TOTEM

LHC optics estimation

Frigyes Nemes

Eötvös Loránd University

on behalf of the

TOTEM collaboration

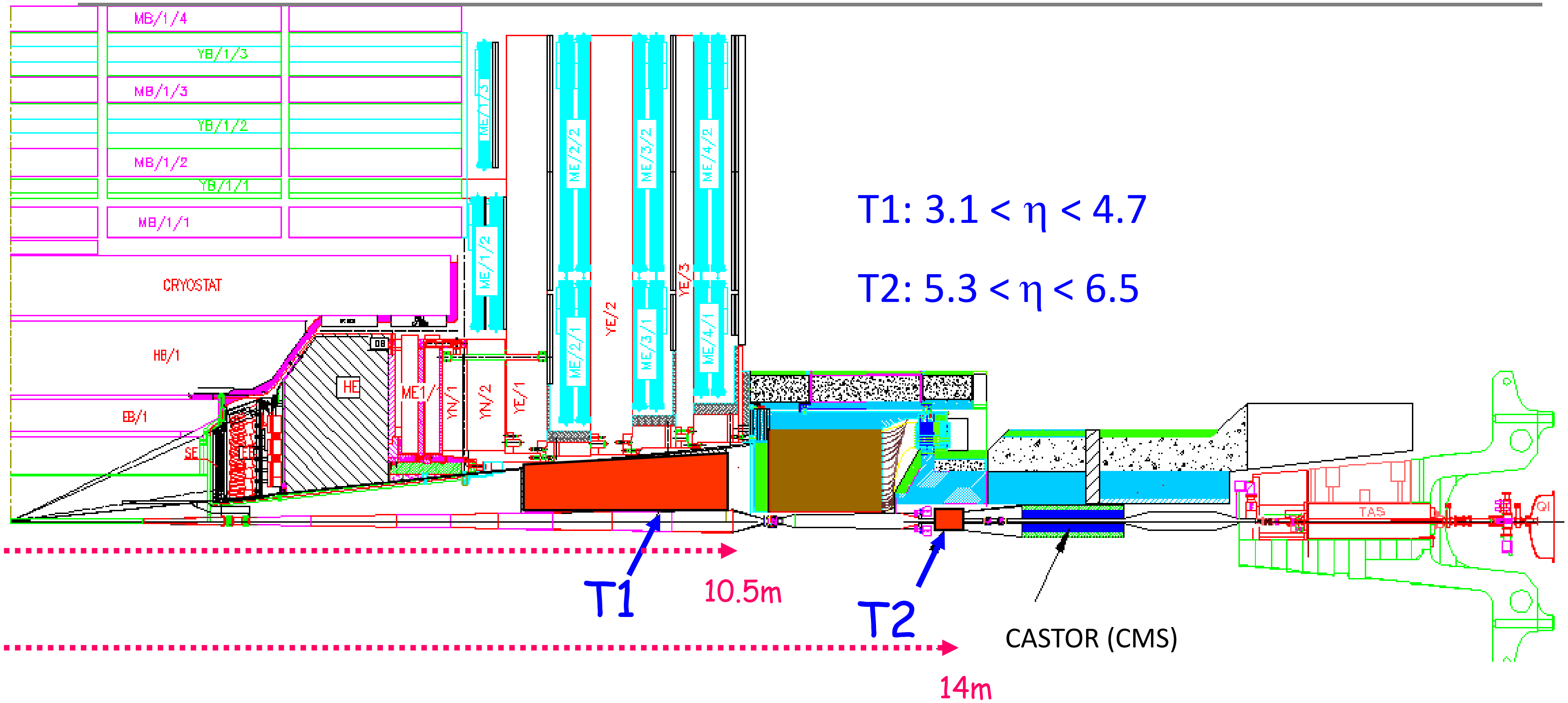
http://totem.web.cern.ch/Totem/

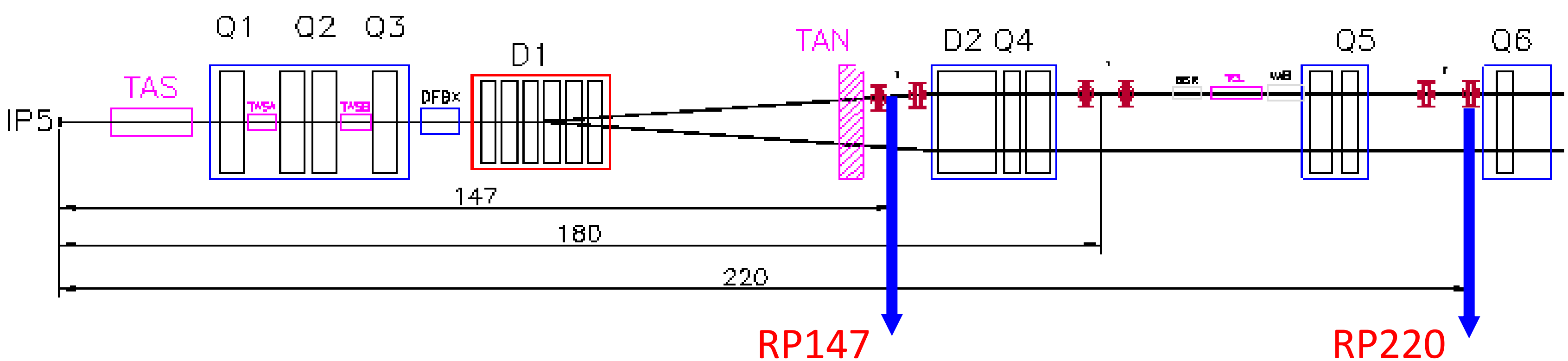
Zimányi Winter School

Budapest

2012, December 3.– 7.

Experimental layout of the TOTEM experiment



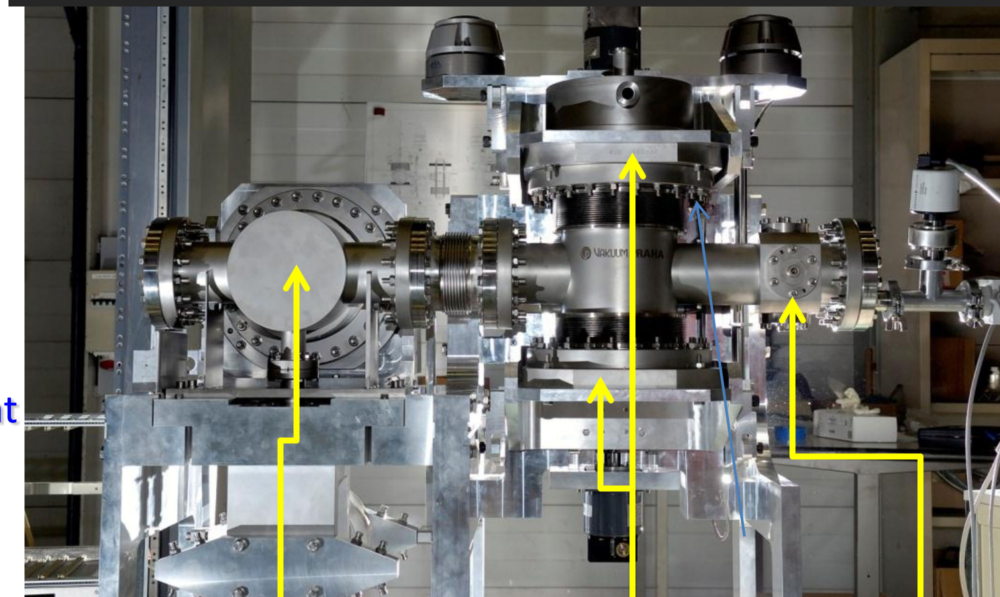


Roman Pot stations

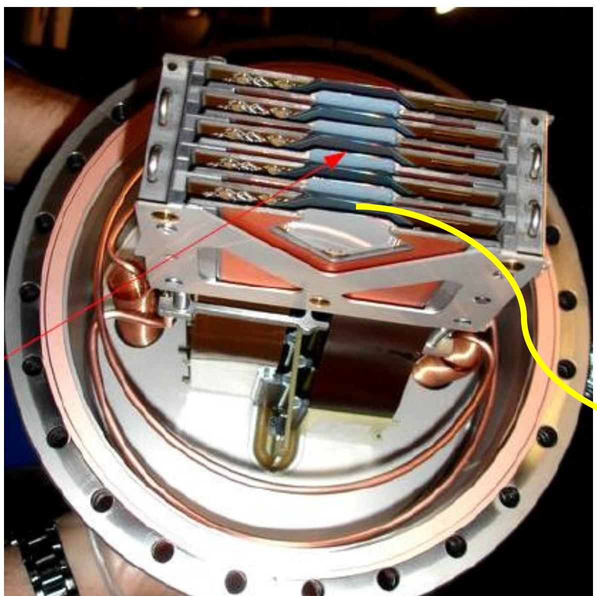
RP stations

- 2 units at about 5 m distance
- Measurement of very small proton scattering angles (few μrad)
- Vertical and horizontal pots mounted as close as possible to the beam
- BPM fixed to the structure gives precise position relative to the beam
- Overlapping detectors: relative alignment (10 μm inside unit between 3 RPs)

