Odderon discovery – issues & objections raised

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on behalf the **D0 & TOTEM collaborations**

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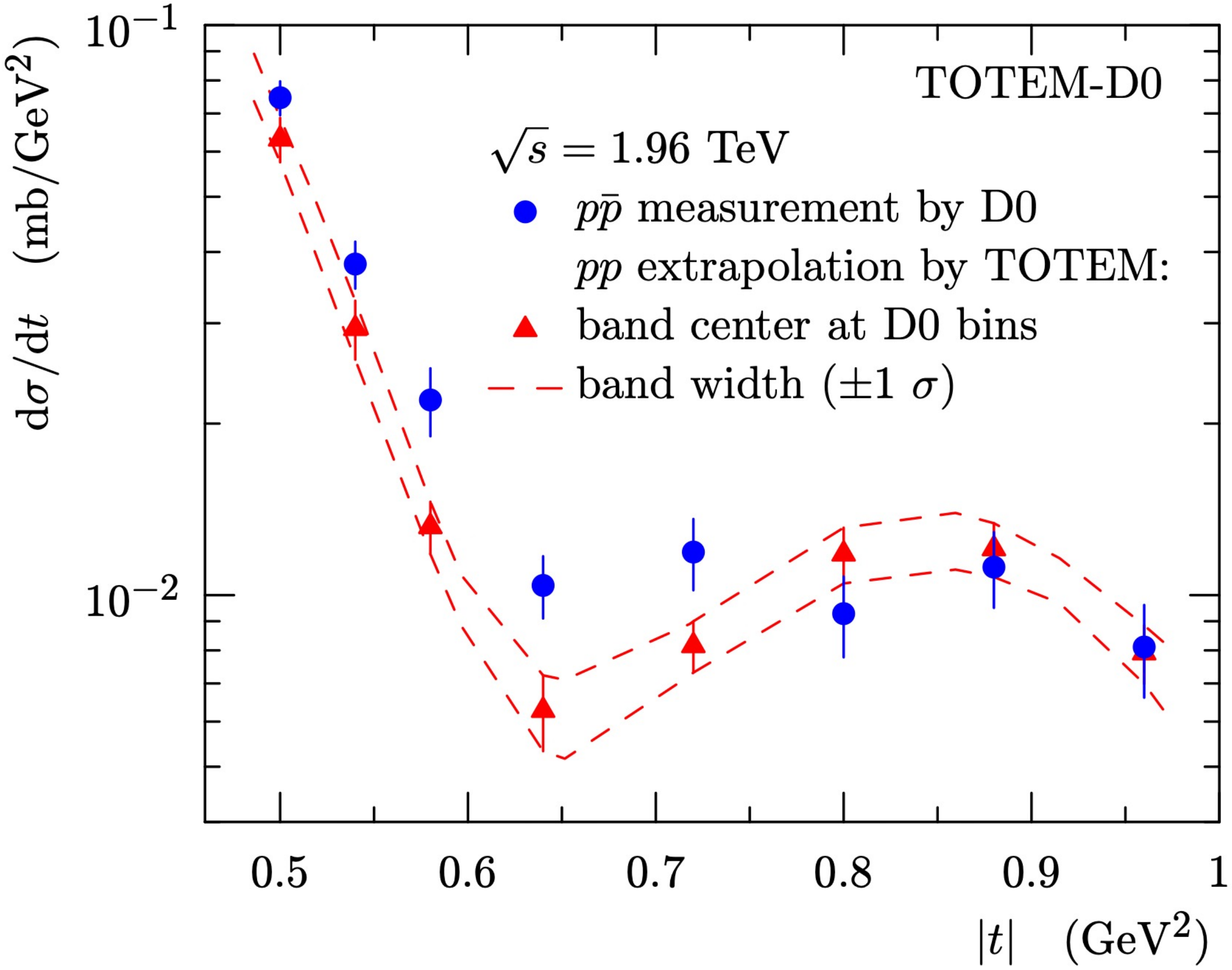
Reference: *D0 & TOTEM collaborations, PRL 127 (2021) 062003*

