



The TOTEM Experiment at the LHC : First Results

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On behalf of the TOTEM Collaboration

*II WORKSHOP ON DIFFRACTIVE PHYSICS AT THE LHC
21-23 September 2011, Rio de Janeiro*

The TOTEM Collaboration

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CERN, Geneva, Switzerland

Estonian Academy of Sciences, Tallinn, Estonia

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Università di Siena and Sezione INFN-Pisa, Italy

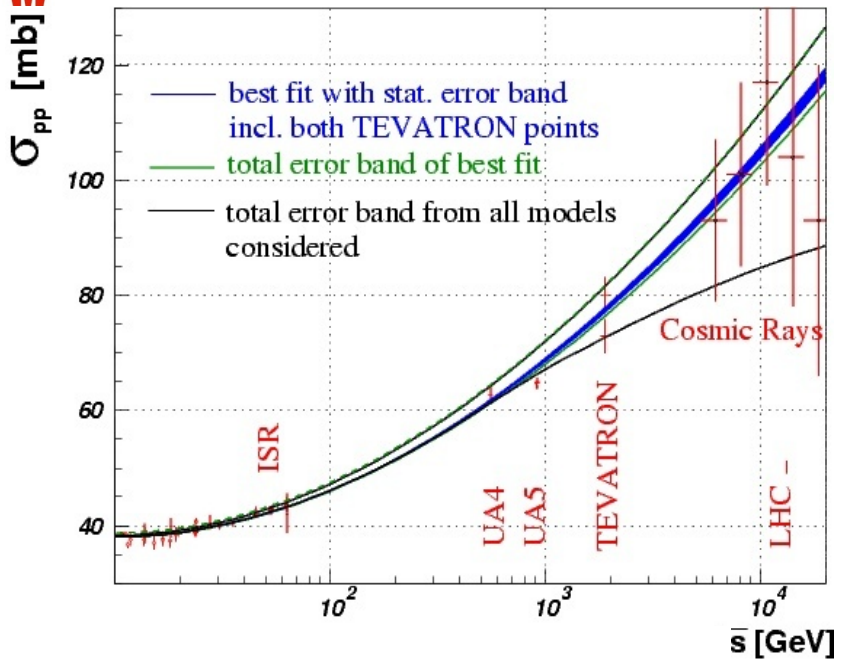
University of Helsinki and HIP, Helsinki, Finland

Academy of Sciences, Praha, Czech Republic

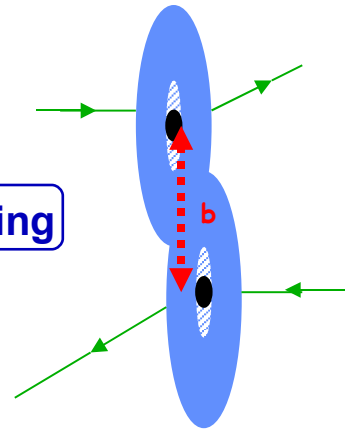
- **Detector Status**
- **Results : Elastic cross-section
Total cross section**
- **Outlook**

TOTEM Physics Overview

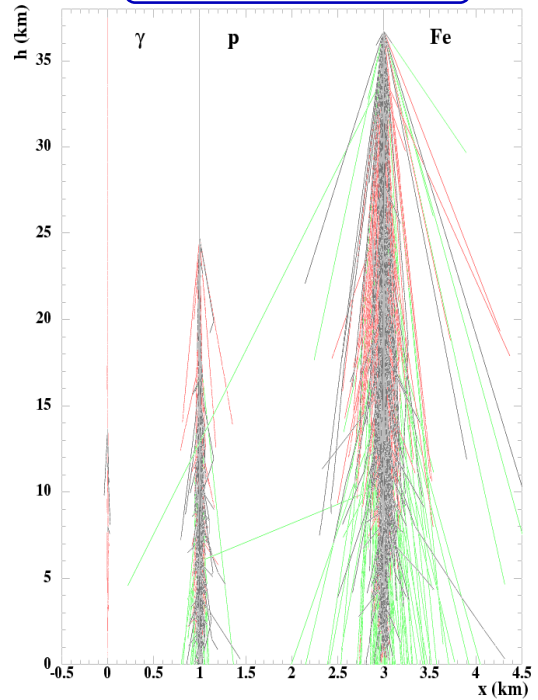
Total cross-section



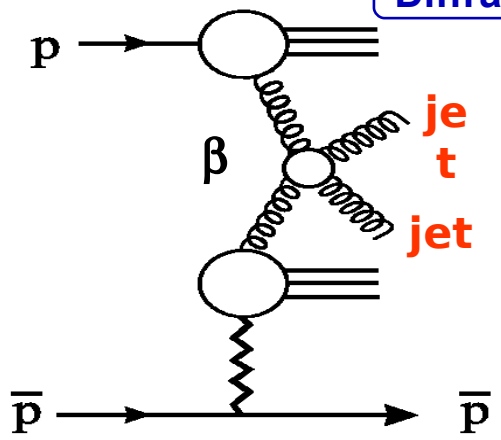
Elastic Scattering



Forward physics

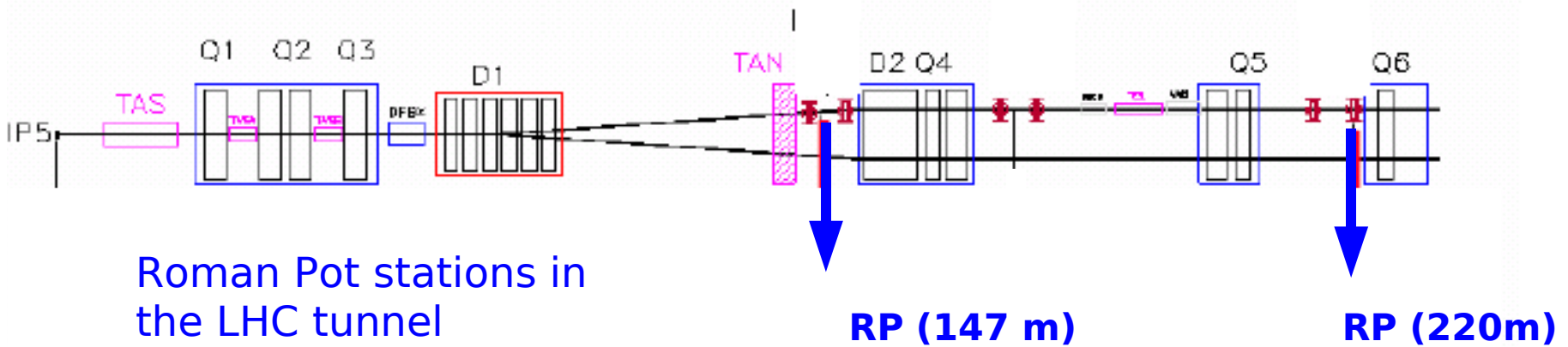
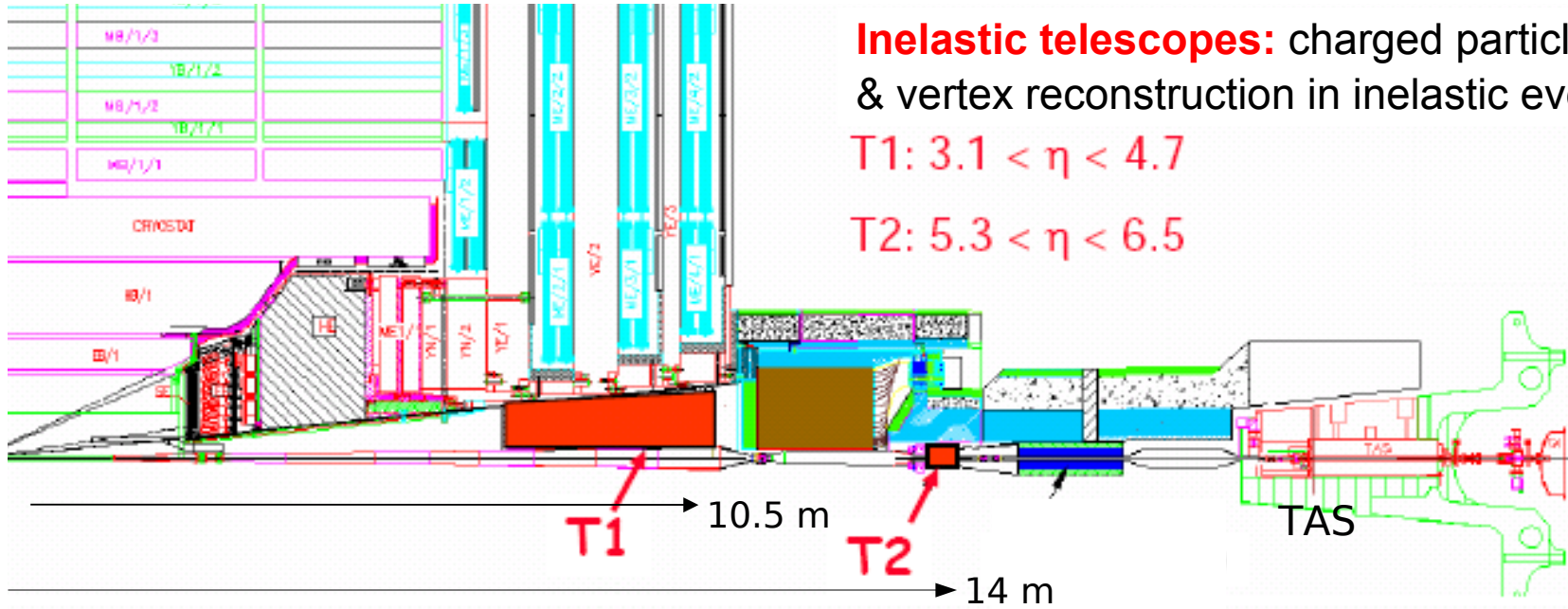


Diffraction: soft and hard



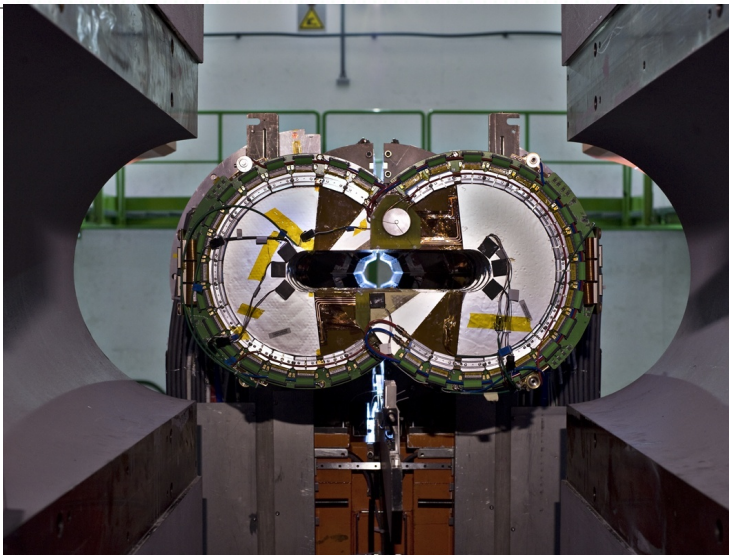


TOTEM Detectors



Roman Pot stations in the LHC tunnel

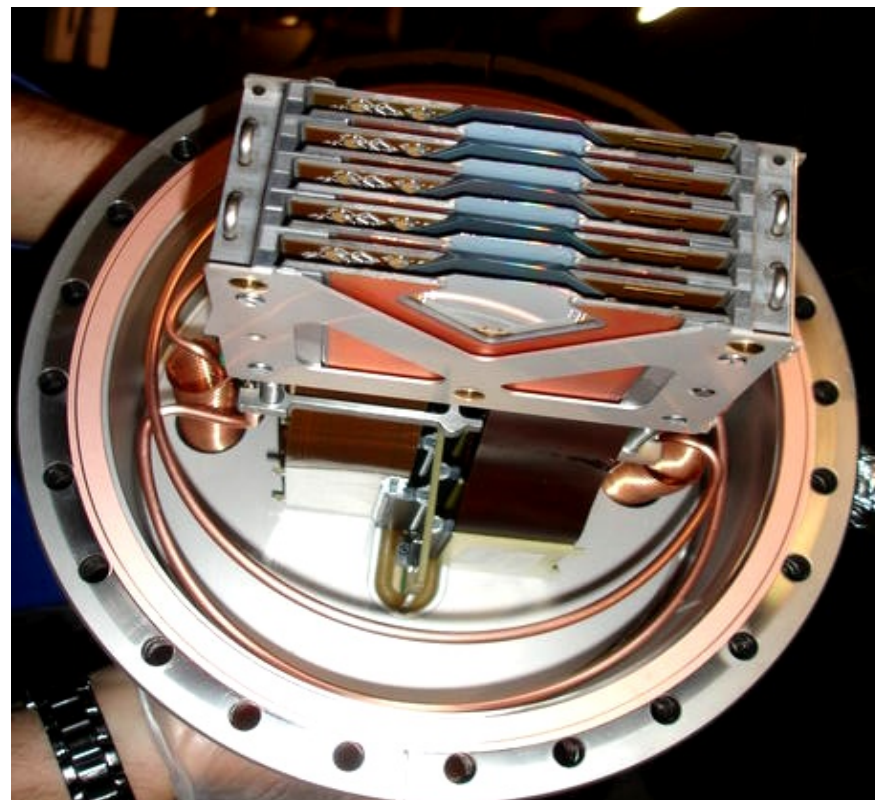
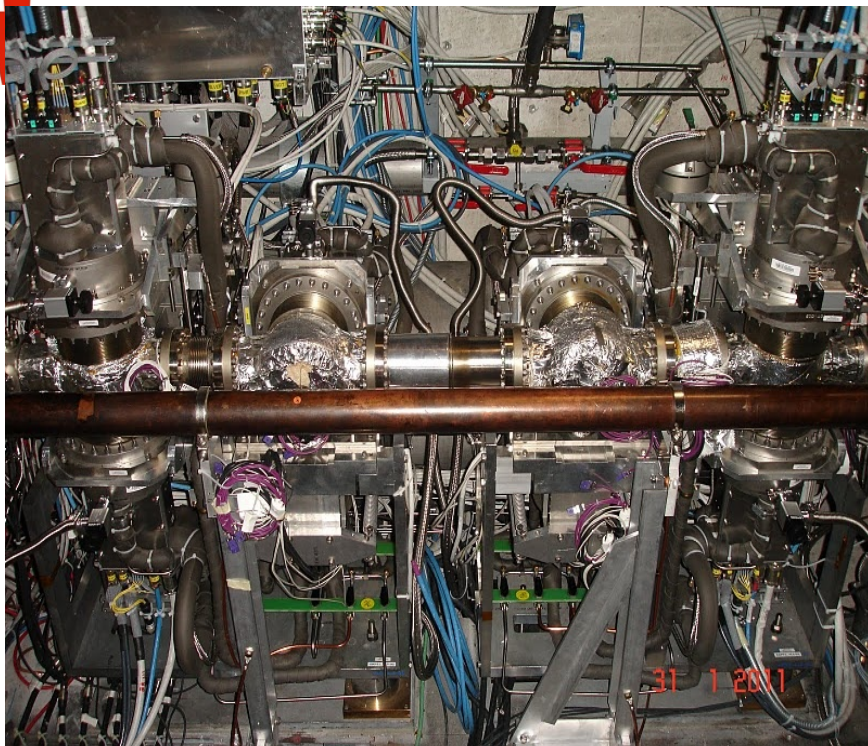
TOTEM Detectors



