Optics measurments of TOTEM

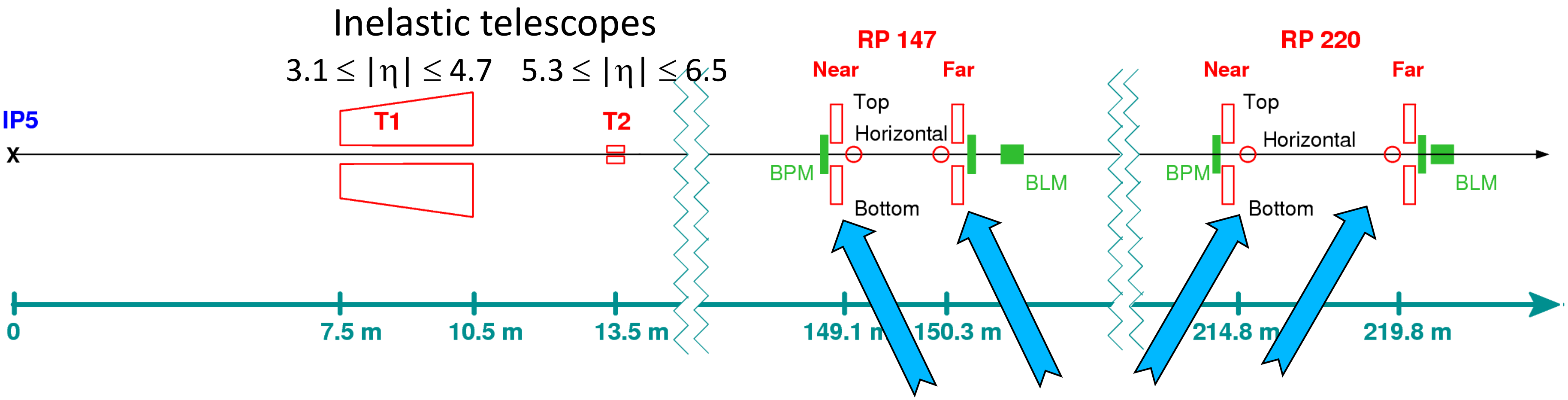
7 sigma runs (β^*=3.5m) on 30/10/2010

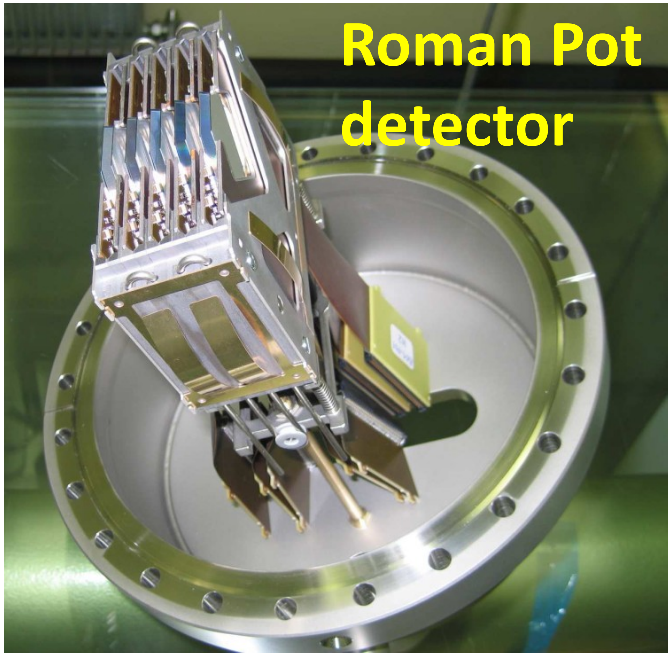
Hubert Niewiadomski

Optics Measurements, Corrections and Modelling for High-Performance Storage Rings workshop (OMCM)

CERN, 20-23.06.2011

TOTEM Roman Pots in the LHC



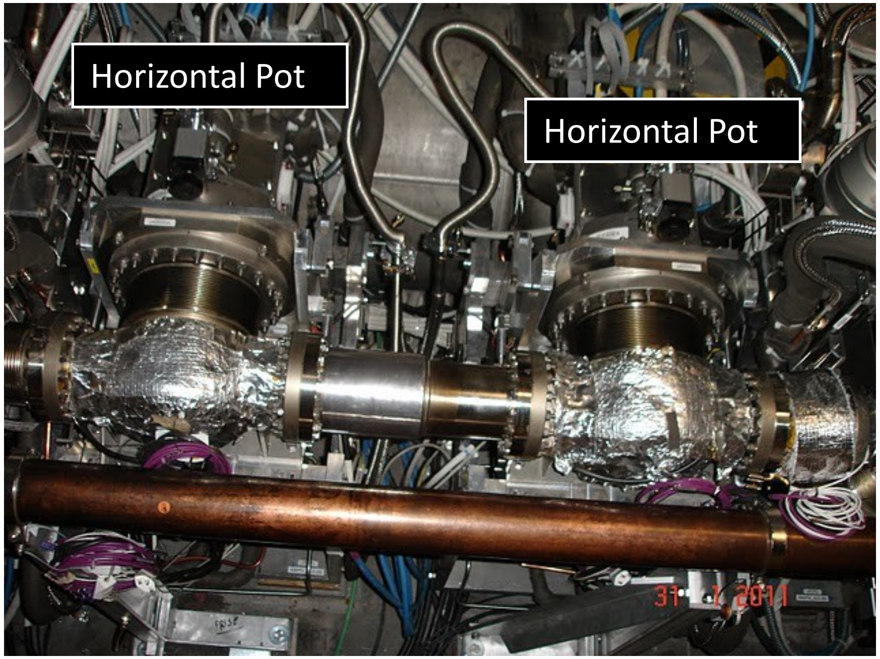


TOTEM Roman Pots

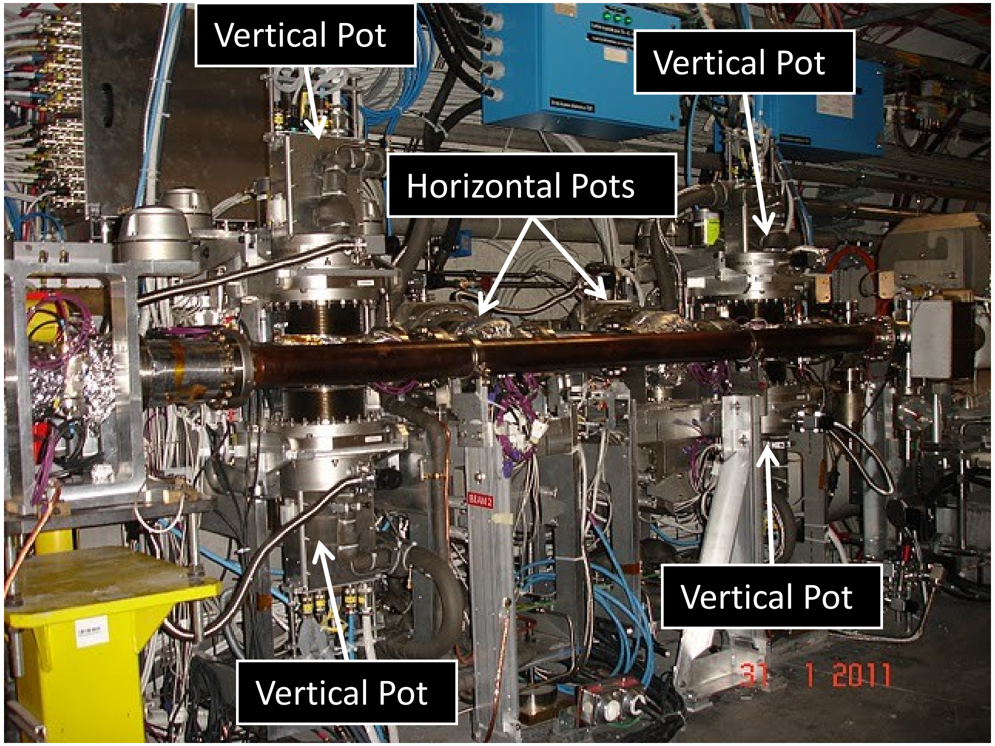
- 4 stations @ s≈±147 and s≈±220m
  - 6 Roman Pots per station
    (4 vertical + 2 horizontal)
- A total of 24 Roman Pots

Roman Pot station outlook

- **High spatial resolution of track reconstruction**
    - $\sigma(x)=\sigma(y)\approx 13\mu m$
    - $\sigma(\theta_x)=\sigma(\theta_y)\approx 3.7\mu rad$

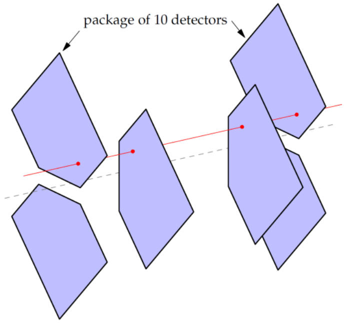


(s=~147m from IP5)

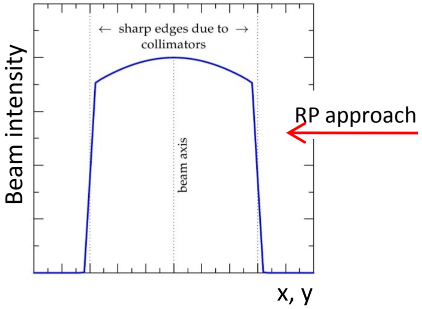


Precise detector alignment

Track based alignment: ~5µm

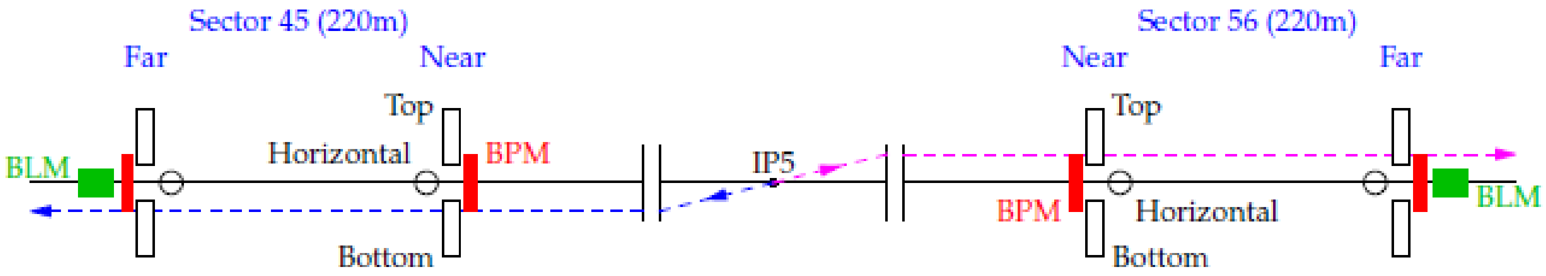


Beam touching alignment: ~20µm



Elastic protons for optics diagnosis

7 sigma runs on 30/10/2010



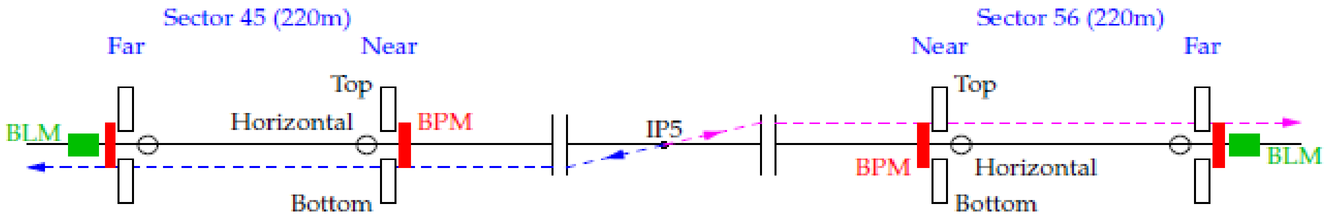
Transport IP5→RP220

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

- **Elastically scattered protons:**
  - Can be easily tagged
  - Pair of collinear protons: $\Theta_{left}^* = \Theta_{right}^*$ (within beam divergence)
  - No momentum loss: $\xi = \Delta p / p = 0$ (within beam momentum spread)
    - Dispersion and tune change eliminated
- **β^*=3.5m optics:**
  - Beam size @ IP5: 59µm, its impact eliminated by antisymmetric event topology
  - @ s=220m : $L_x \approx 0$, $L_y \approx 20$m

Proton tracks of a single diagonal

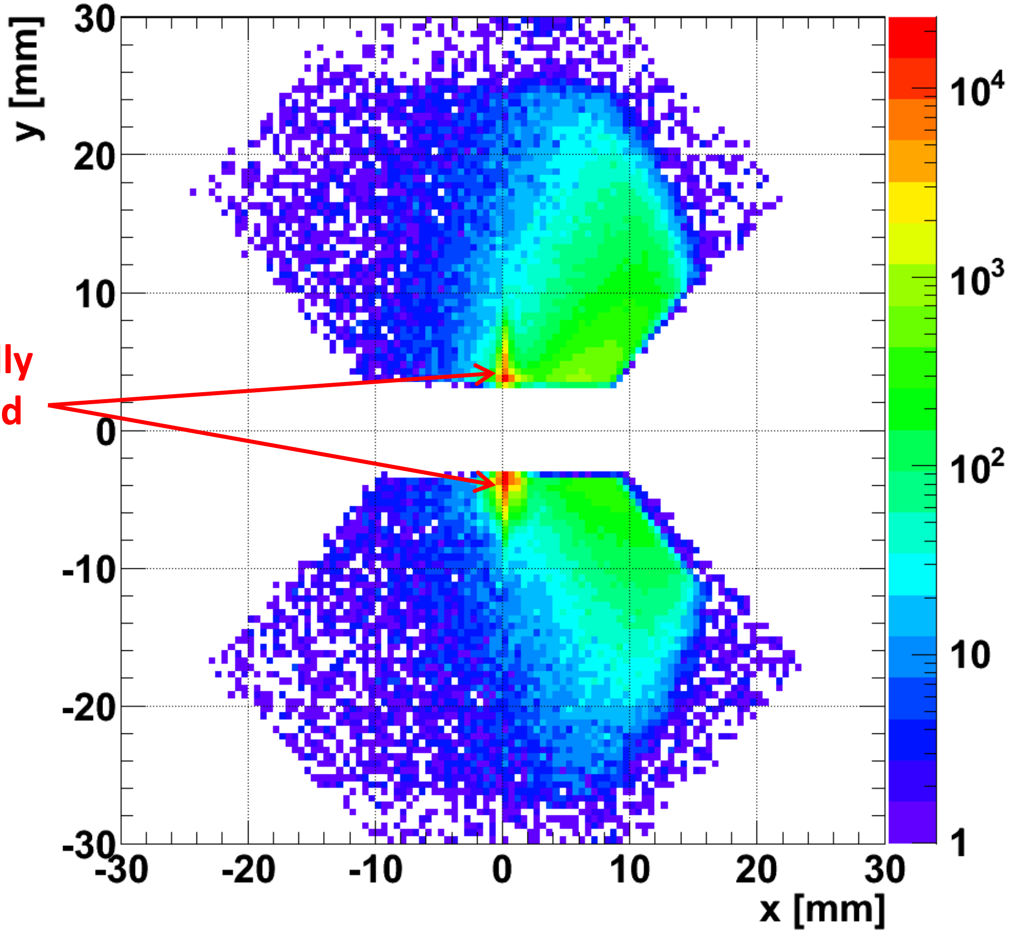
(left-right coincidences)

