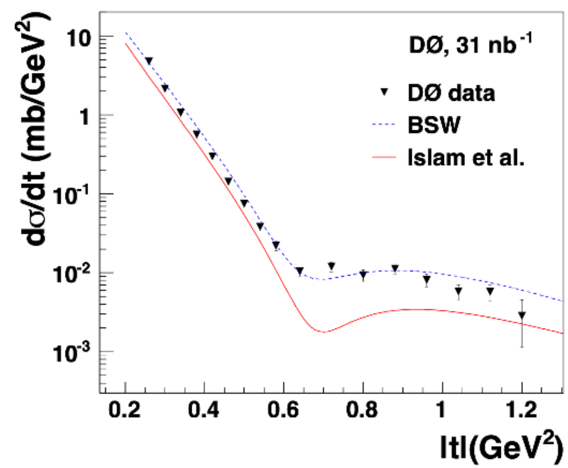
$$\rho = \left.\frac{\mathrm{Re}\,A_{el}^{had}}{\mathrm{Im}\,A_{el}^{had}}\right|_{t=0}$$

Strategy to compare pp and $\bar{p}p$ data sets

- At TeV-scale $pp\ d\sigma/dt$ characterized by a diffractive minimum ("dip") & a secondary maximum ("bump")
- @TeV scale: persistency of dip & bump for pp, absence of dip & bump for $\bar{p}p$
- $p\bar{p}\ d\sigma/dt$ characterized only by a "kink"

