

# Elastic scattering at the LHC

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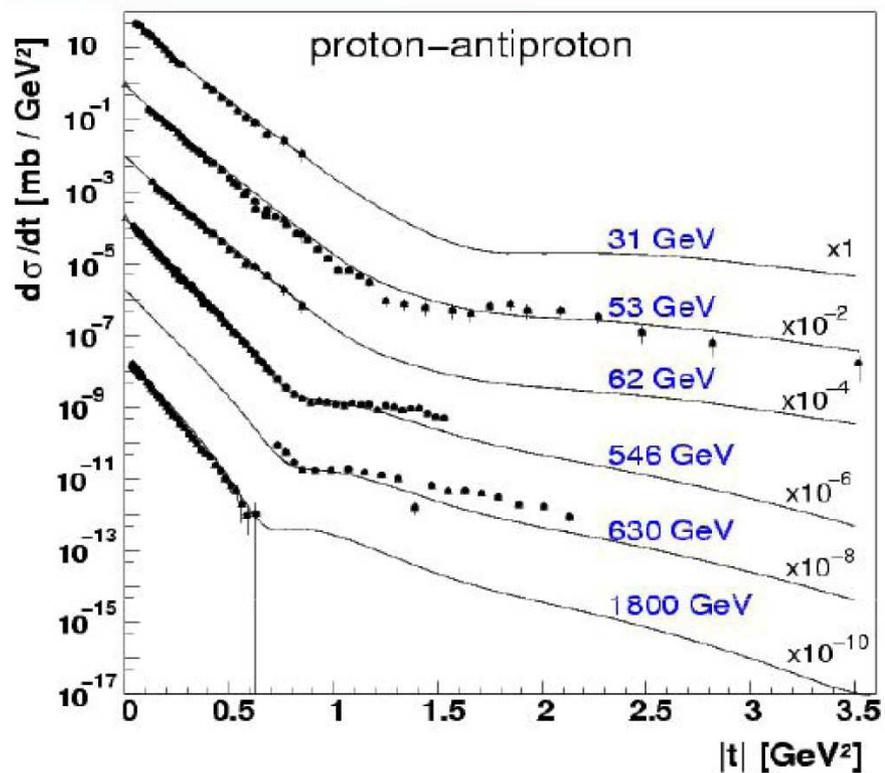
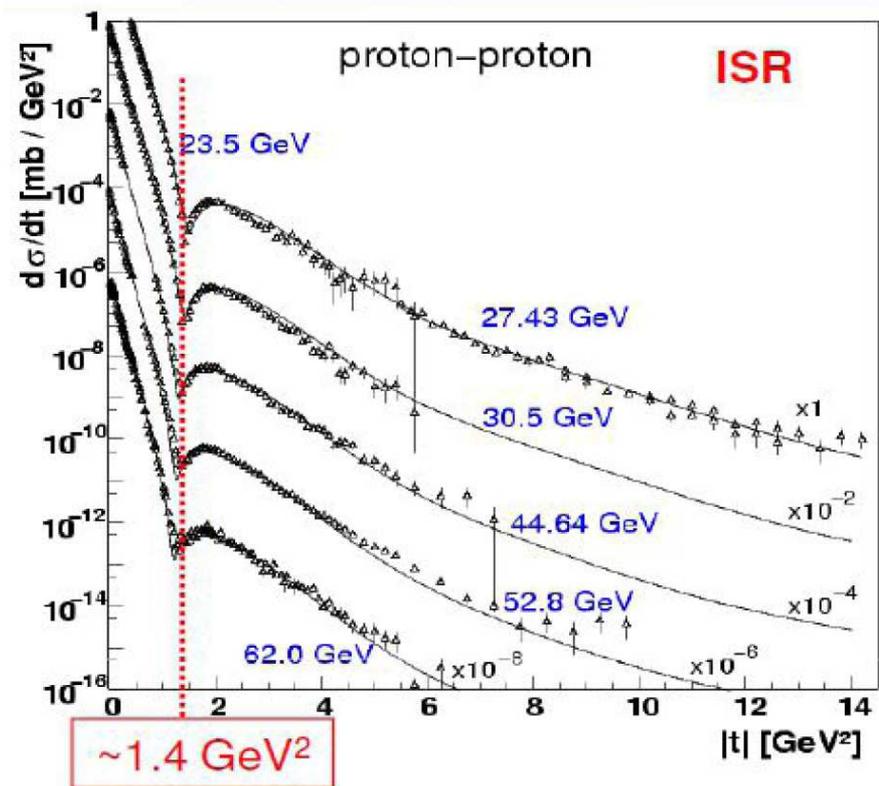
AGH, Cracow, Poland

**Blois EDS Workshop, Borgo, Corsica, June 28- July 4 2015**

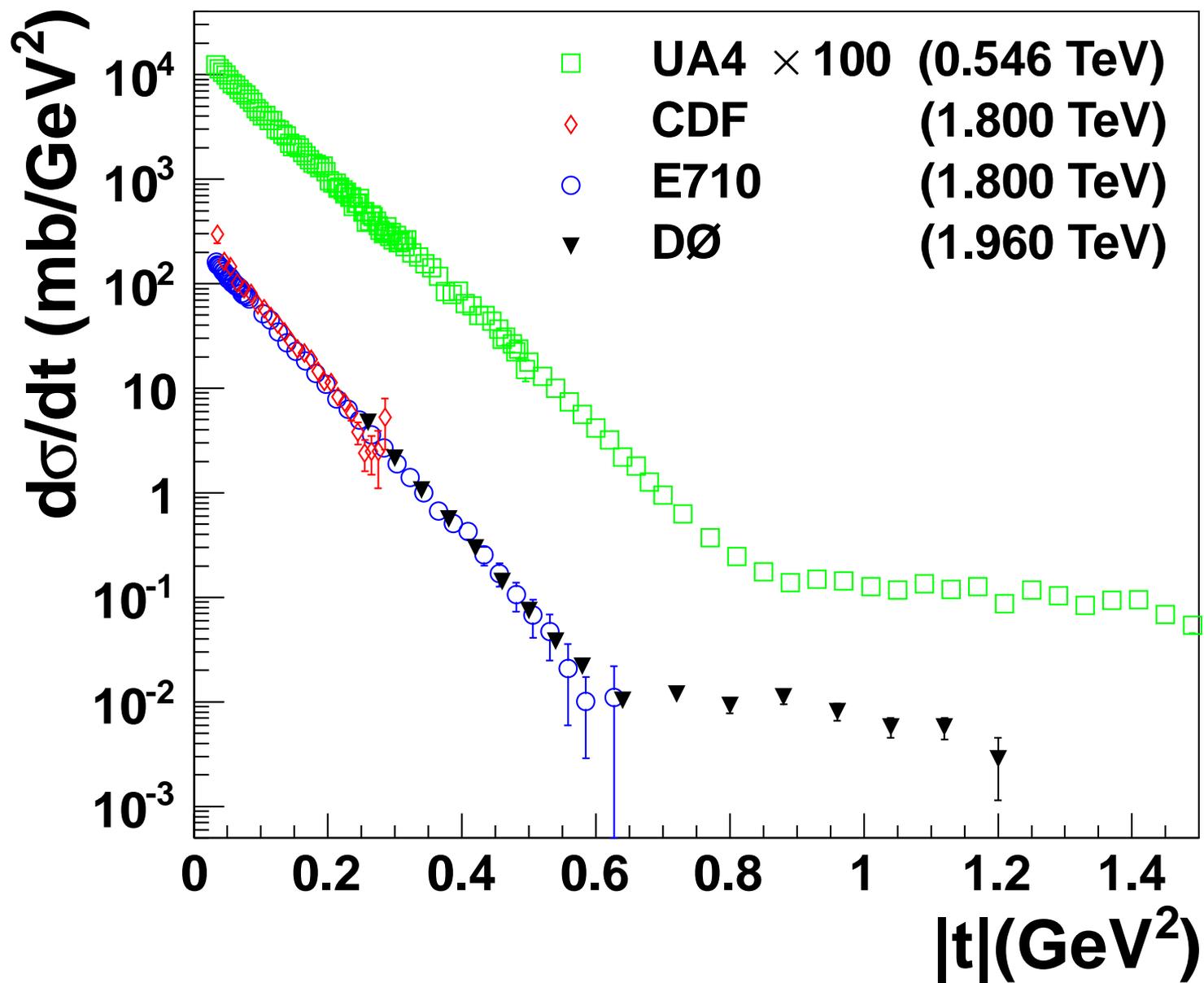
## Contents:

- Elastic scattering from ISR to Tevatron
- ALFA and TOTEM experiments
- ALFA and TOTEM elastic measurements at 7 and 8 TeV
- ALFA and TOTEM total cross section measurements
- Future measurements

