Observation of odderon exchange from proton-proton and proton-antiproton elastic scattering at TeV scale

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on behalf the **D0 & TOTEM collaborations**

HIP seminar 8.6.2021

Outline

- Elastic scattering & odderon
- Experiments & measurements
- Extrapolation of elastic pp $d\sigma/dt$ to $\sqrt{s}$ = 1.96 TeV & comparison with elastic $p\bar{p}$ $d\sigma/dt$
- Combination with other TeV scale odderon evidences
- Conclusions & next steps

CERN-EP-2020-236, FERMILAB-PUB-20-568-E, arXiv:2012.03981

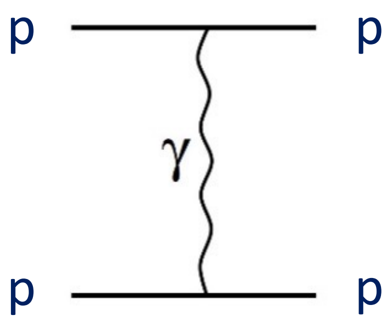
Elastic scattering: t-channel exchange

Elastic proton (anti)proton scattering at TeV scale: gluonic exchange

Experimental variable: $t \approx -P^2\theta^2$, four-momentum transfer squared

Strong interaction (non-pertutative QCD)

Electromagnetism (QED): $J^{PC} = 1^{--}$

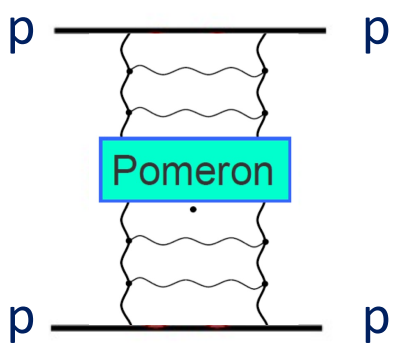


Photon exchange

dominates at very low |t| ($< \approx 10^{-3}$)

Crossing even

C = +



”Pomeron” exchange: system of 2 (or more number of) gluons

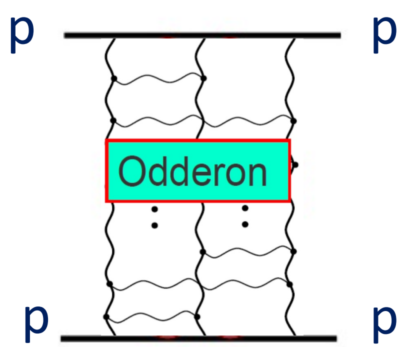
dominates at low |t|,

≈ imaginary part of $A_{\mathrm{el}}^{\mathrm{nucl}}$

same for pp & $p\bar{p}$

Crossing odd

C = –



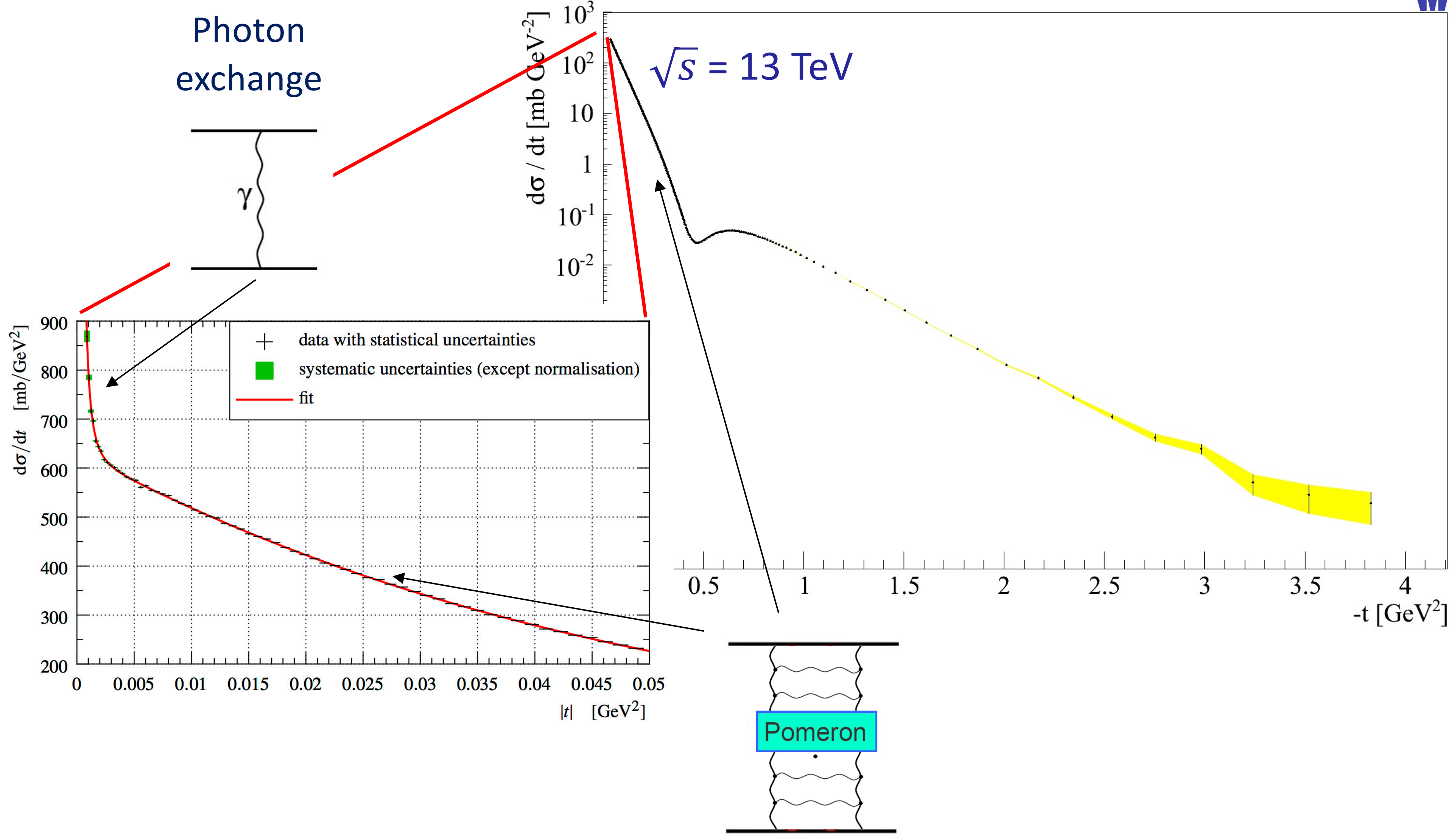
”Odderon” exchange: system of 3 (or more number of) gluons

mostly suppressed,

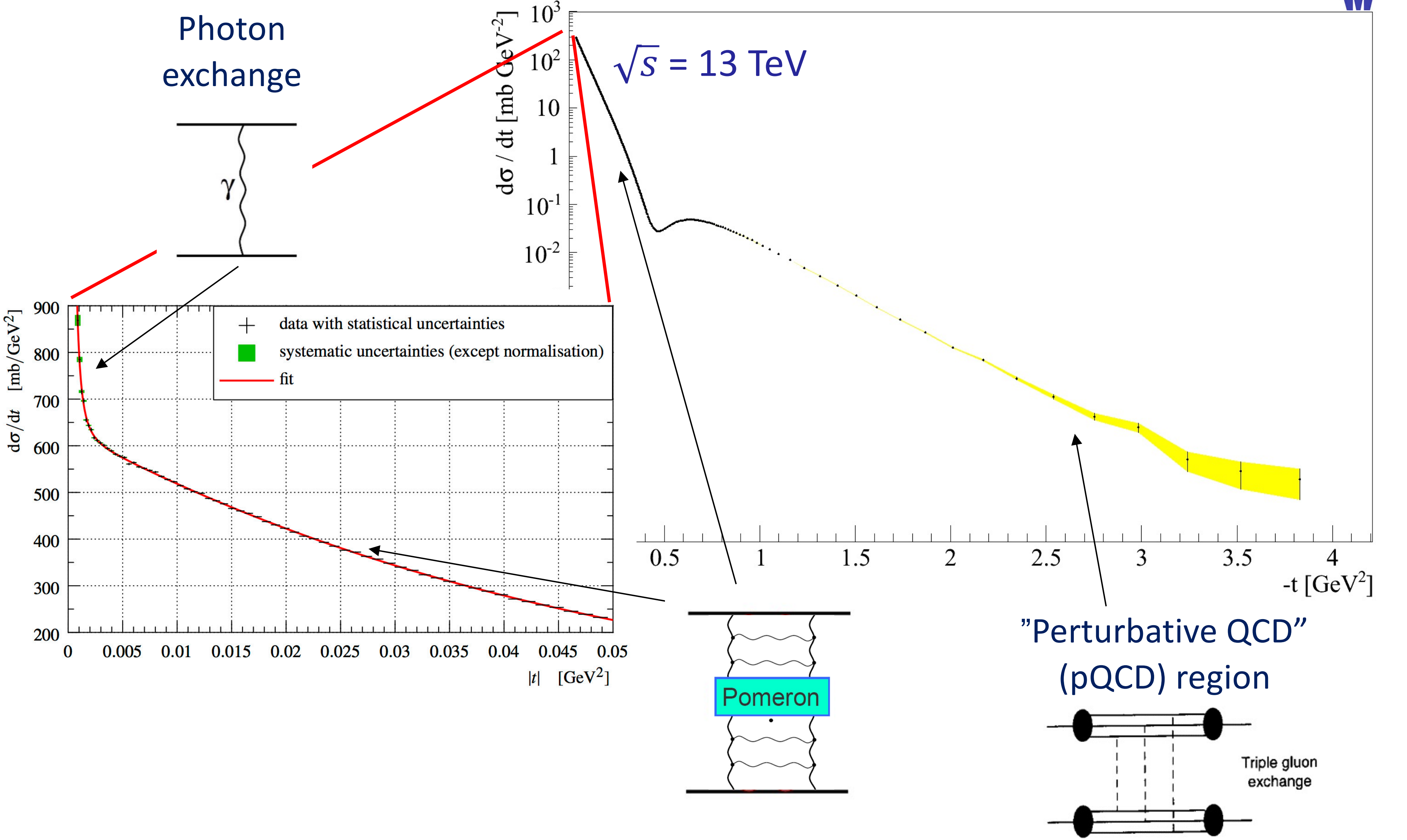
mainly real part of $A_{\mathrm{el}}^{\mathrm{nucl}}$

