


# The first experimental observation of odderon exchange

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**CERN***

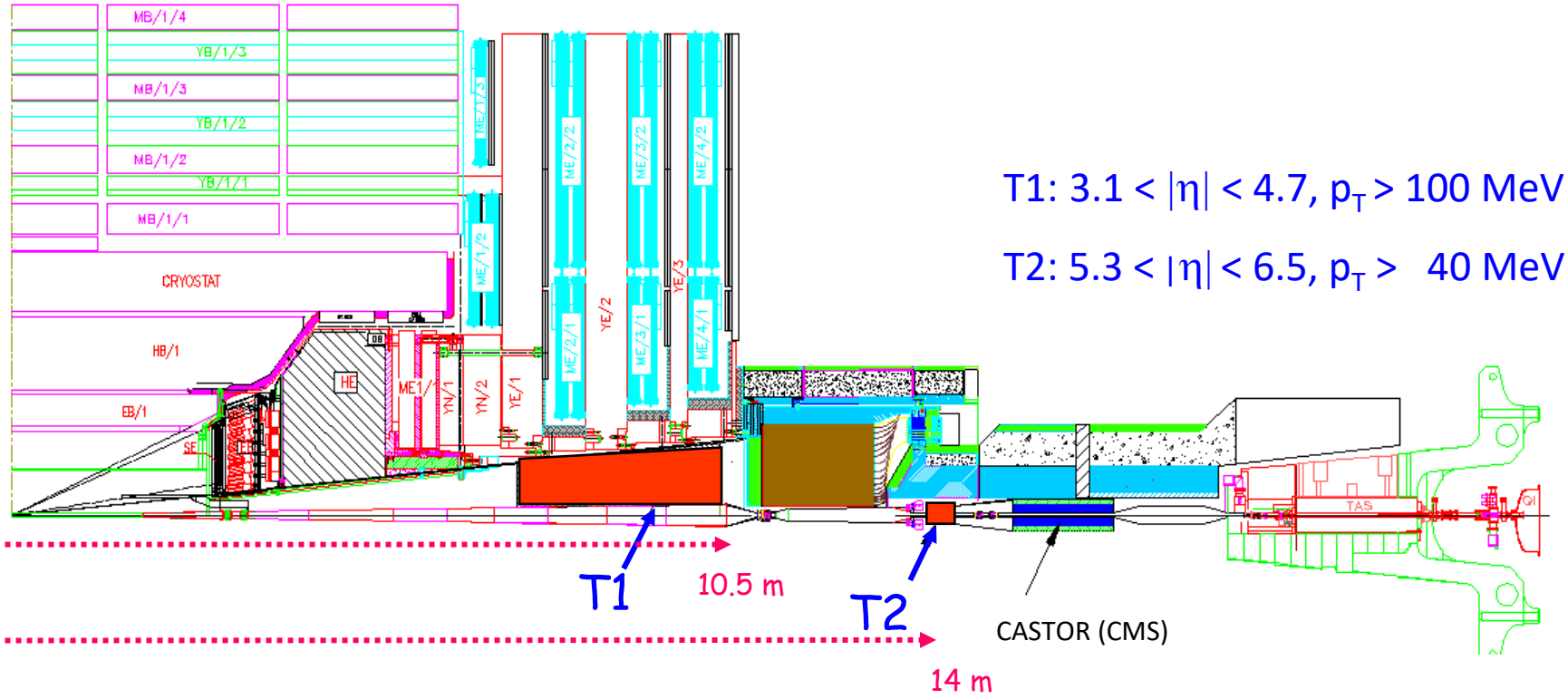
**21st Zimányi School 2021, Winter Workshop**

Budapest, Hungary

2021, December 6 – 10

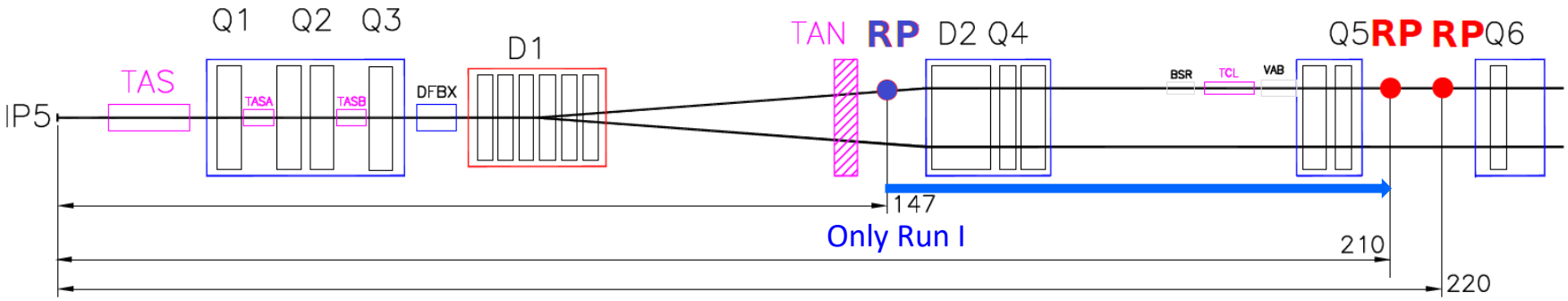
***Also at Wigner RCP, Budapest, Hungary**
**MATE Institute of Technology, KRC, Gyöngyös, Hungary**

# Experimental layout of the TOTEM experiment (LHC Run II)




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

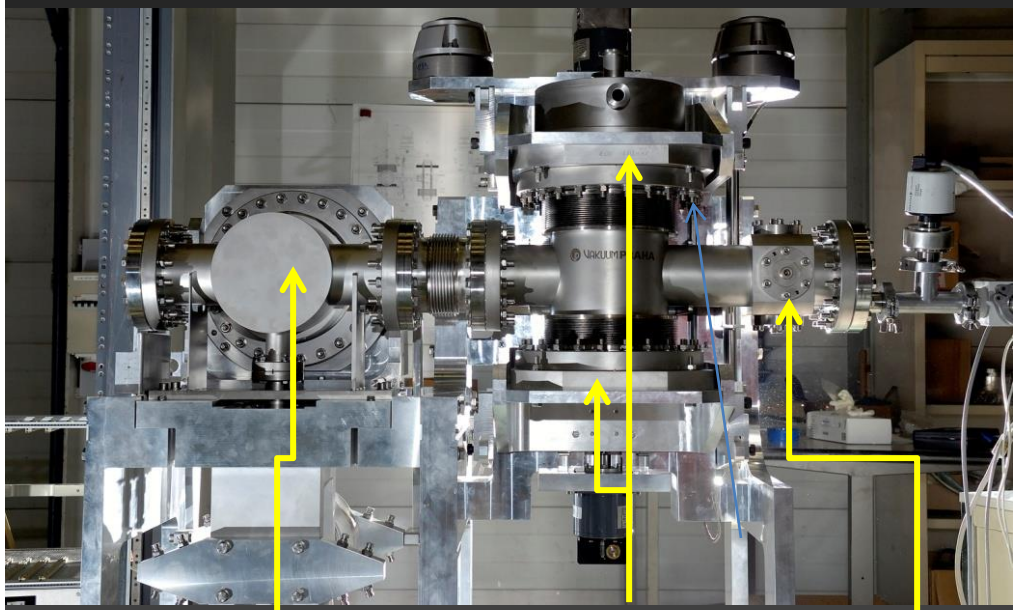
T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

