D0-TOTEM Odderon observation: an update

C. Royon

on behalf of

K. Österberg,

Department of Physics & Helsinki Institute of Physics, University of Helsinki

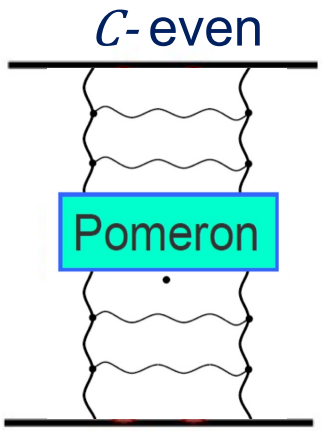
on behalf the **D0 & TOTEM collaborations**

Diffraction and low x 2024

9.9.2024

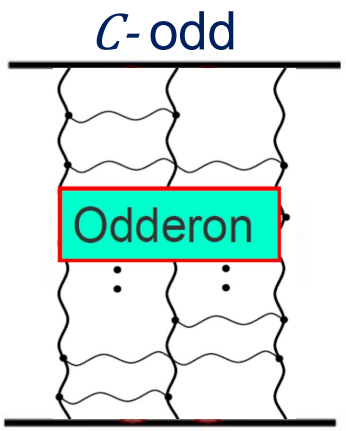
Elastic scattering: multi-gluon exchanges

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



dominates at low |t|,

$\approx Im\left[A_{\mathrm{el}}^{\mathrm{had}}\right]$



suppressed,

mainly $Re\left[A_{\mathrm{el}}^{\mathrm{had}}\right]$

identical for pp & $p\bar{p}$ different sign for pp & $p\bar{p}$

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

Odderon:

- Odderon exchange contribution predicted in Regge-theory

  L. Lukaszuk & B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405

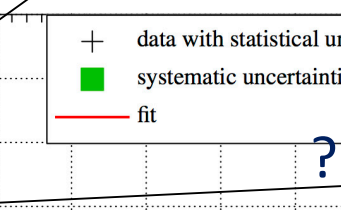
- confirmed in QCD as C-odd exchange of 3 (or odd #) gluons at leading order

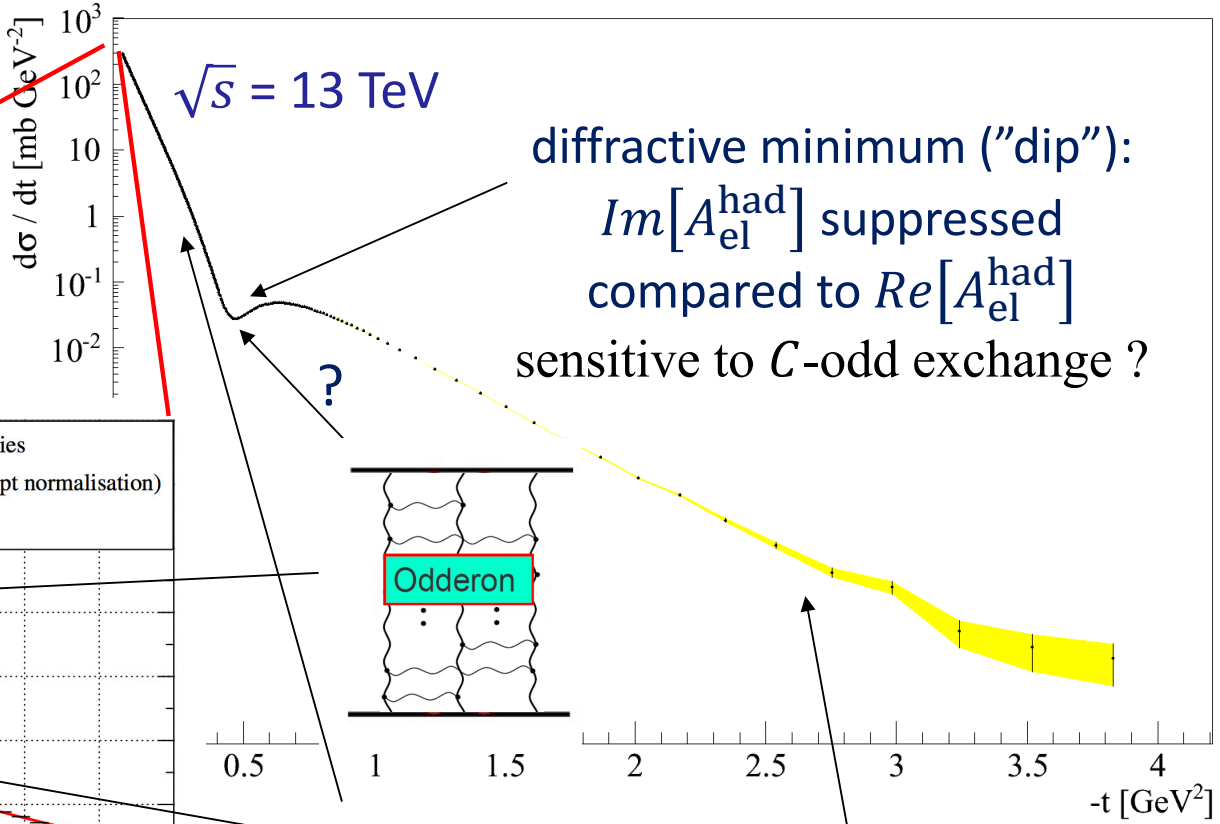
  J. Bartels, Nucl. Phys. B 175 (1980) 365; J. Kwiecinski & M. Praszlowics Phys. Lett. B 94 (1980) 413

- searched for last 50 years, until recently no convincing experimental evidence

Elastic pp differential cross-section

Photon exchange



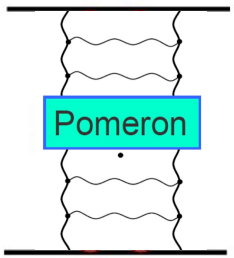


$\sqrt{s}$ = 13 TeV

diffractive minimum ("dip"):
$Im[A_{el}^{had}]$ suppressed
compared to $Re[A_{el}^{had}]$
sensitive to C-odd exchange ?

