Results, Status and Perspectives for 2010/11

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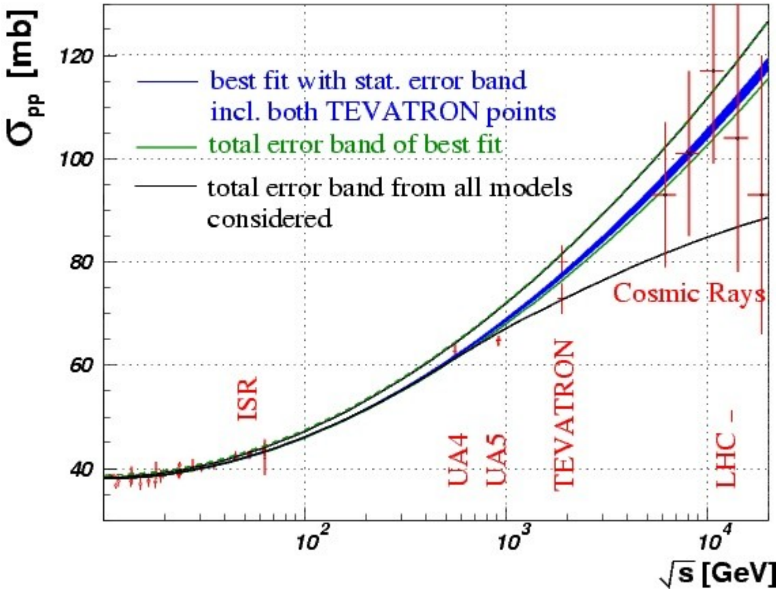
on behalf of the TOTEM Collaboration

Workshop on Hadron – Hadron & Cosmic-Ray Interactions at multi-TeV Energies

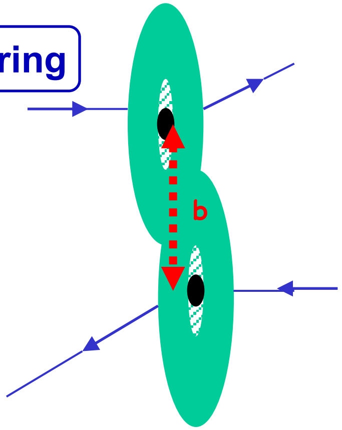
ECT* - Trento, Nov 29th – Dec 3rd, 2010

TOTEM Physics Overview

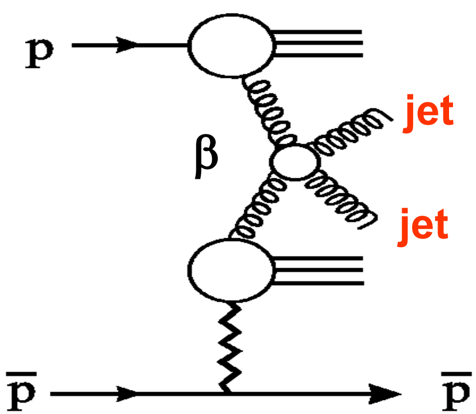
Total cross-section



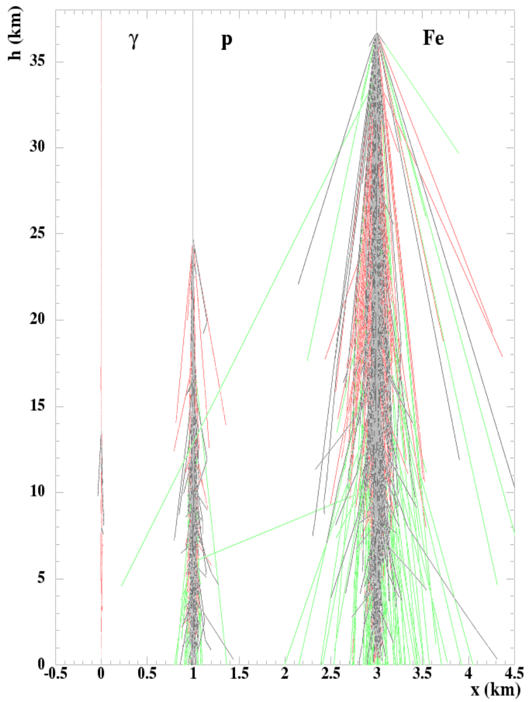
Elastic Scattering



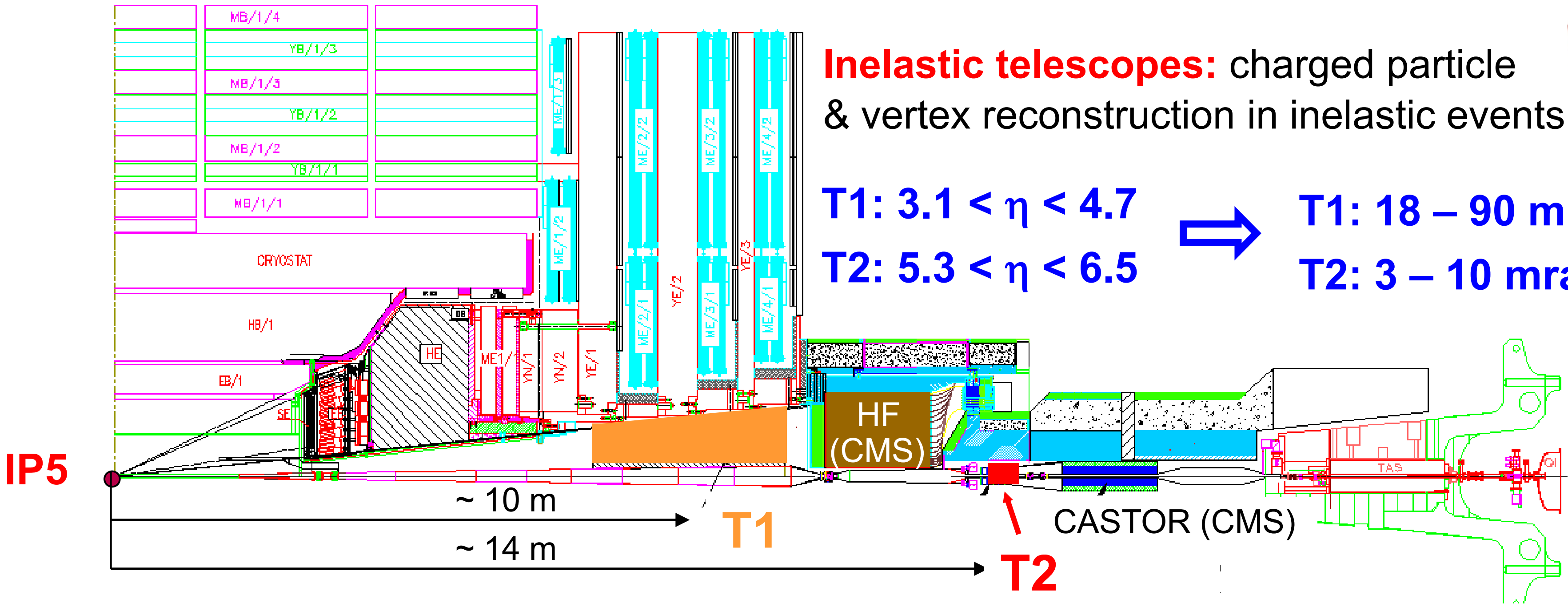
Diffraction: soft and hard



Forward physics



Experimental Setup @ IP5

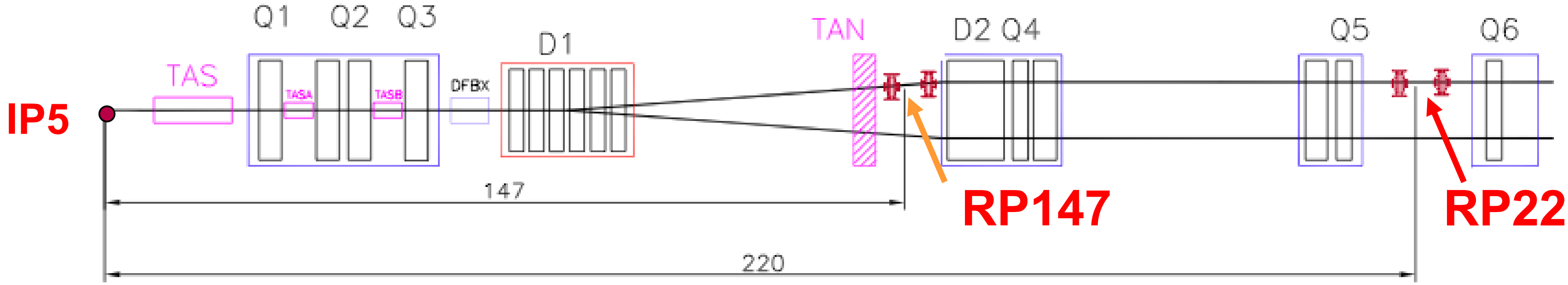


Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

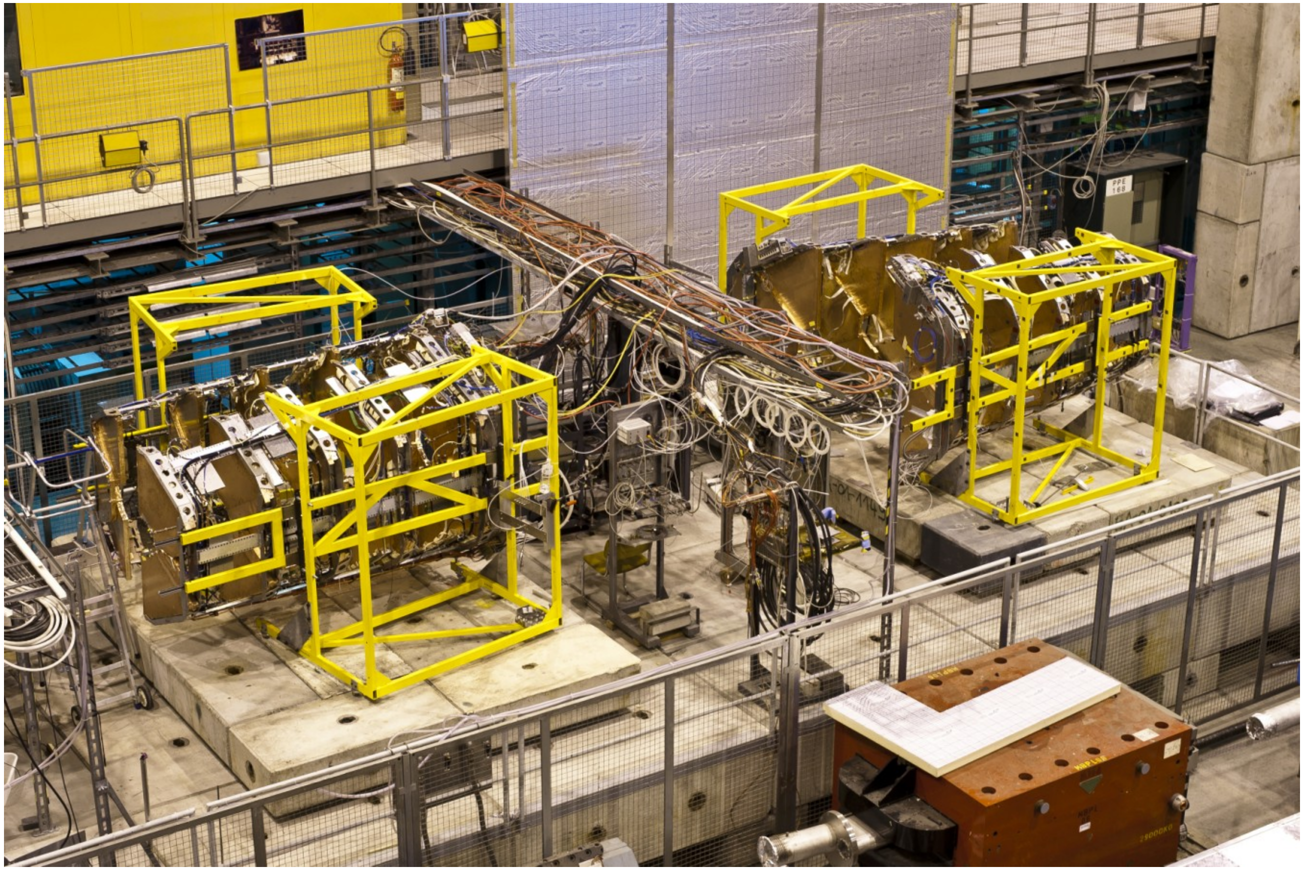
T1: 3.1 < η < 4.7 ⇨ **T1: 18 – 90 mrad**

T2: 5.3 < η < 6.5 ⇨ **T2: 3 – 10 mrad**

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



All T1 Modules Ready in the Test Beam Zone

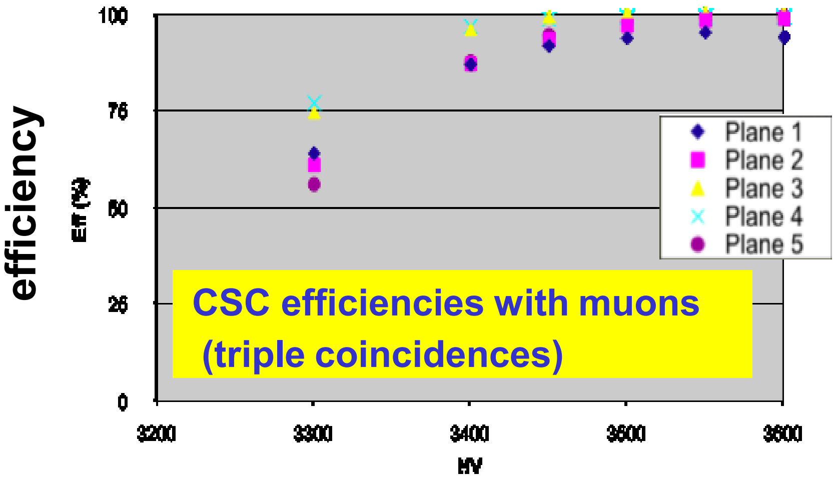


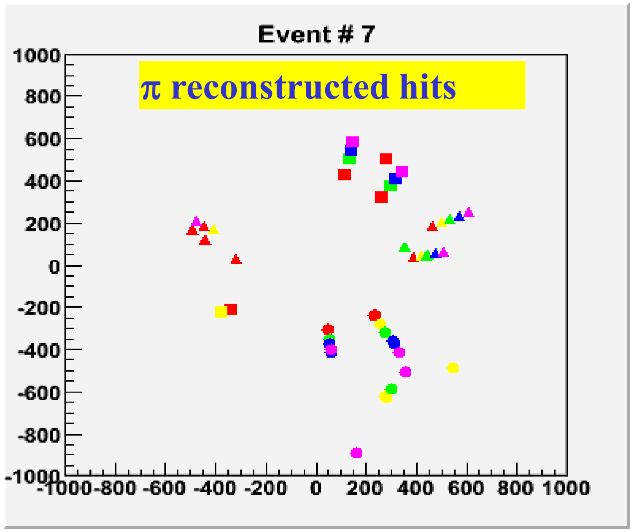
- Successfully tested with pion and muon beams in May – June
- Both arms are completely assembled and equipped in the test beam line H8.
- **Both telescope arms ready for installation**
- **TOTEM aims at the installation of both T1 telescope arms during the winter technical stop to enable first total cross-section measurements in 2011.**

T1 telescope performance

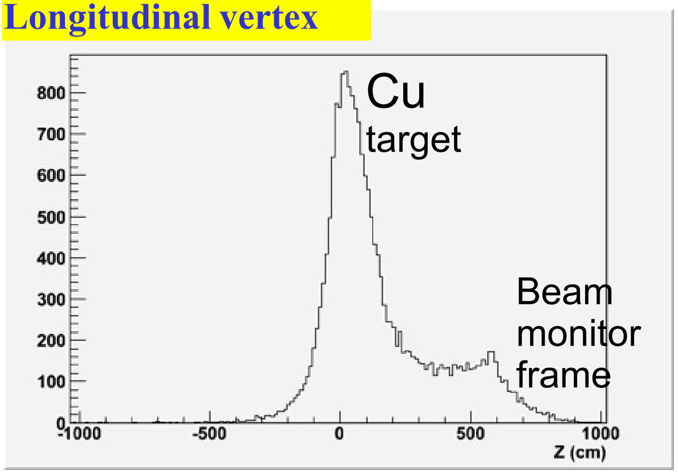
Both arms successfully tested with pion and muon beams

Pions on copper target to get many-tracks events

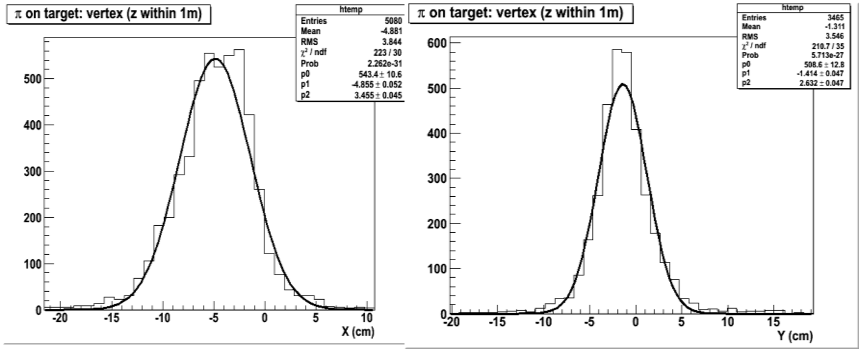




Longitudinal vertex



Transverse vertex

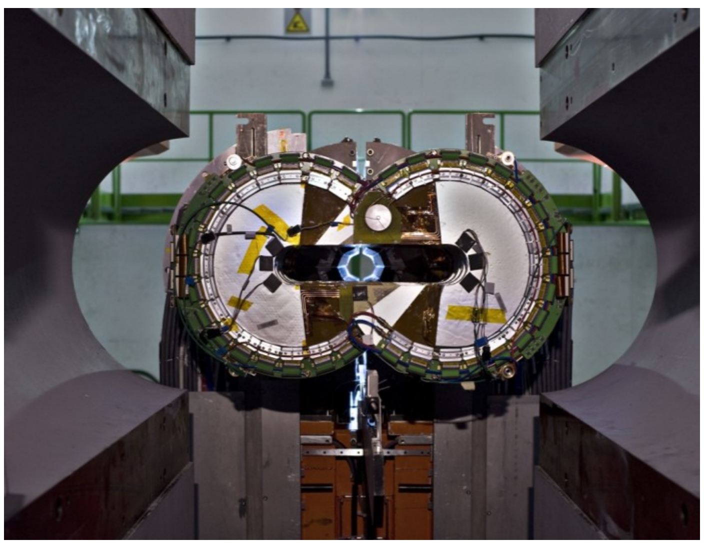


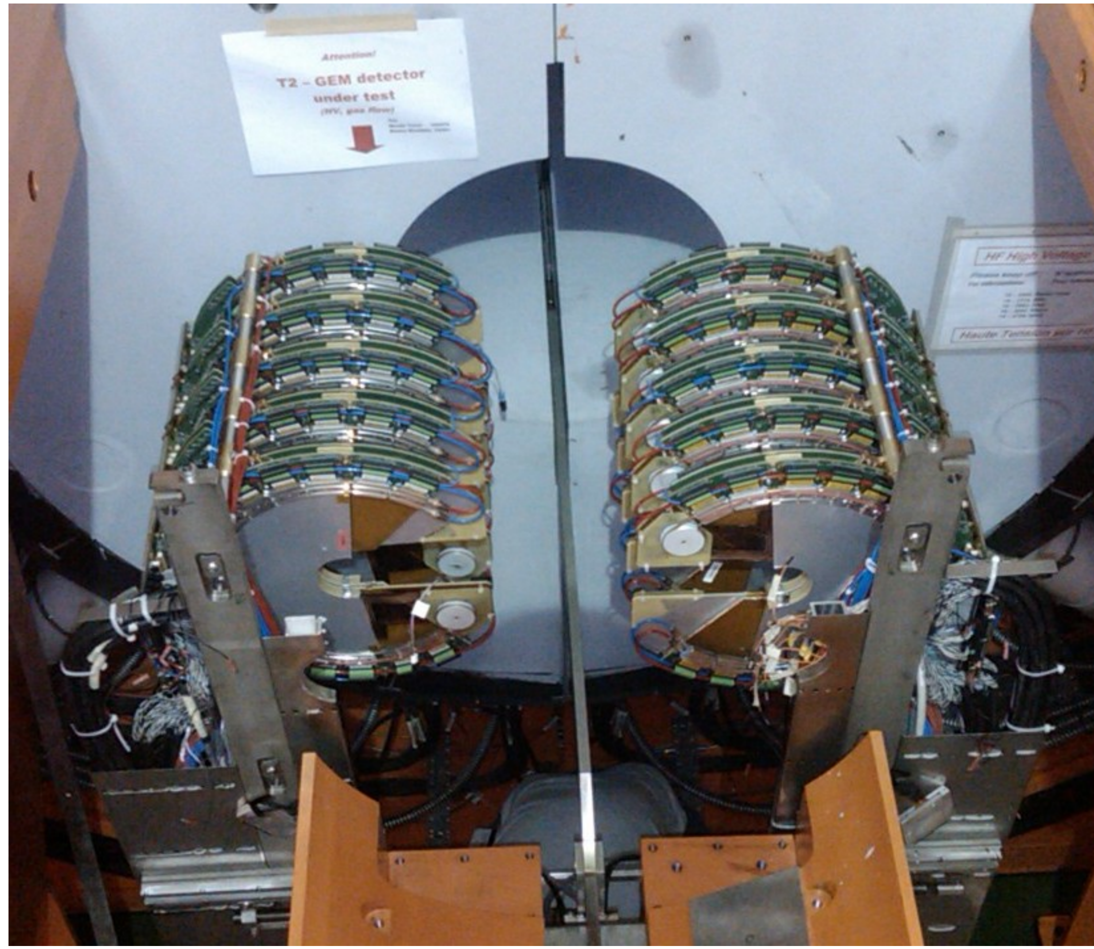
T2 Telescope

2 arms of GEMs for tracks and vertex reconstruction

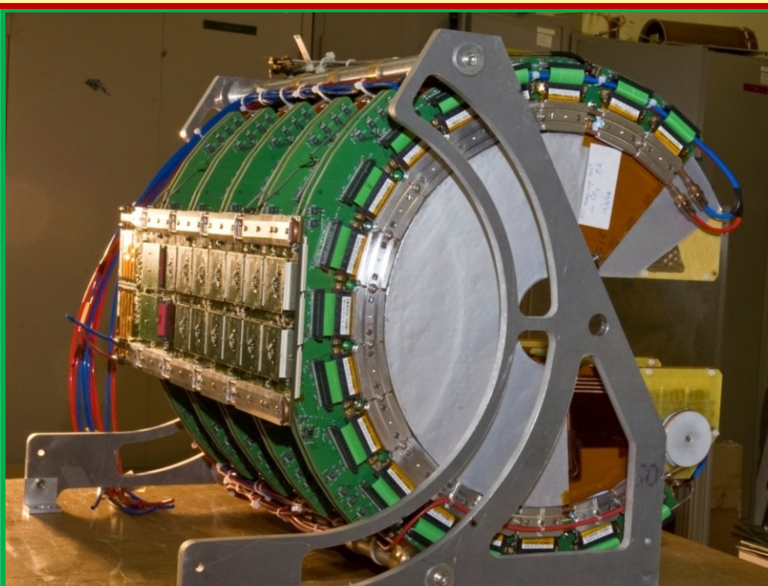
$5.2<|\eta|<6.5 \quad \Delta\phi=2\pi$

Both arms installed and taking data

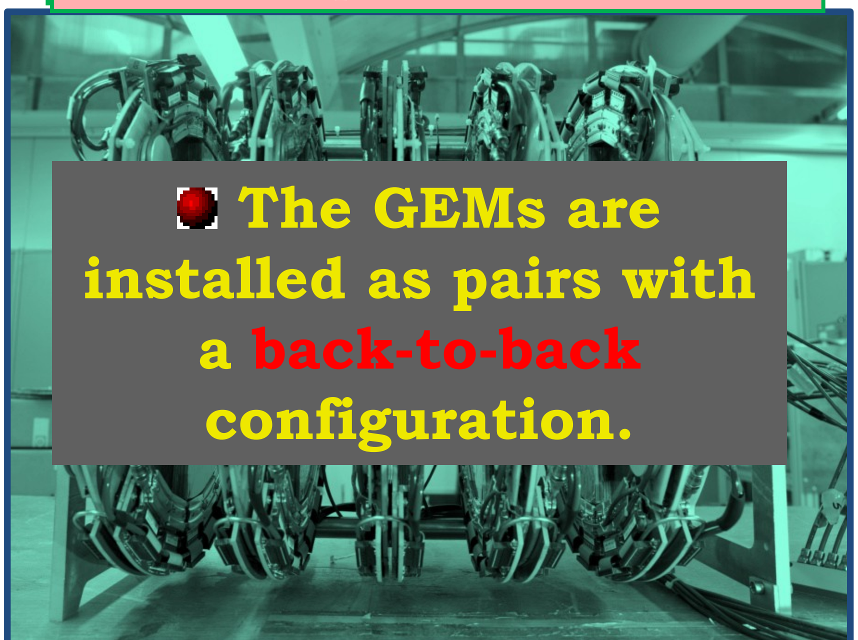




Installation of half T2 Telescope



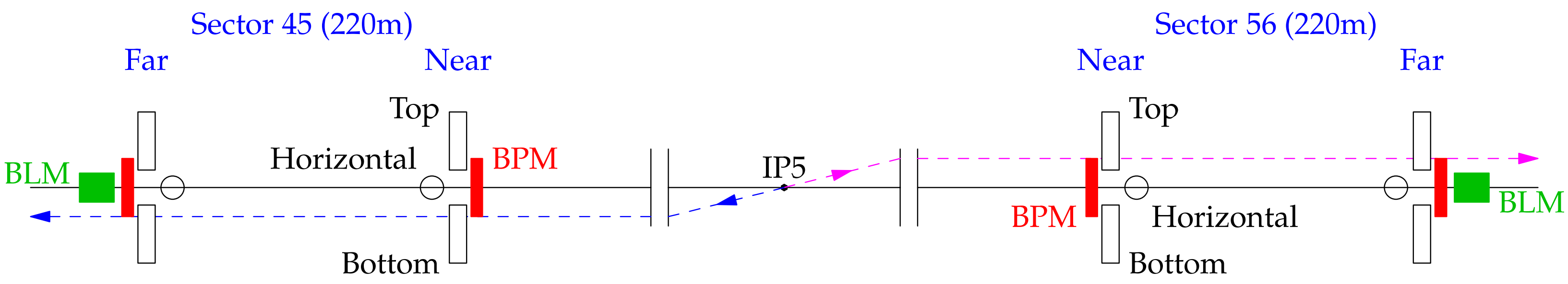
Half a telescope assembled in lab

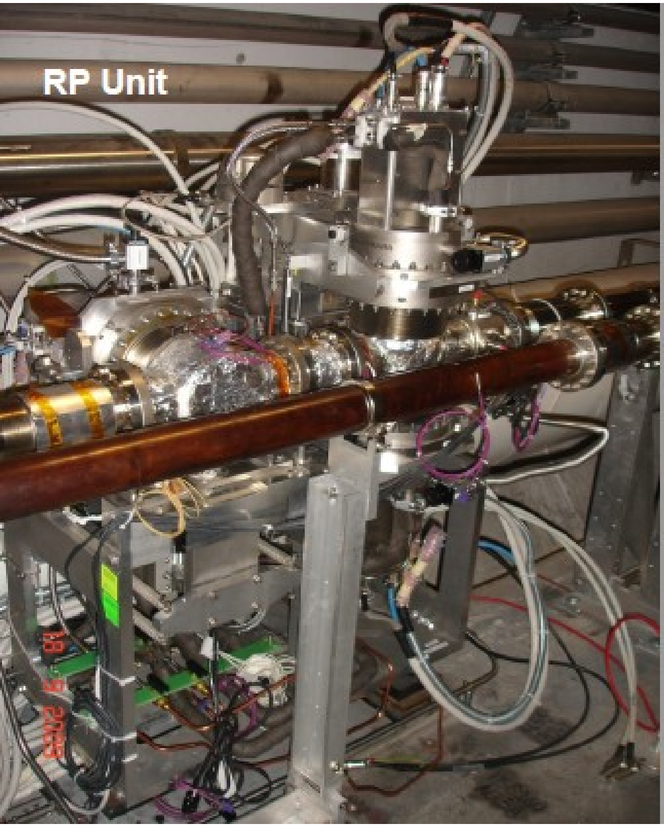


- The GEMs are installed as pairs with a **back-to-back** configuration.

