Odderon observation: an update with answers to questions & objections

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on behalf the **D0 & TOTEM collaborations**

Diffraction and Low-x 2022 29.9.2022

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HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

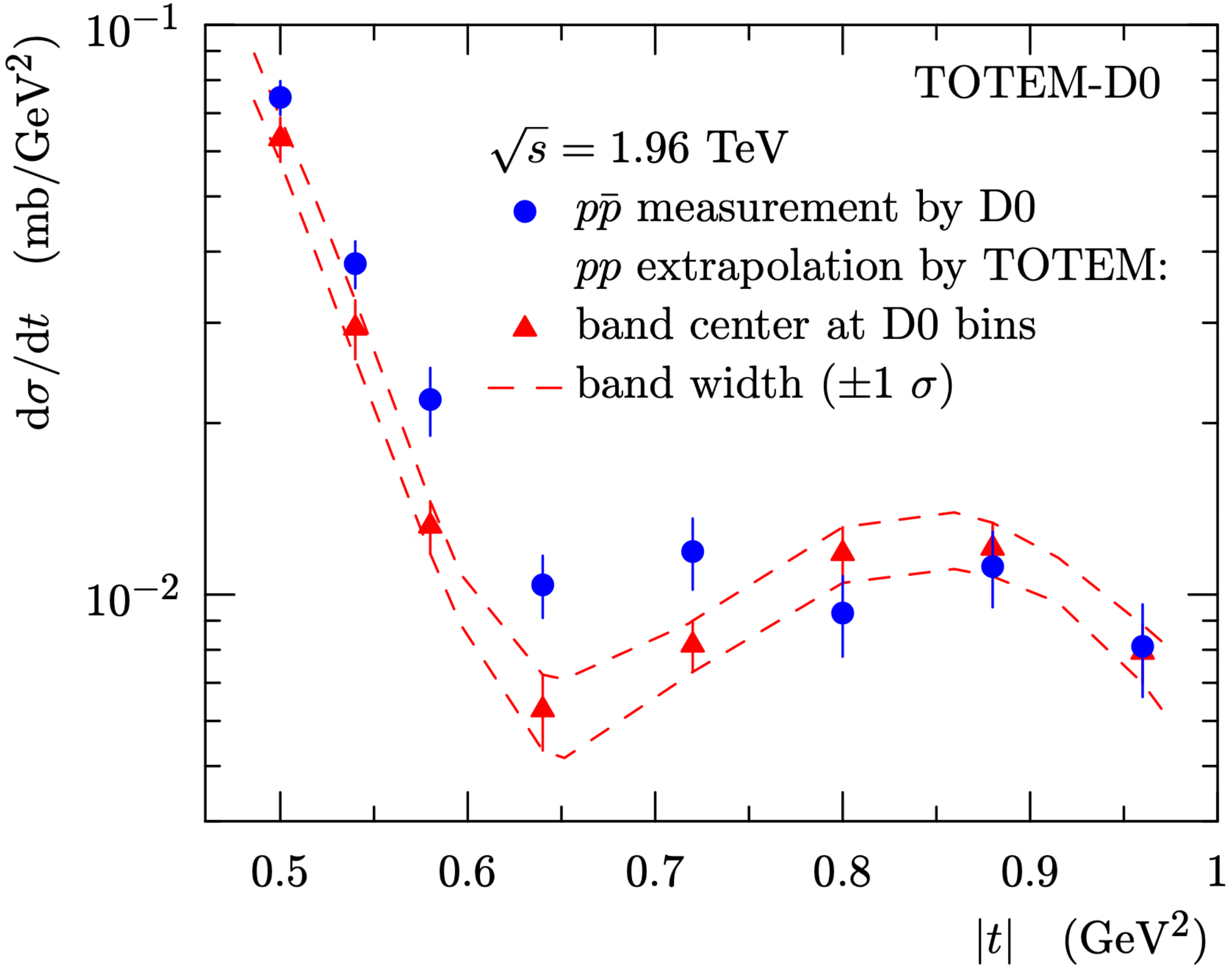
References: *D0 & TOTEM collaborations, PRL 127 (2021) 062003;*
K. Österberg on behalf of D0 & TOTEM collaborations, ArXiv: 2202.03724

Phenomenological studies:

- *E. Martynov & B. Nicolescu, PLB 778 (2018) 414*
- *V. A. Khoze, A.D. Martin & M.G. Ryskin, PRD 97 (2018) 034019*
- *E. Martynov & B. Nicolescu, EPJC 79 (2019) 461*
- *T. Csorgo et al., EPJC 81 (2021) 180*
- *T. Csorgo & I. Szanyi, EPJC 81 (2021) 611*
- *I. Szanyi & T. Csorgo, EPJC 82 (2022) 827*
- *…*

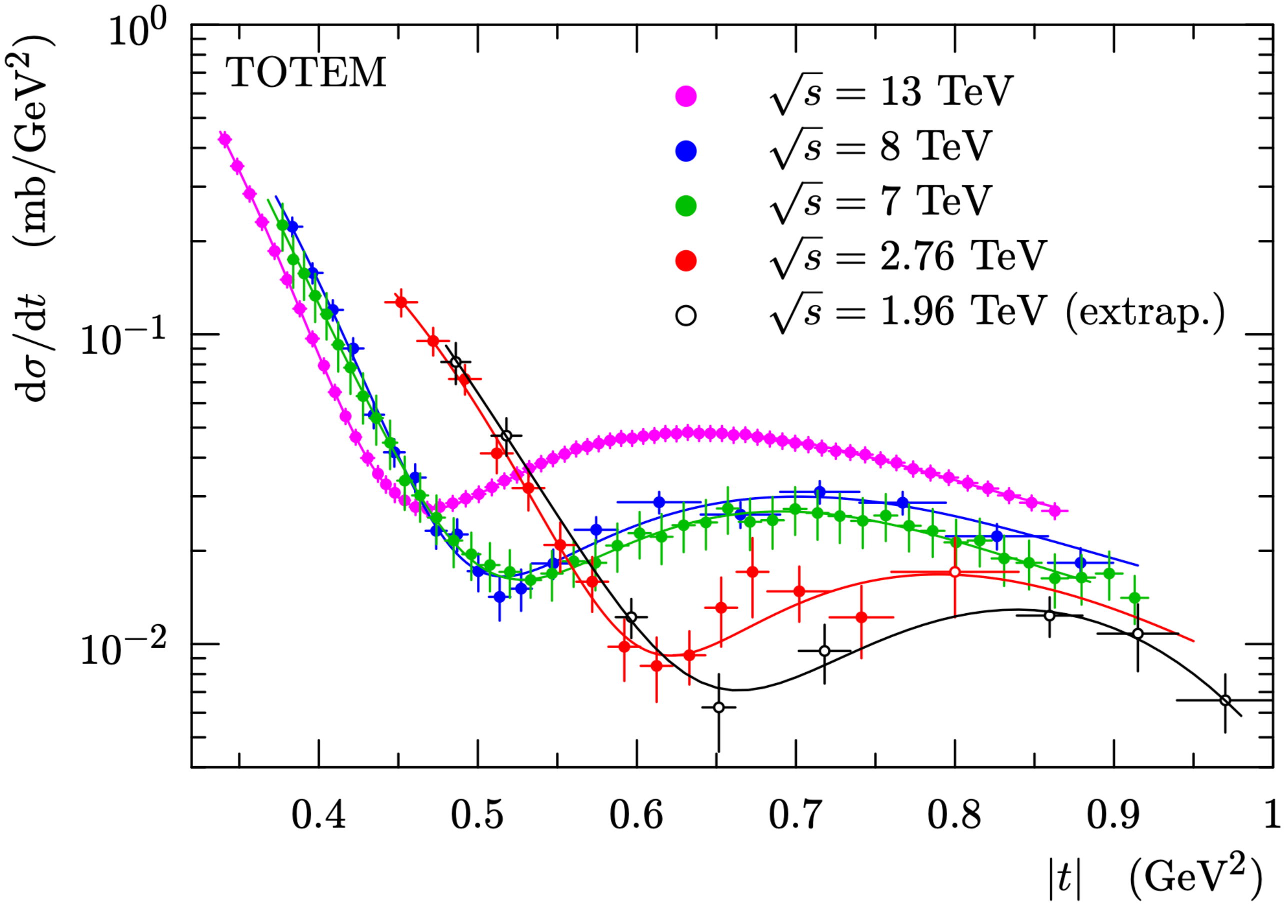
Comparison of pp & $p\bar{p}$ cross section