?

?



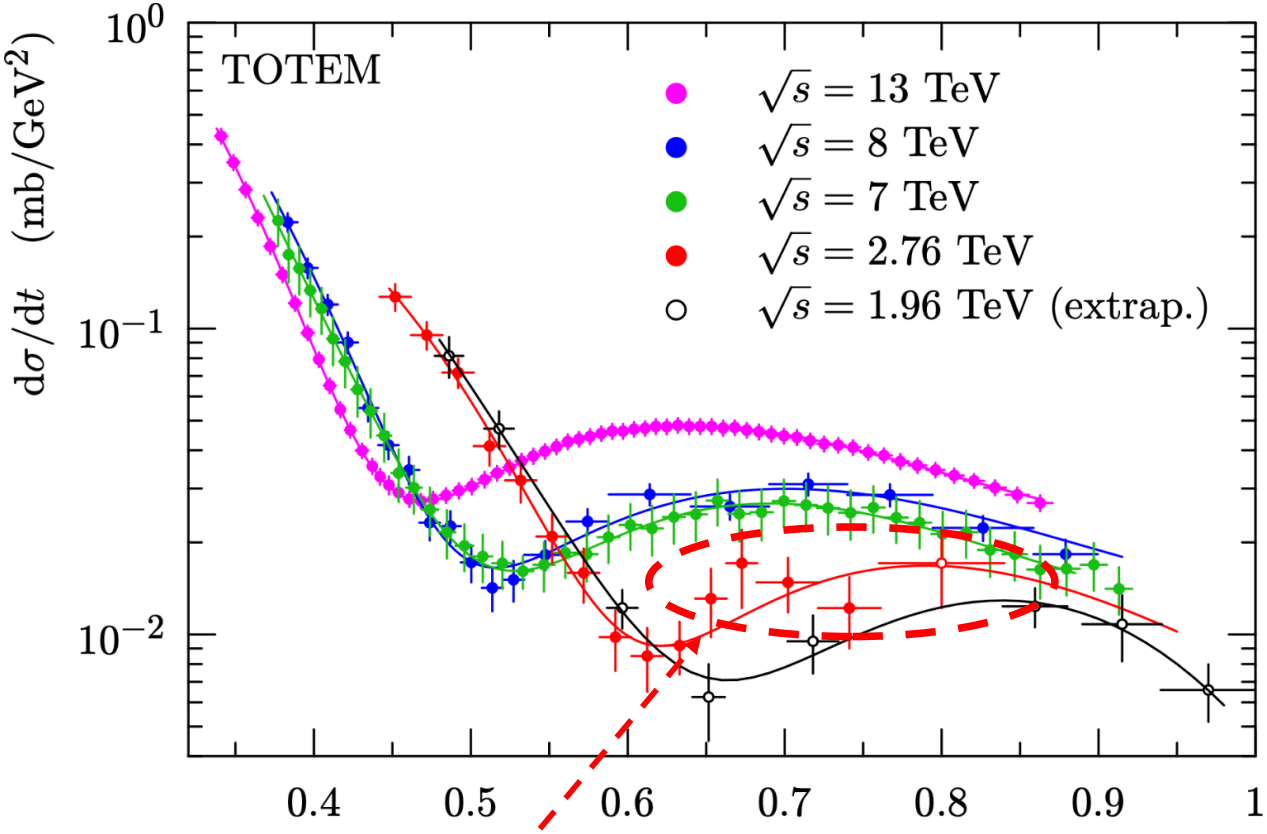
"Perturbative QCD"
(pQCD) region

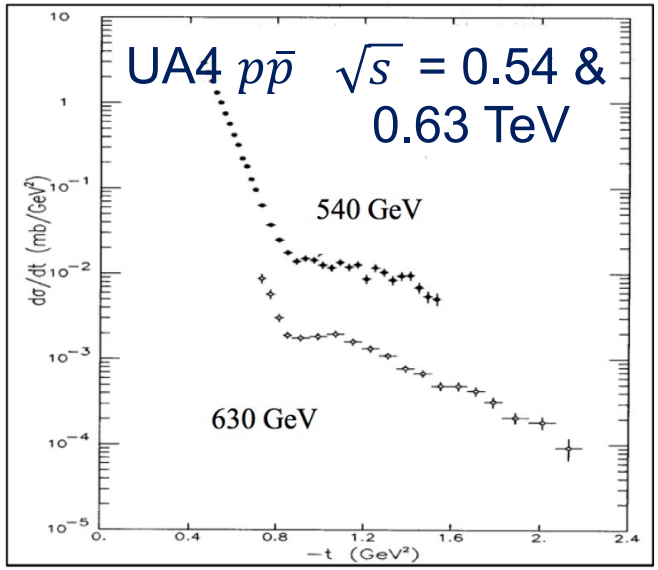
"Coulomb-nuclear
interference" (CNI) region

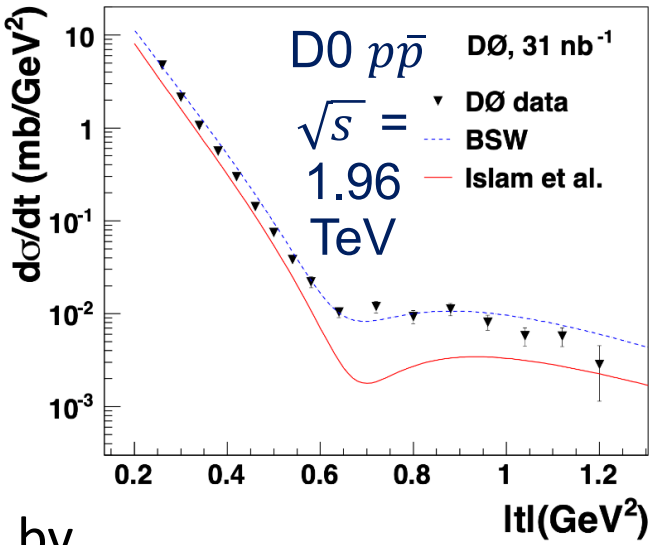
$$\rho \equiv Re\left[A_{el}^{had}\right]/Im\left[A_{el}^{had}\right]\Big|_{t=0}$$

sensitive to C-odd exchange ?