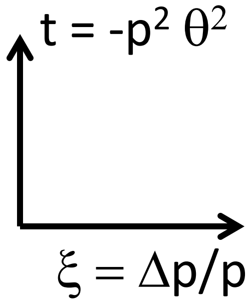


Sector 56

Sector 45

Elastically scattered protons





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

$\xi = \Delta p/p$

$y = L_y \Theta_y$

$x = L_x \Theta_x + \xi D$

$L_x \sim 0$

For details on elastic proton selection see backup slides

Elastic proton reconstruction

- **Elastic proton reconstruction:**

Per arm:

$$\begin{cases} \Theta^{*}_{x,\text{arm}} = \Theta_{x,\text{arm},\text{RP220}} \Big/ \dfrac{dL_{x,\text{arm}}}{ds} \\ \Theta^{*}_{y,\text{arm}} = y_{\text{arm, RP220}} / L_{y,\text{arm}} \end{cases}$$

Arms averaged:

$$\begin{cases} \Theta^{*}_{x} = (\Theta^{*}_{x,45} + \Theta^{*}_{x,56})/2 \\ \Theta^{*}_{y} = (\Theta^{*}_{y,45} + \Theta^{*}_{y,56})/2 \end{cases}$$

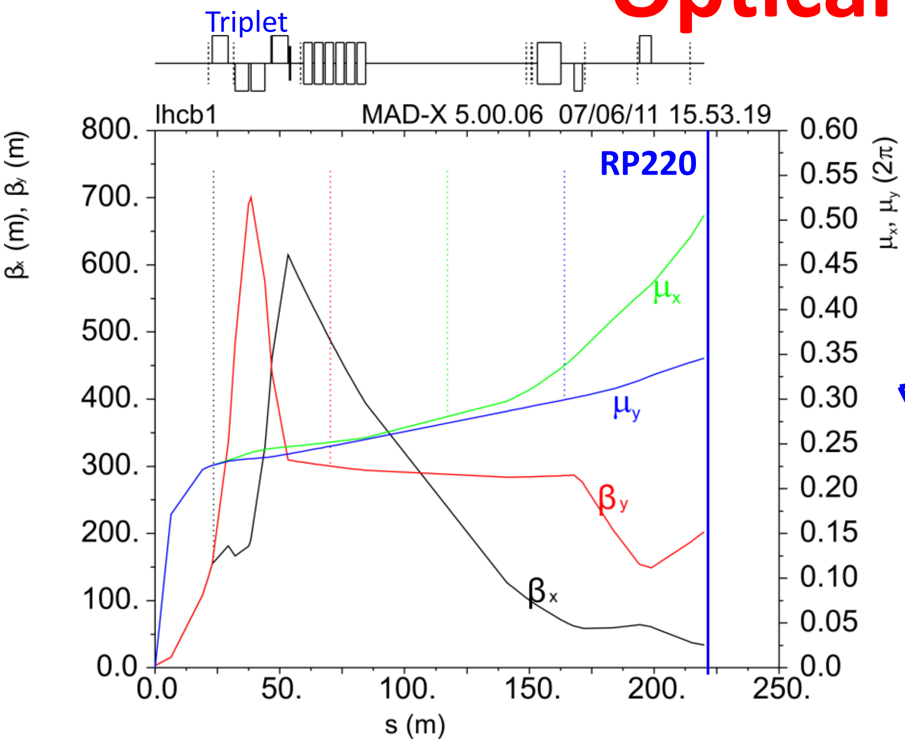
Finally:

$$t = -p^{2}(\Theta^{*2}_{x} + \Theta^{*2}_{y})$$

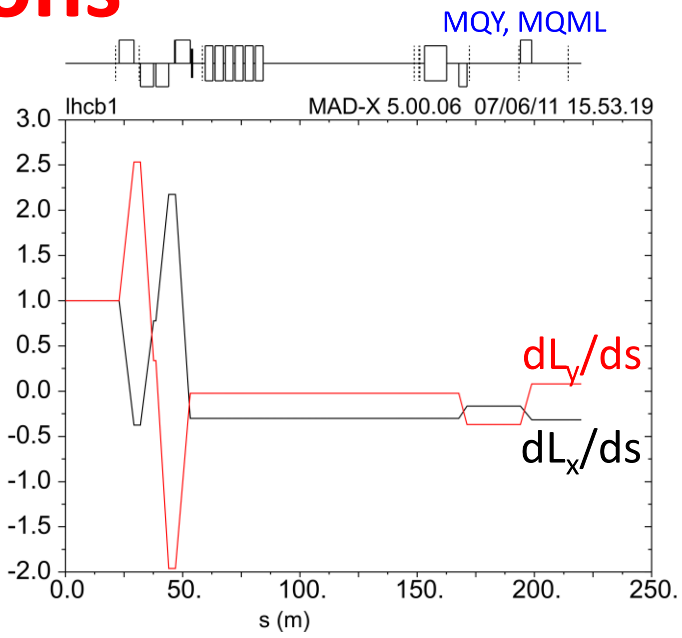
- Precise values of dL_x/ds and L_y @ RP locations needed!
  - enough to have the values, sources of errors of less importance for TOTEM
  - β-measurement based estimations give the error of 5–10%

- Can we measure them with the proton tracks?
- What are the sources of optics imperfections in the range of interest?

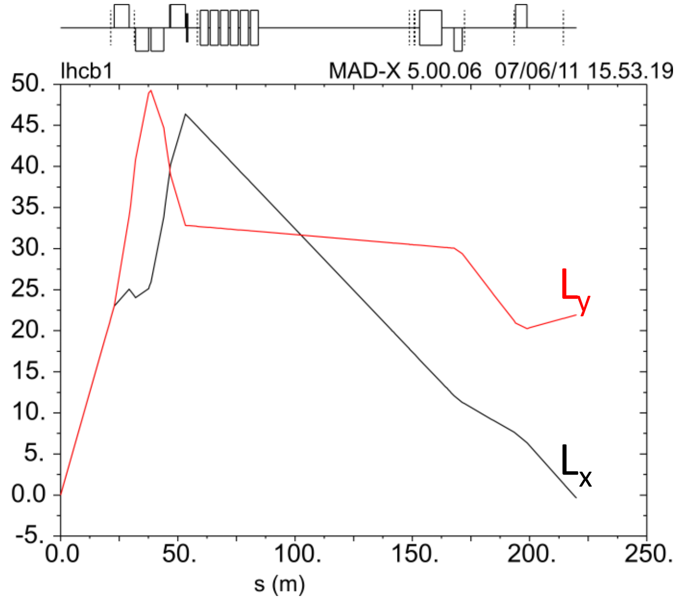
Optical functions



transport matrix



transport matrix



Inner triplet determines
dL_x/ds and dL_y/ds for s=50..220m

$$\begin{cases} L_{x,y}(s) = \int_0^s \frac{dL_{x,y}(\hat{s})}{d\hat{s}} d\hat{s} + C_1 \\ \frac{dL_{x,y}(s)}{ds} = \int_0^s L_{x,y}(\hat{s}) k(\hat{s}) d\hat{s} + C_2 \end{cases}, \quad \text{with} \quad \begin{cases} L_{x,y}(0) = 0 \\ \frac{dL_{x,y}}{ds}(0) = 1 \end{cases}$$

Optics perturbation in IP5

k change by 0.1% (expected limit for the TF error)

Perturbed magnets BEAM 1	BETX	BETY	MUX	MUY	ν_x	ν_y	L_x	L_y	dL_x/ds	dL_y/ds	$s : L_x=0$	$\Delta s : L_x=0$ [m]
Nom. MADX solution (TIMBER Oct 30 2010)	33.7m	208m	0.502 $\cdot 2\pi$	0.344 $\cdot 2\pi$	3.10	4.28	-0.132m	22.4m	-0.321	0.086	220m	
MQXA.1R5	0.29%	1.24%	0.31%	-0.25%	0.13%	-0.20%	**79.59%**	0.98%	-0.46%	3.20%	-0.15%	-0.331
MQXB.A2R5	-0.14%	-2.83%	-0.25%	0.57%	-0.07%	0.37%	**-64.86%**	**-2.24%**	0.33%	-7.46%	0.12%	0.268
MQXB.B2R5	-0.13%	-3.08%	-0.37%	0.60%	-0.06%	0.36%	**-96.49%**	**-2.42%**	0.45%	-8.13%	0.18%	0.398
MQXA.3R5	0.33%	1.91%	1.00%	-0.34%	0.08%	-0.18%	**259.35%**	1.45%	**-1.14%**	4.95%	-0.49%	**-1,086**
MQY.4R5.B1	0.07%	-0.17%	-0.01%	0.01%	0.03%	-0.05%	**-3.83%**	-0.10%	-0.02%	-0.64%	0.01%	0.016
MQML.5R5.B1	-0.12%	0.09%	0.01%	0.00%	-0.06%	0.04%	**2.80%**	0.05%	0.05%	0.54%	-0.01%	-0.011

t-reconstruction

- Only inner triplet really important
- MQY, MQML not really important

- **Roman Pot measurments can be used for optics matching**

Optics determination

Measurements with Roman Pots:

- $\frac{dL_{x,56}}{ds} / \frac{dL_{x,45}}{ds}$
- $L_{y,56} / L_{y,45}$

Constrains between the 2 IP5 triplets (2 sides of IP5)

- $\left. \frac{dL_y}{ds} / L_y \right|_{s=\pm 220}$
- $\left. s : L_x(s) = 0 \right|_{s \approx \pm 220}$
- $\left. x \leftrightarrow y \text{ coupling} \right|_{s=\pm 214, \pm 220}$ $(re_{14}/L_y,\ re_{14} = \frac{x_{RP220}}{\Theta^*_y})$

Independent constraints per triplet

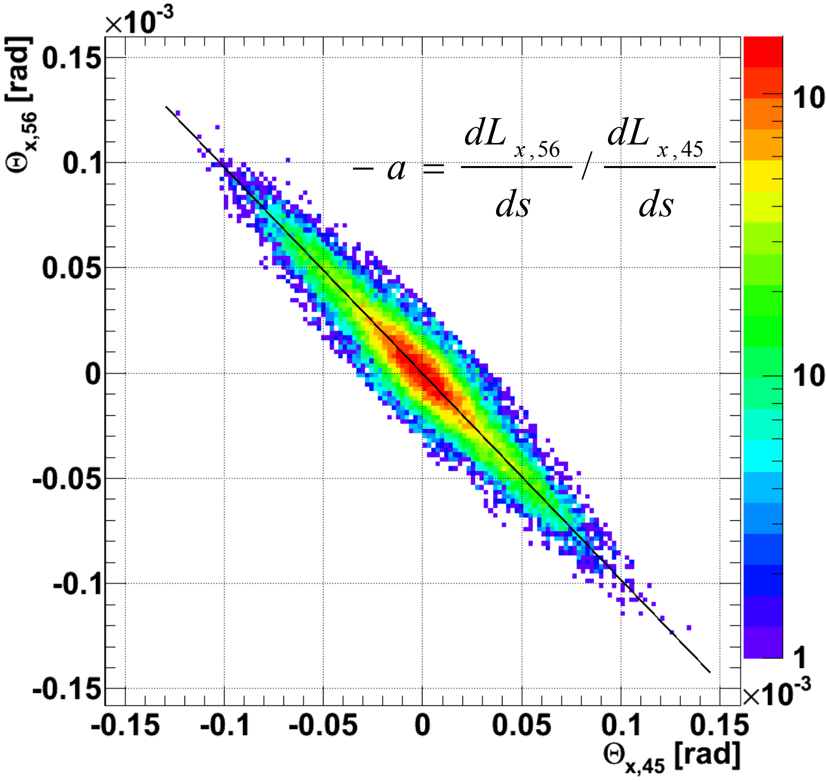
Strategy:

1. Magnet settings from TIMBER/LSA
2. MADX (PTC Twiss) optics model
3. Insertion of the Roman Pots and data taking
4. Elastically scattered protons selection
5. Determination of optics constraints with RP proton tracks
6. Matching of the optics (determination of the transport matrix)

