D0-TOTEM Odderon observation: an update

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on behalf the **D0 & TOTEM collaborations**

LHC Forward Physics meeting

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References:

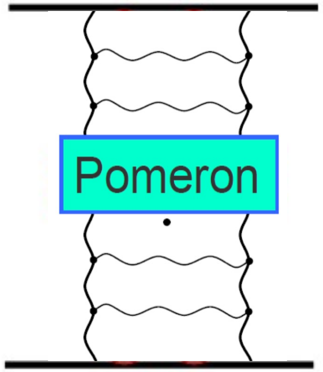
D0 & TOTEM collaborations, CERN-EP 2020-236, FERMILAB PUB-20-568-E (CERN & Fermilab approval December 2020), *PRL 127 (2021) 062003;*
K. Österberg on behalf of D0 & TOTEM collaborations, ArXiv: 2202.03724

For details on TOTEM elastic measurements see F. Nemes talk

Elastic scattering: multi-gluon exchanges

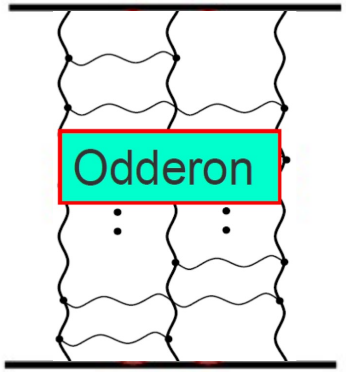
Elastic hadron-hadron scattering: colourless multi-gluon t-channel exchanges

C- even



dominates at low |t|,
$\approx Im\left[A_{\rm el}^{\rm had}\right]$
identical for pp & $p\bar{p}$

C- odd



suppressed,
mainly $Re\left[A_{\rm el}^{\rm had}\right]$ contr.
different sign for pp & $p\bar{p}$

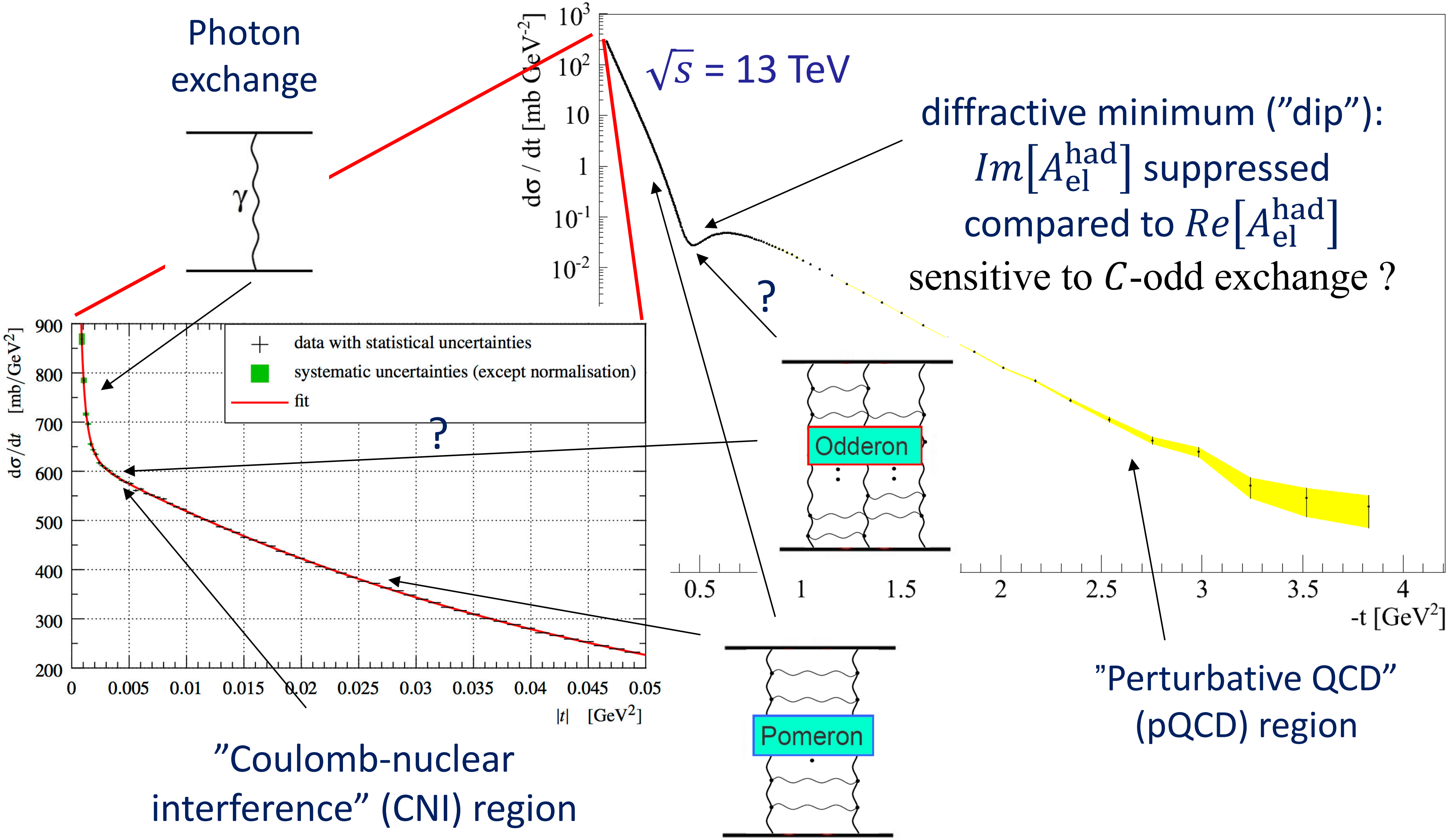
@ TeV-scale: gluon exchanges dominate ⇒ pp & $p\bar{p}$ difference due to C-odd exchange

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, until recently no convincing experimental evidence

