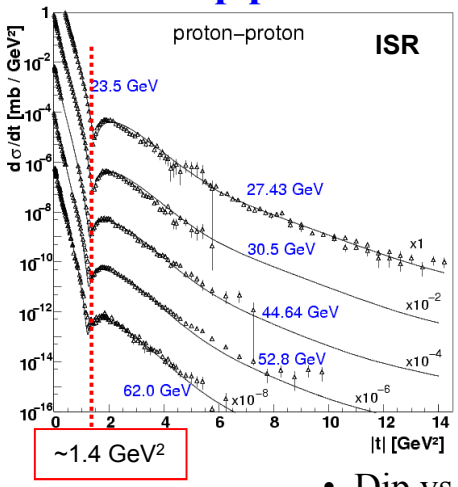
Recent Elastic and Total Cross-Section Measurements by

Mario Deile
on behalf of the TOTEM Collaboration

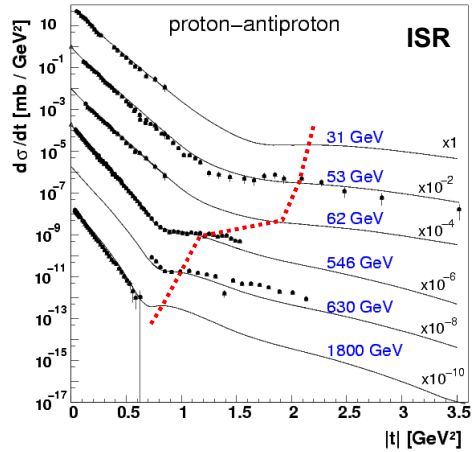
EDS Blois 2019: The 18th Conference on Elastic and Diffractive Scattering
June 23-29, 2019
ICISE, Quy Nhon, Vietnam

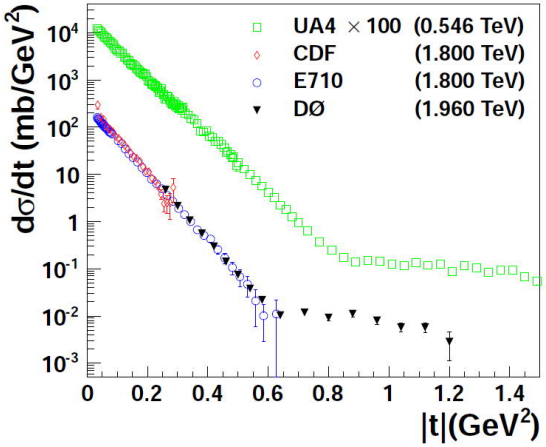
Elastic scattering – from ISR to Tevatron: Old Trends

p p



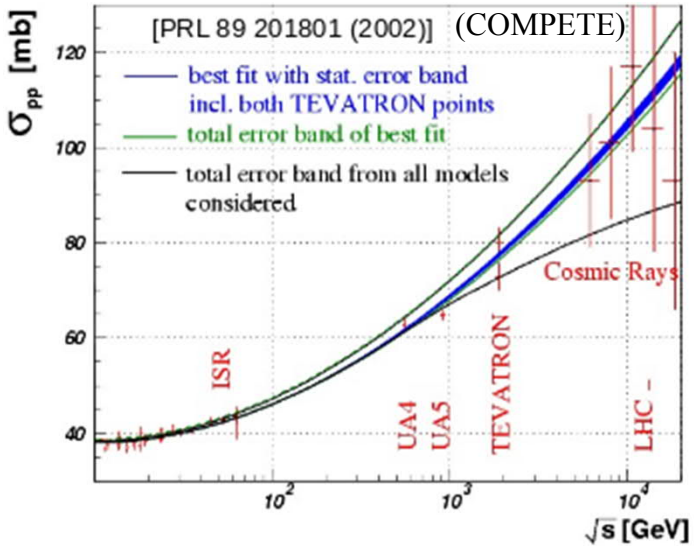
p $\bar{p}$



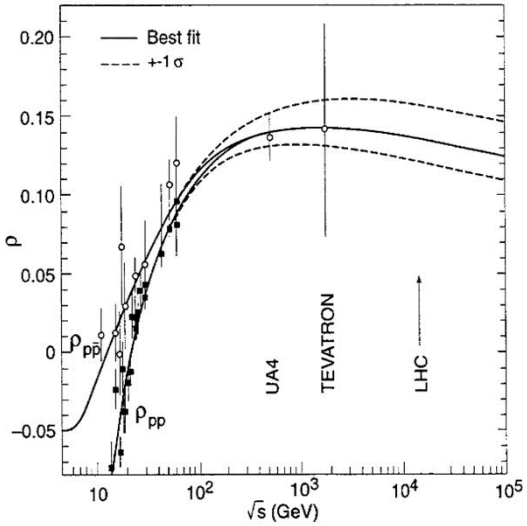


$|t| \approx p^2\,\theta^2$

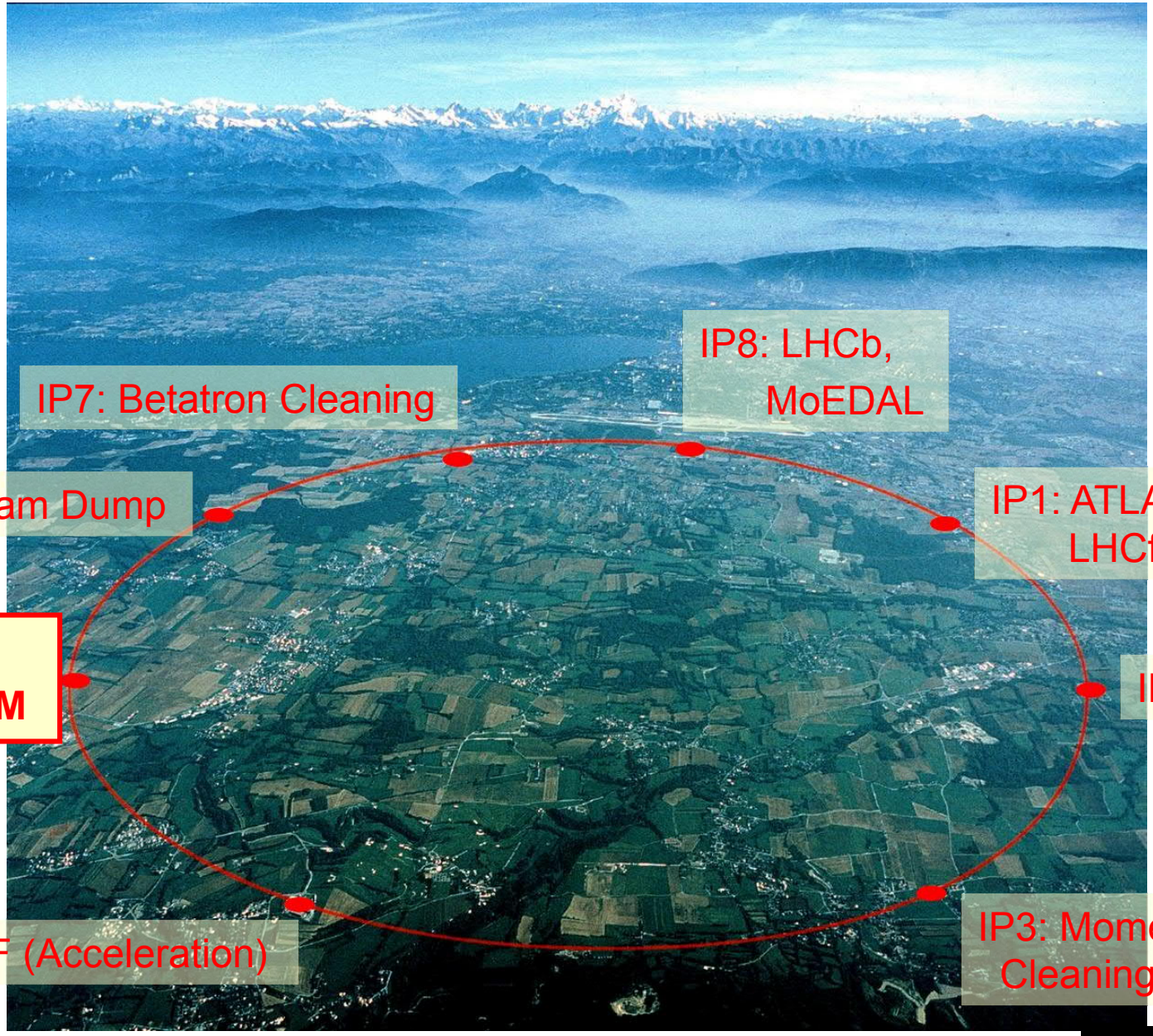
- Dip vs. shoulder
- Dip position: shrinkage of forward peak
- Any further peaks at large |t| ? Wide range of predictions.



- Evolutions $\sigma_{tot}(s)$, $\rho(s)$?
- No pp data after ISR
- $\sigma_{el}/\sigma_{tot}(s)$?



The TOTEM Experiment at the LHC



Experimental Setup at IP5 in Run 1

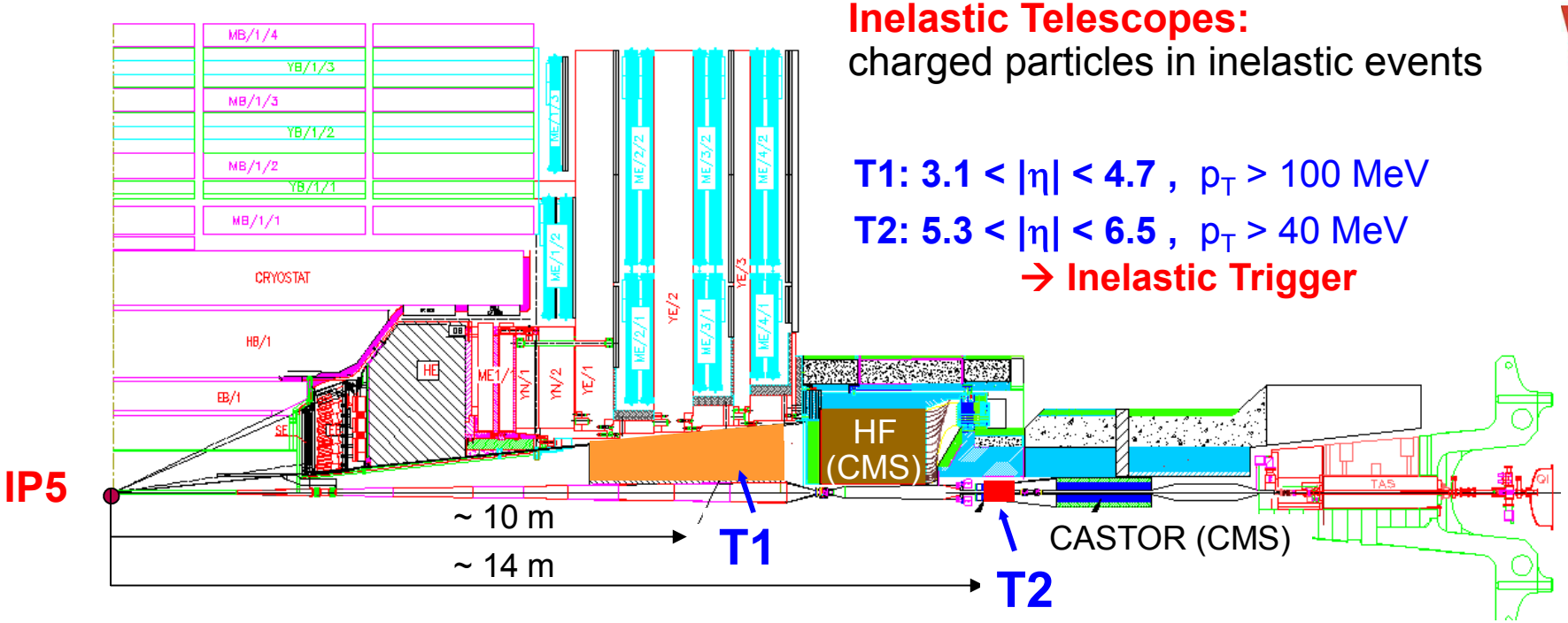
[Ref.: JINST 3 (2008) S08007]

Inelastic Telescopes:
charged particles in inelastic events

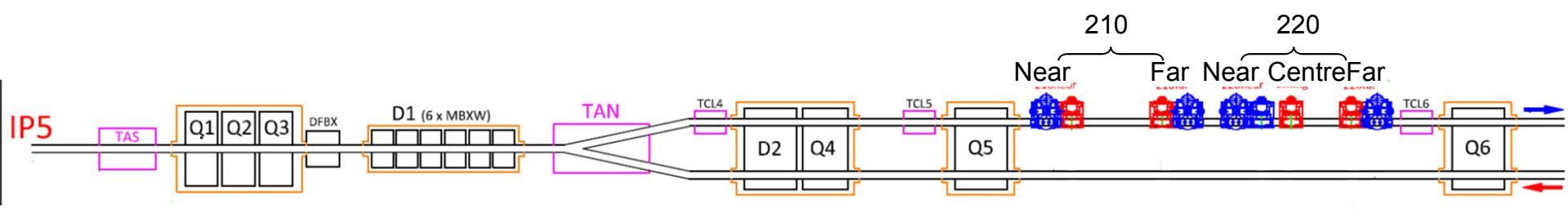
T1: 3.1 < |η| < 4.7 , p_T > 100 MeV

T2: 5.3 < |η| < 6.5 , p_T > 40 MeV

→ Inelastic Trigger



Roman Pots: elastic & diffractive protons close to outgoing beams **→ Proton Trigger**



Measurement and analysis techniques covered in past presentations and in the appendix (just ask!).

