TOTEM experiment: Pomeron and Odderon exchange at LHC energies

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on behalf the **TOTEM collaboration**

Forward Physics and QCD at the LHC and the EIC

25.10.2023

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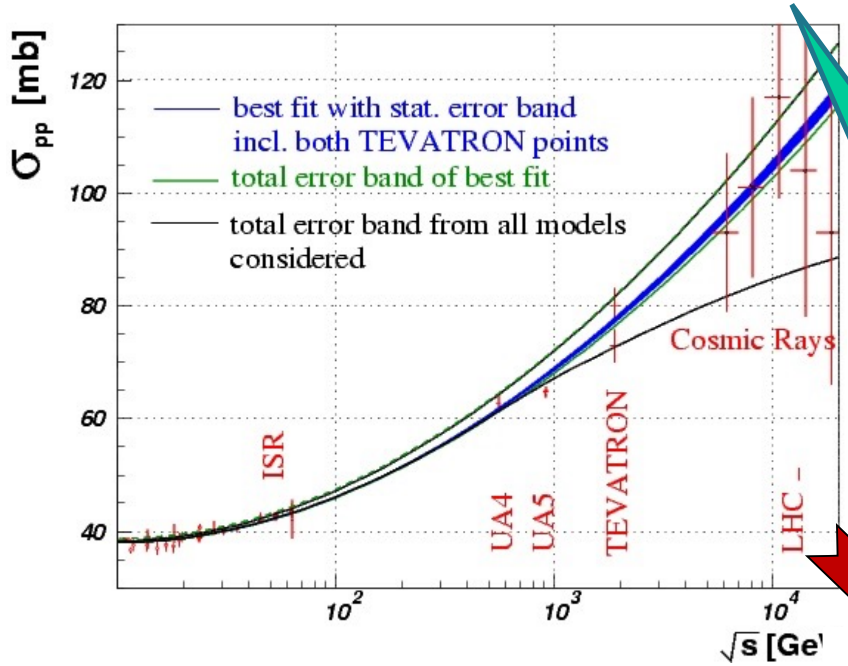
Outline:

- ✓ Introduction: TOTEM experiment / Pomeron & Odderon
- ✓ Elastic scattering: trends & $pp - p\overline{p}$ comparison
- ✓ Total cross section: trends & comparisons
- ✓ Measurement of ρ & Odderon
- ✓ Central exclusive production & Pomeron studies

TOTEM physics menu

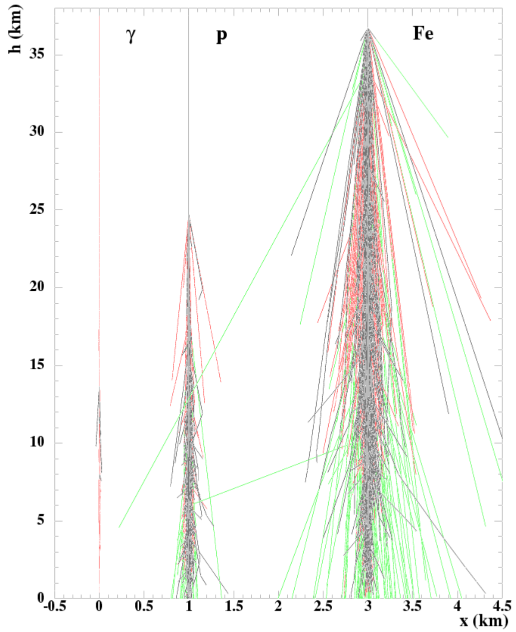
Total pp cross-section

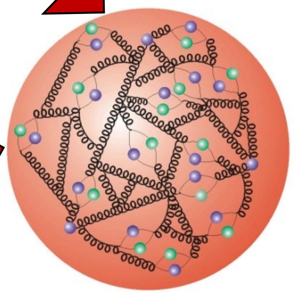


Ultimately few % precision

Forward particle production

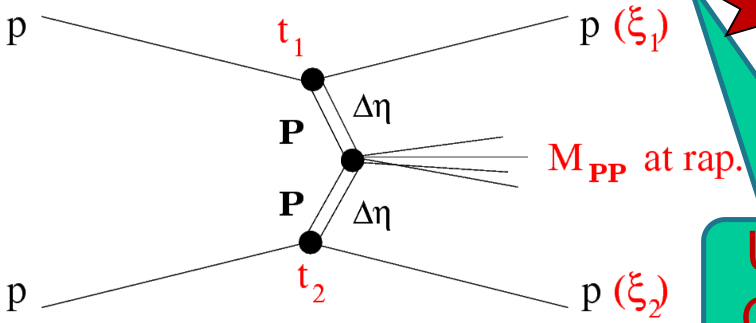
Cosmic ray connection





Proton

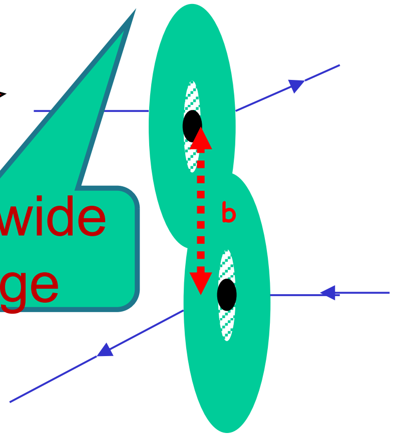
Diffraction: soft and hard



Understand QCD nature

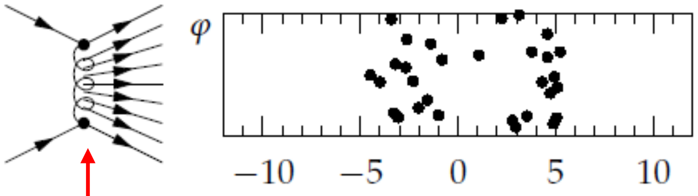
Elastic pp scattering

Over a wide |*t*| range



Classification of soft *pp* collisions

Non-Diffractive process (ND) $\approx$ 60 mb @ $\sqrt{s}$ = 7 – 8 TeV



$$\eta = -\ln\tan\frac{\theta}{2}$$

Non-diffractive

Colour exchange

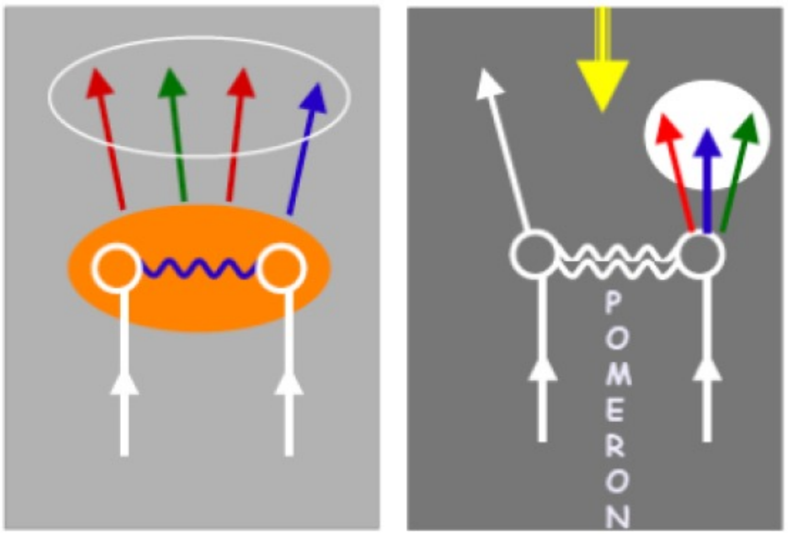
dN / dΔη = exp (-Δη)

Diffractive

Colourless exchange with vacuum quantum numbers

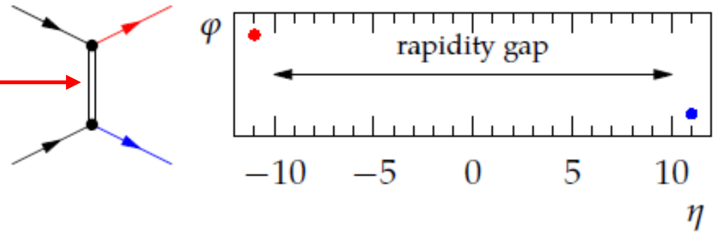
dN / dΔη = const

rapidity gap

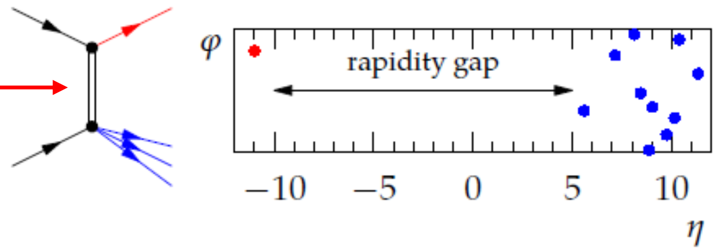


Incident hadrons retain their quantum numbers remaining colourless

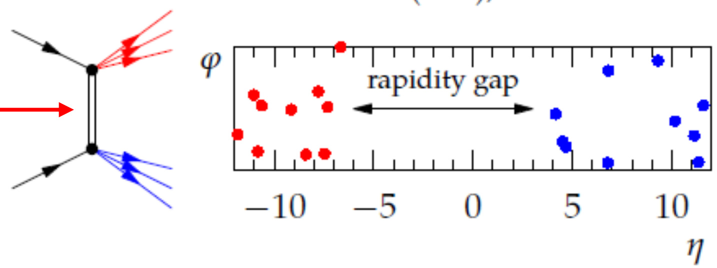
Elastic Scattering (ES), $\approx$ 25 mb



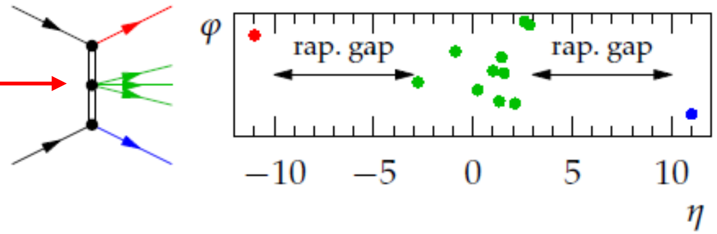
Single Diffraction (SD), $\approx$ 10 mb



Double Diffraction (DD), $\approx$ 5 mb



Central Diffraction (CD), $\approx$ 1 mb



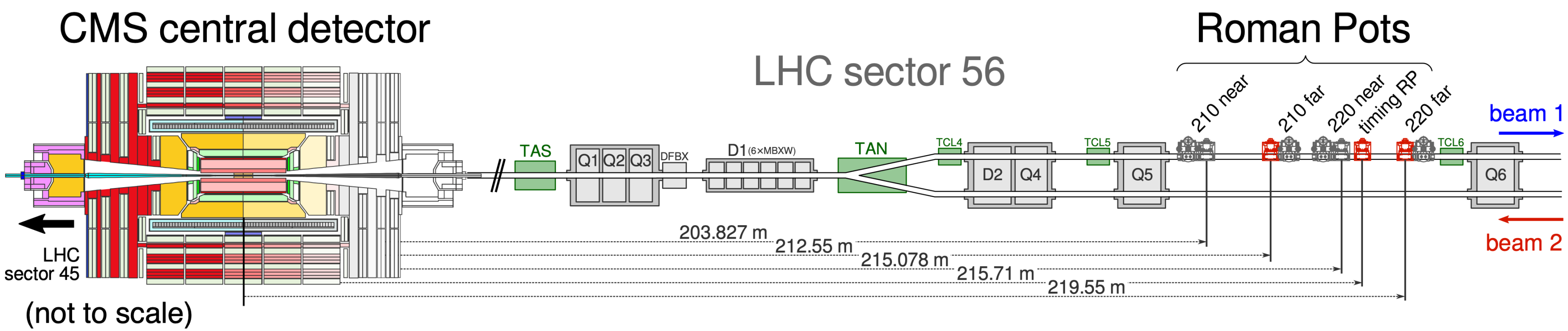
Measure topologies and cross sections:
Substantial fraction of particle and energy flow goes forward; often surviving protons.

TOTEM physics programme

- ✓ **Dedicated special optics runs: TOTEM forward physics experiment**
  - special high /very high β* optics to access leading protons with Romans Pots (RP) at small / very small scattering angles (~μrad)
  - total & elastic cross-section, low & medium mass (m ~ 0.3-100 GeV) exclusive & diffractive processes (together with CMS)
  - common data taking with CMS to be able to reconstruct central system

- ✓ **High luminosity: (CMS-TOTEM) Precision Proton Spectrometer (PPS)**
  - continuous data taking as integral part of CMS; **since 2018 fully CMS**
  - high mass exclusive processes (m > ~350 GeV) & BSM searches

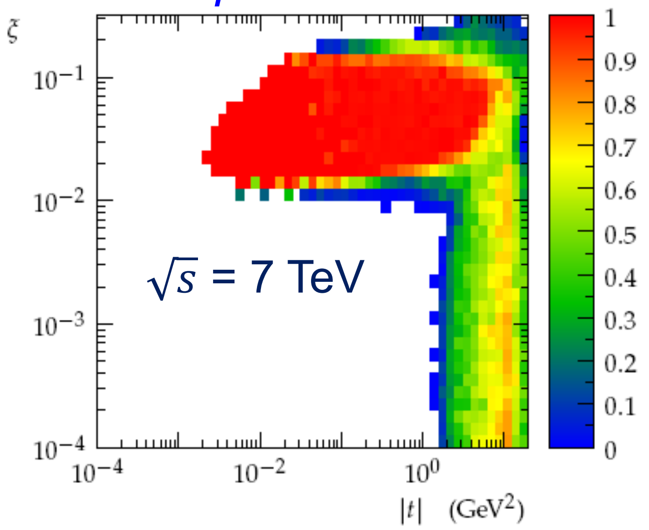
see talk by Andrea Bellora



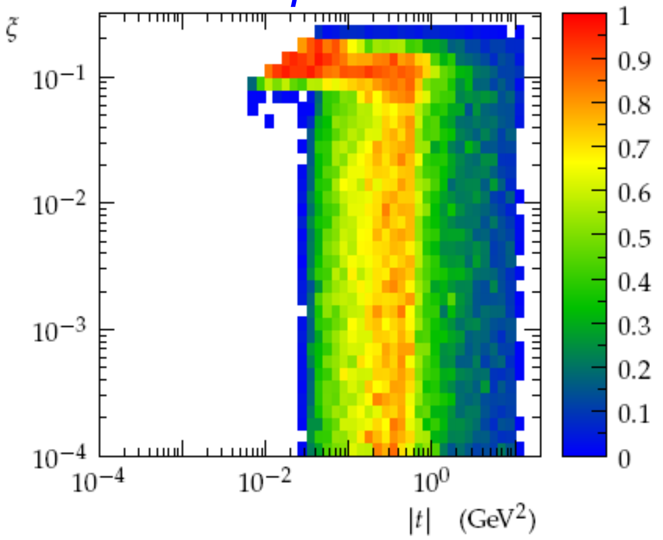
LHC optics & proton acceptance

$t \approx -p^2\theta^2$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

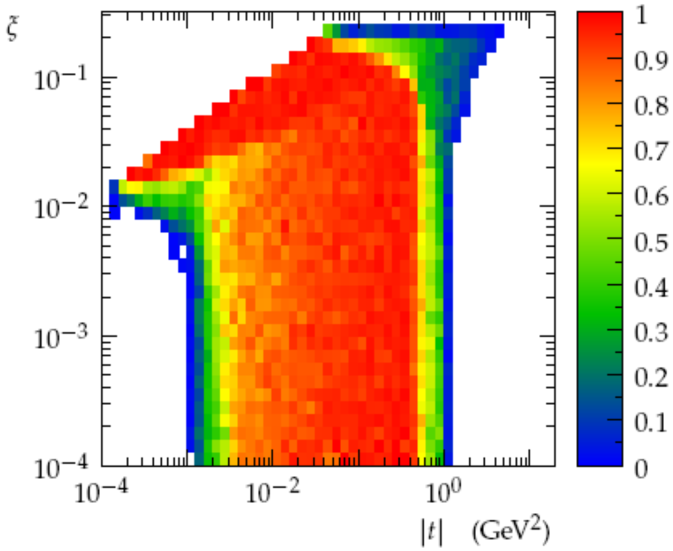
β^*= 0.55 m



β^*= 90 m



β^*= 1 km



$> 10^{33}$ cm^{-2} s^{-1} ← $\mathcal{L} \propto 1/\beta^*$ → $\sim 10^{27}$ cm^{-2} s^{-1}

High mass central exclusive production & diffraction: $\xi > \sim 0.03$, low cross-section processes → high luminosity (PPS)

Low mass central exclusive production & diffraction: all ξ if |t| > $\sim 10^{-2}$ GeV^{2}, Elastic scattering: low-mid|t| Total cross section (TOTEM, CMS-TOTEM)

Elastic scattering: very low |t|, Coulomb-Nuclear Interference (CNI) Total cross section (TOTEM only)