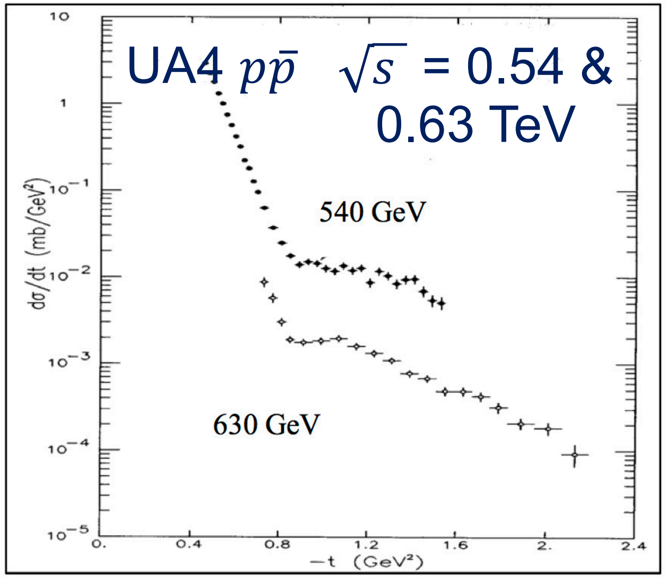
- Extrapolation of TOTEM pp $d\sigma_{el}/dt$ at $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV in dip-bump region to $\sqrt{s}$ = 1.96 TeV for direct comparison with D0 $p\bar{p}$ $d\sigma_{el}/dt$

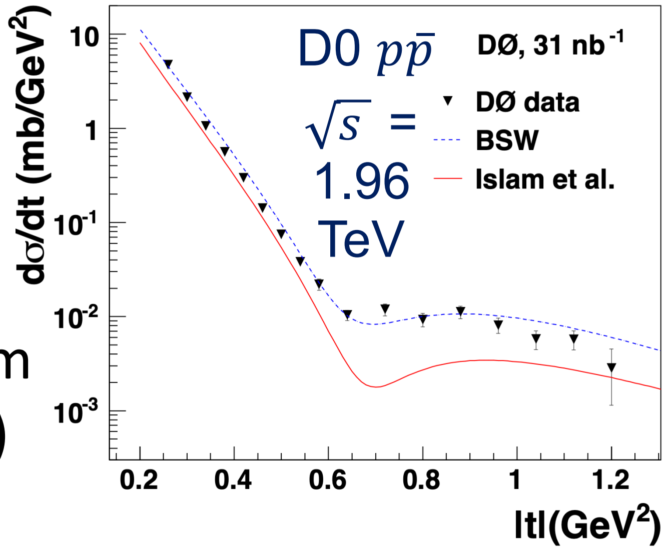


pp & $p\bar{p}$ $d\sigma_{el}/dt$ differ by 3.4σ at $\sqrt{s}$ = 1.96 TeV $\Longrightarrow$ evidence of odderon (C-odd gluonic compound) exchange in TeV energy range (secondary Reggeons negligible)

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



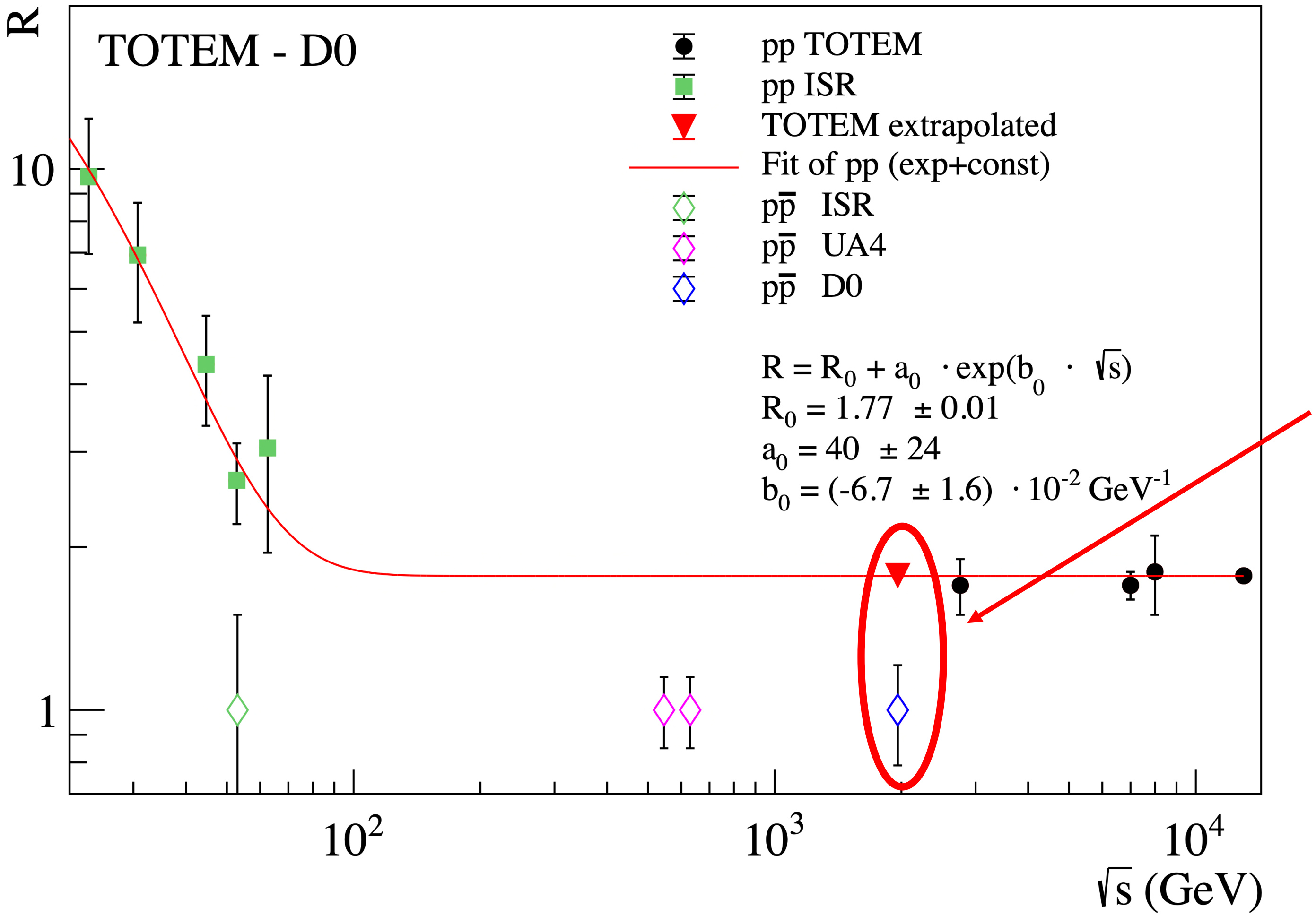




- Diffractive minimum ("dip") & secondary maximum ("bump") clearly observable in pp (contrary to $p\bar{p}$)
- $pp\ d\sigma_{el}/dt$ in dip-bump region well described by $h(t) = a_1 e^{-a_2|t|^2 - a_3|t|} + a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$

Ratio of bump & dip cross sections

$$R \equiv d\sigma/dt_{\text{bump}}/d\sigma/dt_{\text{dip}}$$

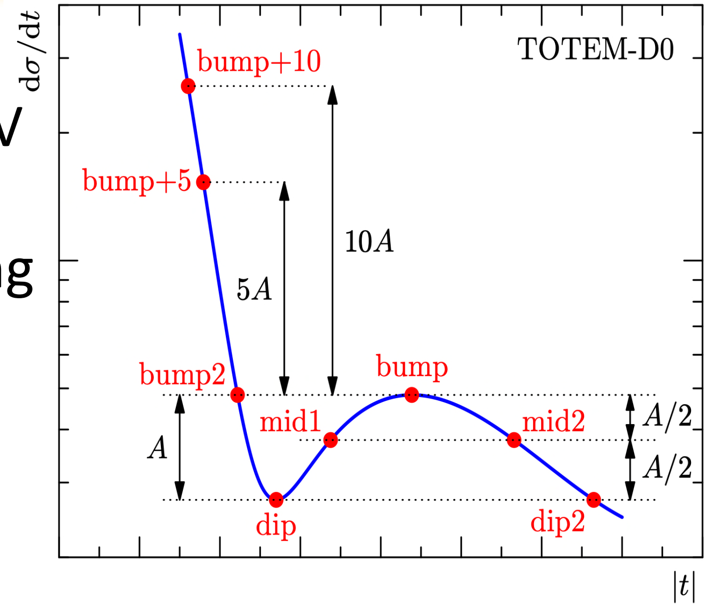


$> 3\sigma$ difference between pp & $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV (assuming flat behaviour above $\sqrt{s} \sim$ 100 GeV)

