



# Measurement of the total cross section and the $\rho$ parameter at 13 TeV by TOTEM

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on behalf of the TOTEM Collaboration



# The TOTEM experiment

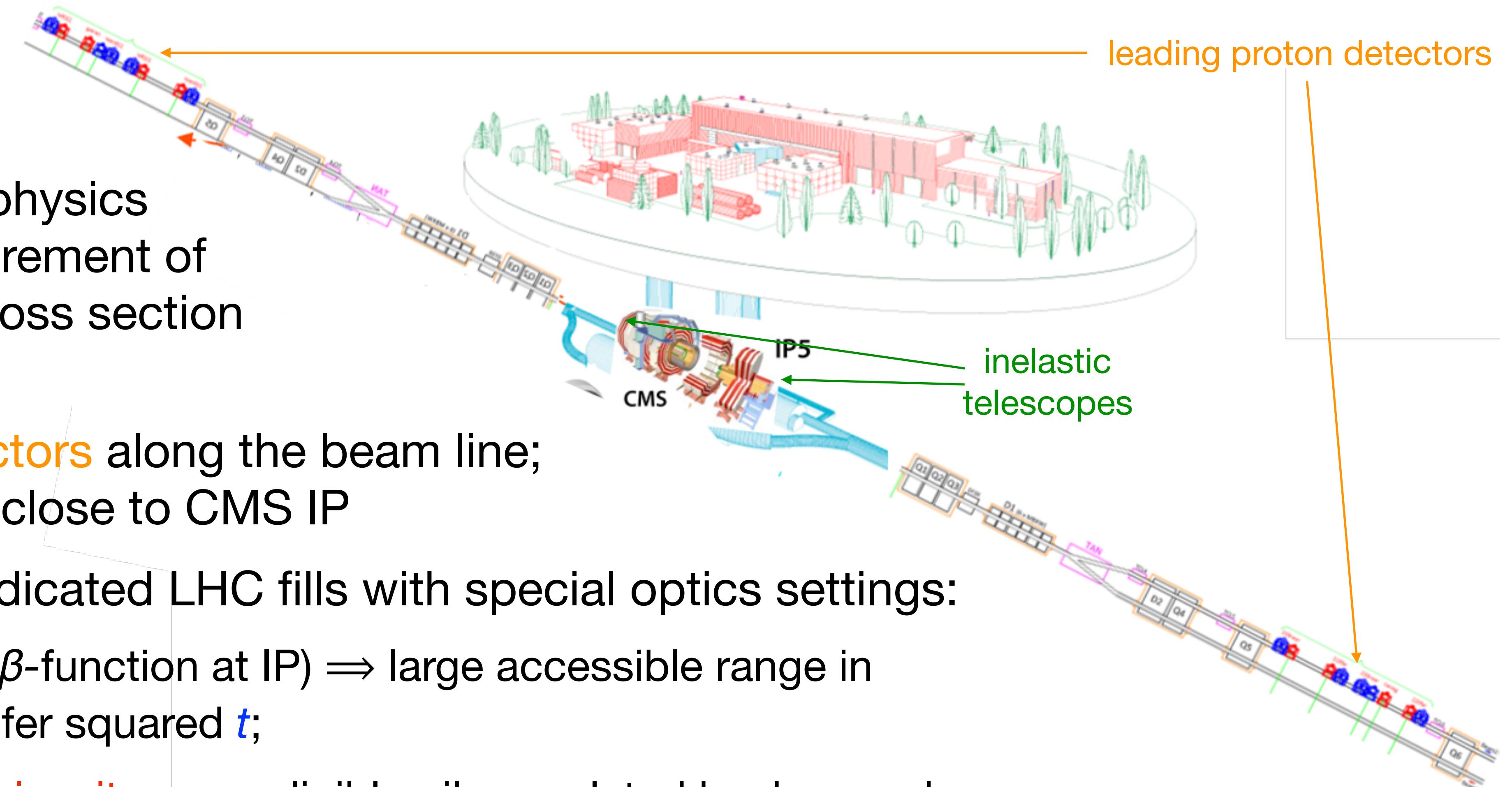
Main goal in TOTEM physics program is the measurement of elastic and total pp cross section

Layout:

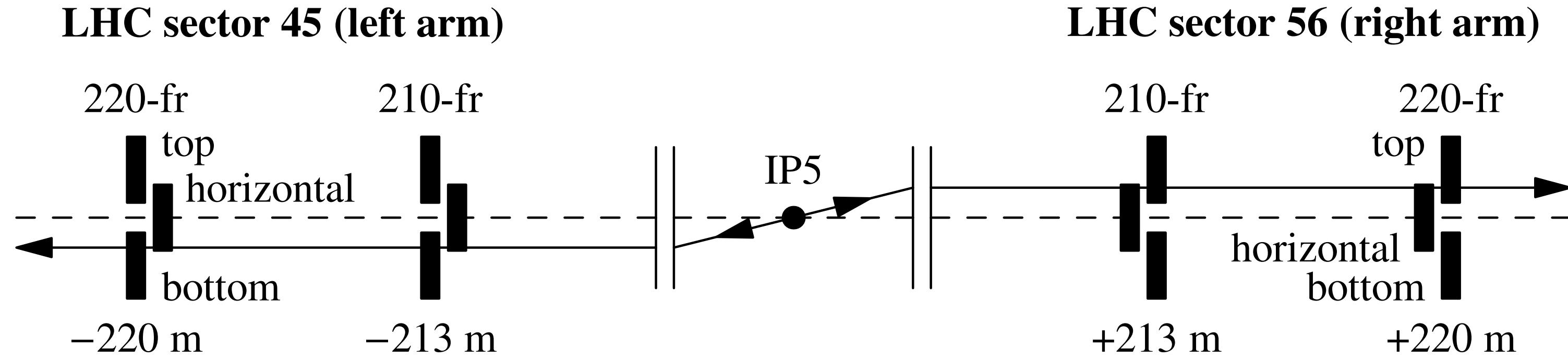
- **leading proton detectors** along the beam line;
- **inelastic telescopes** close to CMS IP

Designed to run in dedicated LHC fills with special optics settings:

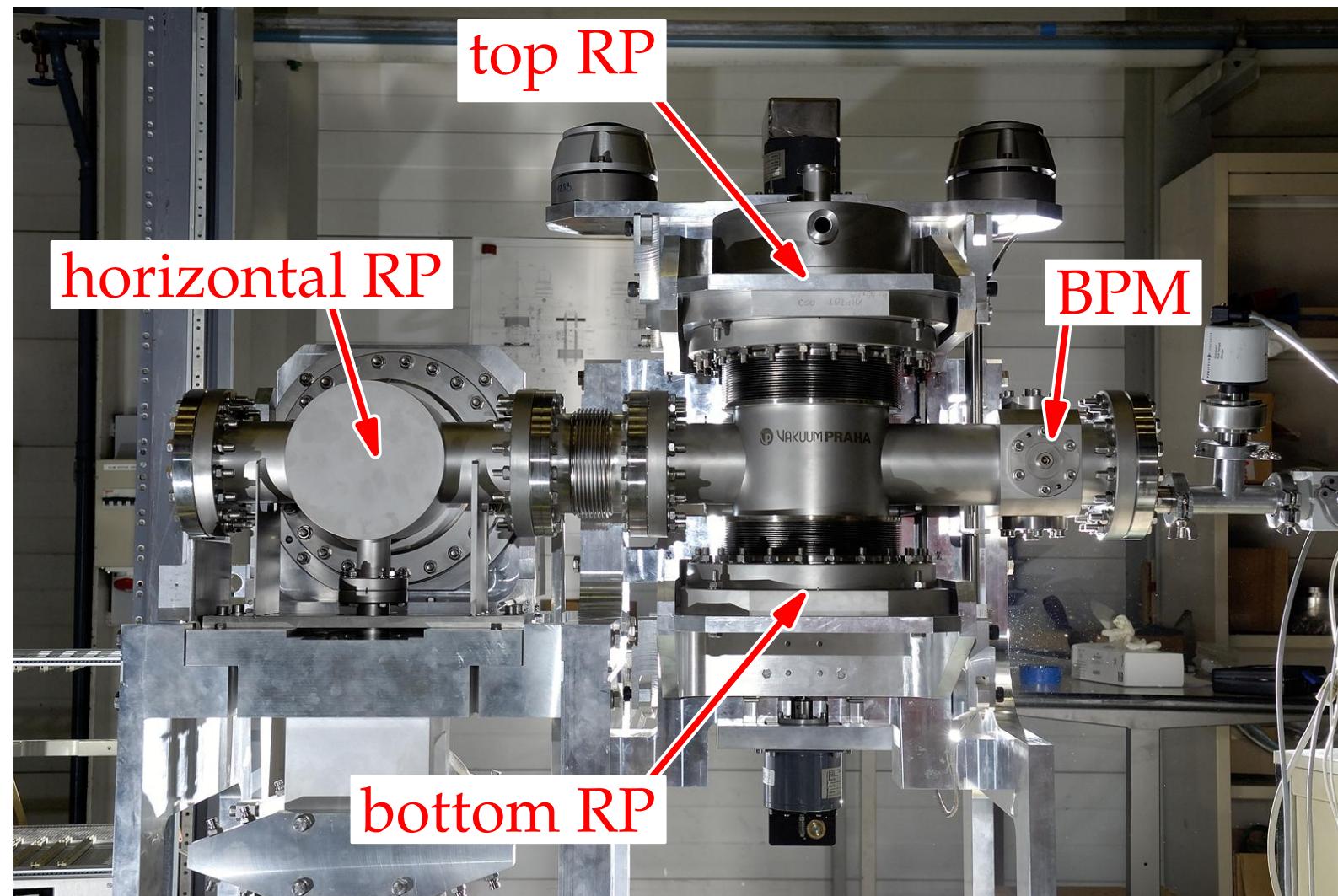
- **different values of  $\beta^*$**  ( $\beta$ -function at IP)  $\Rightarrow$  large accessible range in four-momentum transfer squared  $t$ ;
- **low instantaneous luminosity**  $\Rightarrow$  negligible pileup-related background ( $\sigma_{\text{tot}}(\text{pp}) @ \text{LHC} \sim 100 \text{ mb}$ )



# Leading proton detectors

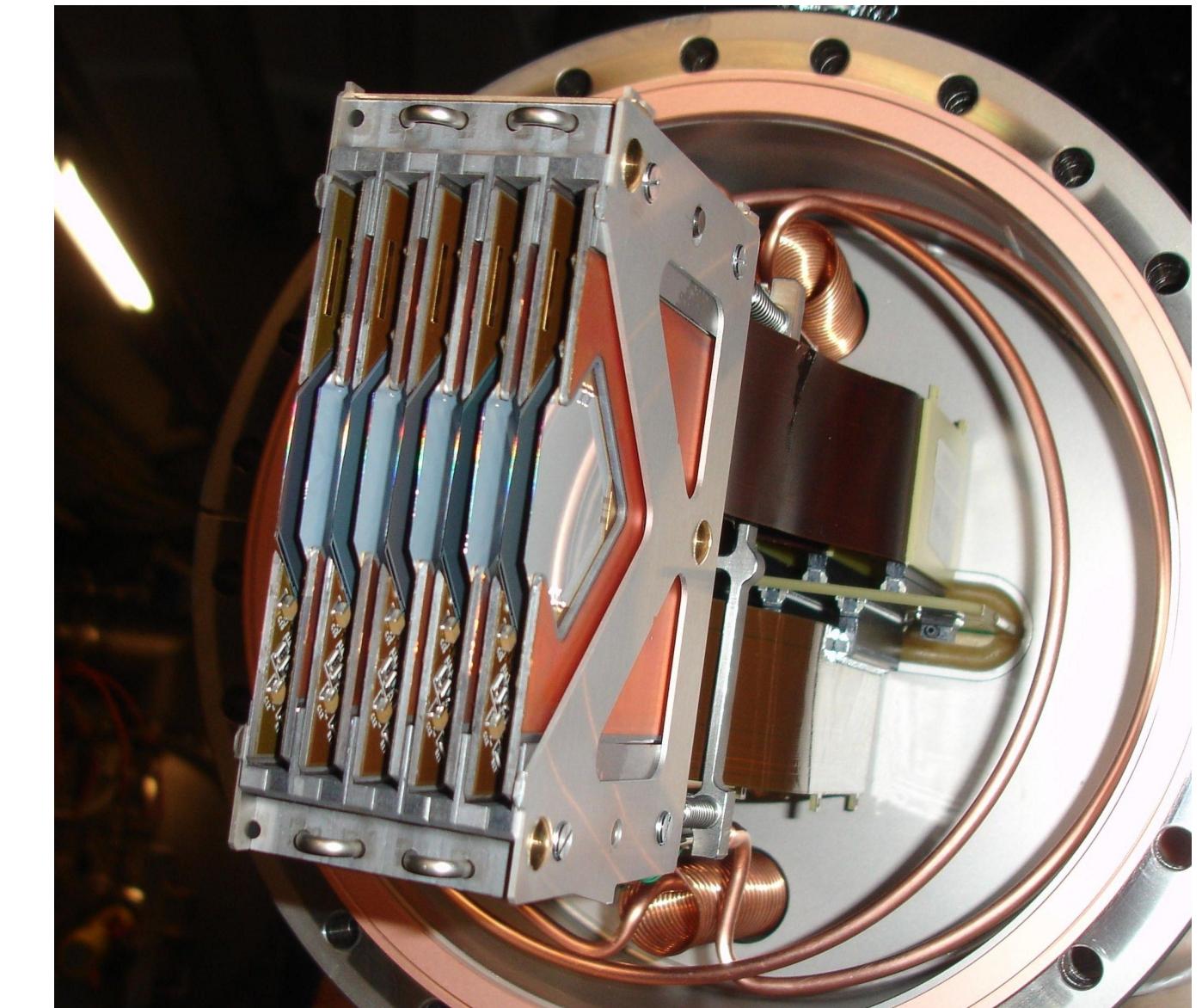


Tracking stations installed along the beam line at  $\sim 200$  m on both sides of the IP