## Elastic scattering: From ISR to Tevatron

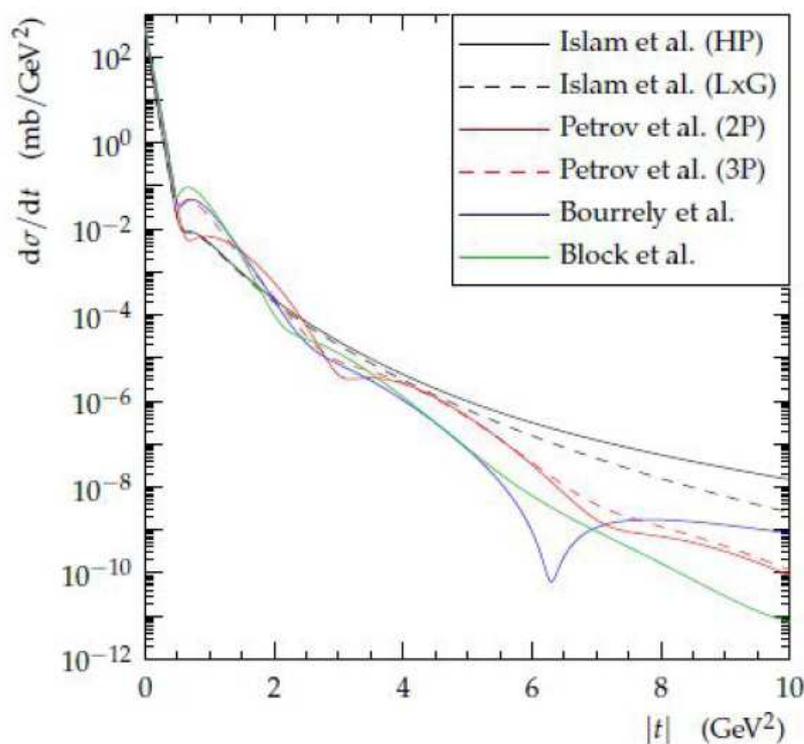


## Elastic scattering: From ISR to Tevatron

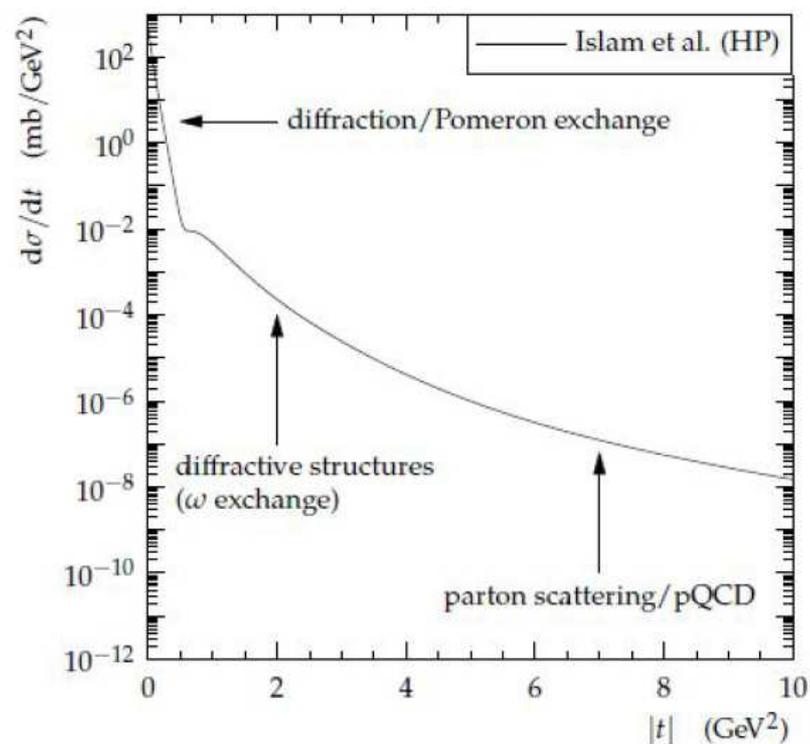


## Elastic scattering at the LHC: variety of predictions

- Variety of models especially at high  $t$
- Regions in  $|t|$  at the LHC sensitive to different kinds of physics: Diffraction/Pomeron exchange at low  $|t|$ , diffractive structures at medium  $|t|$  and parton scattering/QCD at higher  $|t|$



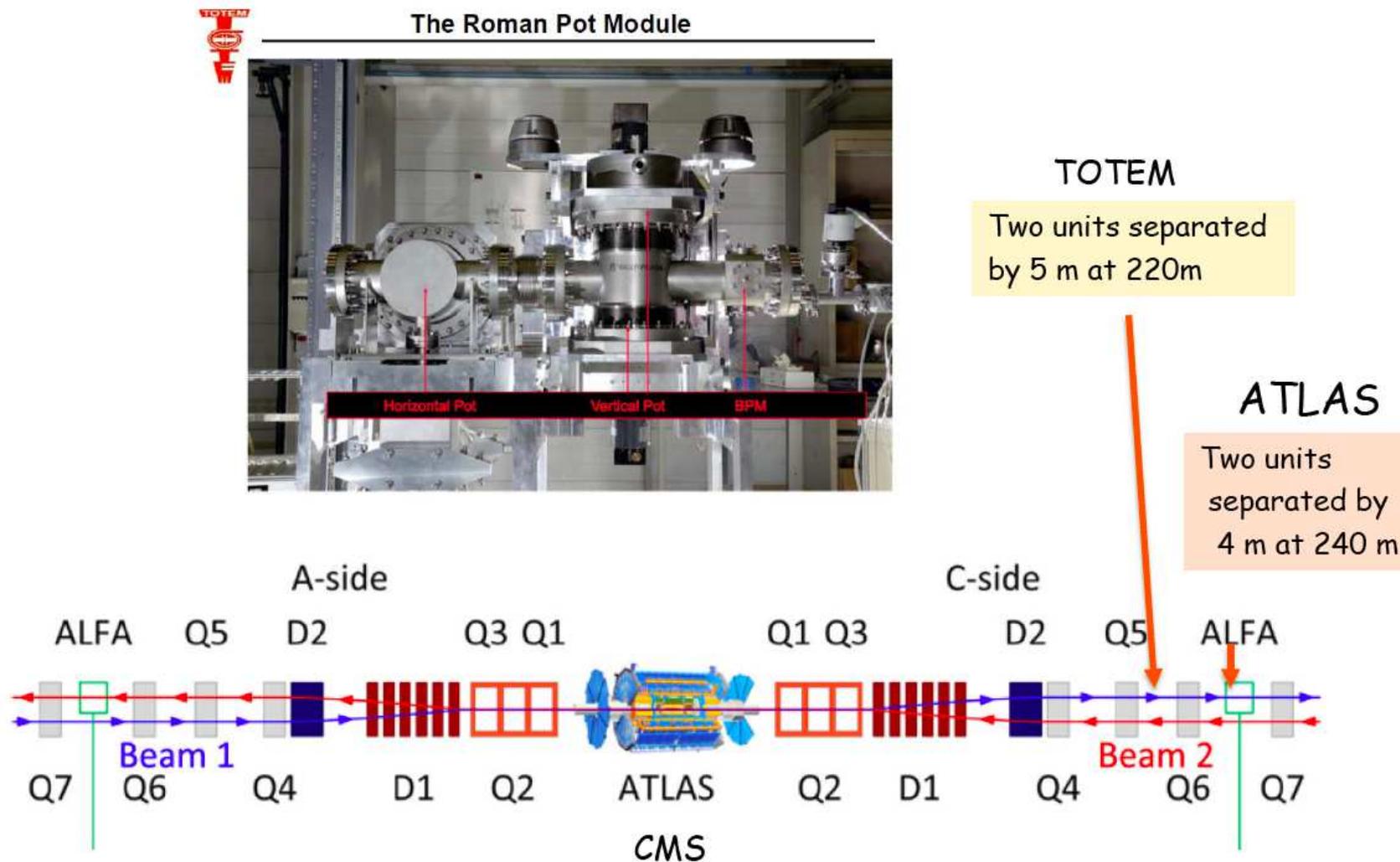
theoretical/phenomenological models:  
very different predictions at large  $|t|$



