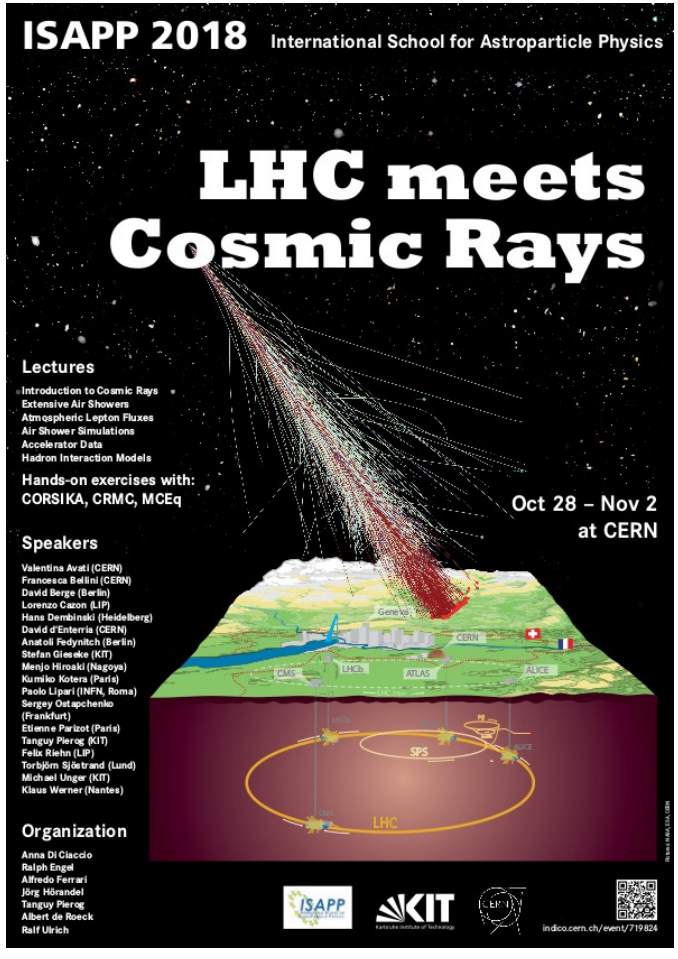
TOTEM @ LHC

V. Avati (AGH, Krakow)



Introduction

When LHC meets CRs….

Cosmic ray connection

TOTEM measurements :
- multiplicities and energy fraction to the secondary particles
- related to the theoretical or phenomenological interaction models

….when CRs meet LHC

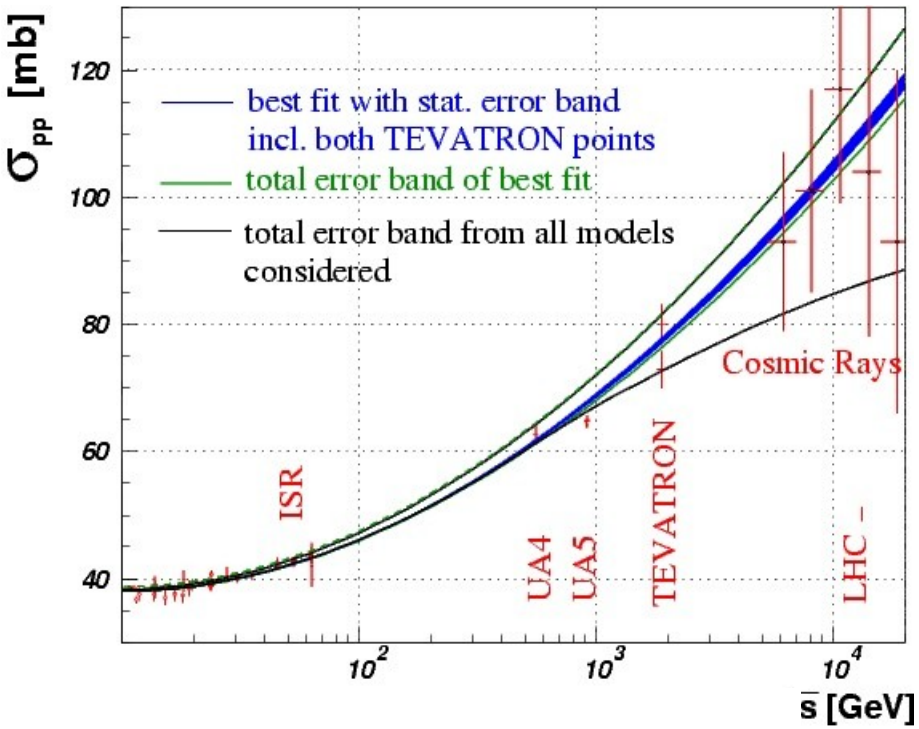
Experimental methods which are specific of an experiment installed in an accelerator beam line

TOTEM (beautiful) results related to the comprehension of proton interactions

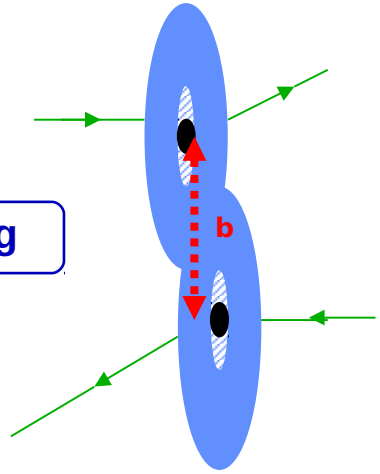
Future prospects

TOTEM Physics Overview

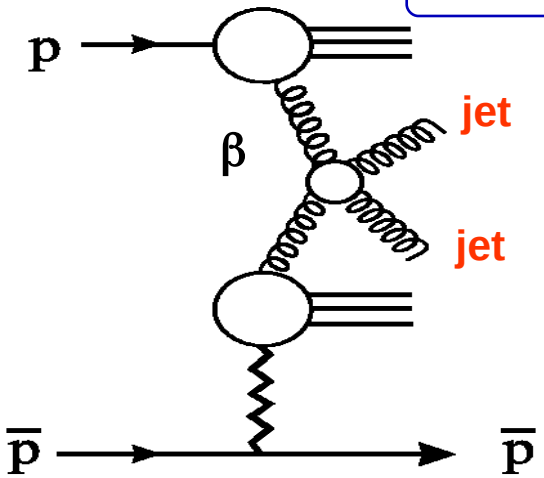
Total cross-section



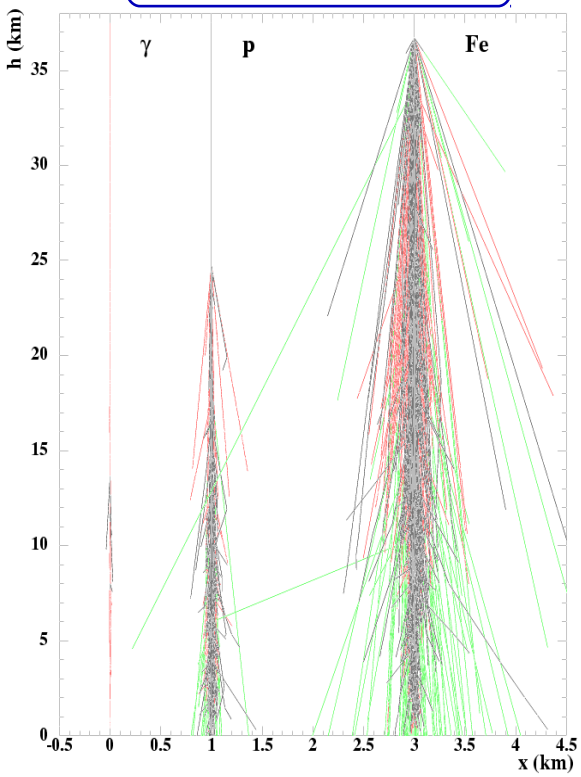
Elastic Scattering



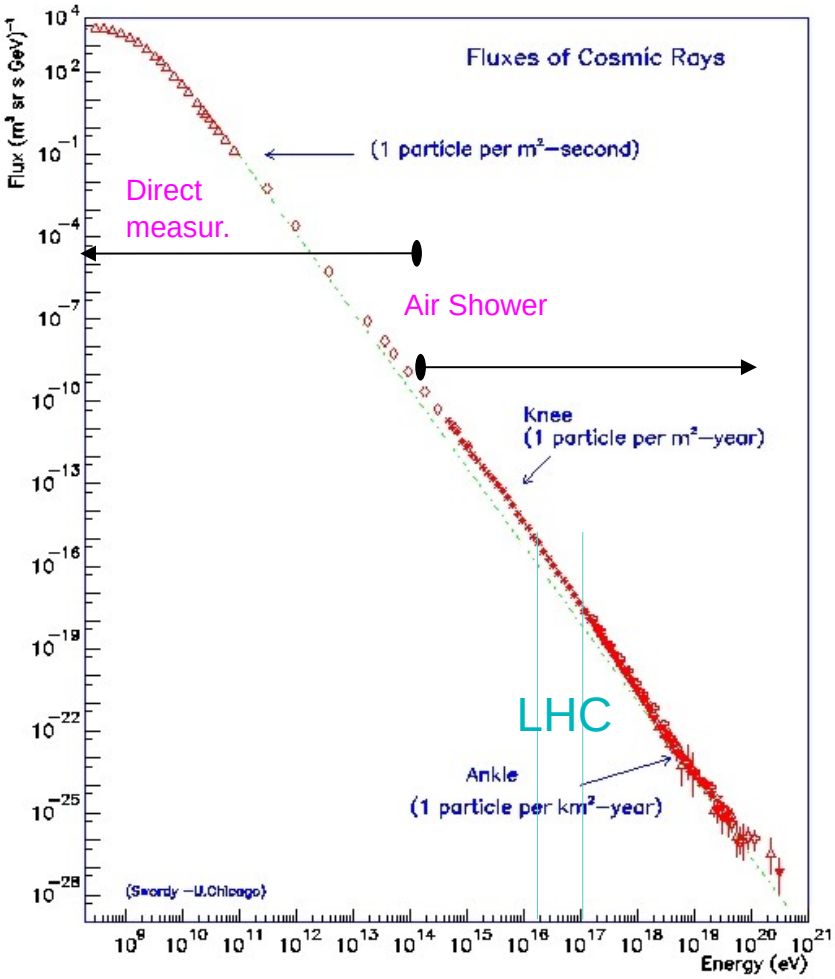
Diffraction: soft and hard

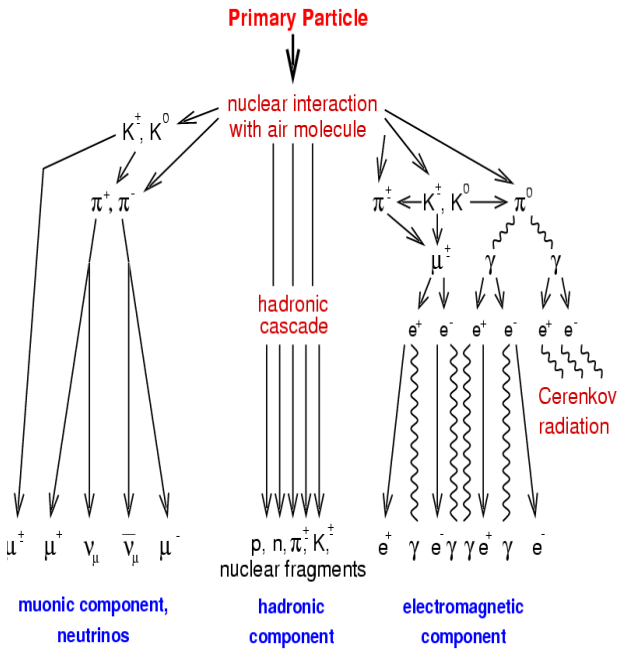


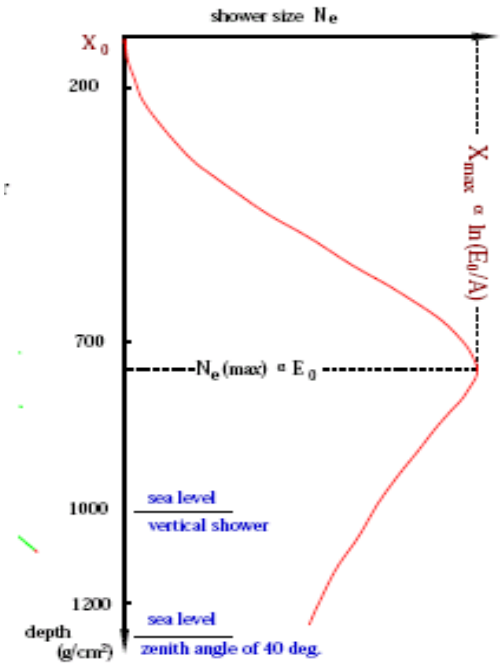
Forward physics



Forward Physics : High Energy Cosmic Rays Connection







Extensive Air Shower characteristics (~ E_0, mass)

X_{max} & N_e : sensitive to cross-sections

N_μ: depends on N^{ch}

=> Disentangle Energy, Mass, hadronic models

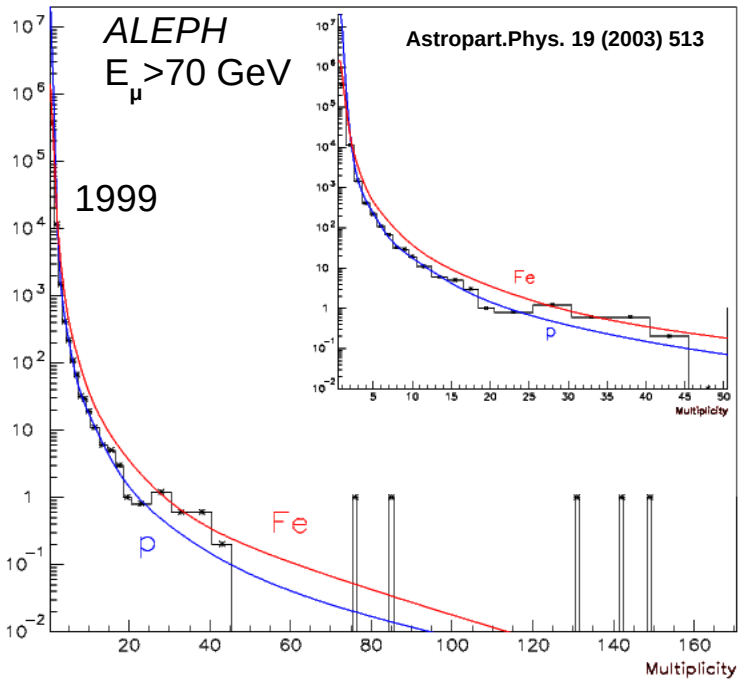
10^4 CR events / km^2 year =>

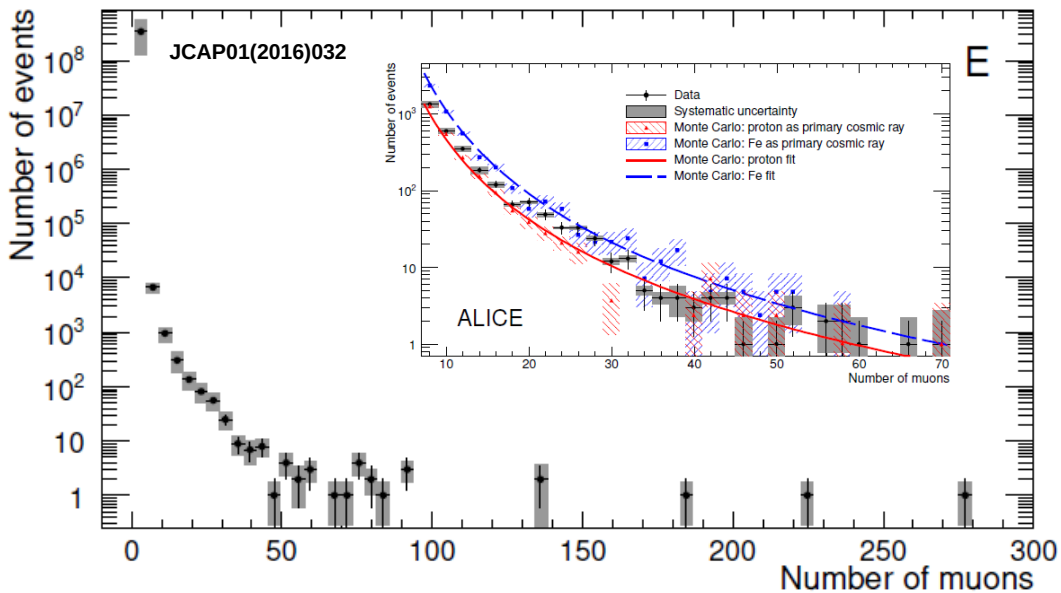
10^4 events /s @ LHC (L=10^{29} cm^{-2} s^{-1})