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*
- *…*

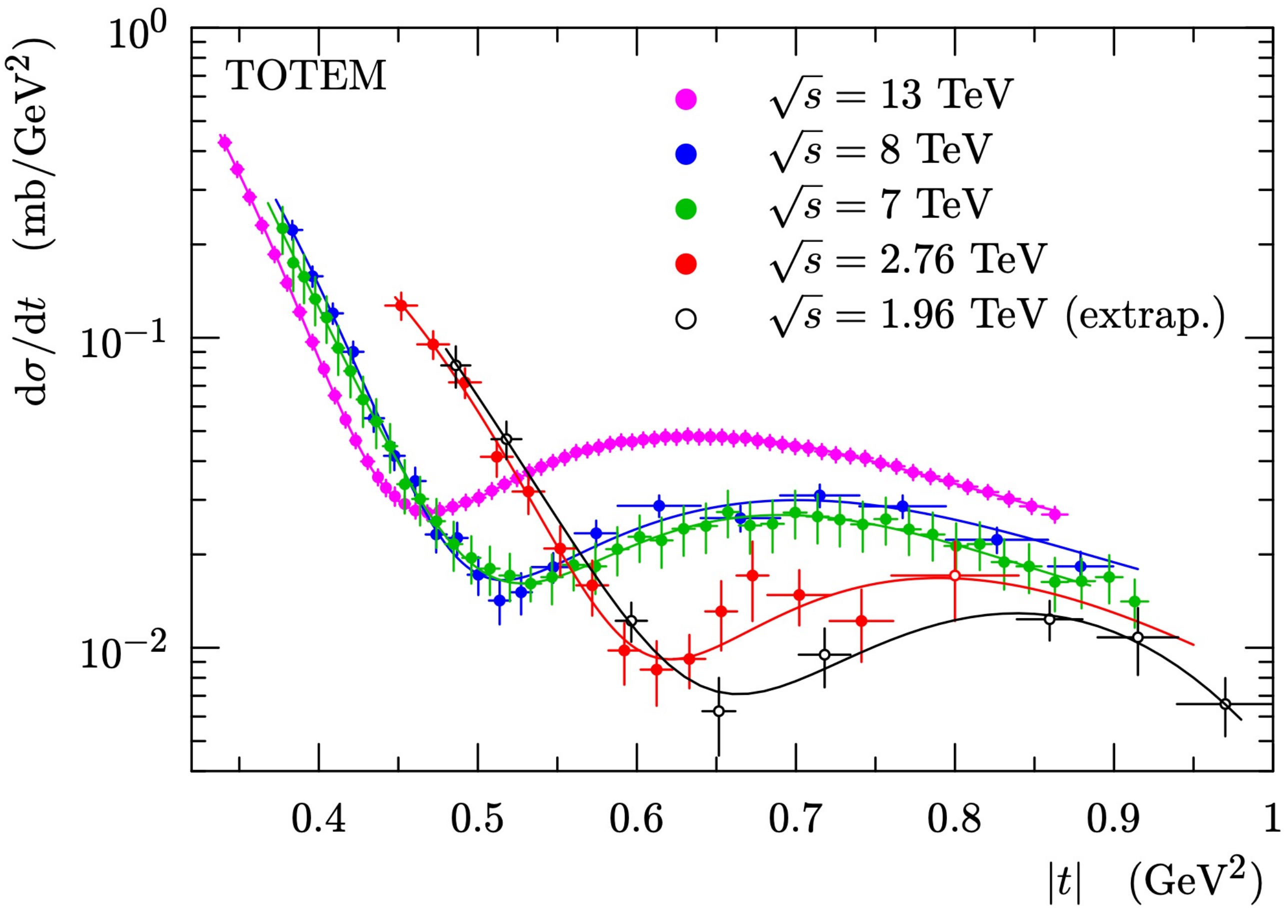
Comparison of pp & $p\bar{p}$ cross section

- 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 a 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 ⟹ evidence of odderon