Installation

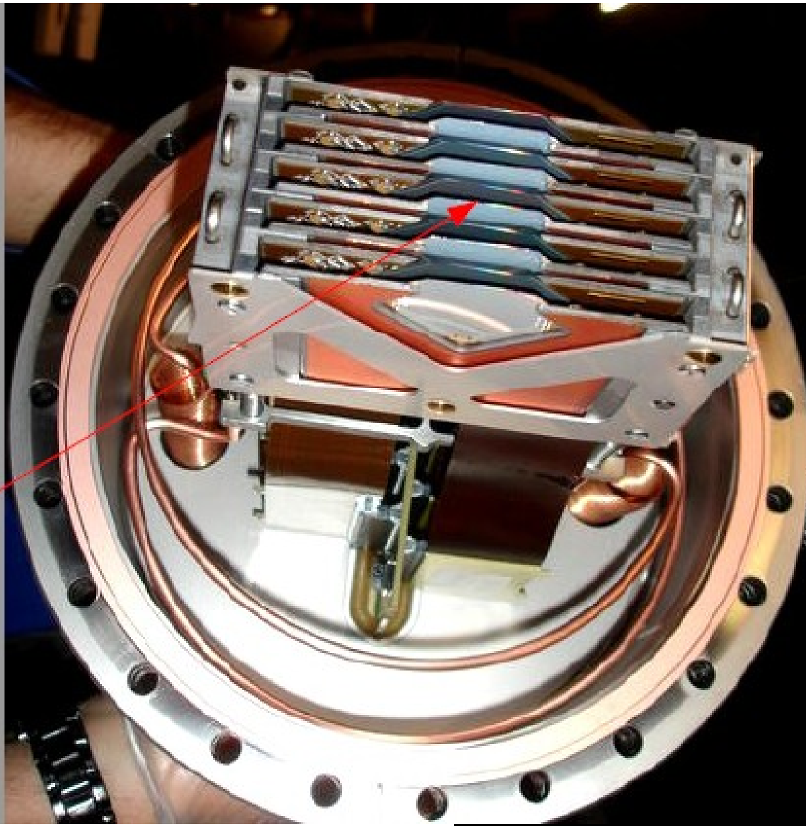
The Roman Pot System





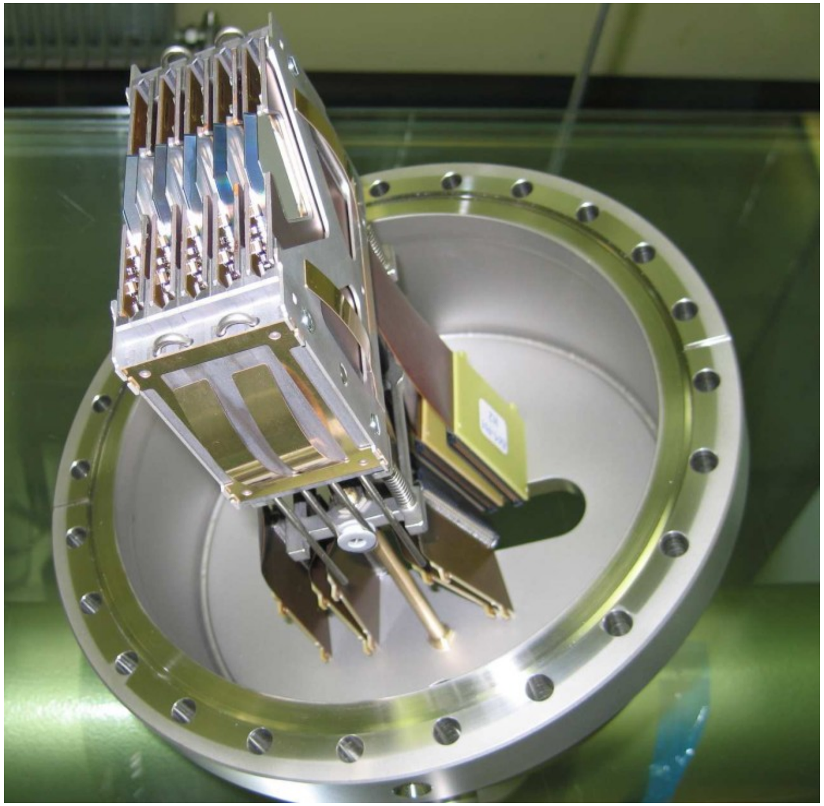
4 Stations
→ 2 Units
→ 3 pots
1 BPM
(Beam Position Monitor)

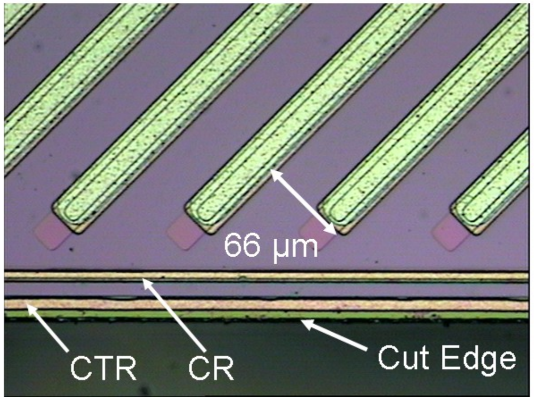
Edgeless Silicon Detectors



Roman Pot System

Roman Pot detector assembly

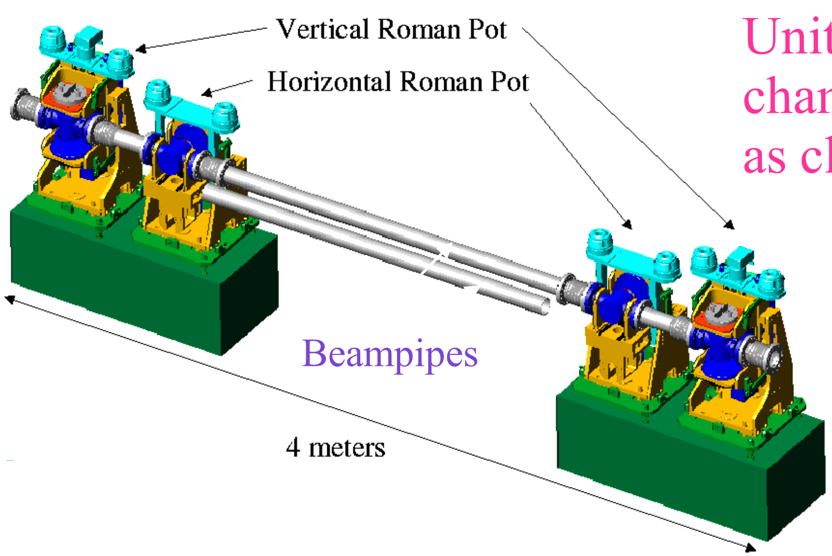




All 12 Roman Pots at ±220 m from IP5 are operational: delivering data with active triggers.

RP147 detector assemblies to be installed in winter technical stop.

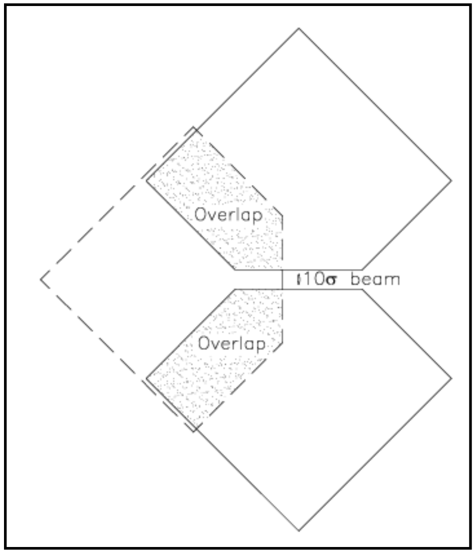
Until June: data were taken with RP220 in retracted position.

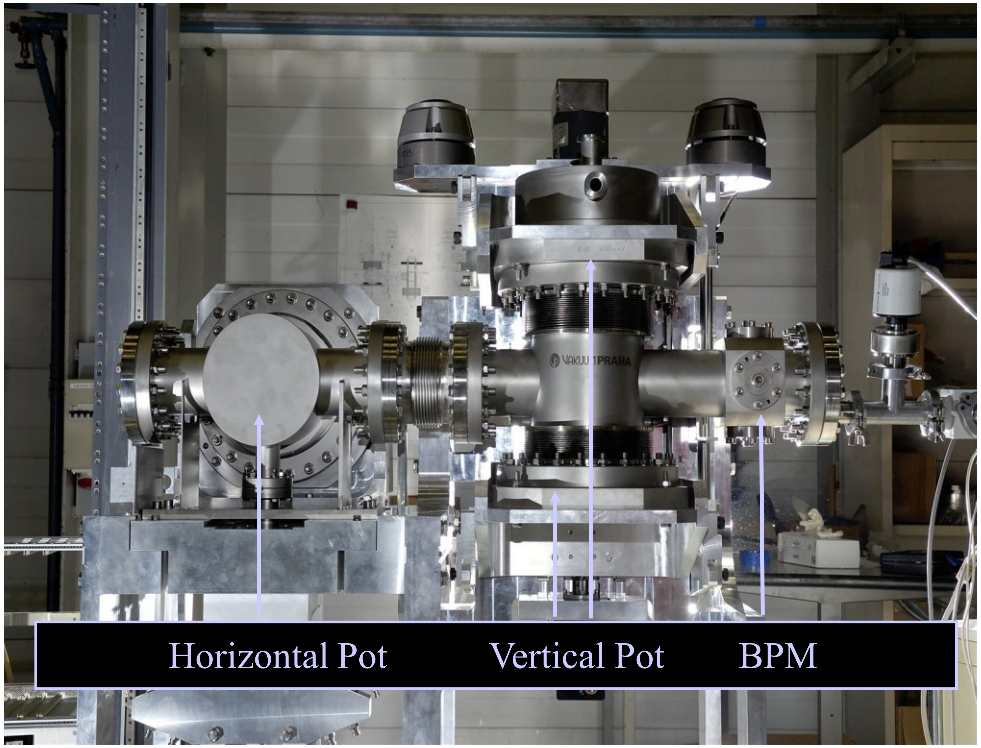


Units installed into the beam vacuum chamber allowing to put proton detectors as close as possible to the beam

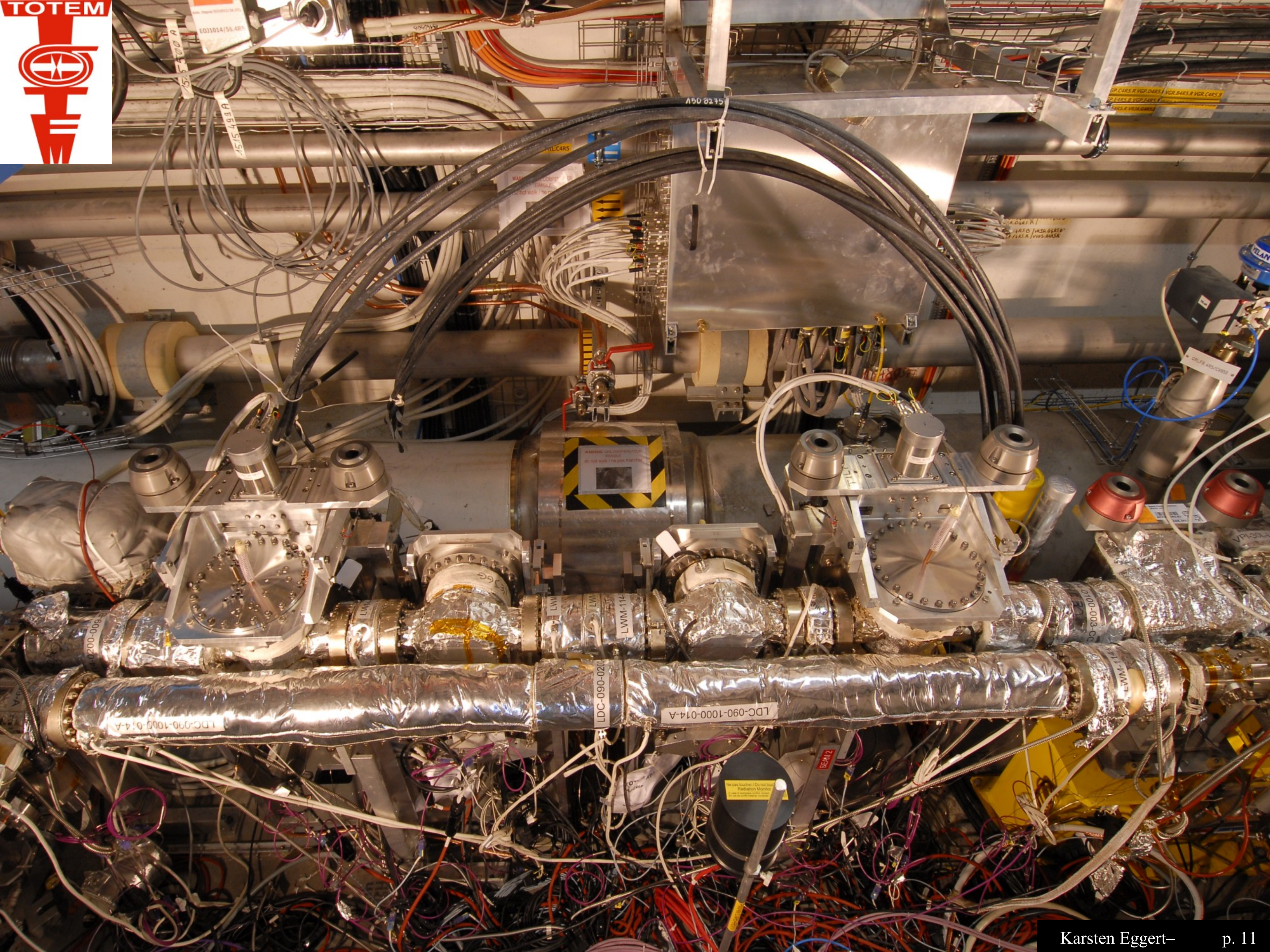
'Edgeless' detectors to minimize d

Each RP station has 2 units, 5m apart.
Each unit has 2 vertical insertions ('pots') and 1 horizontal





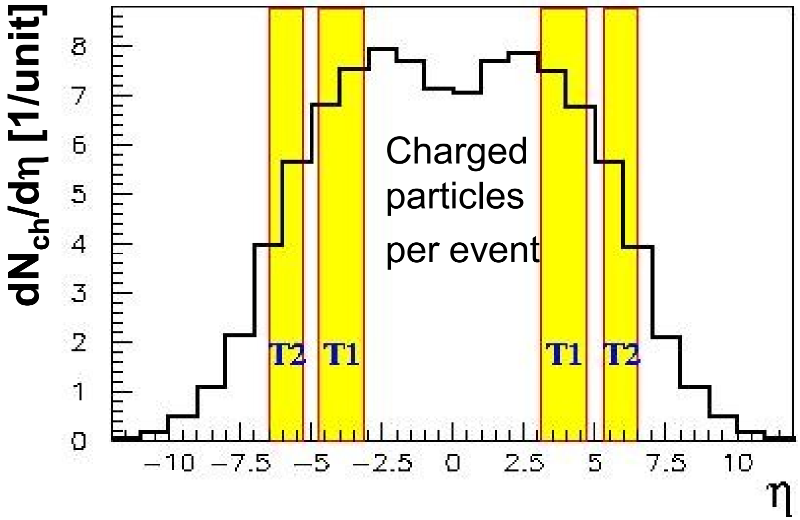
TOTEM



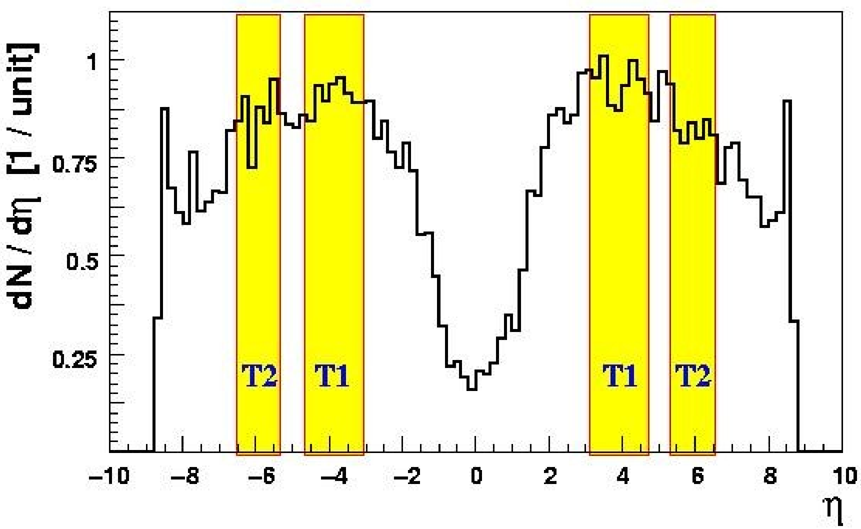
TOTEM: Acceptance

Inelastic Acceptance in η:

non-diffractive minimum bias events:

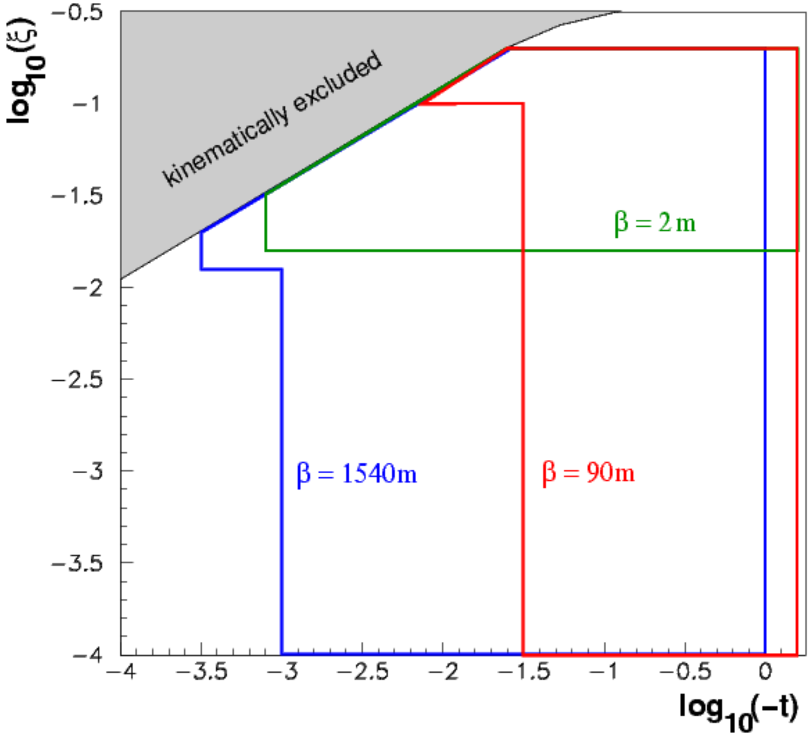


single-diffractive events:



Proton Acceptance in (t, ξ): ($\xi = \Delta p/p$)

(contour lines at A = 10 %)



$t = p^2 \delta^2$

$\xi = \Delta p / p$

All TOTEM detectors have trigger capability.

Overview 2010

30.03.	first T2 run: tracks seen	
April	T2 commissioning with beam, RP comm. in garage position, bunch-crossing trigger	
21.04.	first tracks in RPs in garage position, active trigger	
15.05.	first T2 data with squeezed optics	$\beta^* = 2$m 2 b., 2e10 p/b
25.06.	RP beam-based alignment	450 GeV, $\beta^* = 11$m 1 b., 3e10 p/b later 9e10 p/b
04.07.	first T2 data with nominal bunches	$\beta^* = 3.5$m, 1e11 p/b (nom.)
13.–14. 07.	RP insertion to 30 σ in stable beams	8 nom. b.
15.07.– 04.08.	RP insertion to 25 σ (V) and 30 σ (H) in stable beams	8 – 16 nom. b.
09.08.	partial RP beam-based alignment	3.5 TeV, 1 nom. b.
11.08.	RP loss map measurement to qualify 20 σ settings	
18.08.	first RP insertion to 20 σ (V) and 25 σ (H)	16 nom. b.

