Proton Proton Cross-Sections and Properties of Diffractive Physics

E. Radermacher
on behalf of the TOTEM collaboration

14 june 2016

SUMMARY

- Totem and Atlas-Alfa Detectors
- Forward charged particle pseudorapidity density
- Hadronic elastic scattering
- Non exponential elastic differential cross-section
- Coulomb nuclear interference region
- Total cross-section
- Diffraction
- Upgrade

Experimental Setup at IP5 before LS1

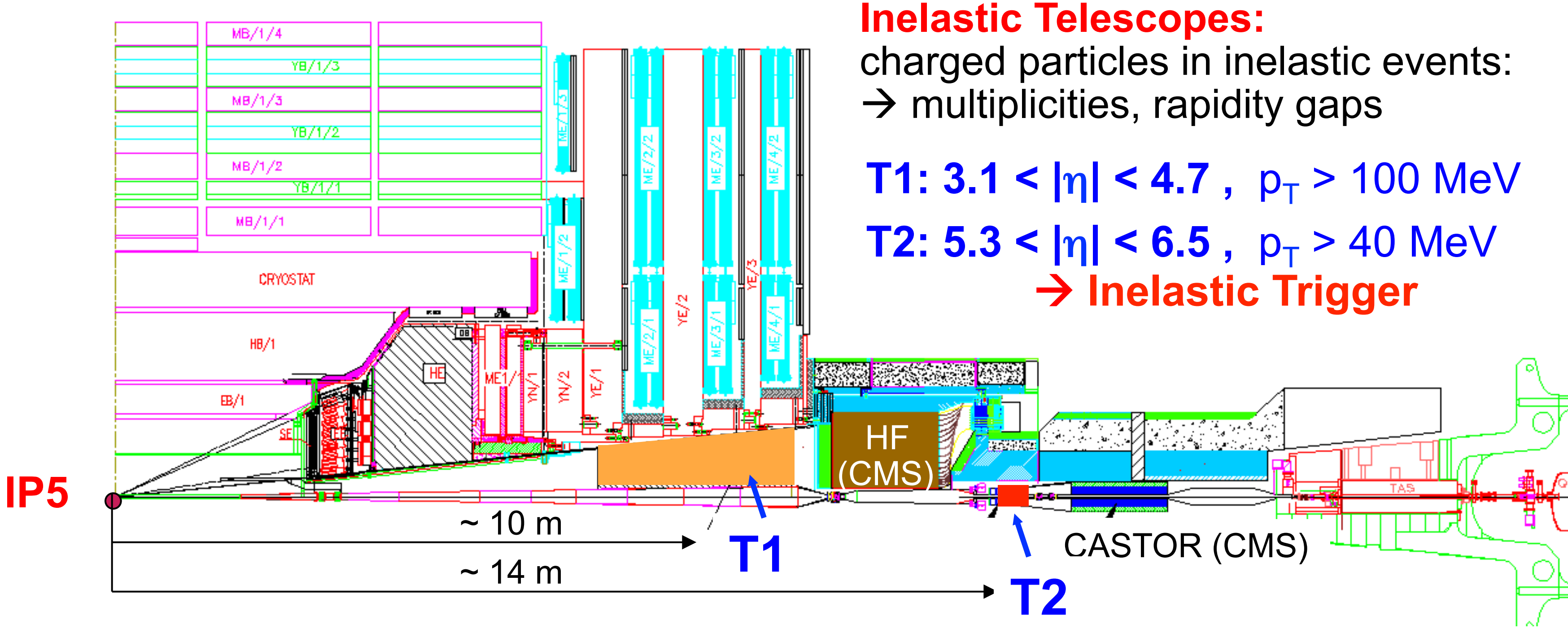
[Ref.: JINST 3 (2008) S08007]

Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

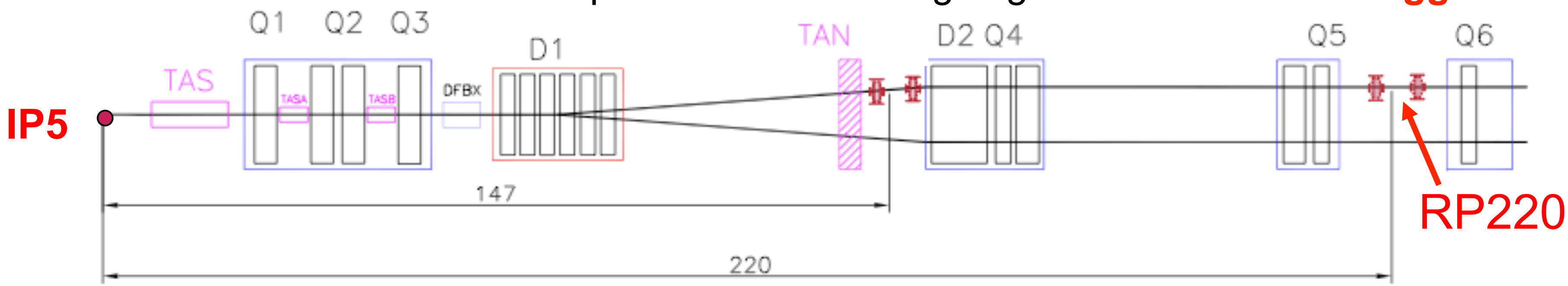
T1: 3.1 < |η| < 4.7 , p_T > 100 MeV

T2: 5.3 < |η| < 6.5 , p_T > 40 MeV

→ **Inelastic Trigger**



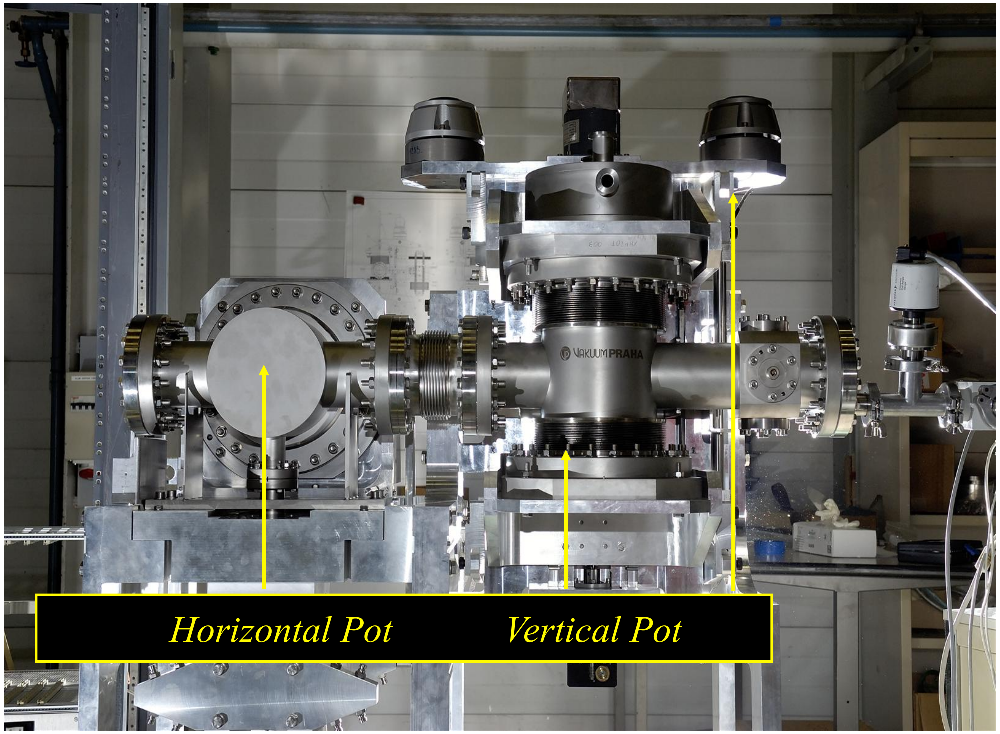
Roman Pots: elastic & diffractive protons close to outgoing beams → **Proton Trigger**