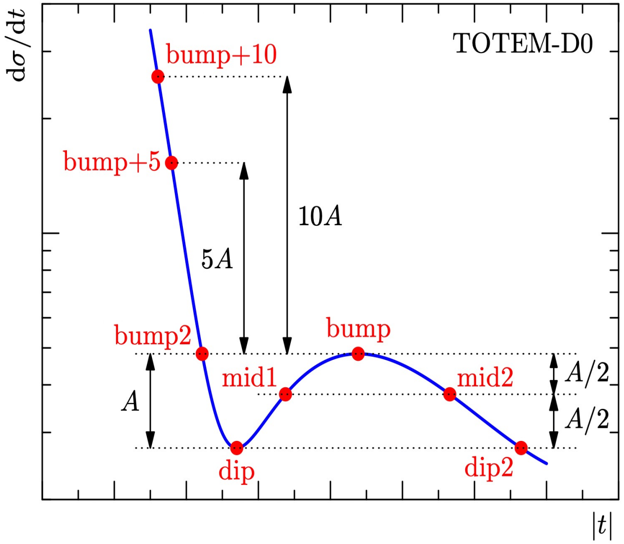
$d\sigma_{el}/dt$ measurements in pp



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

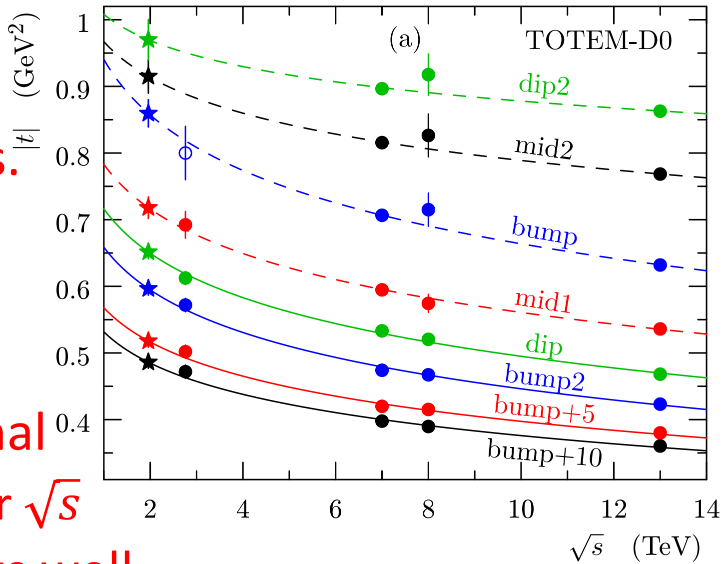
Data-driven estimates

- Short (~8 % of fit range) extrapolation of the 8 characteristic $pp\ d\sigma_{el}/dt$ points to $\sqrt{s}$ = 1.96 TeV
- Interpolation of 1.96 TeV characteristic $pp\ d\sigma_{el}/d$ points to D0 $p\bar{p}\ d\sigma_{el}/dt$ |t| values using $h(t) = a_1 e^{-a_2|t|^2 - a_3|t|} + a_4 e^{-a_5|t|^3 - a_6|t|^2 - a_7|t|}$
- Short extrapolation of σ_{tot}^{pp} to $\sqrt{s}$ = 1.96 TeV

