The first experimental observation of odderon exchange

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

9th Edition of the LHC Conference
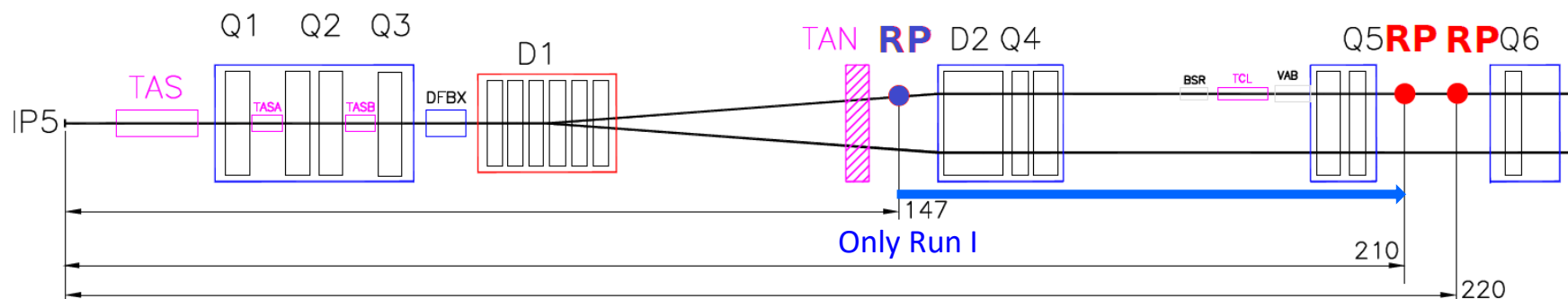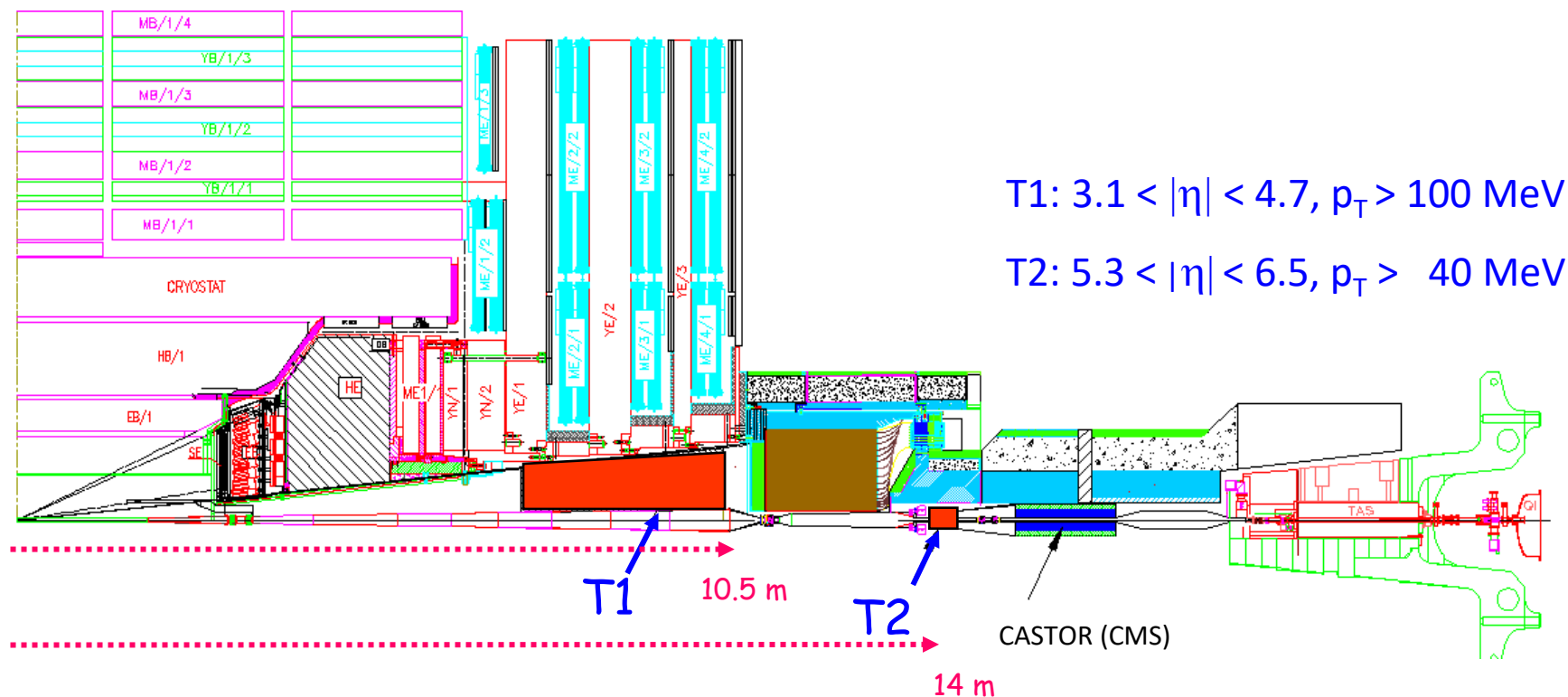
Paris, France

2021, June 7 – 12

***Also at Wigner RCP, Budapest, Hungary**
   **Szent István Egyetem Károly Róbert Campus, Gyöngyös**

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

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

T1   10.5 m

T2   14 m

CASTOR (CMS)

Q1   Q2   Q3

TAS

D1

TAN   RP   D2 Q4   Q5 RP RP Q6

IP5   TASA   TASB   DFBX

BSR   TCL   VAB

147

Only Run I

210

220

- o Two RP stations at 210 and 220 m from the IP contain measuring planes separated by 10 and 5 m respectively

- o Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)