1.5 nb^{-1}
→ first 2 elastic candidates

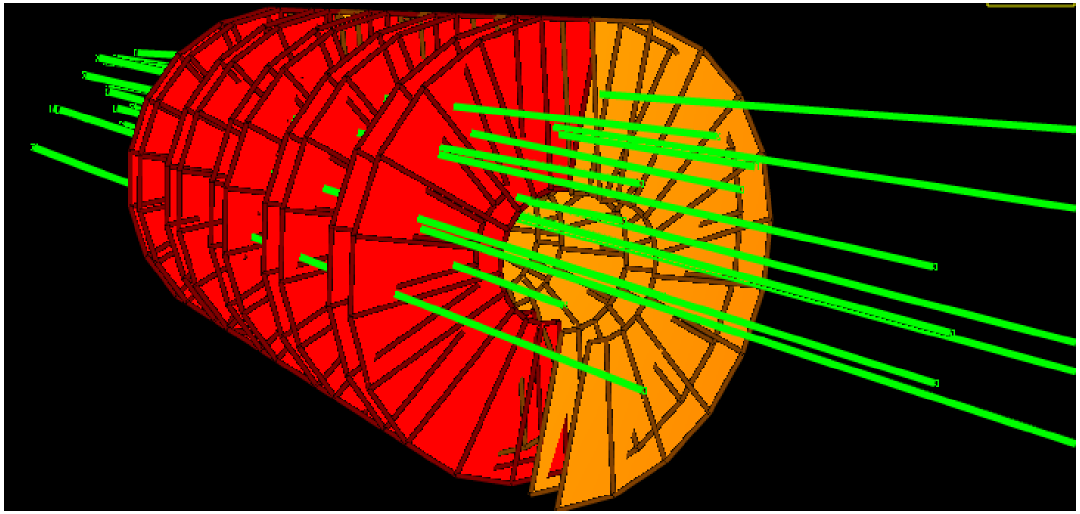
Overview 2010 (continued)

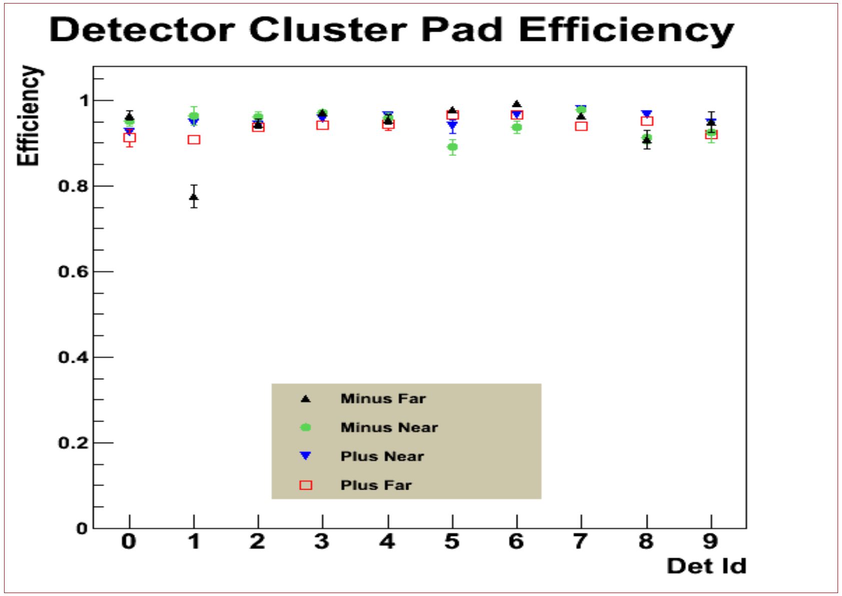
24.-26. 08.	RP insertions to 20 σ (V) and 25 σ (H)	16 nom. b.	184.6 nb^{-1}
21.09.	RP beam-based alignment and run at 7 σ	1 nom. b.	0.88 nb^{-1}
28.09. - 28.10.	RP insertions to 18 σ (V) and 20 σ (H)	93 – 348 nom. b.	3867.1 nb^{-1}
30.10.	special run: RPs inserted to 7 σ (V) and 16 σ (H) pileup-free data for T2 (trigger on pilot) common run RP + T2	1 pilot b. (1e10) + 4 b. x 7e10 p/b.	8.6 nb^{-1}

Total:

25 σ	1.5 nb^{-1}
20 σ	185 nb^{-1}
18 σ	3867 nb^{-1}
7 σ	9.5 nb^{-1}

T2

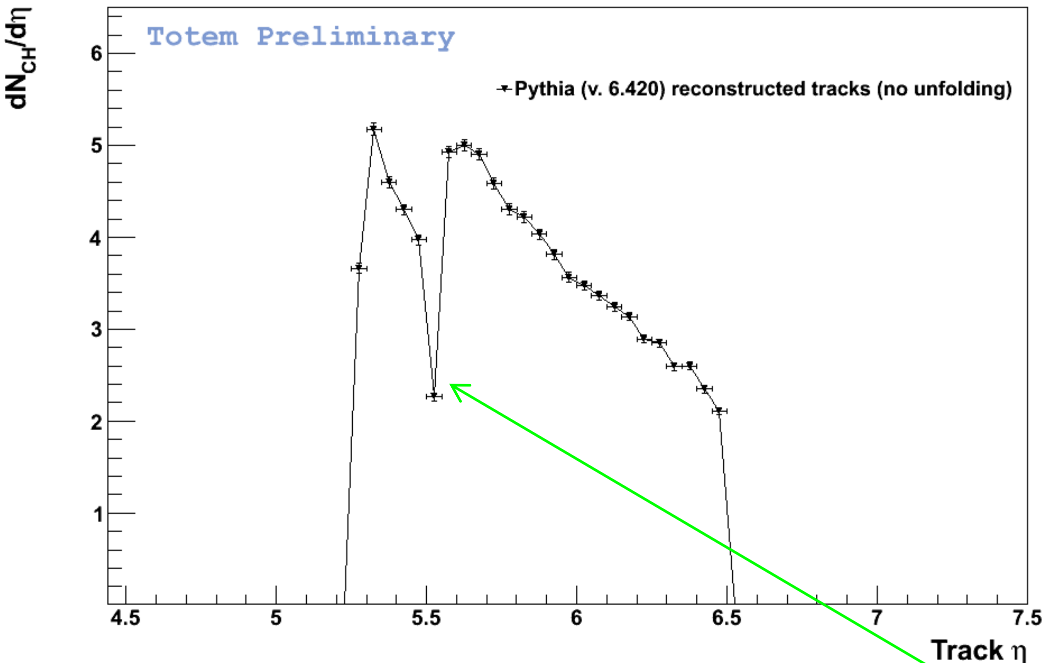




Fully installed, operative and commissioned on data

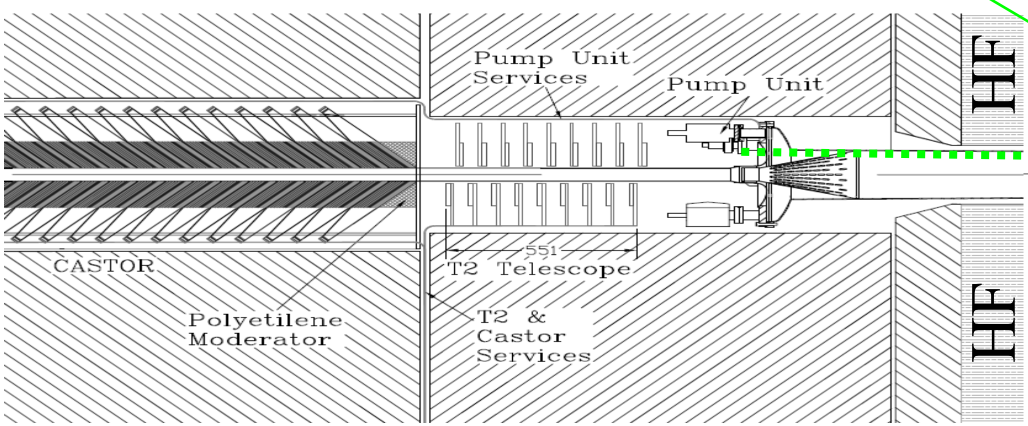
Preliminary studies with Pythia + full Geant detector simulation

Track $dN_{CH}/d\eta$ (Statistical error only)



Work in progress on:

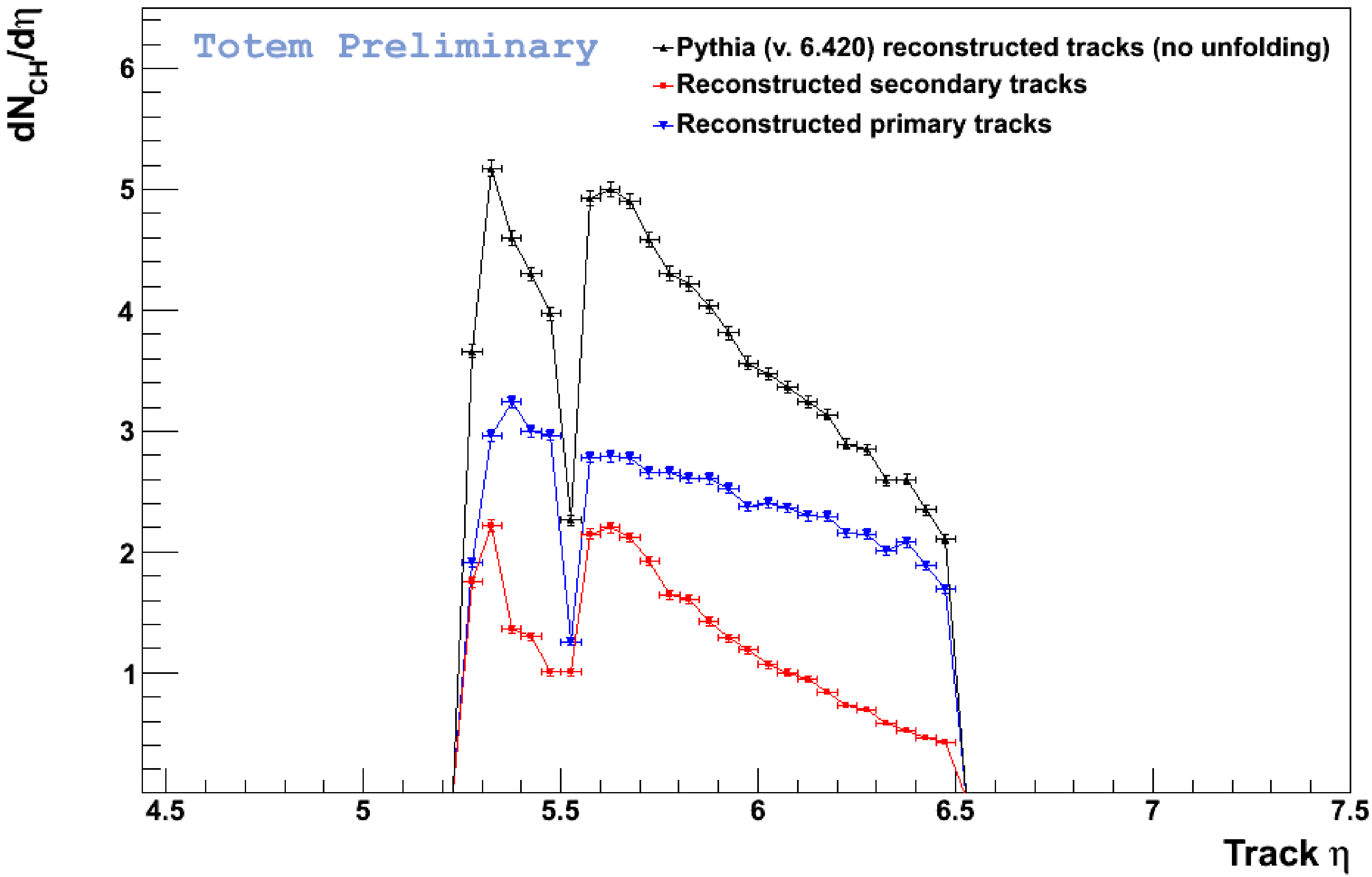
- Understanding secondary contribution and smearing effects
- Proper tuning of detector performance simulation
- Optimization of trk algorithm and selection cuts for improved rejection of secondary charged tracks,
- Estimation of systematic uncertainties



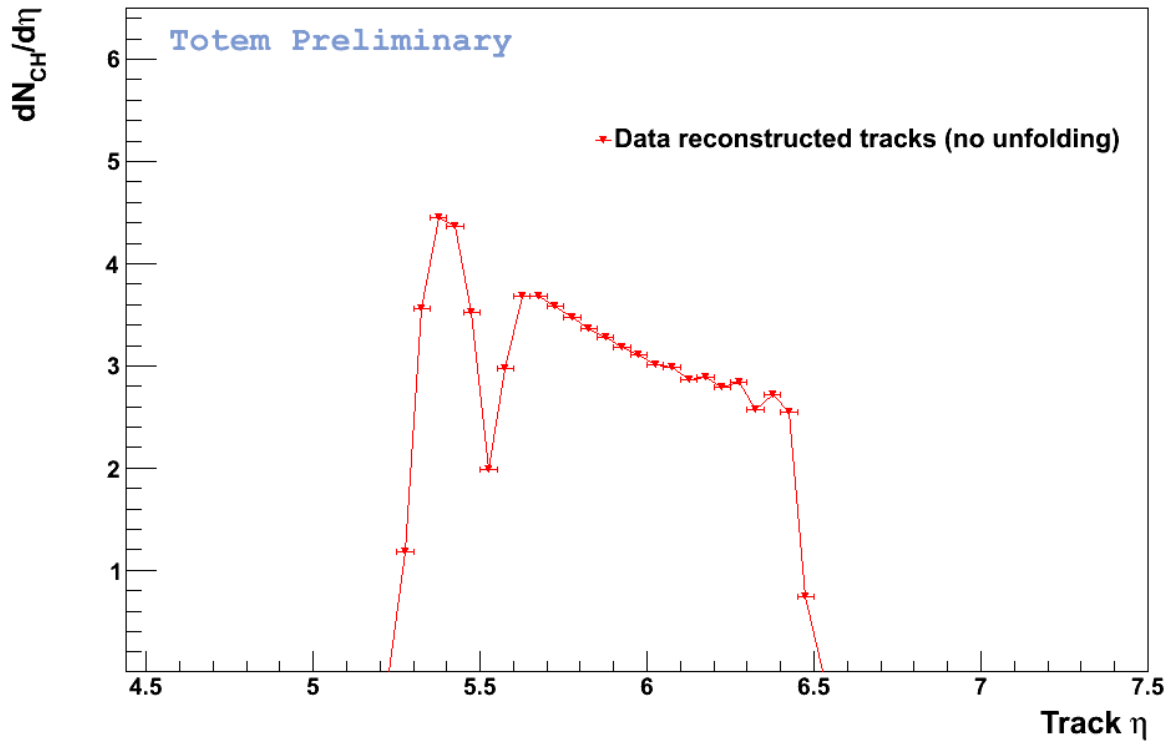
IP5

Beam Pipe cone at η ~ 5.54 (>100 radiation lengths)

Track $dN_{CH}/d\eta$ (Statistical error only)



Track $dN_{CH}/d\eta$ (Statistical error only)



400K inelastic events from dedicated run with low proton density bunches.

“Raw” distribution:

- No smearing corrections
- No efficiency corrections
- No secondaries contribution subtraction

Work ongoing on unfolding corrections

Collimation-Based Roman Pot Alignment w.r.t. the Beam Centre

Alignment is the central problem of Roman Pot measurements

LHC collimation system produces sharp beam edges

→ used to align Roman Pots and to determine the centre of the beam

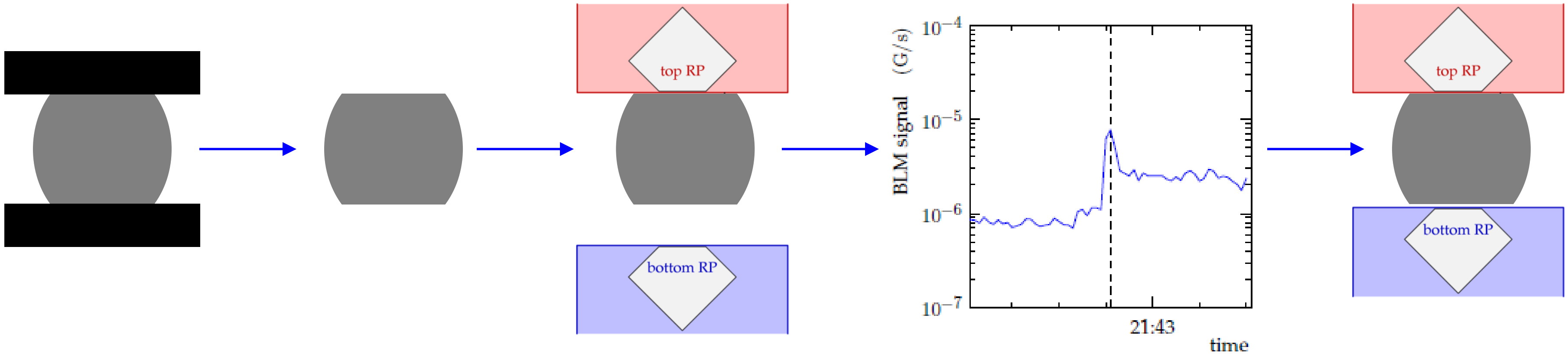
(same procedure as collimator setup)

Collimator cuts a sharp beam edge symmetrically to the centre

RP approaches this edge until it scrapes

produces spike in Beam Loss Monitor downstream

second RP approaches



When both top and bottom pots "feel" the edge:

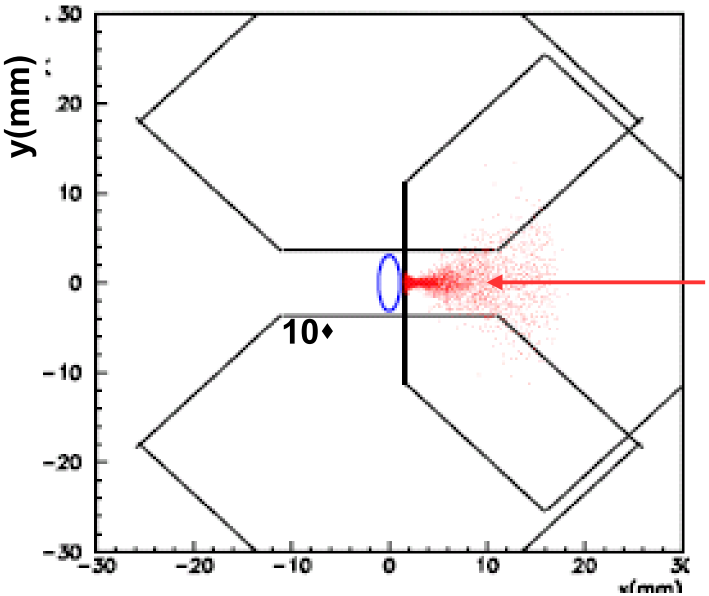
- they are at the **same number of sigmas** from the beam centre **as the collimator**
- the beam centre is exactly in the middle between top and bottom pot

Measurement of Forward Diffractive and Elastic Protons: the principle

Hit distribution @ RP220

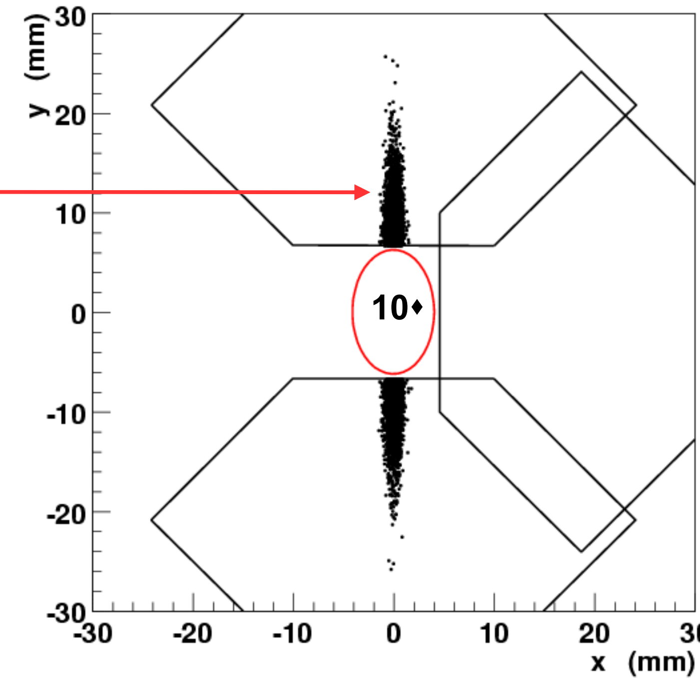
Diffractive protons
low ♌ = 0.5 - 2 m

elastic scattering
high ♌ 🖬 ~◉0 m



$y \sim$ ✈$_y^{scatt} \sim |\, t_y \,|^{1/2}$

x ~ ⌧🖬☟p/p



Detect the proton via:

its momentum loss (low ♌)

its transverse momentum (high ♌)

Detector requirements:

To approach the beam as close as possible: almost edgeless detectors

Reliable movement system with solid mechanical stability for reproducible alignment

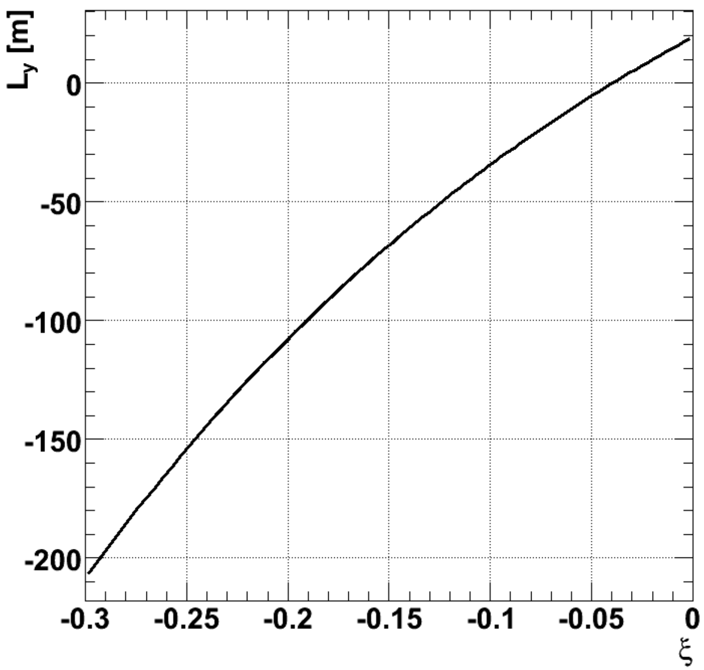
high resolution of typically 20μm

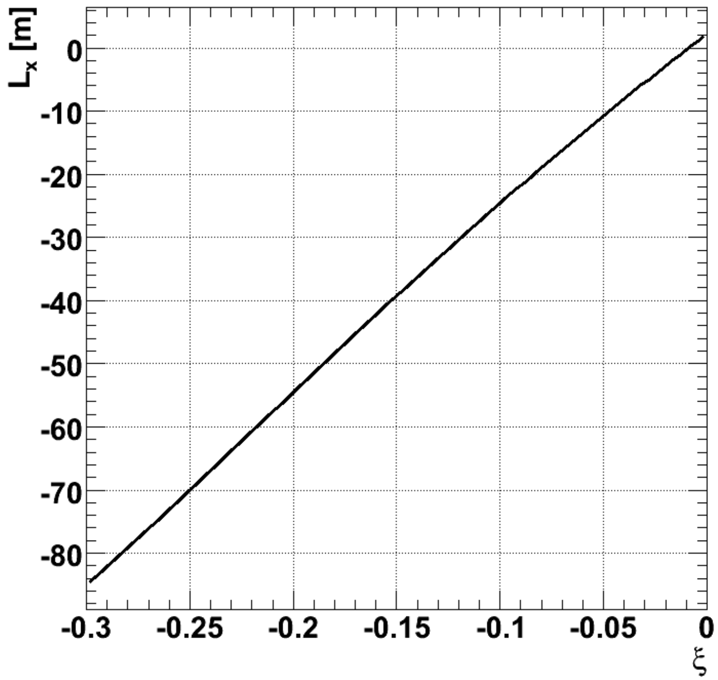
Trigger capability with large flexibility