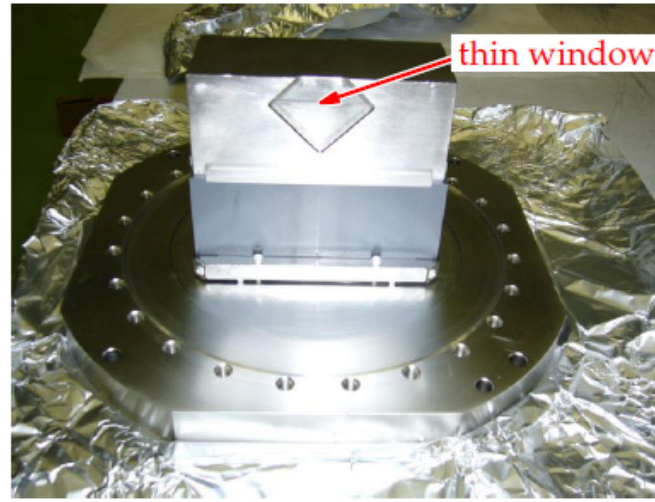


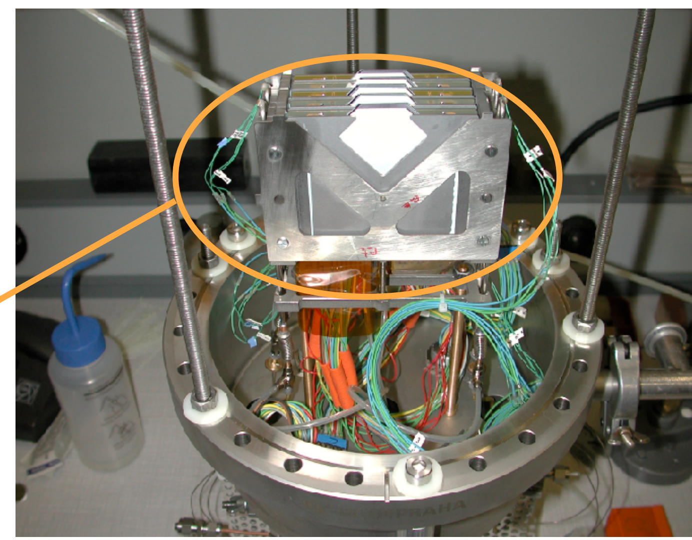
Roman Pots

Roman Pot = movable box inside the beam pipe, housing silicon detectors.

Detectors can approach the beam centre to < 1mm when the beams are stable.





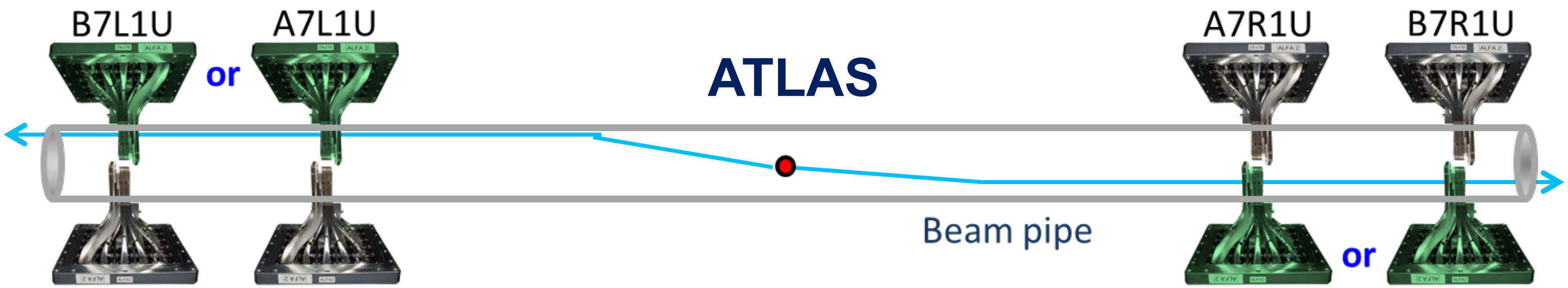


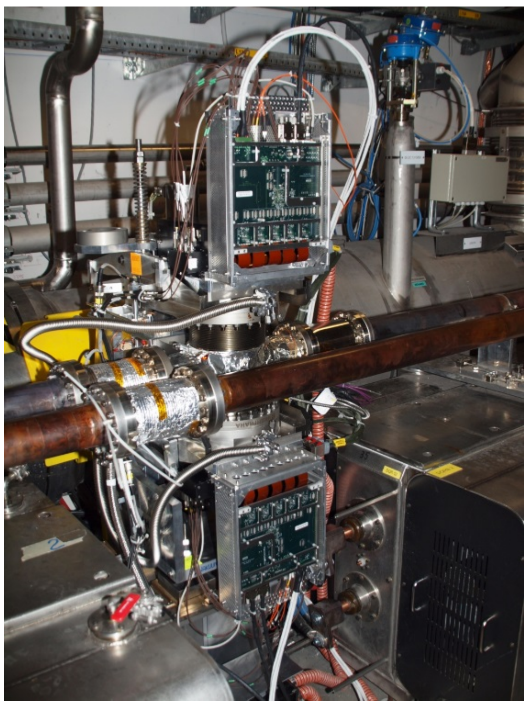
66 μm pitch
20 μm resolution

150 μm window

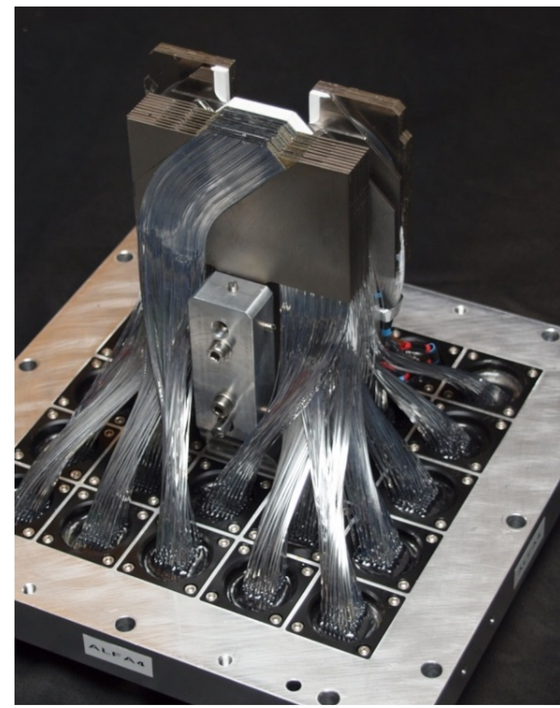
Stack of 10 silicon
strip detectors
(5 pairs back to back)

Alfa Detector





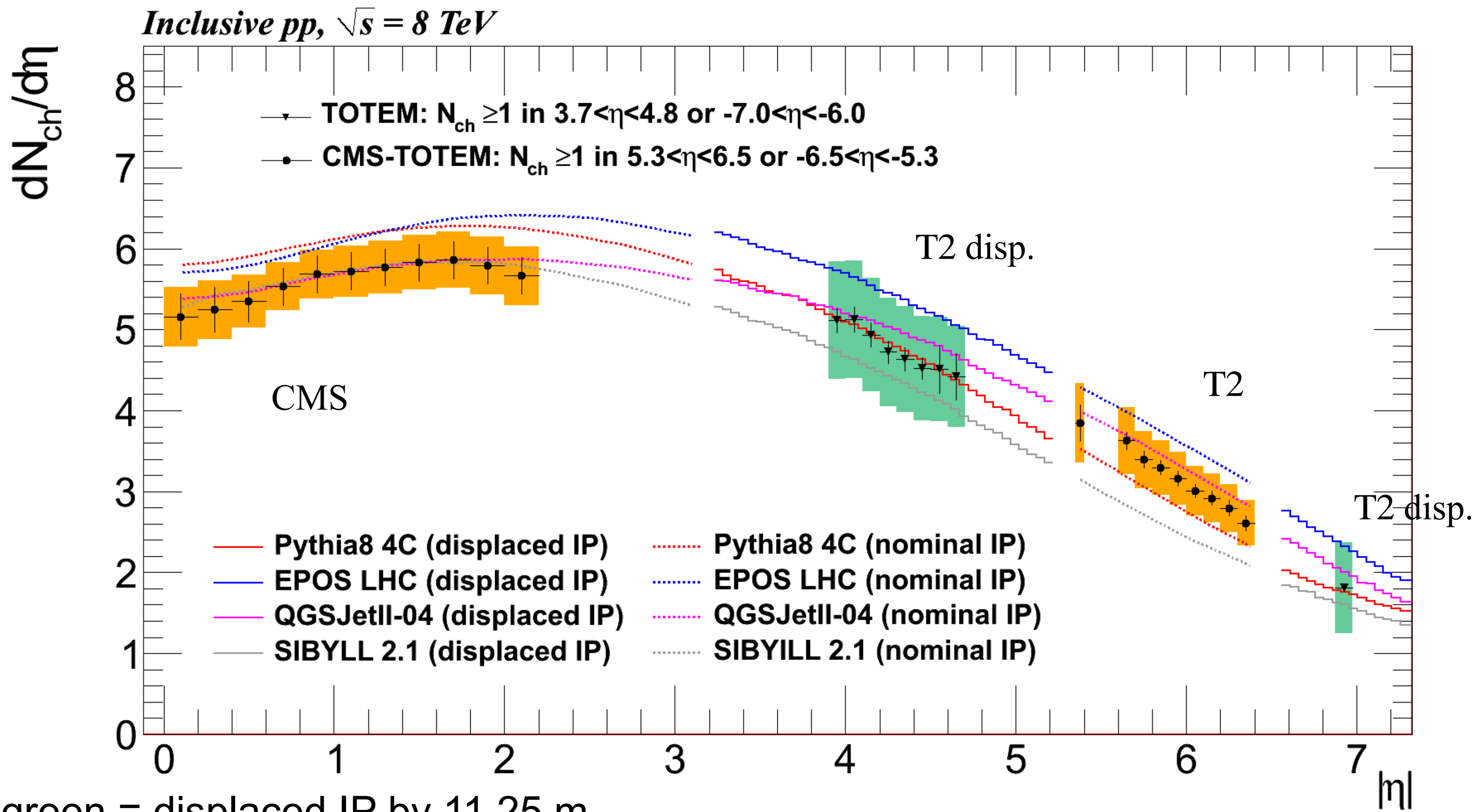
- 2 x 2 stations
  ~ 240 m from ATLAS IP
- 8 fiber detectors with
  2 x 10 layers of 0.5 mm
  quadratic fibers
- Movable in vertical
  direction
- Resolution ~ 35 μm