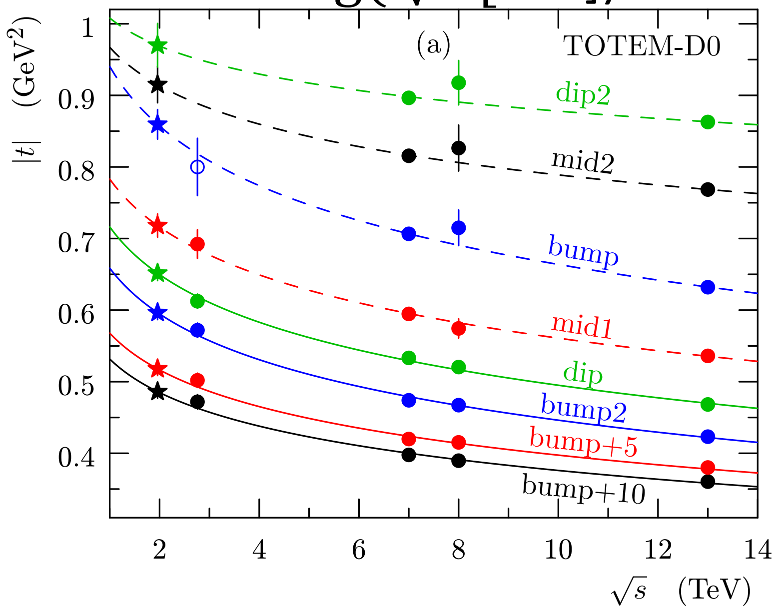
For $p\bar{p}$ R estimate, use t-bins close to expected pp bump & dip position

Data-driven estimates

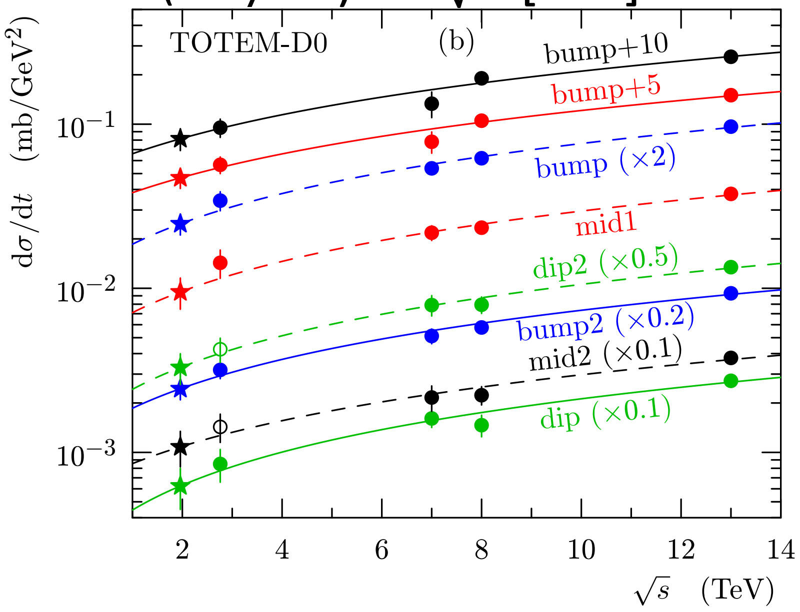
- Short (~8 % of fit range) extrapolation of the 8 characteristic $pp\ d\sigma_{el}/dt$ points to $\sqrt{s}$ = 1.96 TeV
- Interpolation of 1.96 TeV characteristic pp $d\sigma_{el}/dt$ points to D0 $p\bar{p}\ d\sigma_{el}/dt$ |t| values using $h(t) = a_1 e^{-a_2|t|^2 - a_3|t|} + a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$
  - 3-4 data points limit to 2 parameter formulas.
  - All characteristic points give excellent fits.
  - Alternate functional forms (having other $\sqrt{s}$ powers) give results well within fit uncertainties.



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

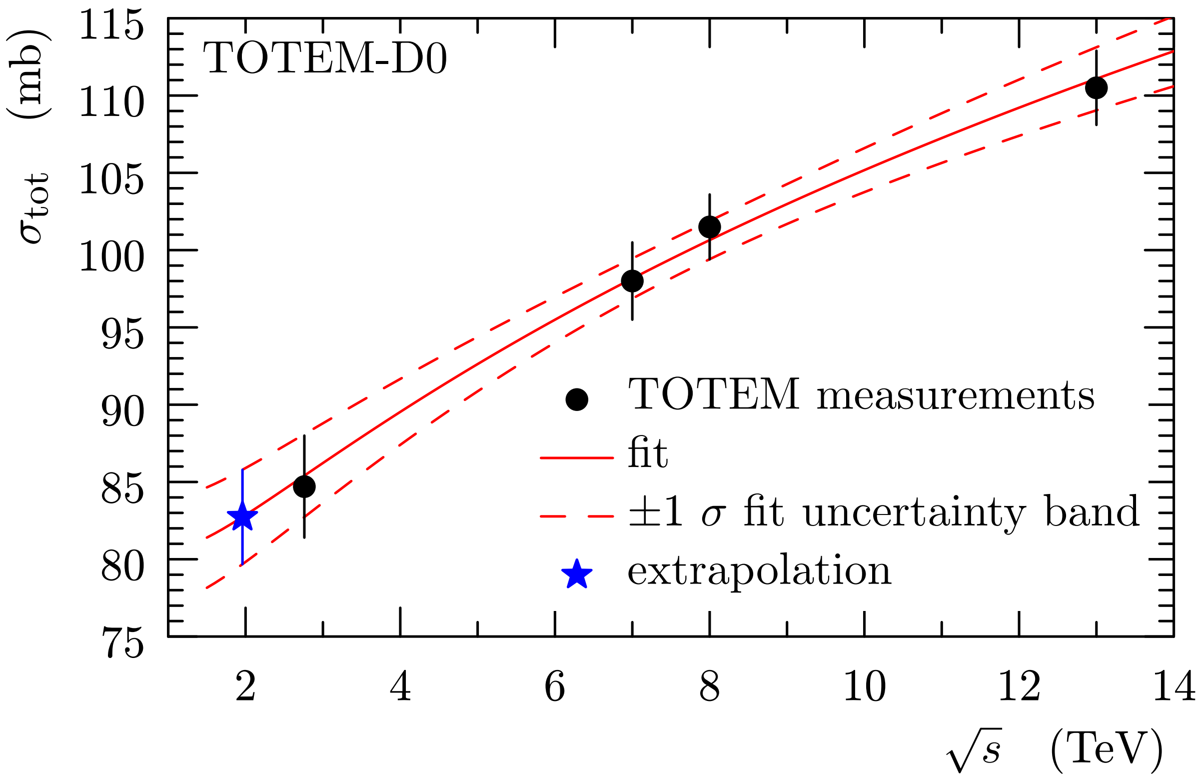


$(d\sigma/dt) = c\sqrt{s}\ [\text{TeV}] + d$



Cross check of σ_{tot}^{pp} extrapolation

- σ_{tot}^{pp} 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

- Short (~8 % of fit range) extrapolation of σ_{tot}^{pp} to $\sqrt{s}$ = 1.96 TeV
- Starting from 4 data points limits to 2-3 parameter formulas.

- 2 TeV in boundary between $\log^2\sqrt{s}$ & $\log\sqrt{s}$ dependence dominated region.
- Also tried $a\log^2 x + b\log x + c$; $ax^2 + bx + c$ and $a\sqrt{x} + b$, where $x = \sqrt{s}$. All alternative extrapolations fall well within estimated uncertainty of extrapolated σ_{tot}^{pp} at $\sqrt{s}$ = 1.96 TeV using baseline function.

Preliminary

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

- Pomeranchuk theorem: $\sigma_{tot}^{pp}/\sigma_{tot}^{p\bar{p}} \xrightarrow[\sqrt{s}\to\infty]{} 1 \Longrightarrow$

  Optical points (OP): $d\sigma_{el}^{pp}/dt\big|_{t=0} / d\sigma_{el}^{p\bar{p}}/dt\big|_{t=0} \xrightarrow[\sqrt{s}\to\infty]{} 1$

- $d\sigma_{el}^{pp}/dt\big|_{t=0}$ = 357 $\pm$ 26 mb/GeV^2 (from σ_{tot}^{pp})
- $d\sigma_{el}^{p\bar{p}}/dt\big|_{t=0}$ = 341 $\pm$ 49 mb/GeV^2 (from extrapolation of D0 data)

- 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 %).