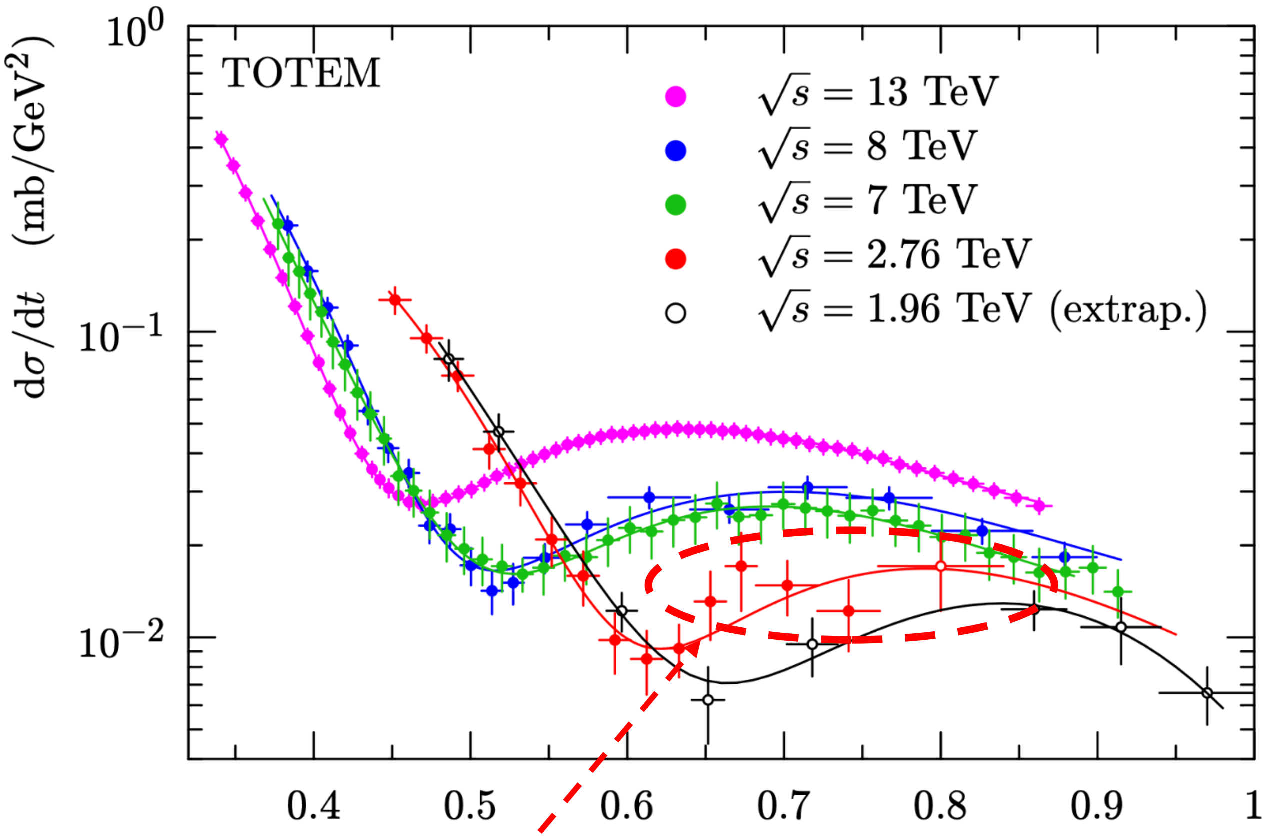
Elastic pp differential cross-section



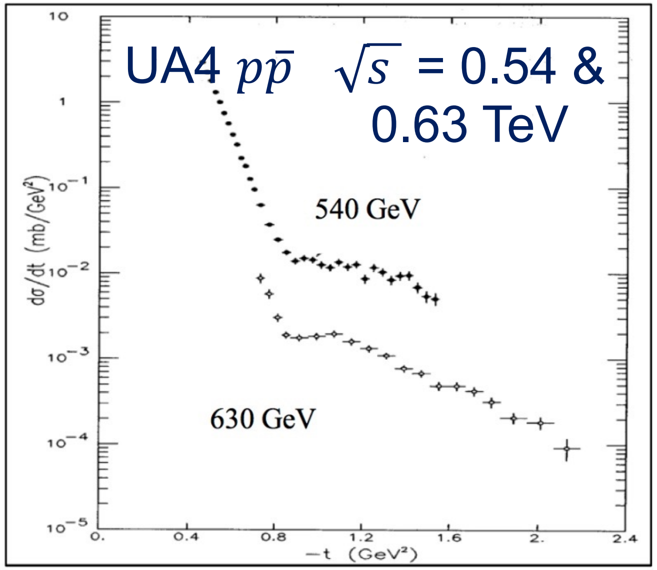
$$\rho \equiv Re[A_{\rm el}^{\rm had}]/Im[A_{\rm el}^{\rm had}]\Big|_{t=0}$$

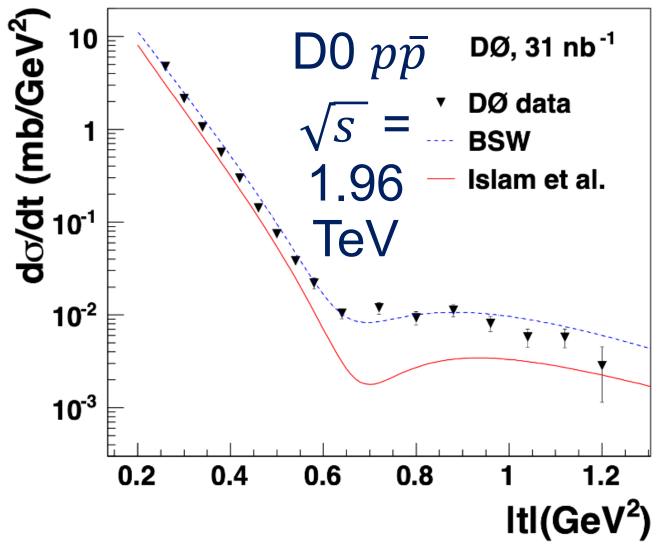
sensitive to C-odd exchange ?