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

Elastic *pp* differential cross-section

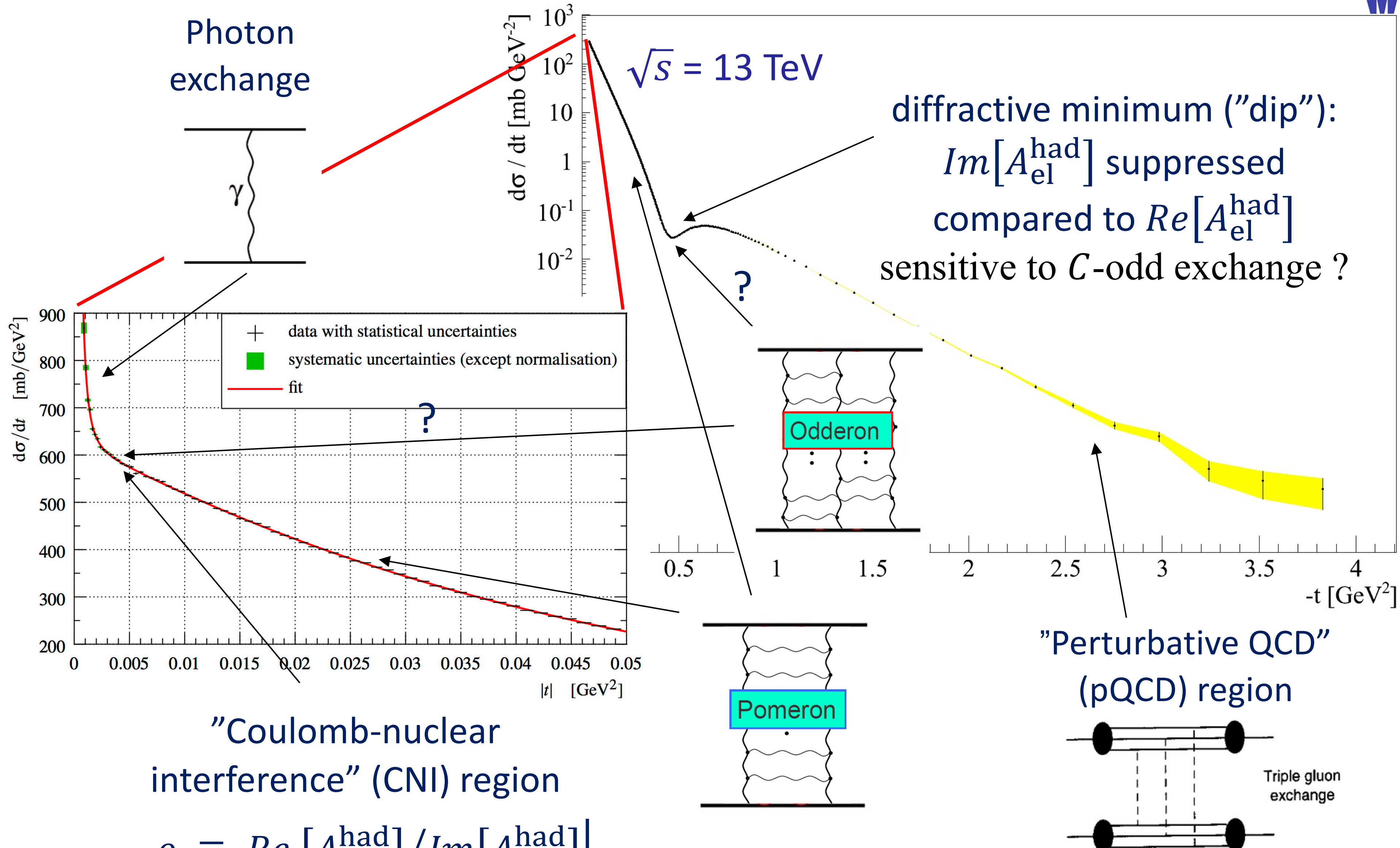


Elastic *pp* differential cross-section



A. Donnachie, P. V. Landshoff, Z. Phys. C 2 (1979) 55.

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 ?

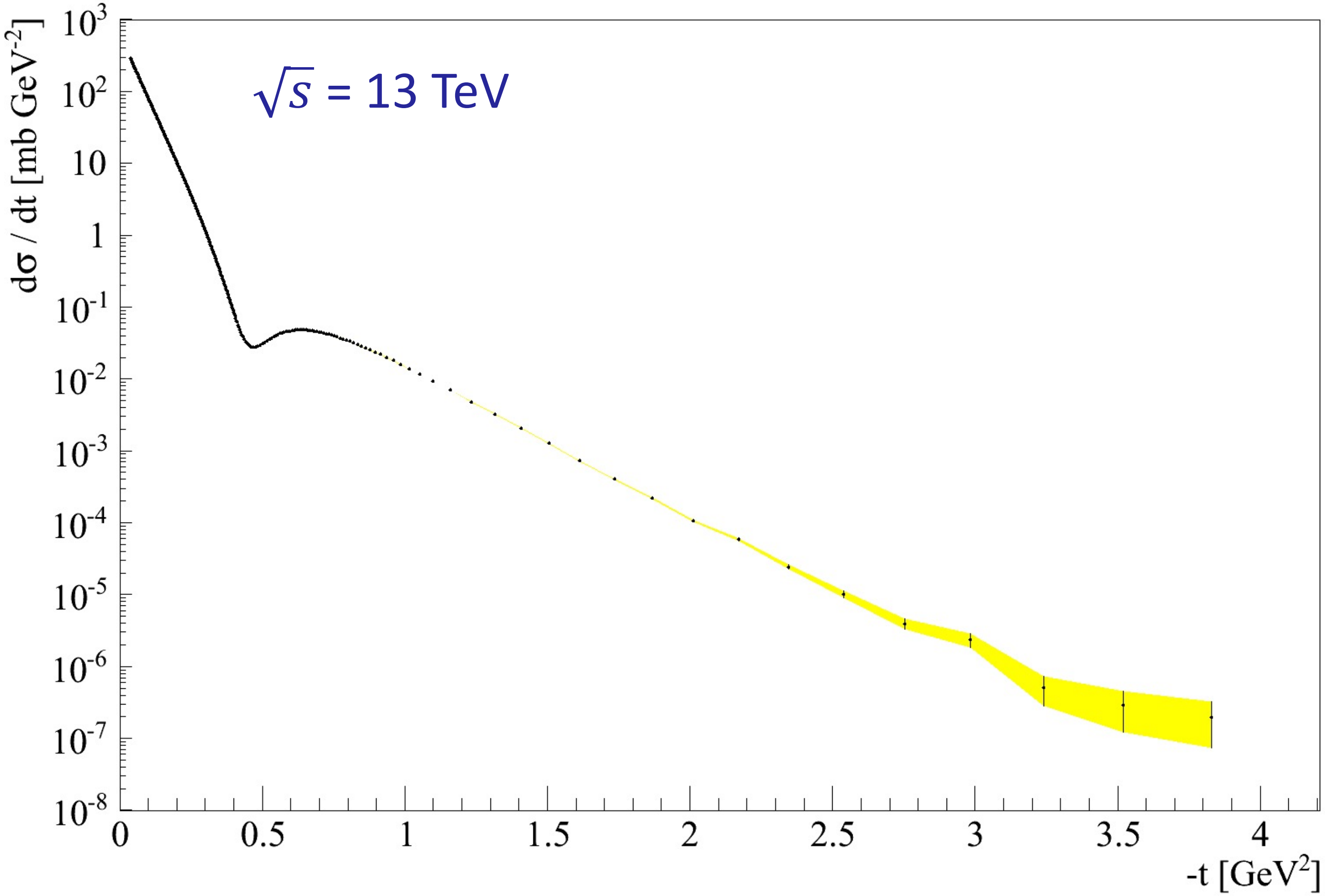
A. Donnachie, P. V. Landshoff, Z. Phys. C 2 (1979) 55.

Elastic scattering: multi-gluon exchanges

- ✓ Multi-gluon exchanges: increases with $\sqrt{s}$
- ✓ Meson (secondary reggeon) exchanges: decreases with $\sqrt{s}$

R. Kirschner & L. Lipatov, Sov. Phys. JETP 56 (1982) 266;

L.V. Gribov, E.M. Levin & M.G. Ryskin, Phys. Rep. 100 (1983) 1



Odderon or C-odd gluonic compound

B. Nicolescu

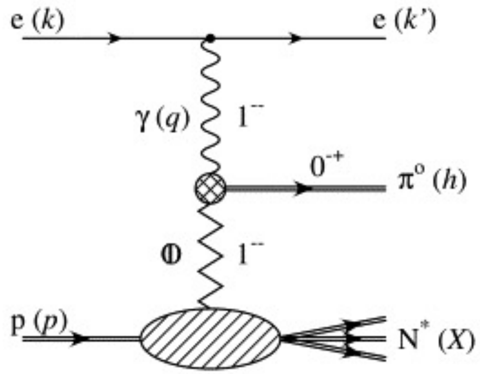
Odderon/C-odd gluonic compound:

- ✓ C-odd exchange predicted in Regge-theory

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

- ✓ Confirmed in QCD as C-odd exchange of three (or odd #) gluons at leading order

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



- ✓ Odderon searched for the last 50 years:
  - modification of exclusive meson production (vs γ)
  - modification of elastic scattering (vs Pomeron)

  $\Rightarrow$ convincing experimental evidence up to now missing

- ✓ Vector glueball in lattice calculations with a mass of 3-4 GeV

  e.g. C.J. Morningstar and M. Peardon, Phys. Rev. D 60 (1999) 03450

- ✓ Gluonic compounds: colourless gluon combinations bound sufficiently strongly not to interact with individual $p/\bar{p}$ parton

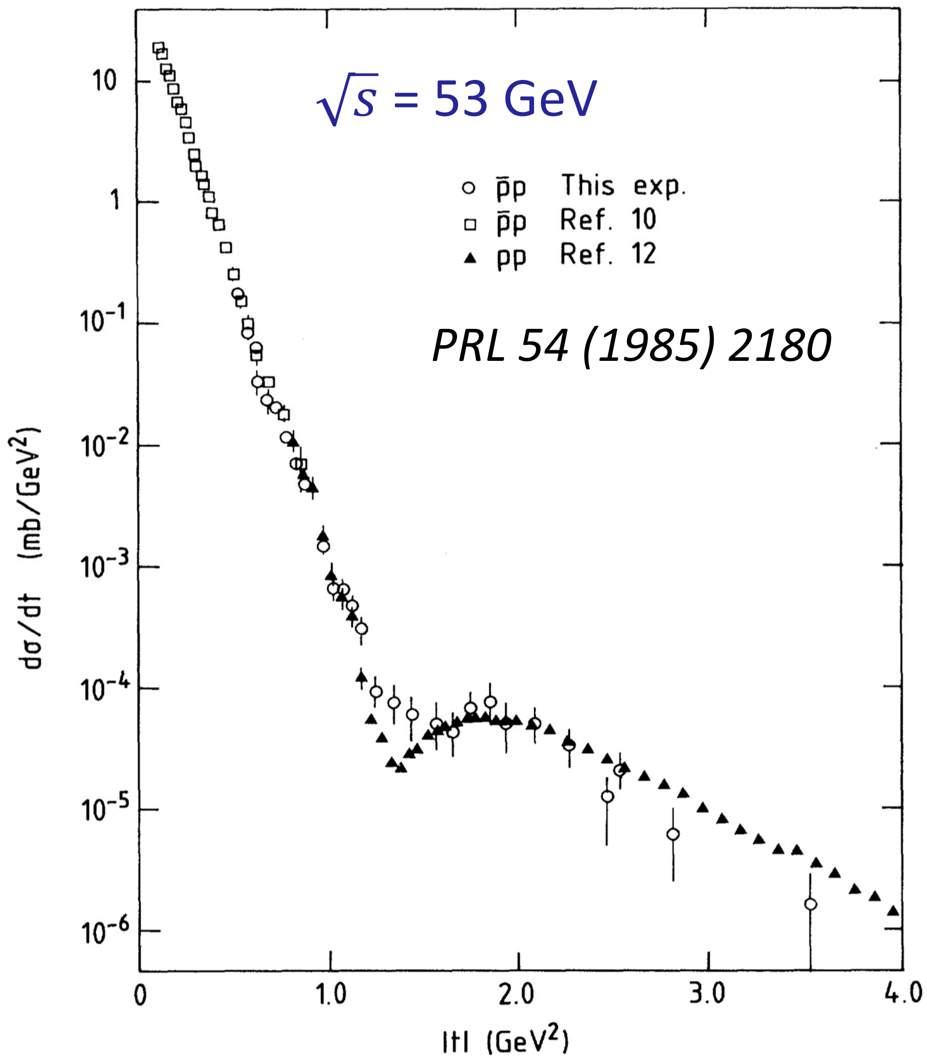
pp & $p\bar{p}$ comparison @ $\sqrt{s}$ = 53 GeV