Measurement @LHC
of the forward energy flux including diffraction
of the total cross section are essential
(shower development, composition)

The evolution of air shower models

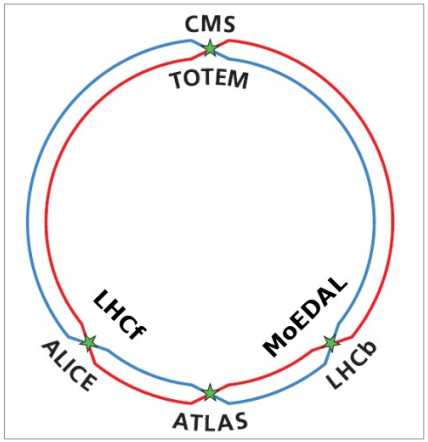
High multiplicity muons events at LEP and LHC

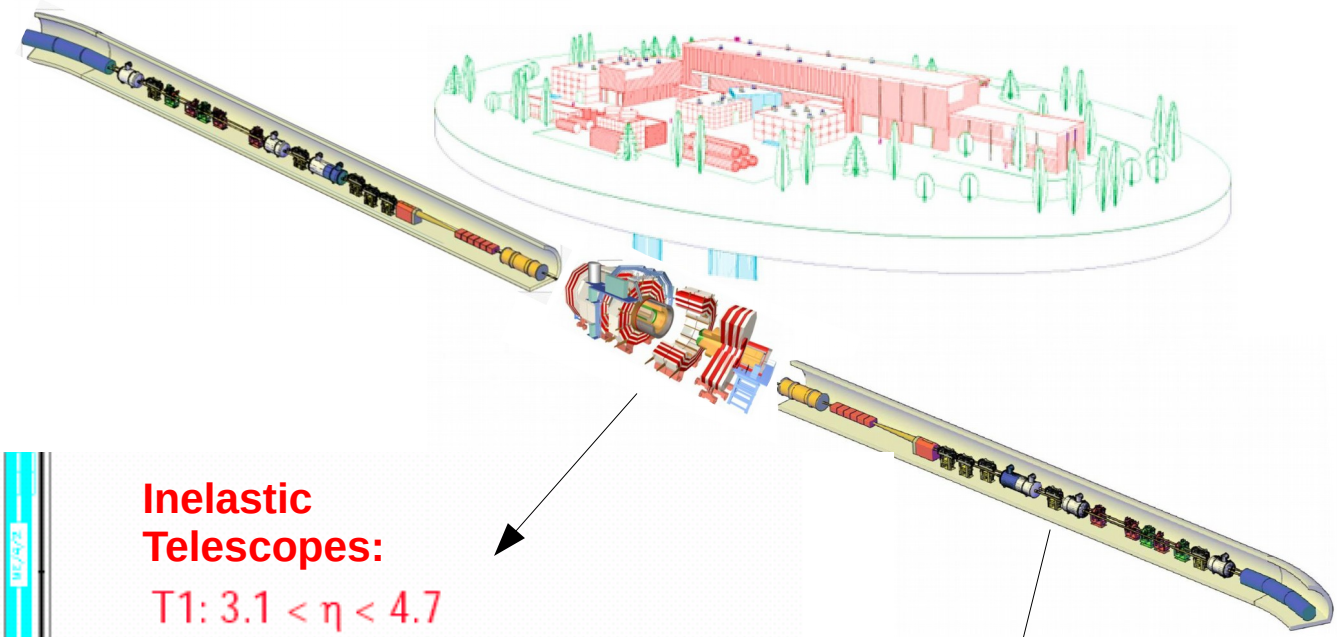


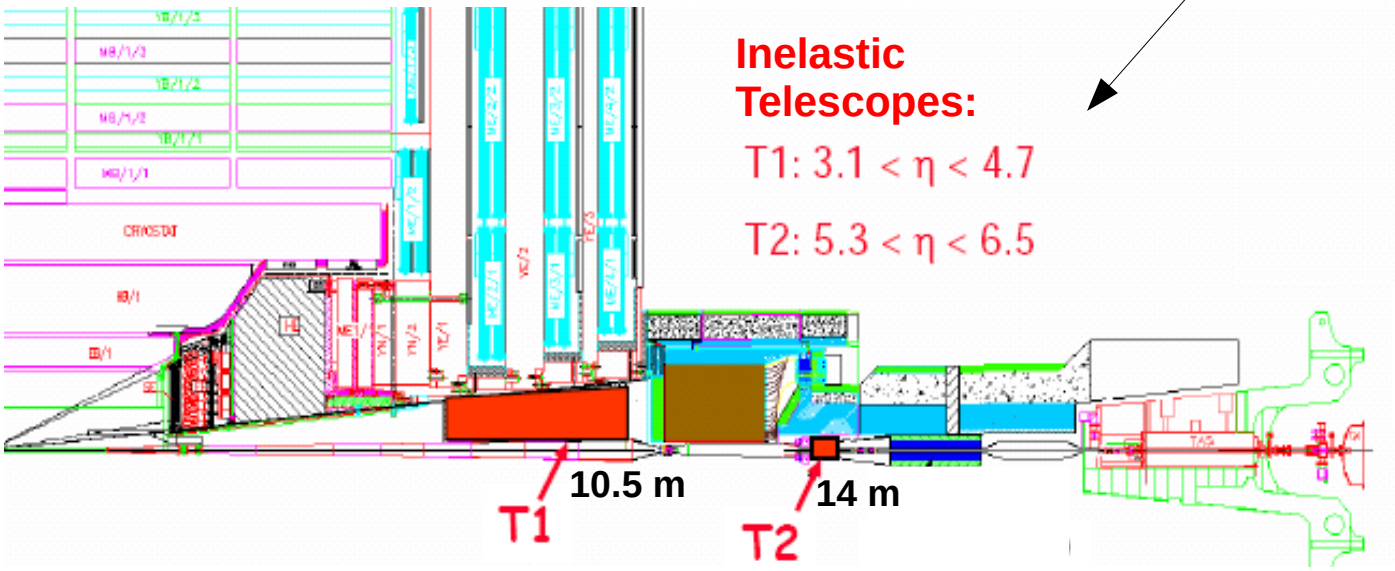


Are these excesses really explained by the post-LHC models?

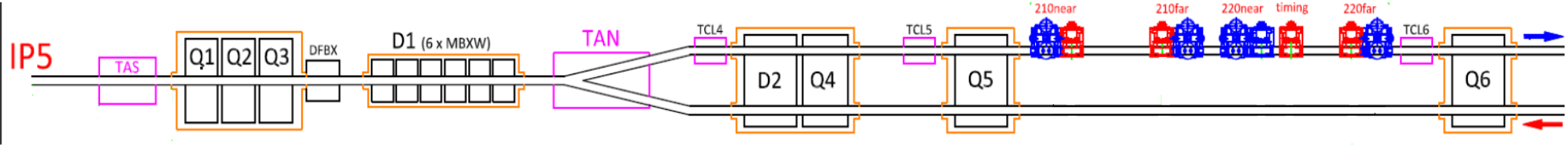
TOTEM Experimental Setup



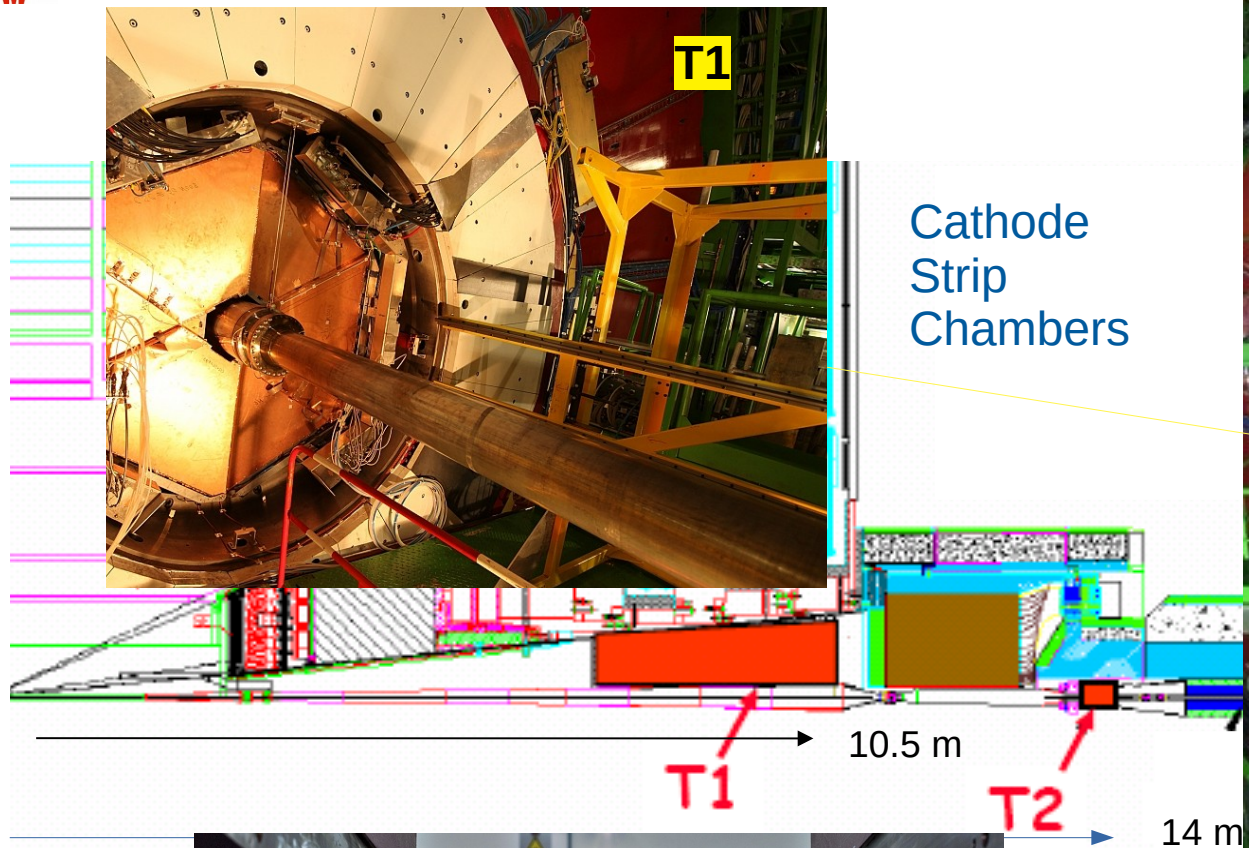




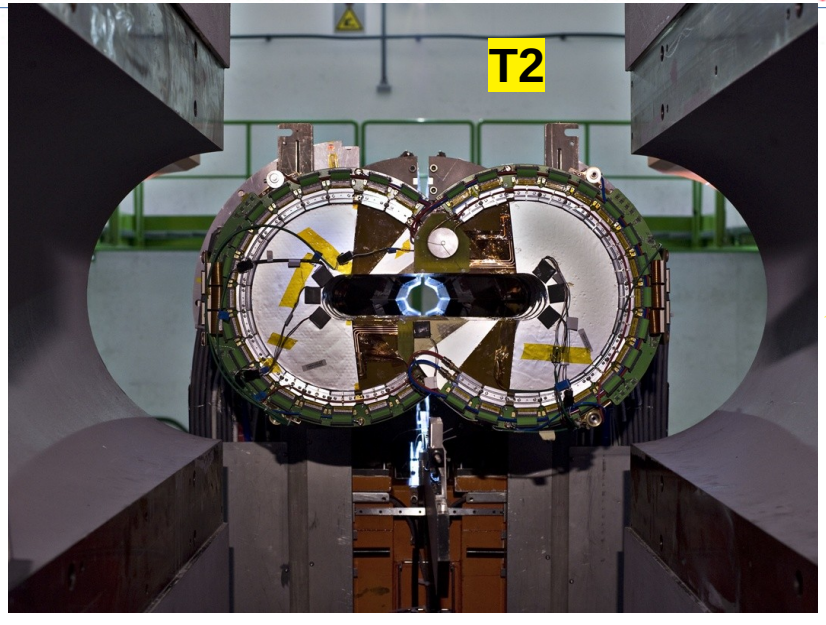
Roman Pot stations in the LHC tunnel



TOTEM Detectors



Cathode
Strip
Chambers

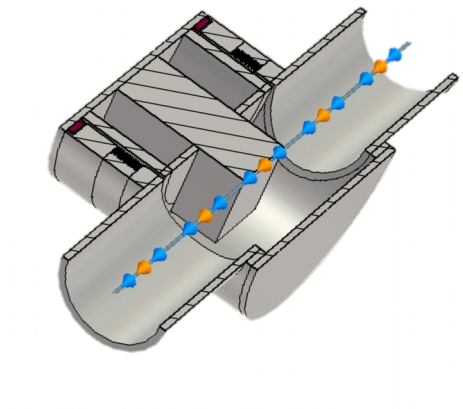


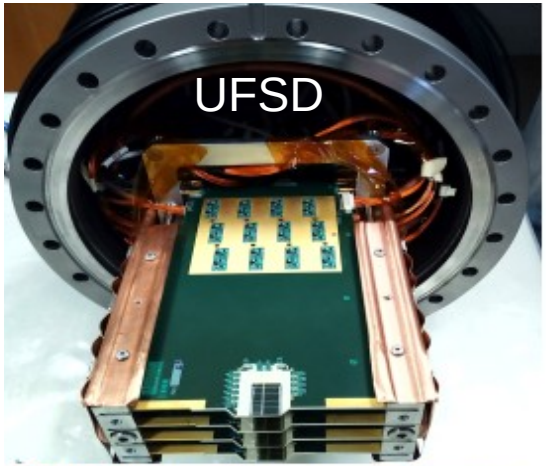
Gas Electron Multiplier

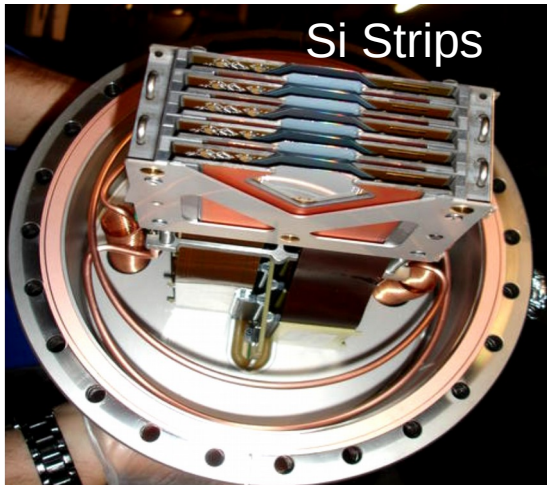
Inelastic telescopes: charged particle
& vertex reconstruction in inelastic events