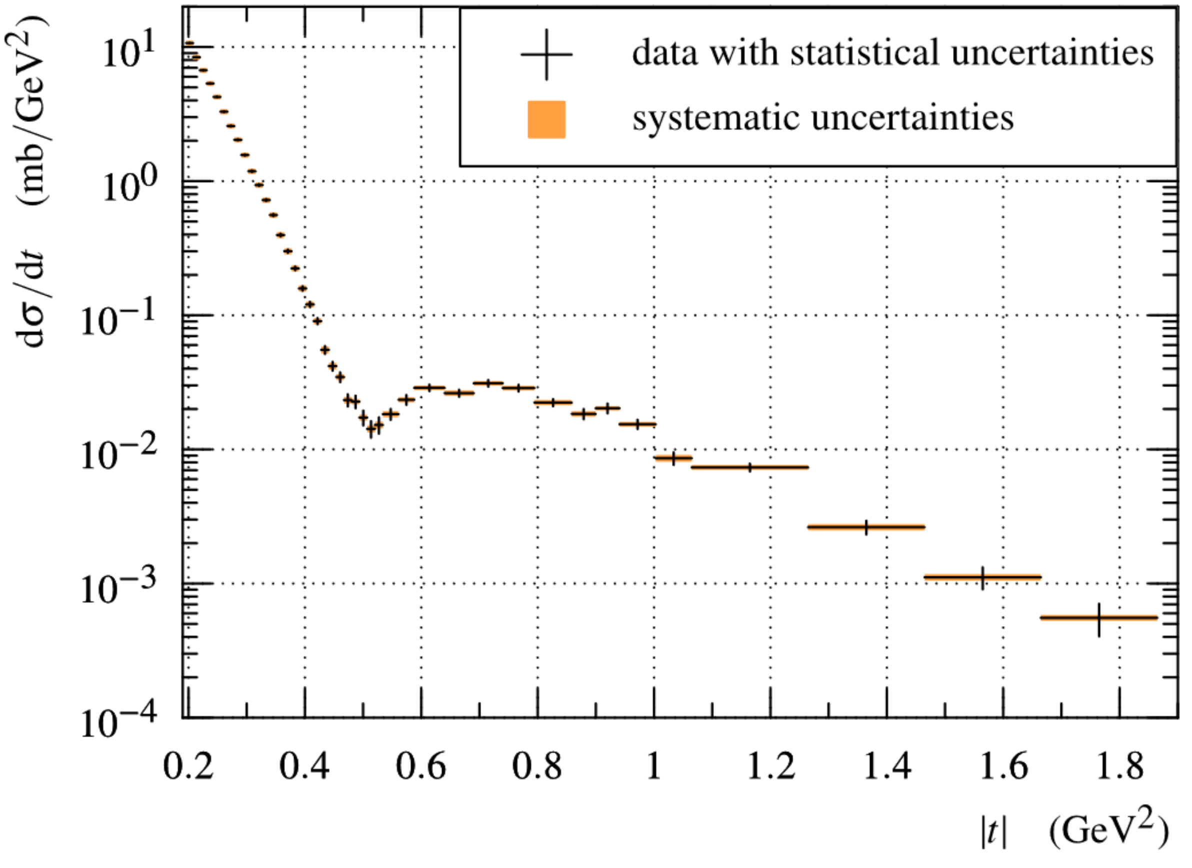






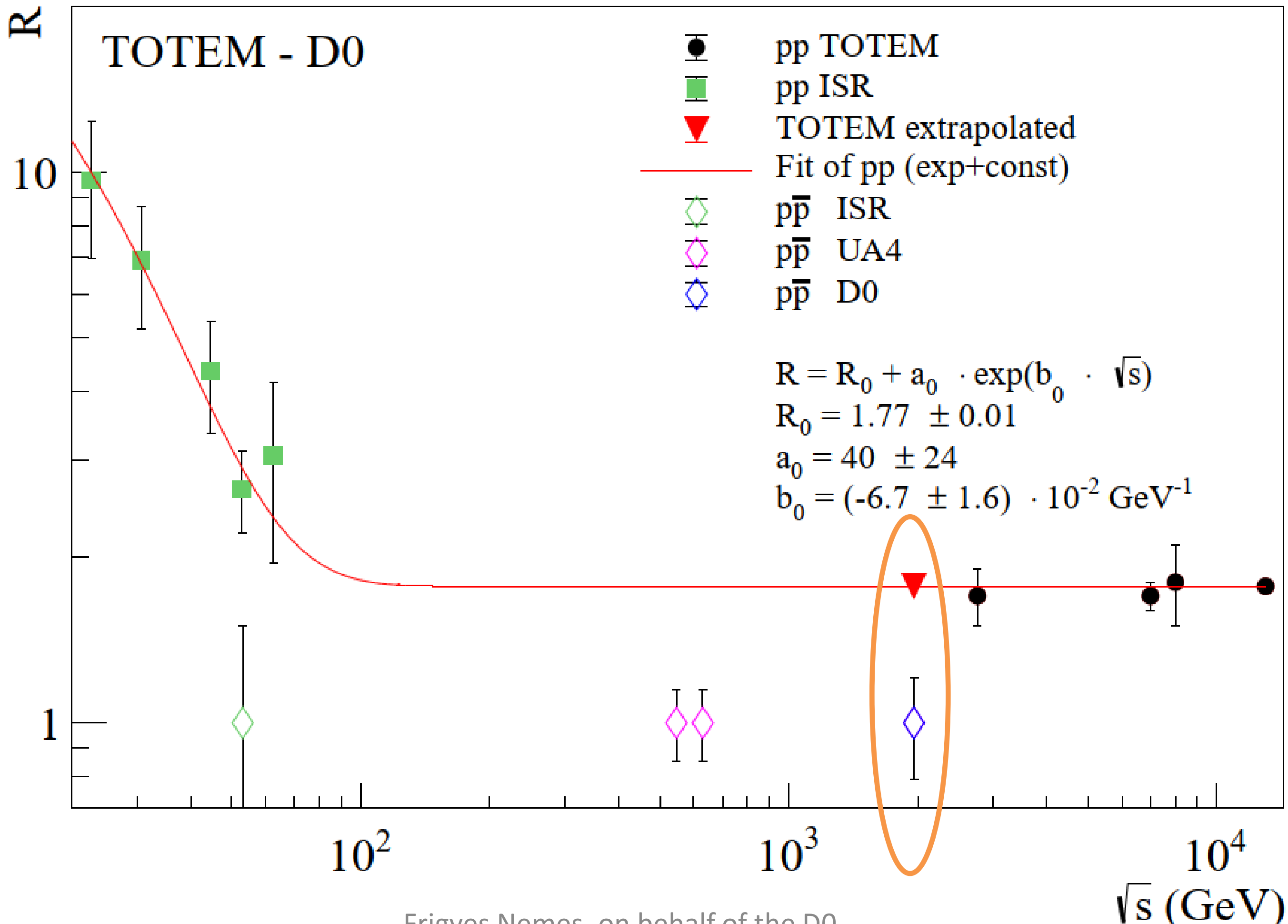
8 TeV publication and results (update)