$d\sigma_{el}/dt$ measurements in $pp/p\bar{p}$



NB! acceptance cutoff @ $\sqrt{s}$ = 2.76 TeV ⇒ bump NOT expt'ly visible (open circles extrapolations)

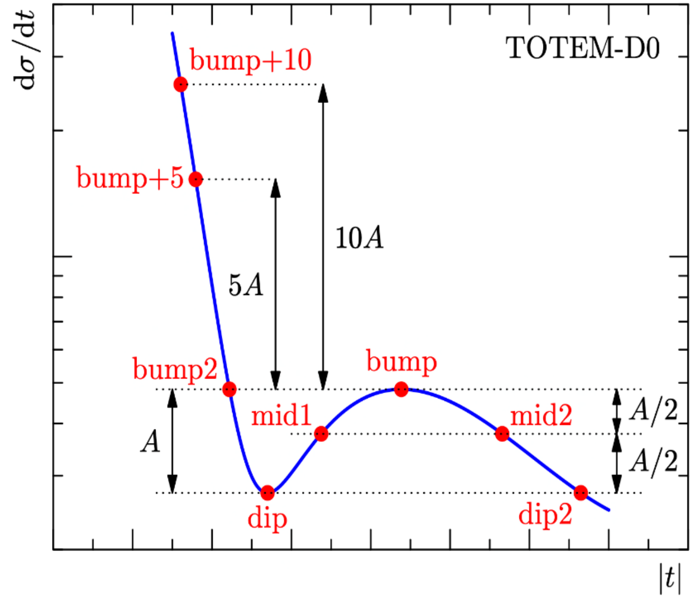




- Diffractive minimum ("dip") & secondary maximum ("bump") clearly observable in pp (contrary to $p\bar{p}$)
- $pp\ d\sigma_{el}/dt$ in dip-bump region well described by $h(t) = a_1 e^{-a_2|t|^2 - a_3|t|} + a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$

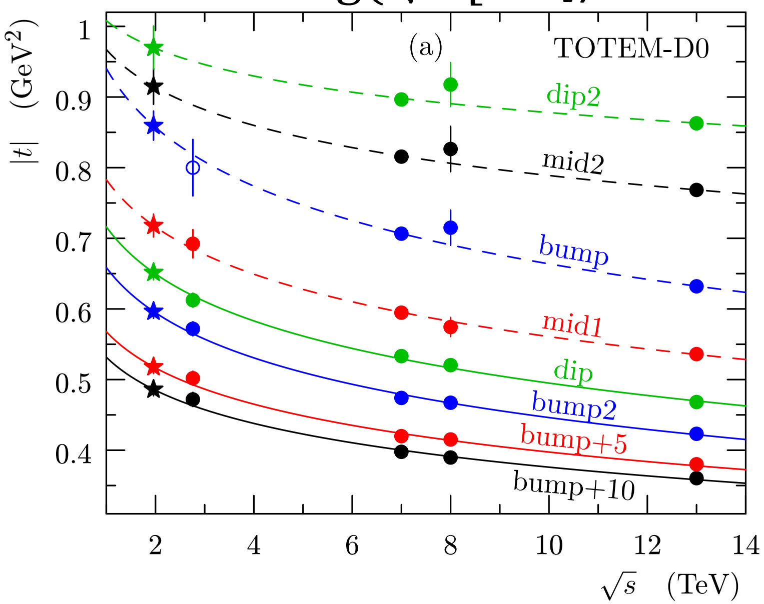
Data-driven estimates

- Short (~8 % of fit range) extrapolation of the 8 characteristic $pp\ d\sigma_{el}/dt$ points to $\sqrt{s}$ = 1.96 TeV.
- Interpolation of $pp\ d\sigma_{el}/dt$ characteristic points using $h(t)$ (see previous slide) allows comparison with D0 measured $p\bar{p}\ d\sigma_{el}/dt$.

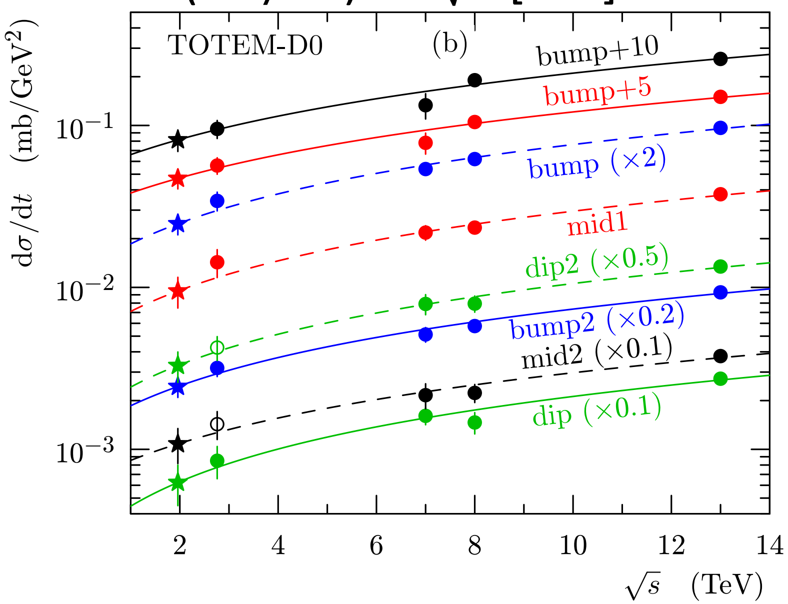


- Only 3-4 $\sqrt{s}$ points limits formulas to 2 parameters.
- Excellent fits for all characteristic points.
- Alternate functions (with other $\sqrt{s}$ powers) give compatible results.