Detectors housed in *roman pots* (RP):

- movable beam pipe insertion: approaching the beam (up to  $\sim 1$  mm) when beam stable;
- for these results, vertical pots at 210-far, 220-far units used



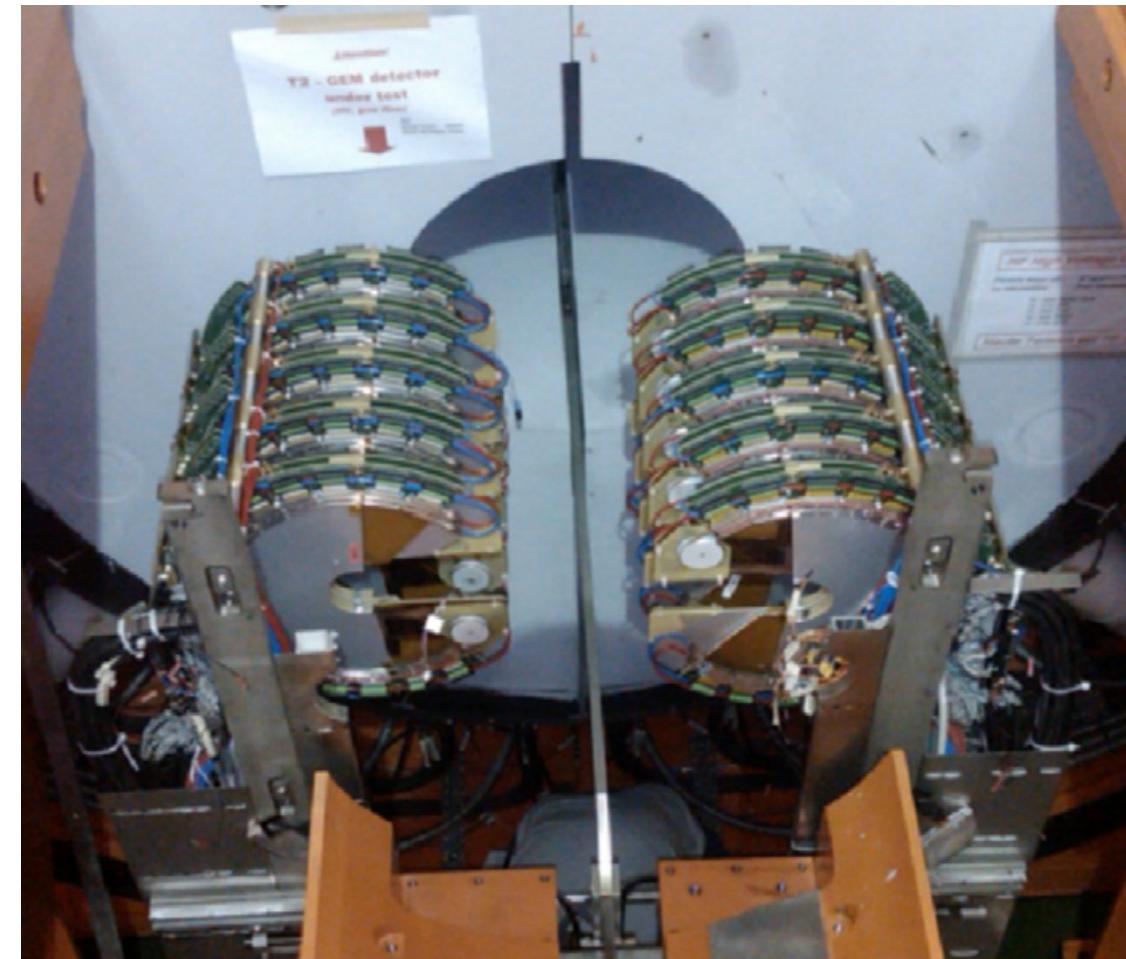
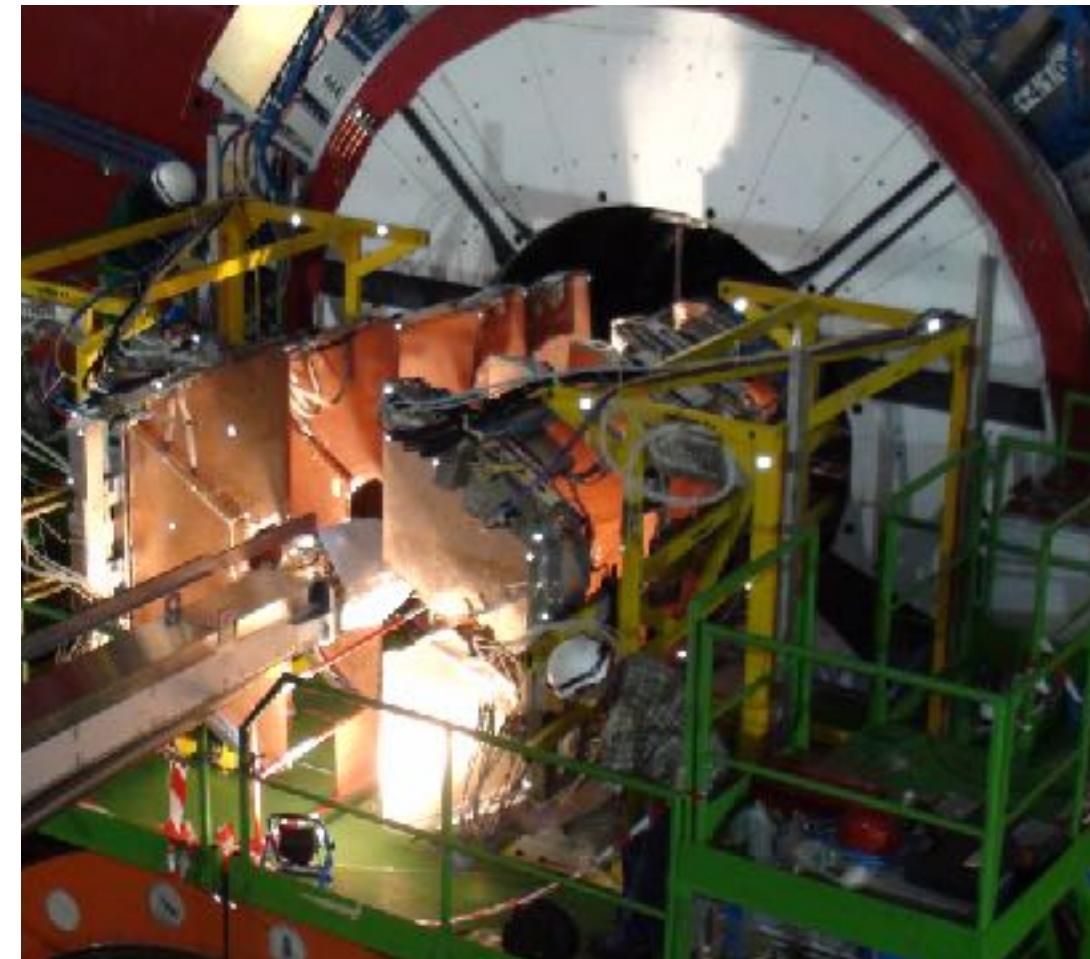
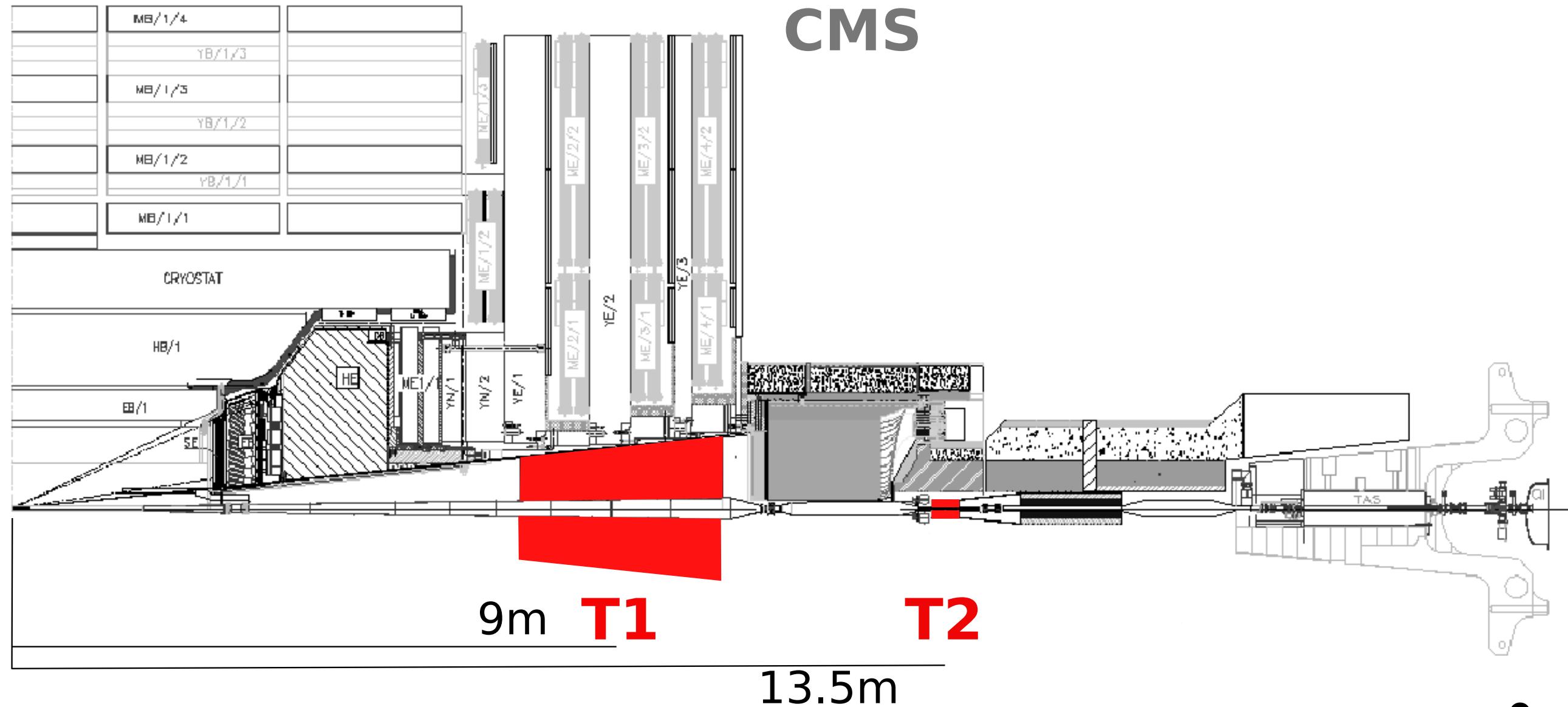
Detector package:

- 10 planes of “edgeless” silicon strip detectors (5 ‘u’ + 5 ‘v’)
- pitch: 66  $\mu\text{m}$ ; track resolution:  $\sim 12 \mu\text{m}$

# Inelastic telescopes

T1

- $3.1 < |\eta| < 4.7$
- 5 layers per side of Cathode Strip Chambers
- 3-coordinate readout ( $0^\circ, \pm 60^\circ$ )



T2

- $5.3 < |\eta| < 6.5$
- 10 layers per side of Gas Electron Multiplier chambers
- readout: radial strips +  $r\phi$  readout
- trigger capability

# The pp elastic cross section

The pp elastic cross section can be measured with a luminosity-independent technique (already used by TOTEM at 7 and 8 TeV):

$$\text{(optical theorem)} \quad \left\{ \begin{array}{l} \mathcal{L}\sigma_{\text{tot}}^2 = \frac{16\pi}{1+\rho^2} \cdot \frac{dN_{\text{el}}}{dt} \Big|_{t=0} \\ \mathcal{L}\sigma_{\text{tot}} = N_{\text{el}} + N_{\text{inel}} \end{array} \right. \implies \sigma_{\text{tot}} = \frac{16\pi}{1+\rho^2} \cdot \frac{dN_{\text{el}}/dt|_{t=0}}{N_{\text{el}} + N_{\text{inel}}}$$

Ingredients:

- inelastic yield;
- integrated and differential (as a function of  $t$ ) elastic yield

$t$  measured from  $\theta_x^*$ ,  $\theta_y^*$

For elastic scattering events:

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \end{pmatrix} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} \\ v'_x & L'_x & m_{23} & m_{24} \\ m_{31} & m_{32} & v_y & L_y \\ m_{41} & m_{42} & v'_y & L'_y \end{pmatrix} \begin{pmatrix} x^* \\ \theta_x^* \\ y^* \\ \theta_y^* \end{pmatrix}$$

Data collected at 13 TeV with special LHC optics with  $\beta^* = 90$  m

- $v_y \approx 0$  (“parallel to point” focussing)

**Selection:**

- RP trigger with double arm coincidence;
- one track in both (top or bottom) units;
- left-right comparison: diagonal topology, track collinearity, consistent  $x^*$
- diffractive event suppression:  $\xi$  consistent with 0

$$\theta_x^* = \frac{1}{L'_x} (\theta_x - v'_x x^*) \quad \left( x^* = \frac{L_{x,220}x_{210} - L_{x,210}x_{220}}{v_{x,220}x_{210} - v_{x,210}x_{220}} \right)$$