- o BPM: precise position rel. to beam

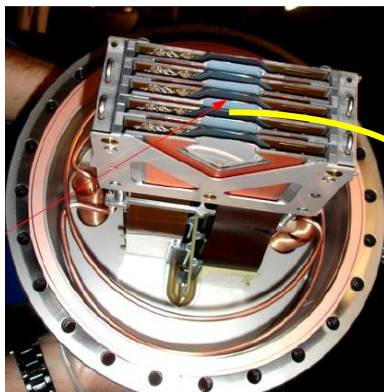- o Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)
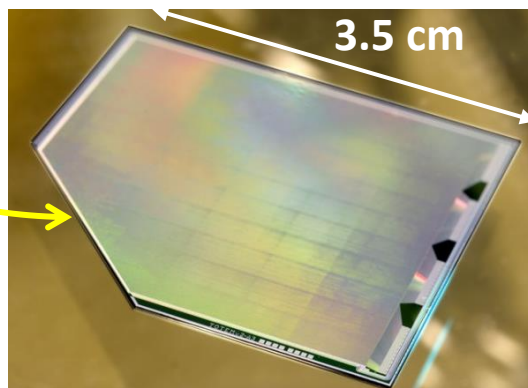
RP unit: 2 vertical, 1 horizontal pot + BPM
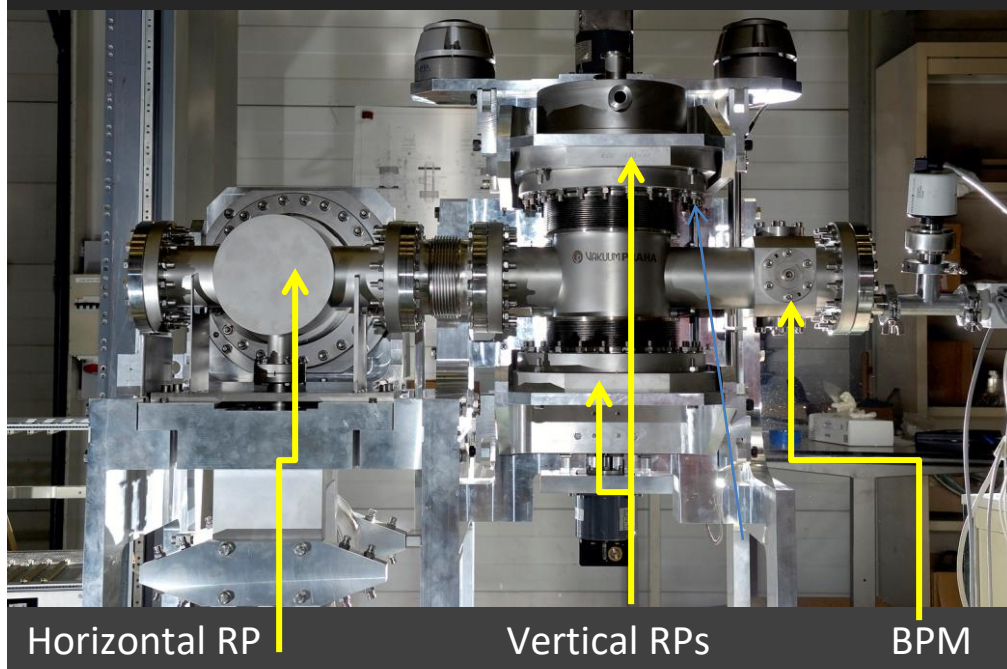
Horizontal RP   Vertical RPs   BPM

3.5 cm
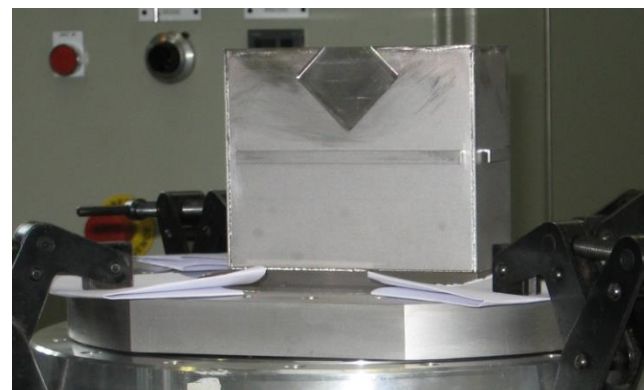
10 planes of edgeless detectors

Si edgeless detector

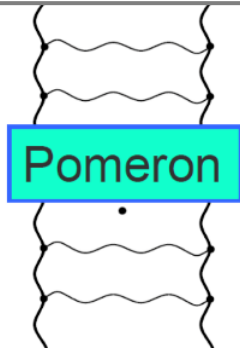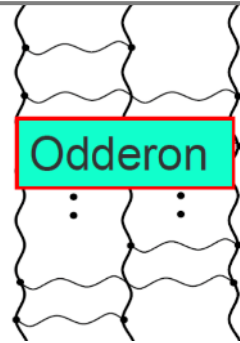1 Roman Pot
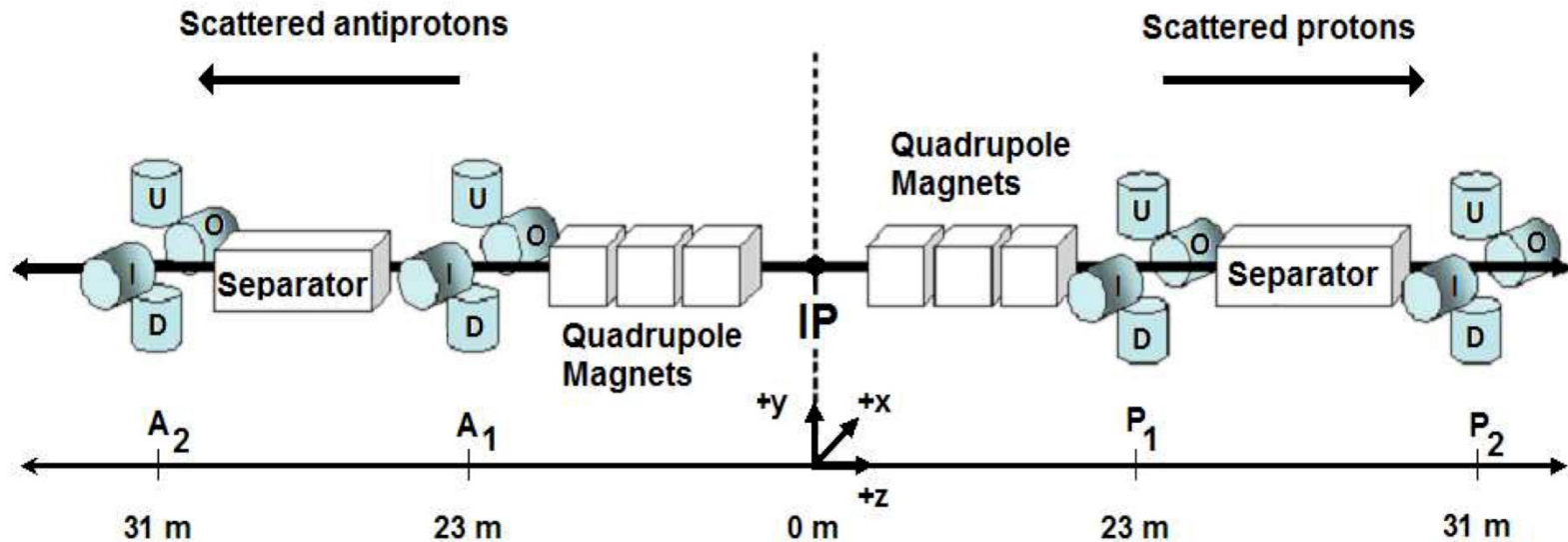
- Elastic $\bar{p}p\ d\sigma/dt$ measurements: measure both the intact $\bar{p}$ & p in D0 Roman Pots at 23 - 31 m from IP with scintillating fibre detectors
- Measurement at $\sqrt{s}$= 1.96 TeV: PRD 86 (2012) 012009.