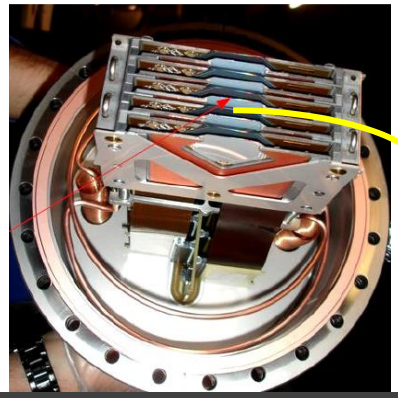


# The Roman Pot (RP) stations of the TOTEM experiment

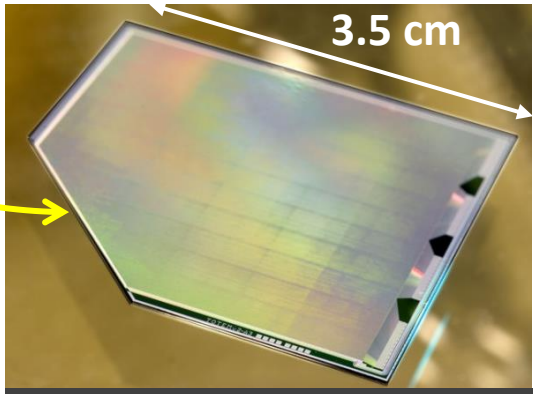
- Two RP stations at 210 and 220 m from the IP contain measuring planes separated by 10 and 5 m respectively
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position rel. to beam
- Overlapping detectors: relative alignment (10 µm inside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

RP unit: 2 vertical, 1 horizontal pot + BPM

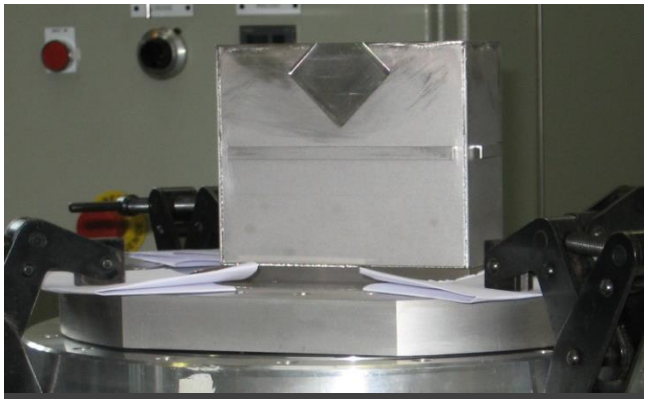


10 planes of edgeless detectors

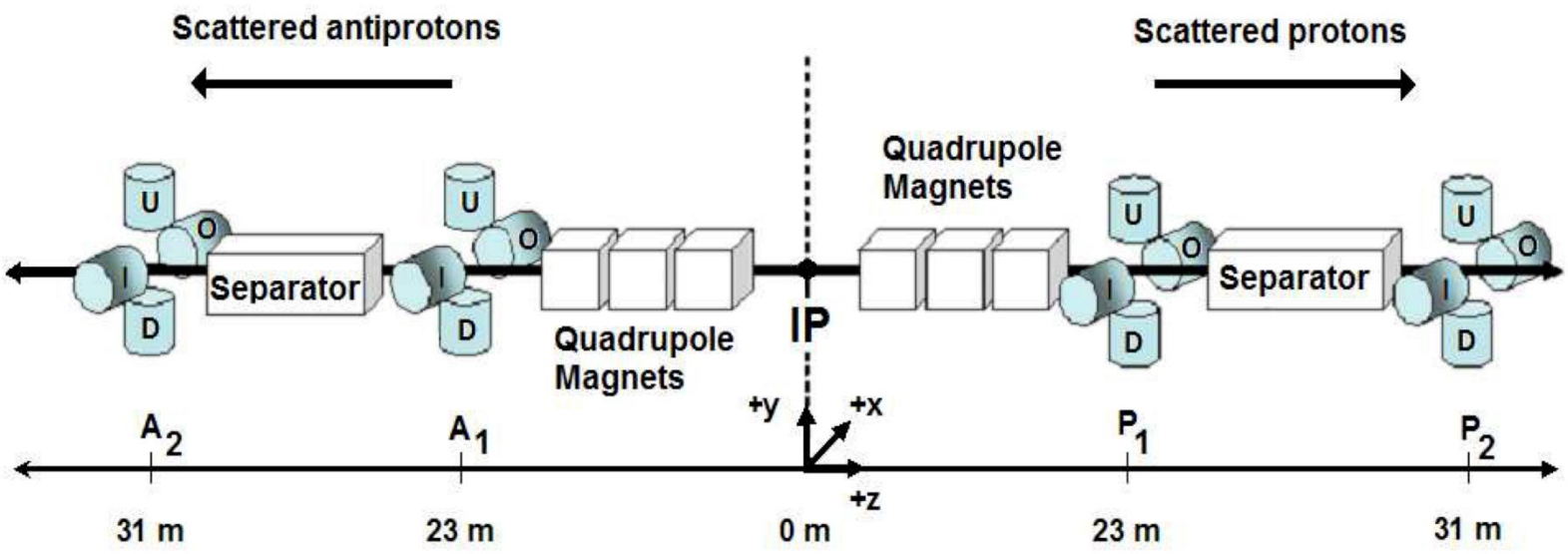



Si edgeless detector



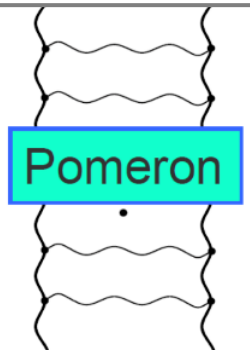
1 Roman Pot

# Experimental layout of the D0 experiment (Tevatron, Fermilab)

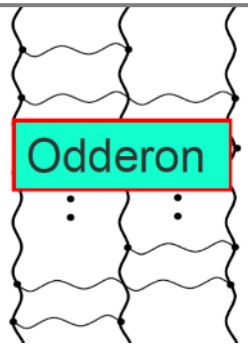



- Elastic $\bar{p}p$ $d\sigma/dt$ measurements: measure both the intact $\bar{p}$ & $p$ in D0 Roman Pots at 23 - 31 m from IP with scintillating fibre detectors
- Measurement at $\sqrt{s}$= 1.96 TeV: PRD 86 (2012) 012009.