History of Elastic and Total Cross-Section Measurements

Run I

Run II

2011

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

2012

- σ_{tot} lumi-independent @7 TeV
- **Elastic**, inelastic cross section
- Elastic: full t-range
EPL 101-21004/21003/21002

2013

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

2015

- $d\sigma/dt$ **elastic** :
non- exponential behaviour @ 8 TeV
NPB 899-527

2016

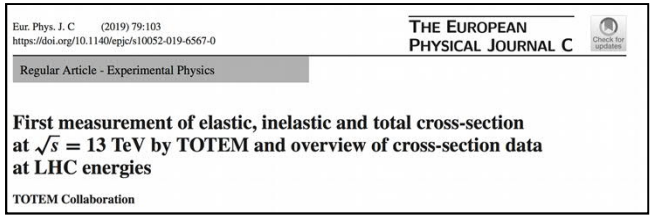
- ρ measurement @ 8 TeV
EPJ C76-661

2017

- σ_{tot} lumi independent @ 2.76 TeV
PoS (DIS2017) 059
- σ_{tot} lumi independent @ 13 TeV
Eur.Phys.J. C79 (2019) 103
- ρ measurement @ 13 TeV
CERN-EP-2017-335, arXiv:1812.04732,
submitted to EPJC

2018

- **$d\sigma/dt$** elastic: dip @ 13 TeV
CERN-PH-EP-2018-338,
arXiv:1812.08283
- **$d\sigma/dt$** elastic: dip @ 2.76 TeV
CERN-PH-EP-2018-341,
arXiv:1812.08610
- data taking at 900 GeV, CNI region


Eur. Phys. J. C (2019) 79:103
https://doi.org/10.1140/epjc/s10052-019-6567-0

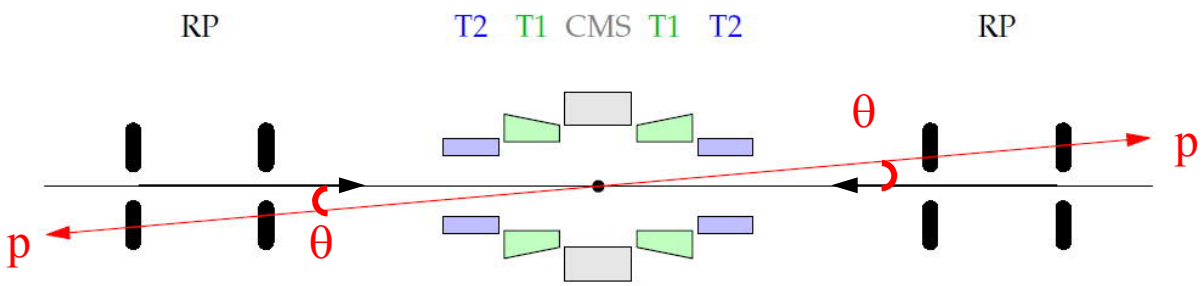
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies

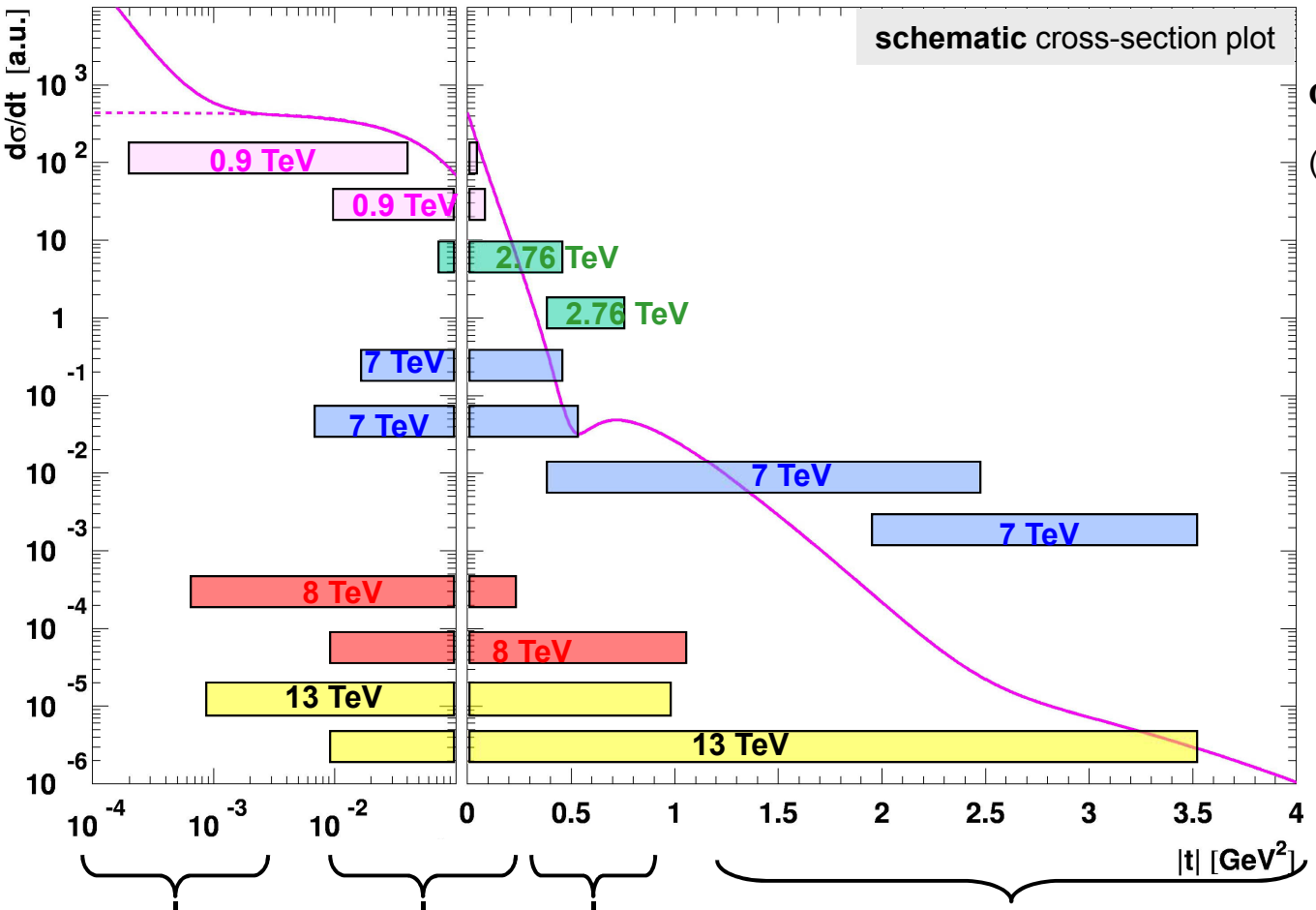
TOTEM Collaboration

Elastic Cross-Section Measurements



Elastic Scattering Cross-Section Measurements

Data sets at different energies covering a wide |t| range



Optics,	XRP Approach distance
(β_x^*, β_y^*) = (70 m, 100 m),	3 σ
β* = 11 m,	3 σ
β* = 11 m,	5 σ
β* = 11 m,	**13 σ**
β* = 90 m,	10 σ
β* = 90 m,	5 σ
β* = 3.5 m,	7 σ
β* = 3.5 m,	18 σ
β* = 1 km,	3σ
β* = 90 m,	6 σ
β* = 2.5 km,	**3 σ**
β* = 90 m,	**5 σ, 10 σ**

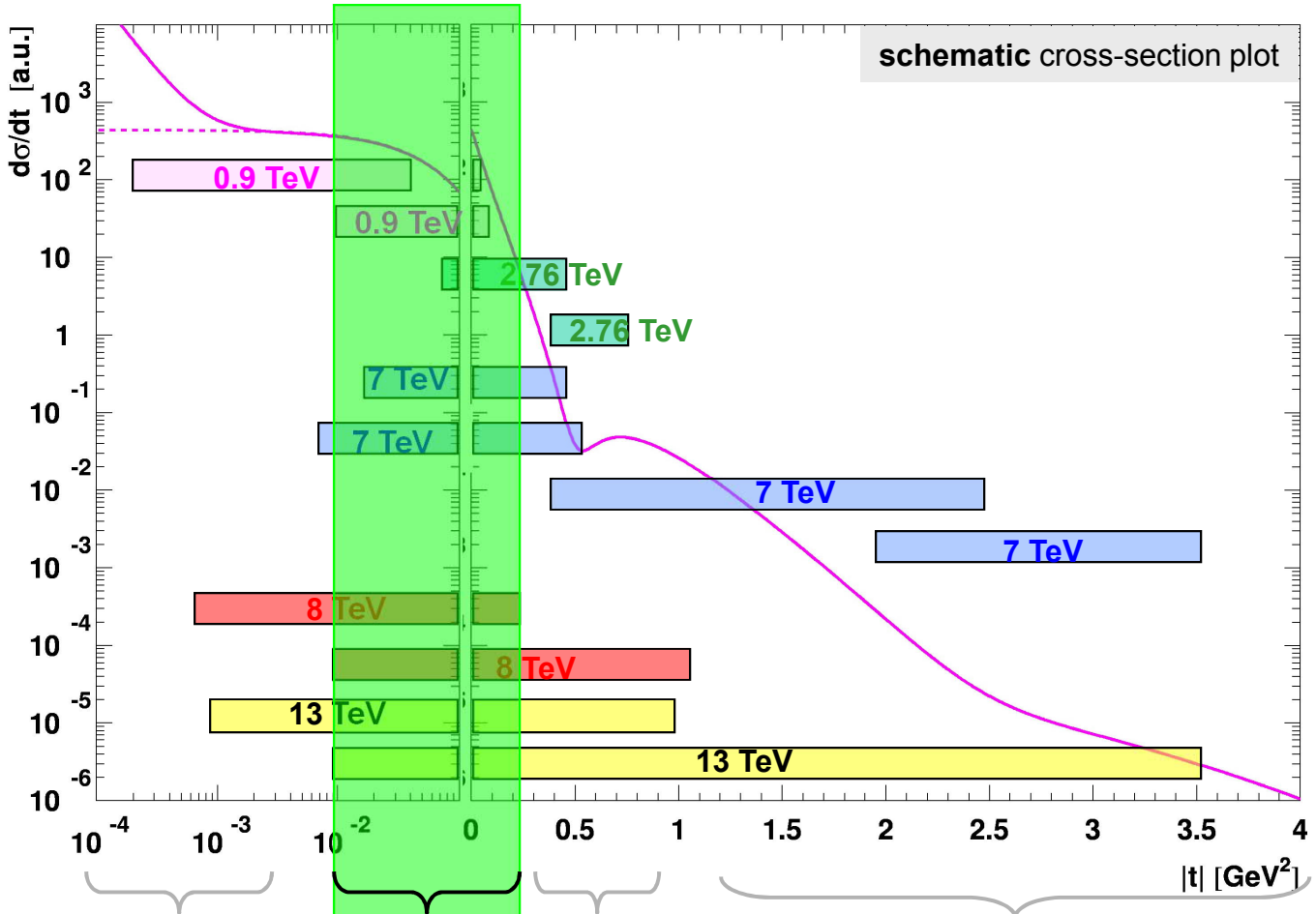
perturbative QCD region: > 1 GeV^2

Dip-bump region: ~0.4 – 1 GeV^2

"Exponential" region ("Pomeron" exchange): O(10^{-2} GeV^2) – O(10^{-1}GeV^2)

Coulomb and CNI region: < ~10^{-3} GeV^2

Elastic Scattering: Exponential Region



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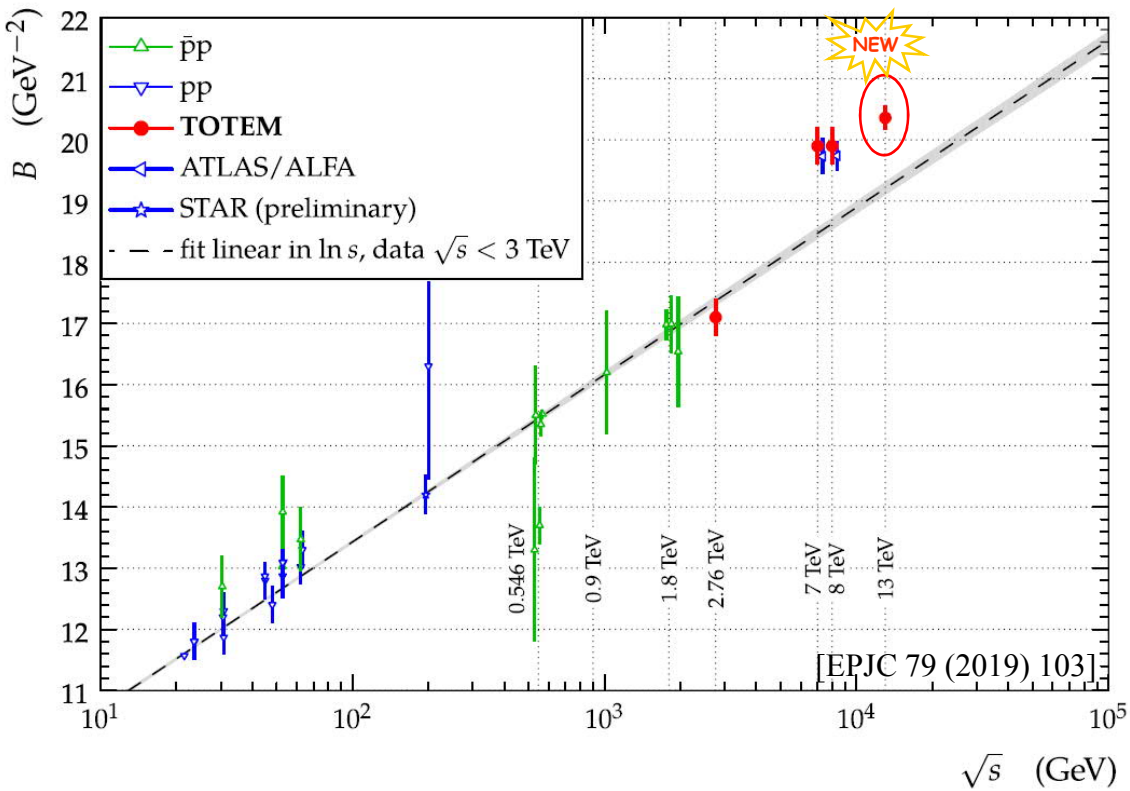
Elastic Scattering: The "Exponential" Region at low |t|

New measurement at 13 TeV confirms:

Steepening increase of nuclear elastic slope B with √s :

$$\frac{d\sigma}{dt} = e^{-B|t|}$$



Up to ~ 3 TeV: compatible with simple Regge model:

$$\frac{d\sigma}{dt} \propto s^{2[\alpha(t)-1]}, \quad \alpha(t) = \alpha_0 + \alpha' t \quad \Rightarrow B = B_0 + 2\alpha' \ln s$$

Around 3 TeV: B(s) trend changes: threshold to new effects ?

E.g. multi-Pomeron exchanges: B ∝ ln s → (ln s)^2 [A. Donnachie, P.V. Landshoff: PRD 85 (2012) 094024]

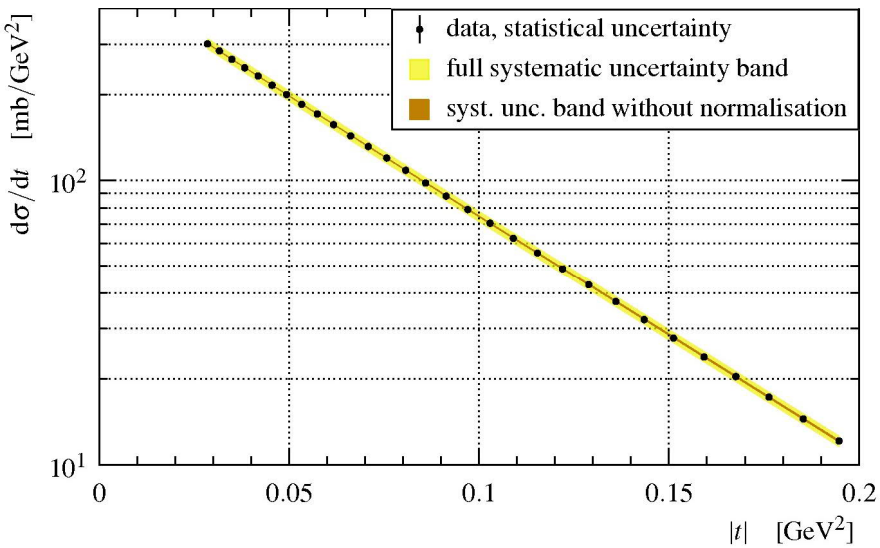
Elastic Scattering: The "Exponential" Region at low |t|

Is it really exponential?