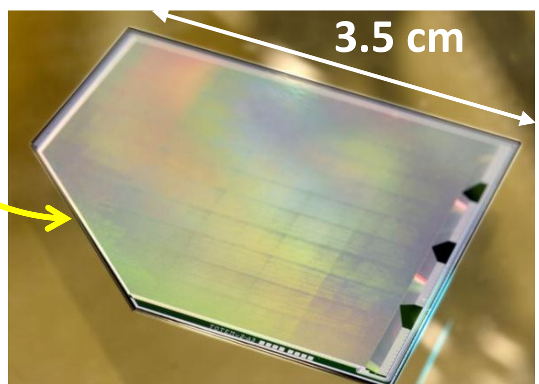
RP unit: 2 vertical, 1 horizontal pot + BPM



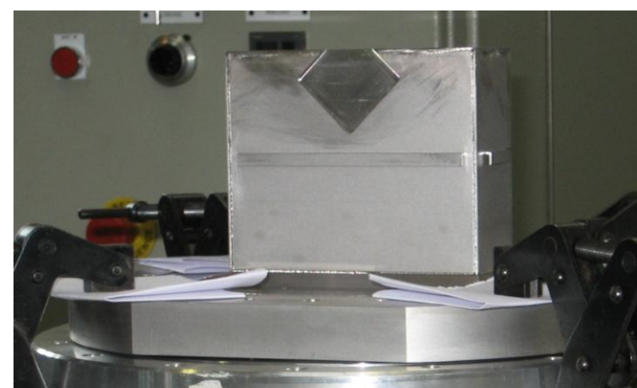
Horizontal RP Vertical RPs BPM



10 planes of edgeless detectors

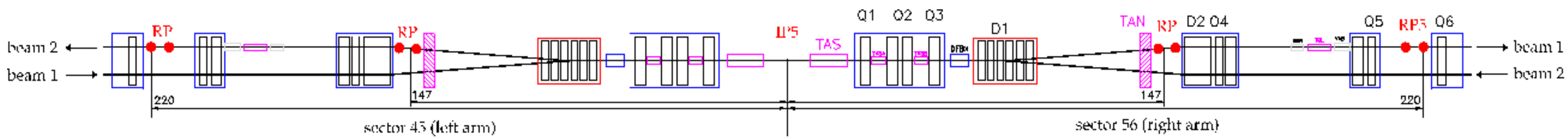


Si edgeless detector



1 Roman Pot

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:

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

The *effective length* and *magnification* expressed with the phase advance

$$L(s) = \sqrt{\beta(s)\beta^*}\sin\Delta\mu(s) \qquad v(s) = \sqrt{\beta(s)\beta^{*-1}}\cos\Delta\mu(s) \qquad \Delta\mu(s) = \int_0^s \beta^{-1}(s')ds'$$

Beam size and divergence at IP5 and RP

$\sigma\ (x) = \sqrt{\varepsilon\beta_x}$ describes the spread of primary vertex and beam size at RP

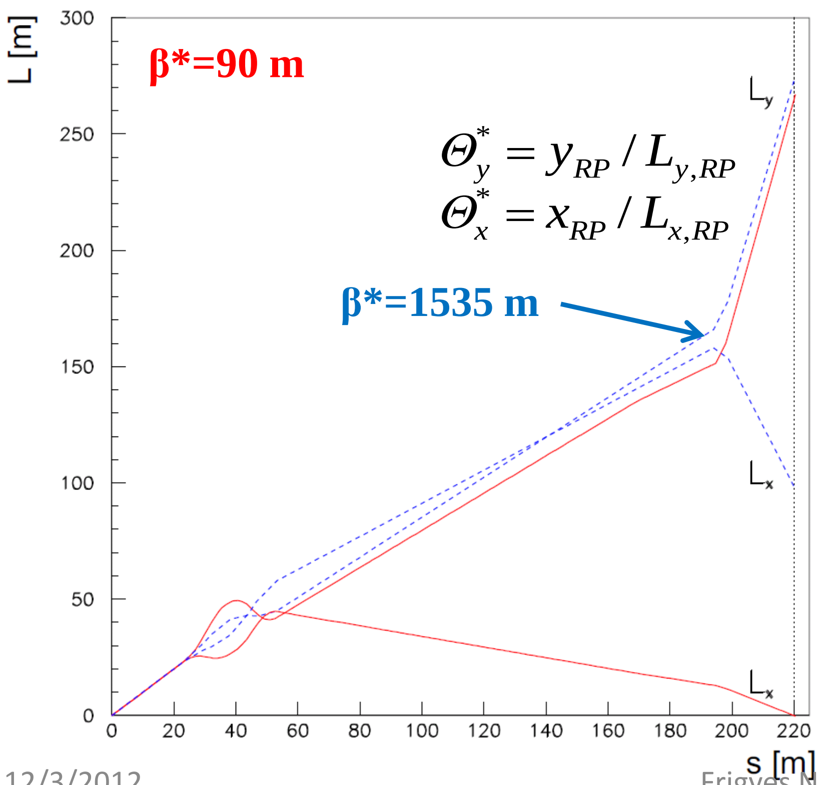
$\sigma\ (\Theta) = \sqrt{\varepsilon / \beta_x}$ beam divergence @IP5 limits the angle measurement precision

High β*=1535 m target optics

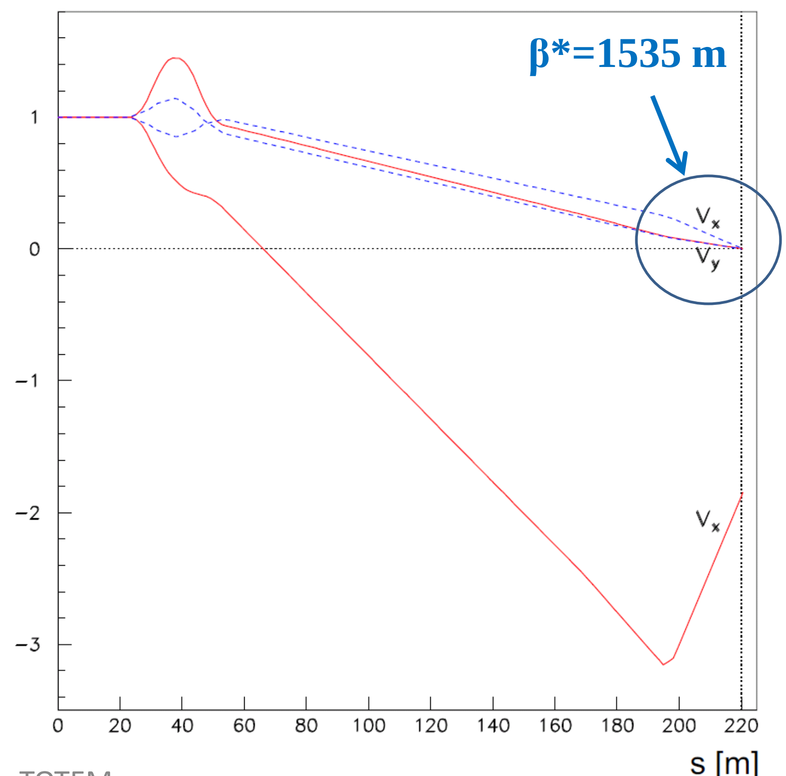
β* = 1535 m is the *target* optics. Requires different injection optics. Properties:

- beam divergence $\sigma_{\Theta*} \approx 0.3$ μrad, vertex size $\sigma_{IP} \approx 450$ μm
- $\Delta\mu_{x,y} = \pi/2 \rightarrow v_{x,y} = 0$. Parallel-to-point focusing **eliminates** the large vertex contribution
- the large (270 m) vertical effective length L_y pushes protons vertically into RP acceptance
- acceptance in momentum transfer, $|t| > 2 \cdot 10^{-3}$ GeV^2, with 10 $\sigma_{\text{beam size@RP}}$

Effective lengths from IP5 to RP @220 m



Magnification from IP5 to RP @220 m



LOW β*=3.5 m OPTICS

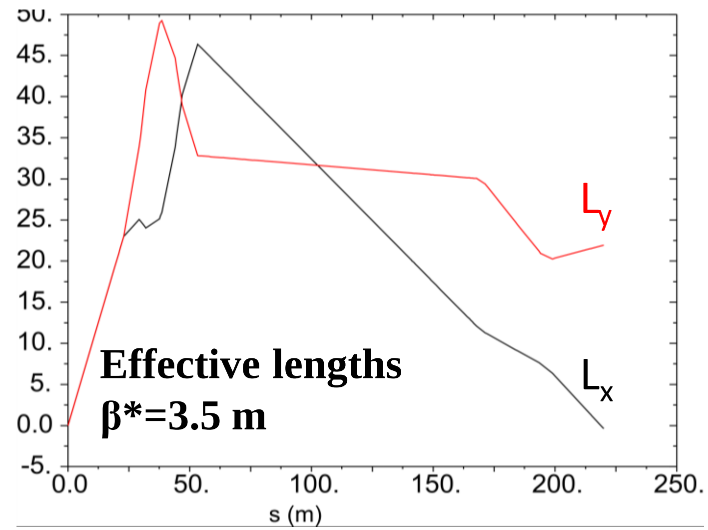
Low β*=3.5m optics

Objective:

- to measure elastic scattering at high |t|

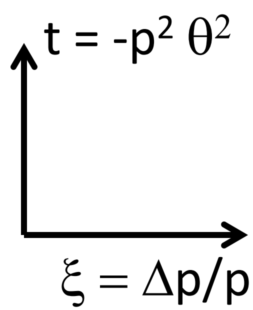
Properties of the optics:

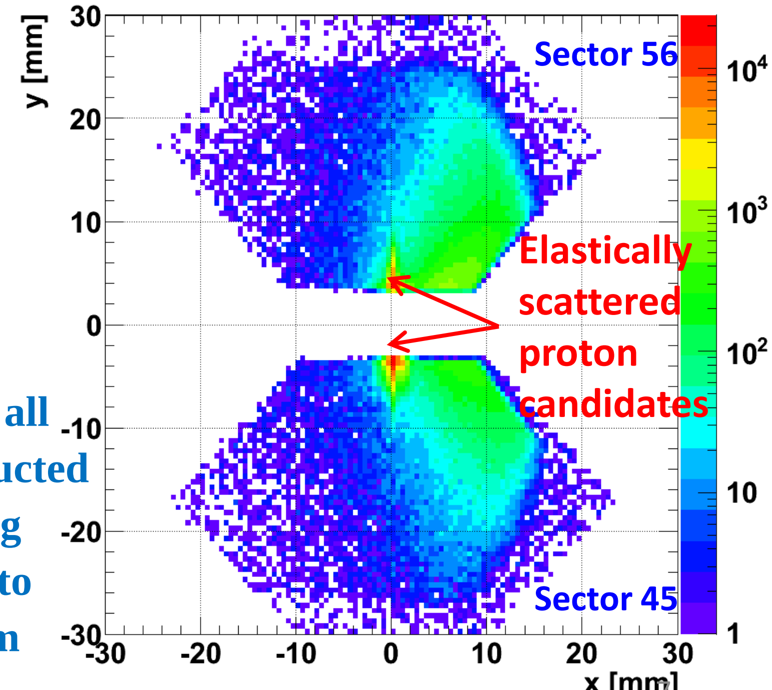
- $\sigma_{IP} \approx 37\ \mu m$ (magnification is not crucial)
- $L_x \approx 0,\ L_y = 22.4\ m$
- beam divergence $\sigma_{\Theta^*} \approx 17\text{-}18\ \mu rad$



Data sources to improve our optics understanding:

- TIMBER database magnet currents
- FIDEL team conversion curves, implemented with LSA
- WISE field harmonics, magnet's displacements`





The intercepts of all selected reconstructed tracks in a scoring plane transverse to the beam at 220 m

The effect of machine imperfections β*=3.5m

Machine imperfections:

- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Beam harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 µm

Imperfections alter the optics !

Perturbed element	$\delta L_{y,b1}/L_{y,b1}$ [%]
MQXA.1R5	0.98
MQXB.A2R5	−2.24
MQXB.B2R5	−2.42
MQXA.3R5	1.45
MQY.4R5.B1	−0.10
MQML.5R5.B1	0.05
Δp/p	−2.19

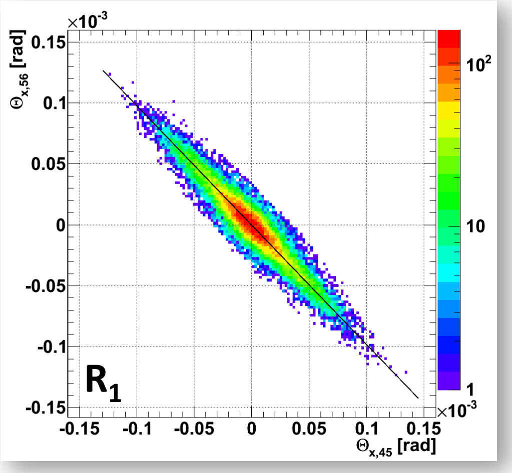
Constraints from proton tracks in the Roman Pots β*=3.5m

Optics imperfections can be determined from proton tracks *measured* in the Roman Pots. The method is based on:

- elastic events are easy to tag
- the elements of the transport matrix are mutually correlated
- elastic scattering ensures that

$$\Theta^*_{y,b1} = \Theta^*_{y,b2}$$
$$\Theta^*_{x,b1} = \Theta^*_{x,b2}$$

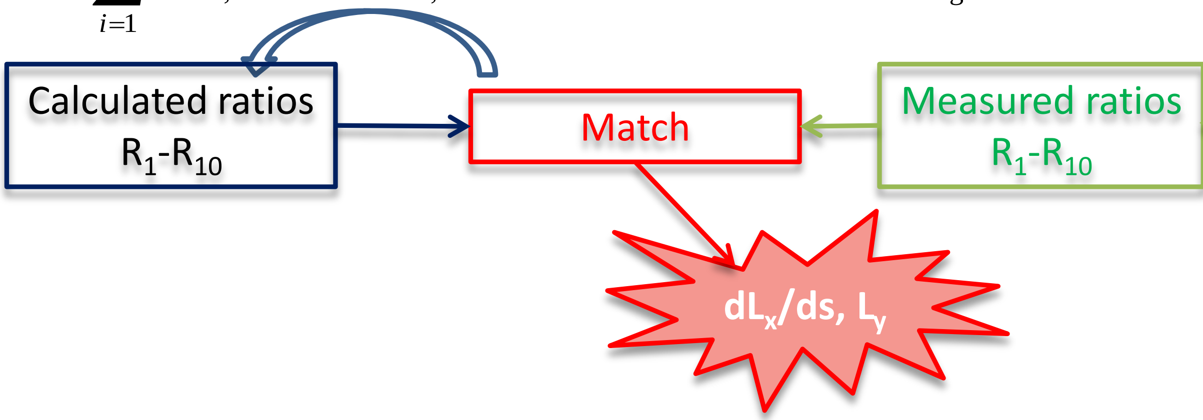
$$\rightarrow R_1 \equiv \frac{\Theta_{x,b1,RP}}{\Theta_{x,b2,RP}} \approx \frac{\frac{dL_{x,b1,RP}}{ds}}{\frac{dL_{x,b2,RP}}{ds}}$$



Matching the optics β*=3.5m

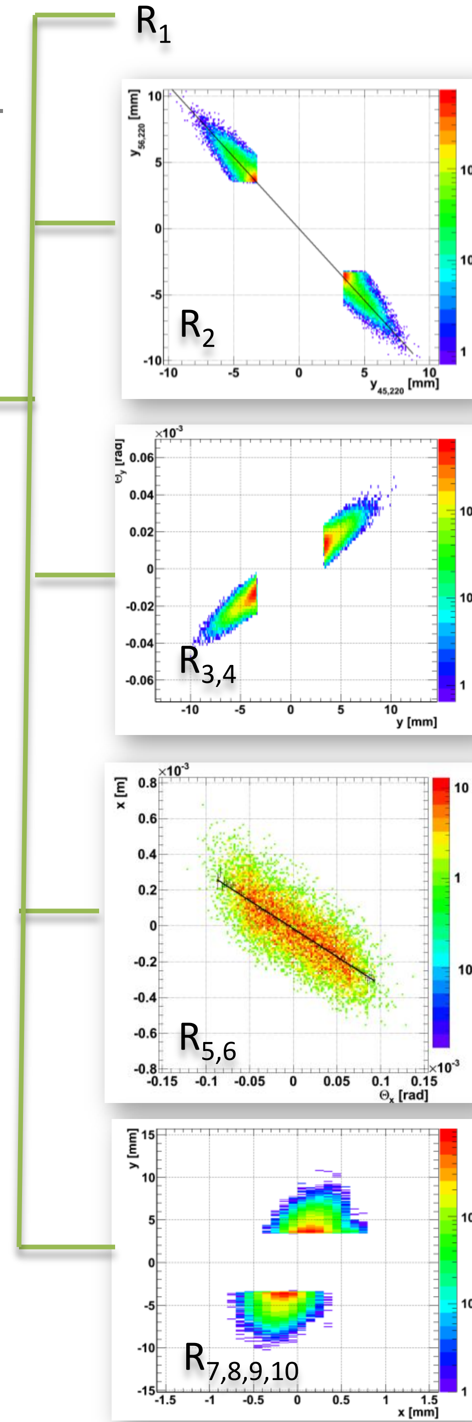
On the basis of constraints R_1-R_{10} the optics can be estimated.