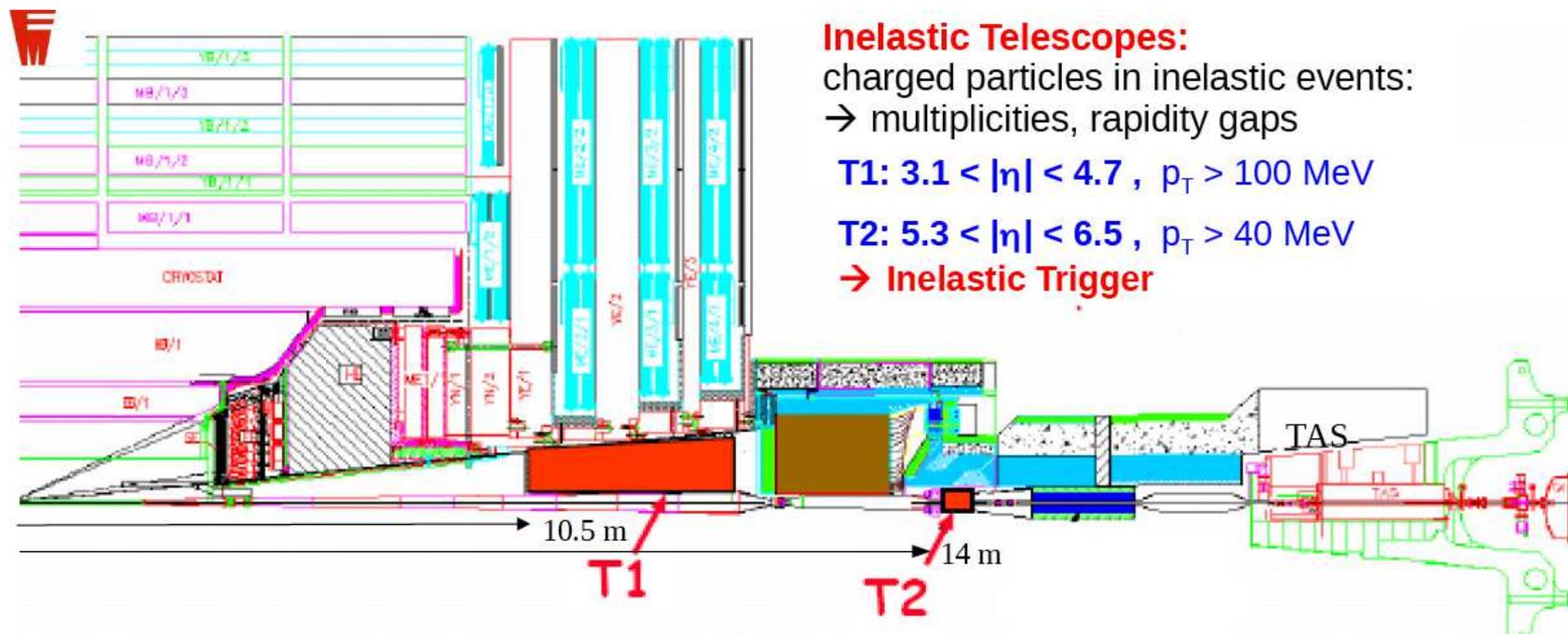
different  $|t|$  regions: different  
scattering mechanisms/QCD regimes

## ATLAS/ALFA and TOTEM Roman pot detectors

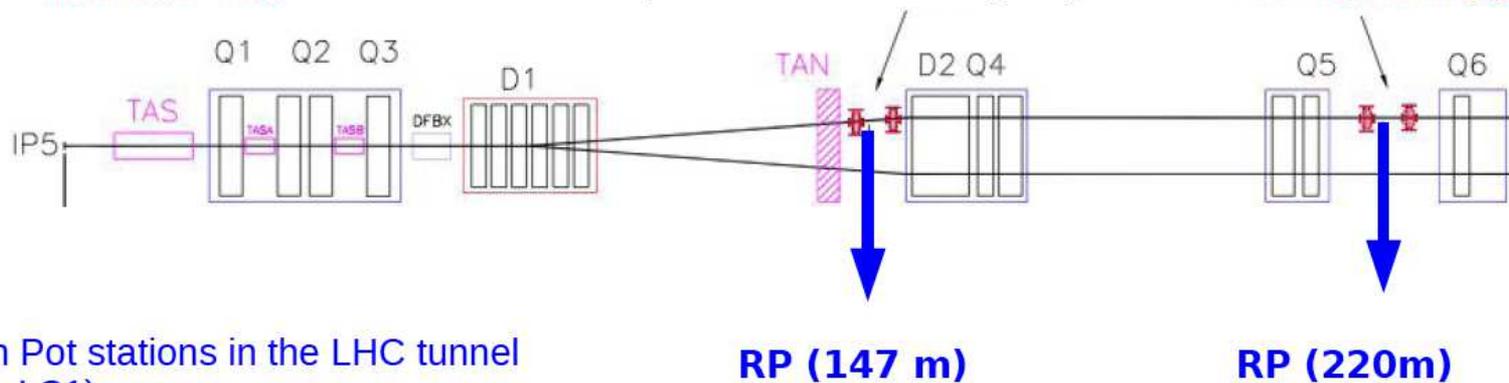
- For elastic measurements, TOTEM installed vertical roman pot detectors at 220 m from CMS
- ATLAS-ALFA installed similar roman pots at 240 m
- Trigger for elastics using proton in opposite configurations: Up (Down) on one side, Down (Up) on the other side



## Forward coverage in CMS-TOTEM



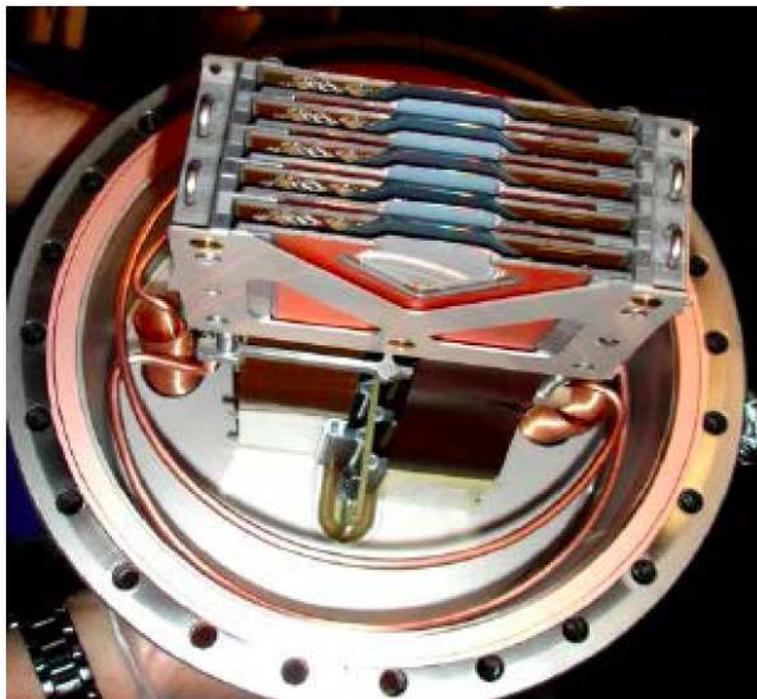
**Roman Pots:** elastic & diffractive protons close to outgoing beams → **Proton Trigger**



Roman Pot stations in the LHC tunnel  
 (before LS1)

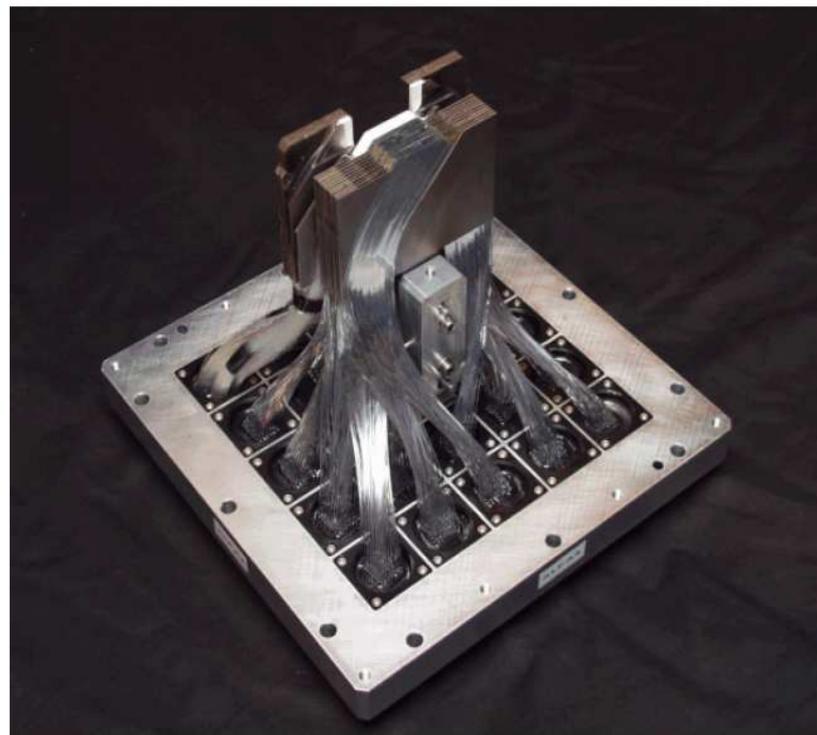
## ALFA and TOTEM detectors

### TOTEM



Planar silicon detectors  
Stack of 10  
Insensitive region  $< 60-70\mu\text{m}$   
Space resolution  $11\mu\text{m}$  per stack