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







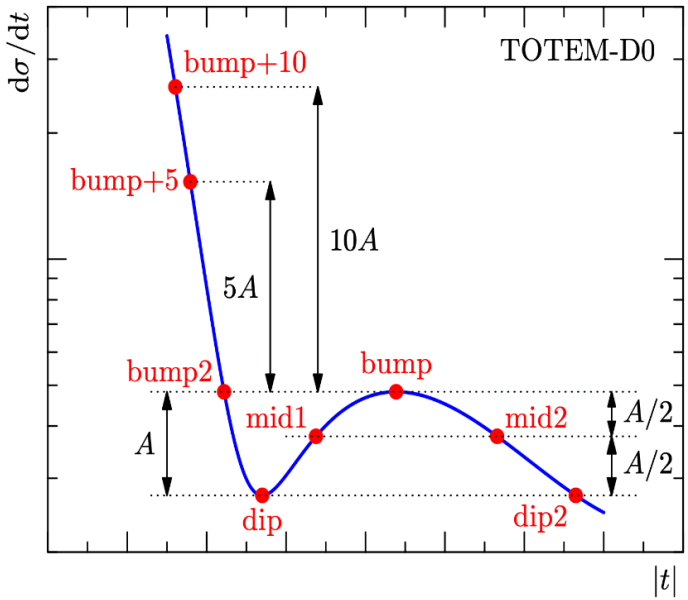
N.B. acceptance cutoff @ $\sqrt{s}$ = 2.76 TeV ⇒ $|t|$ (GeV^2) bump NOT expt'ly visible (open circles extrapolations)

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

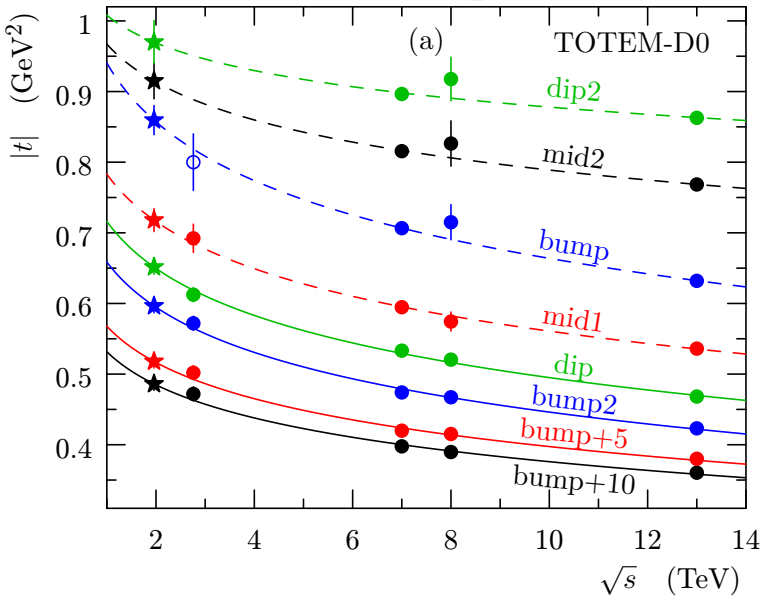
Data-driven extrapolation of $d\sigma_{el}^{pp}/dt$

- ✓ 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 $p\bar{p}\ d\sigma_{el}/dt$

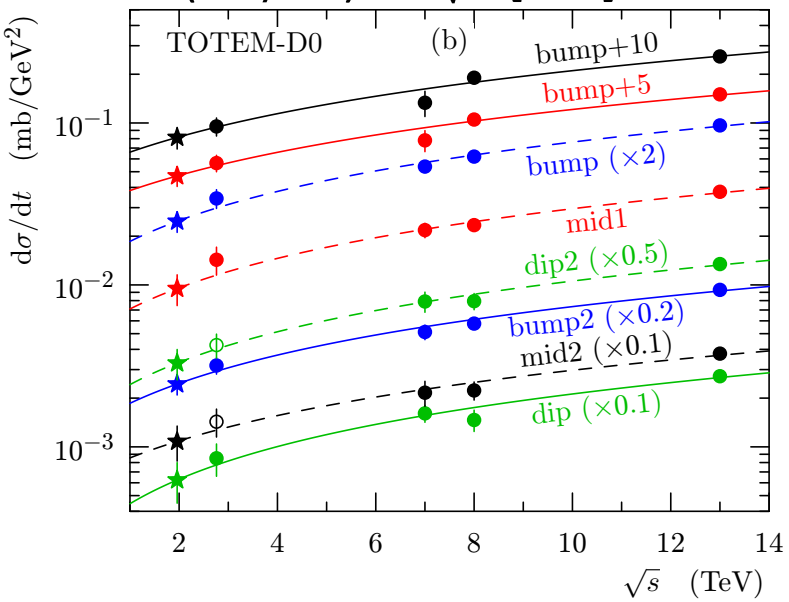
- ✓ Only 3-4 $\sqrt{s}$ points limits formulas to 2 parameters
- ✓ Excellent fits for all characteristic points