Measurement of the forward charged particle dN/dη

Measurement of the forward charged particle pseudorapidity density in pp collisions at sqrt(s) = 8 TeV using a displaced interaction point

Eur. Phys. J. C (2015) 75:126; arXiv:1411.4963



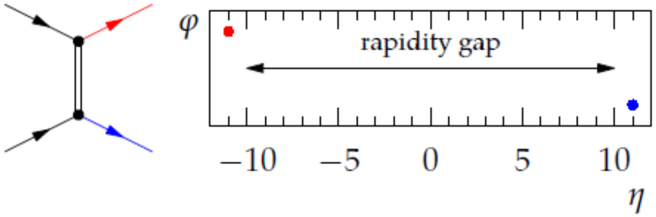
green = displaced IP by 11.25 m

orange = nominal IP

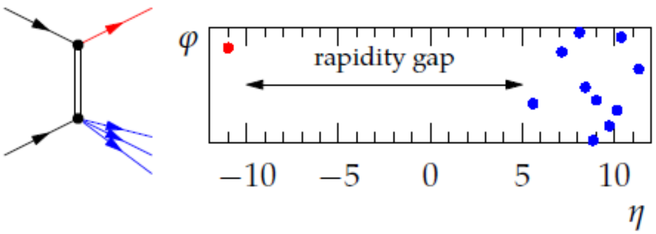
Diffractive and Electromagnetic Processes

Diffractive

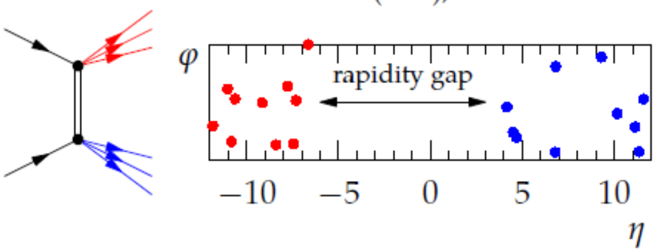
Elastic Scattering (ES), $\approx 25\,\text{mb}$



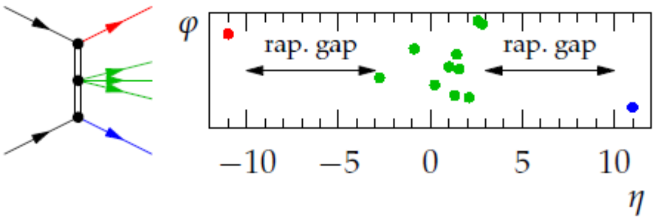
Single Diffraction (SD), $\approx 10\,\text{mb}$



Double Diffraction (DD), $\approx 5\,\text{mb}$



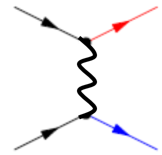
Central Diffraction (CD), $\approx 1\,\text{mb}$



