# TOTEM luminosity independent cross section measurements
## Elastic cross sections
## LHC optics estimation

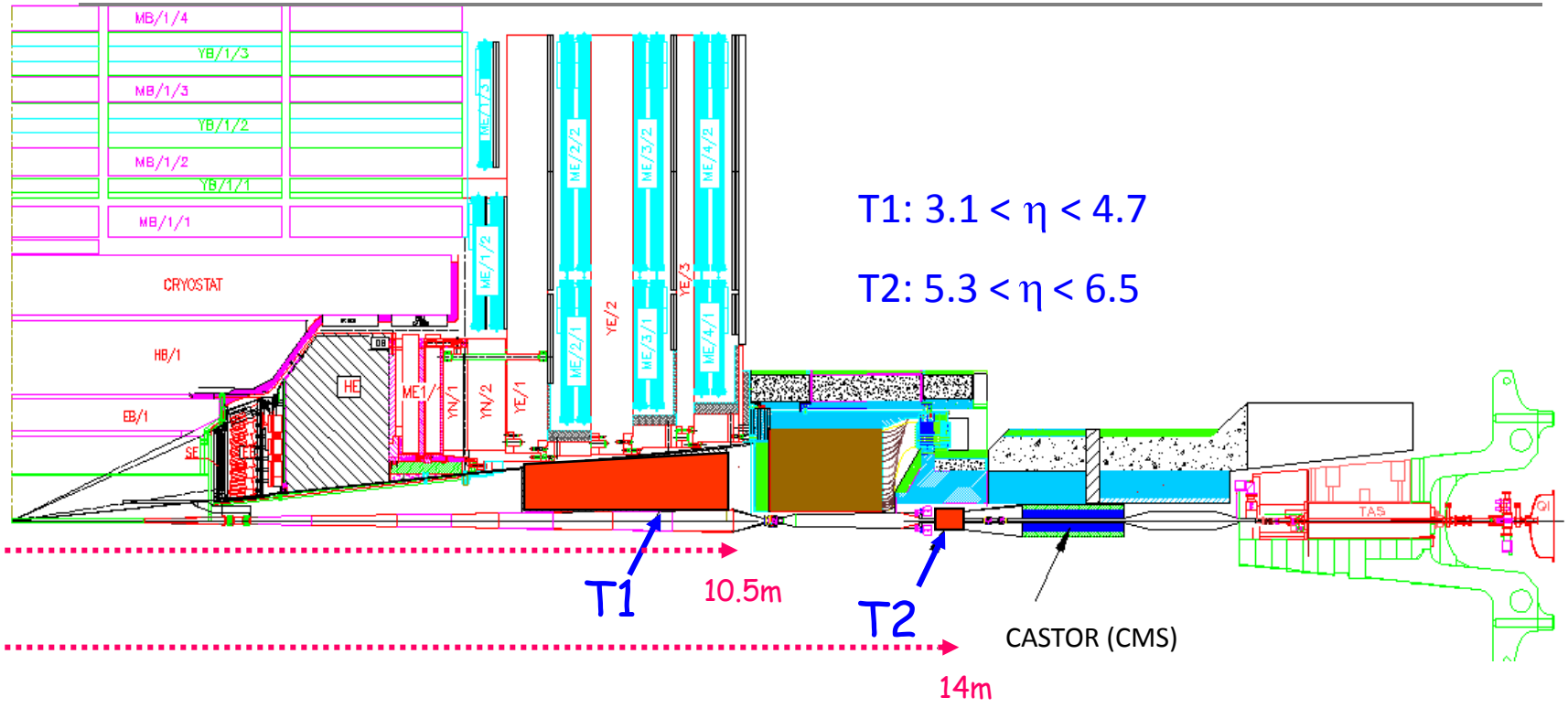
Frigyes Nemes
Eötvös University

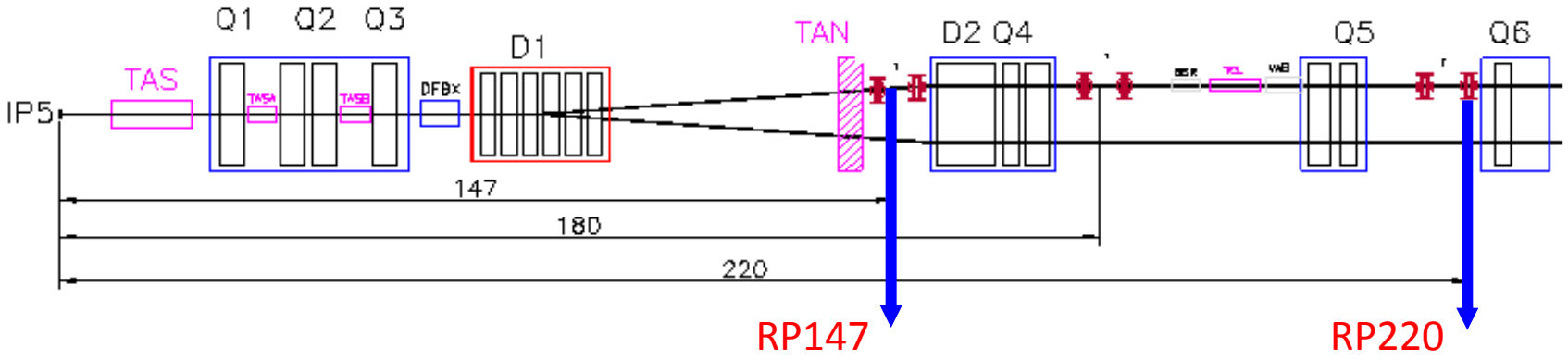
on behalf of the

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

Low-x Workshop, Paphos
2012, 27 June – 1 July

# Experimental layout of the TOTEM experiment



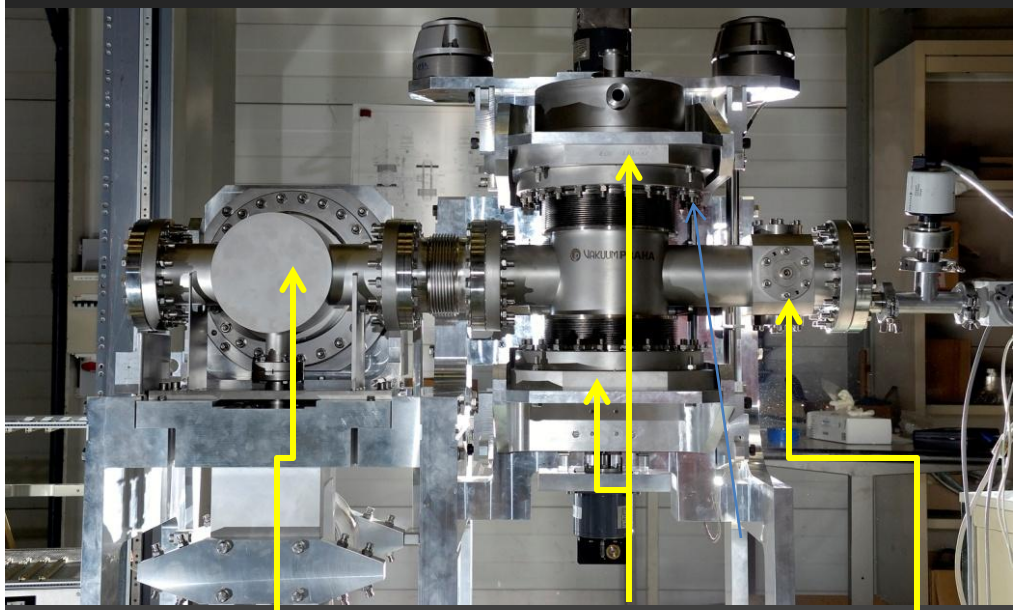



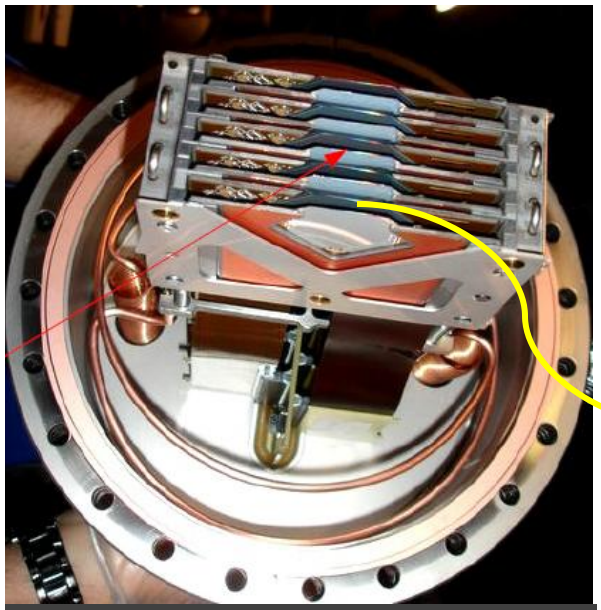
# Roman Pot stations

**RP stations**

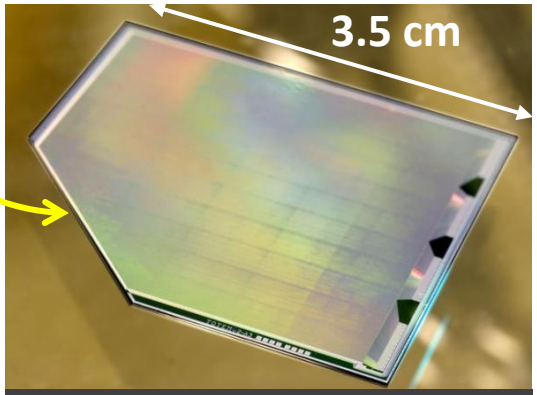
- 2 units at about 5 m distance
- Measurement of very small proton scattering angles (few µrad)