# Elastic scattering: multi-gluon exchanges




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




suppressed
mainly $Re(A_{el}^{had})$
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 ⇒ 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:

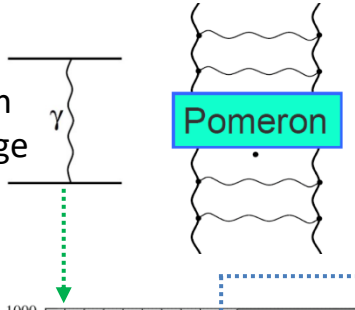
- C-odd exchange contribution predicted in Regge-theory *L. Lukaszuk & B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405*
- Confirmed in QCD as C-odd exchange of 3 (or odd #) gluons at leading order *J. Bartels, Nucl. Phys. B 175 (1980) 365; J. Kwiecinski & M. Praszlowics Phys. Lett. B 94 (1980) 413.*
- Searched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

# Elastic pp differential cross-section & C-odd exchange

**Sensitive to C-odd exchange:**

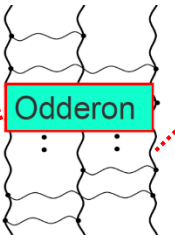
- "Coulomb-nuclear interference" (CNI) region ρ
- Diffractive minimum ("dip"): $Im\ (A_{el}^{had})$ suppressed w.r.t. $Re(A_{el}^{had})$!