TOTEM experiment @ LHC

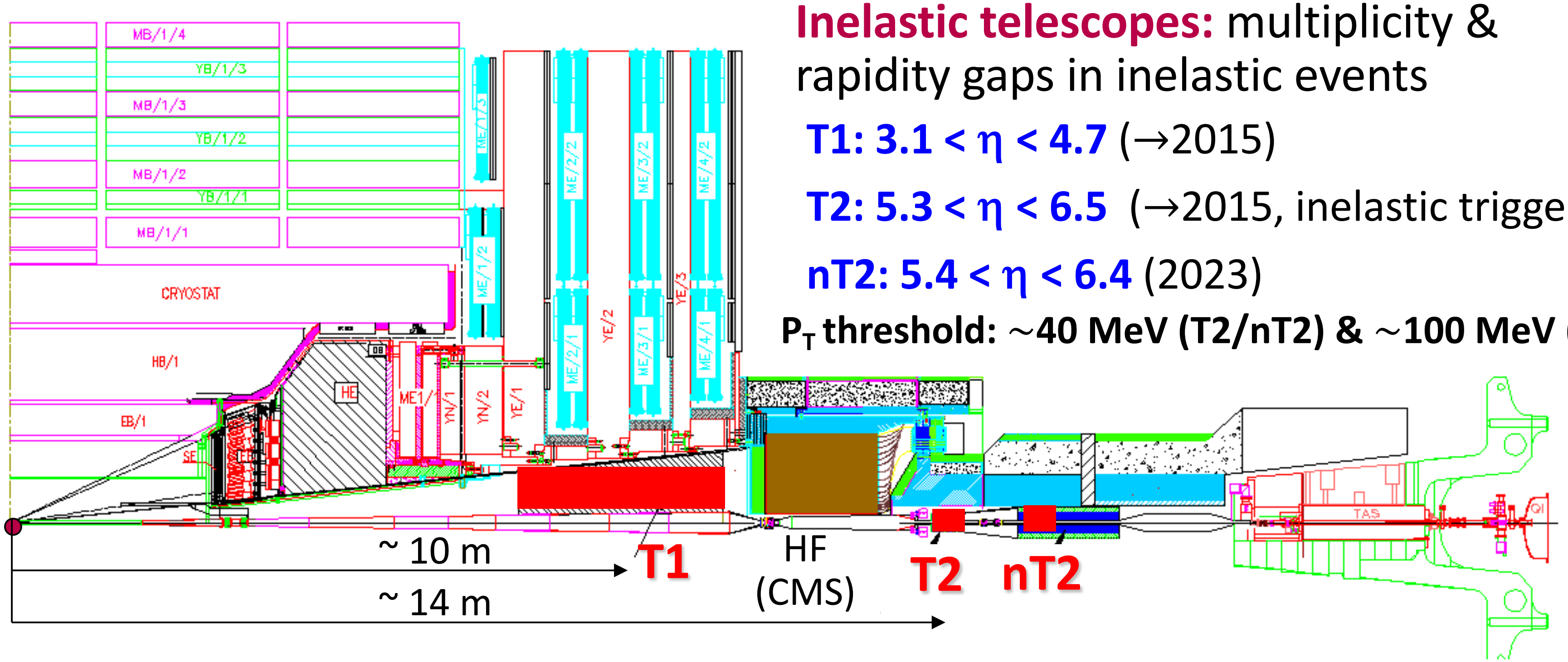
Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

T1: $3.1 < \eta < 4.7$ (→2015)

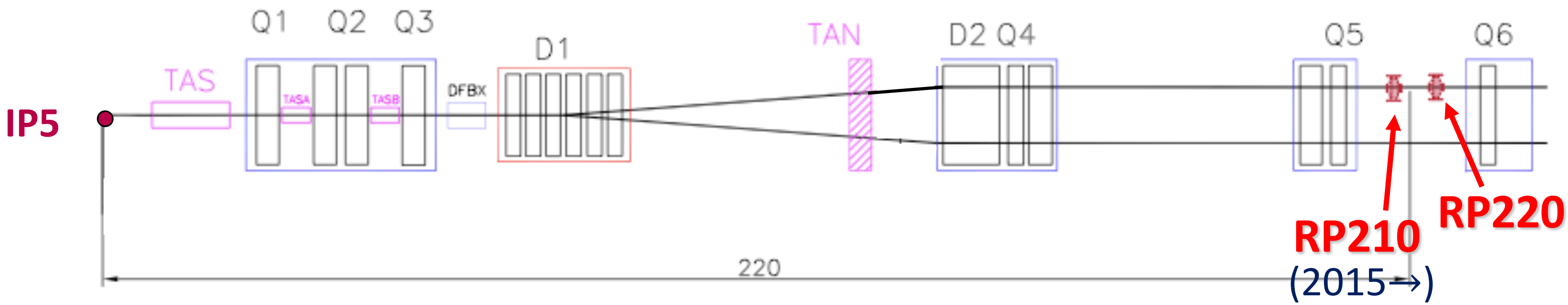
T2: $5.3 < \eta < 6.5$ (→2015, inelastic trigger)

nT2: $5.4 < \eta < 6.4$ (2023)

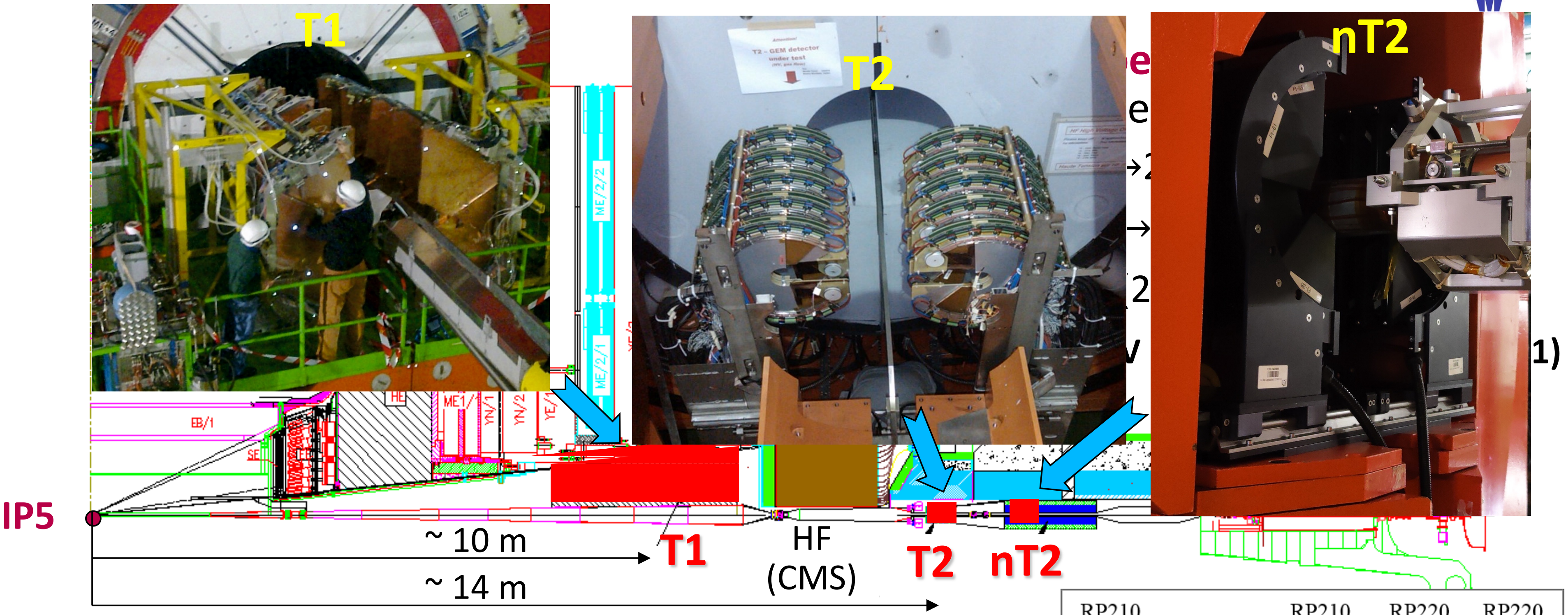
P_T threshold: ~40 MeV (T2/nT2) & ~100 MeV (T1)



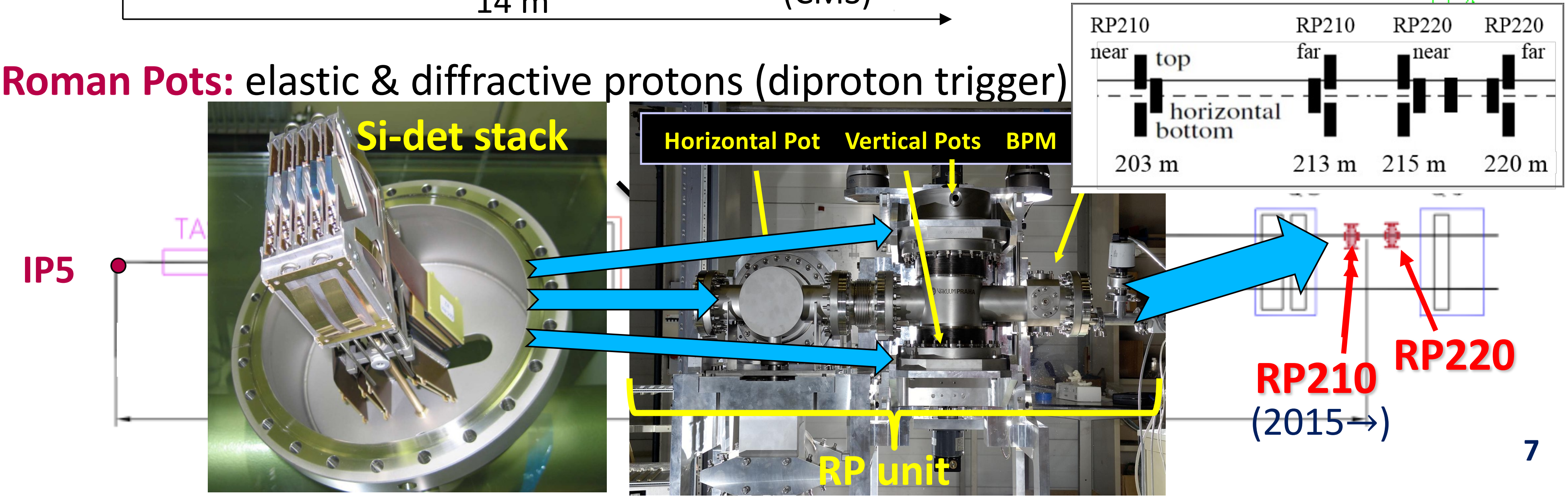
Roman Pots: elastic & diffractive protons (diproton trigger)



TOTEM experiment @ LHC



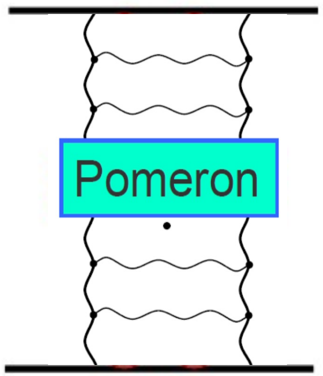
Roman Pots: elastic & diffractive protons (diproton trigger)



Elastic scattering: multi-gluon exchanges

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

C- even

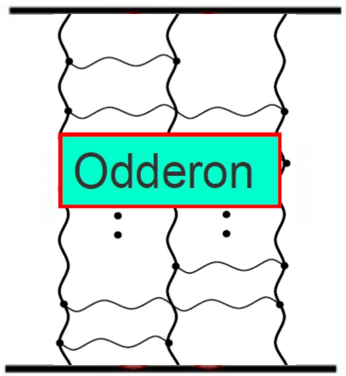


dominates at low |t|,

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

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

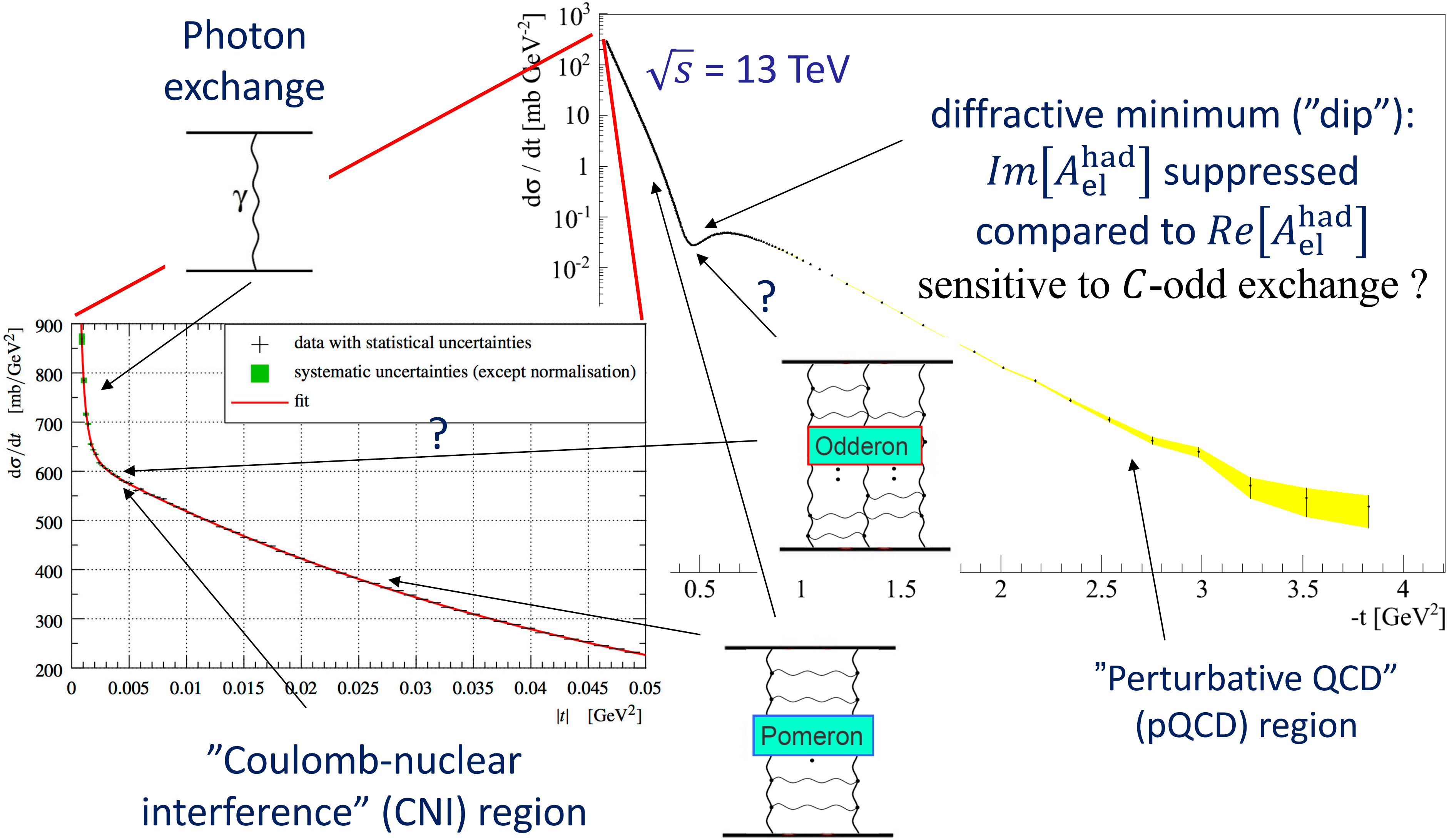
  L. Lukaszuk & B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405

- ✓ 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

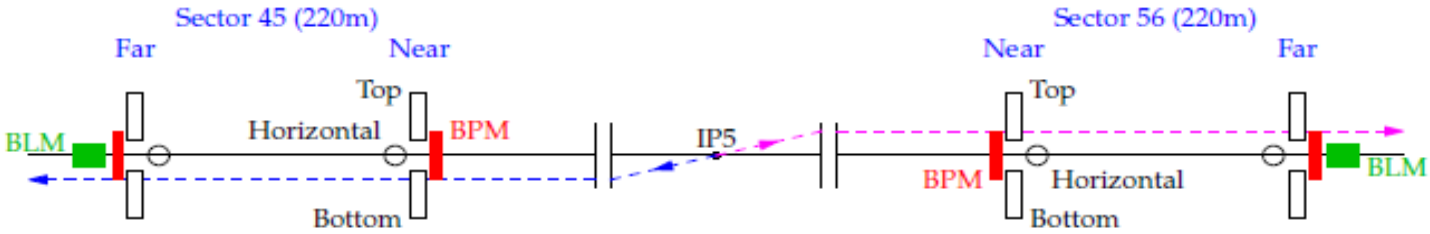


$$\rho \equiv Re\left[A_{el}^{had}\right]/Im\left[A_{el}^{had}\right]\Big|_{t=0}$$

sensitive to C-odd exchange ?

