Latest results for Proton-proton Cross Section Measurements with the TOTEM experiment at LHC.

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On behalf of TOTEM Collaboration

TOTEM Physics goals

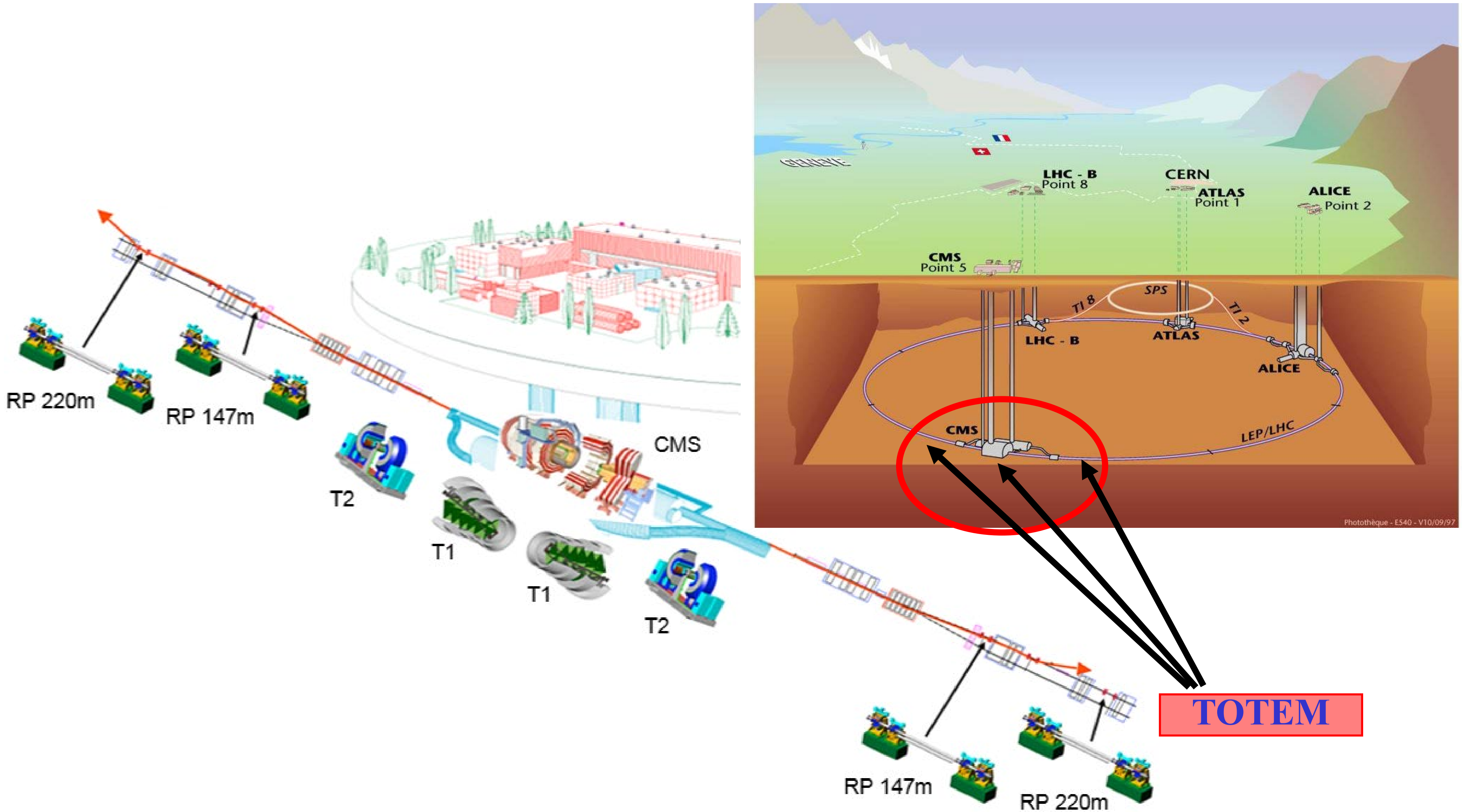
- TOTEM (TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC)
  - σ_{TOT}^{pp} using a luminosity independent method (optical theorem) simultaneously measuring:
    - N_{el} down to -t ~10^{-3} GeV^2
    - N_{inel} with losses < 3%

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

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\frac{d\sigma_{el}}{dt}|_{t=0}, \quad \sigma_{inel} = \sigma_{tot} - \sigma_{el}.$$

  - Elastic pp scattering in the range $10^{-3} < |t| \sim (p\theta)^2 < 10$ GeV^2
  - Soft diffraction (SD and DPE)
  - Particle flow in the forward region (cosmic ray MC validation/tuning)

TOTEM Experiment LHC Run I

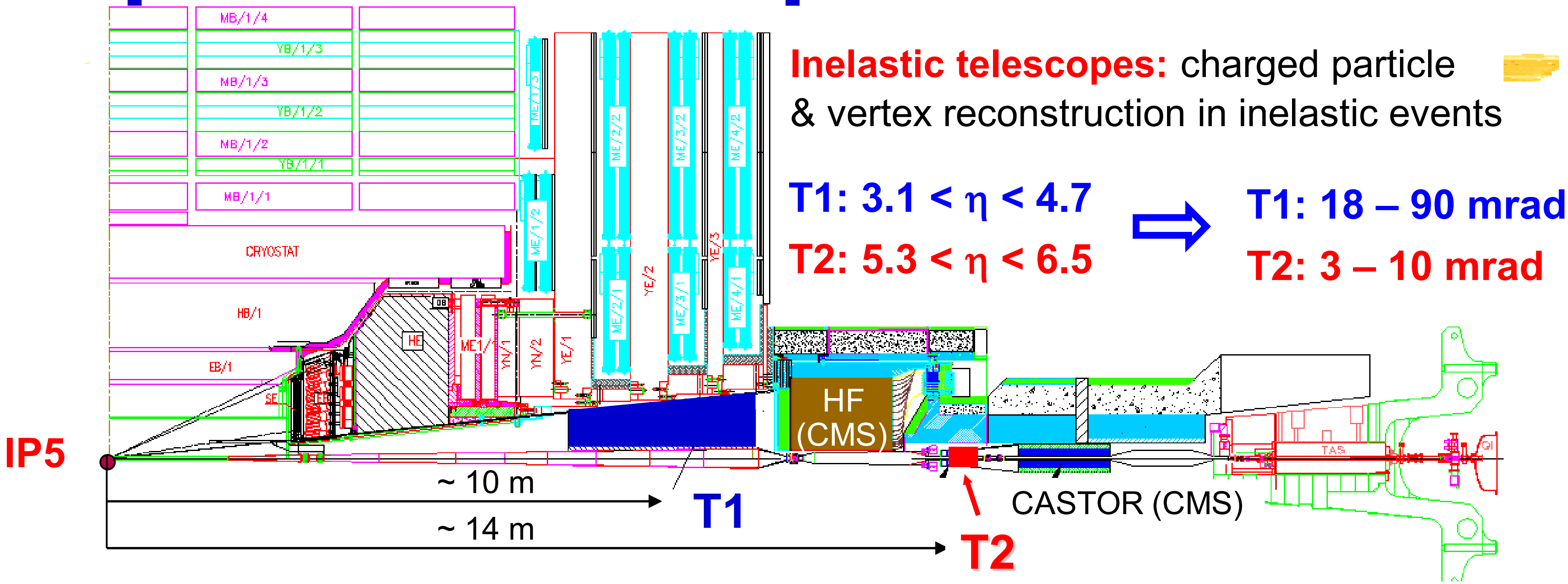


Experimental Setup @ IP5 LHC Run I

Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

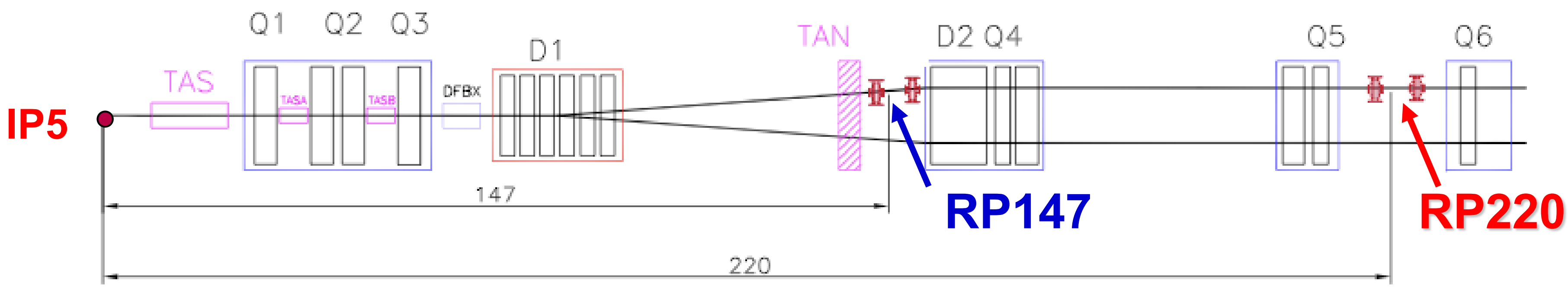
T1: 3.1 < η < 4.7 ⇒ **T1: 18 – 90 mrad**