LHC Optics

$$x(s) = L_x(s,\xi)\,\theta_x^* + v_x(s,\xi)\,x^* + D_x(s,\xi)\,\xi$$
$$y(s) = L_y(s,\xi)\,\theta_y^* + v_y(s,\xi)\,y^* + D_y(s,\xi)\,\xi$$

$$\xi = \frac{\Delta p}{p}$$



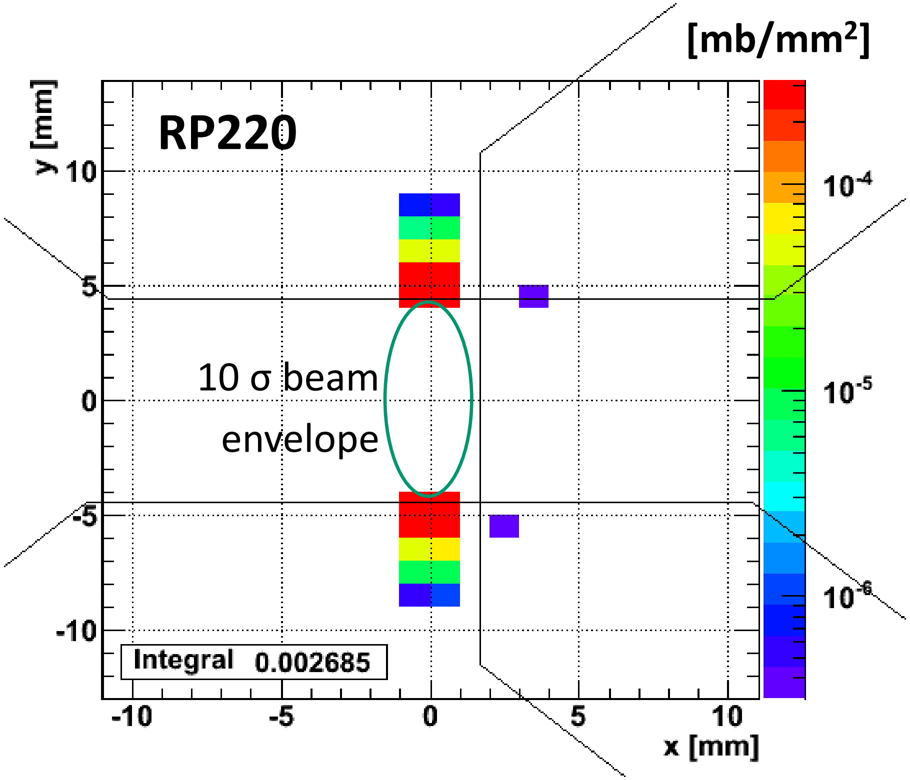


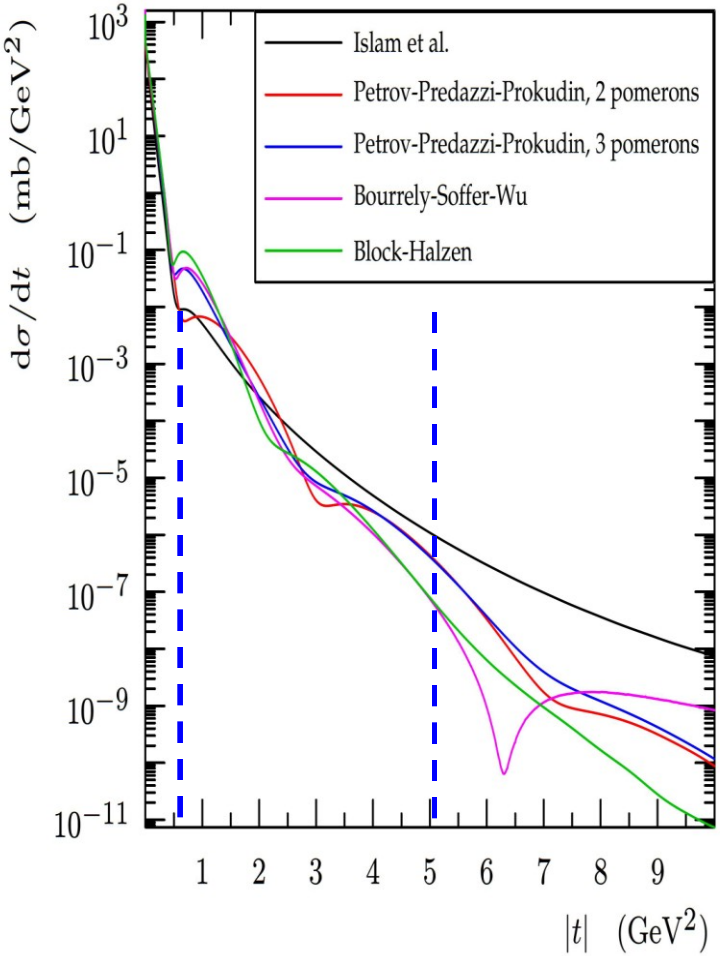
Large Chromaticity effects

Physics with RP detectors

Elastic scattering, $\sqrt{s}$ = 7 TeV, β^* = 2 m

Elastically scattered proton flux





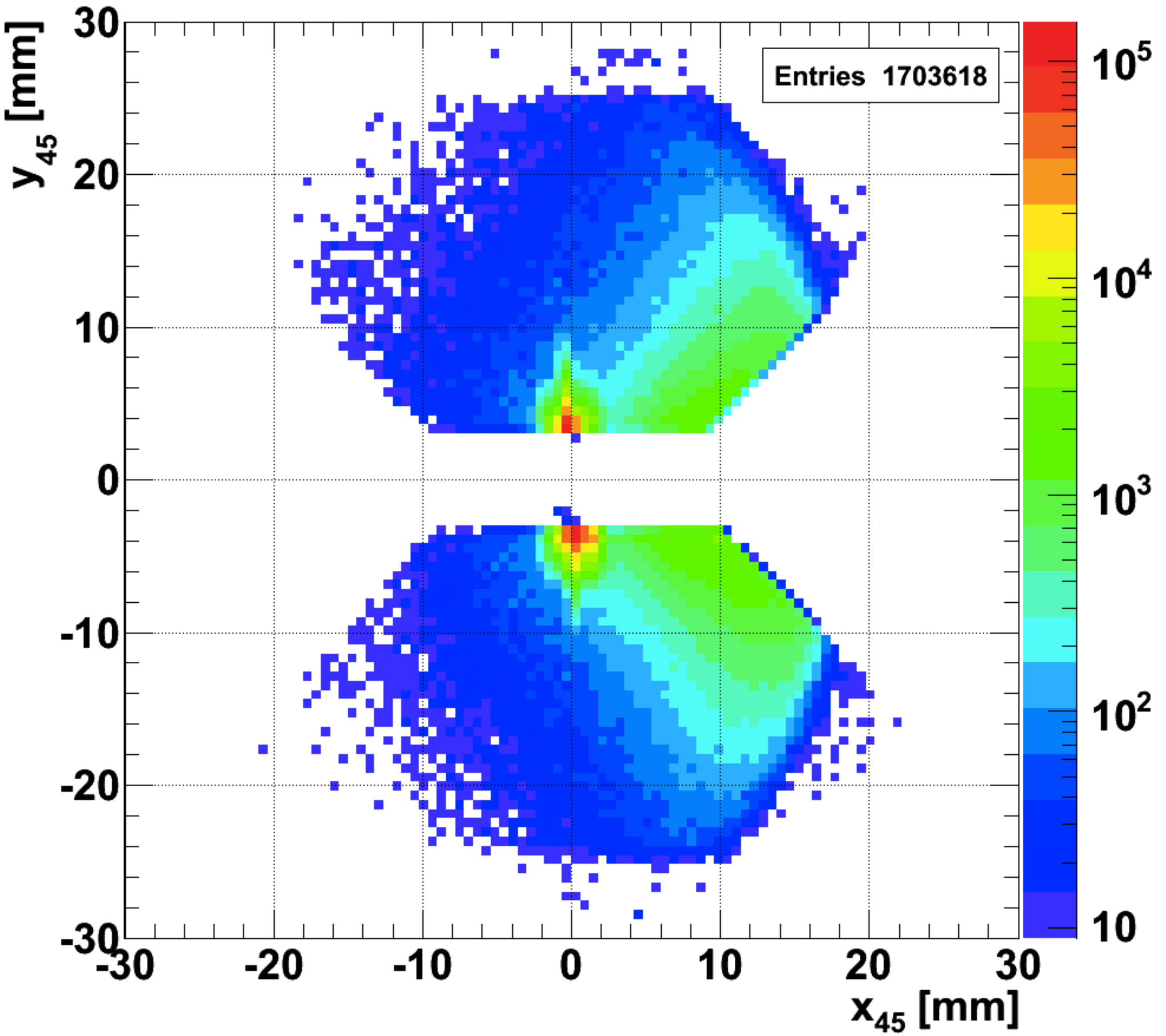
Vertical RPs contain all events

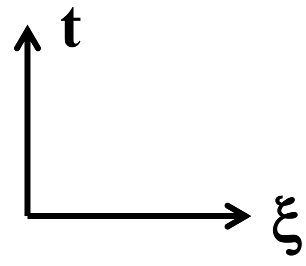
$\sigma(|t|)$ = 0.1 – 0.5 GeV² ($\propto\sqrt{|t|}$)

PPP3, 3 pomeron **model:** $\sigma_{acc} \approx$ **4 µb**

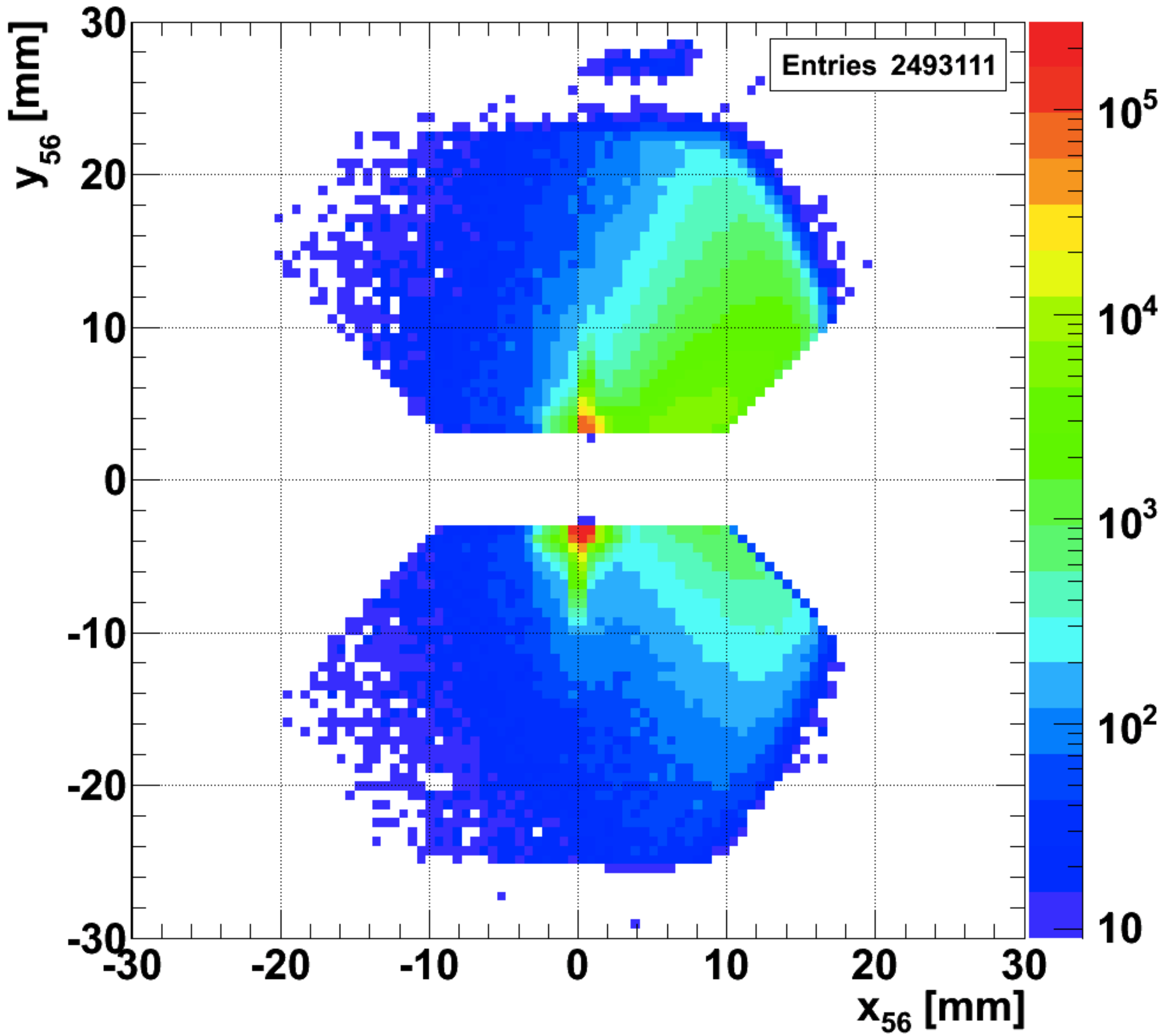
σ_{el} **~ 20 mbarn**

Track map (side 4,5) for left right coincidences



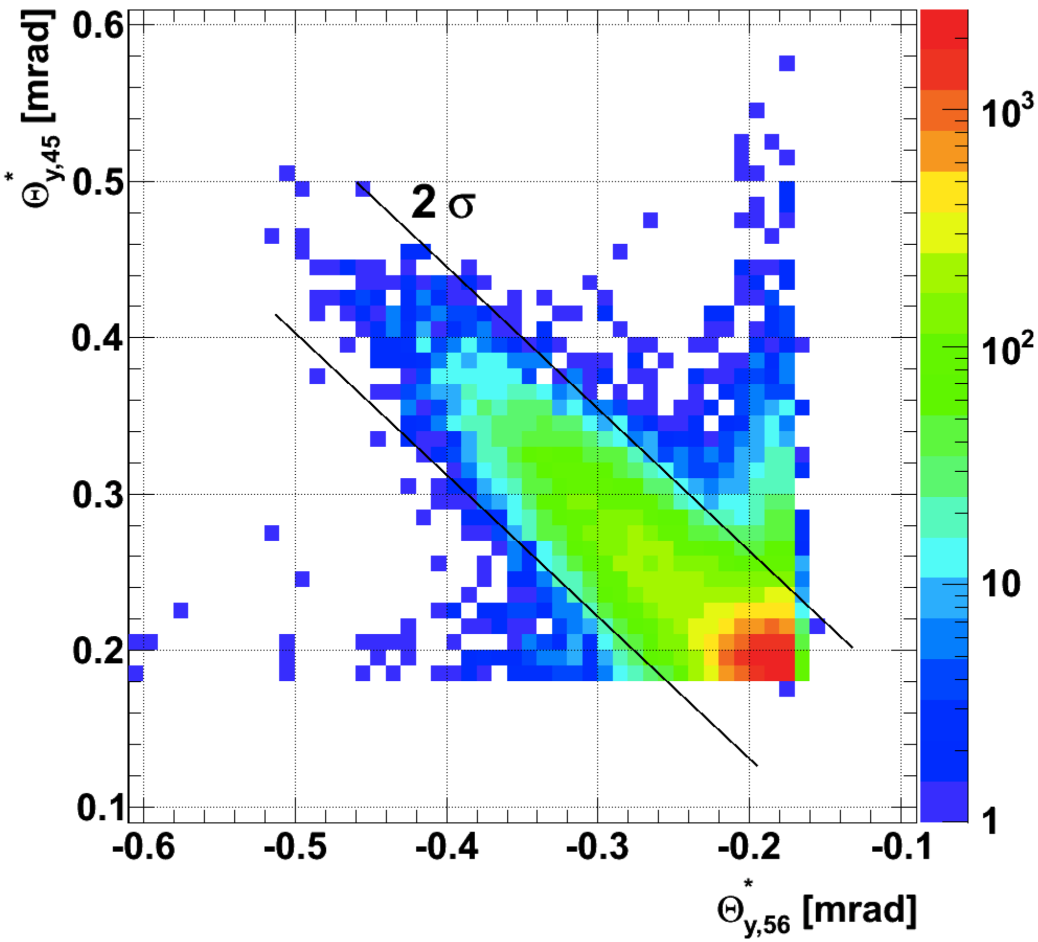


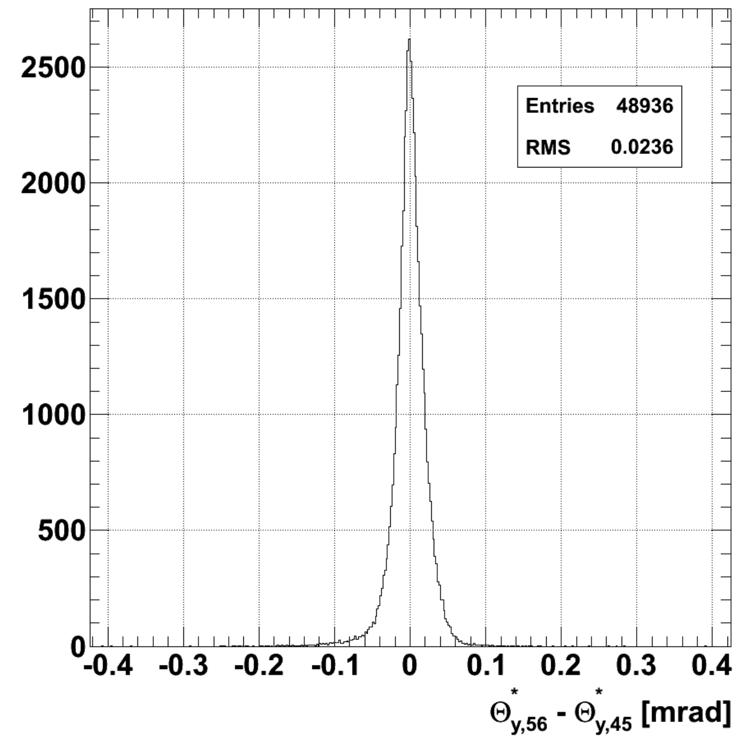
Track map (side 5,6) for left right coincidences



Collinearity in θ_y

Low ξ, i.e. $|x| < 0.4$ mm and 2σ cut in $\Delta\theta_x^*$

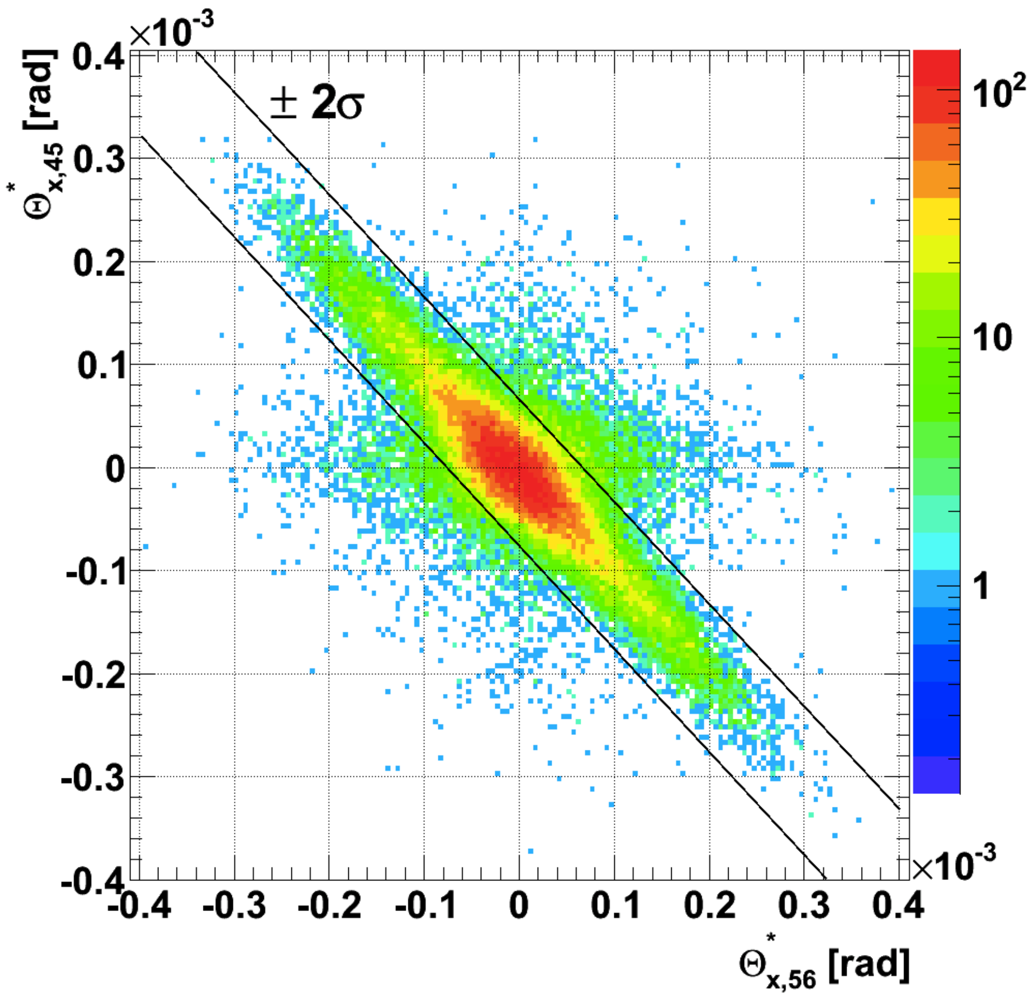


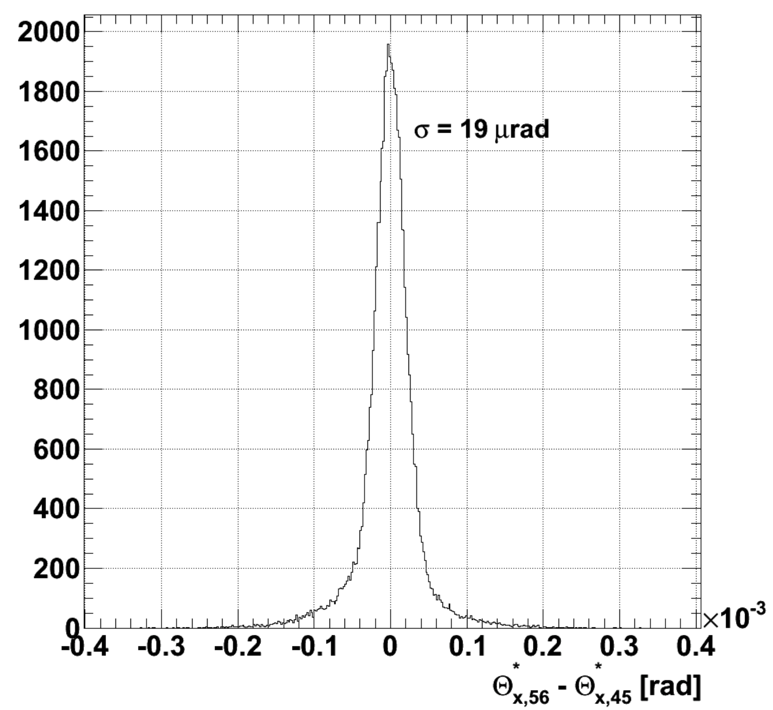


Compatible with the beam divergence

Collinearity in θ_x

Low ξ, i.e. |x| < 0.4 mm and 2σ cut in $\Delta\theta_y^*$



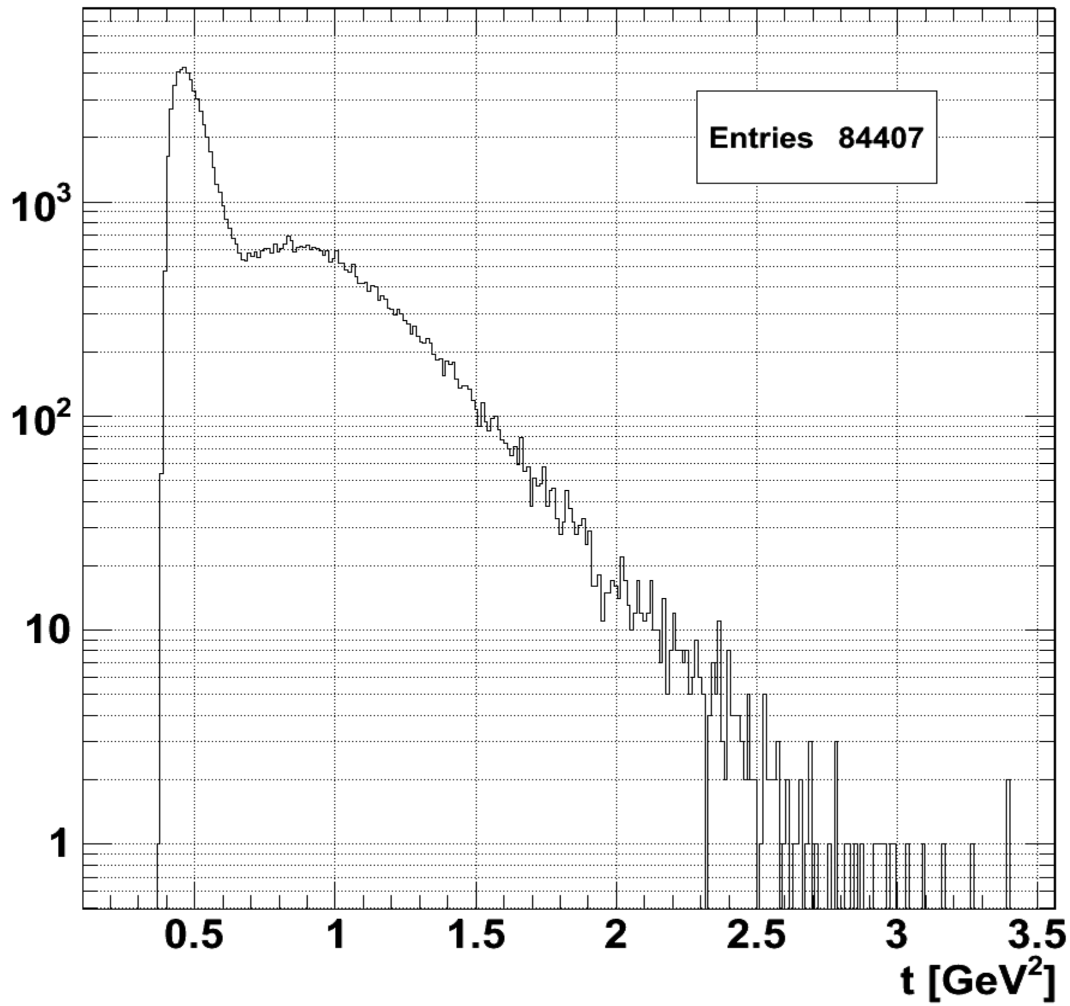


Compatible with the beam divergence

Θ_x is measured with 5m lever arm spectrometer

Preliminary t-distribution

~ 84K elastic scattering candidate events TOTEM special run (~ 8 nb $^{-1}$)