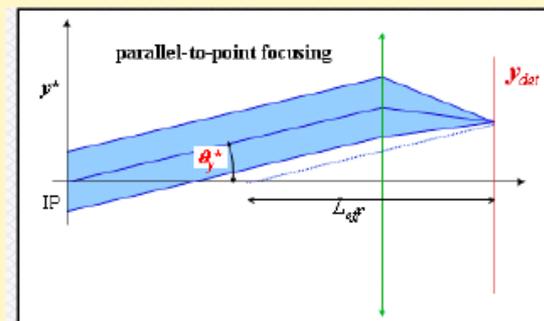
### ATLAS/ALFA



Scintillating fibres  
10 staggered planes  
Insensitive region  $< 20-30\mu\text{m}$   
Space resolution  $35\mu\text{m}$

## Similarities between ALFA and TOTEM

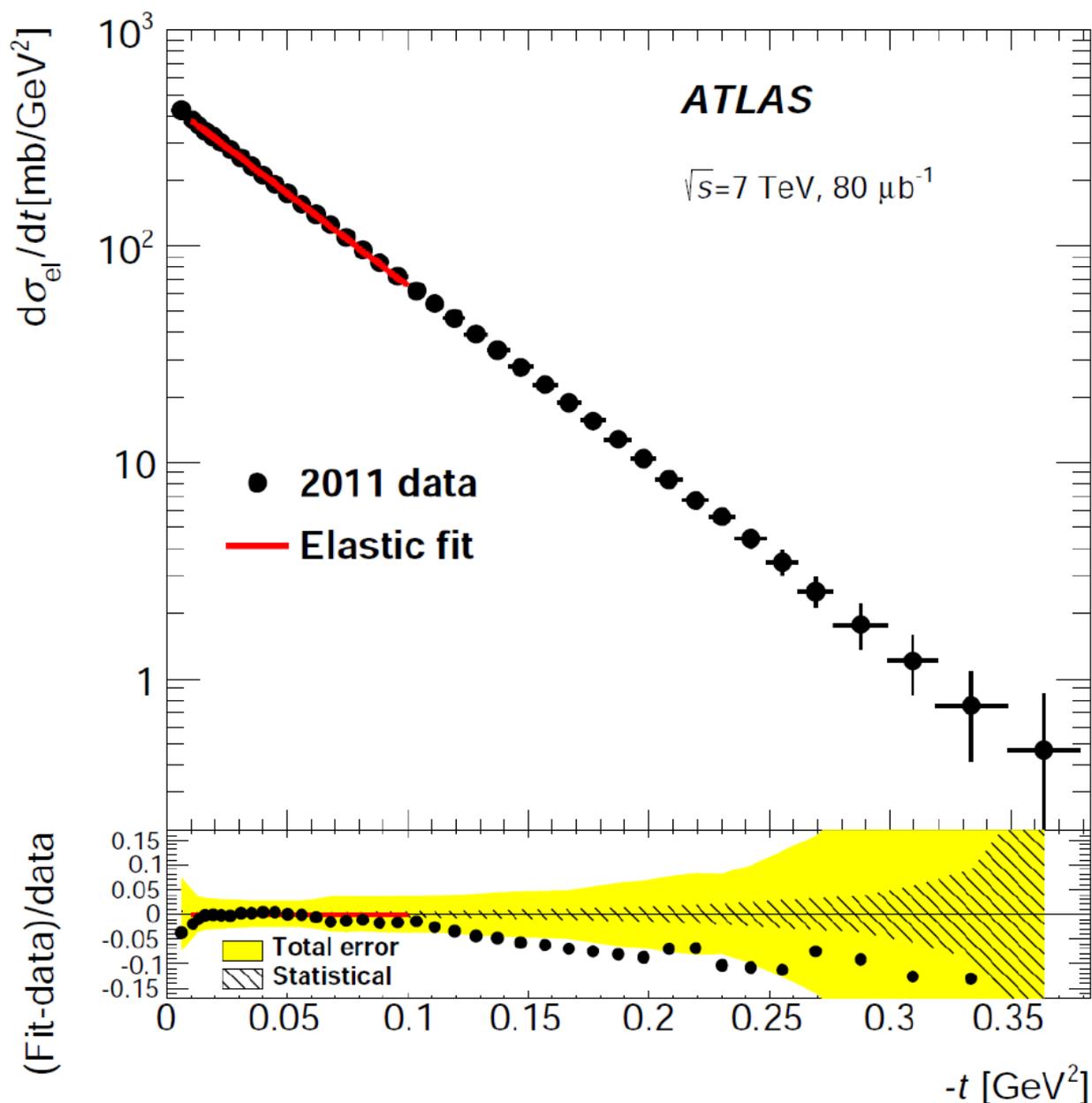
- Divergence smaller than angles to be measured  $\Rightarrow \sqrt{\epsilon}/\beta^*$  small  
 $\Rightarrow$  large  $\beta^*$ ; ATLAS/TOTEM used  $\beta^*=90\text{m}$
- "parallel to point" in at least one plane  
 ATLAS/TOTEM in vertical plane
- Large effective lever arm in at least one plane for good  $t$ -resolution  
 $\theta_y = y/L_y^{\text{eff}}$  ATLAS/TOTEM vertical plane



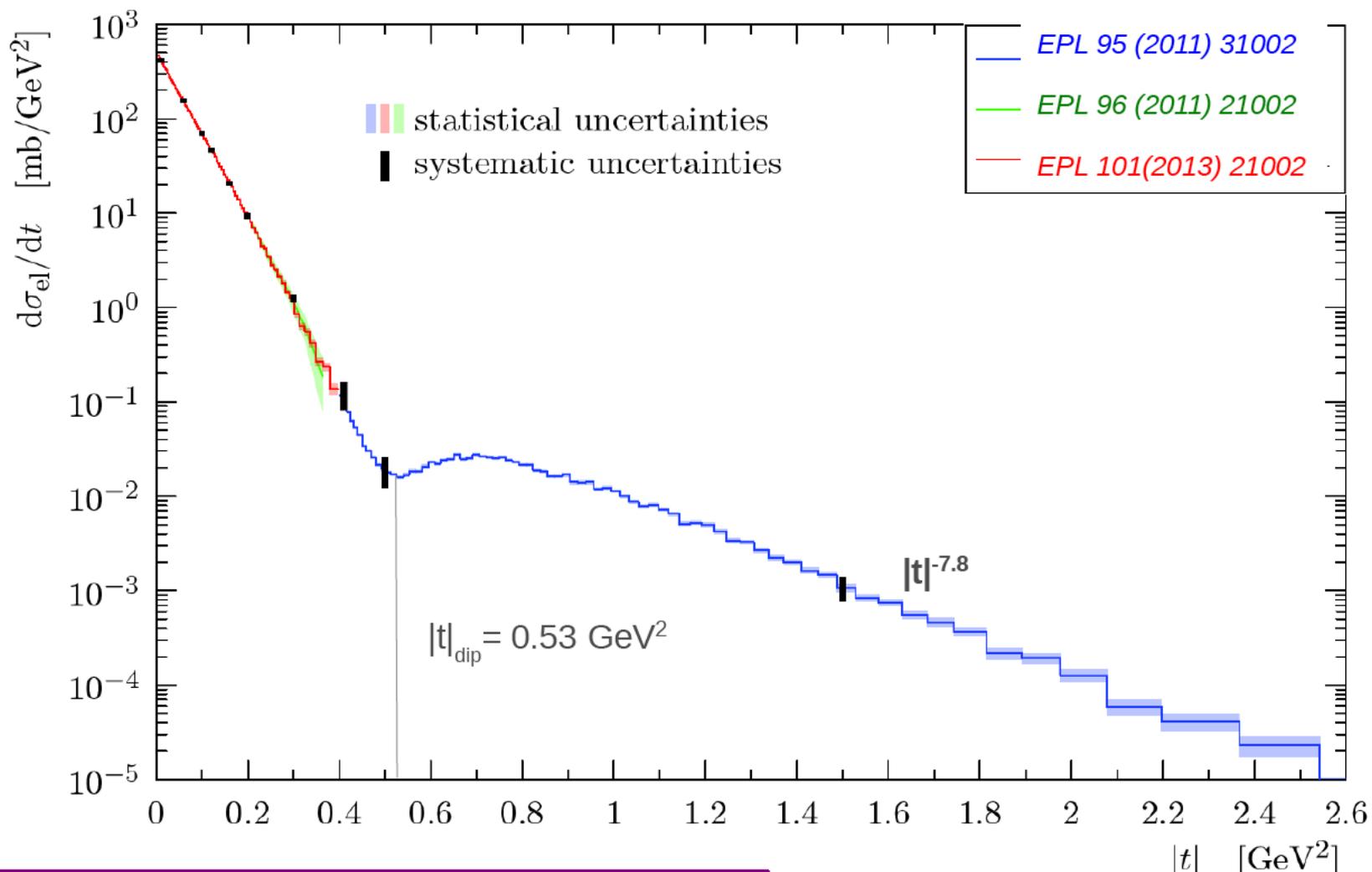
- Different methods used to reconstruct  $t$  (differences in horizontal lever arm)
- Different methods used to extract the elastic and total cross sections
- ATLAS claims smaller uncertainties due to luminosity measurement