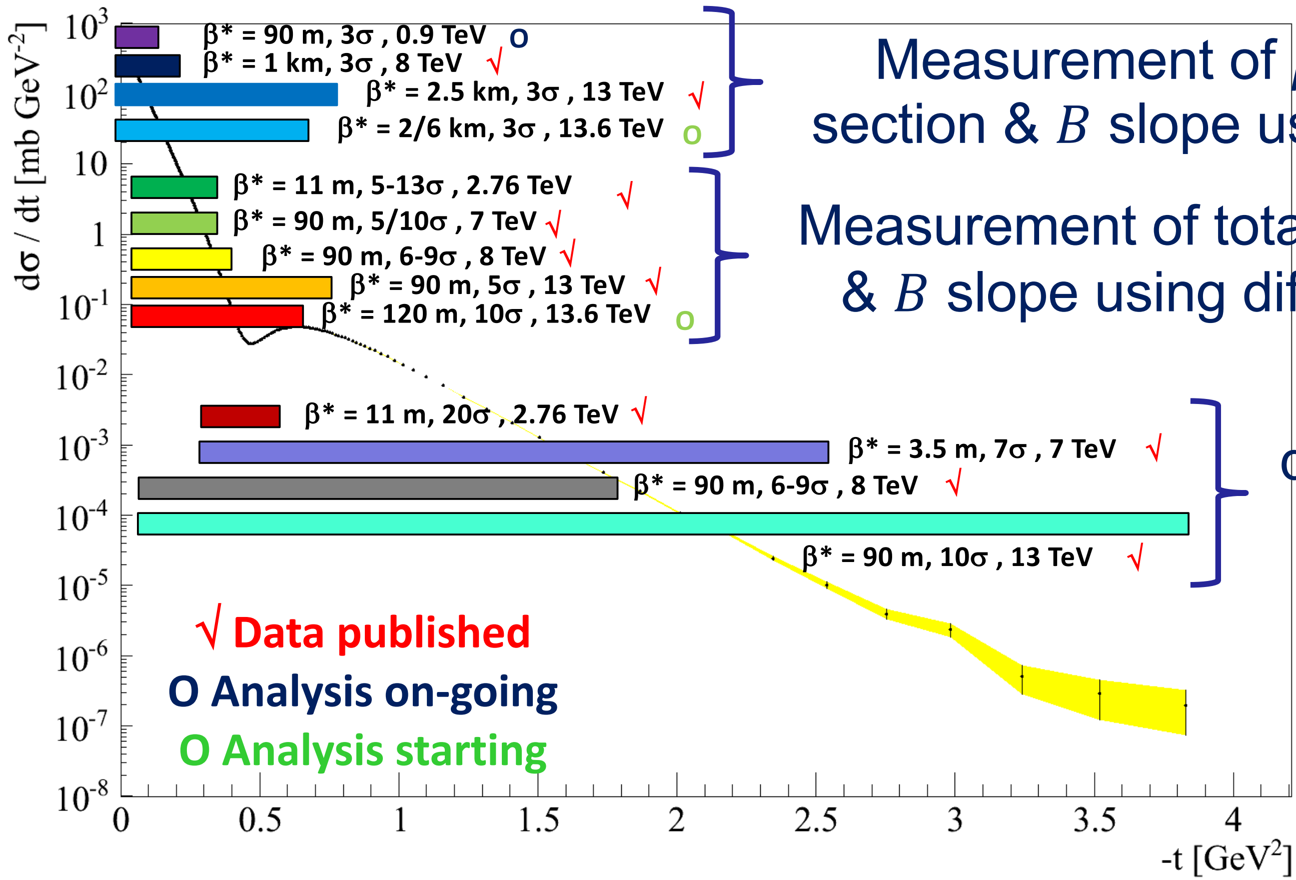
Elastic *pp* scattering: selection & data sets

Selected based on topology, low |ξ|, anti-collinearity & vertex



Key issues: RP alignment & beam optics

Data sets at different conditions to measure over as wide |t|-range as possible



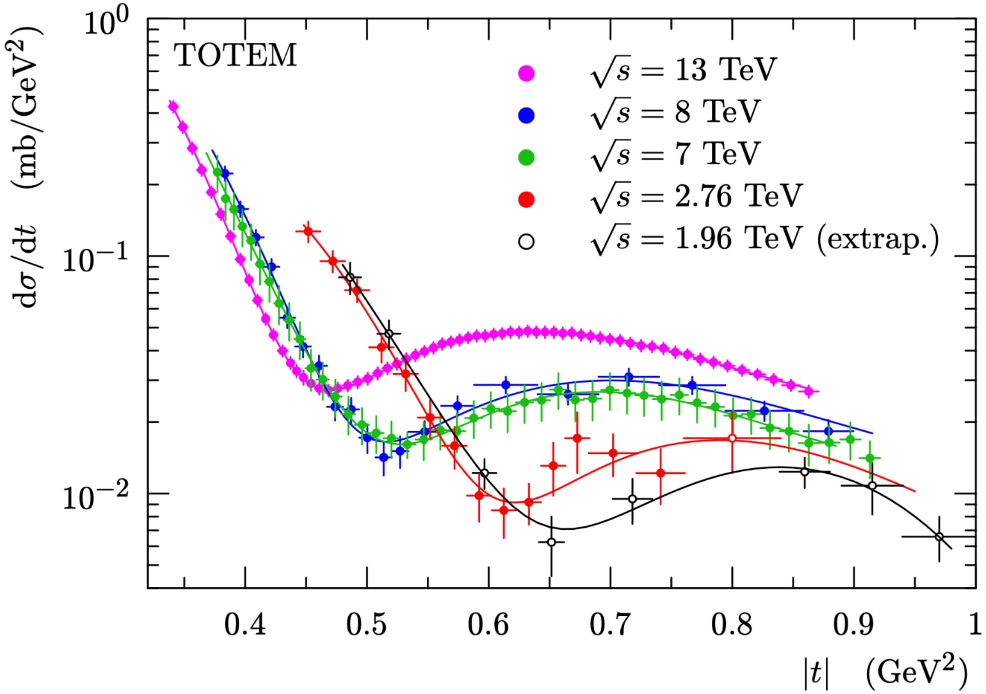
Measurement of ρ, total cross section & B slope using CNI region

Measurement of total cross section & B slope using diffractive cone

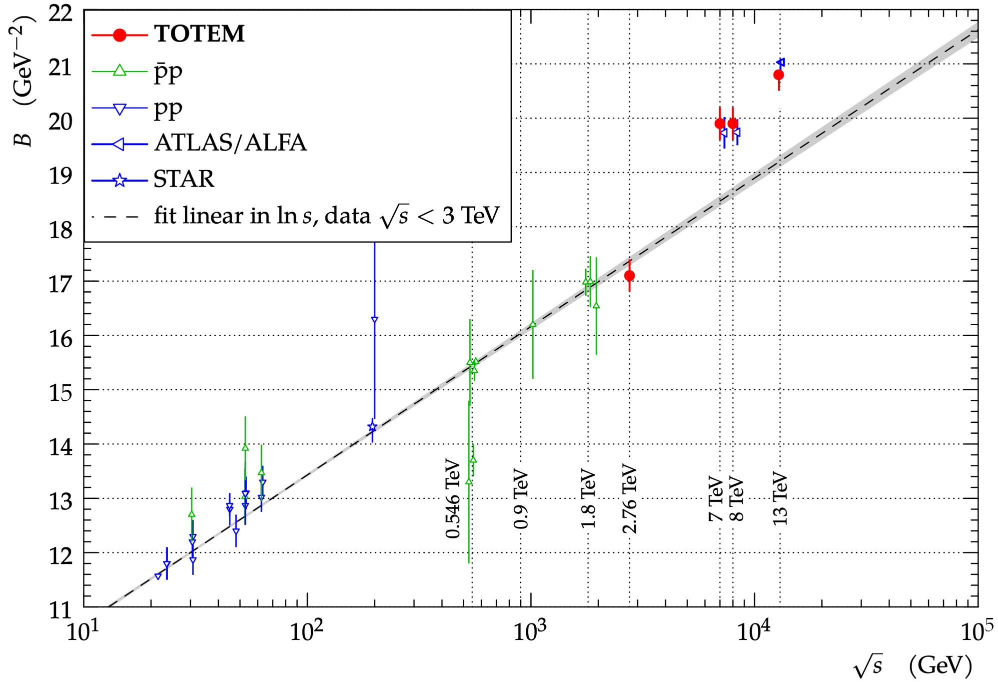
Measurement of diffractive minimum & secondary maximum

Elastic pp scattering: trends

|t|-value of dip position decreases with increasing $\sqrt{s}$



diffractive slope parameter $B = \frac{d}{dt}\ln(\frac{d\sigma}{dt}\Big|_{t=0})$ increase with $\sqrt{s}$



Even if method (CNI sensitivity or not, B polynomial) & |t| range differences give some variation of B-value, a clear trend can be observed

$B \propto \ln s \rightarrow \ln^2 s$ @ LHC: larger impact from contribution of multi-Pomeron exchanges

V. A. Schegelsky and M. G. Ryskin, PRD 85 (2012) 094024

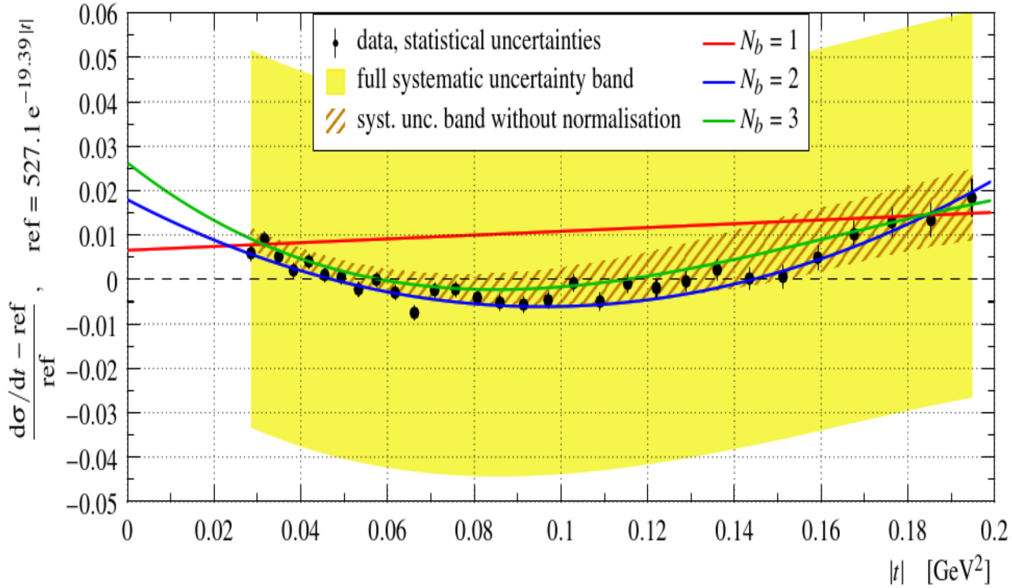
Elastic *pp* scattering: non-single-exponentiality

- Diffractive cone looks almost "perfectly single exponential"
  magnify possible deviations $\Rightarrow$ $(d\sigma_{el}/dt$ – ref. exp.)/ref. exp.

Pure (constant B) exponential slope excluded with > 7σ @ $\sqrt{s}$ = 8 TeV
TOTEM collaboration, NPB 899 (2015) 527

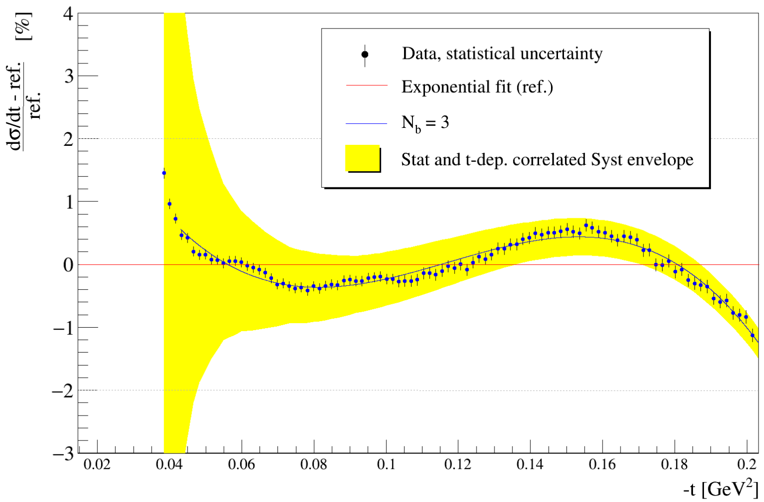
Can only be due to hadronic amplitude having a non-purely exponential slope

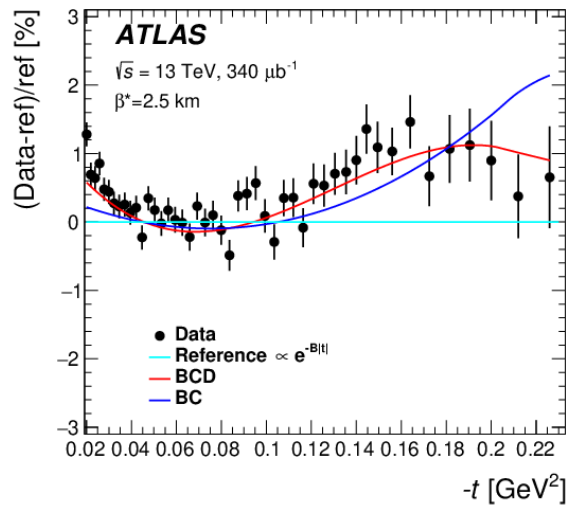
Not only one single hadronic elastic pp scattering diagram $\Rightarrow$ multiple exchange channels exists



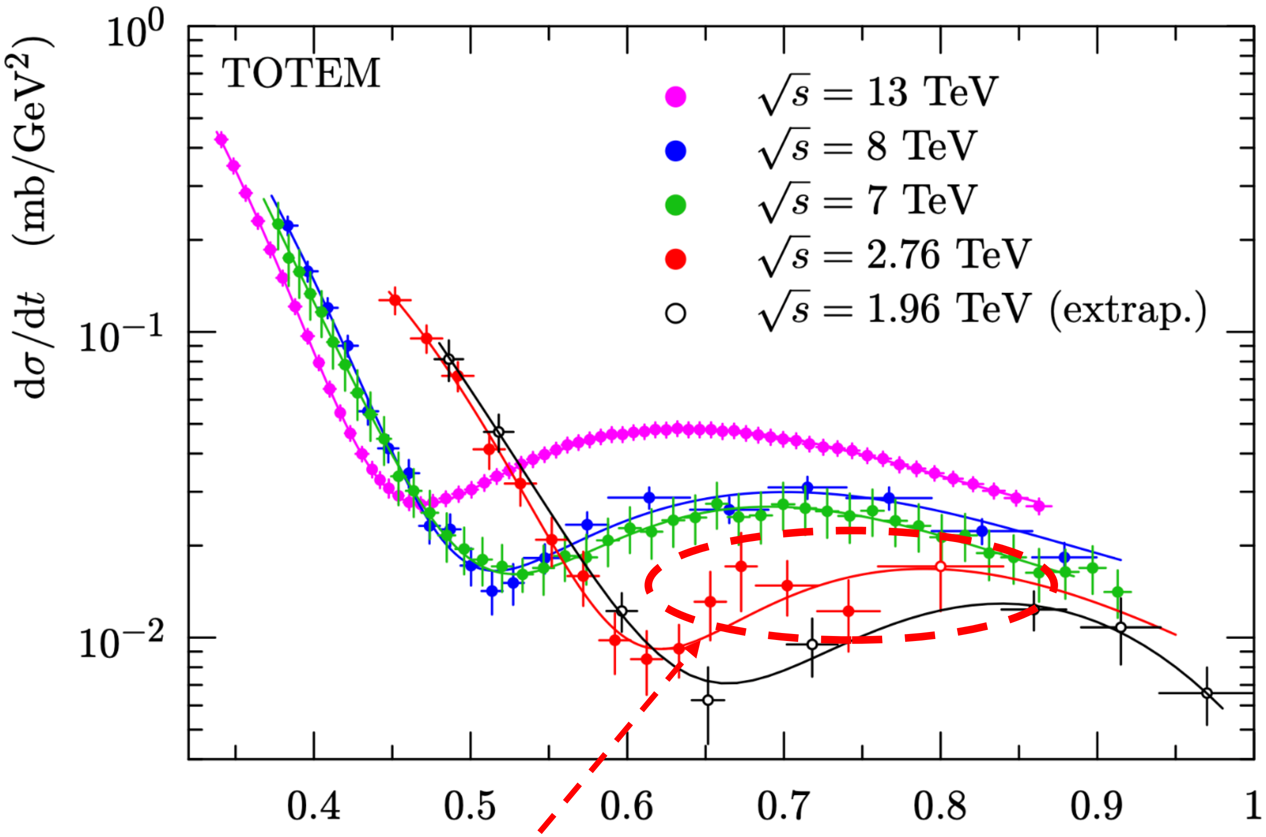
Similar effect observed also at 13 TeV; at 13 TeV also adopted by ATLAS