Data set with 7 M events ($\sqrt{s}$ = 8 TeV, β^* = 90 m):

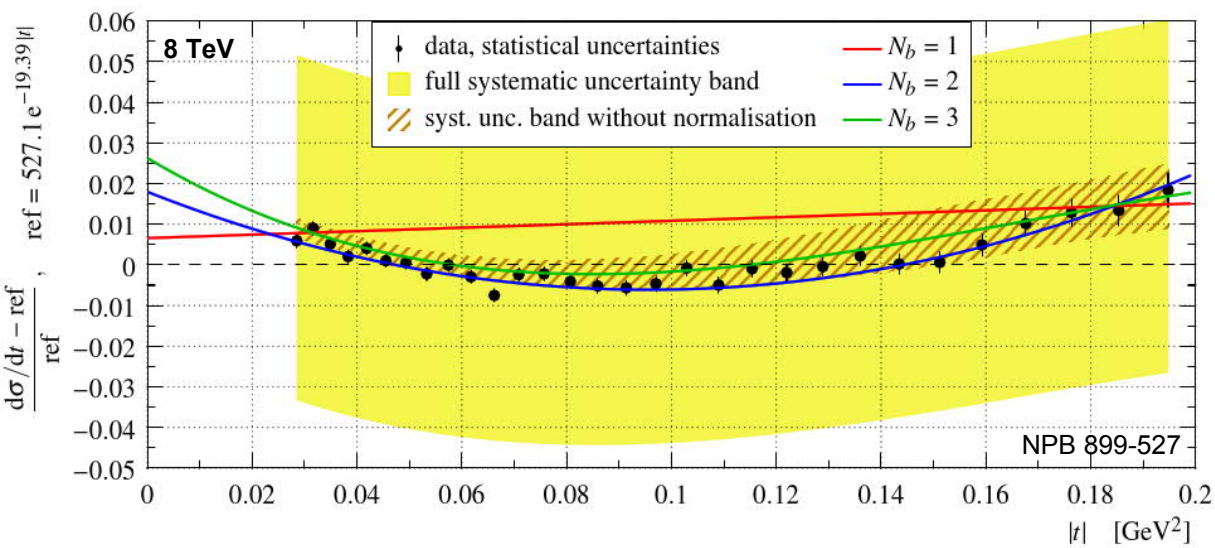
0.027 GeV^2 < |t| < 0.2 GeV^2 ,

i.e. Coulomb effects negligible



Quite exponential at the first glance, but a closer look reveals …

Relative deviation from exponential: $\frac{d\sigma/dt - \text{ref}}{\text{ref}}$



$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i t^i\right),$$

N_b	χ^2/ndf	p-value	significance
1	117.5/28 = 4.20	$6.1 \cdot 10^{-13}$	7.2 σ
2	29.3/27 = 1.09	0.35	0.94 σ
3	25.5/26 = 0.98	0.49	0.69 σ

Pure exponential form (N_b = 1) excluded at 7.2 σ significance.

[NPB 899 (2015) 527]

… a percent-level deviation only visible with very high statistics.

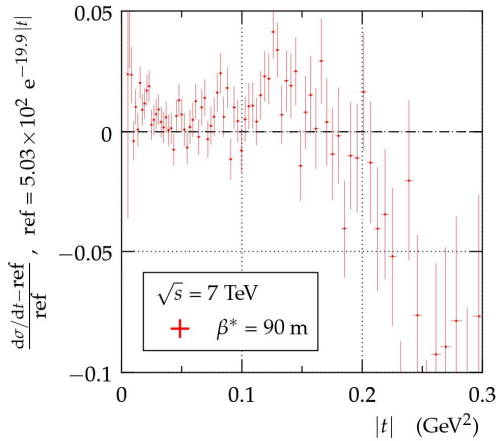
Elastic Scattering: The "Exponential" Region at low |t|

Non-exponentiality at $|t| < 0.2$ GeV^2: similar pattern observed also at $\sqrt{s}$ = 7 and 13 TeV

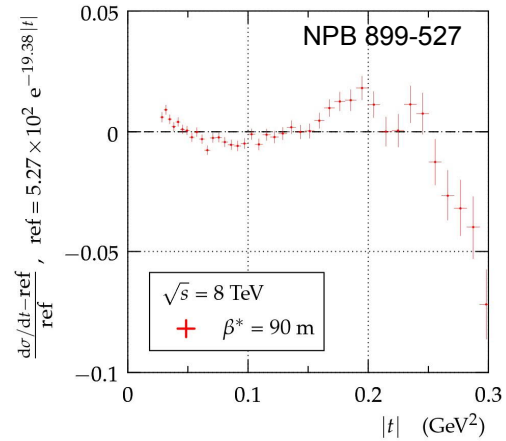
$$\frac{d\sigma/dt - \text{ref}}{\text{ref}}$$

where ref = fixed exponential function $A\, e^{-B|t|}$

7 TeV

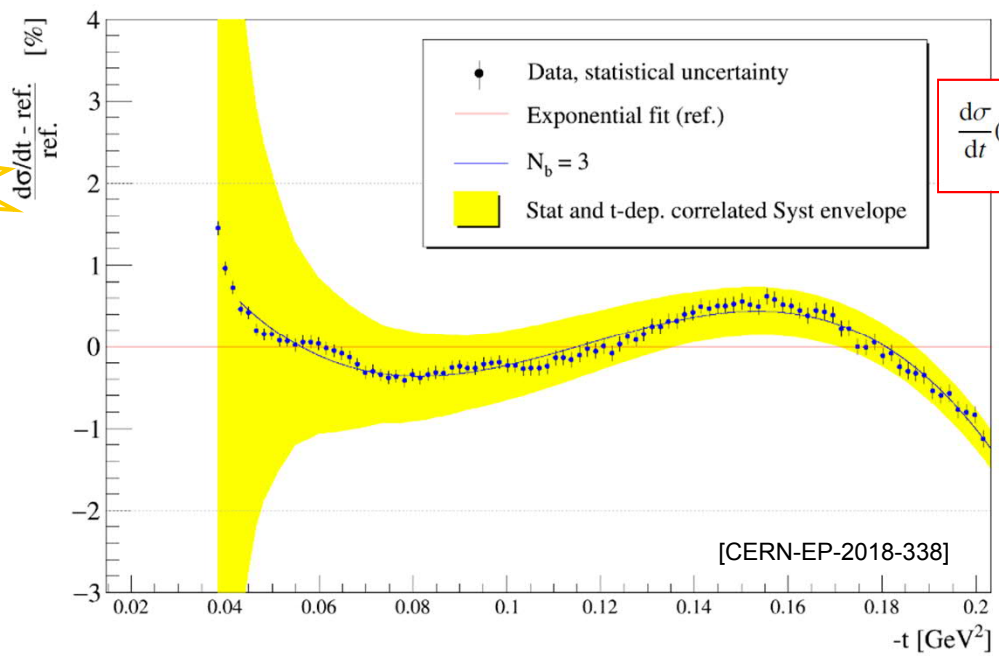


8 TeV



13 TeV

NEW

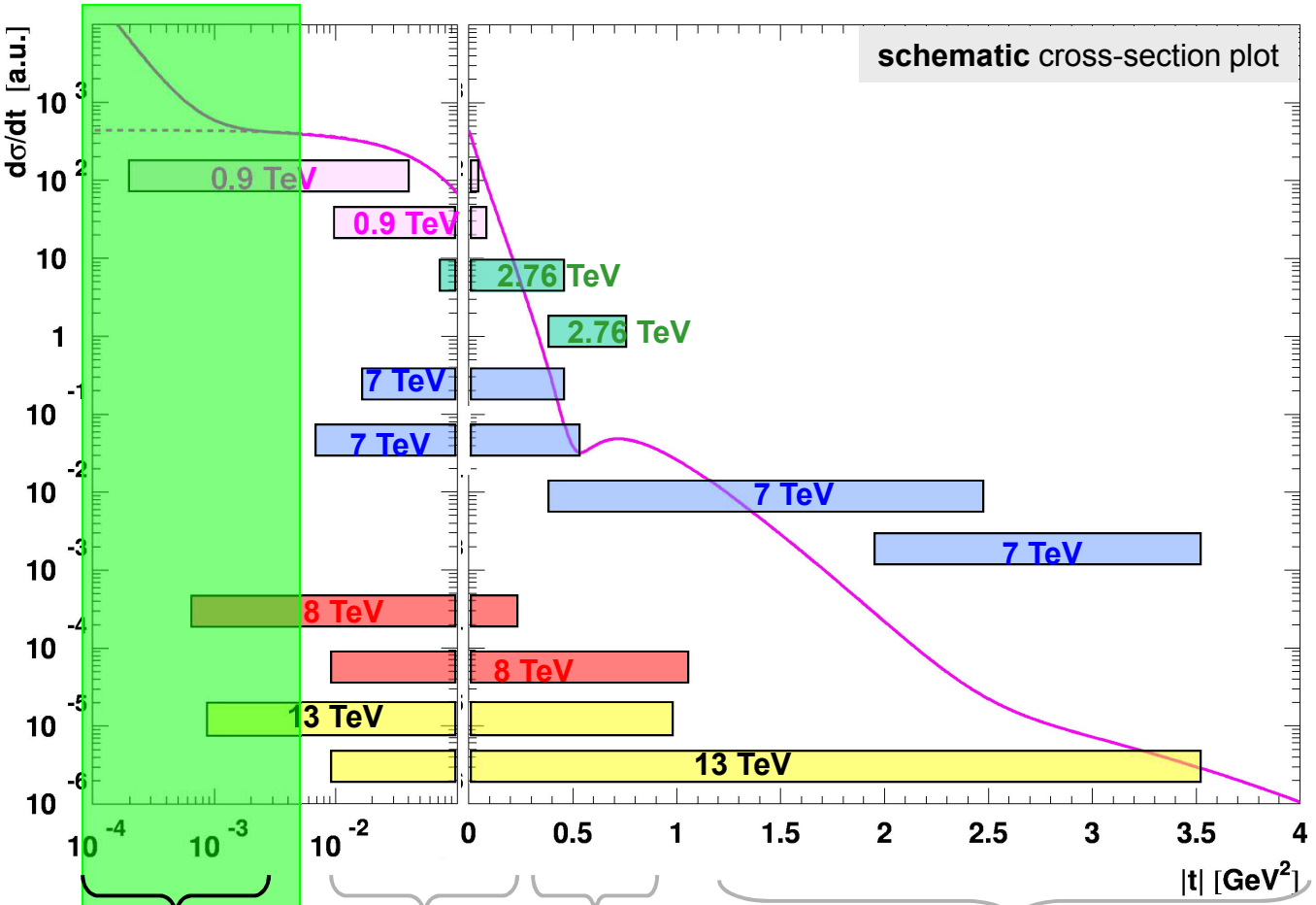


$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i\, t^i\right),$$

Can this be due to CNI effects?
(although fit region strongly dominated by nuclear amplitude)

→ **Include region at even lower |t| !**

Elastic Scattering: Coulomb and CNI Region



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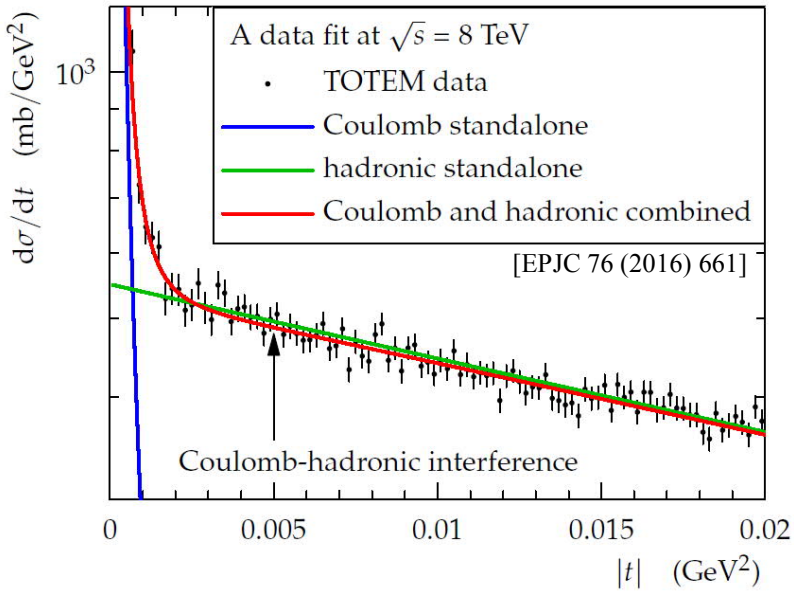
Elastic Scattering: Coulomb-Nuclear Interference Region

Measure elastic scattering at |t| as low as 6 x 10^{-4} GeV^2 (8 TeV) and 8 x 10^{-4} GeV^2 (13 TeV)

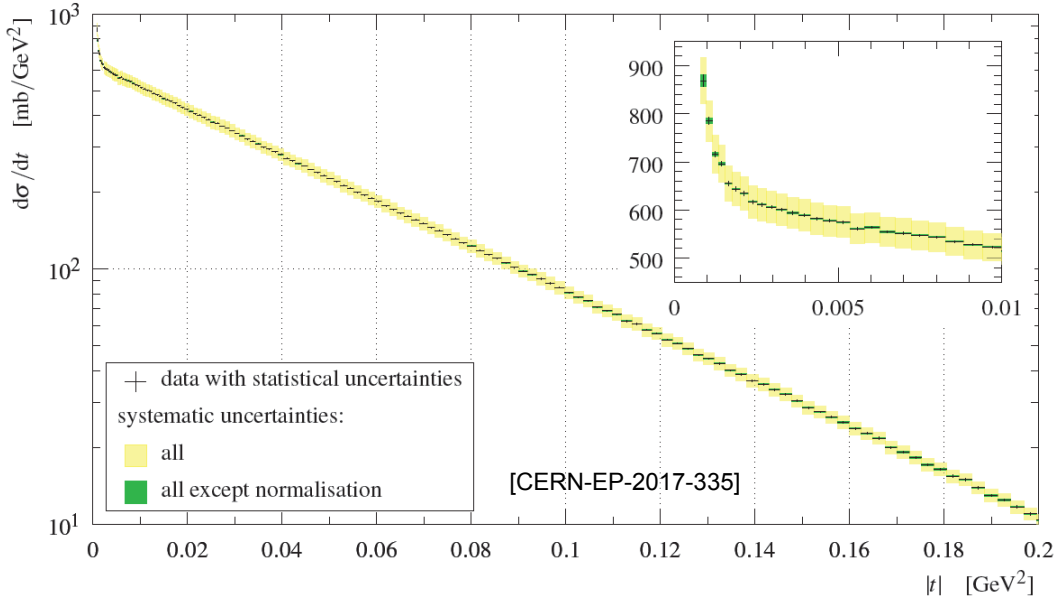
- optics specially developed for measurements at very low |t| ($\beta^* = 1 - 2.5$ km)
- RP approach to 3 σ from the beam centre