Photon exchange

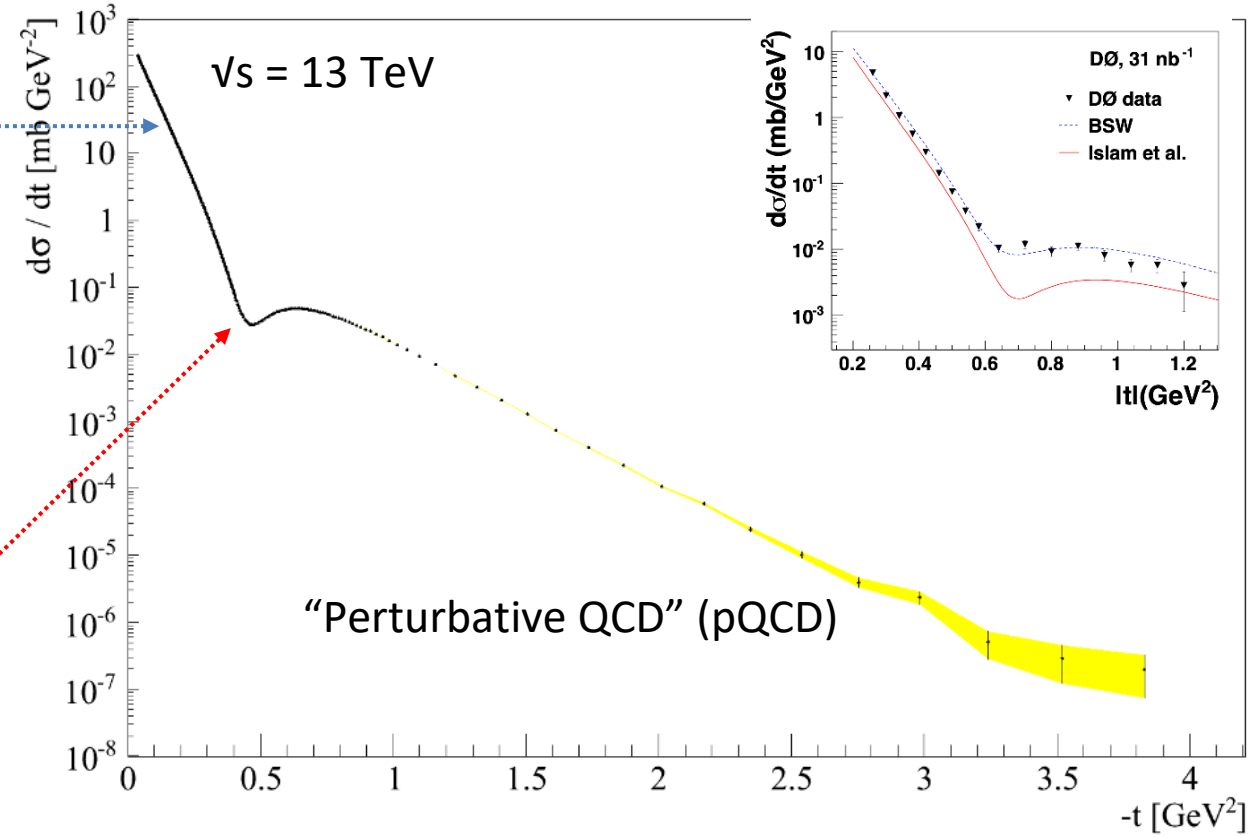






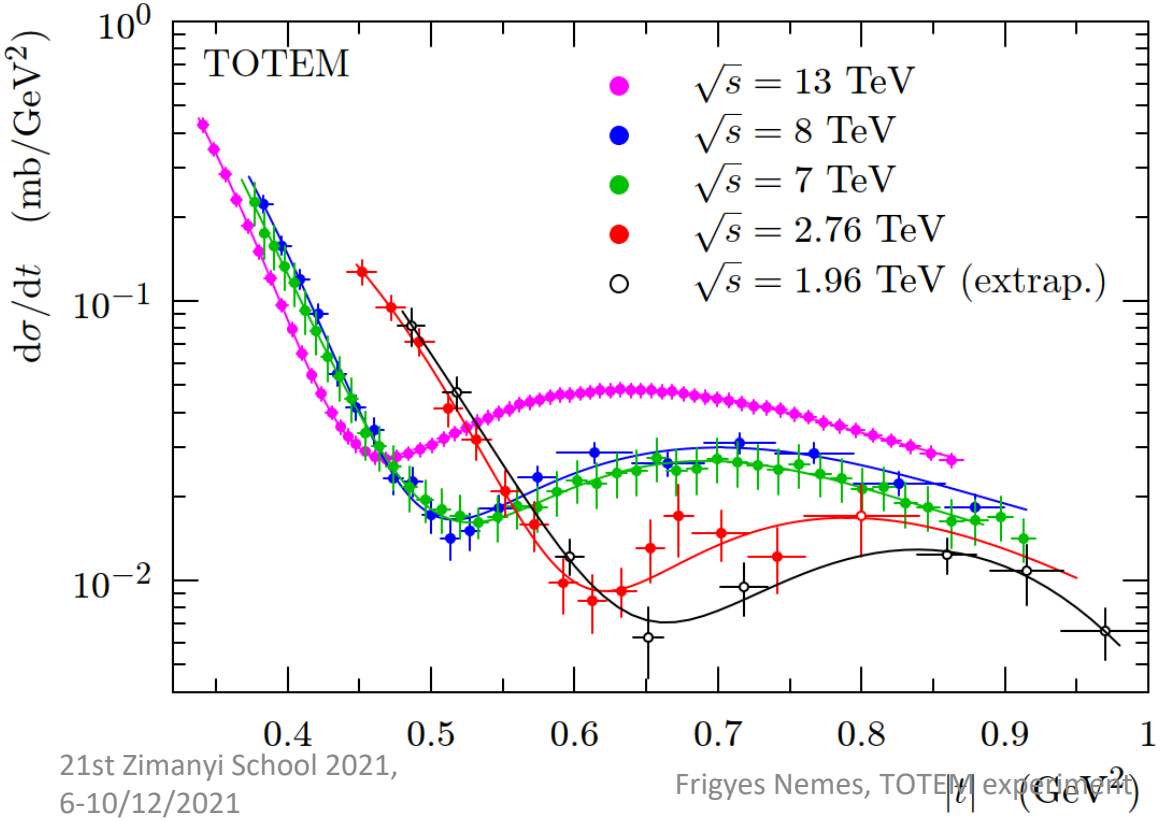


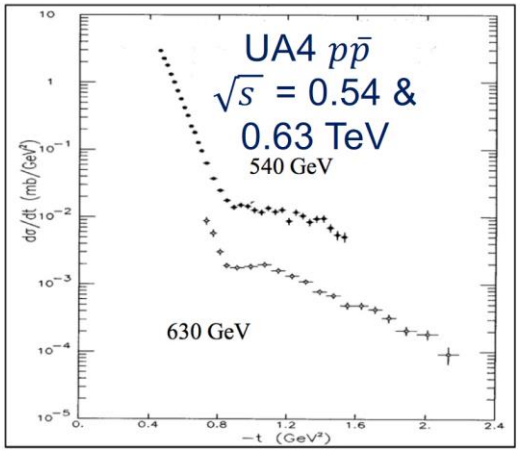

$$\rho = \left.\frac{\mathrm{Re}\, A_{el}^{had}}{\mathrm{Im}\, A_{el}^{had}}\right|_{t=0}$$

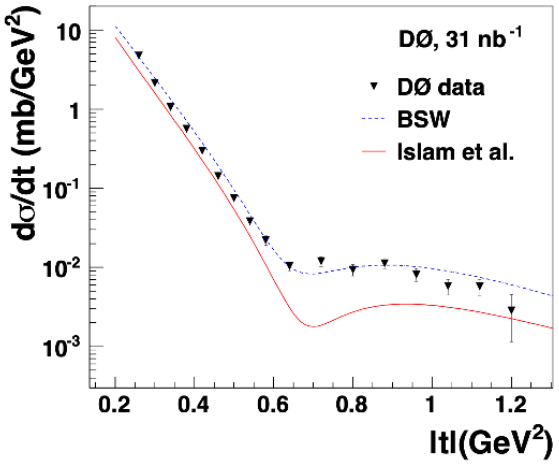


# Strategy to compare pp and $\bar{p}p$ data sets

- 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"

