

The discovery of the Odderon

and forward physics results

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

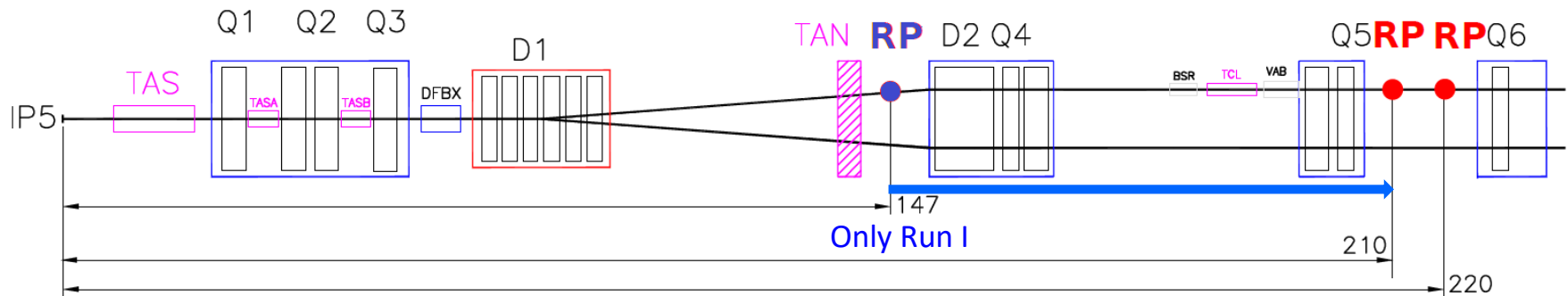
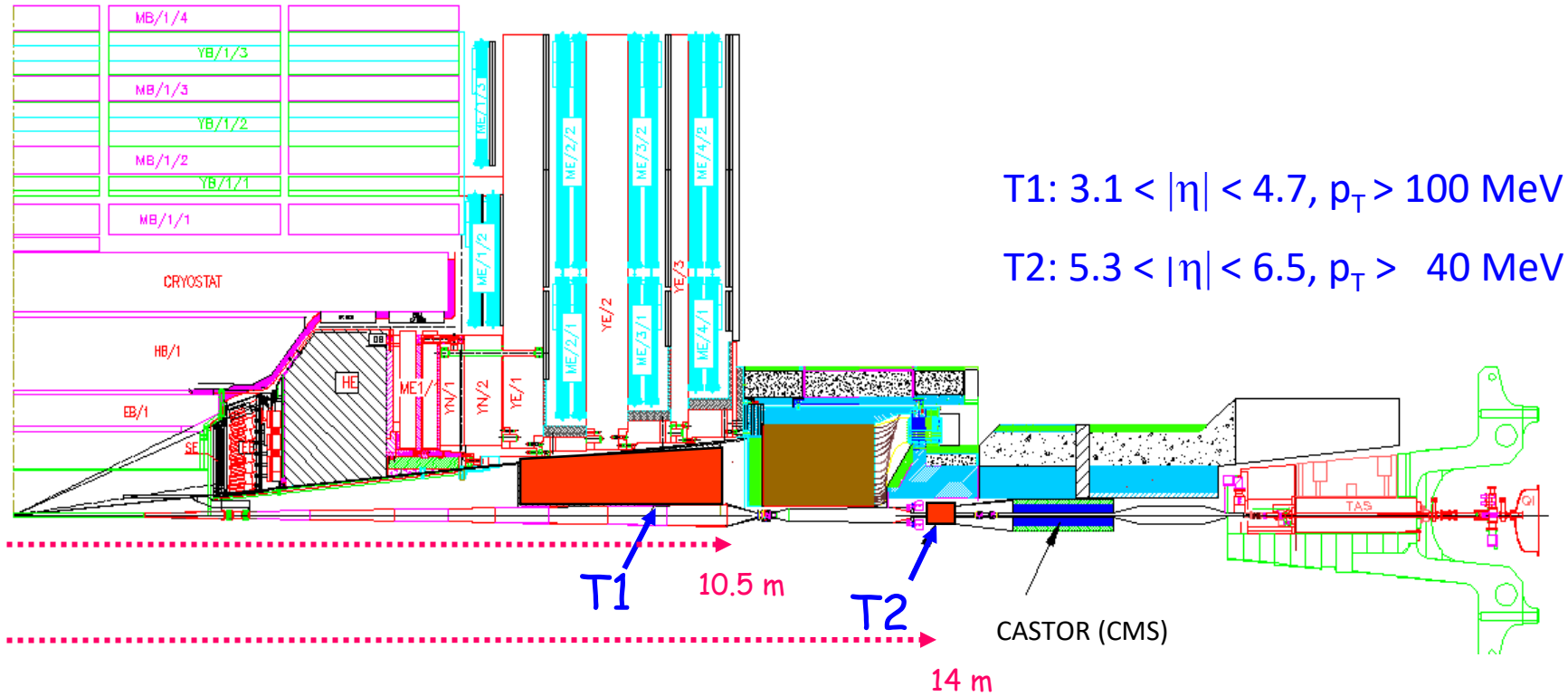
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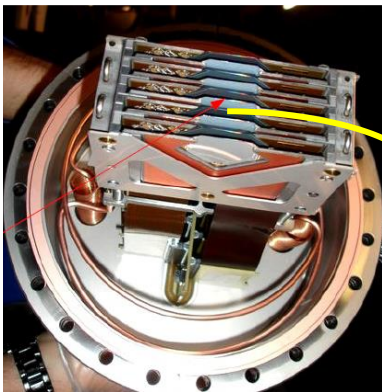
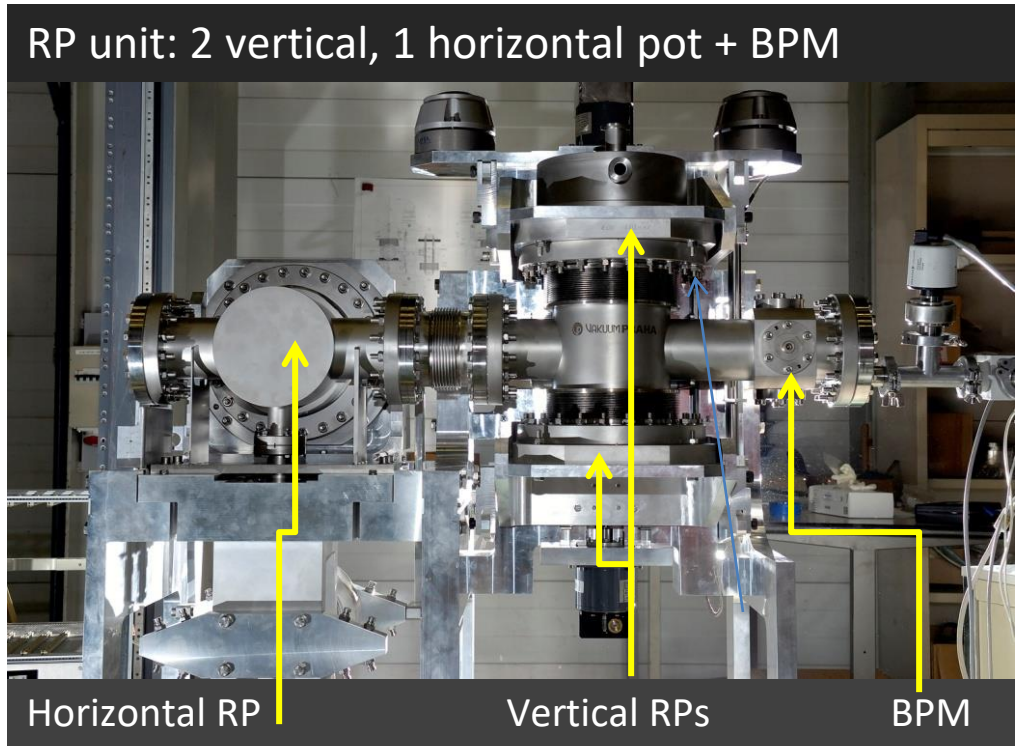
*Also at **MATE, Gödöllő – Gyöngyös**
Wigner RCP, Budapest, Hungary