- $\sigma(p\bar{p}$ OP) neglected since $\sigma(pp$ OP) dominate precision, cf. weighted average

- Scale $d\sigma_{el}^{pp}/dt$ to match $d\sigma_{el}^{p\bar{p}}/dt$ with an overall 7.4 % relative uncertainty due to σ_{tot}^{pp} uncertainty and uncertainties due to pp OP = $p\bar{p}$ OP assumption

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

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

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

- ✓ A = normalization OP(pp) = OP($p\bar{p}$)
- ✓ B = elastic slope $B(pp) = B(p\bar{p})$ (experimentally true within uncertainties)

Cornille-Martin theorem: $\sigma^{pp}_{el}/\sigma^{p\bar{p}}_{el} \xrightarrow[\sqrt{s}\to\infty]{} 1$ & $\frac{d\sigma^{pp/p\bar{p}}_{el}}{dt} \propto e^{-Bt}$ (diffr. cone) $\Longrightarrow$

$B(pp) = B(p\bar{p})$, since pp & $p\bar{p}$ differences in CNI & high |t| negligible for $\sigma^{pp/p\bar{p}}_{el}$

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($p\bar{p}$)
- ✓ B = elastic slope B(pp) = B($p\bar{p}$) (experimentally true within uncertainties)

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B(pp) = B($p\bar{p}$), since pp & $p\bar{p}$ differences in CNI & high |t| negligible for $\sigma_{el}^{pp/p\bar{p}}$

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

$\chi^2 = 23.64$ (d.o.f. = 6) $\Longrightarrow$ pp & $p\bar{p}$ $d\sigma_{el}/dt$ differ by 3.4σ at $\sqrt{s}$ = 1.96 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)
- ✓ Explicit affine transformation assuring pp & $p\bar{p}$ equality of elastic slope *B* & integrated cross section of examined range *A* in χ^2 calculation

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

Preliminary

$\Longrightarrow$ ~0.2σ increase of significance in pp & $p\bar{p}$ comparison at $\sqrt{s}$ = 1.96 TeV

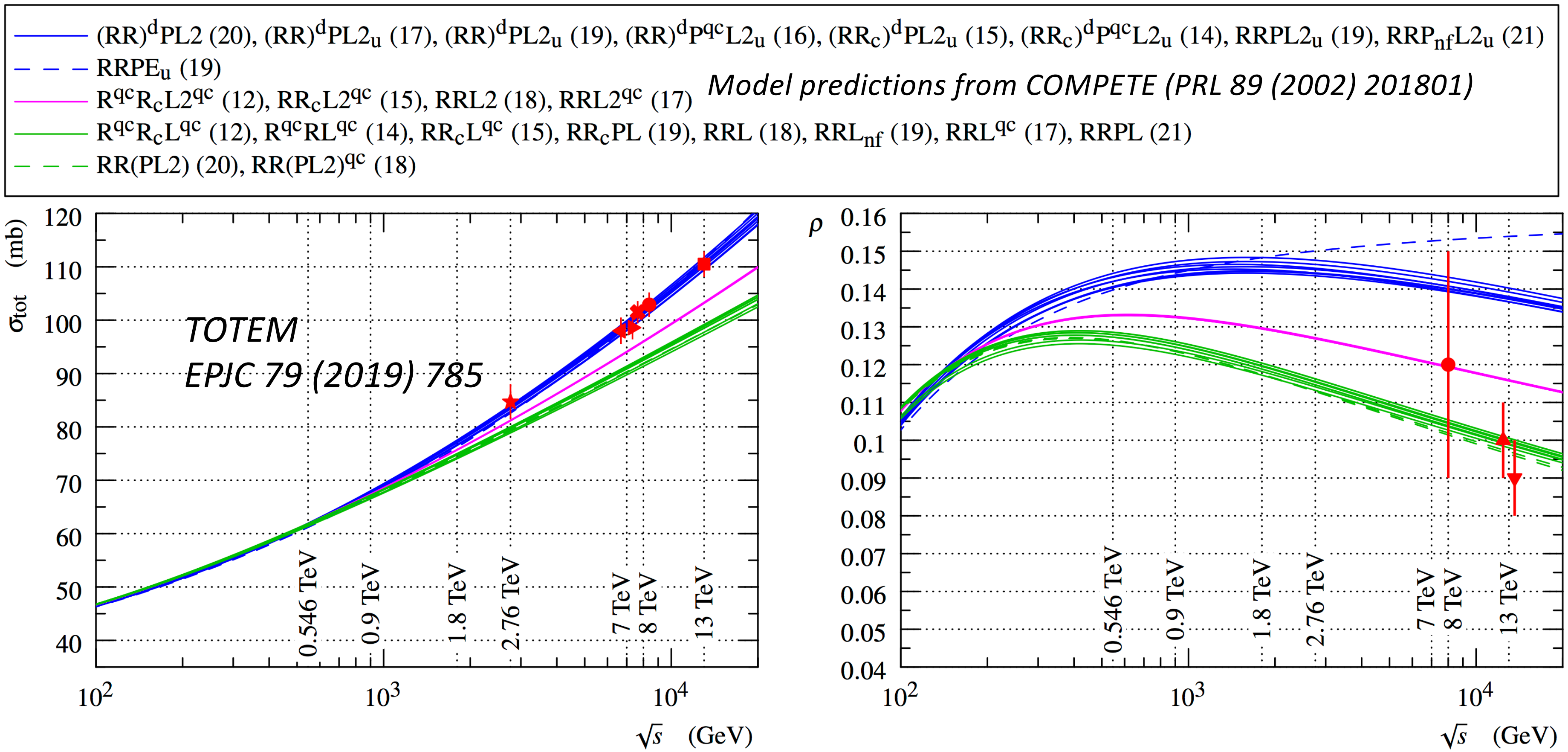
Significance confirmed with a MC based Kolmogorov-Smirnov test, including data point correlations, combined with normalisation using Stouffer method

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

Stay tuned !

TOTEM ρ in pp at $\sqrt{s}$ = 13 TeV

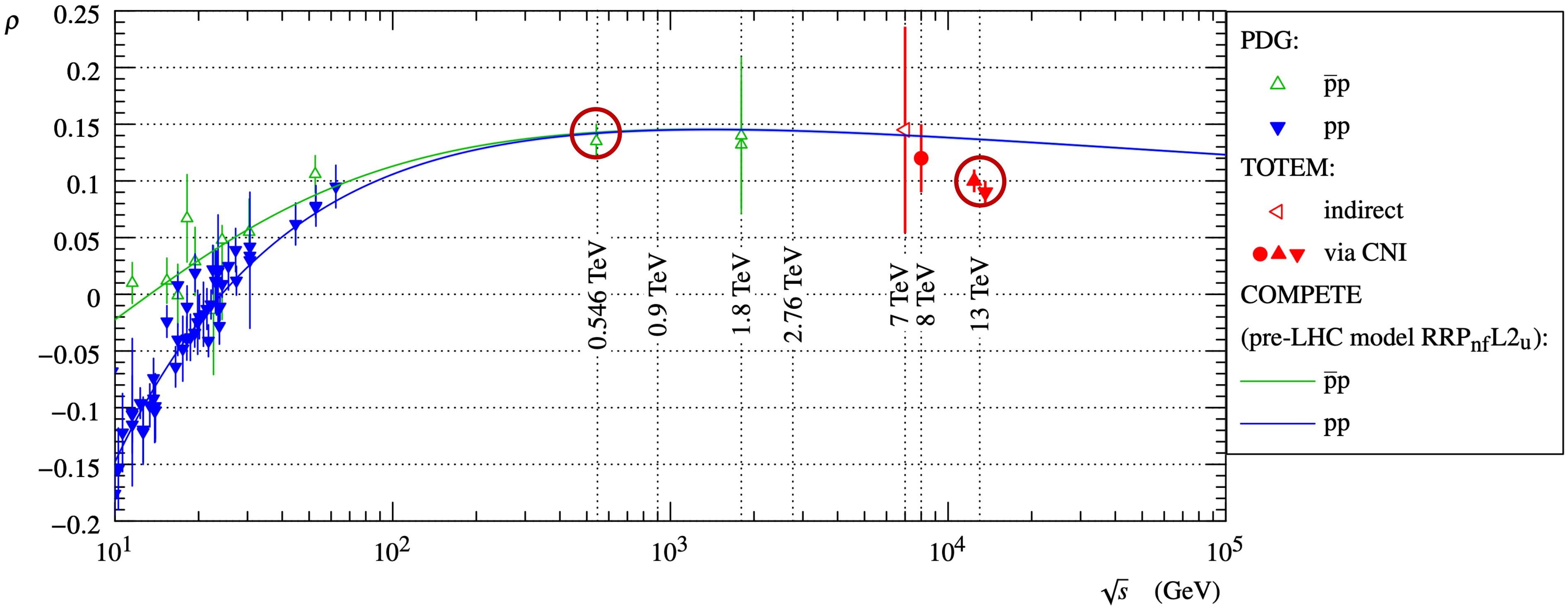
- @ $\sqrt{s}$ = 13 TeV: ρ^{pp} = 0.10 $\pm$ 0.01 / 0.09 $\pm$ 0.01 *(TOTEM, EPJC 79 (2019) 785)*
- Models (*COMPETE, Durham, Block-Halzen*) unable to describe TOTEM ρ & σ_{tot}^{pp} measurements at 3.4-4.6σ level without adding odderon exchange