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



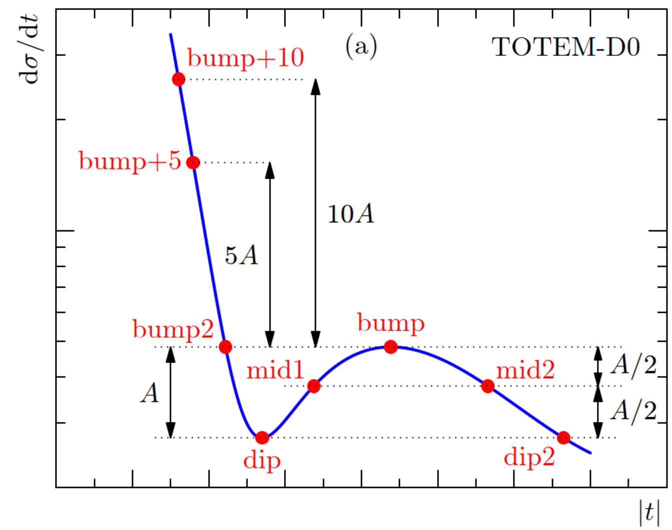
The bump over dip ratio R

- > 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

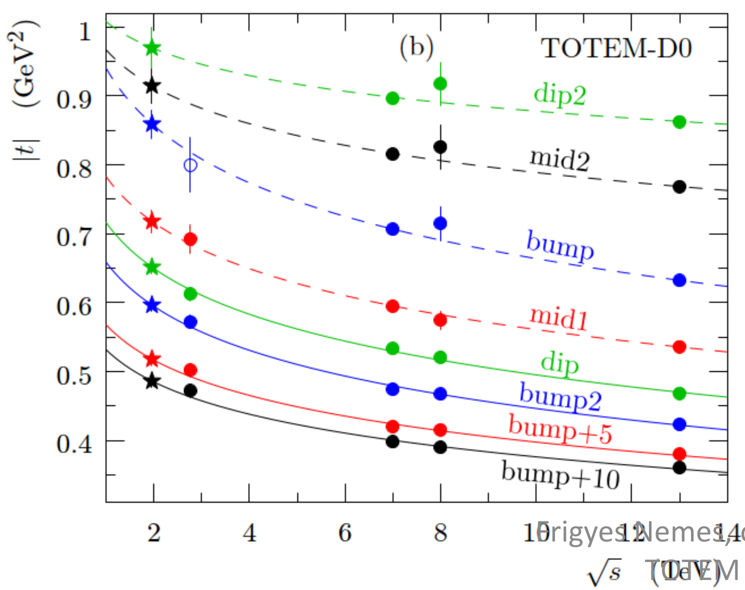


Extrapolation of pp cross-sections

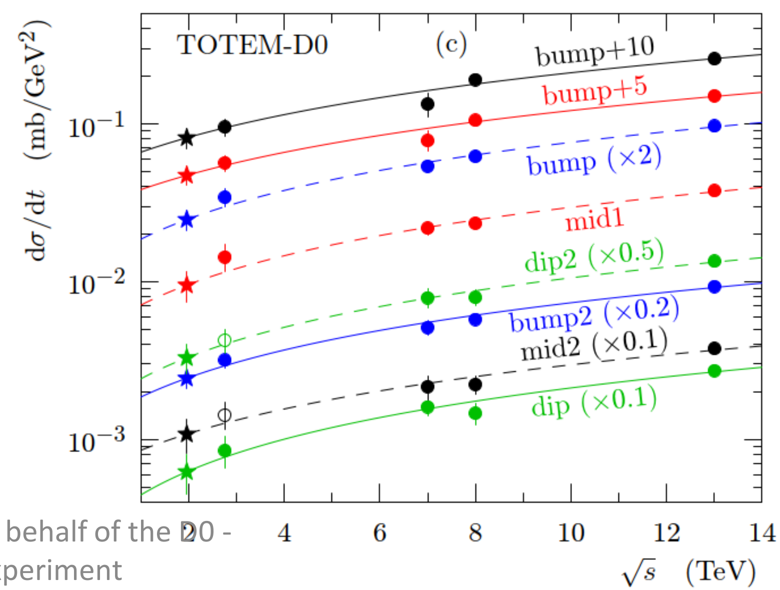
- Extrapolate 8 characteristic points (both their $d\sigma/dt$ & t) in dip-bump region of the pp elastic $d\sigma/dt$@ 2.76, 7, 8 & 13 TeV to 1.96 TeV $\Longrightarrow$ pp elastic $d\sigma/dt$ points @ 1.96 TeV
- Alternative functional forms tested: adequate fits provide consistent values within uncertainties



