Elastic scattering, total cross-section and charged particle pseudorapidity density in 7 TeV pp reactions measured by the TOTEM Experiment at the LHC

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WIGNER RCP

On behalf of the TOTEM Collaboration:

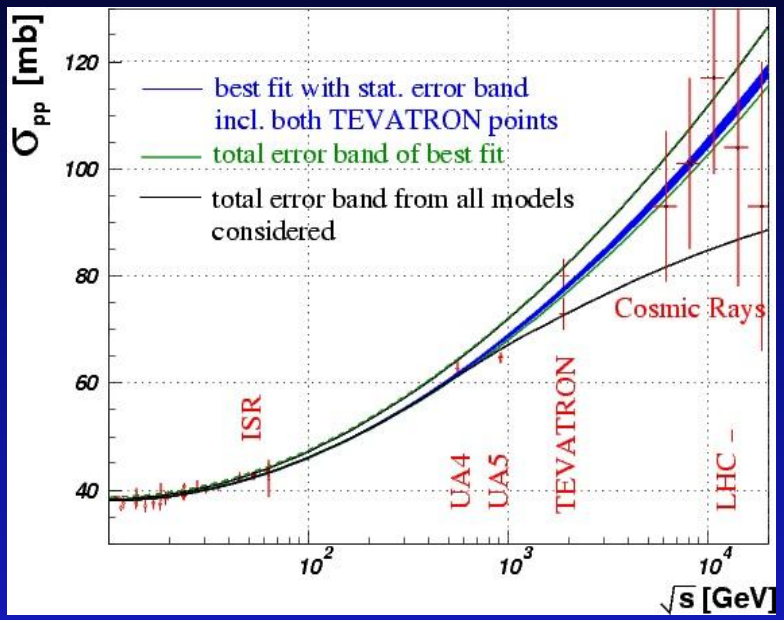
Bari, Budapest, Case Western Reserve, CERN, Genova, Helsinki, Penn State, Pisa/Siena, Prague, Tallin (~ 80 physicists)

OUTLINE

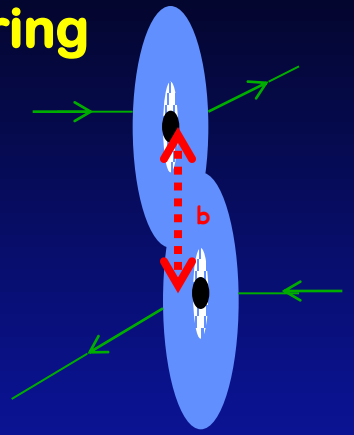
- TOTEM Physics Overview
- TOTEM Detector Setup in LHC IP5
- Measurement of the Elastic pp Cross Section
- Inelastic Cross Section
  direct T1 and T2 measurement
- Total Cross Section
- Measurement of the forward charged particle pseudorapidity density in T2
- Data taking in 2012 at $\sqrt{s}$ = 8 TeV
- TOTEM Running Strategy for 2011 and Conclusions

TOTEM Physics Overview:

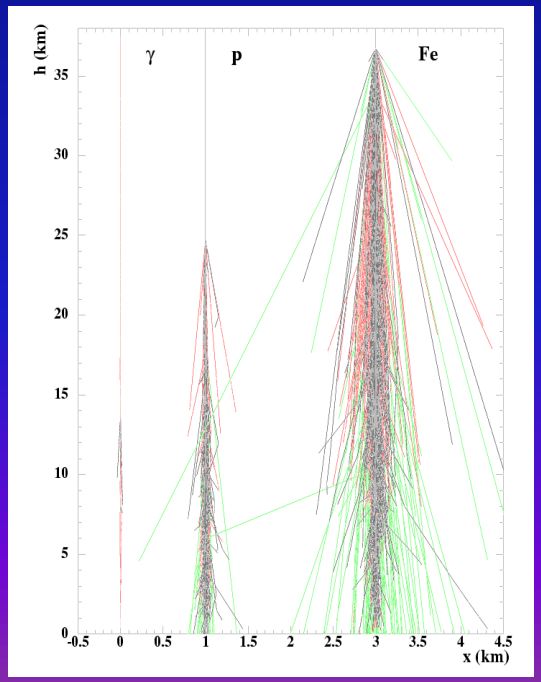
Total cross-section



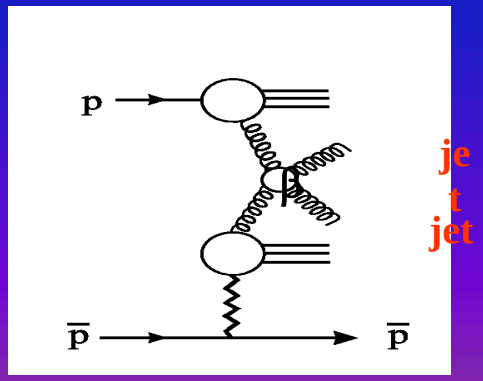
Elastic scattering



Forward physics



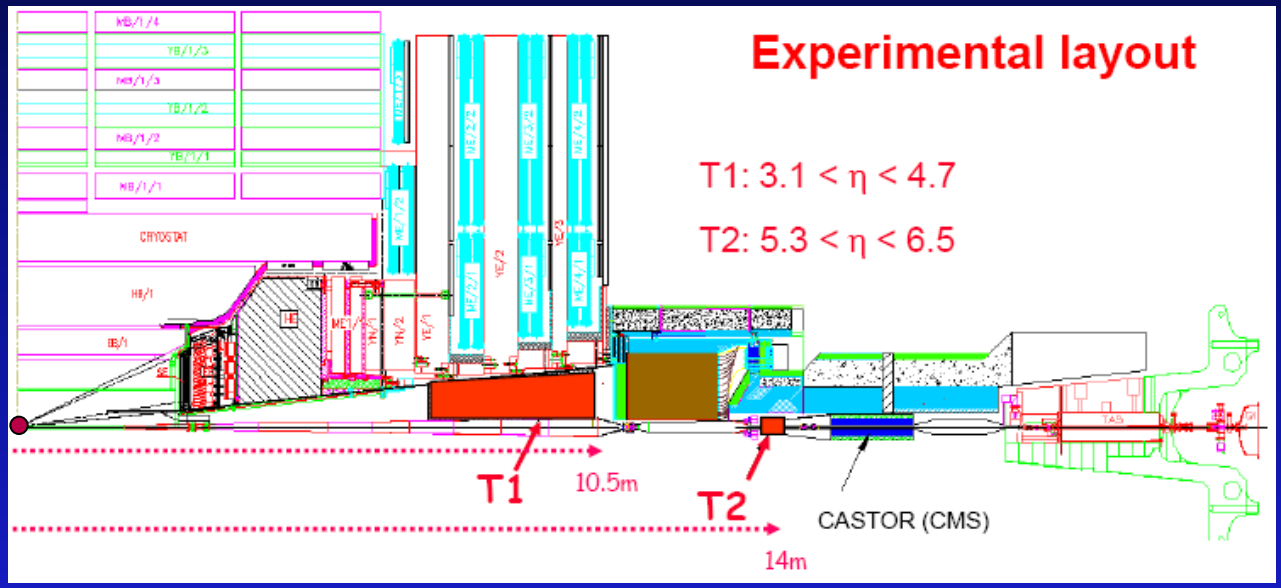
Soft and hard diffraction



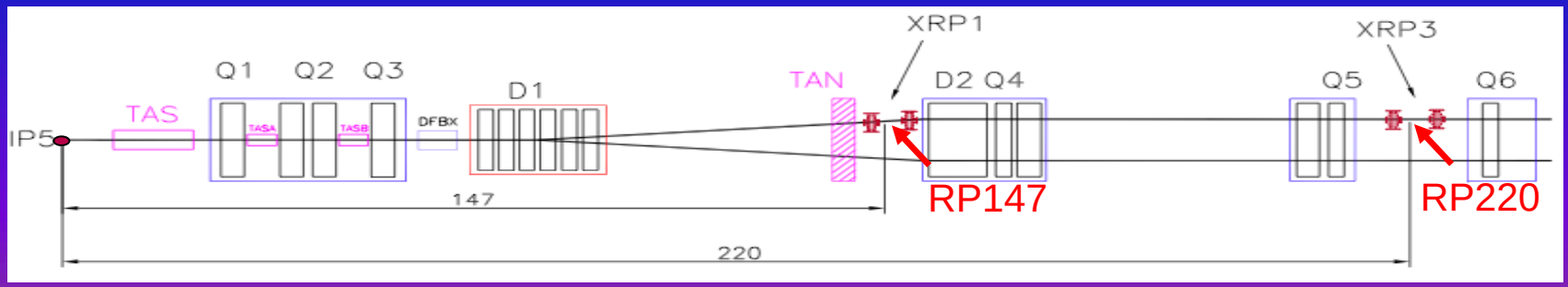
TOTEM Detector Setup in LHC IP5 (together with CMS)

Inelastic detector configurations on both sides of IP5: all capable for tracking and triggering

Purpose: Identifying charged particles in inelastic events & vertex reconstruction

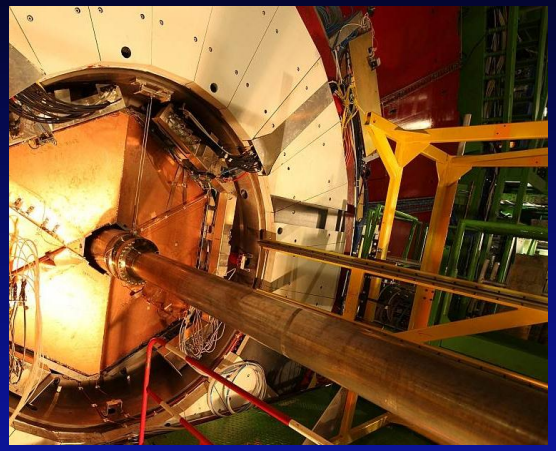


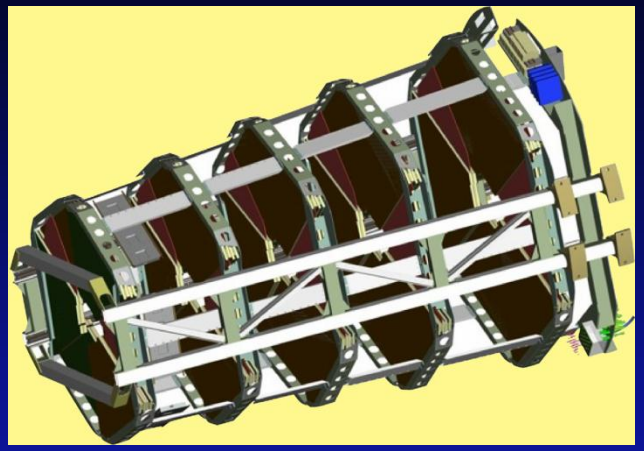
24 Roman Pots on both sides of CMS: measuring the elastic & inelastic protons closed to the beam



TOTEM inelastic telescopes

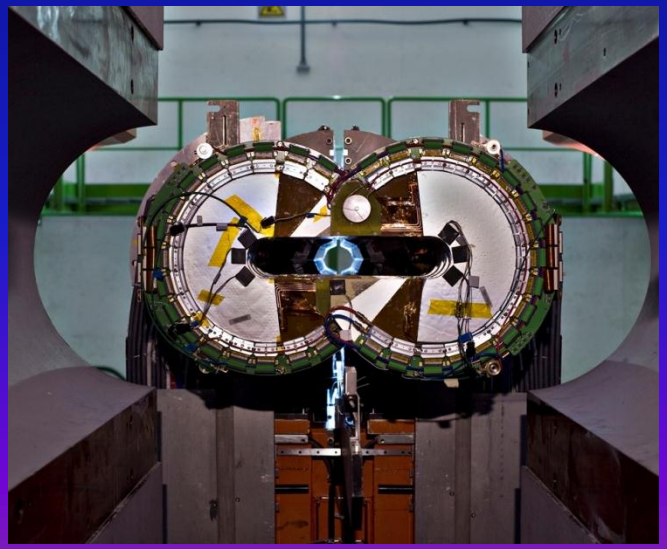
T1 telescope CSC (Chatode Strip Chambers)