ATLAS recently confirmed: ρ^{pp} @ 13 TeV= 0.098 $\pm$ 0.011 (arXiv:2207.12246)
(however TOTEM & ATLAS σ_{tot}^{pp} differs by ~2.2σ)

TOTEM ρ in pp at $\sqrt{s}$ = 13 TeV

- Another explanation for low ρ^{pp}: slower rise of σ_{tot}^{pp} *(TOTEM, EPJC 79 (2019) 785)*
- NB! ρ^{pp} = 0.09 $\pm$ 0.01 @ $\sqrt{s}$ = 13 TeV should be compared with $\rho^{p\bar{p}}$ = 0.135 $\pm$ 0.015 @ $\sqrt{s}$ = 541 GeV *(UA4/2, PLB 316 (1993) 448)*
  (same receipe: hadronic amplitude functional form, CNI formula, $|t|$-range …)



- All (*A. Donnachie & P. Landshoff, J.R. Cudell & O.V. Selyugin, P. Grafström…*) that have taken the 13 TeV TOTEM or ATLAS β^*= 2.5 km data as they are given and extracted ρ using similar CNI formula obtain compatible ρ values (0.08-0.10)

TOTEM & ATLAS σ_{tot} comparison

- 13 TeV TOTEM σ^{pp}_{tot} = 110.5 $\pm$ 2.4 mb
  direct counting experiment

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

- 13 TeV ATLAS σ^{pp}_{tot} = 104.7 $\pm$ 1.1 mb
  need precise (2.15 %) luminosity determination

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

essentially mainly a normalisation difference!

difference from 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 $\Longrightarrow$

significantly smaller σ^{pp}_{tot} difference in mb but only slightly in terms of σ's

preliminary

To explain most of difference would result in a TOTEM low mass diffraction incompatible with estimated ATLAS low mass diffraction (= $\sigma_{tot} - \sigma_{inel}$)!

Questions to ATLAS:

- ✓ How reliable is an absolute luminosity calibration made in van de Meer scans at β^* = 11 m for luminosity of beams at β^* = 2500 m (collision vertex size x 15)?
- ✓ Coulomb-normalized σ_{tot} increase with inclusion of lowest |t| bins (+~2.2 mb)?

Statements of PDG review

V.A. Khoze, M.G. Ryskin & M. Tasevsky, High energy Soft QCD and Diffraction, https://pdg.lbl.gov/

- Reasonable description of elastic pp & $p\bar{p}$ data obtained with Pomeron only
- ✓ Durham model without odderon (*V. A. Khoze, A.D. Martin and M.G. Ryskin, PLB 748 (2018) 192*) fails to describe D0 1.96 TeV $p\bar{p}$ $d\sigma_{el}/dt$ in dip-bump region (4.3σ).

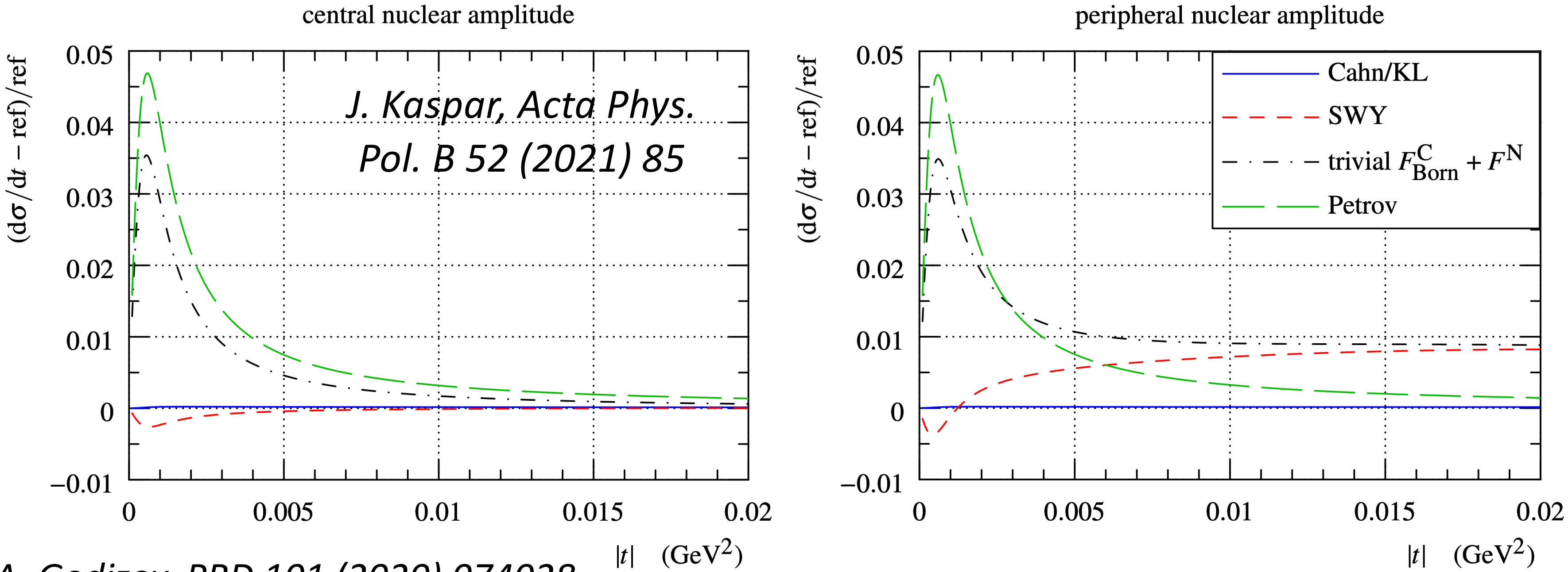
- TOTEM data described within 1σ & ρ = 0.14 obtained in pp at 13 TeV without odderon (*A. Donnachie & P.V. Landshoff, PLB 798 (2019) 135008 & PLB 831 (2022)137199*)
- Using TOTEM 13 TeV β^*= 2.5 km data only: ρ = 0.10
- Using TOTEM 8 TeV β^*= 1 km & 13 TeV β^*= 2.5 km data: ρ = 0.14
- ✓ **Ignores Coulomb-hadronic interference term ($\Delta\rho$ = $-$0.02)**
- ✓ **Sensitivity to ρ only in a few data points in CNI region**. Fits should be made in several steps (hadronic amplitude, Coulomb amplitude & ρ) in separate |t|-regions to avoid that data points without ρ sensitivity influence obtained ρ.
- ✓ Adding TOTEM 8 TeV β^*= 1 km with limited ρ sensitivity can't change ρ value.

- TOTEM 13 TeV ρ & σ_{tot} described by COMPETE RR(PL2)^{qc} model without odderon (*J.R. Cudell & O. Selyugin, ArXiv:1901.05863*)
- ✓ Agreement obtained modifying TOTEM 13 TeV data normalisation by $\geq 2\sigma$ (highly unlikely given two independent σ_{tot}^{pp} measurement at $\sqrt{s}$ = 13 TeV)

Objections on CNI formula used

V.A. Petrov, EPJC 78 (2018) 221 & 414 & ArXiv:2001.06220

- Alleged flaws (inexact approximation of Coulomb amplitude & early truncation of series in powers of α(s)) of the CNI formula used in works of Cahn and Kundrat & Locajicek (KL)
- ✓ Numerical calculation of Coulomb & nuclear eikonals to all orders (*J. Kaspar, Acta Phys. Pol. B 52 (2021) 85*) show Cahn/KL formula to reproduce numerical estimate at $\mathcal{O}(10^{-4})$. Approximations by Cahn/KL do not have any detrimental effect on ρ determination. New CNI formula from Petrov & trivial sum of Coulomb+nuclear amplitudes(*) fails.