T2: 5.3 < η < 6.5 ⇒ **T2: 3 – 10 mrad**

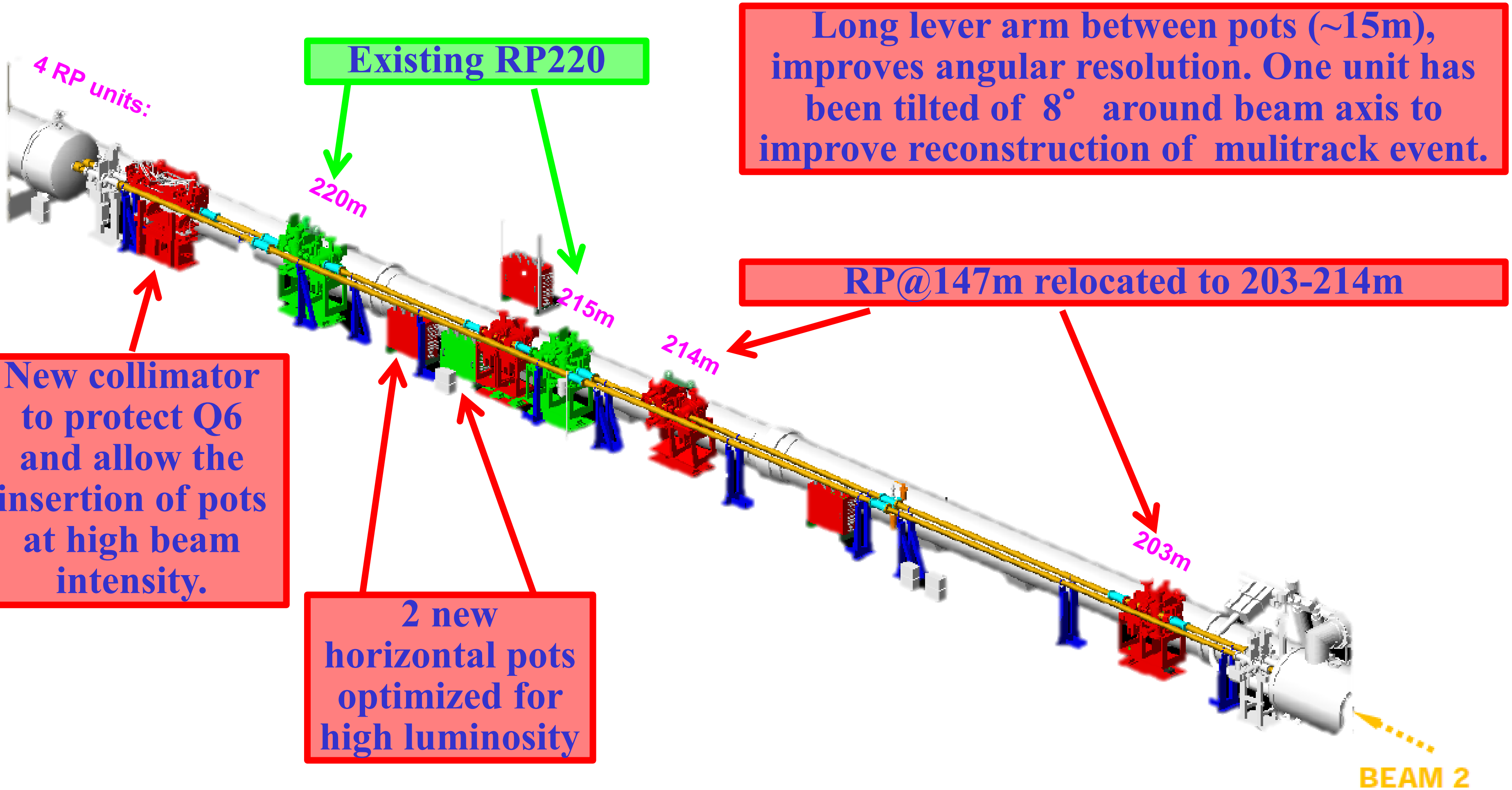


LHC RunI layout

Roman Pots: measure elastic & diffractive protons close to outgoing beam



TOTEM Program for RUN II



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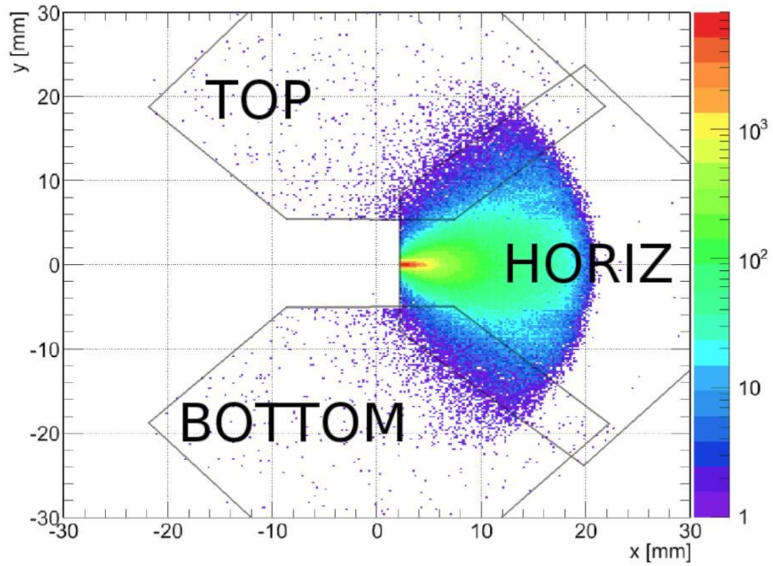
  - Elastic pp scattering in the range $10^{-3} < |t| \sim (p\theta)^2 < 10$ GeV^2
  - Soft diffraction (SD and DPE)
  - Particle flow in the forward region (cosmic ray MC validation/tuning)
  - To access to the smaller t-value region, the colliding beams must have a beam divergence of not more than a few μ-rad. This can be obtained by either **increasing the beta function value, β^***, or by reducing the beam emittance, ε (beam divergence = $\sqrt{\varepsilon/\beta^*}$)

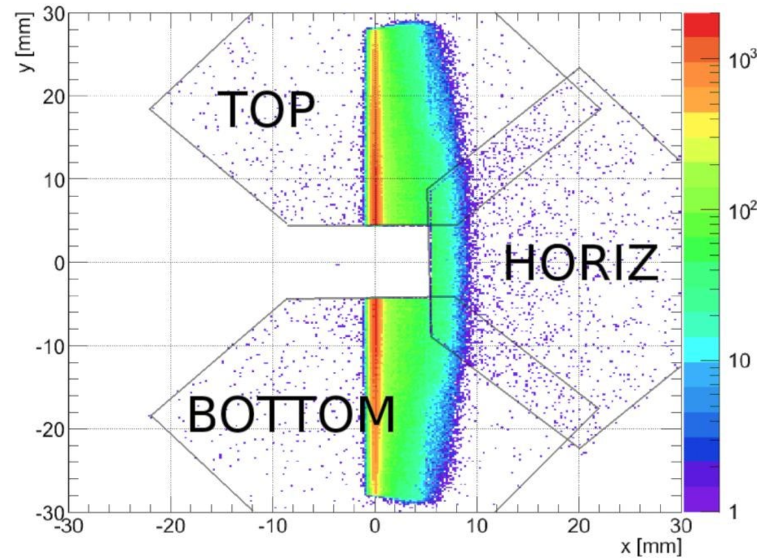
LHC Optics

β* = 0.55 m (low β* = standard at LHC)



- **Diffractive** protons are mainly in the **horizontal** pot
- **Elastic** protons in the **vertical** pot near X~0

β* = 90 m (special optic for RP runs)



- **Diffractive** protons are mainly in the **vertical** pot.
- **Elastic** protons in a **narrow band** at X~0

Cross-sections measurement

Luminosity & ρ dependent. Elastic only.

$$\sigma_{tot}^2 = \frac{16\pi}{1+\varrho^2}\frac{1}{\mathcal{L}}\left.\frac{dN_{el}}{dt}\right|_0$$

$$\sigma_{tot}$$

ρ independent

$$\sigma_{tot} = \frac{1}{\mathcal{L}}(N_{el} + N_{inel})$$

Luminosity independent

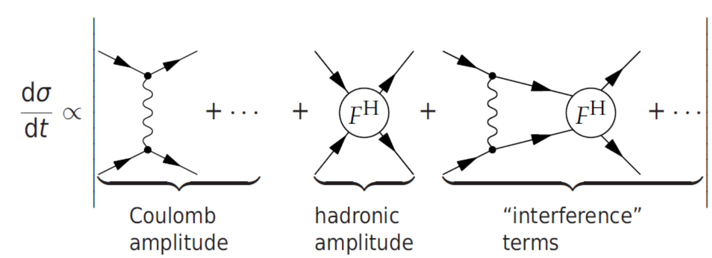
$$\sigma_{tot} = \frac{16\pi}{1+\varrho^2}\frac{dN_{el}/dt|_0}{N_{el}+N_{inel}}$$

- N_{inel} are measured by T1 and T2 telescopes, while N_{el} by the RomanPots detectors.
- Consistency checks using the three independent methods.