- Vertical and horizontal pots mounted as close as possible to the beam
- BPM fixed to the structure gives precise position relative to the beam
- Overlaping detectors: relative alignment (10 µm inside unit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

RP unit: 2 vertical, 1 horizontal pot + BPM

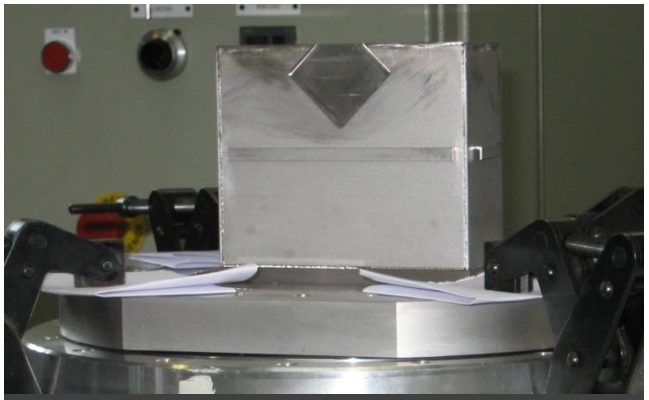


10 planes of edgeless detectors

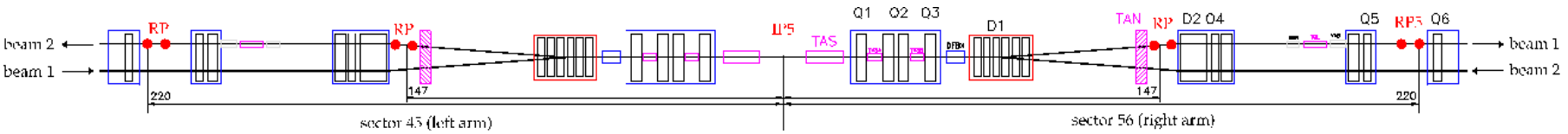



Si edgeless detector



1 Roman Pot

# LHC optics in brief




**Proton position at a given RP (x, y) is a function of position ($x^*$, $y^*$) and angle ($\Theta_x^*$, $\Theta_y^*$) at IP5:**