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

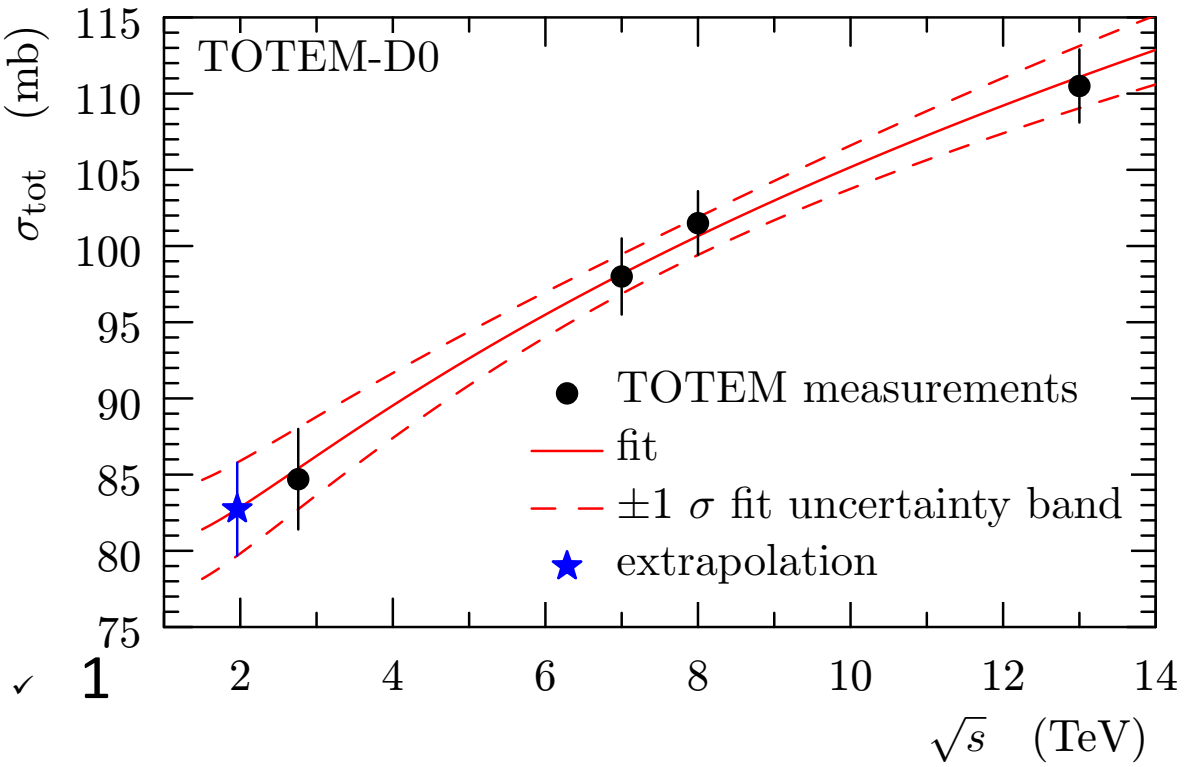


$(d\sigma/dt) = c\sqrt{s}\ [\text{TeV}] + d$



σ_{tot}^{pp} extrapolation for optical point

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



- ✓ 1

$\sigma_{tot}^{pp}(\sqrt{s}$ = 1.96 TeV) = 82.7 $\pm$ 3.7 mb ⇒ $d\sigma_{el}^{pp}/dt\big|_{t=0}$ = 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 2-3 parameters

- ✓ ~2 TeV close to boundary between region best described by $\log^2\sqrt{s}$ (higher $\sqrt{s}$) & region best described by $\log\sqrt{s}$ (lower $\sqrt{s}$) behavior

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 essential 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 constraints $\Longrightarrow$ 8 points, 6 d.o.f.

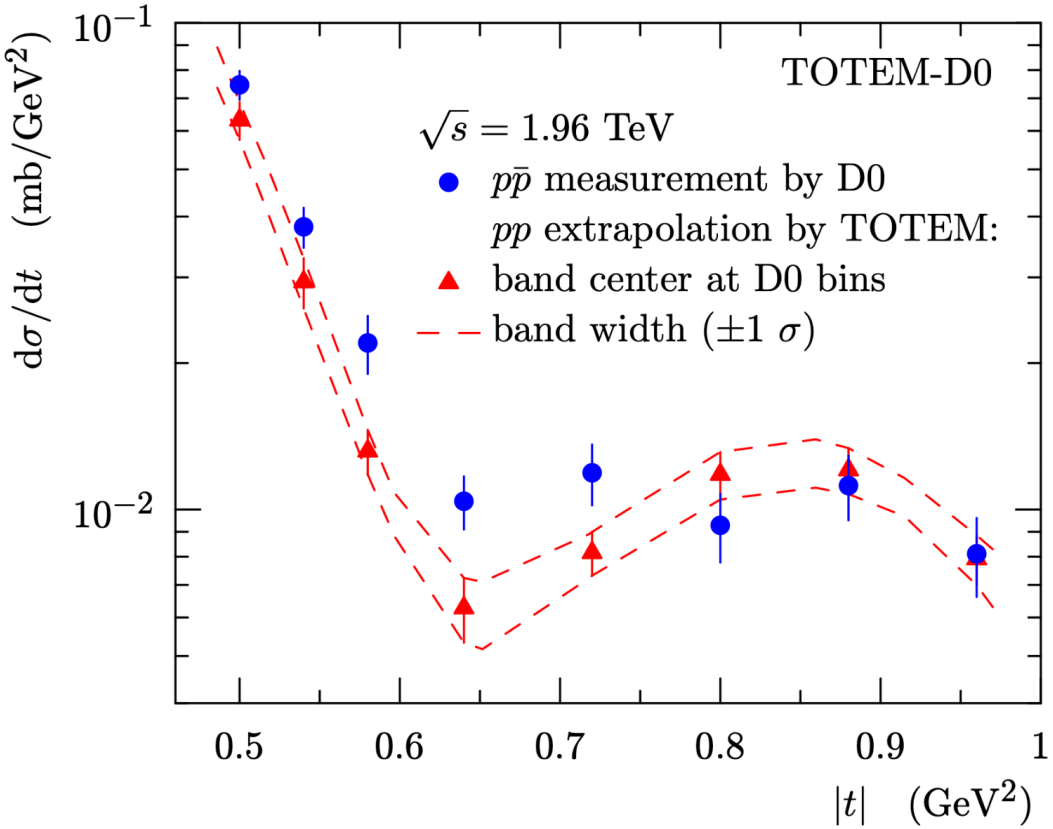
- ✓ A = normalization OP(pp) = OP($p\bar{p}$) (also expt'ly. true within uncertainties)
- ✓ B = elastic slope $B(pp) = B(p\bar{p})$ (also expt'ly true within uncertainties)
- ✓ Assume pp OP = $p\bar{p}$ OP (experimentally true within uncertainties), valid as long as maximal possible C-odd ("maximal odderon 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