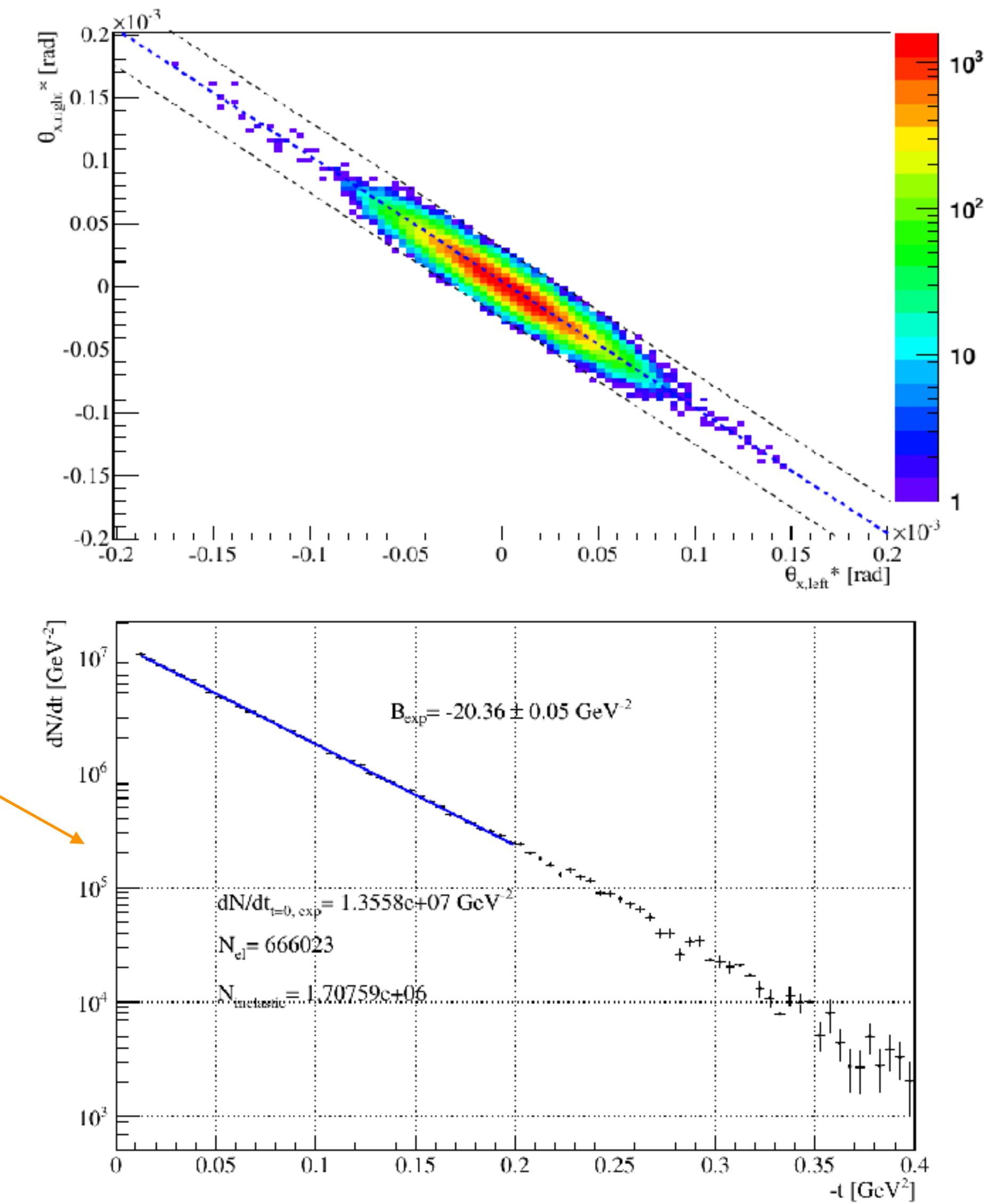
$$\theta_y^* = \frac{y}{L_y}$$

dN/dt, with fit to exponential  
and extrapolation at  $t = 0$

**Corrections:**

- geometrical and beam divergence acceptance;
- resolution unfolding;
- detection and reconstruction efficiency (as a function of  $\theta_{y^*}$ )

$\Rightarrow$  error on  $N_{el}$ : 2.3%; error on  $dN_{el}/dt|_{t=0}$ : 1.6%



## Selection:

- T2 trigger: activity in either arm;
- events classified according to topology:
  - both sides (“2h”): non-diffractive minimum bias + double diffraction;
  - one side (“1h”): single diffraction

## Corrections:

- trigger, reconstruction: from zero bias events and from MC;
- beam-gas background: from triggers on non-colliding bunches;
- pileup: from probability of events with tracks in T2;
- final state particles outside T2 acceptance: from T1 tracks (zero bias) and MC
  - largest contribution from low-mass diffraction (final state particles with  $|\eta| > 6.5$ )

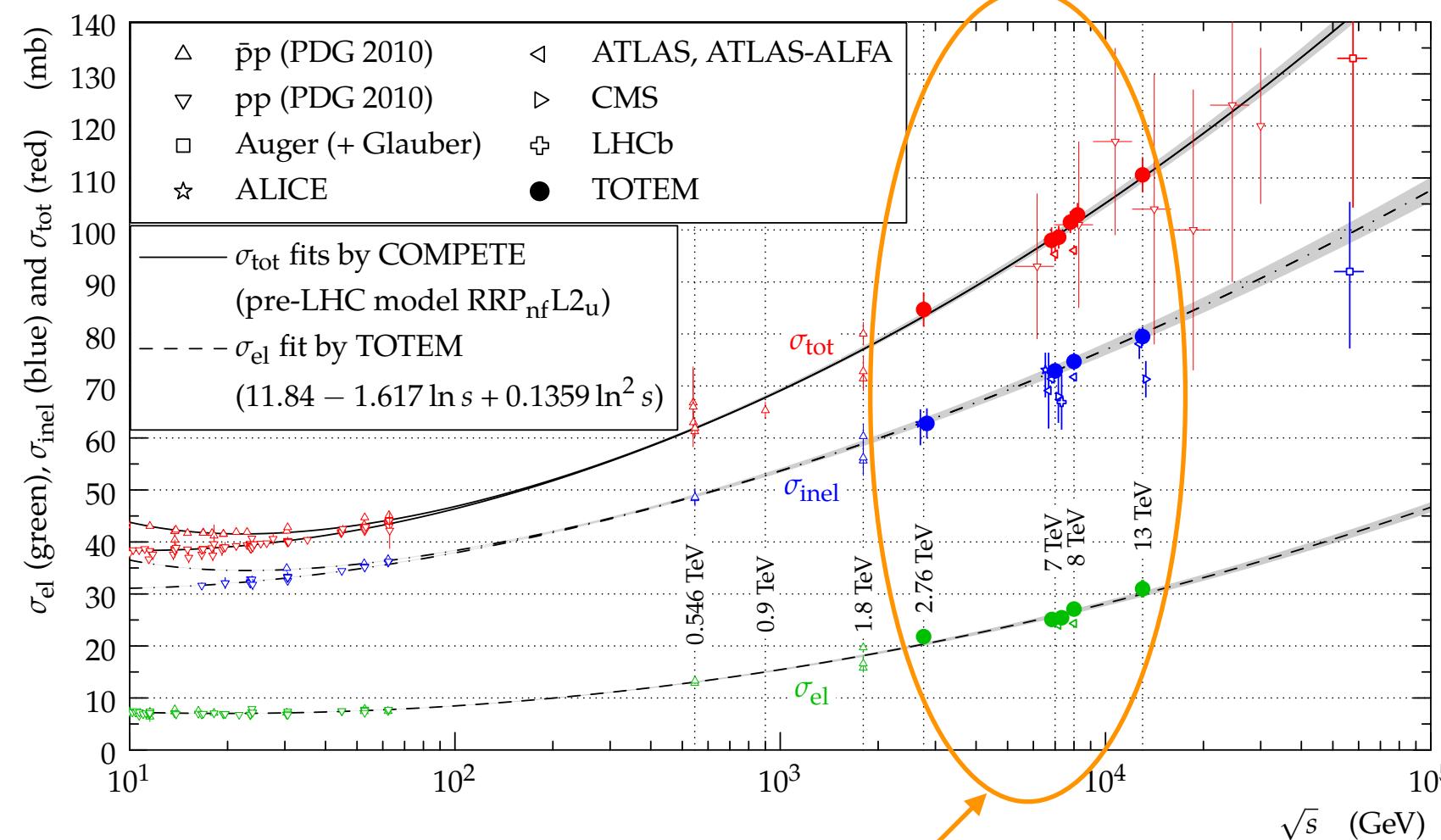
⇒ error on  $N_{\text{inel}}$ : 3.7%

# pp cross section at $\sqrt{s} = 13$ TeV

$$\rho = 0.1 \quad \left( \rho \equiv \frac{\Re A^N}{\Im A^N} \Big|_{t=0} \right)$$



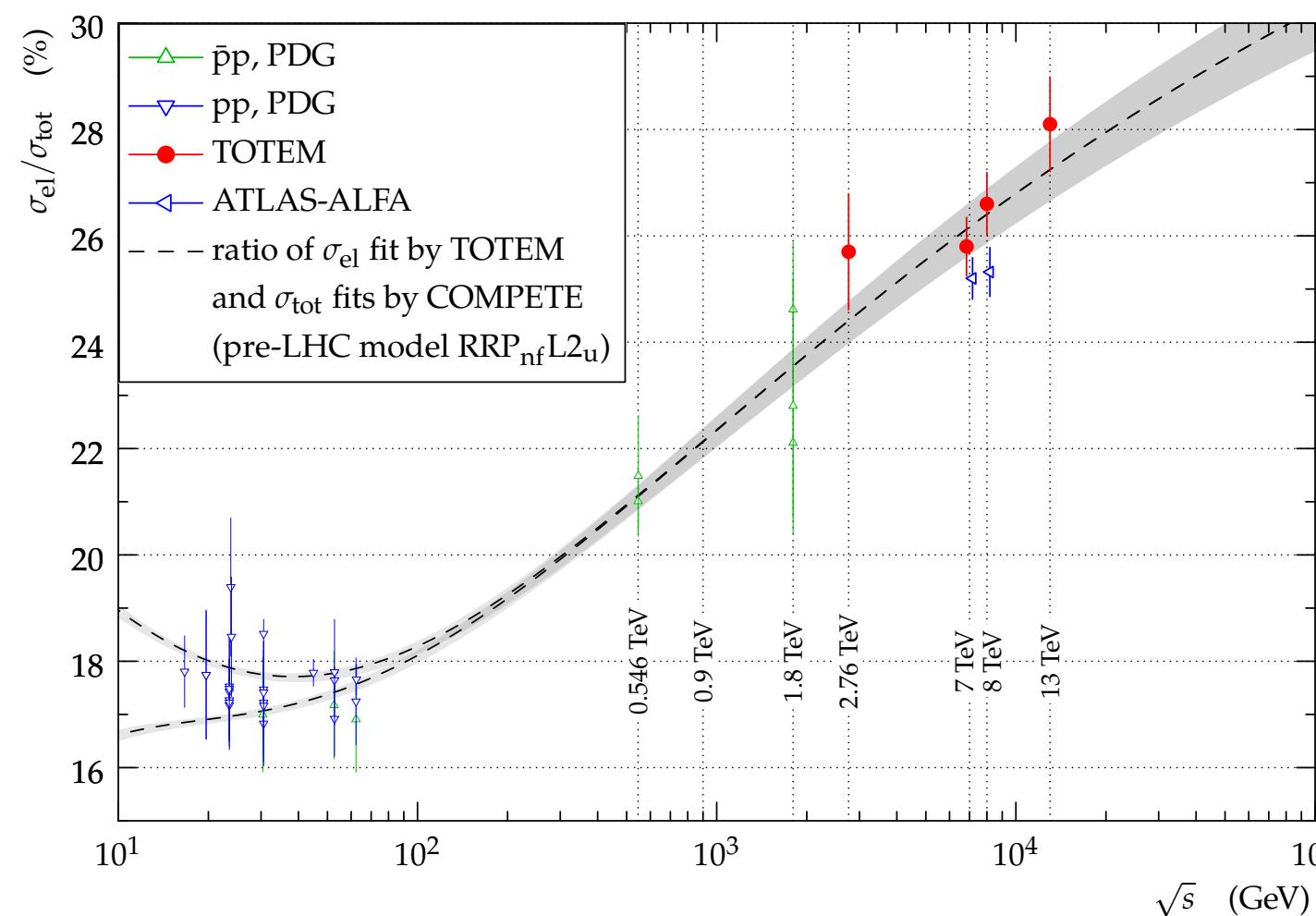
$$\sigma_{\text{tot}} = (110.6 \pm 3.4) \text{ mb}$$