TOTEM Detectors

Several Roman Pots (= movable beam-pipe insertion) host different sensors

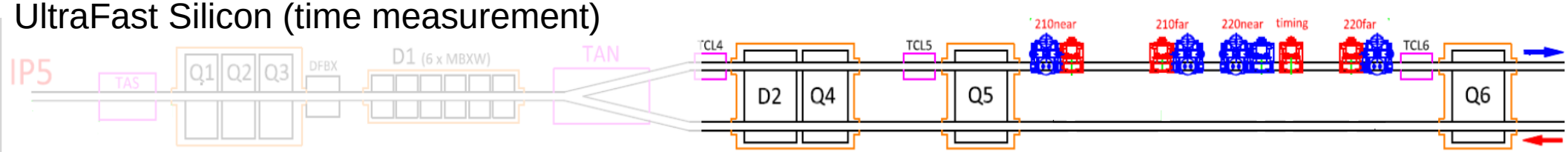




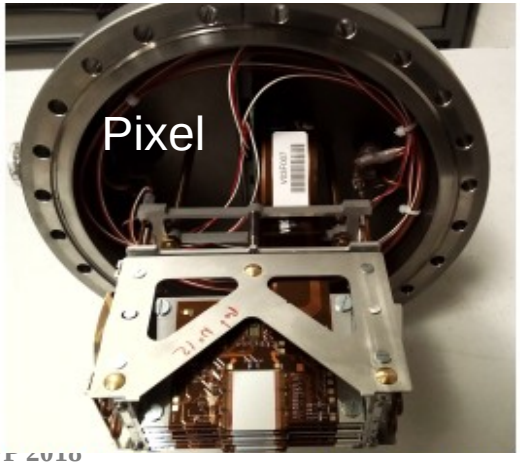


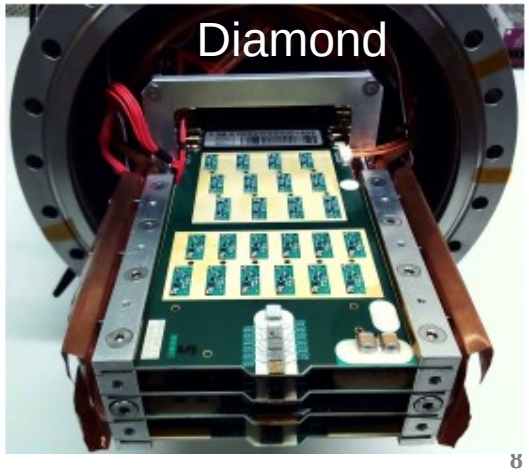
<u>Vertical (Top, Bottom) RPs</u>

Edgeless Si-strips
UltraFast Silicon (time measurement)



<u>Horizontal Rps</u>
Silicon Pixel
Diamond (time measurement)





Cross section related measurements in Totem

Run I

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

Run II

2016

- ρ measurement @ 8 TeV
  EPJ C76-661

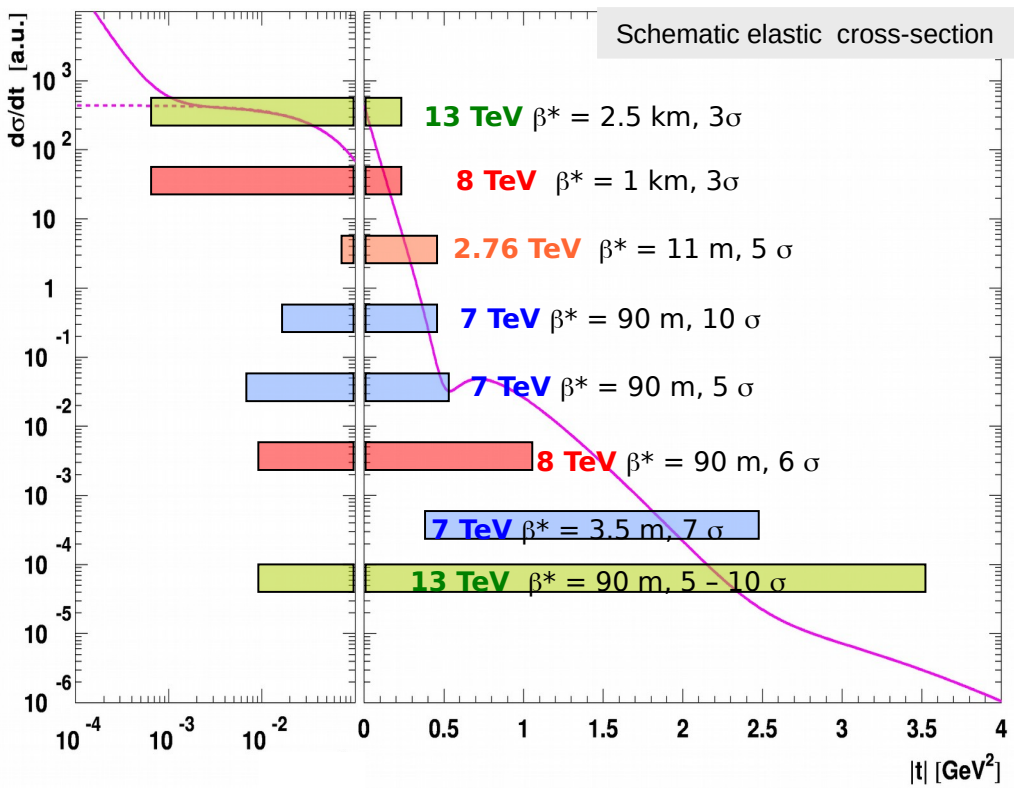
2017

- σ_{tot} lumi independent @ 2.76 TeV
  PoS (DIS2017) 059
- σ_{tot} lumi independent @ 13 TeV
  CERN-EP-2017-321
- ρ measurement @ 13 TeV
  CERN-EP-2017-335

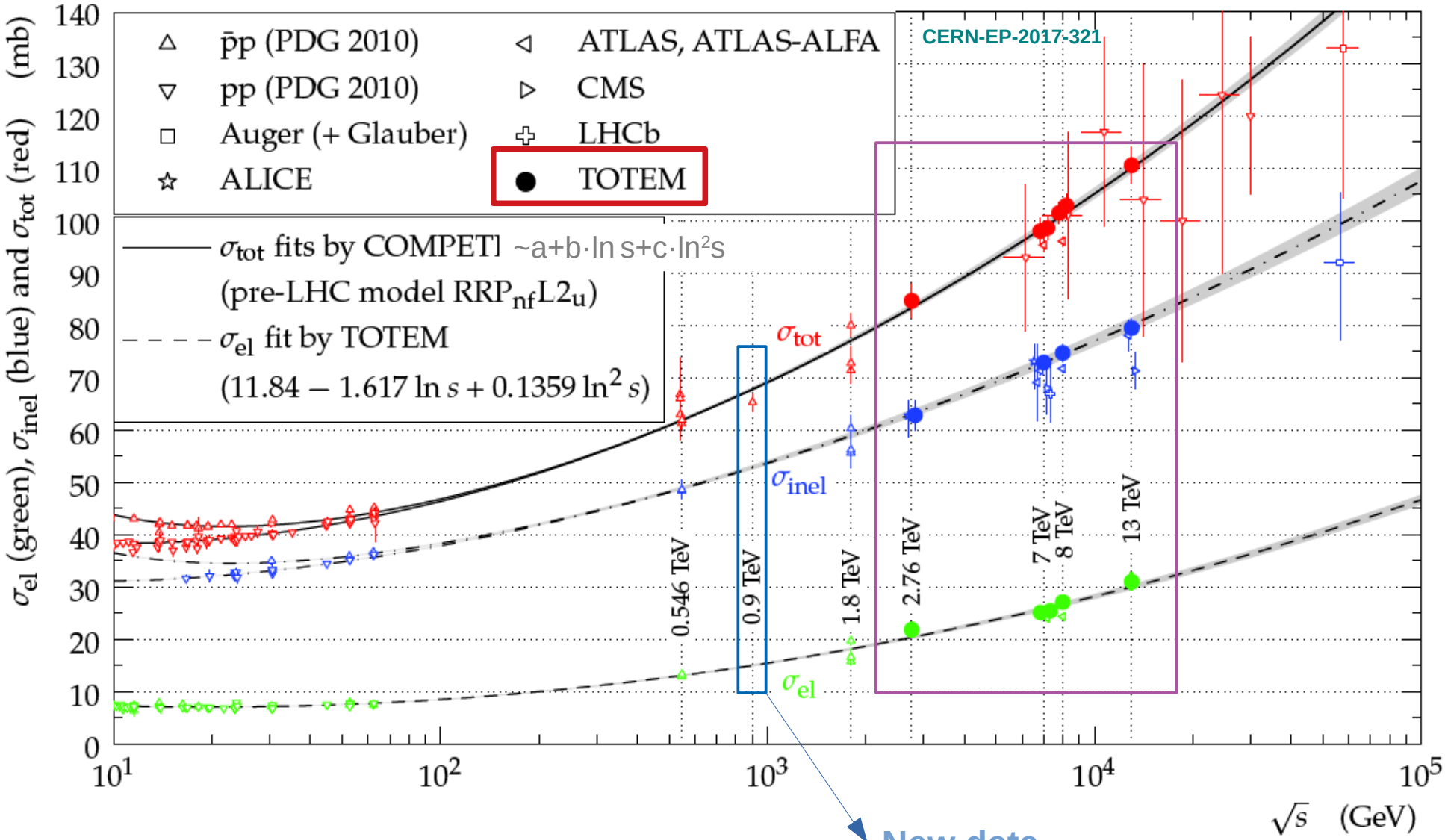
2018

- **$d\sigma/dt$** elastic: DIP @ 13 TeV
- **$d\sigma/dt$** elastic: DIP @ 2.76 TeV

Preliminary



Cross section measurements



New data available!

Errors (TOTEM measurements)