$$\chi^2 = \sum_{i=1}^{10}((R_{i,\mathrm{measured}} - R_{i,\mathrm{calculated}})/\sigma(R_i))^2 + \chi^2_{\mathrm{LHC\,Design}}$$



$$R_2 \equiv \frac{y_{b1,RP}}{y_{b2,RP}} \approx \frac{L_{y,b1,RP}}{L_{y,b2,RP}} \qquad R_3 \equiv \frac{\Theta_{y,b1,RP}}{y_{b1,RP}} \approx \frac{\frac{dL_{y,b1,RP}}{ds}}{L_{y,b1,RP}}$$

$$R_7 \equiv \frac{x_{b1,RP}}{y_{b1,RP}} \approx \frac{m_{14,b1,near\_pots}}{L_{y,b1,near\_pots}} \qquad R_5 \equiv \frac{x_{b1,RP}}{\Theta_{x,b1,RP}} \approx \frac{L_{x,b1,RP}}{dL_{x,b1,RP}/ds}$$



Monte-Carlo confirmation of the method (presented @IPAC 2012)

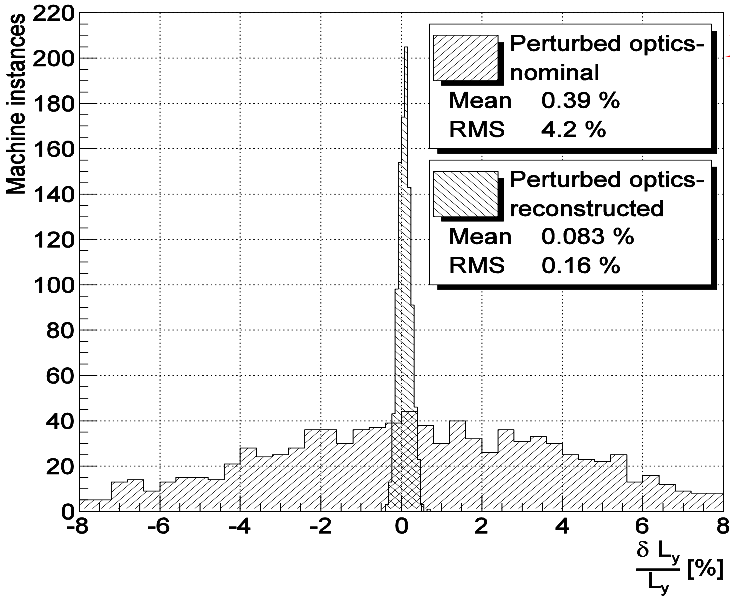
The Monte-Carlo study included the effect of:

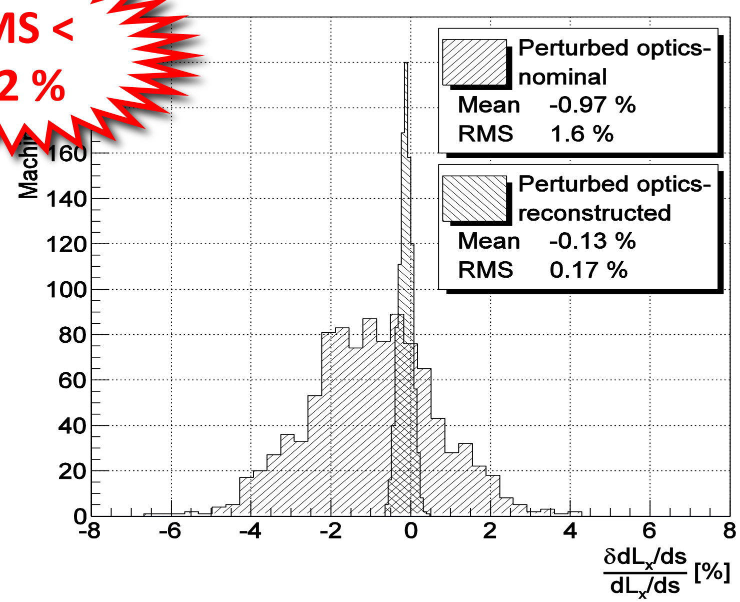
- magnet strengths
- beam momenta
- displacements, rotations
- kickers, field harmonics
- elastic scattering Θ-distributions

Optical function relative error	Before		Matched	
	Mean [%]	RMS [%]	Mean [%]	RMS [%]
$\delta L_{y,b1}/L_{y,b1}$	0.39	4.2	$8.3 \cdot 10^{-2}$	0.16
$\delta (dL_{x,b1}/ds)/(dL_{x,b1}/ds)$	-0.97	1.6	-0.13	0.17
$\delta L_{y,b2}/L_{y,b2}$	-0.14	4.9	0.21	0.16
$\delta (dL_{x,b2}/ds)/(dL_{x,b2}/ds)$	0.10	1.7	$-9.7 \cdot 10^{-2}$	0.17

Conclusion: for β*=3.5m TOTEM can measure the transfer matrix between IP5 and RPs with a precision

RMS < 0.2 %





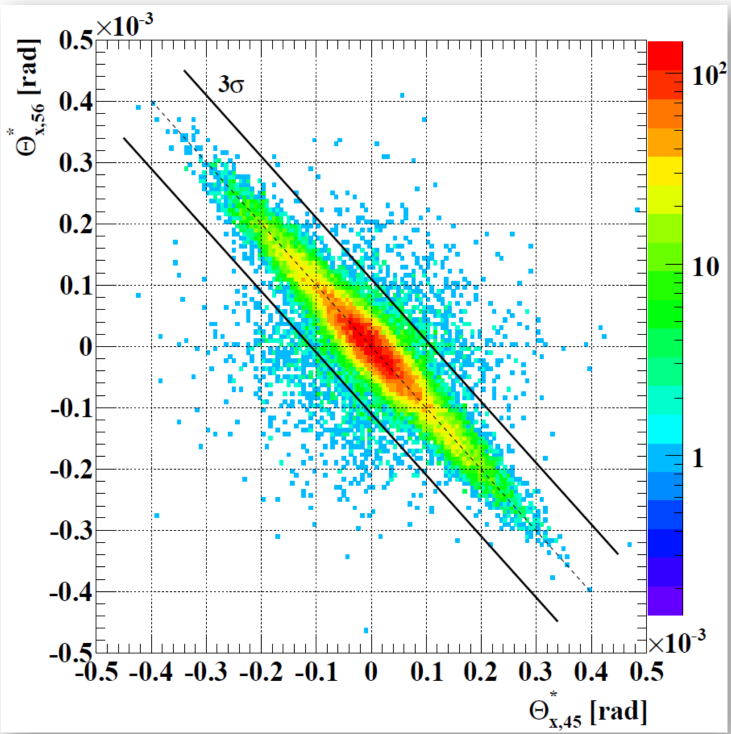
Relative error distributions before and after matching

ELASTIC SCATTERING WITH β*=3.5 m

Elastic scattering with β*=3.5m

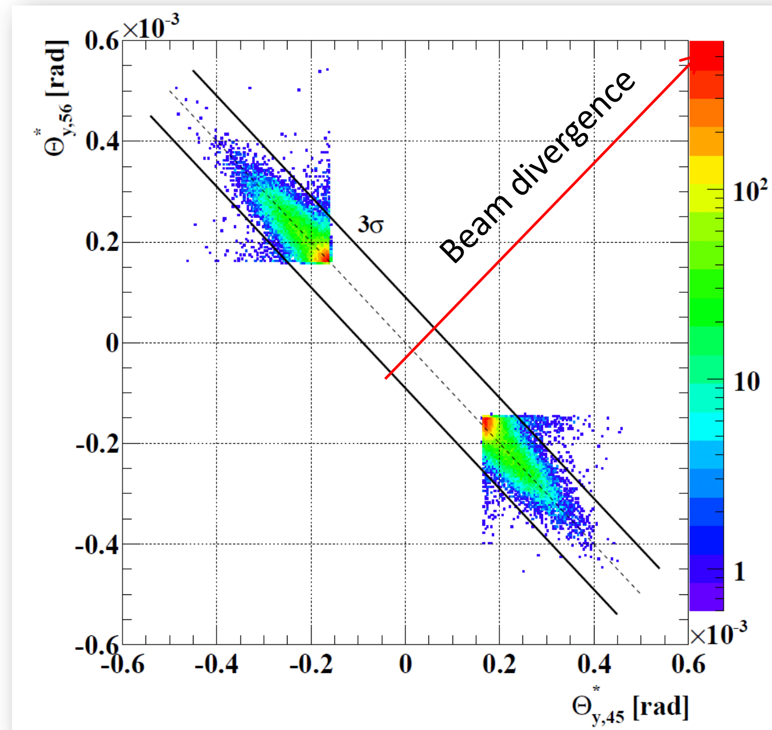
Results (the matched L_y and dL_x/ds are used for reconstruction):

- RP approaches the beam down to 7 $\sigma_{\text{beam size@RP}}$
- published in EPL **95** (2011) 41001
- $\xi \approx 0$



Collinearity Θ_x

Spread in agreement with beam divergence (17-18 μrad)