- Direct comparison between elastic pp & $p\bar{p}$ $d\sigma/dt$ @ $\sqrt{s}$ = 53 GeV: > 3σ difference
  A. Breakstone et al., PRL 54 (1985) 2180;
  S. Erhan et al., PLB 152 (1985) 132

- Not considered as odderon evidence due to influence of mesonic exchanges (secondary Reggeons)

- UA4 $p\bar{p}$ @ $\sqrt{s}$ = 540 GeV vs STAR pp @ $\sqrt{s}$ = 510 GeV (awaiting STAR publication)

- D0 $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV vs TOTEM pp @ $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV



Pomeranchuk + Cornille-Martin theorems

Pomeranchuk theorem:

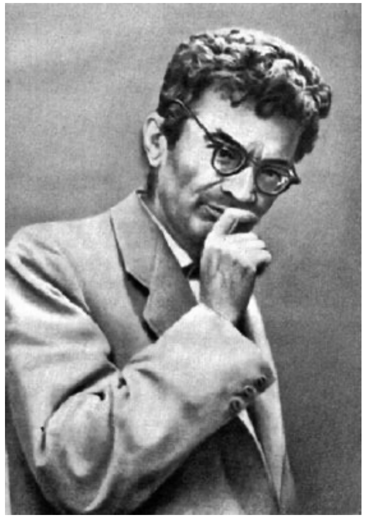
$$\left.\frac{\sigma_{\text{tot}}^{p\bar{p}}}{\sigma_{\text{tot}}^{pp}}\right|_{\sqrt{s}\to\infty} = 1 \Rightarrow$$

at sufficiently high $\sqrt{s}$:

$$\sigma_{tot}^{p\bar{p}} = \sigma_{tot}^{pp}$$

(except some small C-odd contribution)

I.I. Pomeranchuk, Zh. Eksp. Teor. Fiz. 34 (1958) 725



I.I. Pomeranchuk

Cornille-Martin theorem:

$$\left.\frac{d\sigma_{\text{el}}^{p\bar{p}}/dt}{d\sigma_{\text{el}}^{pp}/dt}\right|_{\sqrt{s}\to\infty} = 1 \Rightarrow$$

at sufficiently high $\sqrt{s}$:

$$d\sigma_{\text{el}}^{p\bar{p}}/dt = d\sigma_{\text{el}}^{pp}/dt$$

(in elastic diffractive cone)

H. Cornille & A. Martin, Phys. Lett. B 40 (1972) 671

A. Martin

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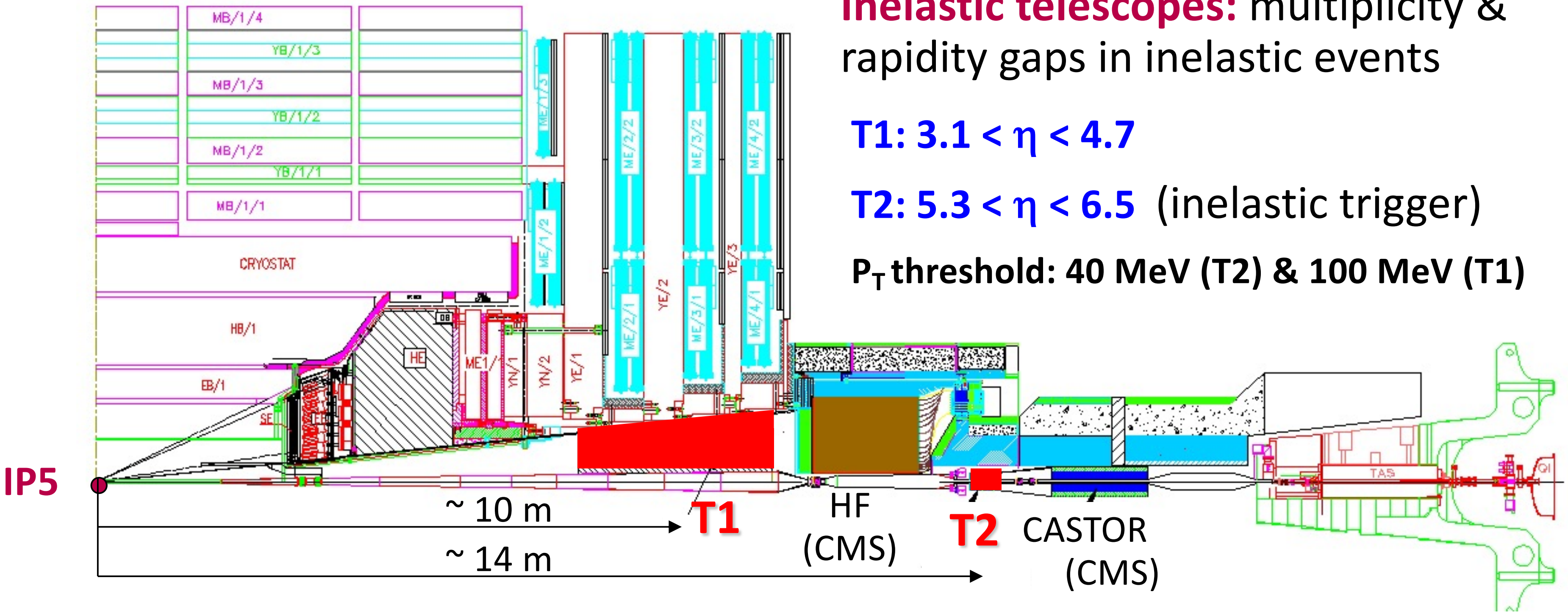
TOTEM experiment @ LHC

Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

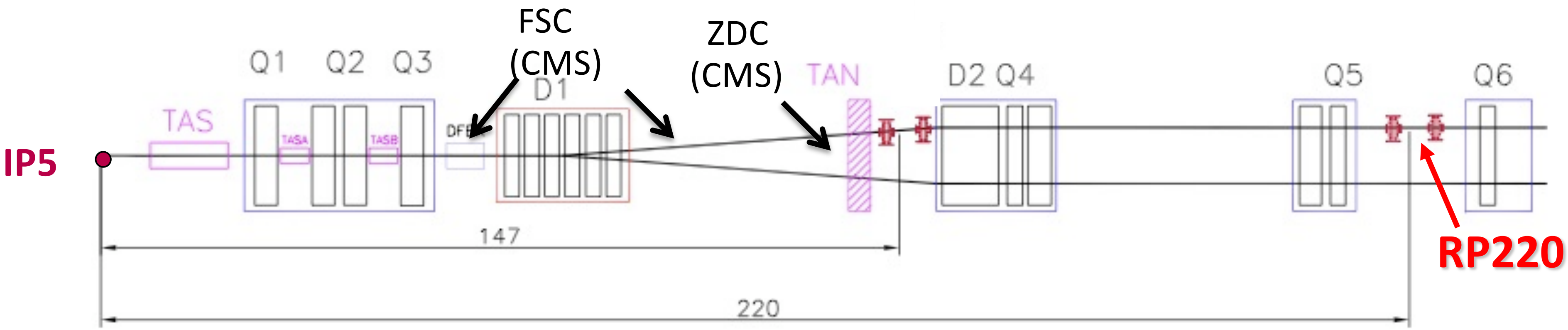
T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$ (inelastic trigger)

P_T threshold: 40 MeV (T2) & 100 MeV (T1)