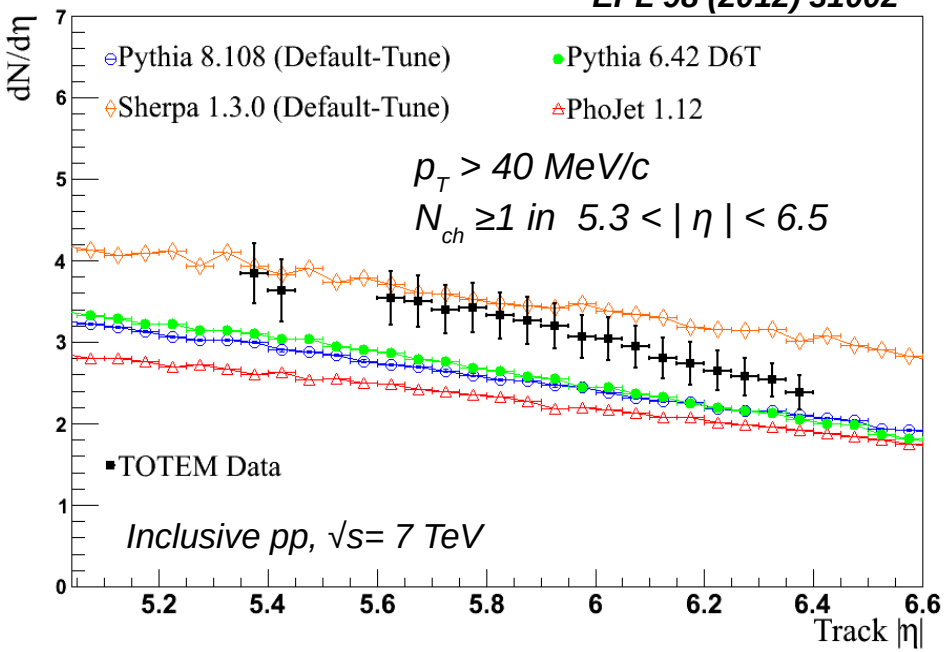
σ_{TOT} ~ 2-3 %

σ_{INEL} ~ 2 %

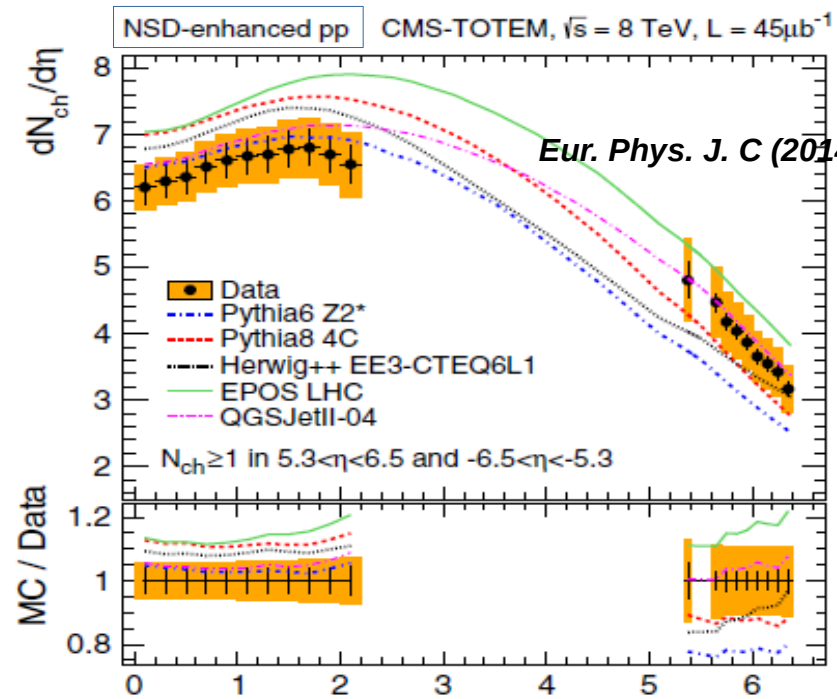
σ_{EL} ~ 2-4 %

Measurement of the forward charged particle pseudorapidity density

EPL 98 (2012) 31002

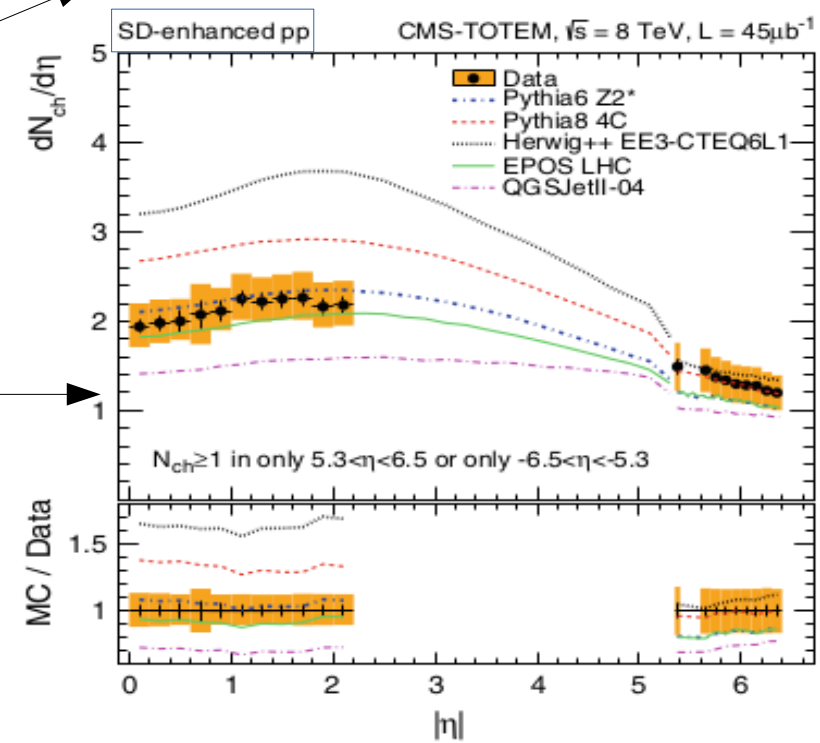


Eur. Phys. J. C (2014) 74

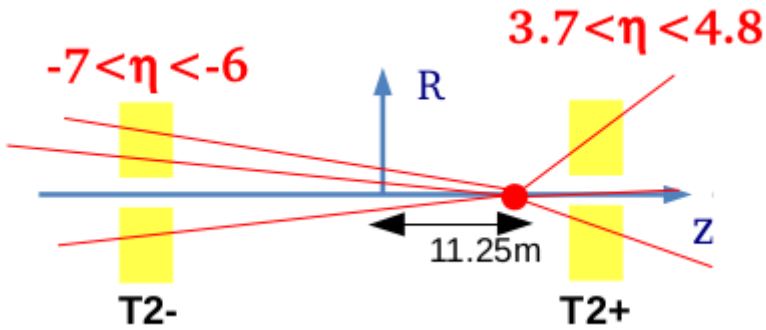


Correlation of central and forward

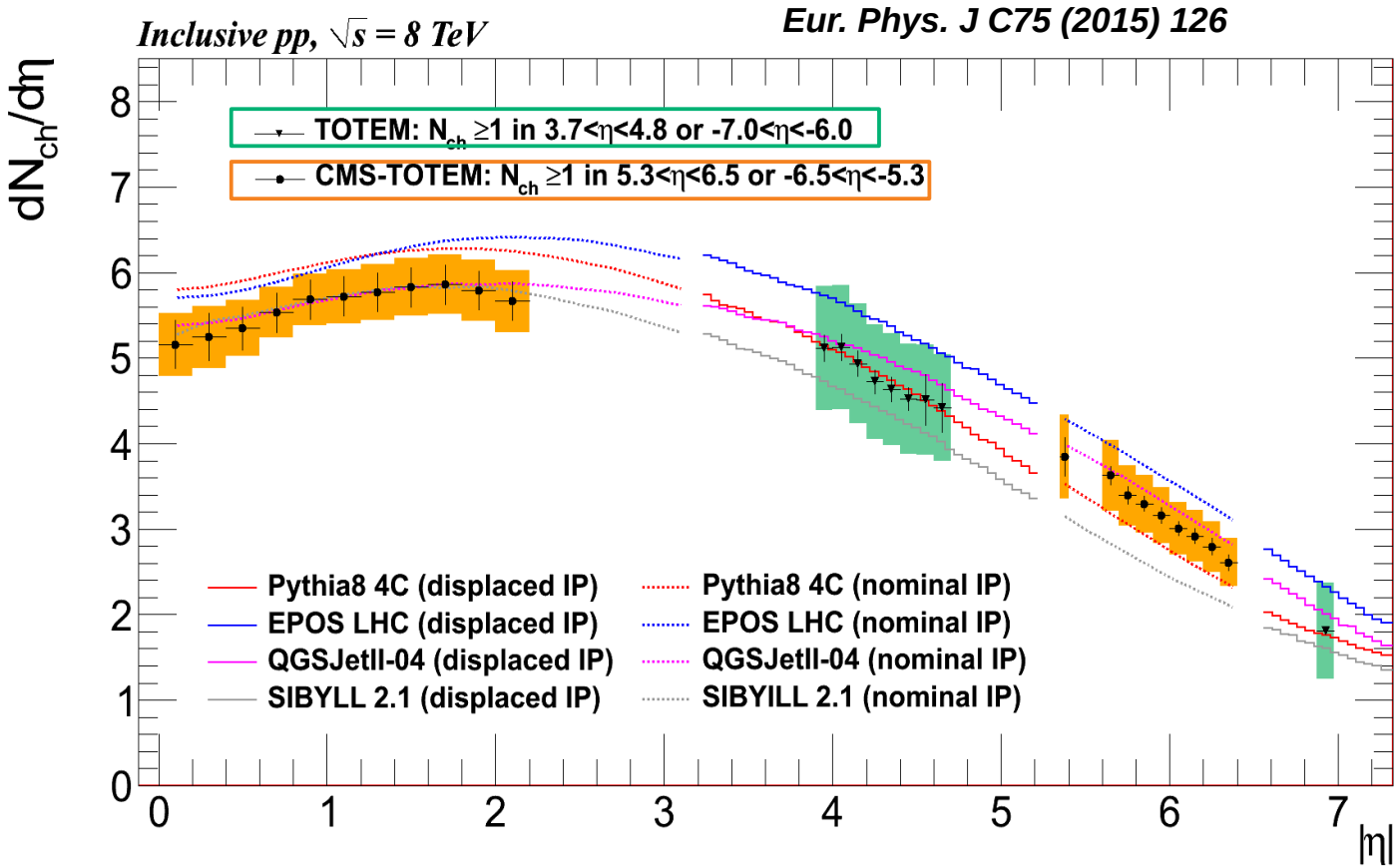
p_T > 0 MeV/c



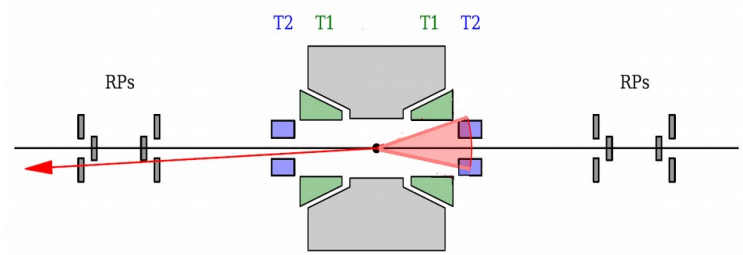
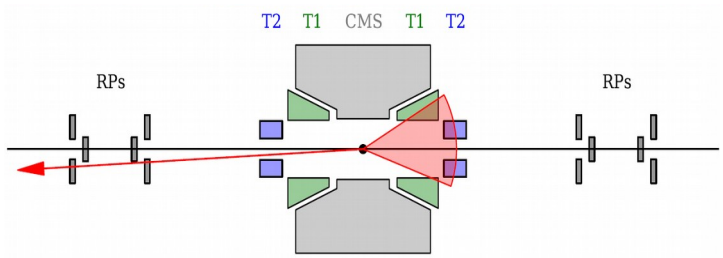
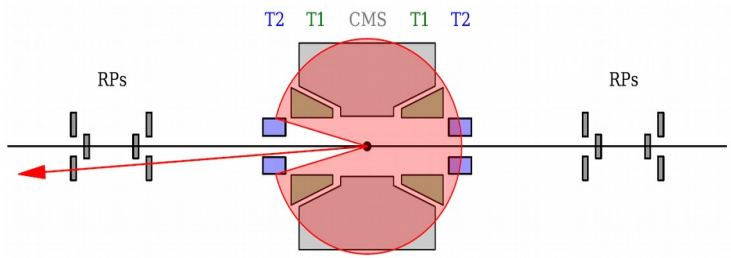
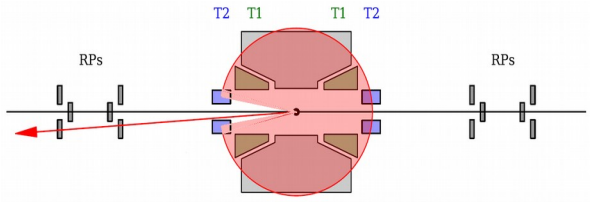
Measurement of the forward charged particle pseudorapidity density

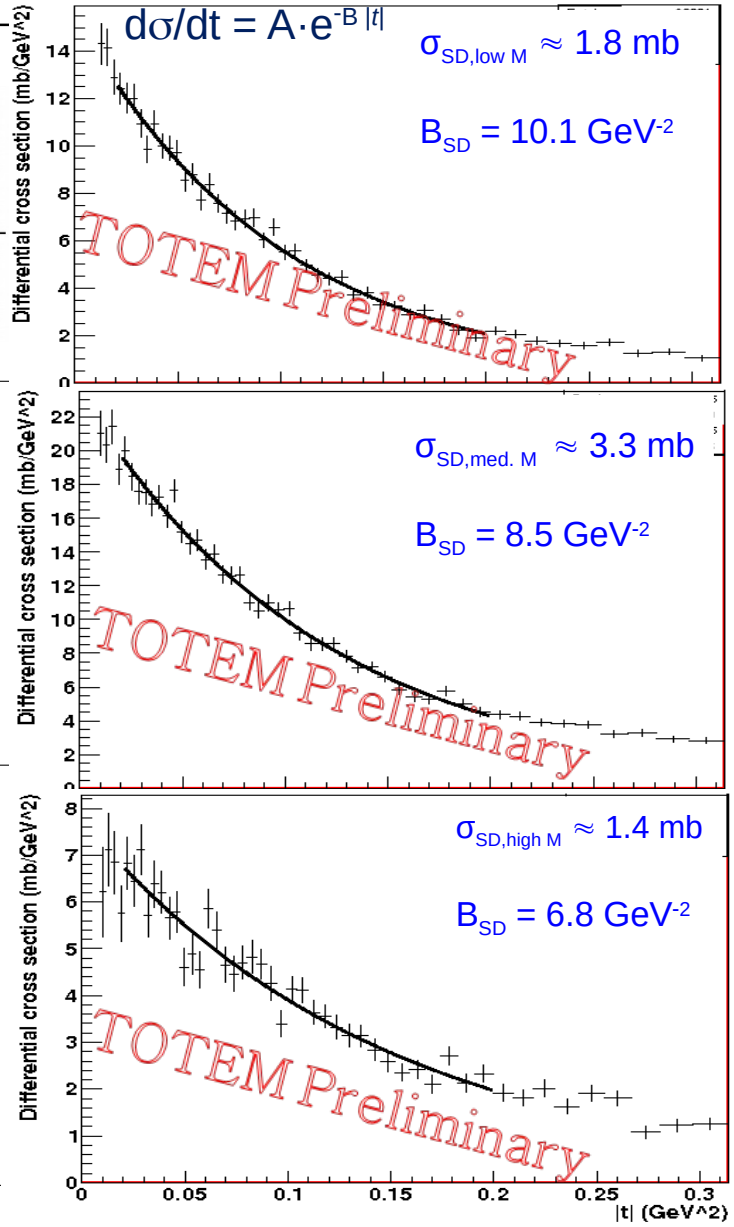


Eur. Phys. J C75 (2015) 126



Soft Single Diffraction (SD)

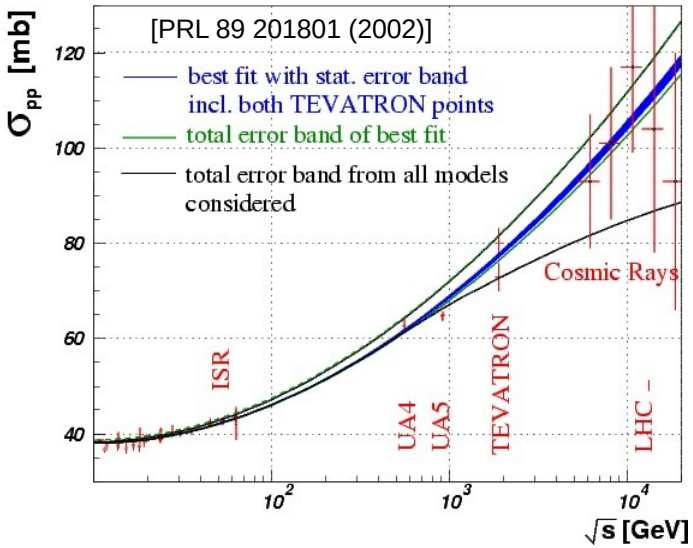
$2\cdot10^{-7} < \xi < 1\cdot10^{-6}$ M = 3.4 – 7 GeV $\Delta\eta = -\ln\frac{M^2}{s}$	proton & opposite T2 
$1\cdot10^{-6} < \xi < 2.5\cdot 10^{-3}$ M = 7 – 350 GeV	proton & opposite T1 + T2 
$2.5\cdot10^{-3} < \xi < 2.5\cdot10^{-2}$ M = 0.35 – 1.1 TeV	proton & opposite T2 (+ T1) & same side T1 
$\xi > 2.5\cdot10^{-2}$ M > 1.1 TeV	proton & opposite T2 (+ T1) & same side T2 (+ T1) 



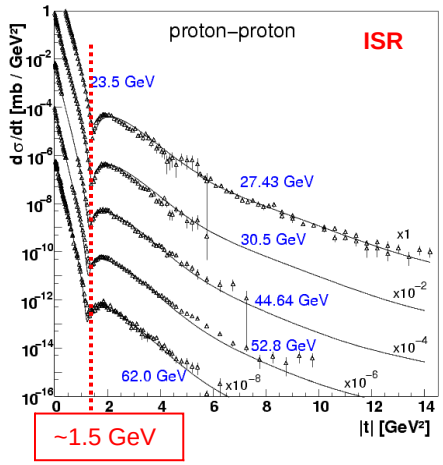
Preliminary:
$\sigma_{SD} = 6.5 \pm 1.3$ mb
$(3.4 < M_{SD} < 1100$ GeV)

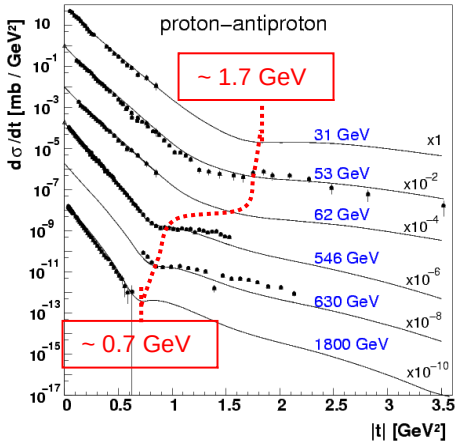
Cross sections status pre-LHC

One of the physics goal of TOTEM is to measure the (elastic, inelastic, total) cross sections at LHC

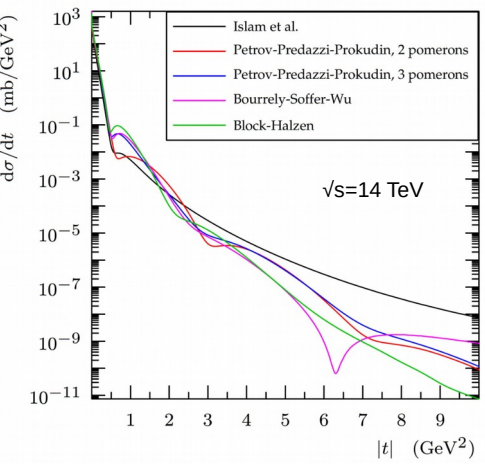


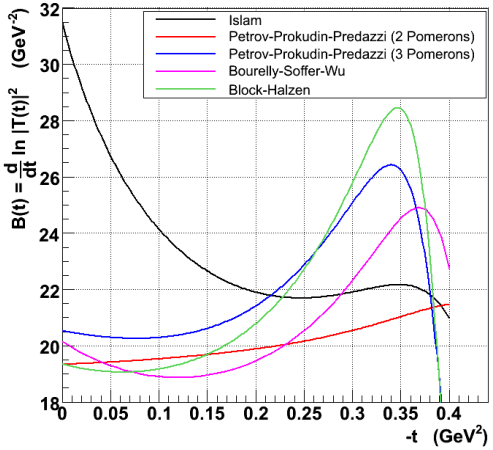
- COMPETE Collaboration fits all available hadronic data and predicts at LHC: σ_{tot} = 111.5 ± 1.2 + 4.1/-2.1 mb [PRL 89 201801 (2002)]
- Last pp data at the ISR; only ppbar at "high" energy
- Difference of σ_{pp} vs $\sigma_{\bar{p}p}$?
- σ_{TOT} (s) ~ (ln s)$^{\gamma}$ γ = 2 ?
- σ_{EL} / σ_{TOT} VS energy