Electromagnetic

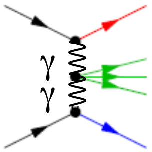
very low momentum transfers

$|t| \sim O(10^{-4}\ \text{GeV}^2)$

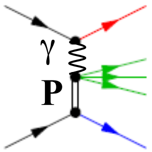


Coulomb scattering

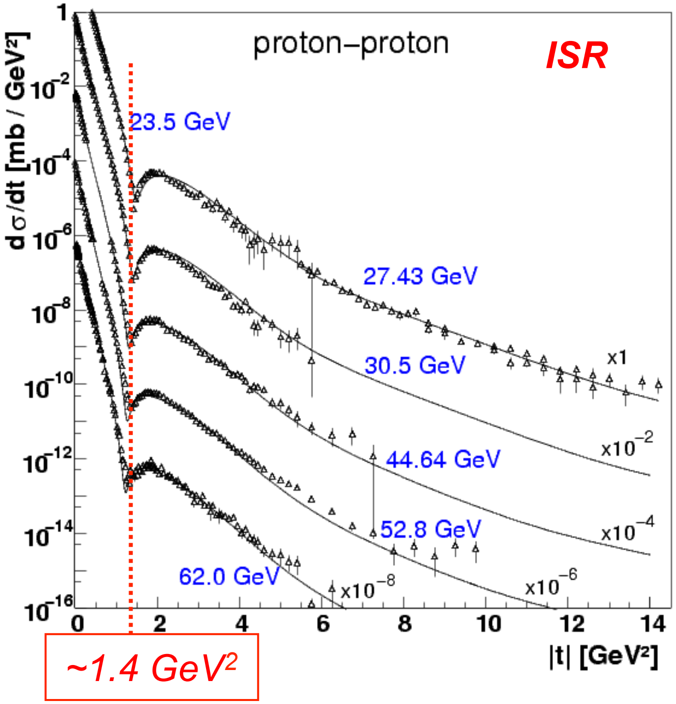
pure QED

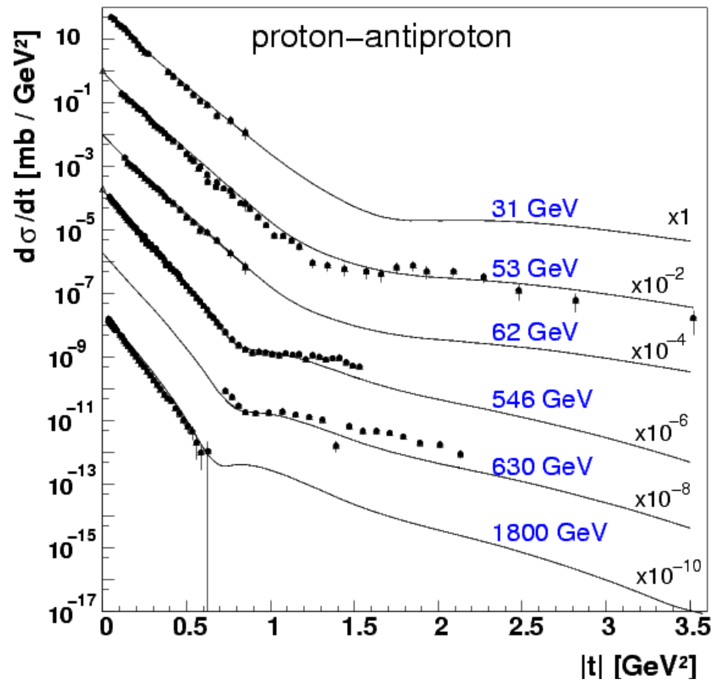


Photoproduction



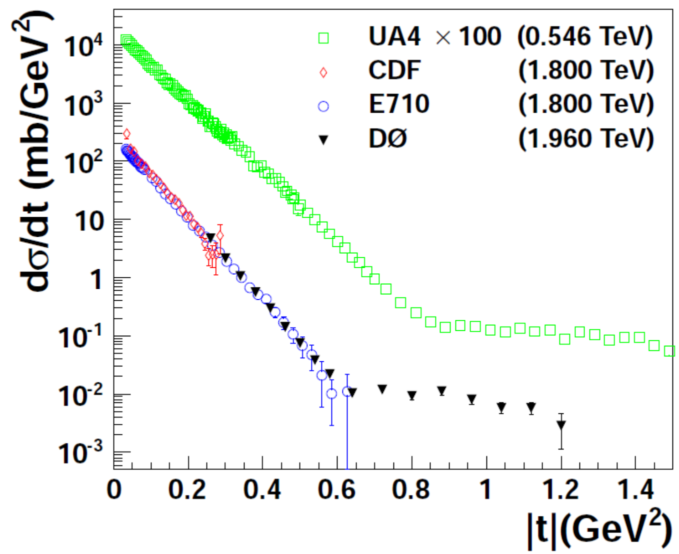
Elastic Scattering – from ISR to Tevatron





ISR
UA4
Tevatron

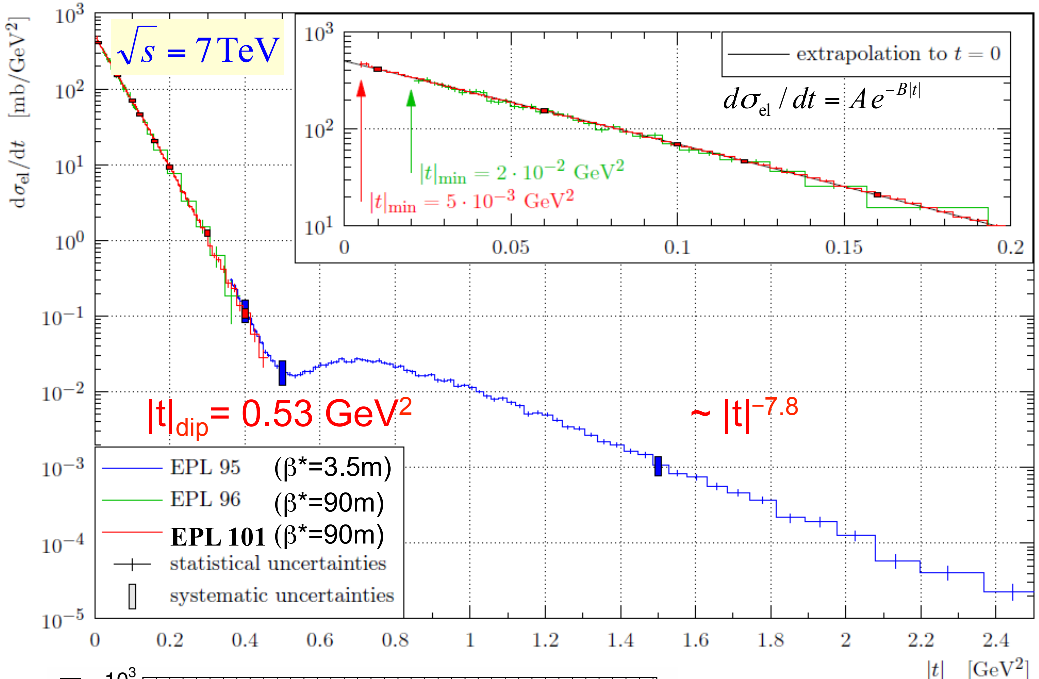
$|t| \approx p^2\ \theta^2$

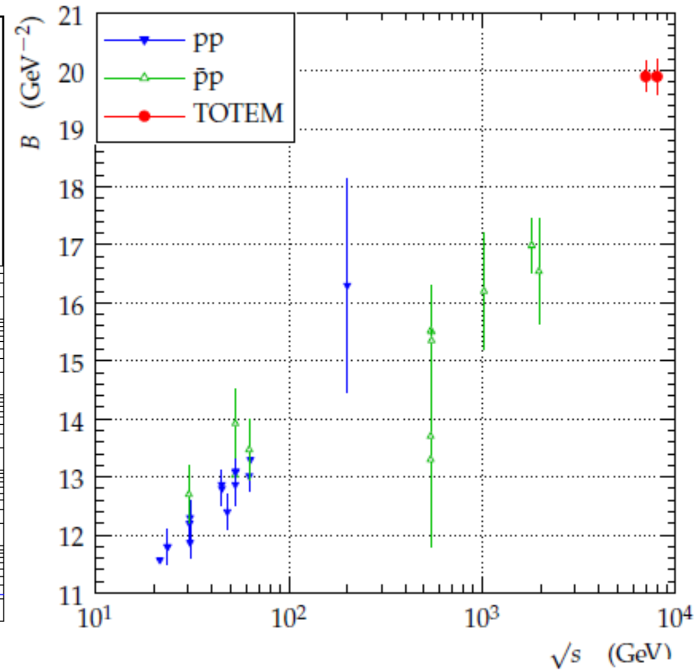


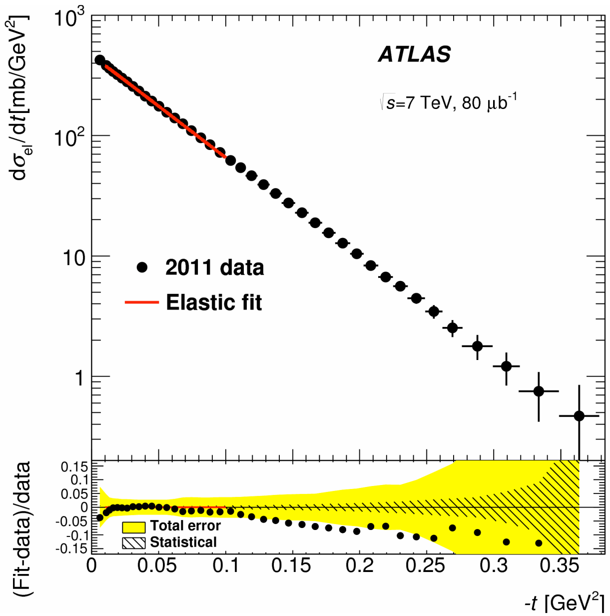
- *Minimum in pp, shoulder in $\bar{p}p$*
  → different mix of processes

- *Minimum / shoulder moves to lower |t| with increasing s*
  → interaction region grows (as also seen from σ_{tot})
  → RMS impact parameter larger

Some Lessons on Hadronic Elastic pp Scattering







At low |t|: nearly exponential decrease:

B_{7TeV} = (19.89 ± 0.27) GeV^{-2}

B_{8TeV} = (19.90 ± 0.30) GeV^{-2}

Extrapolation to t=0 → σ_{tot} via optical theorem:

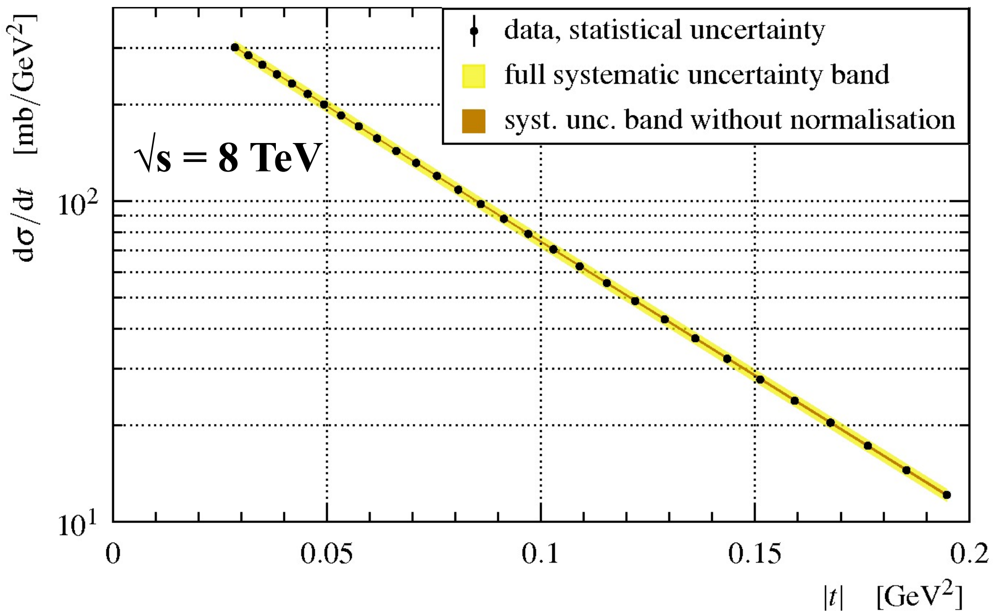
$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$$