Experimental layout of the TOTEM experiment (LHC Run II)

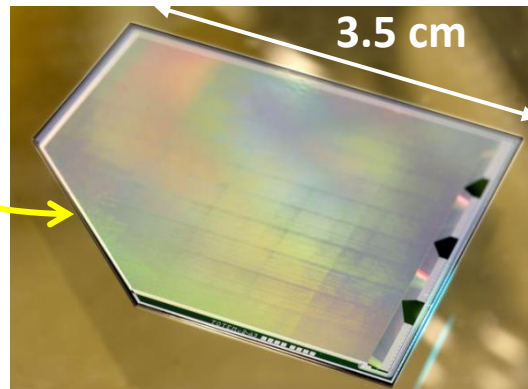


The Roman Pot (RP) stations of the TOTEM experiment

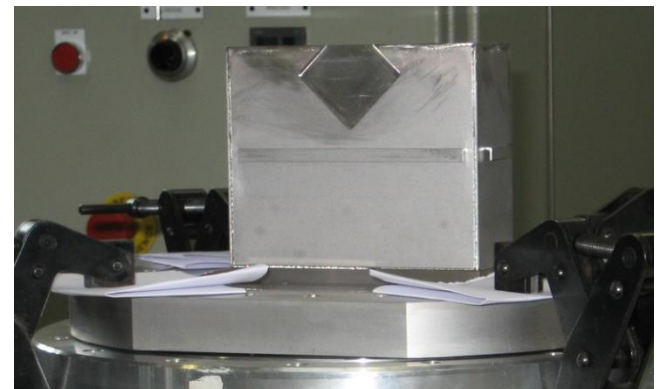
- Two RP stations at 210 and 220 m from the IP contain measuring planes separated by 10 and 5 m respectively
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few μrad)
- BPM: precise position rel. to beam
- Overlapping detectors: relative alignment ($10\ \mu\text{m}$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



10 planes of edgeless detectors

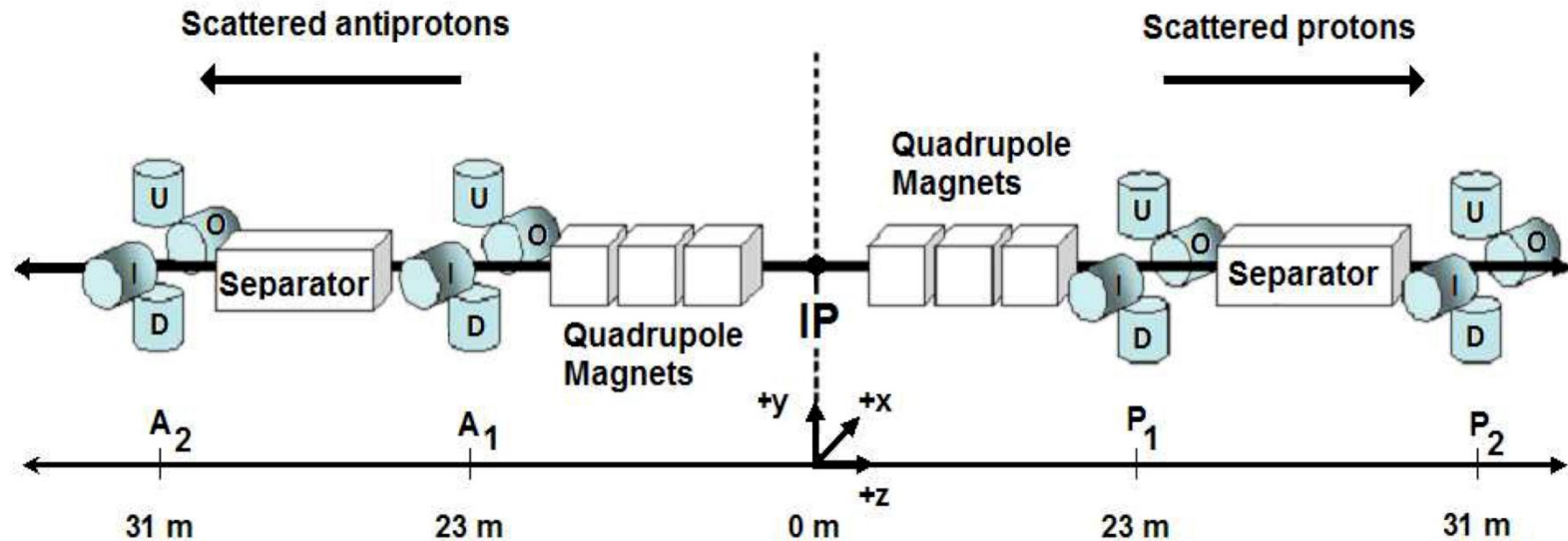


Si edgeless detector



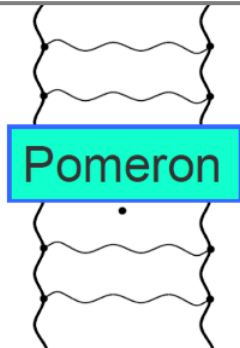
1 Roman Pot

Experimental layout of the D0 experiment (Tevatron, Fermilab)