**measured**

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

**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

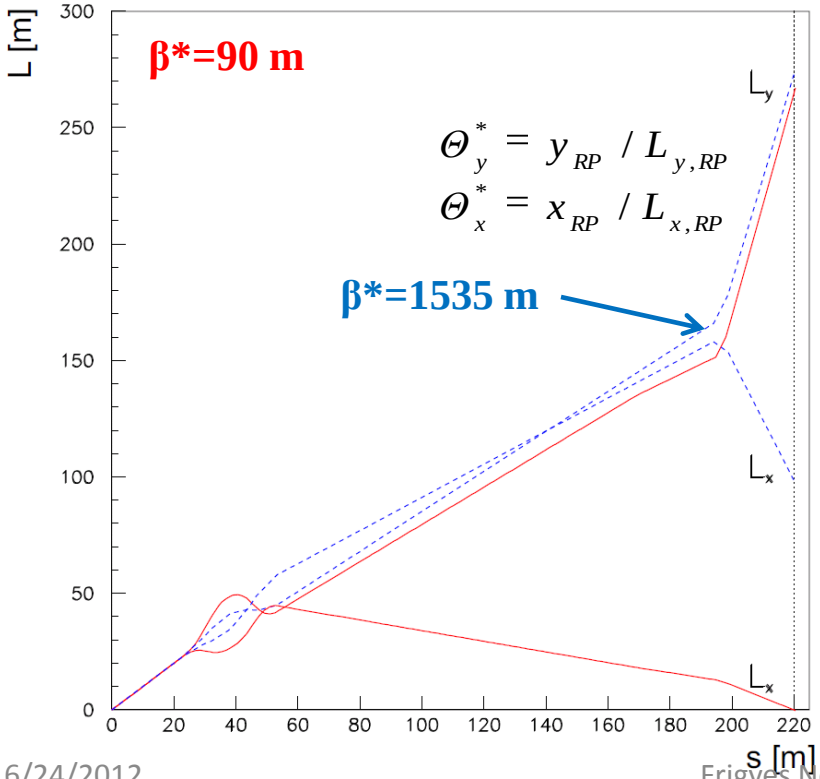
$\sigma(\Theta) = \sqrt{\varepsilon / \beta_x}$ beam divergence @IP5 limits the angle measurement precision

# High β*=1535 m target optics

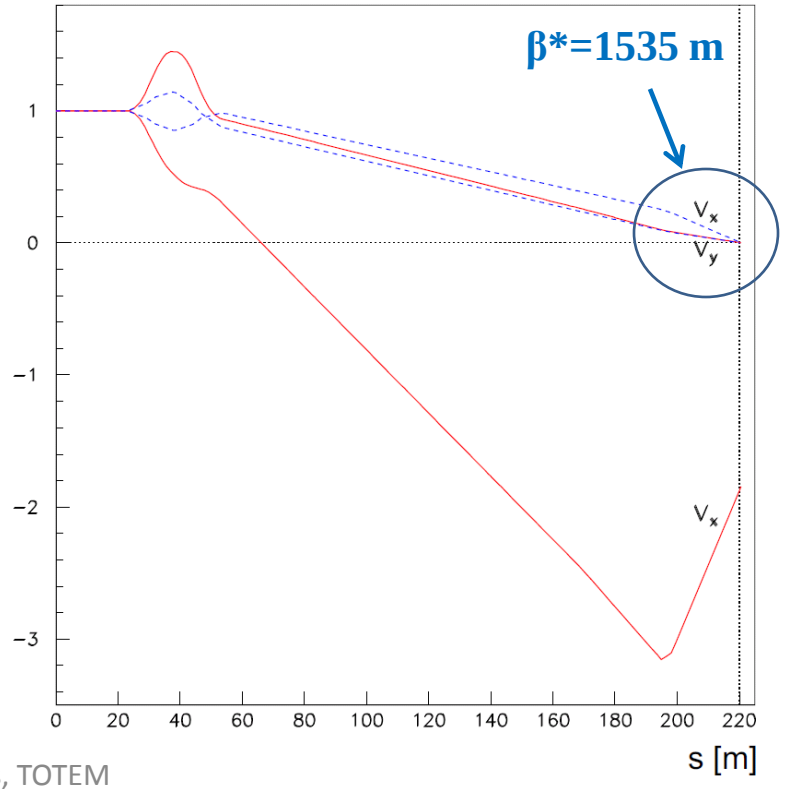
**β* = 1535 m is the *target* optics. Requires different injection optics. Properties:**

- beam divergence $\sigma_{\Theta^*} \approx 0.3$ µrad, vertex size $\sigma_{IP} \approx 450$ µm
- $\Delta\mu_{x,y} = \pi/2 \rightarrow \nu_{x,y} = 0$. 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 lengthsfrom IP5 to RP @220 m**