## *pp* scattering at 7 TeV (ATLAS)

- Coverage in  $t$ :  $0.006 < |t| < 0.38 \text{ GeV}^2$
- Simple exponential fit to data ( $d\sigma/dt = A \exp(-B|t|)$ ) leads to  $A = 474 \pm 13(\text{syst}) \pm 4(\text{stat})$ , and  $B = 19.73 \pm 0.26(\text{syst}) \pm 0.14(\text{stat})$ ,  
 $\sigma_{el} = 24.00 \pm 0.57(\text{syst}) \pm 0.19(\text{stat}) \text{ mb}$

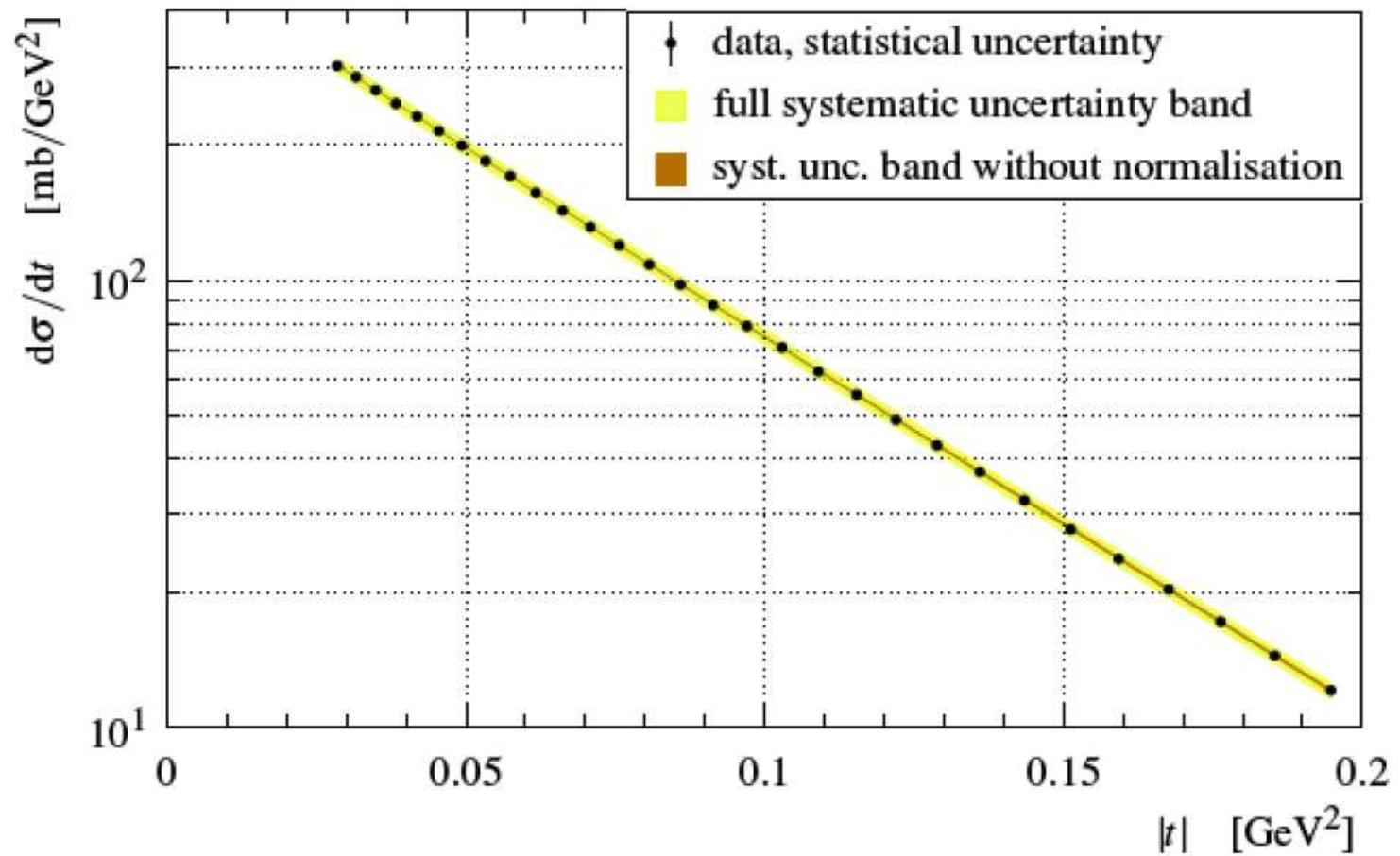


## *pp* scattering at 7 TeV (TOTEM)



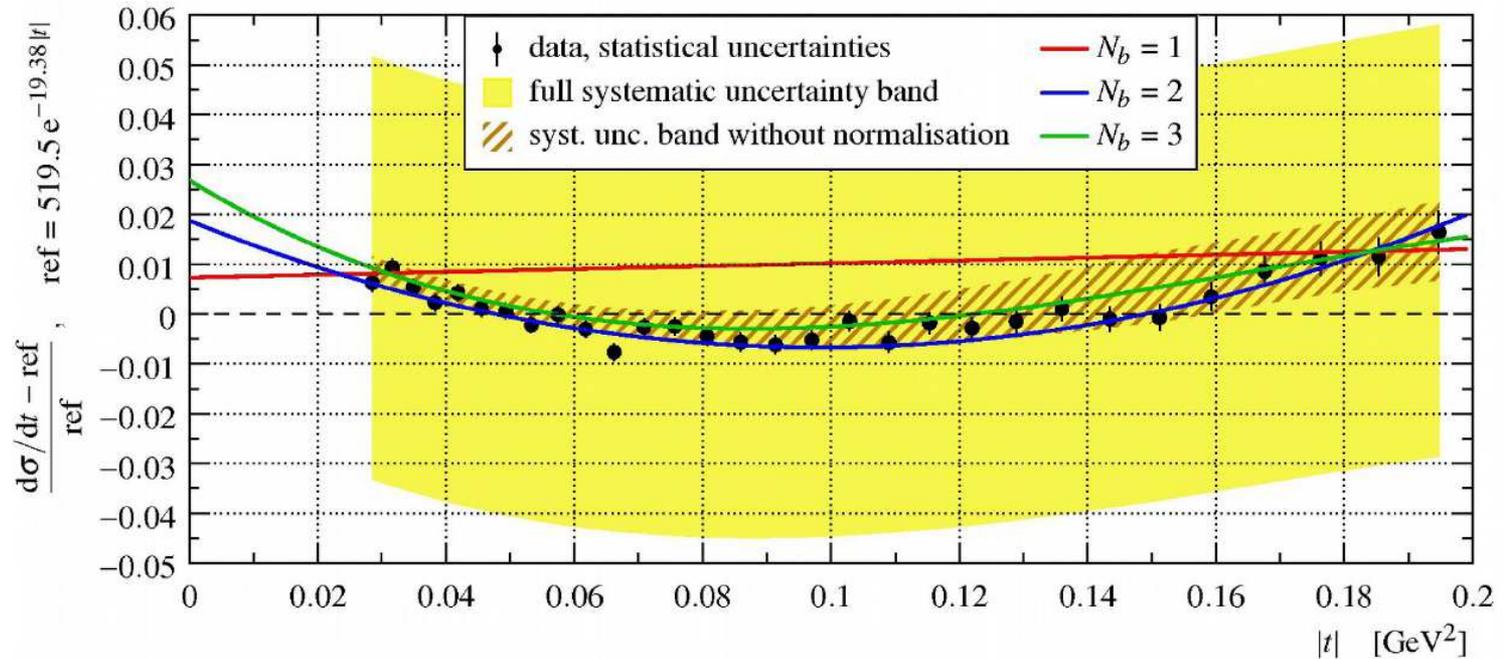
- Wide range of measurement in  $t$ :  $0.005 < |t| < 0.2 \text{ GeV}^2$ , results in red,  $0.002 < |t| < 0.33 \text{ GeV}^2$ , results in green
- Simple exponential fit:  $A = 506.4 \pm 23(stat) \pm 0.9(syst)$ ,  
 $A = 503.0 \pm 26.7(syst) \pm 1.5(stat)$ ;  
 $B = 19.89 \pm 0.27(syst) \pm 0.03(stat)$ ,  $B = 20.1 \pm 0.3(syst) \pm 0.2(stat)$