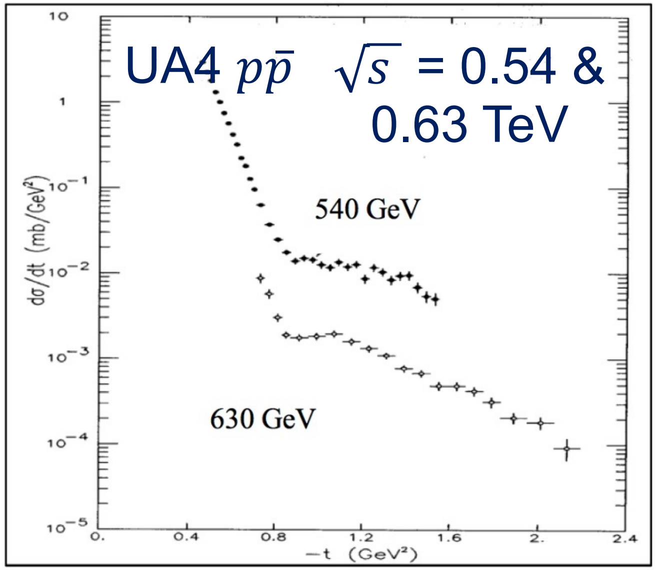
A.D. Martin, V.A. Khoze, M.G. Ryskin, JPG 42 (2015) 025003; D.A. Fagundes et al., IJMPA 31 (2016) 1645022



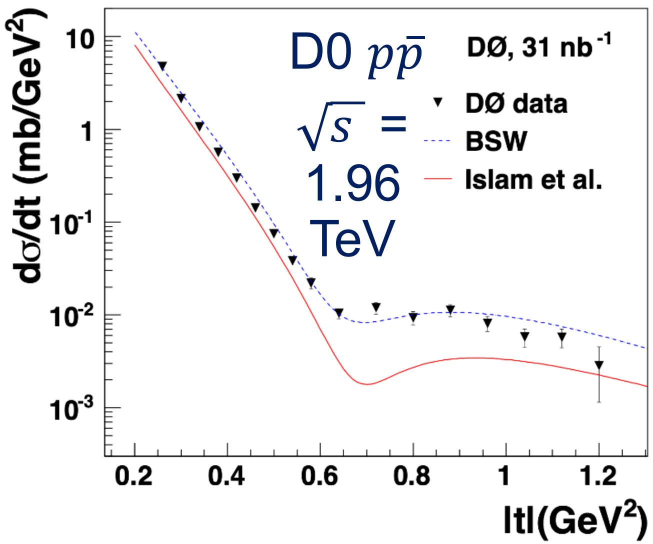


$d\sigma_{el}/dt$ measurements in $pp/p\bar{p}$





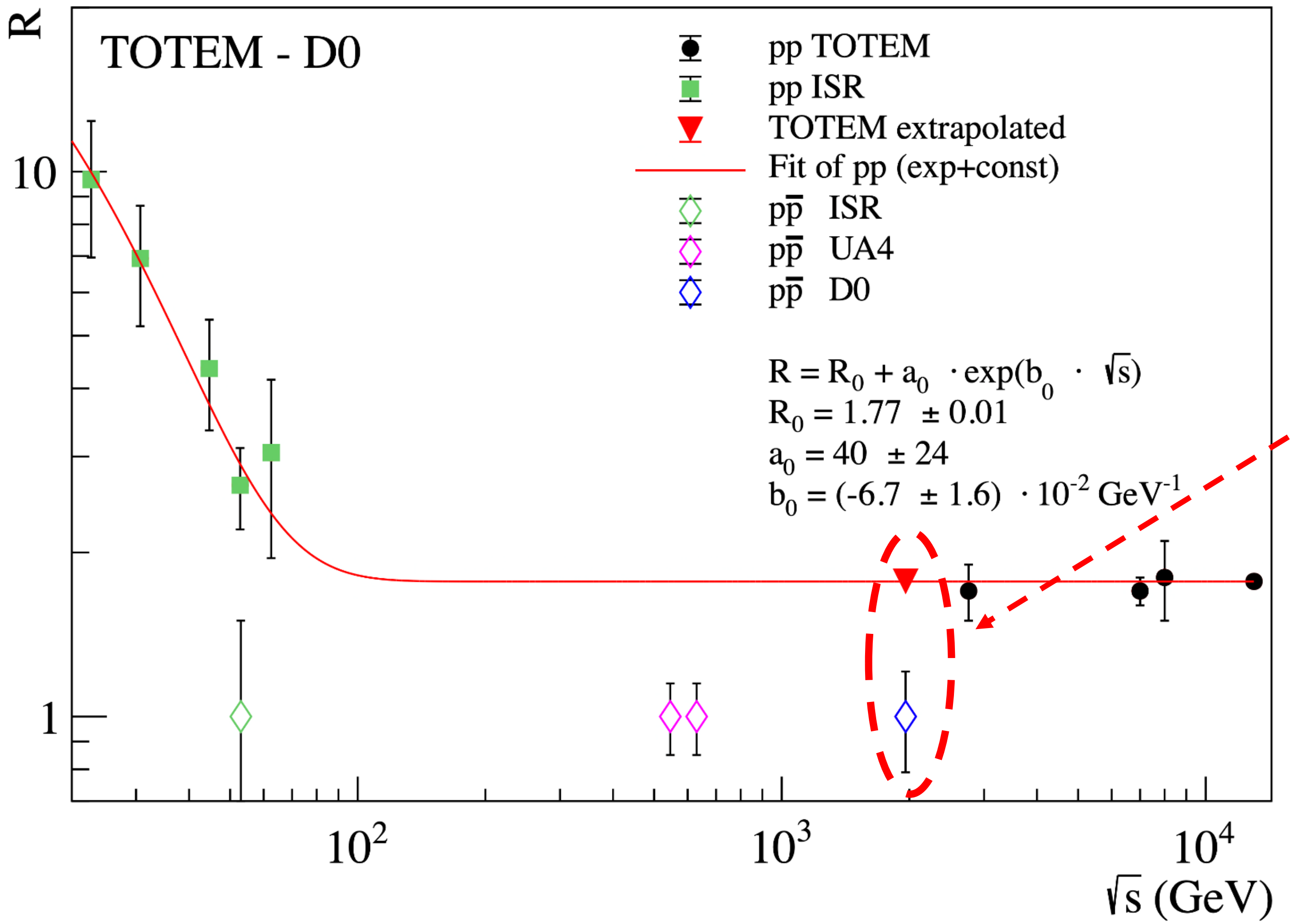
NB! acceptance cutoff @ $\sqrt{s}$ = 2.76 TeV ⇒ $|t|$ (GeV^2)
bump NOT expt'ly visible (open circles extrapolations)



- ✓ Diffractive minimum ("dip") & secondary maximum ("bump") clearly observable in pp (contrary to $p\bar{p}$)
- ✓ pp $d\sigma_{el}/dt$ 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

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

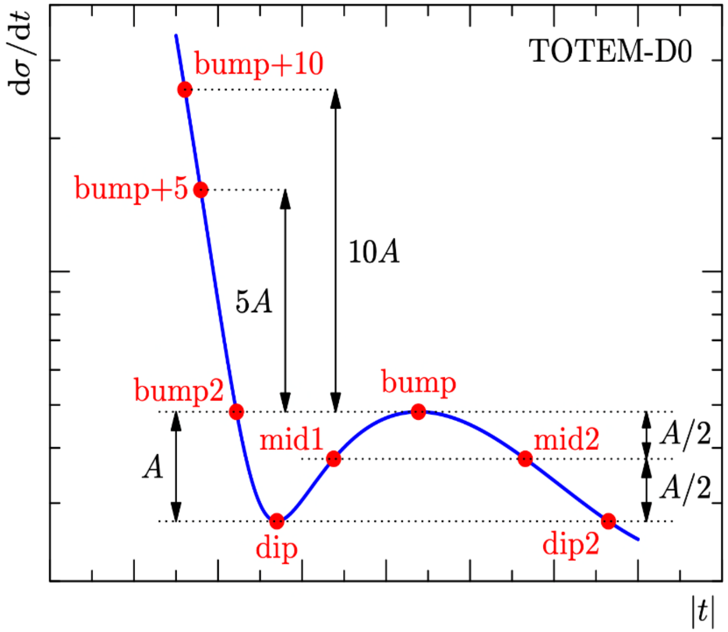


> 3σ difference between pp & $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV (assuming flat behaviour above $\sqrt{s} \sim$ 100 GeV)

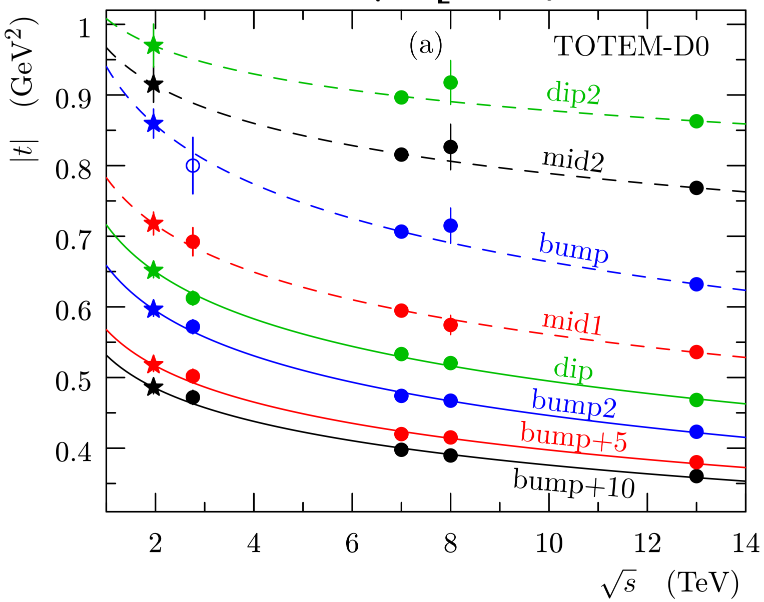
For $p\bar{p}$ R estimate, use t-bins close to expected pp bump & dip position

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

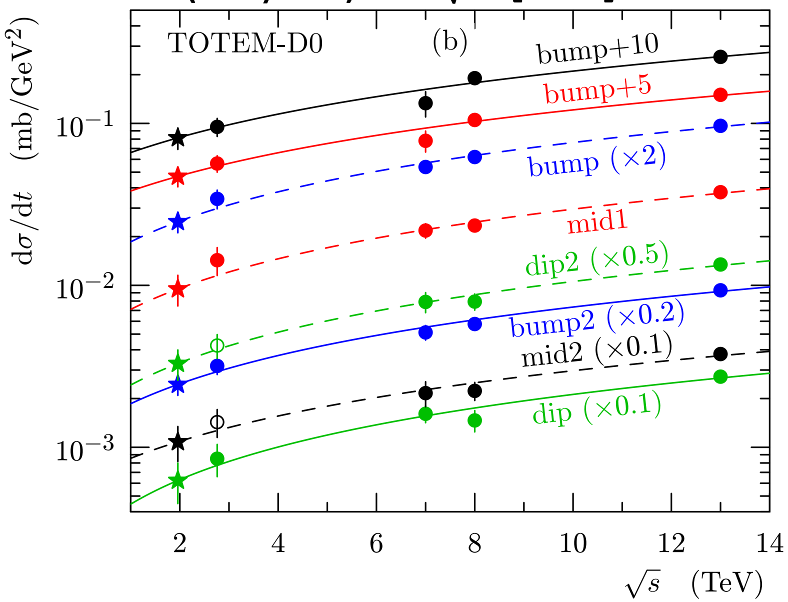
- Short (~8 % of fit range) extrapolation of the **8 characteristic $pp\ d\sigma_{el}/dt$ points** to $\sqrt{s}$ = 1.96 TeV.
- **Interpolation of $pp\ d\sigma_{el}/dt$ characteristic points using $h(t)$** (see slide 13) allows comparison with D0 measured $p\bar{p}\ d\sigma_{el}/dt$.
- 1.96 TeV $pp\ d\sigma_{el}/dt$ normalized by assuming $p\bar{p}$ optical point (OP) equal to pp extracted from $\boldsymbol{\sigma_{tot}^{pp}}$ **extrapolation** to $\sqrt{s}$ = 1.96 TeV using TOTEM σ_{tot}^{pp} measurement & σ_{tot} = e ln$^2\sqrt{s}$ ([TeV]) $+f$



$t = a\ln\sqrt{s}$ [TeV]) + b



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



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

- Due to interpolation, extrapolated $pp\ d\sigma_{el}/dt$ values at neighbouring D0 |t|-values strongly correlated $\Longrightarrow$ full covariance matrix $C_{i,j}$ must be included in χ^2

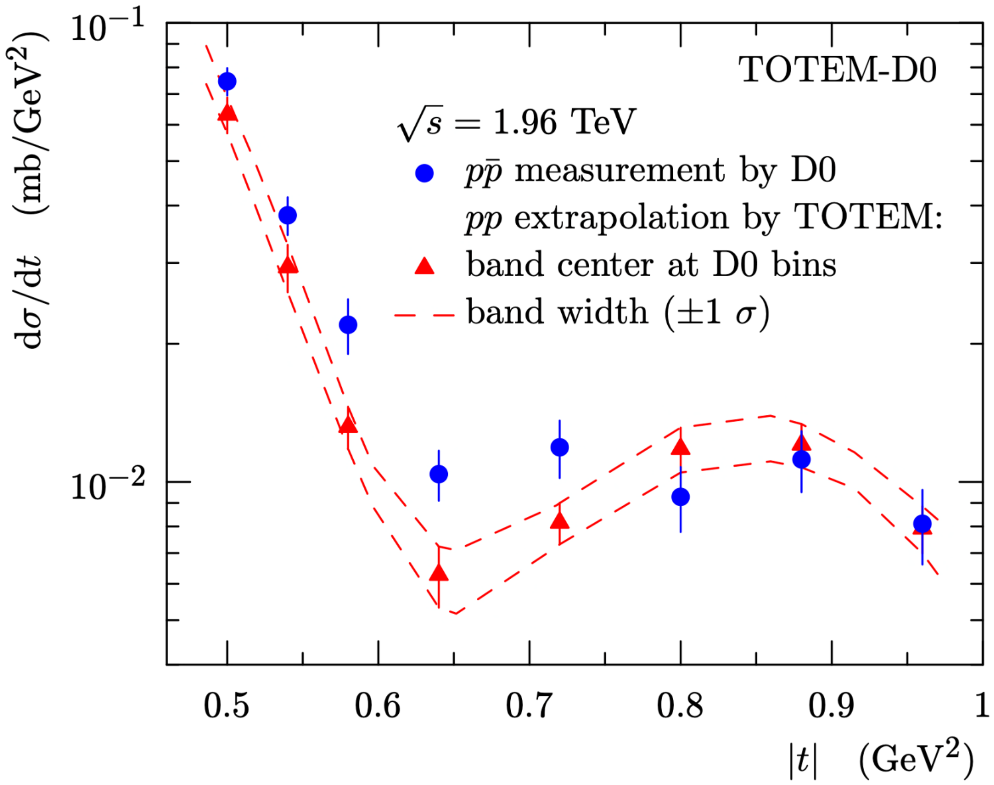
$$\chi^2 = \sum_{\text{points } i,j} \left\{ \left(\frac{d\sigma^{pp}_{el,i}}{dt} - \frac{d\sigma^{p\bar{p}}_{el,i}}{dt} \right) C^{-1}_{i,j} \left(\frac{d\sigma^{pp}_{el,j}}{dt} - \frac{d\sigma^{p\bar{p}}_{el,j}}{dt} \right) \right\} + \frac{(A - A_0)^2}{\sigma_A^2} + \frac{(B - B_0)^2}{\sigma_B^2}$$

- ✓ 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)
- ✓ pp OP = $p\bar{p}$ OP valid as long as maximal possible C-odd & $pp/p\bar{p}$ ρ differences included as systematics (2.9 %).