σ_{tot} = 98.58 ± 2.23 mb $\sqrt{s}$ = 7 TeV

Old trends for increasing s are confirmed:

- "shrinkage of the forward peak": minimum moves to lower |t|
- forward exponential slope B increases

Non-Exponential Elastic pp Differential Cross-Section

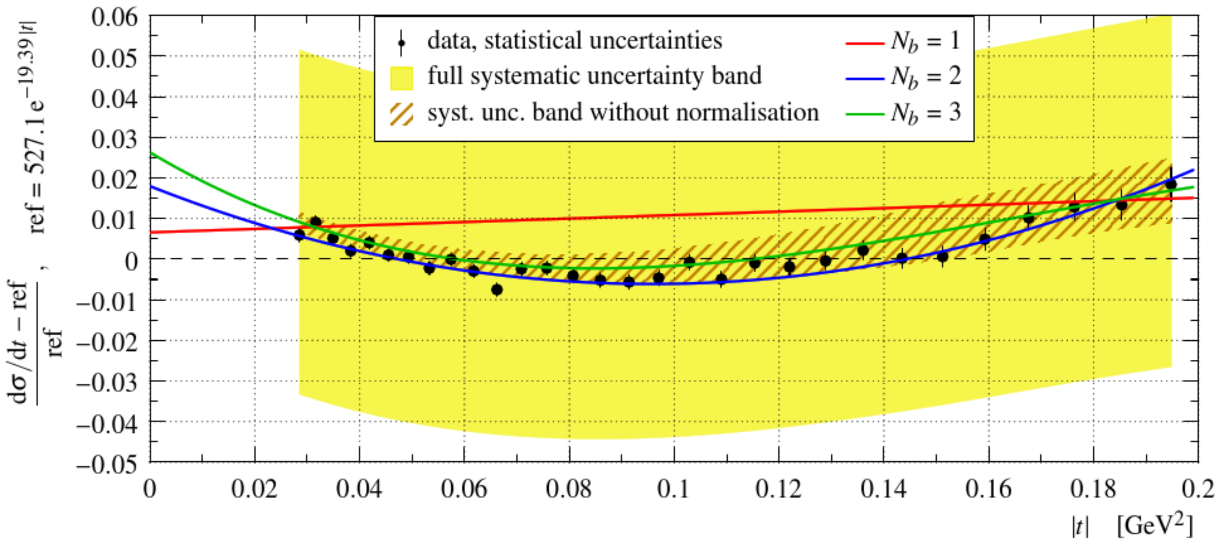


High statistics data set (β*=90m,2012):
7 M elastic events

$0.027\ GeV^2 < |t| < 0.2\ GeV^2$, i.e.
Coulomb effects negligible

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

Plotting relative deviation from exponential and fitting
$d\sigma/dt = A\, e^{-B(t)\,|t|}$, with $B(t) = b_0$ or $B(t) = b_0 + b_1 t$ or $B(t) = b_0 + b_1 t + b_2 t^2$



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

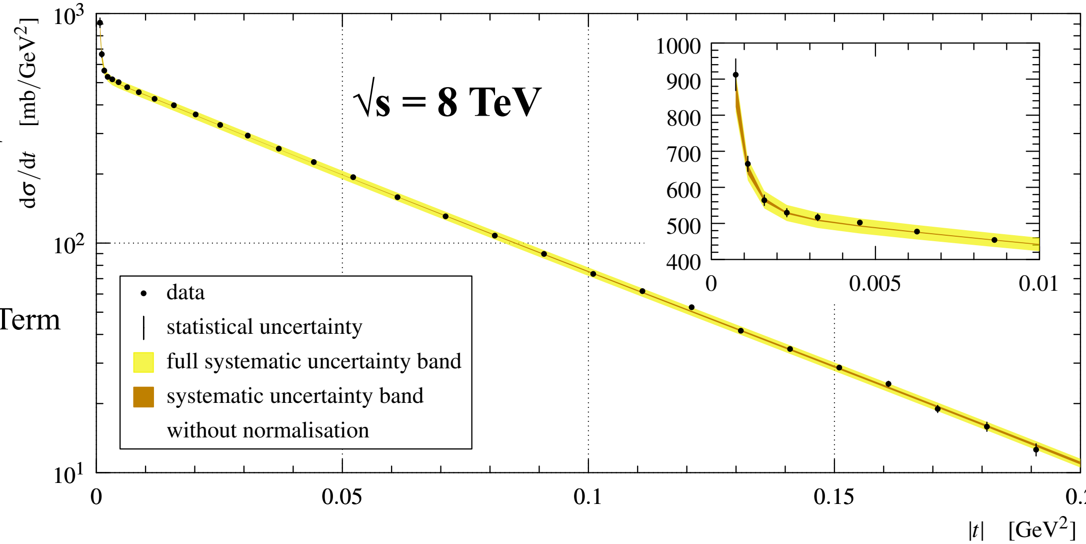
Pure exponential form ($N_b = 1$) excluded at 7.2 σ significance.

Nucl. Phys. B 899 (2015) 527

Elastic Scattering in the Coulomb-Nuclear Interference Region

Measurement down to $|t| \sim 6 \times 10^{-4}$ GeV^2:

- $\beta^* = 1000$ m optics
- Roman Pot approach to 3 σ from the beam



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

InterferenceTerm

$$|F^{H}| \quad \arg(F^{H})$$

$A\, e^{-B(t)\,|t|}$

hadronic phase as function of t:
implications on behaviour of elastic scattering in impact parameter space:
preferentially central or peripheral ?

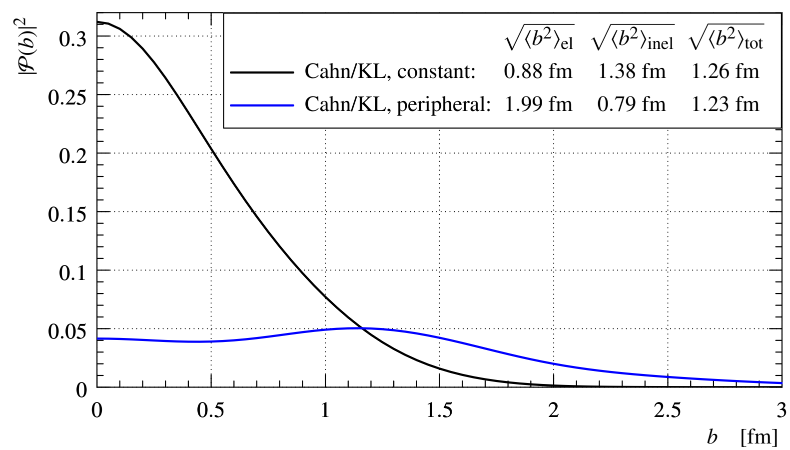
Combined β^*= 1km & 90 m data

- exclude Simplified West & Yennie interference formula (requiring purely exponential hadronic ampl.)
- have constraining power on:
  - hadronic amplitude
  - hadronic phase → impact parameter picture