ρ measurement

- Elastic scattering at very low-t, the Coulomb-Nuclear Interference region (CNI).
- The differential cross section is sensitive to the phase of the nuclear amplitude:

$$\frac{d\sigma}{dt} \sim \left| \mathcal{A}^{C}(t) + \mathcal{A}^{N}(t)\ \left(1 - \alpha G(t)\right) \right|^2$$



- In the CNI both modulus (constrained by measurement in the hadronic t-region) and phase (t-dependent) of nuclear amplitude can be tested to determine:

$$\rho \equiv \cot \arg \mathcal{A}^{N}(0) = \frac{\Re \mathcal{A}^{N}(0)}{\Im \mathcal{A}^{N}(0)}$$

σ related measurements in Totem

2011
Elastic scattering @7TeV. *EPL 95-41001*
First σ_{tot}@ 7TeV. *EPL 96-21002*
σ_{tot} lumi. independent @7TeV.

2012
Elastic (full t-range) @7TeV, σ_{ine}
EPL 101-21004/21003/21002

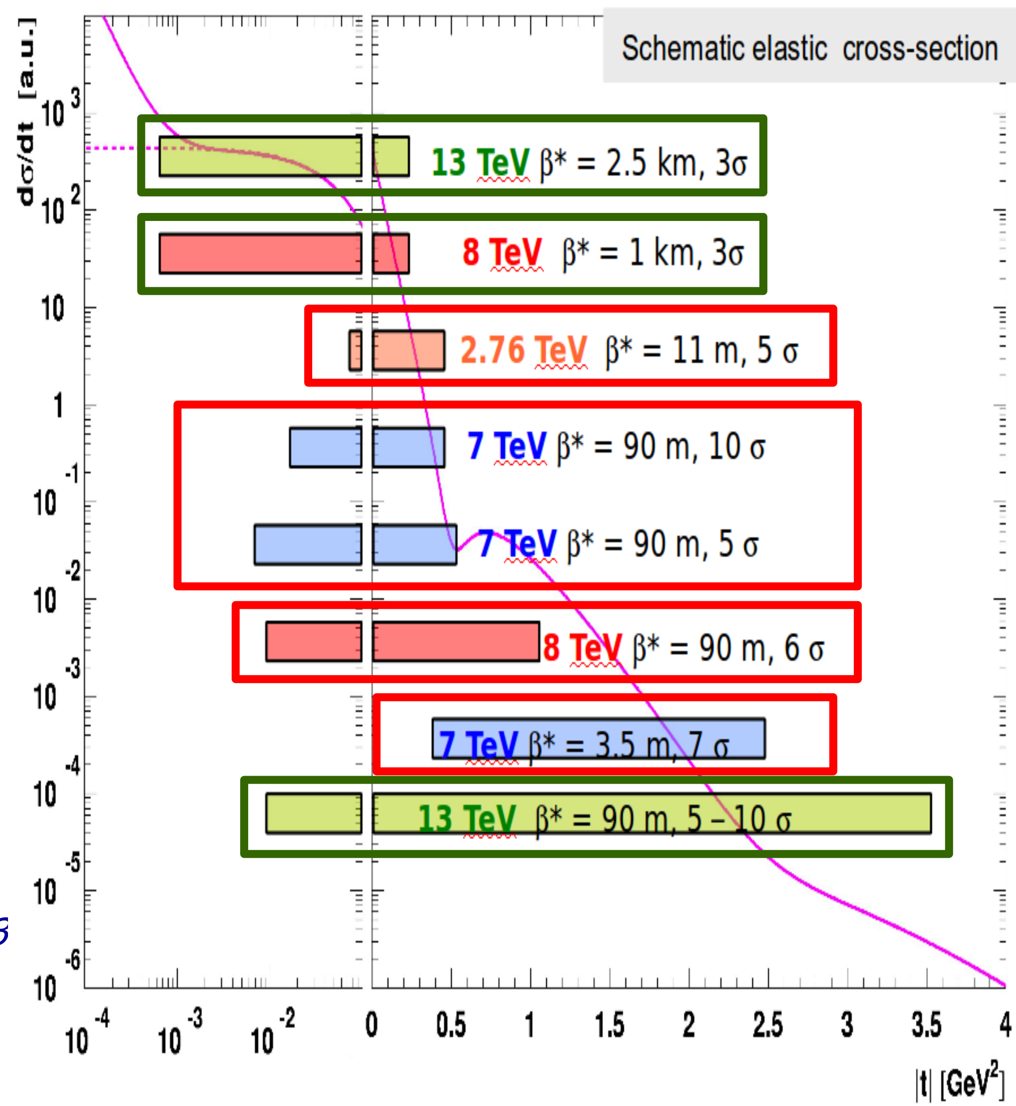
2013
σ_{tot} lumi. independent @ 8TeV.
PRL 111-12001

2015
$^{d\sigma}/_{dt}$ elastic: non-exp. behavior @8TeV.
NPB 899-527

2016
ρ measurement @8TeV. *EPJ C76-661*

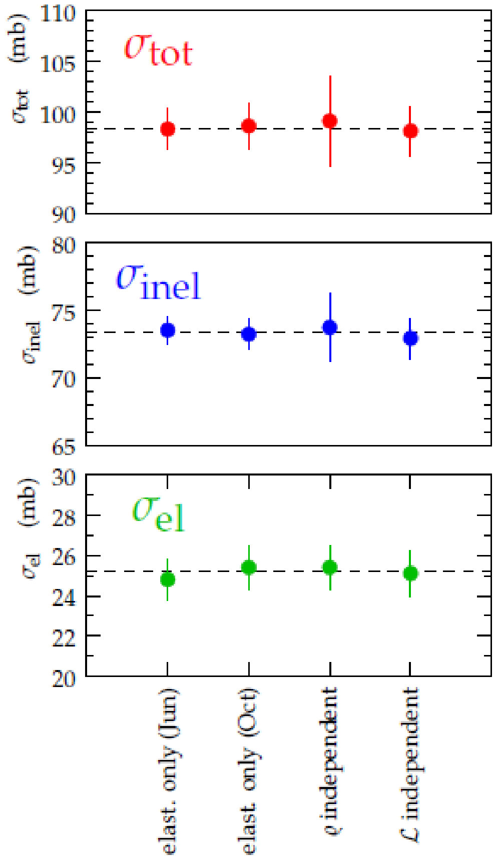
2017
σ_{tot} lumi independent @ 2.76 TeV.
PoS (DIS2017) 059, CERN-EP-2018-341
σ_{tot} lumi independent @ 13 TeV.
CERN-EP-2017-321,EPJC (2019) 79: 103
ρ measurement @ 13 TeV.
CERN-EP-2017-335, accepted in EPJC

2018
$^{d\sigma}/_{dt}$ elastic: DIP @ 13 TeV *CERN-EP-2018-338*



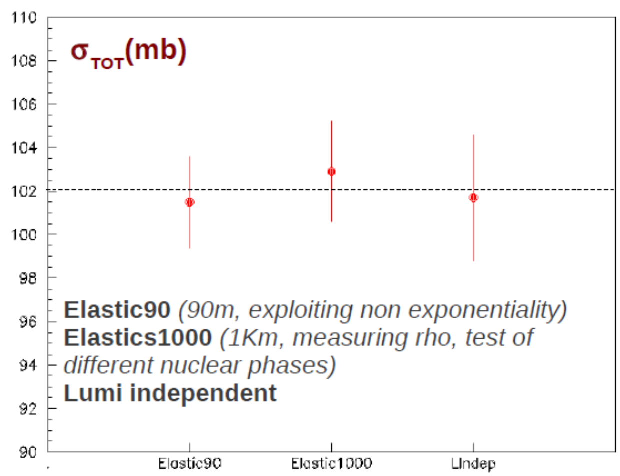
- Run 1
- Run 2

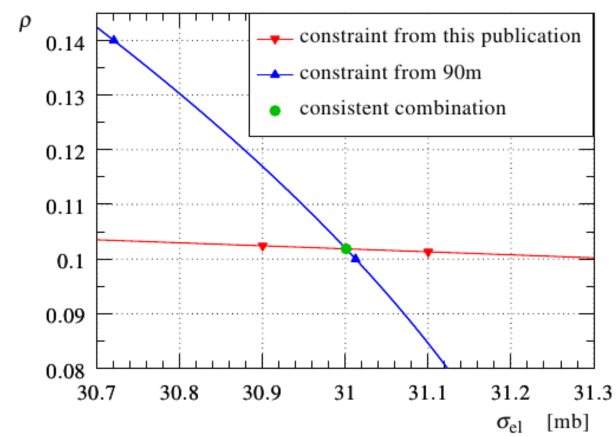
Cross-section measurements



	$\mathcal{L}$ independent using eq. 1.1			
	$\sqrt{2.76}$ TeV [14] (Prelim.)	$\sqrt{7}$ TeV [2]	$\sqrt{8}$ TeV [3]	$\sqrt{13}$ TeV [11]
σ_{tot} (mb)	84.7 ± 3.3	98.0 ± 2.5	101.7 ± 2.9	110.6 ± 3.4
σ_{inel} (mb)	62.8 ± 2.9	72.9 ± 1.5	74.7 ± 1.7	79.5 ± 1.8
σ_{el} (mb)	21.8 ± 1.4	25.1 ± 1.1	27.1 ± 1.4	31.0 ± 1.7