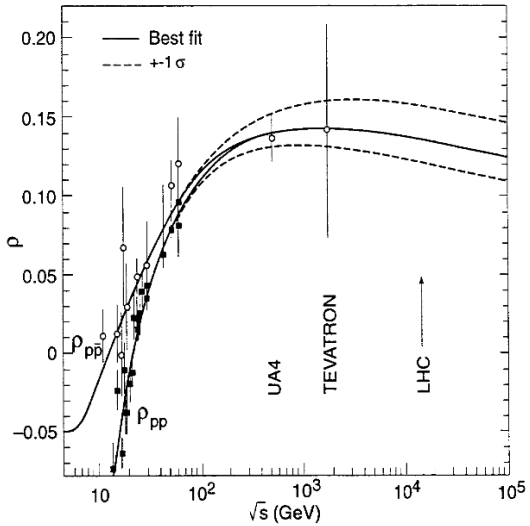
- Is the dip still present at high energy?
- Is the position of the dip changing?
- Large momentum transfer region: oscillations?
- Any break in the elastic slope B(t)?





$$\rho = \Re A^N / \Im A^N |_{t=0}$$

- Foreseen to "decrease" at high energy: how fast?
- Test dispersion relation (mix real and imaginary part)



Total Cross section: analysis methods

From Optical theorem

$$\sigma_{\text{tot}}^2 \propto \left[\Im A_{\text{el,N}}(t=0)\right]^2 \propto \frac{1}{1+\rho^2}\left|A_{\text{el,N}}(t=0)\right|^2 = \frac{16\pi}{1+\rho^2}\frac{d\sigma_{el}}{dt}\Big|_{t=0} \quad \text{with} \quad \rho = \frac{\Re A_{\text{el,N}}}{\Im A_{\text{el,N}}}\Big|_{t=0}$$

$$L\sigma_{\text{tot}} = N_{\text{el}} + N_{\text{inel}}$$

N_{inel} (from T1,T2 telescopes)
N_{el} (from RomanPots detectors)

L independent

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

L dependent
Elastic Only

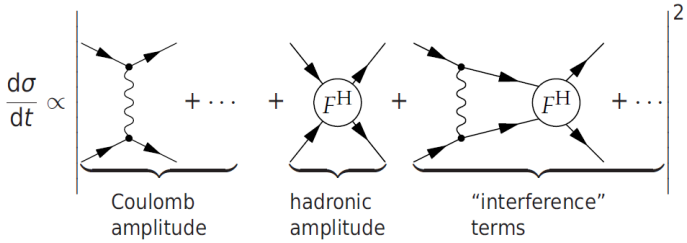
$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)}\frac{1}{\mathcal{L}}\left(\frac{dN_{el}}{dt}\right)_{t=0}$$

ρ independent

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

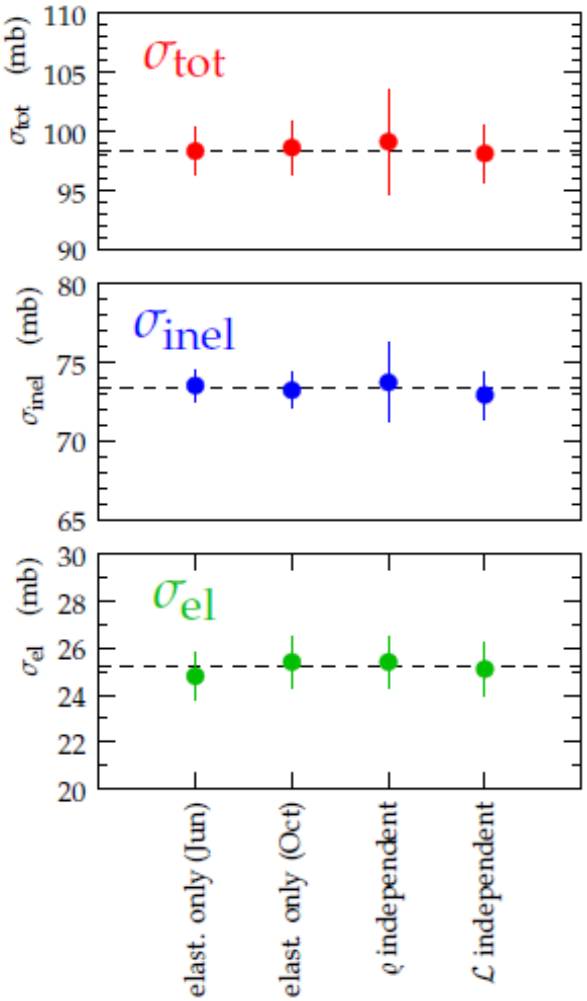
ρ measurement : elastic scattering at very low-t (Coulomb-Nuclear Interference region)

$(d\sigma/dt) \sim |A^C + A^N(1-\alpha\ G(t))|^2$

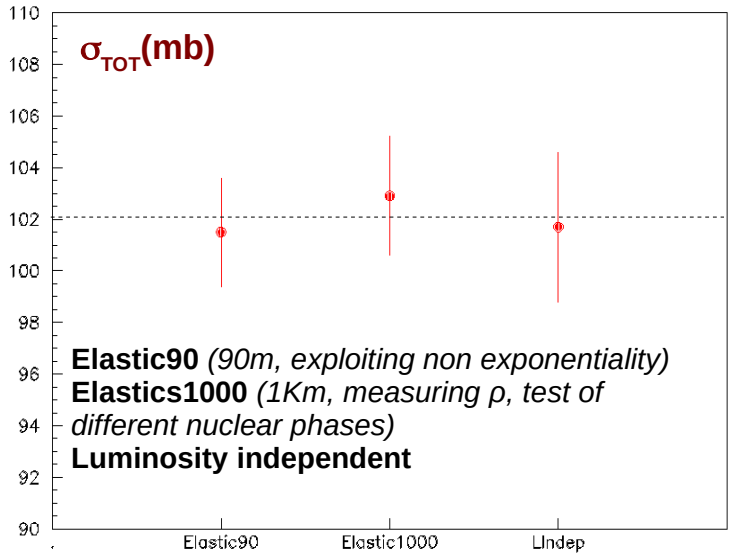


The differential cross section is sensitive to the phase of the nuclear amplitude
In the CNI both modulus (constrained by measurement in the hadronic t-region) and phase (t-dependent) of nuclear amplitude can be tested to dermine ρ

Total Cross section measurements: methods

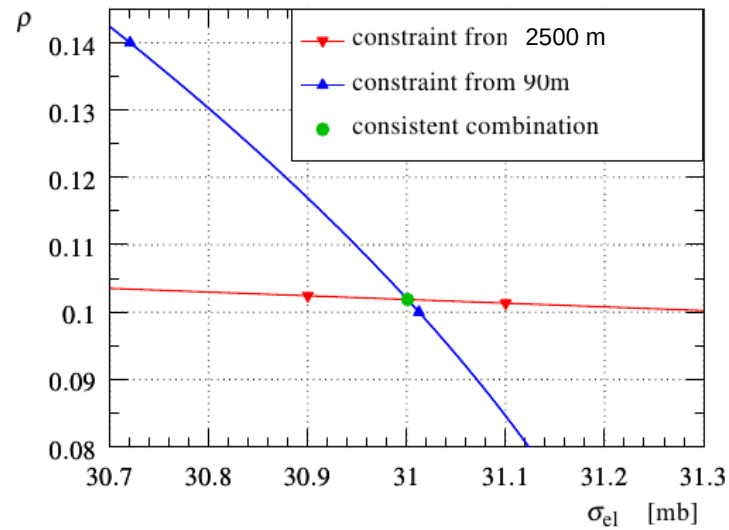


7 TeV, several methods
Same beam conditions



Elastic90 *(90m, exploiting non exponentiality)*
Elastics1000 *(1Km, measuring ρ, test of different nuclear phases)*
Luminosity independent

8 TeV, several methods
Different beam conditions



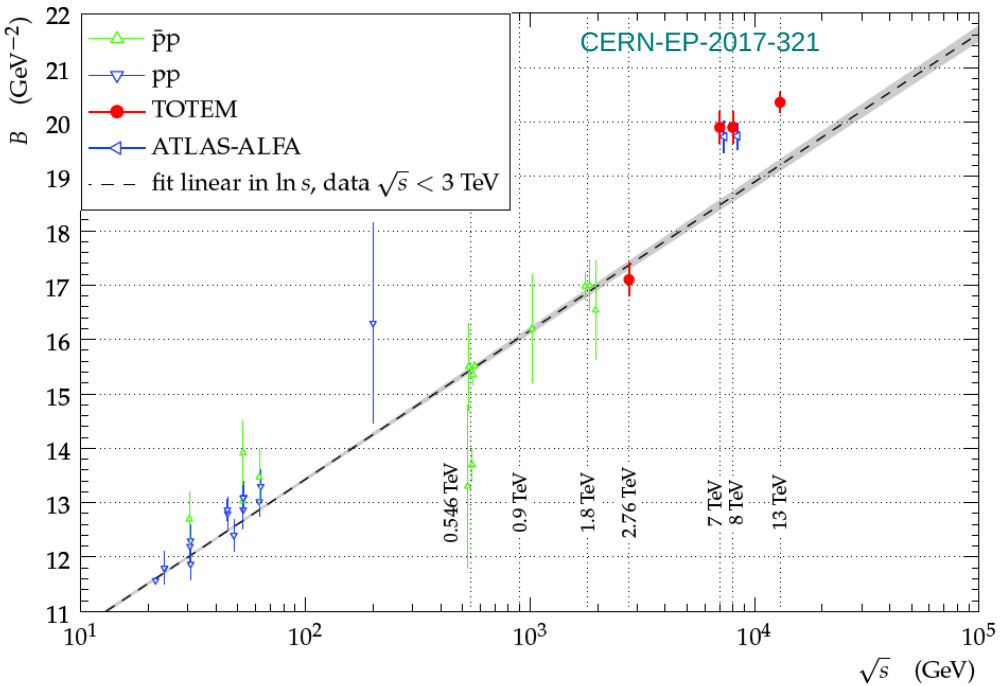
13 TeV
90m : lumi independent
2500m: ρ measurement

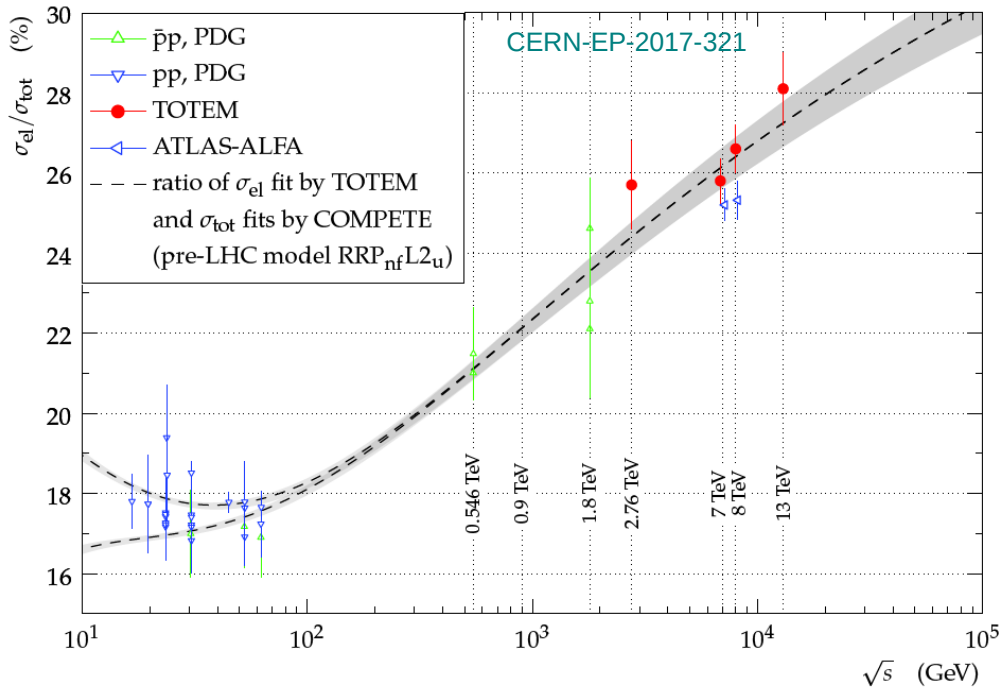
Different beam conditions

Total Cross section measurements: implications

The diffraction cone shrinkage speed up with the collision energy

The increase of σ_{el}/σ_{TOT} with energy is confirmed also at LHC





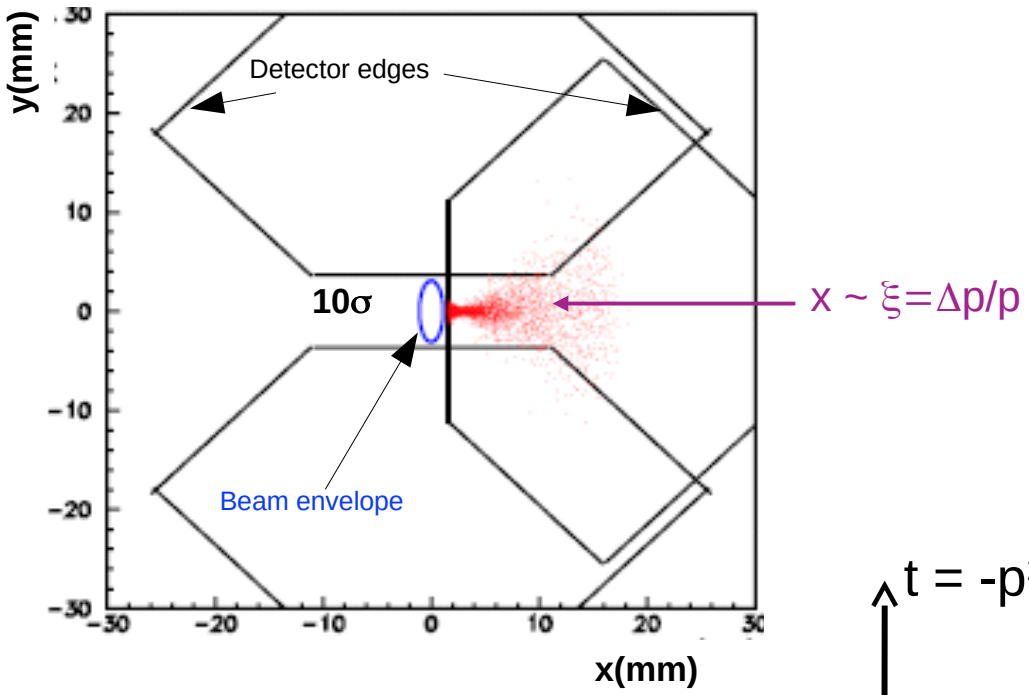
B=d/dn ln (ds/dt) | $_{t=0}$ increases with √s