Pomeron

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

Odderon

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
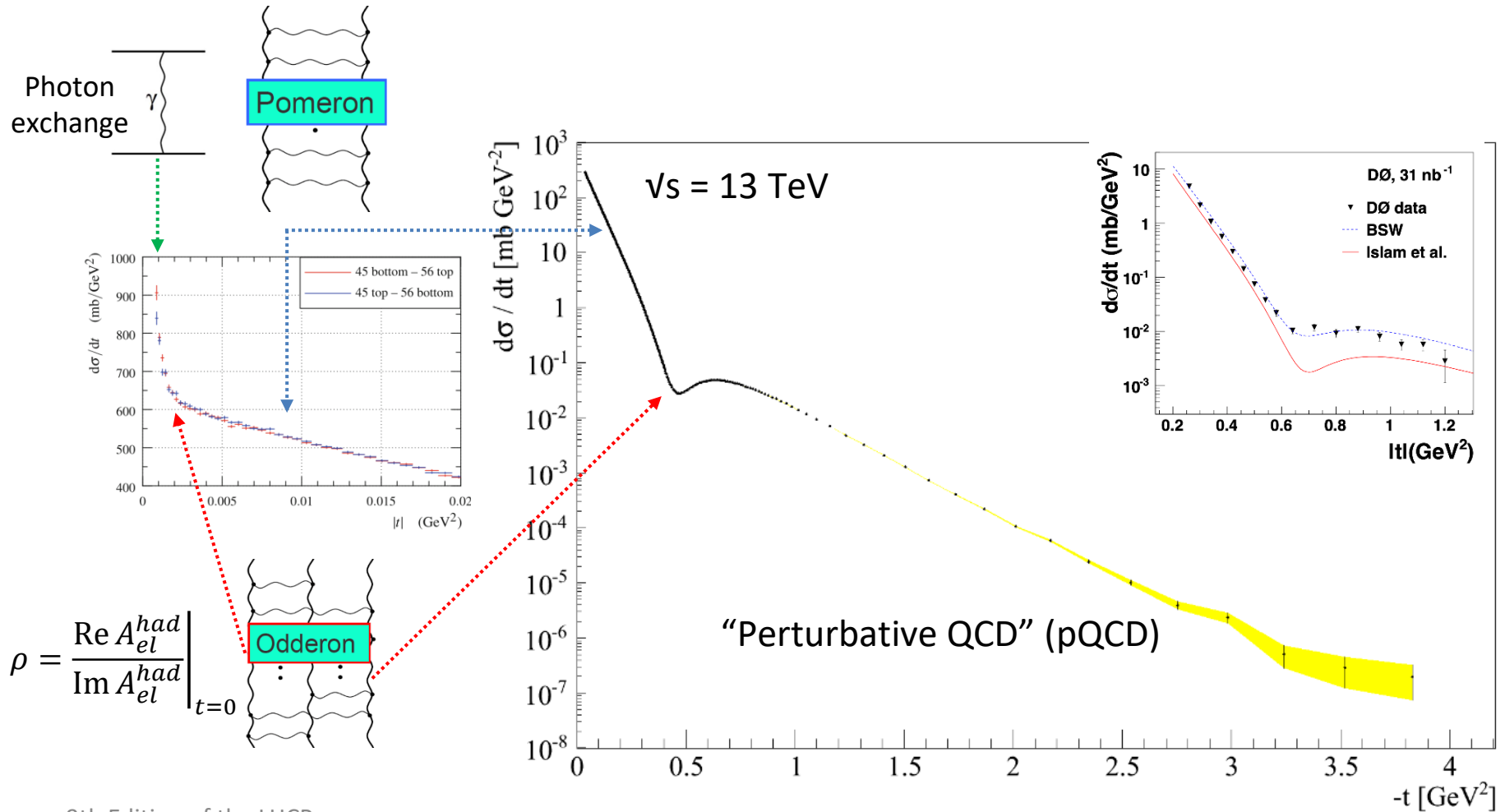
Odderon / C-odd gluon compound:

- 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. $Re(A_{el}^{had})$!

Photon exchange

Pomeron

Odderon

$$\rho = \frac{Re\ A_{el}^{had}}{Im\ A_{el}^{had}}\bigg|_{t=0}$$

√s = 13 TeV

"Perturbative QCD" (pQCD)

DØ, 31 nb⁻¹

- DØ data
- BSW
- Islam et al.