$(dL_x/ds_{45})/(dL_x/ds_{56})$ and $L_{y,45}/L_{y,56}$ determination

beam 1 & 2 together

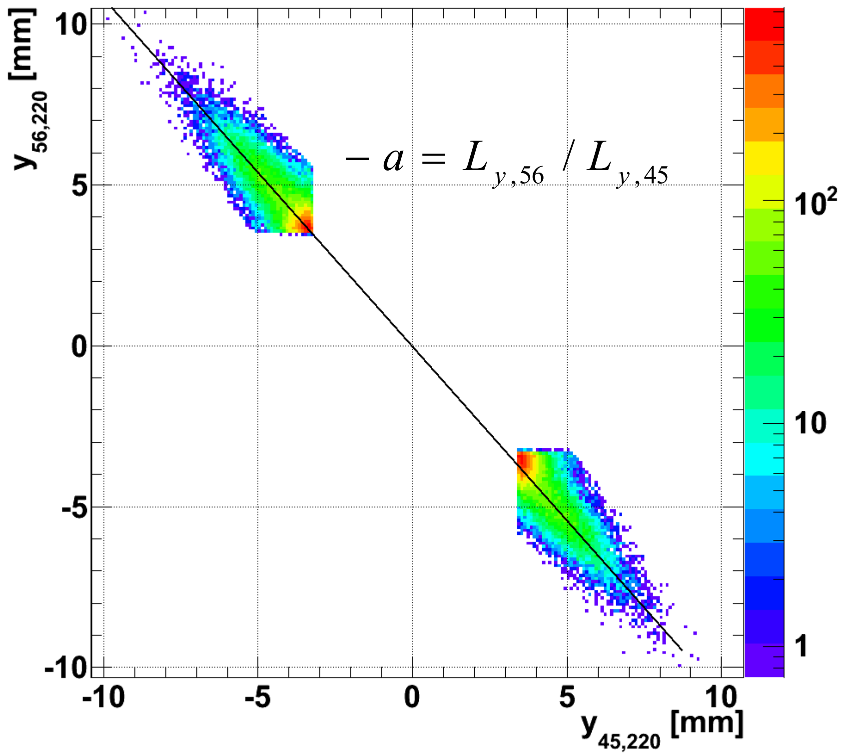
$$\Theta_{x,56} = \frac{dL_{x,56}}{ds}\Theta^*_{x,45} + \frac{dv_x}{ds}x^*_{56}$$



$$-a = \frac{dL_{x,56}}{ds} / \frac{dL_{x,45}}{ds}$$

$$\Theta_{x,45} = \frac{dL_{x,45}}{ds}\Theta^*_{x,45} + \frac{dv_x}{ds}x^*_{45}$$

$$y_{56} = L_{y,56}\Theta^*_{y,56} + v_y y^*_{56}$$



$$-a = L_{y,56} / L_{y,45}$$

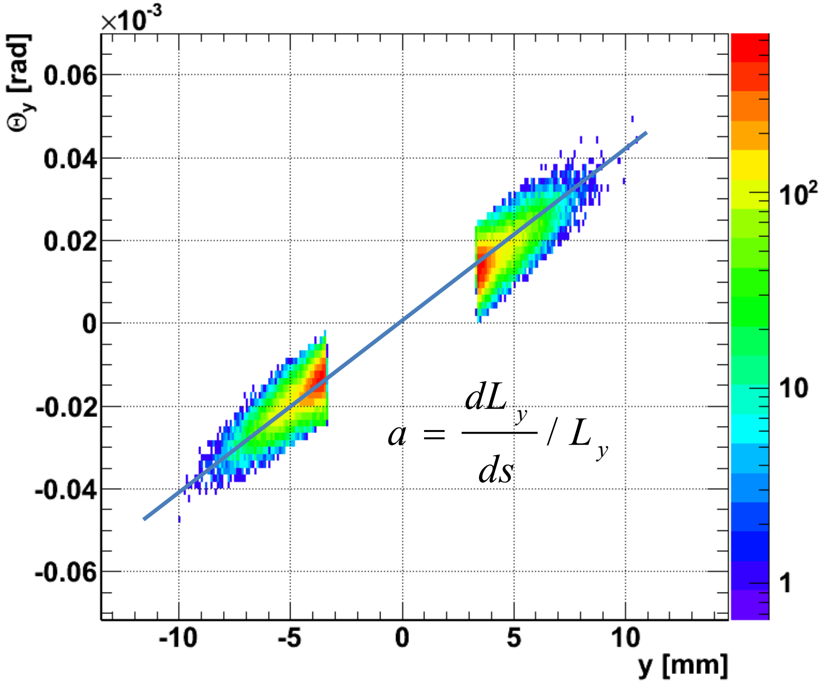
$$y_{45} = L_{y,45}\Theta^*_{x,45} + v_y y^*_{45}$$

Constraints for triplet strenghts matching

$(dL_y/ds)/L_y$ and coupling determination

beam 1 & beam 2 separately

$$\Theta_{y,56} = \frac{dL_{y,56}}{ds}\Theta^*_{y,45} + \frac{dv_y}{ds}y^*_{56}$$

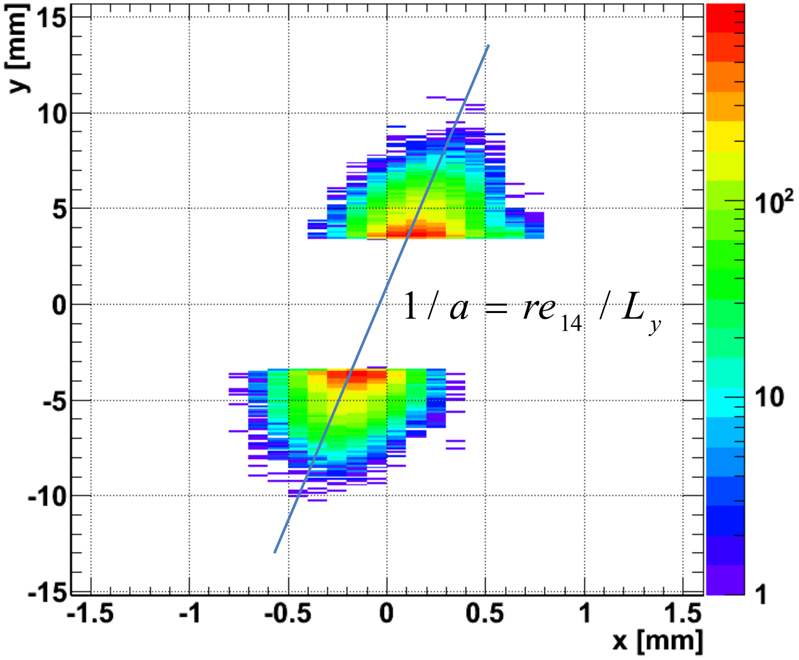


$$y_{56} = L_{y,56}\Theta^*_{y,56} + v_y y^*_{56}$$

(dLy/ds) / Ly near =$3.92 \cdot 10^{-3}$ m^{-1}
Nominally: $2.7 \cdot 10^{-3}$ m^{-1}

Constraint for triplet strenghts matching

$$y_{56} = L_{y,56}\Theta^*_{y,56} + v_y y^*_{56}$$



$$x_{56} = L_{x,56}\Theta^*_{x,56} + v_x x^*_{56} + re_{14}\Theta^*_{y,56}$$

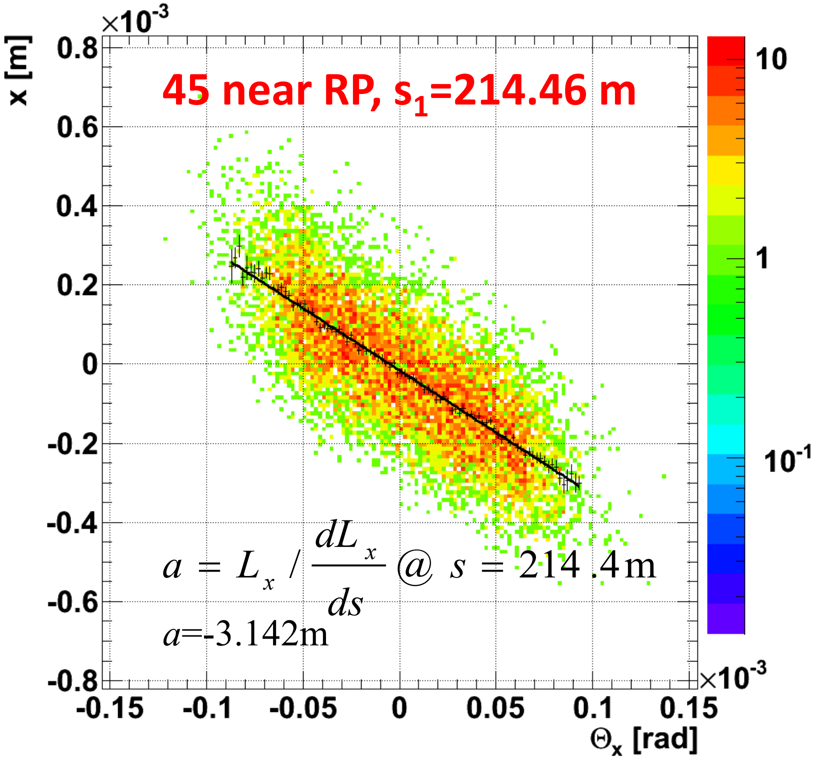
re14/Ly far=36 mrad
Nominally: 0

Constraint for triplet rotation matching

s: $L_x(s)=0$ determination

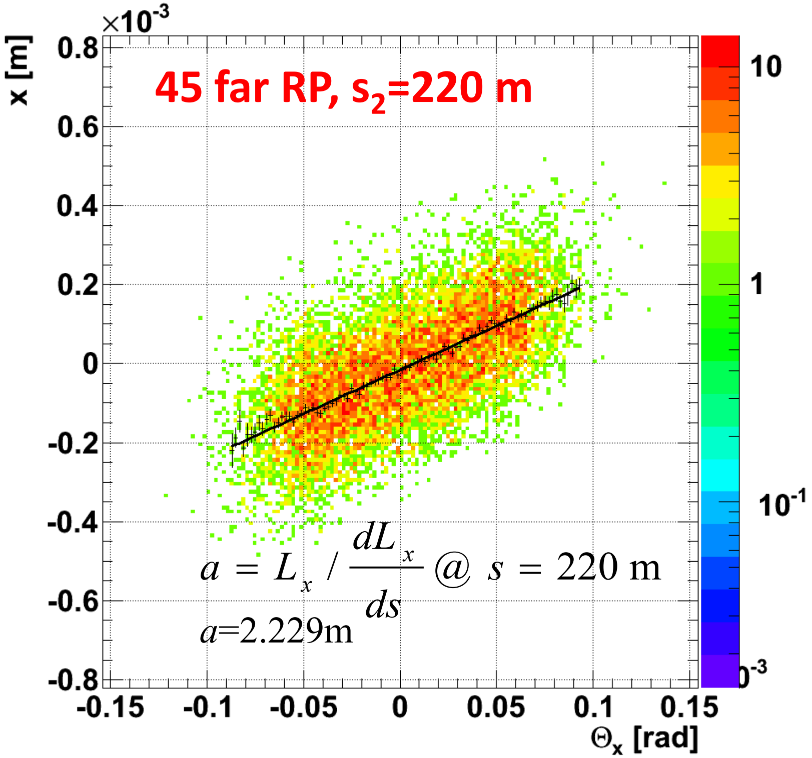
beam 1 & beam 2 separately

$$x_{56} = L_{x,56}\Theta^*_{x,56} + v_x x^*_{56}$$



$$\Theta_{x,56} = \frac{dL_{x,56}}{ds}\Theta^*_{x,45} + \frac{dv_x}{ds}x^*_{56}$$

$$x_{56} = L_{x,56}\Theta^*_{x,56} + v_x x^*_{56}$$



$$\Theta_{x,56} = \frac{dL_{x,56}}{ds}\Theta^*_{x,45} + \frac{dv_x}{ds}x^*_{56}$$

$$\frac{dL_x}{ds} = \text{const with in RP station,} \quad L_x(s_2) = \int_{s_1}^{s_2}\frac{dL_x(\hat{s})}{d\hat{s}}d\hat{s} + L_x(s_1)$$

Interpolation: $L_{x,45}(s) = 0 : s = 217.77$ m

Matched parameters

- Influence of all magnet parameters in ±220m range analysed...
  - ~30 parameters per beam
  - Magnet positions, rotations, k
  - Beam momentum, displacement, crossing angle, harmonics...

- Most significant parameters selected for matching
  - 6 strengths per beam (MQXA, MQXB, MQXB, MQXA, MQY, MQML)
  - 6 corresponding rotations about the beam
  - Mean $\Delta p/p$ per beam
  - Total of 26 fitted parameters

Constraints

- Measured elastic scattering kinematics constraints between arms (a total of 2):
  - Ratio of Ly56 / Ly45 (0.5 % precision)
  - Ratio of (dLx/ds 56) / (dLx/ds 45) (0.5 % precision)
- Measured constraints of individual arms (a total of 8):
  - (dLy/ds)/Ly (0.5%)
  - near unit coupling, far unit coupling (3%)
  - s: Lx=0 (1 m)
- LHC design constraints (a total of 26):
  - sigma(k)/k = 0.1%
  - sigma (rot) = 1mrad
  - Sigma(ξ)/ ξ = 10^{-3}

TOTAL of 36 constraints

Matching solution

Full 4x4 transport matrix IP5→RP220 obtained per beam

Beam 1	dL_x/ds	L_y [m]	rot [mrad]
RP215	-0.311962	22.15	0.0432
RP220	-0.311962	22.62	0.0396
∆ RP215	-2.84%	+0.78%	
∆ RP220	-2.84%	+0.81%	

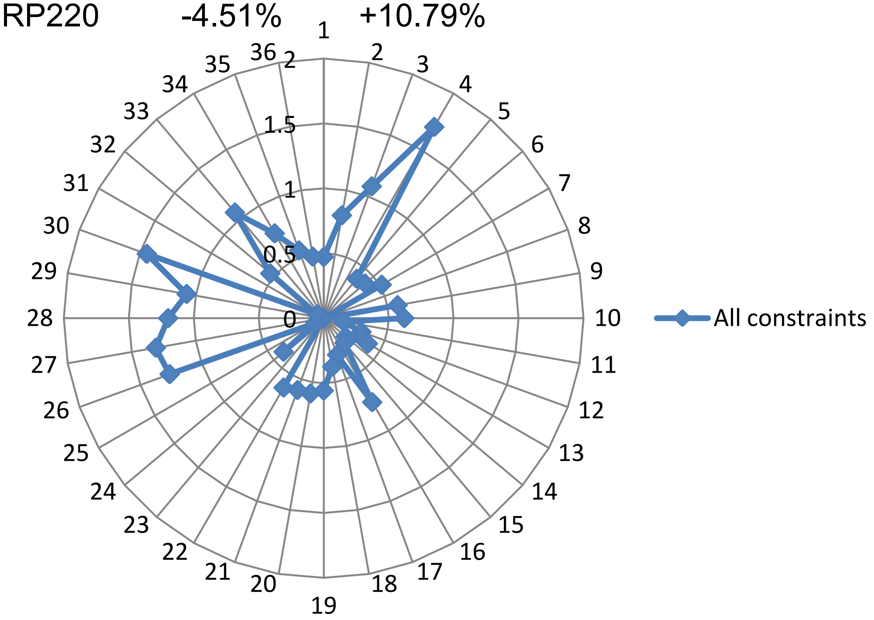
Beam 2	dL_x/ds	L_y [m]	rot [mrad]
RP215	-0.314508	20.3883272	0.0400268
RP220	-0.314508	20.6709463	0.0372828
∆ RP215	-4.51%	+10.19%	
∆ RP220	-4.51%	+10.79%	