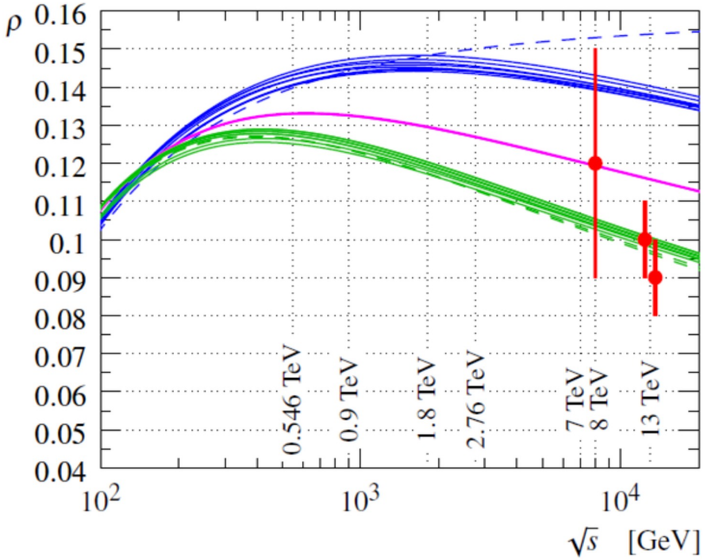
* *A.A. Godizov, PRD 101 (2020) 074028*

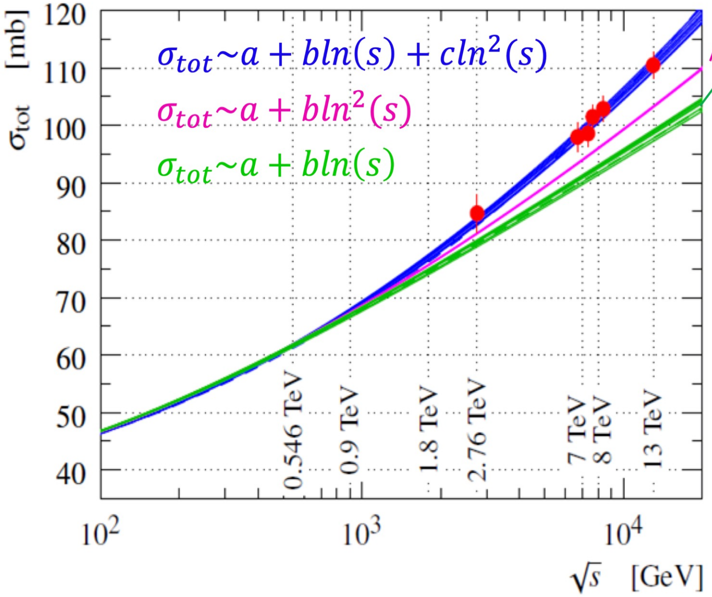
- ✓ Effect of N*'s omitted by eikonal negligible (*V.A. Khoze et al., PRD 101(2020) 016018)*
- ✓ **Conclusion:** Cahn/KL CNI formulas used for 13 TeV ρ determination prefectly fine.

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 $p\bar{p}$ $\frac{d\sigma}{dt}$.

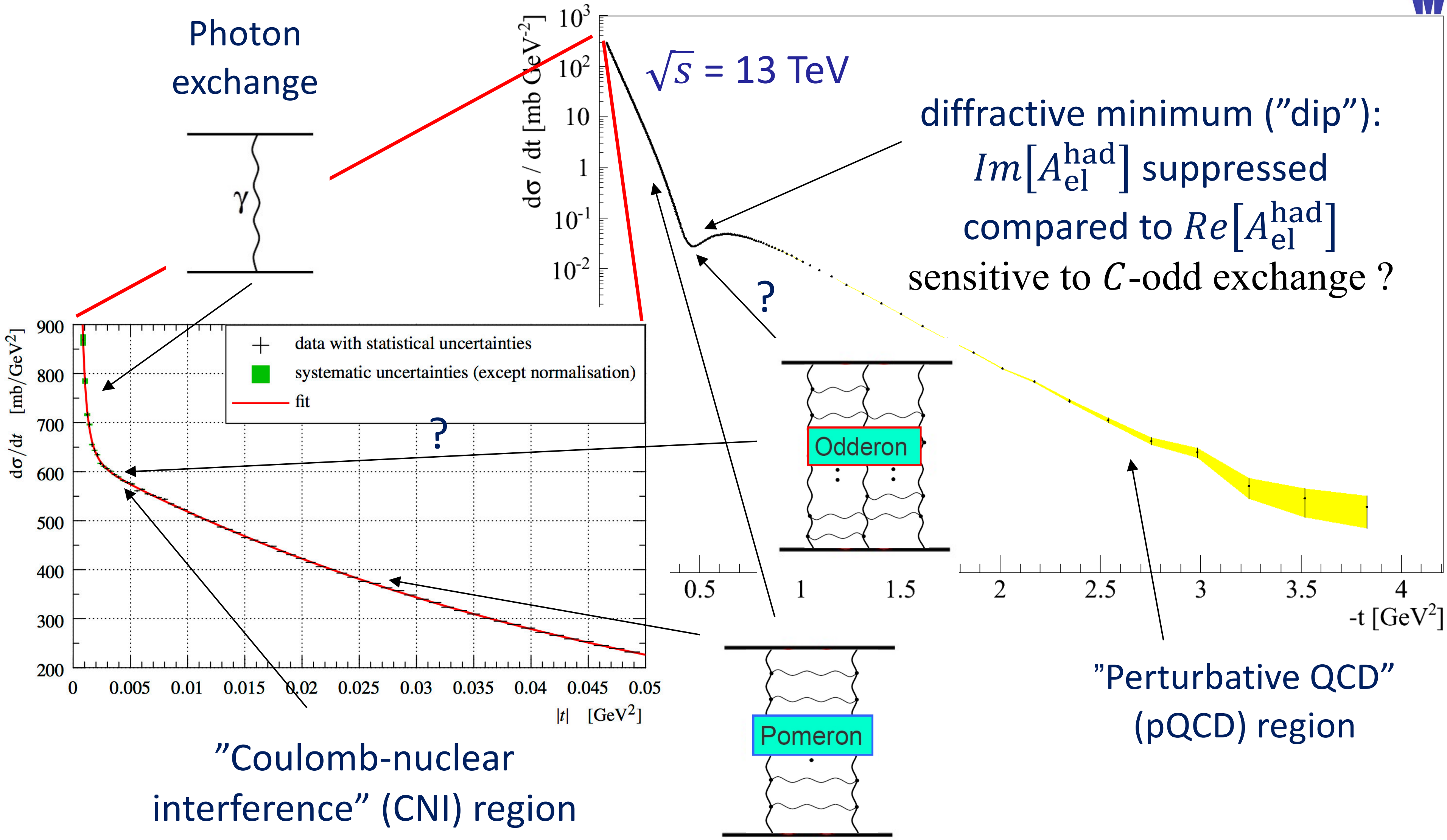
Block-Halzen Model: *PRD 92 (2015) 114021*
- Excluded at **3.9σ** level with TOTEM ρ data.
- Excluded at **5.2σ** level when combining significance from TOTEM ρ data and and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.

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 an increased significance of $\sim 0.2\sigma$ 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."

Backup

Elastic *pp* differential cross-section



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

sensitive to C-odd exchange ?