- 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"
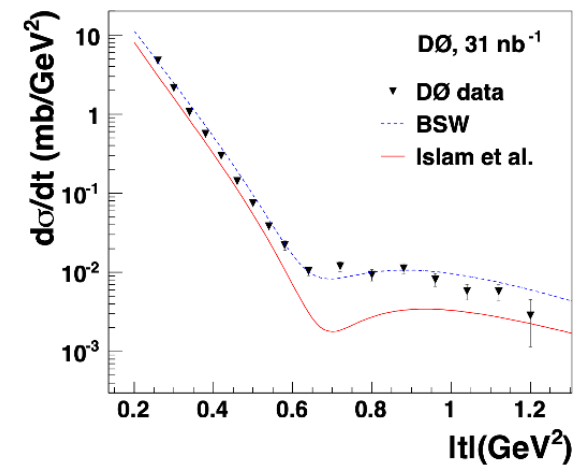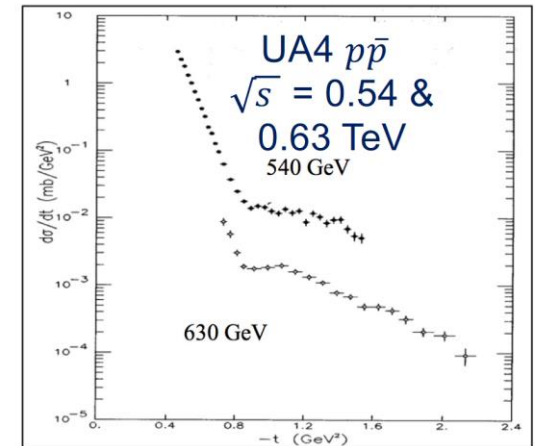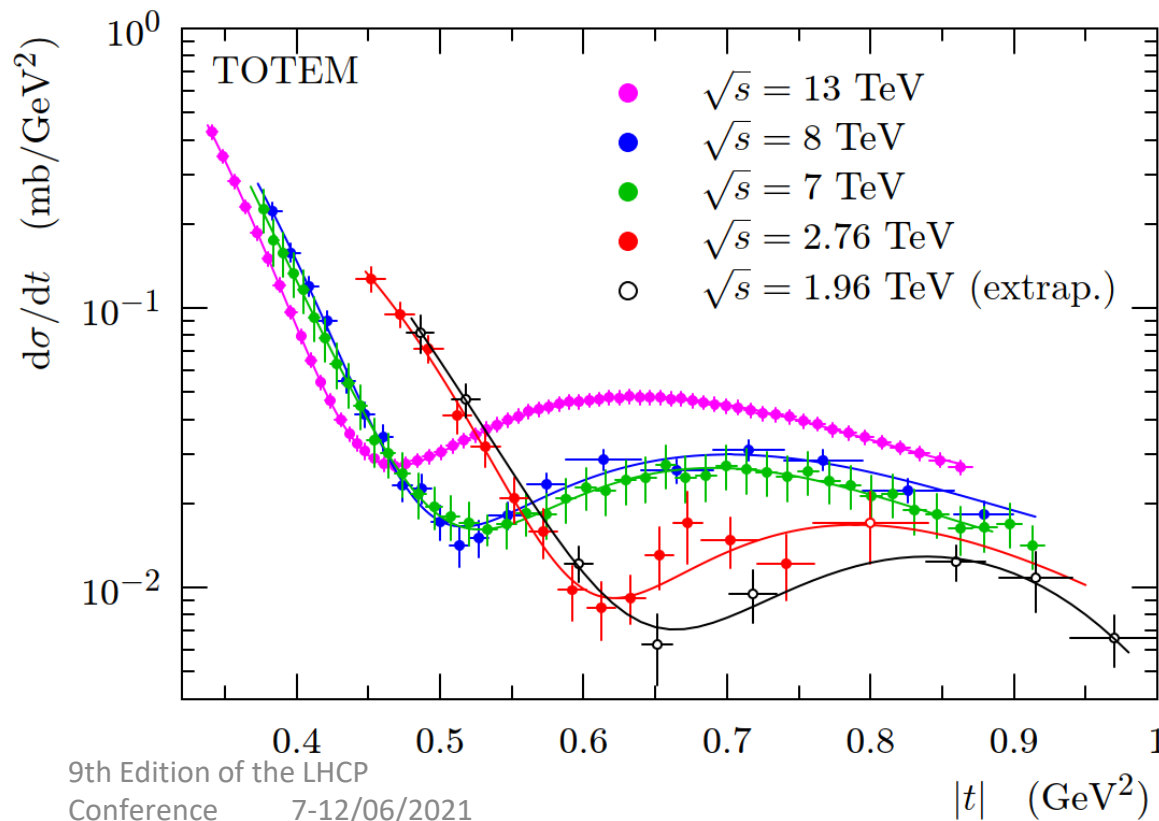
- $> 3\sigma$ difference between pp & $\bar{p}p$ @ s= 1.96 TeV
  (assuming flat behaviour above $\sqrt{s}$ ~ 100 GeV)

- For $\bar{p}p$ R estimate, use $d\sigma/dt$ of t-bins close to expected pp bump & dip position

TOTEM - D0

Legend:
- pp TOTEM
- pp ISR
- TOTEM extrapolated
- Fit of pp (exp+const)
- $p\bar{p}$ ISR
- $p\bar{p}$ UA4
- $p\bar{p}$ D0