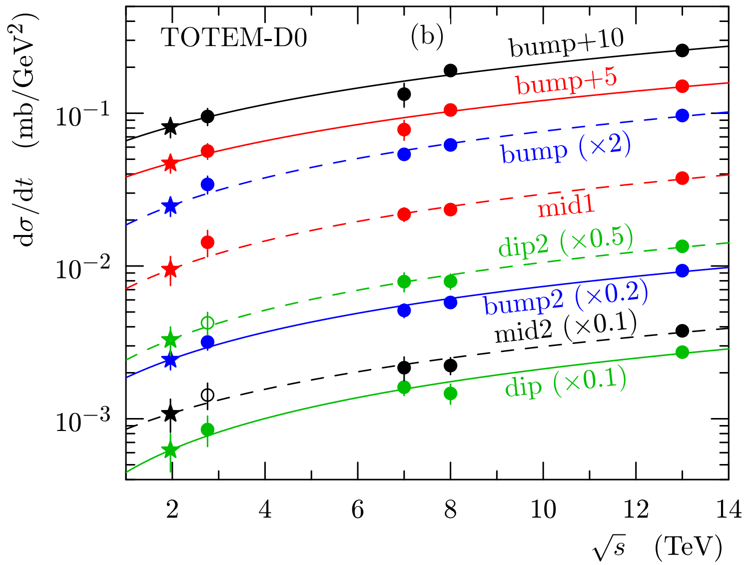


- Starting from 3-4 data points limit formulas to ones with 2 parameters.
- All characteristic points give excellent fits.
- Alternate functional forms (having other $\sqrt{s}$ powers) give results well within fit uncertainties.

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

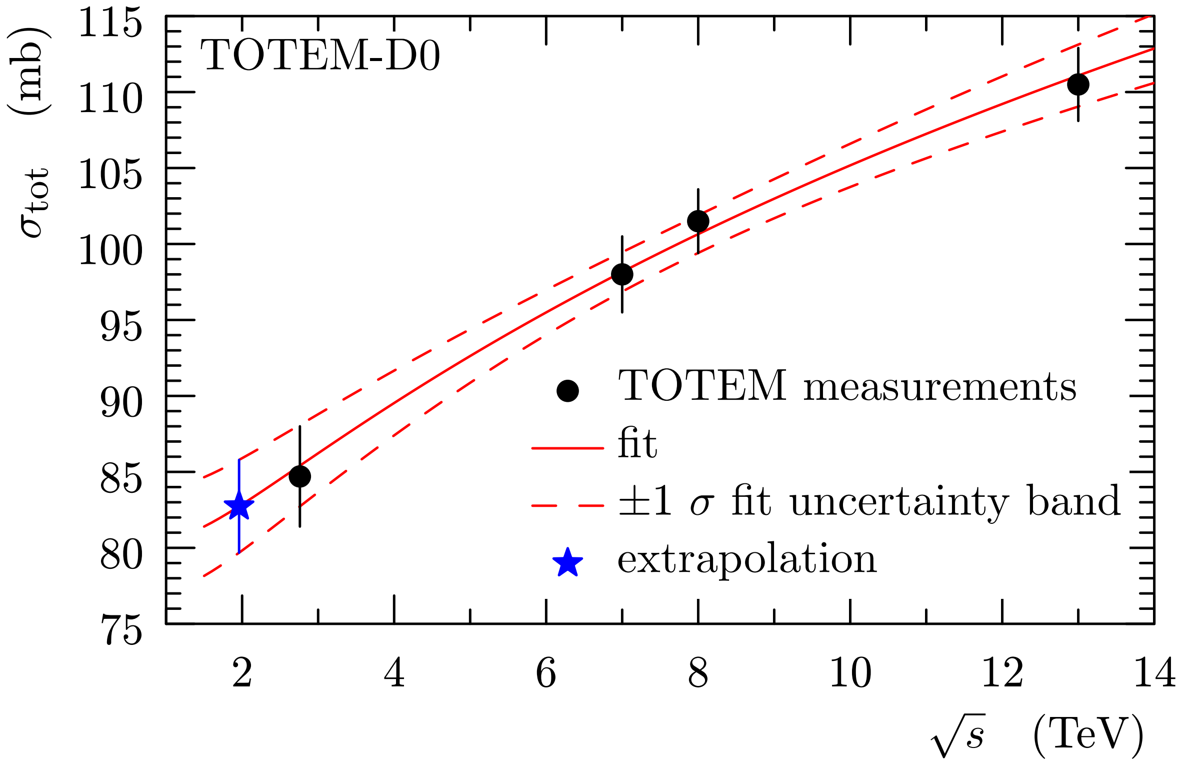


$(d\sigma/dt) = c\sqrt{s}\ [\text{TeV}] + d$



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

Starting from 4 data points limits formulas to ones with 2-3 parameters

- 2 TeV in boundary between region dominated by $\log^2\sqrt{s}$ & $\log\sqrt{s}$ dependence
- 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.