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



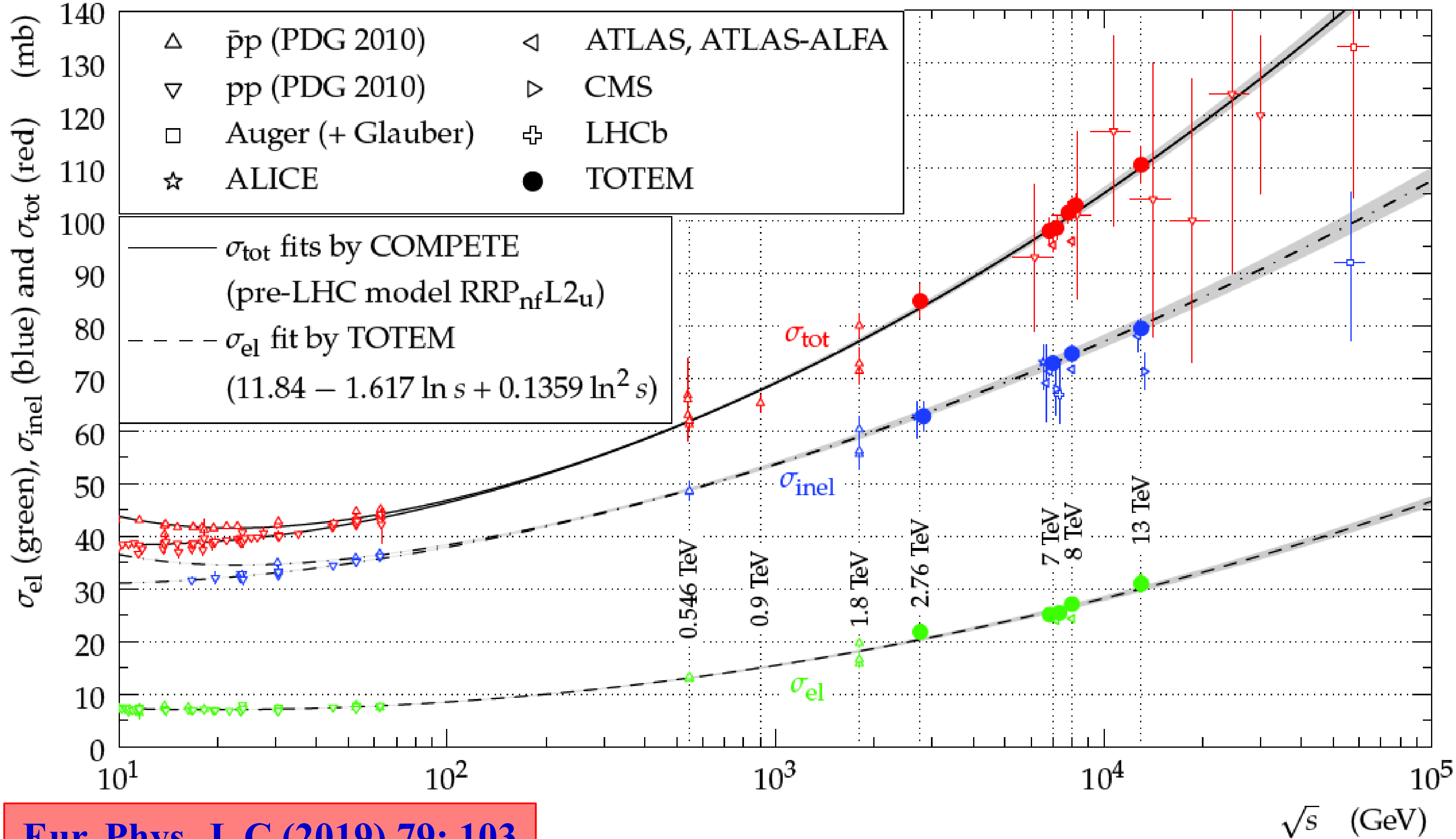


7TeV, several methods
Same beam conditions

8TeV, several methods
Different beam conditions

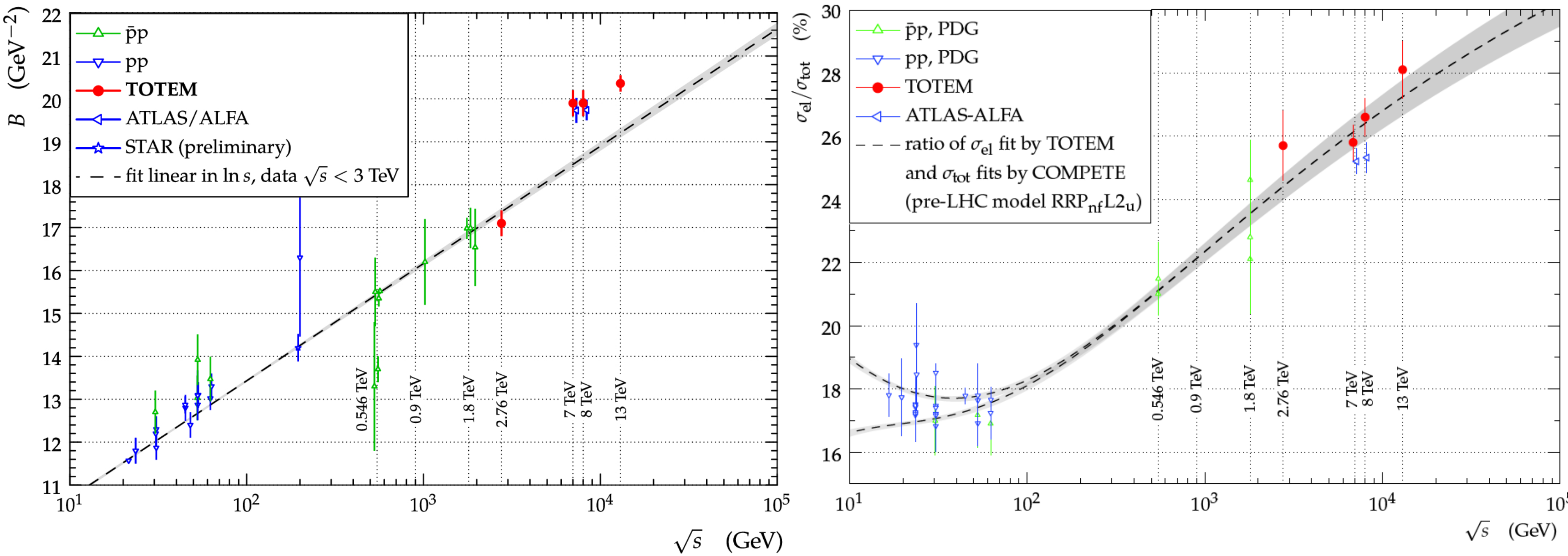
13 TeV
β^* 90m : lumi independent
β^* 2500m: ρ measurement
Different beam conditions