The linear (ln s) behaviour is compatible for √s ≤ 3 TeV

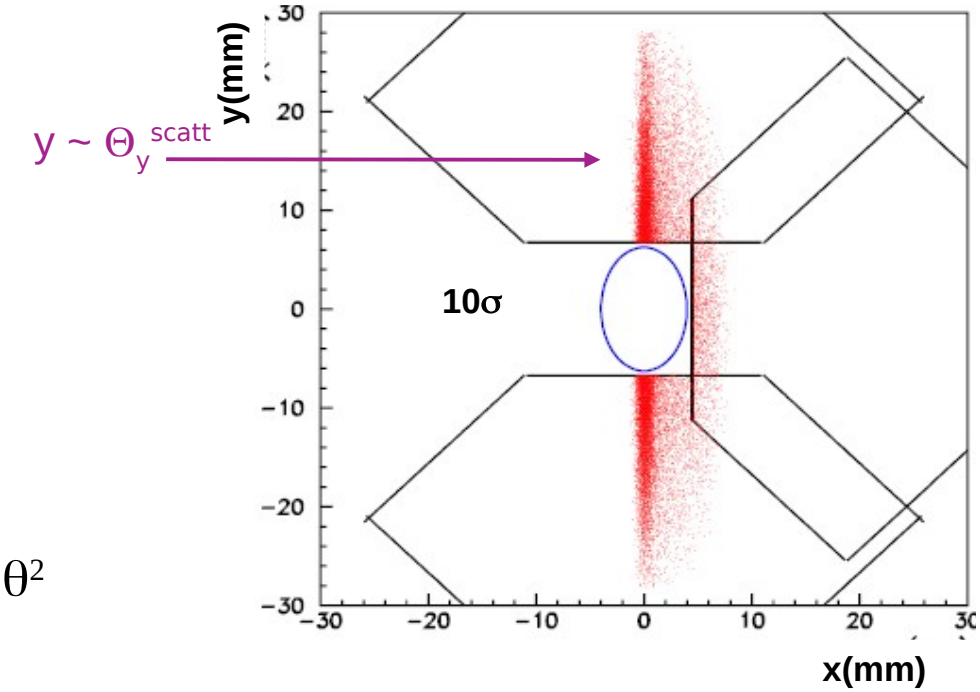
Measurement of Forward Protons: the principle

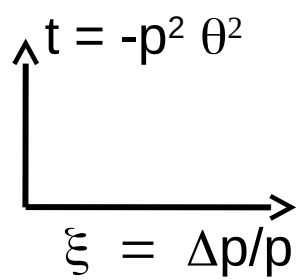
Diffractive protons : hit distribution @ RP220

Low β^* ~ 0.25 - 3 m



High β^* ~ 50 - 2500 m





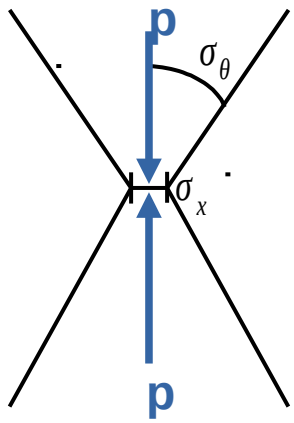
Detect the proton via:

its momentum loss (low β)

its transverse momentum (high β)

Measurement of Forward Protons: the principle

Low β^* ~ 0.25 - 3 m

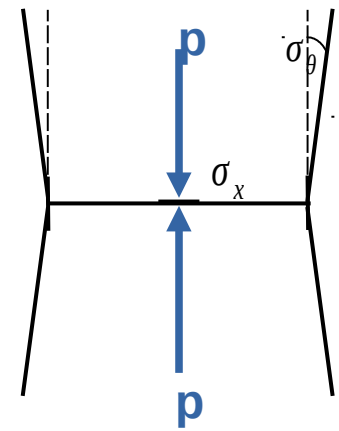


$$\sigma_x \sim 10\text{-}20\ \mu m$$
$$\sigma_\theta \sim 20\text{-}30\ \mu rad$$

Optimized for high luminosity

High β^* ~ 50 - 2500 m

Large β* → small beam divergence



$$\sigma_x \sim 1\ \text{mm}$$
$$\sigma_\theta < 1\ \mu rad$$

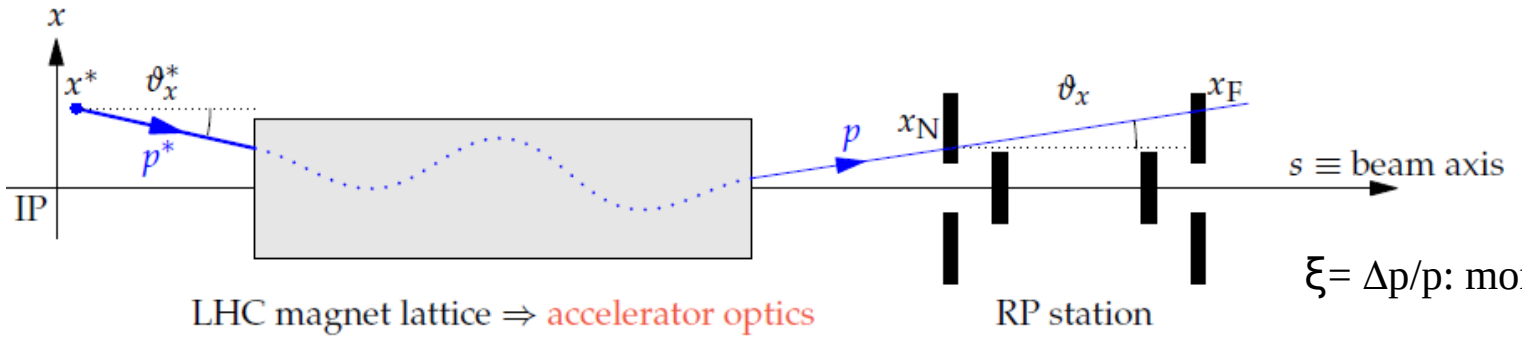
Choice: parallel to point focusing

Optimized for elastic scattering measurement (very low angle)

Measurement of Forward Protons: the principle

(x^*, y^*)
vertex position

(θ_x^*, θ_y^*)
emission angle



$\xi = \Delta p/p$: momentum loss

Product of all lattice element matrices

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

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

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

$L_{x,y}$ effective length ~ $\sqrt{\beta\beta^*}\sin(\Delta\mu)$

$\Delta\mu = \pi/2$

If point to parallel focusing

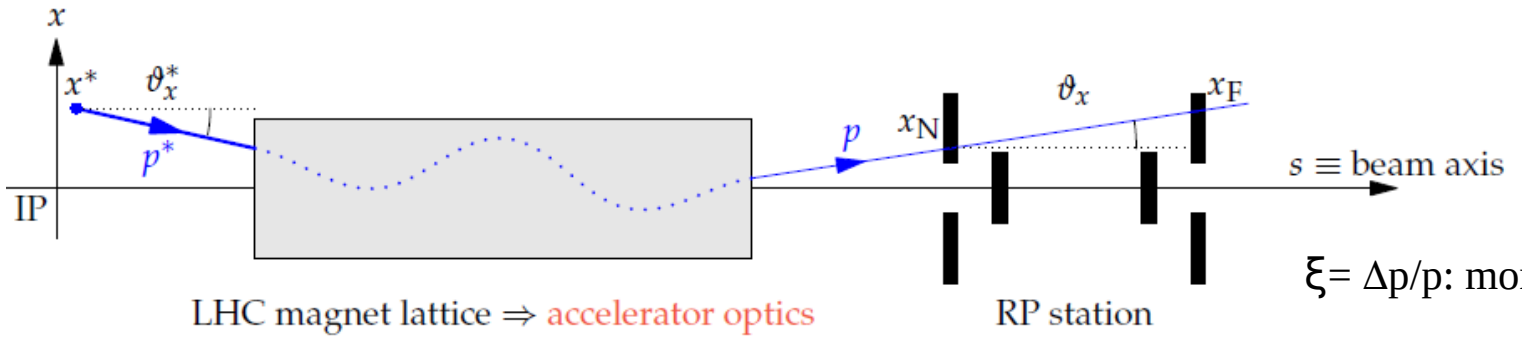
$v_{x,y}$ magnification $\sqrt{\beta/\beta^*}\cos(\Delta\mu)$

D_x dispersion (sensitivity to momentum loss)

Measurement of Forward Protons: the principle

(x^*, y^*)
vertex position

(θ_x^*, θ_y^*)
emission angle



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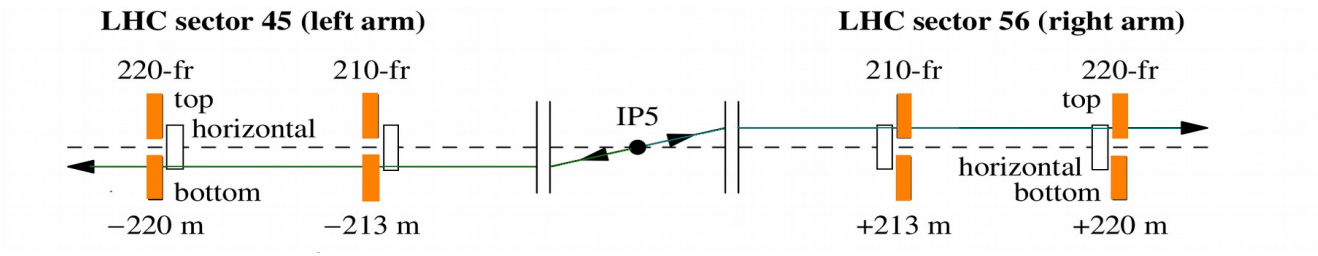
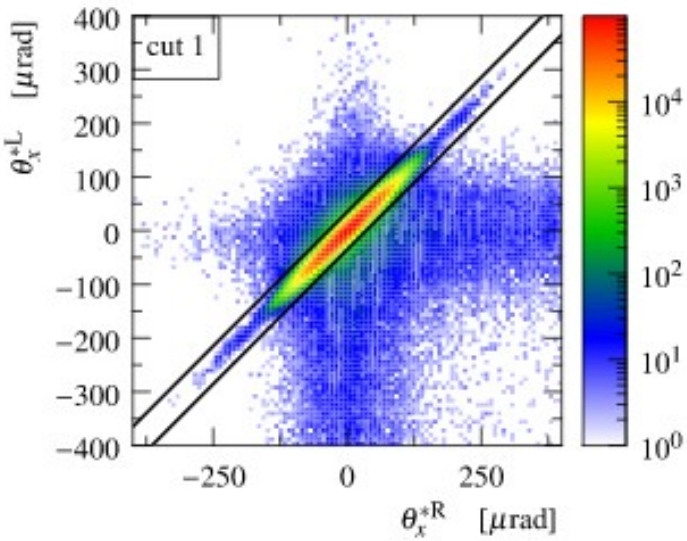
Values at IP5
to be reconstructed

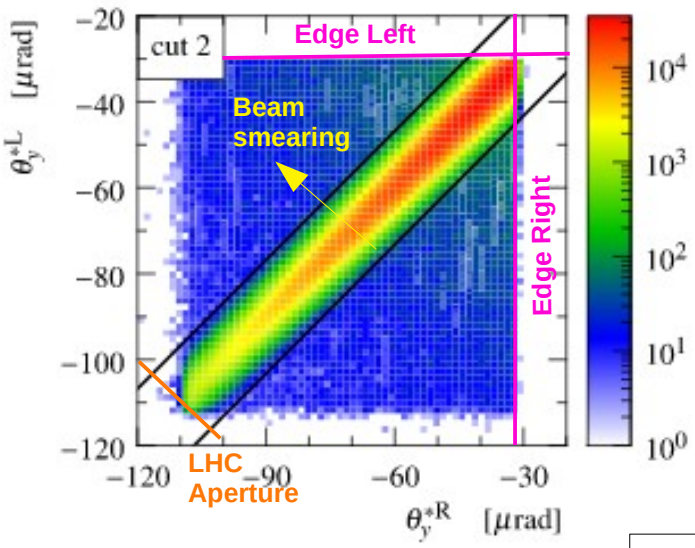
Strategy *[New J. Phys. 16 (2014) 103041]*

- Magnet currents measurements → MADX optics model
- Selection of elastic protons
- Determination of the optics parameters constraints with proton tracks
  - $\Theta^*_{left} = \Theta^*_{right}$ (proton pair collinearity)
  - Proton position ↔ angle correlations
  - L_x=0 determination, coupling corrections
- Matching of the optics (transport matrix) ⇒ $\delta L'_x/L'_x < 1\%$ and $\delta L_y/L_y < 1\%$

Elastic measurement : method



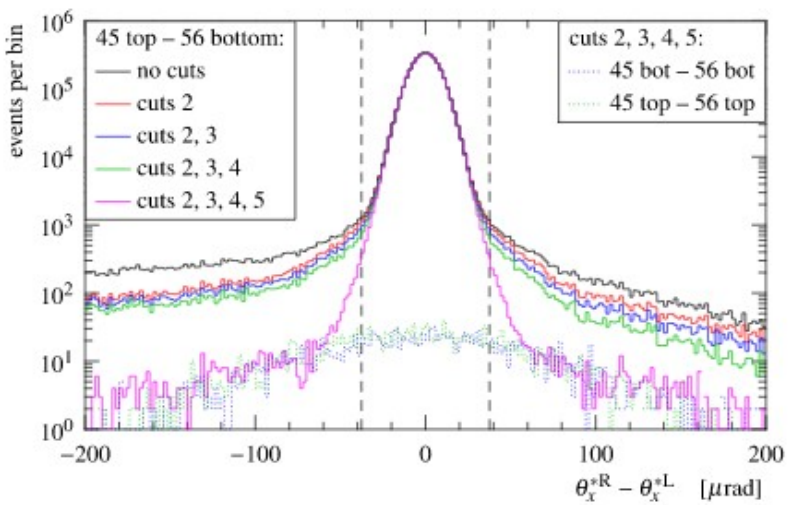




Collinearity cut (left-right)