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

- Pomeranchuk theorem: $\sigma_{tot}^{pp}/\sigma_{tot}^{p\bar{p}} \xrightarrow[\sqrt{s}\to\infty]{} 1 \Rightarrow$
  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") and 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 necessary to include in χ^2 for pp & $p\bar{p}$ comparison

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

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

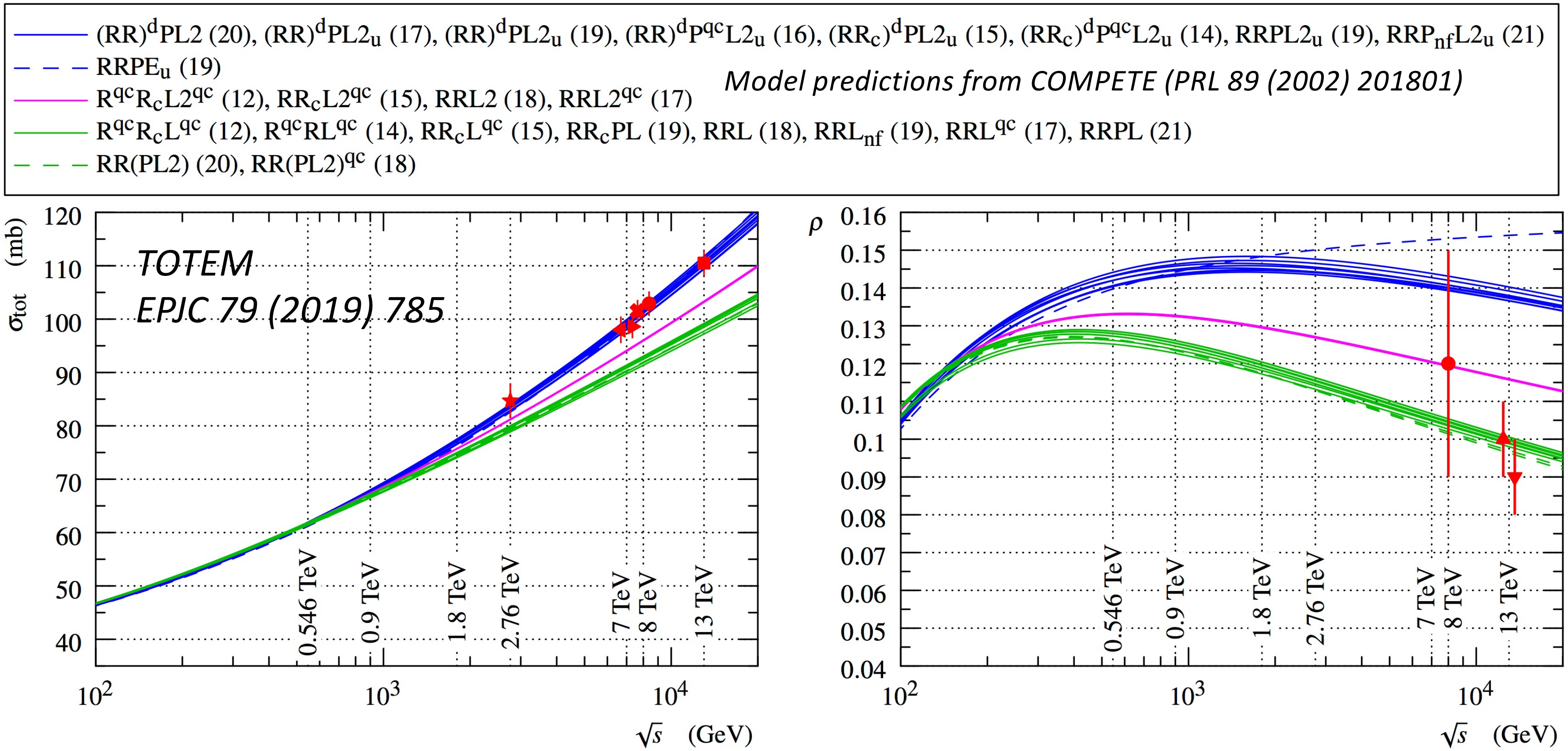
$B(pp) = B(p\bar{p})$, since pp & $p\bar{p}$ differences in CNI & high |t| negligible for $\sigma_{el}^{pp/p\bar{p}}$