Extrapolated TOTEM $pp\ d\sigma_{\mathrm{el}}/dt$ in dip-bump region directly compared to 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)

D0 & TOTEM Coll., PRL 127 (2021) 062003



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
- ✓ Improved estimate of $\sigma_{tot}^{pp}(\sqrt{s}$ = 1.96 TeV) using *a* ln$^2\sqrt{s}$ $+ b\ln\sqrt{s} + c$

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

Preliminary

$\Longrightarrow$ a small 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

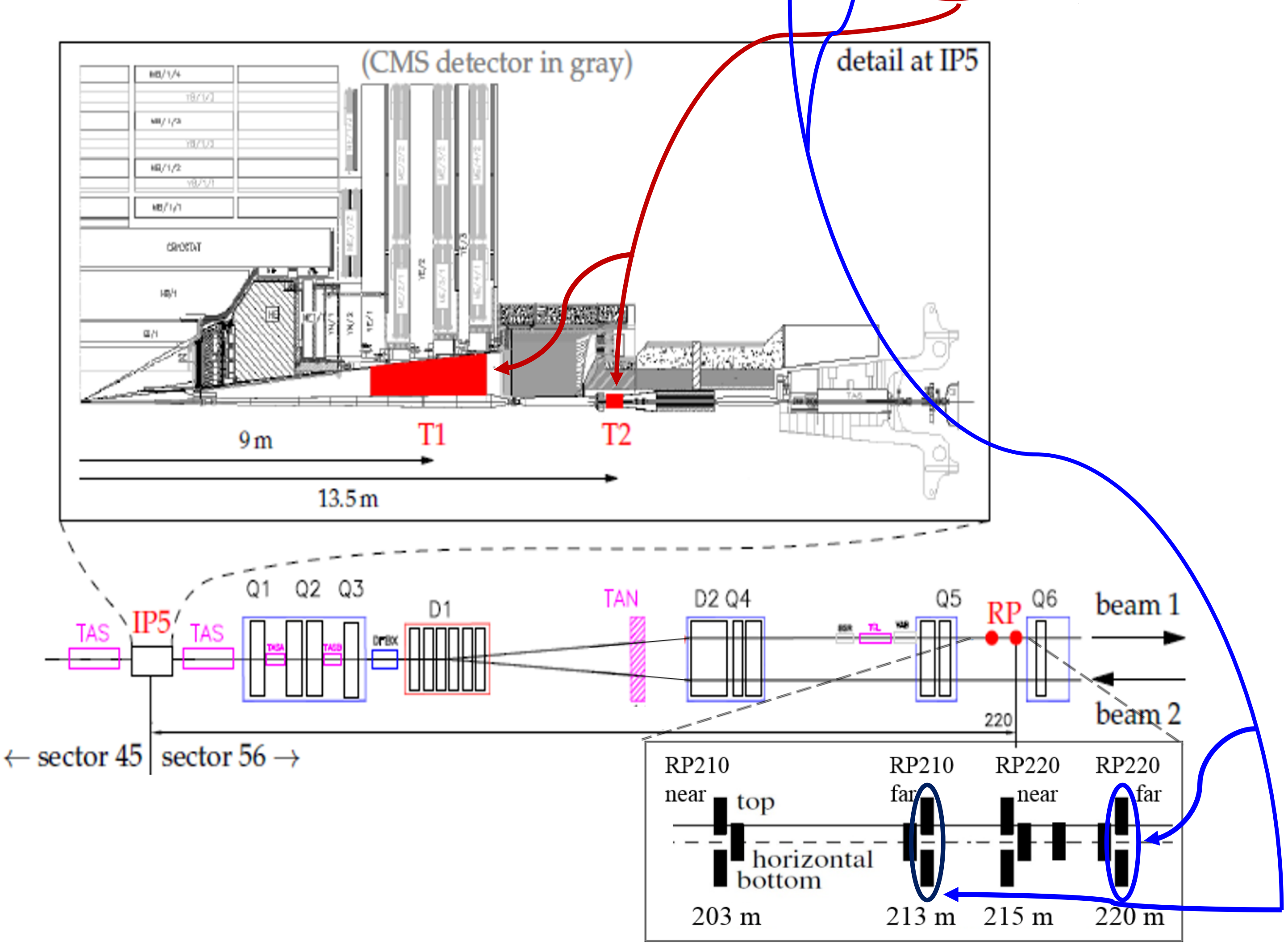
More improvements of the pp & $p\bar{p}$ comparison at $\sqrt{s}$ = 1.96 TeV to come!

Stay tuned !

Luminosity independent total cross section

Luminosity independent method:

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



Total pp cross section: methods & results

Excellent agreement between 7 TeV σ_{tot} measurements (without CNI sensitivity):

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

Using CMS $\mathcal{L} \Rightarrow$ independent of low mass diffraction

σ_{tot} = 98.3 mb $\pm$ 2.0 mb
TOTEM Coll., EPL 96 (2011) 21002

σ_{tot} = 98.6 mb $\pm$ 2.3 mb
TOTEM Coll., EPL 101 (2013) 21002

testing validity of optical theorem at ~5 % level

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

optical theorem & ρ independent

σ_{tot} = 99.1 mb $\pm$ 4.3 mb
TOTEM Coll., EPL 101 (2013) 21004

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

$\mathcal{L}$ independent

σ_{tot} = 98.1 mb $\pm$ 2.4 mb
TOTEM Coll., EPL 101 (2013) 21004

7 TeV

Excellent agreement between 13 TeV σ_{tot} measurements (with/without CNI sensitivity):

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

$\mathcal{L}$ independent

σ_{tot} = 110.6 mb $\pm$ 3.4 mb
TOTEM Coll., EPJC 79 (2019) 103

Fully independent datasets & methods:

$\sigma_{tot,comb}$ = 110.5 $\pm$ 2.4 mb

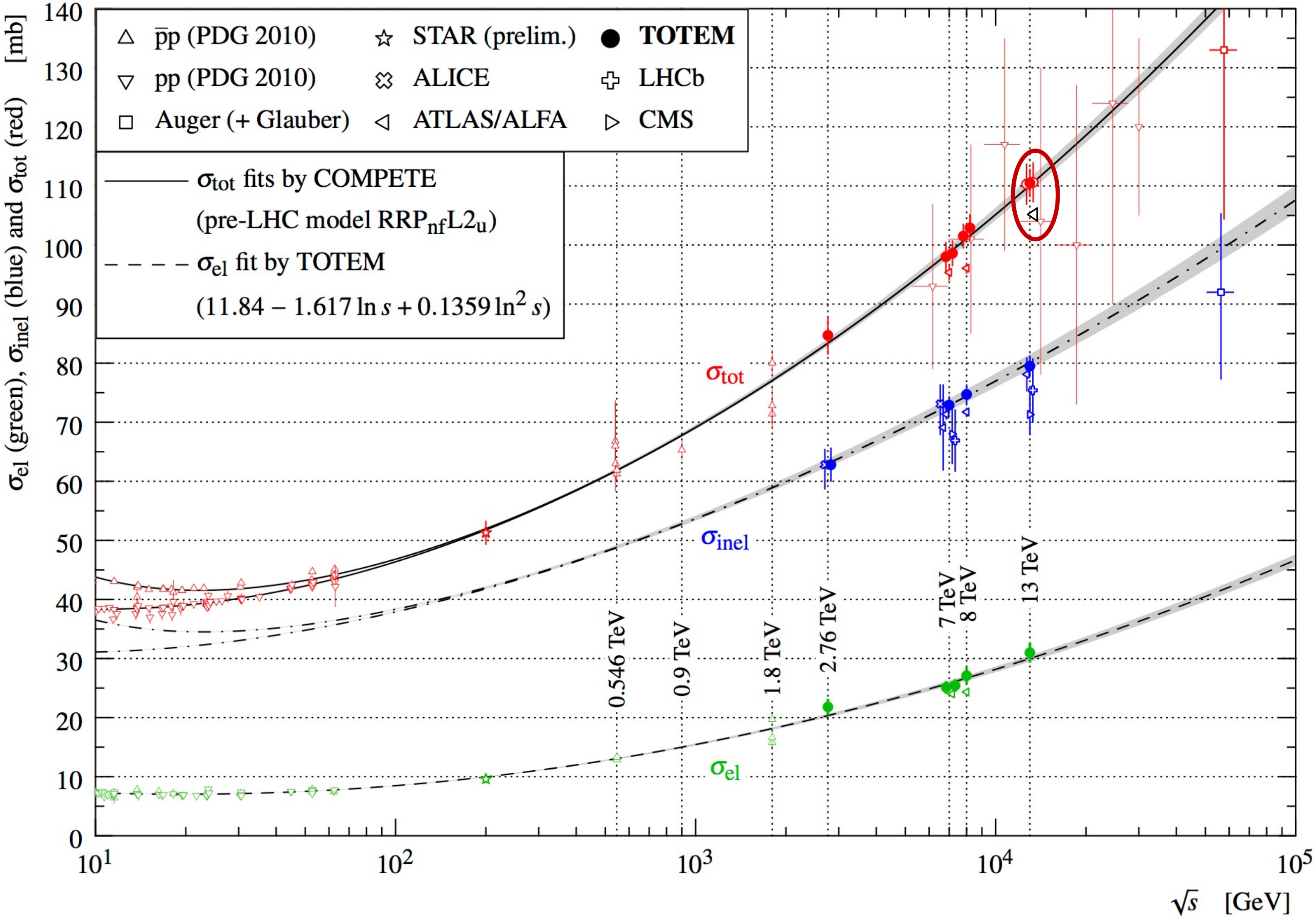
$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)}\left(\frac{d\sigma_{el}}{dt}\right)_{t=0}$$

Coulomb normalisation

σ_{tot} = 110.3 mb $\pm$ 3.5 mb
TOTEM Coll., EPJC 79 (2019) 785

13 TeV

Total *pp* cross section: summary



$\sigma_{tot} \propto \ln\sqrt{s} \rightarrow \ln^2\sqrt{s}$ @ LHC: good agreement with COMPETE preferred model

TOTEM & ATLAS σ_{tot} comparison

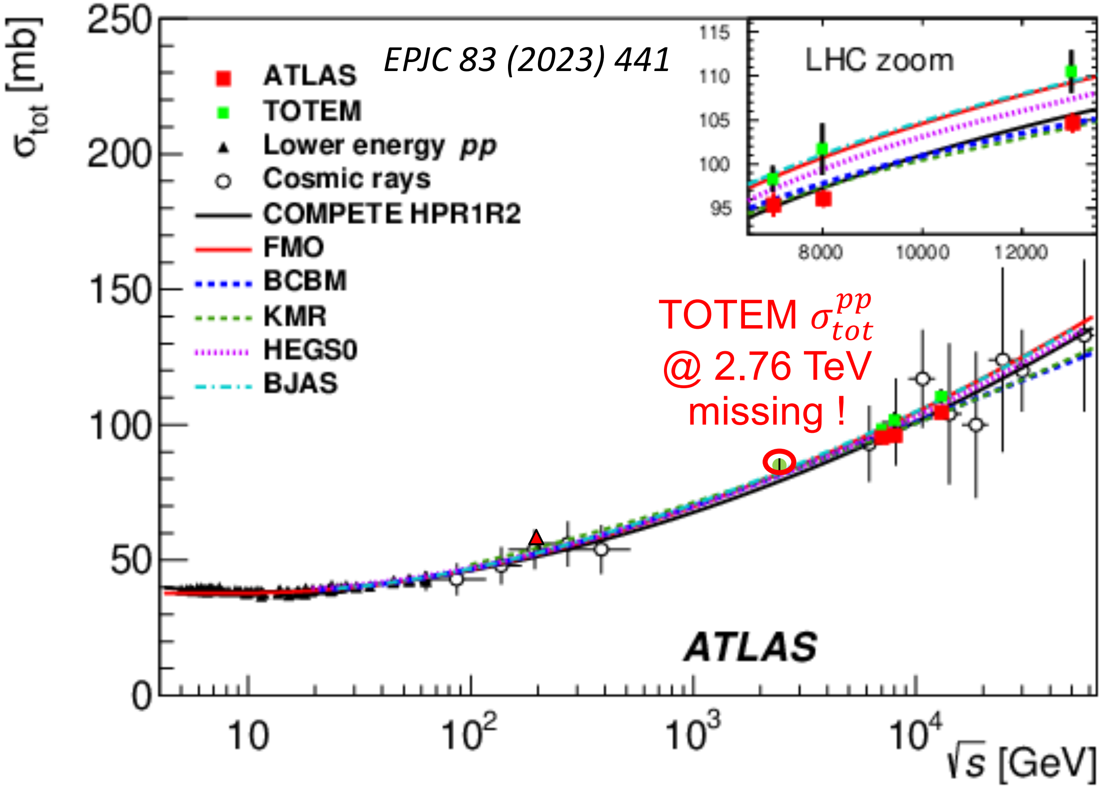
- 13 TeV TOTEM $\sigma^{pp}_{tot,comb}$ = 110.5 $\pm$ 2.4 mb combining rate counting experiment & Coulomb normalisation measurements

2.2σ difference

- 13 TeV ATLAS σ^{pp}_{tot} = 104.7 $\pm$ 1.1 mb relying on precise luminosity determination

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

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



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

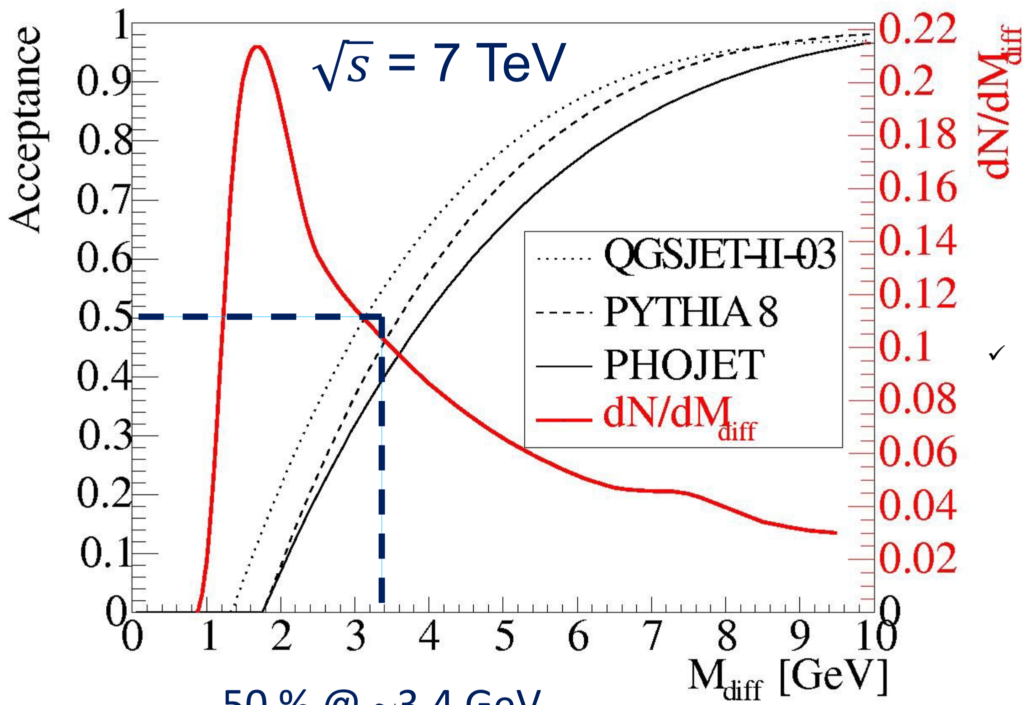
Not whole story: TOTEM has 2-4 consistent σ^{pp}_{tot} measurements using (slightly) different techniques /energy vs. 1 measurement/energy using same technique for ATLAS

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 TOTEM N_{inel}? Not likely

SD acceptance for T1+T2



50 % @ ~3.4 GeV

TOTEM@7 TeV:

$\sigma_{\text{inelastic}, |\eta| > 6.5}$ = = **2.62 ± 2.17 mb**

TOTEM Coll., EPL 101 (2013) 21003

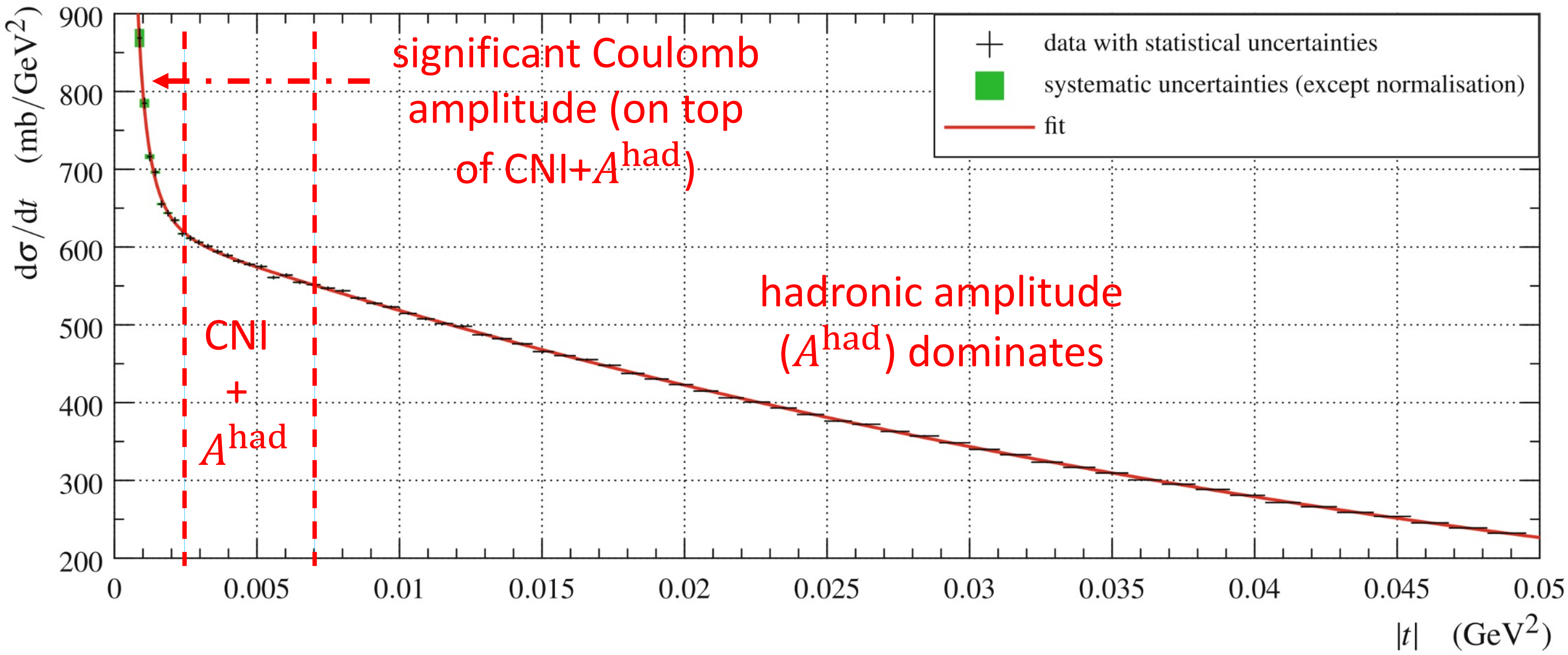
Low mass diffraction correction to N_{inel} estimated from MCs & data