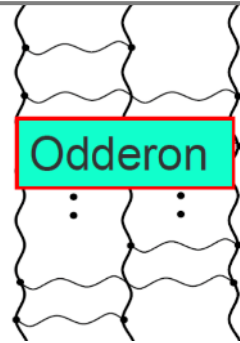


- Elastic $\bar{p}p$ $d\sigma/dt$ measurements: measure both the intact \bar{p} & p in D0 Roman Pots at 23 - 31 m from IP with scintillating fibre detectors
- Measurement at $\sqrt{s} = 1.96$ TeV: PRD 86 (2012) 012009.

Elastic scattering: multi-gluon exchanges



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



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

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

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

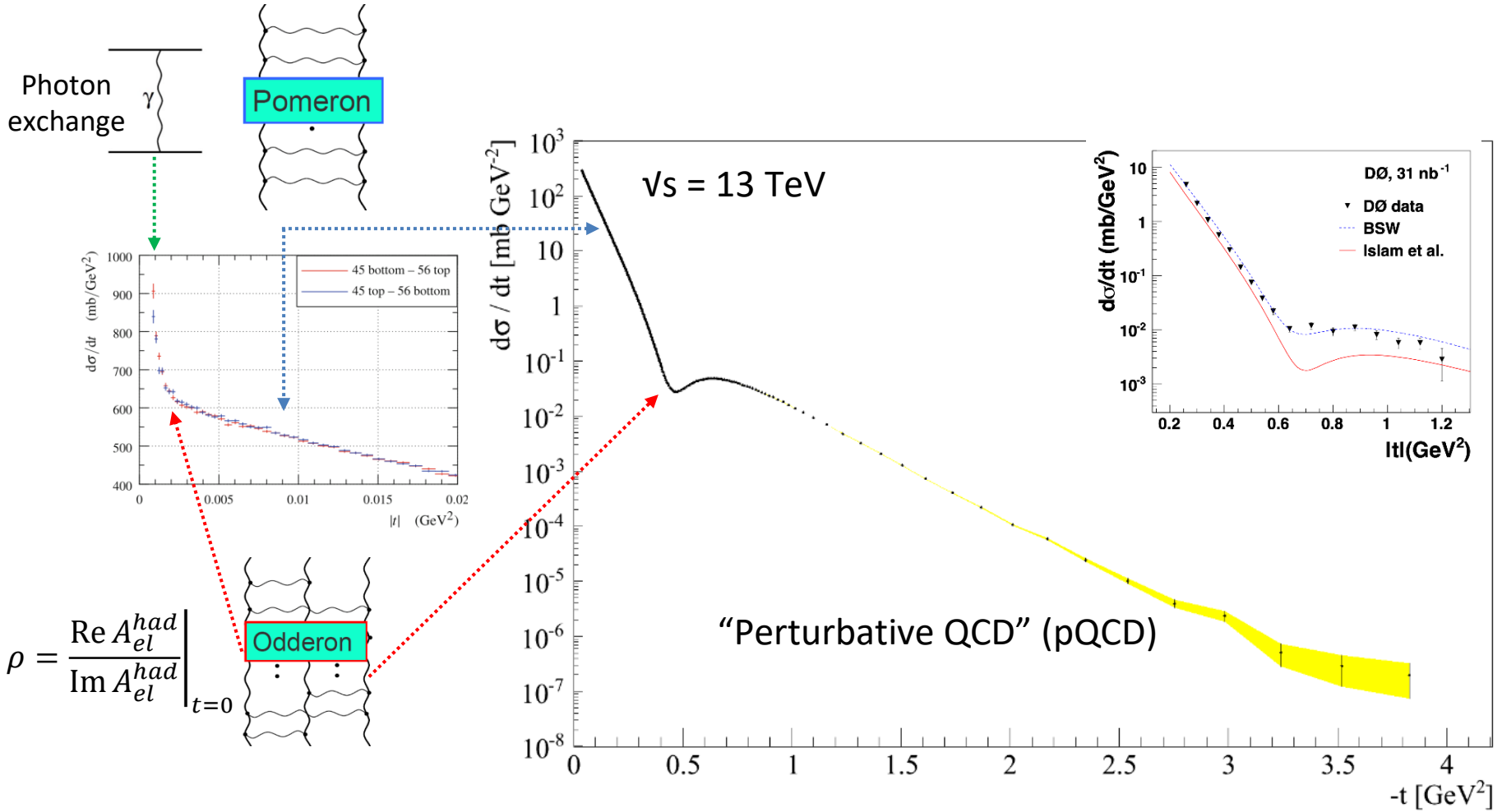
Odderon / C-odd gluon compound:

- 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

Elastic pp differential cross-section & C-odd exchange

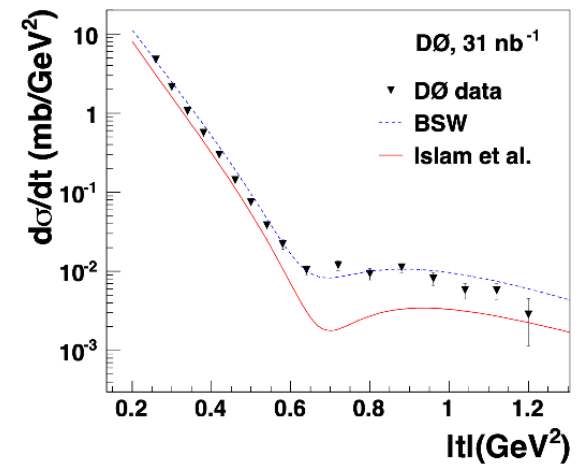
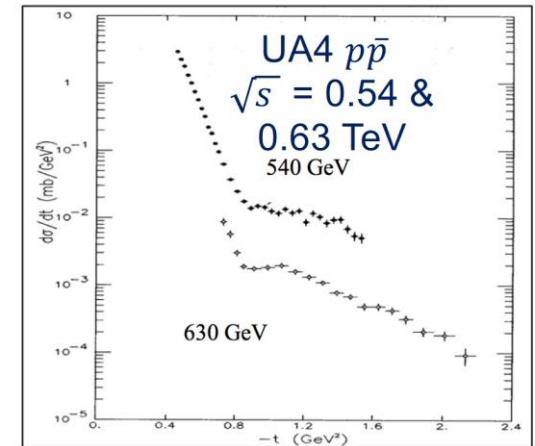
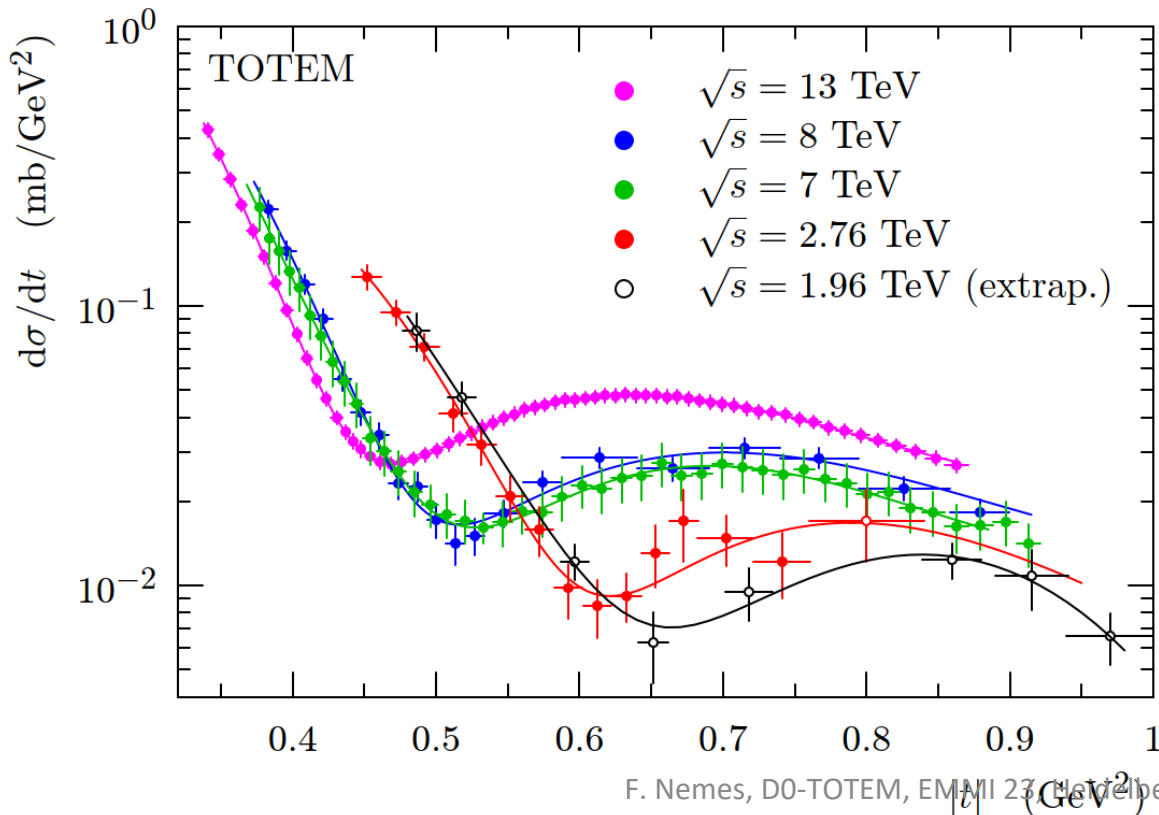
Sensitive to C-odd exchange:

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



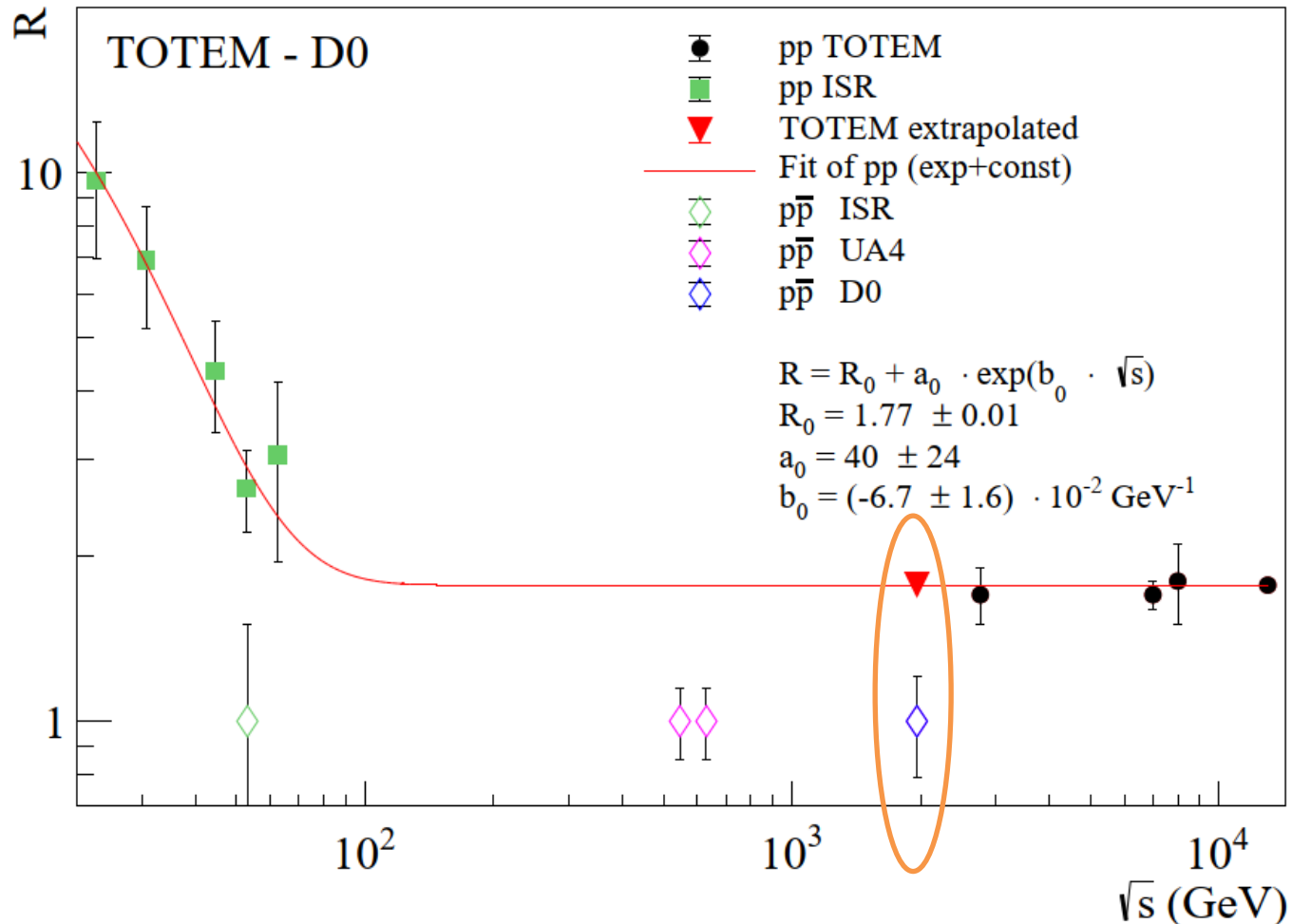
Strategy to compare pp and $p\bar{p}$ data sets