$3.1 < |\eta| < 4.7$

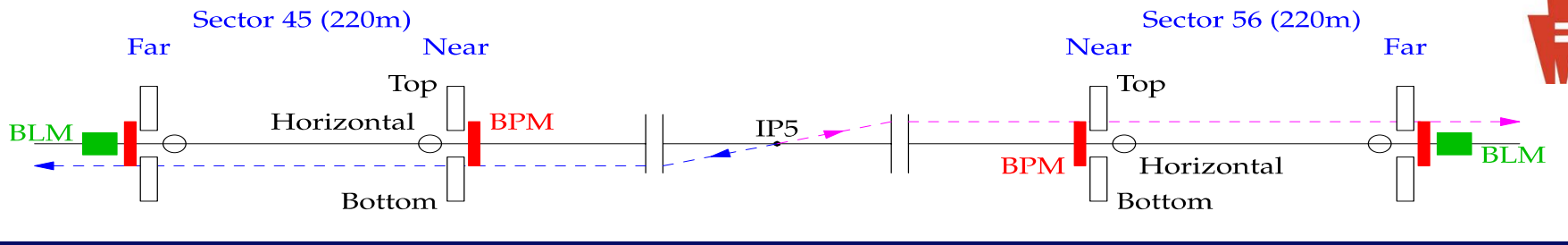
T2 Telescope GEM (Gas Electron Multiplier)

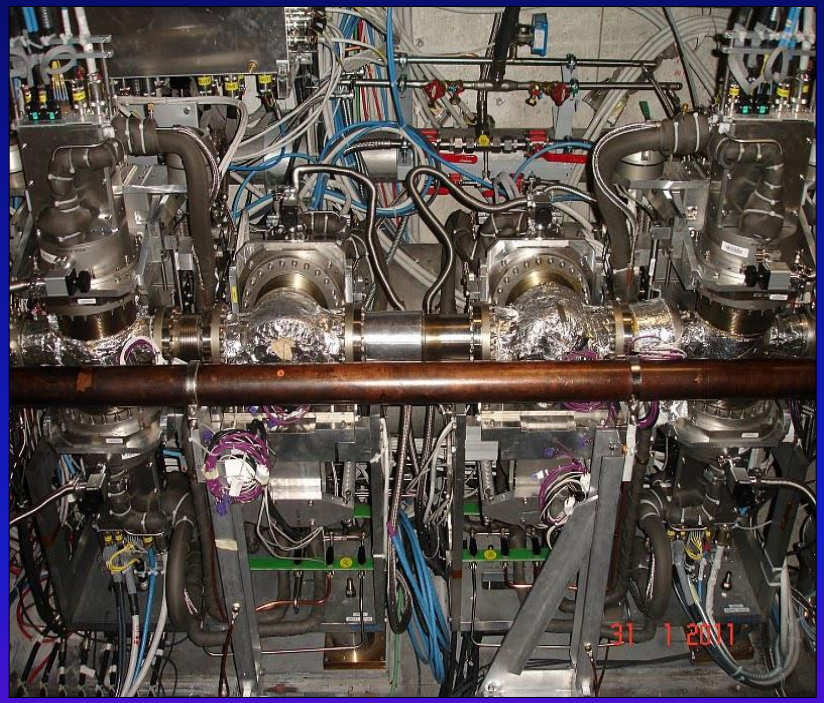


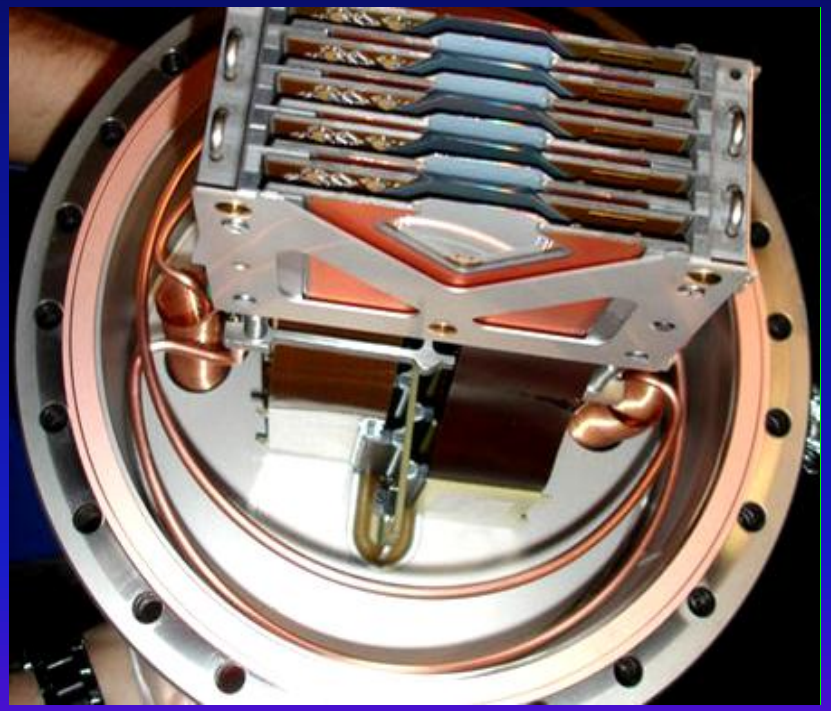
$5.3 < |\eta| < 6.5$

- charged particle detection
- vertex reconstruction
- trigger

Roman Pot detectors



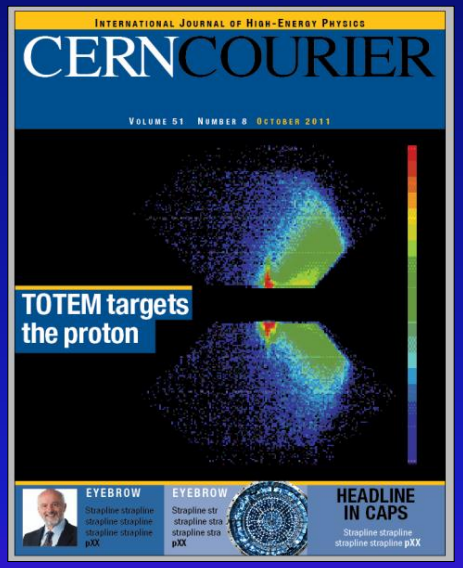




- detect protons scattered at Interaction Point 5
- near-beam movable devices
- equipped with edgeless silicon mycrostrip detectors
- resolution of ~16μm
- trigger capability with FPGA processing

Measurement of the Elastic pp Cross Section

Roman Pots

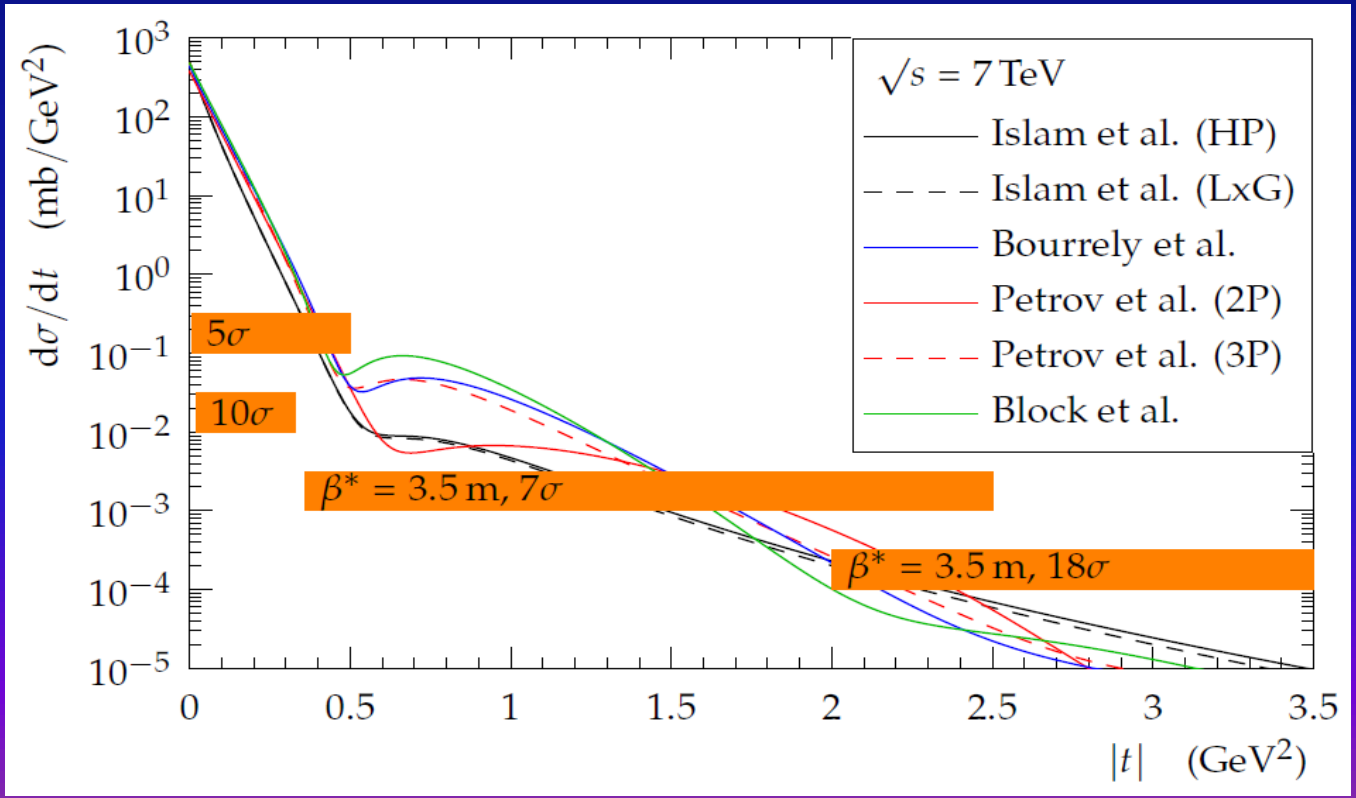


$7\times10^{-3}\ \text{GeV}^2 < |t| < 3.5\ \text{GeV}^2$

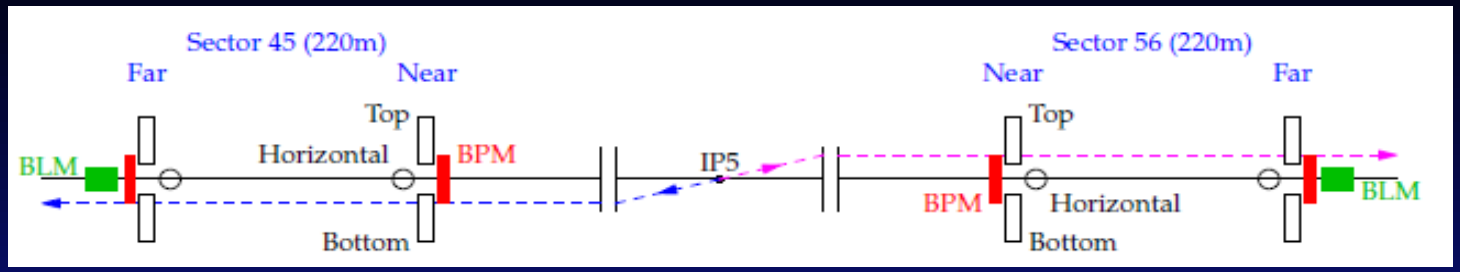
Data samples

Wide range of |t| measured with various LHC configurations

Set	β^*(m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events
1	90	4.8-6.5σ	83	$7\cdot 10^{-3}$ - 0.5	1M
2	90	10σ	1.7	0.02 - 0.4	14k
3	3.5	7σ		0.36 - 3	66k
4	3.5	18σ		2 - 3.5	10k