$\sqrt{s}$ = 7 TeV

β^* = 3.5 m

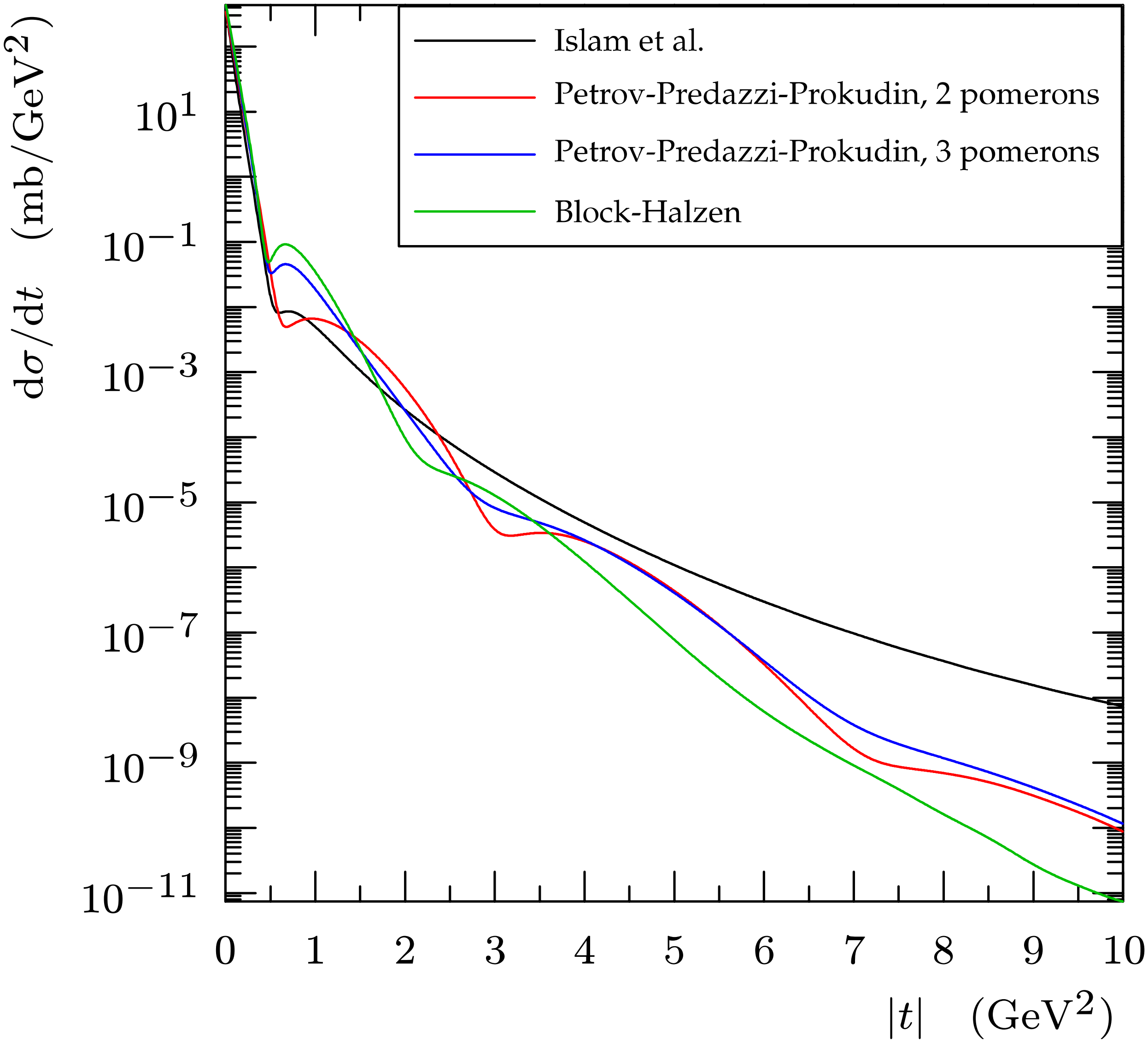
RPs @ 7 σ (V) and 16 σ (H)

"Raw" distribution:

- No smearing corrections
- No acceptance corrections
- No background subtraction

Sys. err. sources under study: alignment, beam position and divergence, background, optical functions, efficiency, …

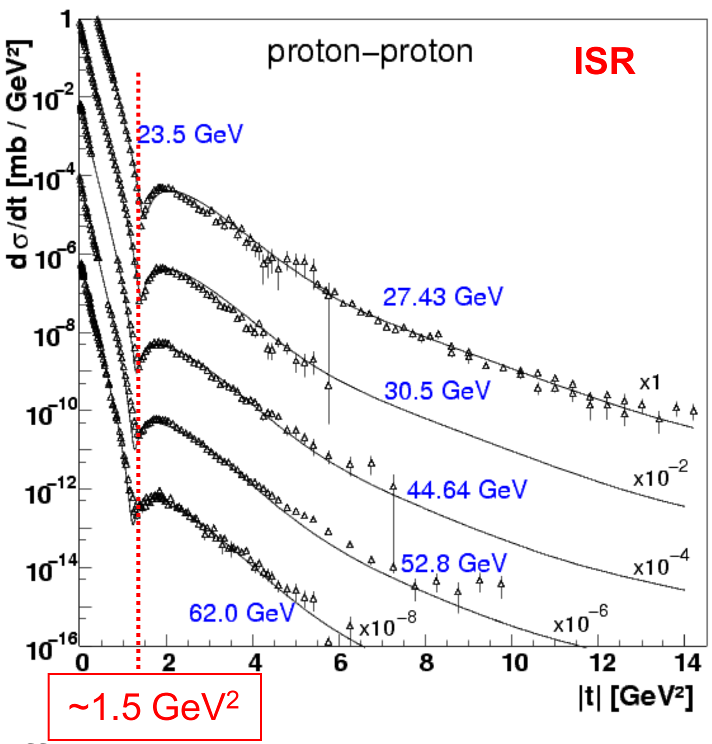
t – distribution : different models

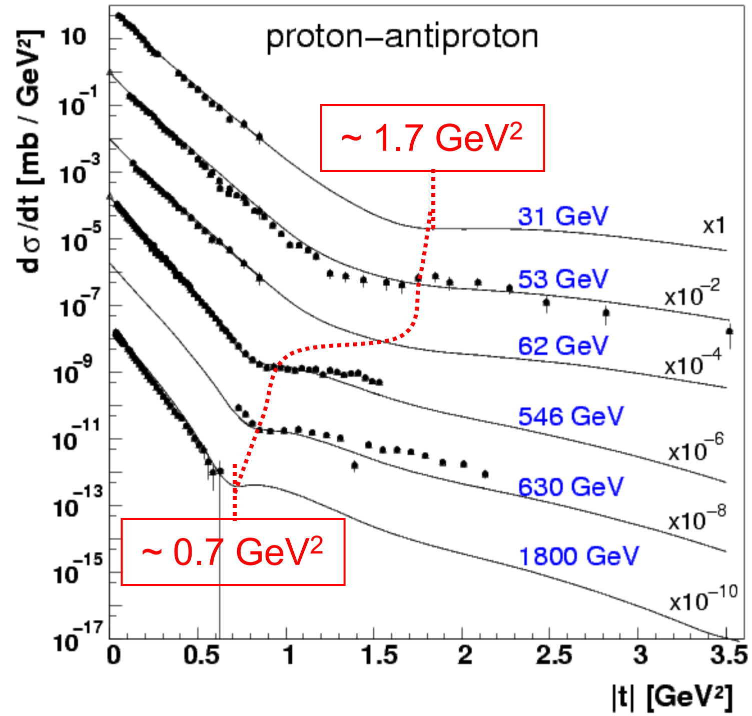


50 k events in t- range:

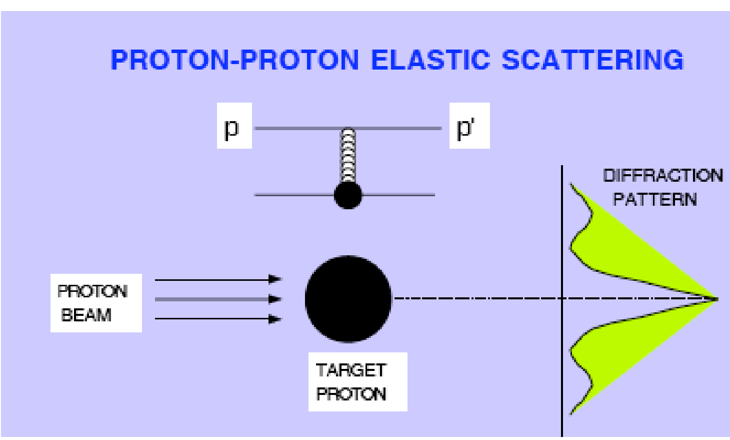
2 – 5 GeV^2

Elastic Scattering - from ISR to Tevatron



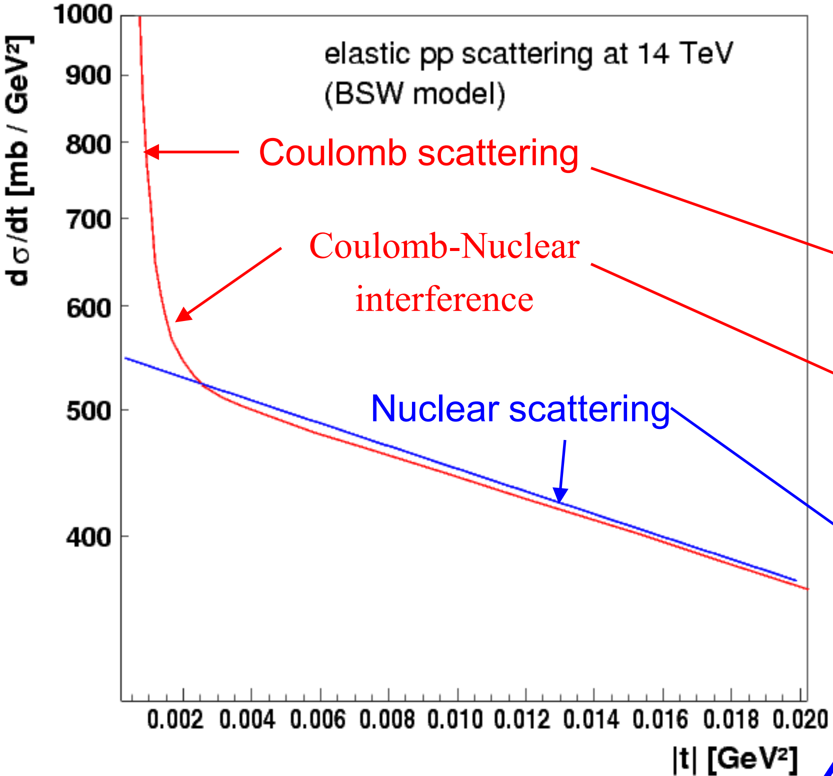


Diffractive minimum: analogous to Fraunhofer diffraction: $|t| \sim p^2\, \theta^2$



- exponential slope B at low |t| increases
- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from σ_{tot})
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, $\bar{p}p$
  → different mix of processes

Total Cross-Section and Elastic Scattering at low |t|



Optical Theorem:

$$\sigma_{tot} = \frac{4\pi}{s}\Im\left(T_{elastic,nuclear}(t=0)\right)$$

$$\frac{d\sigma}{dt} =$$

$$\frac{4\pi\alpha^2(\hbar\ldots)}{|t|^2} +$$

$$\frac{\alpha(\rho-\alpha\phi)\sigma_{tot}G^2(t)}{|t|}e^{-B|t|/2} +$$

$$\frac{\sigma_{tot}^2(1+\rho^2)}{16\pi(\hbar\ldots)}e^{-B|t|}$$

α = fine structure constant

ϕ = relative Coulomb-nuclear phase

G(t) = nucleon el.-mag. form factor = $(1 + |t| / 0.71)^{-2}$

ρ = Re / Im $T_{elastic,nuclear}(t = 0)$

TOTEM Approach:

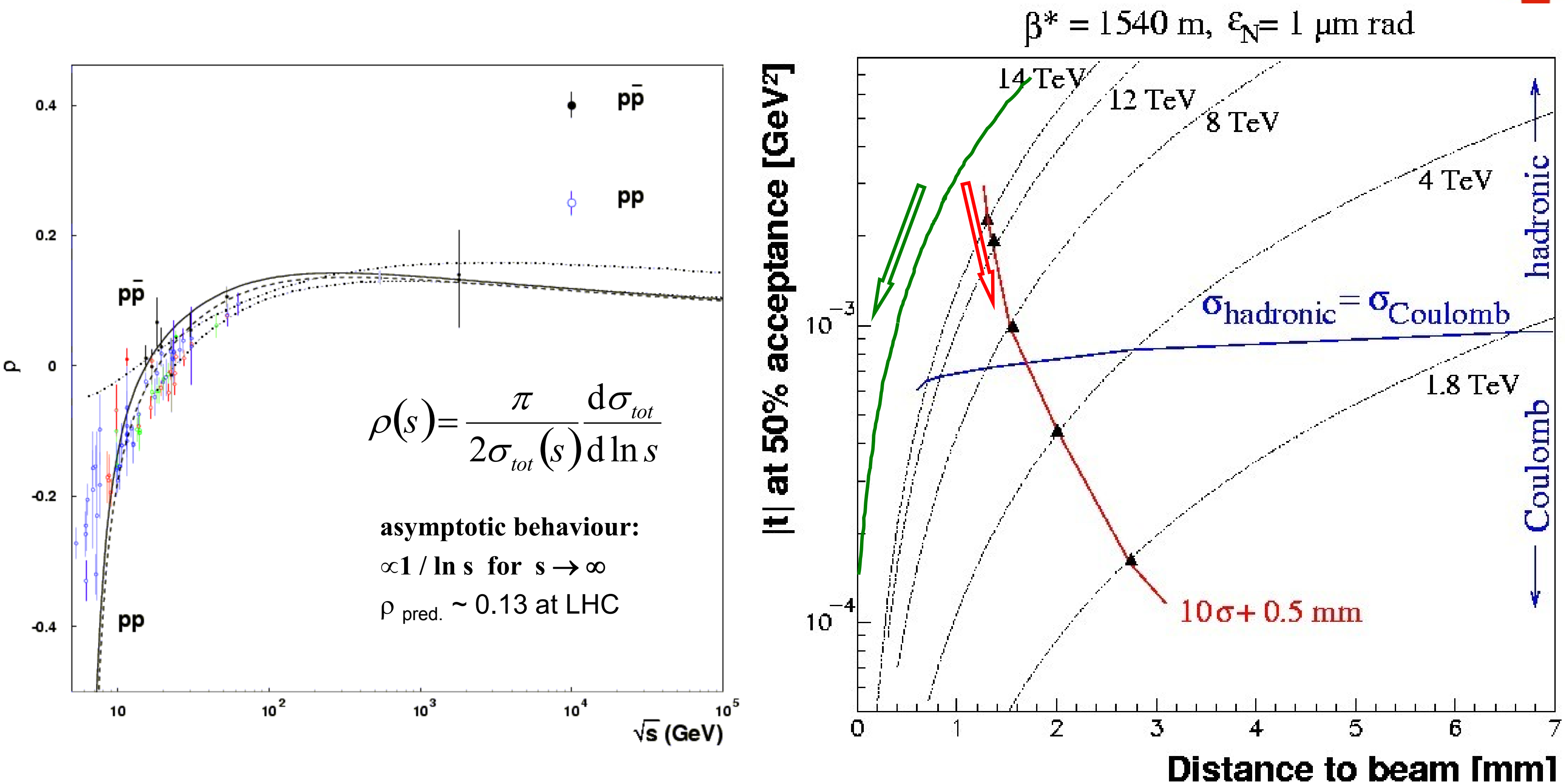
Measure the exponential slope B in the t-range 0.002 - 0.2 GeV² , extrapolate dσ/dt to t=0, measure total inelastic and elastic rates (all TOTEM detectors provide L1 triggers):

$$L\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\times\left.\frac{dN_{elastic,nuclear}}{dt}\right|_{t=0}$$

$$L\sigma_{tot} = N_{elastic,nuclear} + N_{inelastic}$$

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2}\times\frac{(dN_{elastic,nuclear}/dt)|_{t=0}}{N_{elastic,nuclear}+N_{inelastic}}$$

Possibilities of ρ measurement



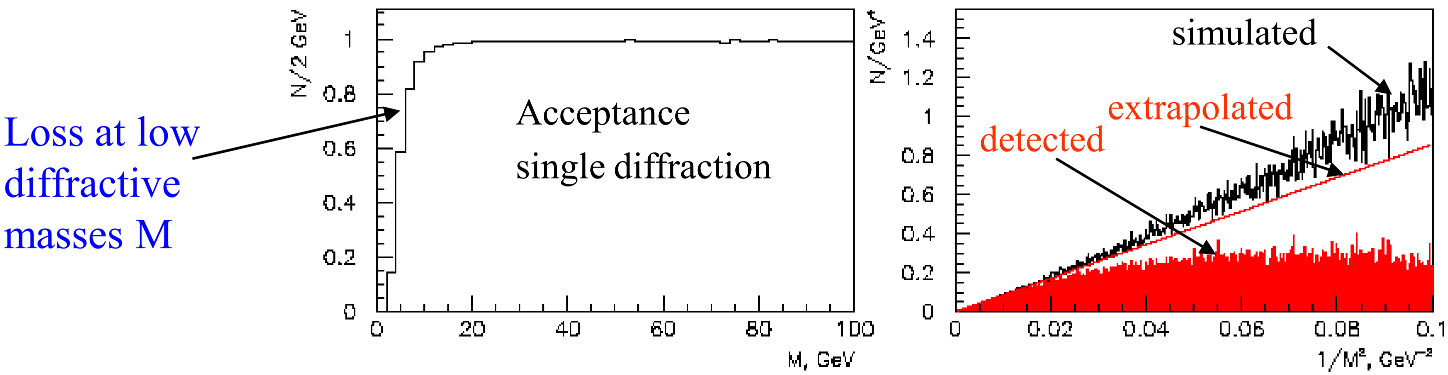
$$\rho(s) = \frac{\pi}{2\sigma_{tot}(s)} \frac{d\sigma_{tot}}{d\ln s}$$

Try to reach the Coulomb region and measure interference:

- move the detectors closer to the beam than 10 σ + 0.5 mm
- run at lower energy @ √s < 14 TeV

Measurement of the Inelastic Rate $N_{inel} = \mathcal{L}\sigma_{inel}$

- Inelastic double arm trigger: robust against background, inefficient at small M
- Inelastic single arm trigger: suffers from beam-gas + halo background, best efficiency
- Inelastic triggers and proton (SD, DPE): cleanest trigger, proton inefficiency to be extrapolated
- Trigger on non-colliding bunches to determine beam-gas + halo rates.
- Vertex reconstruction with T1, T2 to suppress background
- Extrapolation of diffractive cross-section to large $1/M^2$ assuming $d\sigma/dM^2 \sim 1/M^2$



	σ [mb]	trigger loss [mb]	systematic error after extrapolations [mb]
Non-diffractive inelastic	58	0.06	0.06
Single diffractive	14	3	0.6
Double diffractive	7	0.3	0.1
Double Pomeron	1	0.2	0.02
Total	80	3.6	0.8

0.8%

Combined Uncertainty in σ_{tot}

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

	$\beta^* = 90$ m	1540 m
• Extrapolation of elastic cross-section to t = 0:	± 4 %	± 0.2 %
• Total elastic rate (strongly correlated with extrapolation):	± 2 %	± 0.1 %
• Total inelastic rate: (error dominated by Single Diffractive trigger losses)	± 1 %	± 0.8 %
• Error contribution from $(1+\rho^2)$ using full COMPETE error band $\delta\rho/\rho = 33$ %	± 1.2 %	

→ Total uncertainty in σ_{tot} including correlations in the error propagation:

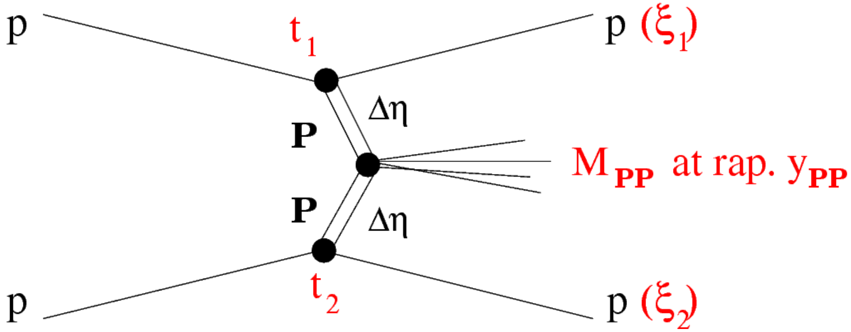
→ $\beta^* = 90$ m : ± 5 %, $\beta^* = 1540$ m : ± (1 ÷ 2) % .

Slightly worse in $\mathcal{L}$ (~ total rate squared!) : ± 7 % (± 2 %).

Precise Measurement with $\beta^* = 1540$ m requires:

- improved knowledge of optical functions
- alignment precision < 50 μm

Central Diffraction (DPE)

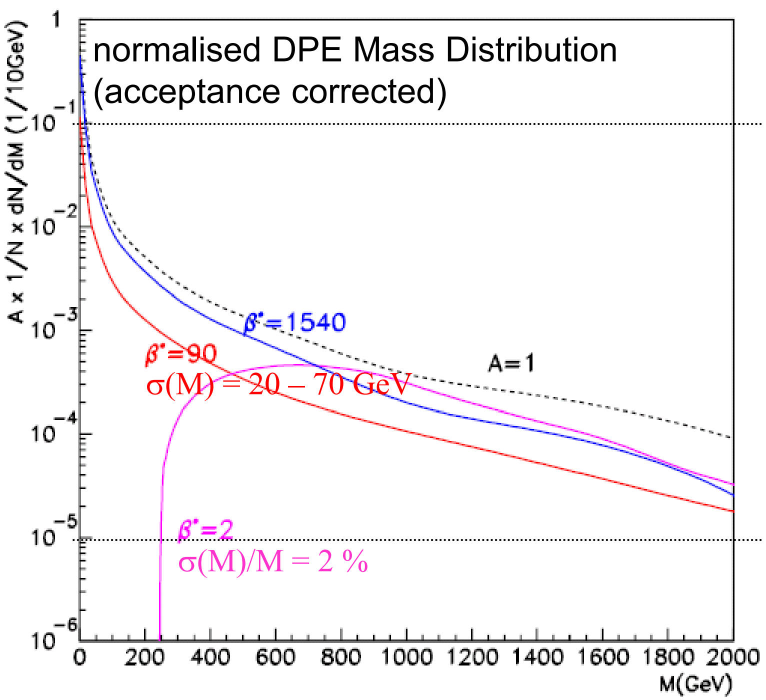


5-dimensional differential cross-section:

$$\frac{d^5\sigma}{dt_1\,dt_2\,d\xi_1\,d\xi_2\,d\phi} \propto \frac{1}{\xi_1^{1+\varepsilon}}\,\frac{1}{\xi_2^{1+\varepsilon}}\,e^{-b|t_1|-b|t_2|}$$

Any correlations?

Mass spectrum: change variables $(\xi_1,\xi_2) \rightarrow (M_{PP}, y_{PP})$: $M_{PP}^2 = \xi_1\,\xi_2\,s\,;\quad y_{PP} = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}$



14 μb / GeV

$$\frac{d^2\sigma}{dM^2\,dy} \propto \frac{1}{\left(M^2\right)^{1+\varepsilon}}$$

β*=90m: σ(M) = 20 – 70 GeV

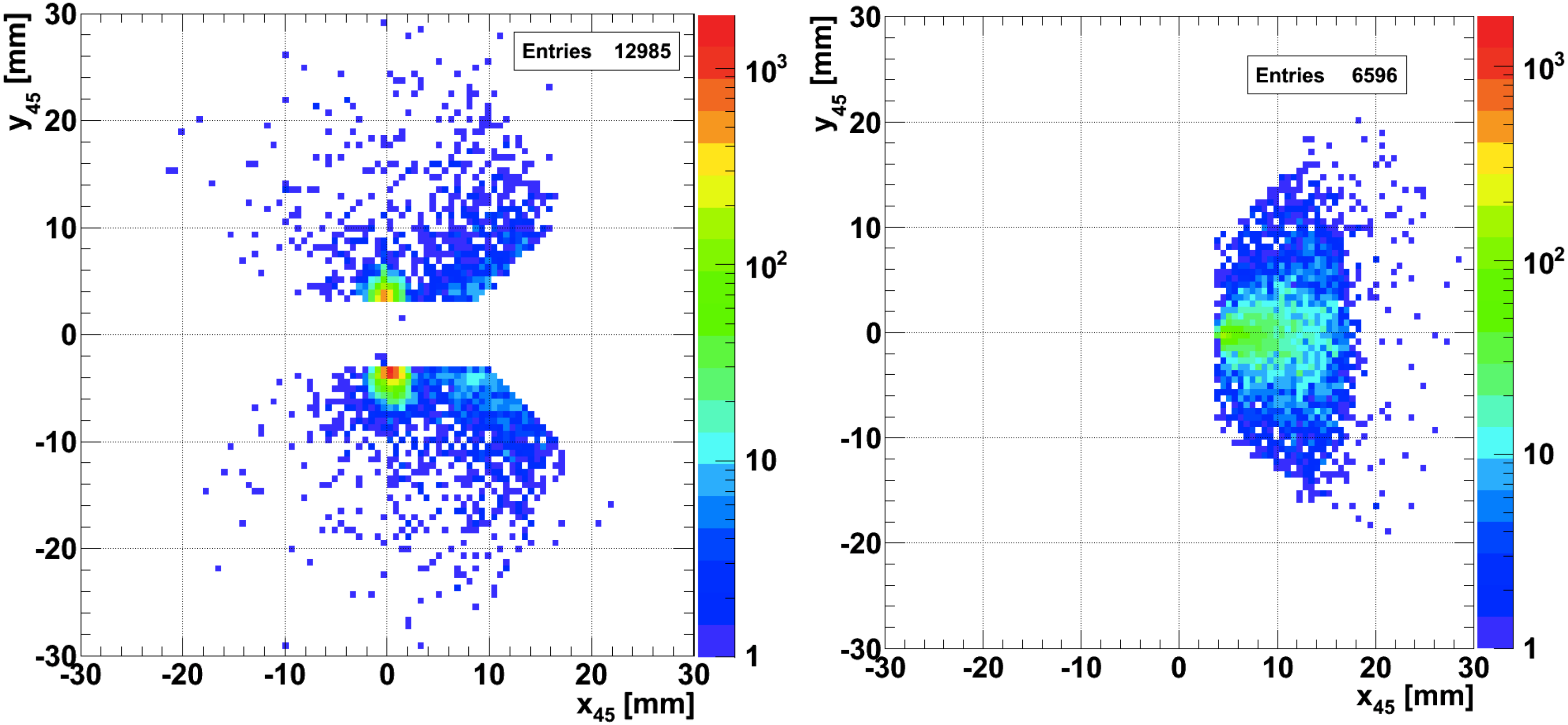
1.4 nb / GeV ⇔ **50 events / (h •10GeV) @ 10^{30} cm^{-2} s^{-1}**