- 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 $p\bar{p}$
- $p\bar{p}$ $d\sigma/dt$ characterized only by a “kink”



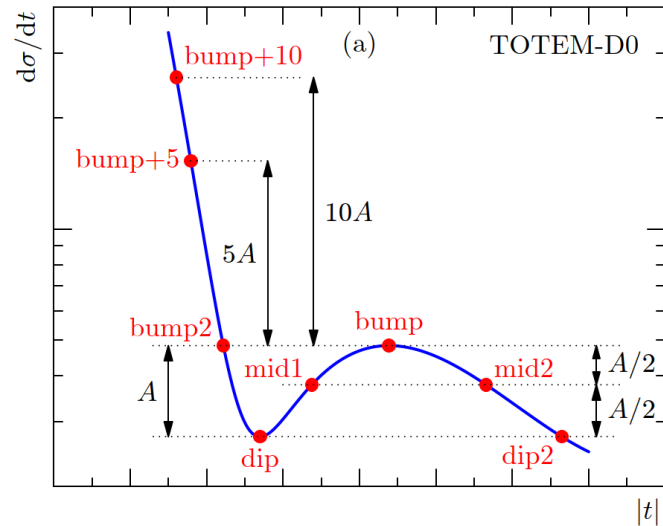
The bump over dip ratio R

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

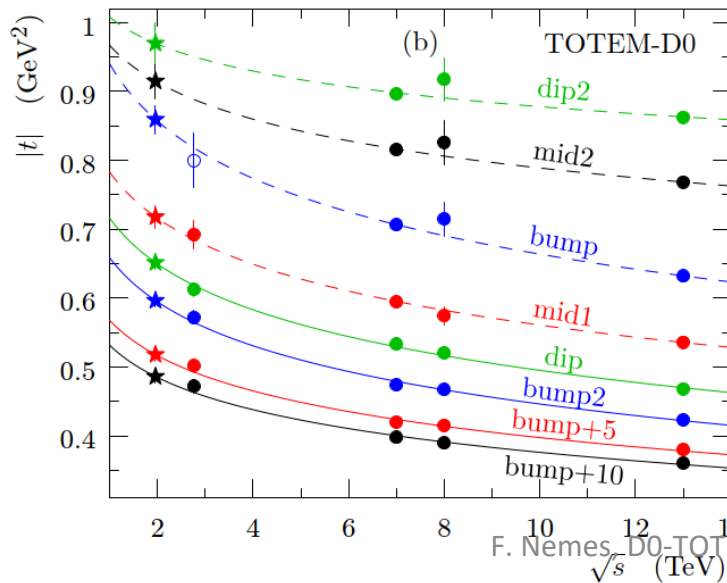


Extrapolation of pp cross-sections

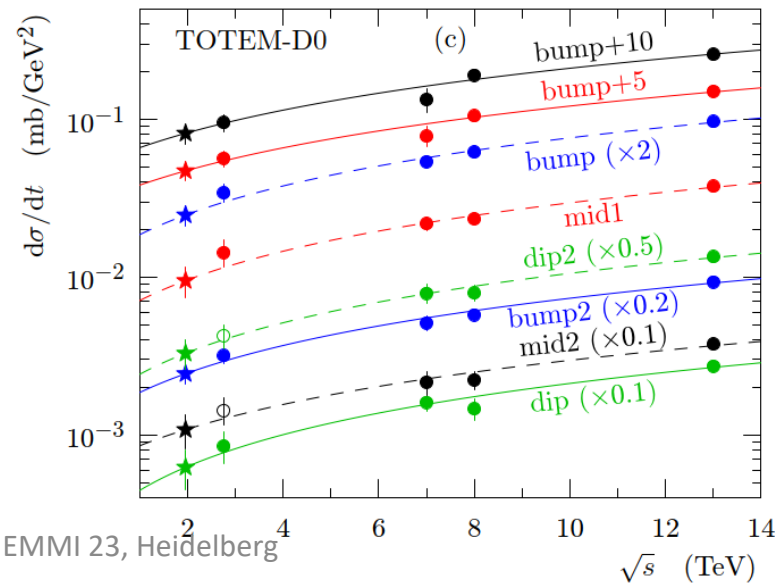
- Extrapolate 8 characteristic points (both their $d\sigma/dt$ & t) in dip-bump region of the pp elastic $d\sigma/dt$ @ 2.76, 7, 8 & 13 TeV to 1.96 TeV \Rightarrow pp elastic $d\sigma/dt$ points @ 1.96 TeV
- Alternative functional forms tested: adequate fits provide consistent values within uncertainties