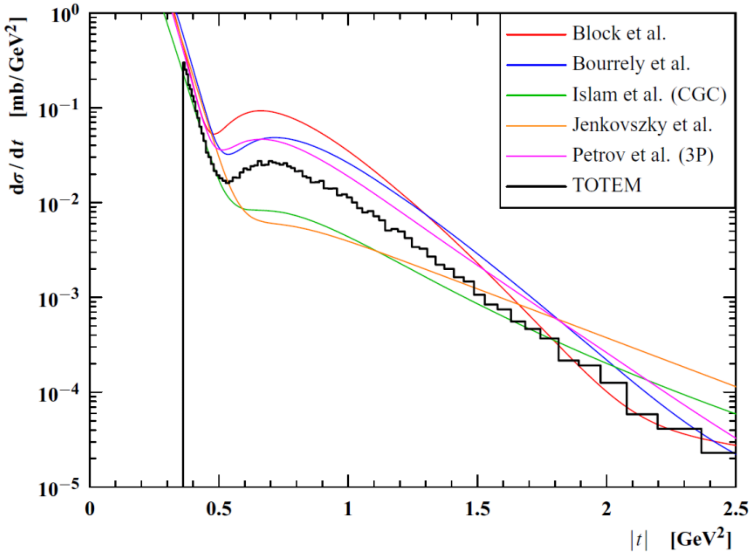


Collinearity Θ_y

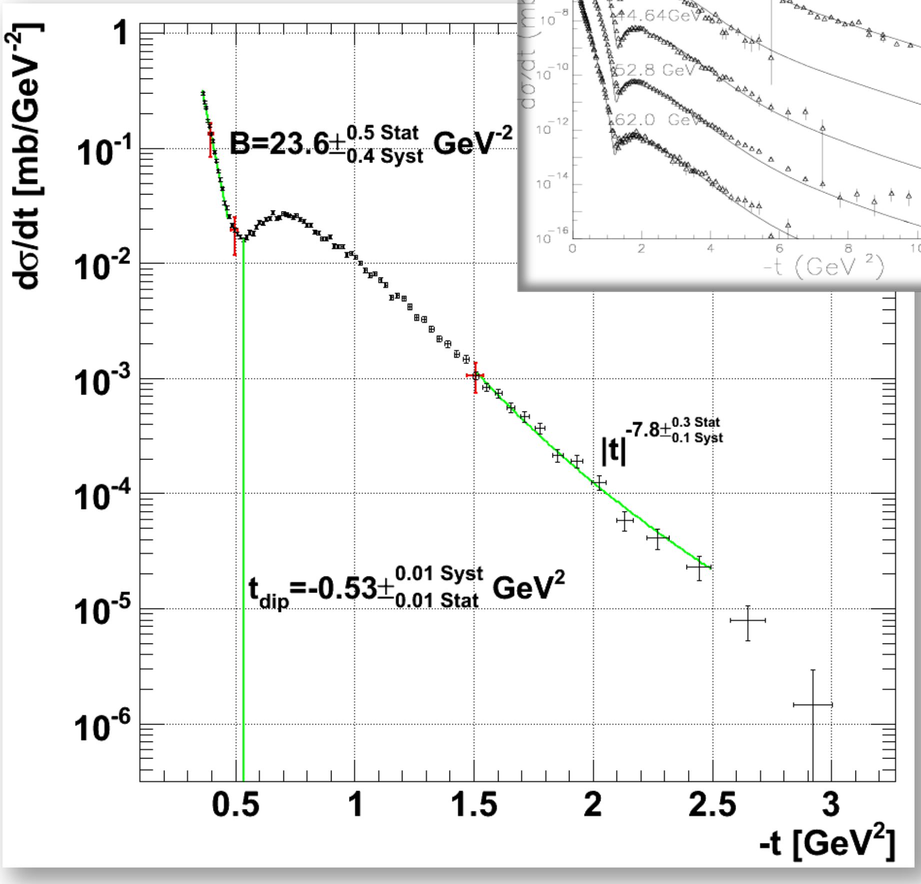
Final result: unfolded elastic scattering distribution β*=3.5m

Published in EPL 95 (2011) 41001:

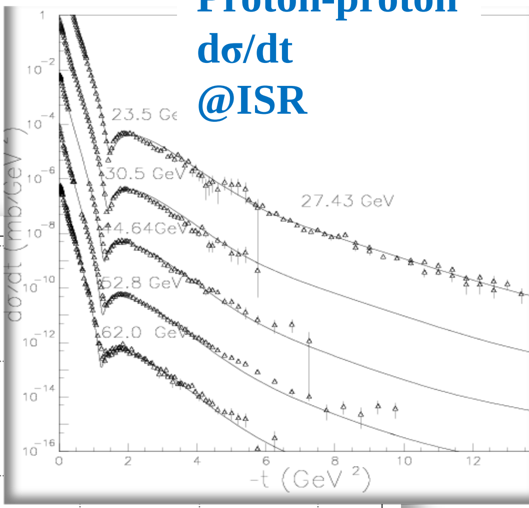
- $|t|$ range spans from 0.36 to 2.5 GeV^2
- below $|t|$ = 0.47 GeV^2 exponential $e^{-B|t|}$ behavior
- dip moves to lower $|t|$, proton becomes "larger"
- 1.5 - 2.0 GeV^2 power low behavior $|t|^{-n}$



The measured dσ/dt compared with predictions of several models



Proton-proton dσ/dt @ISR



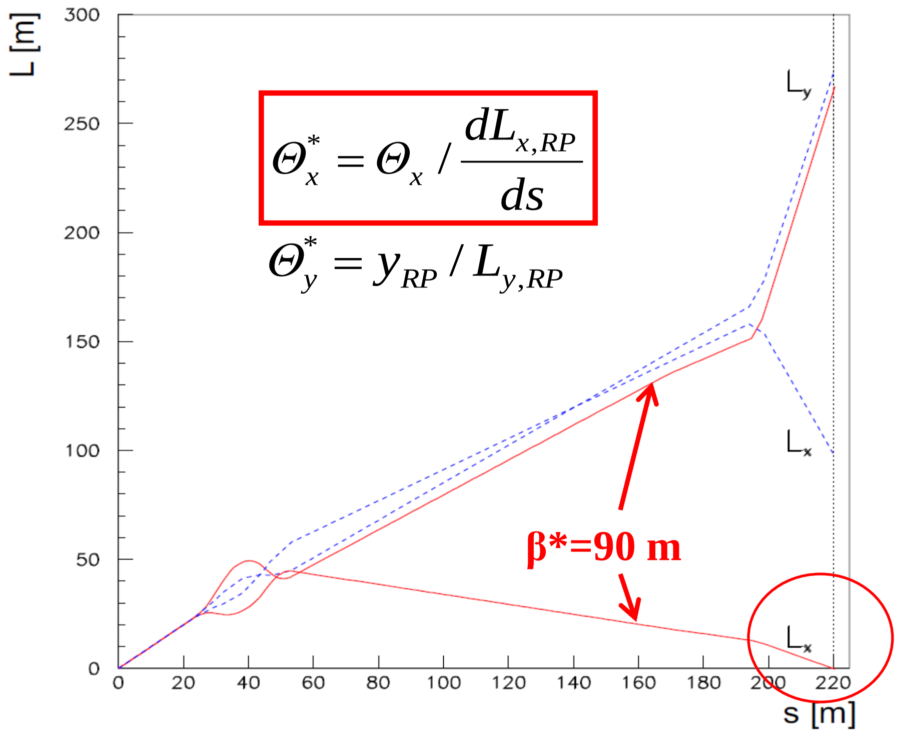
HIGH β* = 90 m OPTICS AND RESULTS

β*=90 m optics in general

β* = 90m optics achievable using the standard LHC injection optics. Properties:

- $\sigma_{\Theta*}$ = 2.5 μrad, $L_x \approx 0$, $L_y \approx 260$ m
- vertex size $\sigma_{IP} \approx 212$ μm
- Acceptance: $|t| > 3 \cdot 10^{-2}$ GeV^2, RP distance from beam center 10 $\sigma_{beam\ size@RP}$
- parallel to point focusing **only** in **vertical** plane @RP220