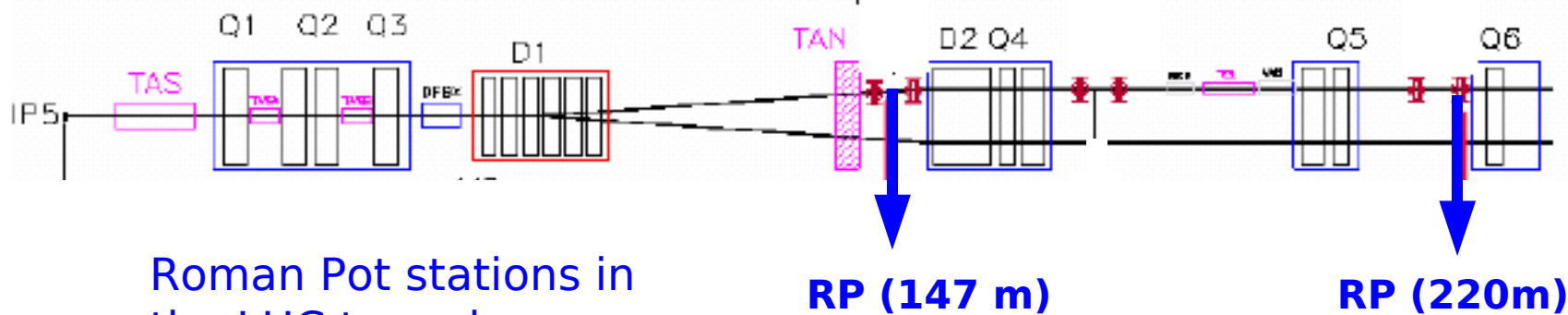
Inelastic telescopes: charged particle
& vertex reconstruction in inelastic events



TOTEM Detectors



Roman Pots: measure elastic & diffractive protons close to outgoing beam



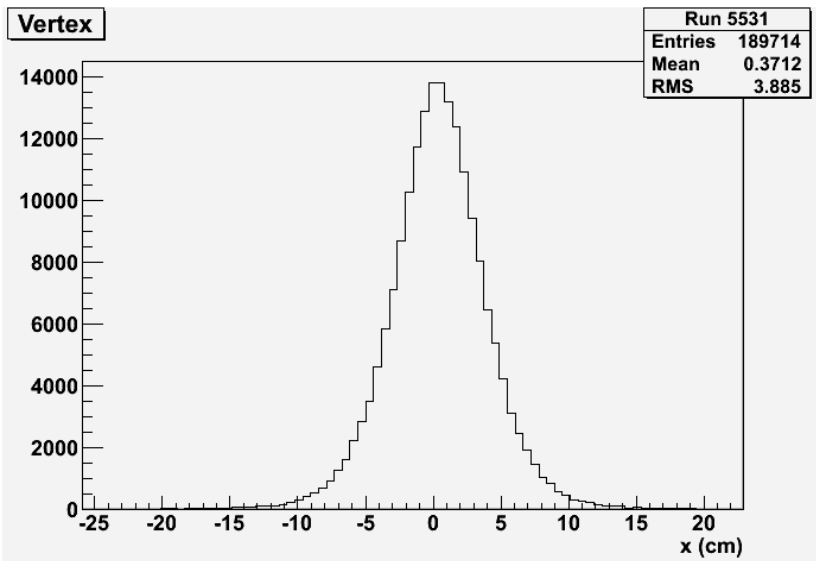
Roman Pot stations in the LHC tunnel



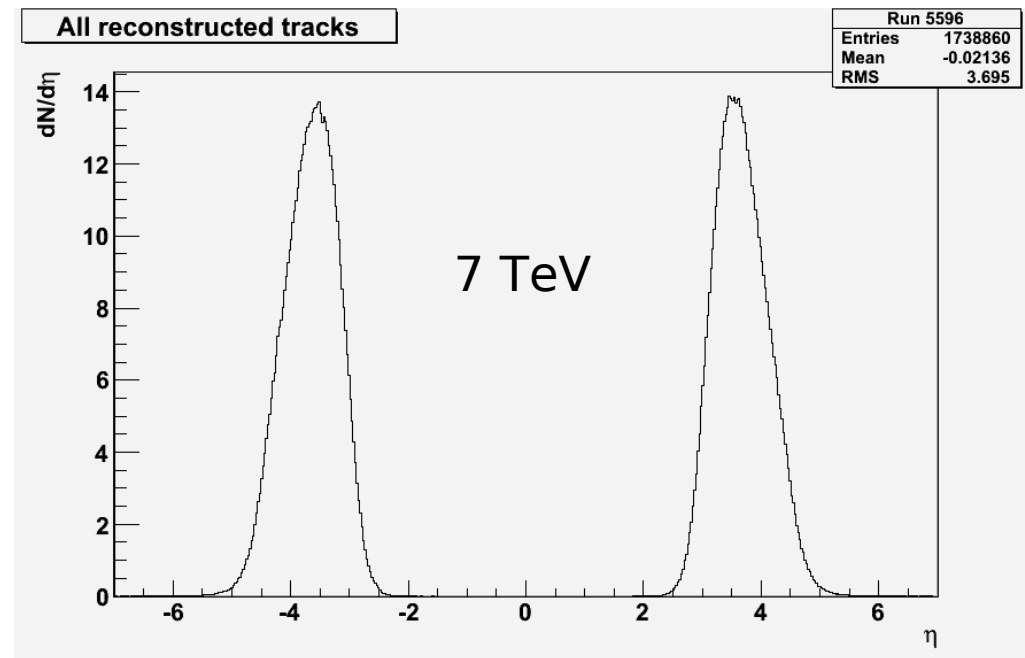
Preliminary $dN/d\eta$ results: T1

- Commissioning and Data analysis in progress

Vertex reconstruction



η Distributions (uncorrected)



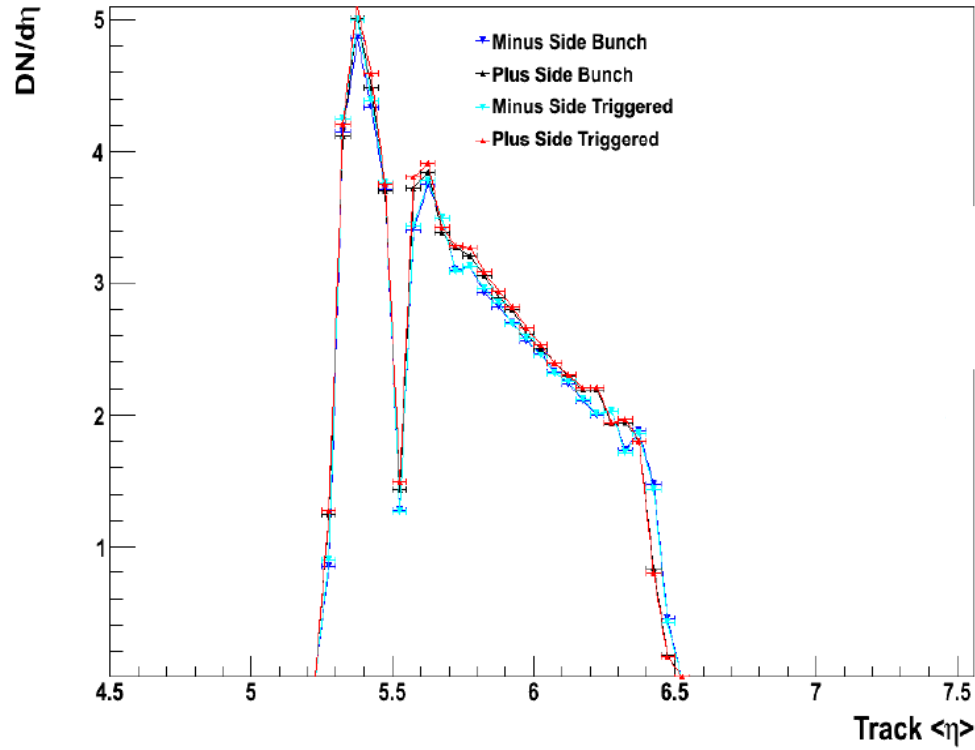
Vertex reconstruction is effected by the CMS magnetic field



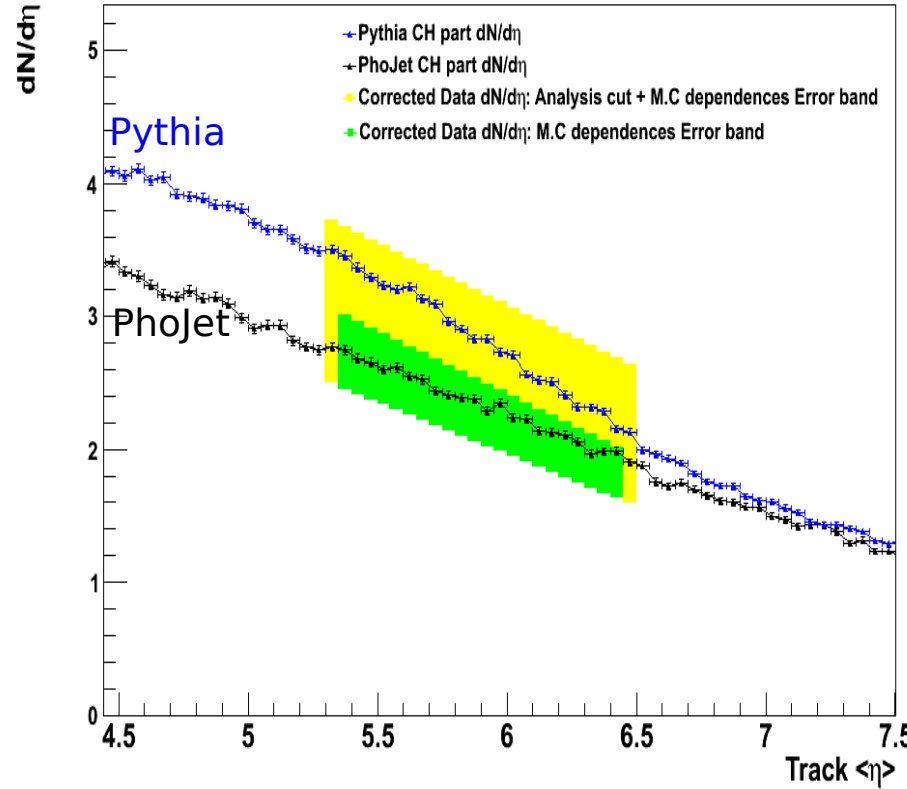
Preliminary $dN/d\eta$ results: T2

Data with low intensity bunches ($\sim 10^{10}$ p; low pile-up)

Data 2011 NOT Unfolded



Unfolded



'Plus' and 'minus' T2 sides superimposed

Very good agreement:
- left and right side
- bunch and active trigger

Low luminosity runs 2010



pp Elastic cross section t-range: 0.36 – 2.5 GeV²

“Elastic pp Scattering at the LHC at $\sqrt{s} = 7$ TeV”

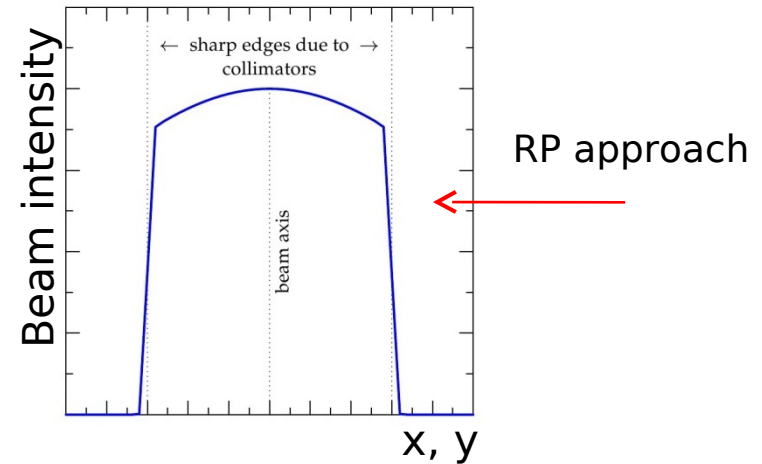
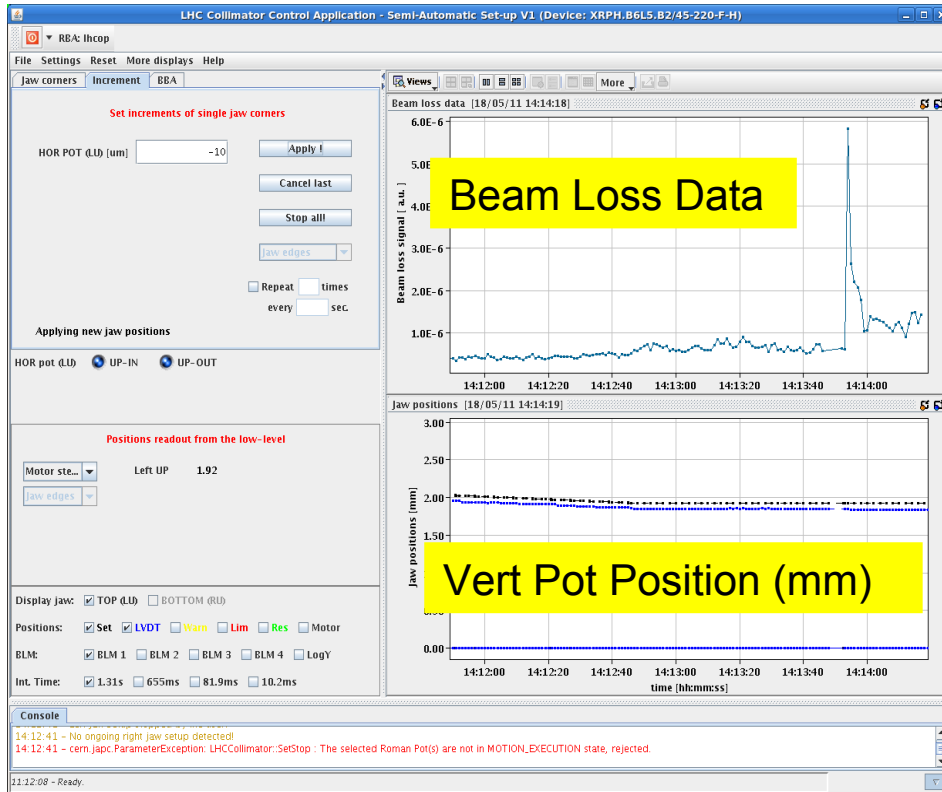
*CERN-PH-EP-2011-101
EPL, 95 (2011) 41001*