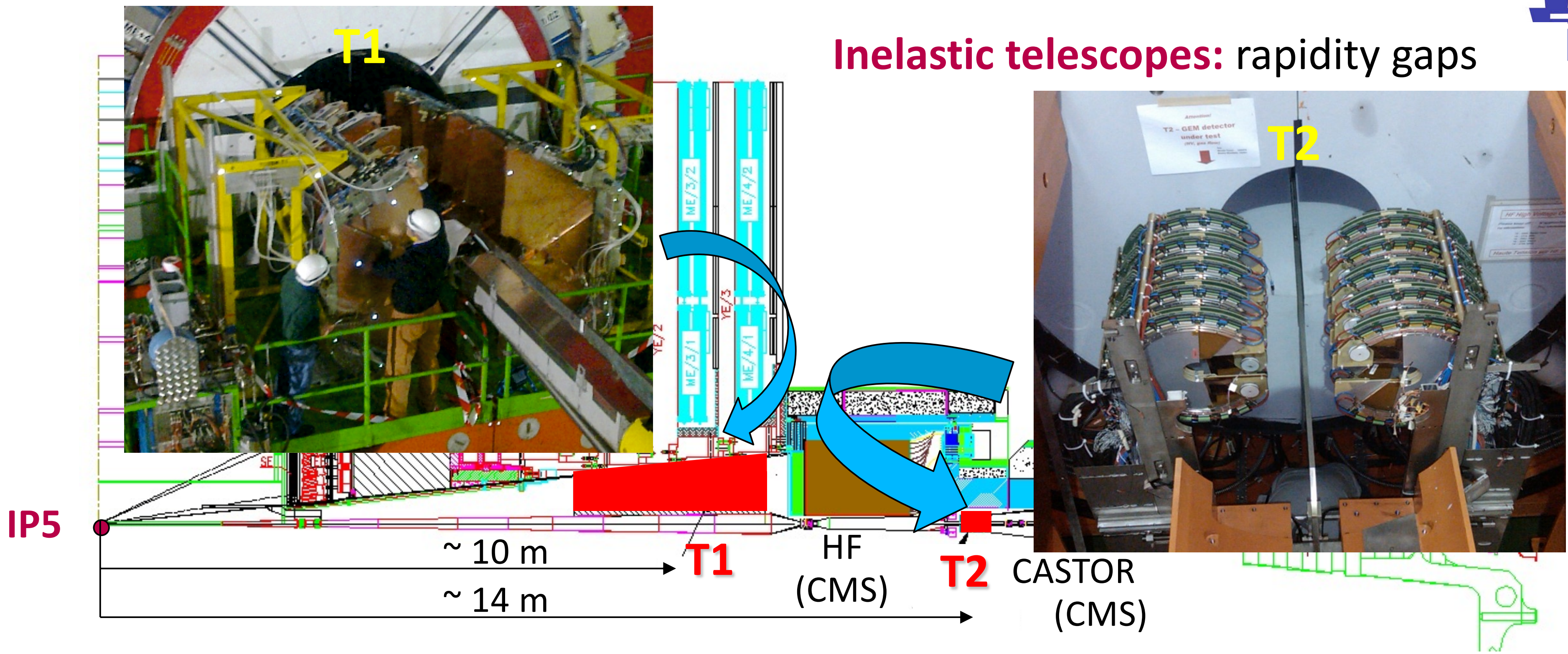


Roman Pots: elastic & diffractive protons

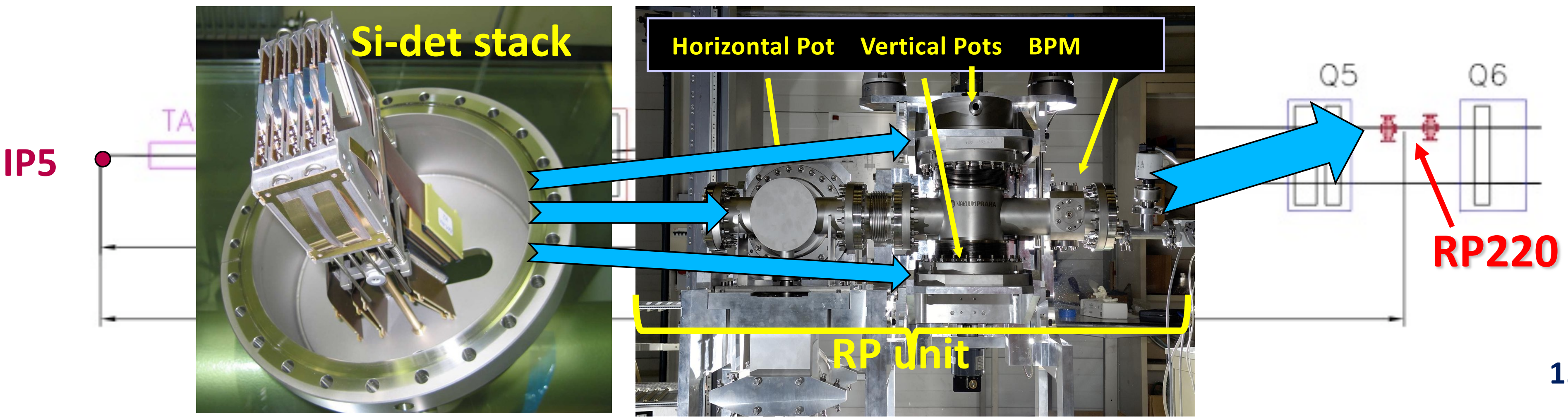


TOTEM experiment @ LHC

Inelastic telescopes: rapidity gaps

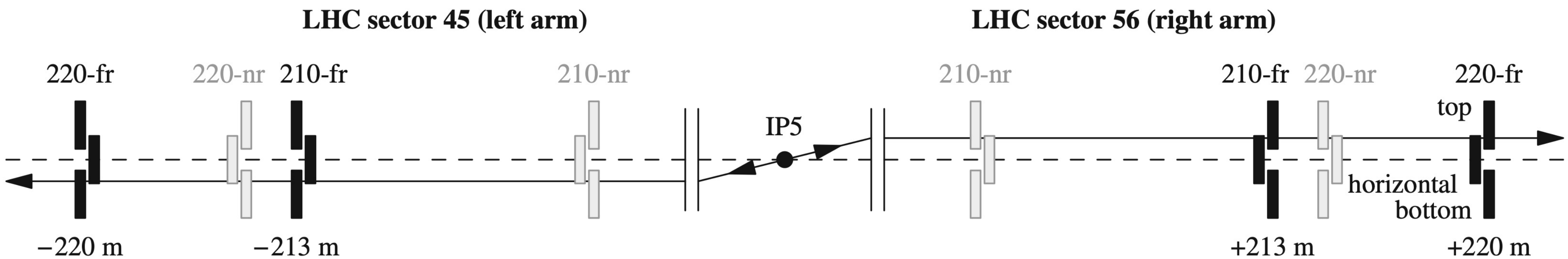


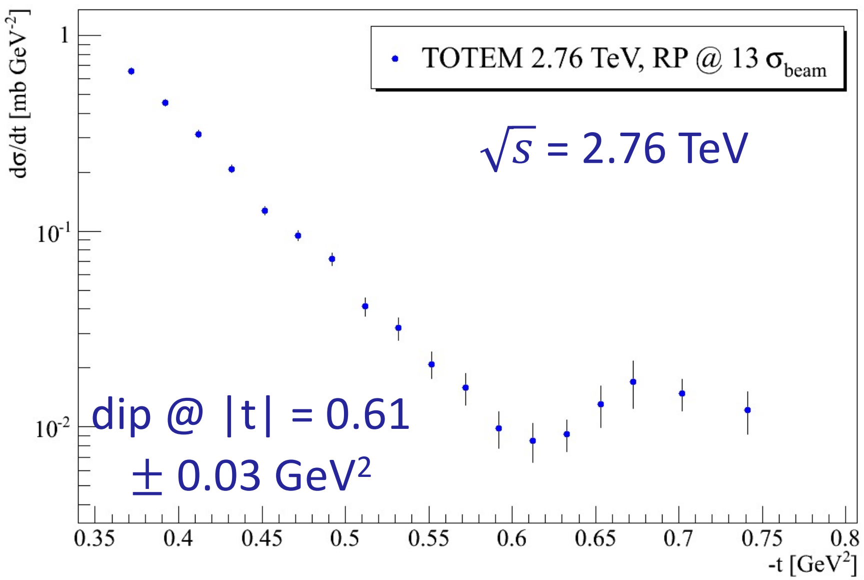
Roman Pots: diffractive protons (di-proton trigger)

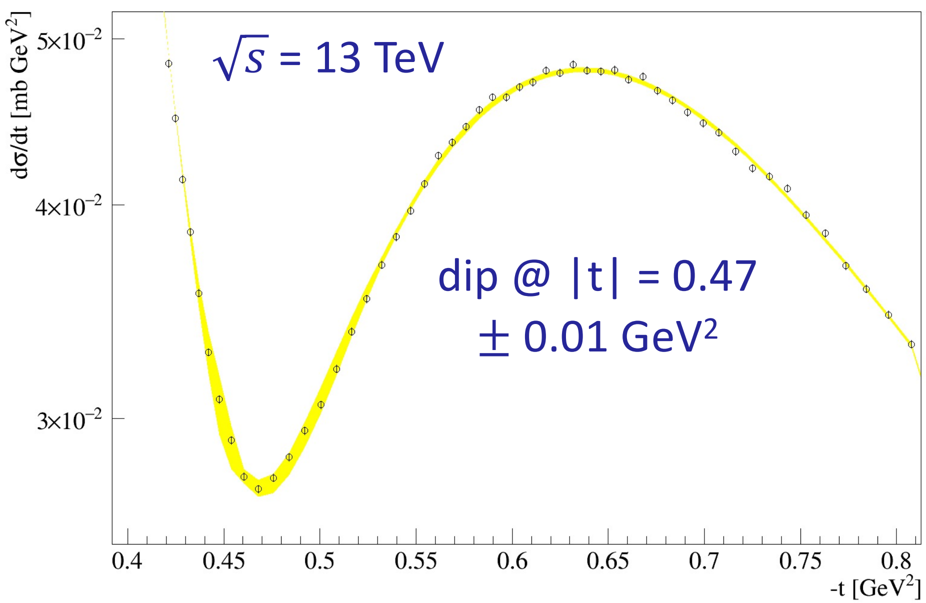


Elastic pp cross-section measurements

- Elastic pp $d\sigma/dt$ measurements: measure both intact p's in TOTEM Roman Pots at 210-220 m from IP with silicon detectors.
- Precise measurements at $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV: EPJC 80 (2020) 91; EPL 95 (2011) 41004; NPB 899 (2015) 527; EPJC79 (2019) 861.