→ measurement of $\rho = \cot \arg\, F^{H}(t=0)$

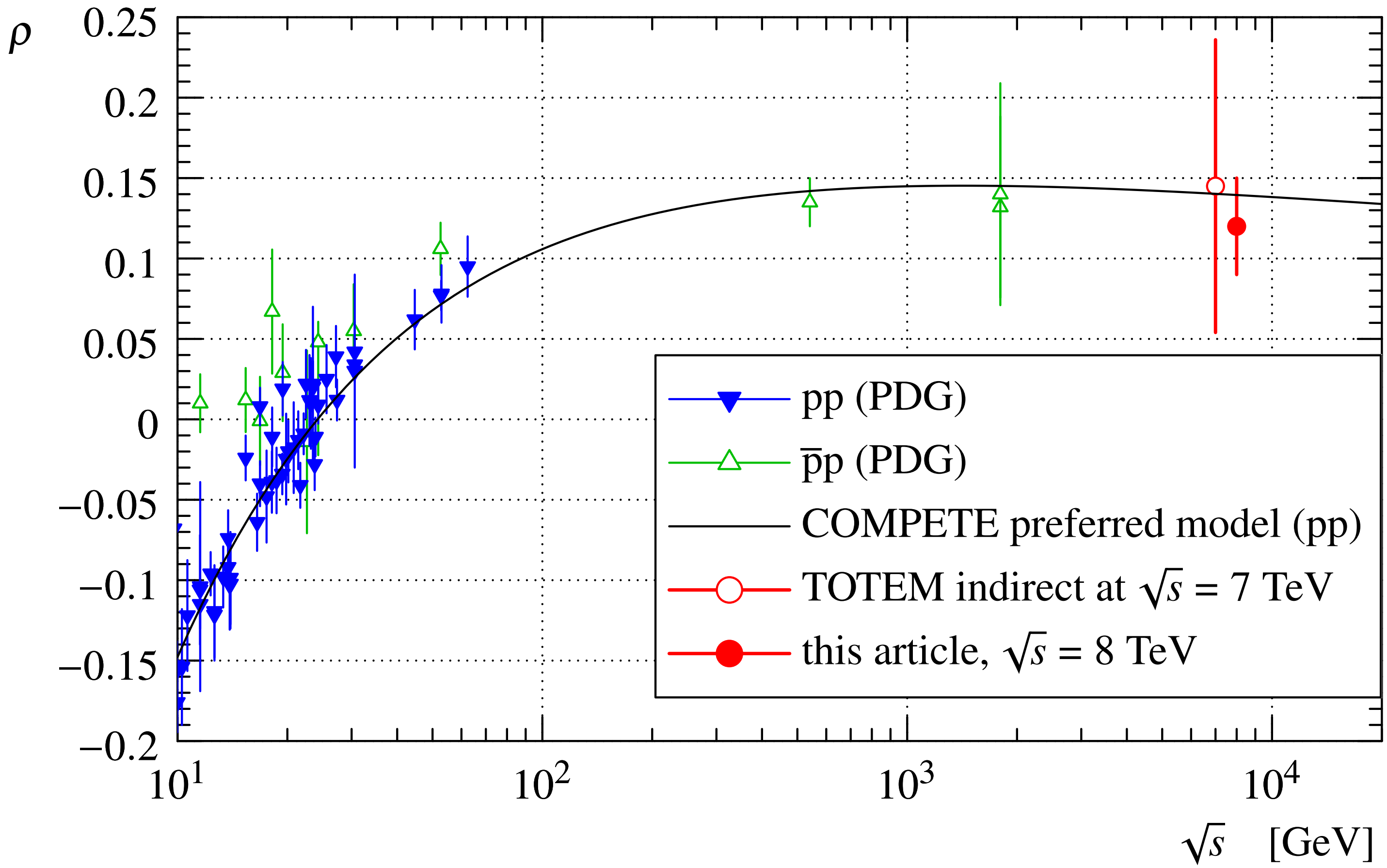
→ previous σ_{tot} measurements (neglecting CNI) confirmed.

CERN-PH-EP-2015-325



Elastic Scattering in the Coulomb-Nuclear Interference Region

Both fits with central and peripheral phase describe the data and give the same result for ρ



TOTEM ($\sqrt{s}$ = 8 TeV): ρ = 0.12 ± 0.03

In 2016: β* = 1000 m, $\sqrt{s}$= 13 TeV

From the Elastic to the Total Cross-Section

TOTEM

Optical Theorem: $\sigma_{\text{tot}}^2 \propto \left[\Im F_{\text{el, had}}(t=0)\right]^2 = \frac{1}{1+\rho^2}\left|F_{\text{el, had}}(t=0)\right|^2$ with $\rho = \left.\frac{\Re F_{\text{el, had}}}{\Im F_{\text{el, had}}}\right|_{t=0}$

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{1+\rho^2}\left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$$

7 TeV

elastic observables only:

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{1+\varrho^2}\frac{1}{\mathcal{L}}\left.\frac{dN_{\text{el}}}{dt}\right|_0$$ (ρ=0.14 [COMPETE extrapol.])

June 2011 (EPL96): $\sigma_{\text{tot}} = (98.3 \pm 2.8)$ mb

Oct. 2011 (EPL101): $\sigma_{\text{tot}} = (98.6 \pm 2.2)$ mb

different beam intensities !

σ_{tot}

ϱ independent:

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

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

luminosity independent:

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

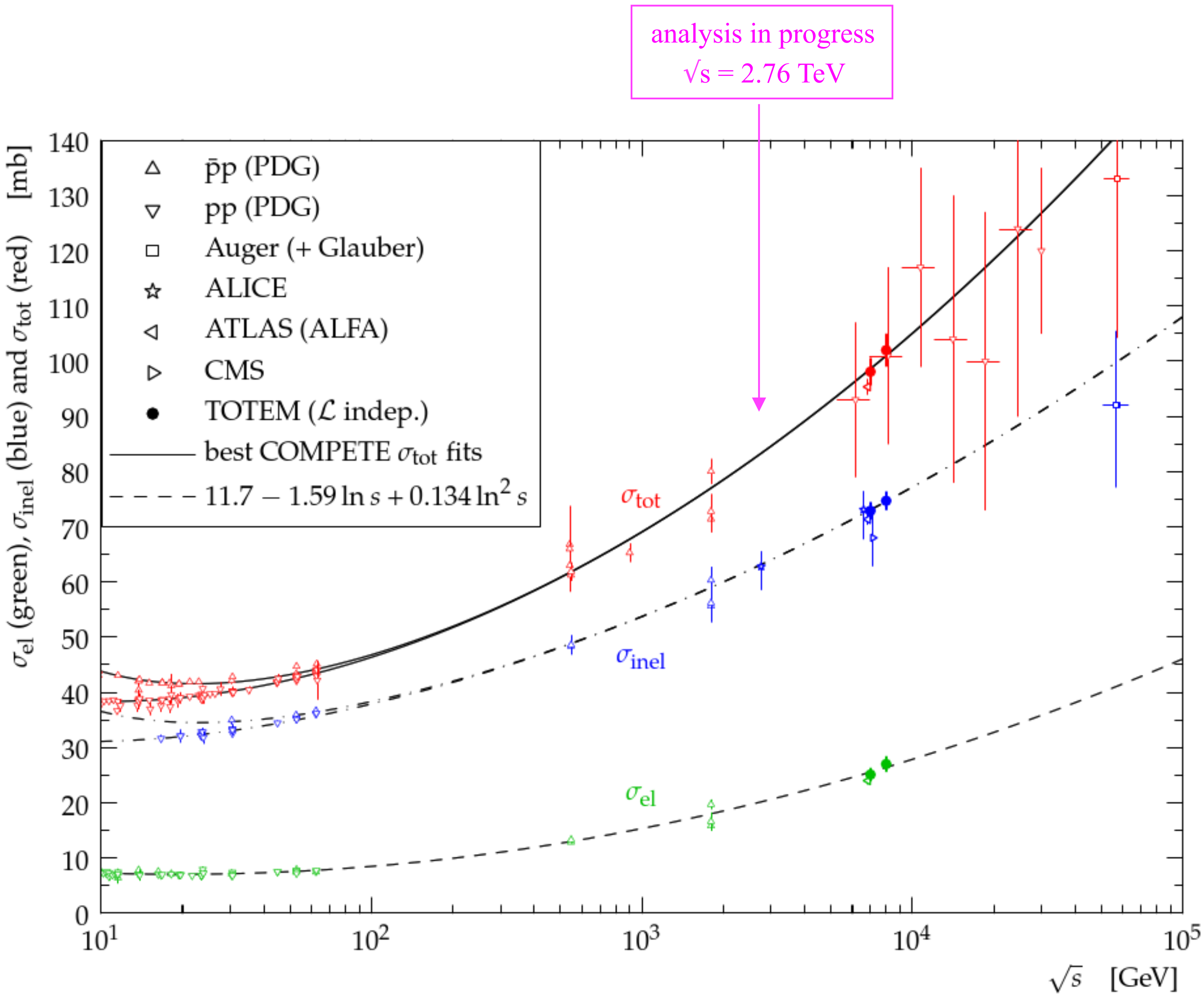
$\sigma_{\text{tot}} = (98.0 \pm 2.5)$ mb

Excellent agreement between cross-section measurements at 7 TeV using
- runs with different bunch intensities,
- different methods with different external inputs.