$\sqrt{s}$ = 8 TeV, $\beta^* = 1000$ m

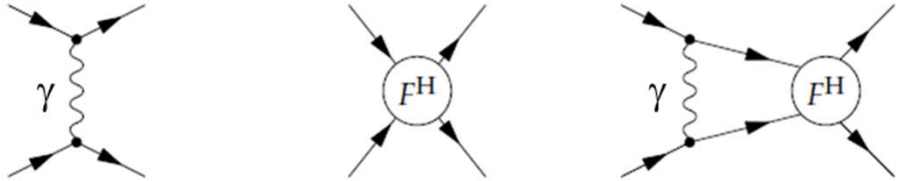


NEW

$\sqrt{s}$ = 13 TeV, $\beta^* = 2500$ m



Elastic Scattering: Coulomb-Nuclear Interference Region



$$F^{C+H} = F^C + F^H e^{i\alpha\Psi}$$

$$F^C = \frac{\alpha s}{t}\mathcal{F}^2(t)$$

- Modulus constrained by measurement in nucl. region: $d\sigma/dt \cong A\, e^{-B(t)\,|t|}$

  $B(t) = b_0 + b_1\, t + \ldots$

- Phase $\arg(F^H)$: very little guidance by data

  Interference region: sensitivity to $\arg(F^H)(t=0)$:

$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0)$$

Simplified West-Yennie (SWY) formula (standard in the past):

- constant slope $B(t) = b_0$ → already excluded by 90m data at higher $|t|$ → SWY incompatible with data !
- constant hadronic phase $\arg(F^H) = p_0$
- $\Psi(t)$ acts as real interference phase

Cahn or Kundrát-Lokajíček (KL) formula:

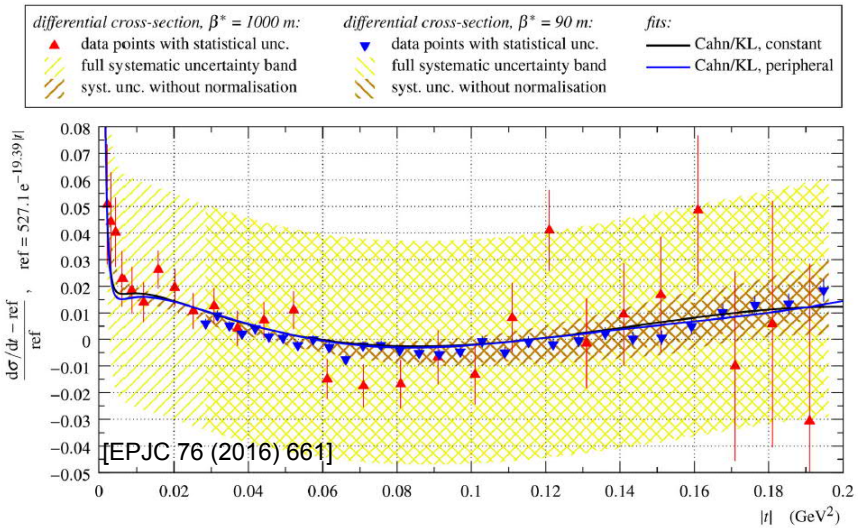
- any slope $B(t)$
- any hadronic phase $\arg(F^H)$: to be chosen as input
- complex $\Psi(t)$!

Choice of hadronic phase $\arg F^H(t)$ controls the behaviour in impact-parameter space (b): elastic scattering preferentially central or peripheral

Elastic Scattering: Coulomb-Nuclear Interference Region

Study of non-exponentiality with Coulomb terms included

8 TeV



Purely exponential hadronic amplitude

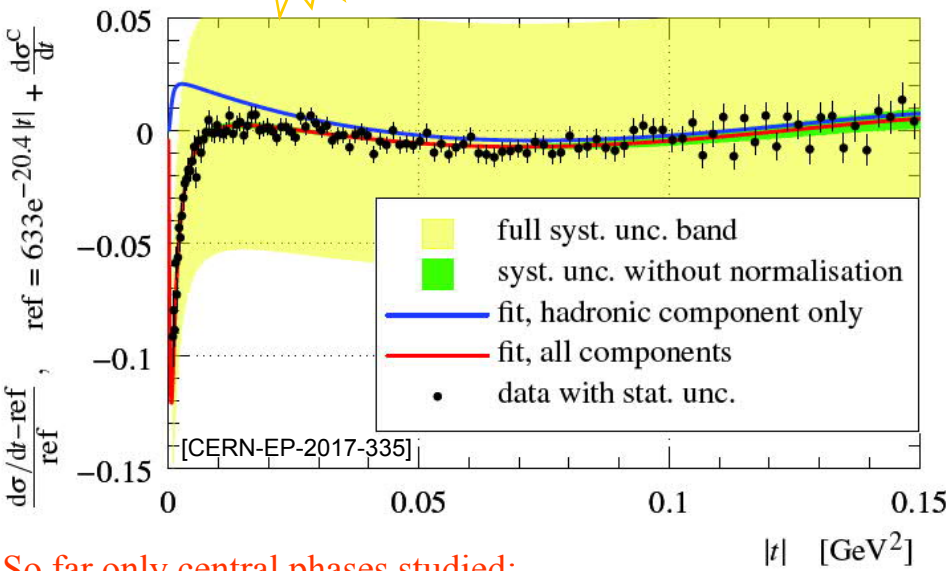
- excluded assuming a central (e.g. constant) phase
- not explicitly excluded by data if peripheral phase

Non-exponential hadronic amplitude

Both central & peripheral phase compatible with data

Same result $\rho = 0.12 \pm 0.03$
for central and peripheral phase

13 TeV NEW



So far only central phases studied:

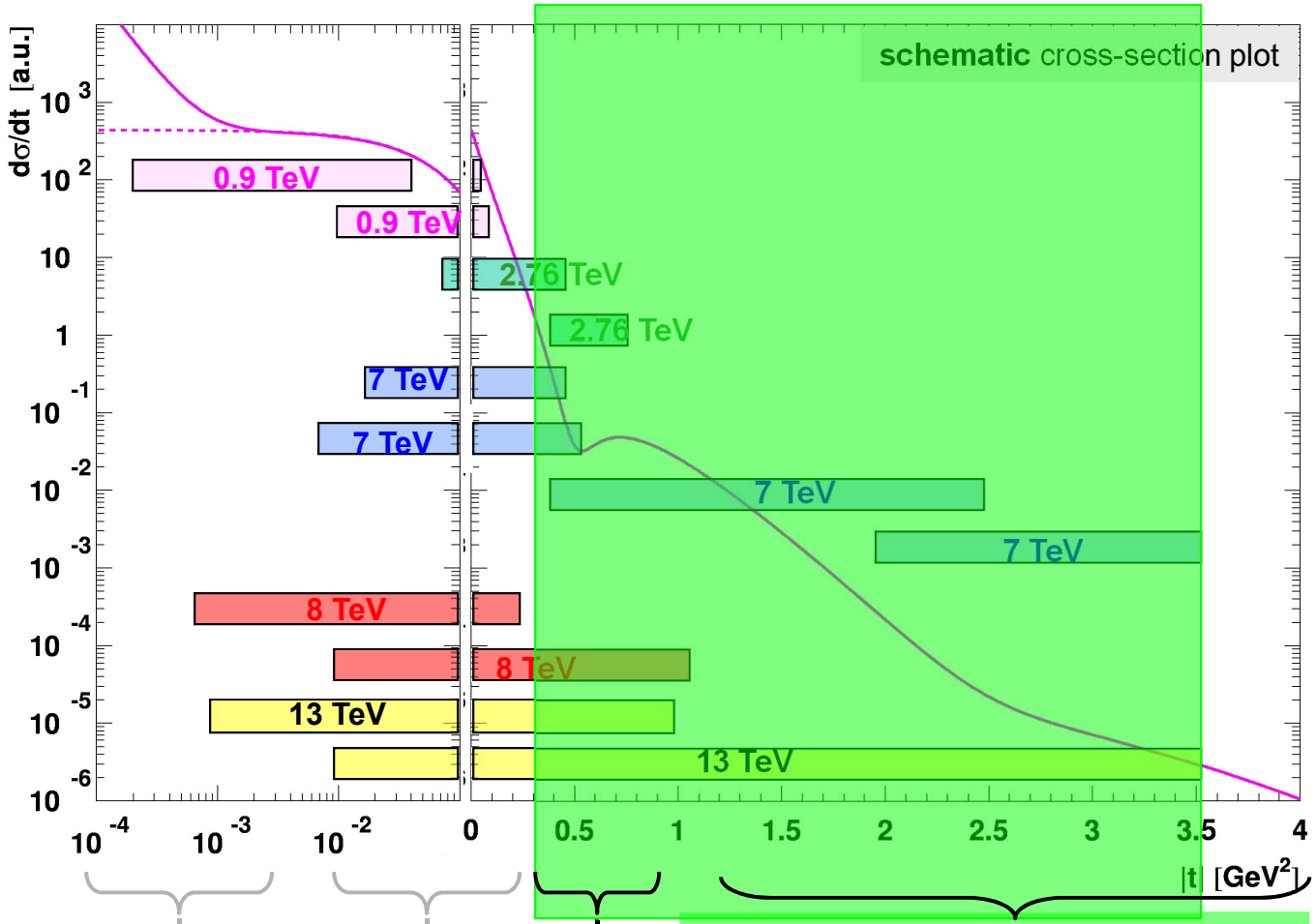
non-exponentiality confirmed.

N_b	$\lvert t\rvert_{max} = 0.07$ GeV^2 χ^2/ndf	ρ	$\lvert t\rvert_{max} = 0.15$ GeV^2 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

$|t|_{max} = 0.07$ GeV^2
→ comparison with UA4/2 (same range)

→ Discussion of $\rho(s)$ after σ_{tot}

Elastic Scattering: The Dip and Beyond



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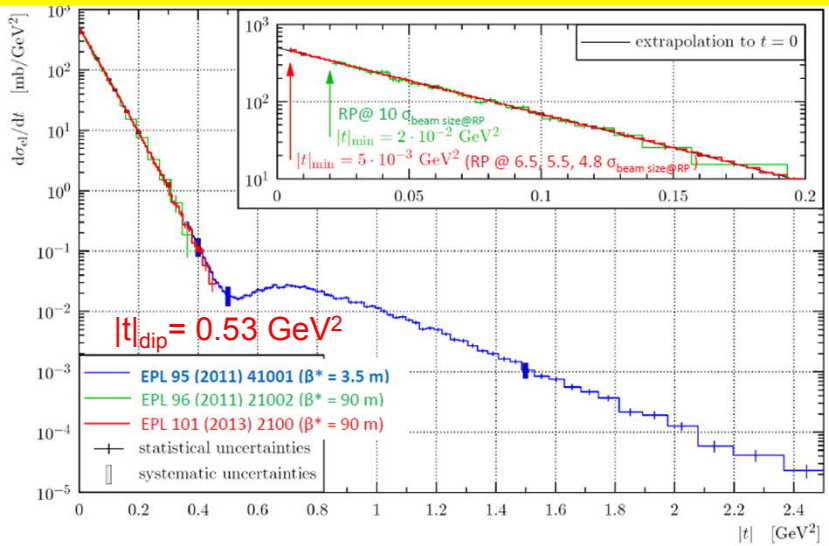
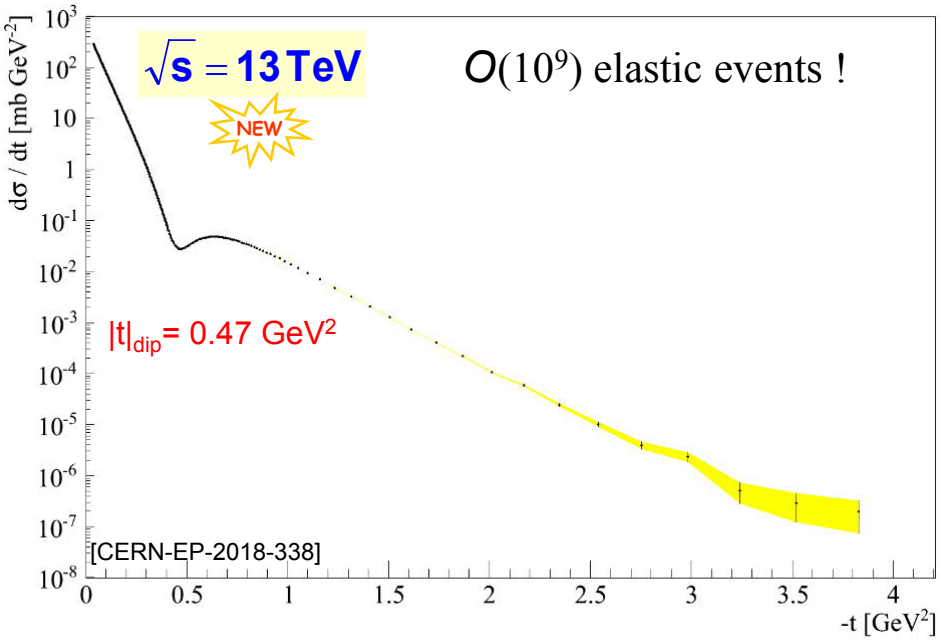
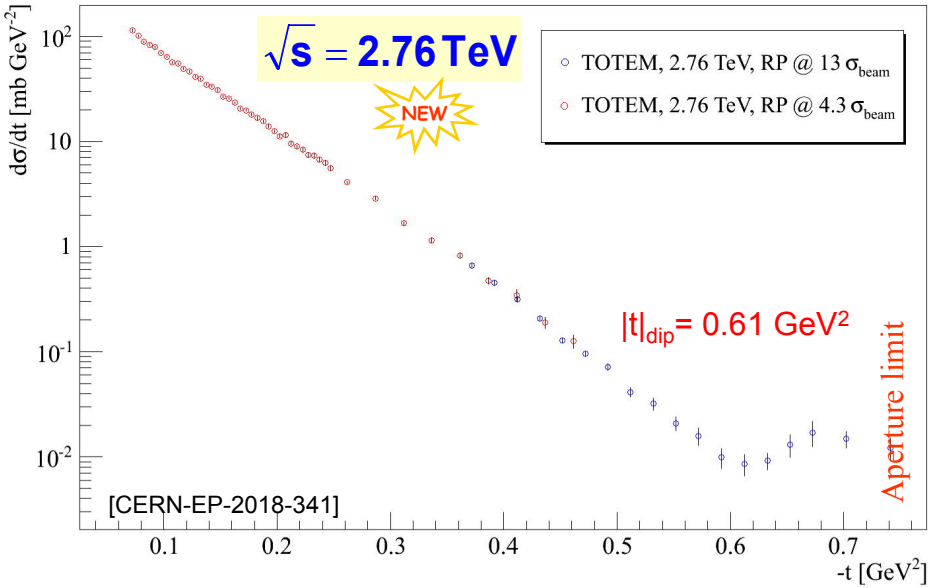
Elastic Scattering: The Dip and Beyond

$\sqrt{s} = 7$ TeV







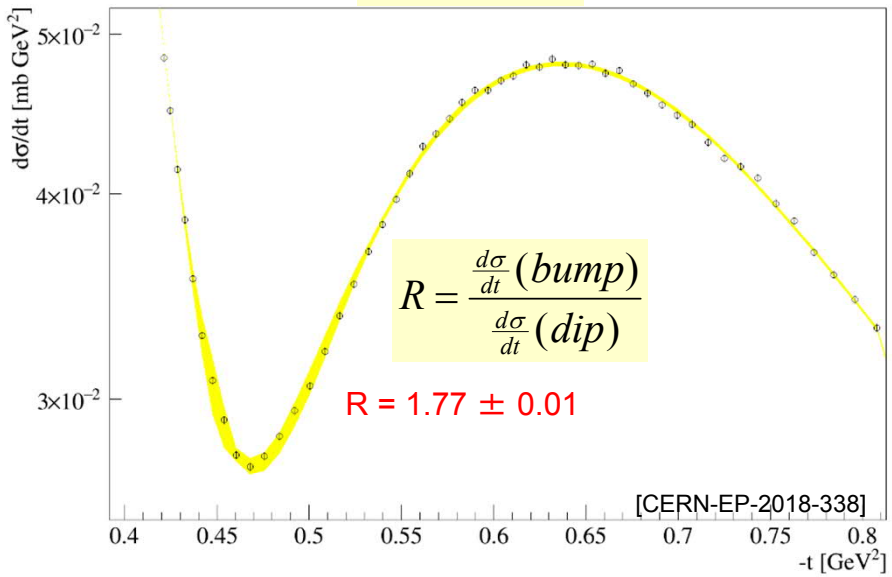
No structure at high |t| beyond the dip/bump !