**Magnification from IP5 to RP @220 m**



# LOW β*=3.5 m OPTICS

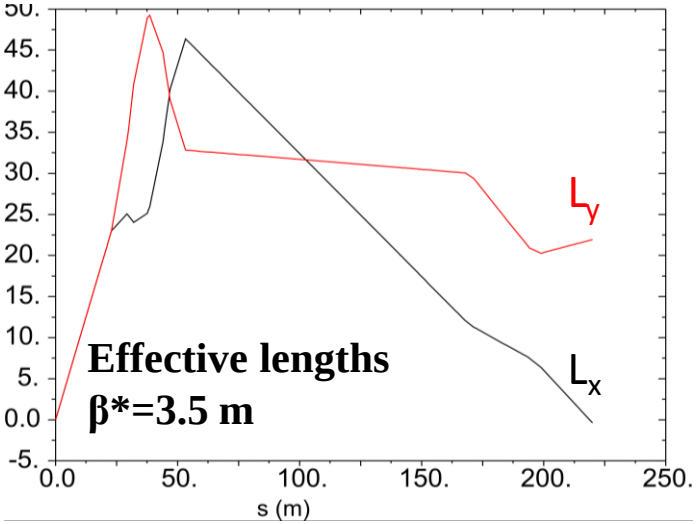
# Low β*=3.5m optics

**Objective:**

- to measure elastic scattering at high |t|

**Properties of the optics:**

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

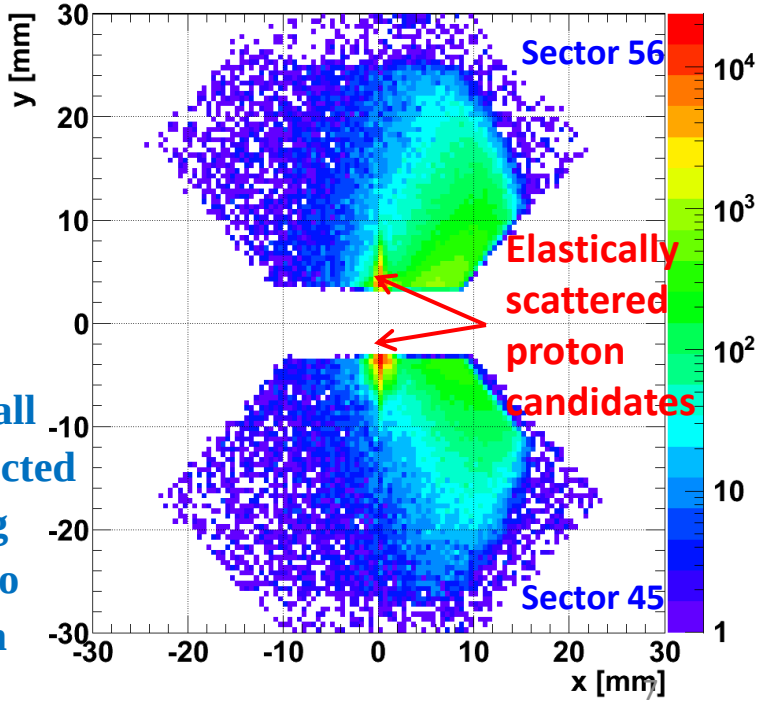



**Data sources** to improve our optics understanding:

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

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

$\xi = \Delta p/p$




**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

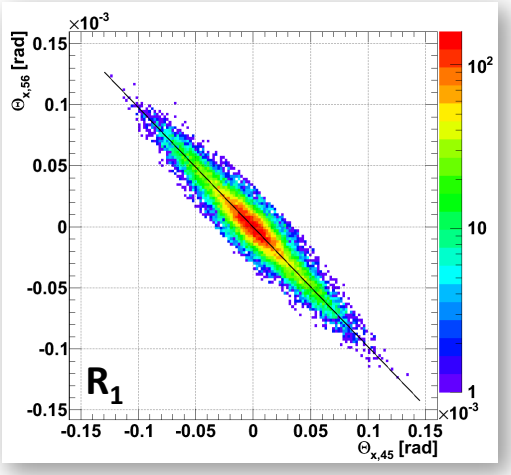
**Optics imperfections can be determined from proton tracks *measured* in the Roman Pots. The method is based on:**

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

$$\Theta^*_{y,b\,1} = \Theta^*_{y,b\,2}$$

$$\Theta^*_{x,b\,1} = \Theta^*_{x,b\,2}$$

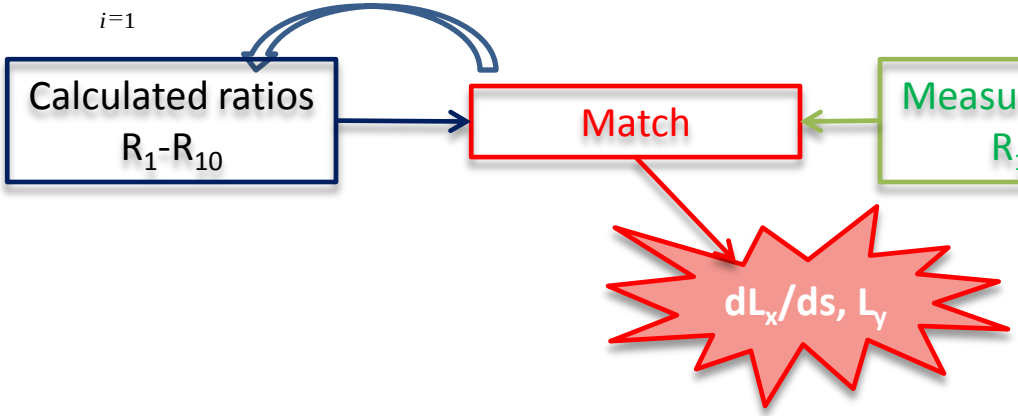
$$\rightarrow \quad R_1 \equiv \frac{\Theta_{x,b\,1,RP}}{\Theta_{x,b\,2,RP}} \approx \frac{\frac{dL_{x,b\,1,RP}}{ds}}{\frac{dL_{x,b\,2,RP}}{ds}}$$



# Matching the optics β*=3.5m

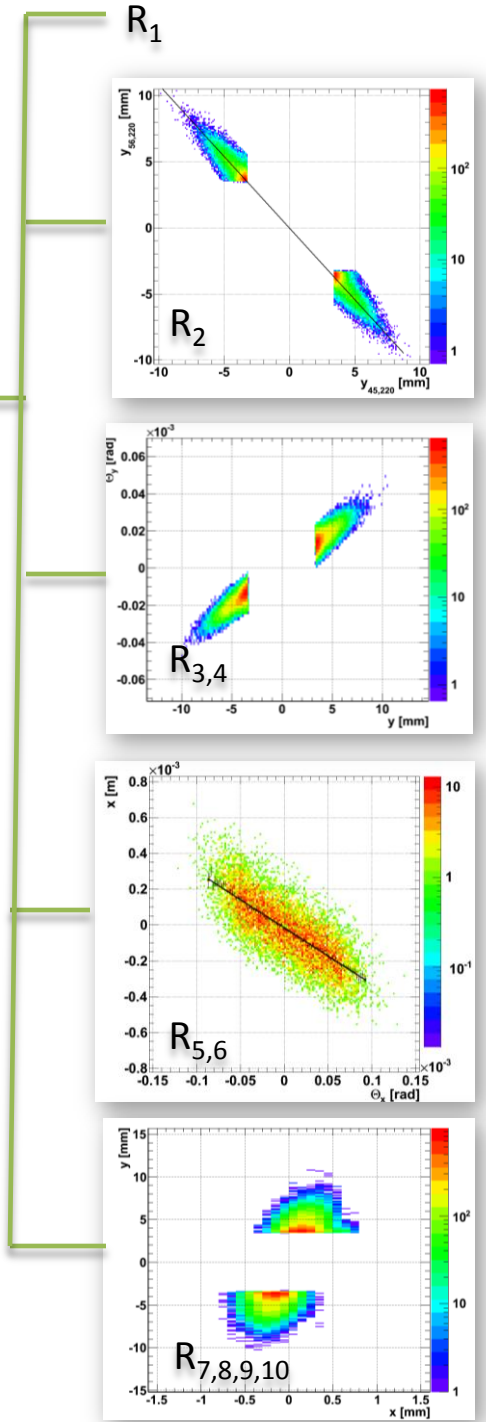
**On the basis of constraints $R_1$-$R_{10}$ the optics can be estimated.**