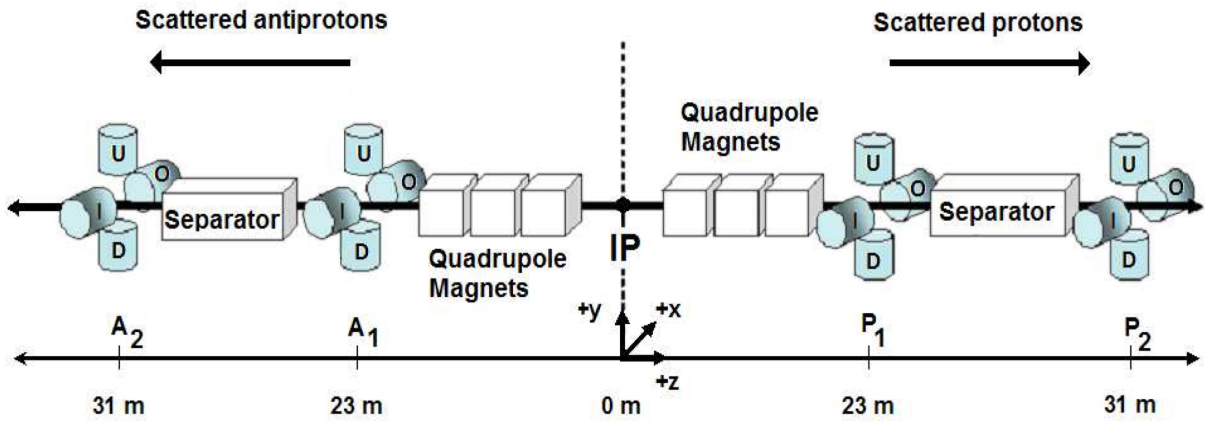


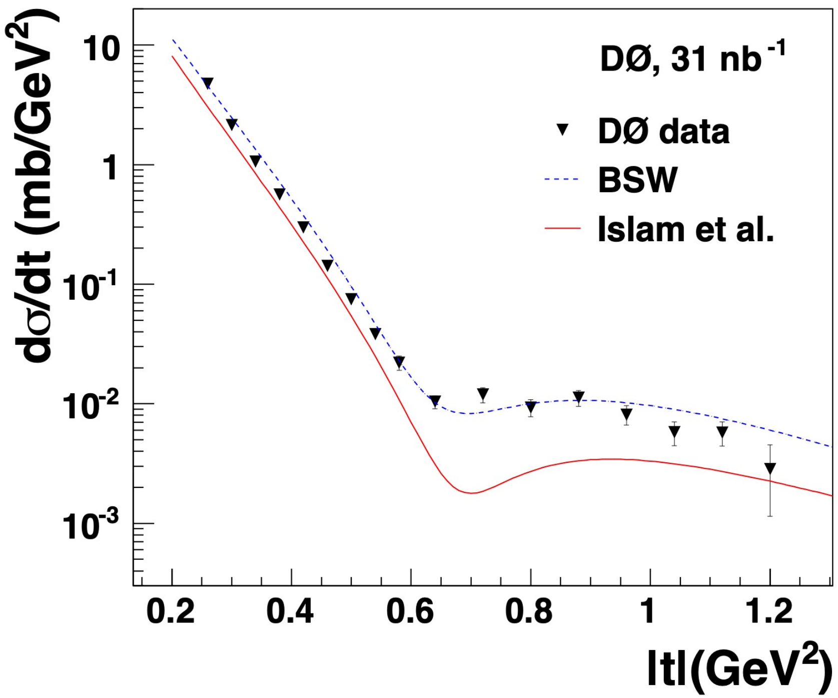




Elastic $p\bar{p}$ cross-section measurements

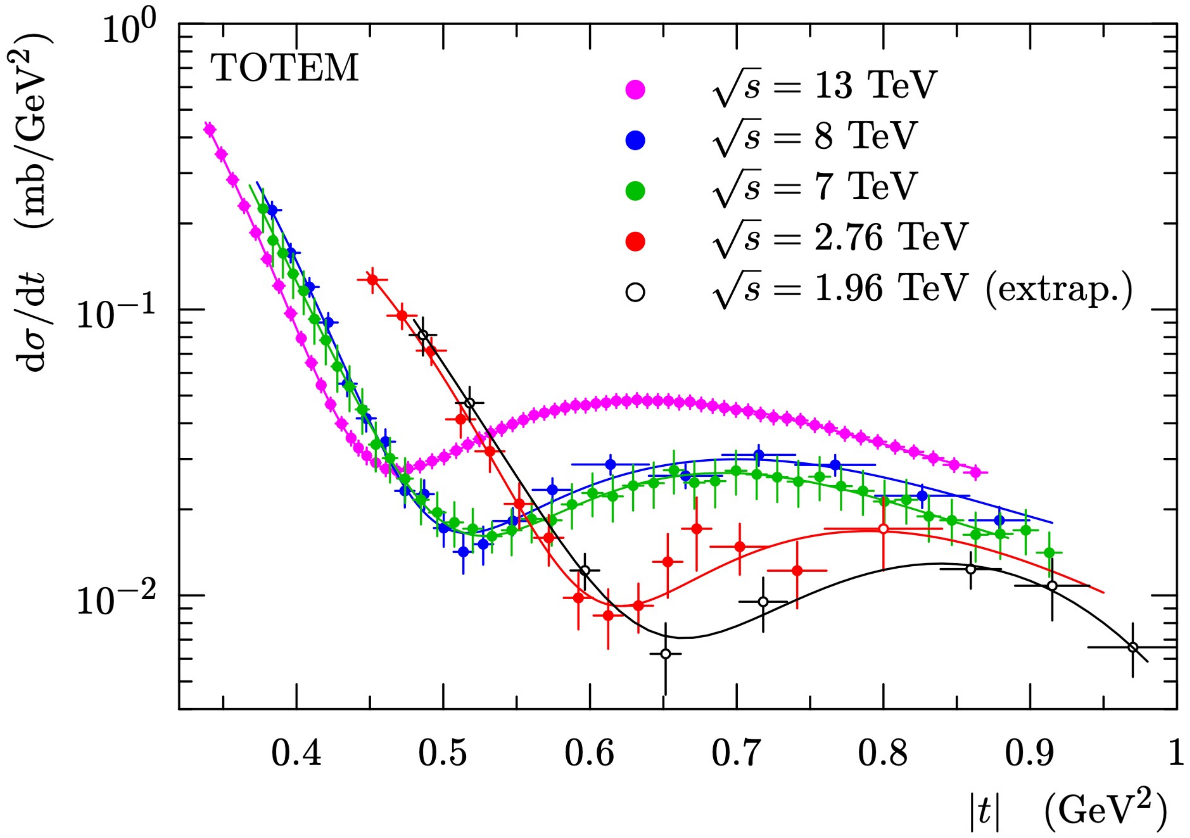
- Elastic $p\bar{p}$ $d\sigma/dt$ measurements: measure both the intact p & $\bar{p}$ in D0 Roman Pots at 23-31 m from IP with scintillating fibre detectors.
- Measurement at $\sqrt{s}$ = 1.96 TeV: PRD 86 (2012) 012009.

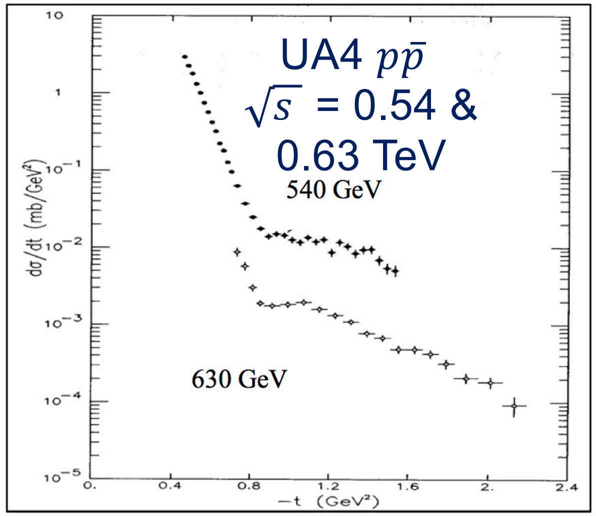


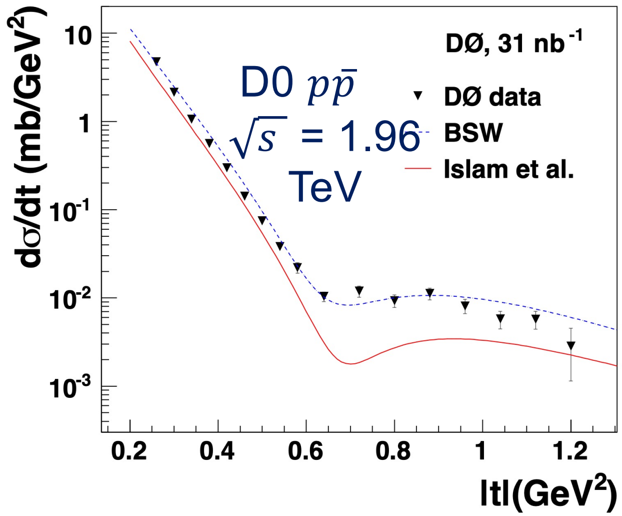


Elastic $pp/p\bar{p}$ cross-section characteristics

At TeV-scale, pp elastic $d\sigma/dt$ characterized by a diffractive minimum (“dip”) & a secondary maximum (“bump”), wheras $p\bar{p}$ $d\sigma/dt$ characterized only by a “kink”.



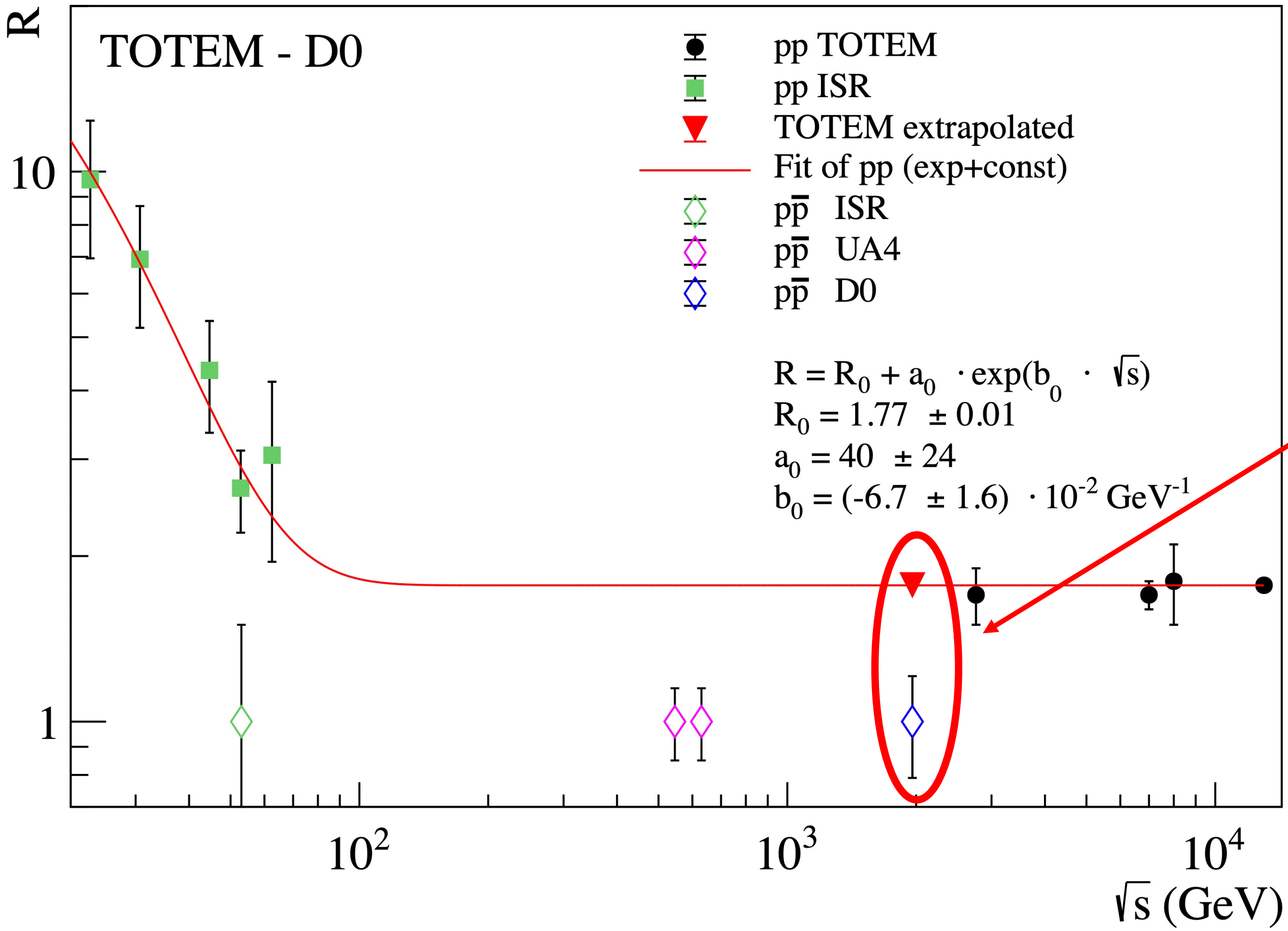




@TeV scale: persistancy of dip & bump for pp, absence of dip & bump for $p\bar{p}$

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 $d\sigma/dt$ of t-bins close to expected pp bump & dip position

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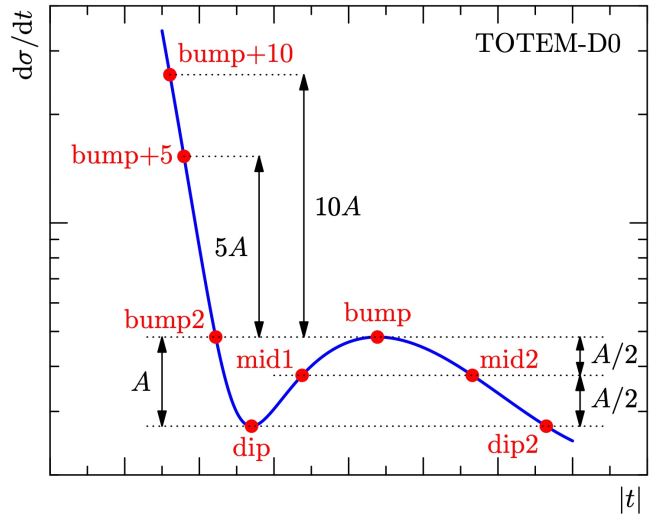
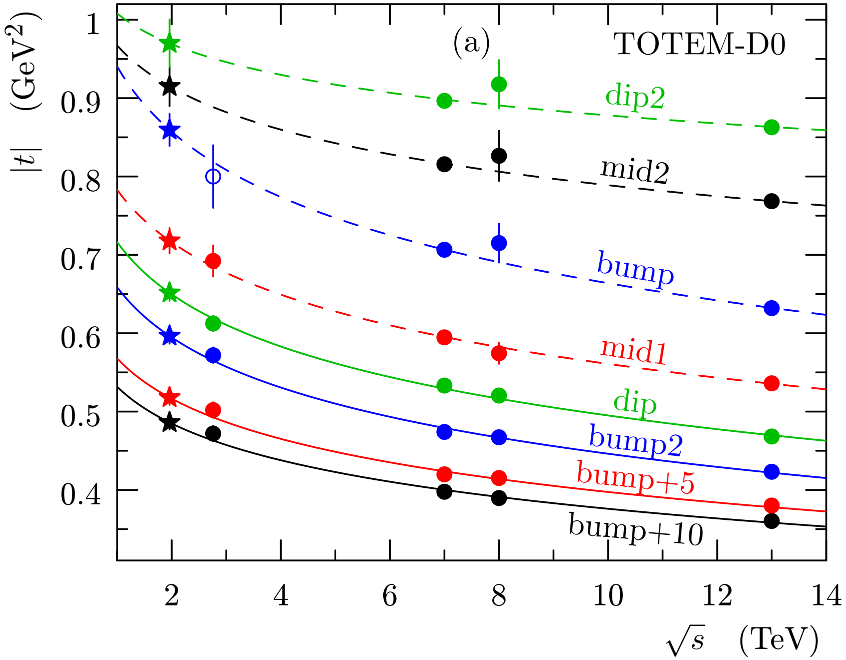
Extrapolation of pp cross section