Cross-section measurements



Eur. Phys. J. C (2019) 79: 103

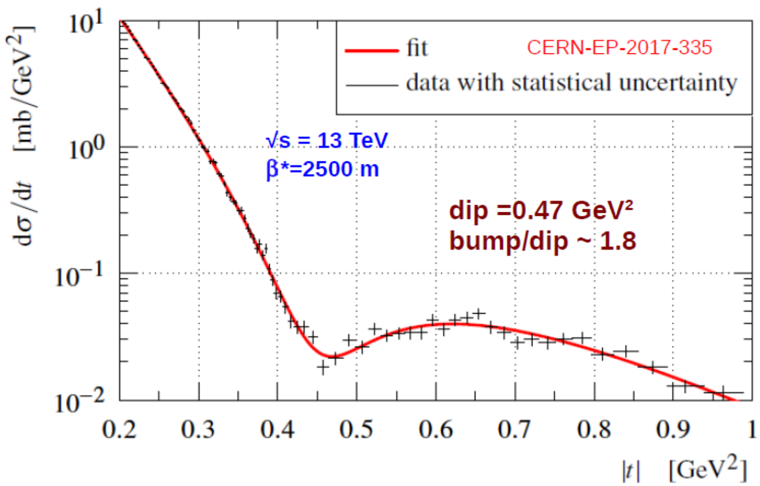
Cross-section measurements

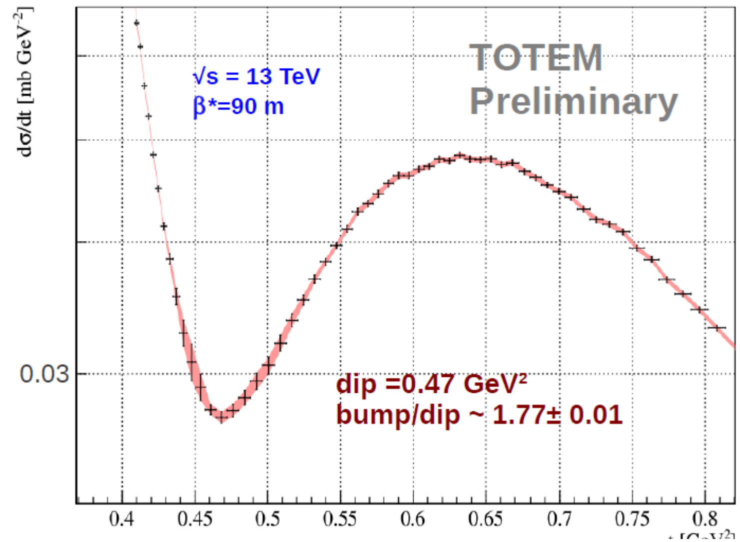


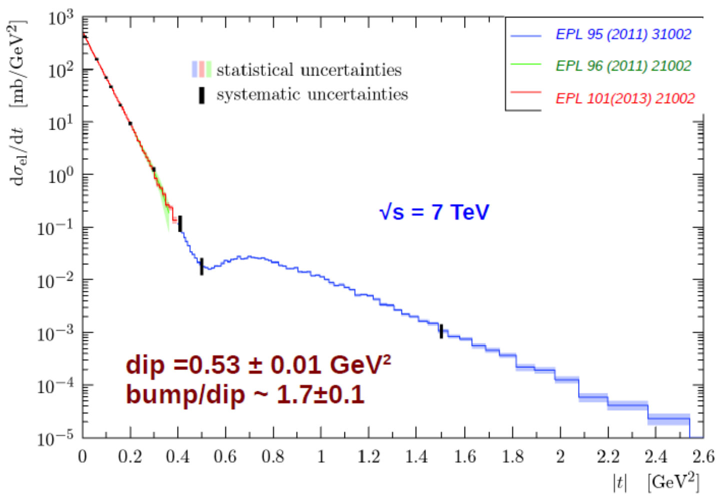
Eur. Phys. J. C (2019) 79: 103

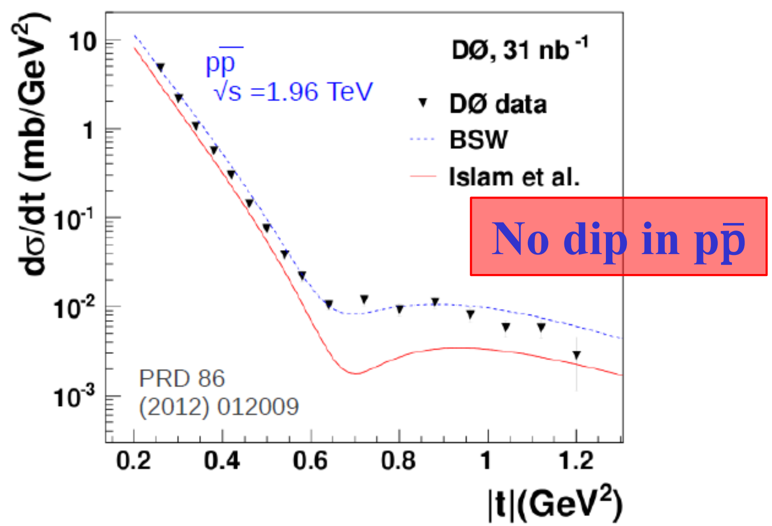
- The exponential slope, *B*, increases with √s. The $\log s$ behavior is not linear for √s>3TeV. The "diffraction cone" shrinkage speed up with the collision energy.
- The increase of $^{\sigma_{el}}/_{\sigma_{TOT}}$ with energy is confirmed also at LHC.

Elastic measurements: dip @13TeV



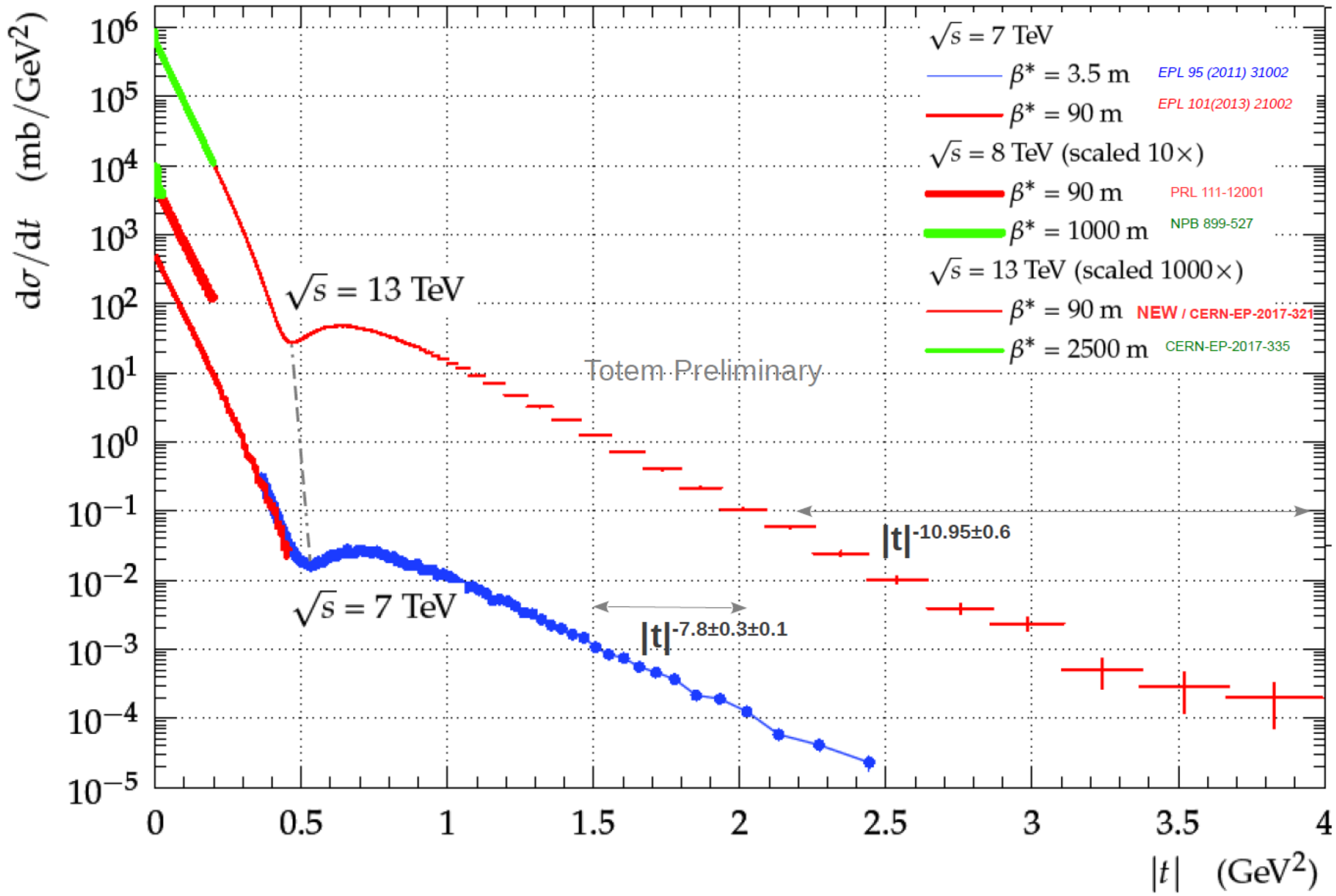






- dip position in |t| decreases with increasing √s

Elastic measurements: dip & high t



- Dip is present at high energy and moves.
- No structure found at high t.