Elastic pp scattering : data collection

- Data taking 2010 with different distances of the Roman pots to the beam center:
 - 7σ runs (this analysis): during special runs dedicated to the RP alignment (5 bunches nominal intensity, $L \sim 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$)
 - 18σ runs: during normal LHC operation (total luminosity collected $\sim 5.8 \text{ pb}^{-1}$)

Alignment: RP220 approached the low intensity beam in $10 \mu\text{m}$ steps



$7\sigma \sim 3 \text{ mm (V)}; 1 \text{ mm (H)}$



Elastic pp scattering : Alignment

Very critical and fundamental for any physics reconstruction

Misalignments within detector assembly: metrology, tracks

Relative positions of the pot & beam:

Constraints between top and bottom pots ($\sim 10\mu\text{m}$)

Scraping: RP aligned vertically wrt beam center ($\sim 20\mu\text{m}$)

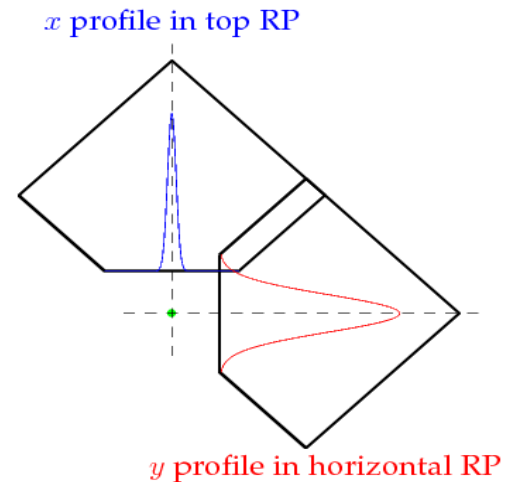
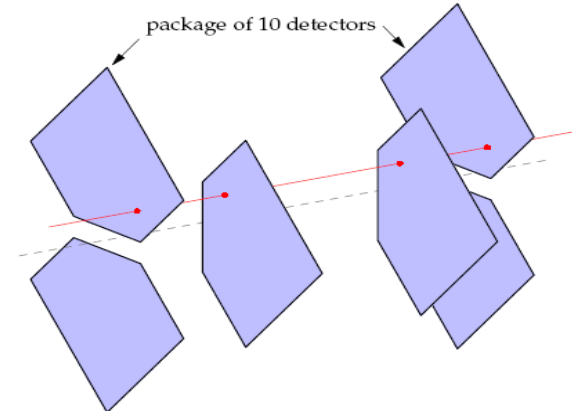
Alignment between pots with overlapping tracks ($\sim \text{few } \mu\text{m}$)

Physics process (“elastic”):

x vs y correlation : horizontal alignment wrt beam

far vs near correlation: vertical alignment between units

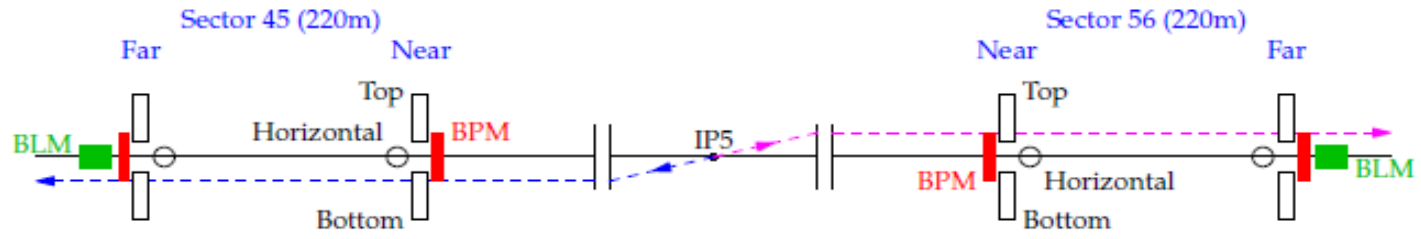
Scattering angle constraint : vertical alignment wrt beam & left-right arm alignment



$$\delta x, \delta y \leq 10\mu\text{m} \quad \delta t/t \sim 0.3-0.6\%$$



Elastic pp scattering : proton reconstruction



$$\text{Measured in RP} \begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{\text{RP}} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{\text{IP5}} \text{Reconstructed}$$

$$\beta^* = 3.5\text{m} \quad L_x \sim 0 ; L_y \sim 20\text{m} @ 220\text{m} \quad (L = \sqrt{\beta\beta^*} \sin \Delta\mu)$$

Both angle projections can be reconstructed:

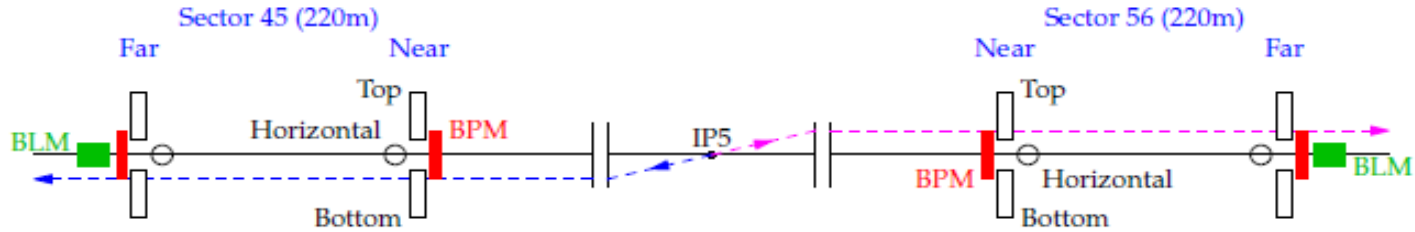
$$\Theta_x = L'_x \Theta_x^* \quad y = L_y \Theta_y^*$$

precise values of $L'_x = dL_x/ds$ and L_y @ RP locations needed

Need excellent optics understanding



Elastic pp scattering : optics



$$\text{Measured in RP} \begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{\text{RP}} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{\text{IP5}} \text{Reconstructed}$$

Strategy:

- Magnet currents measurements → MADX optics model
- Selection of elastic protons
- Determination of the optics parameters constraints with proton tracks
 - $\Theta_{\text{left}}^* = \Theta_{\text{right}}^*$ (proton pair collinearity)
 - Proton position ↔ angle correlations
 - $L_x=0$ determination, coupling corrections
- Matching of the optics (transport matrix) → $\delta L'_x/L'_x \sim 1\%$
 $\delta L_y/L_y \sim 1.5\%$

[cfr. H. Niewiadomski - "Roman Pots for beam diagnostic" - Optics Measurements, Corrections and Modelling for High-Performance Storage Rings workshop (OMCM) CERN, 20-23.06.2011]



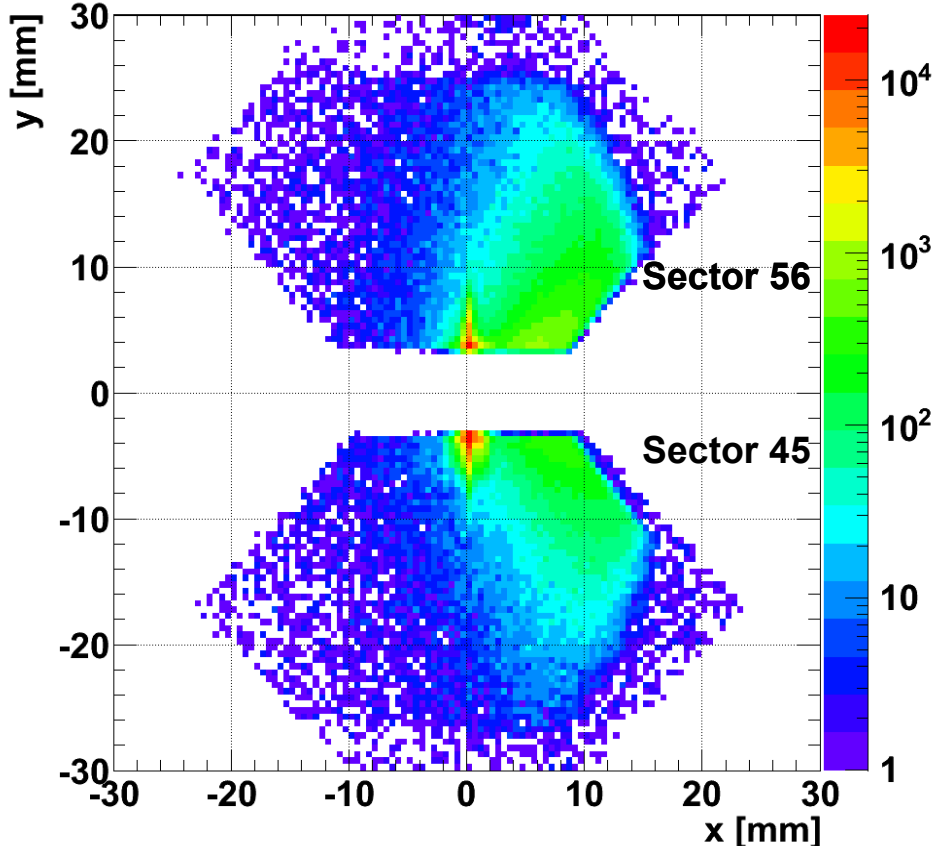
Elastic pp scattering : cuts and data reduction

Integrated luminosity : 6.2 nb⁻¹

Topology:

- near and far units
- diagonals

| | | |
|---|-------|-----------|
| Total triggers | 5.28M | ↑ showers |
| Reconstructed tracks & elastic topology | 293k | |



Two diagonals analysed independently

$$t = -p^2 \theta^2$$

$$\xi = \Delta p/p$$



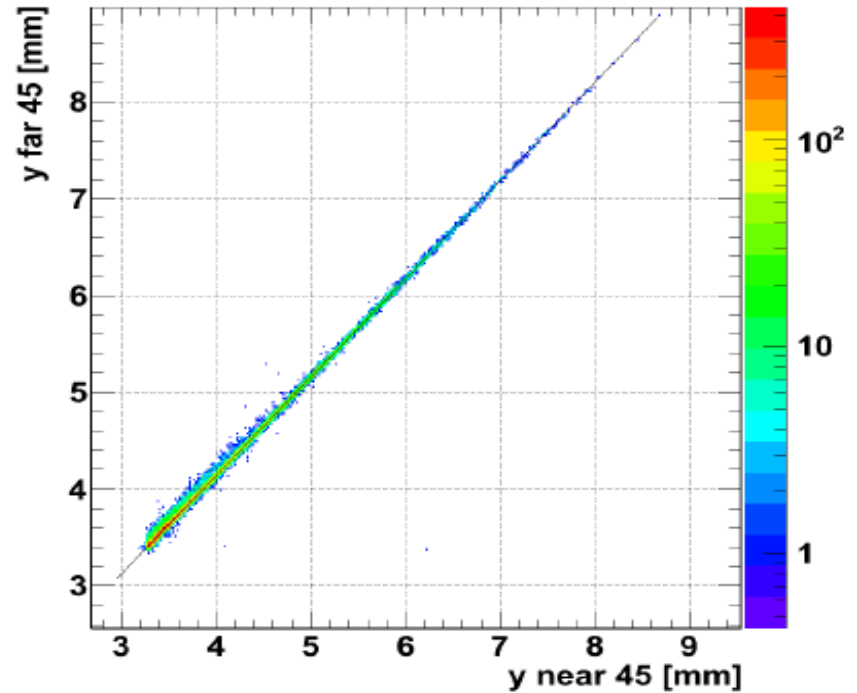
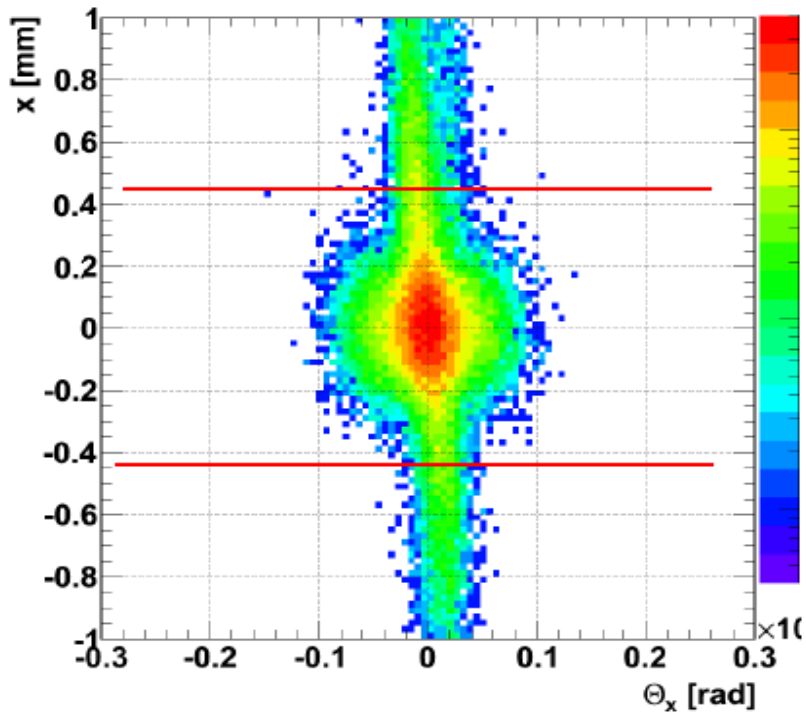
Elastic pp scattering : cuts and data reduction

Low $|\xi|$ selection (3σ):

- $|\mathbf{x}_{RP}| < 3\sigma_x @ L_x=0$
- $\mathbf{y}_{RP_NEAR} \leftrightarrow \mathbf{y}_{RP_FAR}$

| | |
|---|-------|
| Total triggers | 5.28M |
| Reconstructed tracks & elastic topology | 293k |
| Low $ \xi $ selection | 70.2k |