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




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

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



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

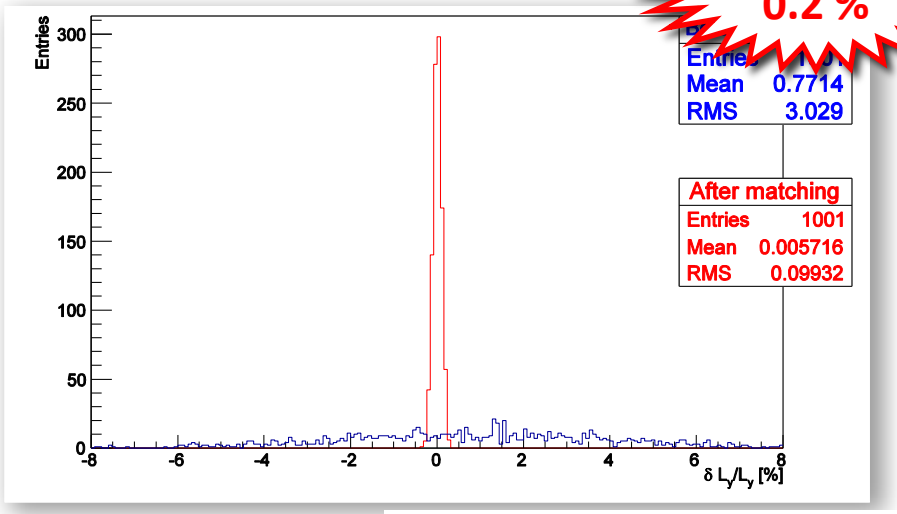
**The Monte-Carlo study included the effect of:**

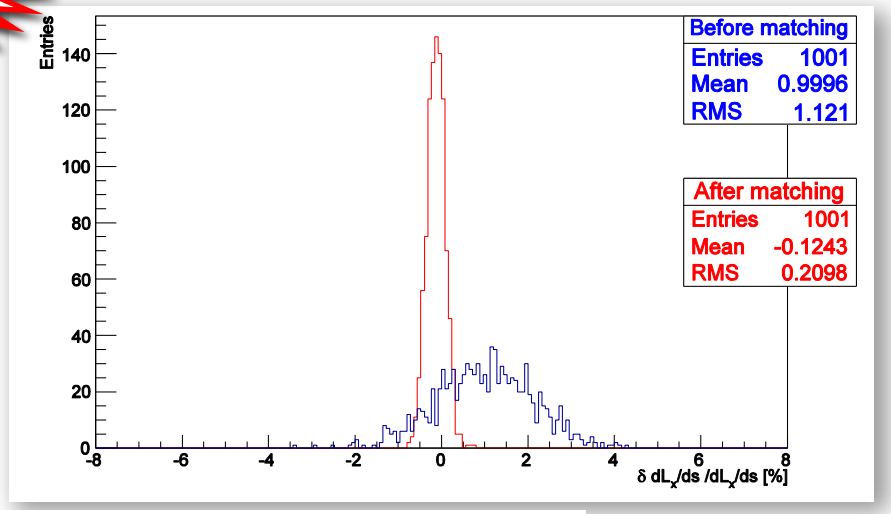
- magnet strengths
- beam momenta
- displacements, rotations
- kickers, field harmonics
- elastic scattering Θ-distributions

| Optical function relative error | Before | | Matched | |
|---|---|---|---|---|
| | Mean [%] | RMS [%] | Mean [%] | RMS [%] |
| $\delta L_{y,b1}/L_{y,b1}$ | 0.77 | 3.0 | $5.7 \cdot 10^{-3}$ | $9.9 \cdot 10^{-2}$ |
| $\delta\ (dL_{x,b1}/ds)/(dL_{x,b1}/ds)$ | 1.0 | 1.1 | $-1.2 \cdot 10^{-1}$ | $2.1 \cdot 10^{-1}$ |
| $\delta L_{y,b2}/L_{y,b2}$ | 2.0 | 3.8 | $1.5 \cdot 10^{-1}$ | $9.5 \cdot 10^{-2}$ |
| $\delta\ (dL_{x,b2}/ds)/(dL_{x,b2}/ds)$ | -1.14 | 1.2 | $-7.6 \cdot 10^{-2}$ | $2.1 \cdot 10^{-1}$ |