$\theta^*_{x,45} \leftrightarrow \theta^*_{x,56}$

$\theta^*_{y,45} \leftrightarrow \theta^*_{y,56}$



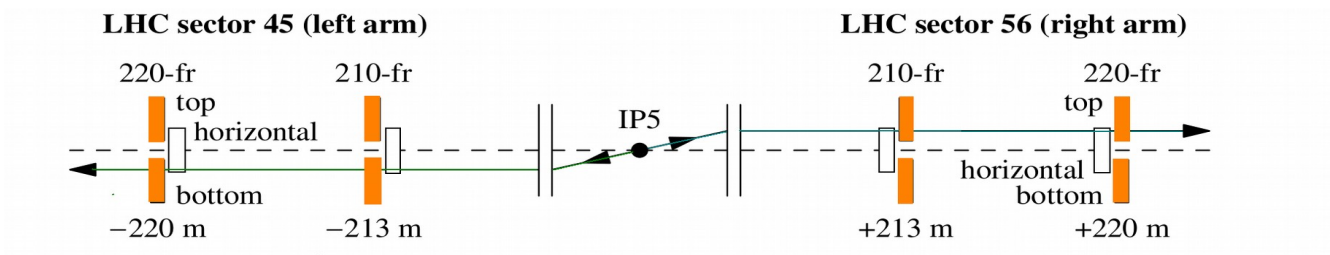
Background subtraction

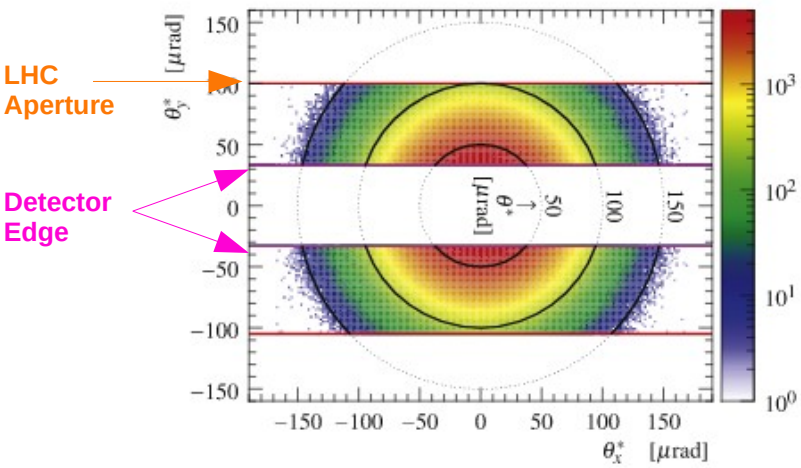
Trigger : double-arm RP

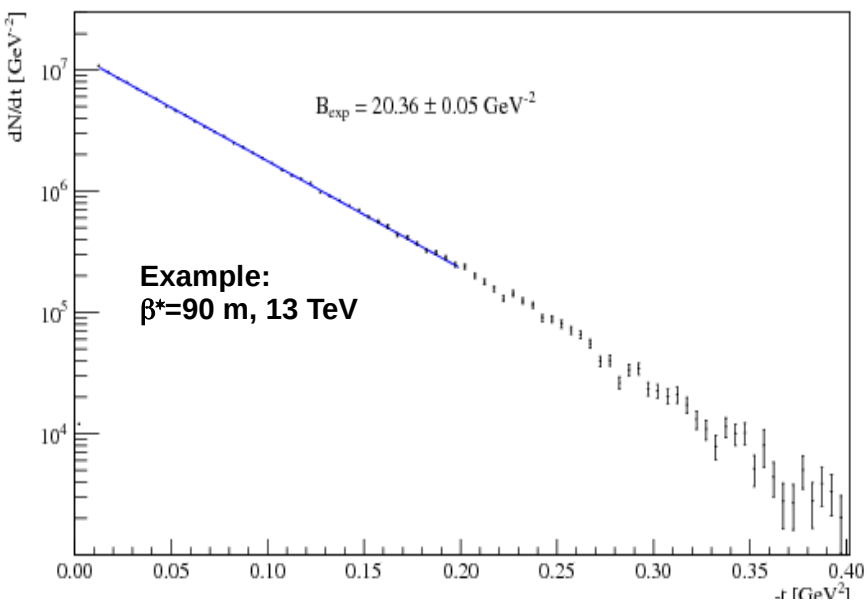
RP tracks in opposite arm in diagonal topology

Cuts: left-right correlation in several kinematics variables

Elastic measurement : method







Corrections to differential rate (mostly data-driven):

acceptance, efficiencies (trigger, DAQ, reconstruction), smearing in |t|

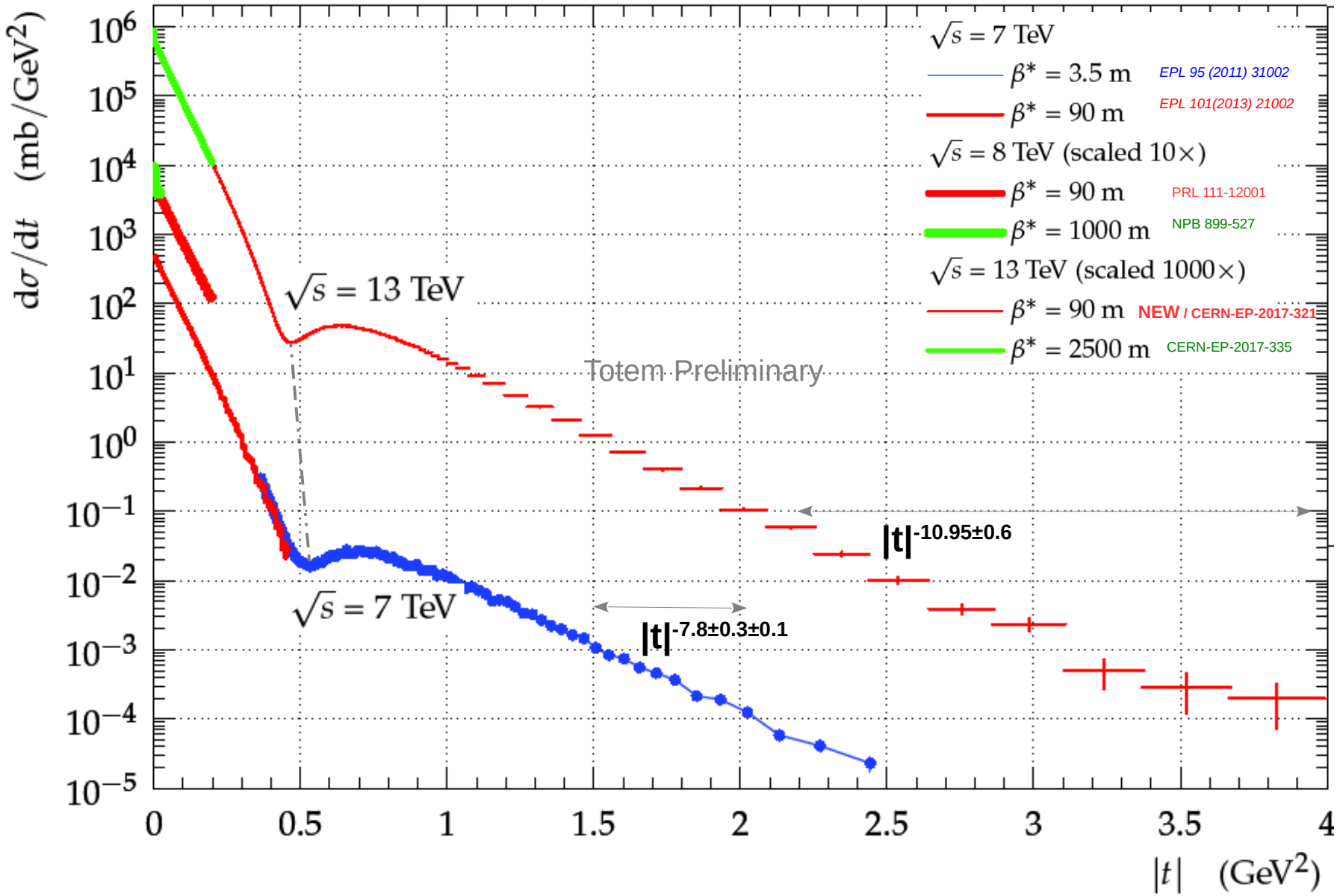
Integrated rate: differential rate extrapolated to low |t| (unobserved)

$\sigma(dN_{el}/d|t|_{t=0}) \sim 1.6$ %

$\sigma(N_{el}) \sim 2.3$ %

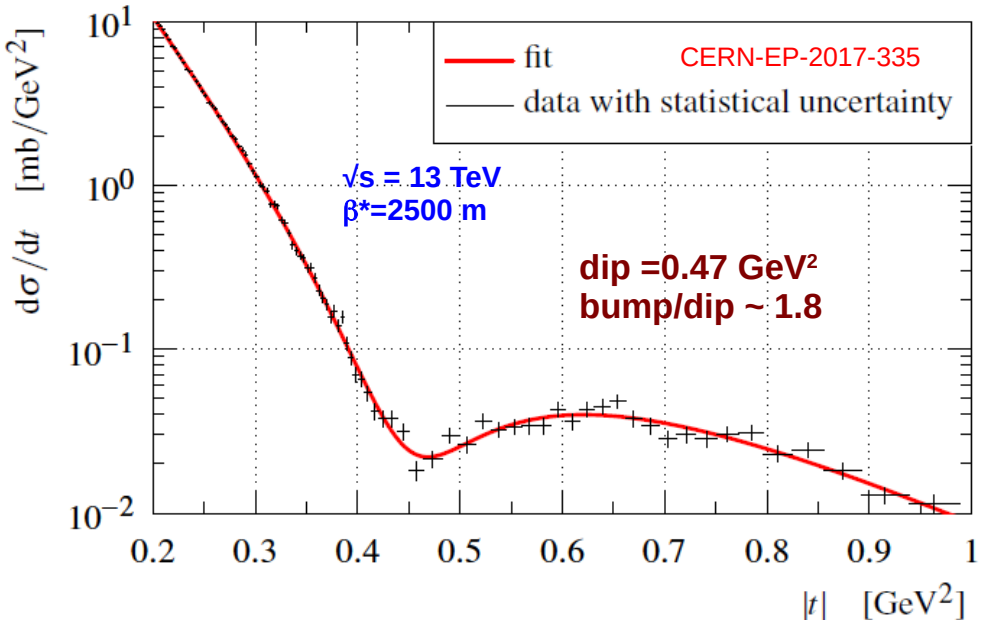
Elastic measurements: dip and structure at high-t

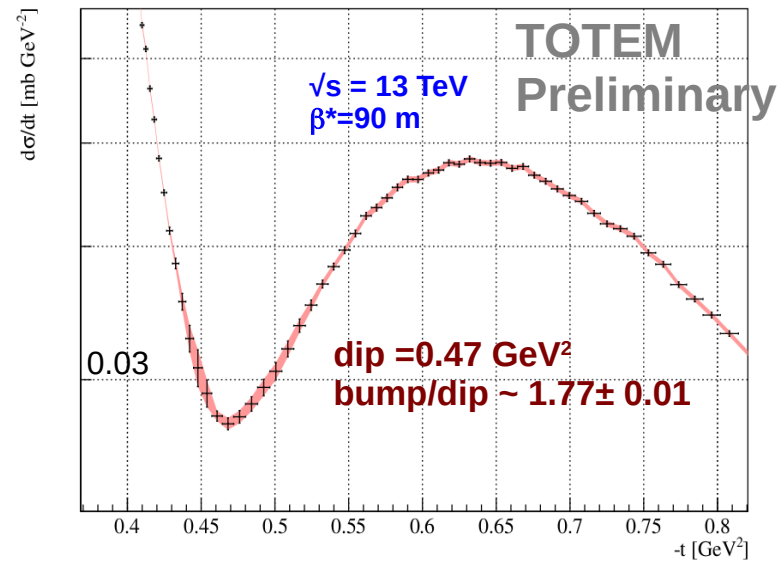
No structure seen at high-t
Dip present at all energies

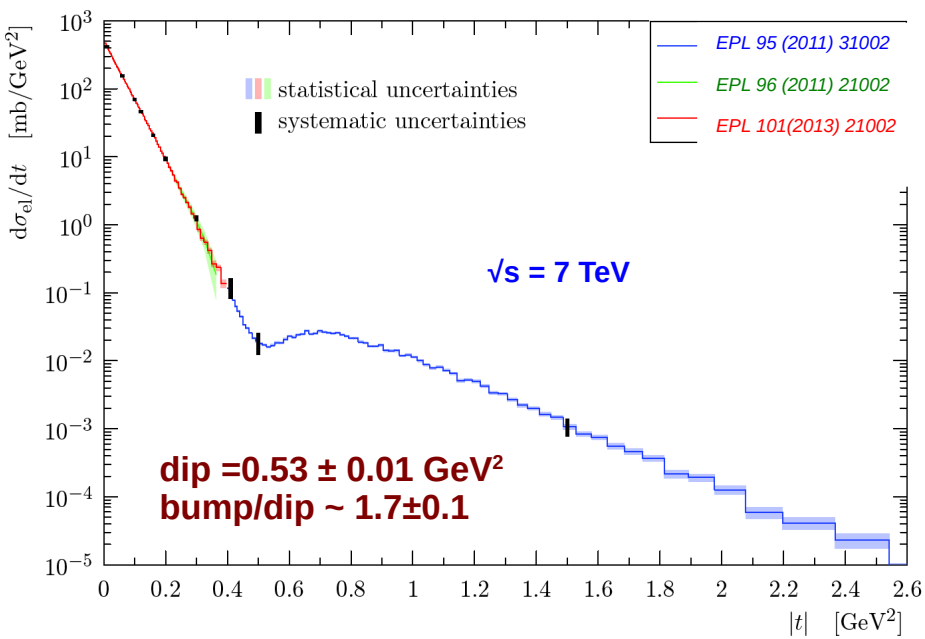


Elastic measurements: dip @ 13 TeV

dip position in |t| decreases with increasing √s



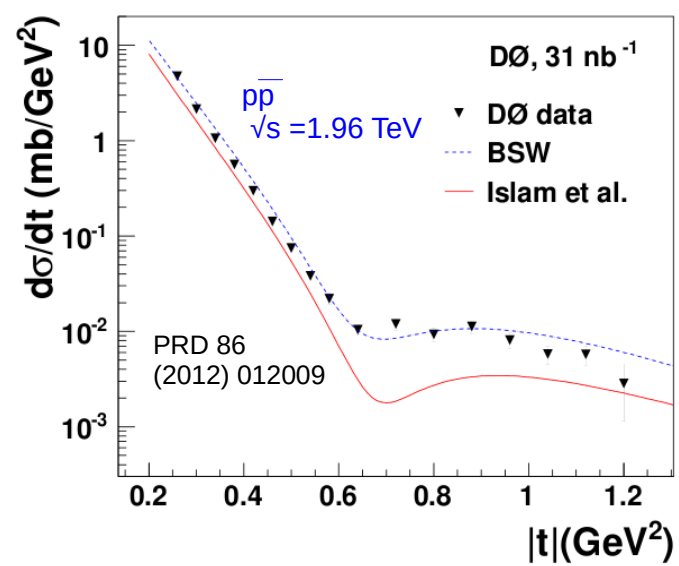




TOTEM Preliminary:

DIP is visible also at √s = 2.76 TeV !