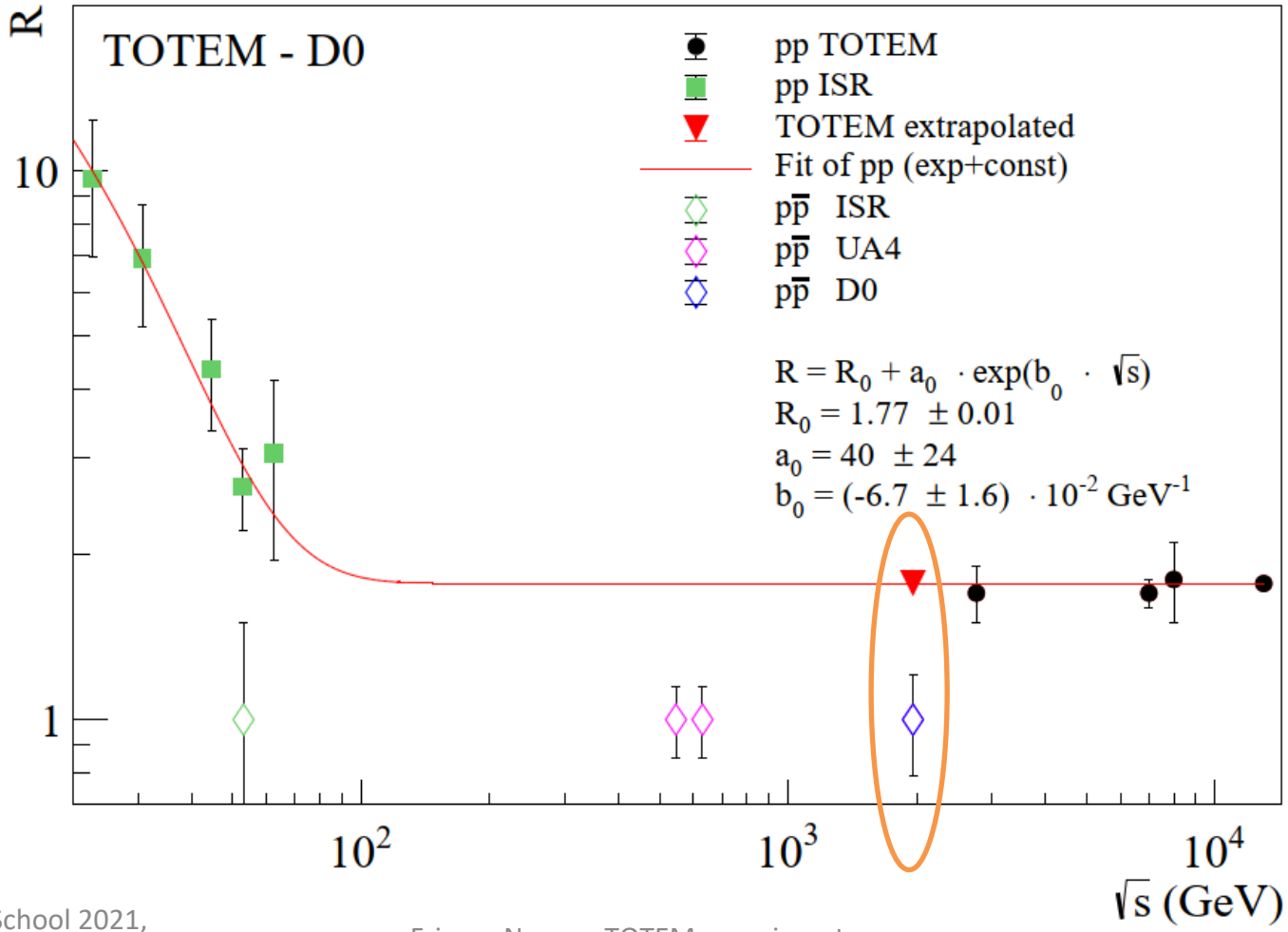


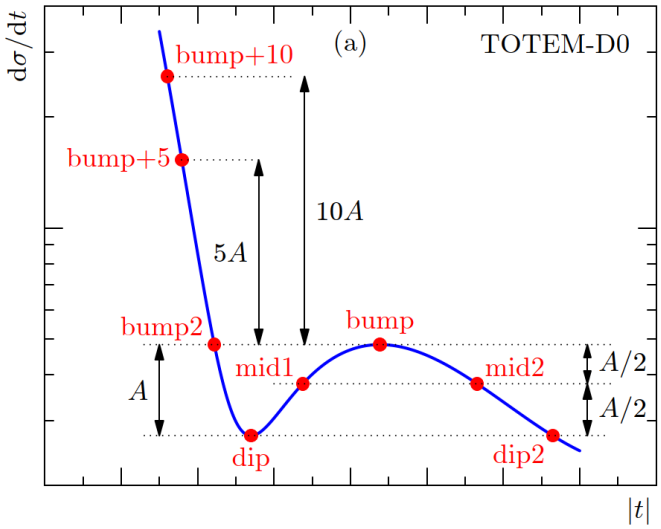
# The bump over dip ratio R

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

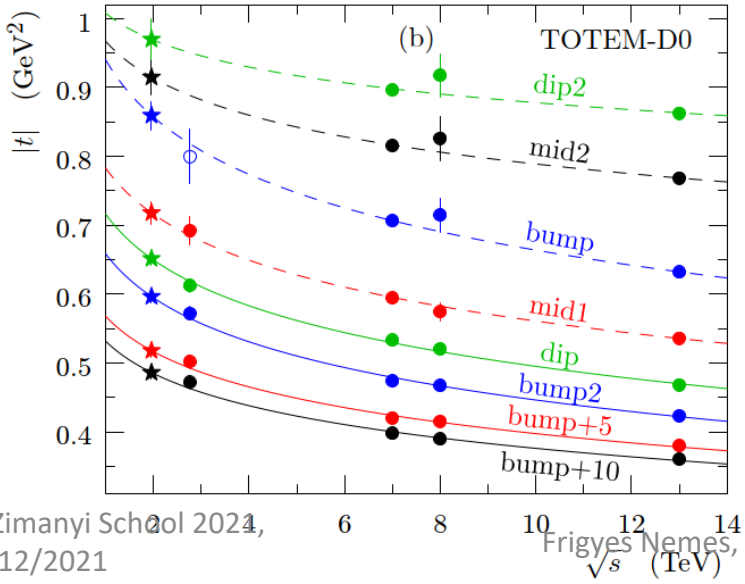


# Extrapolation of pp cross-sections

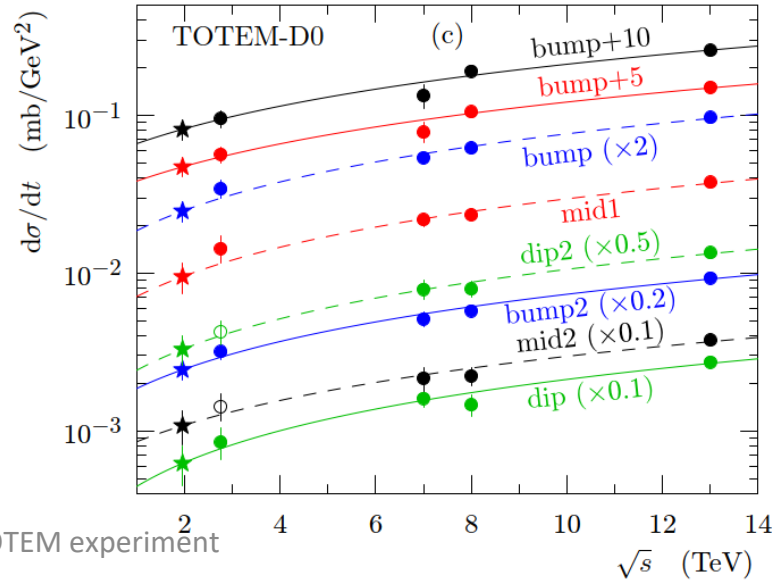
- Extrapolate 8 characteristic points (both their $d\sigma/dt$ & $t$) in dip-bump region of the $pp$ elastic $d\sigma/dt$@ 2.76, 7, 8 & 13 TeV to 1.96 TeV $\Longrightarrow$ $pp$ elastic $d\sigma/dt$ points @ 1.96 TeV
- Alternative functional forms tested: adequate fits provide consistent values within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