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

RMS < 0.2 %



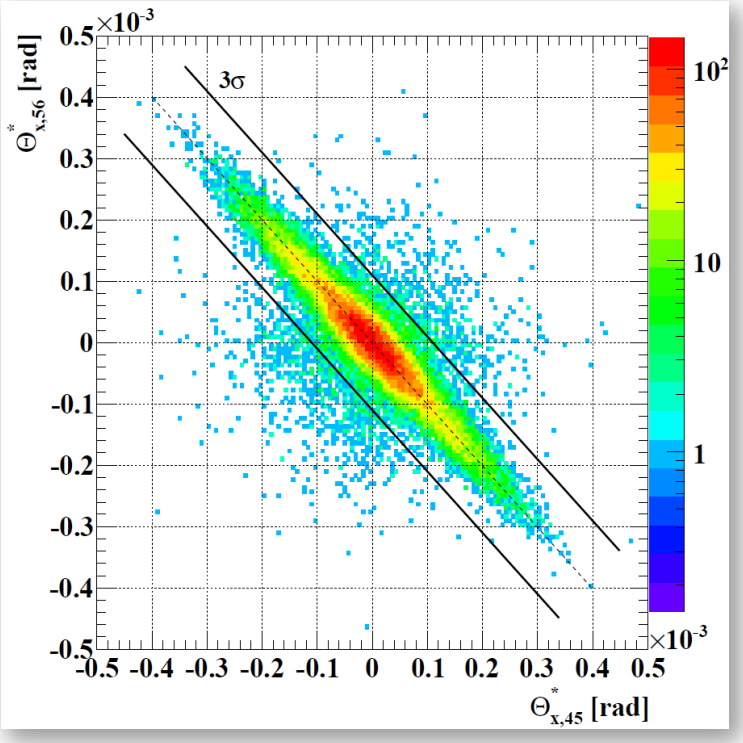

**Relative error distribution before and after matching**

# ELASTIC SCATTERING WITH β*=3.5 m

# Elastic scattering with β*=3.5m

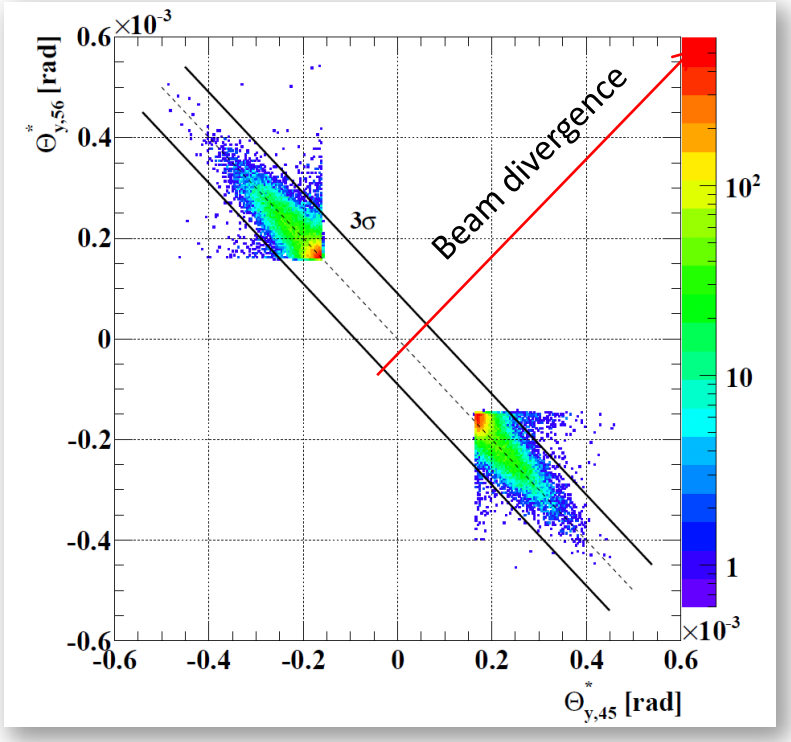
**Results (the matched $L_y$ and $dL_x/ds$ are used for reconstruction):**