pp & $p\bar{p}\ d\sigma_{el}/dt$ differ by 3.4σ at $\sqrt{s}$ = 1.96 TeV $\Longrightarrow$ evidence of odderon

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

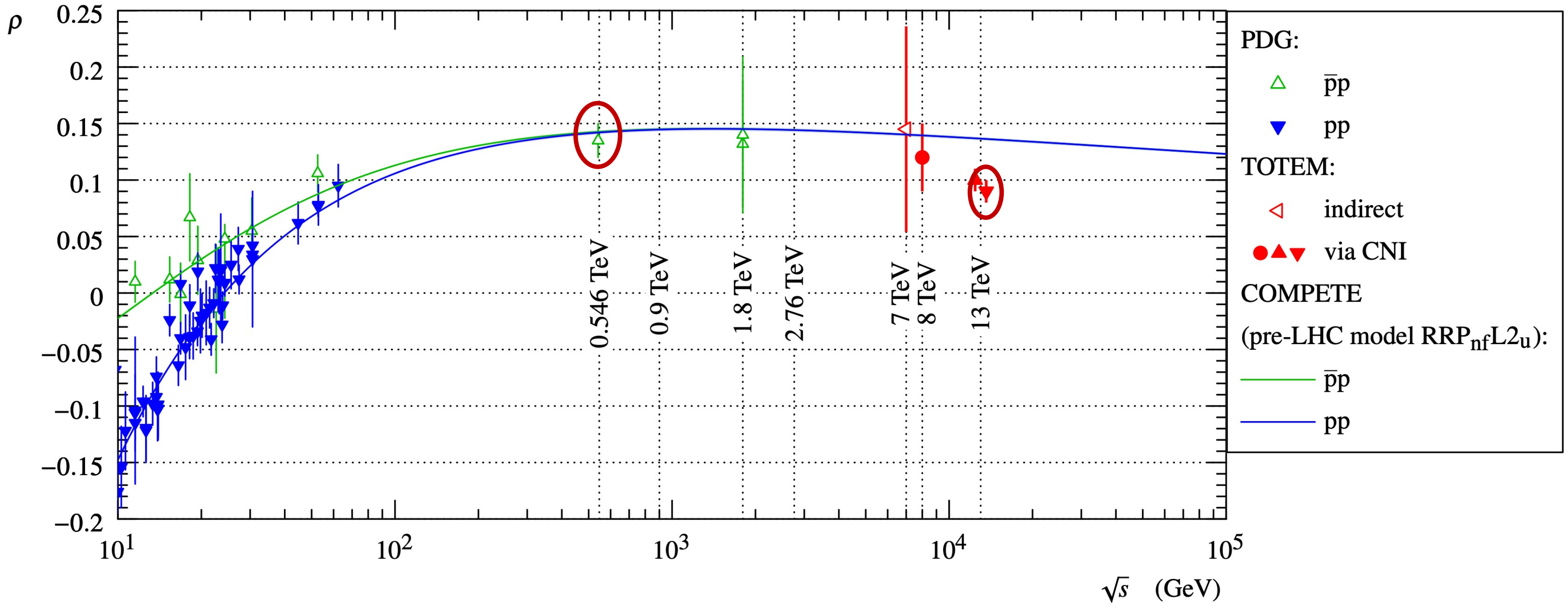
TOTEM ρ in pp at $\sqrt{s}$ = 13 TeV

- Very low |t| data @ $\sqrt{s}$ = 13 TeV: $\rho = 0.09 \pm 0.01$ *(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