Elastic Scattering: The Dip and Beyond

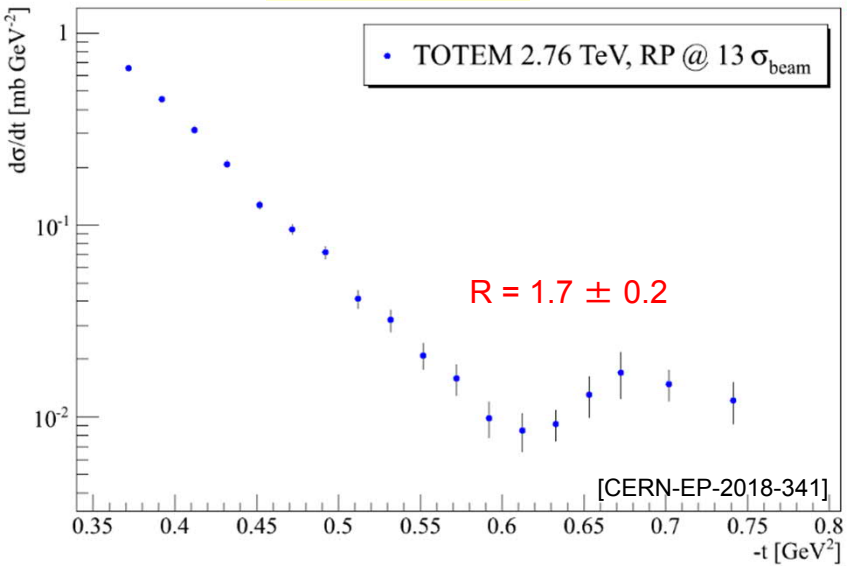
NEW

Focus on the Dip; Comparison pp – p pbar

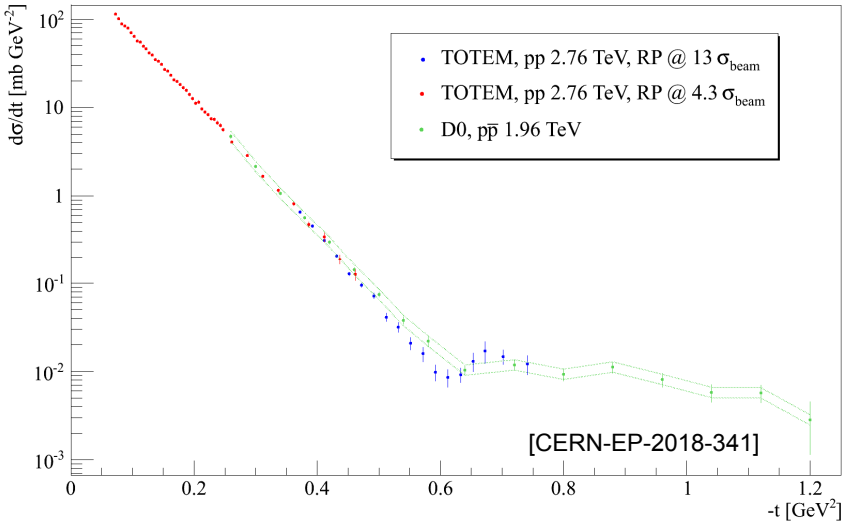
$\sqrt{s} = 13\,\text{TeV}$



$\sqrt{s} = 2.76\,\text{TeV}$



Joint D0 – TOTEM analysis in progress to quantify dip / shoulder difference:



- Persistence of dip+bump in pp at TeV scale:
  R ~ 1.7 ~ constant
- Absence of dip in ppbar
  R ~ 1

→ Evidence for exchange of colourless C-odd three-gluon compound state ("Odderon")

Total pp Cross-Section

Total Cross-Section: Methods and Results

7 TeV

elastic observables only: (with optical theorem)

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

(ρ=0.14 [COMPETE extrapolation])

June 2011: $\sigma_{tot} = (98.3 \pm 2.8)$ mb [EPL 96 (2011) 21002]

Oct. 2011: $\sigma_{tot} = (98.6 \pm 2.2)$ mb [EPL 101 (2013) 21002]

different beam intensities !

σ_{tot}

ρ independent: (without optical theorem)

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

$\sigma_{tot} = (99.1 \pm 4.3)$ mb

luminosity independent: (with optical th.)

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

$\sigma_{tot} = (98.0 \pm 2.5)$ mb

8 TeV

- Luminosity-independent (β* = 90 m): $\sigma_{tot} = (101.7 \pm 2.9)$ mb [PRL 111(2013) 012001]
- ... improved with non-exponentiality ($N_b = 3$): $\sigma_{tot} = (101.9 \pm 2.1)$ mb [NPB 899 (2015) 527]
- Combining β* = 90 m & 1 km data: Improved extrapolation of hadronic amplitude to t = 0 using CNI fit:
  $\sigma_{tot} = (102.9 \pm 2.3)$ mb (assuming central hadronic phase)
  $\sigma_{tot} = (103.0 \pm 2.3)$ mb (assuming peripheral hadronic phase)
  [EPJC 76 (2016) 661]

2.76 TeV

Luminosity-independent: $\sigma_{tot} = (84.7 \pm 3.3)$ mb using ρ = 0.145 [COMPETE]

Total Cross-Section: Methods and Results

13 TeV NEW

2 Data Sets

First normalisation via Coulomb!

$\beta^* = 90$ m
$|t| \in [0.01; 3.75]$ GeV^2
CNI not covered,
with inelastic data

$\beta^* = 2500$ m
$|t| \in [0.0008; 0.2]$ GeV^2
CNI covered,
no inelastic data

Normalisation

Normalisation constraint

Lumi-independent method

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

$\sigma_{tot} = (110.6 \pm 3.4)$ mb

CNI Fit (for $N_b = 1$)

$\sigma_{tot} = (111.8 \pm 3.2)$ mb, $\rho = 0.09 \pm 0.01$

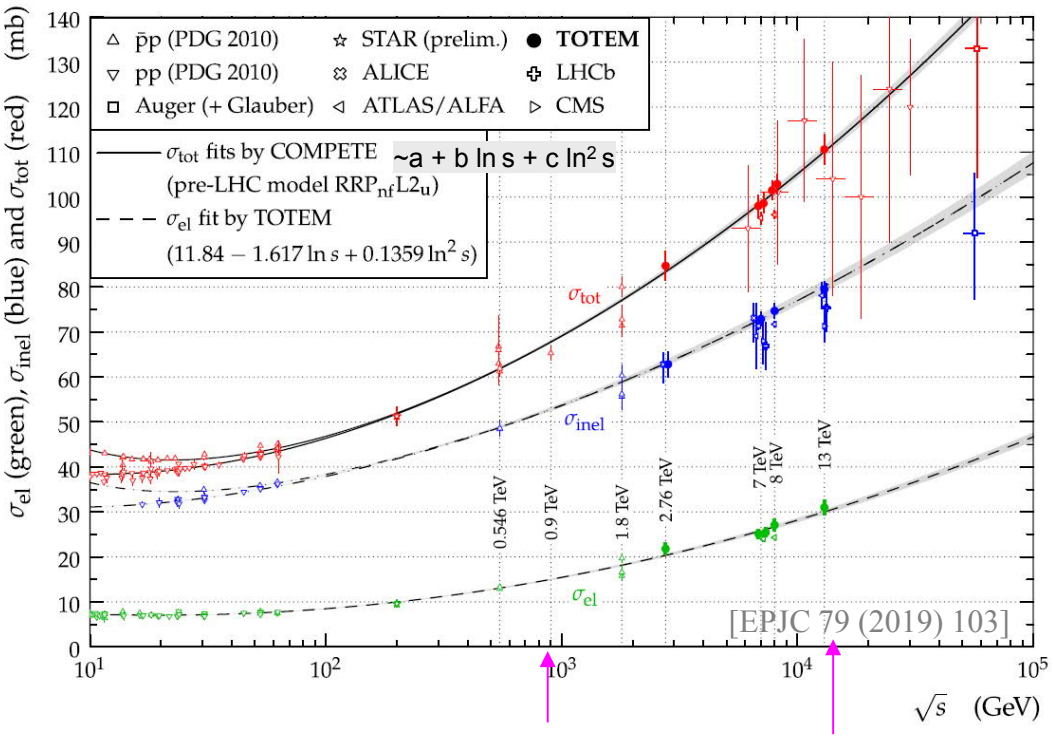
$\sigma_{tot} = (111.3 \pm 3.2)$ mb, $\rho = 0.09 \pm 0.01$

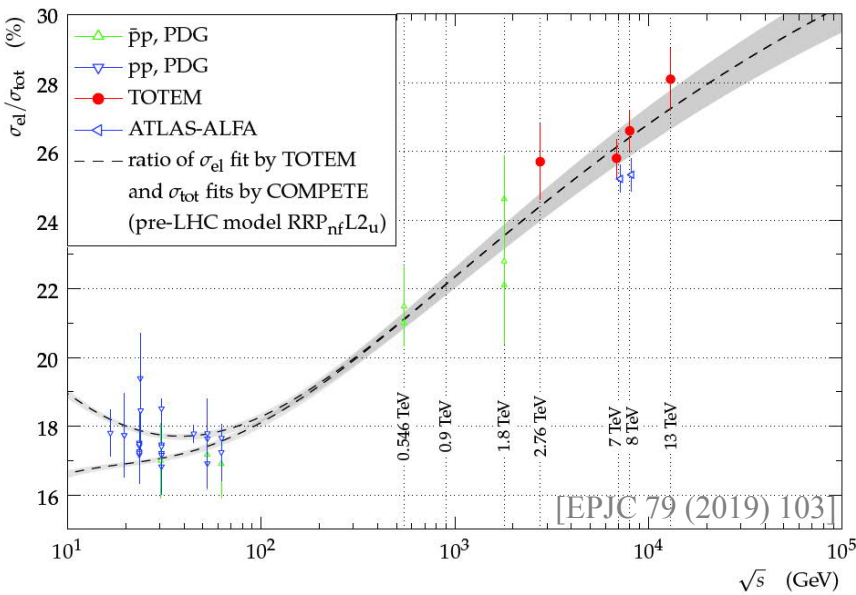
2 variants:
$\sigma_{tot} = (110.3 \pm 3.5)$ mb, $\rho = 0.08(5) \pm 0.01$
$\sigma_{tot} = (109.3 \pm 3.5)$ mb, $\rho = 0.10 \pm 0.01$

fully independent → weighted average

$\sigma_{tot} = (110.5 \pm 2.4)$ mb

pp Cross-Section Measurements





Increase of σ_{el} / σ_{tot} continues.

900 GeV:
data taken in 2018
analysis in progress

14 TeV:
planned for LHC Run 3

√s Trends of ρ and Total Cross-Section

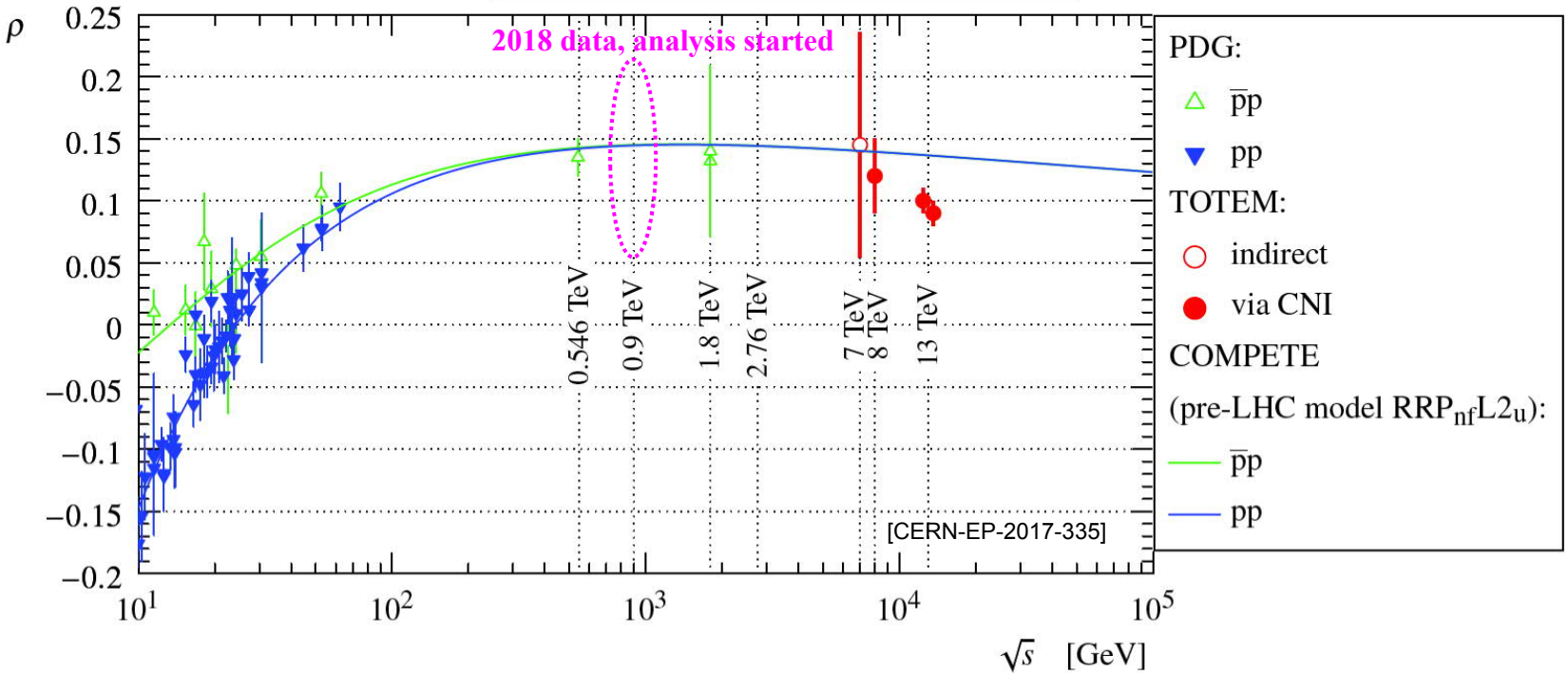
$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0)$$

from CNI analysis (see earlier).