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

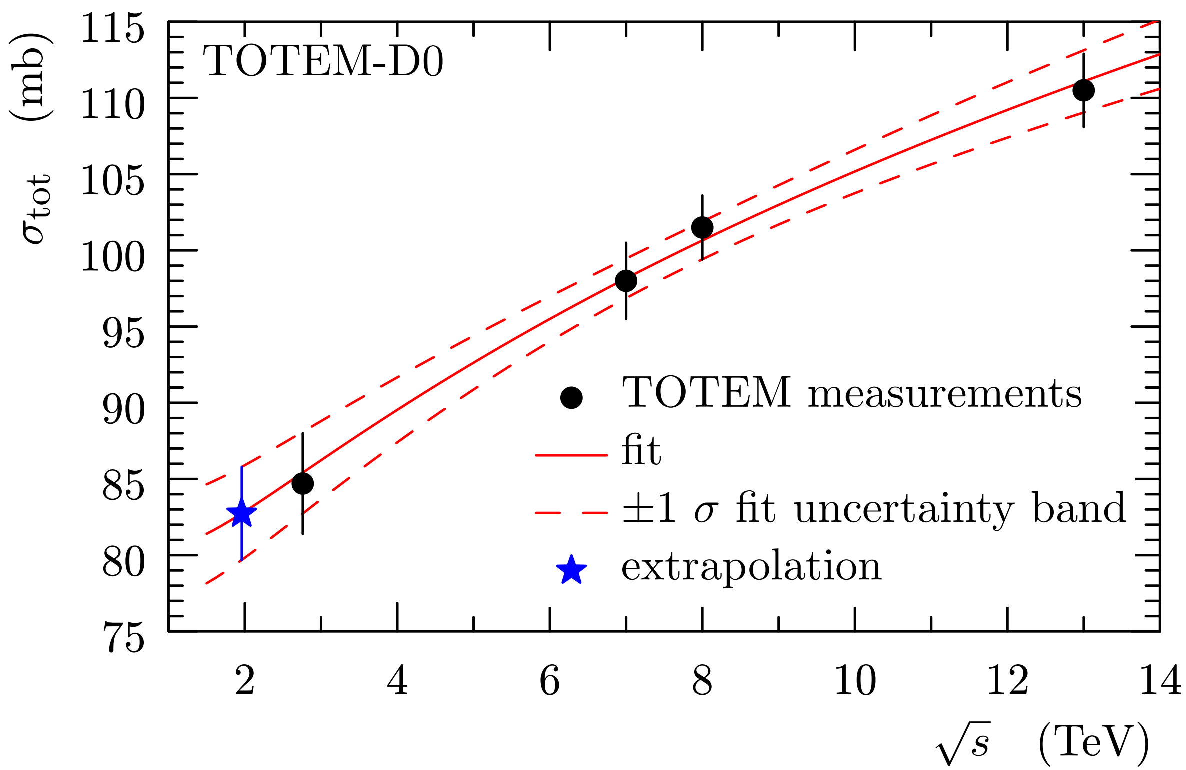


$(d\sigma/dt) = c\sqrt{s}\ [\text{TeV}] + d$



σ_{tot}^{pp} extrapolation for optical point (OP)

- σ_{tot}^{pp} (and $d\sigma_{\rm el}^{\rm tot}/dt|_{t=0}$) at $\sqrt{s}$ = 1.96 TeV extrapolated from TOTEM σ_{tot}^{pp} at $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV using formula: $\sigma_{tot} = a \log^2\sqrt{s}$ ([TeV]) $+ b$



$\sigma_{tot}^{pp}(\sqrt{s}$ = 1.96 TeV) = 82.7 $\pm$ 3.7 mb $\Rightarrow$ $d\sigma_{el}^{pp}/dt|_{t=0}$ = 357 $\pm$ 26 mb/GeV^2

- Short (~8 % of fit range) extrapolation of σ_{tot}^{pp} to $\sqrt{s}$ = 1.96 TeV
- Only 4 $\sqrt{s}$ data points limits formulas to 2 parameters.

- ~2 TeV close to boundary between $\log^2\sqrt{s}$ & $\log\sqrt{s}$ dominant regions.
- All alternative extrapolations fall well within estimated uncertainty.

χ^2 for pp & $p\bar{p}$ comparison

- As a result of interpolation, extrapolated $pp\ d\sigma_{el}/dt$ values at neighbouring D0 |t|-values strongly correlated $\Longrightarrow$ full covariance matrix (with vital diagonal protection) included in χ^2 for pp & $p\bar{p}$ comparison

$$\chi^2 = \sum_{\text{points } i,j} \left\{ \left(\frac{d\sigma_{el,i}^{pp}}{dt} - \frac{d\sigma_{el,i}^{p\bar{p}}}{dt} \right) C_{i,j}^{-1} \left(\frac{d\sigma_{el,j}^{pp}}{dt} - \frac{d\sigma_{el,j}^{p\bar{p}}}{dt} \right) \right\} + \frac{(A - A_0)^2}{\sigma_A^2} + \frac{(B - B_0)^2}{\sigma_B^2}$$

≈ 0

where $C_{i,j}$ covariance matrix and A & B two contraints $\Longrightarrow$ 8 points, 6 d.o.f.