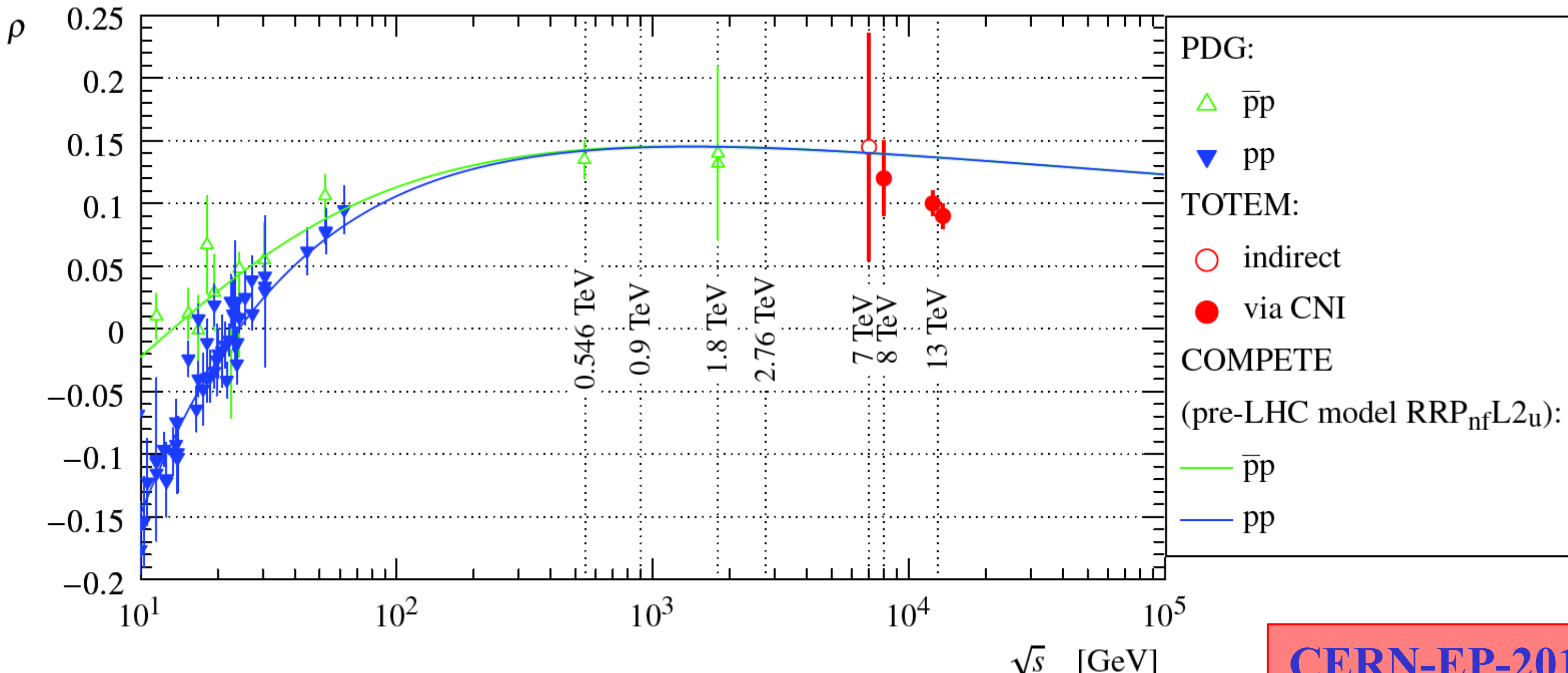
Cross section: 13TeV analysis

- To verify the results of the luminosity independent method σ_{tot} and ρ, from β^*= 2.5km, has been computed using QED normalization method.
- Three approaches (all using Coulomb-nuclear interference):
  1. normalization fixed using β^*= 90m data from lumi-independent method.
  2. partial QED normalization with a χ^2 term corresponding to the lumi-independent result.
  3. full QED normalization.
- All σ_{tot} and ρ results consistent within uncertainties: σ_{tot} results 110.3 ± 3.5 mb and 109.3 ± 3.5 mb, obtained with fully independent methods and disjoint data sets: should be averaged and should lead to smaller uncertainty: **~ 110.5 ± 2.4 mb**.

data	method	ρ	σ_{tot} [mb]
$\beta^* = 90\,\mathrm{m}$	Ref. [6]	-	110.6 ± 3.4
$\beta^* = 2500\,\mathrm{m}$	approach 1	0.09 ± 0.01	111.8 ± 3.2
	approach 2	0.09 ± 0.01	111.3 ± 3.2
	approach 3	$0.08(5) \pm 0.01$	110.3 ± 3.5
	approach 3 (single fit)	0.10 ± 0.01	109.3 ± 3.5
$\beta^* = 90$ and $2500\,\mathrm{m}$	Ref. [6] $\oplus$ approach 3		110.5 ± 2.4

CERN-EP-2017-335-v3, accepted in EPJ C

Coulomb Nuclear interference: ρ



CERN-EP-2017-335

- First LHC determination from Coulomb-hadronic interference at $\sqrt{s}$=8TeV: ρ = 0.12±0.03. Uncertainty still too high due to the low statistics.
- At 13 TeV : sample with very high statistics allows an unprecedented precision. The new points are too low respect to the prediction.

	$\lvert t\rvert_{max} = 0.07$ GeV^2		$\lvert t\rvert_{max} = 0.15$ GeV^2	
N_b	χ^2/ndf	ρ	χ^2/ndf	ρ
1	0.7	0.09 ± 0.01	2.6	–
2	0.6	0.10 ± 0.01	1.0	0.09 ± 0.01
3	0.6	0.09 ± 0.01	0.9	0.10 ± 0.01

Elastic scattering: Non-exponential behavior at low-t

- High-statistics data with β^*=90m at $\sqrt{s}$ = 8 & 13TeV, can be used to compare differential elastic cross-section, with a pure exponential

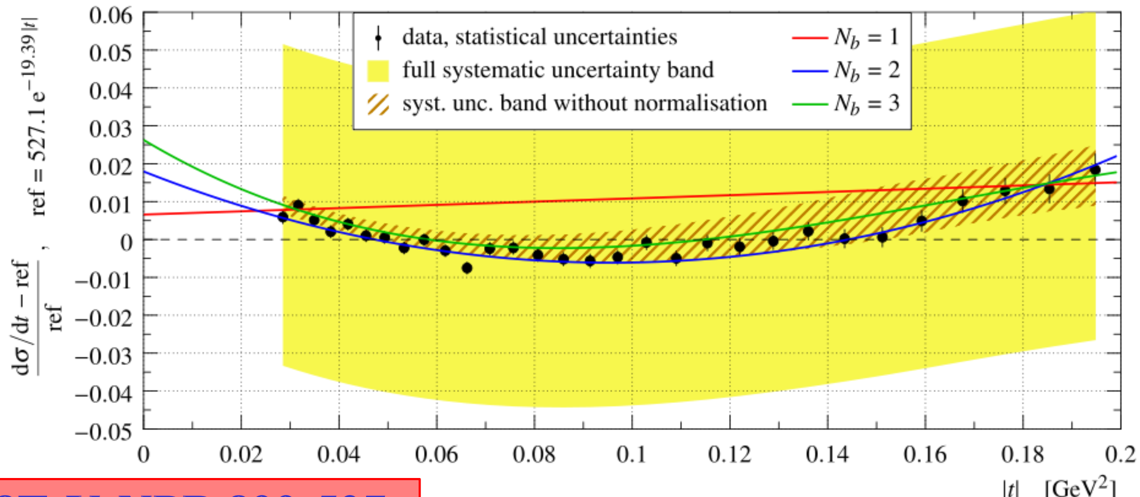
$$d\sigma/dt \propto |F^{C+H}|^2 = \text{Coulomb} + \text{hadronic} + \text{"interference"}$$

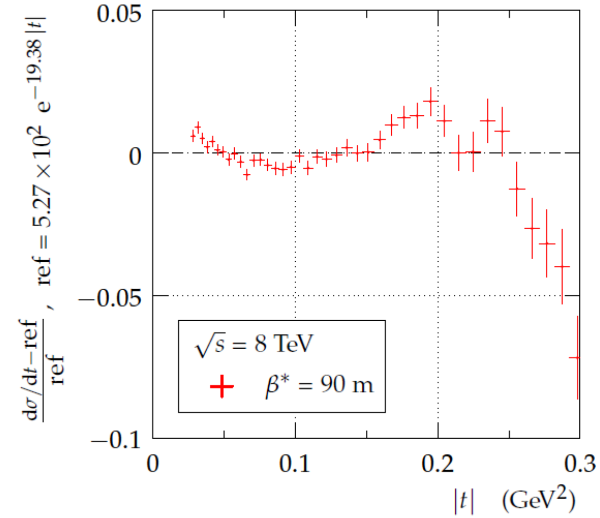
from QED

constrained by measured $e^{-B(t)}$
$B(t) = b_1 t + b_2 t^2 + \ldots$
N_b = # parameters in exp.