Elastic pp scattering in Roman Pots



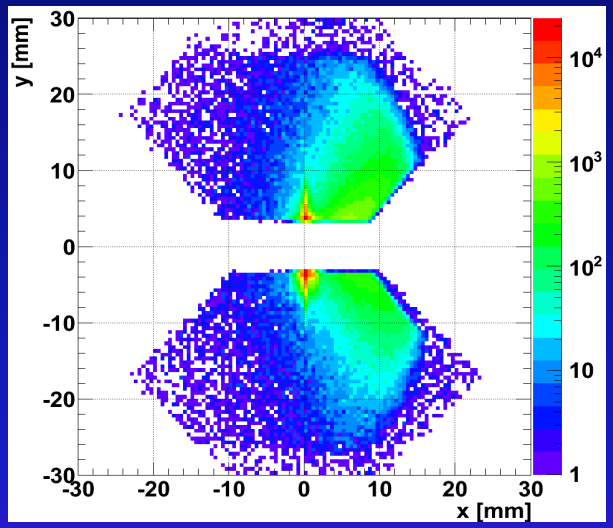
β^*=3.5m (7σ)

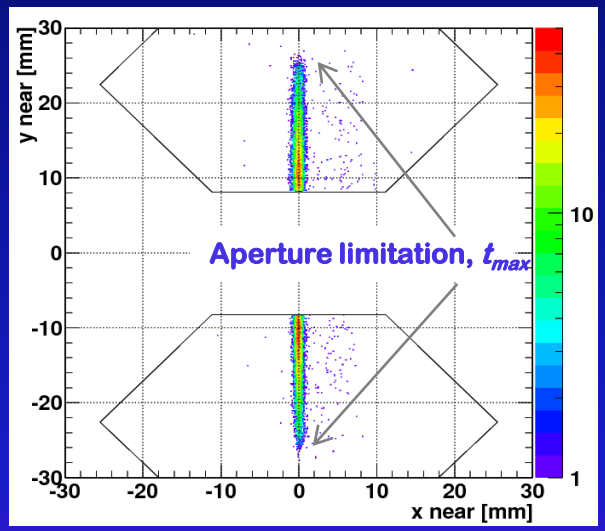
β^*=90m (10σ)

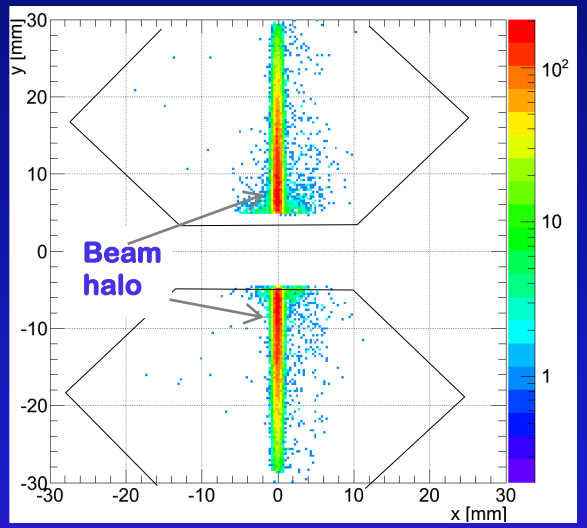
β^*=90m (5σ)

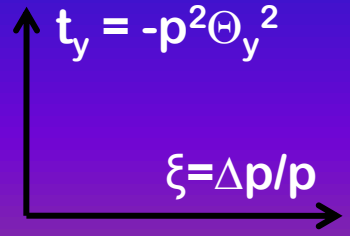
Sector 56

Sector 45



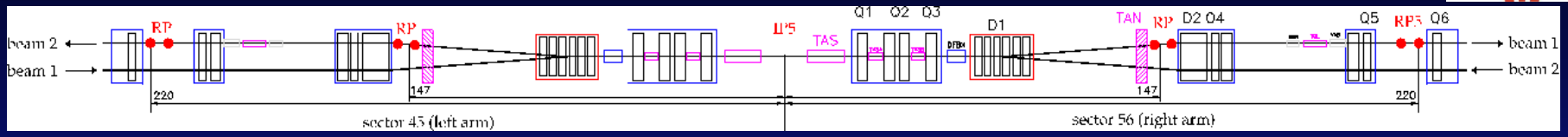






Diagonals analysed independently

LHC optics in brief



Proton position at a given RP (x, y) is a function of position (x^*, y^*) and angle (Θ_x^*, Θ_y^*) at IP5:

measured in Roman Pots

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v_x' & L_x' & 0 & 0 & D_x' \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v_y' & L_y' & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{IP5}$$

reconstructed

Proton transport matrix

Elastic proton reconstruction:

- Scattering angle reconstructed in both projections
- High Θ^*-reconstruction resolution available
  - $\sigma(\Theta_y^*)$=**1.7 µrad** for β^*=90 m and low t-range
  - $\sigma(\Theta_y^*)$=**12.5 µrad** for β^*=3.5 m and high t-range

$$\begin{cases} \Theta_x^* = \left(\Theta_{x,RP} - \dfrac{dv_x}{ds} x^* \right) \Big/ \dfrac{dL_x}{ds}, \\ \Theta_y^* = \left(y_{RP} - v_y y^* \right) / L_y \end{cases} \qquad \frac{\Delta p}{p} = 0$$

Excellent optics calibration and alignment required

Calibrations per beam fill

Optics determination Special TOTEM runs, optics can change from fill to fill !!

Novel method of TOTEM

- Analysis of transport matrix sensitivity to LHC imperfections (MADX optics model)
- Machine tolerances and measured errors combined
  - magnet currents
  - magnet conversion curves, field imperfections
  - magnet displacements
- Measured optics constraints from RP proton tracks distributions
- Optics matched with MADX
- Procedure verified with MC studies

$$\begin{cases} \dfrac{\delta dL_x^{'}}{dL_x^{'}} < 1\% \\ \dfrac{\delta L_y}{L_y} < 1\% \end{cases} \Rightarrow \frac{\delta t}{t} \approx 0.8\% - 2.6\% \text{ for } \beta^* = 90\text{m}$$

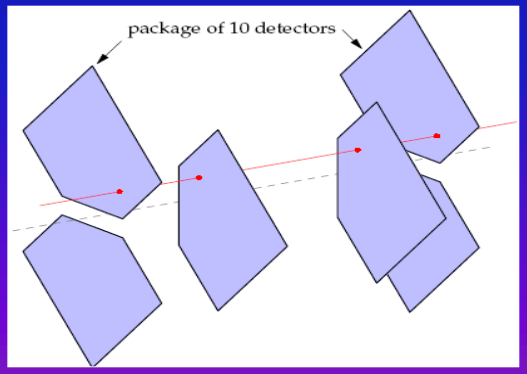
Optics related systematic errors

H. Niewiadomski, ***Roman Pots for beam diagnostic***, OMCM, CERN, 20-23.06.2011
H. Niewiadomski, F. Nemes, ***LHC Optics Determination with Proton Tracks***, IPAC'12, Louisiana, USA, 20-25.05.2012

Alignment of Roman Pots ->Movable devices by definition !!

- internal components : metrology, tracks
- with respect to LHC beams : beam touching exercise (<200 µm)
- relative between RPs with overlapping tracks (a few µm)
- physics based : exploits coinearity of elastically scattered protons, constraints especially the 2 sides of IP5 (a few µm)

Final overall precision of 10 µm achieved!



Track based alignment

Elastic pp scattering : analysis highlights I

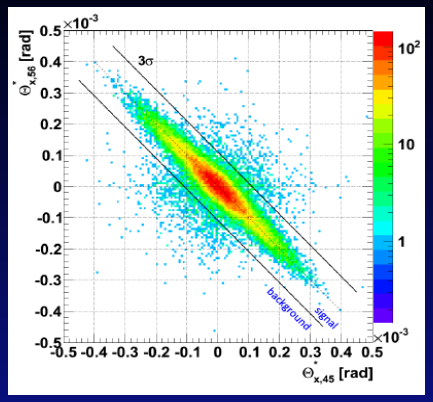
Proton selection cuts

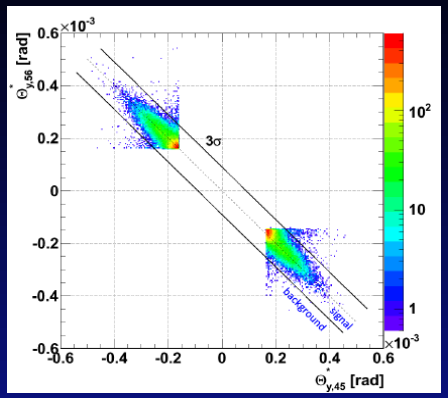
+ collinearity cuts (left-right)

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

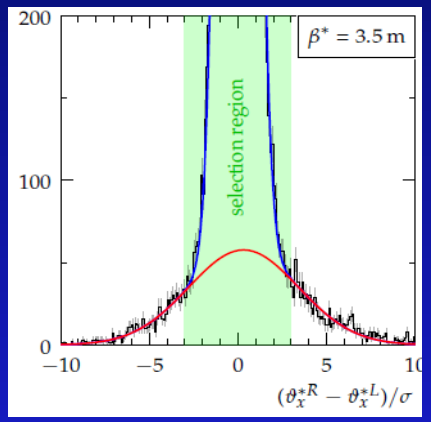
$\Theta^*_{y,}45 \leftrightarrow \Theta^*_{y,}56$

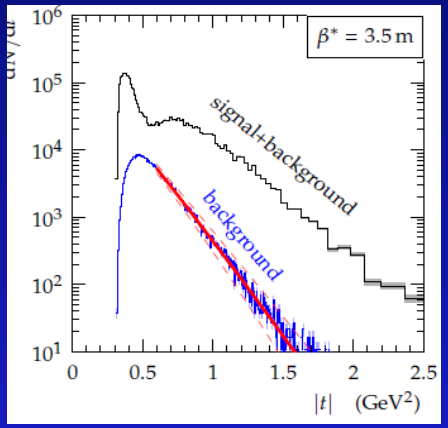
+ low ξ cuts
+ vertex cuts
+ optics related cuts