$d\sigma_{el}/dt\ p\bar{p}$ D0-Durham comparison

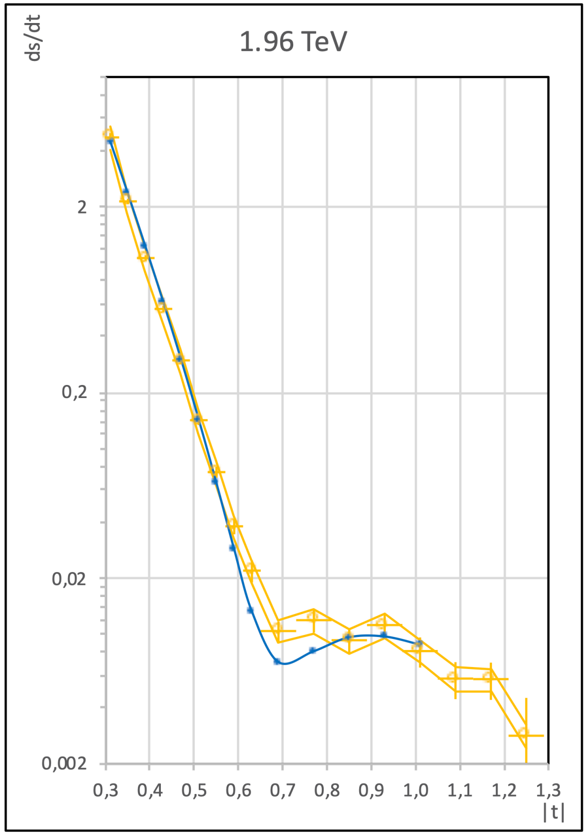
1.96 TeV

|t|	σ_t	ds/dt	σ_ds/dt	kmr	Chi2_i	+ norm	- norm
0,26	0,02	4,73	0,26	4,49702		5,41112	4,04888
0,30	0,02	2,14	0,072	2,34737		2,44816	1,83184
0,34	0,02	1,06	0,037	1,20944		1,21264	0,90736
0,38	0,02	0,564	0,022	0,61177		0,645216	0,482784
0,42	0,02	0,298	0,014	0,30099		0,340912	0,255088
0,46	0,02	0,142	0,0083	0,14271		0,162448	0,121552
0,50	0,02	0,0746	0,0051	0,06490	3,6144952	0,0853424	0,0638576
0,54	0,02	0,0381	0,0036	0,02862	6,929528	0,0435864	0,0326136
0,58	0,02	0,022	0,003	0,01325	8,51534104	0,025168	0,018832
0,64	0,04	0,0104	0,0013	0,00708	6,52975477	0,0118976	0,0089024
0,72	0,04	0,0119	0,0017	0,00810	4,98408162	0,0136136	0,0101864
0,80	0,04	0,00928	0,0015	0,00963	0,05502591	0,01061632	0,00794368
0,88	0,04	0,0112	0,0017	0,00972	0,75749433	0,0128128	0,0095872
0,96	0,04	0,00811	0,0015	0,00878	0,19776665	0,00927784	0,00694216
1,04	0,04	0,00577	0,0013			0,00660088	0,00493912
1,12	0,04	0,00573	0,0013			0,00655512	0,00490488
1,20	0,04	0,00284	0,0017			0,00324896	0,00243104

Chi2
31,5834875

C.L.
1,961E-05

n σ
4,26930909



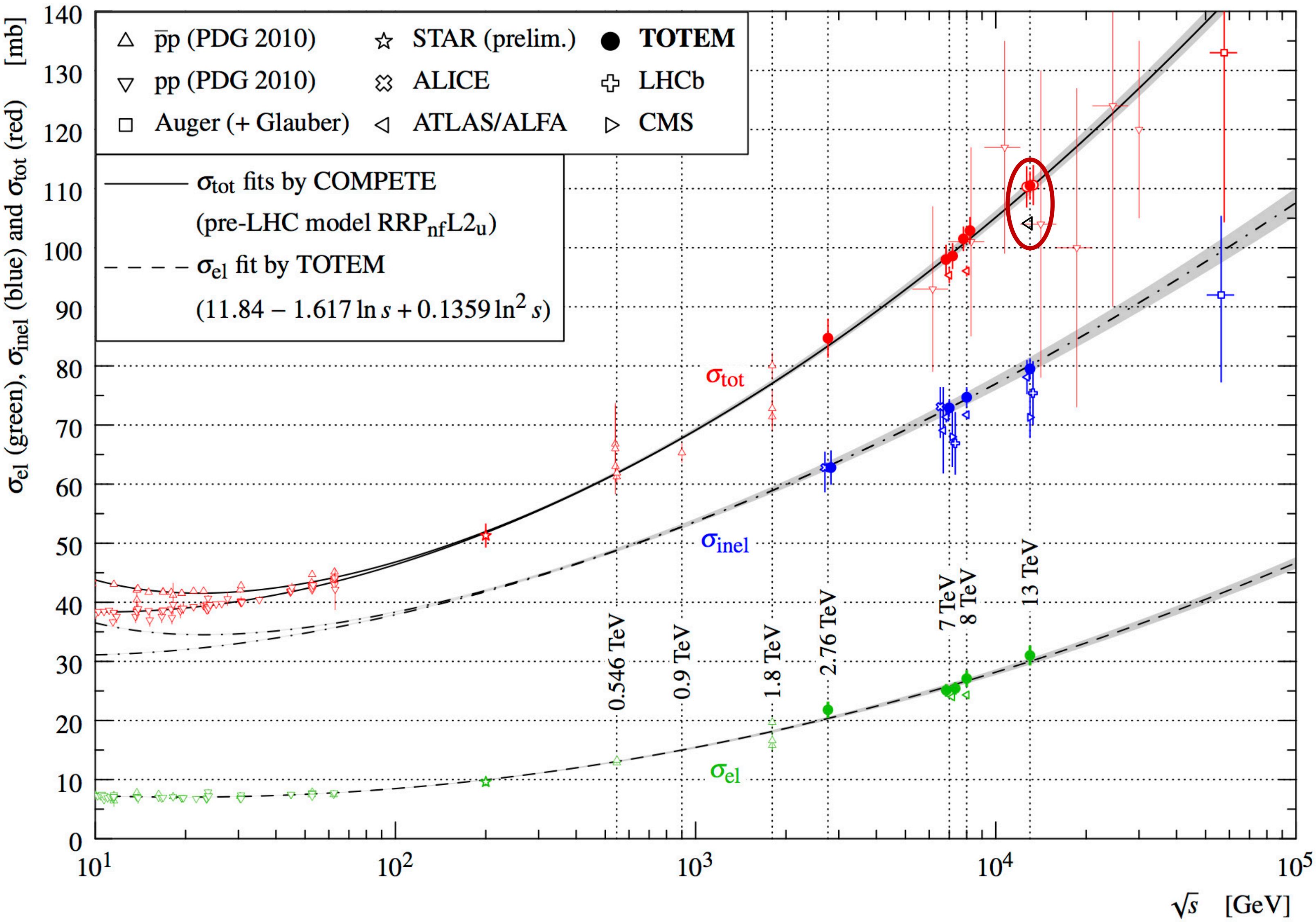
OP	OP kmr
340,848376	324,096

OP +norm
389,930542

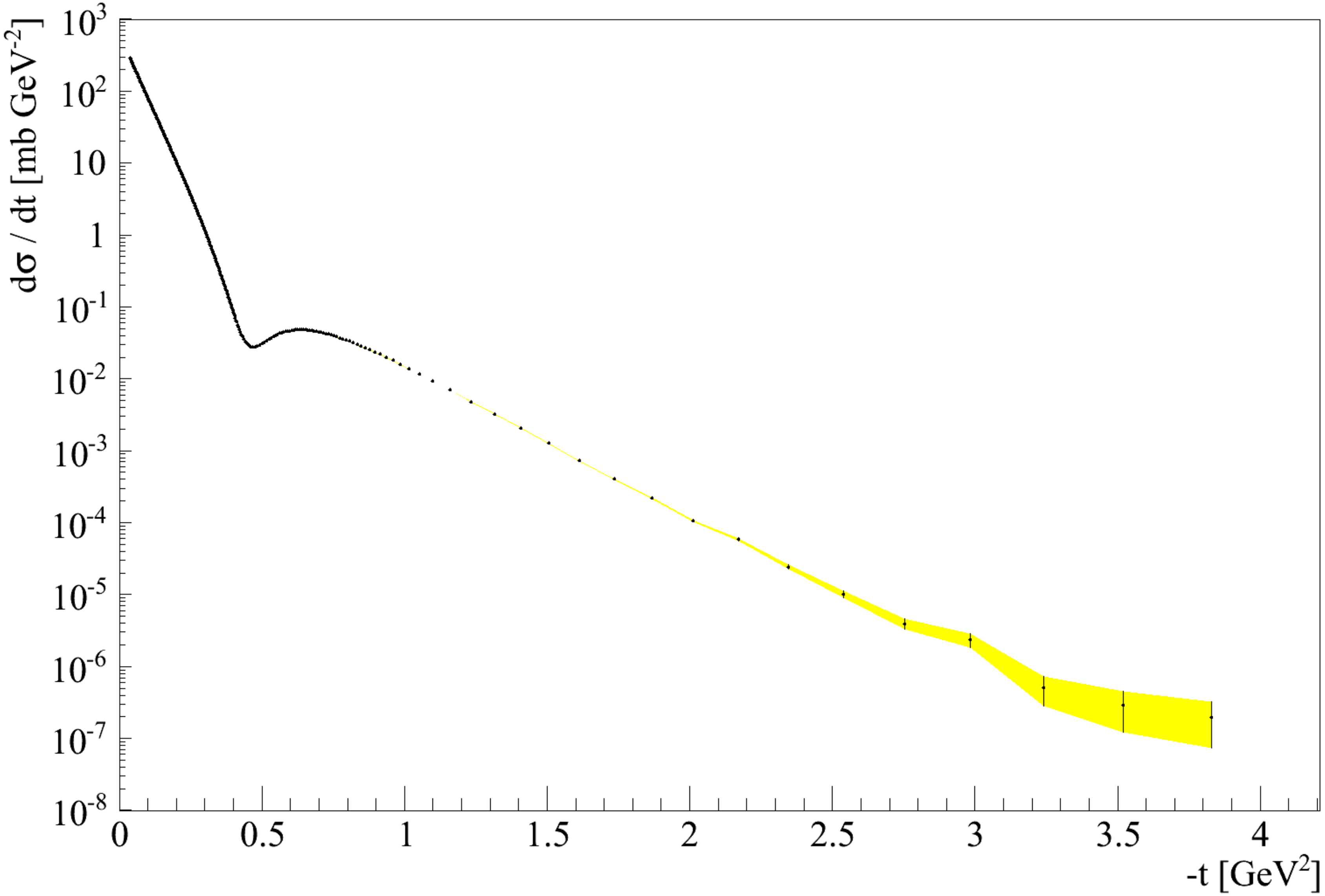
OP -norm
291,76621

- ✓ Motivation: Durham model prediction (without odderon) tuned to TOTEM pp data and will therefore have to compromise its description of $p\bar{p}$.