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




**Collinearity $\Theta_x$**

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

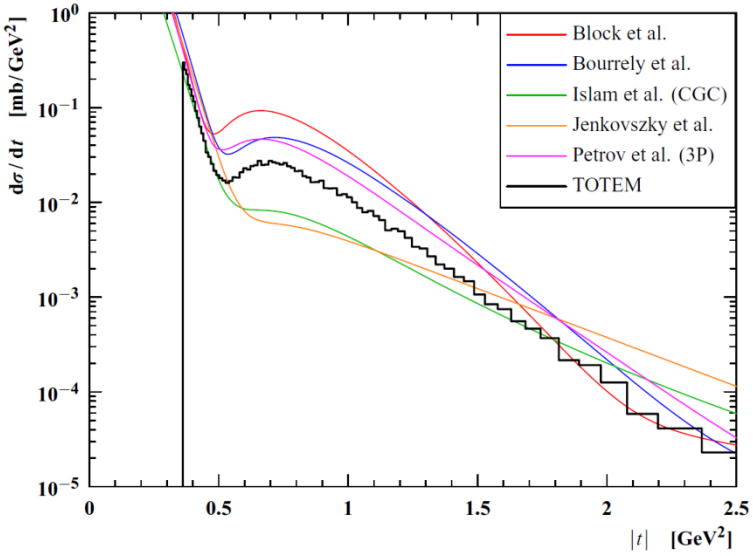



**Collinearity $\Theta_y$**

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

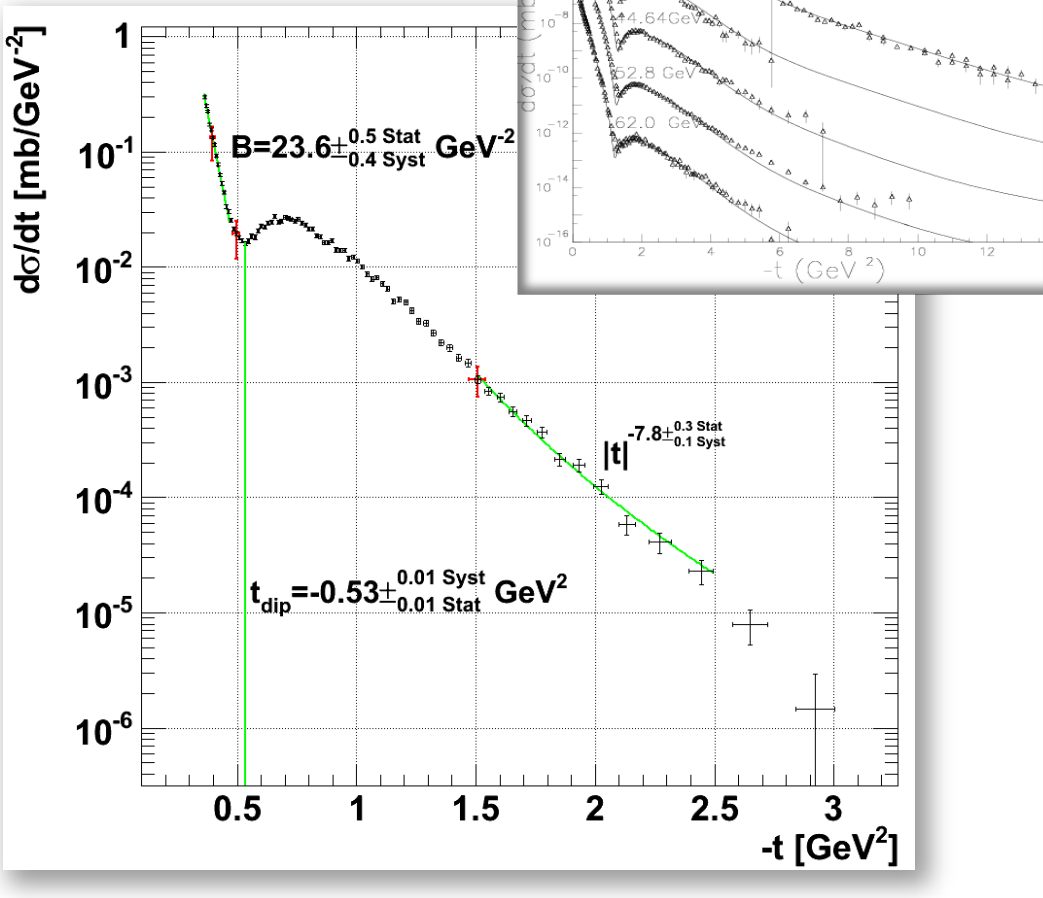
**Published in EPL 95 (2011) 41001:**

- $|t|$ 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**



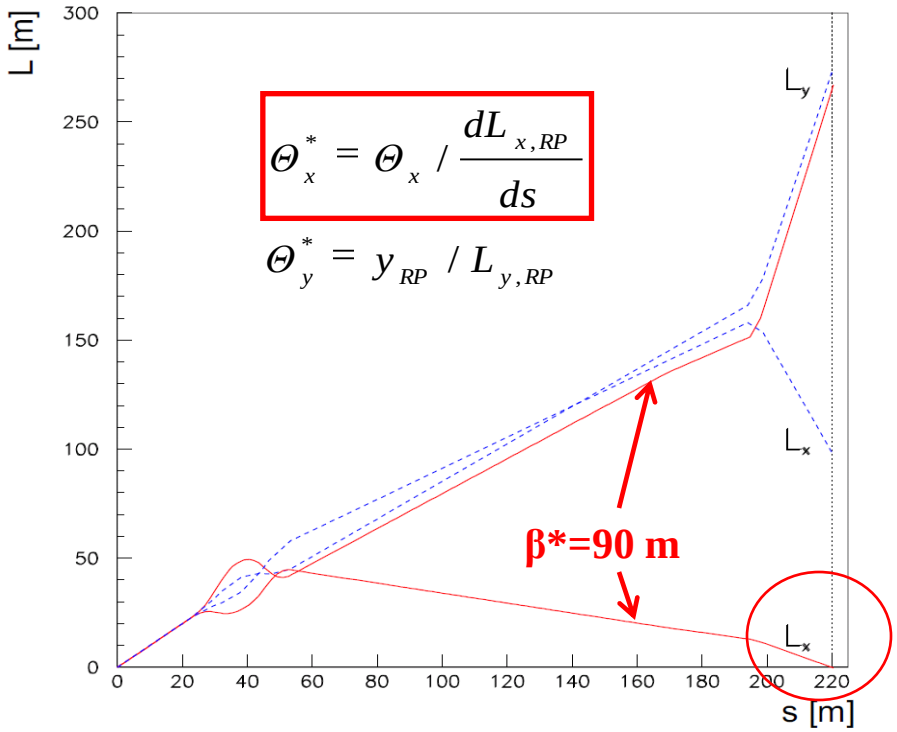
# HIGH β* = 90 m OPTICS AND RESULTS

# 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 $\sigma_{\text{beam size@RP}}$
- parallel to point focusing **only** in **vertical** plane @RP220

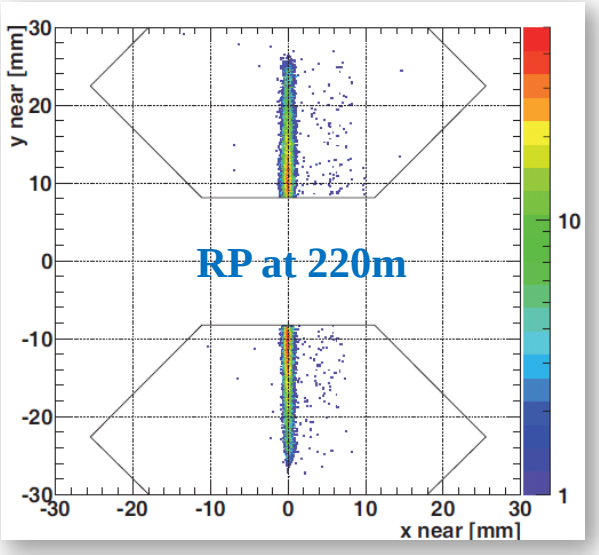
**Effective lengths from IP5 to RP @220 m**

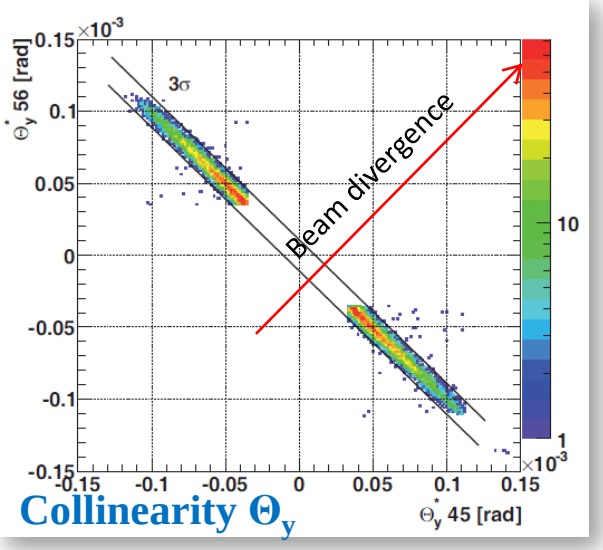


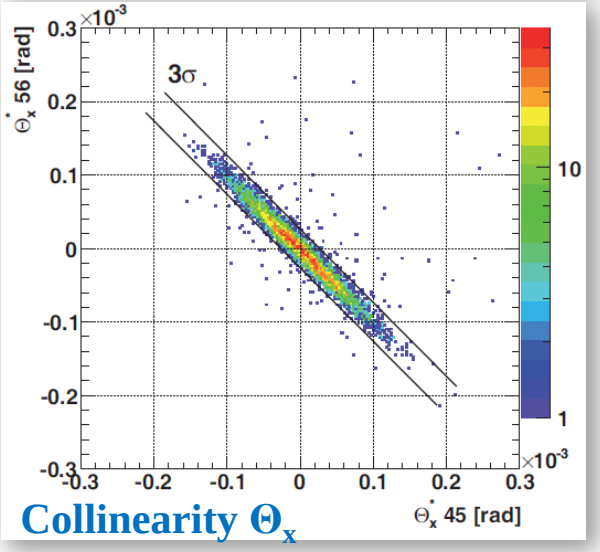
# Very clean data obtained with β*=90 m

**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 $\sigma_{tot}$ 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**