→ sufficient statistics to measure the inclusive mass spectrum

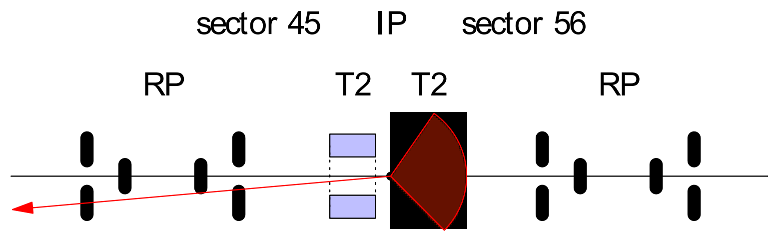
Track distribution for an inclusive trigger (global “OR”)

Trigger on minibunch

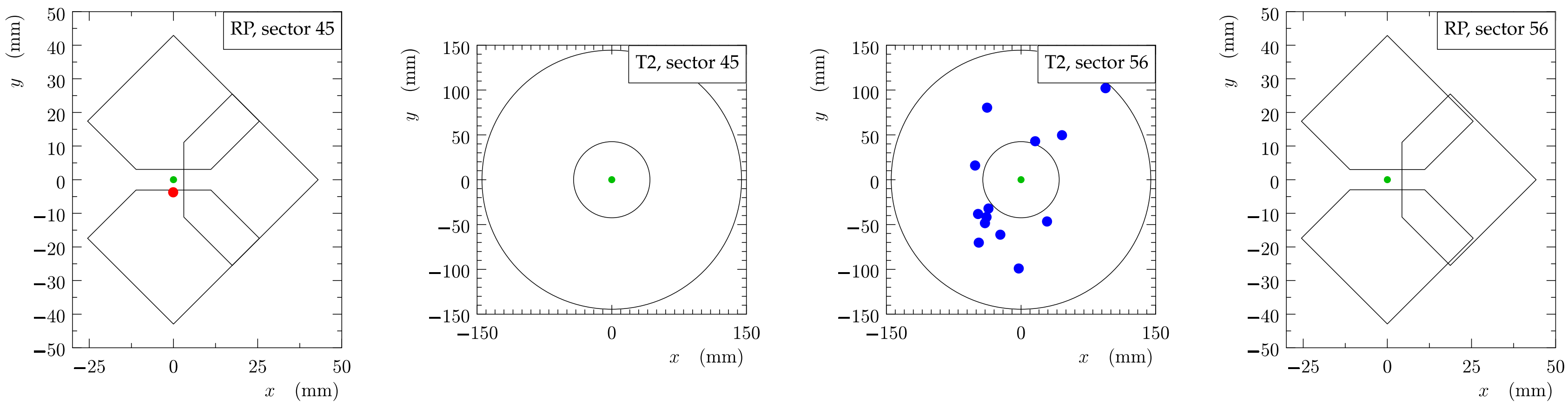
Average number of min. bias events per bunch crossing : 0.02



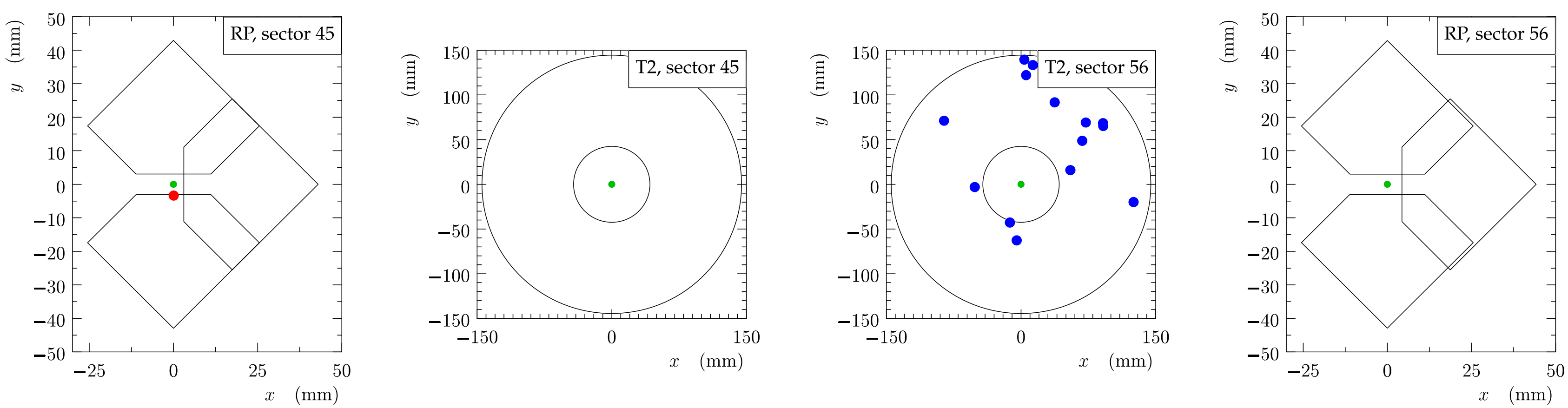
Single diffraction low ξ



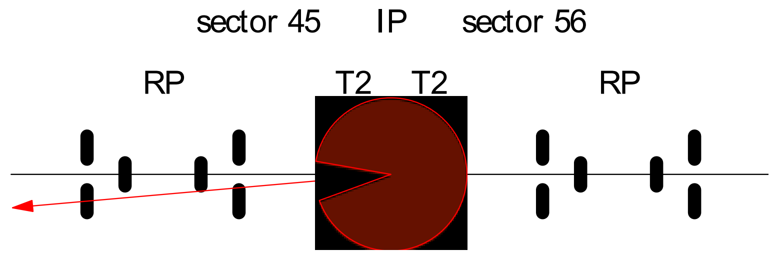
run: 37280003, event: 3000



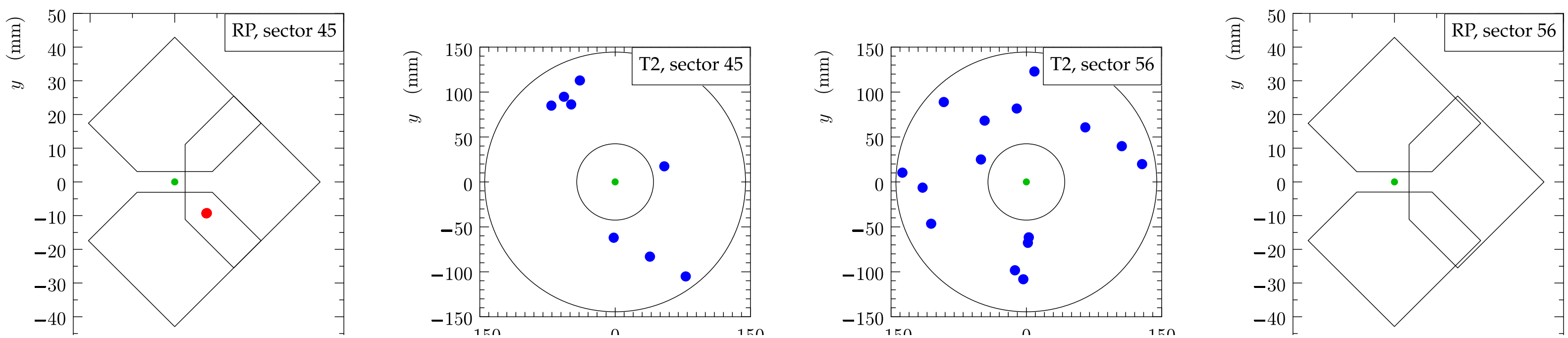
run: 37280004, event: 22784



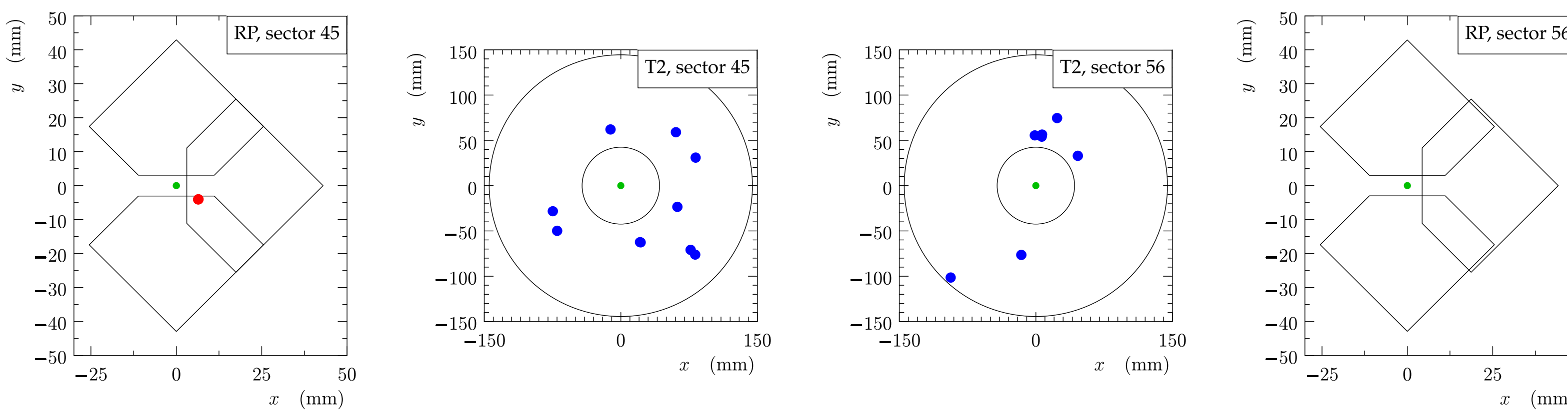
Single diffraction large ξ



run: 37280006, event: 9522

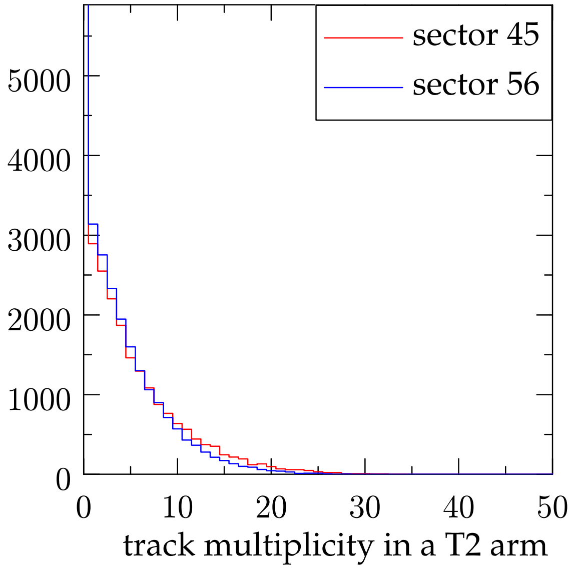


run: 37280006, event: 6074



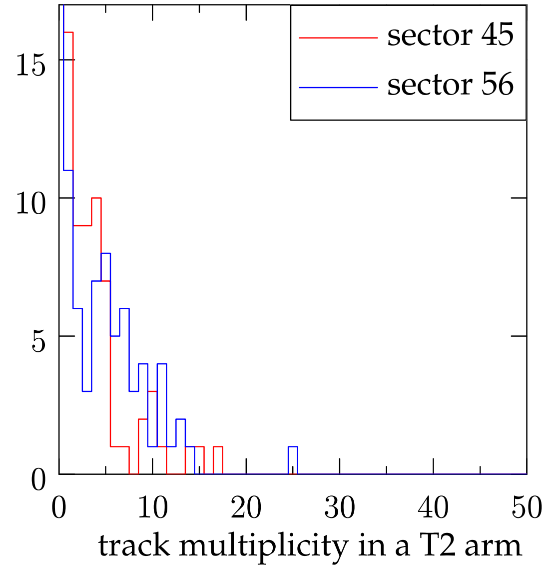
Min. Bias and diffractive events

all events



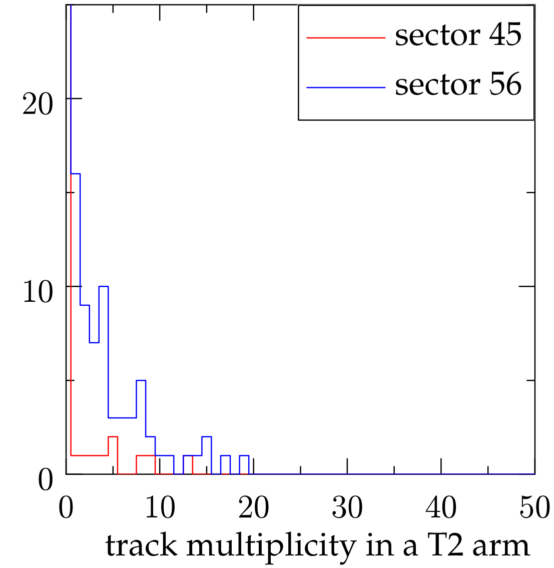
no cut

high-ξ SD candidates



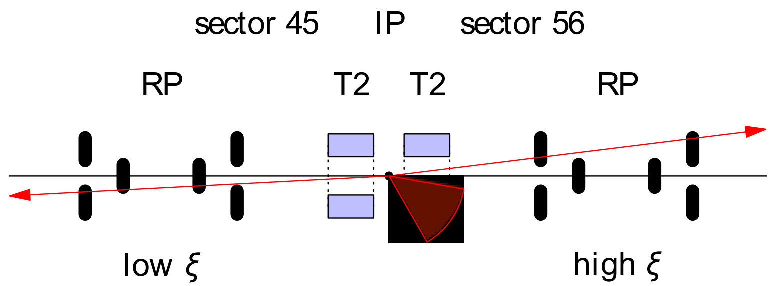
track in 45 bottom, no track in 56 top, cut in RPs: $y > -4\,\mathrm{mm}$ and $x > 5\,\mathrm{mm}$

low-ξ SD candidates

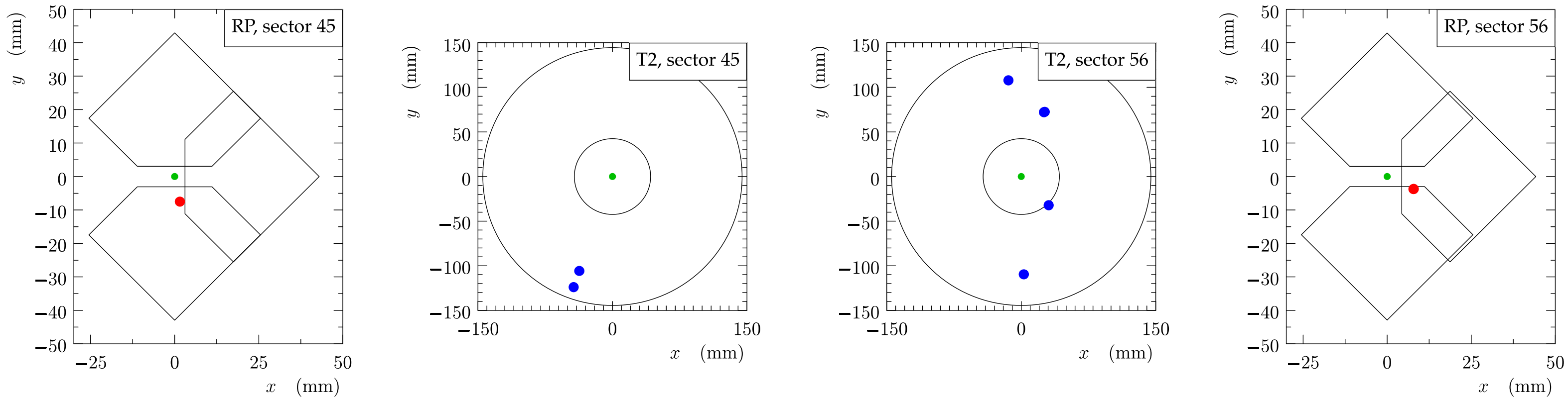


track in 45 bottom, no track in 56 top, cut in RPs: $y > -4\,\mathrm{mm}$ and $|x| < 0.1\,\mathrm{mm}$

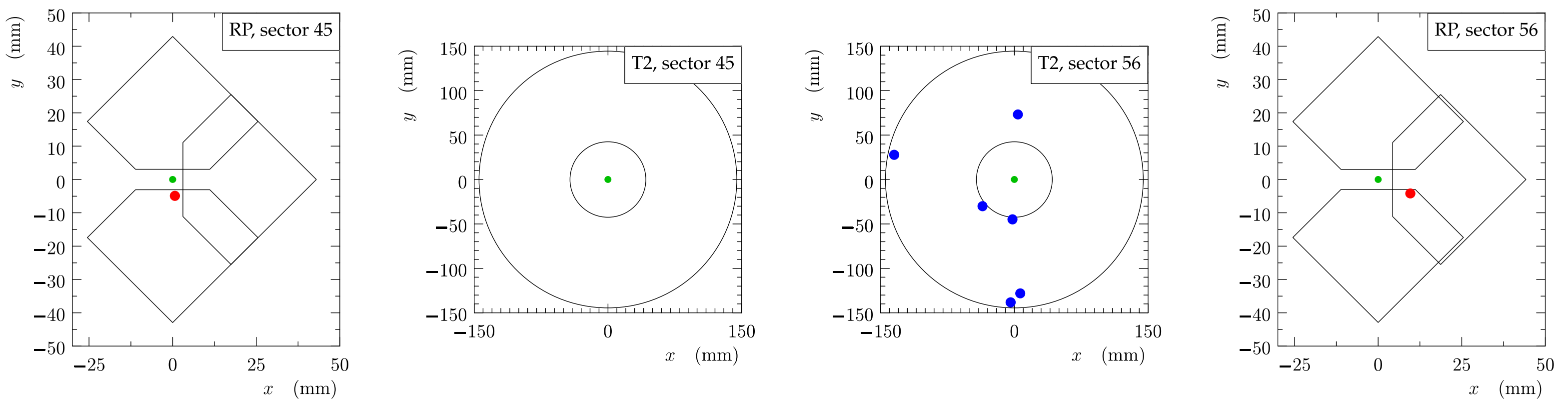
Double Pomeron Exchange



run: 37250009, event: 14125



run: 37220007, event: 9904



Expected Results from 2010

Elastic scattering t –distribution from 0.4 - 5 GeV^2

Double Pomeron: mass distribution and kinematics

Single diffraction: correlation of η and rapidity gaps

Forward multiplicity distributions

Multiplicity correlations over large rapidity gap

Running Strategy for 2011

Repeat RP alignment at nominal conditions to understand new optics

approach the RP detectors to the sharp beam edges produced by the LHC collimators

This will enable constant running at closer approaches to the beams (~15 σ) in normal runs

improve statistics at large *t*-values

Special runs with several low proton density bunches plus one normal bunch:

approach RP to ~ 5 σ to reach lowest t around 0.2 GeV^2

Add one low-intensity bunch to the standard bunch train if possible

Take data with T2 at reduced pile-up (< 10^{-2})

Prepare the β^* = 90 m optics

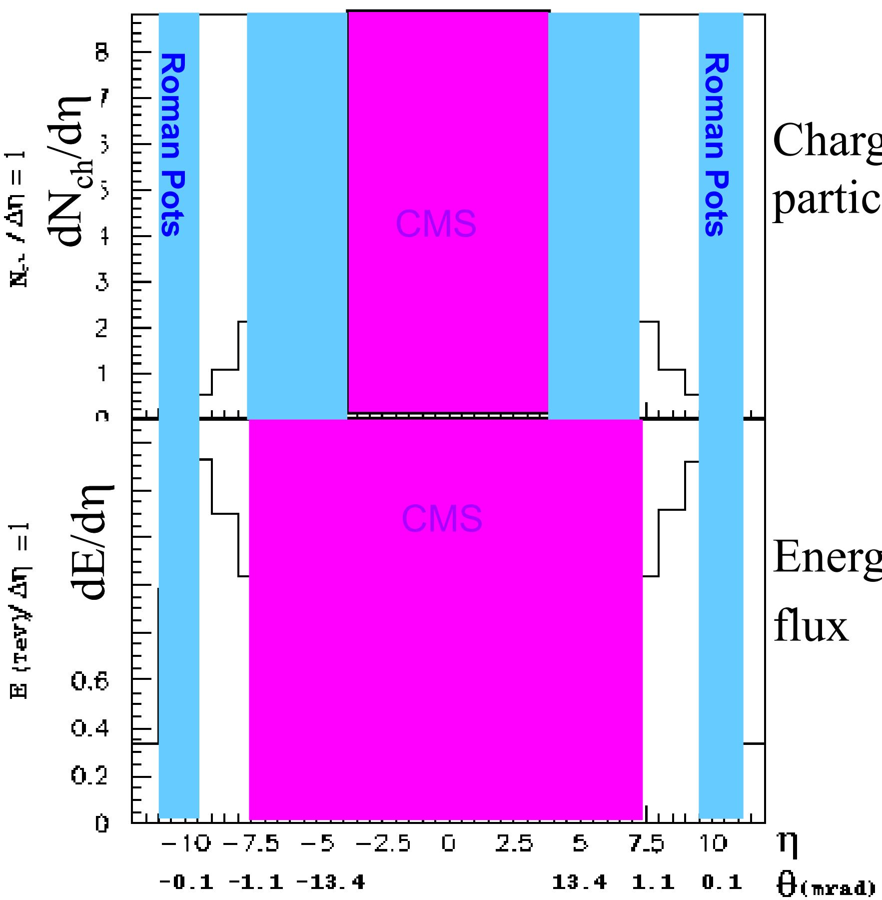
measure the total cross-section and luminosity

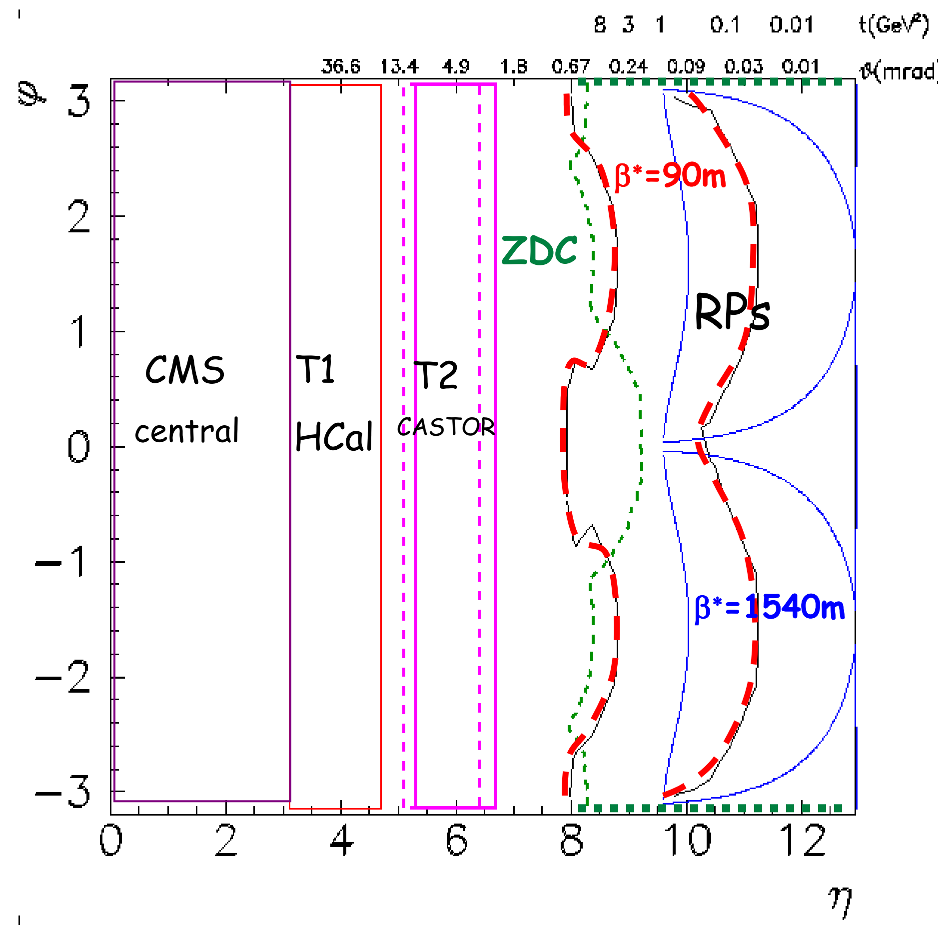
Targets: Approaching the RP closer to the beams enables σ_{tot} and σ_{el} with β^*=90m
Rich programme with single diffraction and Double Pomeron
Correlations between the forward proton and topologies in T1 and T2
With larger β^* ~ 500 – 1000m Coulomb region might be accessible