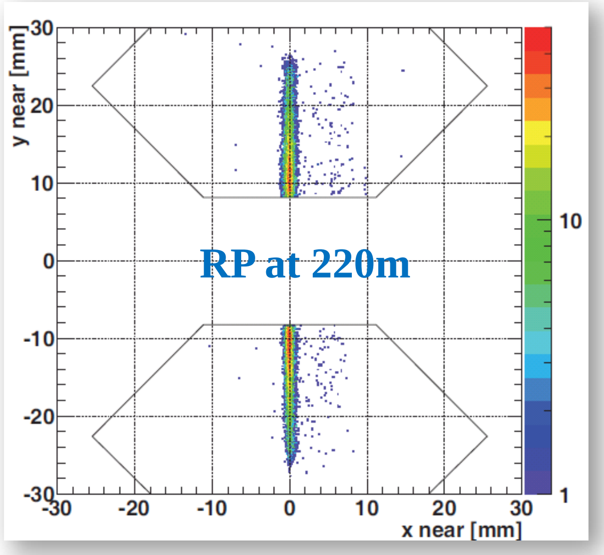
Effective lengths from IP5 to RP @220 m

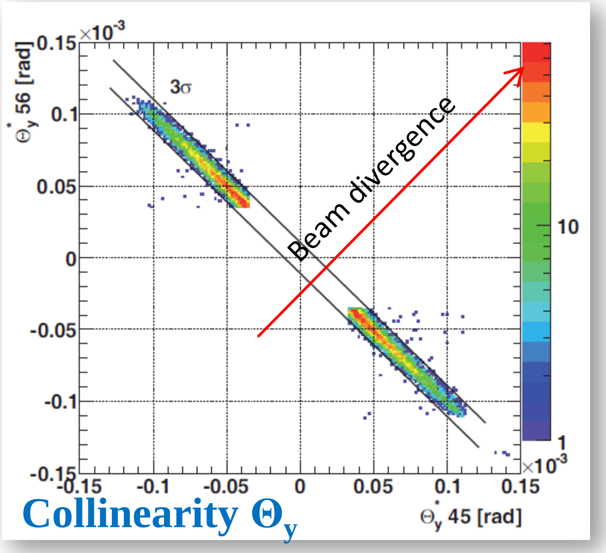


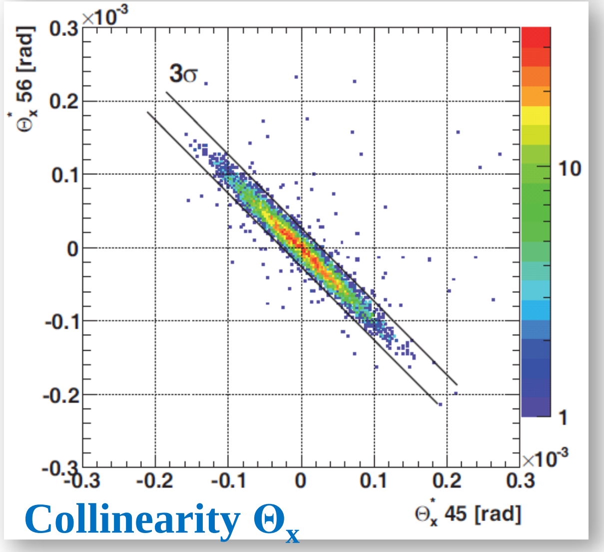
Very clean data obtained with β*=90 m

The properties of the measured data:

- divergence is reduced with respect to 3.5 m optics (from 17-18 μrad to 2.5 μrad)
- lower background compared to 3.5 m (< 0.1%)
- uncertainty of luminosity 4% (CMS)
- low intensity bunches and β*=90 m -> no pile-up from single diffraction







Intermediate β*=90 m optics: robustness

Objectives:

- First measurement of σ_{tot} elastic scattering in a wide |t| range
- inclusive studies of diffractive processes
- measurement of forward charged multiplicity

Sensitivity of the effective length L_y :

- 1 ‰ perturbations magnet strength, beam momenta
- **Conclusion: not necessary to improve our understanding about β*=90 m optics**

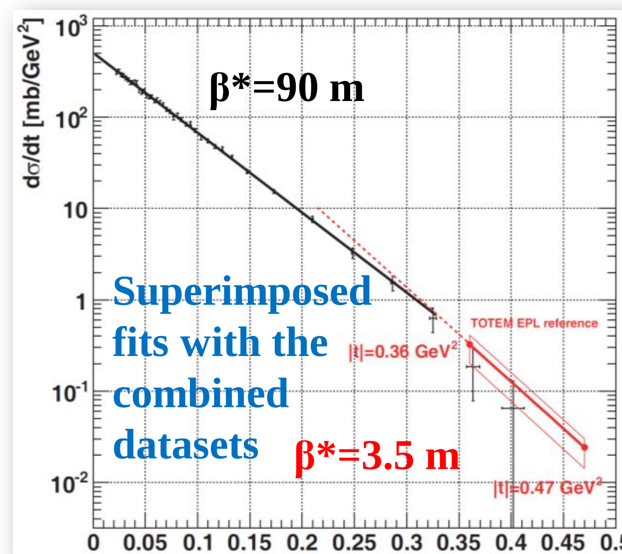
Perturbed element	$\delta_{Ly,b1}/L_{y,b1}$ [%]
MQXA.1R5	0.14
MQXB.A2R5	−0.23
MQXB.B2R5	−0.25
MQXA.3R5	0.20
MQY.4R5.B1	−0.01
MQML.5R5.B1	0.04
Δp/p	0.01

Obtained dσ/dt with β*=90 m optics

Published in EPL 96 (2011) 21002

Properties:

- |t| range of the new set is 0.02 - 0.33 GeV^2
- $B = (20.1 \pm 0.2^{stat} \pm 0.3^{syst})\ GeV^{-2}$ confirms that B increases with √s
- excellent agreement between the two measurements with different optics



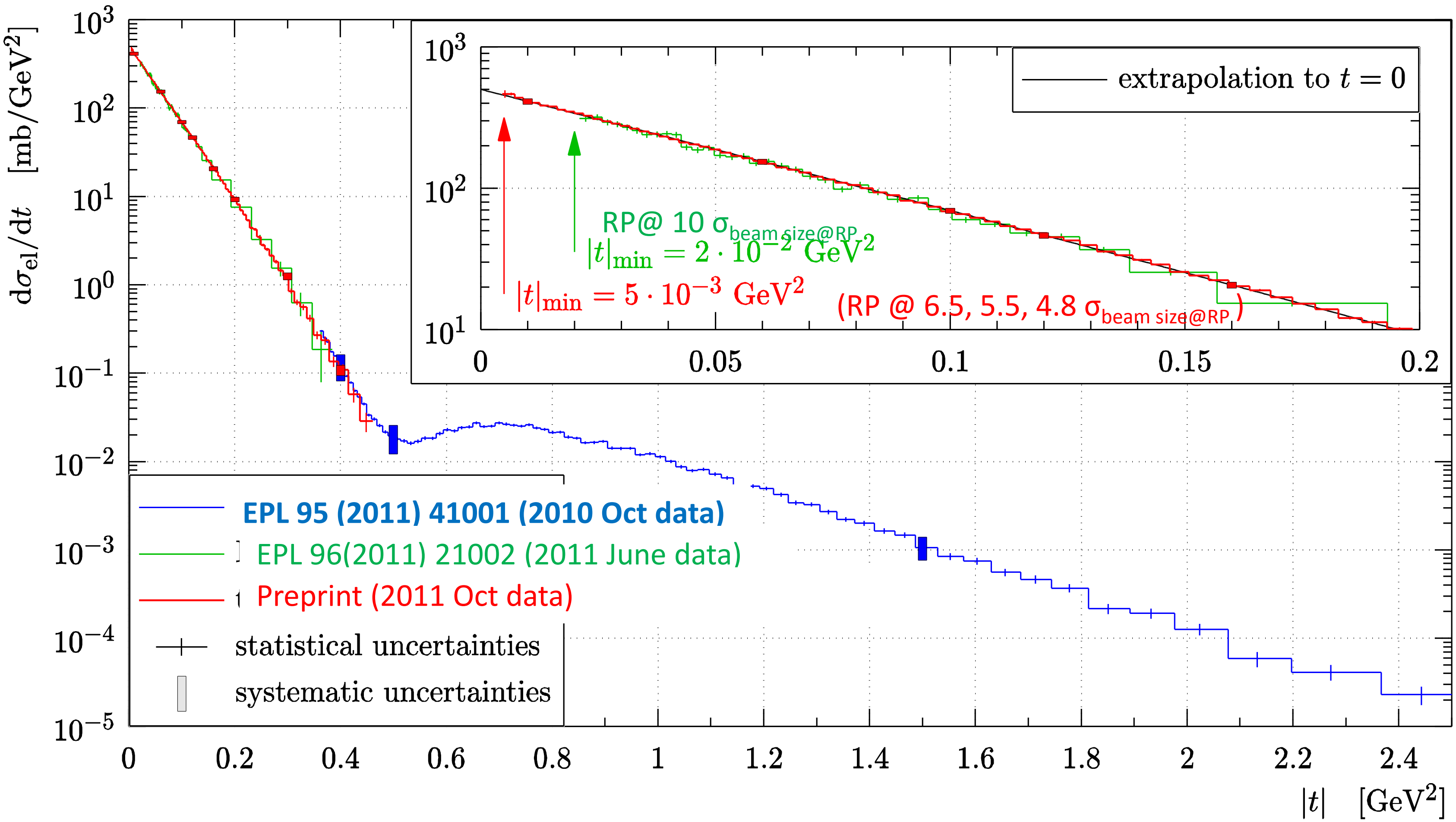
Conclusions

- **TOTEM has measured the inelastic and elastic cross sections and the total cross section with the luminosity independent method at $\sqrt{s}$=7 TeV**
- Measurement of elastic scattering at very low-t and determination of the ρ parameter will be in reach during the high β (β*= 500 m, 1000 m) runs
- Several analyses on diffractive physics are going on, results are expected soon

Thank you for you attention !