$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b$$



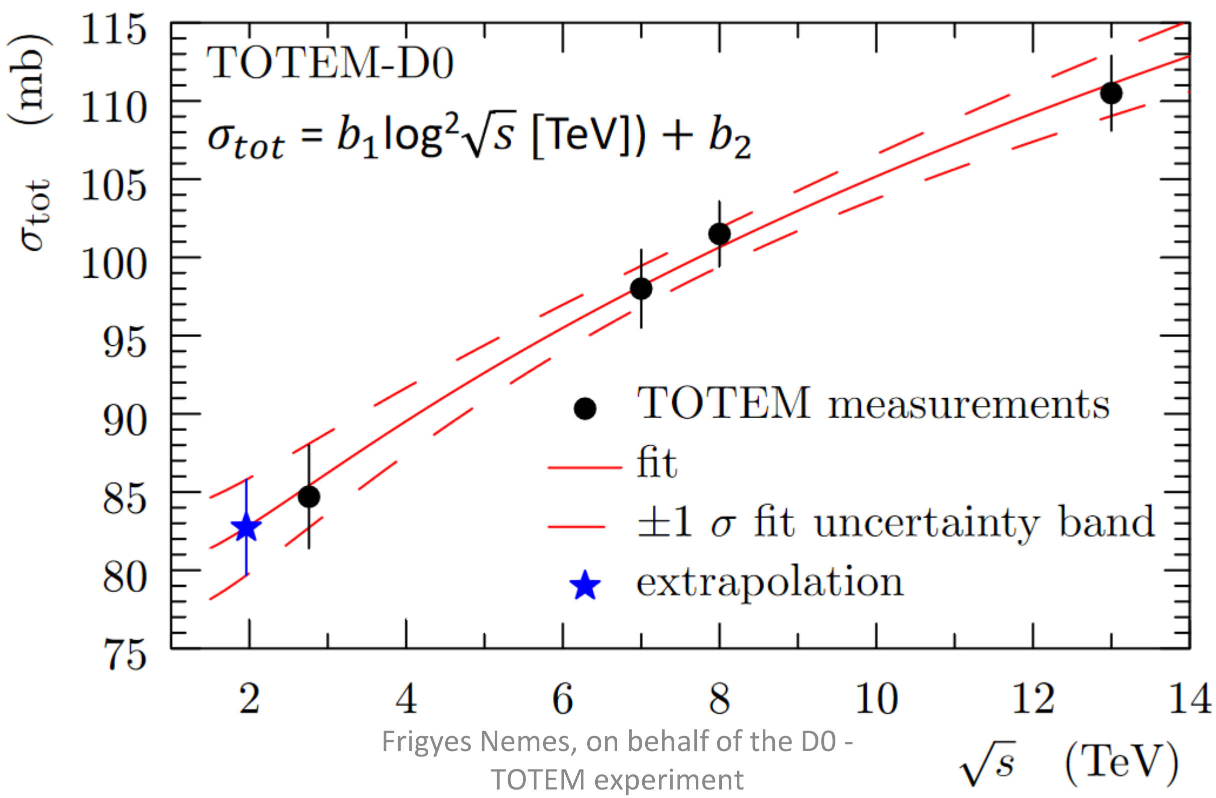
$$(d\sigma/dt) = c\sqrt{s}\,[\mathrm{TeV}] + d$$



Normalization of pp cross-sections

- pp σ_{tot} @ 1.96 TeV estimated from pp σ_{tot} @ 2.76, 7, 8 & 13 TeV
- OP ($d\sigma/dt|_{t=0}$) of pp consistent with OP of $\bar{p}p$ data
- Normalize pp $d\sigma/dt$ to a common OP with $\bar{p}p$ (same σ_{tot} within experimental & theoretical uncertainties)
- Normalization factor of TOTEM OP: 0.954 ± 0.076
- Elastic slopes B preserved during scaling