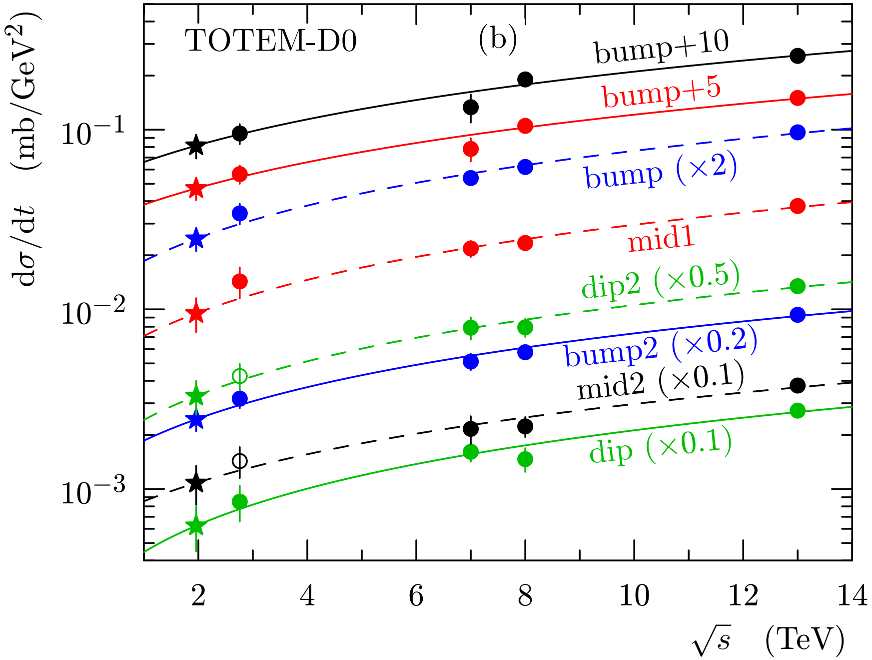
- Extrapolate 8 characteristic points (both their $d\sigma/dt$ & t) in dip-bump region of the pp elastic $d\sigma/dt$ @ 2.76, 7, 8 & 13 TeV to 1.96 TeV $\Longrightarrow$ pp elastic $d\sigma/dt$ points @ 1.96 TeV
- Alternative forms lead to compatible results within quoted uncertainties



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



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



Extrapolated pp $d\sigma/dt$ @ D0 |t|-values

- Extrapolated pp points fitted using a double-exponential to provide pp $d\sigma/dt$ values @ D0 measured |t|-values:

$$h(t) = a_1 e^{-b_1|t|^2 - c_1|t|} + d_1 e^{-f_1|t|^3 - g_1|t|^2 - h_1|t|}$$

- First exponential describes diffractive cone, second asymmetric dip/bump

- Such formula leads also to good description of TOTEM data in dip/bump region for $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV

- pp $d\sigma/dt$ uncertainties @ D0 measured |t|-values evaluated from ensemble of MC experiments in which the cross sectiom values of the characteristic points varied within their Gaussian uncertainties. MC experiments with double-exponential fits giving dip and bump values not matching extrapolated values are rejected.

Normalization of pp cross section

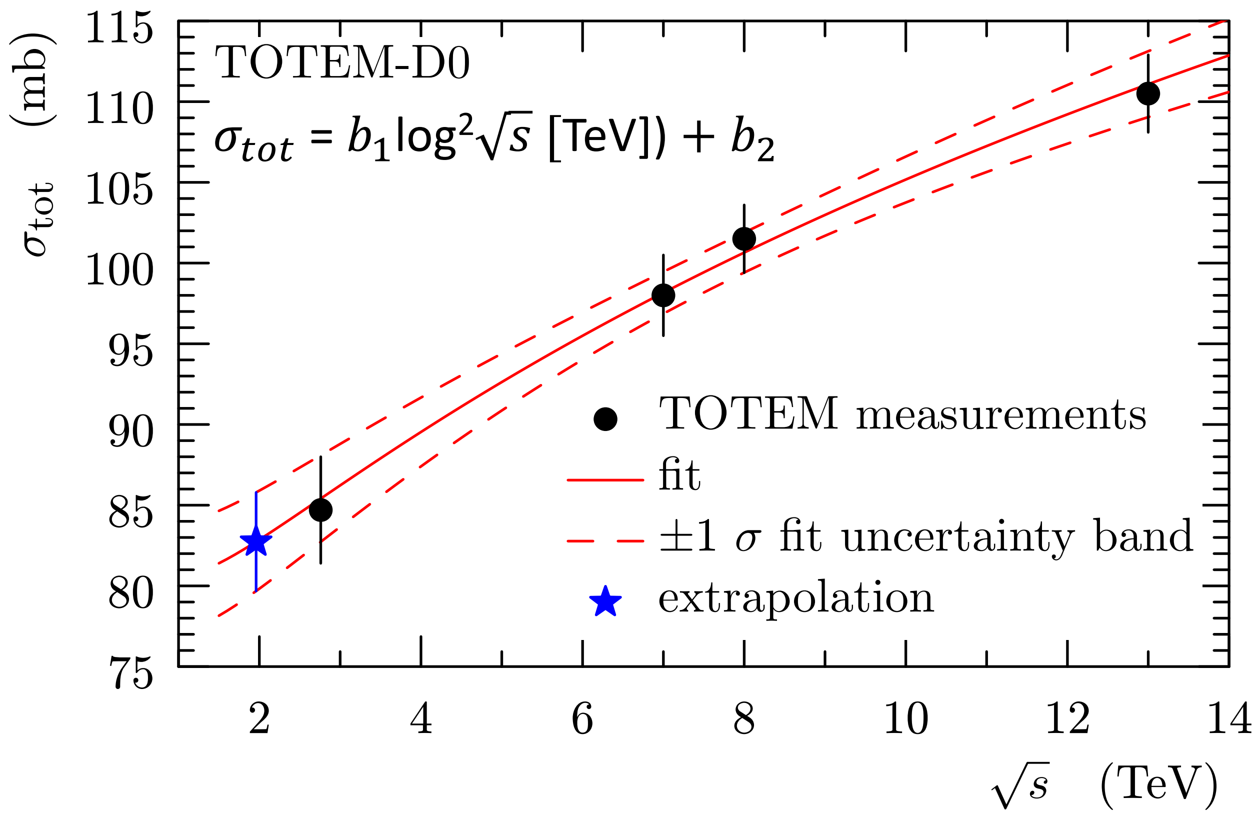
- ✓ σ_{tot}^{pp} @ 1.96 TeV = 82.7 $\pm$ 3.1 mb from σ_{tot}^{pp} @ 2.76, 7, 8 & 13 TeV
- ✓ OP ($d\sigma_{\rm el}/dt|_{t=0}$) of pp (from σ_{tot}^{pp}) consistent with OP of $p\bar{p}$ data
- ✓ Normalize pp $d\sigma/dt$ to a common OP with $p\bar{p}$
  (σ_{tot}^{pp}= $\sigma_{tot}^{p\bar{p}}$ within experimental & theoretical uncertainties)

Optical theorem:

$$\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = \frac{\sigma_{tot}^2(1+\rho^2)}{16\pi(\hbar c)^2}$$

TOTEM pp: $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} =$
357.1 $\pm$ 26.4 mb/GeV^2

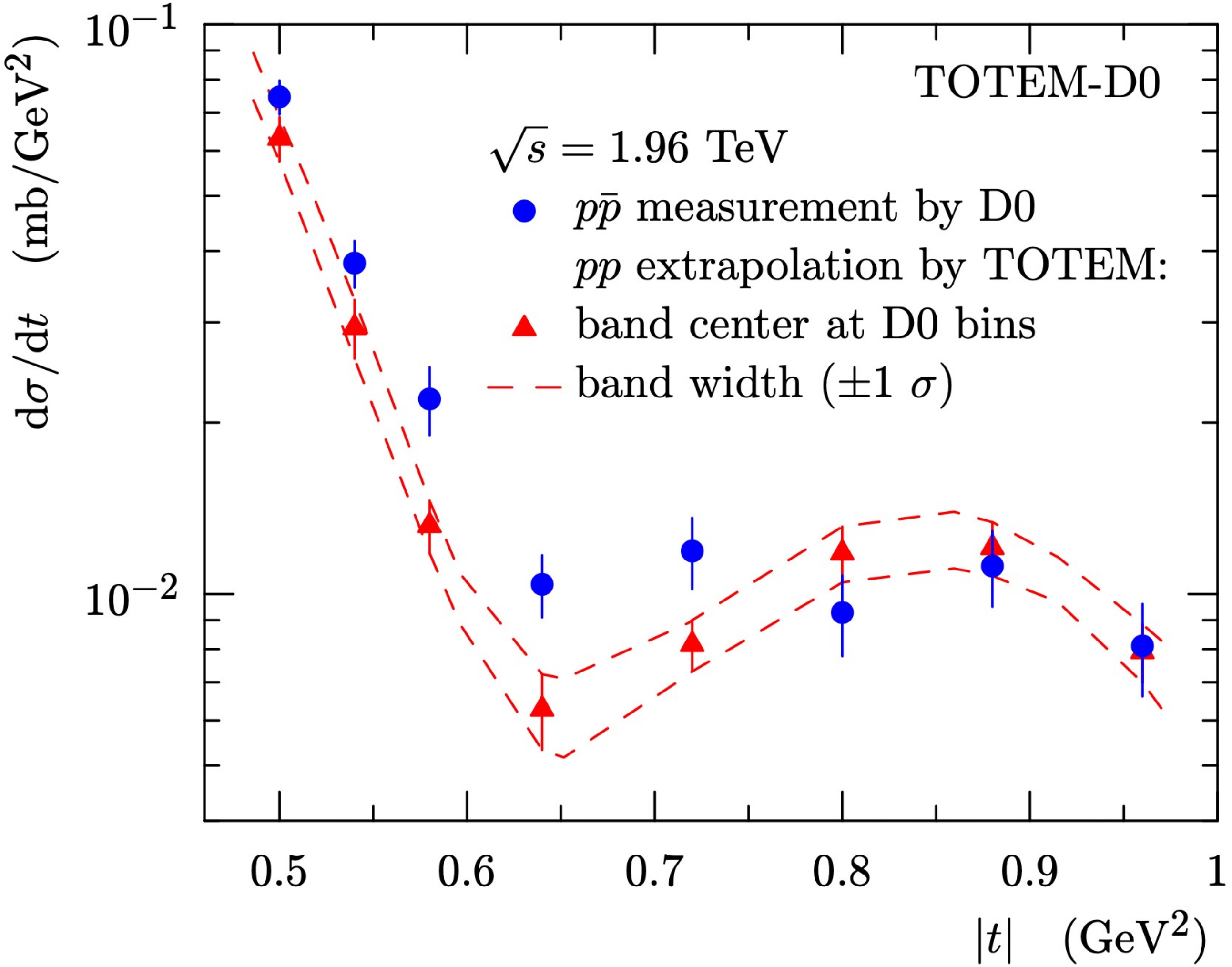
D0 $p\bar{p}$: $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} =$
341 $\pm$ 48 mb/GeV^2