At 13 TeV : sample with very high statistics allows an unprecedented precision:

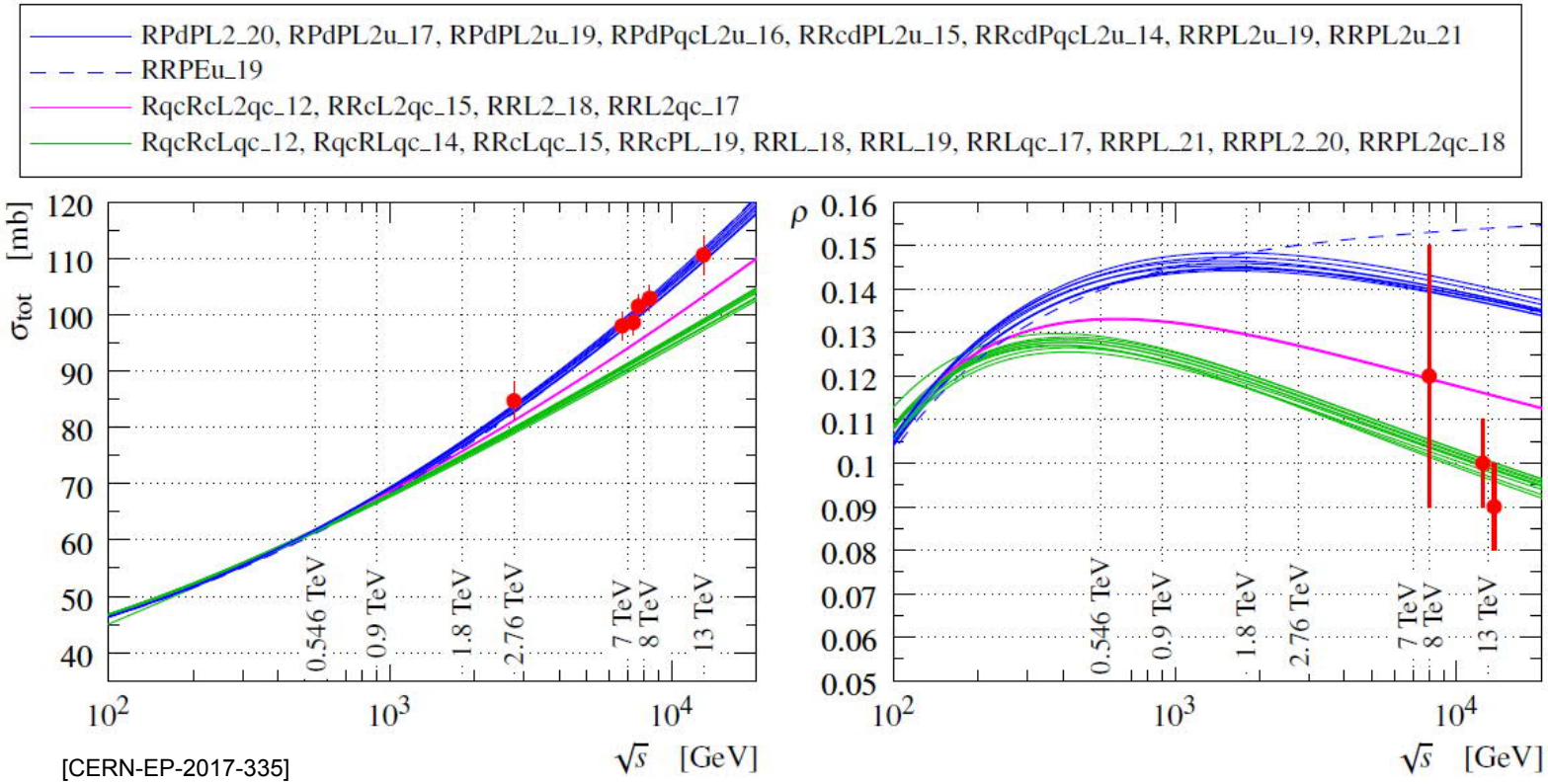
	$\lvert t\rvert_{max}$ = 0.07 GeV^2		$\lvert t\rvert_{max}$ = 0.15 GeV^2	
N_b	χ^2/ndf	ρ	χ^2/ndf	ρ
1	0.7	0.09 ± 0.01	2.6	–
2	0.6	0.10 ± 0.01	1.0	0.09 ± 0.01
3	0.6	0.09 ± 0.01	0.9	0.10 ± 0.01

$\lvert t\rvert_{max}$ = 0.07 GeV^2
→ comparison with UA4/2 (same range)



The 13 TeV measurement (for both fit range choices) lies significantly (4 – 4.7 σ) below the prediction.

√s Trends of ρ and Total Cross-Section

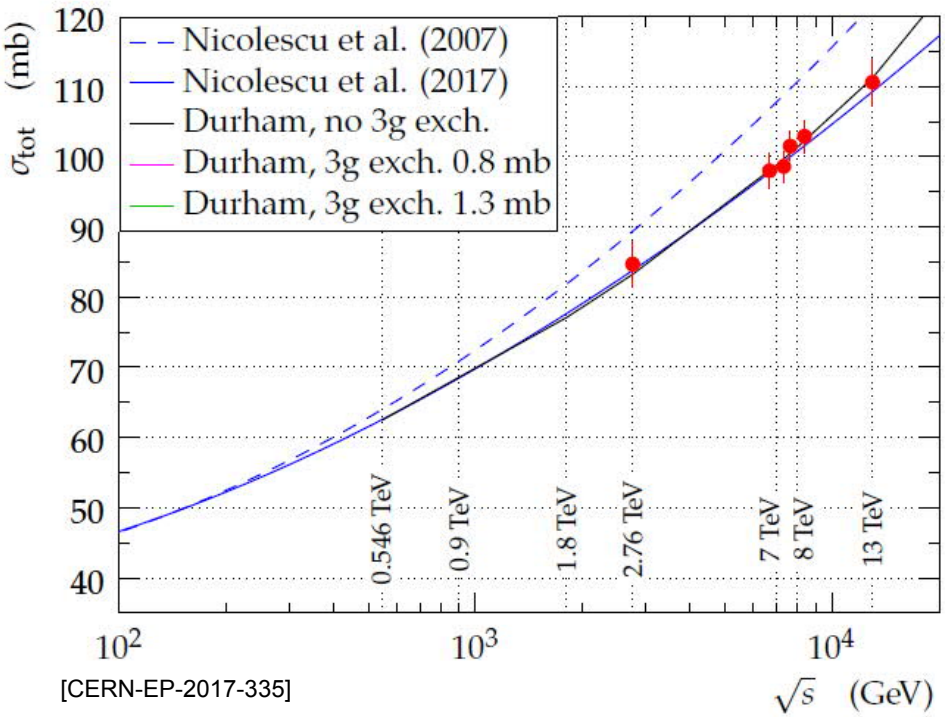


[CERN-EP-2017-335]

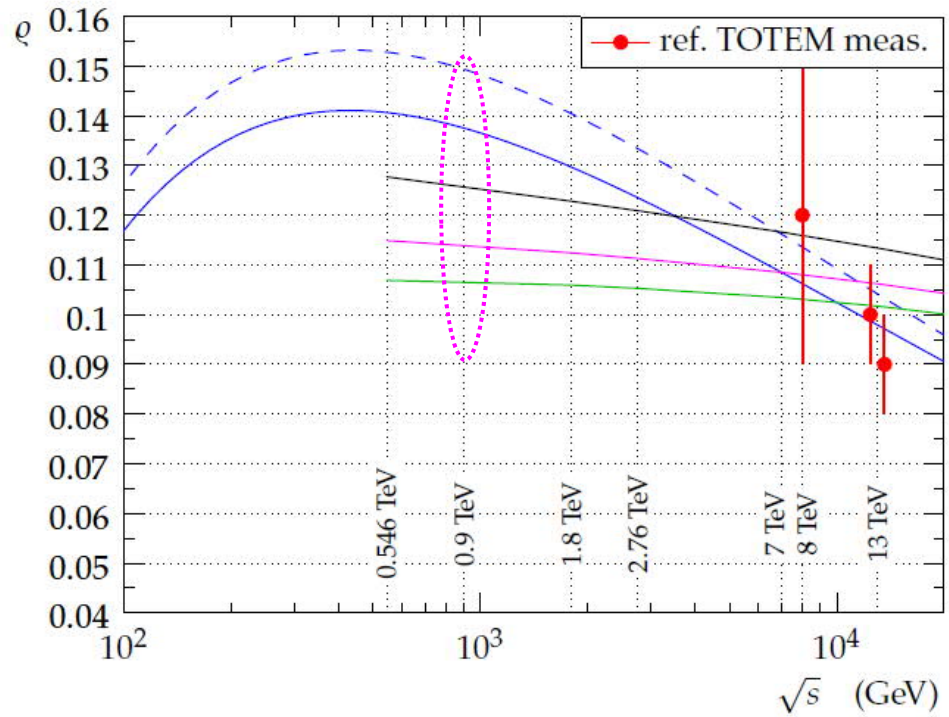
None of COMPETE models (all without Odderon!) is able to describe simultaneously σ_{tot} and ρ.

√s Trends of ρ and Total Cross-Section

Exchange of a colourless 3-gluon CP-odd compound state ("Odderon") in the t-channel could decrease ρ in pp collisions at large energy:



[CERN-EP-2017-335]



900 GeV point will have discrimination power.

... or is it a hint at a slower growth of $\sigma_{tot}(\sqrt{s})$ at higher √s ? (dispersion relations!)

Summary & Outlook

New measurements:

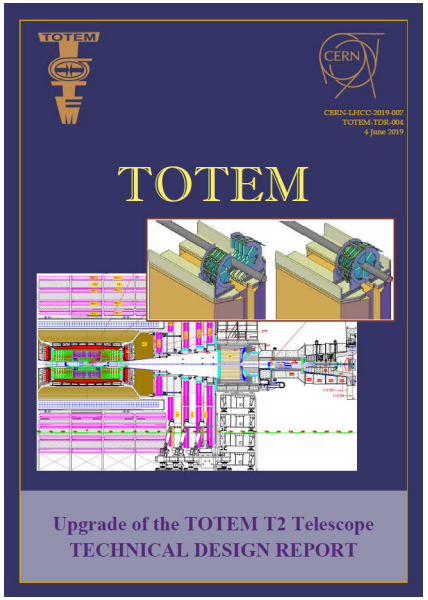
- 13 TeV: σ_{tot}, $d\sigma_{el}/dt$ from 8 x 10^{-4} to 3.8 GeV^2 , ρ
- 2.76 TeV: $d\sigma_{el}/dt$ up to dip/bump region

Lessons:

- Two pieces of evidence for "Odderon":
  - dip/bump in pp vs. shoulder in ppbar
  - decrease of $\rho(\sqrt{s})$ at $\sqrt{s} > 8$ TeV
  - still missing: glueball in s-channel
- Steepening of $B(\sqrt{s})$ confirmed at 13 TeV
- Low $|t|$: non-exponential structure of $d\sigma_{el}/dt$ confirmed at 13 TeV
- High $|t|$: no further structure beyond first dip/bump

Outlook:

- Data at $\sqrt{s}$=900 GeV taken in 2018:
  Analysis of σ_{tot}, $d\sigma_{el}/dt$, ρ started
- Plans for LHC Run 3 @ 14 TeV:
  - $\beta^* \sim 90$ m run for σ_{tot} (lumi-independent with **new T2 detector**)
  - $\beta^* \sim 5 - 6$ km run for CNI analysis

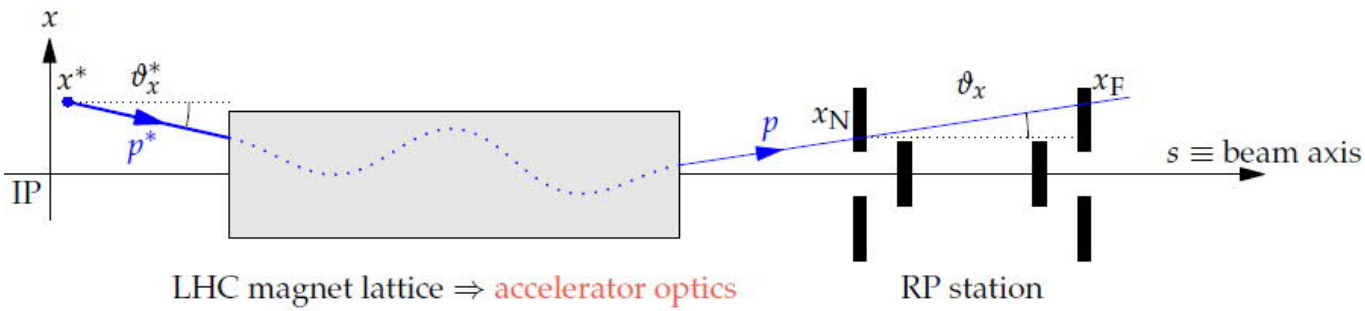


New T2 TDR

The End

Appendix

Proton Transport and Reconstruction via Beam Optics



(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

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

Values at IP5 to be reconstructed

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

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

L_x, L_y: effective lengths (sensitivity to scattering angle)

v_x, v_y: magnifications (sensitivity to vertex position)

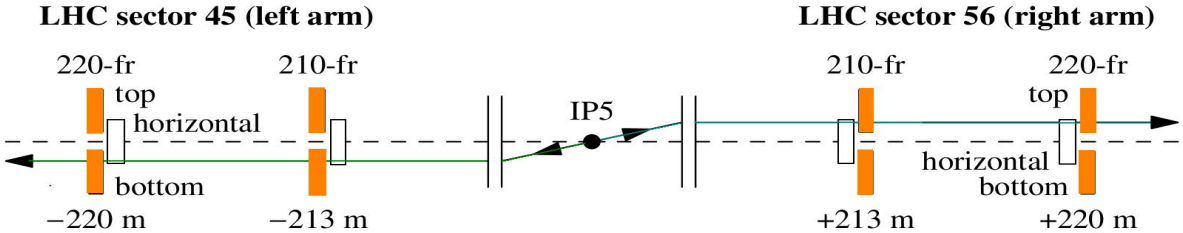
D_x : dispersion (sensitivity to momentum loss); $D_y \sim 0$

Reconstruction of proton kinematics = inversion of transport equation

Excellent beam optics understanding needed.