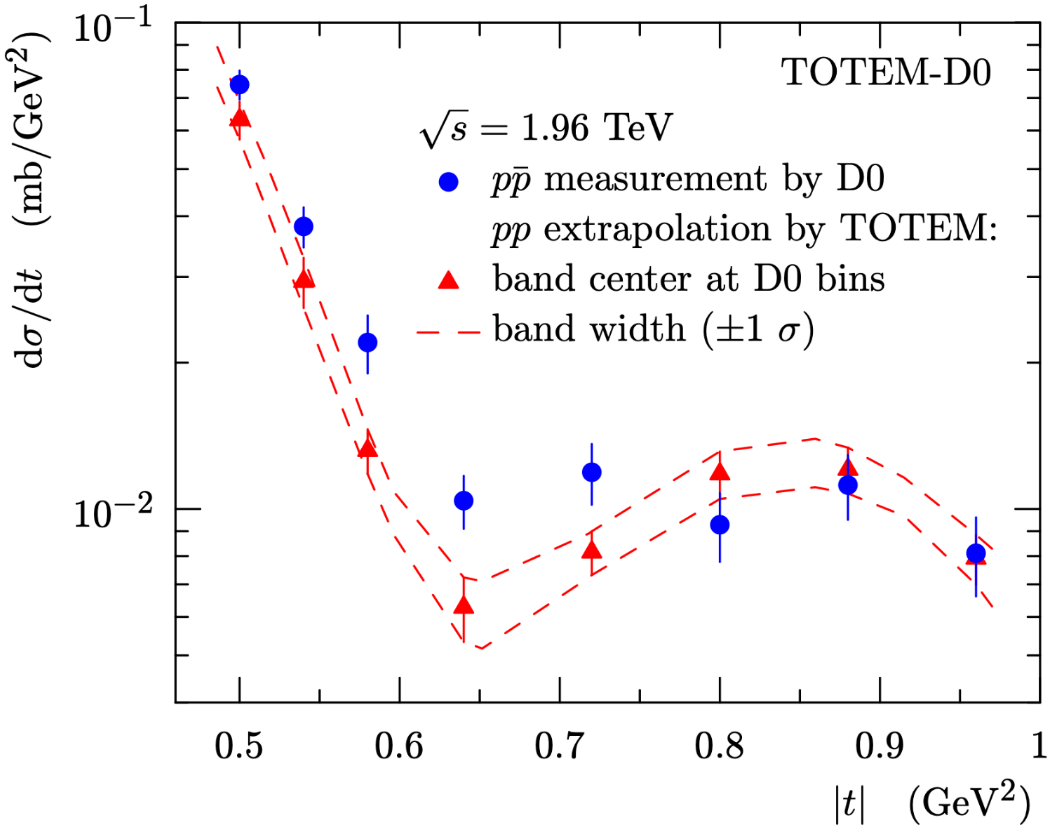
- ✓ A = normalization OP(pp) = OP($p\bar{p}$) (also expt'ly. true within uncertainties)
- ✓ B = elastic slope $B(pp)$ = $B(p\bar{p})$ (also expt'ly true within uncertainties)
- ✓ Assume pp OP = $p\bar{p}$ OP (experimentally true within uncertainties), valid as long as maximal possible C-odd ("maximal odderon model"), secondary Reggeon effects & $pp/p\bar{p}$ ρ differences included as systematics (2.9 %).

a) D0 & TOTEM covariance matrices diagonalized separately
b) first term of χ^2 estimated using the sum of the two diagonalized matrices

χ^2 = 23.64 (d.o.f. = 6) $\Longrightarrow$ pp & $p\bar{p}$ $d\sigma_{el}/dt$ differ by 3.4σ at $\sqrt{s}$ = 1.96 TeV

Comparison of pp & $p\bar{p}$ cross section

- Extrapolation of TOTEM pp $d\sigma_{\mathrm{el}}/dt$ at $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV in dip-bump region to $\sqrt{s}$ = 1.96 TeV for direct comparison with D0 $p\bar{p}$ $d\sigma_{\mathrm{el}}/dt$



Elastic pp & $p\bar{p}$ $d\sigma/dt$ differ by 3.4σ at $\sqrt{s}$ = 1.96 TeV $\Longrightarrow$ evidence of odderon exchange (C-odd gluonic compound exchange) in TeV energy range (where secondary Reggeons are negligible)

Cui et al. *(PLB 839 (2023) 137826)* aims at reproducing the D0-TOTEM analysis obtaining significances of 2.2-2.6σ: fails on 2.76 TeV bump location (@ too low |t|), adds ISR pp data (involves secondary Reggeons?) & full correlation of normalisation error not taken into account.

Updated χ^2 for pp & $p\bar{p}$ comparison

TOTEM-D0 preparing a longer (more detailed) paper that also will include an updated version of the pp & $p\bar{p}$ comparison at $\sqrt{s}$ = 1.96 TeV

- ✓ Improved TOTEM pp covariance matrix (with refined diagonal protection)
- ✓ MC method for combining the diagonal D0 $p\bar{p}$ covariance matrix (Gaussian) with the non-diagonal TOTEM pp covariance matrix (Cholesky)
- ✓ Explicit affine transformation assuring pp & $p\bar{p}$ equality of elastic slope B & integrated cross section A in χ^2 calculation
- ✓ D0 cross-sections placed at cross section weighted t-positions

$$\chi^2 = \sum_{\text{points } i,j} \left\{ \left(\frac{d\sigma_{el,i}^{pp}}{dt} - \frac{d\sigma_{el,i}^{p\bar{p}}}{dt} \right) C_{i,j}^{-1} \left(\frac{d\sigma_{el,j}^{pp}}{dt} - \frac{d\sigma_{el,j}^{p\bar{p}}}{dt} \right) \right\} + \frac{(A - A_0)^2}{\sigma_A^2} + \frac{(B - B_0)^2}{\sigma_B^2}$$

$\Longrightarrow$ a small increase of significance in pp & $p\bar{p}$ comparison at $\sqrt{s}$ = 1.96 TeV:

Preliminary

Significance confirmed with a MC based Kolmogorov-Smirnov test, including data point correlations, combined with normalisation using Stouffer method

More improvements of the pp & $p\bar{p}$ comparison at $\sqrt{s}$ = 1.96 TeV to come!

Stay tuned !

TOTEM & ATLAS σ_{tot} comparison

- 13 TeV TOTEM σ_{tot}^{pp} = 110.6 ± 3.4 mb
  direct counting experiment (needs correction for low mass diffraction)
- 13 TeV TOTEM σ_{tot}^{pp} = 110.3 ± 3.5 mb
  $d\sigma_{\text{el}}/dt$ normalisation from σ_{Coulomb}
- 13 TeV ATLAS σ_{tot}^{pp} = 104.7 ± 1.1 mb
  need precise luminosity determination