Dip is missing in $p\bar{p}$



Elastic Scattering : Coulomb interference and ρ parameter

First LHC determination from Coulomb-hadronic interference at 8TeV : $\rho=0.12\pm0.03$
Uncertainty still too high (low statistics)

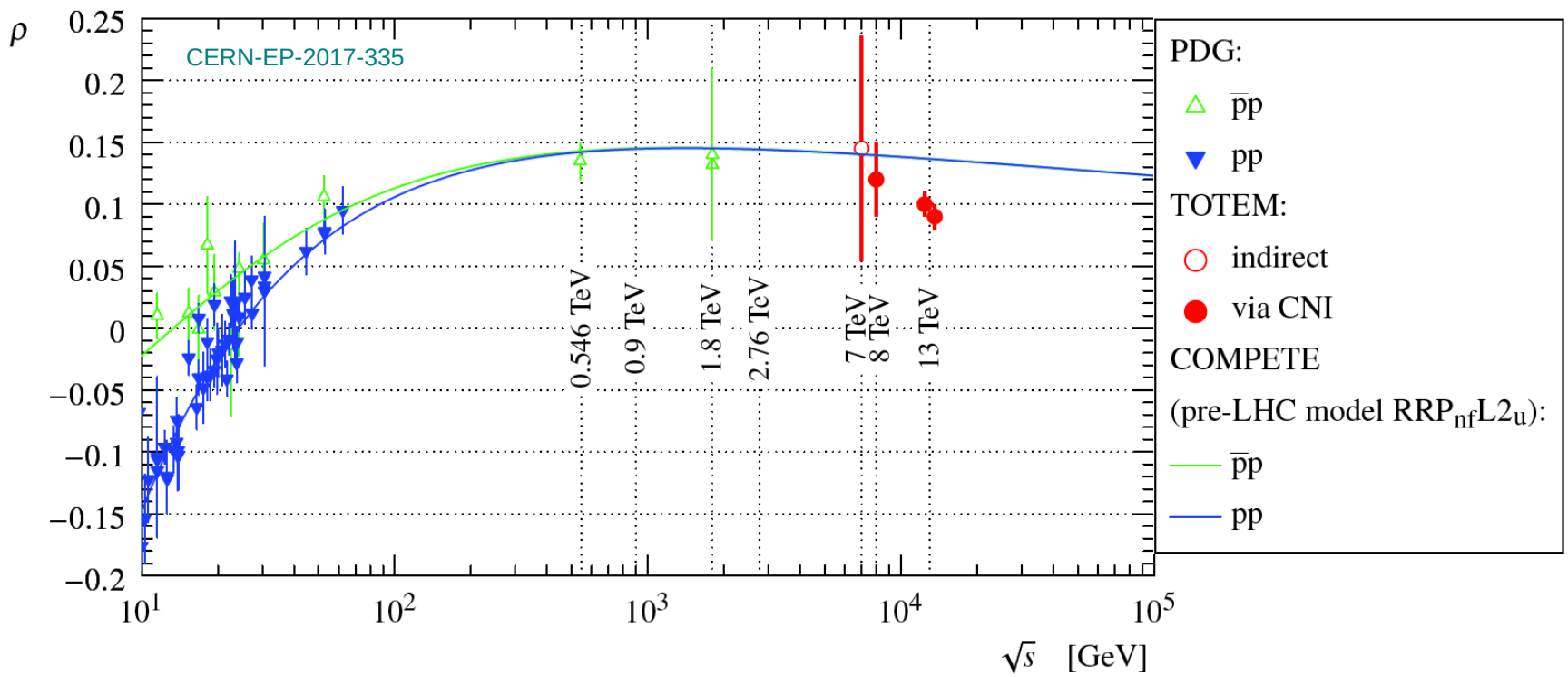
At 13 TeV : sample with very high statistics allows an unprecedented precision:

Modulus nuclear amplitude (low-|t|) ~

$$a \exp\left(\sum_{n=1}^{N_b} b_n t^n\right)$$

	$\lvert t\rvert_{max}$ = 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

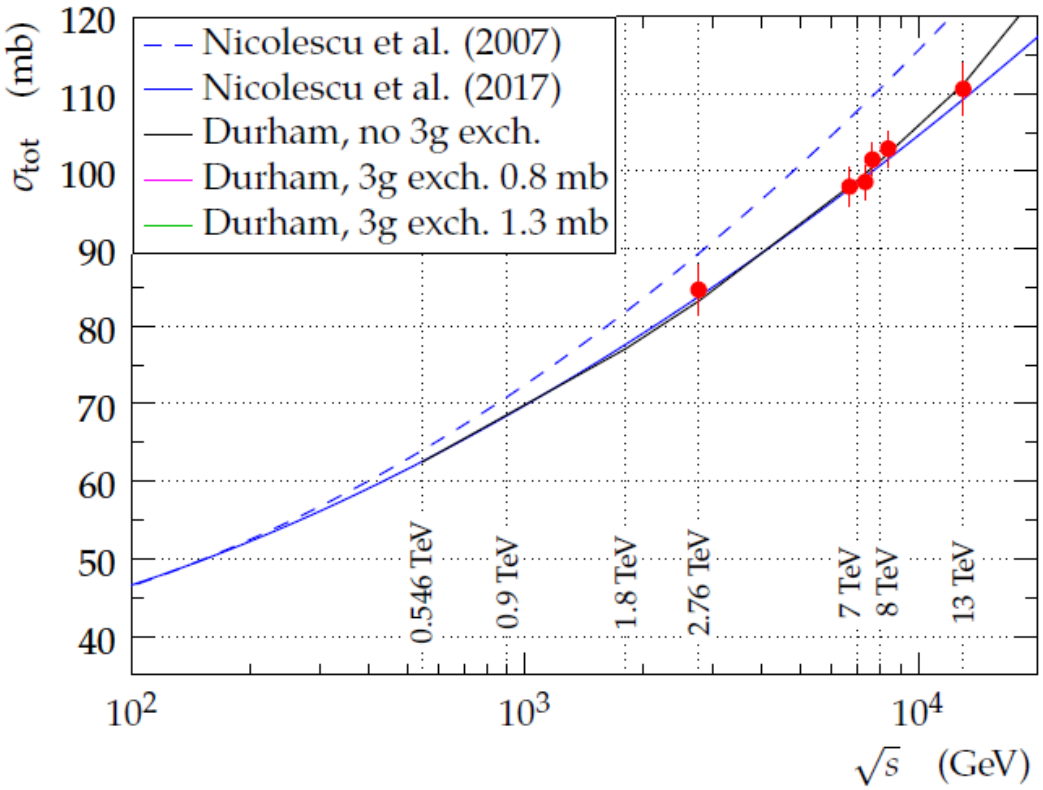
$|t|_{max}$= 0.07 GeV2
Comparison with UA4/2
(same t-range)

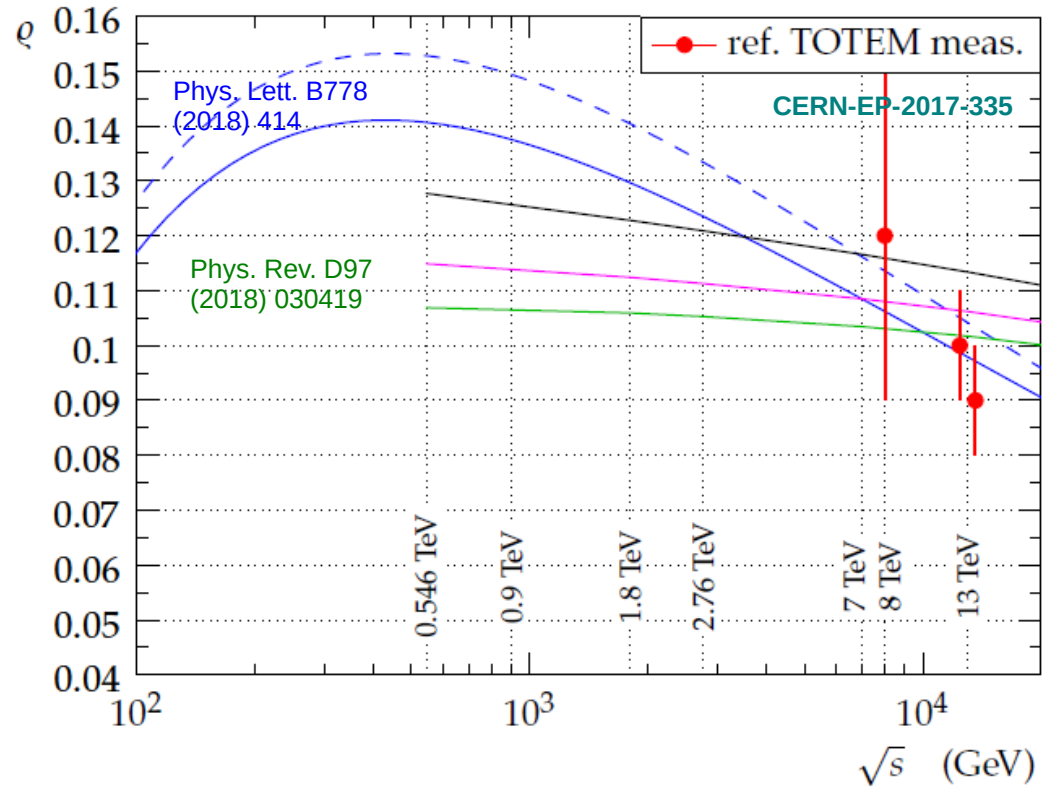


The new measurement is clearly below the predictions

σ_{TOT} and ρ parameter : possible interpretation?

t-channel exchange of a colourless **3-gluon bound state** ($J^{PC} = 1^{--}$) could decrease ρ in pp collisions at high energy

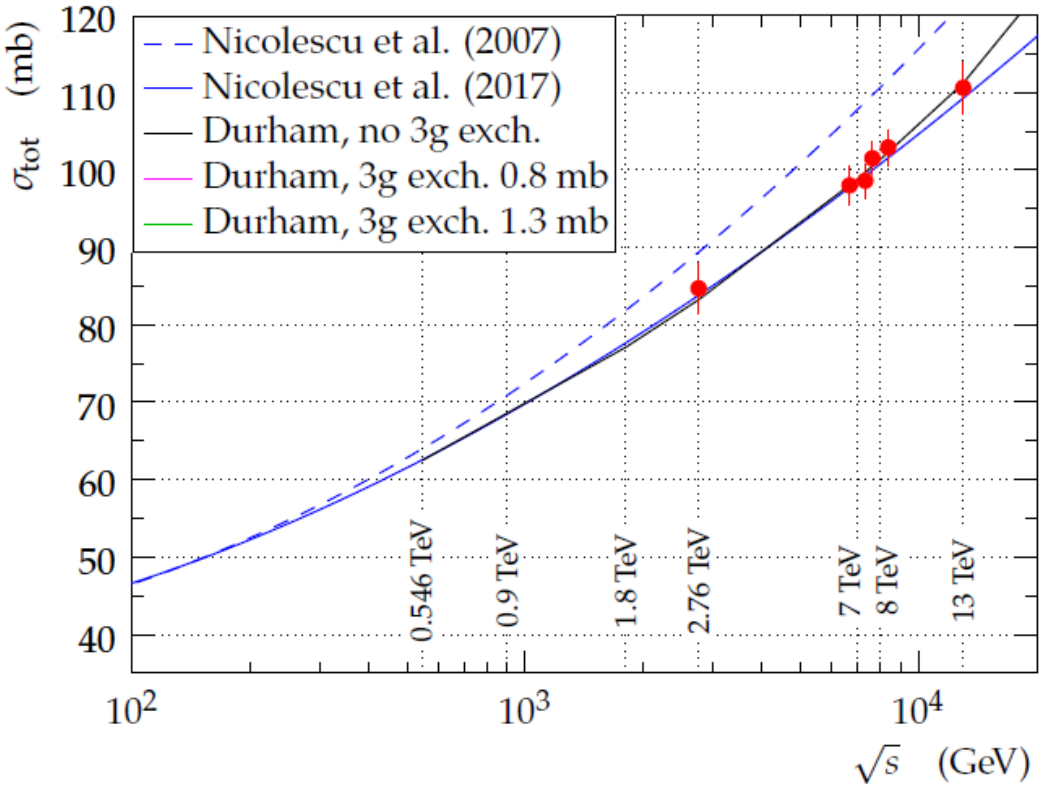


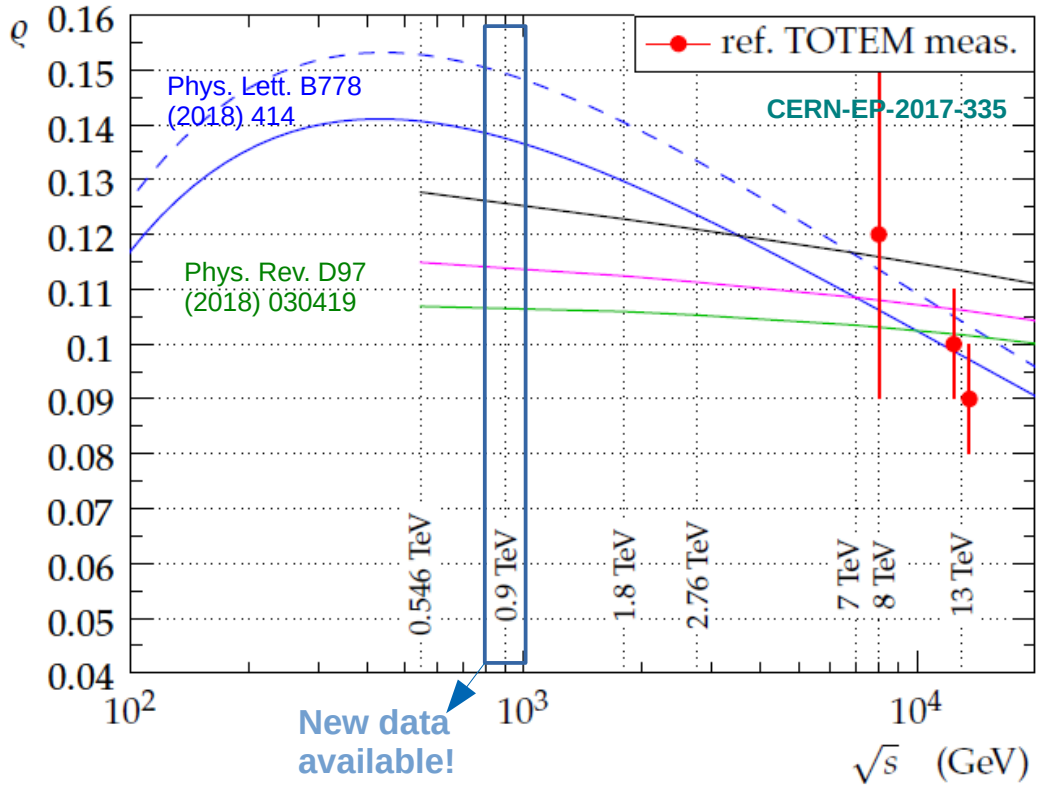


"Odderon" hint or first evidence of "slowing down" of σ_{TOT} growth at higher energy?

σ_{TOT} and ρ parameter : possible interpretation?

t-channel exchange of a colourless **3-gluon bound state** ($J^{PC} = 1^{--}$) could decrease ρ in pp collisions at high energy





Other observations:

- diffractive dip in the proton-proton elastic t-distribution
- the deviation of the elastic differential cross-section at low-|t| from a pure exponential
- no oscillations of the elastic differential cross-section at large-|t |

Extended Physics programme: CMS + TOTEM

Combine central detector with forward protons measurement in Roman Pot

Joint data taking started already in Run-I
Now all RP detectors are integrated in CMS DAQ

1) Low luminosity/pileup: collected ~40/nb @8 TeV, ~5.4/pb @ 13 TeV,
Acceptance: low and moderate diffractive mass M_x
Low-mass resonances in Central Exclusive Production, Diffraction with proton tag

- Measurement of dijet production with a leading proton in pp collisions at $\sqrt{s}$ = 8 TeV [CMS-PAS-FSQ-12-033,TOTEM-NOTE-2018-001]

Ongoing analyses:
- Jet-Gap-Jet with proton tag (ongoing)
- Study of resonances in the M_x<4 GeV mass range.

Search for scalar (0^{++}) and tensor (2^{++}) glueball candidates and their decays: ππ, KK, ρρ, …
Potentially wide possibility for measurements of inclusive and exclusive diffraction with proton(s) tag

2) High luminosity/pileup : since 2016 , collected ~ 100/fb
Acceptance : M_x>400 GeV (Central Exclusive Production, 2 tagged protons)
High-mass/low cross section BSM, electroweak, and QCD & top physics with forward protons: gauge boson pair production (WW, ZZ, Zγ, γγ), searches for anomalous couplings, new resonances,...

Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV [JHEP 07 (2018) 153]

Summary

Totem has made extensive measurements related to pp cross sections and elastic scattering
Some of the pre-LHC questions are nevertheless still open

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)

Several measurements related to the Cosmic Ray domain have been performed and more results are expected in the future

The extended programme with CMS has excellent prospects to study exclusive production, photon-photon physics and new physics searches