TOTEM  
published measurements

$$\sigma_{\text{el}} = (31.0 \pm 1.7) \text{ mb}$$

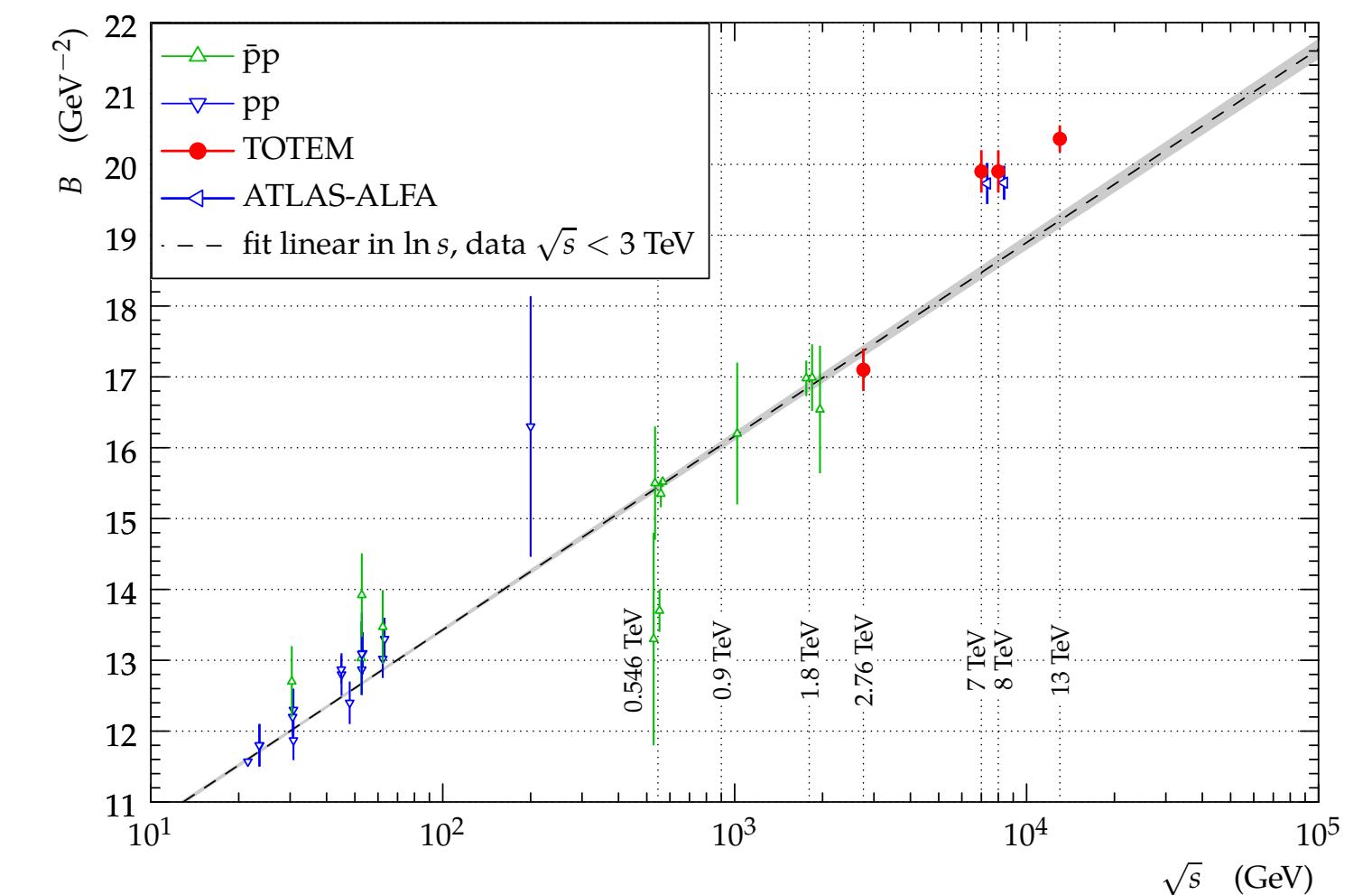
$$\sigma_{\text{inel}} = (79.5 \pm 1.8) \text{ mb}$$



arXiv:1712.06153

nuclear slope

$$B = 20.36 \pm 0.19$$



# Measurement of the $\rho$ parameter

The ratio  $\rho$  of the real to imaginary part of the forward nuclear pp amplitude  $A^N$ , and its evolution with  $\sqrt{s}$ , can be predicted in several phenomenological models

The phase of  $A^N$  can be measured by studying pp elastic scattering in the region at very low  $|t|$  ( $-t \sim 10^{-4} \text{ GeV}^2$ ):

- higher  $|t| \Rightarrow$  strong (nuclear) interaction dominates;
- lower  $|t| \Rightarrow$  electromagnetic (“Coulomb”) interaction dominates;
- transition region  $\Rightarrow$  comparable magnitude  $\Rightarrow$  sizeable interference (**CNI**)

Experimentally challenging:

- tiny scattering angles  $\Rightarrow$  very small initial fluctuation needed  $\Rightarrow$  special LHC optics with large  $\beta^*$
- RP need to approach the beam very closely;
- special collimation scheme needed to reduce beam halo background

LHC settings:

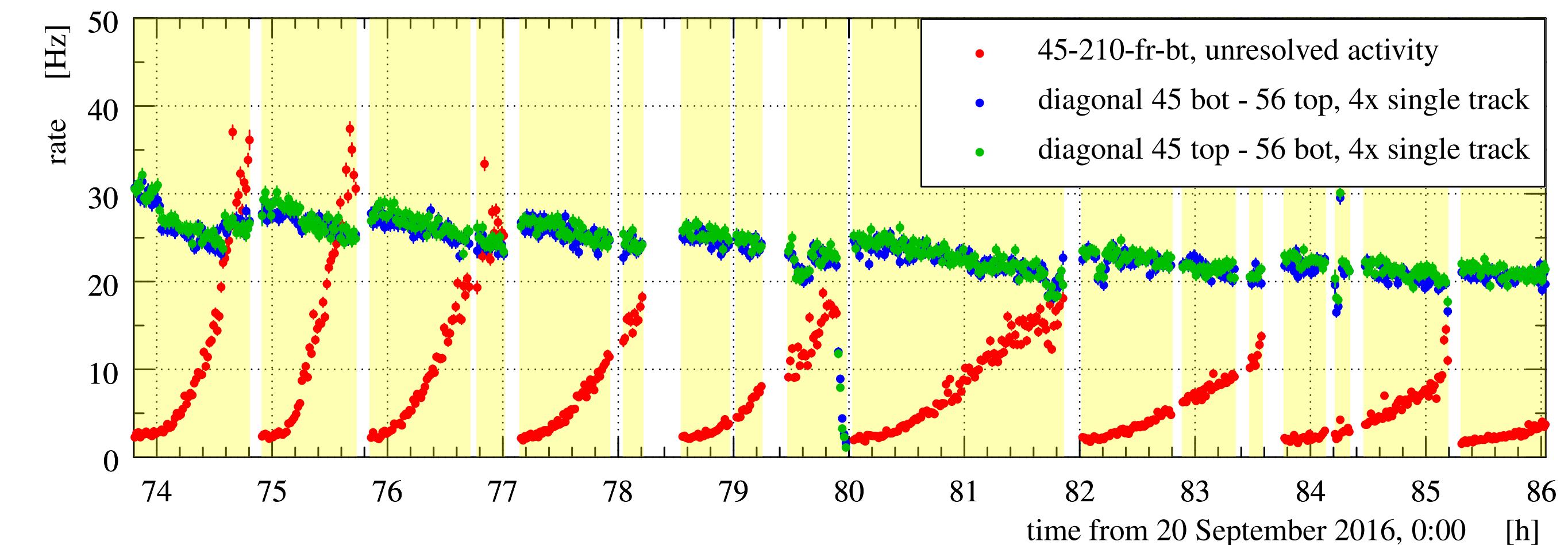
- $\beta^* = 2500$  m;
- parallel-to-point focus in  $y$ , sizeable  $L_x(\sim 200$  m);
- low beam intensity: 4-5 bunches with  $5 \times 10^5$  protons

Beam regularly scraped by collimators to allow vertical roman pot approach down to  $3 \sigma_y \approx 0.4$  mm

Horizontal pots at  $8 \sigma_x$ , only used for alignment

Trigger: double arm coincidence

Data collected:  $0.4 \text{ nb}^{-1} \Rightarrow > 7\text{M}$  elastic events



# Differential cross section

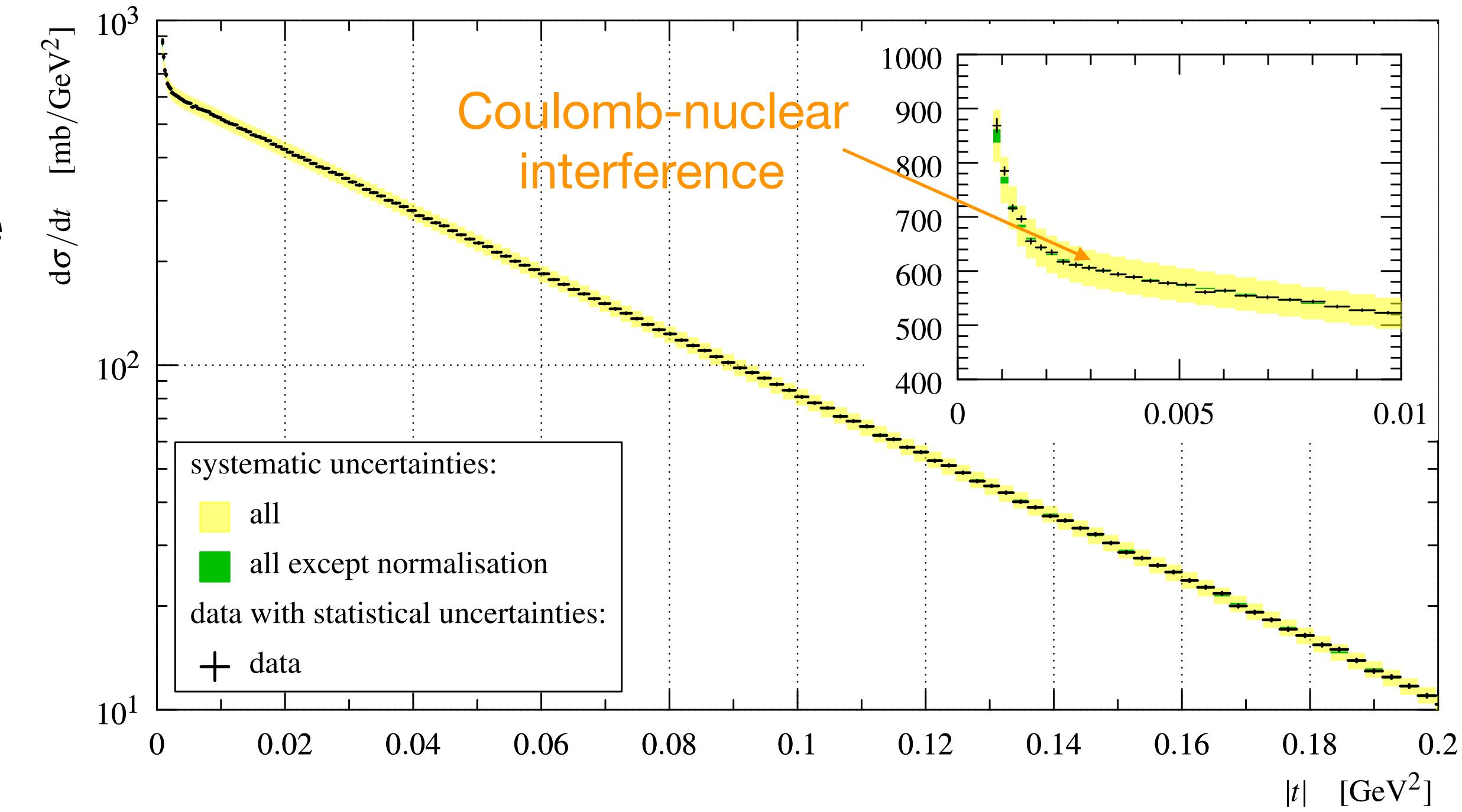
RP at 220F used for main analysis (210F used for cross check)

Angles only from x, y, and then averaged on both arms to remove dependence on  $x^*$ ,  $y^*$ :

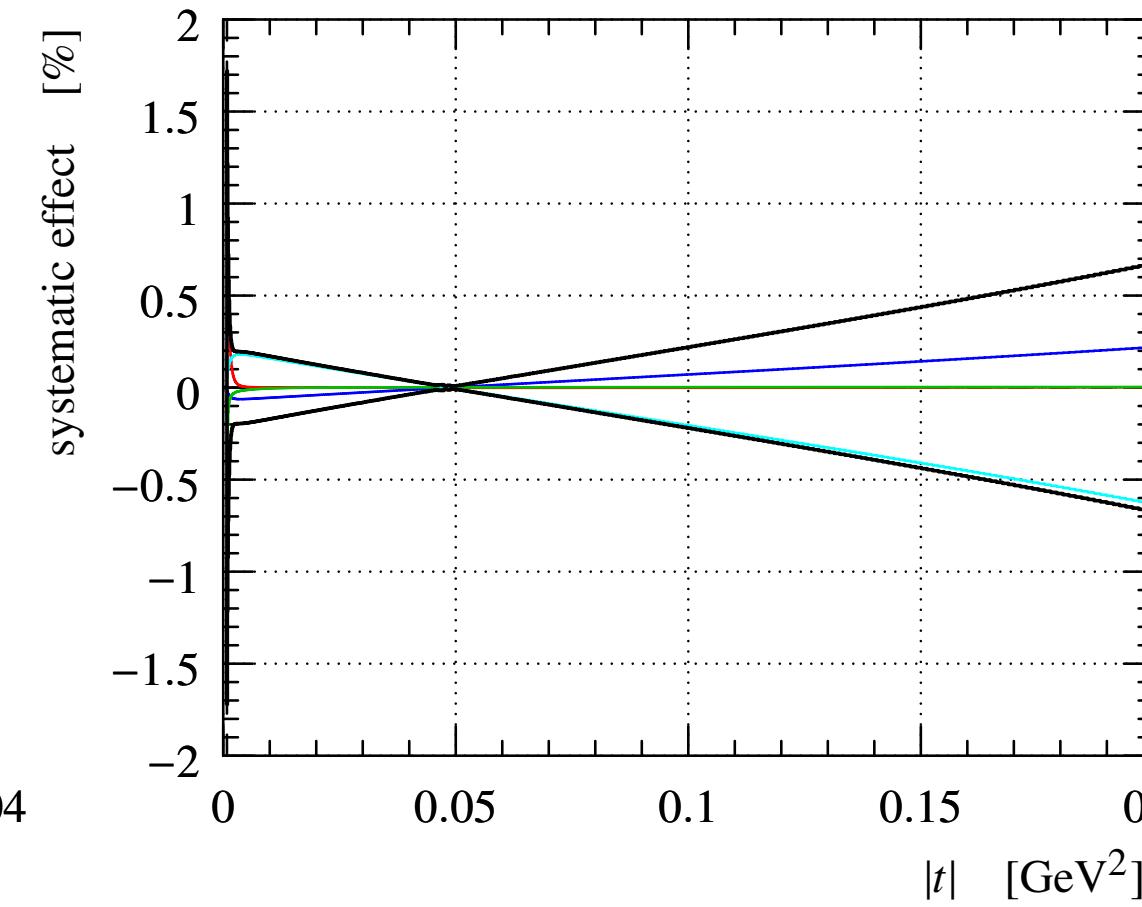
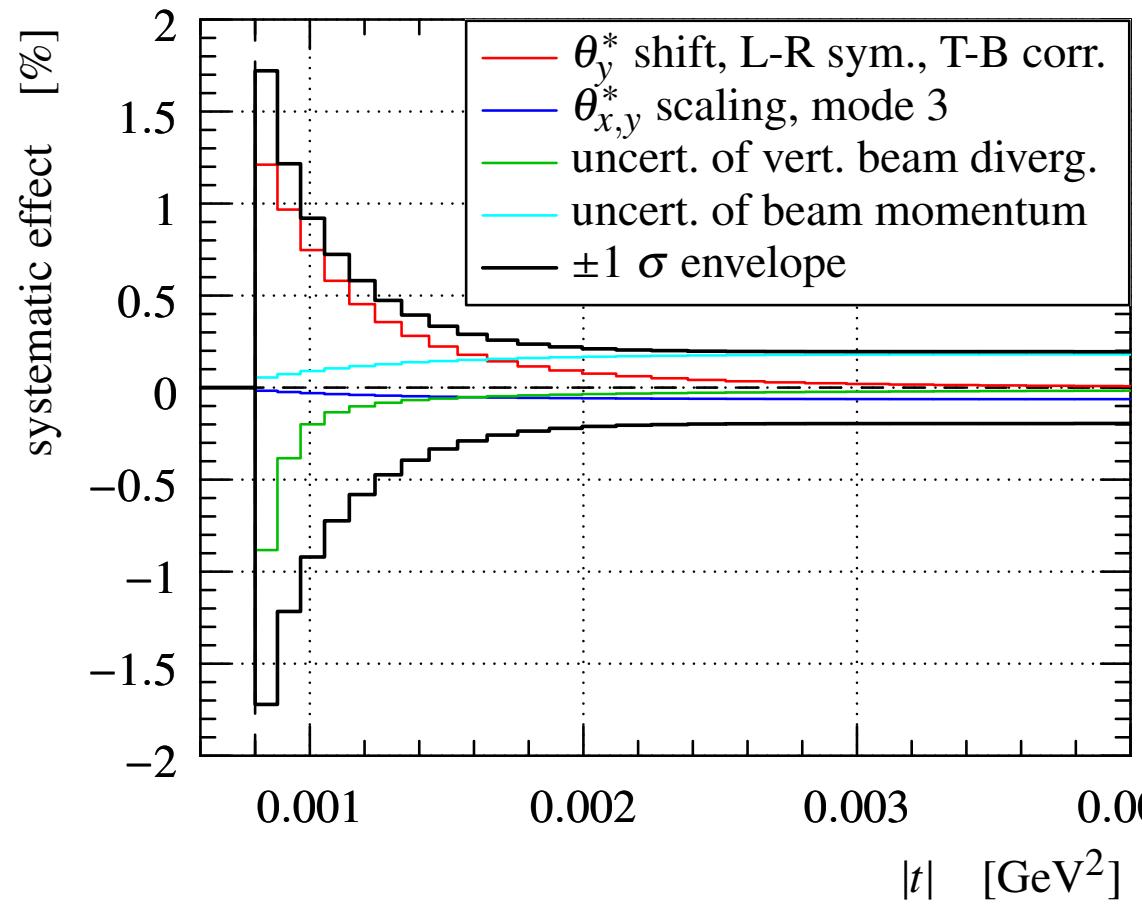
$$\theta_x^{*L,R} = \frac{x}{L_x}, \quad \theta_y^{*L,R} = \frac{y}{L_y} \quad \rightarrow \quad \theta_x^* \equiv \frac{1}{2}(\theta_x^{*L} + \theta_x^{*R}), \quad \theta_y^* \equiv \frac{1}{2}(\theta_y^{*L} + \theta_y^{*R})$$