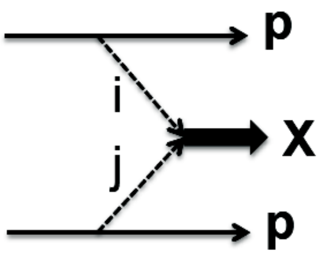
8 TeV: only luminosity independent method (no external lumi. meas. available)

$\sigma_{\text{tot}}(8\ \text{TeV}) = (101.7 \pm 2.9)$ mb

pp Cross-Section Measurements



Central Diffraction ("Double Pomeron Exchange")



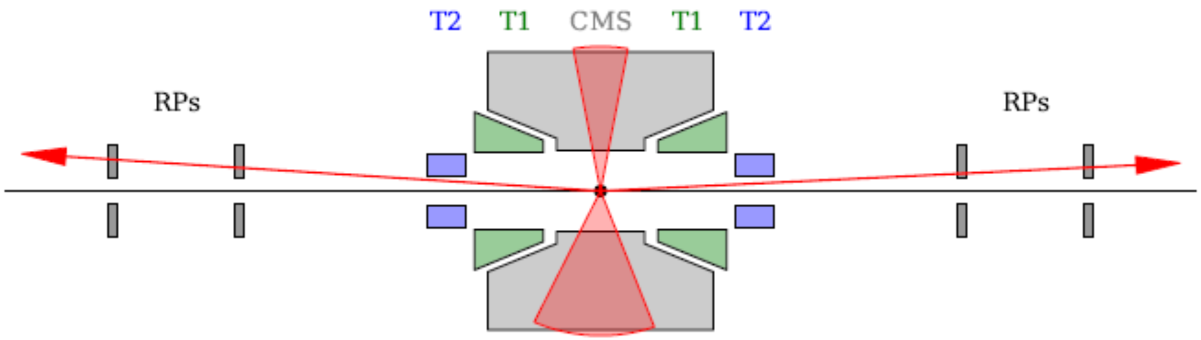
Glueballs ?   750 GeV Resonance ?

X = high E_T jets, Z, WW, ZZ, … measured in central CMS detectors

kinematic redundancy proton system – central system, e.g. $M_X^2 = \xi_1 \xi_2 s$

p_x, p_y from t, ϕ
P_z from ξ

- both protons survive with momentum losses ξ_1, ξ_2
- diffractive mass M in the centre
- 2 rapidity gaps $\Delta\eta_1$, $\Delta\eta_2$



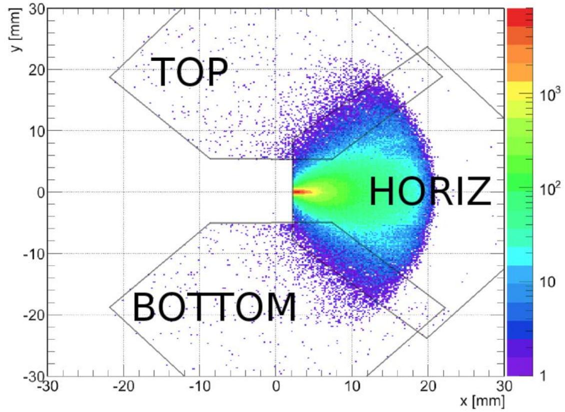
$$\Delta\eta_{1,2} = -\ln \xi_{1,2}, \quad M^2 = \xi_1 \xi_2 s$$

Joint data taking CMS + TOTEM:
kinematic redundancy between protons and central diffractive system
$M_{CMS} = M_{TOTEM}(pp)$?

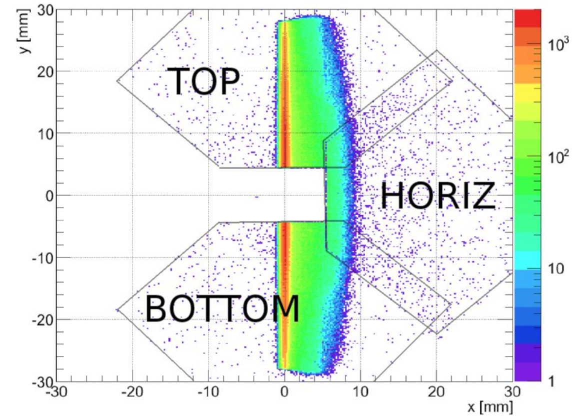
RP Upgrade Projects at IP5

Hit maps of simulated diffractive events for 2 optics configurations

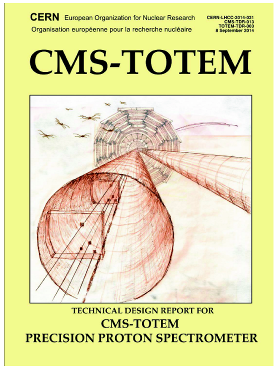
$\beta^* = 0.55$ m (low β^* = standard at LHC)



$\beta^* = 90$ m (special development for RP runs)



Operation at low β^* (< 1 m),
high luminosity (O(fb^{-1}/day)), standard runs
diffractive masses > ~300 GeV

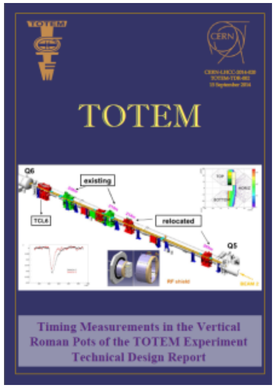


750 GeV resonance ?

CMS-TOTEM Precision Proton Spectrometer (CT-PPS):
Tracking and Timing detectors in horizontal Roman Pots

[CERN-LHCC-2014-021]

Operation at high β^* (19 m, 90 m, > 1 km),
Low - medium lumi. (< 6 pb^{-1}/day), special runs
all diffractive masses



Low-mass glueballs ?

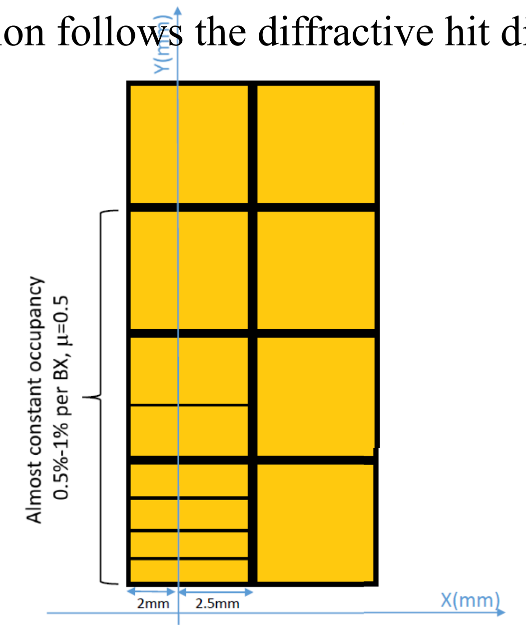
Timing Measurements in the Vertical Roman Pots of the TOTEM Experiment

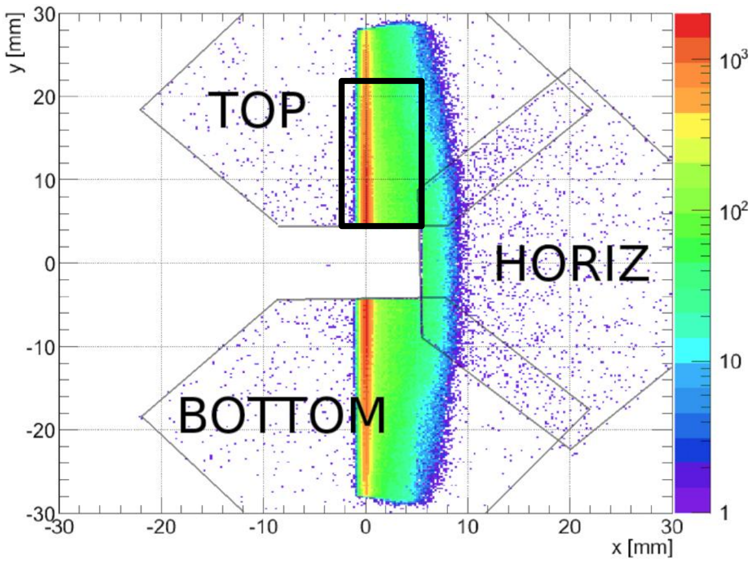
Tracking and thin diamond timing detectors in vertical Roman Pots

[CERN-LHCC-2014-020]

Diamond Detector Layout and Prototype Time Resolution

Segmentation follows the diffractive hit distribution.