## $pp$ scattering at 8 TeV (TOTEM)



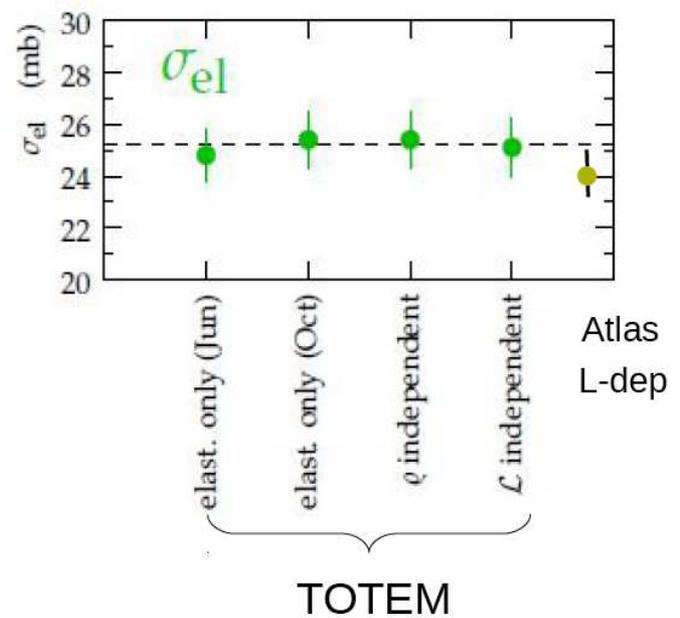
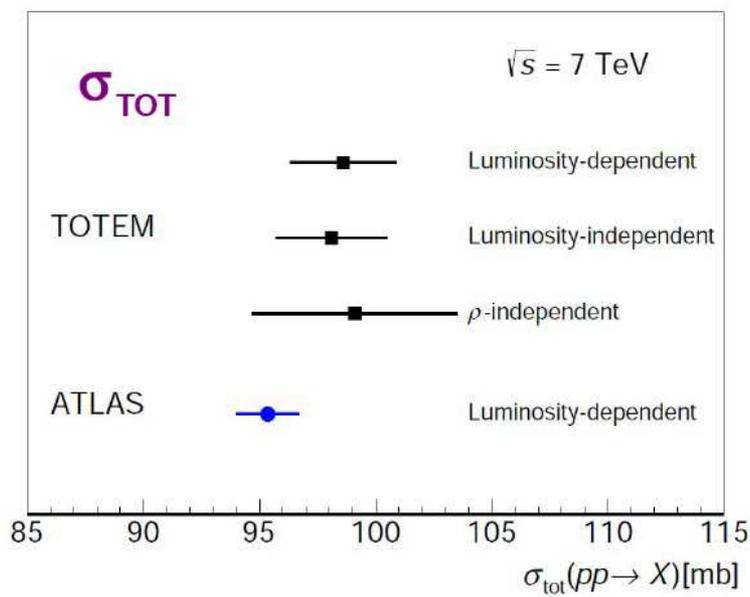
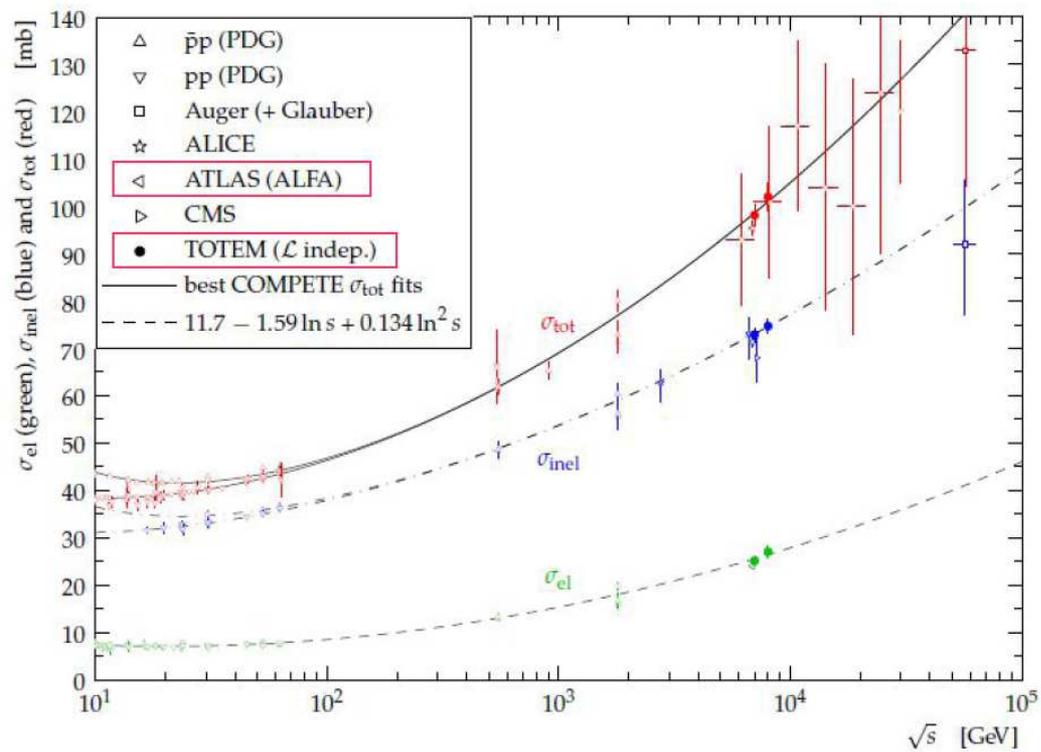
- High statistics data set ( $\beta^* = 90\text{m}$ , 7 million elastic events,  $0.027 < |t| < 0.2 \text{ GeV}^2$ )
- $\sigma_{el} = 27.1 \pm 1.4 \text{ mb}$

## pp scattering at 8 TeV (TOTEM)

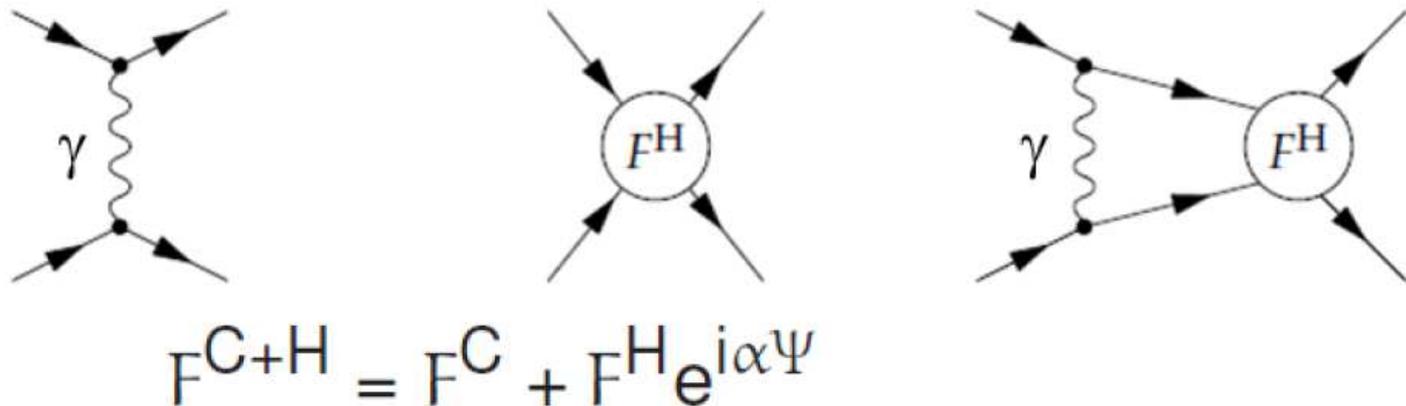


- Exponential fit:  $d\sigma/dt = A \exp(-B(t)|t|)$
- Pure exponential form ( $N_b = 1$ ) excluded at  $7.2 \sigma$ 
  - $N_b = 1$   $B = b_1$ , reference
  - $N_b = 2$ ,  $B = b_1 + b_2 t$
  - $N_b = 3$ ,  $B = b_1 + b_2 t + b_3 t^2$