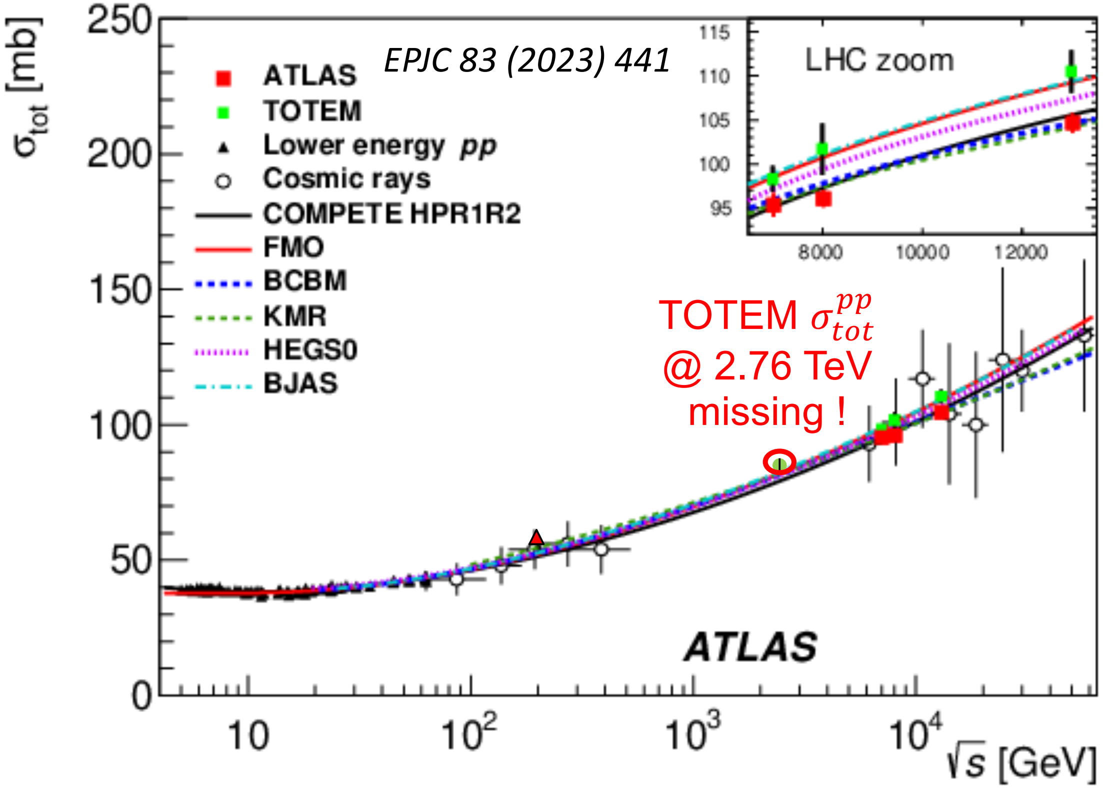
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

Fully independent datasets & methods:

$\sigma_{tot,TOTEM}^{pp,13\ TeV}$ = 110.5 ± 2.4 mb

2.2σ difference

$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt}\right)_{t=0}$$



Trend same as @ $\sqrt{s}$ = 7 & 8 TeV, essentially only a normalisation difference!

Not whole story: TOTEM has 2-4 consistent σ_{tot}^{pp} measurements using (slightly) different techniques /energy vs. 1 measurement/energy using same technique for ATLAS

Measuring σ_{tot} & low mass diffraction

- NB! Any σ_{tot}^{pp} measurement makes assumptions e.g. elastic hadronic slope used for dN_{el}/dt extrapolation to t = 0 ($e^{-B|t|}$ vs. $e^{-B|t|-C|t|^2-D|t|^3}$) and treatment of Coulomb & CNI (fitted/subtracted/ignored depending on |t|-range) easily resulting in $\mathcal{O}$(1 mb) changes ⇒ not viable to claim precision ≤ ~1.5 mb

difference due to non-measured low mass diffraction in N_{inel} ?

(*P. Grafström, ArXiv: 2209.01058*)

13 TeV TOTEM correction: 5.3 $\pm$ 2.6 mb → 8.2 $\pm$ 1.4 mb ⟹

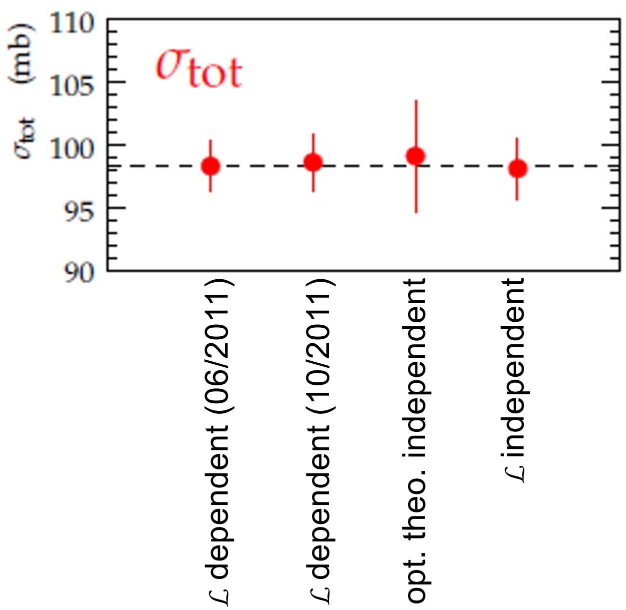
smaller σ_{tot}^{pp} ATLAS-TOTEM difference but only slightly in # of σ's & no explain. of $\sigma_{tot,C\ norm}^{pp}$

Also if full σ_{tot}^{pp} difference low mass diffraction ⇒ correction ≥ ATLAS ($\sigma_{incl}^{ALFA} - \sigma_{inel}^{central}$)!

<u>TOTEM @ 7 TeV:</u>

4 consistent measurements of σ_{tot}^{pp} using 3 different methods:

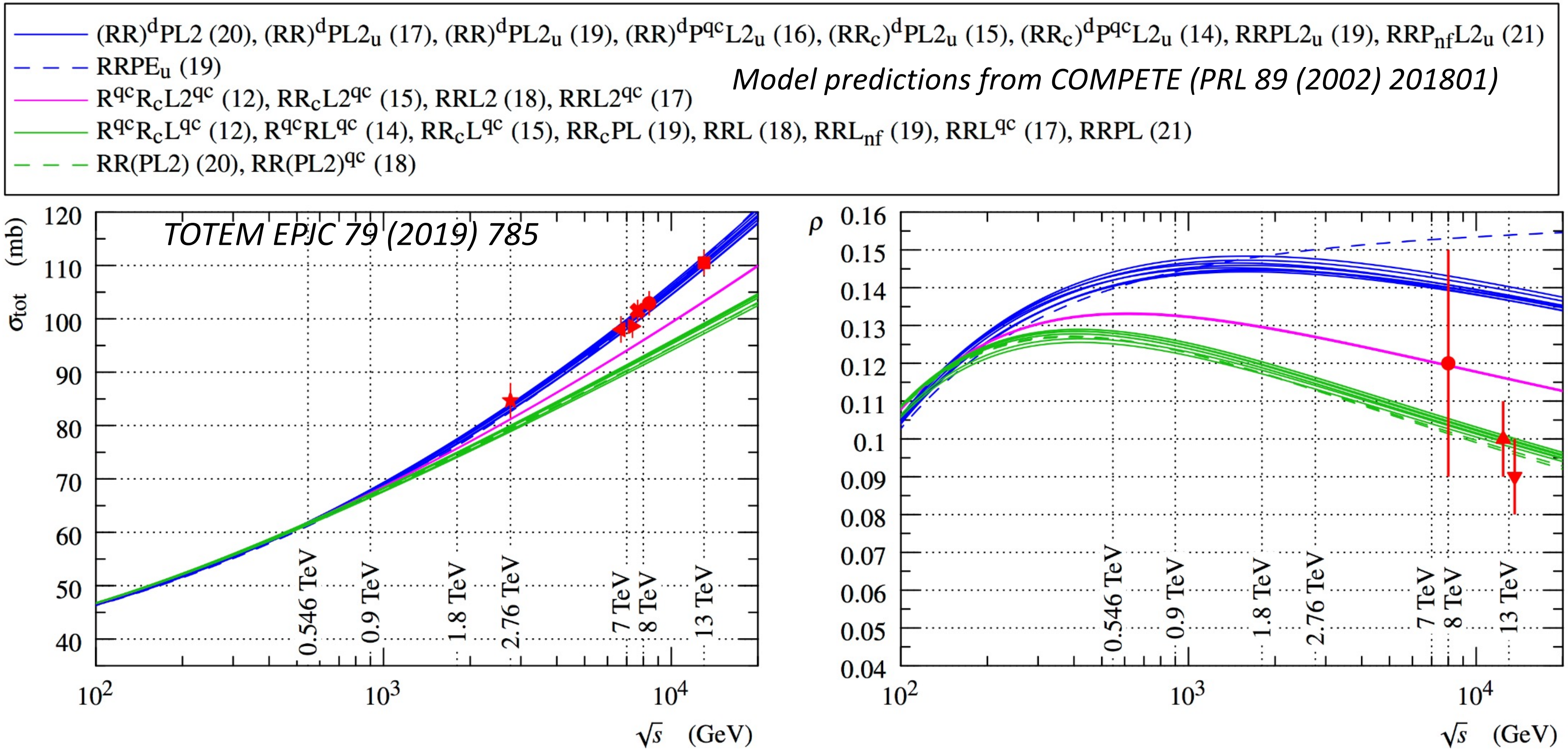
EPL 101 (2013) 21004



- Regarding ATLAS σ_{tot}^{pp}: How reliable are absolute luminosity calibrations (precision @ $\sqrt{s}$ = 13 TeV: 2.15 %) made in van de Meer scans at β^* = 11 m for the luminosity of beams at β^* = 2500 m (with very different LHC optics and an interaction point transverse size 15 times larger)?

TOTEM ρ in pp at $\sqrt{s}$ = 13 TeV

- @ $\sqrt{s}$ = 13 TeV: ρ^{pp} = 0.10 $\pm$ 0.01 / 0.09 $\pm$ 0.01 *(TOTEM, EPJC 79 (2019) 785)*
- Models (*COMPETE, Durham, Block-Halzen*) unable to describe TOTEM ρ & σ_{tot}^{pp} measurements at 3.4-4.6σ level without adding odderon exchange
- Alternative non-excluded explanation for low ρ^{pp}: slower rise of σ_{tot}^{pp} @ $\sqrt{s} > \sqrt{s}_{\text{LHC}}$

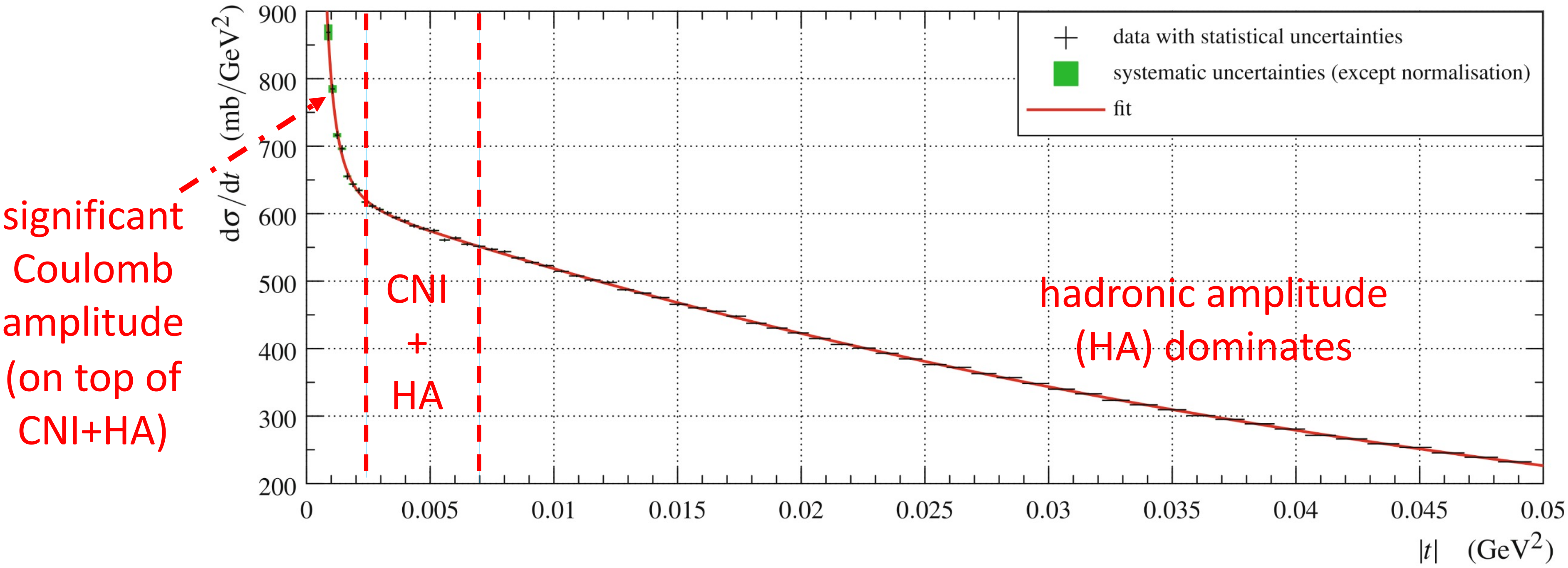


ATLAS confirmed: ρ^{pp} @ 13 TeV = 0.098 $\pm$ 0.011 *(EPJC 83 (2023) 441)*

Comments about 13 TeV ρ measurements

- Main sensitivity to ρ only in limited |t|-range in CNI region (only few data points). Fits have to be made in steps (hadronic amplitude, Coulomb amplitude & ρ) in separate |t|-regions to avoid points without ρ sensitivity to influence ρ measurement.