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



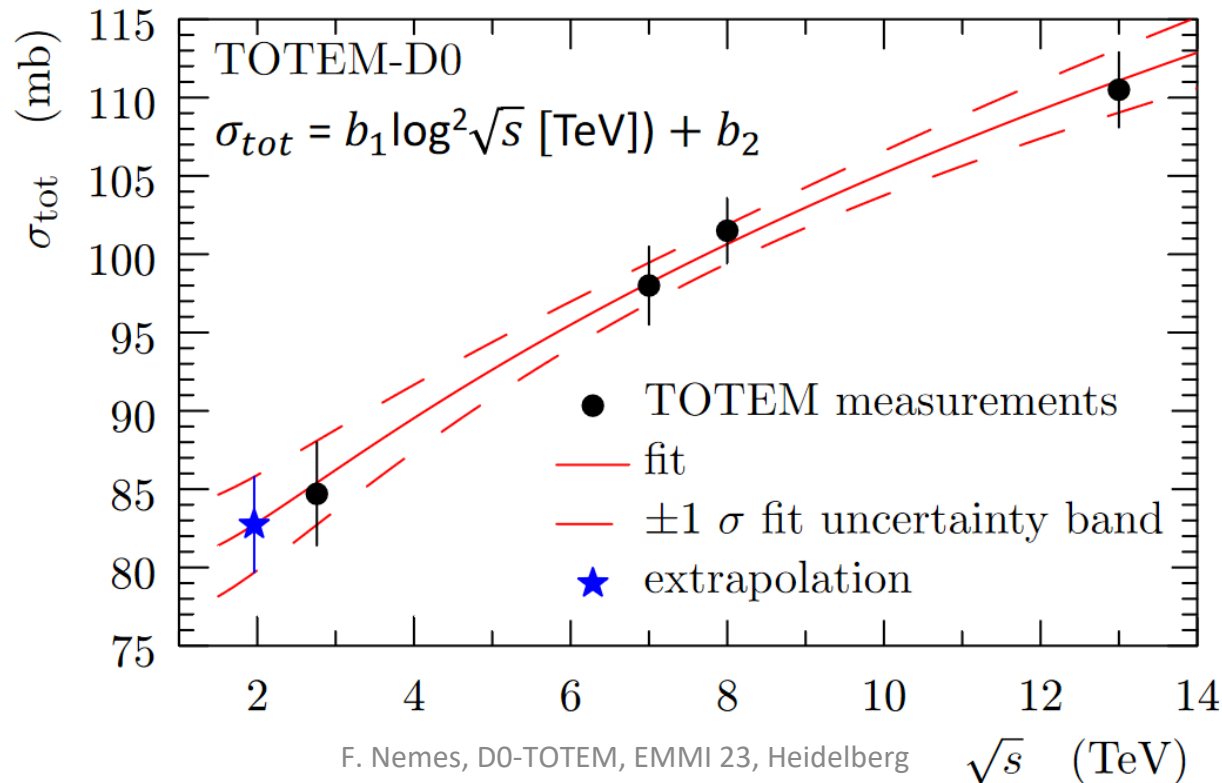
$$(d\sigma/dt) = c\sqrt{s} [\text{TeV}] + d$$



Normalization of pp cross-sections

- $pp \sigma_{\text{tot}}$ @ 1.96 TeV estimated from $pp \sigma_{\text{tot}}$ @ 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

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

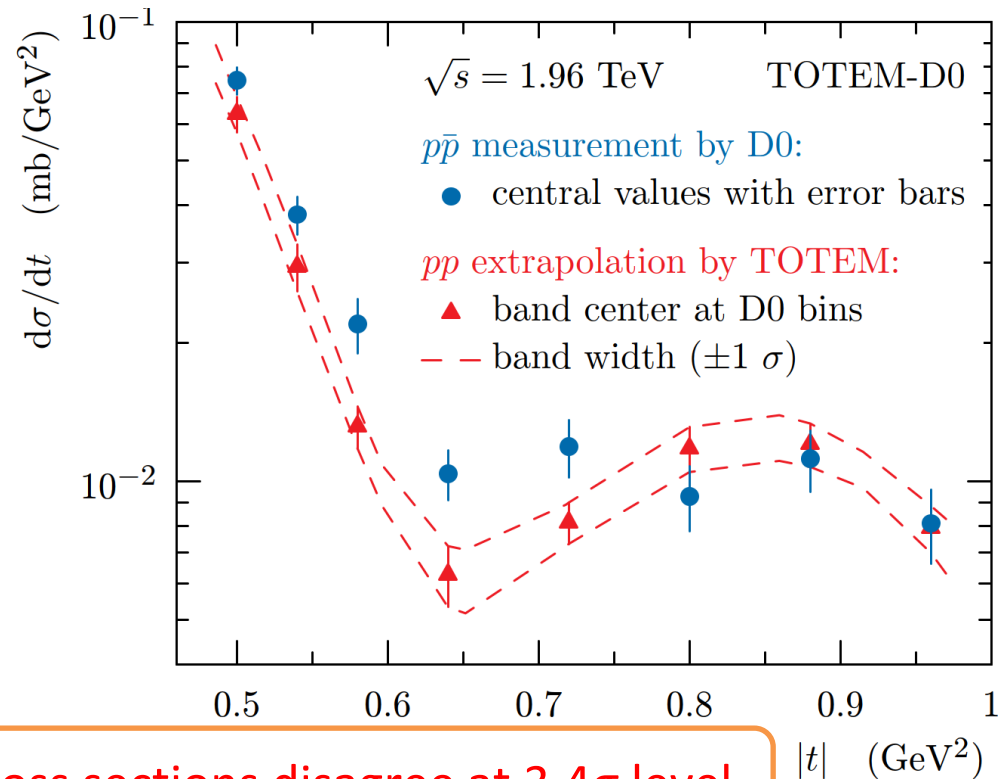


Comparison pp & $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

- The extrapolated pp cross-section is normalized to the measured $p\bar{p}$ cross-section by requiring the optical points ($d\sigma/dt$ @ $t = 0$) 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 (backup sl.)
- MC used to determine pp $d\sigma/dt$ uncertainties @ D0 measured $|t|$ -values