TOTEM ρ in pp at $\sqrt{s}$ = 13 TeV

- NB! $\rho = 0.09 \pm 0.01$ in pp @ $\sqrt{s}$ = 13 TeV should be compared with $\rho = 0.135 \pm 0.015$ in $p\bar{p}$ @ $\sqrt{s}$ = 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 β^*= 2.5 km data as they are given and extracted ρ using similar CNI formula obtain compatible ρ values (0.08-0.10)

Objections of PDG review

V.A. Khoze, M.G. Ryskin & M. Tasevsky, High energy Soft QCD and Diffraction, https://pdg.lbl.gov/ (2020)

- 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 TOTEM ρ & σ_{tot} in pp at $\sqrt{s}$ = 7, 8 and 13 TeV (3.4σ) and D0 $p\bar{p}$ $d\sigma/dt$ in dip-bump region at $\sqrt{s}$ = 1.96 TeV (4.3σ).

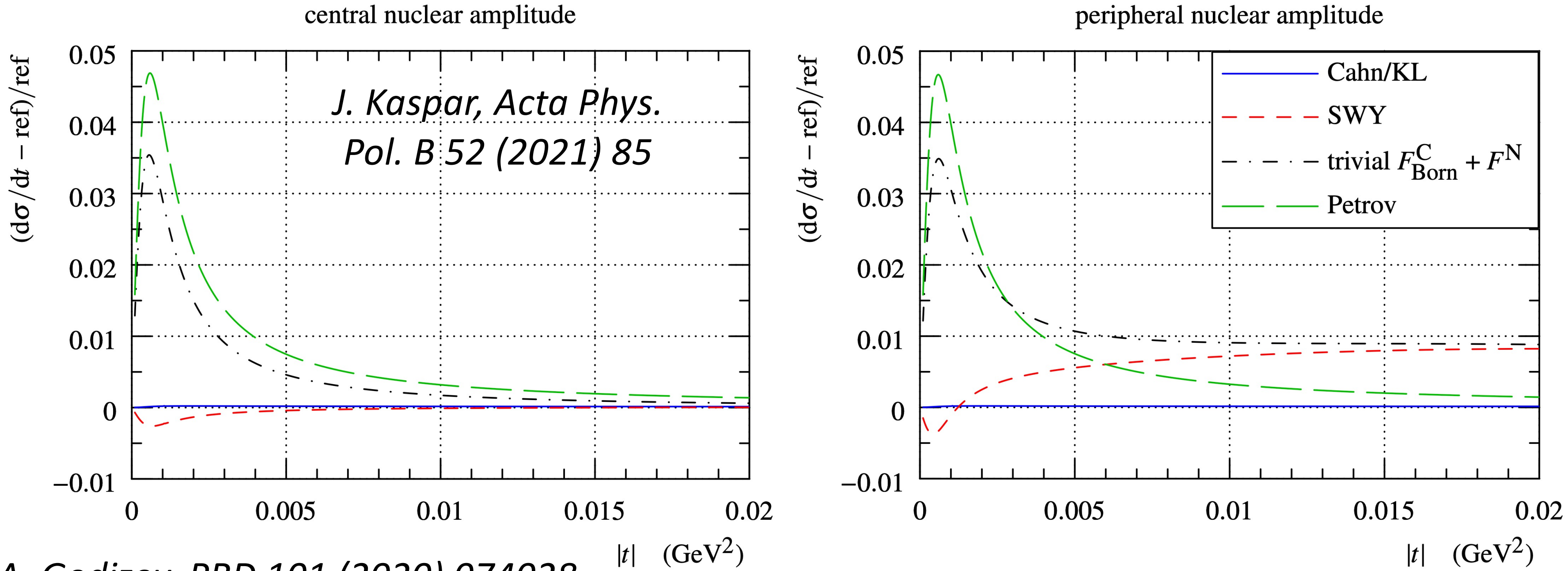
- Describe TOTEM data within 1σ & obtain ρ = 0.14 in pp at 13 TeV without odderon. (*A. Donnachie & P.V. Landshoff, PLB 798 (2019) 135008*)
- Using TOTEM 13 TeV β^*= 2.5 km data only: ρ = 0.10
- Using TOTEM 8 TeV β^*= 1 km & 13 TeV β^*= 2.5 km data: ρ = 0.14
- ✓ Impossible to obtain if experimental uncertainties treated correctly!
- ✓ Precision (excluding normalization) of 13 TeV data factor ~3 better than 8 TeV. Evidently the normalization was not treated correctly as a separate term in χ^2.
- ✓ Sensitivity to ρ only in a few data points in CNI region. From experience, we know that fits must be made in steps in separate |t|-regions to avoid that data points without ρ sensitivity influence the obtained ρ. Not clear whether fits have been performed here that way or whether fits performed in a single step.