↑ showers
↓



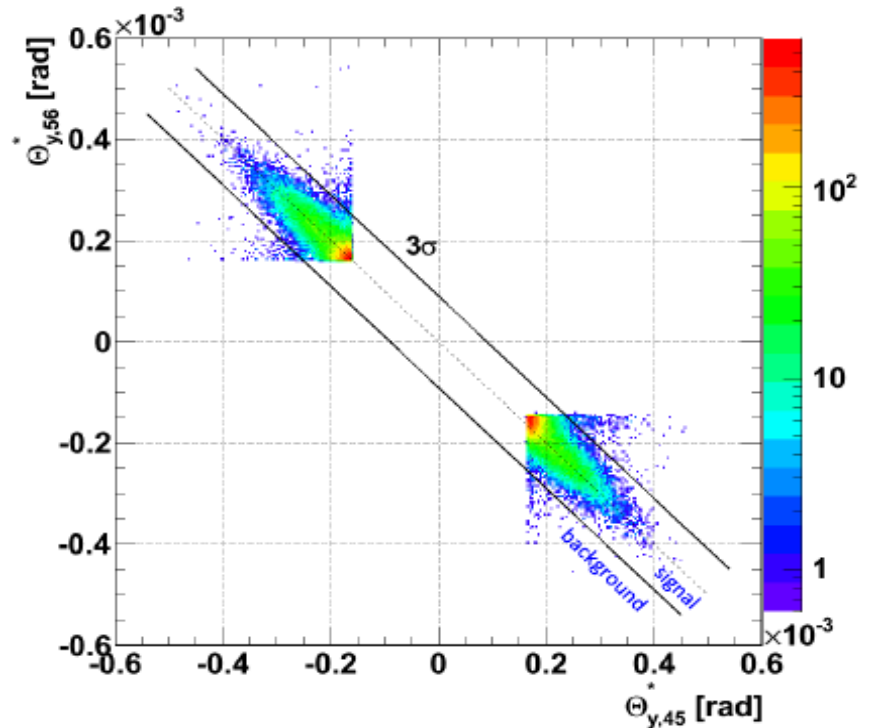
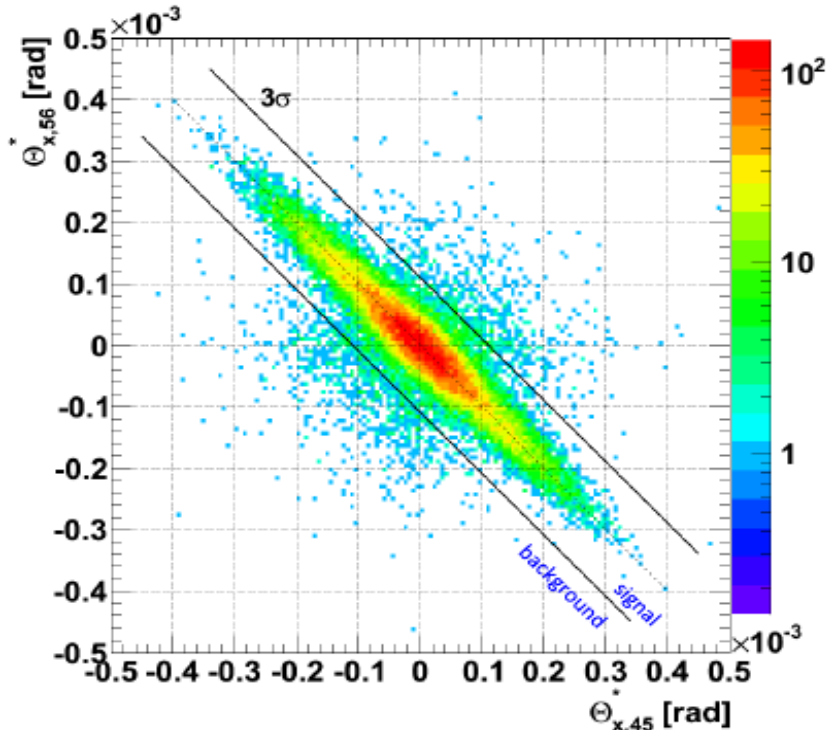


Elastic pp scattering : cuts and data reduction

Elastic collinearity (3σ):

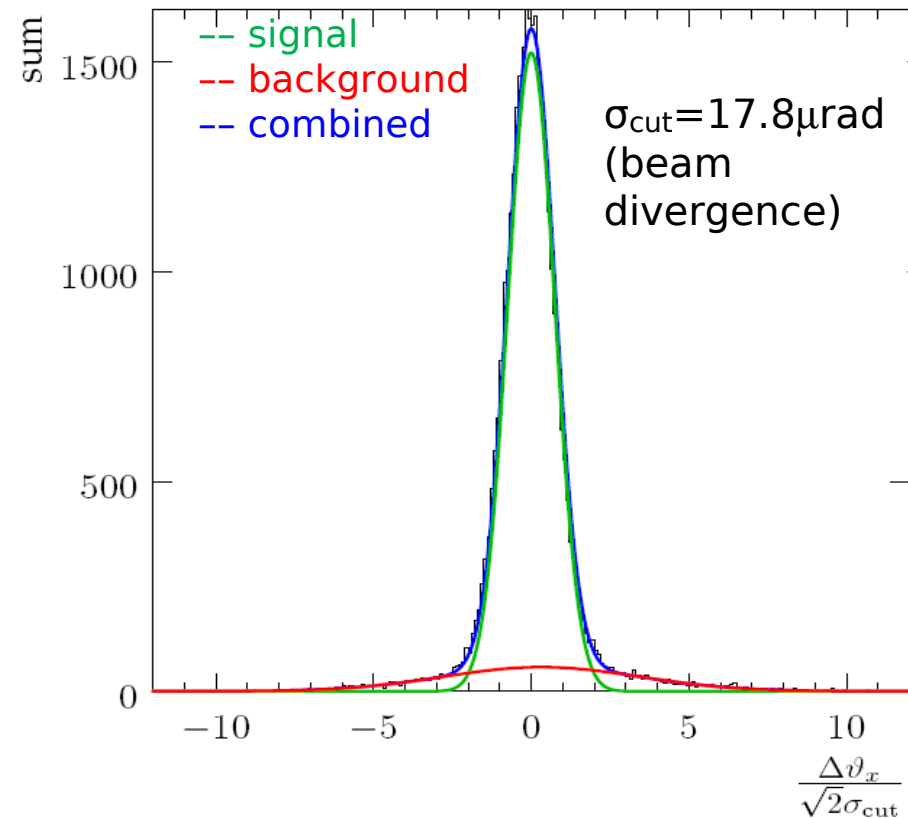
- $\theta_{x,45}^* \leftrightarrow \theta_{x,56}^*$
- $\theta_{y,45}^* \leftrightarrow \theta_{y,56}^*$

| | | |
|---|-------|-----------|
| Total triggers | 5.28M | ↑ showers |
| Reconstructed tracks & elastic topology | 293k | |
| Low $ \xi $ selection | 70.2k | |
| Collinearity cuts | 66.0k | |

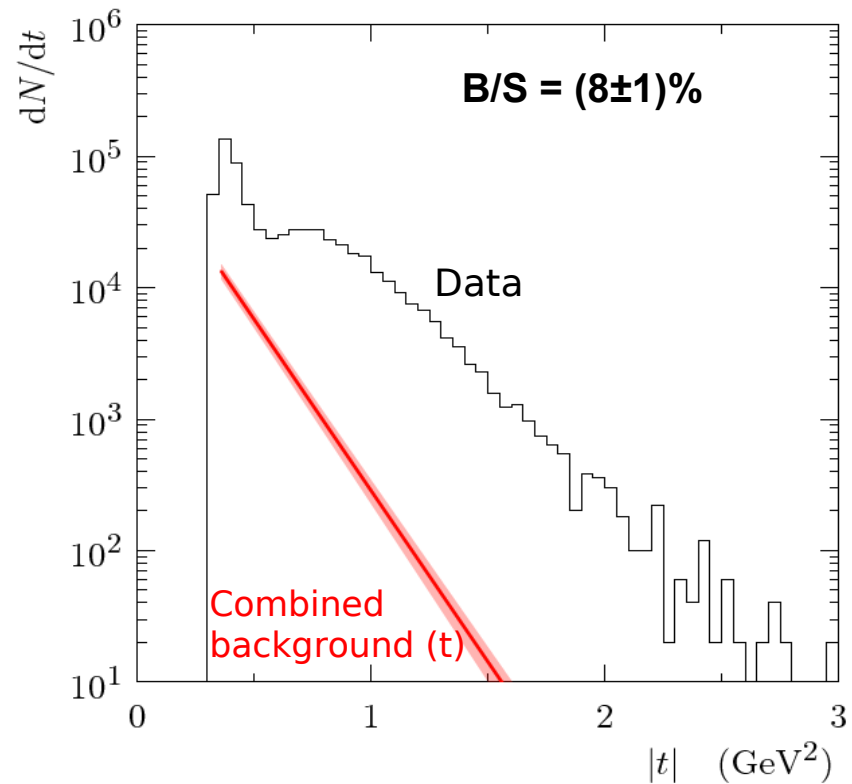




Elastic pp scattering : background



Signal to background normalisation

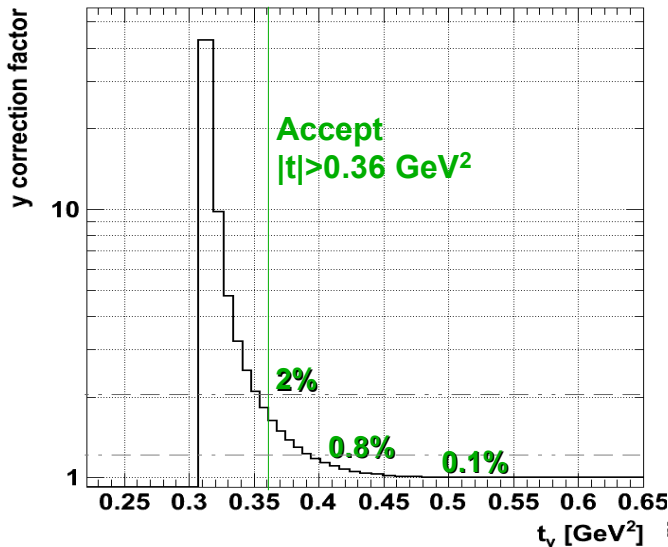
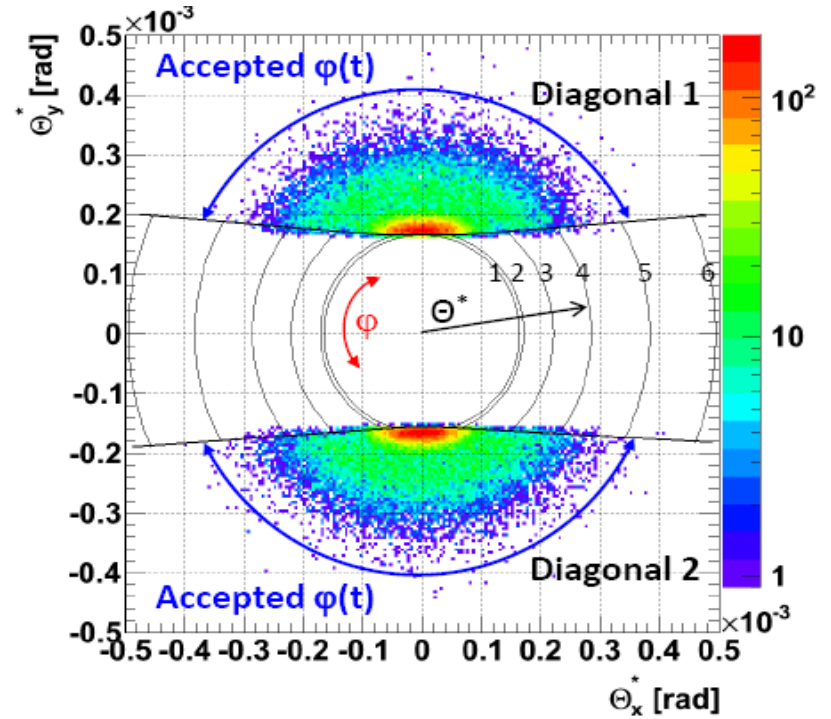
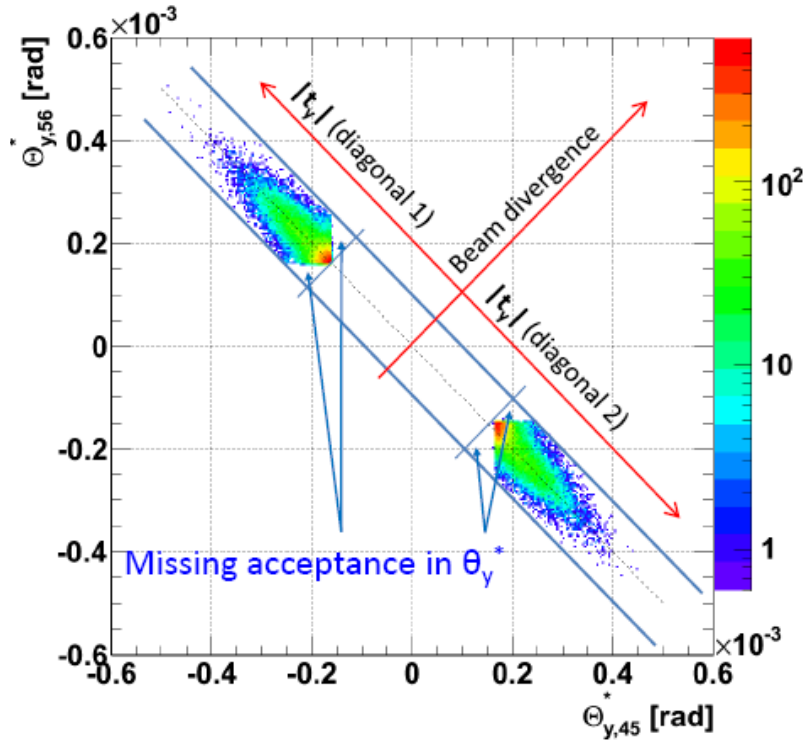


Signal vs. background (t)

$|t|=0.4\text{GeV}^2$: B/S = $(11\pm 2)\%$
 $|t|=0.5\text{GeV}^2$: B/S = $(19\pm 3)\%$
 $|t|=1.5\text{GeV}^2$: B/S = $(0.8\pm 0.3)\%$



Elastic pp scattering: acceptance corrections



| | t [GeV 2] | θ^* [mrad] | Accepted ϕ (2 diag.) [°] | ϕ correction |
|---|--------------------|----------------------|----------------------------------|----------------------|
| 1 | 0.33 | 165 | 38.6 | 9.3±4.7% |
| 2 | 0.36 | 171 | 76.4 | 4.7±1.8% |
| 3 | 0.60 | 221 | 162.5 | 2.2±0.3% |
| 4 | 1.00 | 286 | 209.8 | 1.7±0.1% |
| 5 | 1.80 | 383 | 246.3 | 1.5 % |
| 6 | 3.00 | 495 | 269.0 | 1.3 % |