Strong correlations between fitted parameters

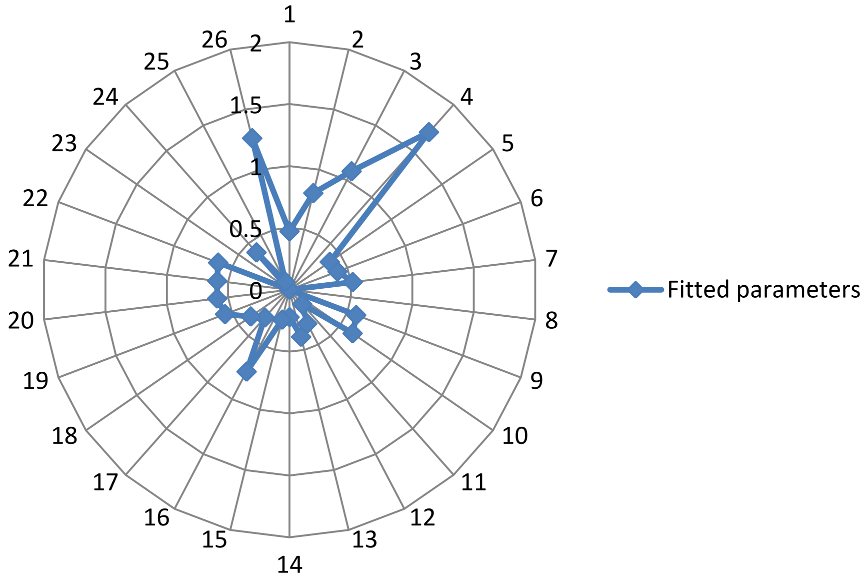
PCA should ideally be applied

χ^2/NDF = 25.8/(36-26)=2.6

(would be lower in correlations are elmininated)



Abs(Pulls) of constraints



Abs(Pulls) of fitted parameters

Complete solution

Beam 1

	BETX	BETY	MUX	MUY
nominal	3.37E+01	2.08E+02	5.13E-01	3.43E-01
obtained	3.41E+01	2.10E+02	5.02E-01	3.44E-01
difference	0.96%	1.07%	2.24%	-0.20%

Obtained transport matrix

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \end{pmatrix} = \begin{pmatrix} -3.11E+00 & -9.18E-01 & 2.35E-02 & 8.89E-01 \\ 3.11E-02 & \mathbf{-3.12E-01} & -2.23E-04 & -1.13E-02 \\ 3.09E-02 & 1.40E+00 & -4.27E+00 & \mathbf{2.26E+01} \\ 4.49E-04 & 1.82E-02 & -6.08E-02 & 8.79E-02 \end{pmatrix} \cdot \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \end{pmatrix}$$

Obtained changes

$$\begin{pmatrix} 0.31\% & 85.59\% & 114.70\% & 100.02\% \\ 0.38\% & \mathbf{-2.84\%} & 115.46\% & 96.83\% \\ 84.59\% & 101.79\% & -0.15\% & \mathbf{0.81\%} \\ 84.88\% & 100.53\% & -0.28\% & 2.13\% \end{pmatrix}$$

Beam 2

	BETX	BETY	MUX	MUY
nominal	3.40E+01	1.60E+02	4.90E-01	3.58E-01
obtained	3.39E+01	1.81E+02	5.08E-01	3.47E-01
difference	-0.41%	11.93%	3.51%	-3.04%

Obtained transport matrix

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \end{pmatrix} = \begin{pmatrix} -3.12E+00 & -5.39E-01 & 2.42E-02 & 6.87E-01 \\ 3.33E-02 & \mathbf{-3.15E-01} & -2.33E-04 & -8.42E-03 \\ 1.32E-02 & 1.07E+00 & -4.16E+00 & \mathbf{2.07E+01} \\ 2.05E-04 & 1.33E-02 & -5.90E-02 & 5.26E-02 \end{pmatrix} \cdot \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \end{pmatrix}$$

Obtained changes

$$\begin{pmatrix} 0.38\% & 226.67\% & 85.69\% & 100.11\% \\ 0.70\% & \mathbf{-4.51\%} & 84.17\% & 104.35\% \\ 135.55\% & 98.09\% & -1.44\% & \mathbf{10.79\%} \\ 132.41\% & 99.80\% & -1.23\% & 54.60\% \end{pmatrix}$$

Error estimation

- **All the measurements provoke magnet corrections in the same direction**
  - Observed optics imperfections in x and y per beam provoke identical needs for strengths corrections
  - Independent corrections of beam 1 and beam 2 lead to the observed ratios of **$(dL_x/ds_{45})/(dL_x/ds_{56})$** and **$L_{y,45}/L_{y,56}$**

- **Which part of the triplet is precisely responsible? Difficult to say**
  - main source of systematic error of corrected optics

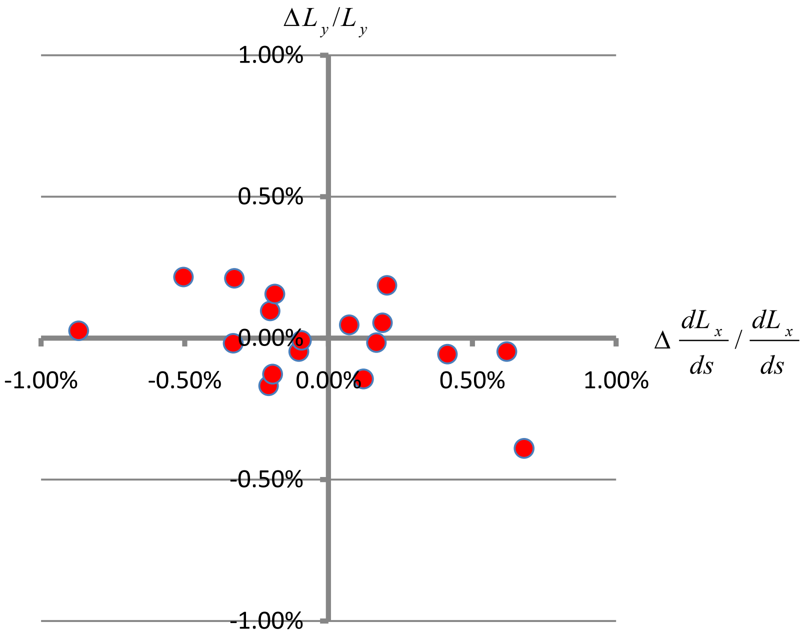
- Optics error estimation
  - Required corrections of up to 10% of the nominal optics values of Ly and dLx/ds
  - Values of corrections of Ly and dL_x/ds change by up to 10% depending on the quadrupole of the triplet to which the error is attributed
  - The error of the optics estimation is therefore ~10%·10%=1%

MC error verification

(in progress)

Verification procedure

1) Randomly perturbate the initial optics within magnet tolerances
2) Measure optics parameters with RPs
3) Match the optics
4) Compare matched optics to the initial perturbated conditions

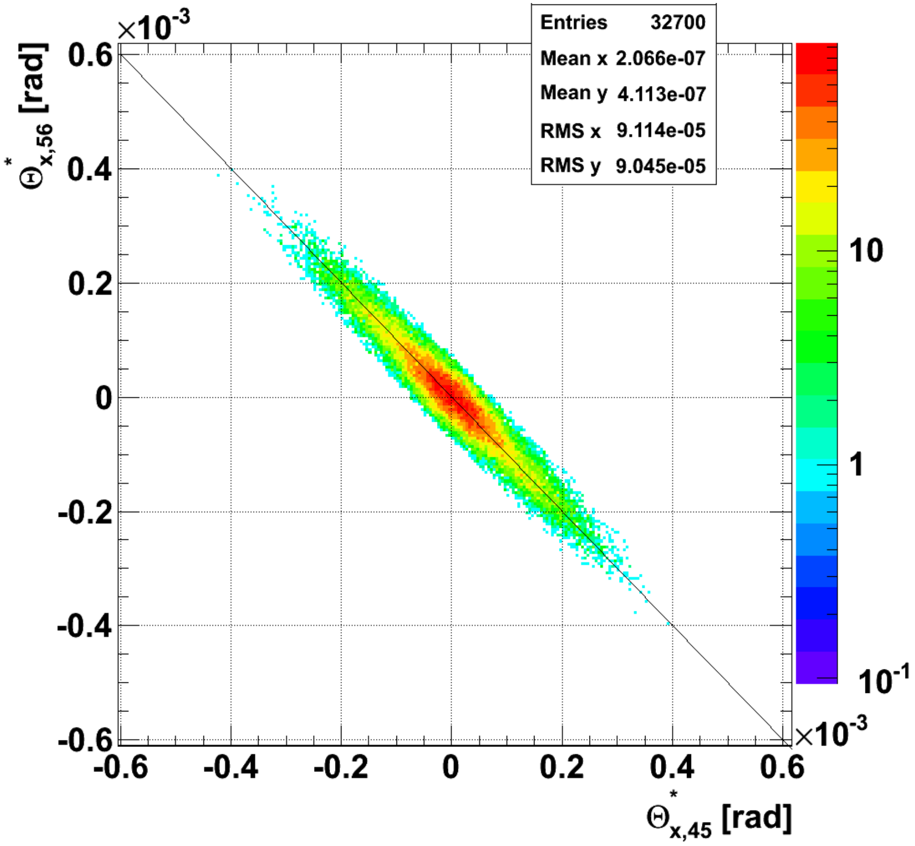


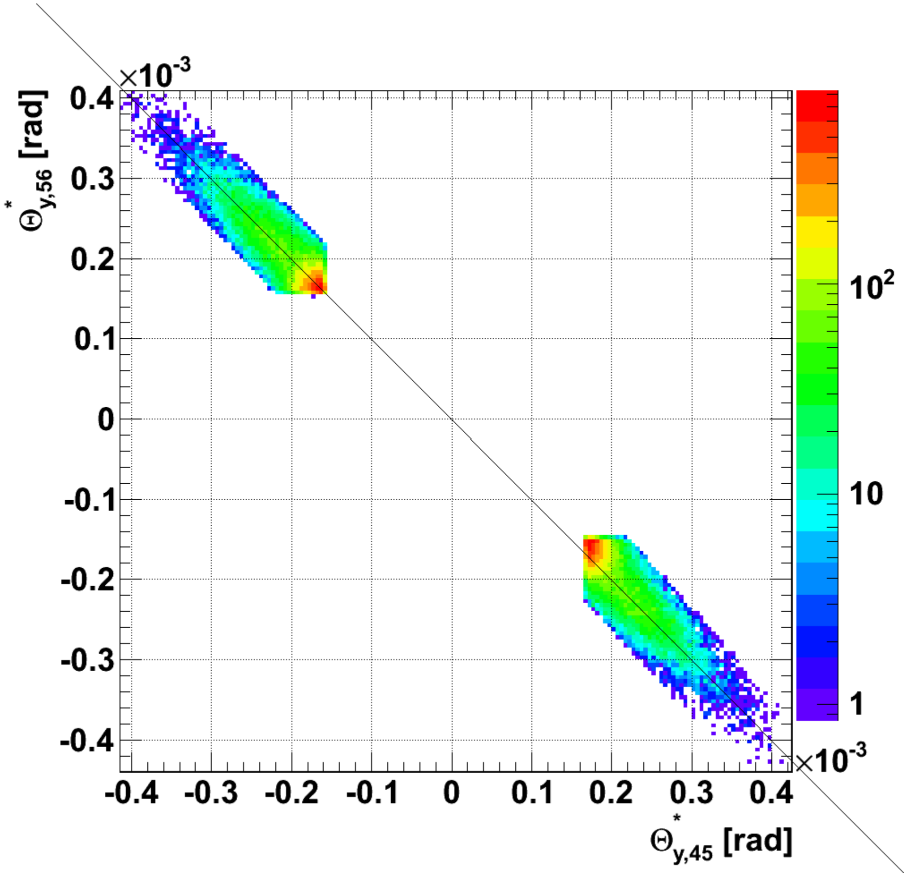
Obtained errors:

$$\sigma\left(\Delta \frac{dL_x}{ds} / \frac{dL_x}{ds}\right) = 0.4\%$$

$$\sigma\left(\Delta L_y / L_y\right) = 0.2\%$$

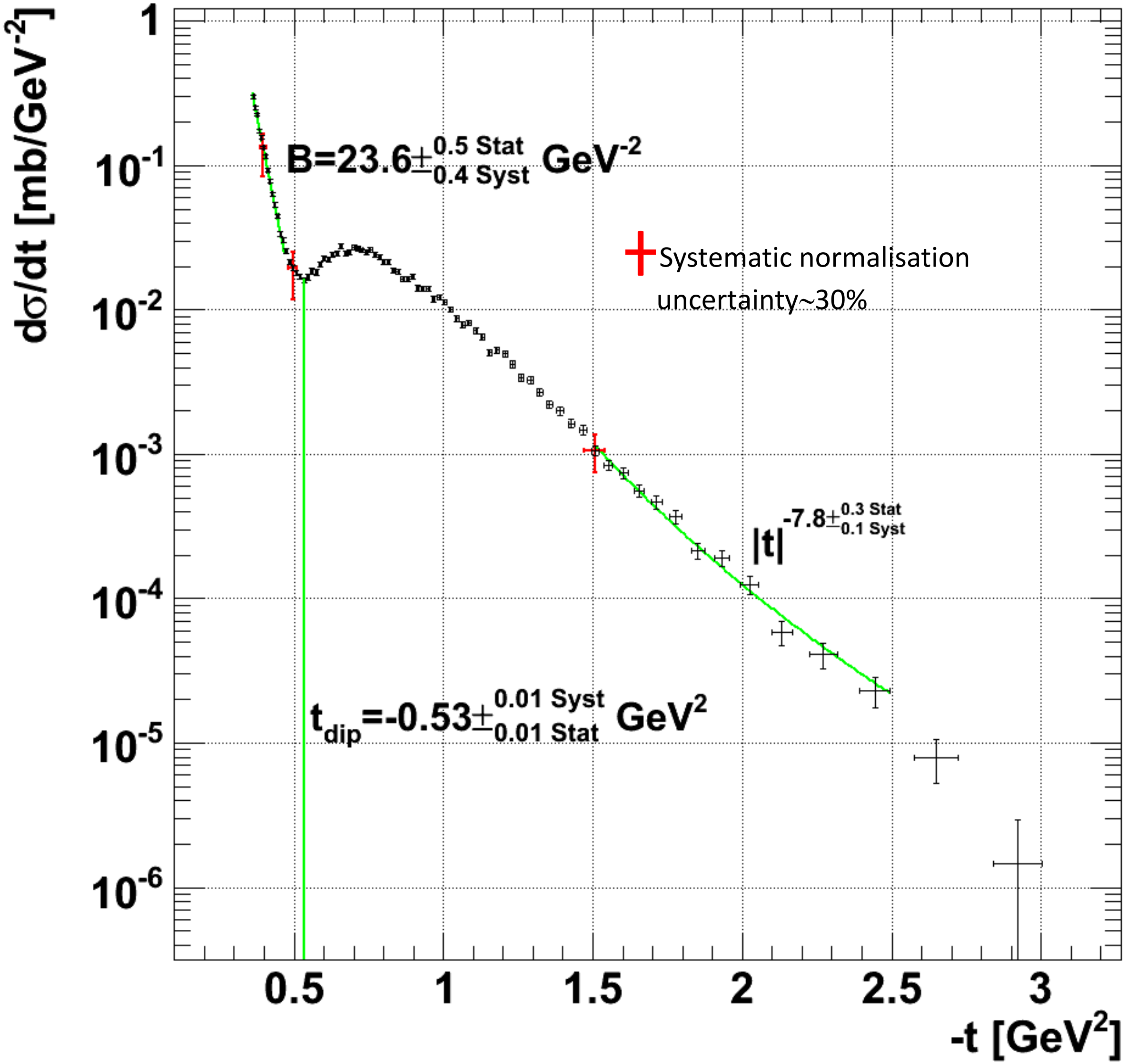
After matching, reconstructed protons



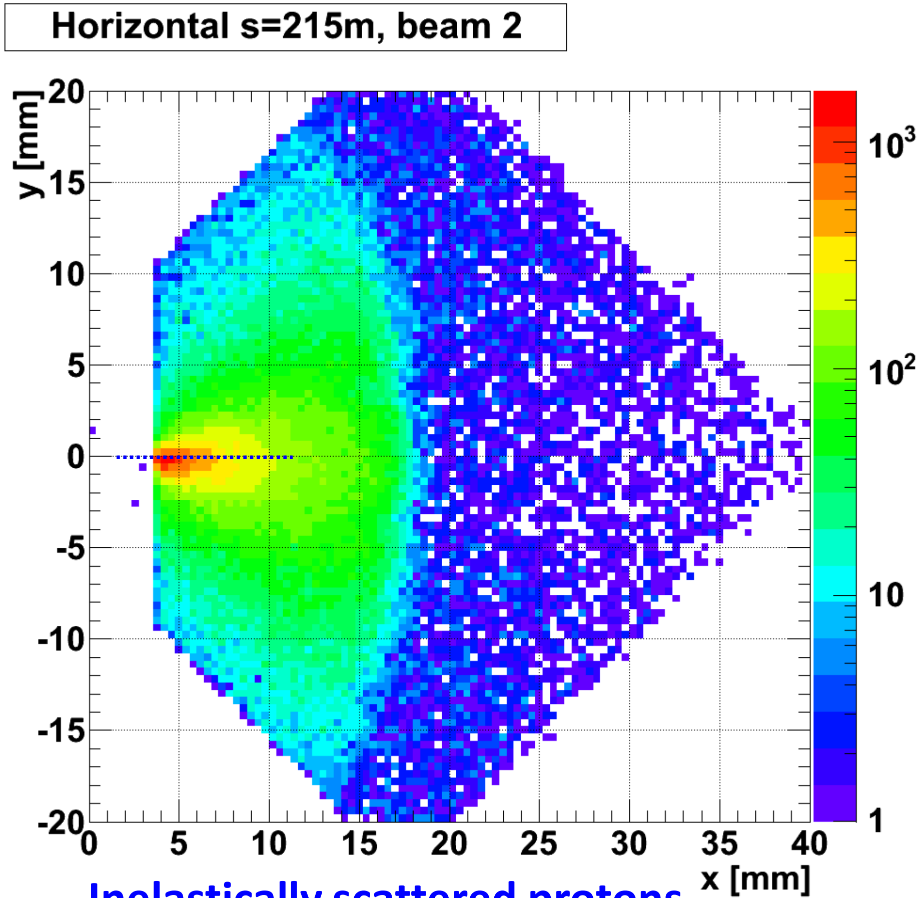


Arms and diagonals in perfect agreement

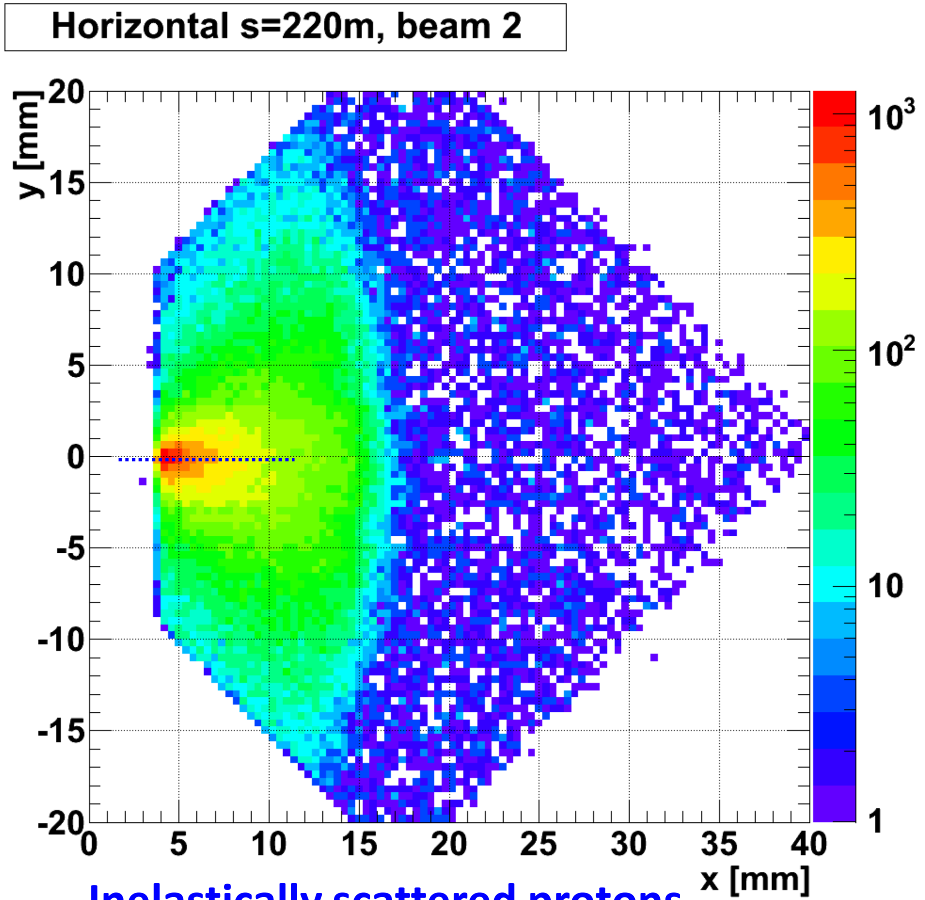
Final result: unfolded el. scat. distribution



Further steps: inelastic protons, D_y



Inelastically scattered protons

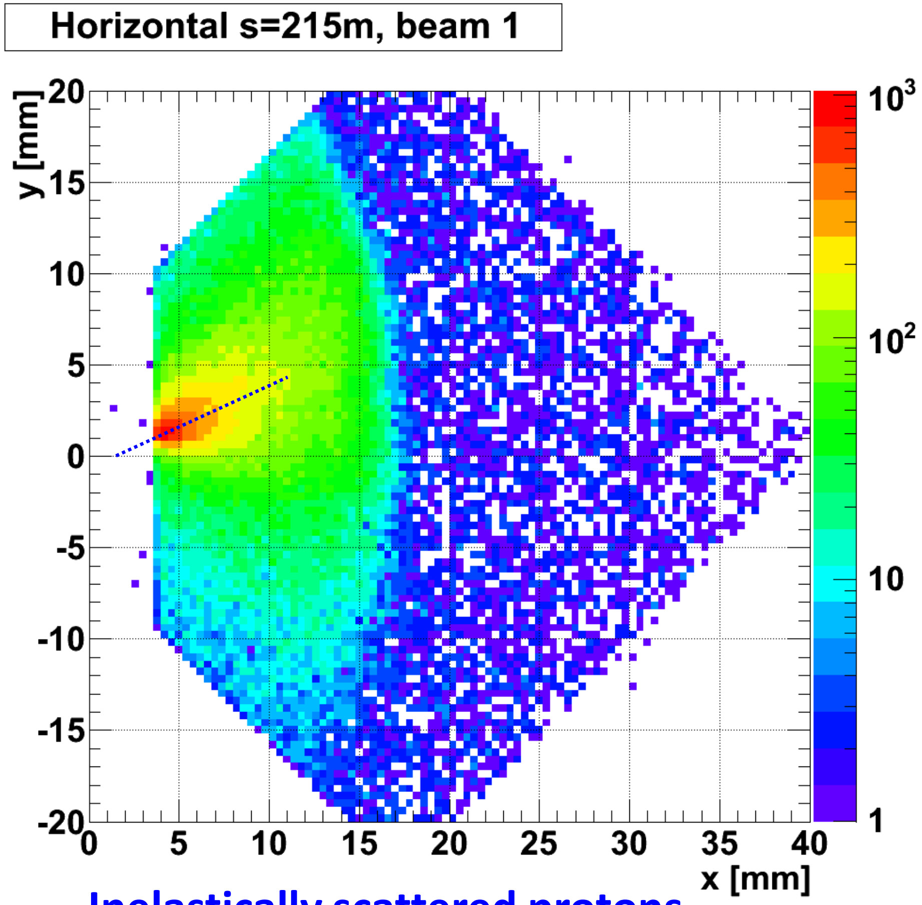


Inelastically scattered protons

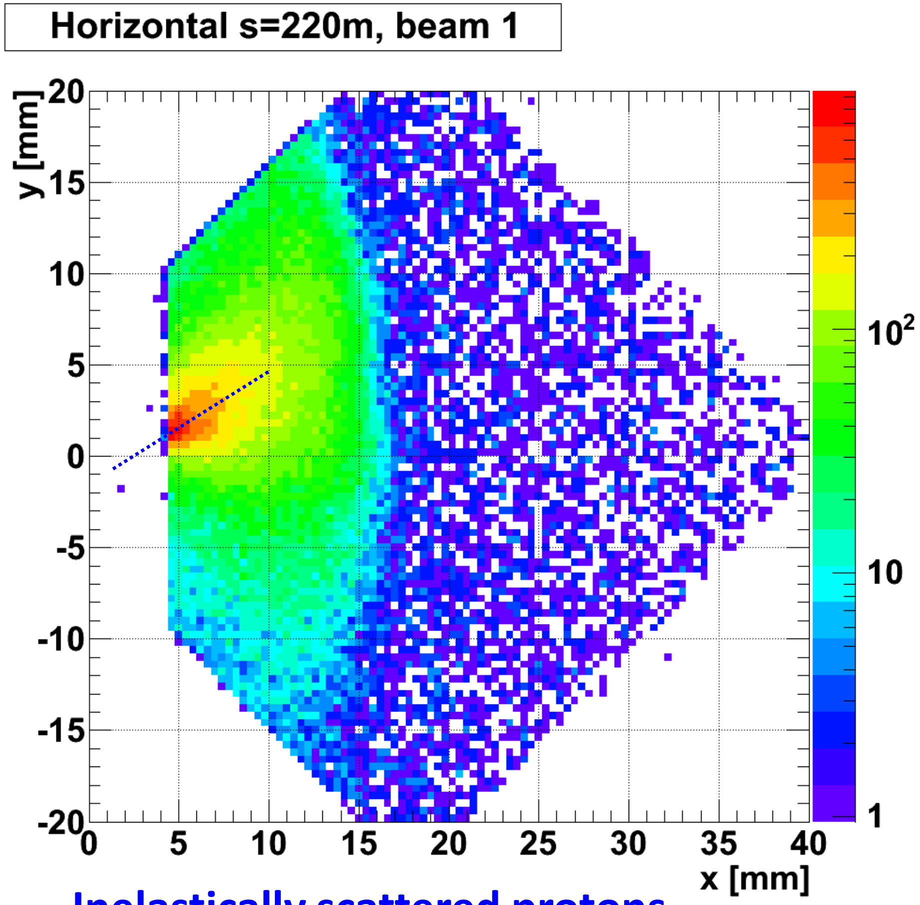
$$\begin{cases} \mathrm{x(s)} = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + D_x(s) \cdot \xi \\ \mathrm{y(s)} = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* + D_y(s) \cdot \xi \end{cases} \qquad \xi = \frac{\Delta p}{p} \neq 0$$

Beam $2 : D_y \approx 0$

Further steps: inelastic protons, D_y



Inelastically scattered protons



Inelastically scattered protons

$$\begin{cases} \mathrm{x(s)} = v_x(s)\cdot x^* + L_x(s)\cdot\Theta_x^* + D_x(s)\cdot\xi \\ \mathrm{y(s)} = v_y(s)\cdot y^* + L_y(s)\cdot\Theta_y^* + D_y(s)\cdot\xi \end{cases}$$

$$\xi = \frac{\Delta p}{p} \neq 0$$

$\text{Beam } 1: D_y \neq 0, \text{is of the order of } D_x$

Further steps

- Analysis of the results on the basis of different 2010 runs at different RP distances from the beam
- Analysis of the dispersion for inelastic proton reconstruction
- Analysis of optics for/from future 2011 TOTEM runs (β^*=1.5m, 90m)

We would like to thank you for all your help

Massimo Giovannozzi, Helmut Burkhardt, Ralph Assmann, Rogelio Garcia, Ezio Todesco, Marek Strzelczyk, Gabriel Mueller, Frank Schmidt, Carmen Alabau Pons, ...

Thank you!