Backup part

Obtained dσ/dt with the most recent result



Total Cross-Section with 4 methods

1. Low luminosity (CMS) + Elastic dσ/dt + Optical th. (EPL 96(2011) 21002)

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

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

σ_{TOT} = 98.3 ± 2.8 mb

2. High luminosity (CMS) + Elastic + Optical theorem (to be published)

σ_{TOT} = 98.6 ± 2.2 mb

3. High luminosity (CMS) + Elastic + Inelastic (to be published)

   - minimizes dependence on elastic efficiencies and **ρ independent**

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

σ_{TOT} = 99.1 ± 4.3 mb

4. Elastic ratios + Inelastic ratios + Optical theorem (preprint)

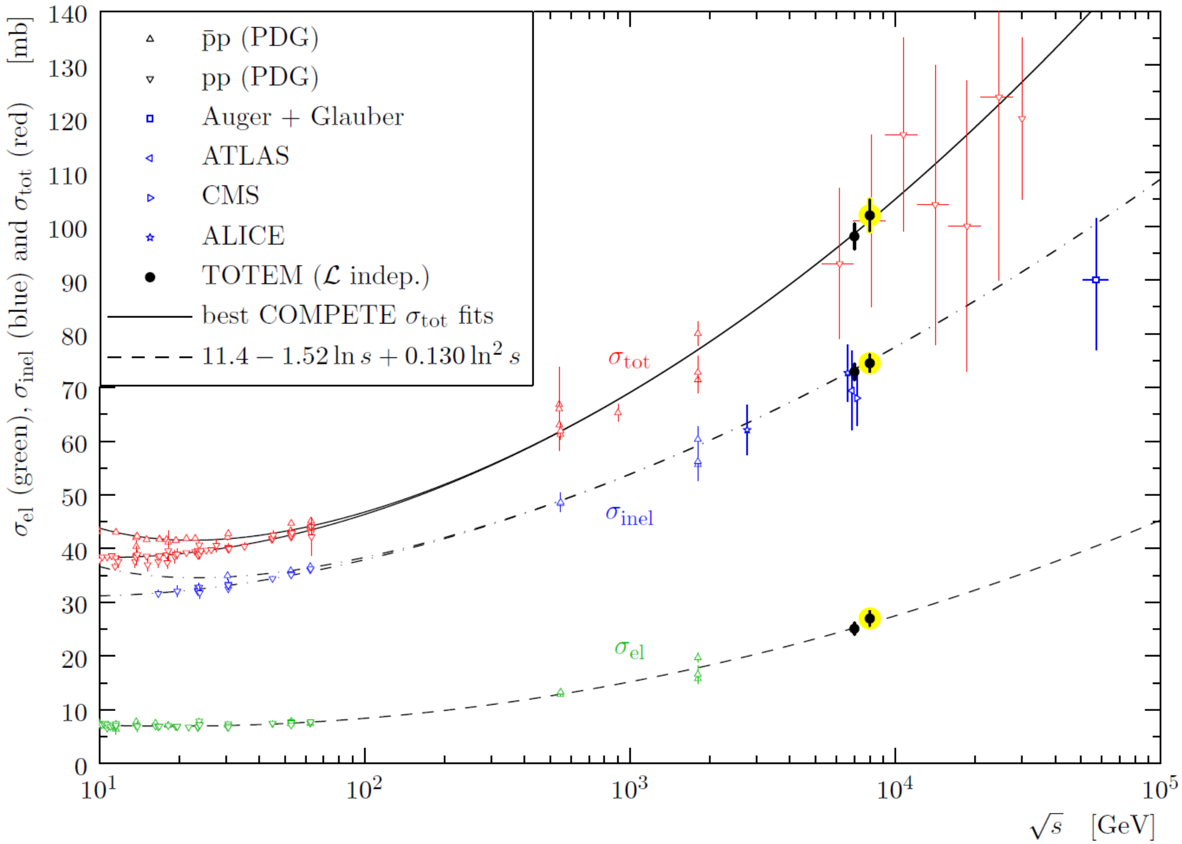
   - **Eliminates dependence on luminosity**

$$\sigma_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{EL}}{dt}\right|_{t=0}}{N_{EL} + N_{INEL}}$$

$\sigma_{TOT, 7\ TeV}$ = 98.0 ± 2.5 mb

$\sigma_{TOT, 8\ TeV}$ = 101.7 ± 2.9 mb

Total Cross-Section with the luminosity independent method including the 8 TeV result



Luminosity calibration

TOTEM is able to determine the CMS luminosity:

- Elastic and inelastic rates are used

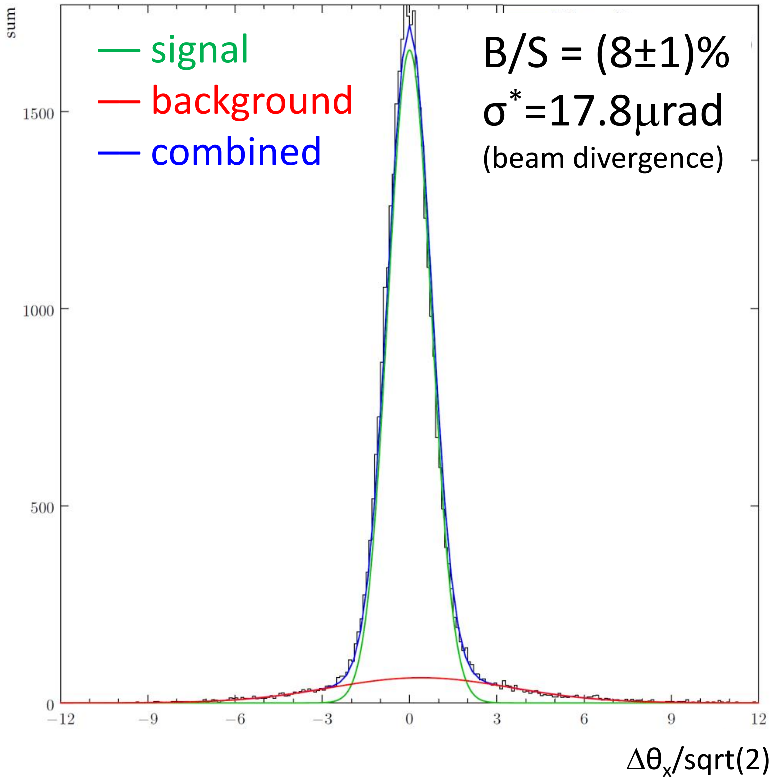
$$L = \frac{1+\rho^2}{16\pi(\hbar c)^2} \cdot \frac{(N_{EL} + N_{INEL})^2}{dN_{EL} / dt|_{t=0}}$$

Obtained luminosity values

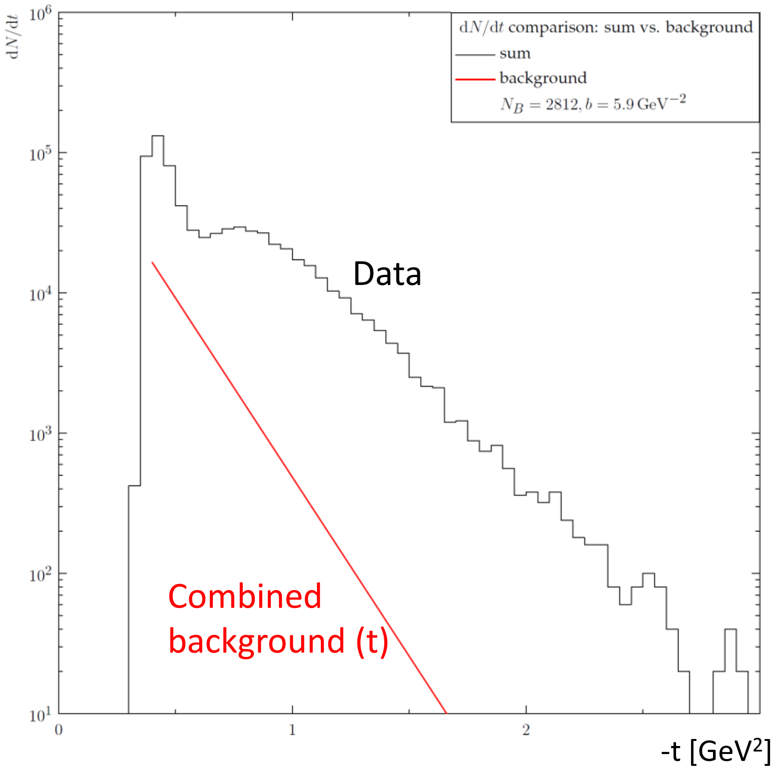
$$\text{October data: } L_{CMS} = 82.8\,\mu b^{-1} \pm 4\% \qquad L_{TOTEM} = 83.7\,\mu b^{-1} \pm 3.8\%$$

$$\text{June data: } L_{CMS} = 1.65\,\mu b^{-1} \pm 4\% \qquad L_{TOTEM} = 1.65\,\mu b^{-1} \pm 4.5\%$$

Background and resolution determination β*=3.5m



Signal to background normalisation
(also as a function of $\Delta\theta_y$)