Elastic pp scattering: corrections & systematics

Resolution unfolding:

*Smearing only due to beam divergence ;
detector resolution negligible*

t-reconstruction resolution: $\delta t/t = \sqrt{2} p \sigma_{\text{beam}}/\sqrt{t} \sim 0.1 \sqrt{t}$

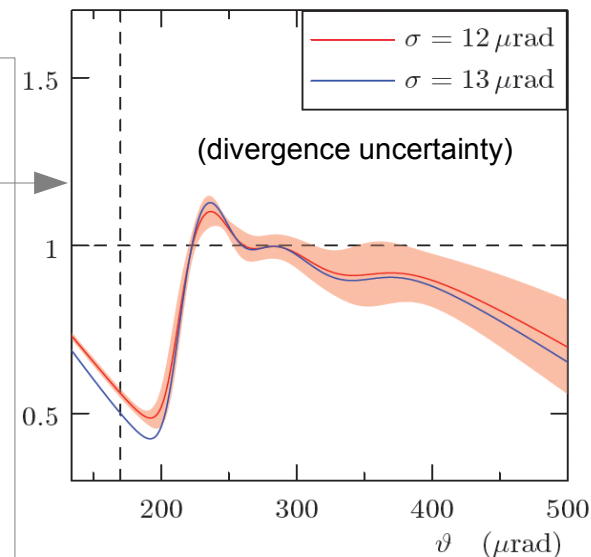
Luminosity : 4%

[CMS-PAS-EWK-10-004; CMS-DP-2011-002 C]

Event reconstruction Inefficiency : (29± 10)%

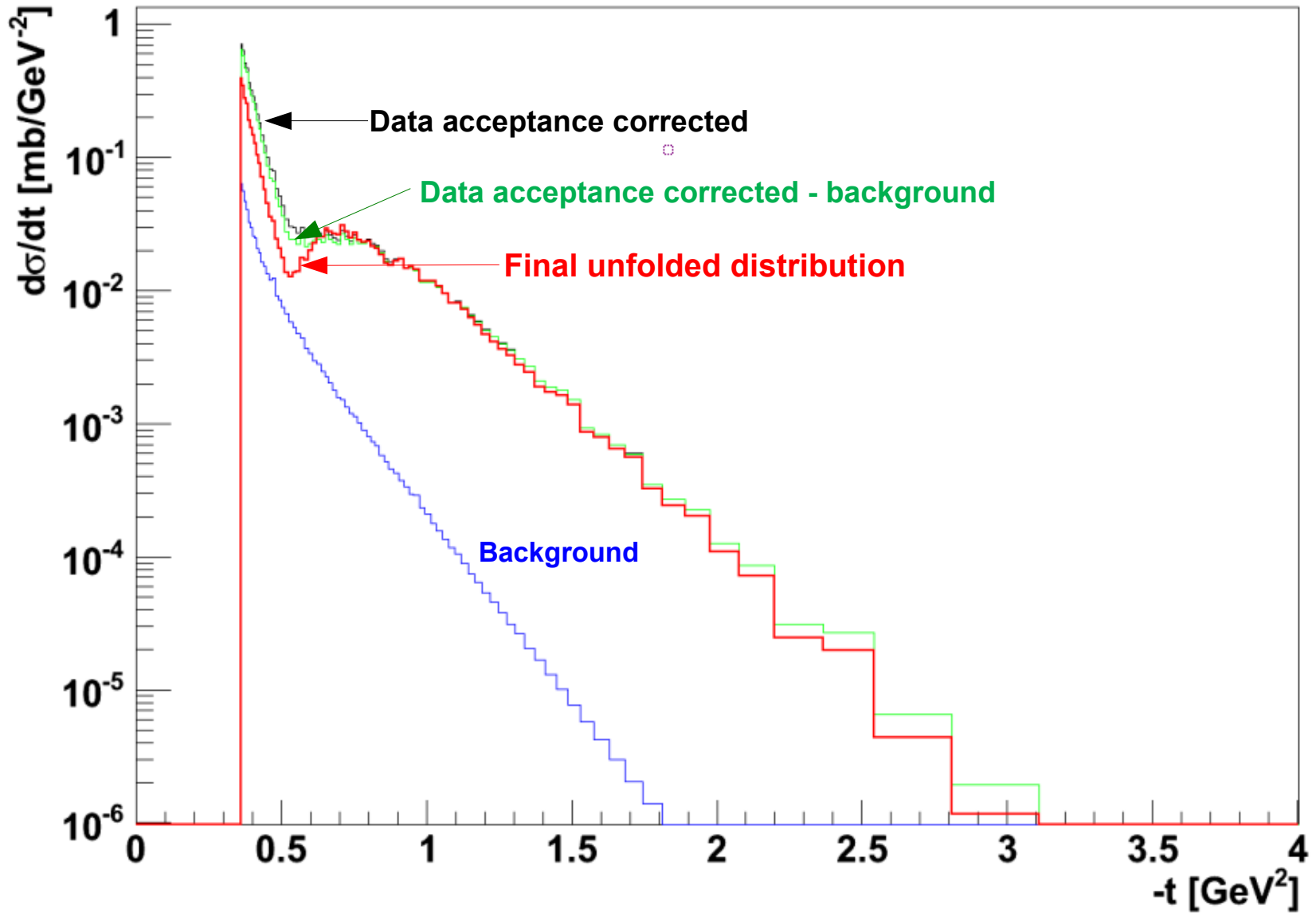
*Multiple tracks due to showers;
average inefficiency /pot : 3 – 7 % &
tracks induced correlations;
Pile-up < 0.5%*