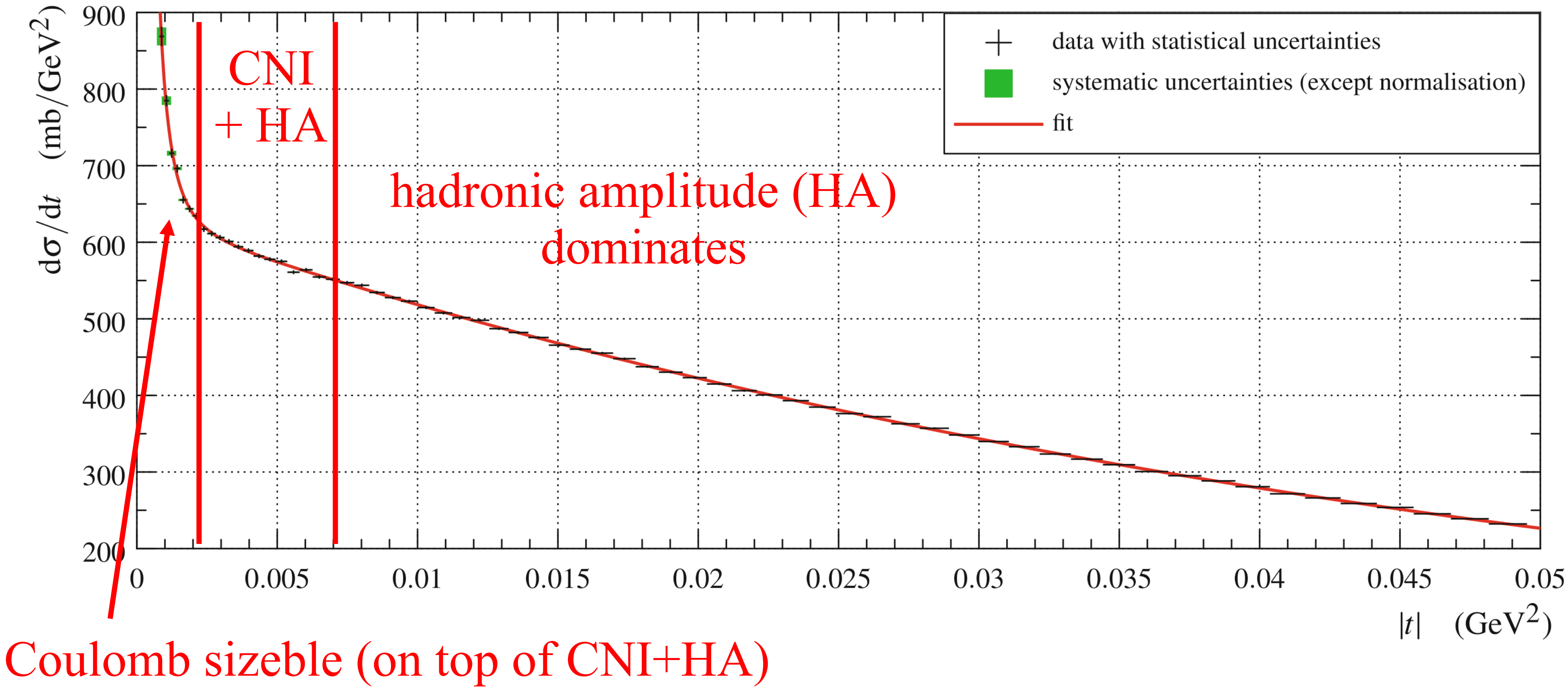
σ_{tot}, σ_{inel} & σ_{el} vs $\sqrt{s}$



TOTEM $d\sigma_{el}/dt$ @ $\sqrt{s}$ = 13 TeV

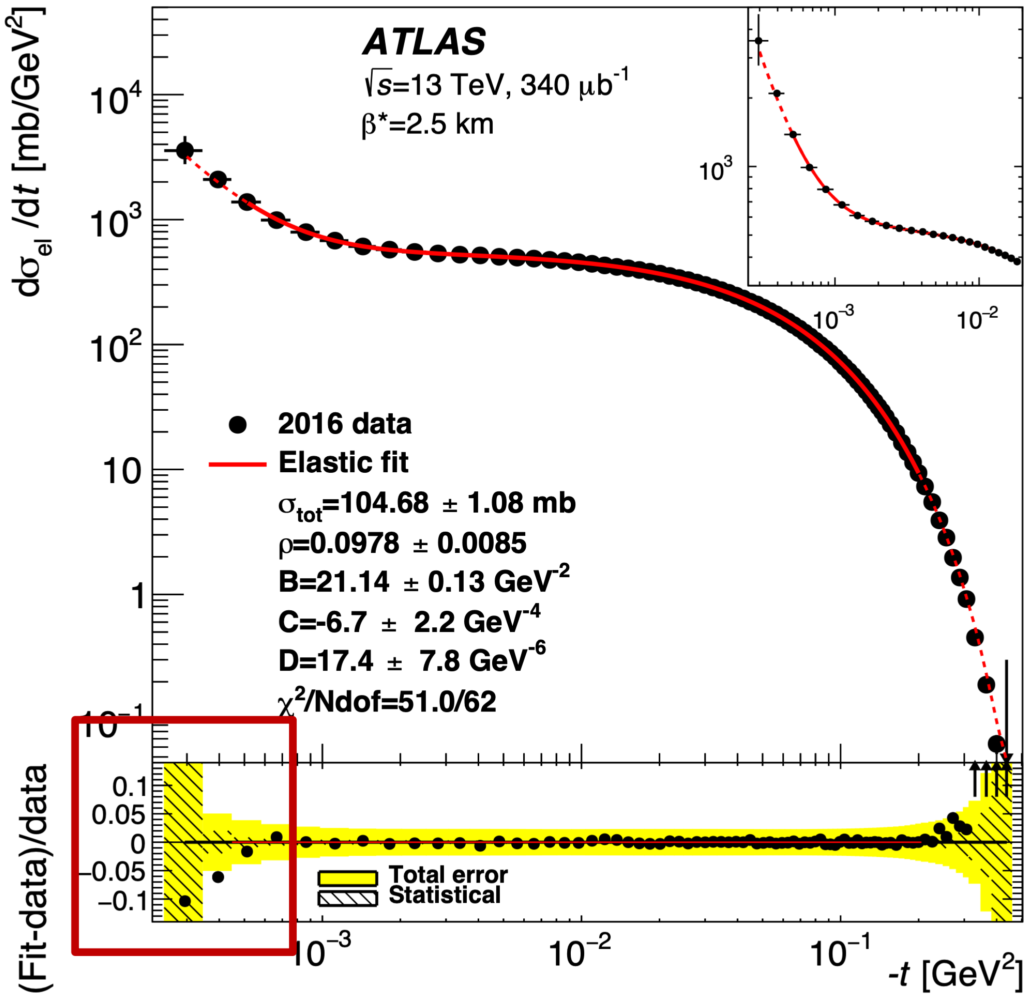


TOTEM CNI fit @ √s = 13 TeV



Fit goes right through the lowest |t| points that are most sensitive to combined Coulomb + Coulomb-hadronic interference + hadronic amplitude

ATLAS CNI fit @ √s = 13 TeV



Fit undershoot the lowest |t| points that are most sensitive to combined Coulomb + Coulomb-hadronic interference + hadronic amplitude