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

ρ measurements using CNI data

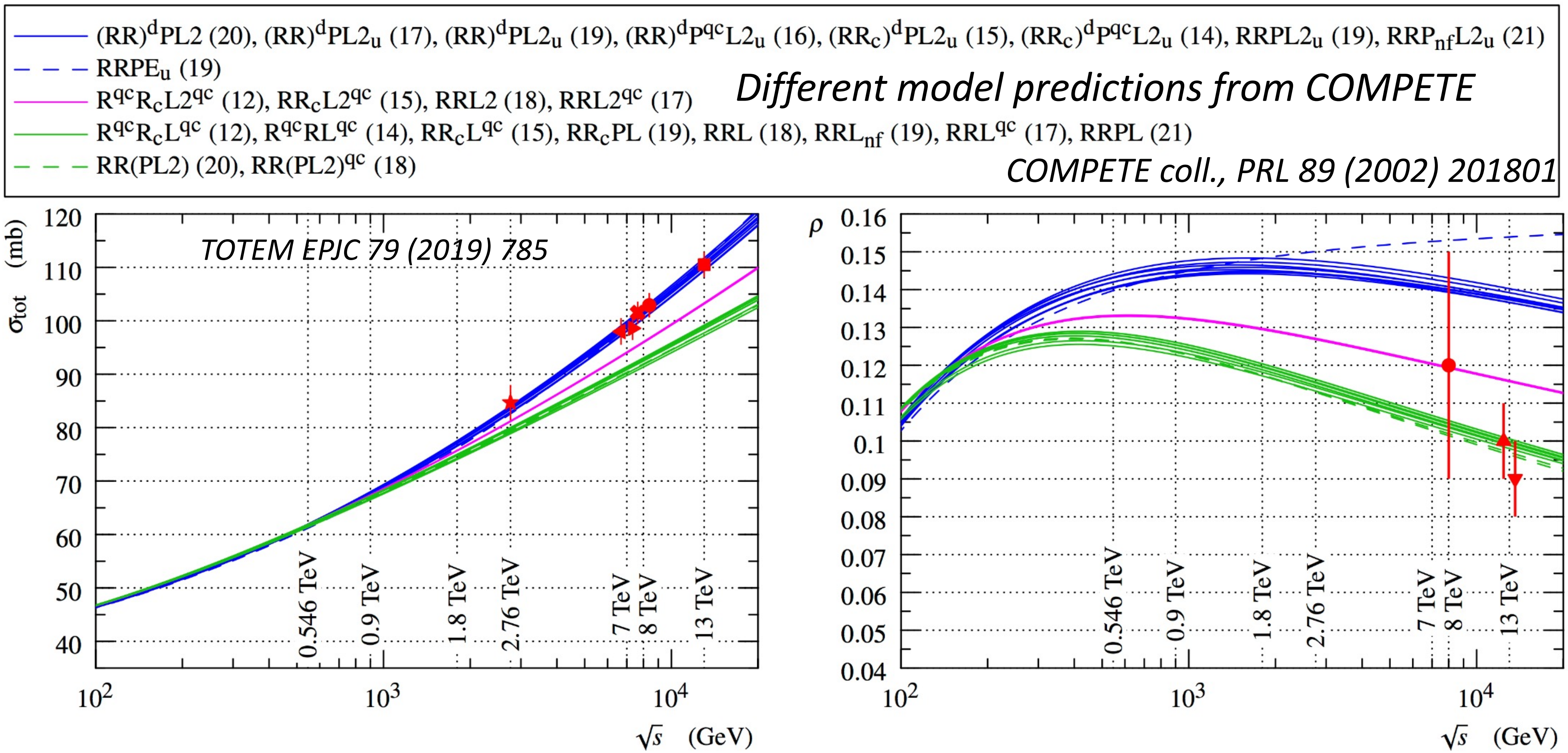
$$\rho \equiv \left.\frac{Re\left[A_{\mathrm{el}}^{\mathrm{had}}\right]}{Im\left[A_{\mathrm{el}}^{\mathrm{had}}\right]}\right|_{t=0}$$

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 or very little ρ sensitivity to influence ρ measurement.



TOTEM ρ & σ_{tot} in pp

- @ $\sqrt{s}$ = 13 TeV: ρ^{pp} = 0.10 $\pm$ 0.01 / 0.09 $\pm$ 0.01 *(TOTEM Coll., 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 not excluded explanation for low ρ^{pp}: slower rise of σ_{tot}^{pp} @ $\sqrt{s}$ > $\sqrt{s}_{\mathrm{LHC}}$

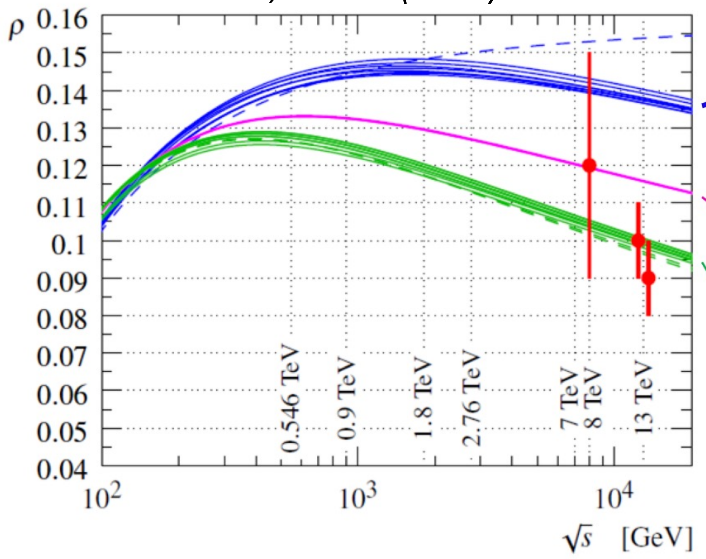


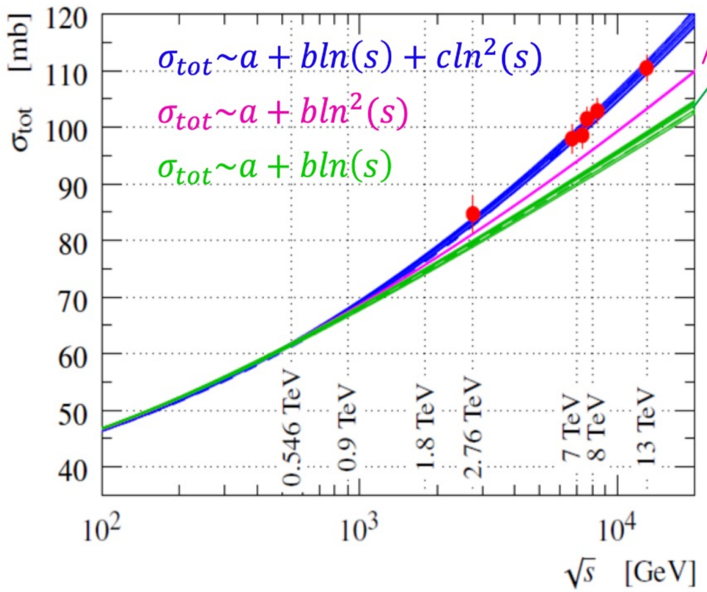
ATLAS confirmed: ρ^{pp} @ 13 TeV = 0.098 $\pm$ 0.011 *(EPJC 83 (2023) 441)*

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

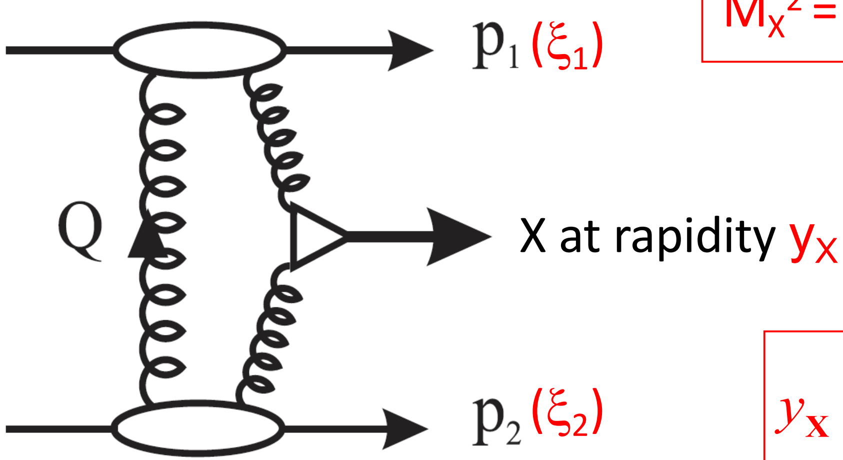
- Excluded at **4.6σ** level with TOTEM $\rho + \sigma_{tot}$ data.
- Excluded at **5.7σ** level when combining significance from TOTEM $\rho + \sigma_{tot}$ data and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.

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

No Odderon hypothesis excluded @ > 5σ

Central exclusive production (CEP)



$M_X^2 = \xi_1 \xi_2 s$

$$y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$

selection rules for system X:
$J^{PC} = 0^{++}, 2^{++}, \ldots$ ($\mathbb{P}\mathbb{P}$, gg, $\gamma\gamma$)
$J^{PC} = 1^{--}$ ($\gamma\mathbb{P}$)

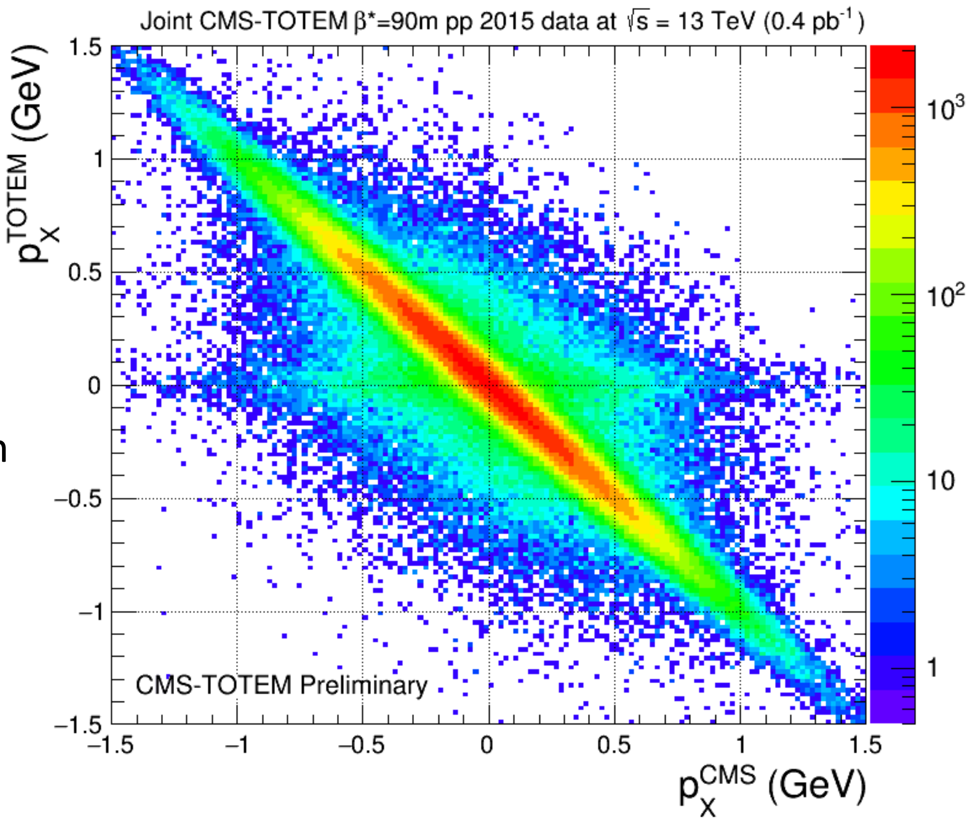
- ✓ CEP exclusivity verified by rapidity gaps or intact forward protons (p)
- ✓ Rapidity gap method: p dissociation contamination (giving only particles outside instrumented η regions)
- ✓ Intact forward protons: possible contamination from pileup p's
- ✓ Intact proton method: require forward vs central system compatibility: M(pp) = M(central), y(pp) = y(central), $p_{T,z}$(pp) = $p_{T,z}$(central), vertex(pp) = vertex(central)

but limited p acceptance at LHC: high β*: $|t_p|$ > 0.01 GeV^2, low β*: M_X > 350 GeV

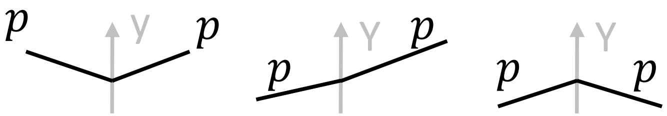
Low mass resonance CEP

$pp \rightarrow p + \pi^+\pi^- + p$ candidates

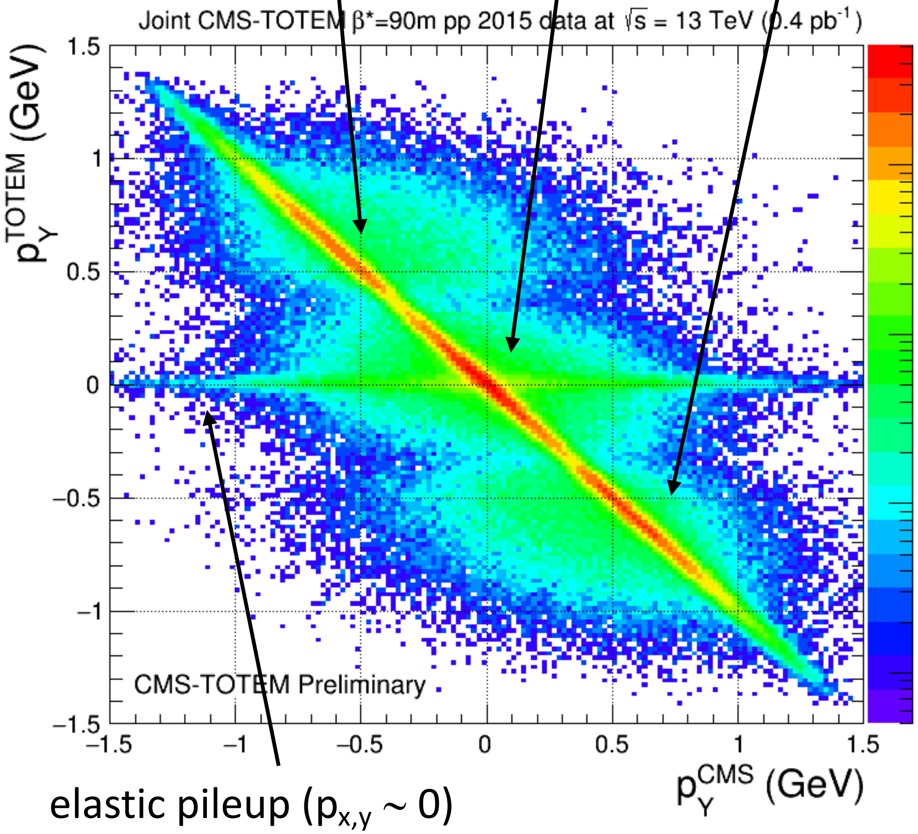
Transverse momentum sum of protons ($p_{x,y}^{TOTEM}$) vs transverse momentum sum of charged particles in tracker ($p_{x,y}^{CMS}$)



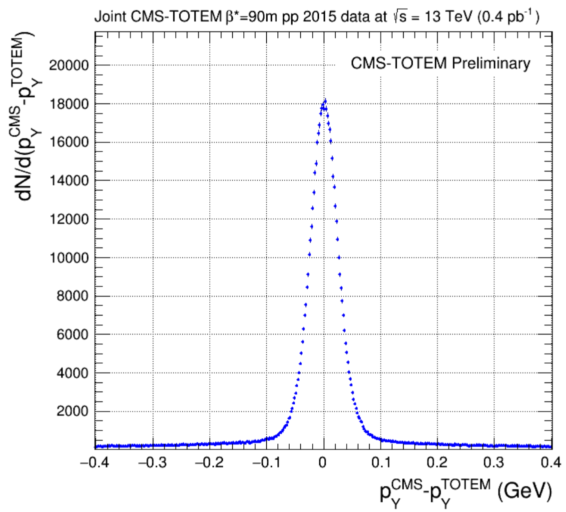
Different RP combi-nations



top-top diagonal bottom-bottom



elastic pileup ($p_{x,y} \sim 0$)



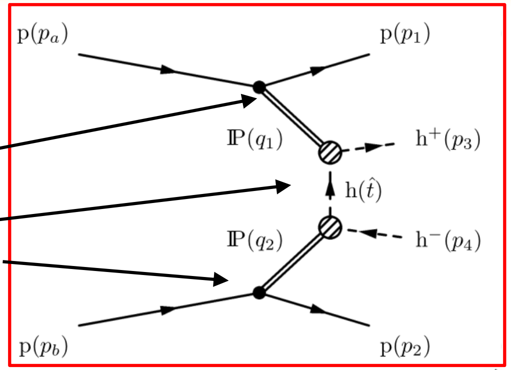
Very pure exclusive sample selected !!