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}(t=0)\right)$$

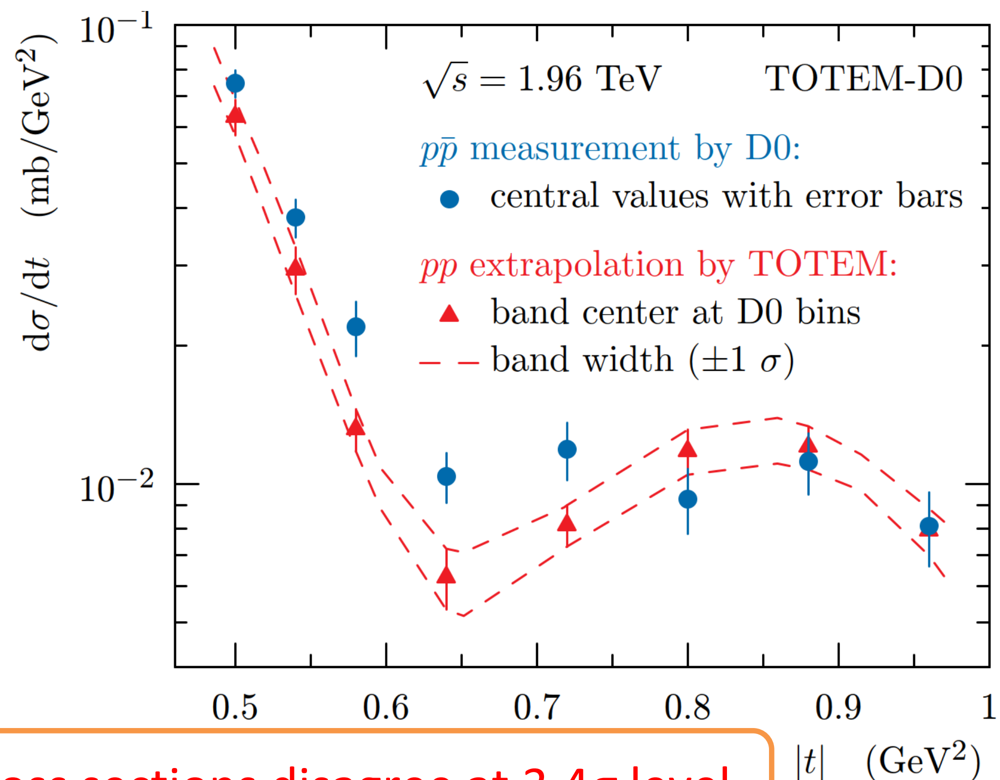


Comparison pp & $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV

- The extrapolated pp cross-section is normalized to the measured $\bar{p}p$ cross-section by requiring the optical points (dsigma/dt @ t = 0) to be equal
- Extrapolated pp points fitted using a double-exponential to provide $pp\ d\sigma/dt$ values @D0 measured|t|-values. Excellent fits @ 2.76, 7, 8,13 TeV (c.f. slide 7)
- MC used to determine $pp\ d\sigma/dt$ uncertainties @ D0 measured |t|-values
- Updated χ^2 test: ~0.2σ increase of significance (c.f. presentation)

Uncertainties of pp data points @ D0 measured |t|-values strongly correlated; full covariance matrix used

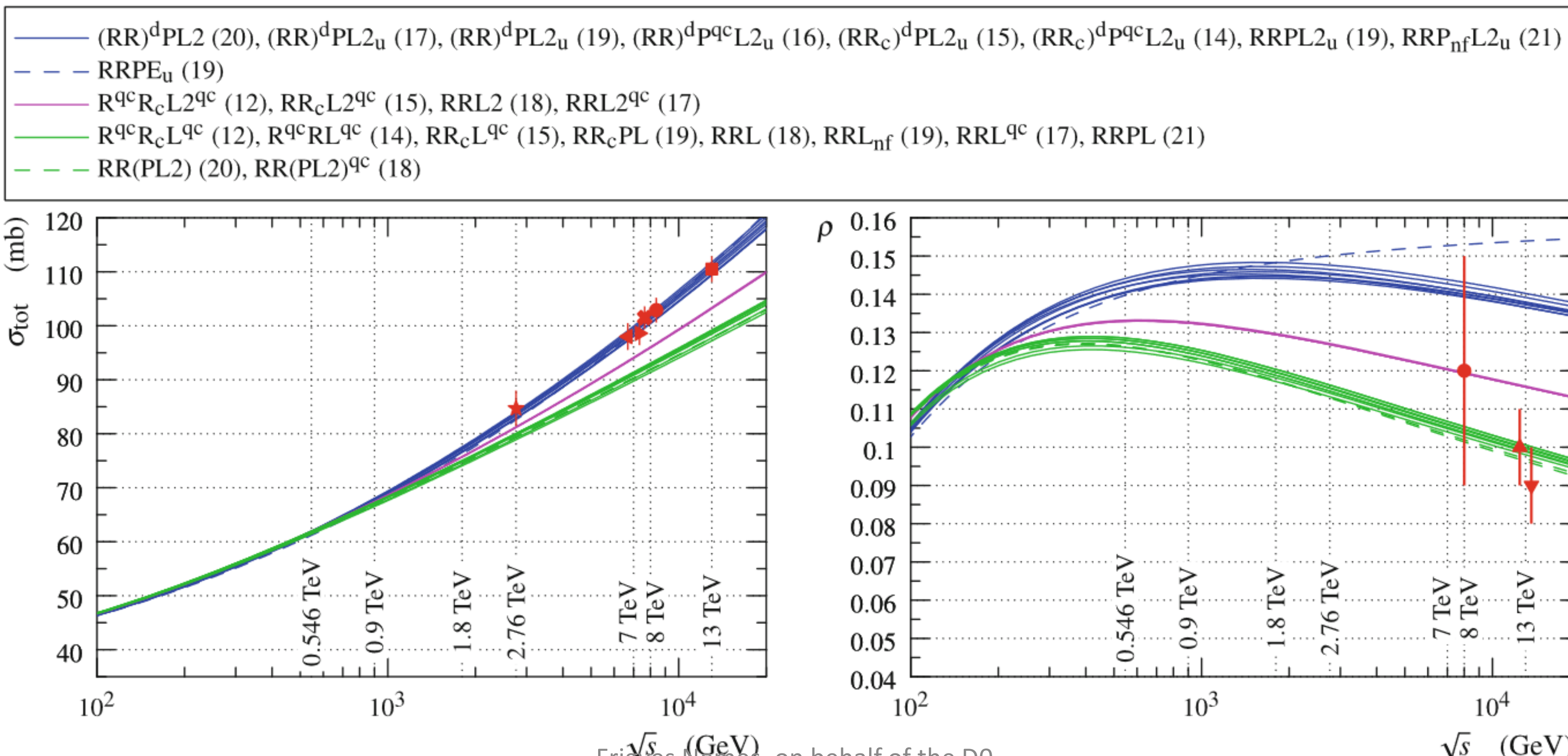
Significance confirmed by a combined Kolmogorov-Smirnov & normalization test