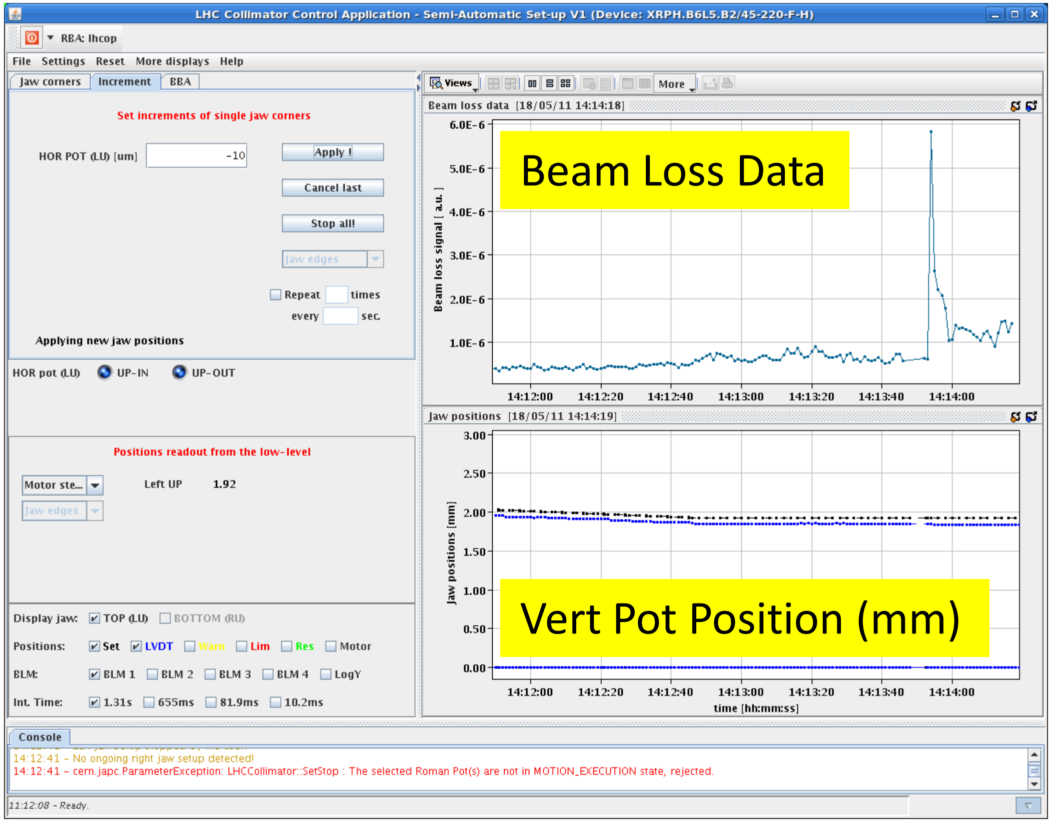
BACKUP

Beam based alignment of RPs @220m and data taking (T1,T2,RP220m) (18 May 2011)

Scraping exercise:

RP220 approached the low intensity beam in 10 μm steps

RP220 now ready for routine insertions in 2011



HOR POT (LU) [um] -10

☐ Repeat times every sec.

Applying new jaw positions

HOR pot (LU) ● UP-IN ● UP-OUT

Left UP 1.92

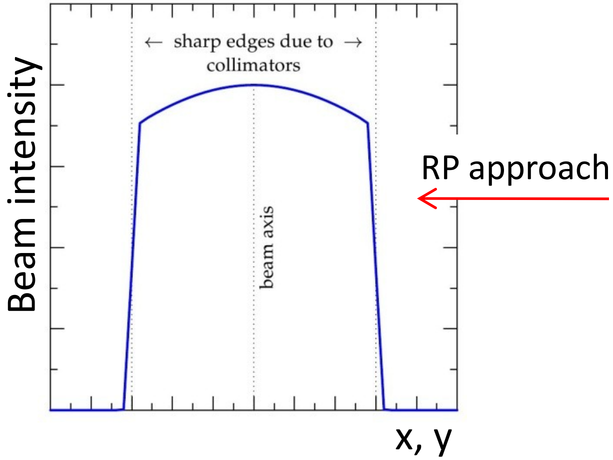
Display jaw: ☑ TOP (LU) ☐ BOTTOM (RU)

Positions: ☑ Set ☑ LVDT ☐ Warn ☐ Lim ☐ Res ☐ Motor

BLM: ☑ BLM 1 ☐ BLM 2 ☐ BLM 3 ☐ BLM 4 ☐ LogY

Int. Time: ☑ 1.31s ☐ 655ms ☐ 81.9ms ☐ 10.2ms

```
14:12:41 - No ongoing right jaw setup detected!
14:12:41 - cern.japc.ParameterException: LHCCollimator::SetStop : The selected Roman Pot(s) are not in MOTION_EXECUTION state, rejected.
11:12:08 - Ready.
```



Data taking with RPs @ 220 close to the beams

- vertical RPs @ 5σ = 2.2 mm
- horizontal RPs @ 7σ = 1 mm
- low pile-up

Alignment of RP147 planned in August

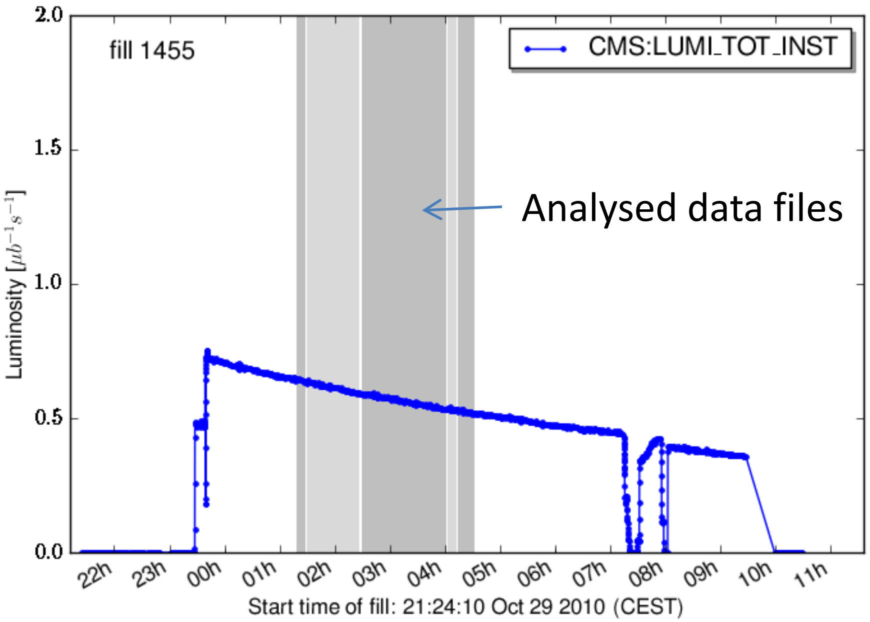
ELASTIC pp SCATTERING

t-range: 0.36 – 3 GeV^2

Elastic pp scattering

- Several runs were taken during 2010 with different distances of the Roman pots to the beam center
- The 7 σ runs were analyzed
- The 18 σ runs with a total luminosity of ~5.8 pb^{-1} will follow

Luminosity



Analysed data files

RP dist.	Integrated luminosity
25 σ	1.5 nb^{-1}
20 σ	185 nb^{-1}
18 σ	5800 nb^{-1}
7 σ	9.5 nb^{-1}

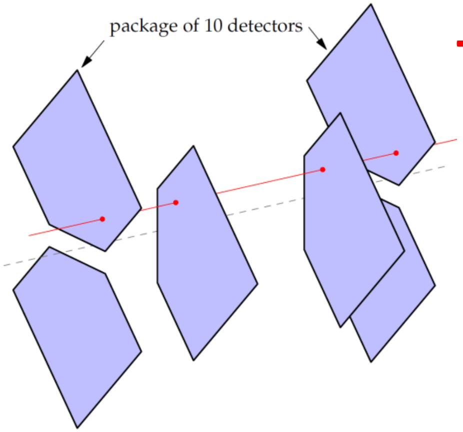
important for large t

Proton reconstruction

- **Both angle projections reconstructed: Θ_x^* and Θ_y^***
  - Θ_x^* from Θ_x @ RP220 (through dL_x/ds) $\Theta_x = dL_x/ds\ \Theta_x^*$
  - Θ_y^* from y @ RP220 (through L_y) $y = L_y\ \Theta_y^*$

→ **Excellent optics understanding**

- Magnet currents measured
- Measurements of optics parameters with elastic scatt.
  - $\Theta_{left}^* = \Theta_{right}^*$ (proton pair collinearity)
  - Proton position ↔ angle correlations
  - L_x=0 determination, coupling corrections

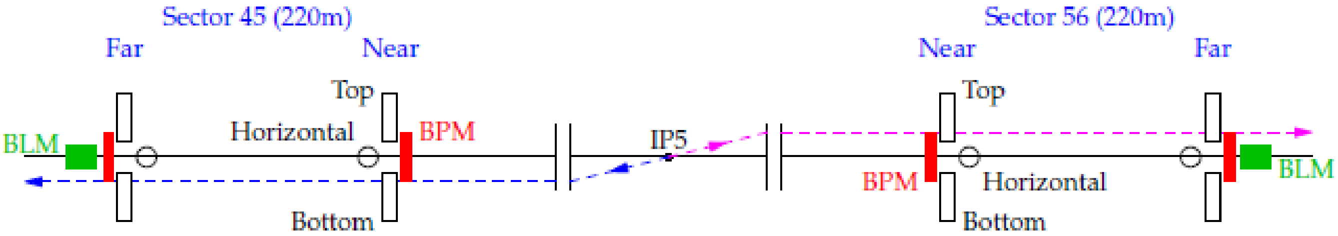


Track based alignment

→ **Fine alignment**

- Alignment between pots with overlapping tracks (~1μm)
- Alignment with respect to the beam – scraping exercise (~20μm)
- Mechanical constraints between top and bottom pots (~10μm)

Cuts and data reduction



Intergrated luminosity : 6.2 nbarn^{-1}

- Topology
  - near and far units
  - diagonals
- Low |ξ| selection (3σ)
  - $|x_{RP,45}|<3\sigma_x$ @ $L_{x,45}=0$
  - $|x_{RP,56}|<3\sigma_x$ @ $L_{x,56}=0$
  - corr. $y_{RP216,45} \leftrightarrow y_{RP220,45}$
  - corr. $y_{RP216,56} \leftrightarrow y_{RP220,56}$
- Elastic collinearity (3σ)
  - $\theta_{x,45}^* \leftrightarrow \theta_{x,56}^*$
  - $\theta_{y,45}^* \leftrightarrow \theta_{y,56}^*$

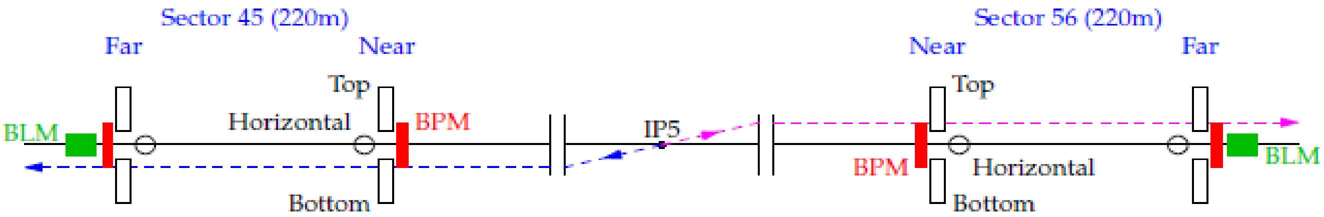
Total triggers	5.28M
Reconstructed tracks & elastic topology	293k
Low |ξ| selection	70.2k
Collinearity cuts	66.0k

$\updownarrow$ **showers**

Diagonals analysed independently

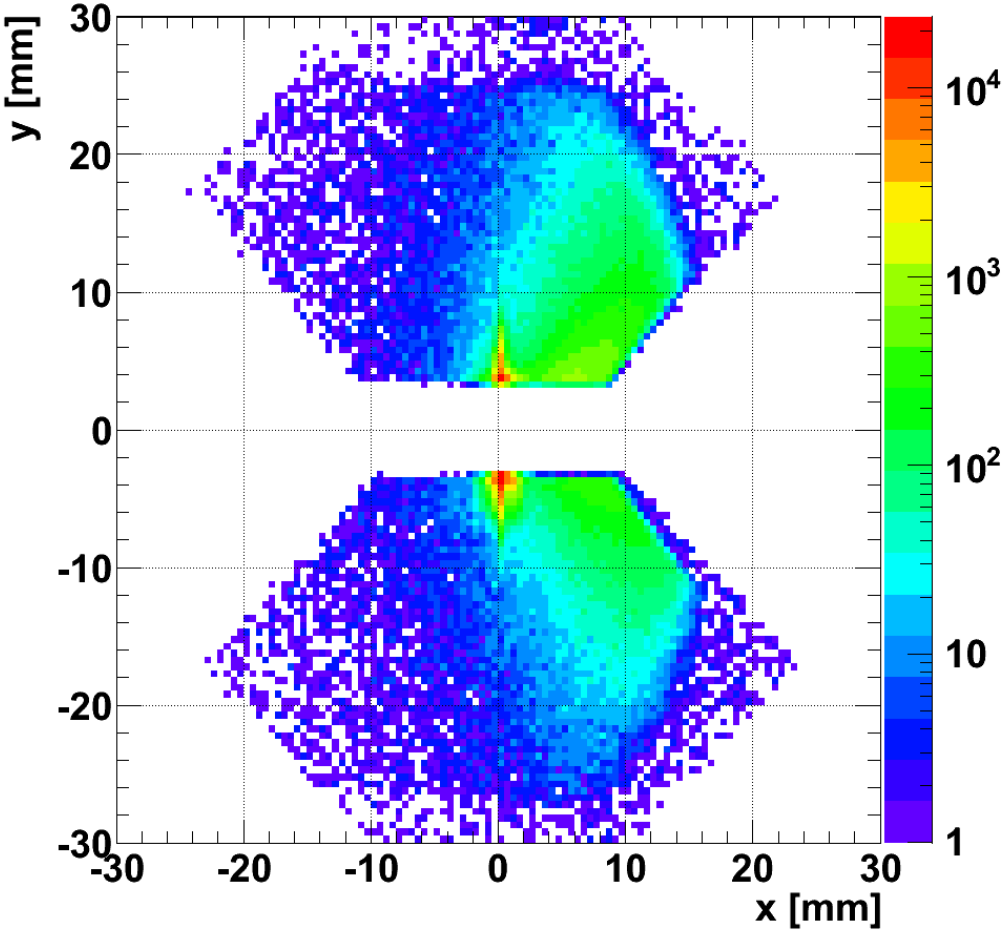
Proton tracks of a single diagonal

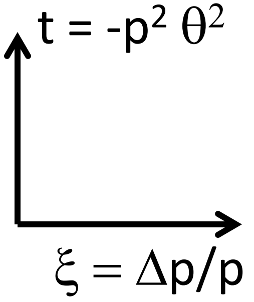
(left-right coincidences)