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




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



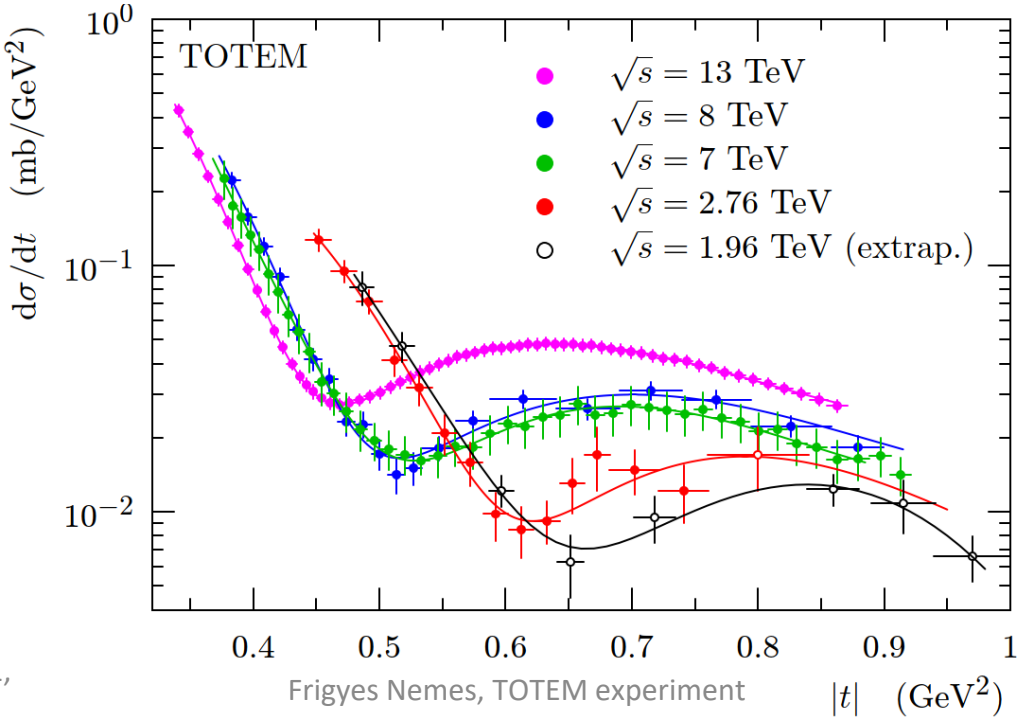
# Fits of TOTEM data sets and extrapolation to 1.96 TeV

- Double exponential function h(t)
- Excellent fits for all $pp$ data sets @ 2.76, 7, 8 & 13 TeV

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

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

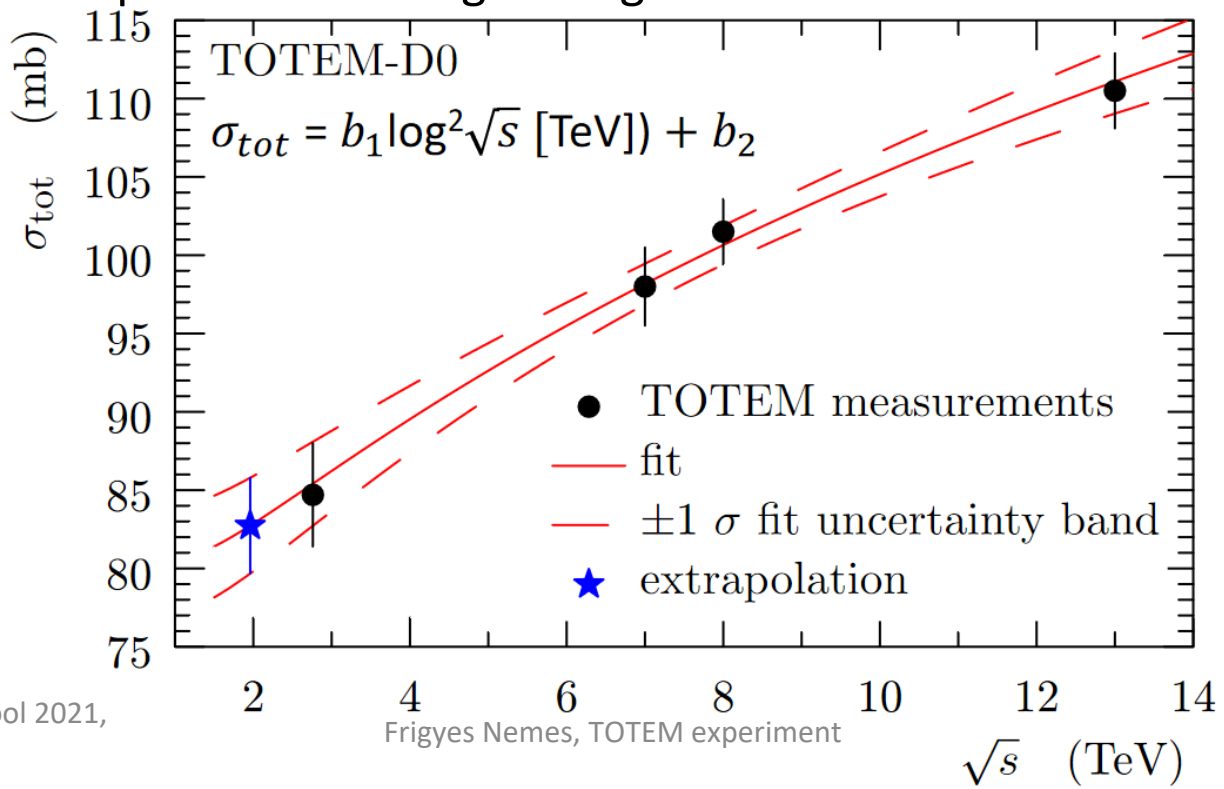
$$h(t) = a_1 e^{-a_2|t|^2 - a_3|t|} + a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$$



# 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 OP within experimental & theoretical uncertainties)
- Normalization factor of TOTEM OP: 0.954 ± 0.076 (experimental & theoretical uncertainty)
- Elastic slopes B preserved during scaling