χ^2 test: pp & p$\bar{\text{p}}$ cross sections disagree at 3.4σ level

Previous evidence from pp ρ and σ_{tot}

- Using very low |t| TOTEM data @ $\sqrt{s}$= 13 TeV: ρ= 0.09 ± 0.01 (TOTEM, EPJC (2019) 785)
- Unable to describe TOTEM ρ & σ_{tot} measurements without adding colourless C-odd exchange (comparison to COMPETE predictions shown below)



Combining with pp ρ and σ_{tot} evidence

- Combine independent evidence of colourless C-odd exchange from TOTEM ρ & σ_{tot} measurements in a completely different $|t|$-domain with evidence from the pp & $\bar{p}p$ comparison

- Compared to all the COMPETE models, the TOTEM ρ & σ_{tot} measurement provide an odderon evidence between 3.4 and 4.6 σ, giving a total significance between 5.2 and 5.7 σ for t-channel exchange of a colourless C-odd gluonic compound (odderon) when combined with the TOTEM-D0 result

- Combination excludes models (*) without C-odd exchange@ 5.2 - 5.7σ $\Rightarrow$ observation of colourless C-odd gluonic compound(”odderon”)

* 1. COMPETE Coll., PRL 89 (2002) 201801; Durham group, PLB 748 (2018) 192.

2. Block-Halzen model, PRD 92 (2015) 114021: excluded at 5.2σ

The ATLAS σ_{tot} at 13 TeV

- TOTEM (direct counting experiment ⊗ Coulomb normalized elastic scattering)

$$\sigma_{tot}^{pp} = (110.5 \pm 2.4)\ \text{mb} \qquad \sigma_{\text{tot}} = \frac{16\pi}{1+\rho^2} \cdot \frac{\left.\frac{dN_{\text{el}}}{dt}\right|_{t=0}}{N_{\text{el}} + N_{\text{inel}}}$$

- ATLAS (luminosity dependent, van de Meer β*=11 m → 2500 m)

$$\sigma_{tot}^{pp} = (104.7 \pm 1.1)\ \text{mb} \qquad \sigma_{tot}^{2} = \frac{16\pi}{1+\rho^2} \frac{\left.\frac{dN_{\text{el}}}{dt}\right|_{t=0}}{\mathcal{L}}$$