Sector 56

Sector 45



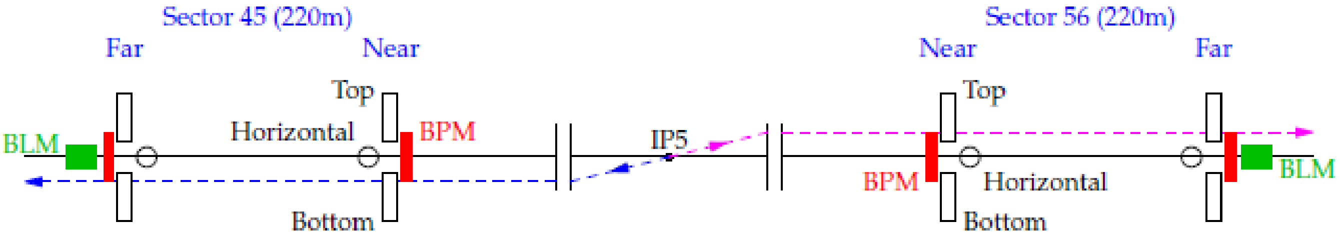


$y = L_y \Theta_y$

$x = L_x \Theta_x + \xi D$

$L_x \sim 0$

Cuts and data reduction



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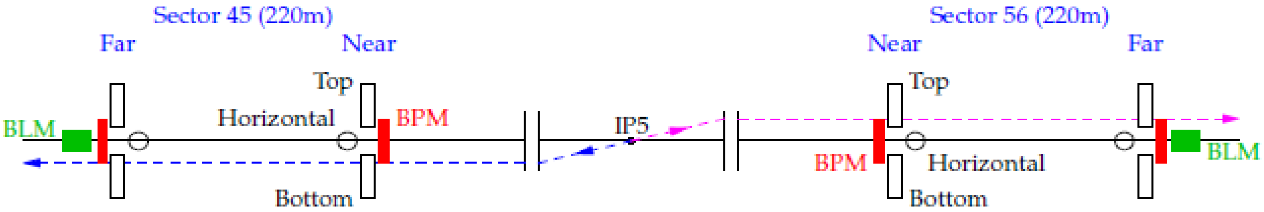
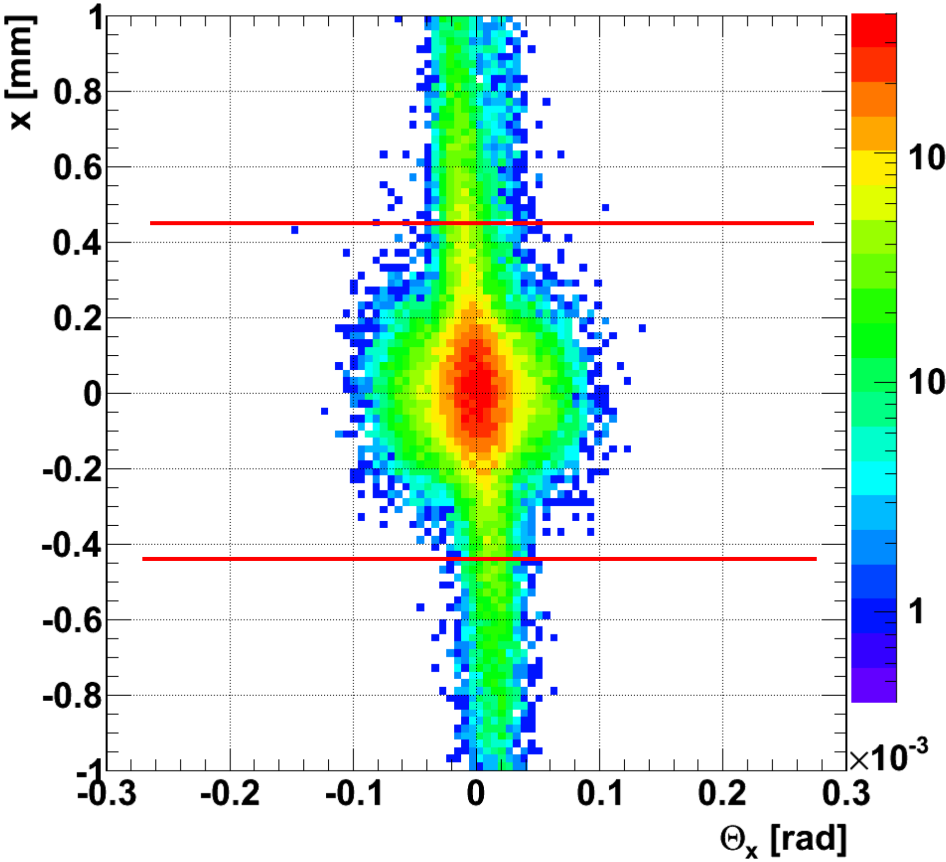
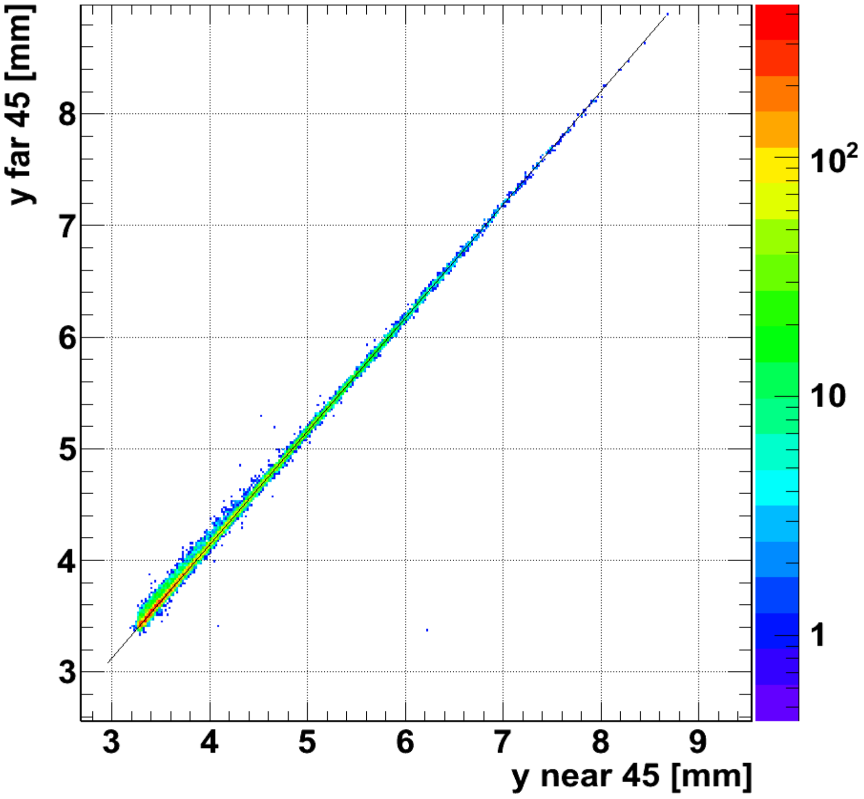
showers

Low $\xi = \Delta p/p$ cuts





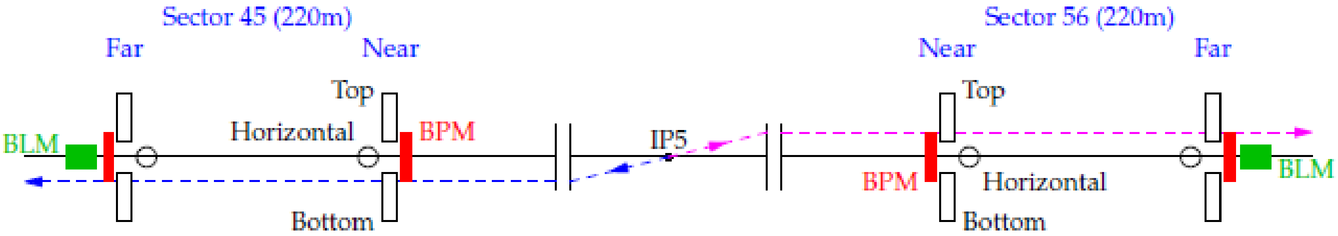
$|x| < 3\sigma_x$ @ $L_x = 0$



$y_{RP\ near,45} \leftrightarrow y_{RP\ far,45}$

(dLy/ds≈0)

Cuts and data reduction



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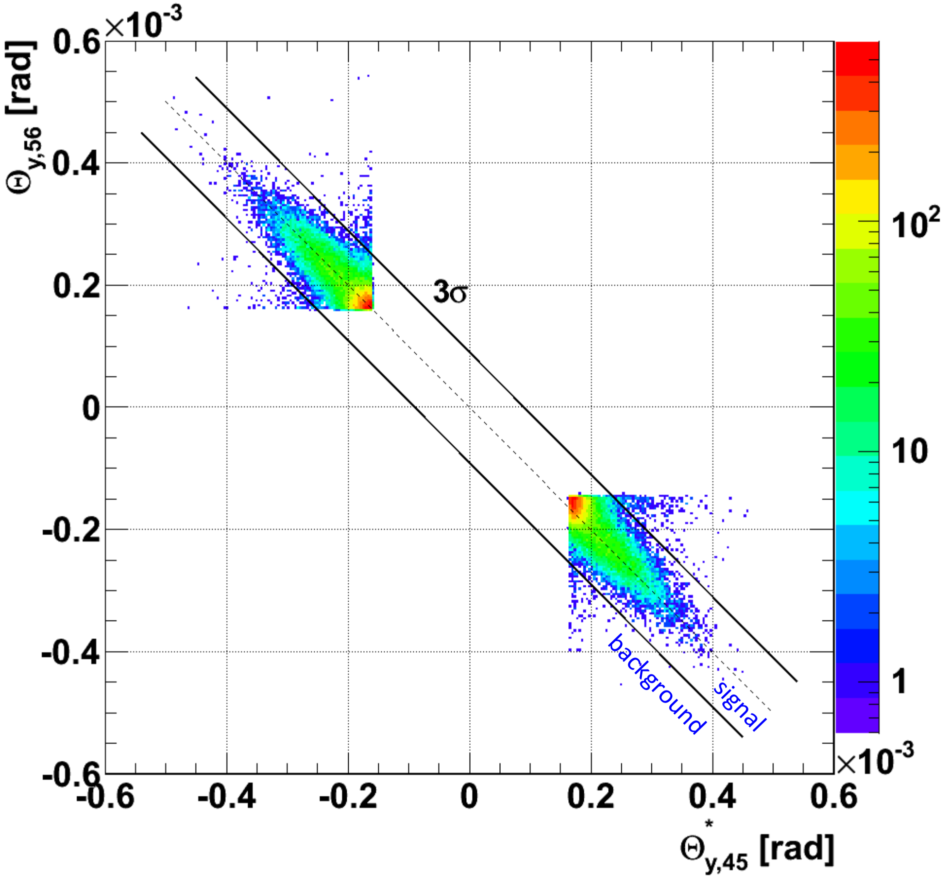
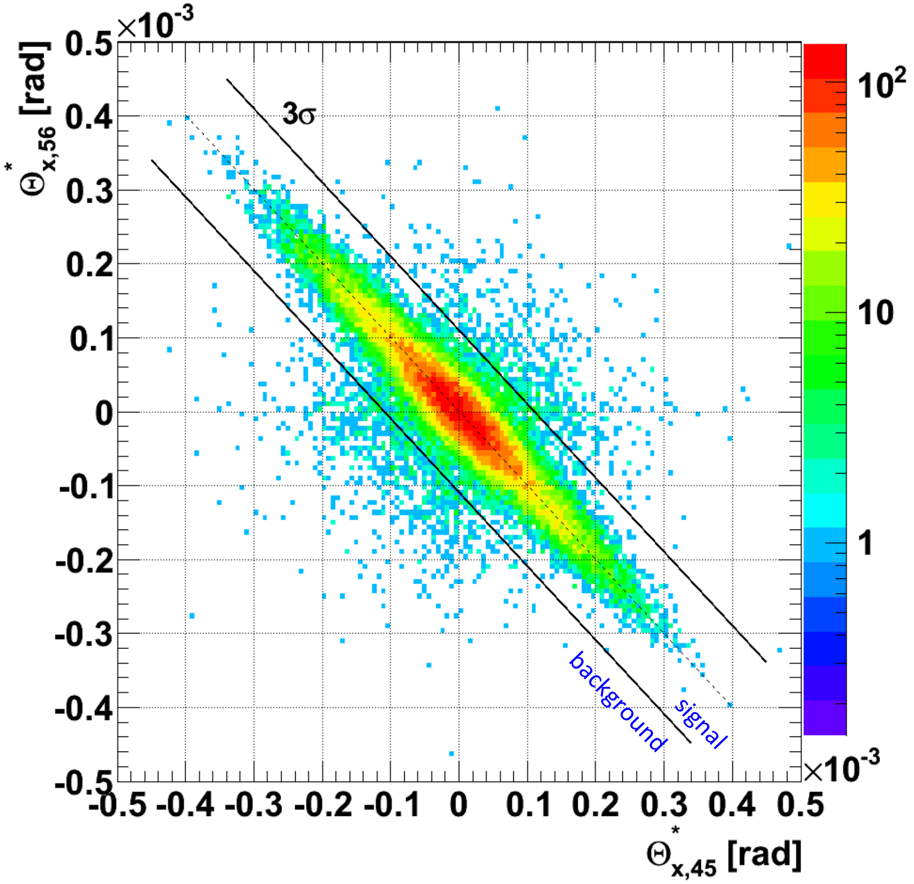
↕ **showers**