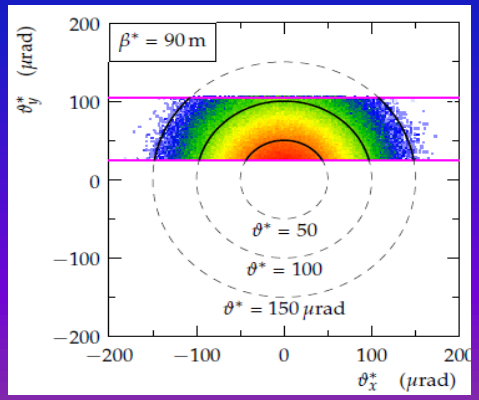


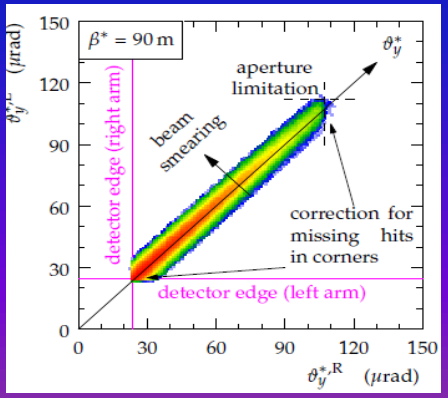
Background subtraction





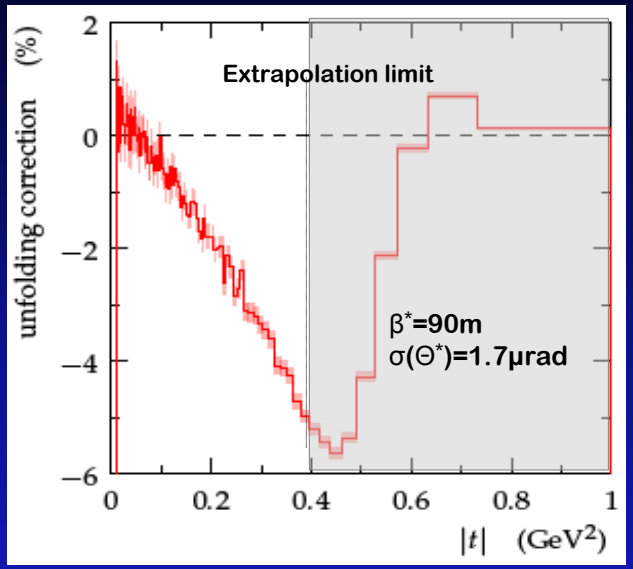
Acceptance correction

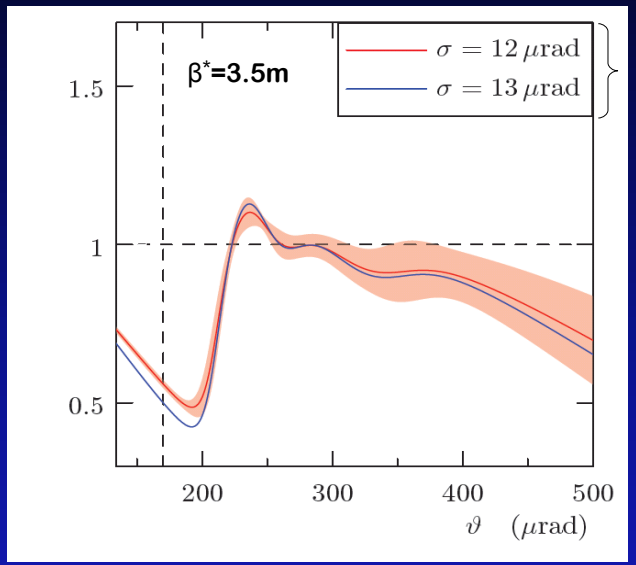




Elastic pp scattering : analysis highlights II

Resolution unfolding





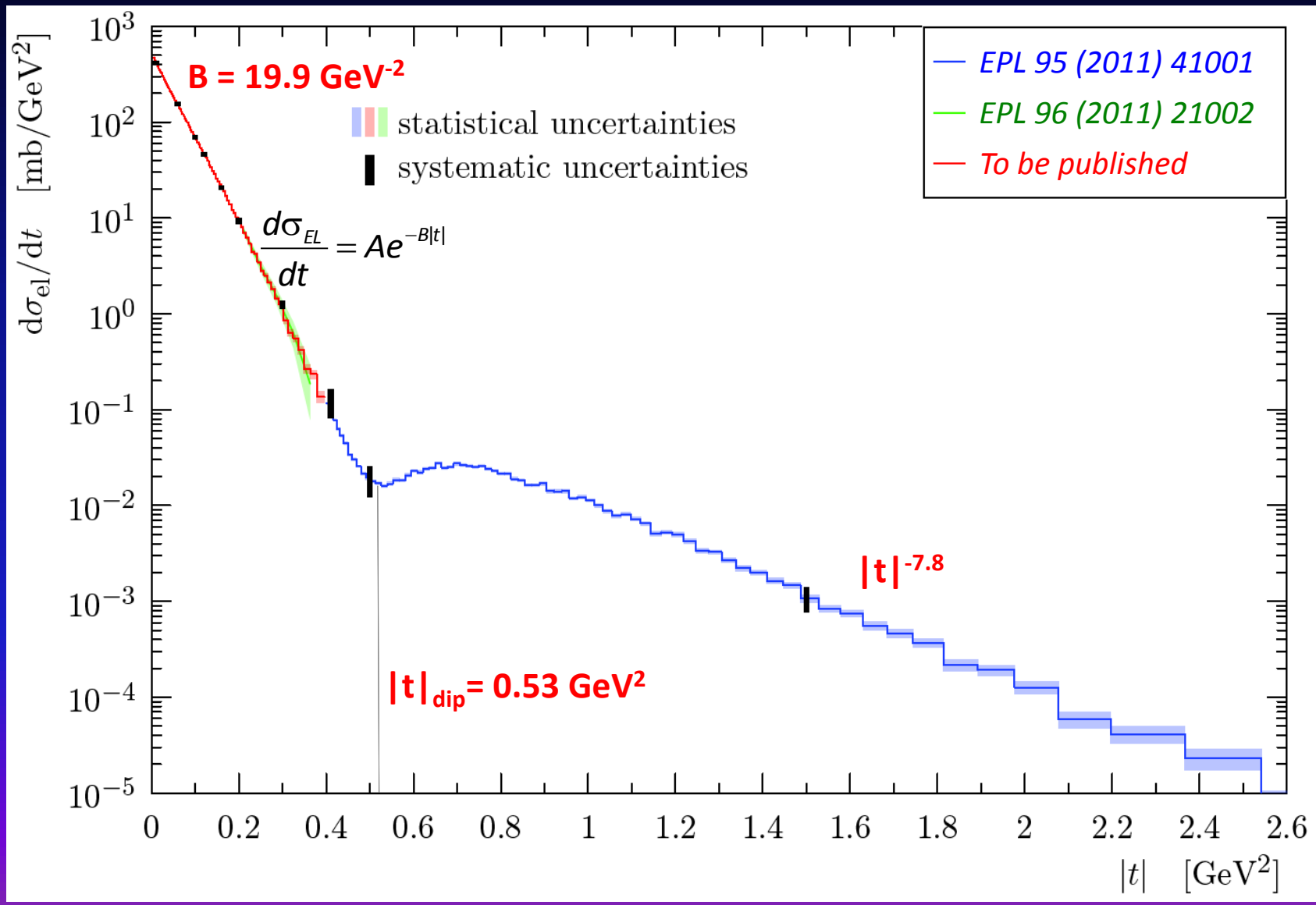
divergence uncertainty

Normalization **Reconstruction efficiency**

- intrinsic detector inefficiency: 1-2% / pot
- elastic proton loss due to interaction: 1.5%/pot
- event lost due to overlap with beam halo (depends on dataset and diagonal) 4% - 8% (β*=90m); 30% (β*=3.5m)

Luminosity from CMS **systematic error of 4%**

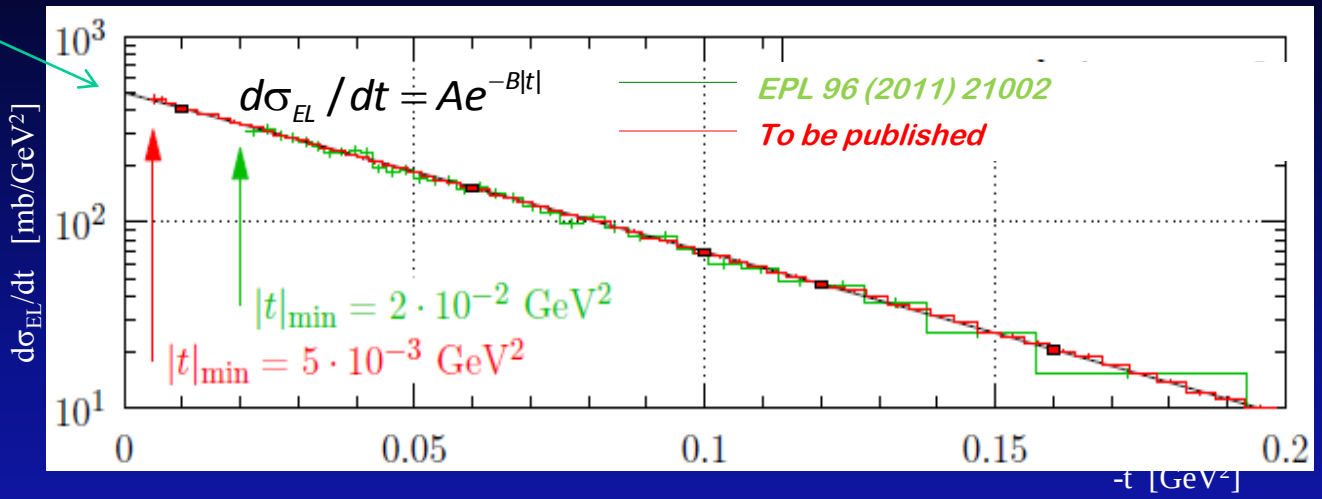
Elastic scattering cross-section



Elastic scattering cross-section

Extrapolation to t=0

$$A = \left.\frac{d\sigma_{EL}}{dt}\right|_{t\to 0}$$



$$\left.\frac{d\sigma_{EL}}{dt}\right|_{t\to 0} =$$

A = 506 $\pm 22.7^{syst} \pm 1.0^{stat}$ mb/GeV^2

A = 503$\pm 26.7^{syst} \pm 1.5^{stat}$ mb/GeV^2

B = 19.9$\pm 0.26^{syst} \pm 0.04^{stat}$ GeV^{-2}

Elastic cross-section

$$\sigma_{EL} = \sigma_{EL,extrapol.} + \sigma_{EL,meas} =$$

25.4 $\pm$ 1.0^{lumi} $\pm$ 0.3^{syst} $\pm$ 0.03^{stat} mb (*90% directly measured*)

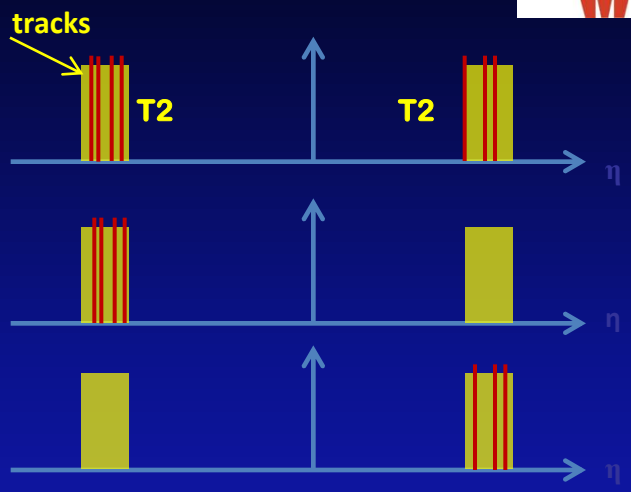
24.8 $\pm$ 1.0^{lumi} $\pm$ 0.2^{syst} $\pm$ 0.2^{stat} mb (*50% directly measured*)

Inelastic Cross Section direct T1 and T2 measurement

Inelastic events in T2: classification

- **tracks in both hemispheres**
  non-diffractive minimum bias
  double diffraction

- **tracks in a single hemisphere**
  mainly single diffraction
  $M_X > 3.4\ GeV/c^2$



Corrections to the T2 visible events

- Trigger Efficiency: **2.3 %**
  (measured from zero bias data with respect to track multiplicity)
- Track reconstruction efficiency: **1 %**
  (based on MC tuned with data)
- Beam-gas background: **0.54 %**
  (measured with non colliding bunch data)
- Pile-up (μ =0.03): **1.5 %**
  (contribution measured from zero bias data)

$$\sigma_{inelastic,\ T2\ visible} = 69.7 \pm 0.1^{\ stat} \pm 0.7^{\ syst} \pm 2.8^{\ lumi}\ mb$$

Total Cross Section: 4 approaches

1. **CMS Luminosity (small bunches) + Elastic Scattering+ Optical Theorem**

   depends on CMS luminosity for low-L bunches & elastic efficiencies & ρ

   σ_{TOT} = 98.3 mb ± 2.0 mb EPL 96 (2011) 21002

2. **CMS Luminosity (large bunches) + Elastic Scattering + Optical Theorem**

   compare the CMS luminosity measurement for high-L vs. low-L bunches

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

   ρ=0.14±0.09 (Compete)