CMS + TOTEM: Acceptance

largest acceptance detector ever built at a hadron collider

Studies in a new kinematical range might lead to unforeseen discoveries

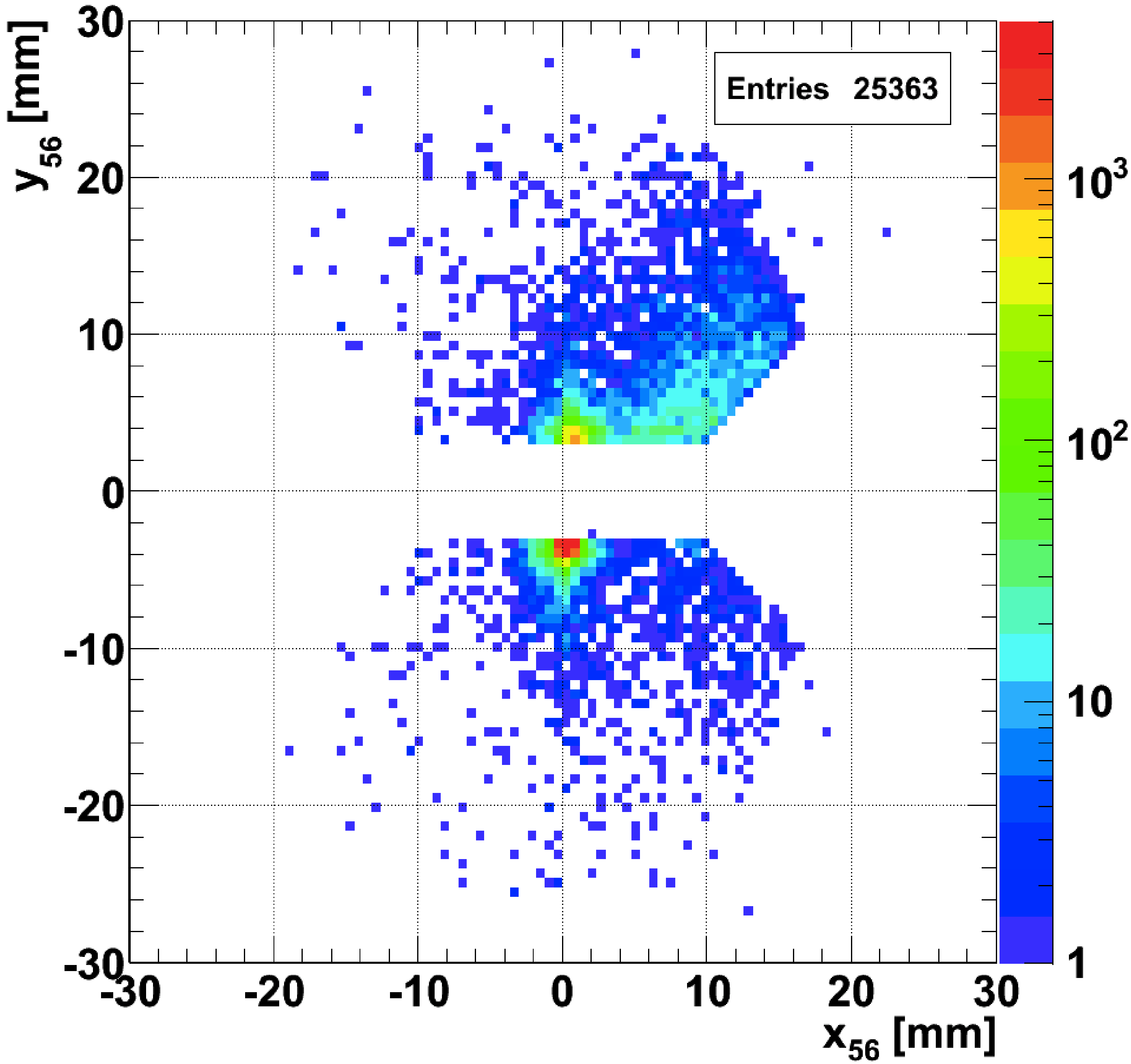




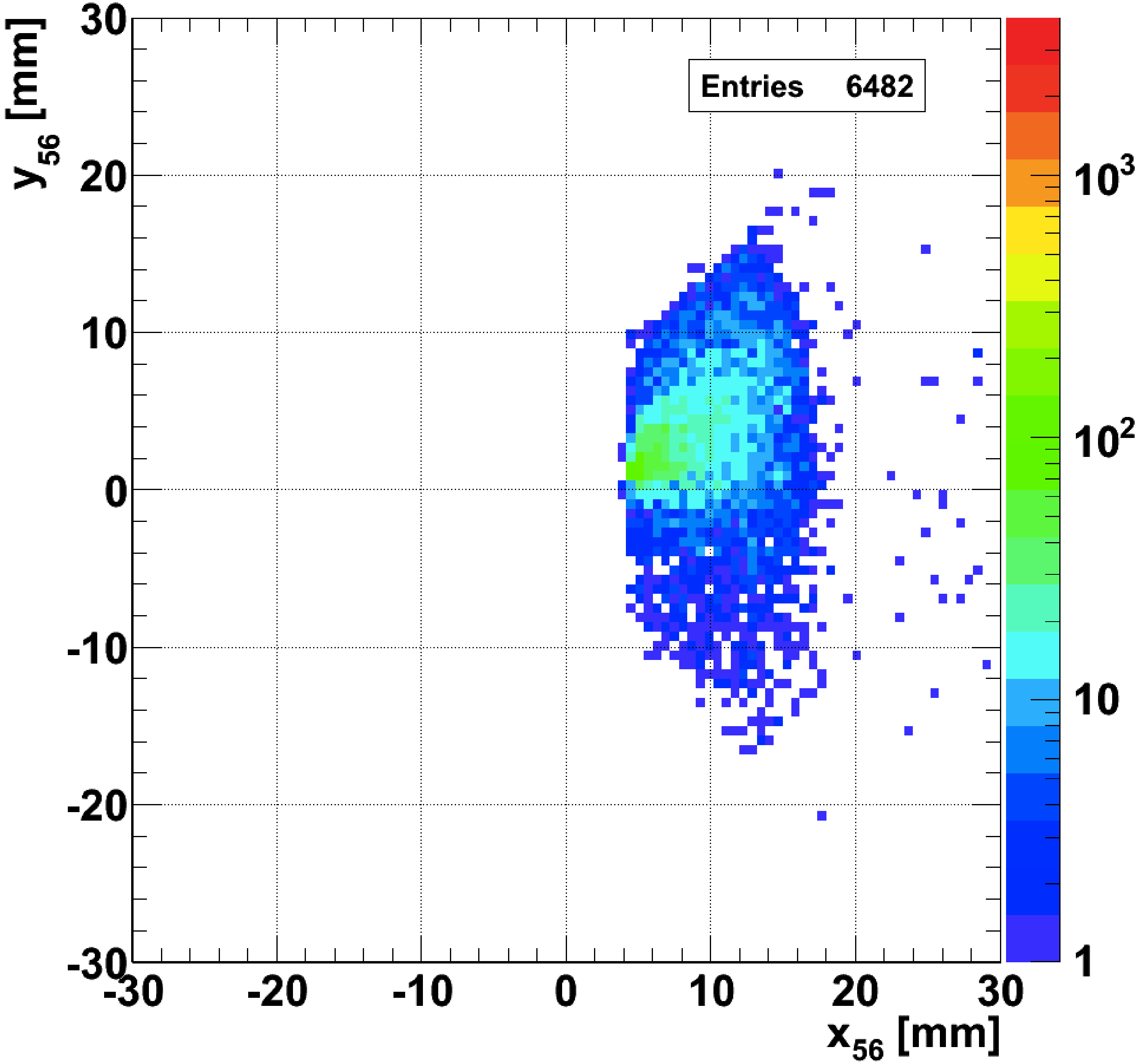
$\eta = -\ln \mathrm{tg}\, \theta/2$

The TOTEM Collaboration

End



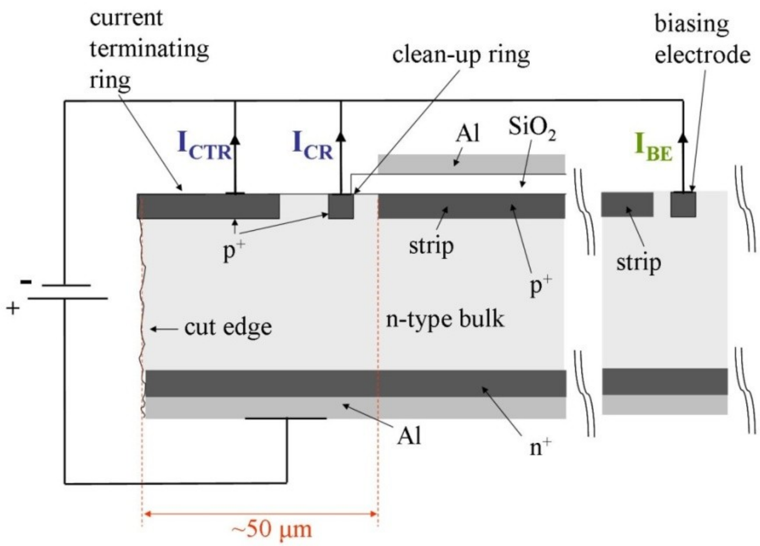
Entries 25363
y_{56} [mm]
x_{56} [mm]
30
20
10
0
-10
-20
-30
-20
-10
0
10
20
30
10^3
10^2
10
1



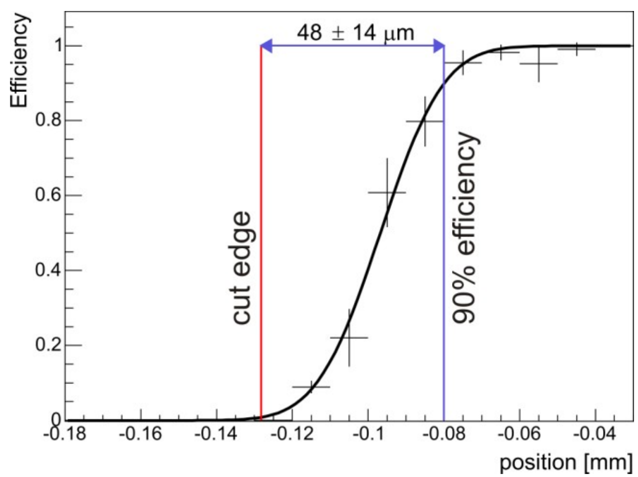
Entries 6482
y_{56} [mm]
x_{56} [mm]
30
20
10
0
-10
-20
-30
-30
-20
-10
0
10
20
30
10^3
10^2
10
1

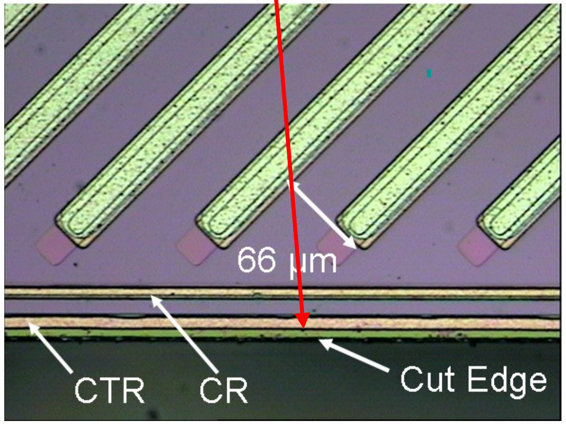
Silicon Edgeless Sensor for Roman Pots

Planar technology with CTS (Current Terminating Structure)



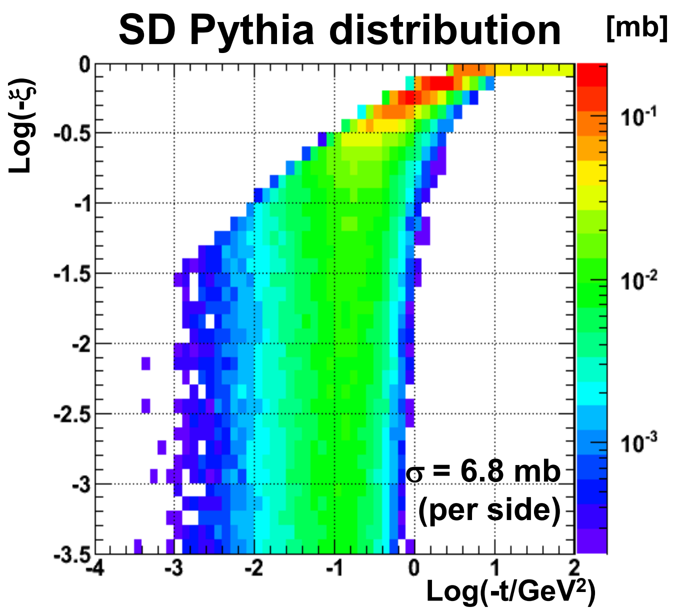
Efficiency at the edge

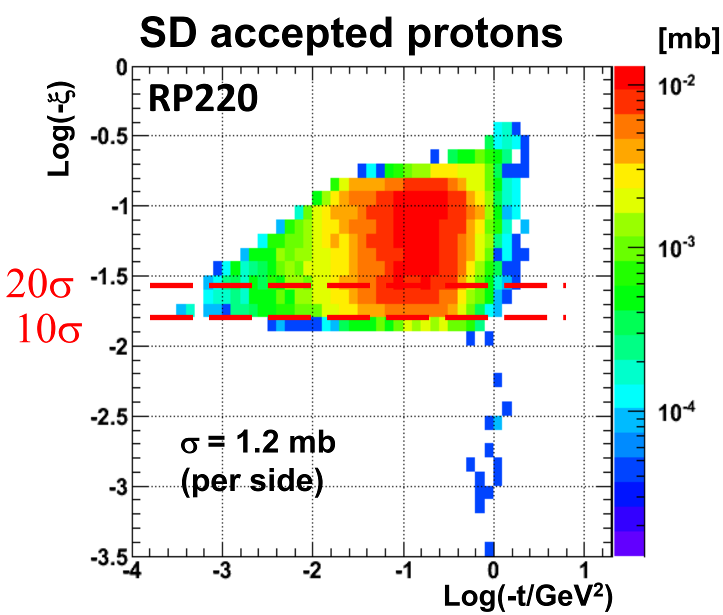


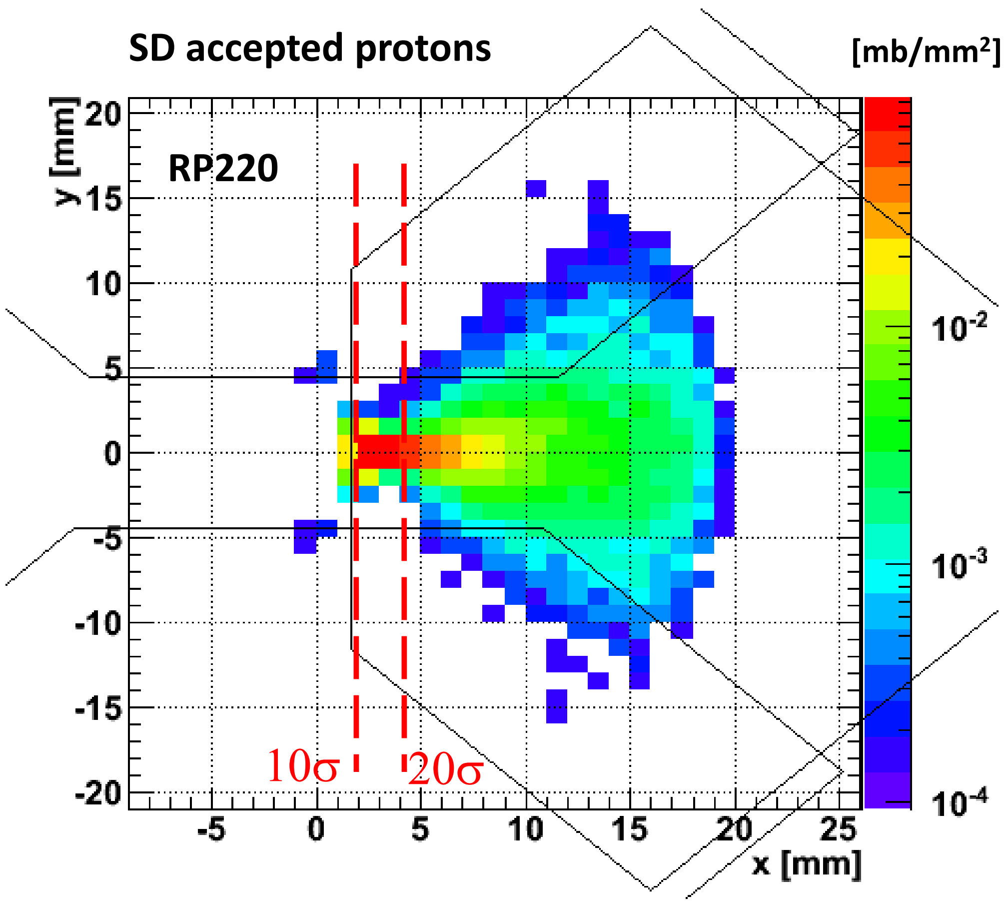


$\sigma = 20\ \mu m$

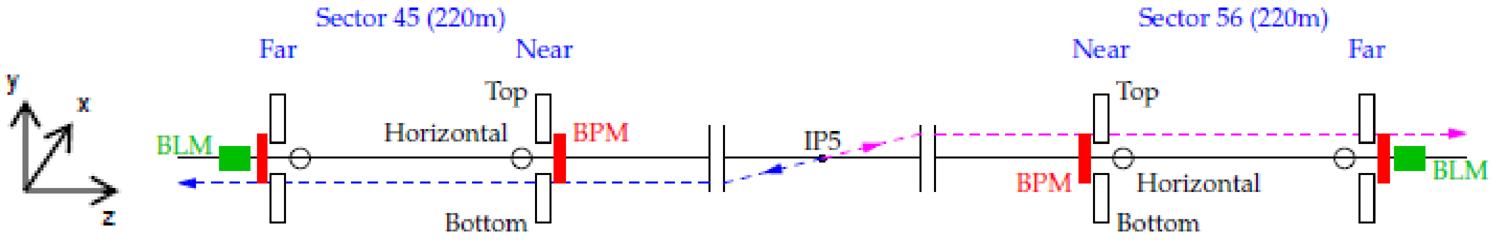
Single Diffraction, √s = 7 TeV, β* = 2 m

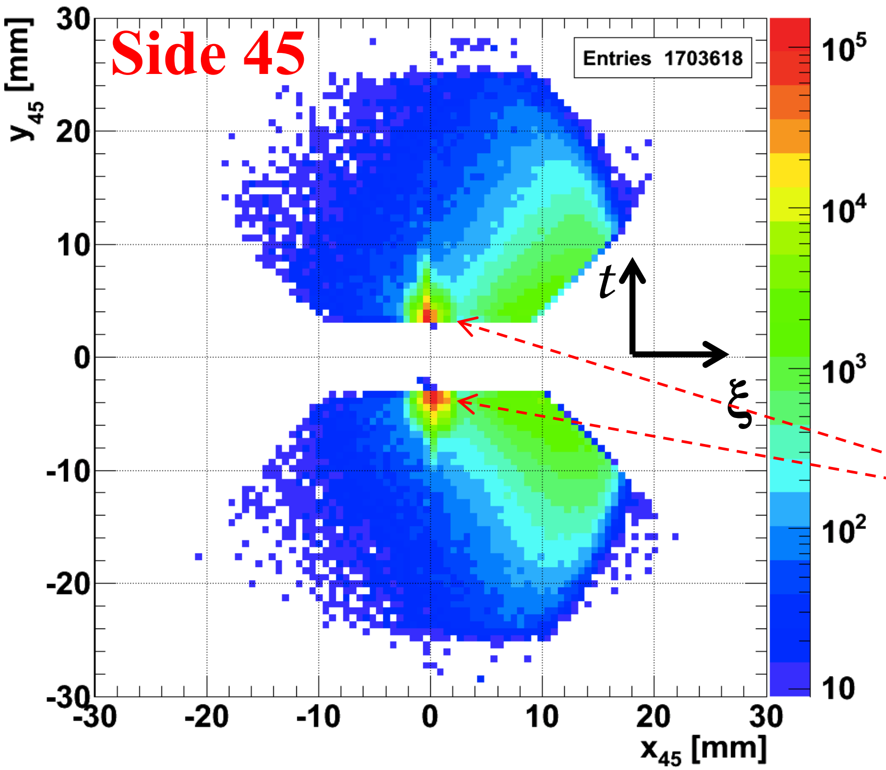






"Raw" Data: Hit Map for Left-Right Coincidences





$$y(s) = v_y(\xi, s) \cdot y^* + L_y(\xi, s) \cdot \Theta_y^*$$
$$x(s) = v_x(\xi, s) \cdot x^* + L_x(\xi, s) \cdot \Theta_x^* + \xi \cdot D(\xi, s)$$

with

$\xi = \Delta p/p$; $t = t_x + t_y$; $t_i \sim -(p\theta_i^*)^2$

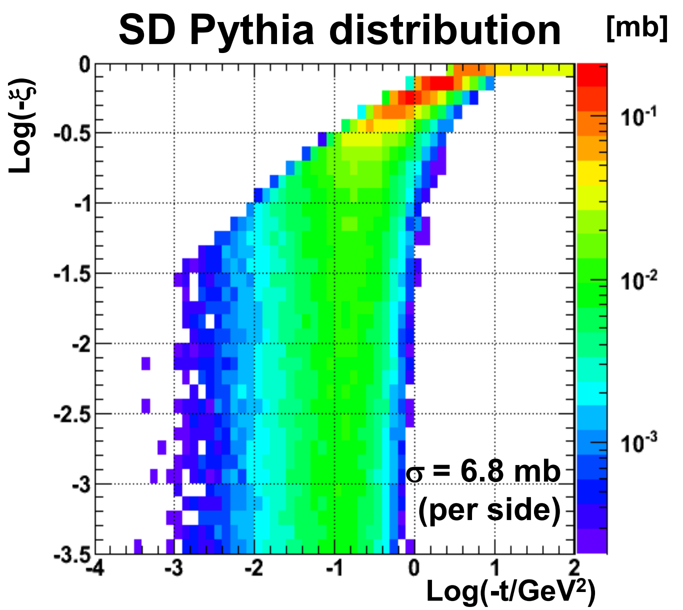
(x^*, y^*): vertex position at IP

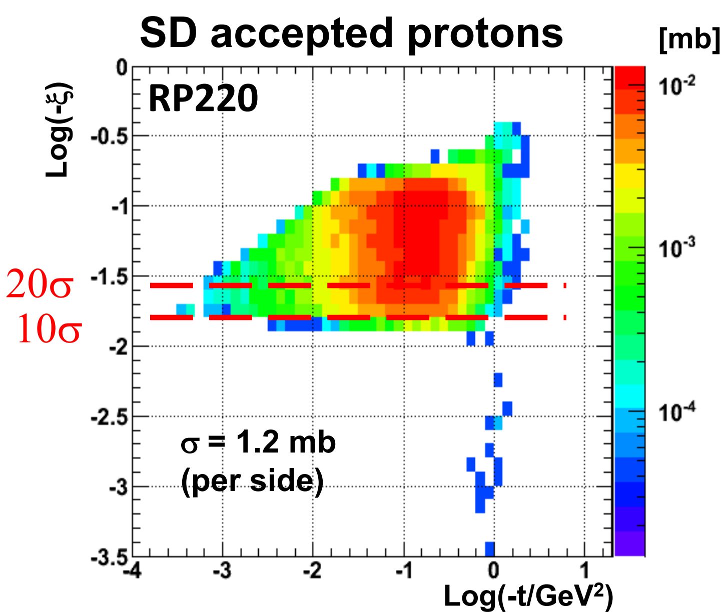
(θ_x^*, θ_y^*): emission angle at IP

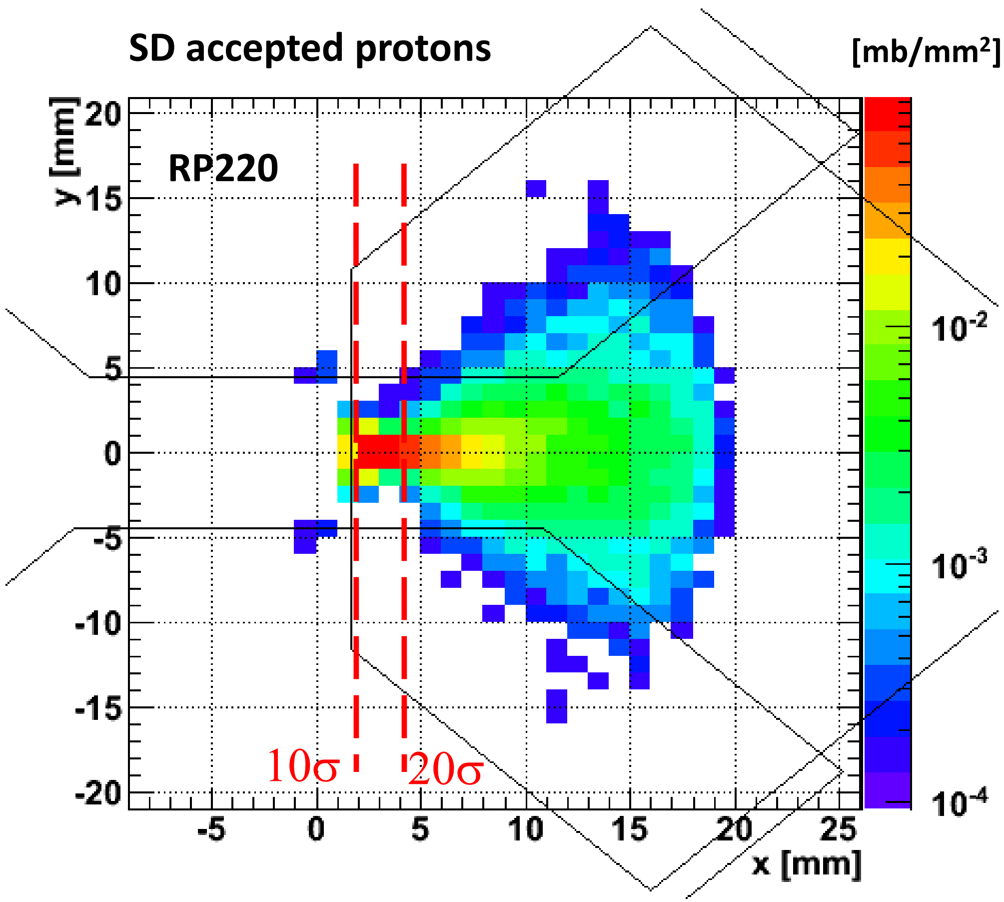
Hits related to elastic scattering candidates