***Simplified West-Yennie (SWY)*: often used "standard", only compatible with pure exponential amplitude & constant phase**

- Now exclude Coulomb-hadronic interference with constant phase & constant exponential slope for hadronic amplitude (N_b= 1) at >7σ using same data ⇒ ruling out SWY approach

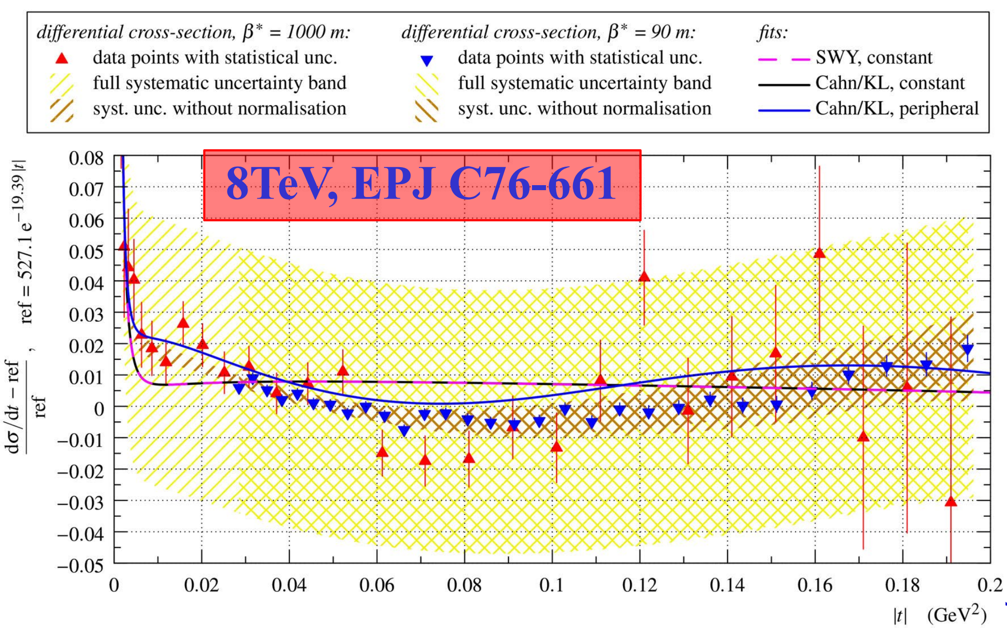


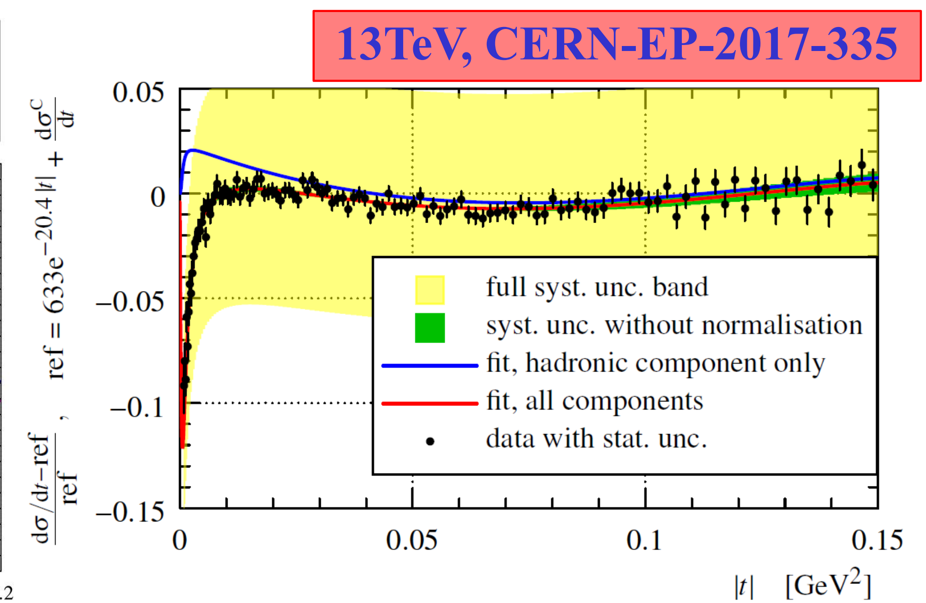


8TeV, NPB 899-527

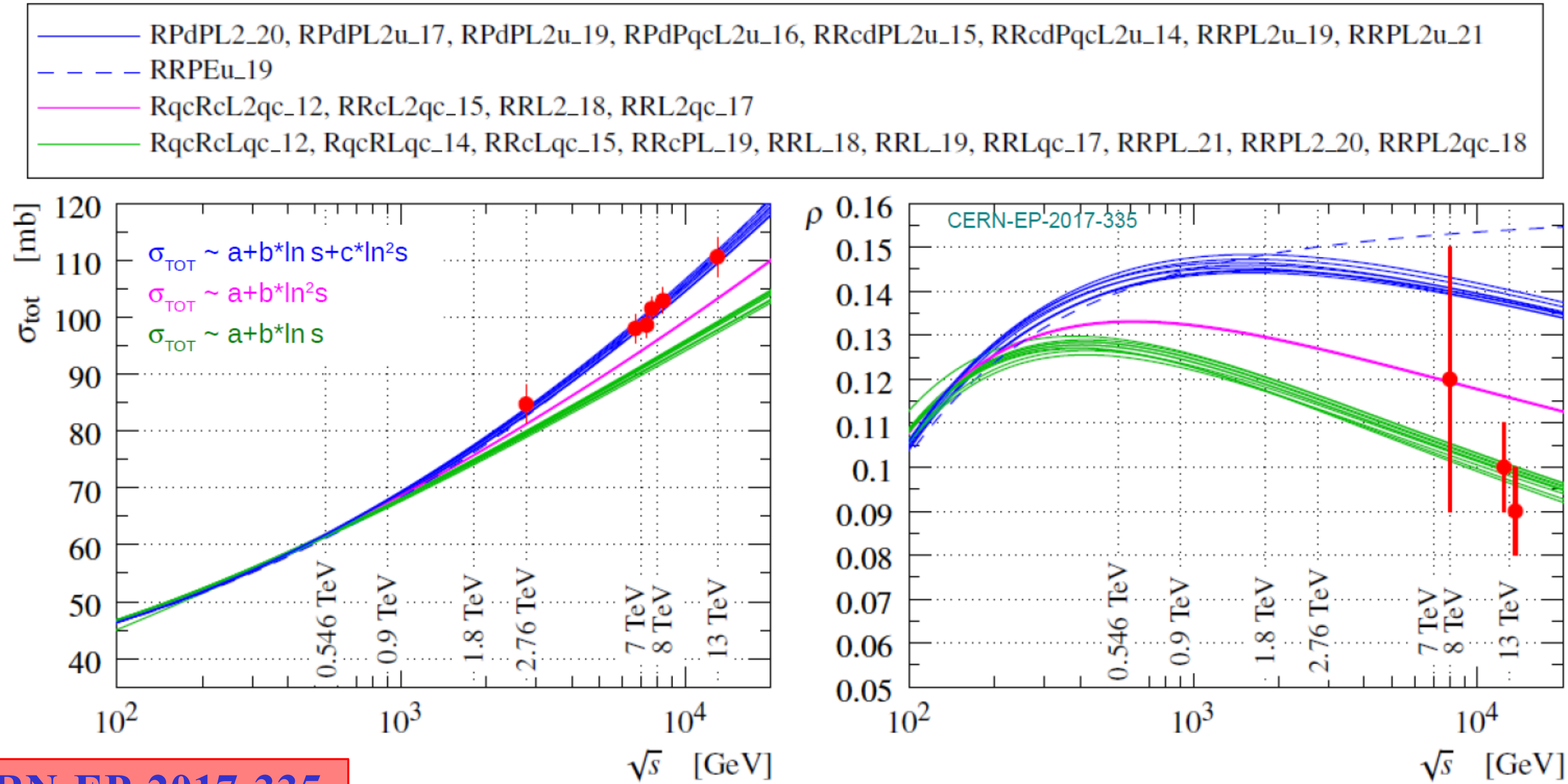
Elastic scattering: Non-exponential behavior at low-t

- Already observed at ISR and SPS: confirmed at LHC energies a change of slope ~ 0.1GeV^2 with faster decrease $|t|>0.2$ GeV^2
- The pure exponential behavior of nuclear amplitude is excluded (constant phase excluded,peripheral phase disfavored)
- Non exponential ($N_b=3$) with both constant and peripheral phase is compatible with data.