Non-resonant exclusive dipion production

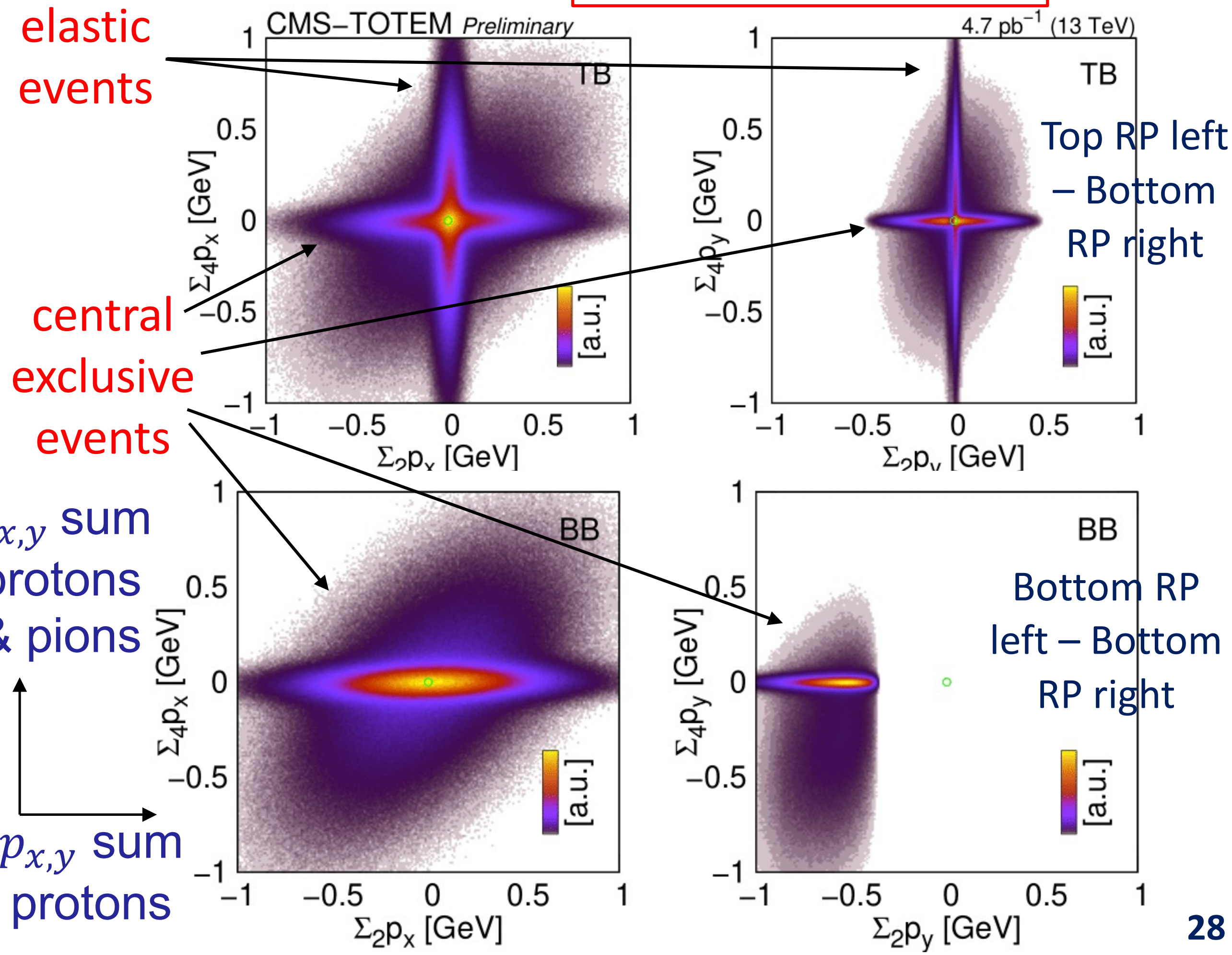
CMS PAS SMP-21-004, TOTEM NOTE 2023-001, https://cds.cern.ch/record/2867988

Matrix element non-resonant $\mathbb{PP}$:

$$\mathcal{M} = M_{13}(t_1, s_{13}) \frac{F^2(\hat{t})}{\hat{t} - m^2} M_{24}(t_2, s_{24})$$



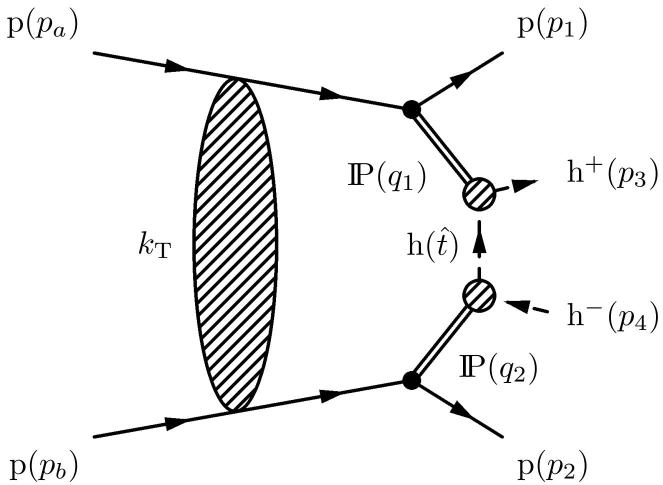
- Detailed study of Pomeron interactions using a very large sample (~ 80 M) non-resonant central exclusive $\pi^+\pi^-$ with protons measured in TOTEM RPs & charged pions in CMS tracker
- Require diproton and dipion p_x & p_y to match ($\sum_4 p_x \approx 0$ & $\sum_4 p_y \approx 0$)
- Main background: elastic + inelastic pileup ($\sum_2 p_x \approx 0$ & $\sum_2 p_y \approx 0$)

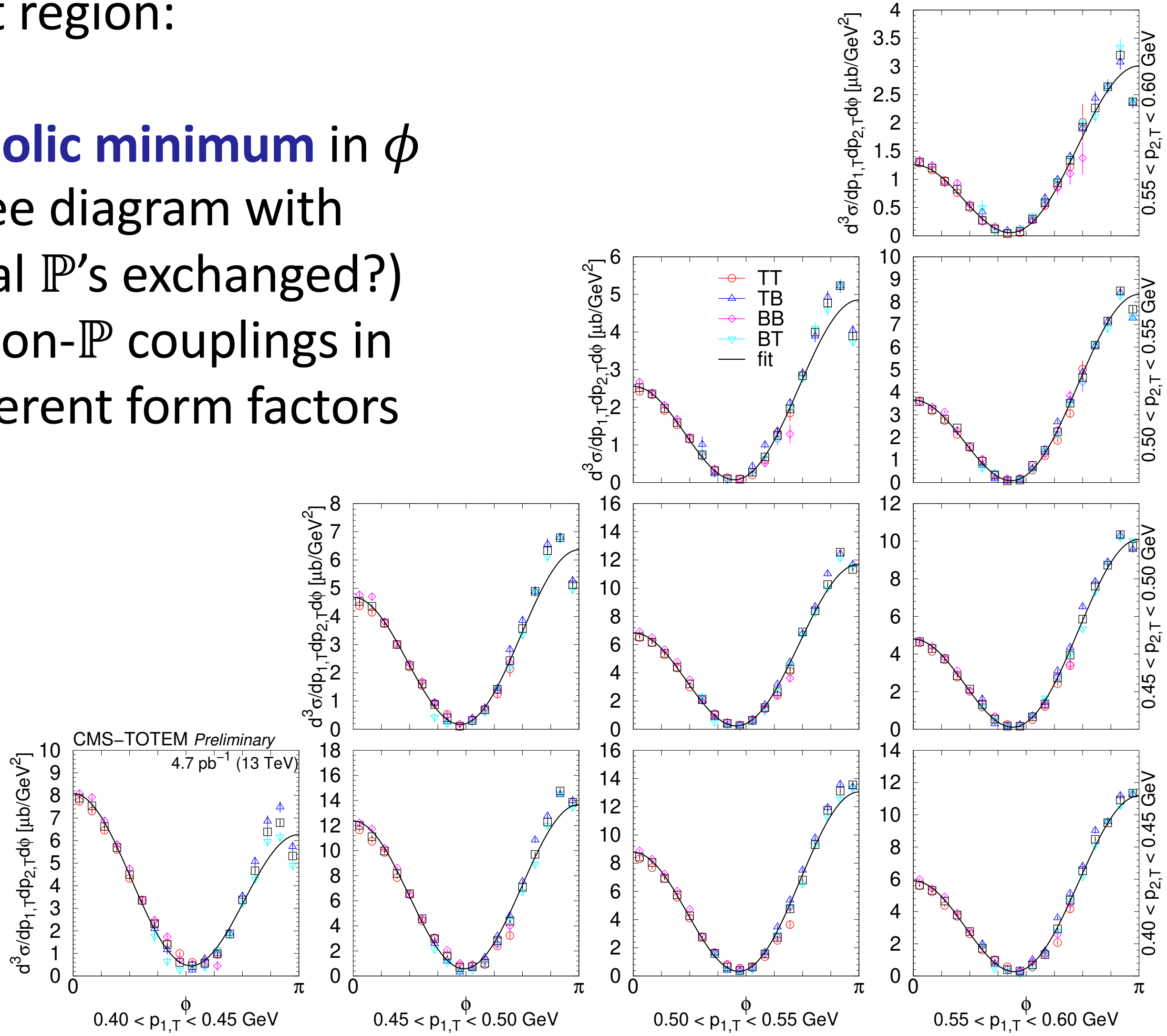


Non-resonant exclusive dipion production

- ✓ Variables studied: $m_{\pi+\pi-}$, proton p_T's and ϕ (2-proton azimuthal angle difference)
- ✓ Focusing on non-resonant region: $0.35 < m_{\pi+\pi-} < 0.65$ GeV
- ✓ First observation of **parabolic minimum** in ϕ (due to interference of tree diagram with diagrams having additional $\mathbb{P}$'s exchanged?)
- ✓ Study nucleon-$\mathbb{P}$ and meson-$\mathbb{P}$ couplings in different models with different form factors

$$\frac{d^3\sigma}{dp_{1,T}dp_{2,T}d\phi} = [A(R - \cos\phi)]^2 + c^2,$$





Exclusive dipion production: model tuning

Proton-pion "matrix element":

$$M_{ik}(t_i, s_{ik}) = i s_{ik} C_{\mathbb{P}} \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_i)-1} F_i$$

- **Models:**
  - empirical (measured $d\sigma_{el}/dt$)
  - one channel (p in ground state) $F_p(t) = \exp(B_{\mathbb{P}}/2 \cdot t)$
  - two channel (p + N*)

$$F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$$

- **Form factors:**
  - $\mathbb{P}$-meson (exponential, Orear-like power-law):

$$\exp(b_{\exp}(\hat{t} - m^2))$$
$$\exp(b_{\text{ore}}[a_{\text{ore}} - \sqrt{a_{\text{ore}}^2 - (\hat{t} - m^2)}])$$
$$1/(1 - b_{\text{pow}}(\hat{t} - m^2)),$$

  - p-$\mathbb{P}$

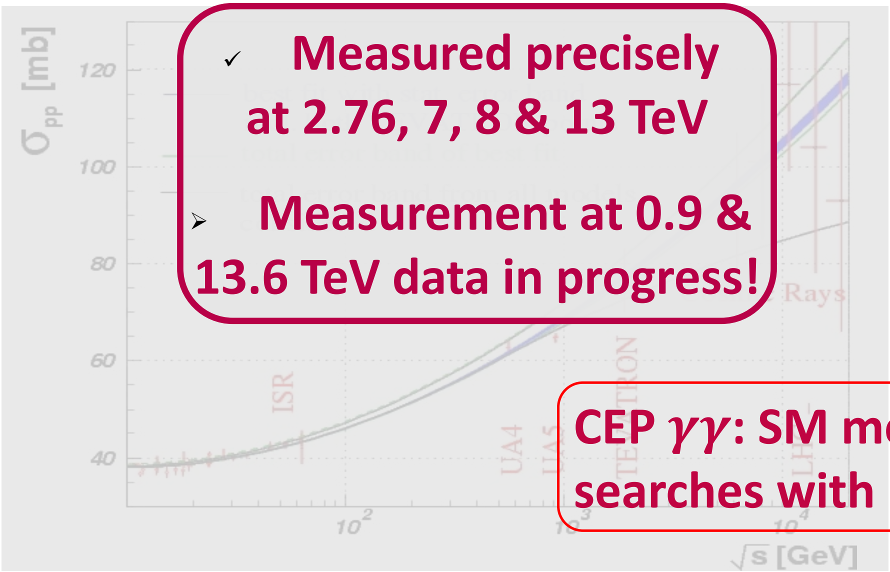
Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
empirical model				
a_{ore} [GeV]	—	0.735 ± 0.015	—	
$b_{\exp/\text{ore}/\text{pow}}$ [GeV^{-2} or $^{-1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{\mathbb{P}}$ [GeV^{-2}]	3.757 ± 0.033	3.934 ± 0.027	4.159 ± 0.019	
χ^2/dof	9470/5796	10059/5795	11409/5796	
one-channel model				
σ_0 [mb]	34.99 ± 0.79	27.98 ± 0.40	26.87 ± 0.30	
$\alpha_P - 1$	0.129 ± 0.002	0.127 ± 0.001	0.134 ± 0.001	
α'_P [GeV^{-2}]	0.084 ± 0.005	0.034 ± 0.002	0.037 ± 0.002	
a_{ore} [GeV]	—	0.578 ± 0.022	—	
$b_{\exp/\text{ore}/\text{pow}}$ [GeV^{-2} or $^{-1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{\mathbb{P}}$ [GeV^{-2}]	2.745 ± 0.046	4.271 ± 0.021	4.072 ± 0.017	
χ^2/dof	7356/5793	7448/5792	8339/5793	
two-channel model				
σ_0 [mb]	20.97 ± 0.48	22.89 ± 0.17	23.02 ± 0.23	23 / 33
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001	0.13 / 0.115
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001	0.08 / 0.11
a_{ore} [GeV]	—	0.718 ± 0.012	—	
$b_{\exp/\text{ore}/\text{pow}}$ [GeV^{-2} or $^{-1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\|a\|^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011	−0.04 / −0.25
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023	0.55 / 0.4
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040	8.5 / 8.0
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006	0.18 / 0.18
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003	0.45 / 0.63
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060	4.5 / 6.0
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006	0.58 / 0.58
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004	0.45 / 0.47
χ^2/dof	5741/5786	6415/5785	7879/5786	

Remarkable agreement with DIME ("soft model 1")

Two-channel model with exponential $\mathbb{P}$-meson form factor seems to be favoured by data

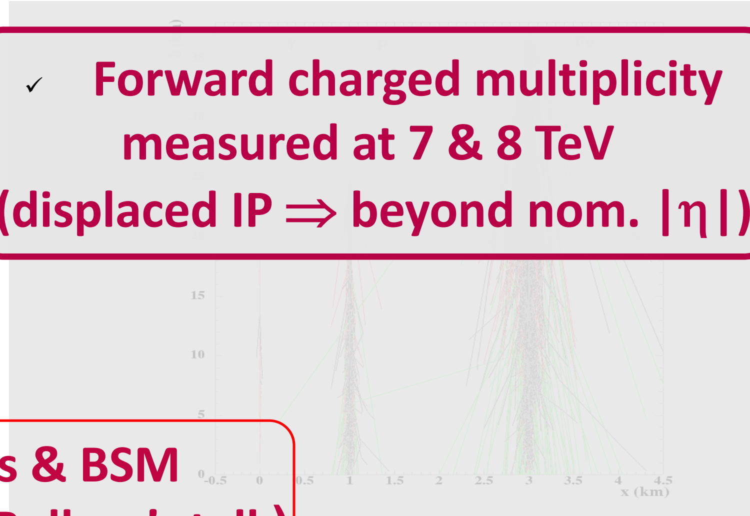
TOTEM summary

Total pp cross-section



- ✓ Measured precisely at 2.76, 7, 8 & 13 TeV
- ➢ Measurement at 0.9 & 13.6 TeV data in progress!