$$R = R_0 + a_0 \cdot \exp(b_0 \cdot \sqrt{s})$$
$$R_0 = 1.77 \pm 0.01$$
$$a_0 = 40 \pm 24$$
$$b_0 = (-6.7 \pm 1.6) \cdot 10^{-2} \text{ GeV}^{-1}$$
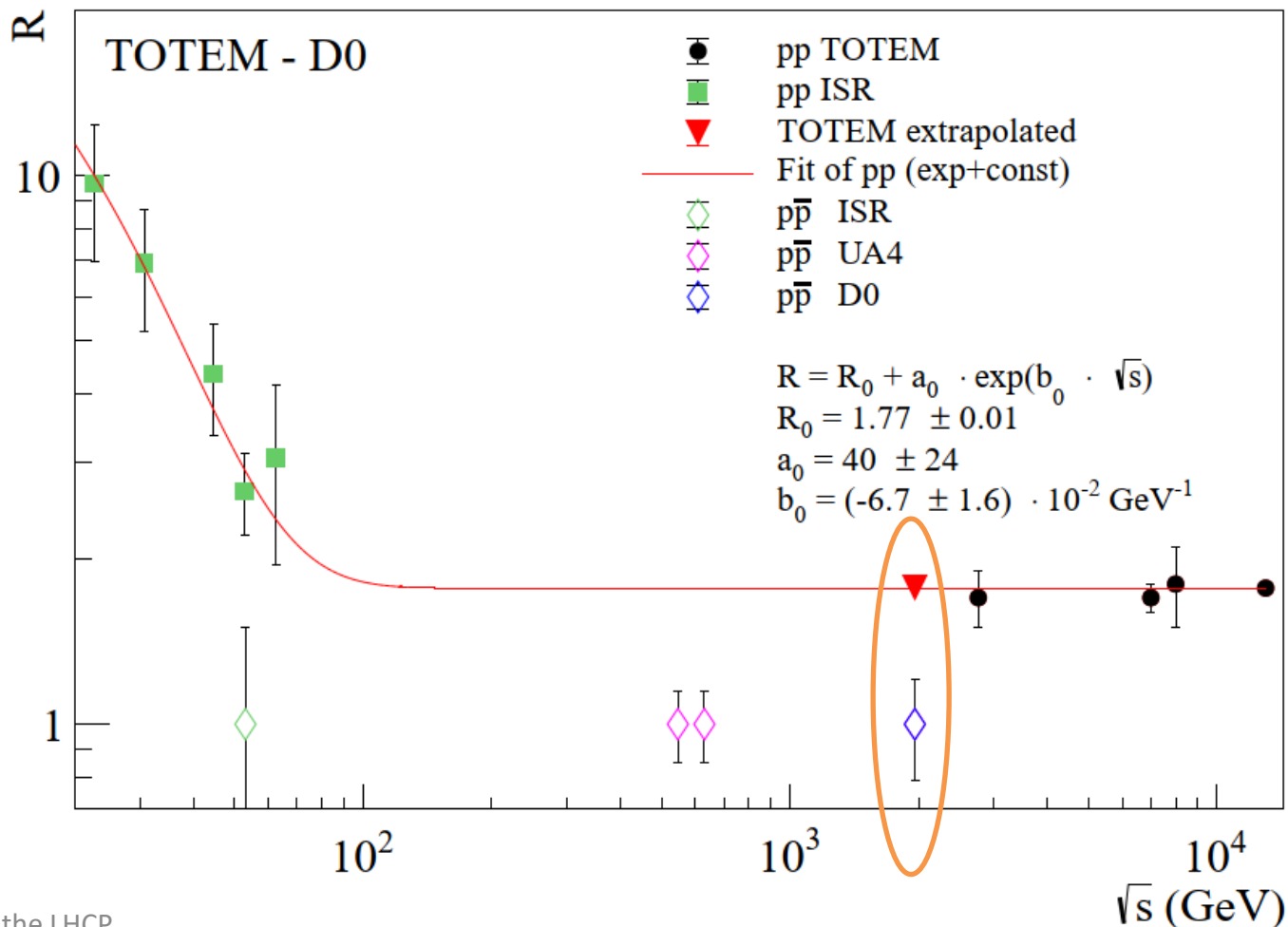
Extrapolation of pp cross-sections

- 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


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

$$(d\sigma/dt) = c\sqrt{s}\,[\text{TeV}] + d$$
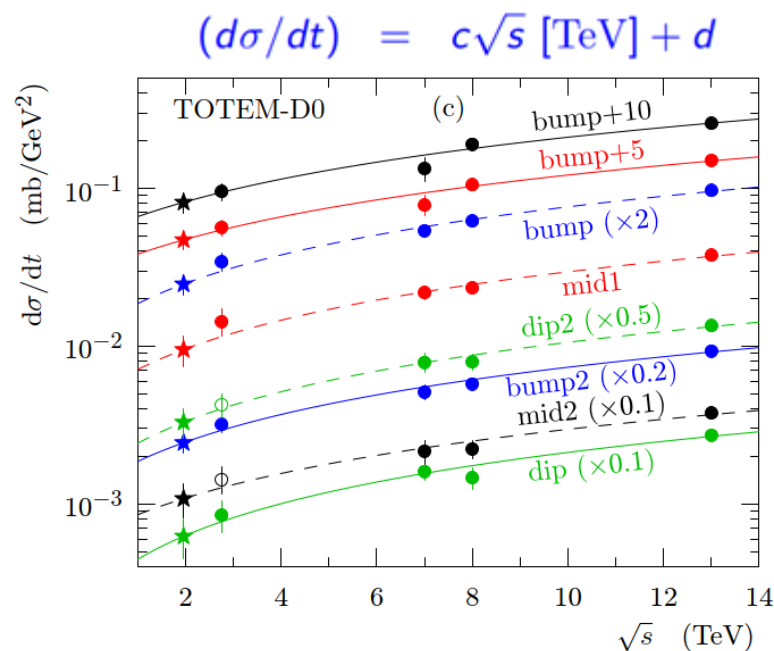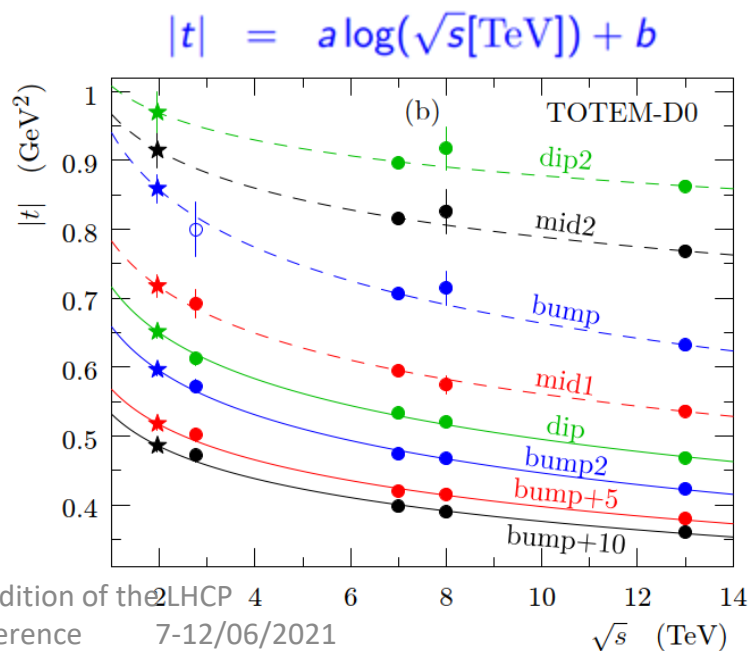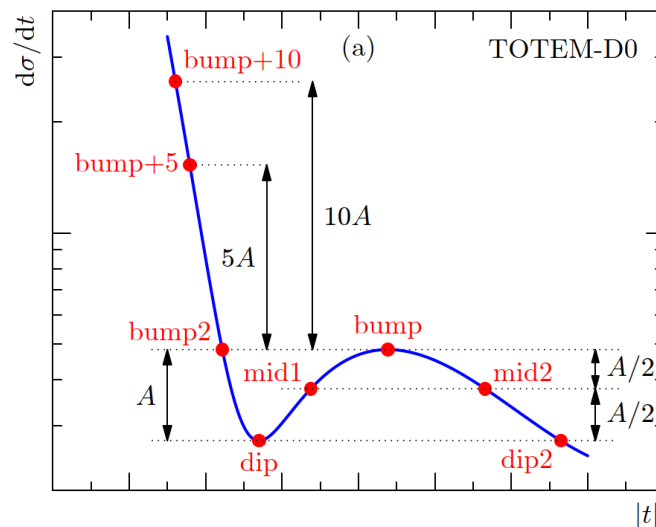
- The extrapolated pp cross-section is normalized to the measured $\bar{p}p$ cross-section by requiring the optical points (dsigma/dt @ t = 0) to be equal