Extracting the  $|t|$  distribution:

- optics corrected from RP observables;
- background subtraction with kinematic cuts;
- geometrical and beam divergence acceptance correction;
- detection and reconstruction efficiency correction (as a function of  $\theta_y^*$ );
- resolution unfolding by iterative procedure;
- normalisation from elastic cross section measurement at  $\beta^* = 90$  m



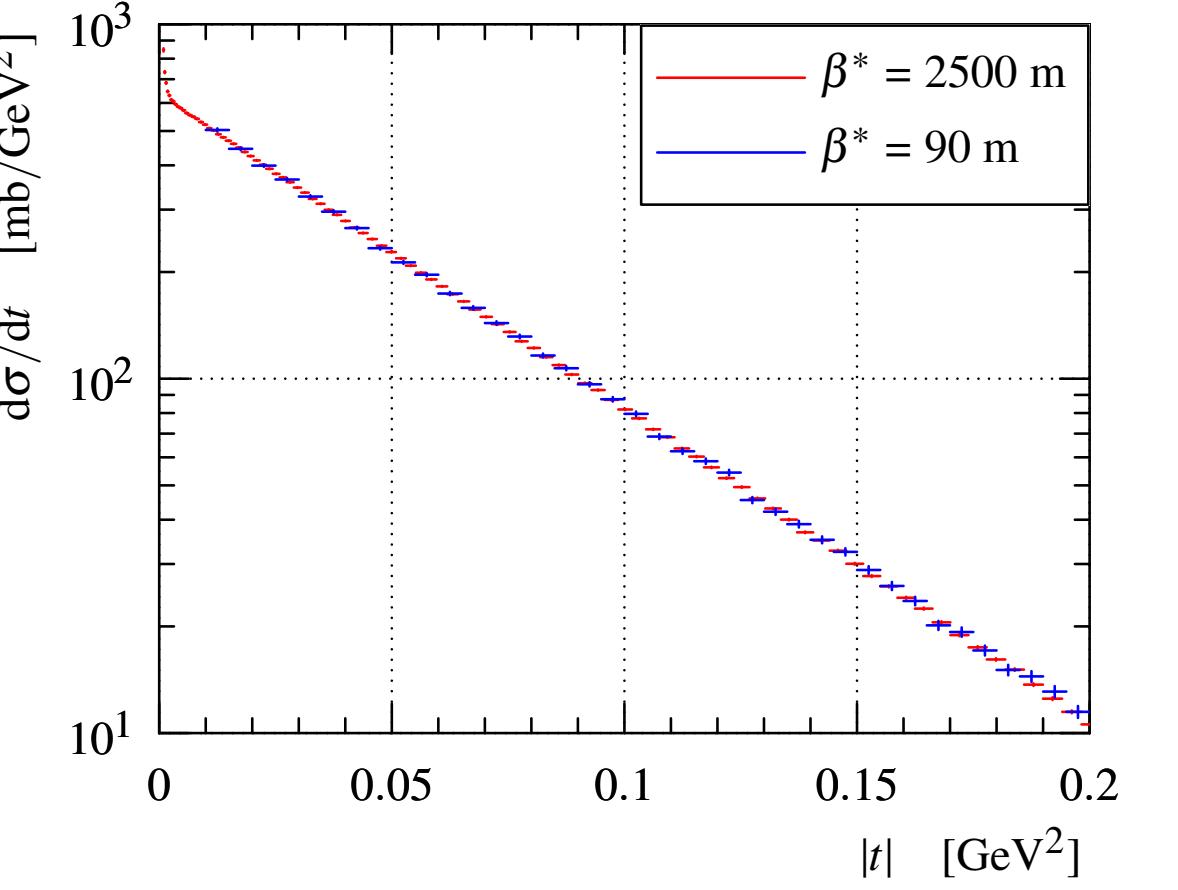
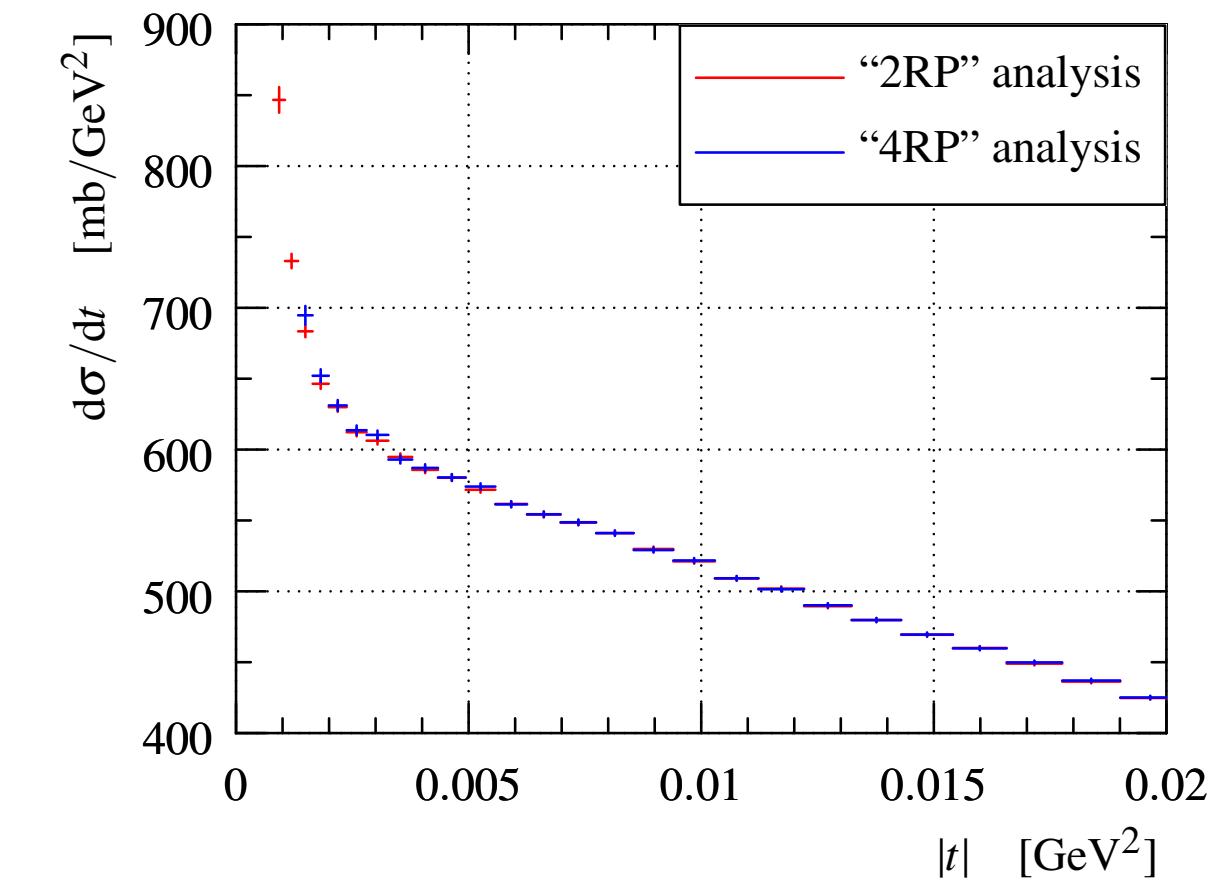
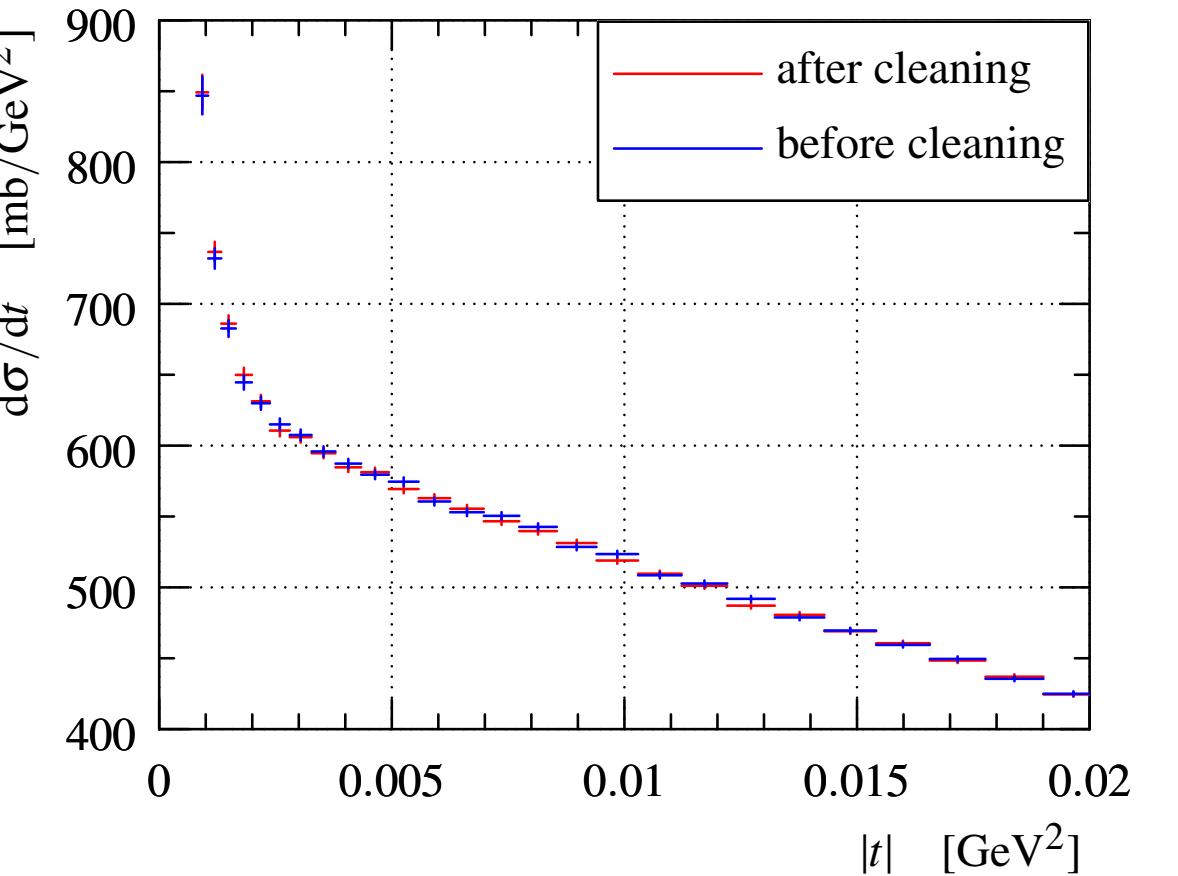
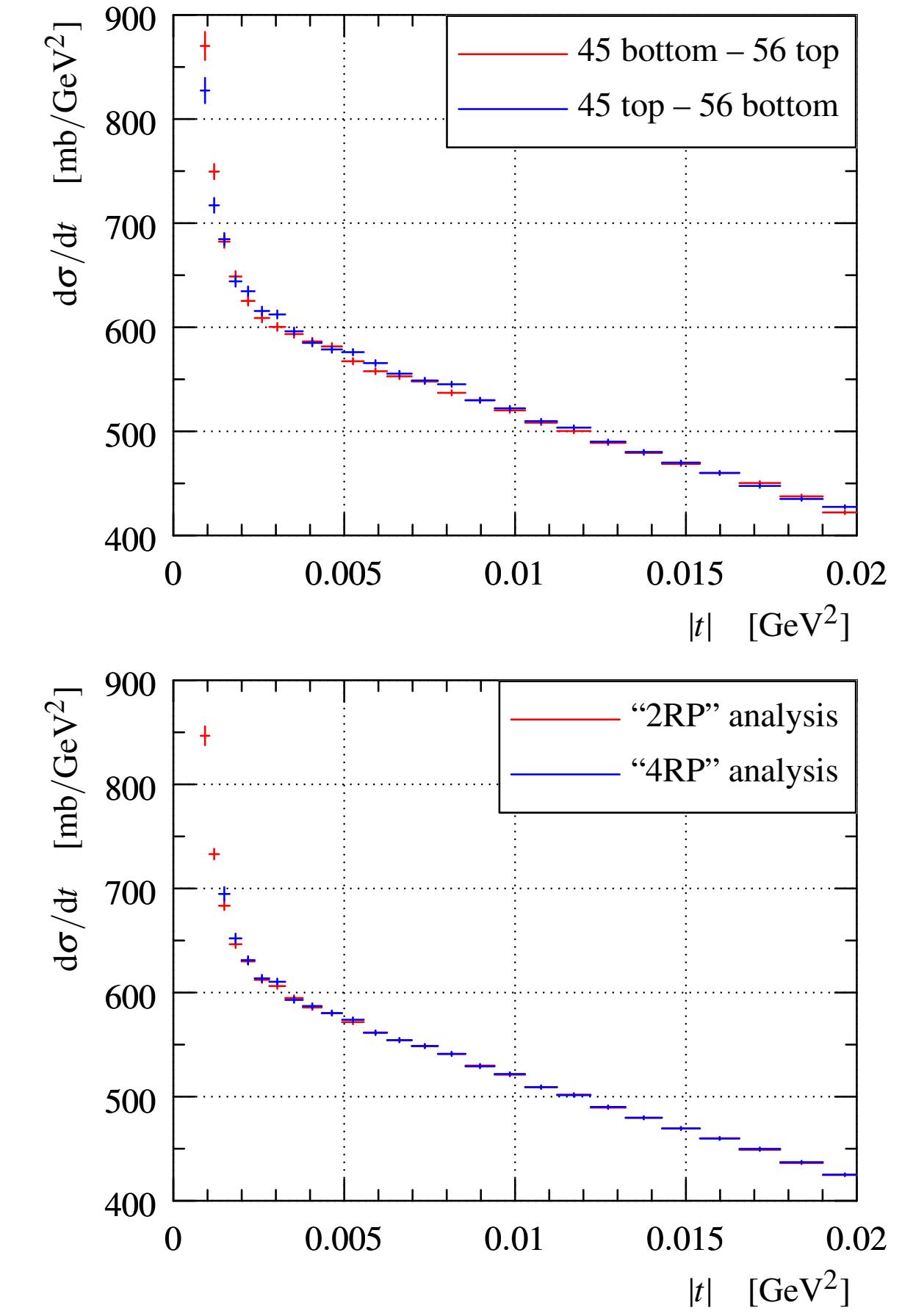
# Systematic uncertainties