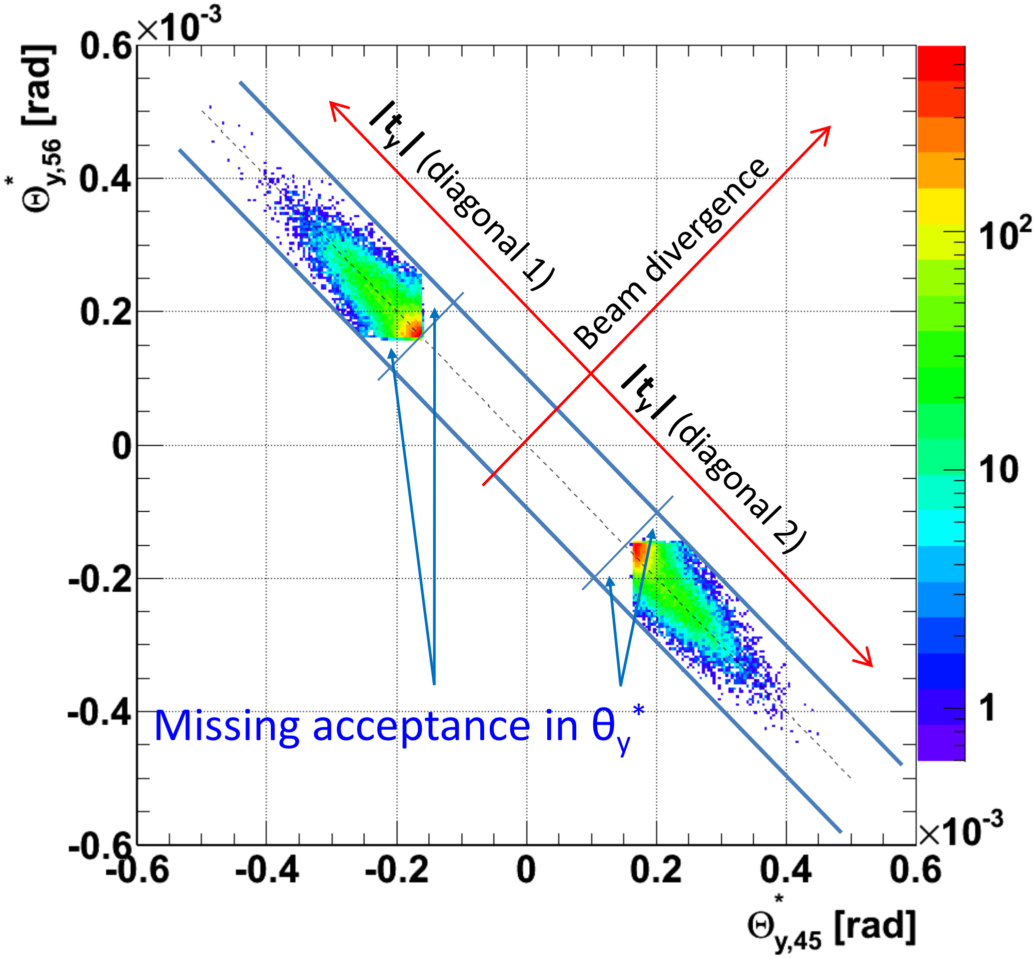
Signal vs. background (t)

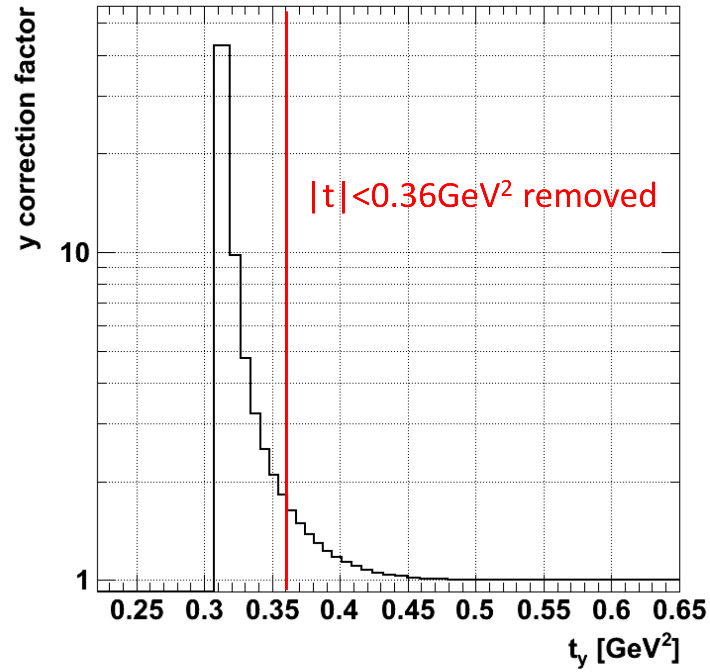
$\sigma^* \rightarrow$ t-reconstruction resolution:

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

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

t_y-acceptance corrections $\beta^*=3.5m$





Correction error (t_y):

0.31 GeV^2 : 30%

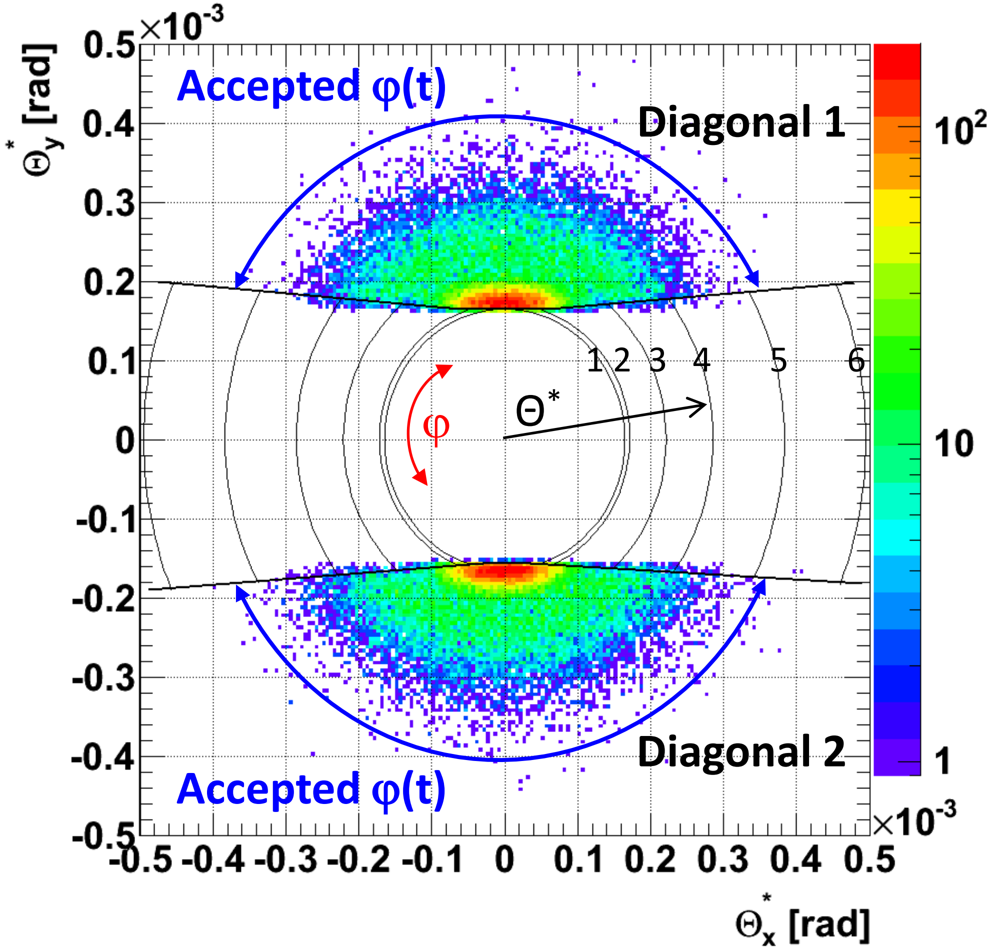
0.33 GeV^2 : 11%

0.35 GeV^2 : 2%

0.4 GeV^2 : 0.8%

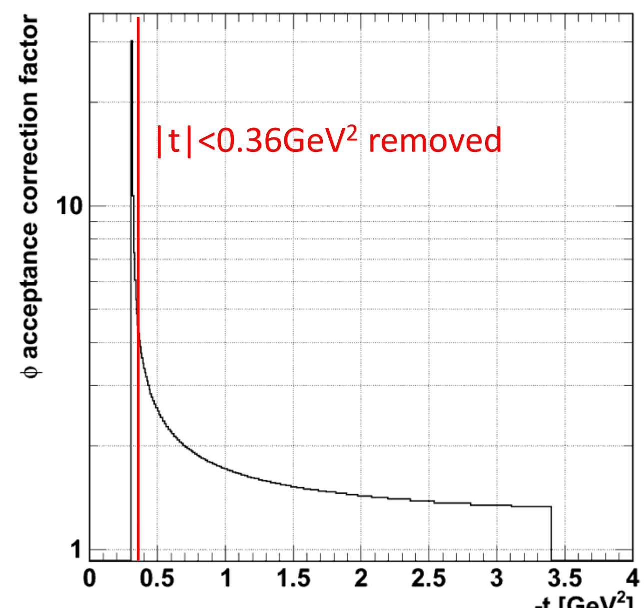
0.5 GeV^2 : 0.1%

Acceptance corrections β*=3.5m



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**



Critical at low t-acceptance limit