$\chi^2 = 23.6$ (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 ⟹ evidence of odderon exchange (C-odd gluonic compound exchange) in TeV energy range (where secondary Reggeons are negligible)

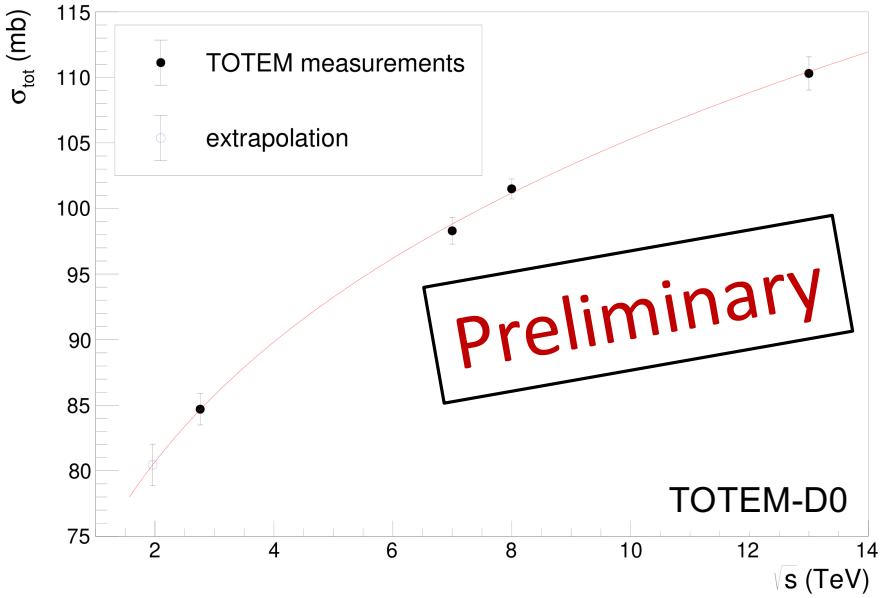
Cui et al. *(PLB 839 (2023) 137826)* obtains significances of 2.2-2.6σ when attempting to repeat the extrapolation: fails on the position of the bump @ 1.96 and 2.76 TeV (ends up @ too low |t|) & disregards the full correlation of both slope & overall normalisation

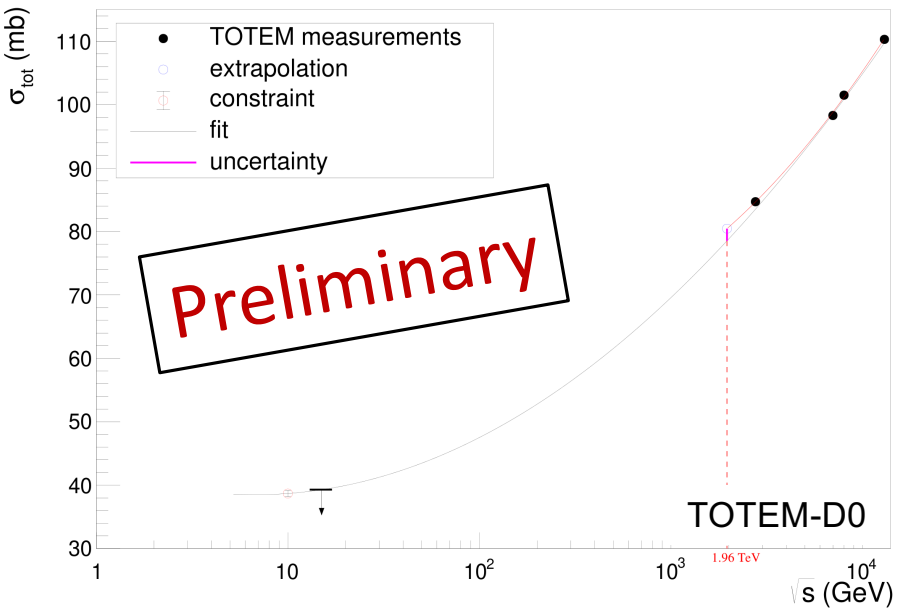
Csorgo et al. *(EPJC 81 (2021) 2)* claims larger Odderon evidence using scaling properties of elastic scattering: scaling fails for most precise data set, TOTEM $d\sigma_{\mathrm{el}}/dt$ @ $\sqrt{s}$ = 13 TeV