   σ_{TOT} = 98.6 mb ± 2.3 mb

3. **CMS Luminosity (large bunches) + Elastic Scattering + Inelastic Scattering**

   minimizes dependence on elastic efficiencies and no dependence on ρ

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

   σ_{TOT} = 99.1 mb ± 4.4 mb

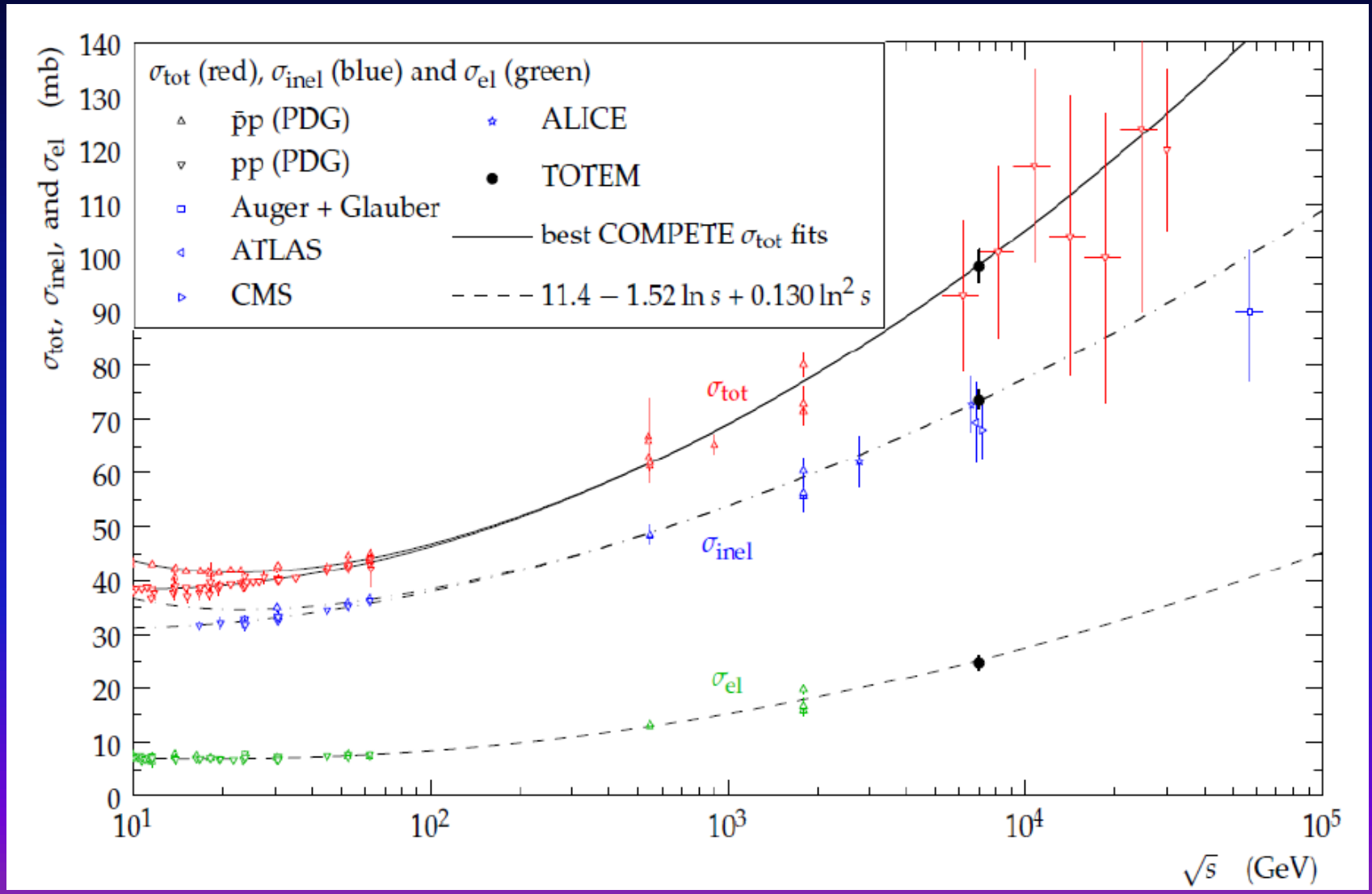
4. **(L-independent) + Elastic Scattering + Inelastic Scattering+ Optical Theorem**

   eliminates dependence on luminosity

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

   σ_{TOT} = 98.1 mb ± 2.4 mb

Total Cross Sections: Summary



Measurement of the forward charged particle pseudorapidity density in T2

dNch/dη in $5.3 < \eta < 6.5$ range at $\sqrt{s} = 7$ GeV

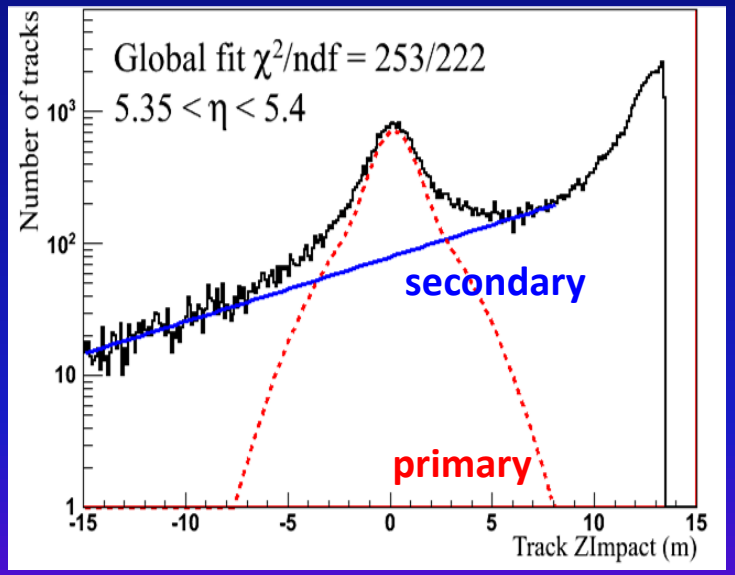
Data sample: events at low luminosity and low pile-up, triggered with T2

Selection: at least one track reconstructed

Primary particle definition: charged particle with $t > 0.3 \times 10^{-10}$ s & $p_t > 40$ MeV/c

Primary particle selection:

- primary/secondary discrimination with primary vertex reconstruction

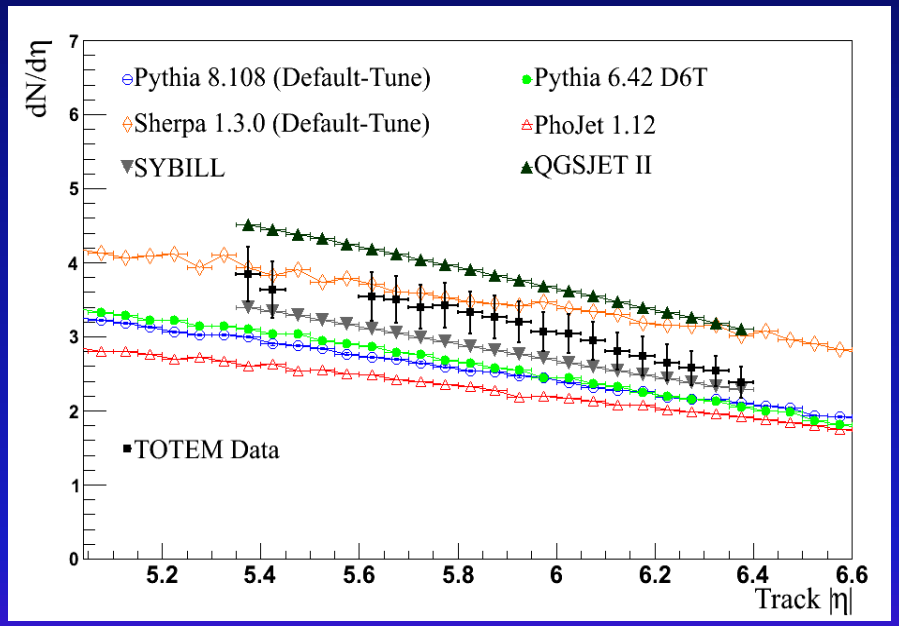


Primary track reconstruction efficiency

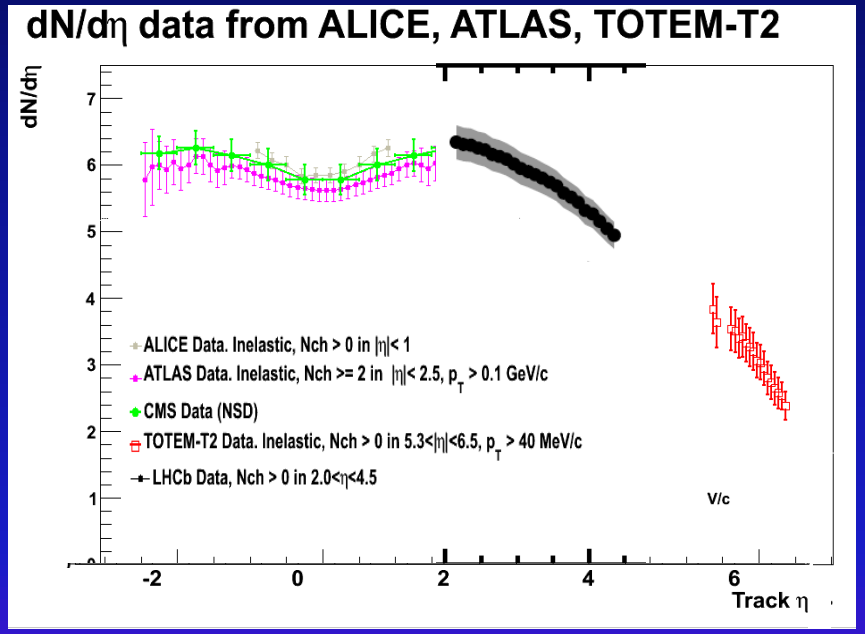
- evaluated as a function of the track η and the multiplicity
- efficiency of 80%
- fraction of primary tracks within the cuts of 75% – 90% (η dependent)

dNch/dh in T2 : results

TOTEM measurements compared to MC predictions



TOTEM measurements combined with the other LHC experiments



Published: EPL 98 (2012) 31002

Data taking foreseen (done) in 2012 at √s = 8 TeV

β*=90m, 2 bunches (done)

elastic scattering and cross-sections

β*=90m, 156 bunches (done together with CMS)

test for diffractive 2 jet events
hard diffraction, 2 jets (p_t > 20 GeV) plus protons
proton coverage : full range in ξ , -t > 0.02 GeV2
integrated luminosity: 6nb^{-1}/h, 10 hours of data taking
several million events

β*=0.6m, ~1400 bunches, full luminosity (also some runs with CMS)

tests for diffractive 2 jet events at high lumnosities
proton coverage : ξ > 2-3%, full range of t
important test for the future
hard diffraction, 2 jets (p_t > 50 GeV) plus protons

β*~1000m

t > 5 10^{-4} GeV2
measurement of ρ

p A runs planned at the beginning of 2013

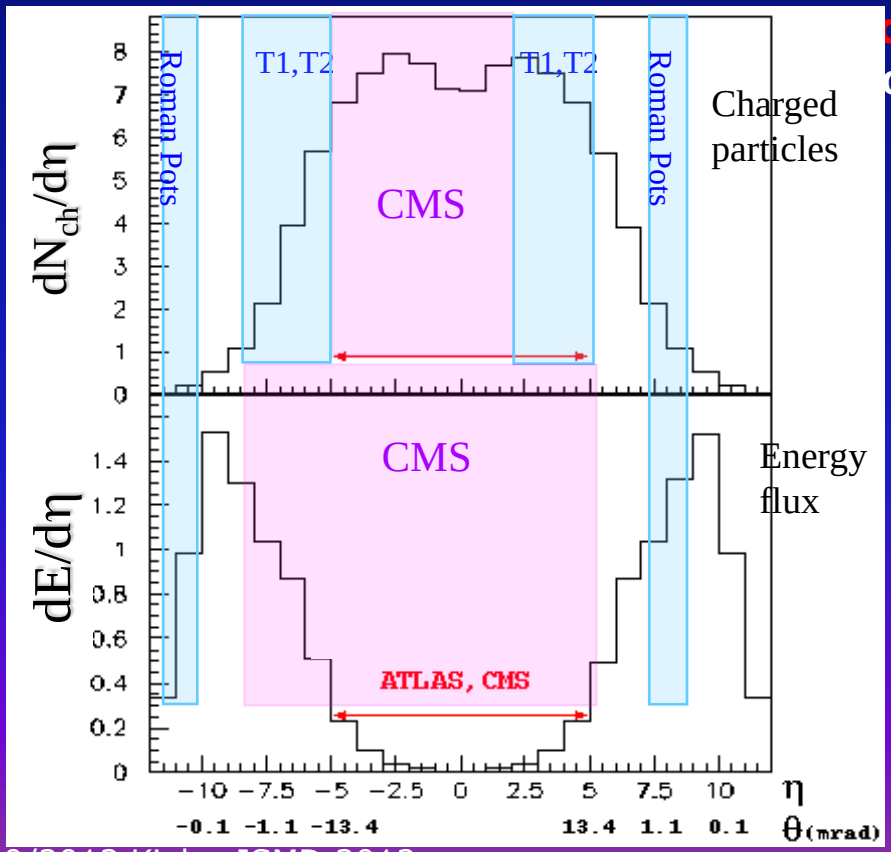
Questions ?