Forward particle production



- ✓ Forward charged multiplicity measured at 7 & 8 TeV (displaced IP ⇒ beyond nom. |η|)

CEP $\gamma\gamma$: SM measurements & BSM searches with PPS (see A. Bellora's talk)

Diffraction: soft and hard

- ✓ Pomeron precision study with central exclusive dipions,
- ✓ Low mass DD measured at 7 TeV,
- ✓ SD dijets at 8 & 13 TeV
- ➢ Study of glueball candidates in low mass CEP on-going

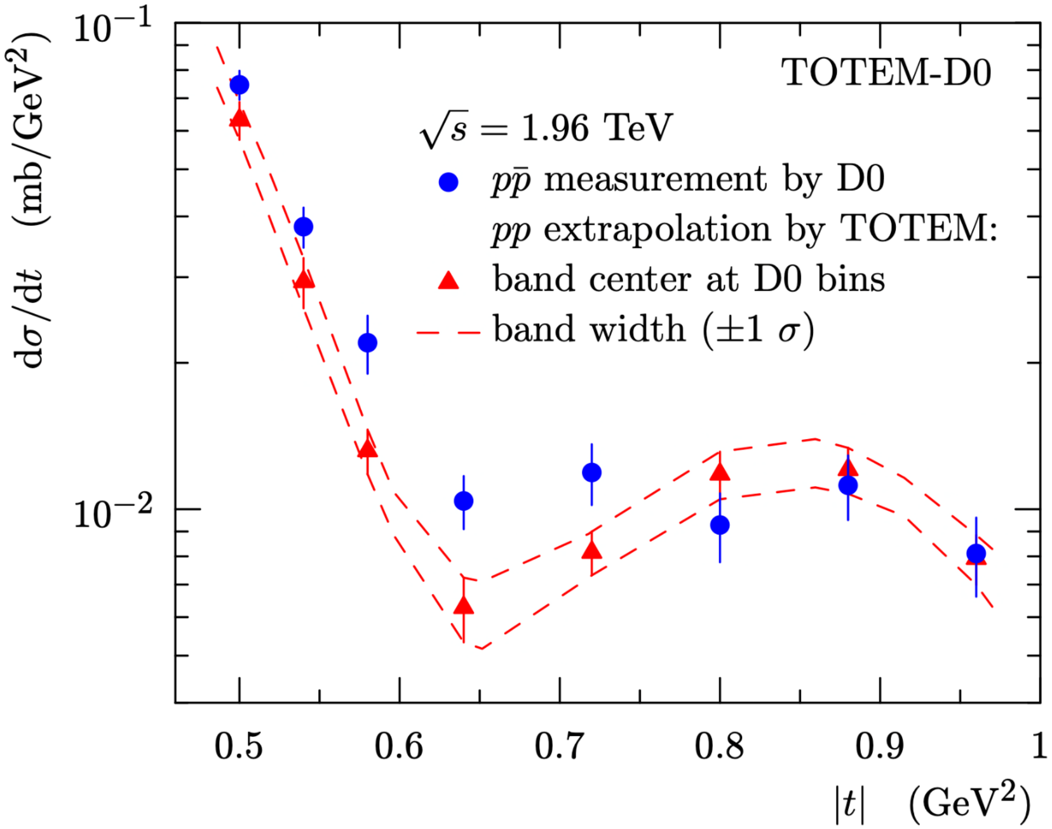
Elastic pp scattering

- ✓ Differential cross section measured at 2.76, 7, 8 & 13 TeV for wide |t|-range
- ✓ ρ parameter measured at 8 & 13 TeV
- ✓ Odderon observation! (from $pp/p\bar{p}$ comparison + ρ & σ_{tot})
- ➢ Analysis for Odderon as well as of 0.9 & 13.6 TeV elastic continuing!

Backup

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.

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 ± 2.6 mb → 8.2 ± 1.4 mb ⟹

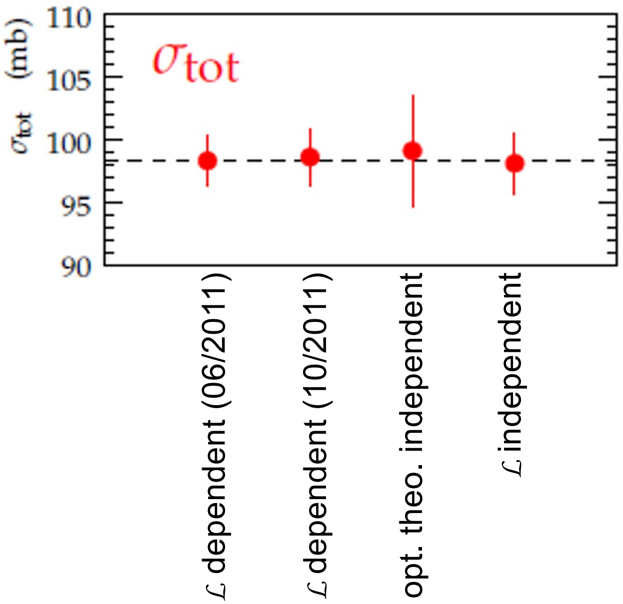
smaller σ_{tot}^{pp} ATLAS-TOTEM difference but only slightly in # of σ's & no explain. of $\sigma_{tot,C\ norm}^{pp}$

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

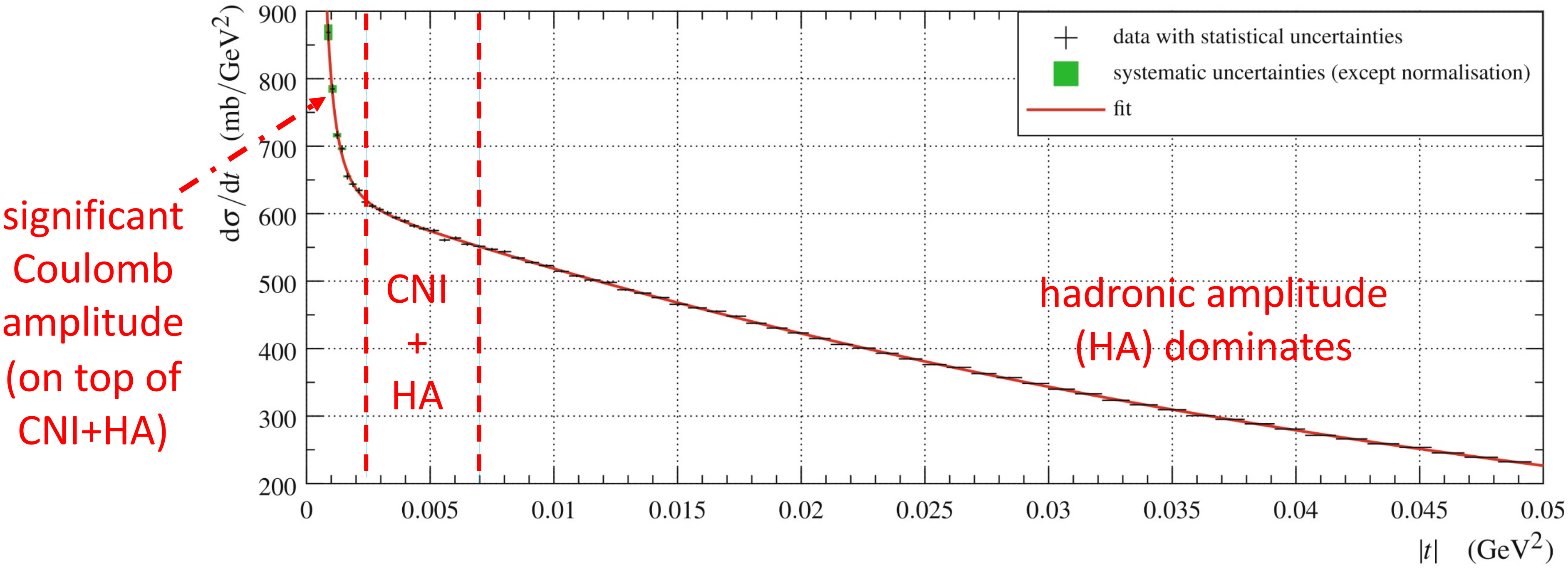


- Regarding ATLAS σ_{tot}^{pp}: How reliable are absolute luminosity calibrations (precision @ $\sqrt{s}$ = 13 TeV: 2.15 %) made in van de Meer scans at β^* = 11 m for the luminosity of beams at β^* = 2500 m (with very different LHC optics and an interaction point transverse size 15 times larger)?

ρ measurements using CNI data

- 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)

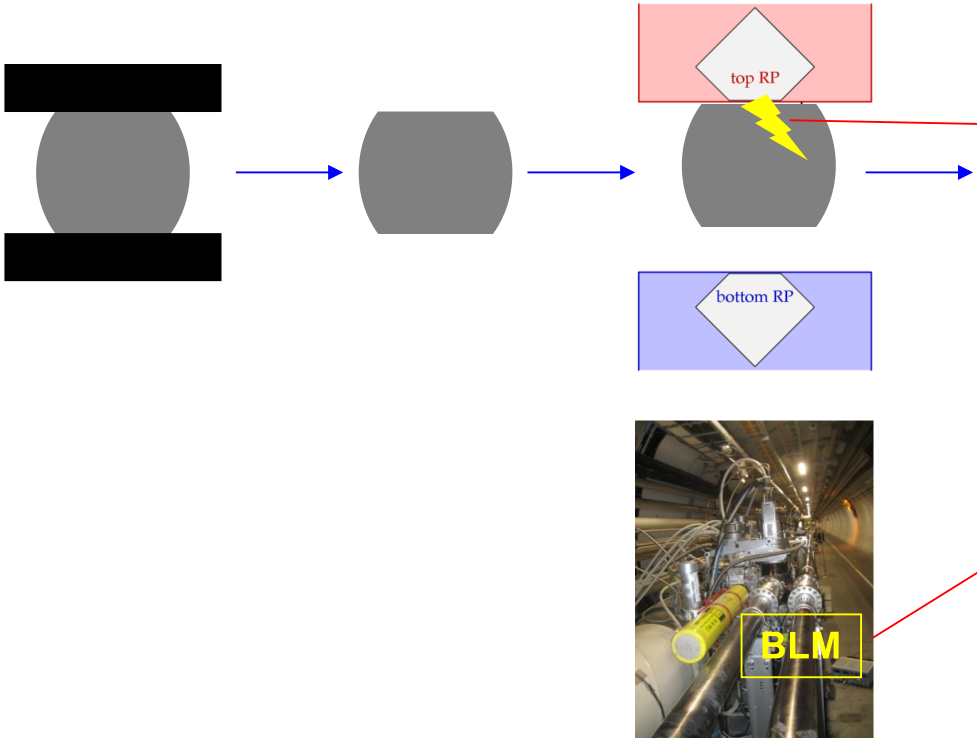
Beam based RP alignment

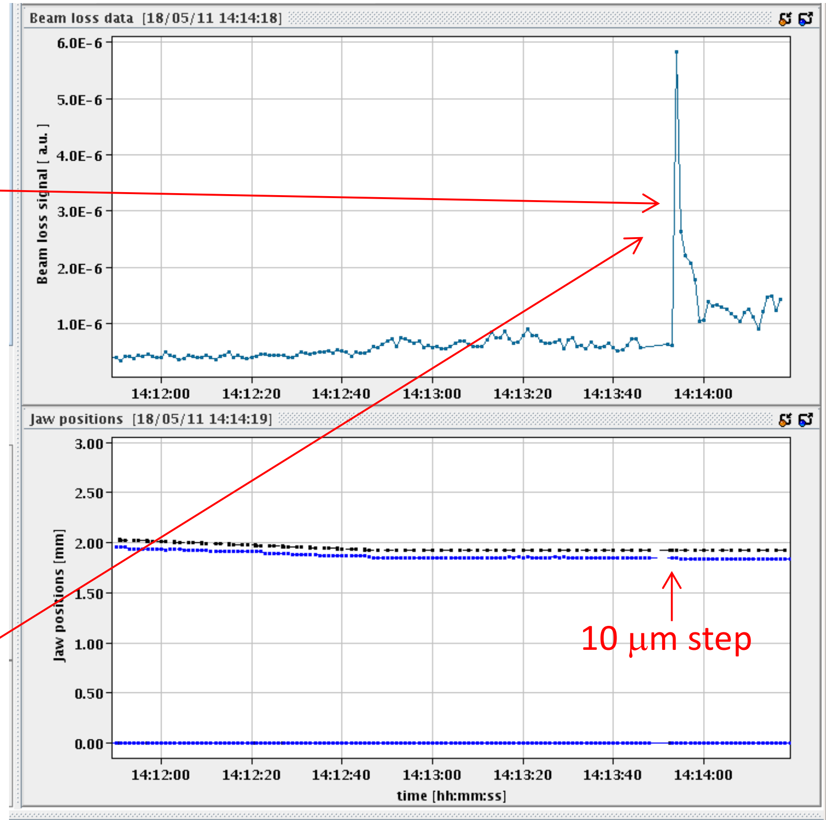
Standard Procedure for LHC Collimators

A primary collimator cuts a sharp edge into the beam, symmetrical to the centre

The top RP approaches the beam until it touches the edge

The last 10 μm step produces a spike in a **Beam Loss Monitor** downstream of the RP



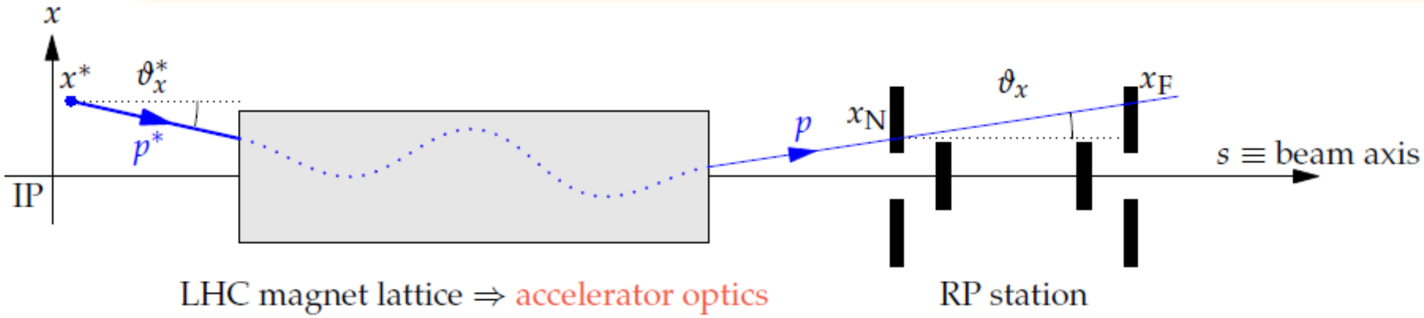


When both top and bottom pots are touching the beam edge:

- they are at the same number of sigmas from the beam centre as the collimator
- the beam centre is exactly in the middle between top and bottom pot

→ **Alignment of the RP windows relative to the beam (~ 20 μm)**

Proton transport & reconstruction



(x^*, y^*): vertex position
(θ_x^*, θ_y^*): emission angle: $t \approx -p^2 (\theta_x^{*\,2} + \theta_y^{*\,2})$
$\xi = \Delta p/p$: momentum loss (elastic case: $\xi = 0$)

Measured in RP

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{IP5}$$

Values at IP5 to be reconstructed

Product of all lattice element matrices

$$x_{RP} = L_x \Theta_x^* + v_x x^* + D_x \xi$$

$$y_{RP} = L_y \Theta_y^* + v_y y^*$$

L_x, L_y: effective lengths (sensitivity to scattering angle)
v_x, v_y: magnifications (sensitivity to vertex position)
D_x : dispersion (sensitivity to momentum loss); $D_y \sim 0$

Reconstruction of proton kinematics = inversion of transport equation
Transport matrix elements depend on ξ ➔ non-linear problem (except in elastic case!)

Excellent optics understanding needed.

Optics reconstruction

Machine imperfections alter the optics:

- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Magnetic field harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 μm

$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ Precise model of the LHC optics is indispensable!

Novel method from TOTEM:

- Use **measured** proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- http://iopscience.iop.org/1367-2630/16/10/103041/