- 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 (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
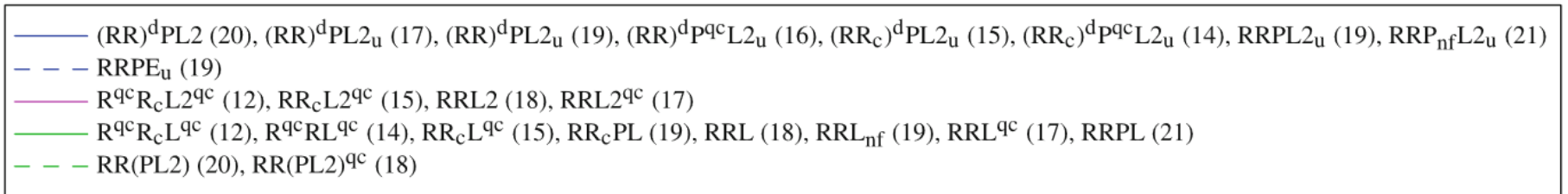
Significance confirmed by a combined Kolmogorov-Smirnov & normalization test
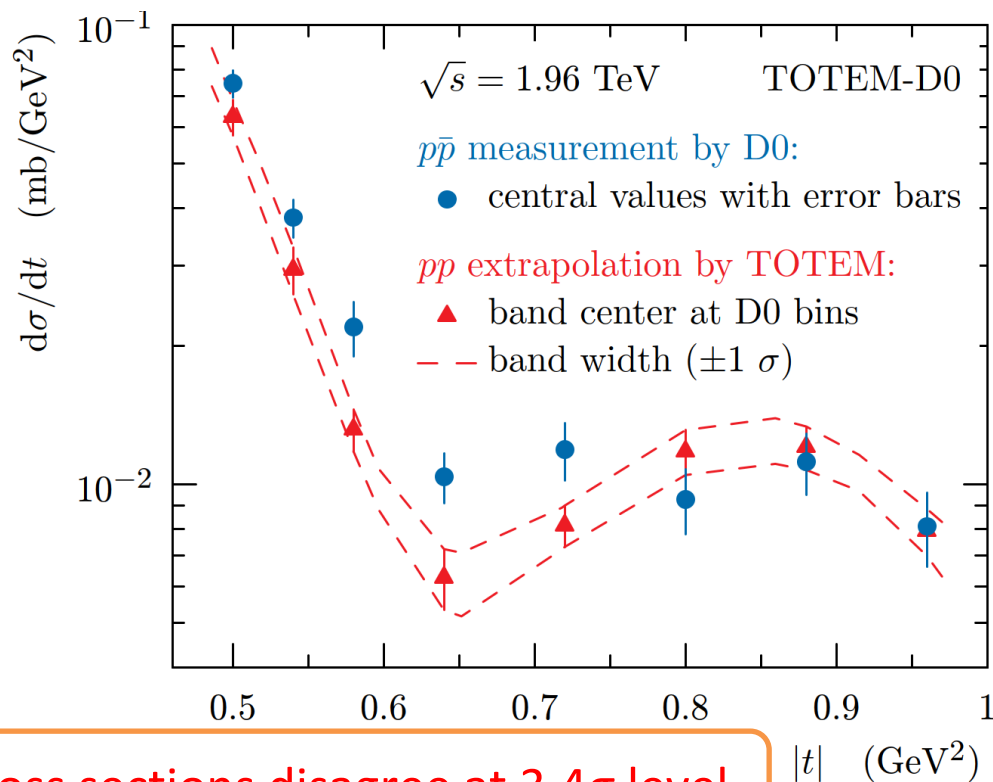
χ² test: pp & p$\bar{p}$ cross sections disagree at 3.4σ level