## Main contributions:

- alignment;
- optics;
- acceptance correction (beam divergence);
- beam momentum

## Systematic checks



# Measuring $\rho$ from CNI

Cross section in CNI region:

$$\frac{d\sigma}{dt}^{C+N} \propto \left| \text{electromagnetic} + \dots + \text{nuclear} + \text{mixed terms} + \dots \right|^2$$

The diagram illustrates the decomposition of the total cross section into its components. It shows a vertical line representing the incoming particle interacting with a target (N) through three different mechanisms: electromagnetic (two external lines), nuclear (one external line interacting with a circular target labeled  $A^N$ ), and mixed terms (one external line interacting with both the target and the incoming particle).

Model:

- Coulomb amplitude: QED + experimental form factors;
- $A^N$  modulus: parametrised at low  $|t|$  from observed cross section as

$$|A^N(t)| = \sqrt{\frac{s}{\pi}} p \sqrt{a} \cdot \exp \left( \frac{1}{2} \sum_{n=1}^{N_b} b_n t^n \right)$$

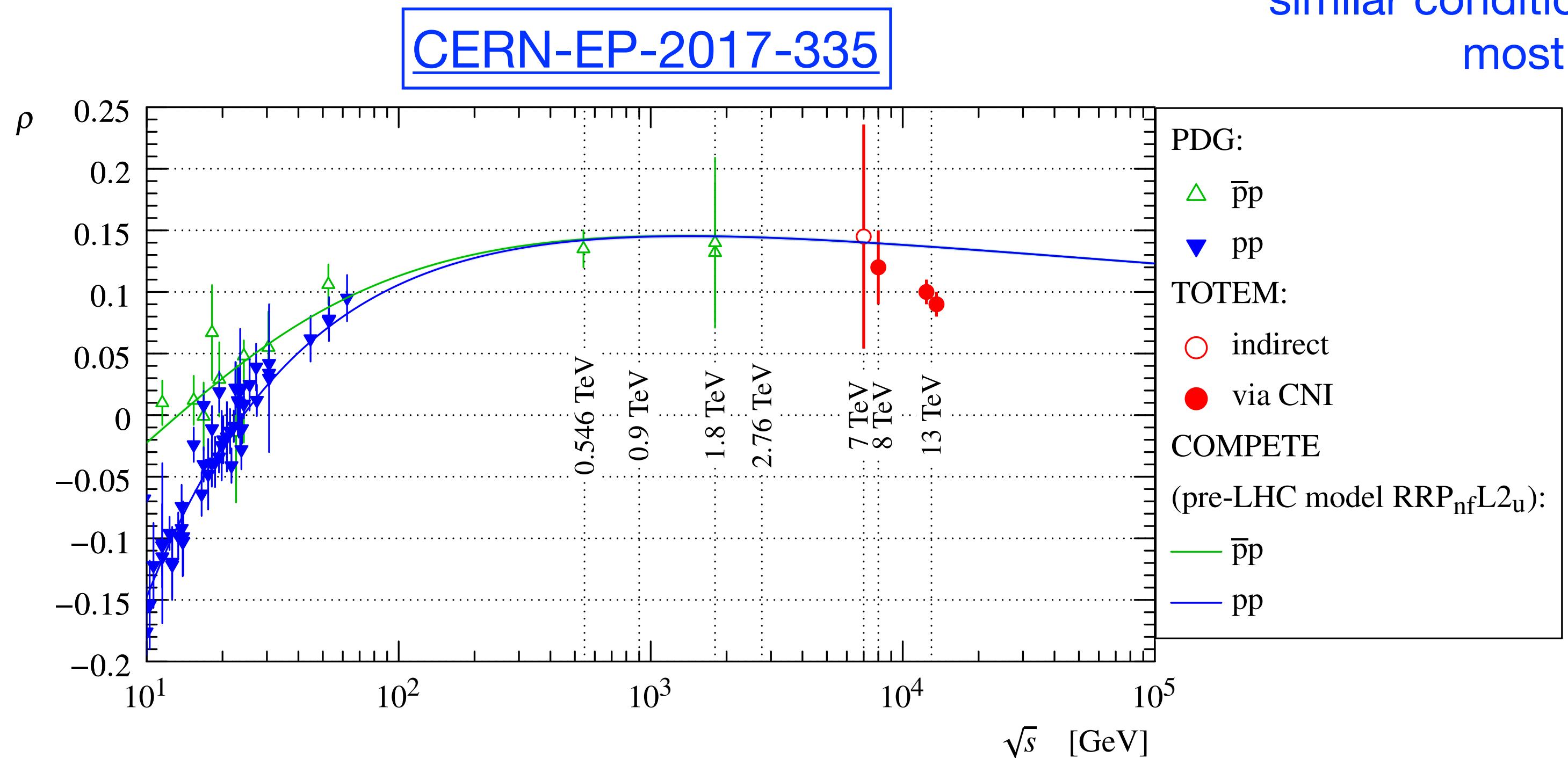
- $A^N$  phase: various parametrisations considered with slow variation at low  $|t|$ : used  $\arg A^N(t) = \frac{\pi}{2} - \arctan \rho(t) = \text{const.}$
- interference: most general “KL” formula used

# Results on $\rho$

Least-squares fit on distribution:

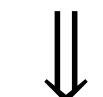
- systematic uncertainty included;
- different ranges in  $|t|$  tried;
- different values for  $N_b$  tried

$N_b$	$ t _{\max} = 0.07 \text{ GeV}^2$		$ t _{\max} = 0.15 \text{ GeV}^2$	
	$\chi^2/\text{ndf}$	$\rho$	$\chi^2/\text{ndf}$	$\rho$
1	0.7	$0.09 \pm 0.01$	2.6	-
2	0.6	$0.10 \pm 0.01$	1.0	$0.09 \pm 0.01$
3	0.6	$0.09 \pm 0.01$	0.9	$0.10 \pm 0.01$



similar conditions to past measurement,  
most fair comparison

largest range,  
“best measurement”



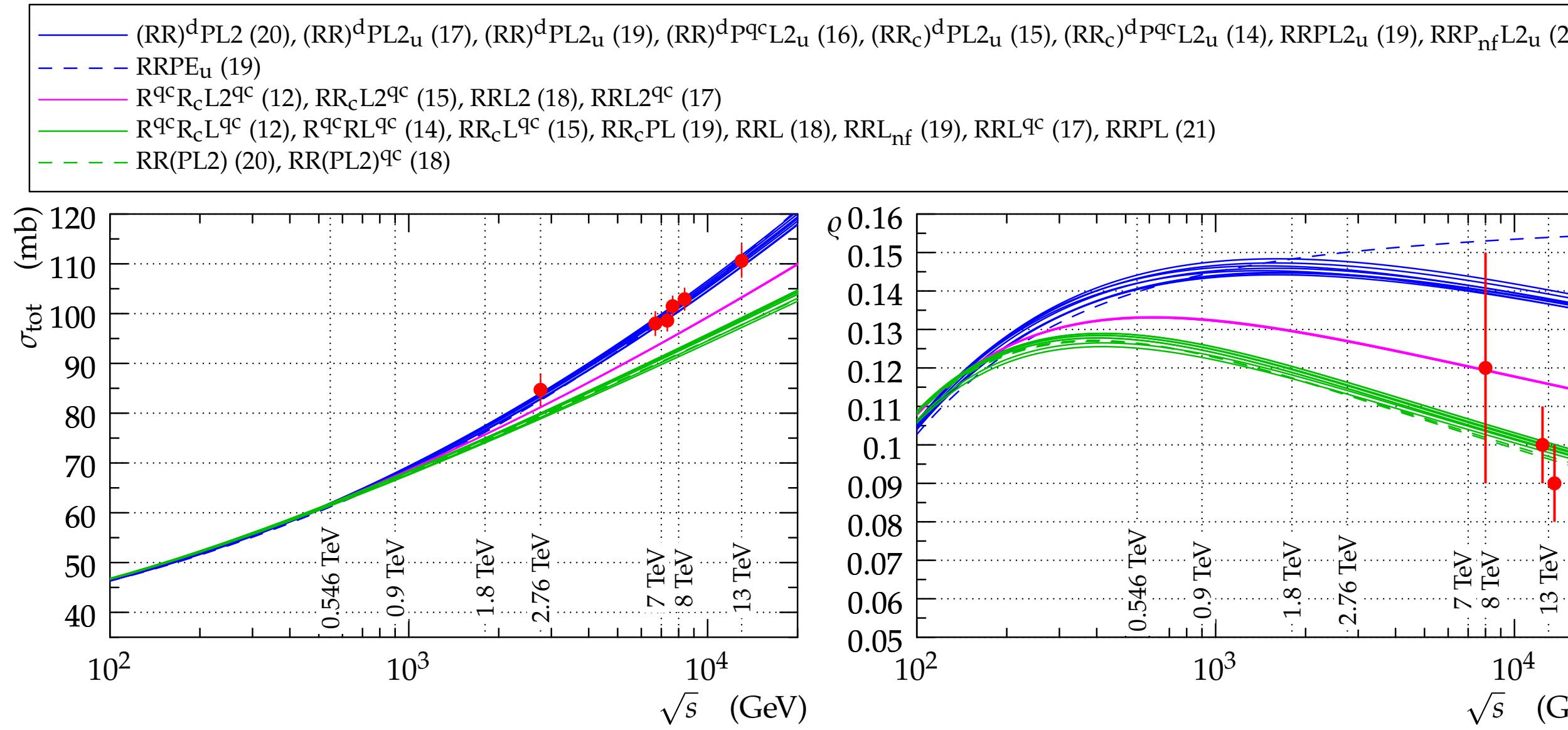
High precision measurement

Significantly lower than preferred  
COMPETE prediction:

- incompatible at  $4.7 \sigma$  level

Result stable against several fit variations

# Interpretations



Possible indication of odd-signature component in amplitude (“**odderon**”)