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

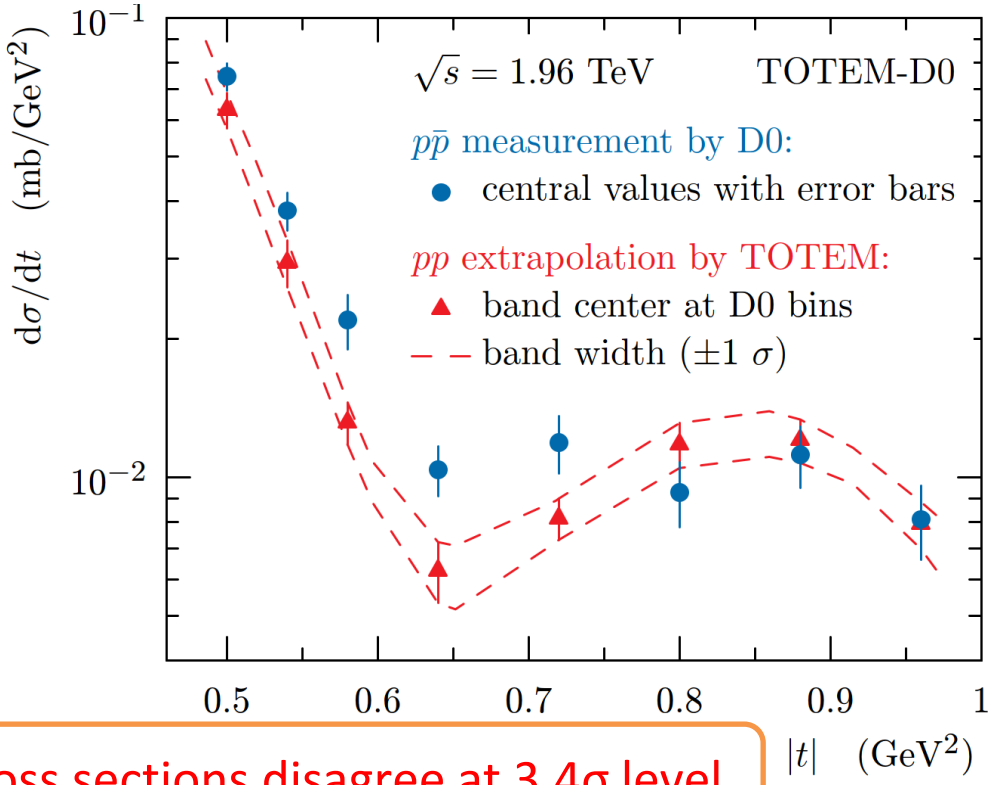


# Comparison $pp$ & $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV

- The extrapolated $pp$ cross-section is normalized to the measured $\bar{p}p$ cross-section by requiring the optical points ($d\sigma/dt$ @ 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
- 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

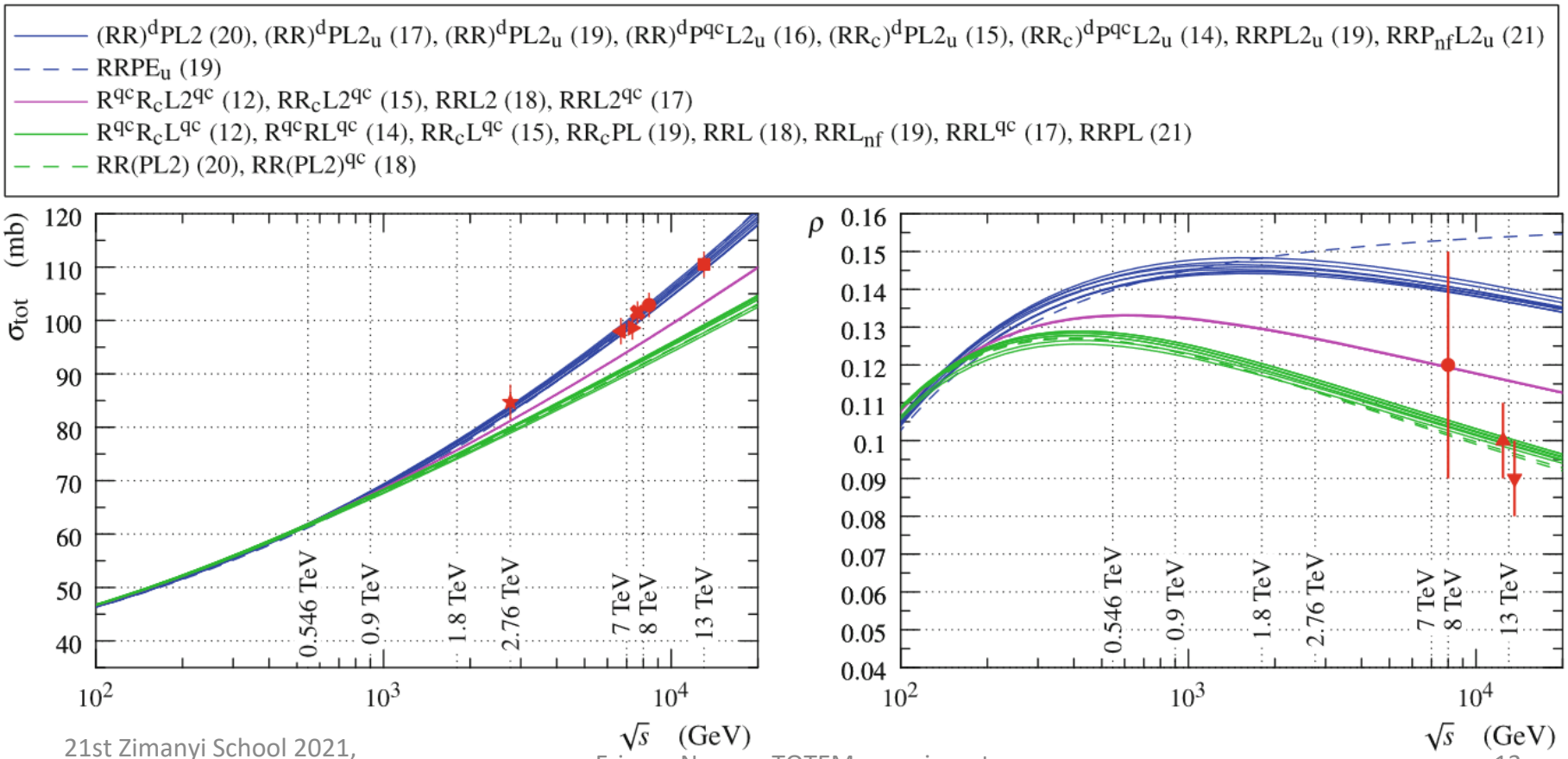
Significance confirmed by a combined Kolmogorov-Smirnov & normalization test




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

# Previous evidence from pp ρ and $\sigma_{tot}$

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



# Combining with pp ρ and $\sigma_{tot}$ evidence

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

- Compared to all the COMPETE models, the TOTEM $\rho$ & $\sigma_{tot}$ measurement provide an odderon evidence between 3.4 and 4.6 $\sigma$, giving a total significance between 5.3 and 5.7 $\sigma$ 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$\sigma$ ⇒ observation of colourless $C$-odd gluonic compound("odderon")

- Publication: "Odderon Exchange from Elastic Scattering Differences between pp and $\bar{p}p$ Data at 1.96 TeV and from pp Forward Scattering" PRL 127 (2021) 062003