NB! Not a σ_{tot} measurement, only a way to obtain a common normalization point

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

Uncertainties of pp data points @ D0 measured |t|-values strongly correlated; full covariance matrix used



χ^2 test of pp & $p\bar{p}$ difference:
3.4σ significance for t-channel exchange of a colourless C-odd gluonic compound ("odderon")

Significance confirmed by a combined Kolmogorov-Smirnov & normalization test

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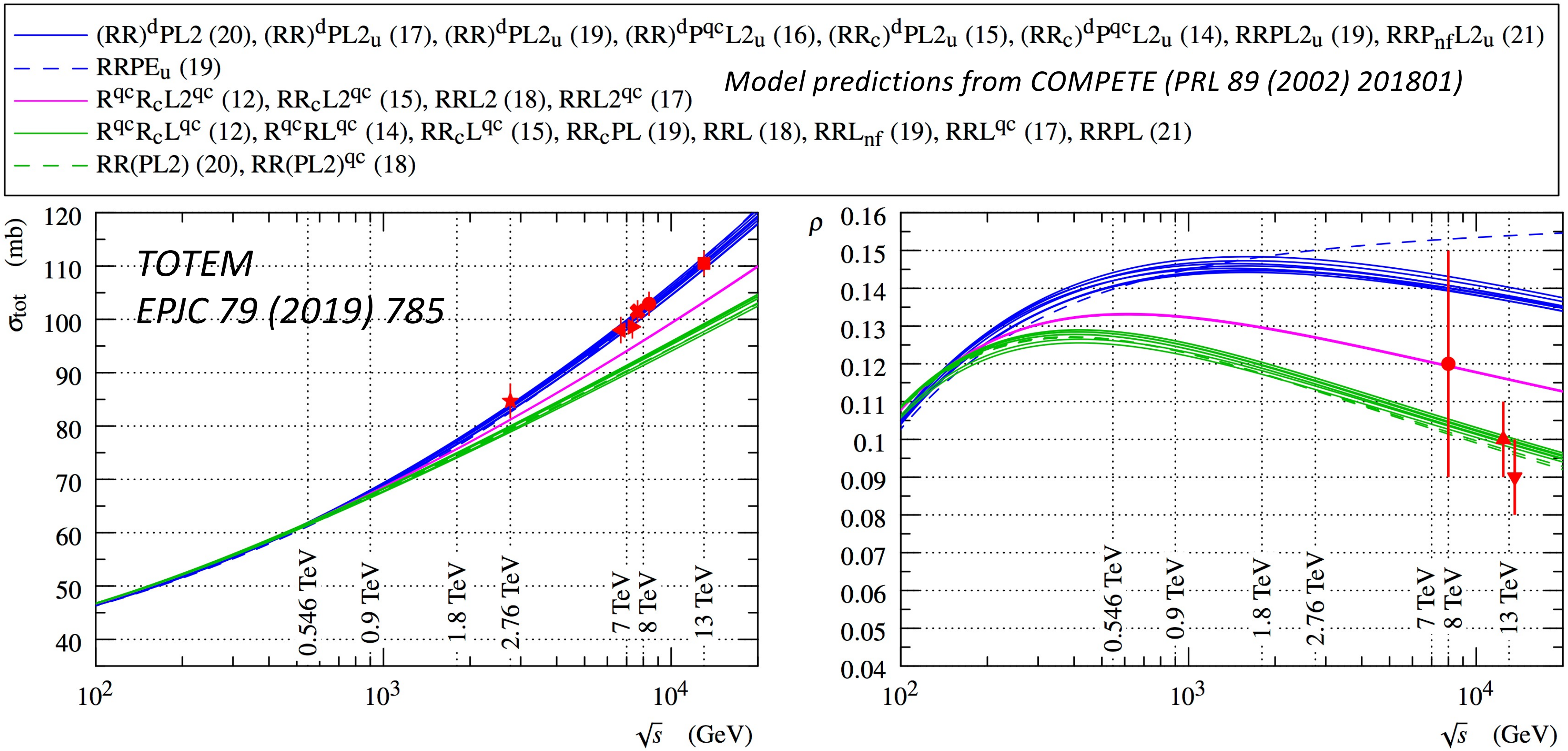
Previous evidence from pp ρ & σ_{tot}

- ✓ Using very low |t| TOTEM data @ $\sqrt{s}$ = 13 TeV: ρ = 0.09 $\pm$ 0.01
  (TOTEM, EPJC (2019) 785)
- ✓ Unable to describe TOTEM ρ & σ_{tot}^{pp} measurements without adding colourless C-odd exchange (comparison to COMPETE predictions shown below)



Combining with pp ρ & σ_{tot} evidence

- ✓ Combine independent evidence of colourless C-odd exchange from TOTEM ρ & σ_{tot}^{pp} measurements in a completely different $|t|$-domain with evidence from the pp & $p\bar{p}$ comparison.

- ✓ Combination made using Stouffer method† in order of sensitivity starting from 13 TeV ρ measurement & the pp & $p\bar{p}$ comparison adding σ_{tot}^{pp} measurements if needed

- ✓ Partial combination of TOTEM ρ & σ_{tot}^{pp} measurements provide a 3.4 - 4.6σ significance, giving to a total significance of 5.2 - 5.7σ for odderon exchange when combined with the TOTEM-D0 result

- ✓ Combination excludes models‡ without odderon exchange @ 5.2-5.7σ ⇒ observation of colourless C-odd gluonic compound / odderon

† S. Bityokov et al. , Proc. of Sc. (ACAT08) 118 (20008)
‡ COMPETE Coll., PRL 89 (2002) 201801; M.M. Block et al., PRD 92 (2015) 114021; Durham group, PLB 748 (2018) 192.

Conclusions

- Data-driven comparison between $p\bar{p}$ (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

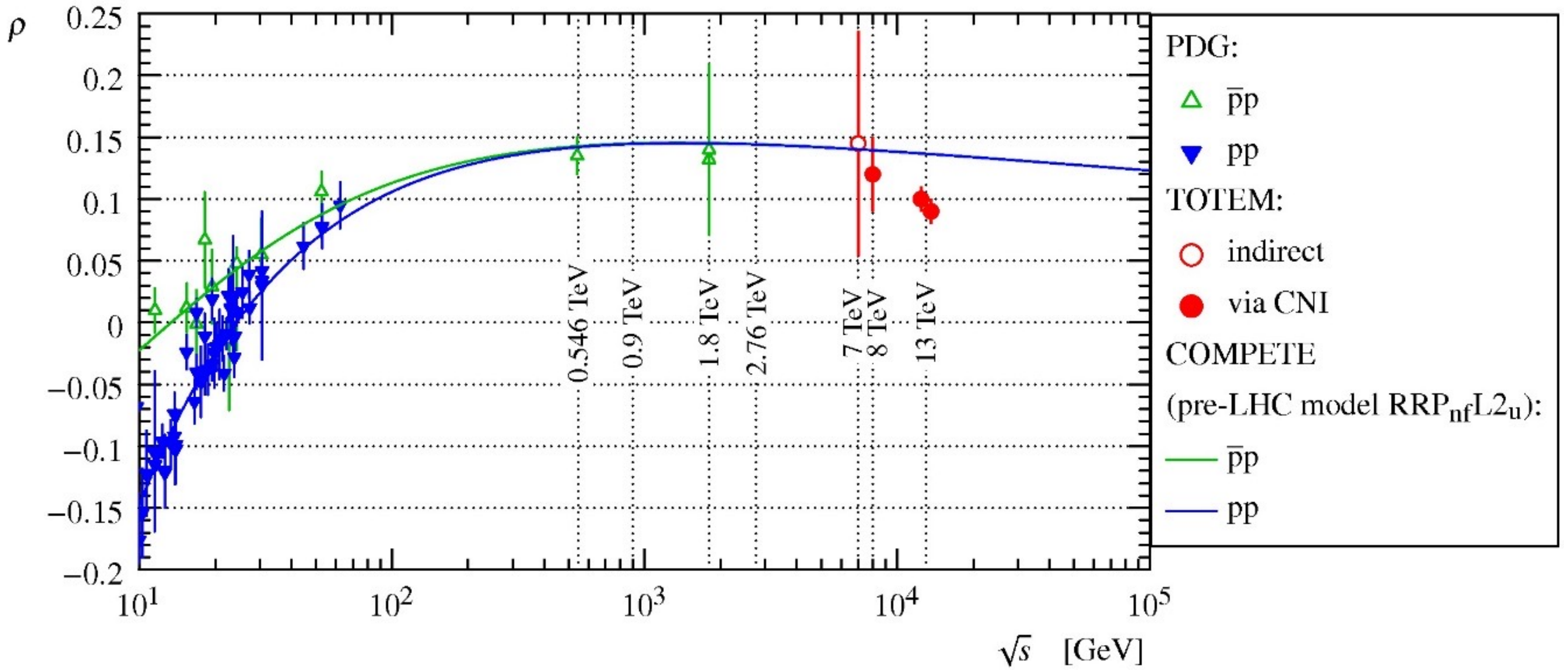
- Extrapolate "characteristic" points of elastic pp $d\sigma/dt$ to predict elastic pp $d\sigma/dt$ @ $\sqrt{s}$ = 1.96 TeV

- Elastic pp and $p\bar{p}$ cross sections differ @ 3.4σ at $\sqrt{s}$ = 1.96 TeV $\Longrightarrow$ evidence of t-channel exchange of odderon.