- Normalisation difference (follows trend @7 & 8 TeV)
- Elastic |t| slope and non-exponentiality $e^{-B|t|-C|t|^2-D|t|^3}$: ~ +1 mb
- ATLAS results @7 & 8 TeV:
  - Only B (whereas B,C, D @ 13 TeV): results unchanged
  - Beam energy uncertainty 0.5 % → 0.1 % @ 13 TeV: results not corrected by ATLAS
- ATLAS on Low-mass diff.: in clear contradiction with constraints from 7 TeV

$$\sigma_{inel}^{|\eta|>6.5} \leq 6.3\ \text{mb} \quad @95\ \%\ \text{CL}$$

Conclusions

- Data-driven comparison between $\bar{p}p$ (D0 @ √s= 1.96 TeV) & pp (TOTEM @ √s= 2.76, 7, 8, 13 TeV) elastic $d\sigma/dt$
  PRL 127 (2021) 062003
- Extrapolate "characteristic" points of elastic pp $d\sigma/dt$ to predict elastic pp $d\sigma/dt$@ √s= 1.96 TeV
- Elastic pp and $\bar{p}p$ cross sections differ @ 3.4σ at √s= 1.96 TeV ⟹ evidence of t-channel exchange of a colourless C-odd gluonic compound i.e. odderon
- Combined with TOTEM ρ & total cross section results ⟹ 5.2 - 5.7σ & thus first experimental observation of a colourless C-odd gluonic compound i.e. odderon
- Odderon observation answers to questions and objections
- E. Leader, Discovery of the odderon, Nature Review Physics (2021)
- Major discovery @ LHC & Tevatron

Backup slides

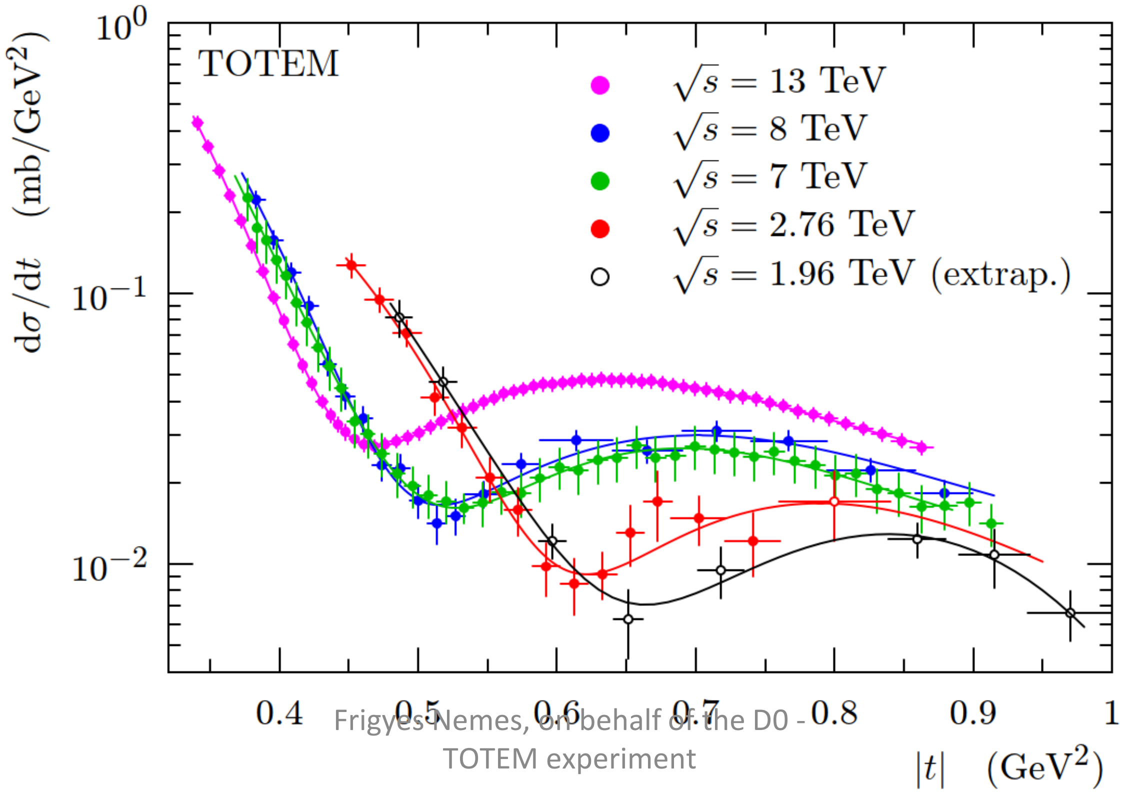
Double exponential fits of TOTEM data sets