correction = unsmearred / fit



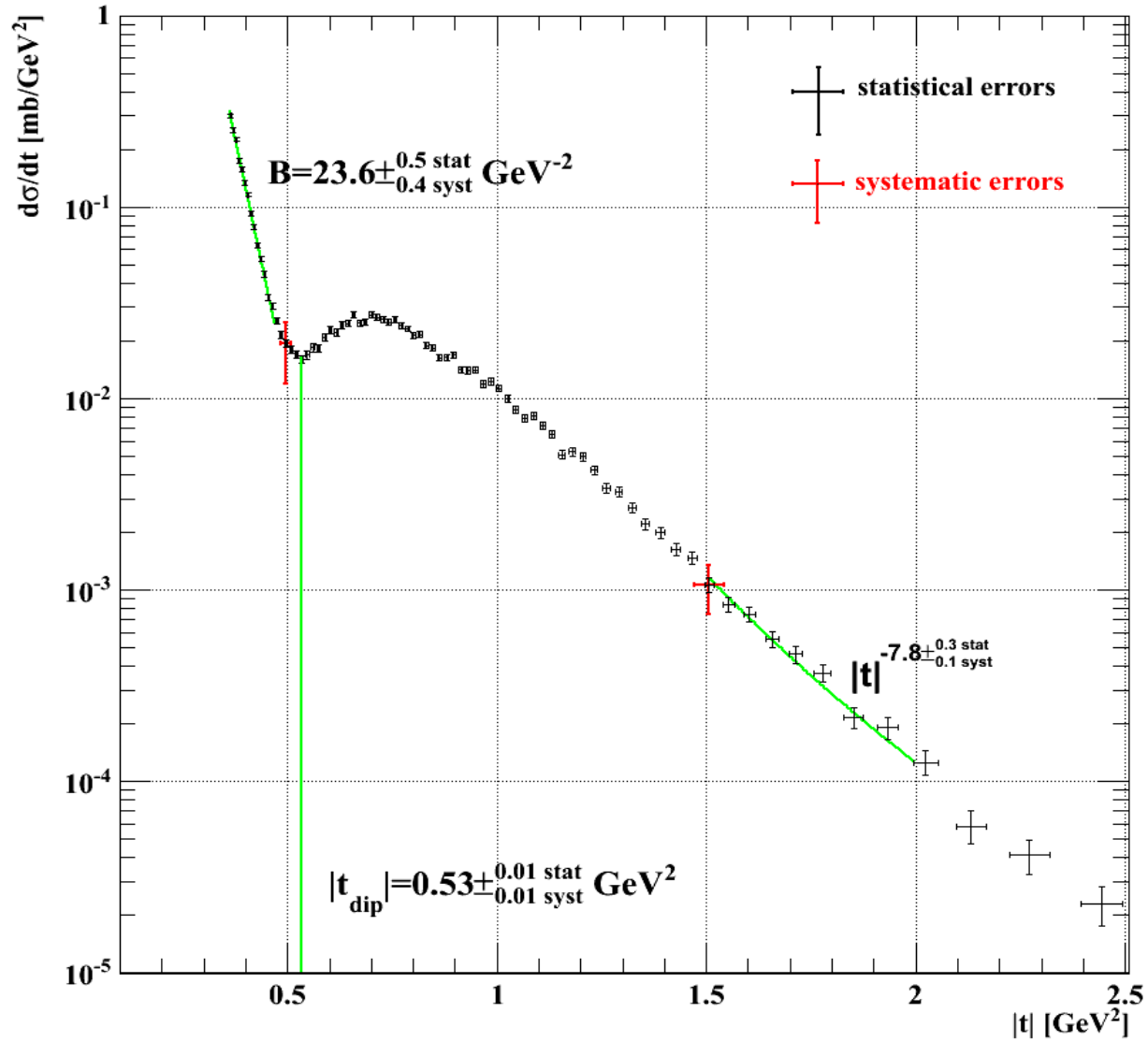


Elastic pp scattering: all corrections



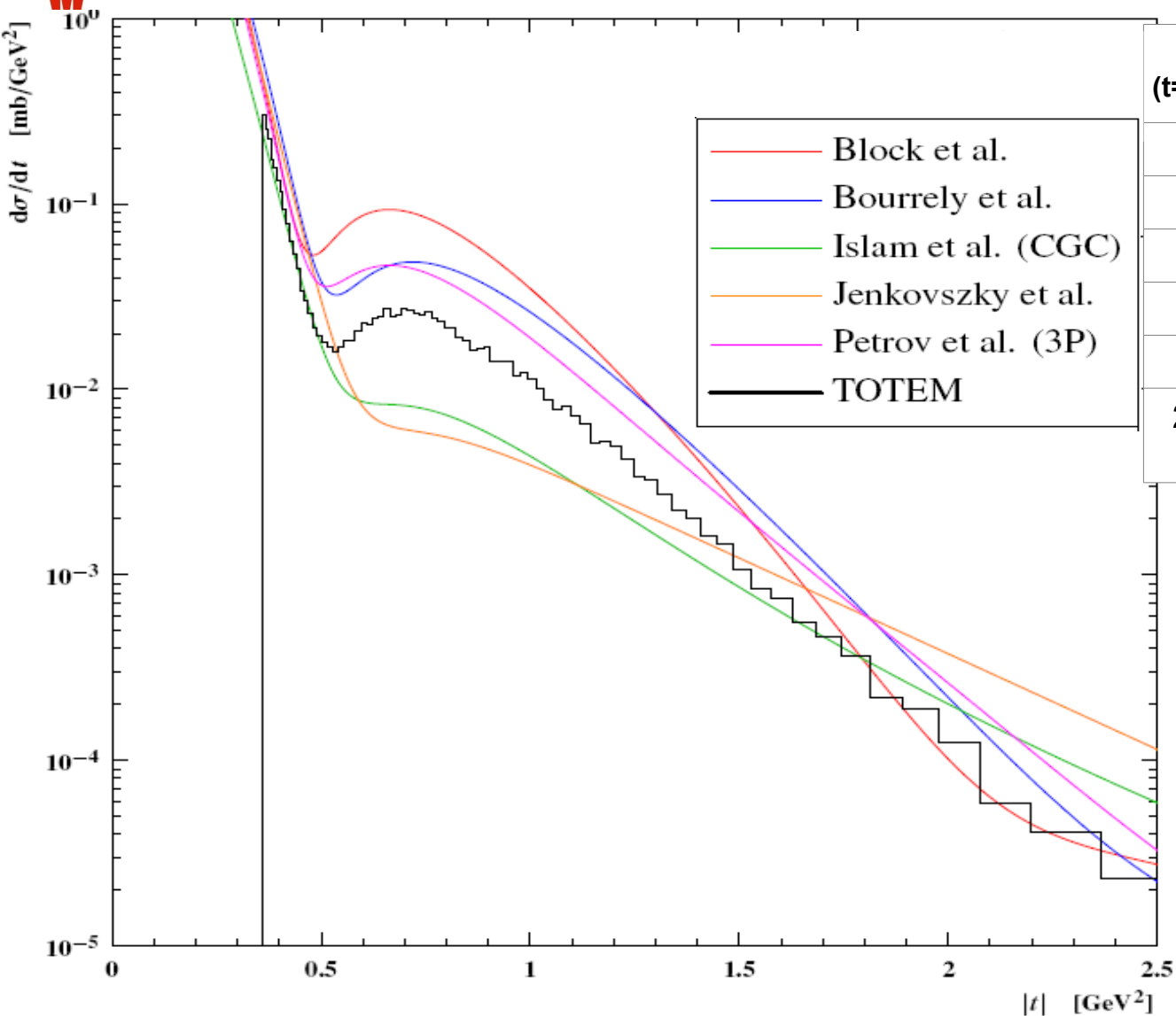


Elastic pp scattering: cross-section





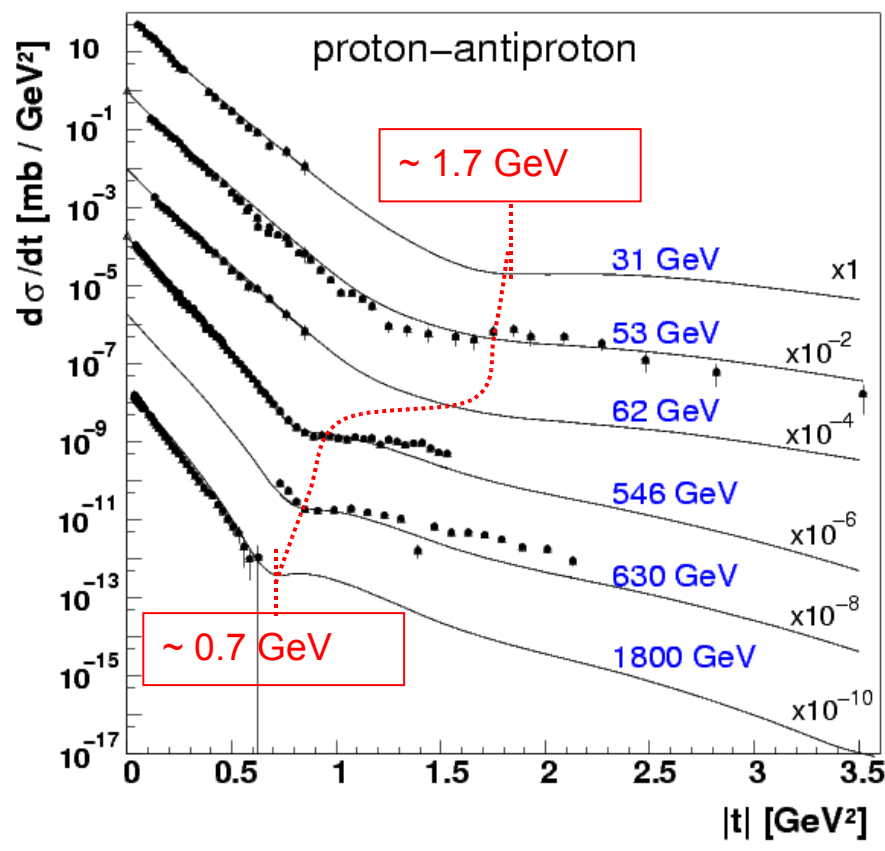
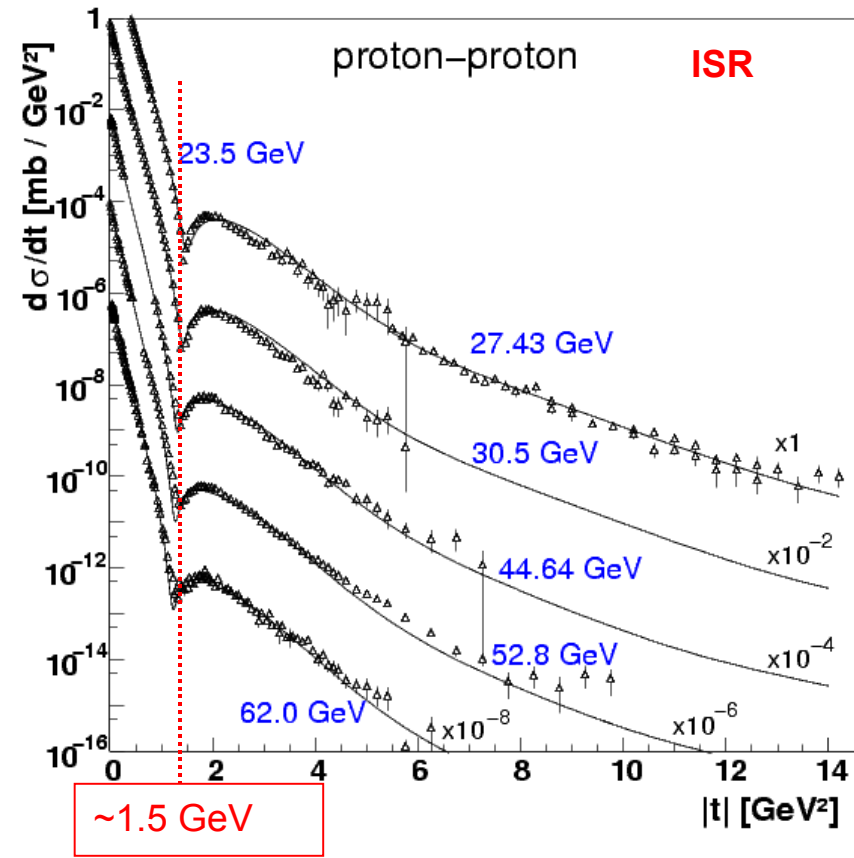
Elastic pp scattering: comparison to some models



| B ($t=-0.4 \text{ GeV}^2$) | t_{DIP} | t^{-n} [1.5–2 GeV ²] |
|---|--|--|
| 24.4 | 0.48 | 10.4 |
| 21.7 | 0.54 | 8.4 |
| 19.9 | 0.65 | 5.0 |
| 20.1 | 0.72 | 4.2 |
| 22.7 | 0.52 | 7.0 |
| 23.6±0.5 ±0.4 _{syst} | 0.53 ±0.01 ±0.01 _{syst} | 7.8±0.3 ±0.1 _{syst} |



Elastic pp Scattering – from ISR to Tevatron





pp low-t Elastic Scattering & Total Cross-Section at 7 TeV

“First measurements of the total proton-proton cross section at the LHC energy of $\sqrt{s} = 7\text{TeV}$ ”

CERN-PH-EP-2011-158

K. Eggert : “TOTEM Status Report and First Measurement of the Total Cross-section”

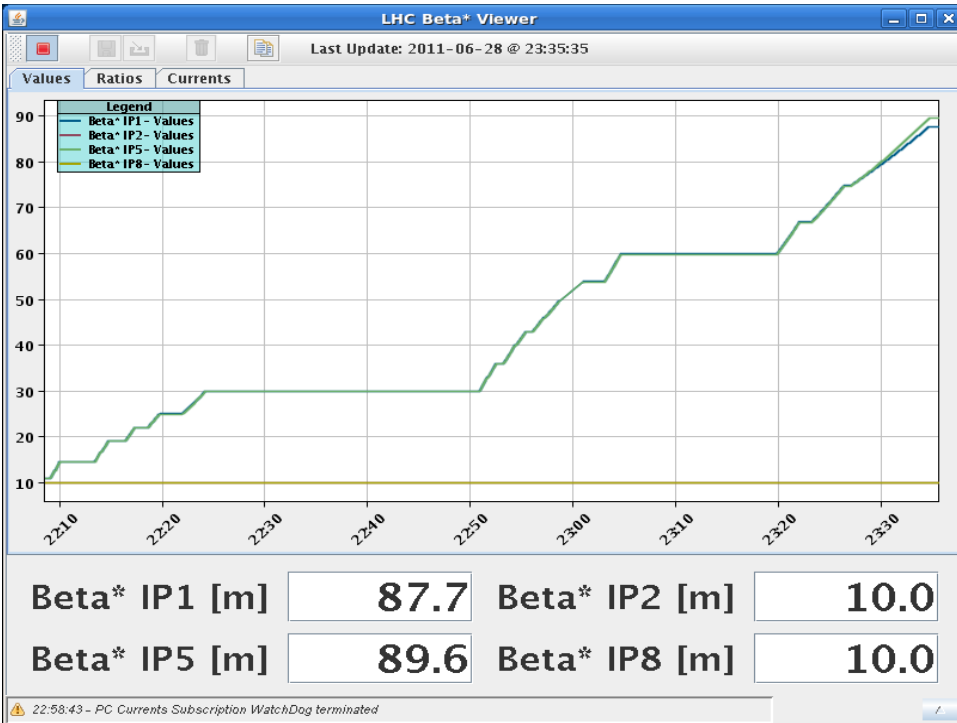
LHCC Open Session, 21 September 2011

<http://indico.cern.ch/getFile.py/access?contribId=6&sessionId=0&resId=1&materialId=slides&confId=153317>



$\beta^* = 90$ m optics

- 1st MD : successful for separated beams
- 2nd MD (28. June): successful ; established collisions & data taking for optics diagnostics (this analysis)



$$\Delta\mu_y = \pi/2; \Delta\mu_x = \pi$$

$$L_x = 0; L_y \sim 260\text{m} @ 220\text{m}$$

$$(L = \sqrt{\beta\beta^*} \sin \Delta\mu)$$

Both angle projections can be reconstructed:

$$L'_x \Theta^*_x = \Theta_x - \mathbf{v}'\mathbf{x}^*$$

$$L_y \Theta^*_y = y$$



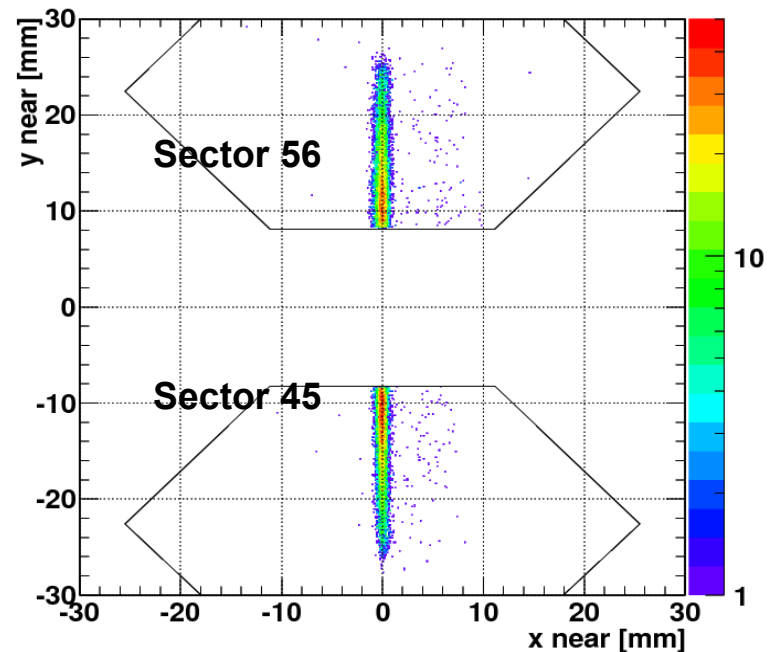
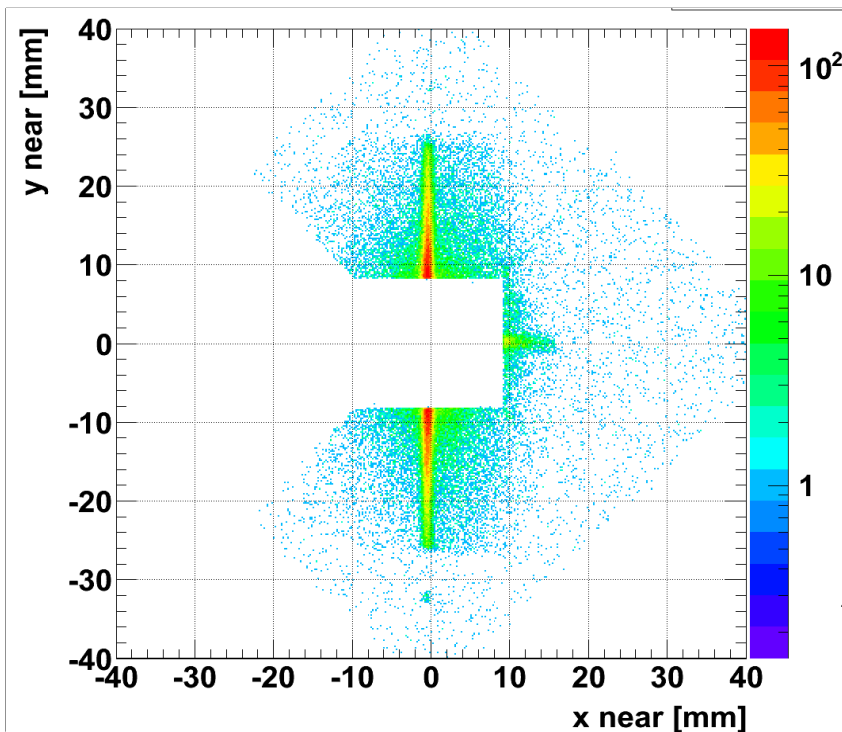
Low-t elastic pp scattering : cuts and data reduction

Integrated luminosity : 1.65 nb⁻¹

Topology:

- near and far units
- diagonals

| | |
|---|-----|
| Total triggers | 66k |
| Reconstructed tracks & elastic topology | 16k |



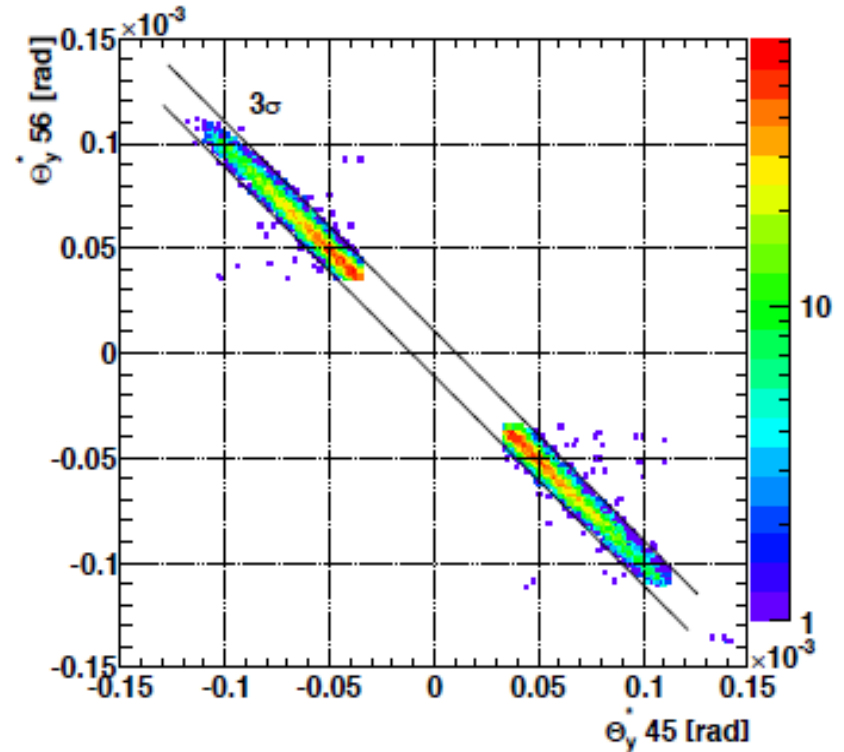
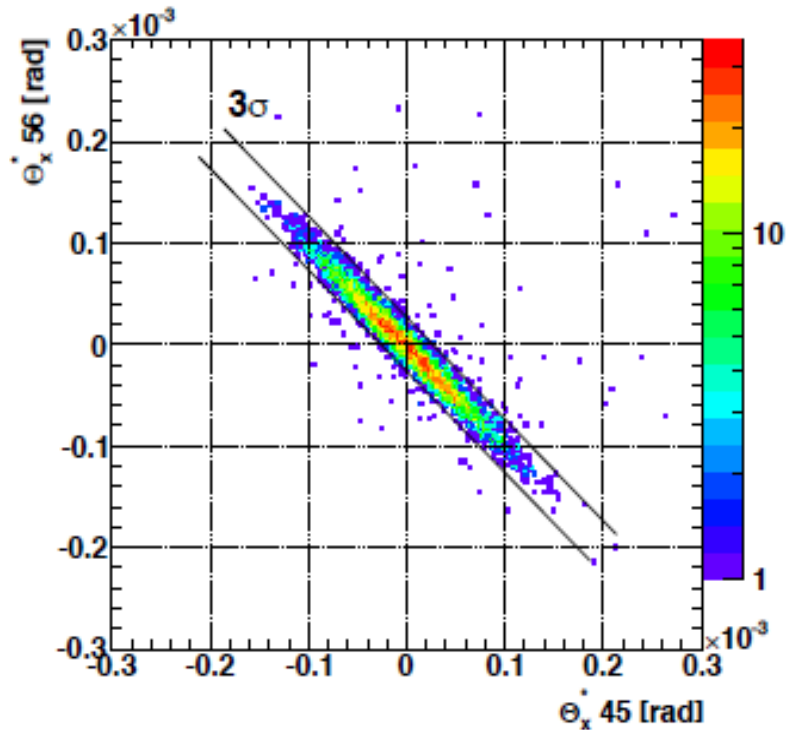