TOTEM method: optics calibration using proton tracks [New J. Phys. 16 (2014) 103041]

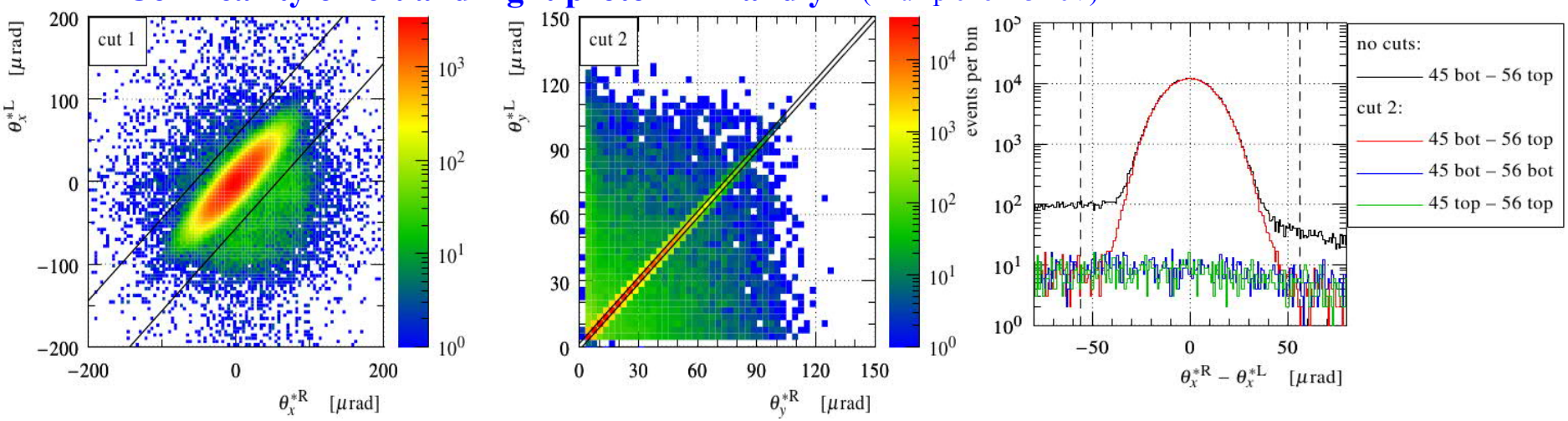
Elastic Measurement Method



Trigger: double arm in XRPs

Cuts: collinearity, common vertex, position-angle correlation, low ξ

Collinearity of left and right proton in x and y (Example for 13 TeV)

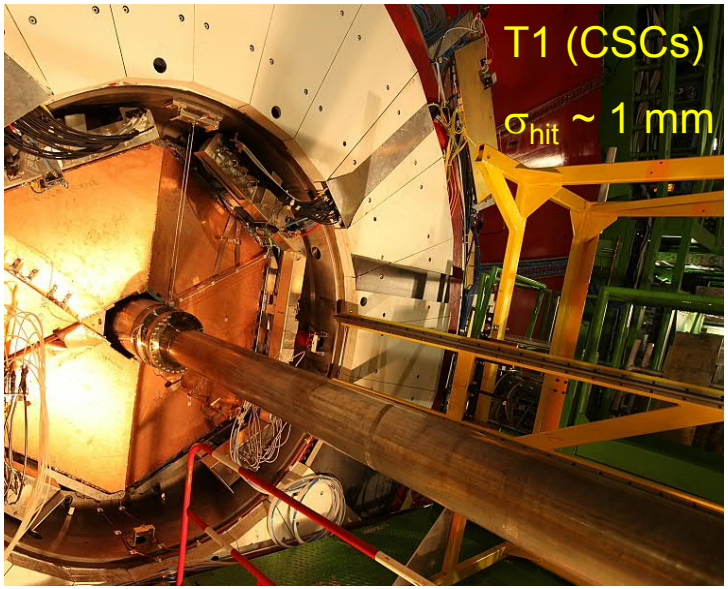


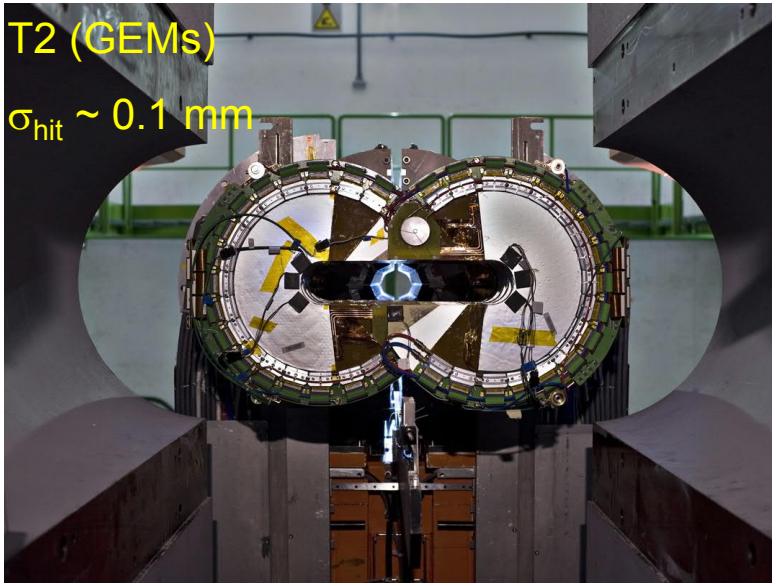
Corrections: acceptance, efficiency (trigger, DAQ, reconstruction), smearing in t

Extrapolation to t=0 (for σ_{tot} with opt. theorem):

$\sigma(dN_{el}/d|t|_{t=0}) \sim 1.6$ % **$\sigma(N_{el}) \sim 2.3$ %** **@ 13 TeV**

Inelastic Measurement Method





Trigger: activity in T2 (either arm)

T1+T2 Acceptance ~ 92% of the inelastic rate

Experimental corrections (mostly data-driven):
beam-gas background, efficiency (trigger & reconstruction), T1-only events, pileup

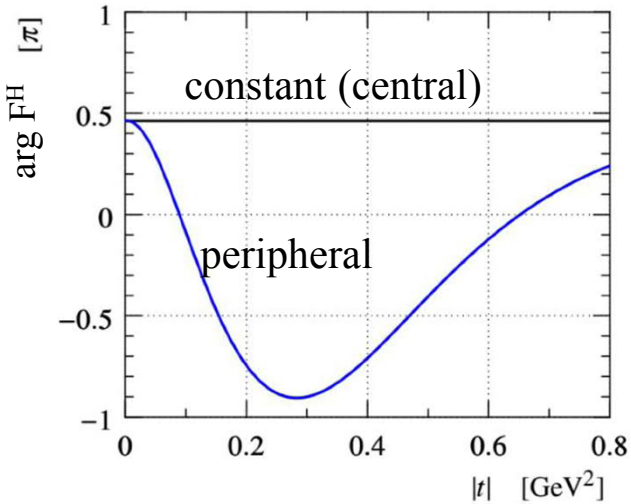
MC corrections for event classes invisible to T1/T2:
central diffraction, rapidity gap over T2, low-mass diffraction ($M < 4.6$ GeV, $|\eta| > 6.5$)

$\sigma(N_{inel}) = 3.7\%$ @ 13 TeV

Elastic Scattering: Coulomb-Nuclear Interference Region (Phases)

Choice of hadronic phase arg $F^H(t)$ controls the behaviour in impact-parameter space (b)

Phase examples:

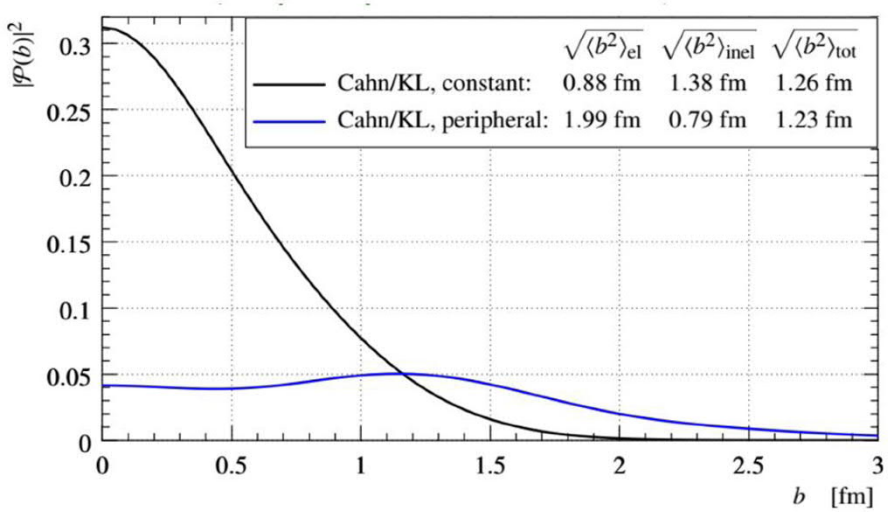


$$\arg F(t) = p_0$$

$$\arg F(t) = p_0 + \zeta_1 \left|\frac{t}{t_0}\right|^{\kappa} \exp(\nu t) \qquad (t_0 = 1\,\mathrm{GeV}^2)$$

$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0) = \cot p_0$$ in both cases.

Impact parameter distributions:



constant (central): most commonly used:
$\langle|b|\rangle_{el} < \langle|b|\rangle_{inel}$

peripheral:
$\langle|b|\rangle_{el} > \langle|b|\rangle_{inel}$

[EPJC 76 (2016) 661]

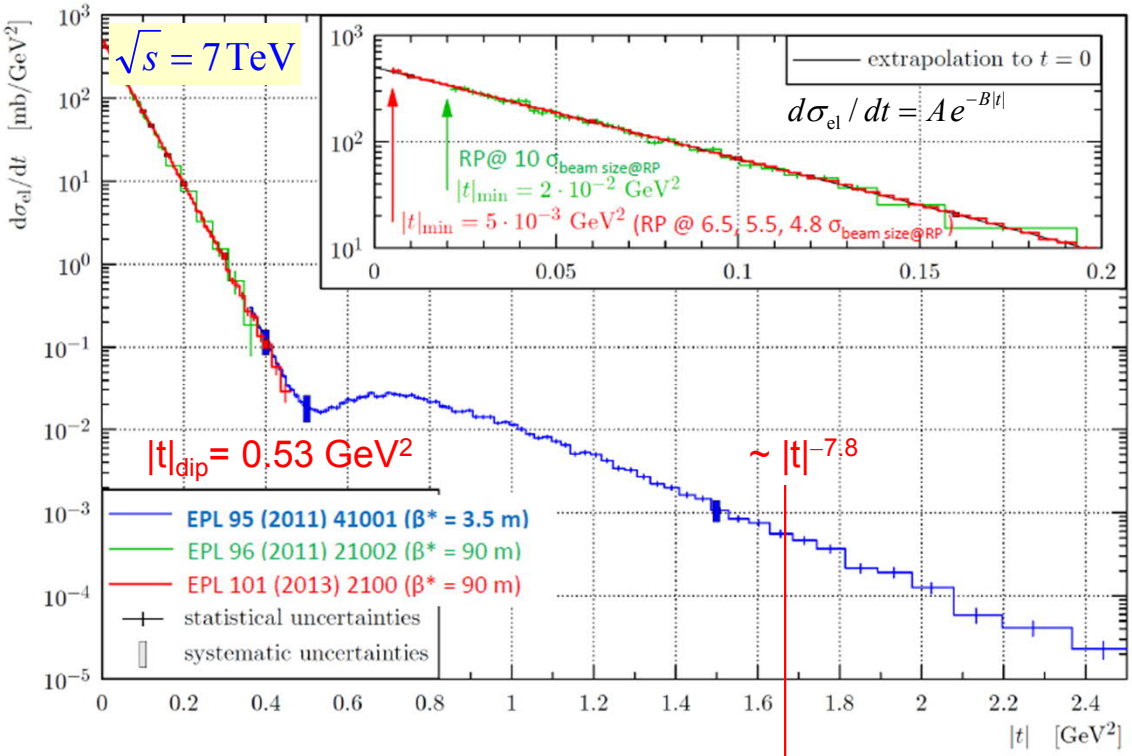
TOTEM 8 TeV data compatible with both phases (same result for ρ: 0.12 ± 0.03)

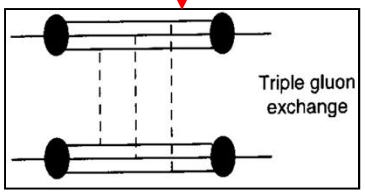
→ elastic pp scattering not necessarily central

Elastic Scattering: The Dip and Beyond (A1)

The 7 TeV Measurements

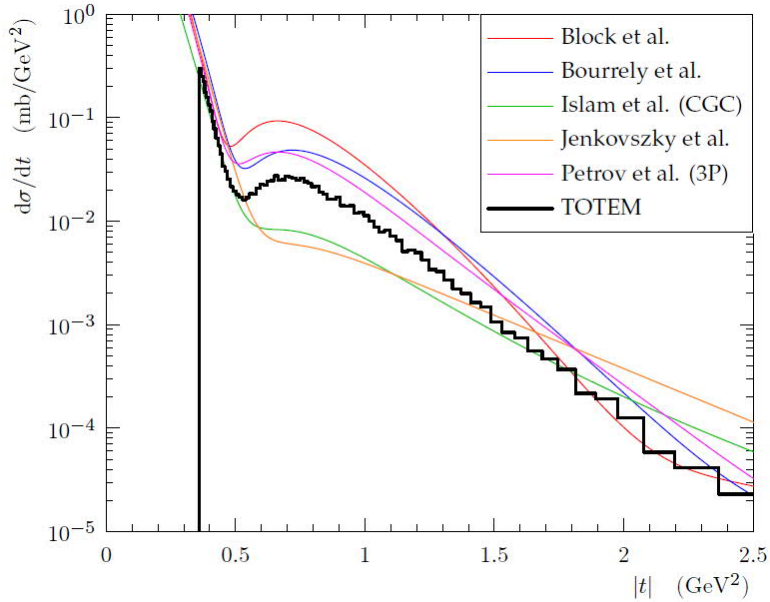
(3 data sets at different optics and RP distances to cover max. t-range)