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

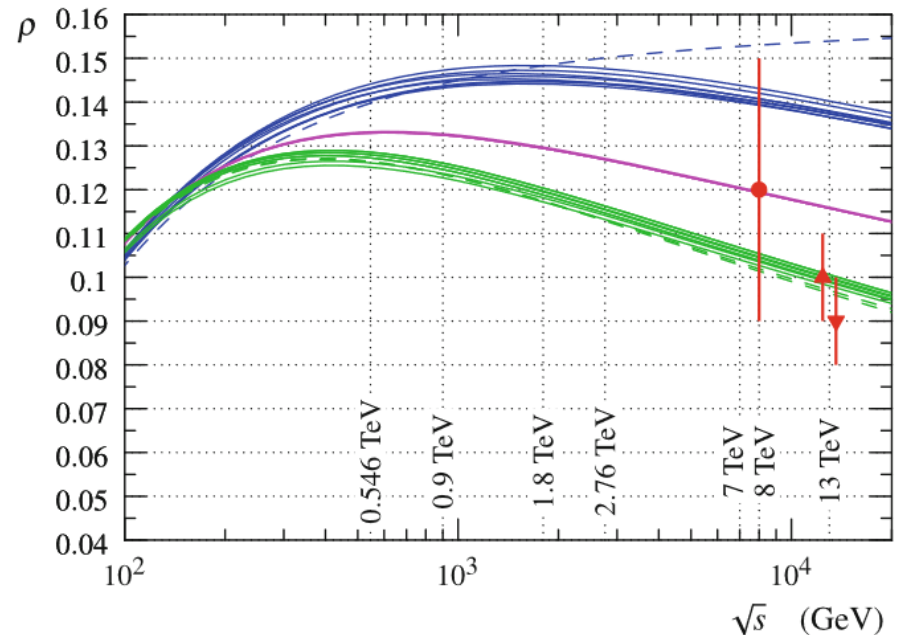
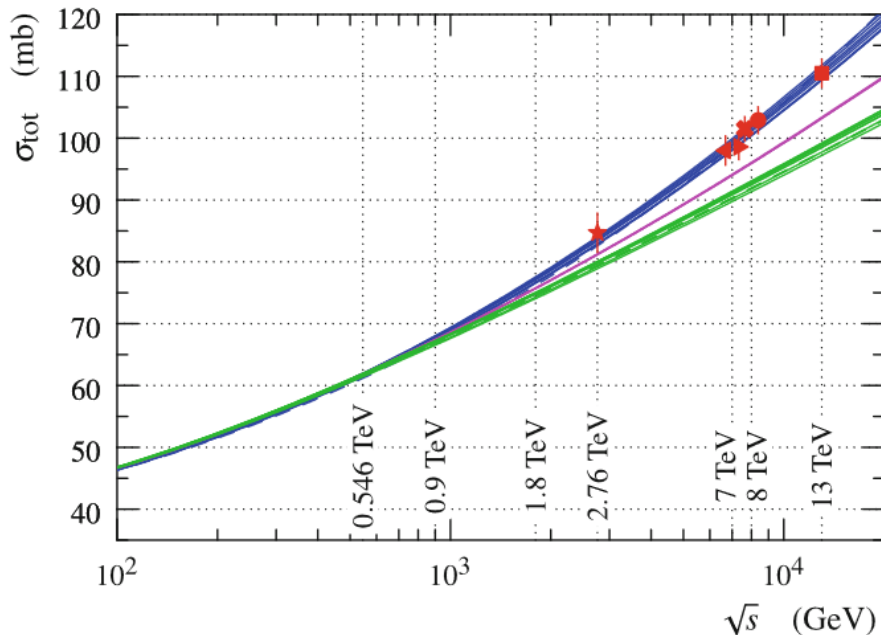
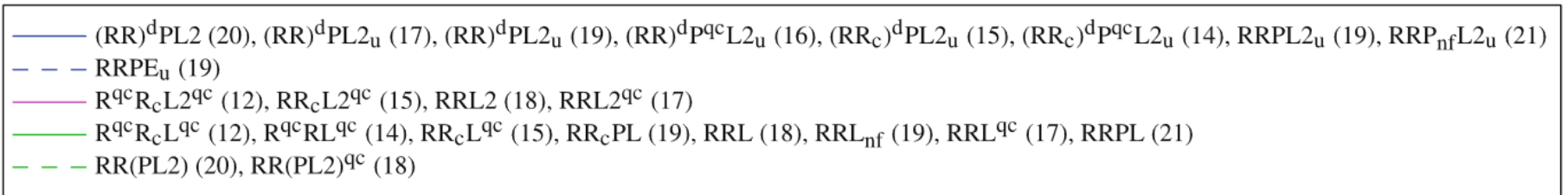
Significance confirmed by a combined Kolmogorov-Smirnov & normalization test



χ^2 test: pp & $p\bar{p}$ 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: $\rho = 0.09 \pm 0.01$ (TOTEM, EPJC (2019) 785)
- Unable to describe TOTEM ρ & σ_{tot} measurements without adding colourless C -odd exchange (comparison to COMPETE predictions shown below)



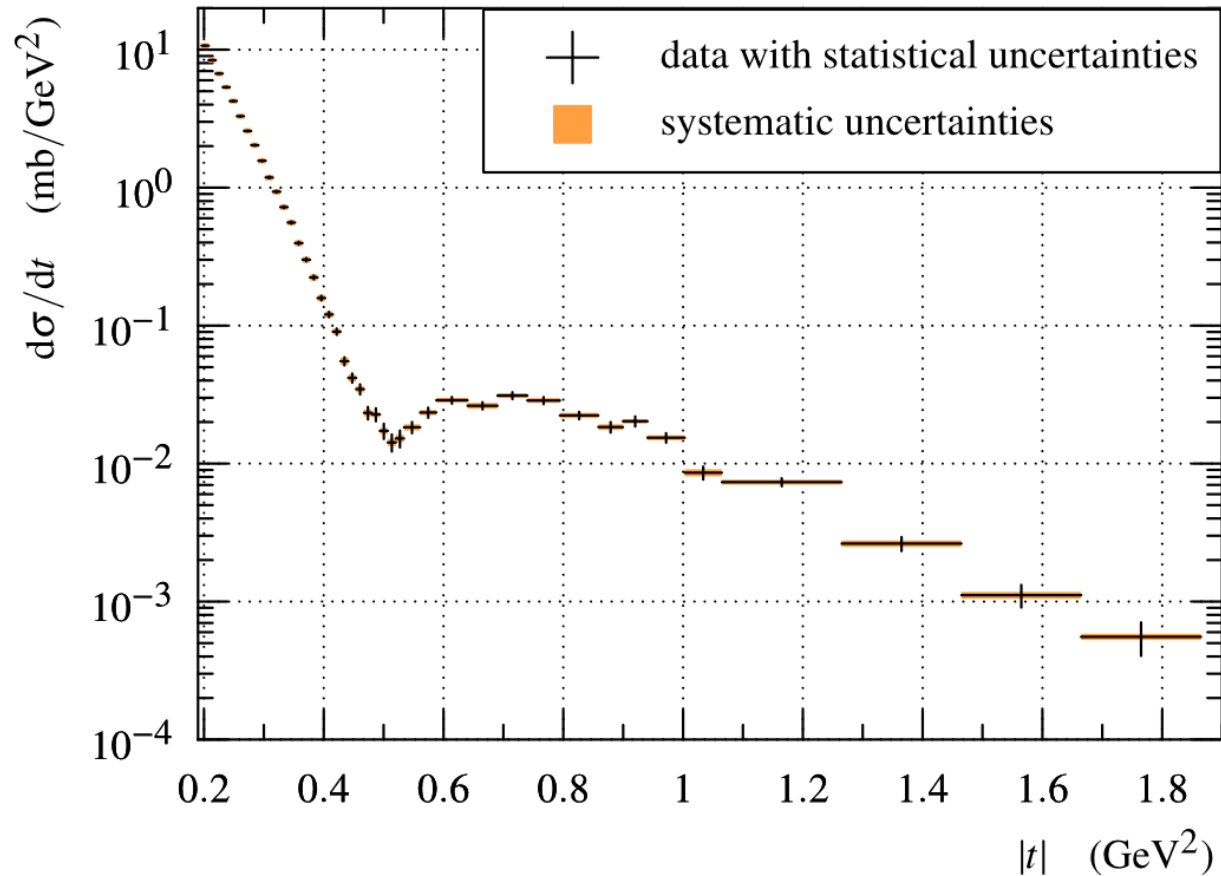
Combining with pp ρ and σ_{tot} evidence