Low-t elastic pp scattering : cuts and data reduction

| | |
|---|-------|
| Total triggers | 70k |
| Reconstructed tracks & elastic topology | 16k |
| Collinearity cuts | 14.6k |

Elastic collinearity (3σ):

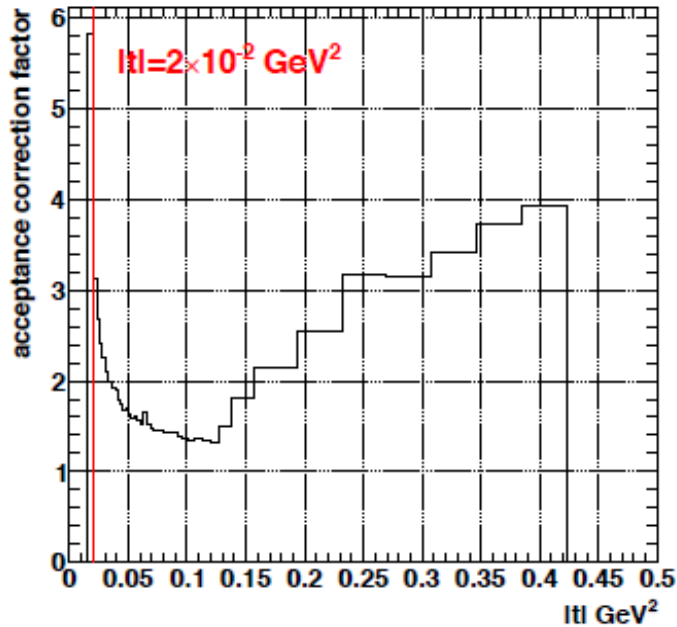
- $\theta_{x,45}^* \leftrightarrow \theta_{x,56}^*$
- $\theta_{y,45}^* \leftrightarrow \theta_{y,56}^*$





Low-t elastic pp scattering: corrections

Acceptance



Resolution:

$$\sigma(\theta_x^*) = \sqrt{1.7^2 (\text{beam div.}) + 4^2 (\text{det. res.})} = 4.4 \mu \text{ rad}$$