## Total cross section measurement (7 TeV)



## Elastic scattering in the Coulomb-Nuclear interference region

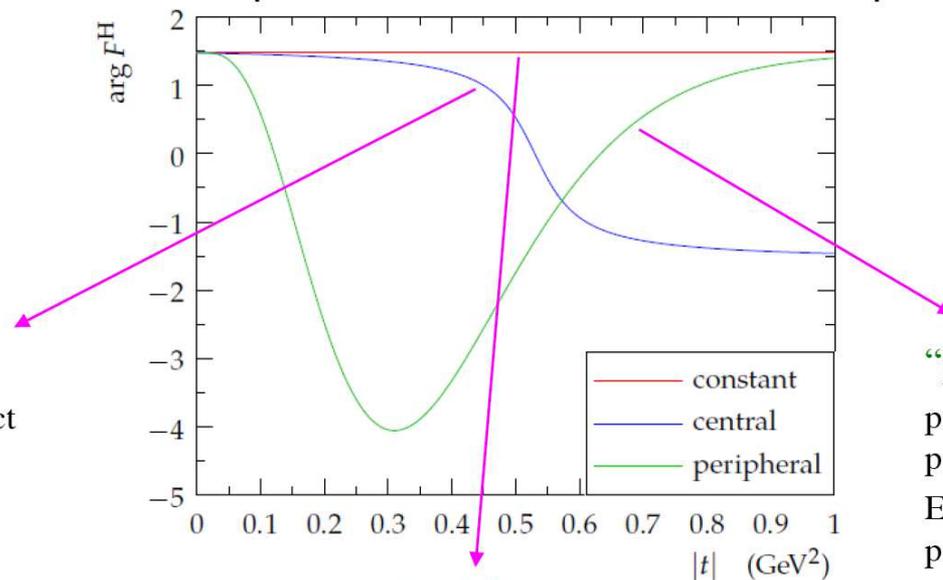


- $F^C = \alpha_S/t^2(t)$
- $F^H$ : Modulus constrained by measurement in hadronic  $t$ -region ( $d\sigma/dt = A \exp(-B(t)|t|)$  and  $B(t) = b_0 + b_1 t$ ); Hadronic phase  $\arg(F^H(t))$ : very little guidance by data
- Interference formula for  $\exp i\alpha\Psi$  term:
- Simplified West-Yennie formula:
  - Constant slope  $B(t) = b_0$ , already excluded by data
  - Constant hadronic phase  $\arg(F^H) = p_0$
  - $\Psi(t)$  acts as real interference phase
- Kundrat-Lokajicek formula:
  - Any slope  $B(t)$
  - Any hadronic phase  $\arg(F^H) = p_0$
  - Complex  $\Psi(t)$

## Different options for the unknown nuclear phase



Different options for the unknown nuclear phase:



“central phase”:  
profile function in impact  
parameter picture:  
Elastic scattering  
preferentially central

“peripheral phase”:  
profile function in impact  
parameter picture:  
Elastic scattering  
preferentially peripheral

$$\arg F(t) = \frac{\pi}{2} - \operatorname{atan} \frac{\cot p_0}{1 - \frac{t}{t_d}}$$

constant phase:  
also central behaviour

$$\arg F(t) = p_0 + p_A \exp \left[ \kappa \left( \ln \frac{t}{t_m} - \frac{t}{t_m} + 1 \right) \right]$$