* 1. COMPETE Coll., PRL 89 (2002) 201801; Durham group, PLB 748 (2018) 192.
  2. Block-Halzen model, Phys. Rev. D 92 (2015) 114021)

# Conclusions

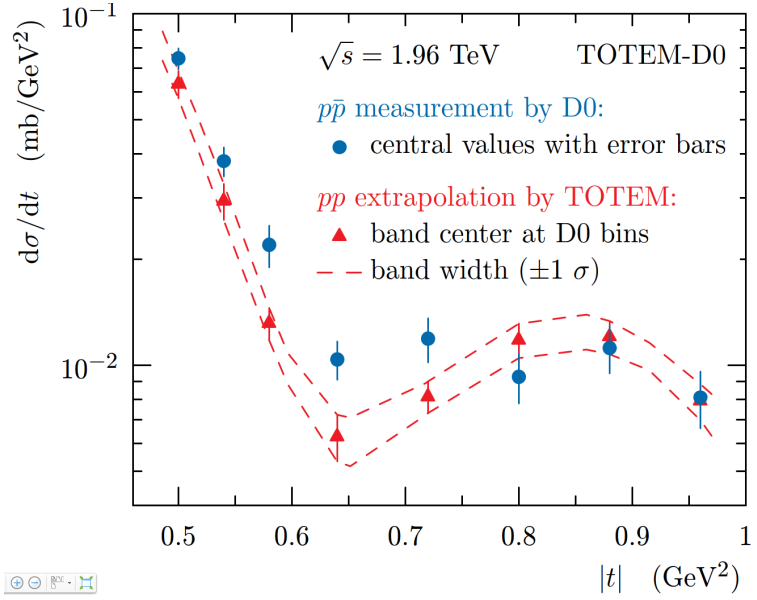
- Data-driven comparison between $\bar{p}p$ (D0 @ √$s$= 1.96 TeV) & $pp$ (TOTEM @ √$s$= 2.76, 7, 8, 13 TeV) elastic $d\sigma/dt$
- Extrapolate ”characteristic” points of elastic $pp$ $d\sigma/dt$ to predict elastic $pp$ $d\sigma/dt$@ √$s$= 1.96 TeV
- Elastic $pp$ and $\bar{p}p$ cross sections differ @ 3.4$\sigma$ at √$s$= 1.96 TeV $\Longrightarrow$ evidence of t-channel exchange of a colourless $C$-odd gluonic compound i.e. odderon
- Combined with TOTEM ρ & total cross section results $\Longrightarrow$ 5.2 - 5.7$\sigma$ & thus 1st exp. observation of a colourless $C$-odd gluonic compound i.e. odderon
- Major discovery @ LHC & Tevatron: PRL 127 (2021) 062003
- Cf. E. Leader, “Discovery of the odderon”, Nature Review Physics (2021)

# Backup slides

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

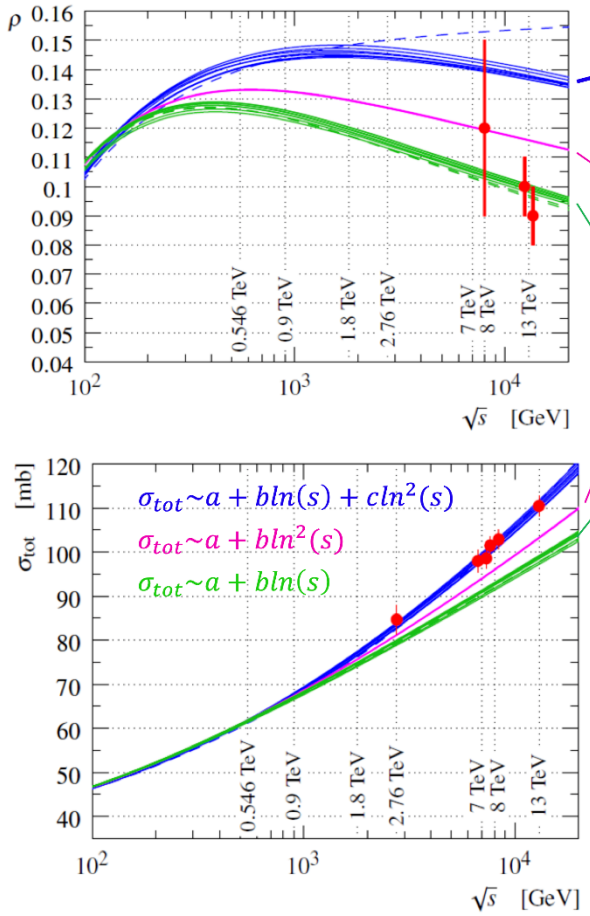
- A = normalization, B = elastic slope

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




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

# Excluded models: significance values




- Excluded at **4.6$\sigma$** level with $\rho(13\ TeV) = 0.09$
- Excluded at **5.7$\sigma$** level when combining significance from $\rho$ and from difference in $pp$ and $p\bar{p}$ $\frac{d\sigma}{dt}$.

- Excluded at **4.0$\sigma$** level with TOTEM $\rho +\ \sigma_{tot}$ data.
- Excluded at **5.3$\sigma$** level when combining significance from TOTEM $\rho +\ \sigma_{tot}$ data and from difference in $pp$ and $p\bar{p}$ $\frac{d\sigma}{dt}$.

- Excluded at **4.6$\sigma$** level with TOTEM $\rho +\ \sigma_{tot}$ data.
- Excluded at **5.7$\sigma$** level when combining significance from TOTEM $\rho +\ \sigma_{tot}$ data and from difference in $pp$ and $p\bar{p}$ $\frac{d\sigma}{dt}$.

Durham Model:
- Excluded at **3.4$\sigma$** level with TOTEM $\rho +\ \sigma_{tot}$ data.
- Excluded at **5.2$\sigma$** level when combining significance from TOTEM $\rho +\ \sigma_{tot}$ data and from Durham prediction for D0 $p\bar{p}$ $\frac{d\sigma}{dt}$.

Block-Halzen Model:
- Excluded at **3.9$\sigma$** level with TOTEM $\rho$ data.
- Excluded at **5.2$\sigma$** level when combining significance from TOTEM $\rho$ data and and from difference in $pp$ and $p\bar{p}$ $\frac{d\sigma}{dt}$.

# The diffractive minimum at 8 TeV

- Most recent CERN preprint by TOTEM: CERN-EP-2021-242
- E-Print: 2111.11991 [hep-ex]