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

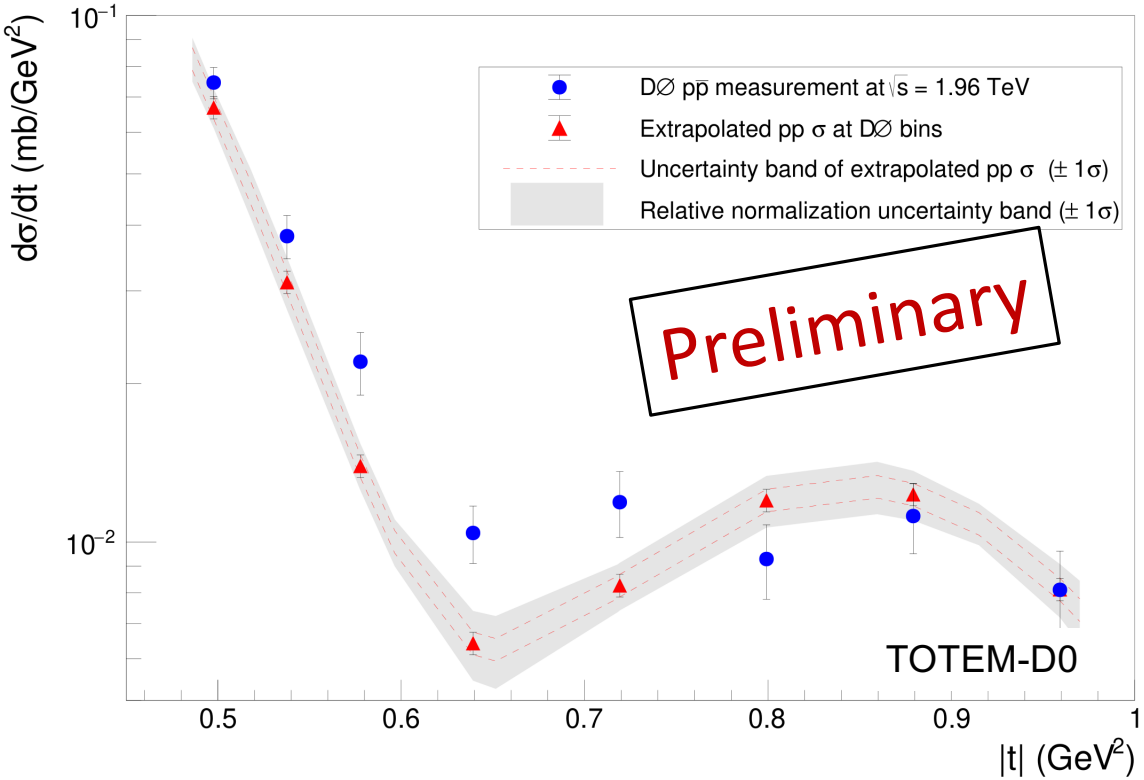
- ✓ Improved TOTEM pp covariance matrix (with refined diagonal protection)
- ✓ MC method for combining the diagonal D0 $p\bar{p}$ covariance matrix (Gaussian) with the non-diagonal TOTEM pp covariance matrix (Cholesky)
- ✓ Extrapolation of uncorrelated TOTEM σ_{tot} measurements to 1.96 TeV using scale-independent formula: $\sigma_{tot} = a \log^2\sqrt{s} + b \log\sqrt{s} + c$ enforcing p-value of fit to 0.5 (validity of uncertainty estimate cross checked by constraining fit to ISR σ_{tot} measurements in $\sqrt{s} \sim 10$ GeV region where the cross section is expected to be almost constant)





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

- ✓ Explicit affine transformation assuring pp & $p\bar{p}$ equality of elastic slope *B* & integrated cross section *A* in χ^2 calculation (for A & B definition see slide 7)
- ✓ D0 measurements placed at the average value of fit with $h(t)$ (see slide 4) within bin

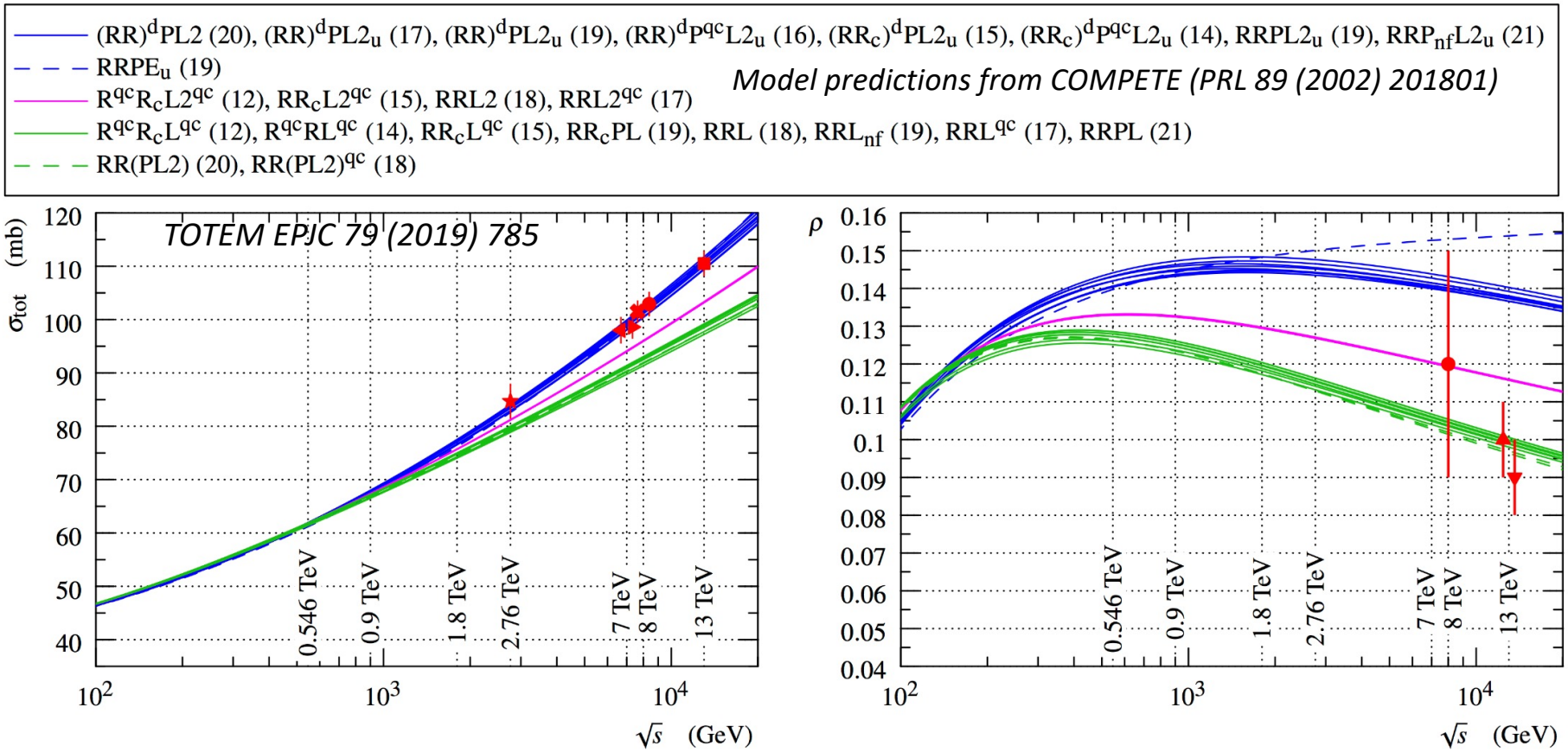


⟹ a small increase in significance obtained from the improvements in updated analysis