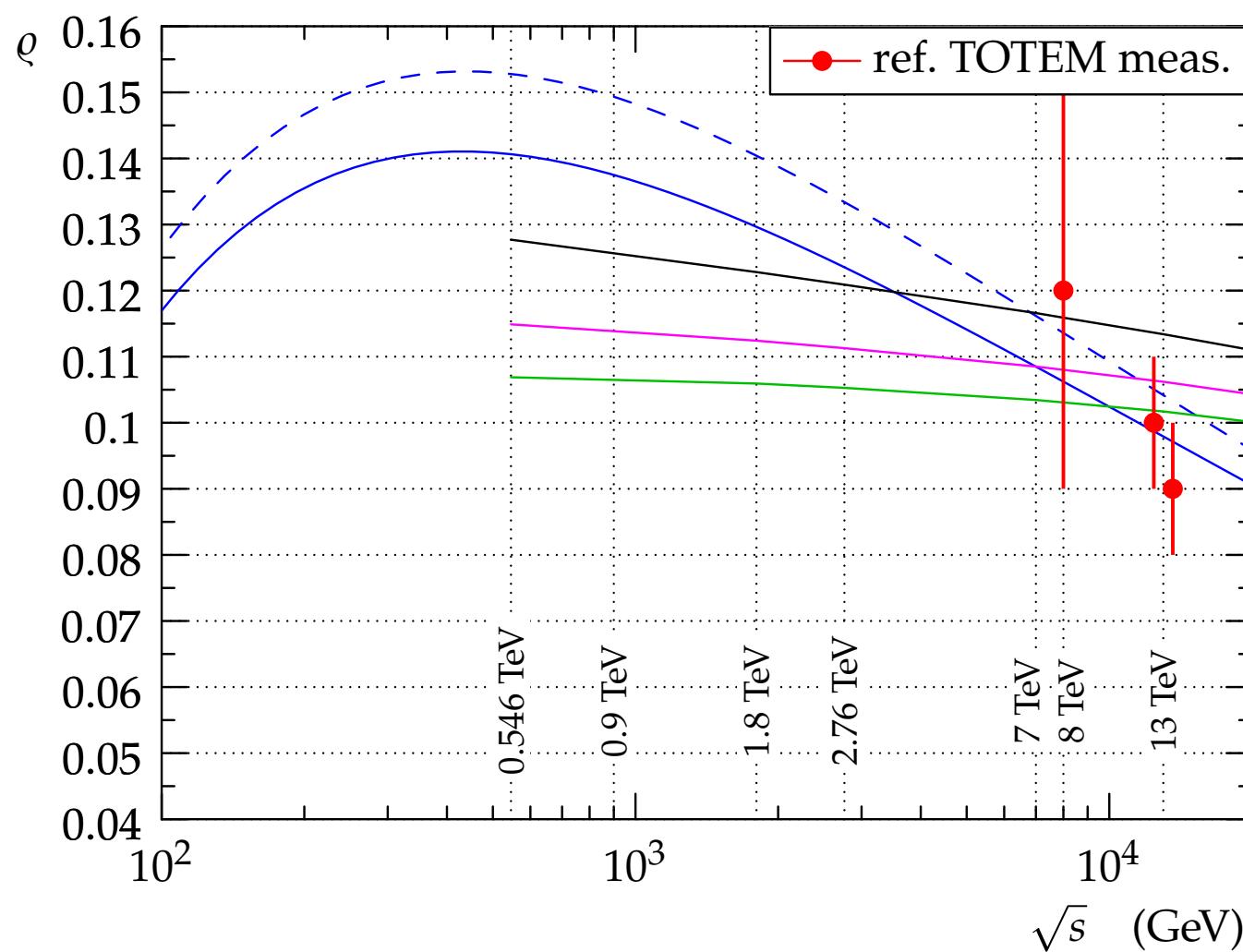
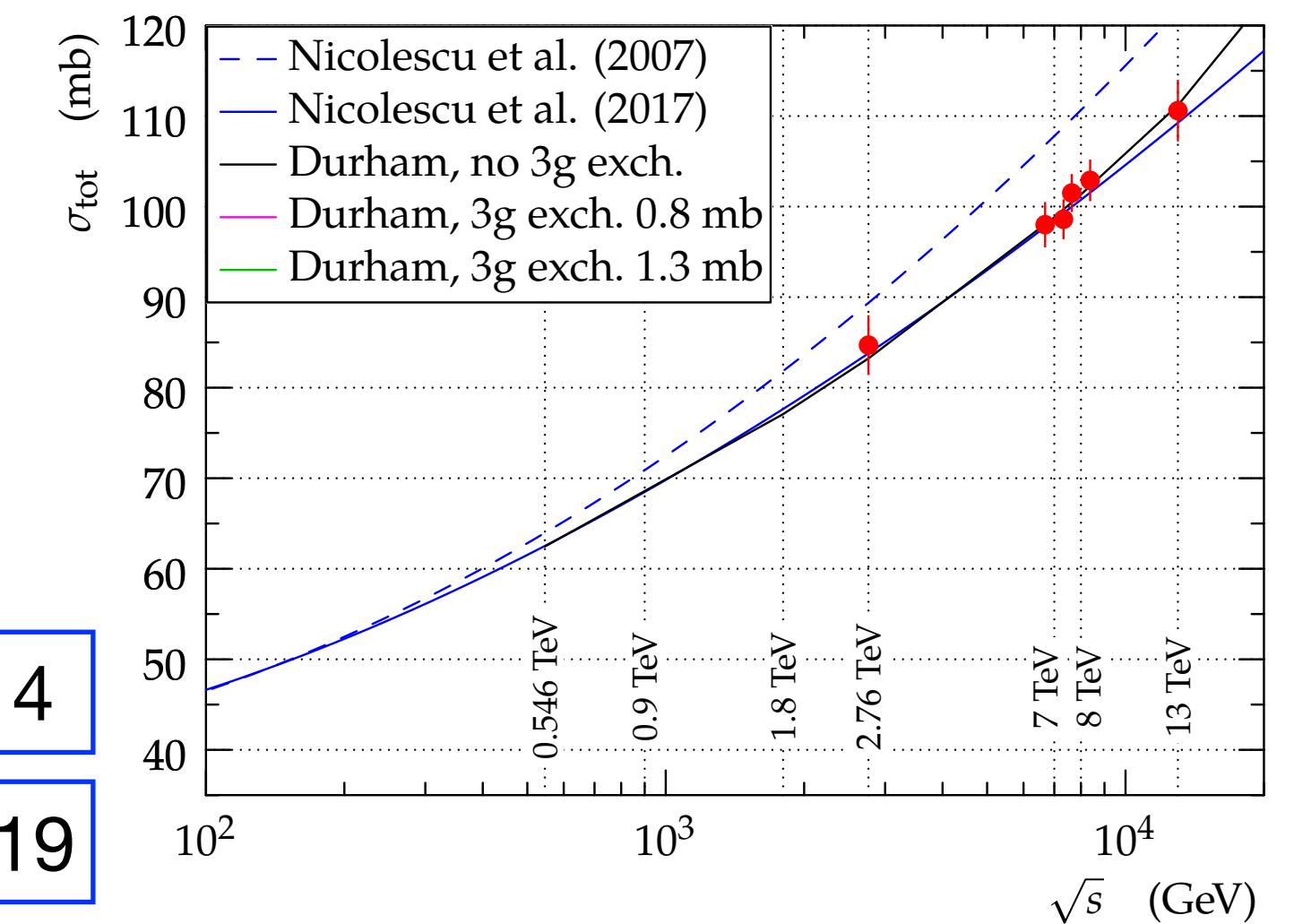
Models with crossing-odd exchange component seem to reach better agreement

Phys. Lett. B 778 (2018) 414

Phys. Rev. D 97 (2018) 030419

Very comprehensive study by COMPETE Collaboration on pre-LHC data

- 23 models found to agree with measurements
- grouped in 3 sets: no set simultaneously compatible with TOTEM  $\sigma_{tot}$  and  $\rho$  measurement at 13 TeV;



First measurement of the total, elastic and inelastic pp cross section at 13 TeV by TOTEM

Precise measurement of the  $\rho$  parameter of the nuclear amplitude through analysis of elastic cross section at very low values of  $|t|$

Measurements incompatible with COMPETE predictions

- $\Rightarrow$  possible indication of the existence of a three-gluon bound state (**odderon** or else, of a slow-down of the cross section growth at increasing energies)

TOTEM to continue its program at 14 TeV in Run 3: new measurements could shed light on the subject:

- new measurement of the total, elastic and inelastic pp cross section;
- new precise determination of  $\rho$ ;
- detailed study of the “dip” region in  $\sigma_{\text{tot}}$  ( $\sim 0.45 \text{ GeV}^2$ ), potentially sensible to the contribution of 3-gluon exchange

Special run planned at  $\sqrt{s} \sim 1 \text{ TeV}$  to measure  $\rho$  and the diffractive dip region