- Using very low|t| TOTEM data @ √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)
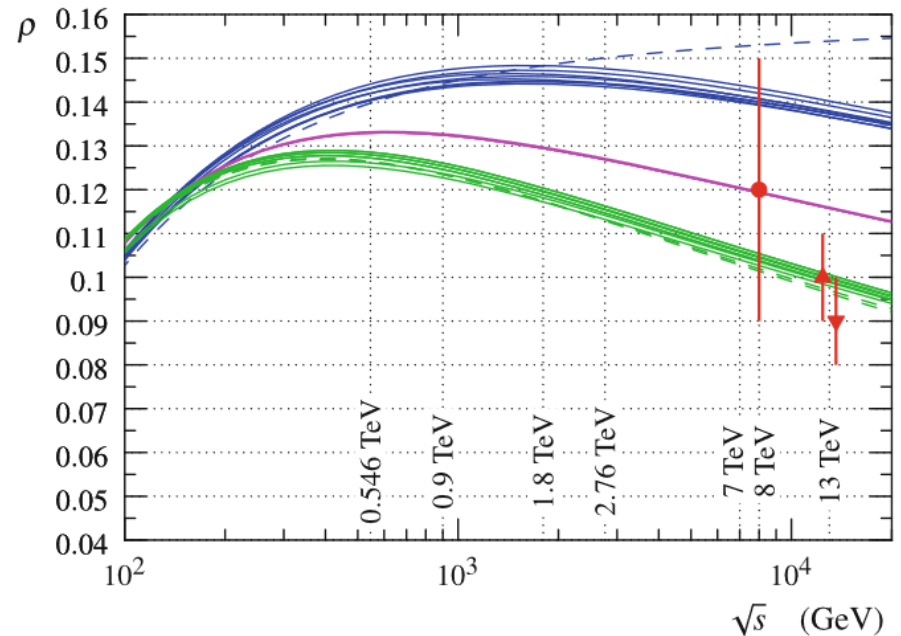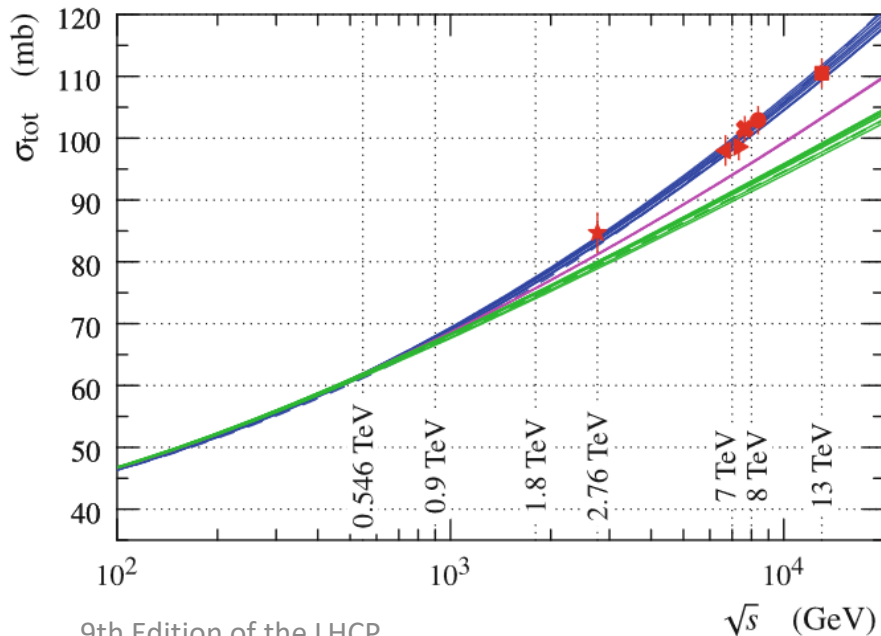
- Combine independent evidence of colourless C-odd exchange from TOTEM ρ & σ_{tot} measurements in a completely different $|t|$-domain with evidence from the pp & $\overline{p}p$ comparison

- 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 5.3 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 ⇒ observation of colourless C-odd gluonic compound("odderon")

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

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 $d\sigma/dt$ data-FERMILAB-PUB-20-568-E; CERN-EP-2020-236, arXiv:2012.03981

- 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 $\Longrightarrow$ 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 - 5.7σ & thus first experimental observation of a colourless C-odd gluonic compound i.e. odderon
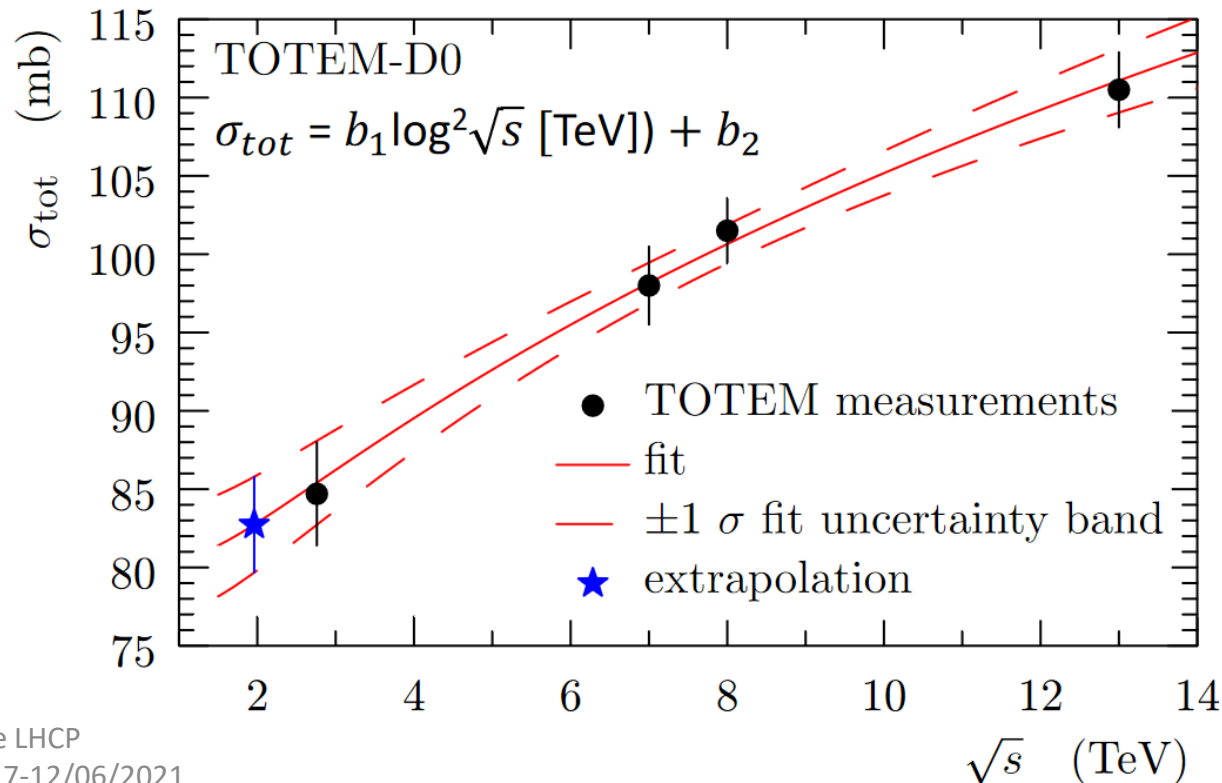
- Major discovery @ LHC & Tevatron