- Combined with TOTEM ρ & total cross section results $\Longrightarrow$ 5.2-5.7σ & thus first experimental observation of odderon.
  Major discovery @ LHC & Tevatron

Next steps

- Model-dependent comparisons between $p\bar{p}$ (D0 @ $\sqrt{s}$ = 1.96 TeV) & pp (TOTEM @ $\sqrt{s}$ = 2.76, 7, 8, 13 TeV) elastic $d\sigma/dt$ data
- ρ & σ_{tot} measurements @ $\sqrt{s}$ = 900 GeV (data taken in 2018) for a comparison with ρ measurement @ $\sqrt{s}$ = 546 GeV in $p\bar{p}$



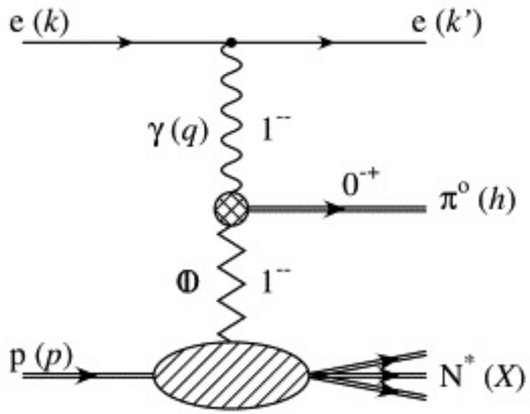
- ρ & σ_{tot} measurements @ $\sqrt{s}$ = 14 TeV (data to be taken in 2022)
- Odderon searches in exclusive meson production

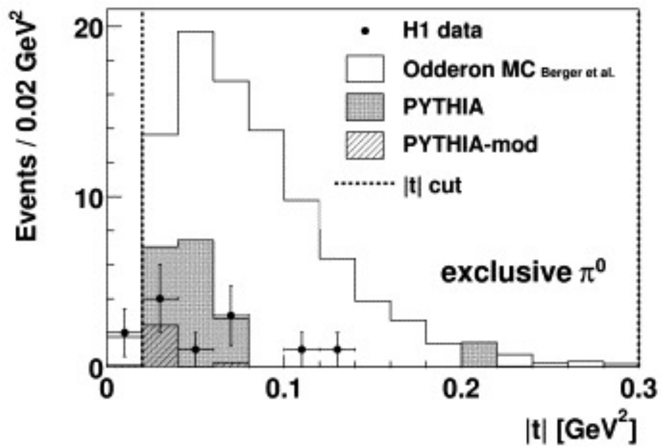
Backup

Other 3g t-channel manifestations

Contribution to (large p_T) exclusive meson production (vs γ)

Exclusive pseudoscalar meson production at HERA

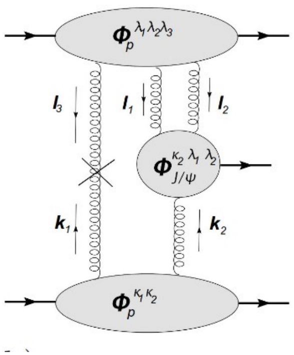




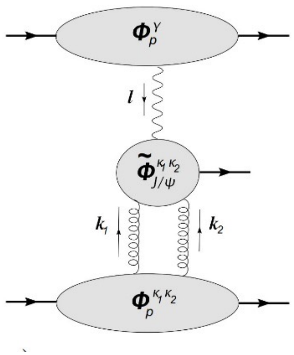
H1 Collaboration, C. Adloff et al., Phys. Lett. B 544 (2002) 35.

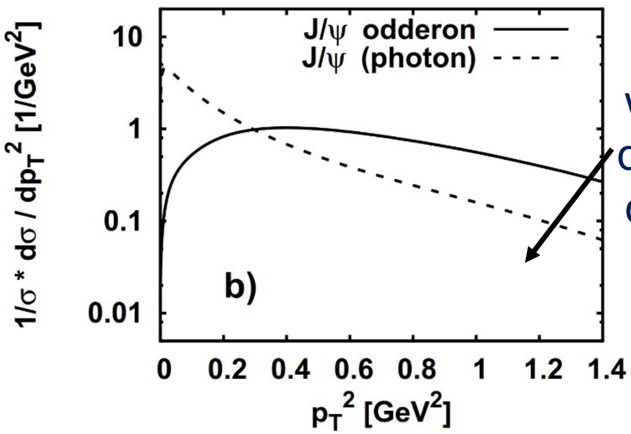
Exclusive vector meson production at hadron colliders (in competation with γ & Pomeron + p dissociation)

Odderon-Pomeron



γ-Pomeron



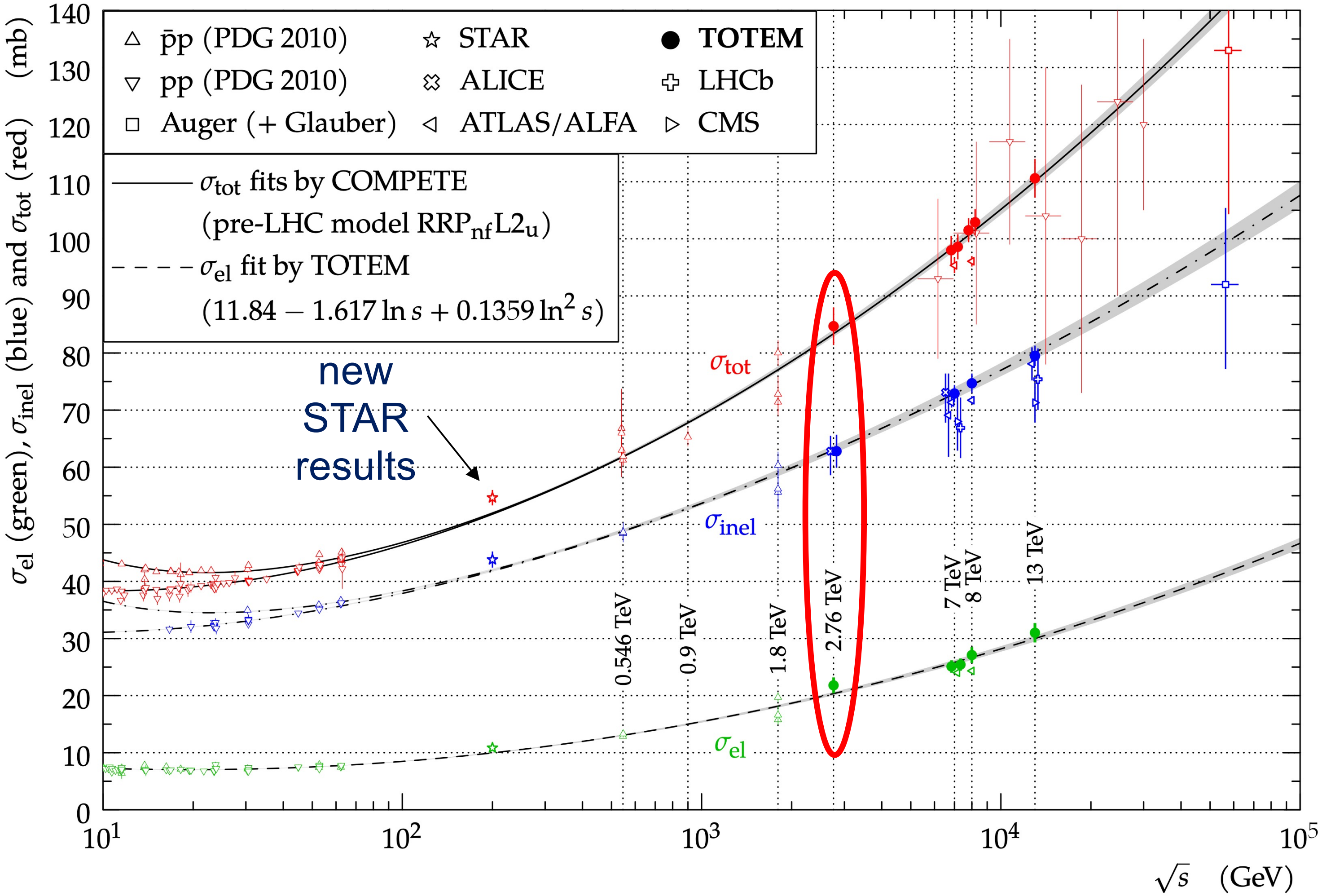


Pomeron with proton dissociation contributes here

L. Motyka, arXiv:0808.2216

No convincing evidence of effect !

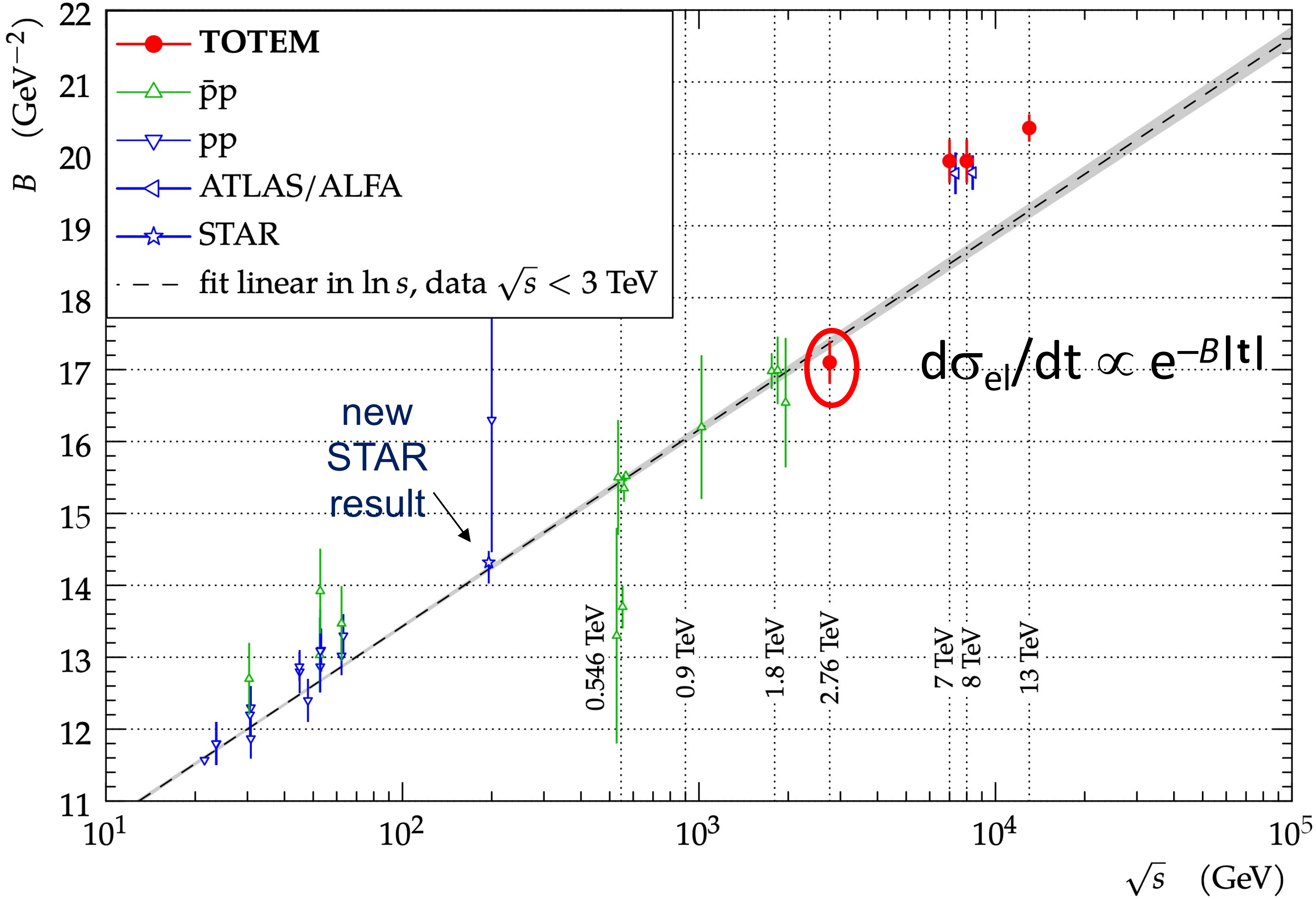
σ_{tot}, σ_{inel} & σ_{el} vs $\sqrt{s}$



TOTEM @ $\sqrt{s}$ = 2.76 TeV (ρ = 0.145): σ_{tot} = 84.7 ± 3.3 mb,

σ_{inel} = 62.8 ± 2.9 mb & σ_{el} = 21.8 ± 1.4 mb

B slope vs $\sqrt{s}$



TOTEM @ $\sqrt{s}$ = 2.76 TeV: $B = 17.1 \pm 0.3$ GeV^{-2}