pQCD (e.g. Donnachie-Landshoff): $\sim |t|^{-8}$

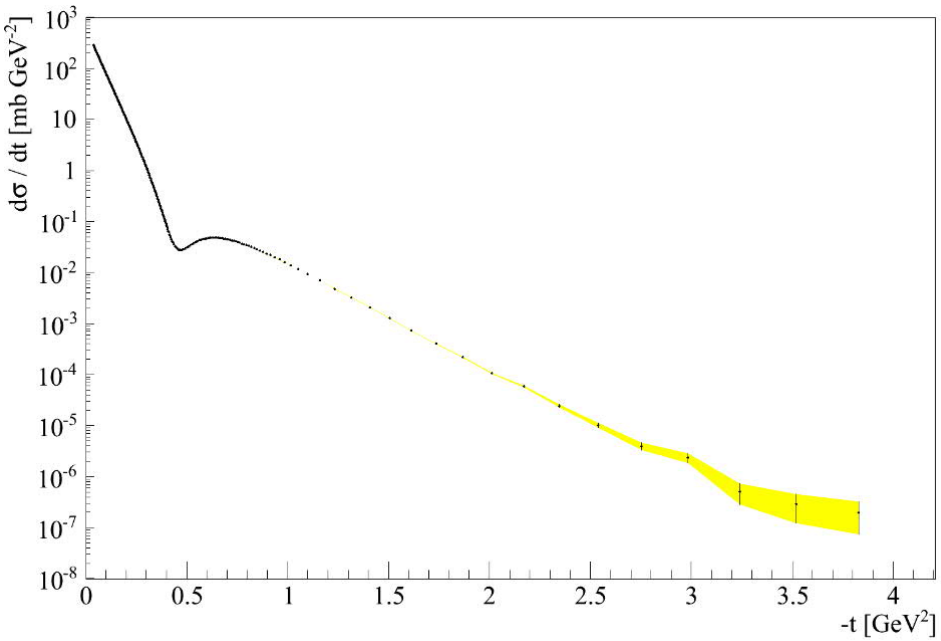
Comparison with 7 TeV Predictions



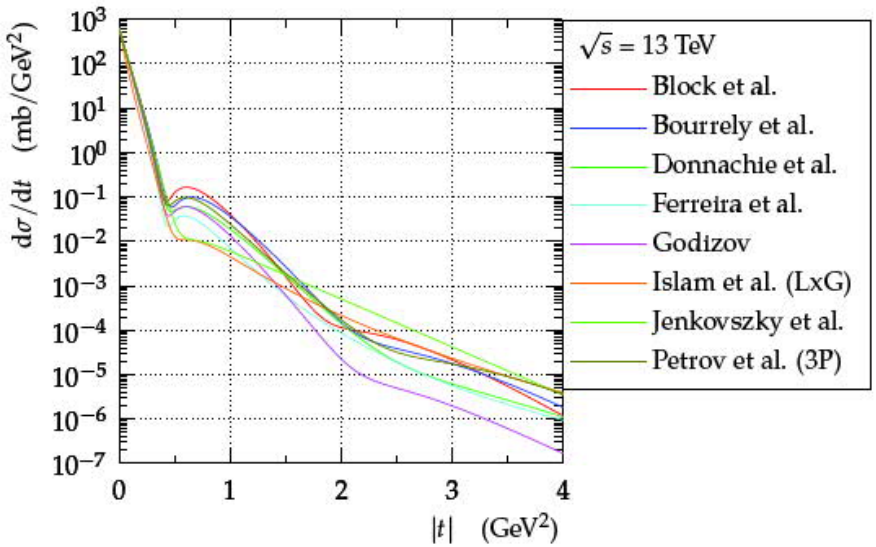
At the time of the first publication:
No model described the TOTEM data.

Elastic Scattering: the Dip and beyond (A2)

The 13 TeV Measurement



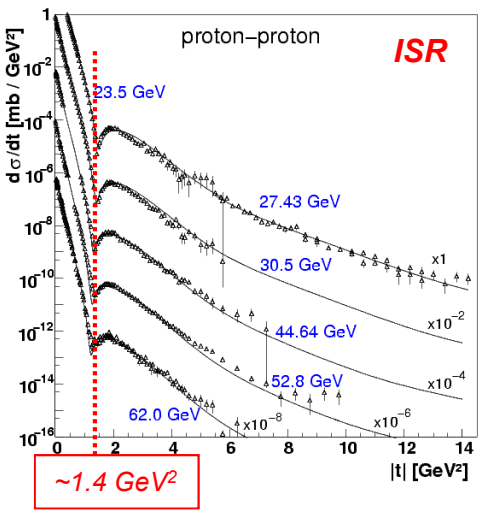
model predictions:

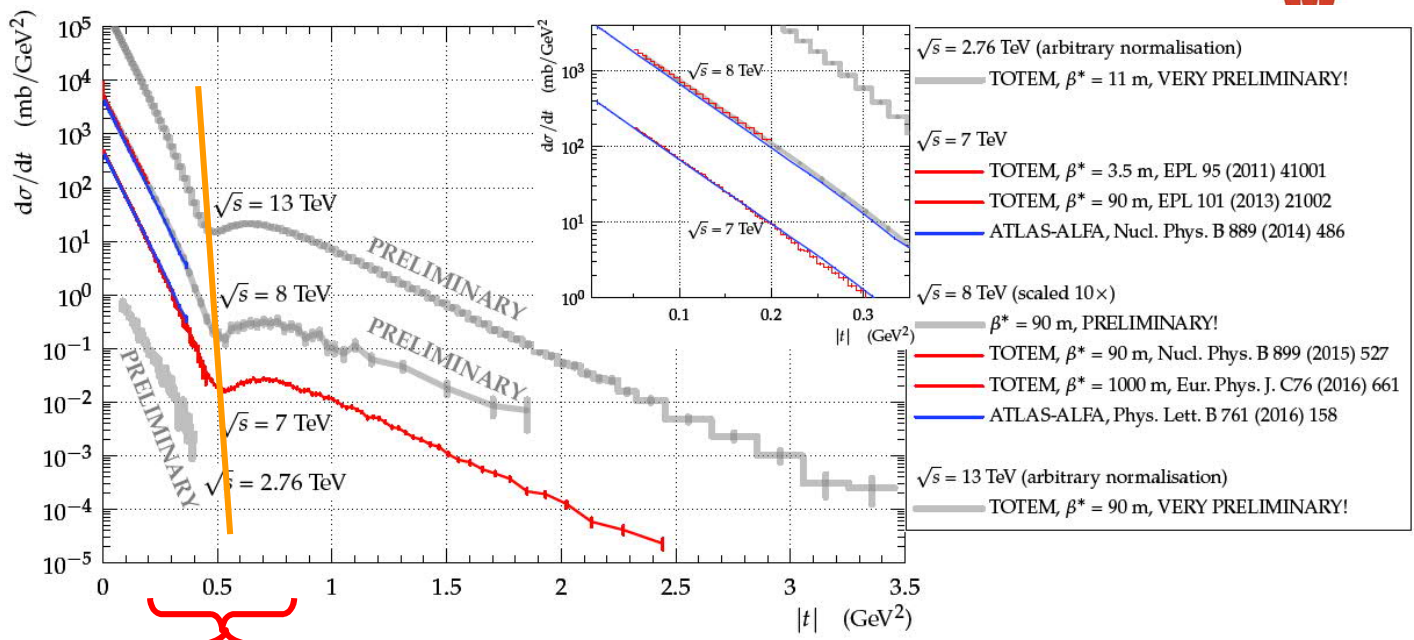


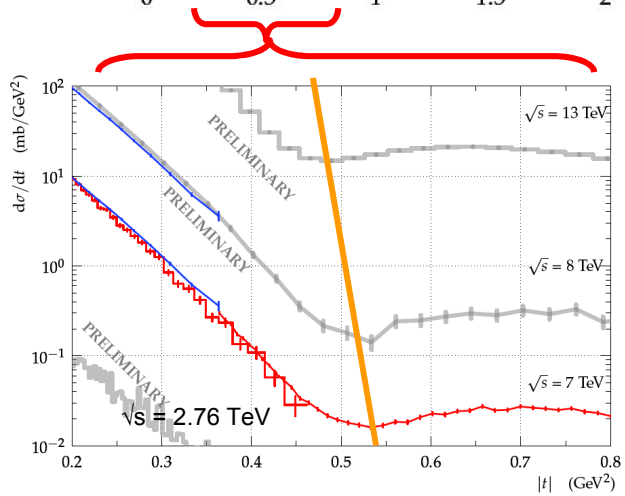
data: no structure at large |t|
→ rules out most models

Elastic Scattering: the Dip and beyond (A3)

Dip position: moves to lower |t| with increasing energy



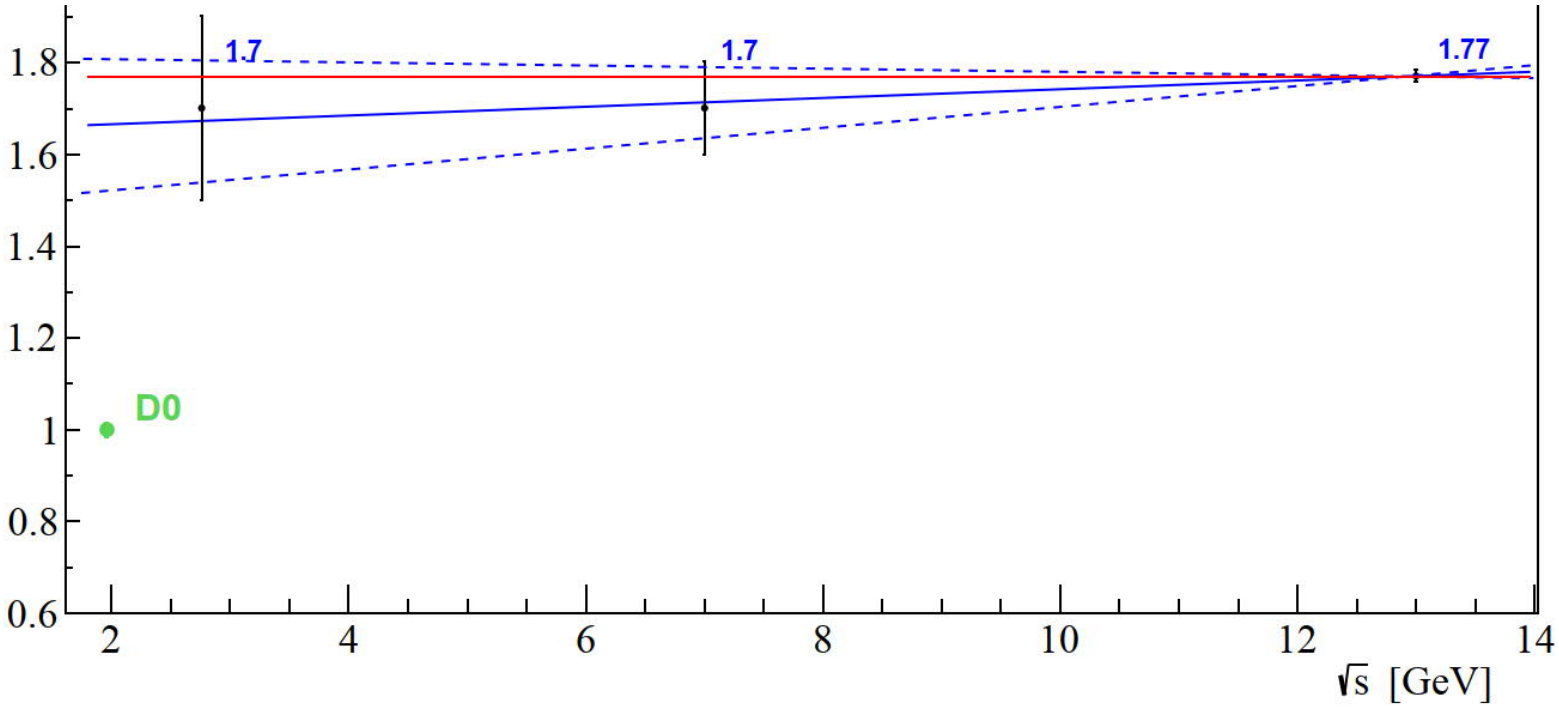




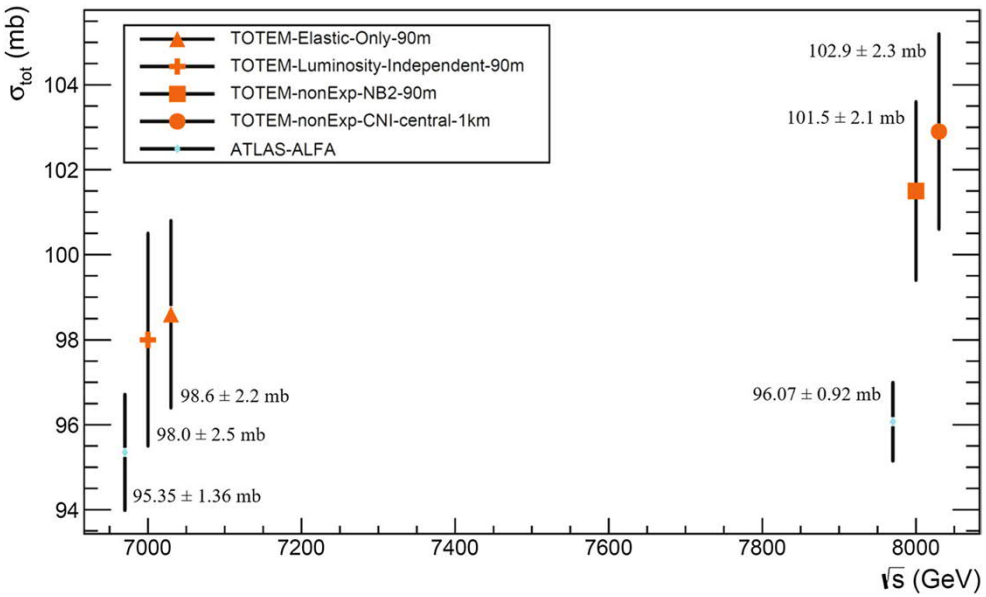
New measurement @ 2.76 TeV, β* = 11m:
very limited t-range (0.08 – 0.4 GeV^2) → dip not reached

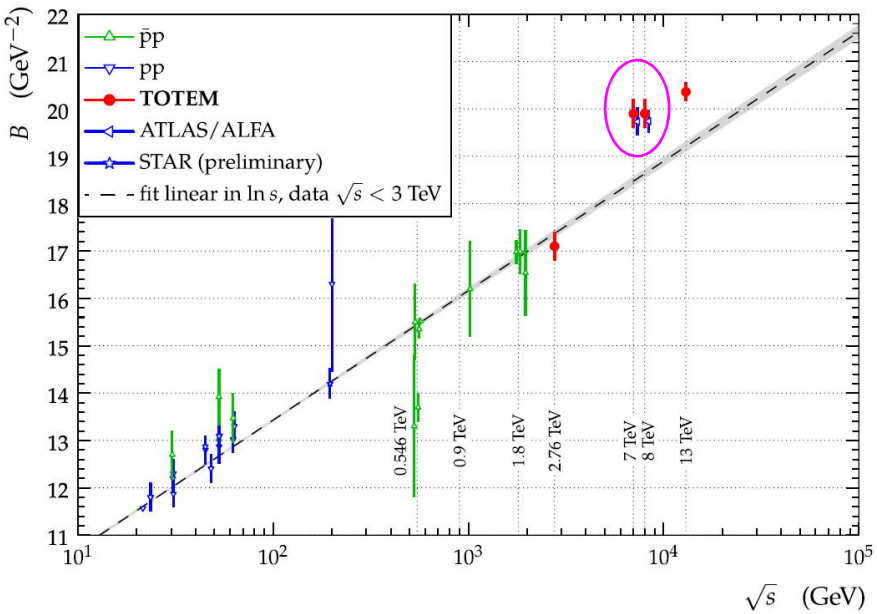
Elastic Scattering: the Dip and beyond (A4)

$$R = \frac{\frac{d\sigma}{dt}(bump)}{\frac{d\sigma}{dt}(dip)}$$



pp Cross-Section Measurements: TOTEM vs. ALFA





8 TeV: tension with ATLAS-ALFA due to normalisation (elastic slopes compatible)