- Excellent fits for all *pp* data sets @ 2.76, 7, 8 & 13 TeV

$$h_1(t) = a_1 e^{-a_2|t|^2 - a_3|t|}$$

$$h_2(t) = a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$$

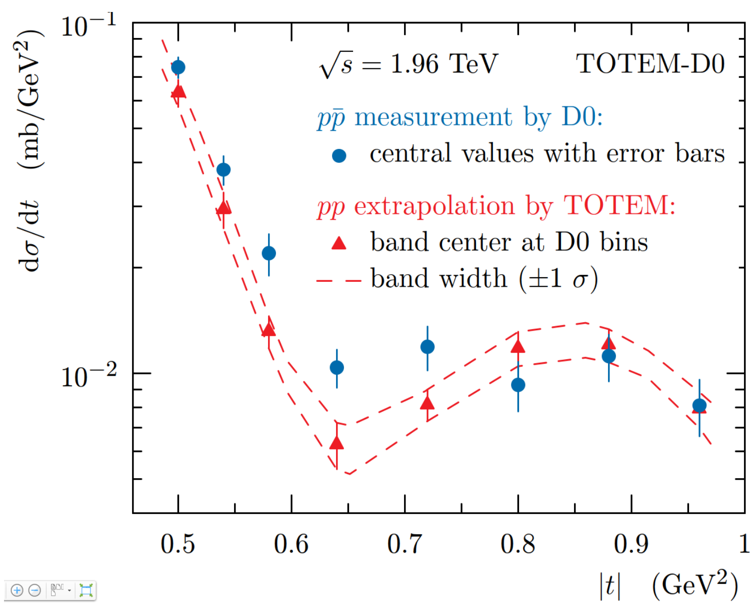
$$h(t) = a_1 e^{-a_2|t|^2 - a_3|t|} + a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$$



Comparison of pp & $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV: the χ^2 formula

- A = normalization, B = elastic slope

$$\chi^2 = \Sigma_{data\ points\ i\ j}(Tot_i - D0_i)C^{-1}_{ij}(Tot_j - D0_j) + \frac{(A-A_0)^2}{\sigma_A^2} + \frac{(B-B_0)^2}{\sigma_B^2}$$

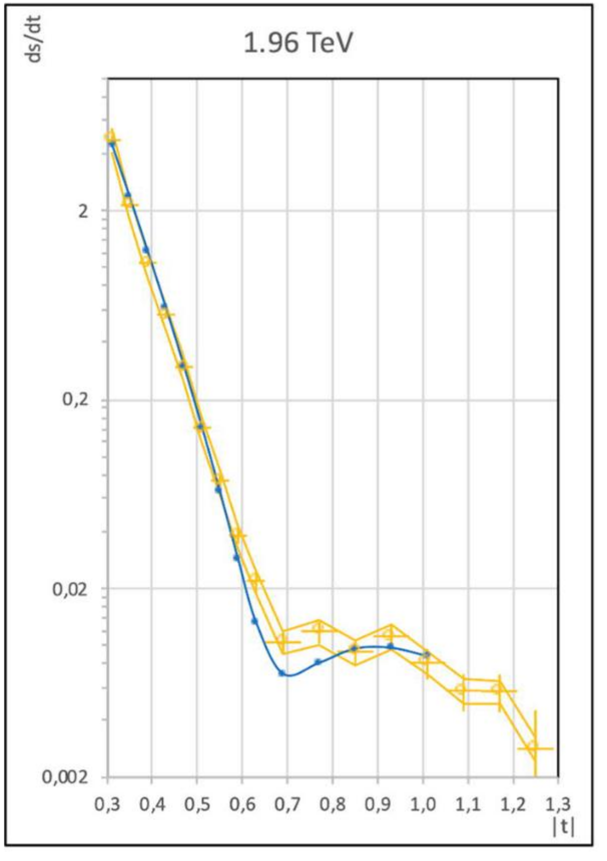


χ^2 test: pp & p$\bar{p}$ cross sections disagree at 3.4σ level

The Durham model of elastic scattering (used in PDG review)

V.A. Khoze, M.G. Ryskin & M. Tasevsky, High energy Soft QCD and Diffraction, https://pdg.lbl.gov/

- PDG: reasonable description of elastic pp & $\bar{p}p$ obtained with Pomeron only
- Durham model without odderon (V. A. Khoze, A.D. Martin & M.G. Ryskin, PLB 748 (2018))
- Tuned to TOTEM pp data $\Longrightarrow$ compromise its description of $p\bar{p}$
- Fails to describe D0 1.96 TeV elastic $\bar{p}p$ in dip-bump region (4.3σ)



TOTEM experiment