- 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 - 5.7 $\sigma \Rightarrow$ 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 5.2 σ

8 TeV publication and results (update)

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



Conclusions

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

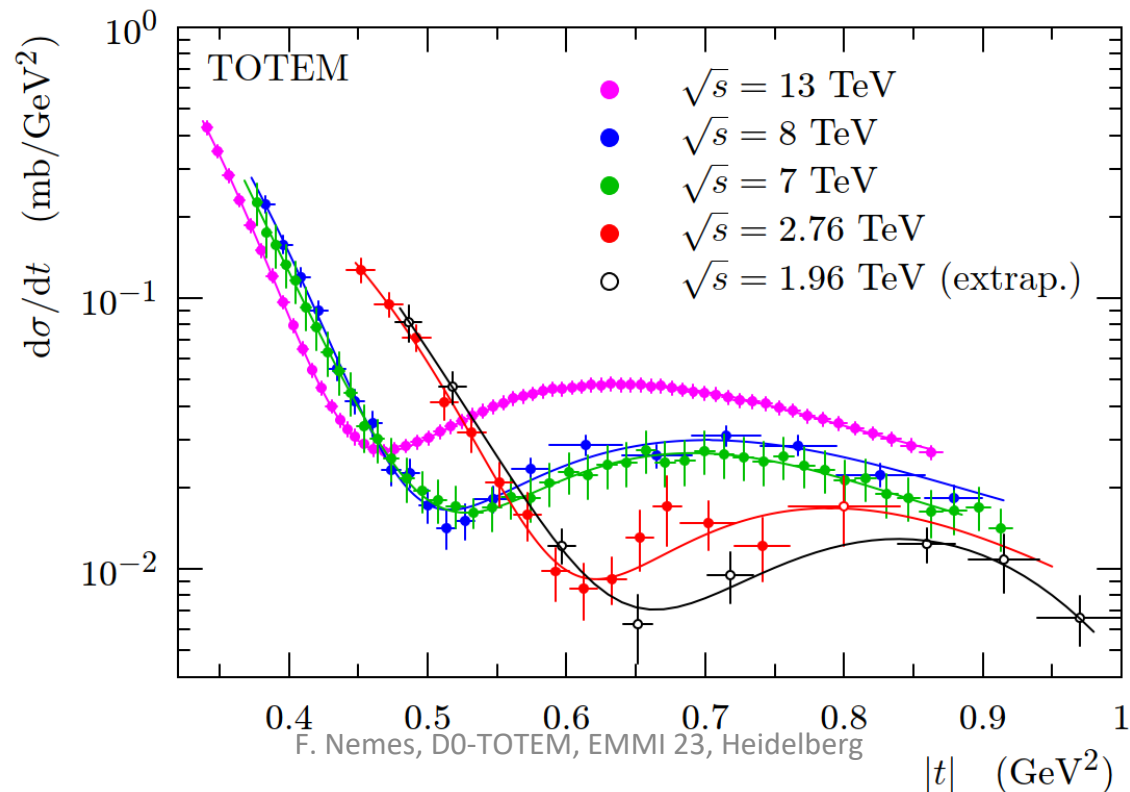
Backup slides

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

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

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

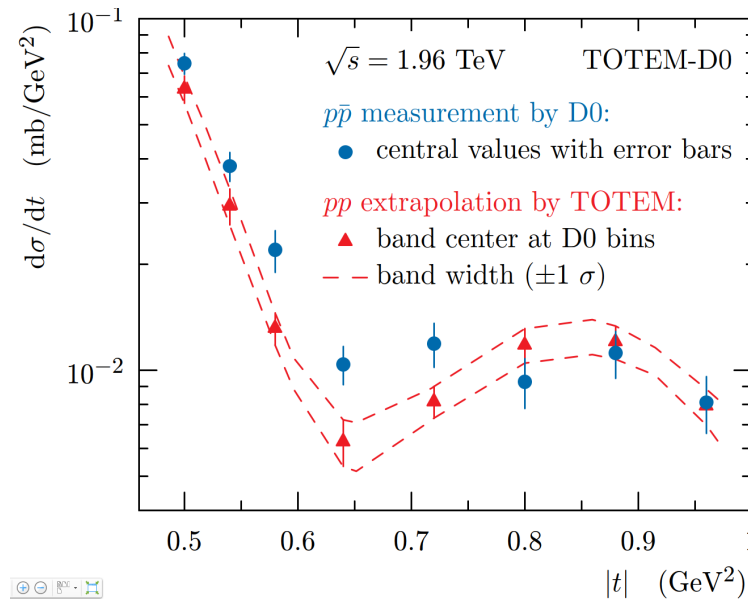
$$h(t) = a_1 e^{-a_2 |t|^2 - a_3 |t|} + a_4 e^{-a_5 |t|^3 - a_6 |t|^2 - a_7 |t|}$$



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

- A = normalization, B = elastic slope

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



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