$$\sigma(\theta_y^*) = 1.7 (\text{beam div.}) \mu \text{ rad}$$

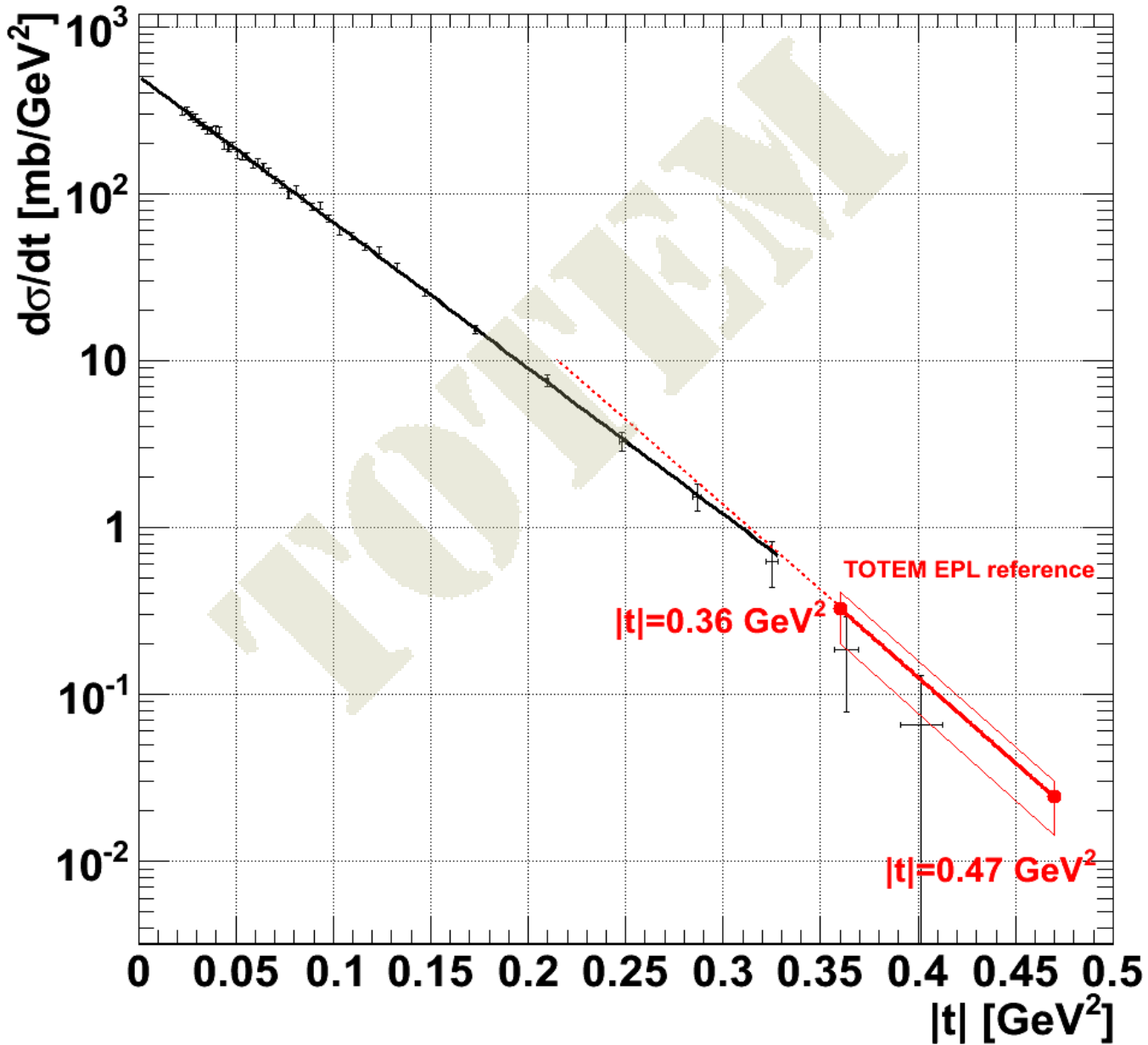
Luminosity: $\sim 4\%$

Background: negligible

Reconstruction efficiency : 91%

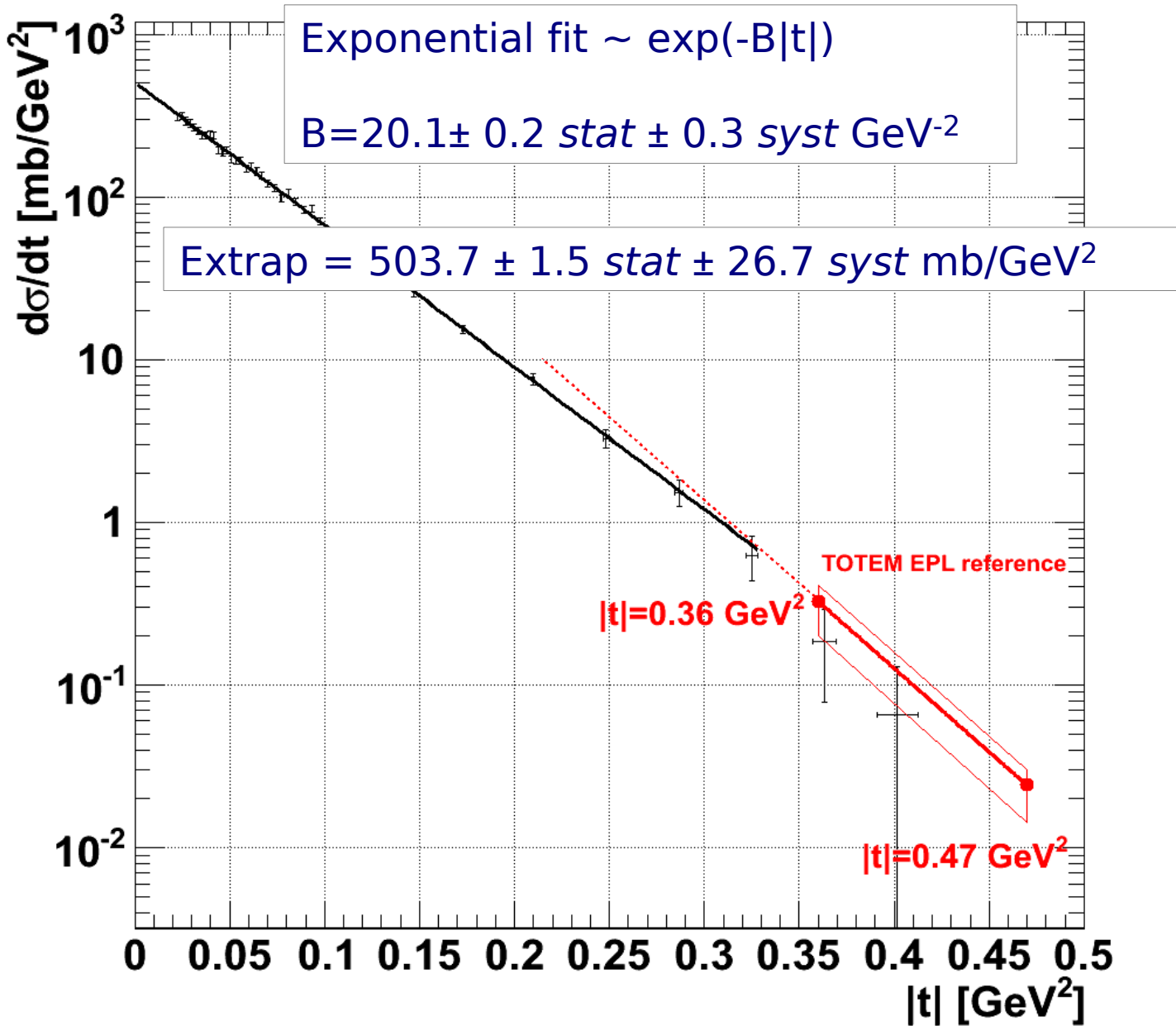


Low-t elastic pp scattering: cross section



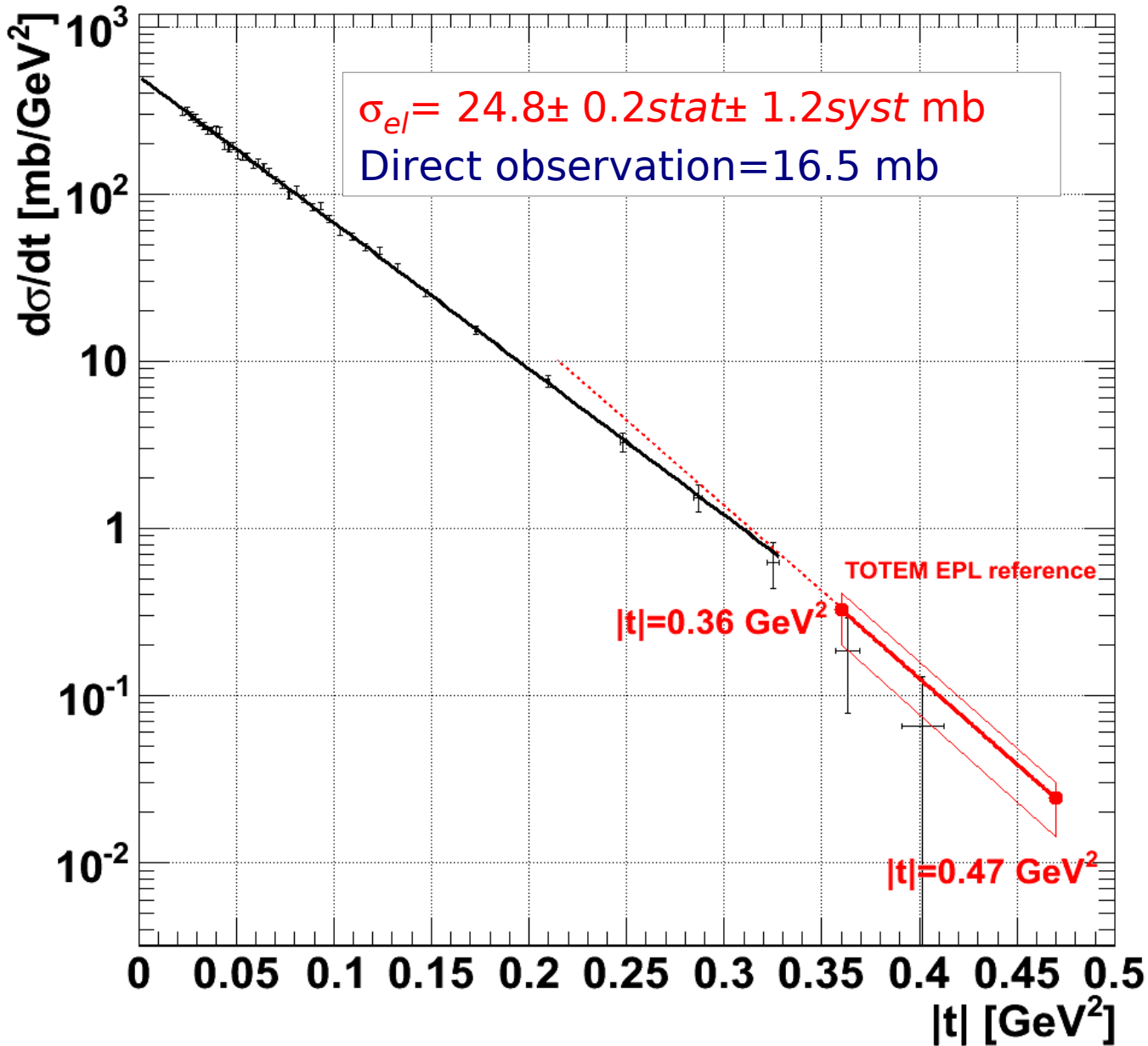


Low- t elastic pp scattering: cross section





Low-t elastic pp scattering: cross section





pp total cross section

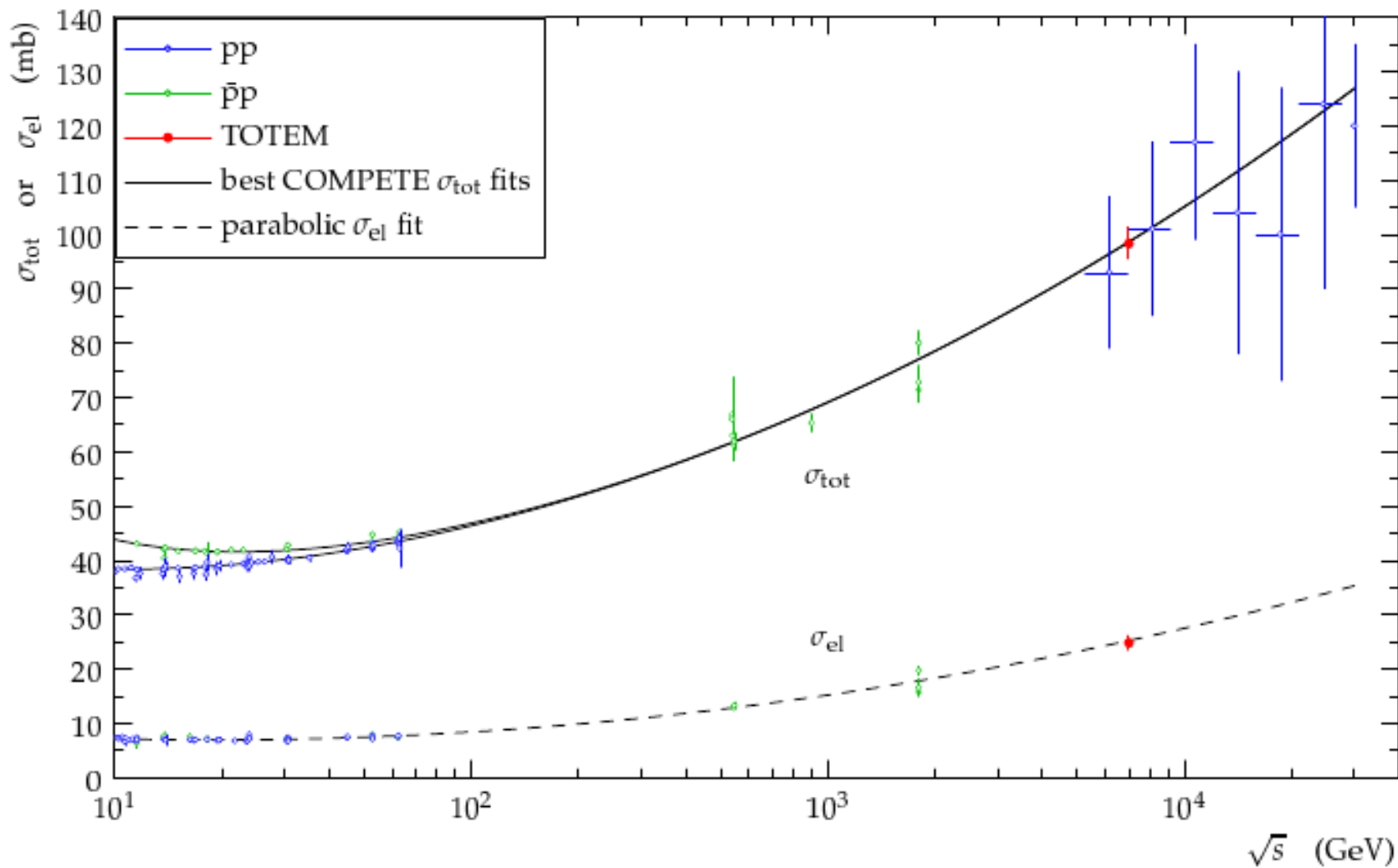
$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1 + \rho^2} \cdot \left. \frac{d\sigma_{el}}{dt} \right|_{t=0} = (98.3 \pm 0.2 \text{ stat} \pm 2.8 \text{ syst}) \text{ mb}$$

$$\rho = 0.14^{+0.01}_{-0.08} \text{ (Compete)}$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left(73.5 \pm 0.6 \text{ stat} \begin{matrix} +1.8 \\ -1.3 \end{matrix} \text{ syst} \right) \text{ mb}$$



pp total cross section





Outlook

Next analyses:

- 18σ 2010 data ($\sim 5 \text{ pb}^{-1}$)
- Double Pomeron Exchange, RP +T1 and T2 (2011 data - *low intensity runs*)
- T1, T2 Pseudorapidity distributions (including RP information)
- Multiplicity distributions and correlations
- Visible inelastic cross section

Data taking 2011

$\beta^* = 90 \text{ m}$ optics (next week) \rightarrow data for σ_{tot} luminosity indep. method

RP 220 m fully “validated” (14σ V, 17σ H in normal runs):
large- t elastic scattering, $\beta^*=1.0 \text{ m}$

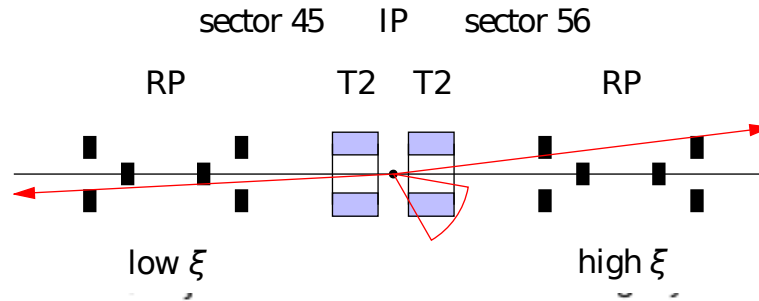
RP 147 m beam based alignment with data taking



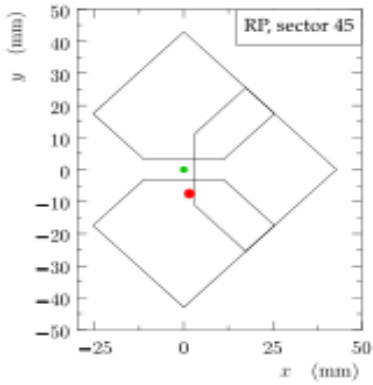
Backup



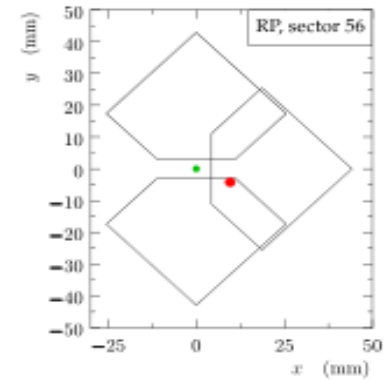
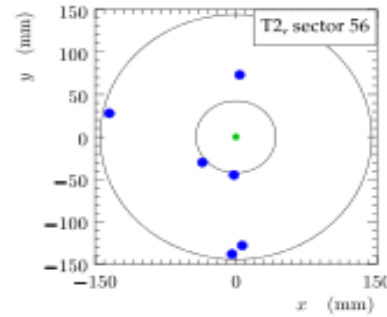
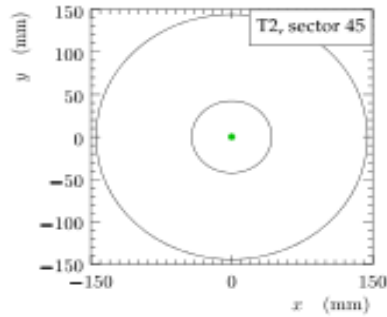
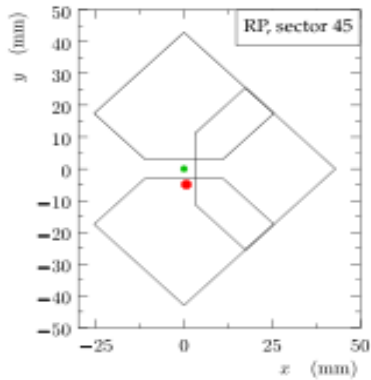
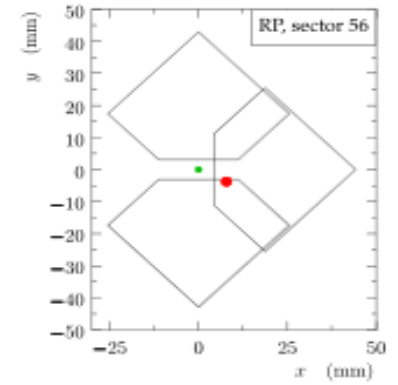
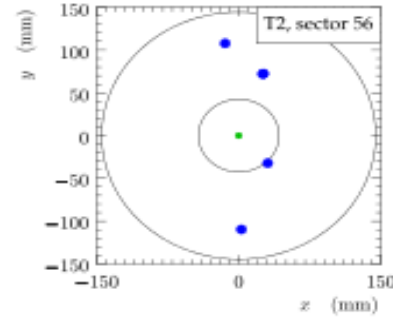
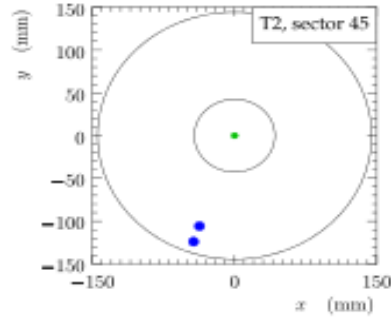
Double Pomeron Exchange



run: 37250009, event: 14125

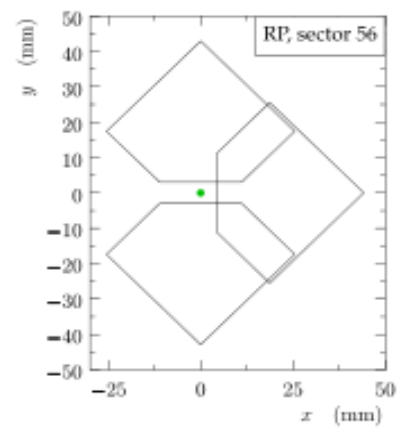
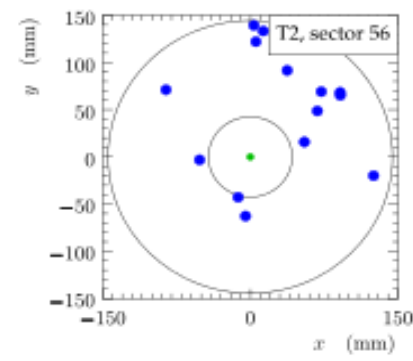
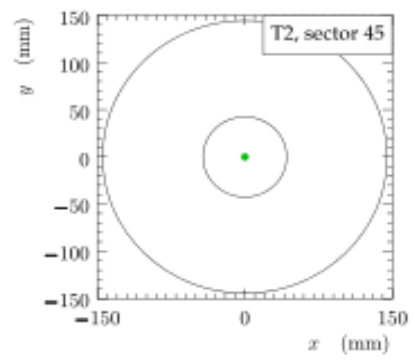
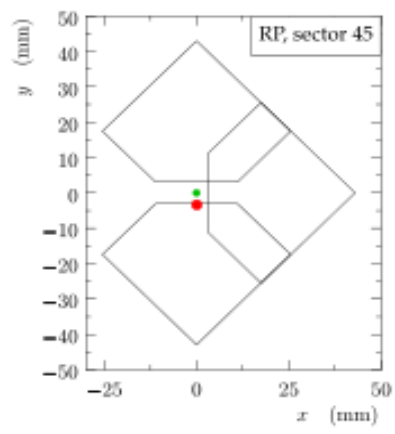
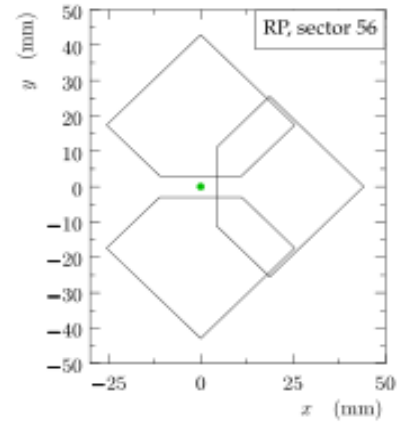
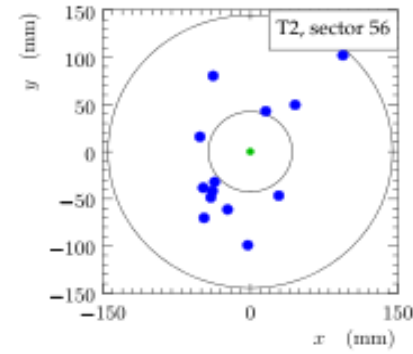
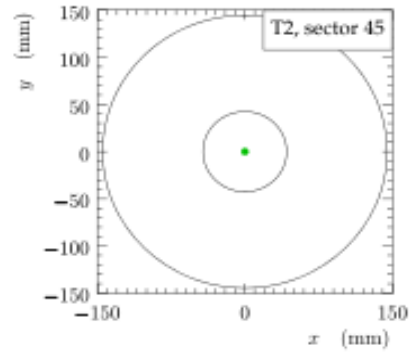
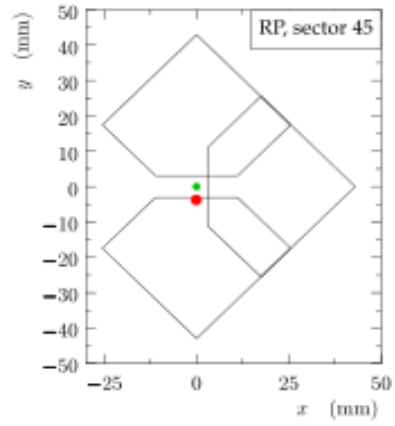
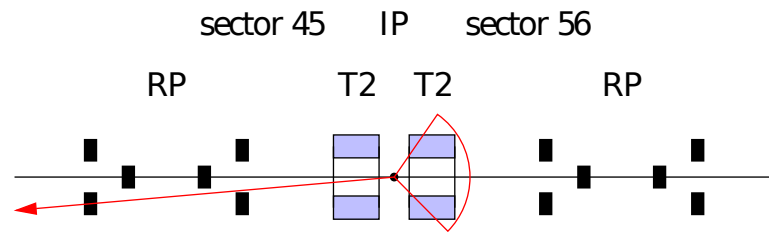


run: 37220007, event: 9904



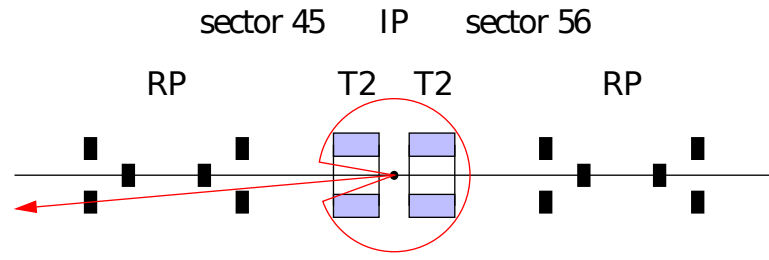


Single diffraction low ξ





Single diffraction large ξ



run: 37280006, event: 9522