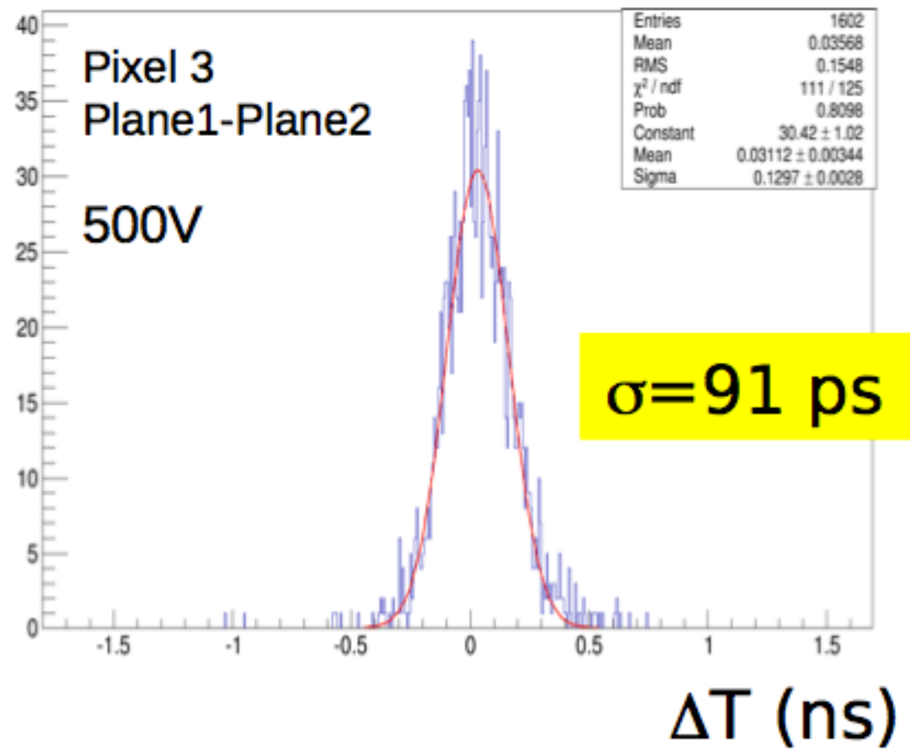




Test Hybrid 1: 1 large pixel (C = 2 pF)

Test Hybrid 2: 4 small strip pixels (C = 0.29 – 0.6 pF)

Resolution measured at LHC

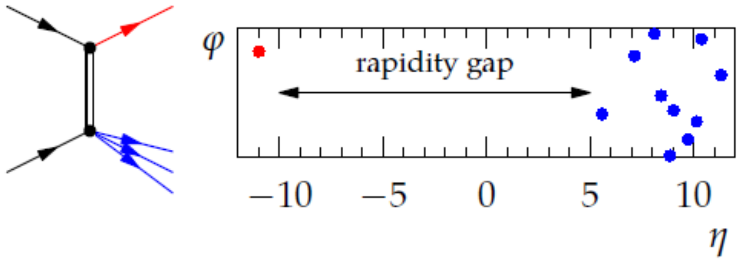


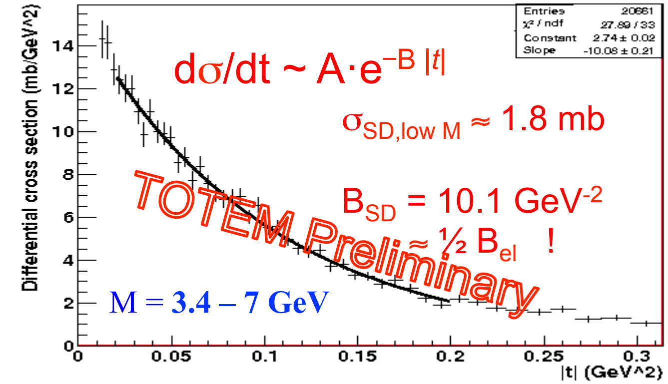
Efficiency measured > 98%

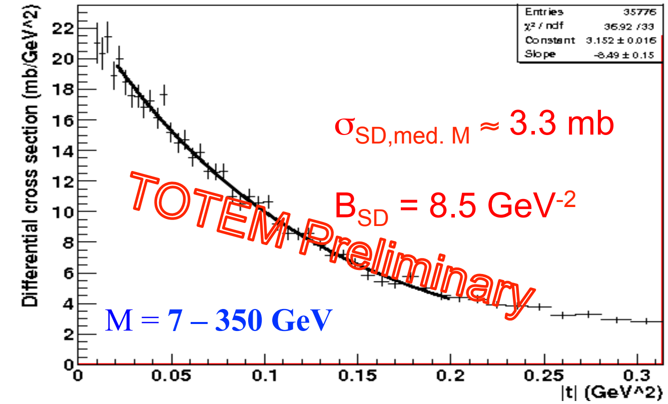
Back-Up

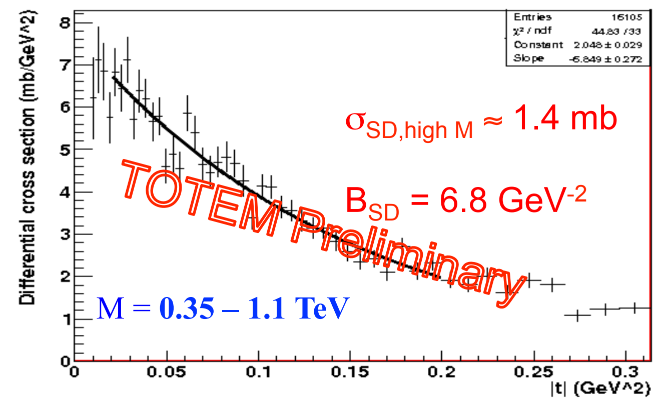
Soft Single Diffraction at LHC

SD events tagged by proton, ξ from rapidity gap



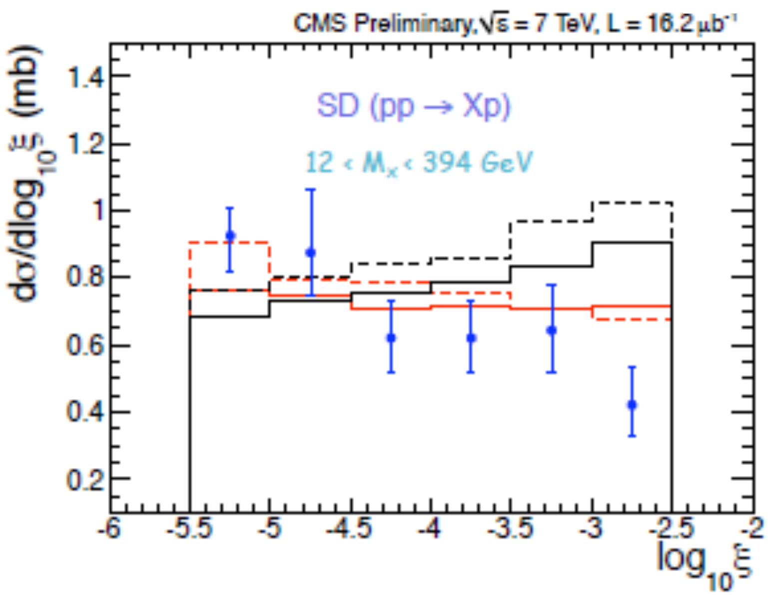






SD events tagged by rapidity gap,
ξ from diffractive system:

$$\xi = \frac{M_X^2}{s} = \frac{\sum\left(E^i + p_Z^i\right)}{\sqrt{s}}$$



→ Single diffractive cross section integrated over $-5.5 < \log \xi < -2.5$:

$\sigma_{vis}^{SD} = 4.27 \pm 0.04(stat.) + 0.65/-0.58(syst.)$ mb for $1.1 < \log(M_X/GeV) < 2.6$