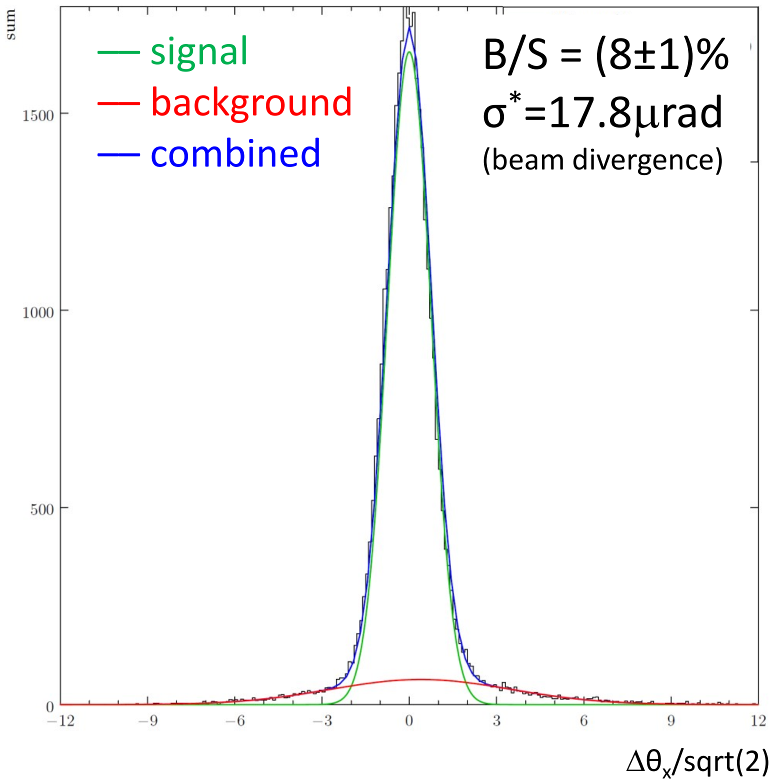
Elastic collinearity cuts





Data outside the 3σ cuts used for background estimation

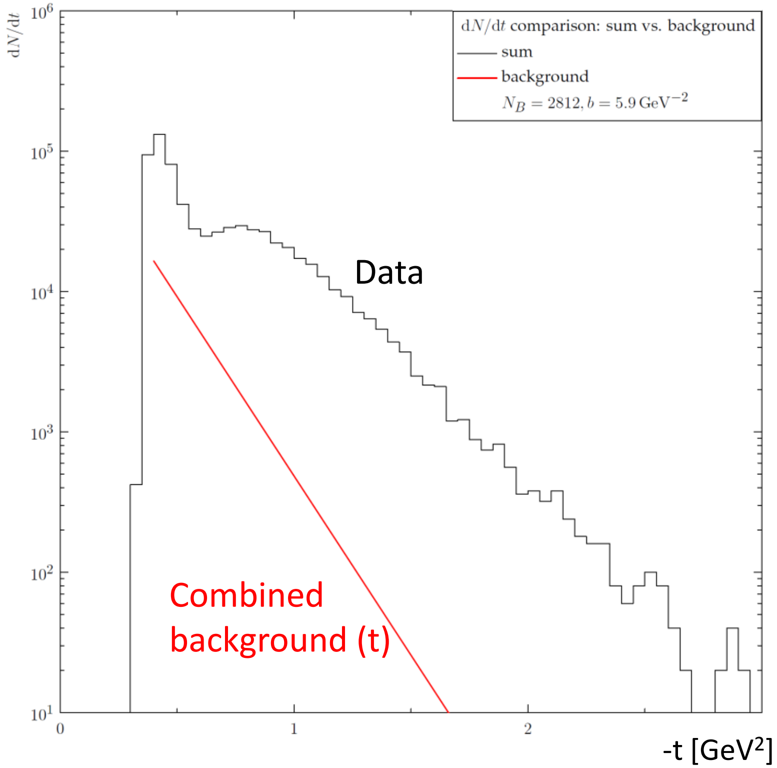
Background and resolution determination



B/S = (8±1)%
σ^*=17.8μrad
(beam divergence)

Signal to background normalisation

(also as a function of $\Delta\theta_y$)



Data

Combined background (t)

Signal vs. background (t)

σ^* → t-reconstruction resolution:

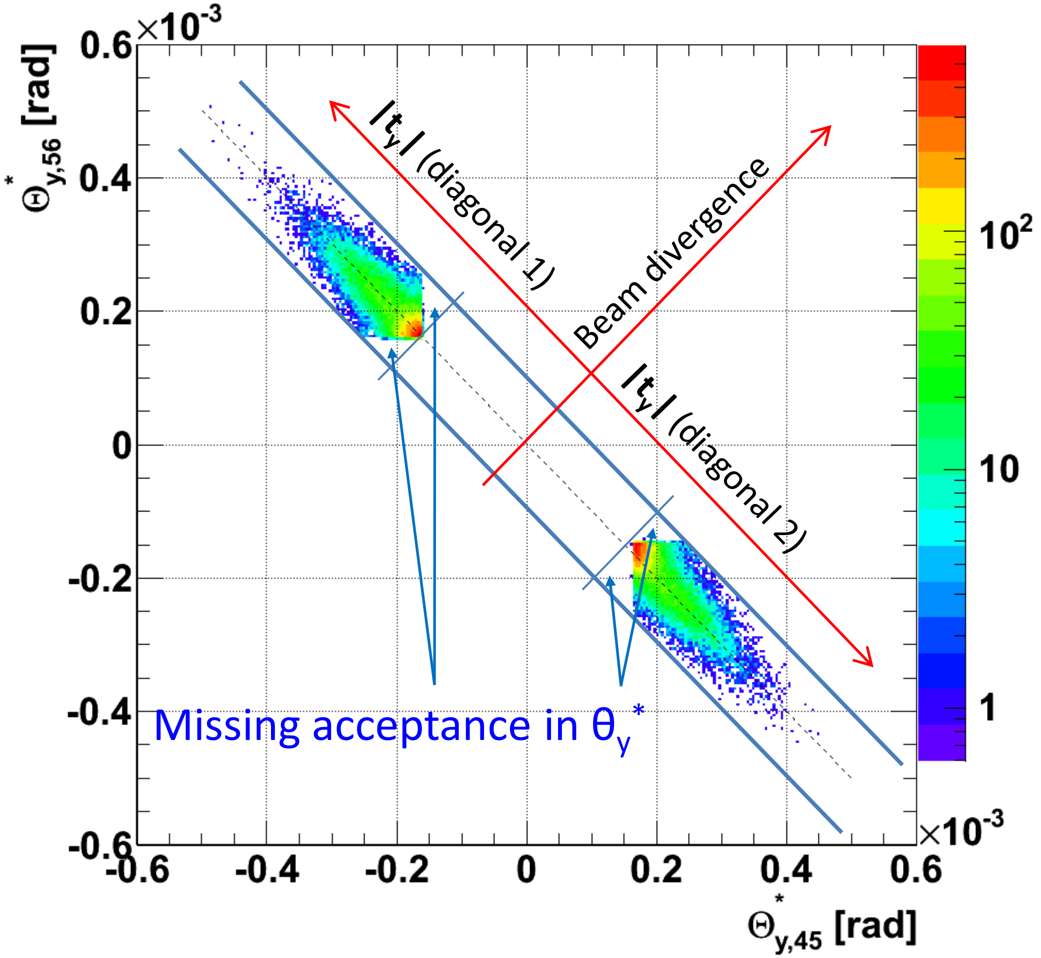
$$\frac{\sigma(t)}{t} = \frac{\sqrt{2}\,p\,\sigma^*}{\sqrt{t}}: \quad \begin{array}{l} 0.4\ \text{GeV}^2 : 14\% \\ 1\ \text{GeV}^2 : 8.8\% \\ 3\ \text{GeV}^2 : 5.1\% \end{array}$$

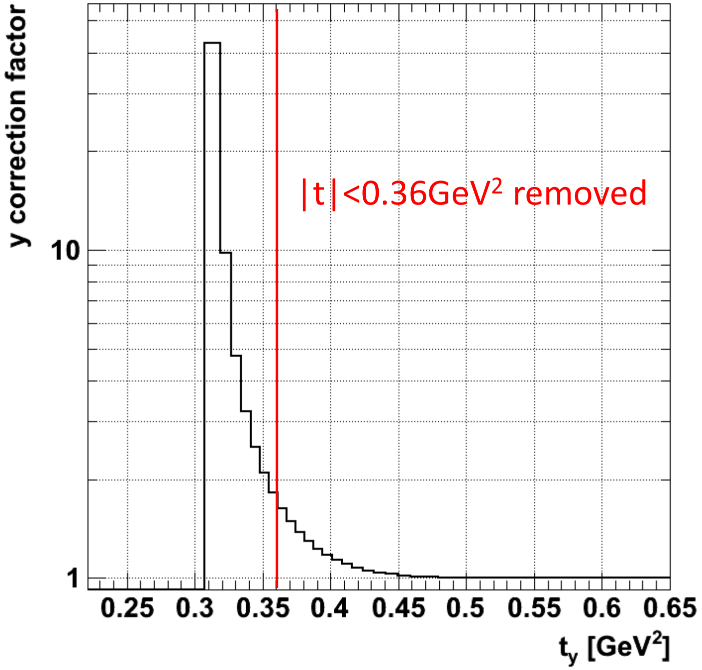
|t|=0.4GeV^2: B/S = (11±2)%

|t|=0.5GeV^2: B/S = (19±3)%

|t|=1.5GeV^2: B/S = (0.8±0.3)%

t_y-acceptance corrections





Correction error (t_y):

0.31 GeV^2 : 30%

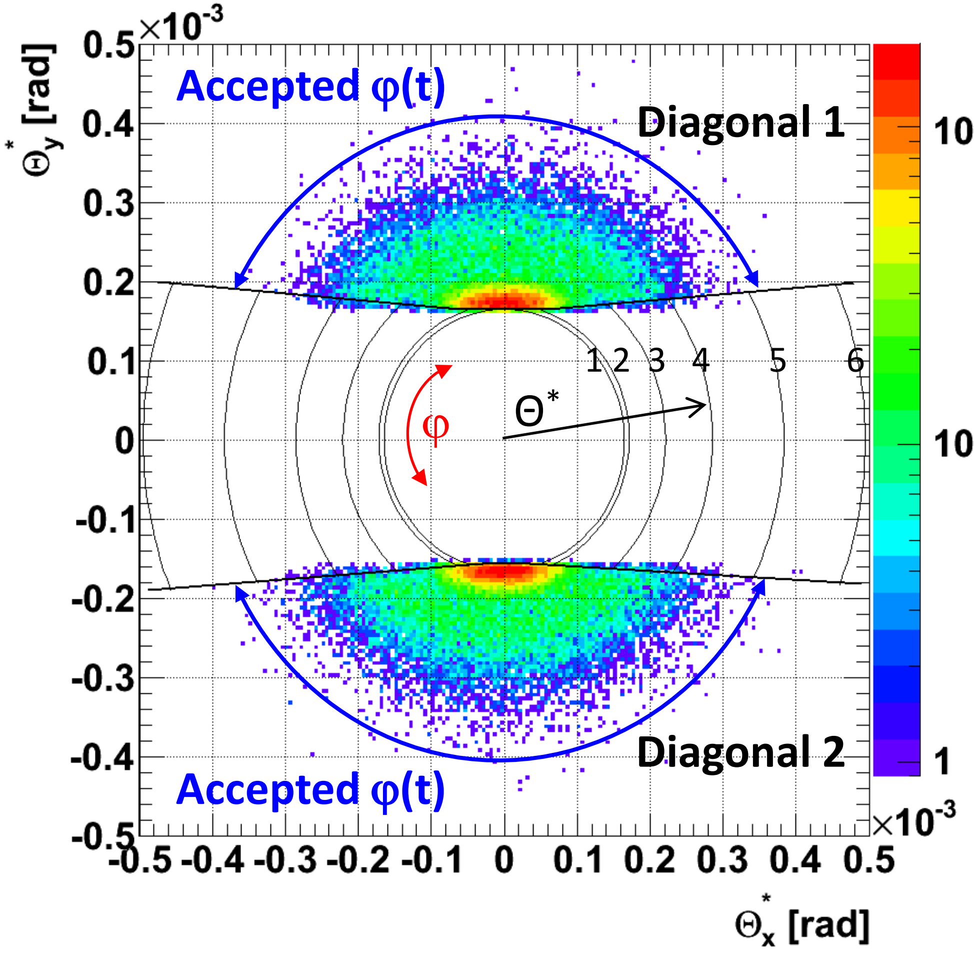
0.33 GeV^2 : 11%

0.35 GeV^2 : 2%

0.4 GeV^2 : 0.8%

0.5 GeV^2 : 0.1%

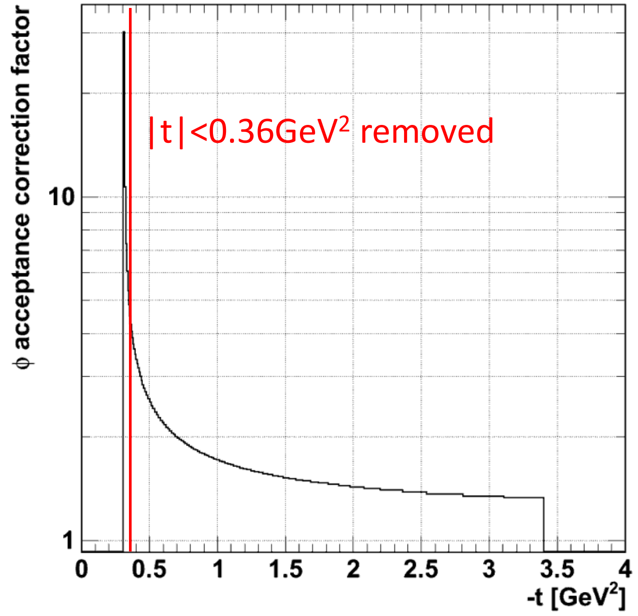
φ-acceptance correction



Critical at low t-acceptance limit

Total φ-acceptance correction

No.	t [GeV²]	Θ* [rad]	Accepted φ (2 diag.) [°]	φ accept. correct. factor
1	**0.33**	1.65E-04	38.6	**9.3±4.7%**
2	**0.36**	1.71E-04	76.4	**4.7±1.8%**
3	**0.60**	2.21E-04	162.5	**2.2±0.3%**
4	**1.00**	2.86E-04	209.8	**1.7±0.1%**
5	**1.80**	3.83E-04	246.3	**1.5**
6	**3.00**	4.95E-04	269.0	**1.3**



Final unfolded distribution