Backup slides

- 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 ± 0.071
- Slopes B preserved during scaling

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}(t=0)\right)$$
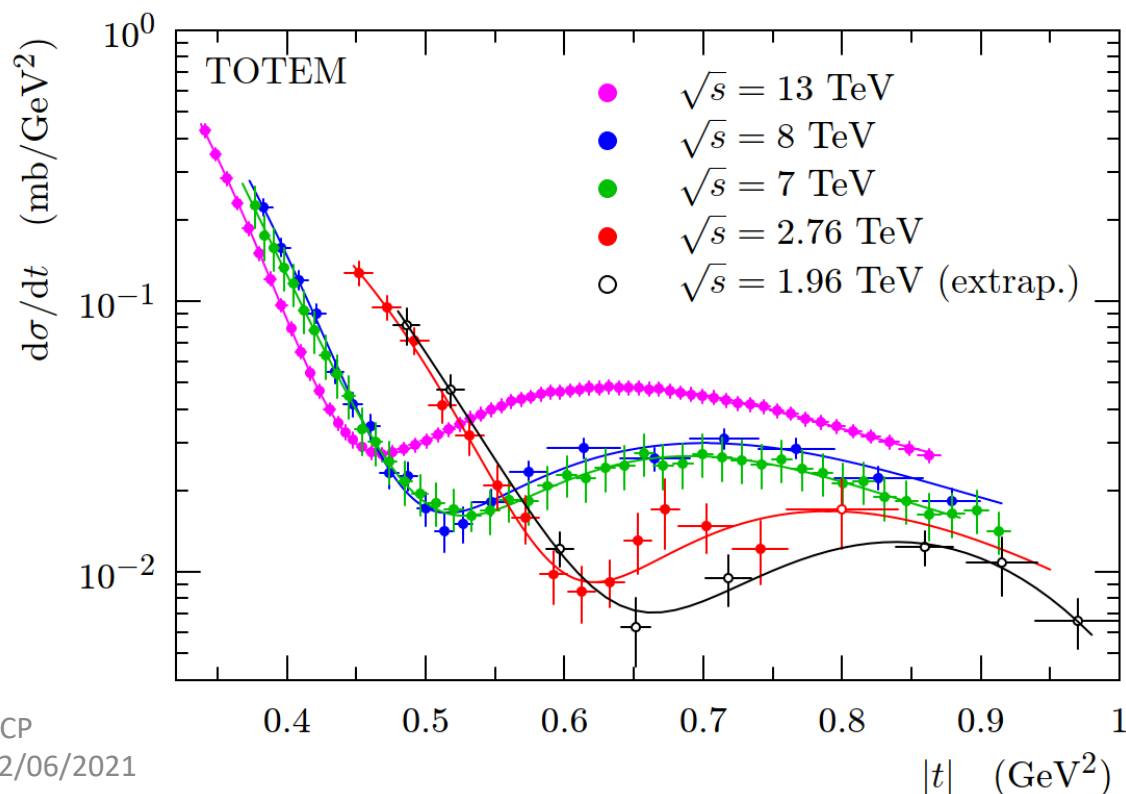
- Excellent fits for all pp data sets @ 2.76, 7, 8 & 13 TeV

$$h_1(t) = a_1 e^{-a_2|t|^2 - a_3|t|}$$
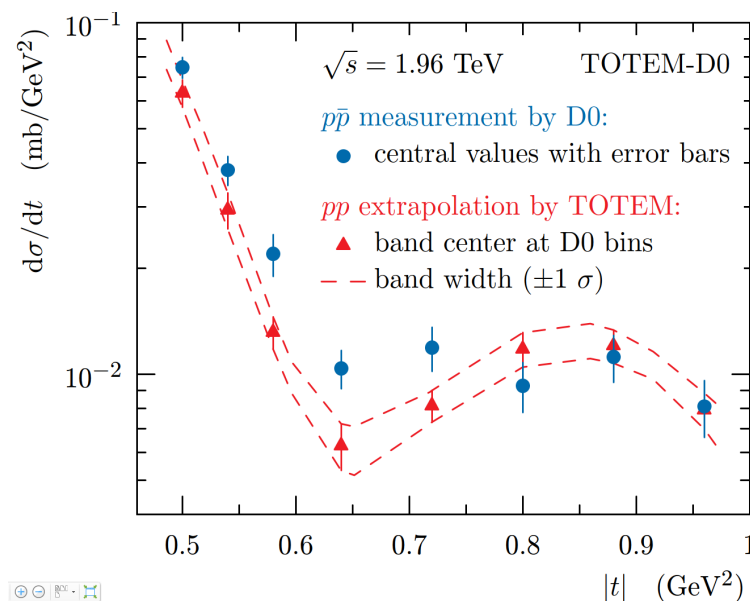
$$h_2(t) = a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$$

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

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

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