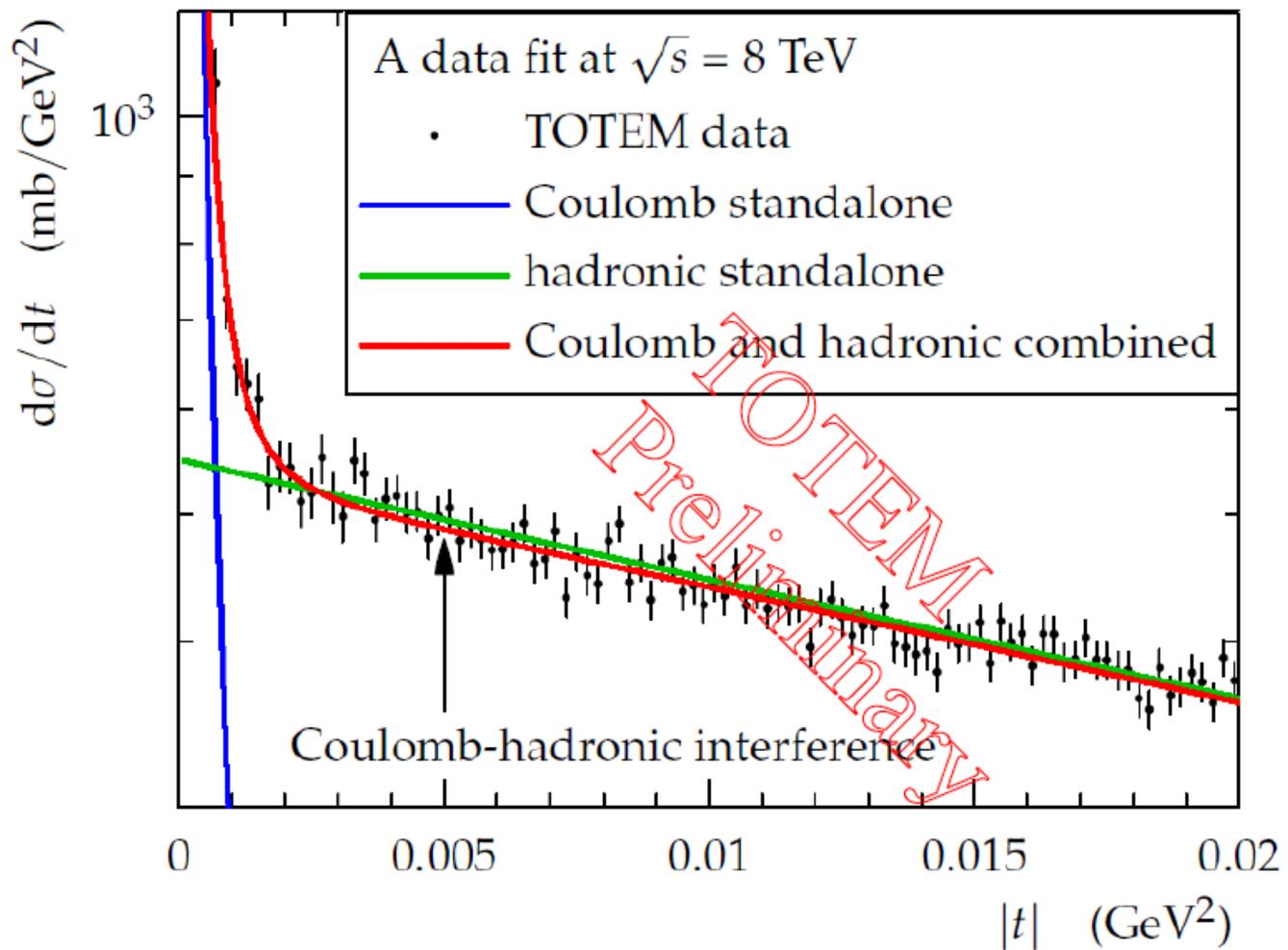
$$\arg F(t) = p_0$$

Result for

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

is model dependent

## Elastic scattering in the Coulomb-Nuclear interference region

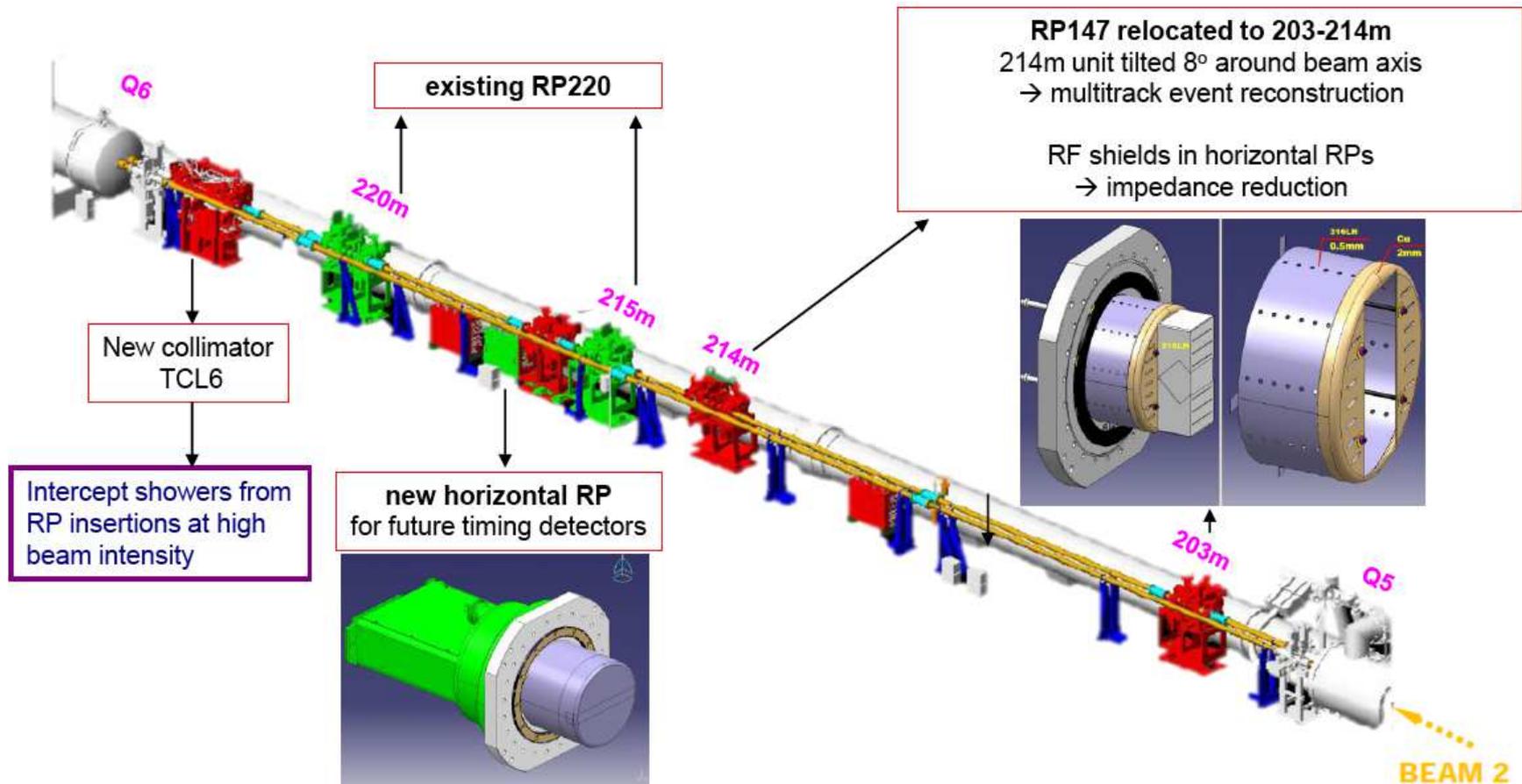


- Measure elastic scattering at  $|t|$  as low as  $6 \cdot 10^{-4}$  GeV<sup>2</sup> using high  $\beta^* = 1000$  m optics
- Detectors approach the beam at  $3\sigma$  from the beam center
- Measurement of  $\rho$  expected soon!

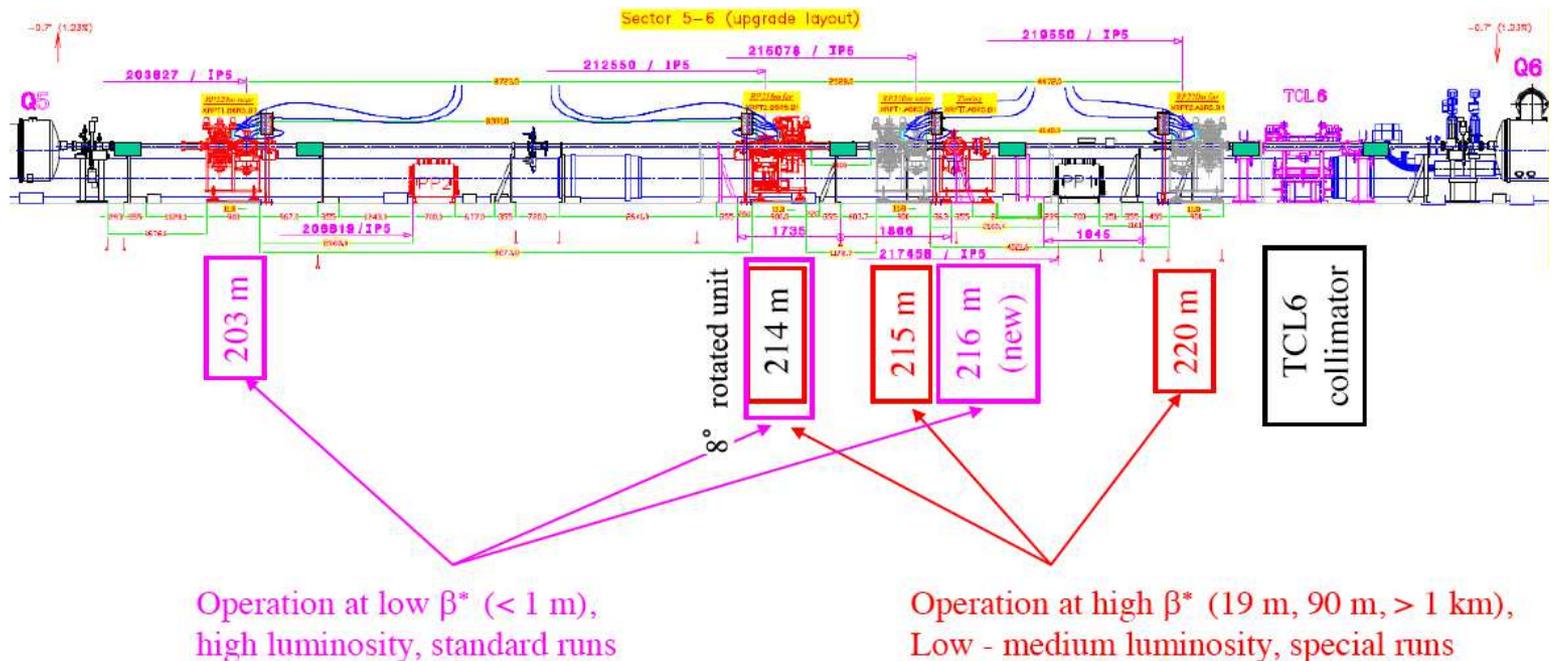
## More data available: Stay tuned!

Experiment	$\sqrt{s}$ (TeV)	$\beta^*(m)$	RP approach (beam $\sigma$ )	$ t $ - range (GeV <sup>2</sup> )	Elastic events	Reference
ATLAS	7	90	6.5	0.01– 0.38	805K	Nucl. Phys. B 889 (2014), 486
	8	90	6-10			In progress
	8	1000	3-10			In progress
TOTEM	7	90	4.8 – 6.5	$5 \cdot 10^{-3} - 0.4$	1M	EPL 101 (2013), 21002
	7	90	10	0.02 – 0.33	15K	EPL 96 (2011), 21002
	7	3.5	7	0.36 – 2.5	66K	EPL 95 (2011), 41001
	7	3.5	18	2 – 3.5	10K	In progress
	8	90	6 – 9.5	0.01 – 0.3	0.65M	PRL 111, 012001 (2013)
	8	90	9.5	0.03 – 1.4	7.2M	ArXiv:1503.08111 Submit Nucl. Phys. B
	8	1000	3 – 10	$6 \cdot 10^4 - 0.2$		In progress
	2.76	11	5 – 13	0.06 – 0.5	45K	In progress

## The future: roman pot system now!



## The future: upgrades for AFP CMS-TOTEM and CT-PPS



- Finalise measurements at 8 TeV: measurement of  $\rho$  parameter, hard diffraction (jets,  $Z$ ...) with CMS
- Elastic and total cross section measurements at 13 TeV using TOTEM and ALFA
- Special high  $\beta^* = 2.5$  km runs in order to access the Coulomb interference region foreseen in 2016
- In parallel, measurements of low and medium mass diffraction using high  $\beta^*$  runs in CMS-TOTEM: glueballs, jets,  $W$  bosons, vector mesons in SD and DPE, exclusive events...
- High mass diffraction using CT-PPS and AFP: sensitivity to new physics via anomalous couplings

## Conclusion - Opening for discussion

- What impact have LHC results on Models? Islam et al., Maor at al., Soffer et al. revisited and refined their models
- Non exponential form of  $d\sigma/dt$
- Could new measurements in the pipeline ( $\rho...$ ) already lead to a better understanding?
- Which additional measurements should be performed at the LHC to have a better understanding of the elastic scattering mechanism?
- Broad diffractive program at the LHC for the future