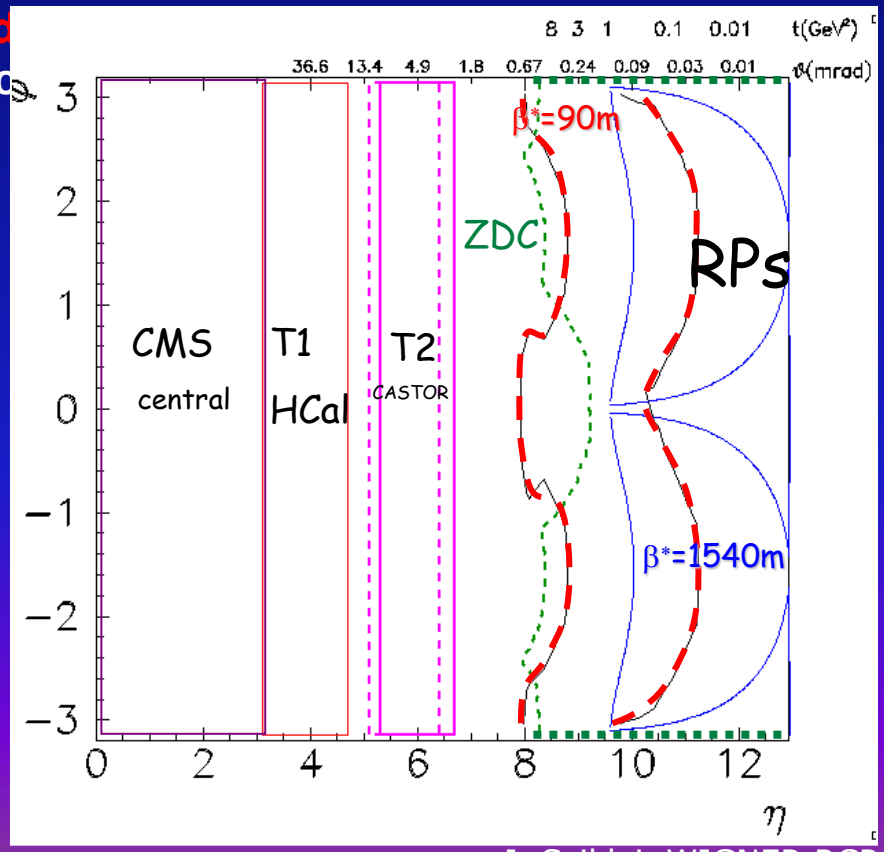
Thank you!

Backup Slides

TOTEM capabilities

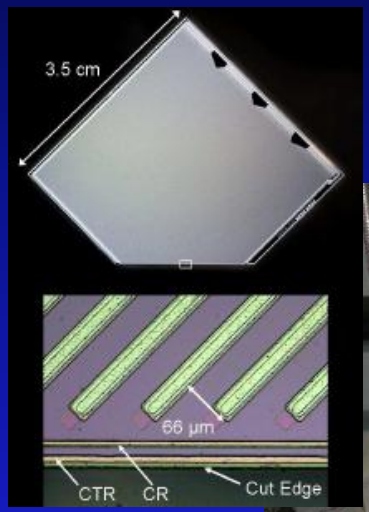
- Unique possibility of detecting charged particles with high pseudorapidity
- Ideal tool for studying forward phenomena (elastic & diffractive scattering)
- In case of inelastic events the energy flow and the multiplicity increases in forward angles

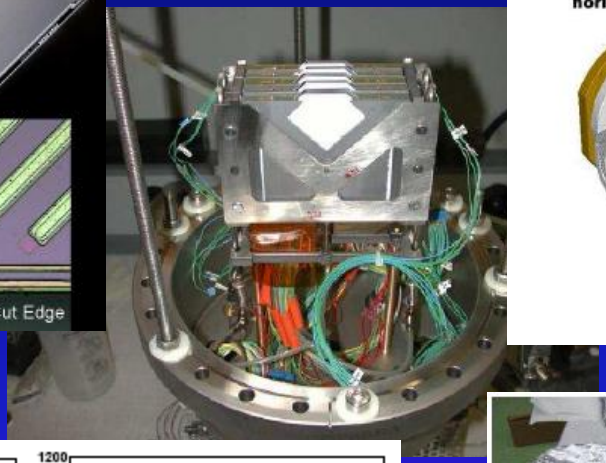


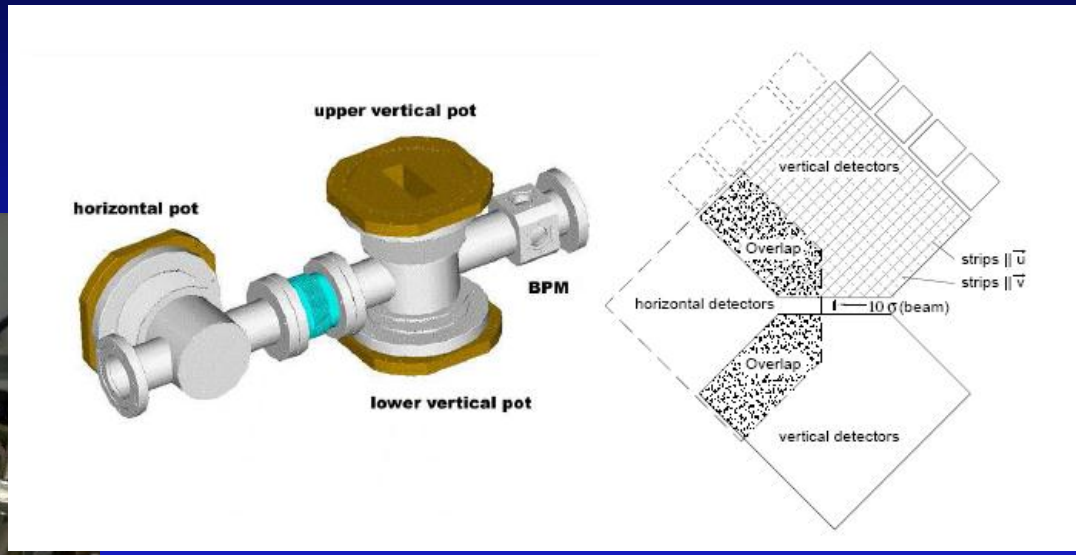


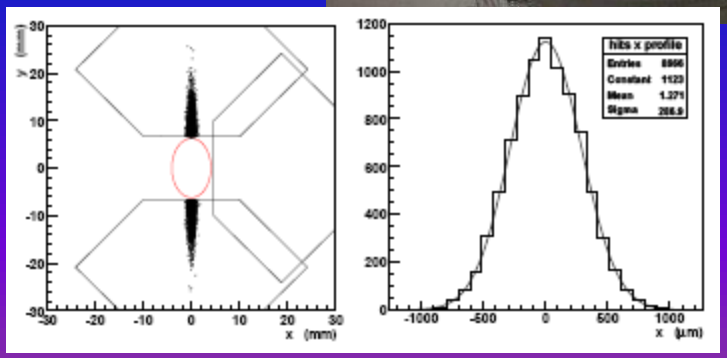
The Roman Pot System

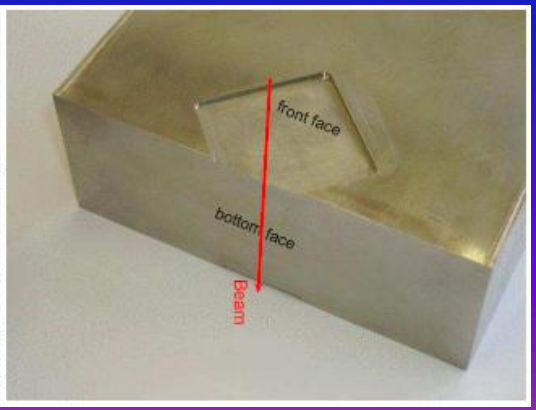
- Special movable detector assembly in a separate vacuum space
- Roman Pot pairs at a distance of 4 meters at 147 és 220 m from IP





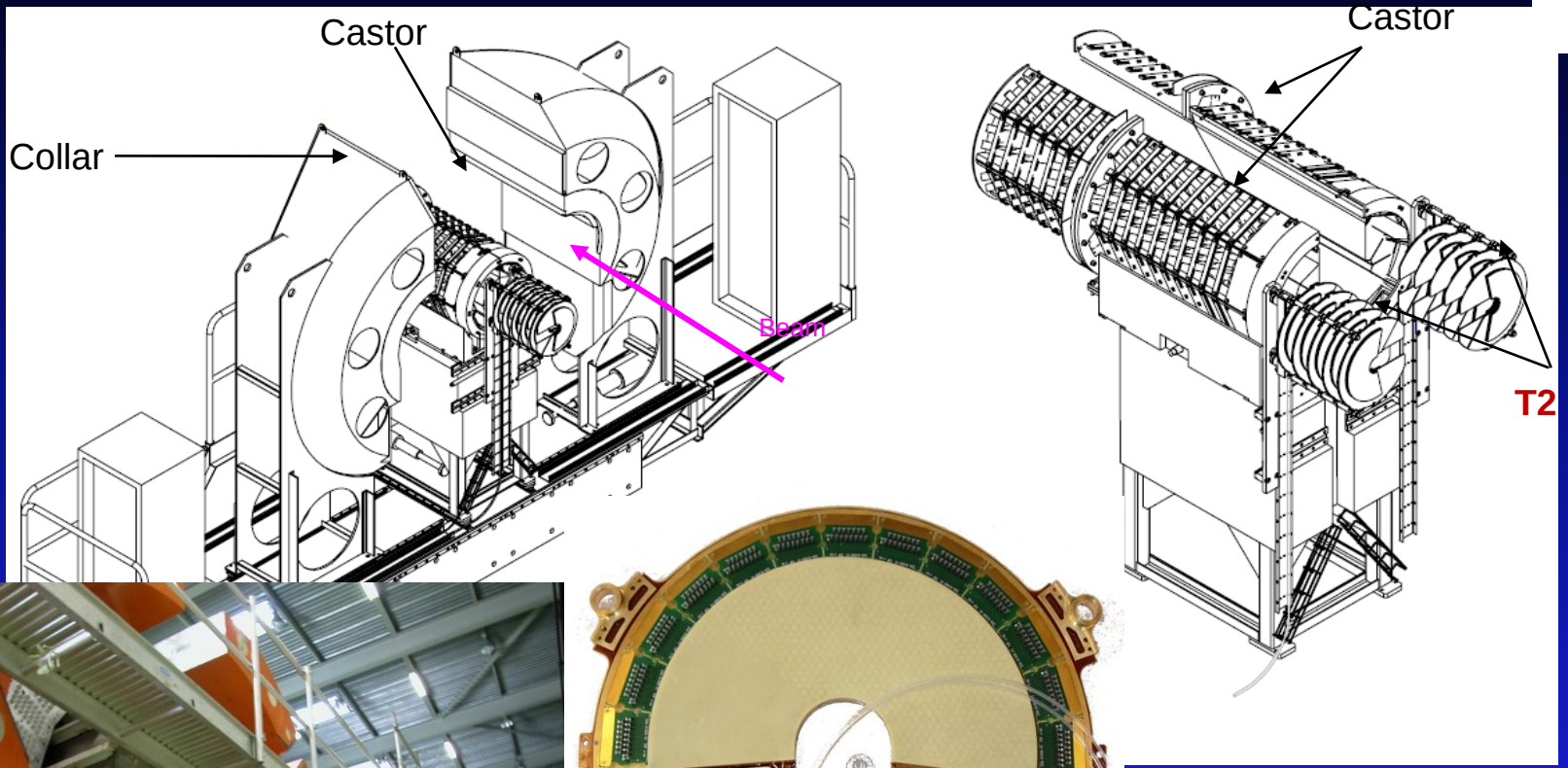






T2 Telescope GEM (Gas Elecron Multiplier)