Tracks reconstructed in "left" (45) and "right" (56) sides

Single Diffraction, $\sqrt{s}$ = 7 TeV, β^* = 2 m

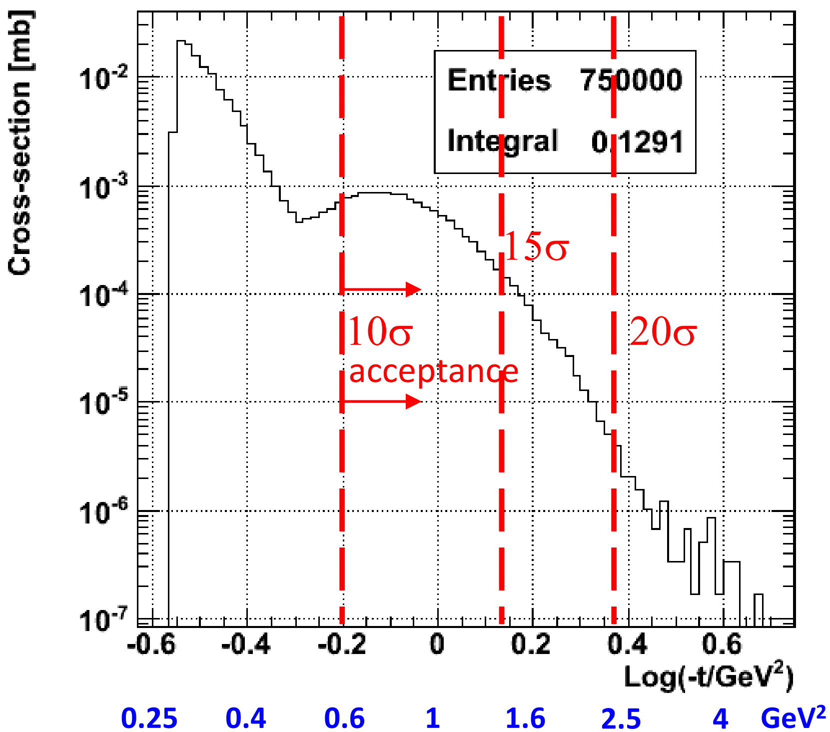




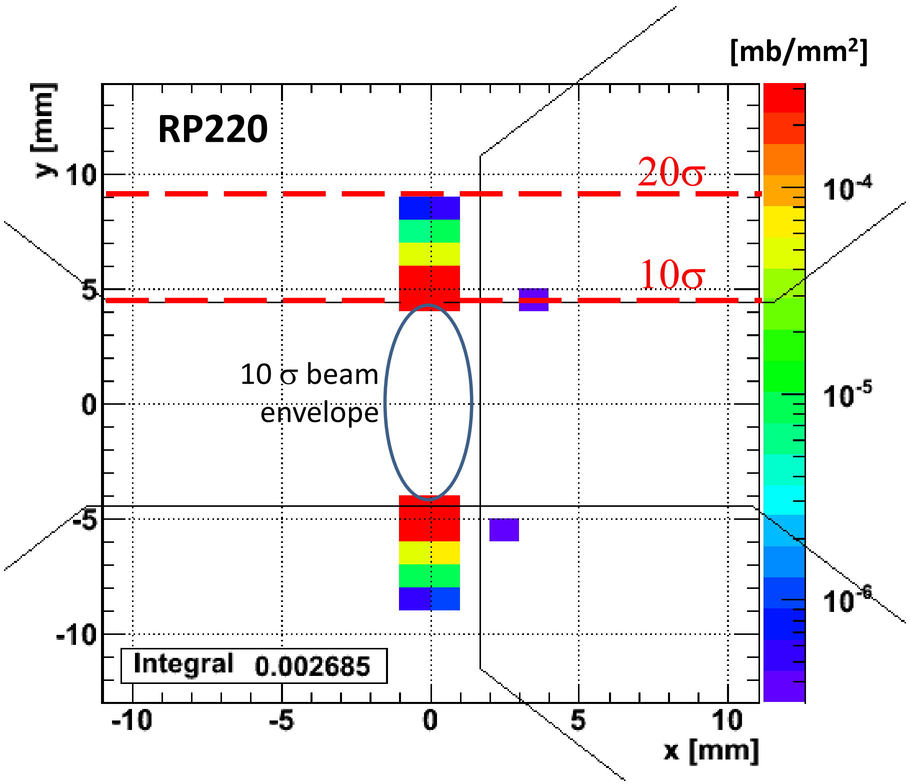


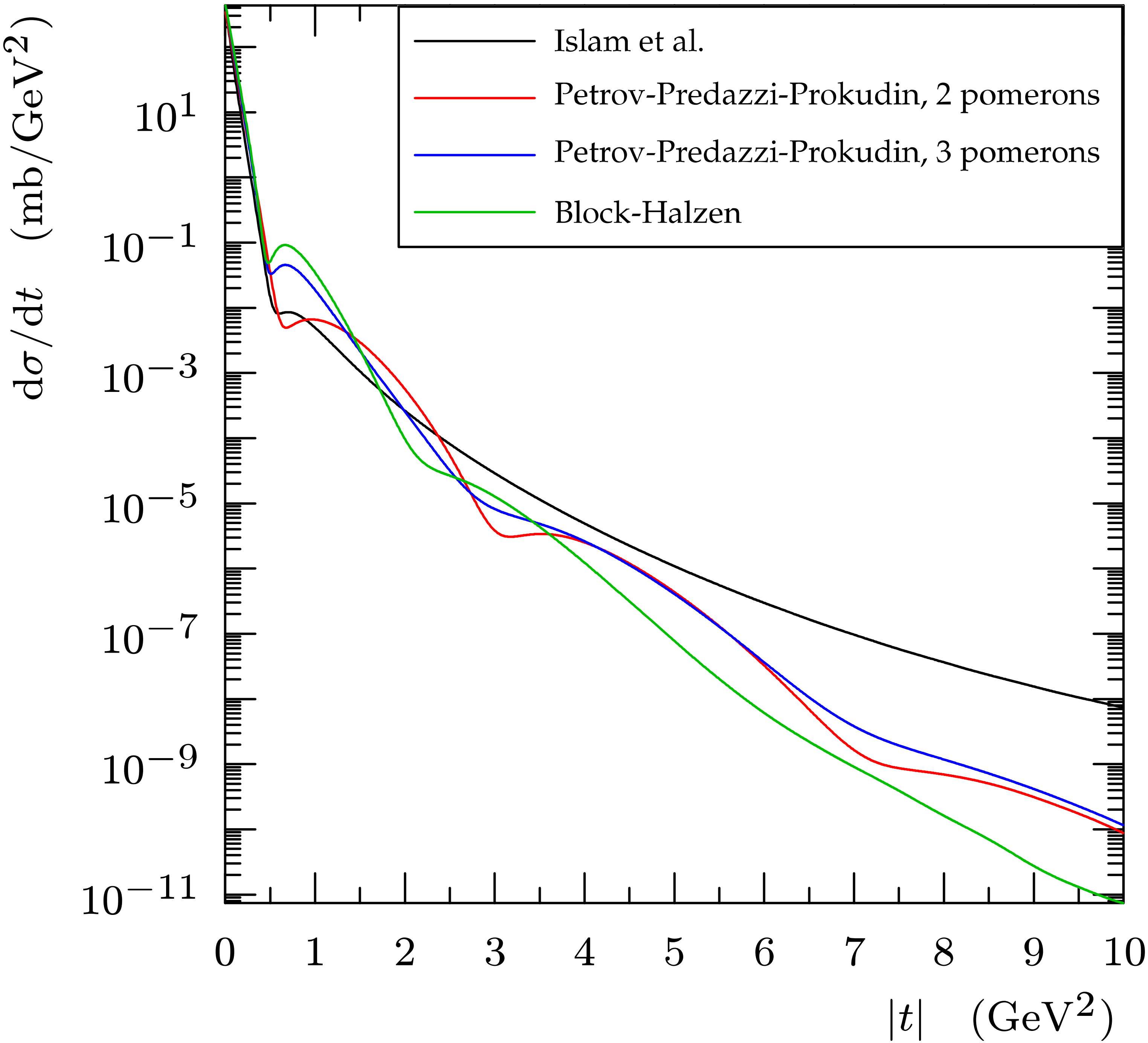
Elastic Scattering, $\sqrt{s}$ = 7 TeV, β* = 2 m

Elastic scattering cross-section
KL/PP3 model, subrange of -t > 0.3 GeV^2



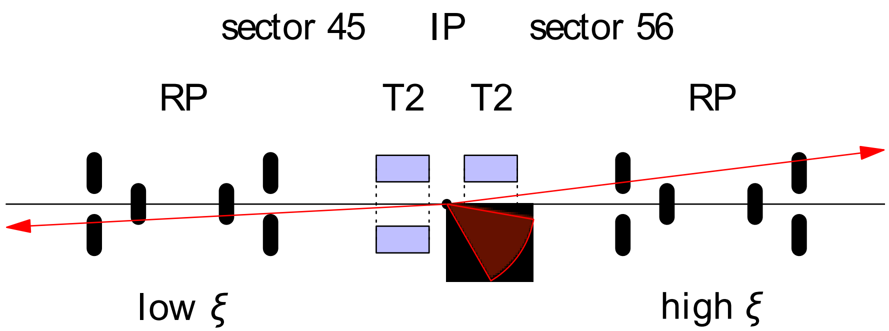
Elastically scattered proton flux

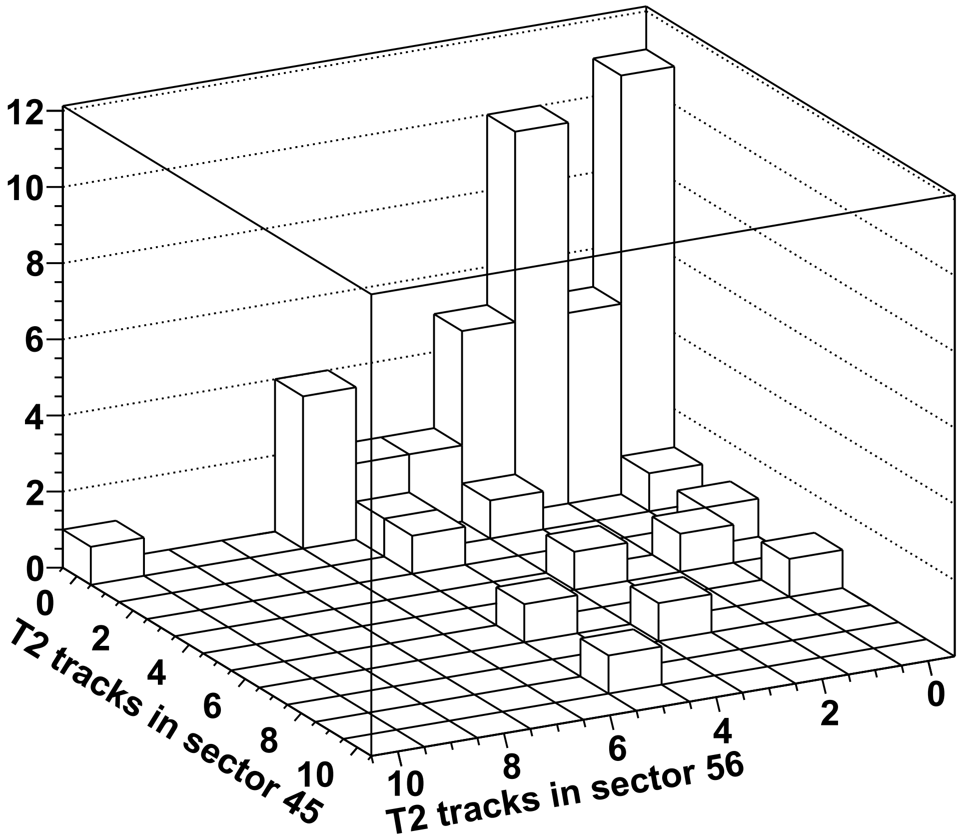




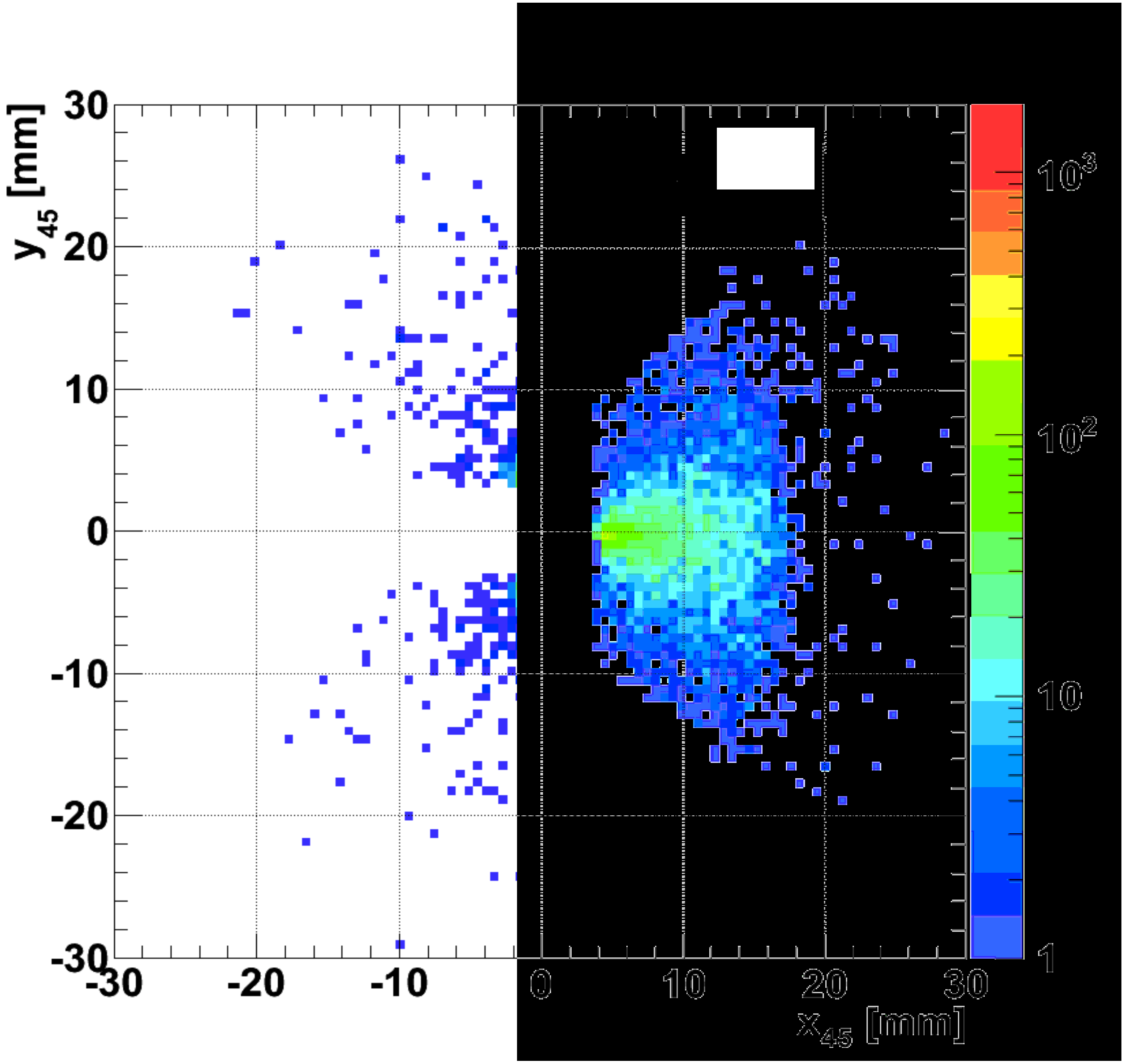
Islam et al.
Petrov-Predazzi-Prokudin, 2 pomerons
Petrov-Predazzi-Prokudin, 3 pomerons
Block-Halzen
$d\sigma/dt$ (mb/GeV^2)
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
0
1
2
3
4
5
6
7
8
9
10
$|t|$ (GeV^2)

Double Pomeron exchange





Hit distribution for an inclusive trigger (global "OR")

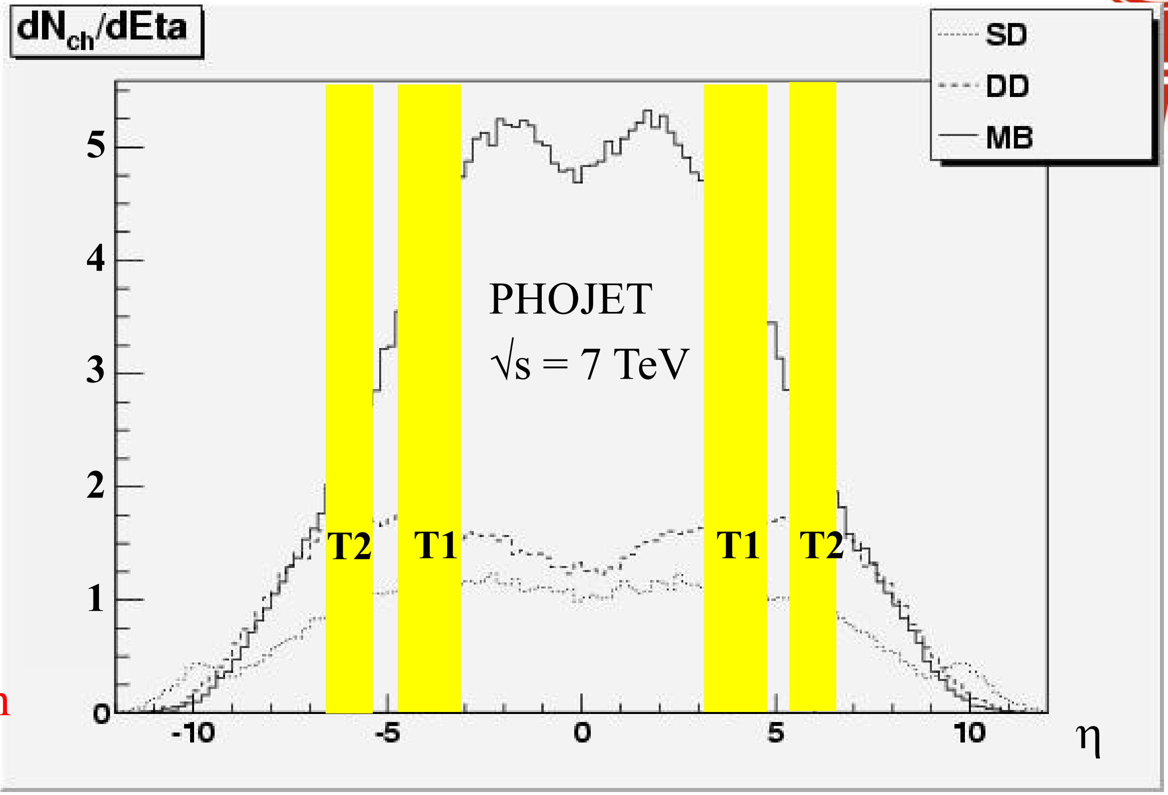


Acceptance for inelastic events (1)

Uncertainties in inelastic cross sections large:

- non-diffractive minimum bias (MB) 40 – 60 mb
- single diffraction (SD) 10 – 15 mb
- double diffraction (DD) 4 – 11 mb

Low multiplicities in diffraction



Accepted event fraction:

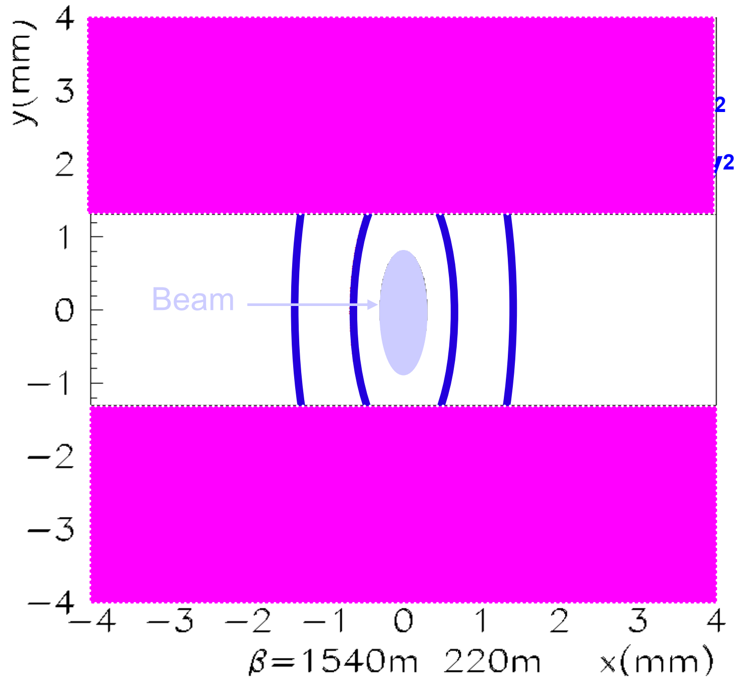
Min. number of tracks	MB T1+T2	MB 1/2 T1 + T2	MB T2 only	DD T1+T2	DD 1/2 T1 + T2	DD T2 only	SD T1+T2	SD 1/2 T1 + T2	SD T2 only
≥1(L + R)	100,0%	100,0%	98,2%	94,1%	92,9%	89,8%	77,6%	75,4%	71,3%
≥2(L + R)	100,0%	99,5%	95,1%	88,9%	83,4%	73,8%	68,6%	61,9%	51,3%
≥3(L + R)	99,9%	98,1%	89,0%	83,9%	75,3%	57,5%	61,4%	49,9%	32,3%
≥4(L + R)	99,1%	95,9%	82,2%	78,2%	66,3%	45,5%	55,0%	40,0%	19,0%
≥5(L + R)	98,3%	93,2%	71,7%	73,3%	59,5%	33,3%	48,4%	31,4%	11,5%

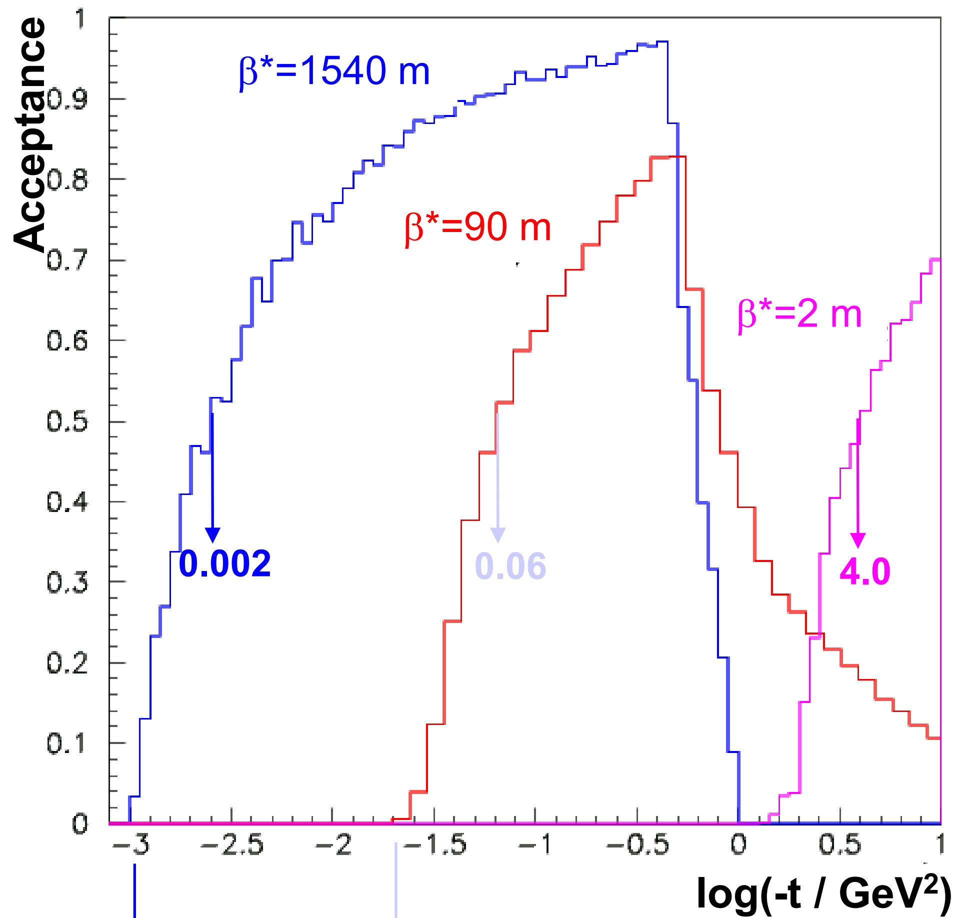
Efficiency increases

Elastic Scattering Acceptances
β* = 1540 90 2 m

β* = 1540 m

Detector distance to the beam: 10σ+0.5mm





Detector distance 1.3 mm 6 mm