Significance confirmed with a MC based Kolmogorov-Smirnov test, including data point correlations, combined with normalisation using Stouffer method (*S. Bityukov et al., Proc. Sci. ACAT08 (2009) 18*)

TOTEM ρ & σ_{tot} at LHC

- ✓ @ $\sqrt{s}$ = 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} @ $\sqrt{s} > \sqrt{s}_{\mathrm{LHC}}$



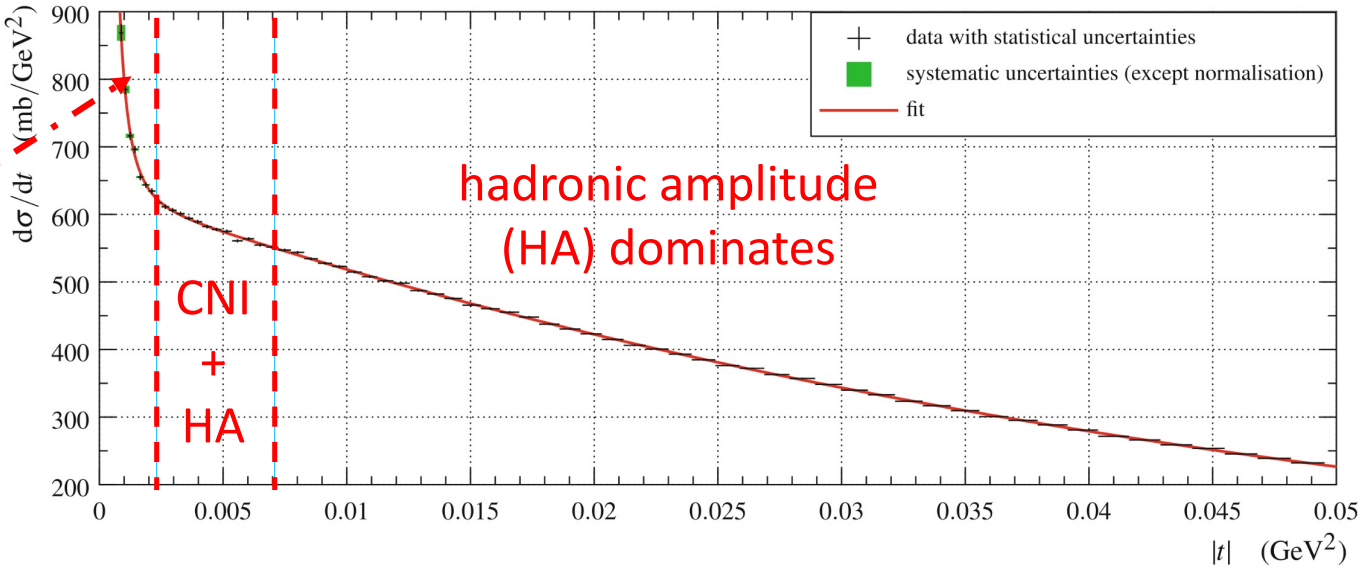
ATLAS confirmed: ρ^{pp} @ 13 TeV = 0.098 $\pm$ 0.011 *(EPJC 83 (2023) 441)*

Comments about ρ determination

- Sensitivity to ρ only in limited |t|-range in CNI region (only limited number of 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)

significant Coulomb amplitude (on top of CNI+HA)



- Claim: TOTEM (/ATLAS?) data described within 1σ & ρ = 0.14 for pp at 13 TeV without odderon (*A. Donnachie & P.V. Landshoff, PLB 798 (2019) 135008 & PLB 831 (2022)137199*): Have not included the standard "Bethe" phase in the CNI formula (give a change of $\rho \geq +0.02$)
- Reasonable description of elastic pp & $p\bar{p}$ data obtained with Pomeron only: Durham model without odderon (*PLB 748 (2018) 192*) fails to describe D0 1.96 TeV elastic $p\bar{p}$ $d\sigma/dt$ in dip-bump region (4.3σ) after being tuned on LHC elastic pp $d\sigma/dt$ data

TOTEM & ATLAS σ_{tot}^{pp} 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 $d\sigma_{el}/dt$ normalisation from $\sigma_{Coulomb}$
- ✓ 13 TeV ATLAS σ_{tot}^{pp} = 104.7 ± 1.1 mb need precise luminosity determination