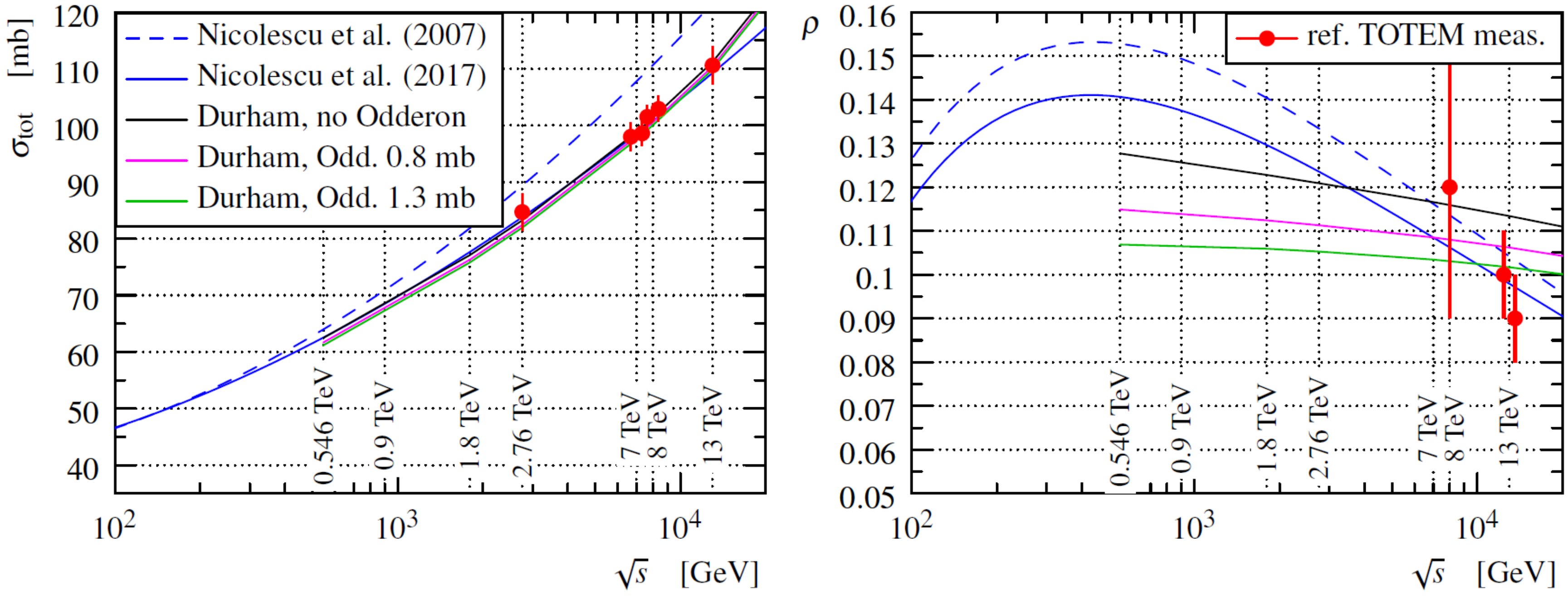
σ_{tot} & ρ: model comparisons



CERN-EP-2017-335

- None of the COMPETE models is able to describe σ_{tot} and ρ at the same time.

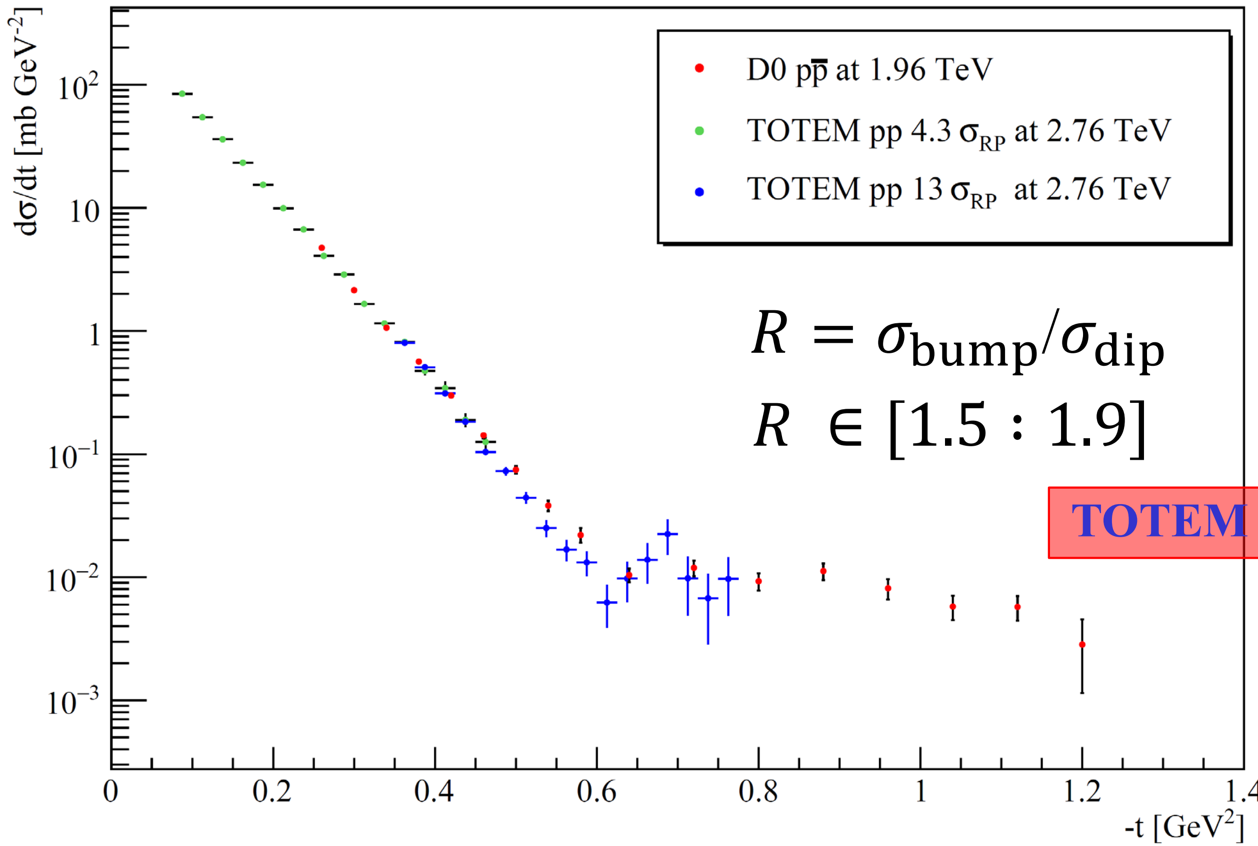
σ_{tot} & ρ: odderon hints?



CERN-EP-2017-335

- t-channel exchange of a colourless 3-gluon bound state (JPC = 1--) could decrease ρ in pp collisions at large energy.

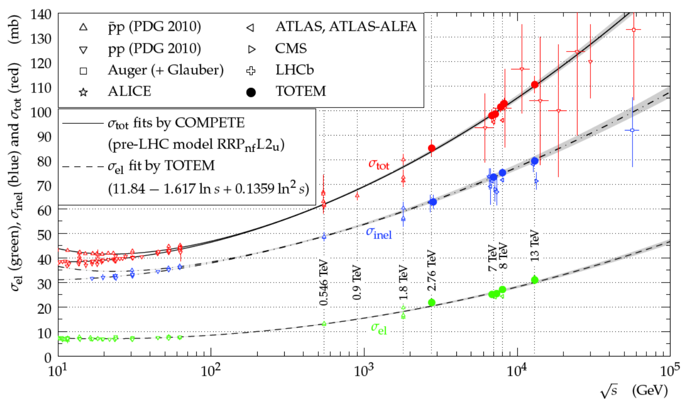
σ_{tot} & ρ: odderon hints?



- Theoretical prediction for R @ 2.76 TeV:
  - No-odderon model -> 1.16 [Durham]
  - Odderon models -> ~1.5 [Nicolescu] - 1.82 [Durham]
- Physics goal is to probe differences of pp and $p\bar{p}$ differential cross section at the TeV energy scale. Work in progress with D0 collaboration.
- These TOTEM preliminary results support the existence of a 3-gluons odderon exchange

Conclusion

- TOTEM has made extensive measures related to σ_{tot} and elastic scattering at LHC.
- The (experimental) hints of odd-state seems confined in the sensitivity in the t-channel, although several theories predict the existence of such object (Odderon, 3g-bound state, vector glueball).
- TOTEM contributions (observed/confirmed) to the predictions:
  - the growth rate of the total cross-section;
  - decrease of ρ at high energies;
  - diffractive dip in the proton-proton elastic t-distribution;
  - the deviation of the elastic differential cross-section from a pure exponential;
  - the deviation of the elastic diffractive slope, B, from a linear log(s) dependence;
  - the variation of the nuclear phase as a function of t;
  - the large-|t | power-law behavior of the elastic t -distribution with no oscillatory behavior.
- What next:
  - Precise measurement of ρ at low energy (900 GeV);
  - σ_{tot} at 14TeV (Run III).



THANKS!!!