  Not properly taken into account by V. A. Petrov and N.P. Tkachenko, PRD 106 (2022) 054003 & A.Donnachie and P.V. Landshoff, PLB 798 (2019) 135008 + PLB 831 (2022)137199

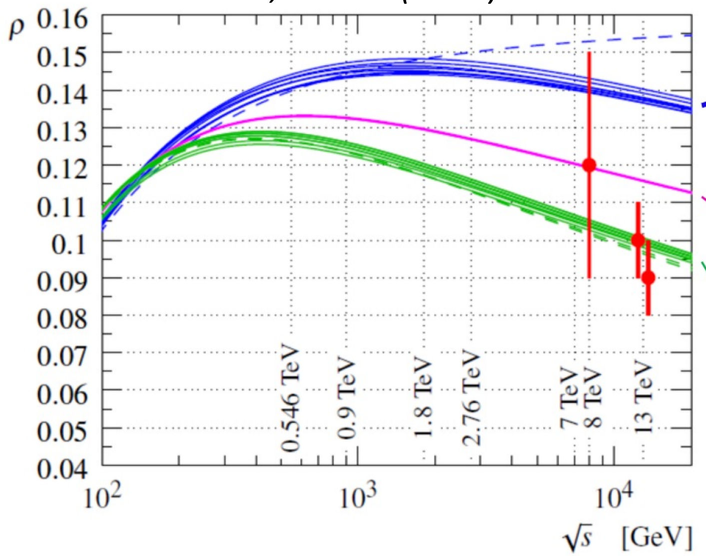


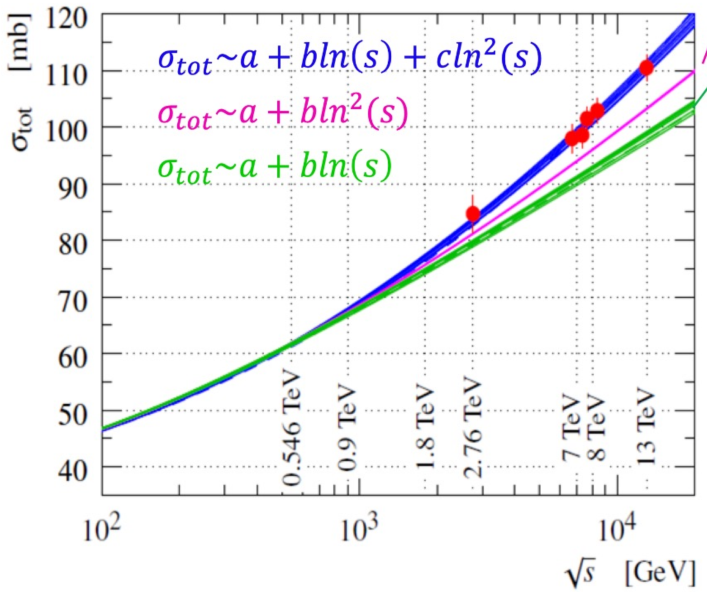
- TOTEM (/ATLAS?) data described within 1σ and ρ = 0.14 for pp at 13 TeV without odderon (*A. Donnachie & P.V. Landshoff, PLB 798 (2019) 135008 & PLB 831 (2022)137199*): Are not taking the Coulomb phase into account ($\Delta\rho$ = +0.02)

Combine $pp/p\bar{p}$ comparison & pp $\rho + \sigma_{tot}$

using Stouffer method (*S. Bityukov et al., Proc. Sci. ACAT08 (2009) 18*).

COMPETE Coll., PRL 89 (2002) 201801





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

- Excluded at **4.0σ** level with TOTEM $\rho + \sigma_{tot}$ data.
- Excluded at **5.3σ** 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 **4.6σ** level with TOTEM $\rho + \sigma_{tot}$ data.
- Excluded at **5.7σ** 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: *PLB 748 (2018) 192*
- Excluded at **3.4σ** level with TOTEM $\rho + \sigma_{tot}$ data.
- Excluded at **5.2σ** 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: *PRD 92 (2015) 114021*
- Excluded at **3.9σ** level with TOTEM ρ data.
- Excluded at **5.2σ** level when combining significance from TOTEM ρ data and and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.

Conclusions

- Issues & objections raised regarding D0-TOTEM $p\bar{p}$ & pp elastic $d\sigma/dt$ comparison at $\sqrt{s}$ = 1.96 TeV as well as TOTEM 13 TeV ρ & total cross section measurements addressed

- Updated $p\bar{p}$ & pp elastic $d\sigma/dt$ comparison at $\sqrt{s}$ = 1.96 TeV show a small increased significance for odderon

- Tension between TOTEM & ATLAS total cross section @ $\sqrt{s}$ = 13 TeV

- *E. Leader, Discovery of the odderon, Nature Review Physics (2021):*
  "In a recent article in *Physical Review Letters* the CERN TOTEM and the Fermilab DØ collaborations reported the discovery of the odderon. This result is based mainly on an almost model-independent extrapolation down in the energy of the *pp* differential cross-sections measured at the LHC and a comparison with the $p\bar{p}$ differential cross-section measured at the Tevatron. The significant difference in the shape of differential cross-sections at this ultra-high energy is at last convincing evidence for the existence of the odderon"