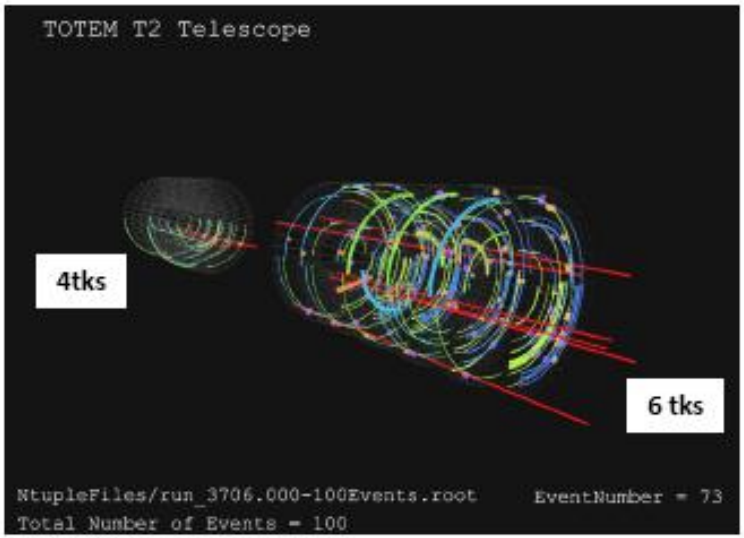
Design & installation together with CMS

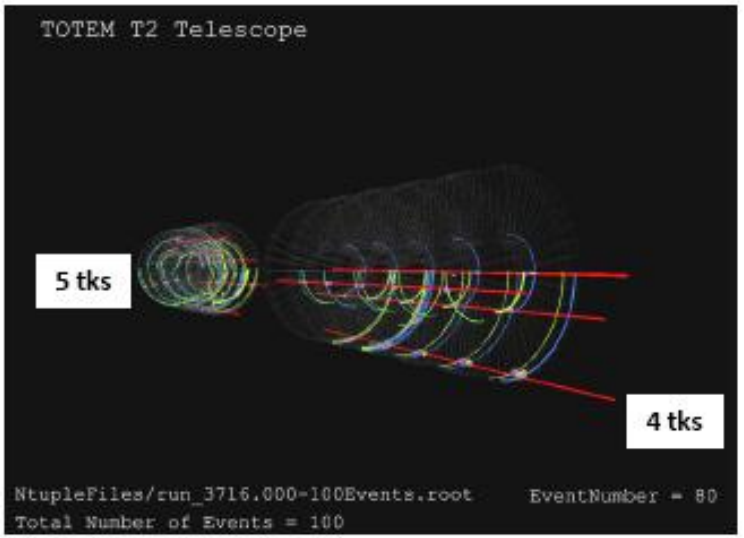


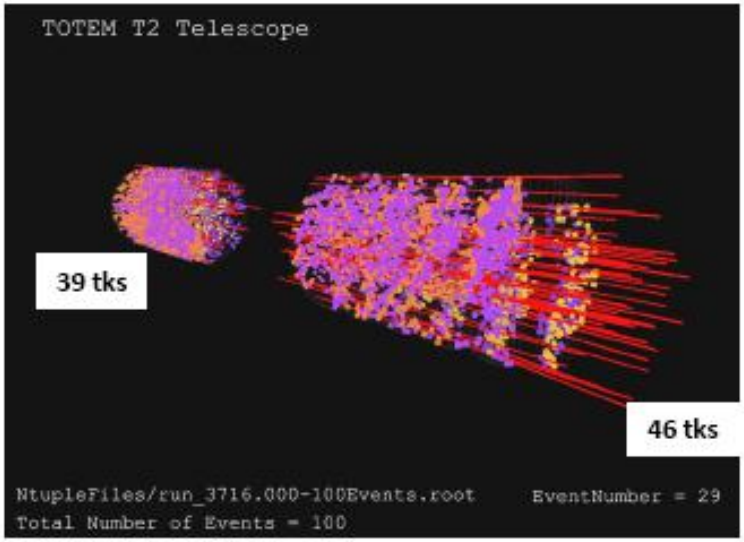
Final GEM chamber

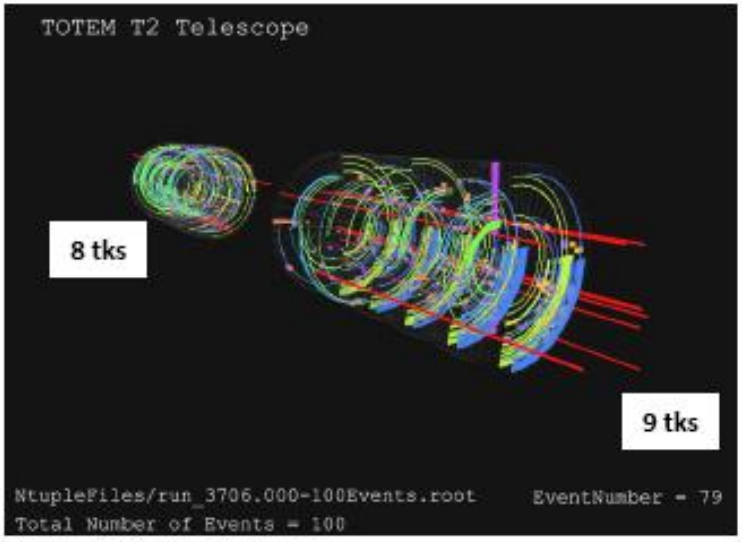
10 tripple GEM layers on both sides of the IP to tolerate high particle fluxes in $5.3 < |\eta| < 6.6$ pseudorapidity range

T2 events reconstruction



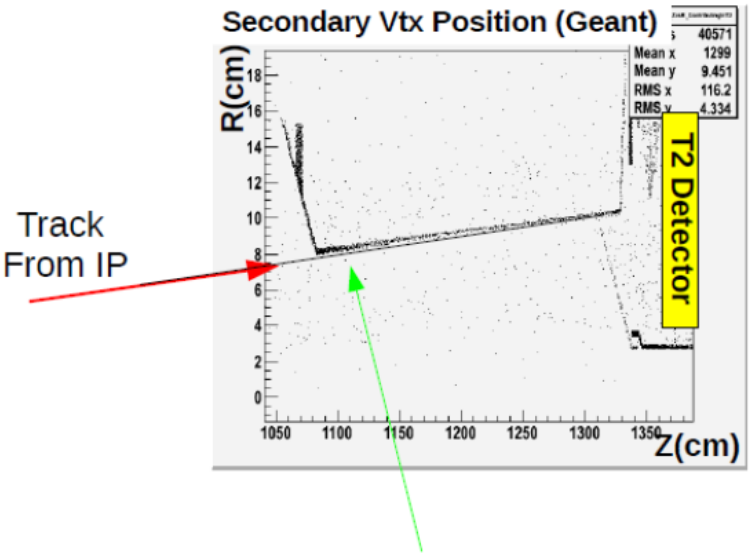


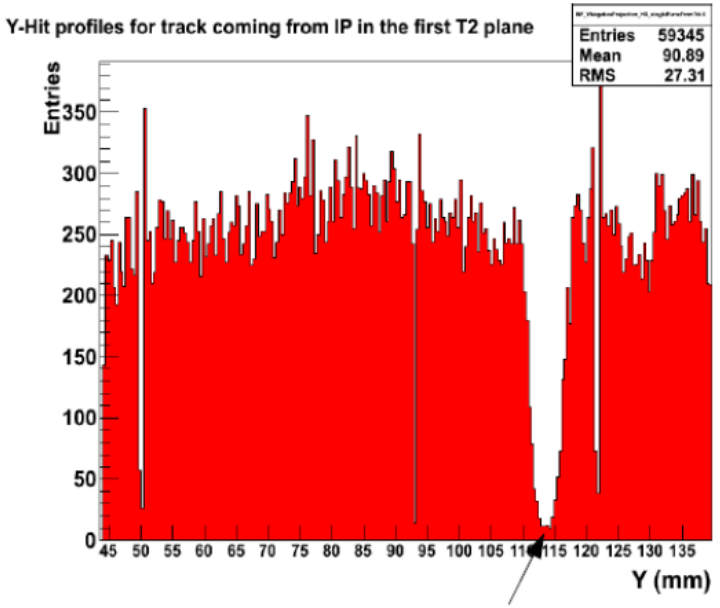




Hit profile in T2:

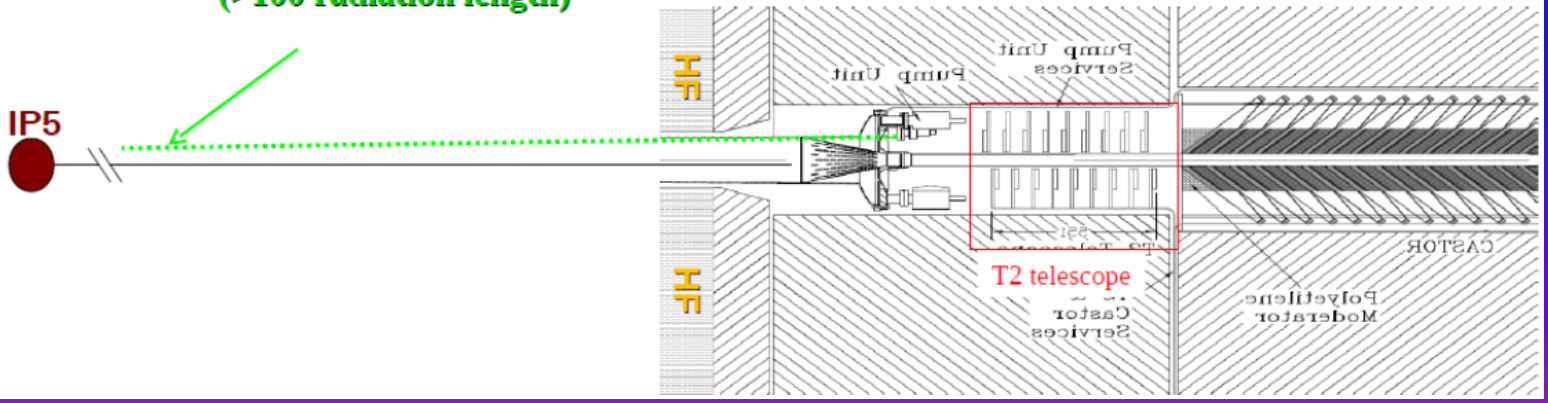
Beam pipe shadow



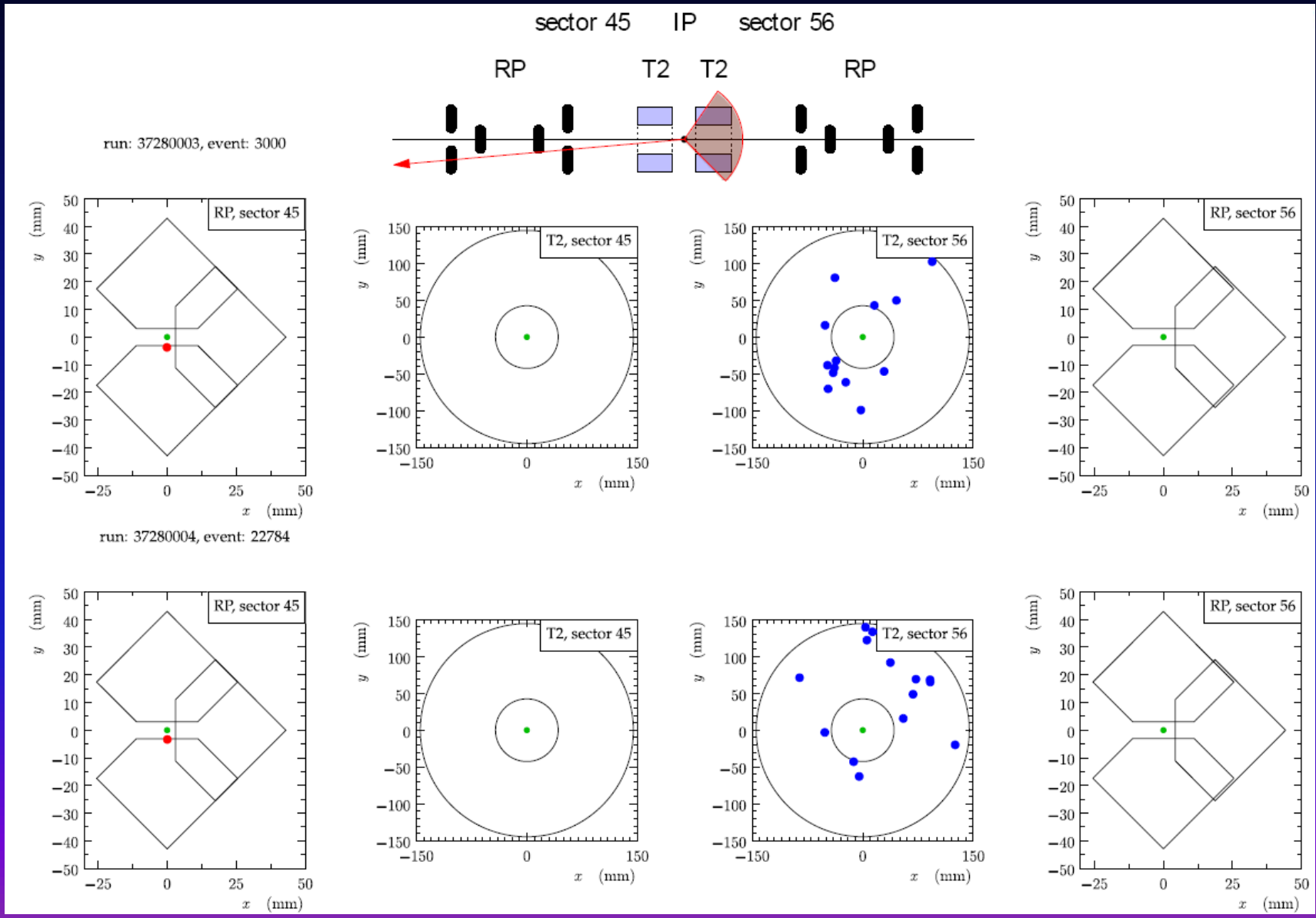


Beam pipe producing missing track hits in an well defined position of each T2 plane. This properties can be used for absolute detector alignment.

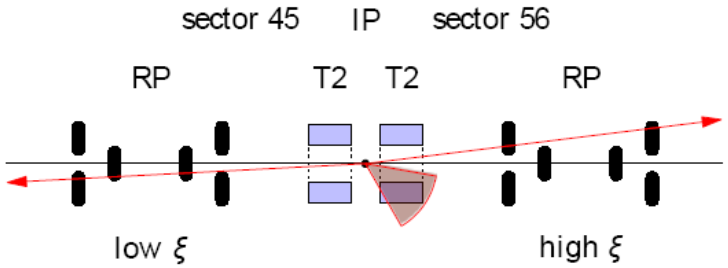
BeamPipe cone at η~5.54 (>100 radiation length)



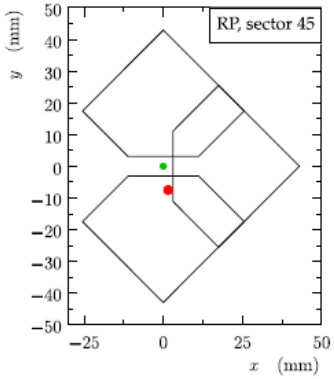
Single diffraction low ξ = Δp/p

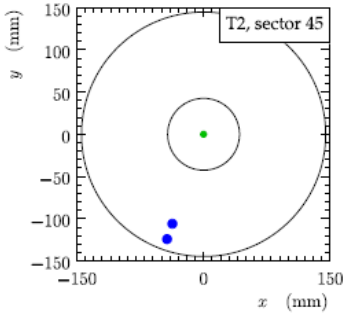


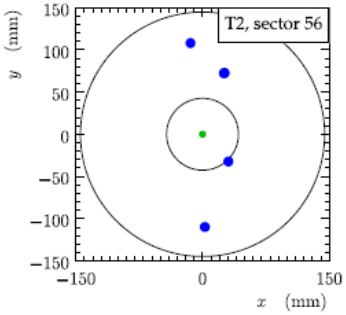
Double POMERON exchange

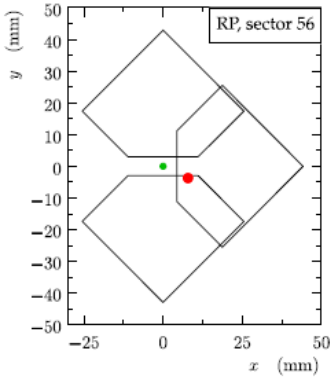


run: 37250009, event: 14125

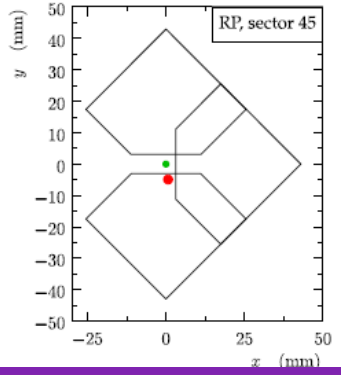


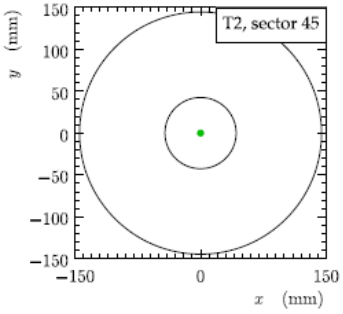


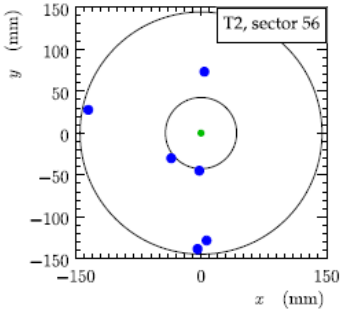


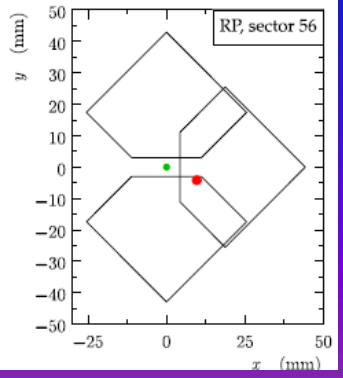


run: 37220007, event: 9904

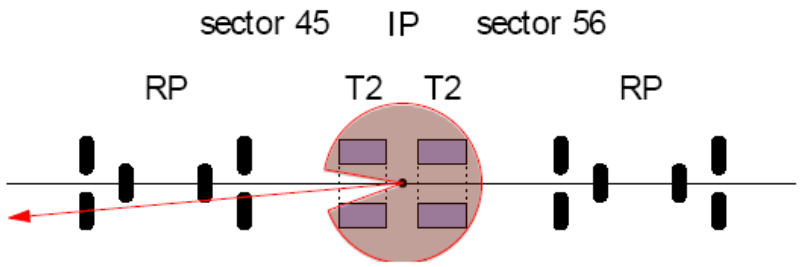




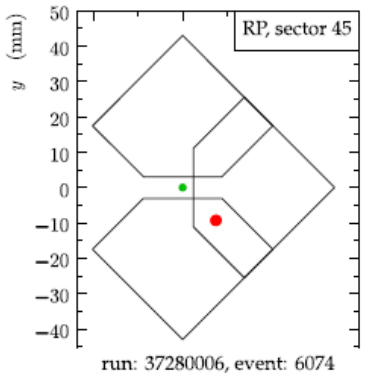


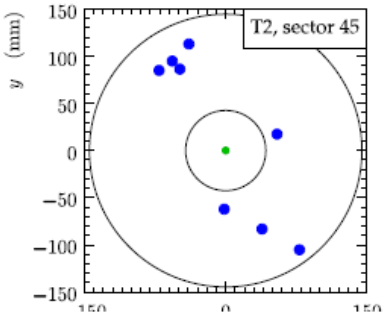


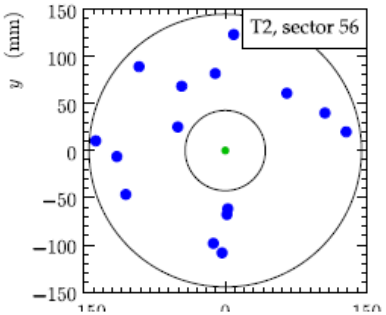
Single diffraction large ξ

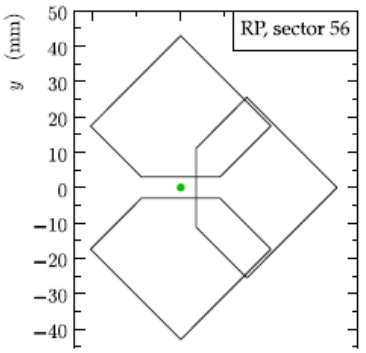


run: 37280006, event: 9522

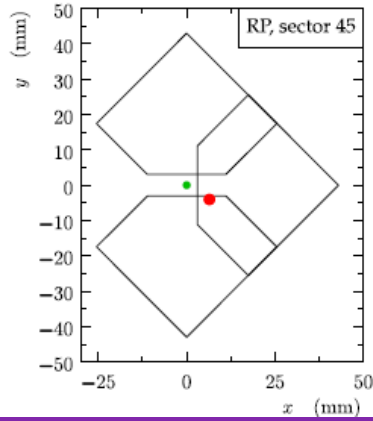


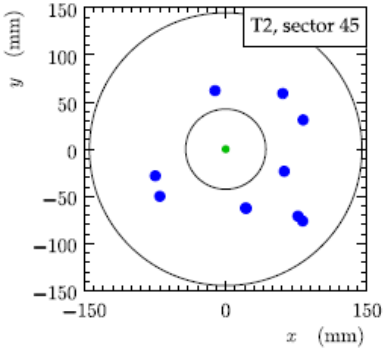


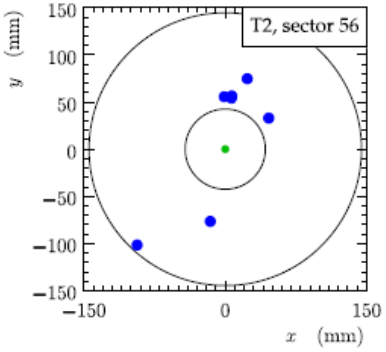


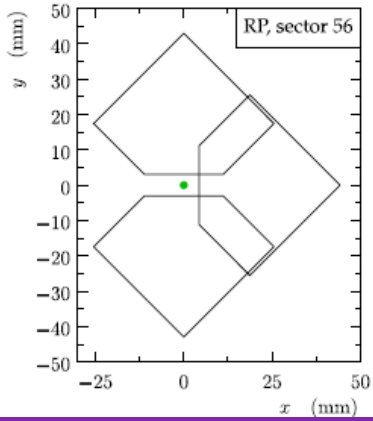


run: 37280006, event: 6074









Double POMERON exchange