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 $\alpha(s)$) 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 that Cahn/KL formula 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*

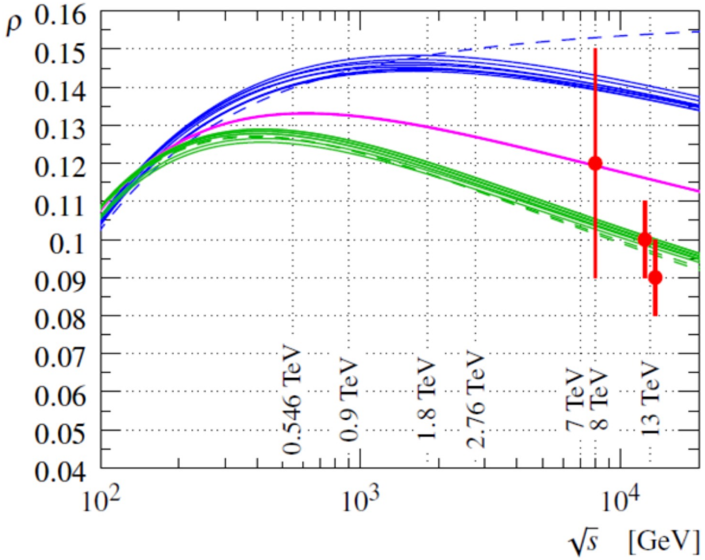
✓ Effect of N*'s omitted by eikonal negligible *(V.A. Khoze et al., PRD 101(2020) 016018)*

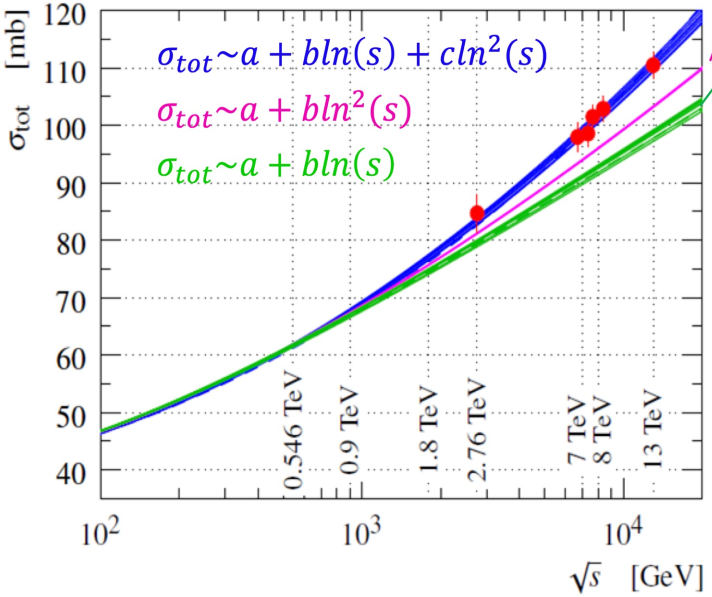
✓ **Conclusion:** Cahn/KL CNI formulas used for 13 TeV ρ determination prefectly fine.

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 adequately addressed.

- *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."