# Backup plots

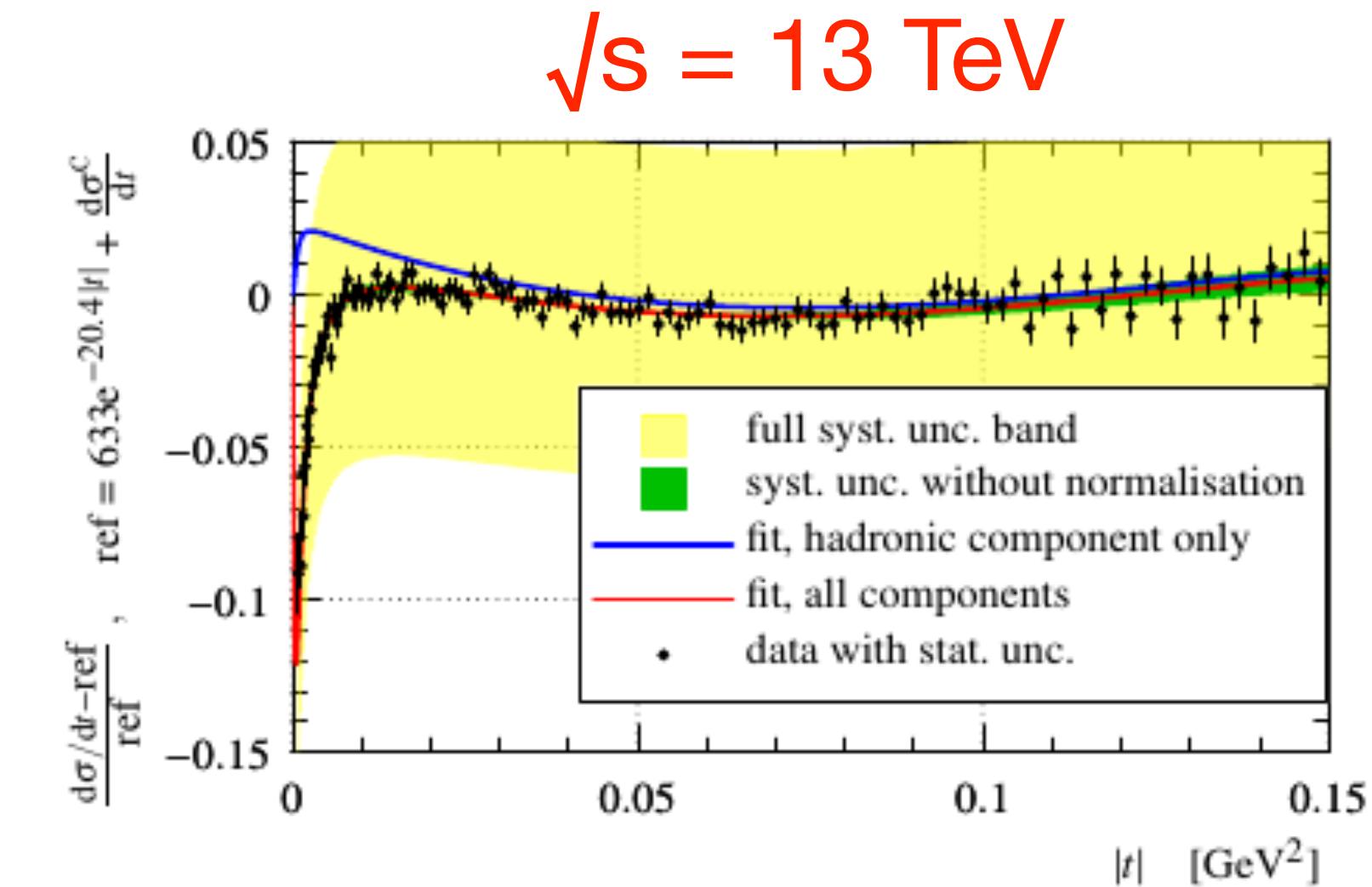
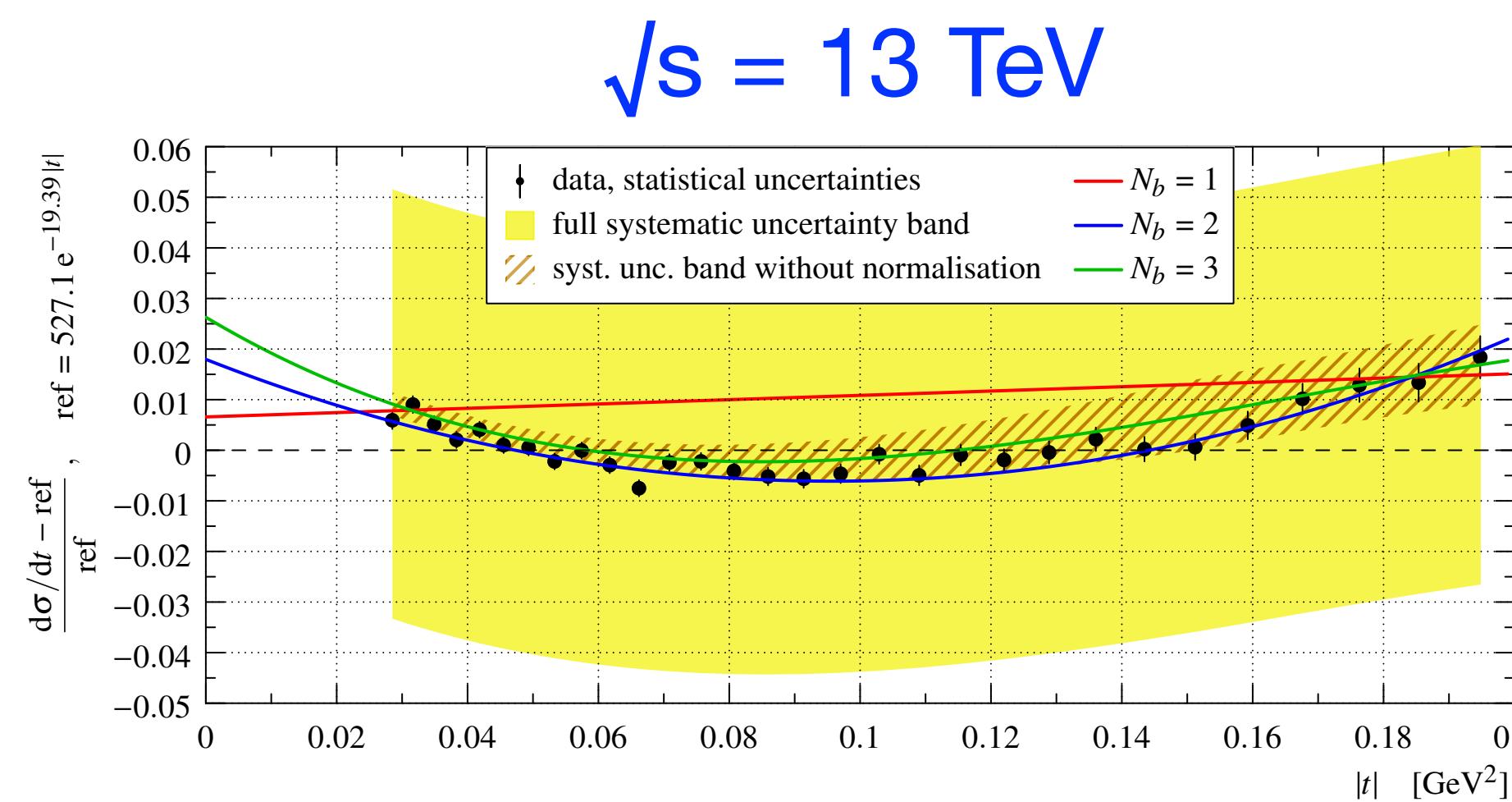
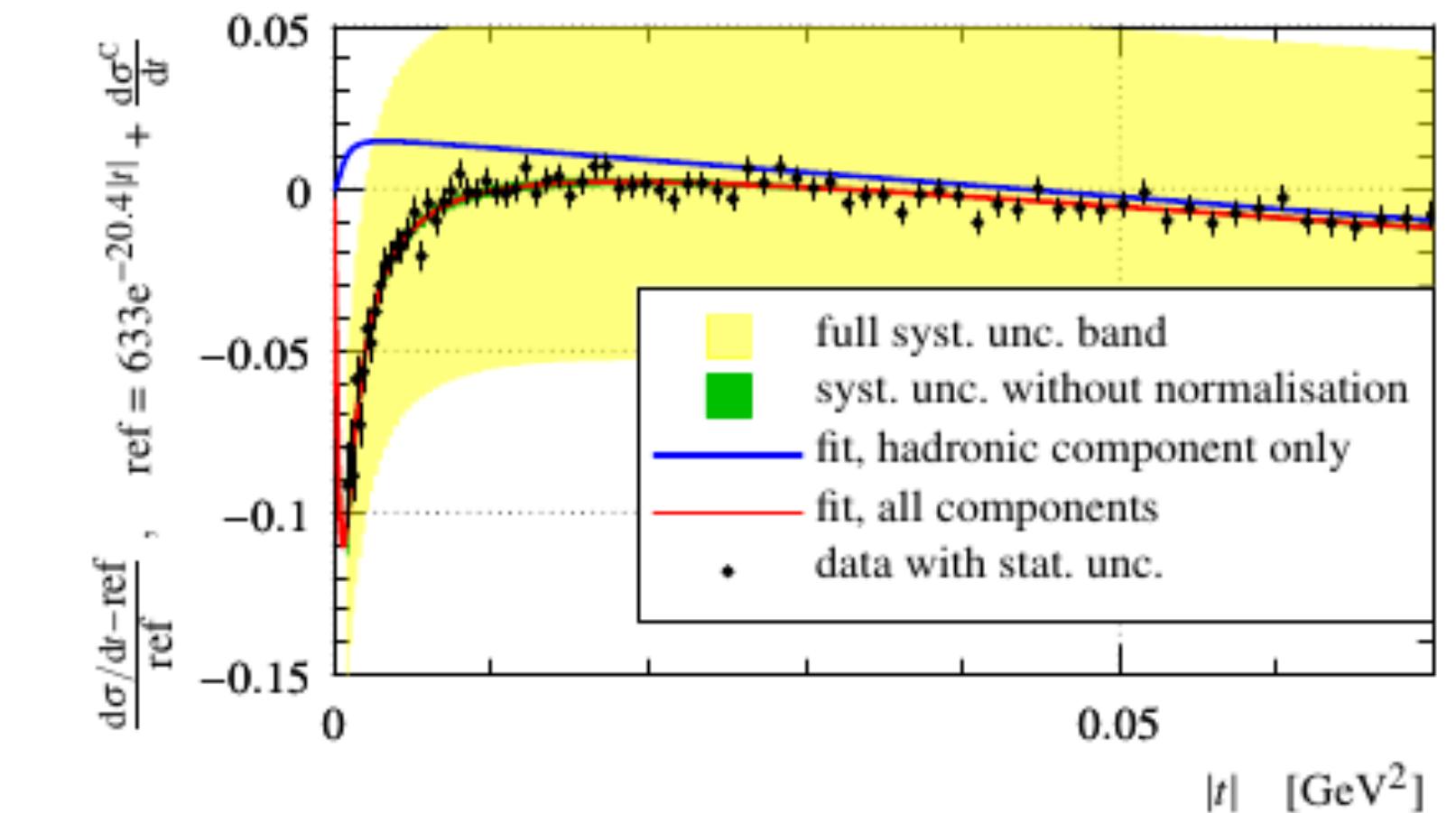
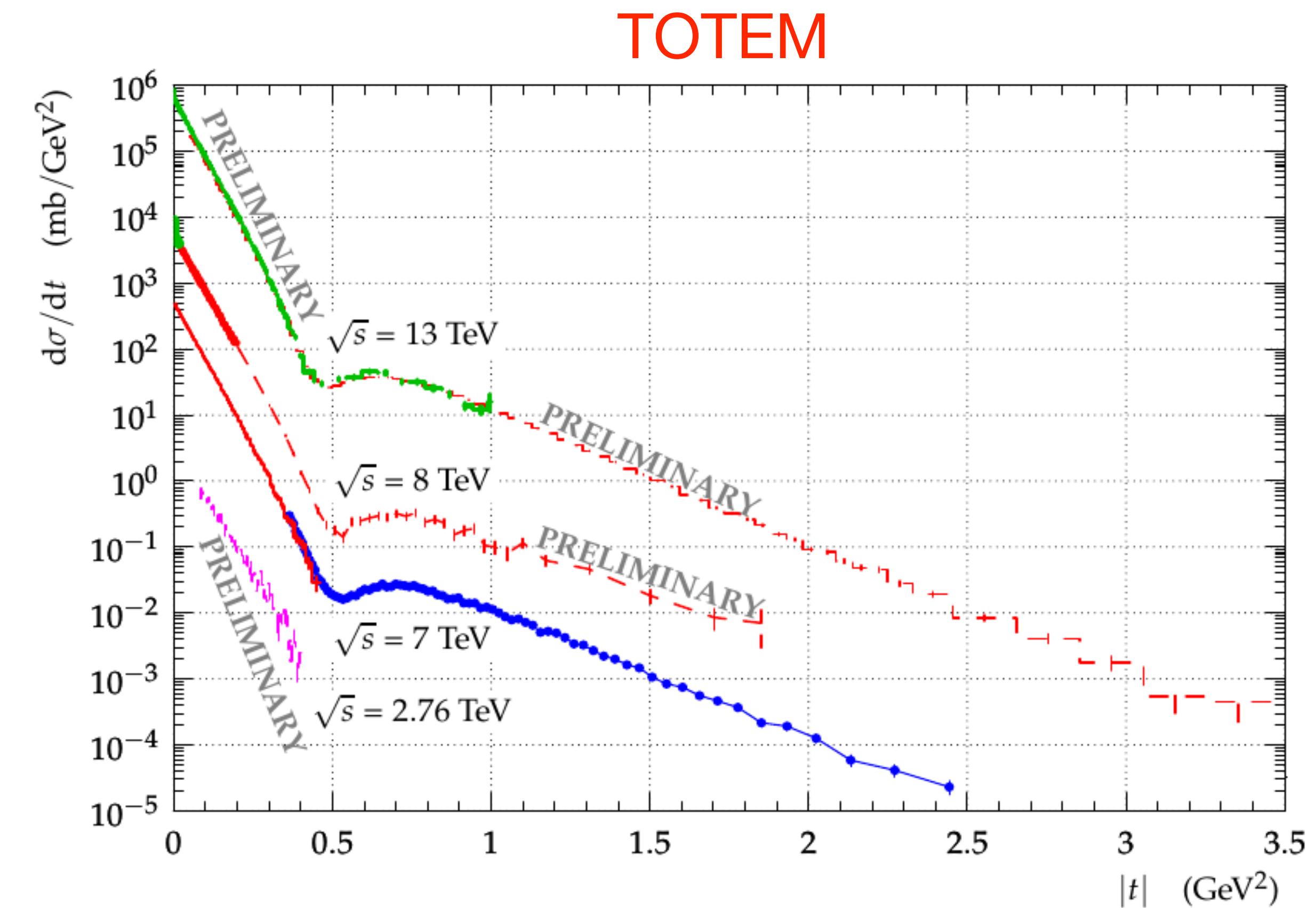
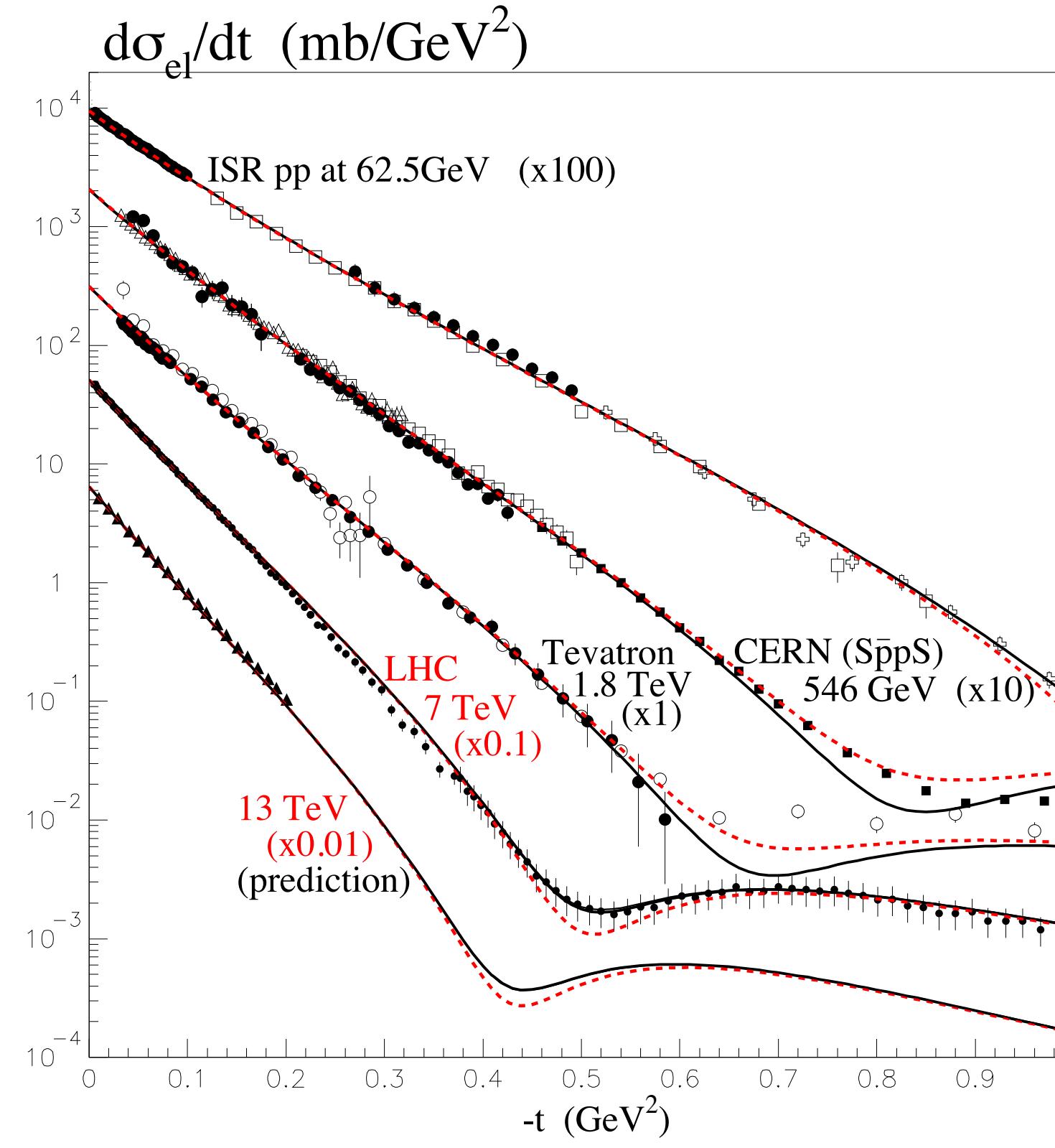


Fig. 14: Details of fit with  $N_b = 3$  and  $|t|_{\text{max}} = 0.15 \text{ GeV}^2$ .



# pp ( $p\bar{p}$ ) cross section in the “dip” region

from arXiv:1712.00325 [hep-ex]



# with odderon contribution included

from arXiv:1712.00325 [hep-ex]