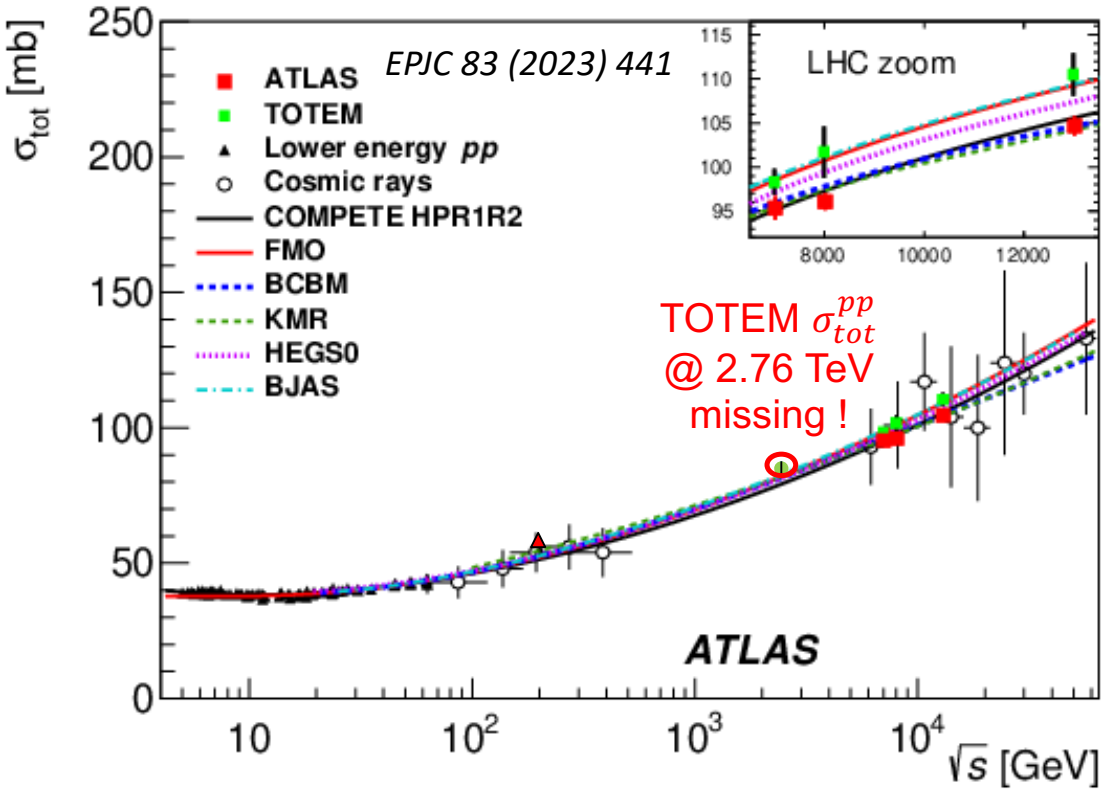
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

Fully independent datasets & methods:

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

2.2σ difference

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



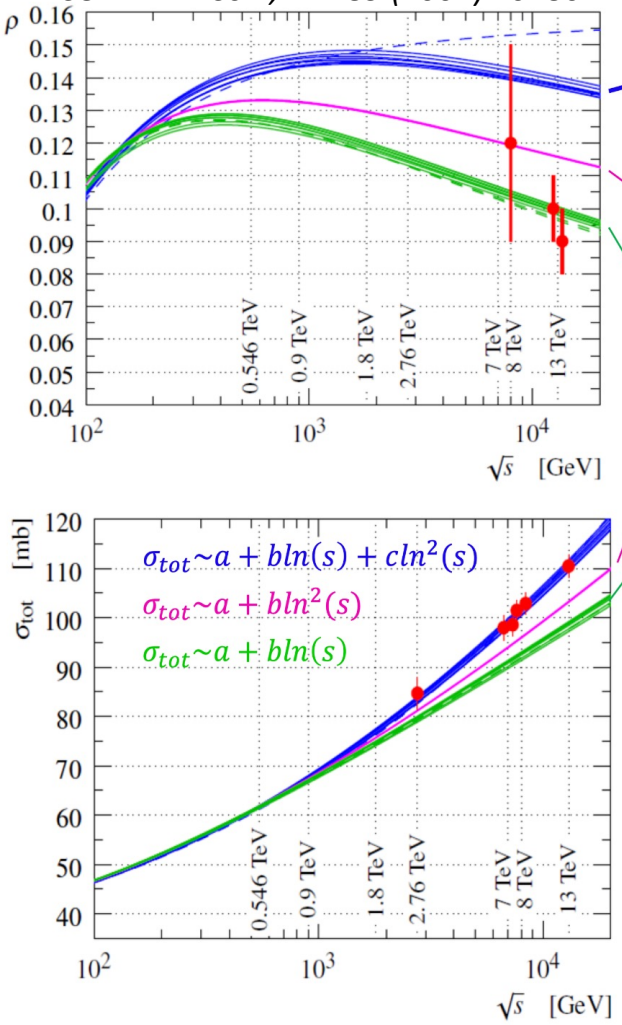
Trend same as @ $\sqrt{s}$ = 7 & 8 TeV, essentially only a normalisation difference!

Not whole story: TOTEM has 2-4 consistent σ_{tot}^{pp} measurements using different extrapolation & normalisation methods, |t|-ranges and treatment of CNI/energy vs. 1 measurement/energy by ATLAS using basically the same method

Combine $pp/p\bar{p}$ comparison & pp ρ + σ_{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 $p\bar{p}$ $\frac{d\sigma}{dt}$.

Using updated $pp/p\bar{p}$ comparison: a rather small increase in the significance obtained in the exclusion of models without Odderon

Conclusions

- Extrapolation to $\sqrt{s}$ = 1.96 TeV of TOTEM elastic pp $d\sigma/dt$ measurements at LHC in dip-bump region provide evidence of Odderon exchange in elastic scattering when compared to the D0 elastic $p\bar{p}$ $d\sigma/dt$ measurement at Tevatron
- Combined with TOTEM pp σ_{tot} & ρ measurements at LHC, the $p\bar{p}$ & pp elastic $d\sigma/dt$ comparison is excluding models without Odderon
- The updated $p\bar{p}$ & pp elastic $d\sigma/dt$ comparison at $\sqrt{s}$ = 1.96 TeV results in a rather small increase in the exclusion significance of models without Odderon
- Issues & objections raised regarding TOTEM-D0 $p\bar{p}$ & pp elastic $d\sigma/dt$ comparison at $\sqrt{s}$ = 1.96 TeV as well as TOTEM 13 TeV ρ & total cross section measurements have been addressed