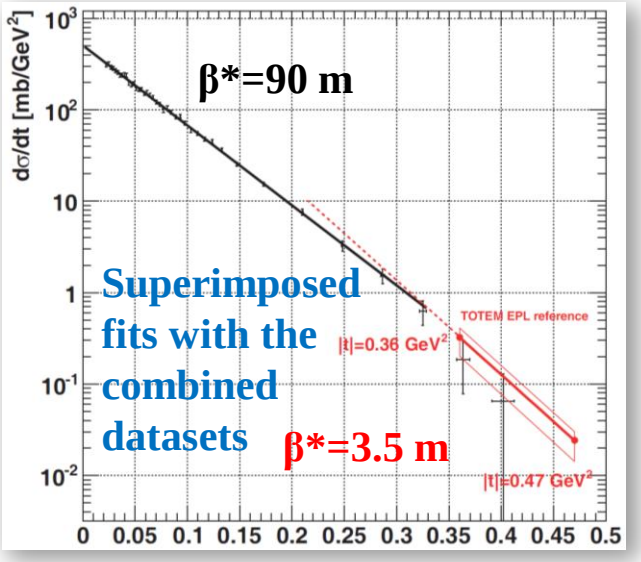
| Perturbed element | $\delta_{Ly,b1}/L_{y,b1}$ [%] |
|---|---|
| MQXA.1R5 | 0.14 |
| MQXB.A2R5 | −0.23 |
| MQXB.B2R5 | −0.25 |
| MQXA.3R5 | 0.20 |
| MQY.4R5.B1 | −0.01 |
| MQML.5R5.B1 | 0.04 |
| Δp/p | 0.01 |

## Obtained dσ/dt with β*=90 m optics

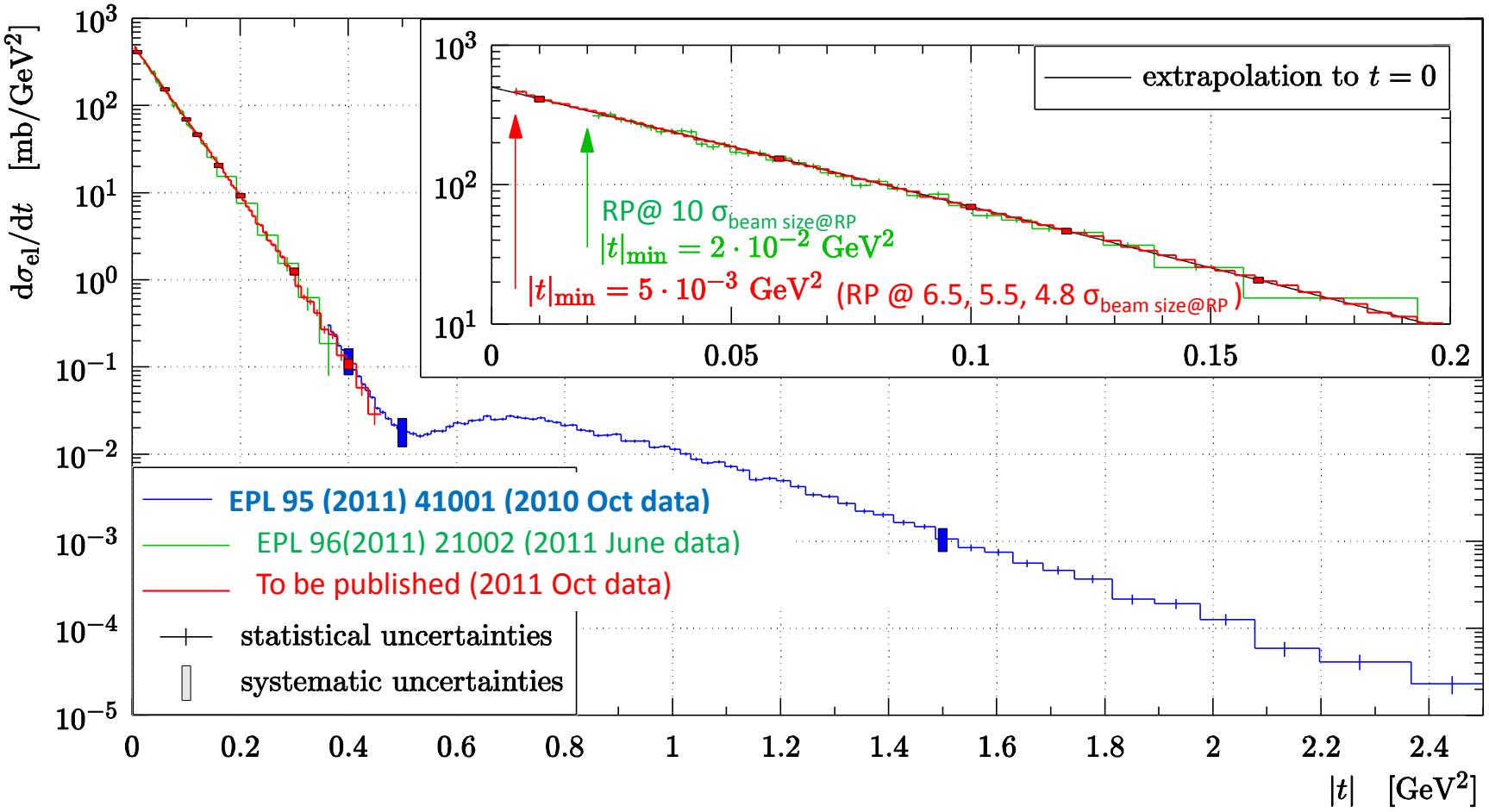
Published in EPL 96 (2011) 21002

**Properties:**

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



# 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

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

$\sigma_{TOT}$ = 98.3 2.0 mb

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

$\sigma_{TOT}$ = 98.6 2.3 mb

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

   - minimizes dependence on elastic efficiencies and **no dependence on ρ**

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

$\sigma_{TOT}$ = 99.1 4.4 mb

4. Elastic ratios + Inelastic ratios + Optical theorem (to be published)

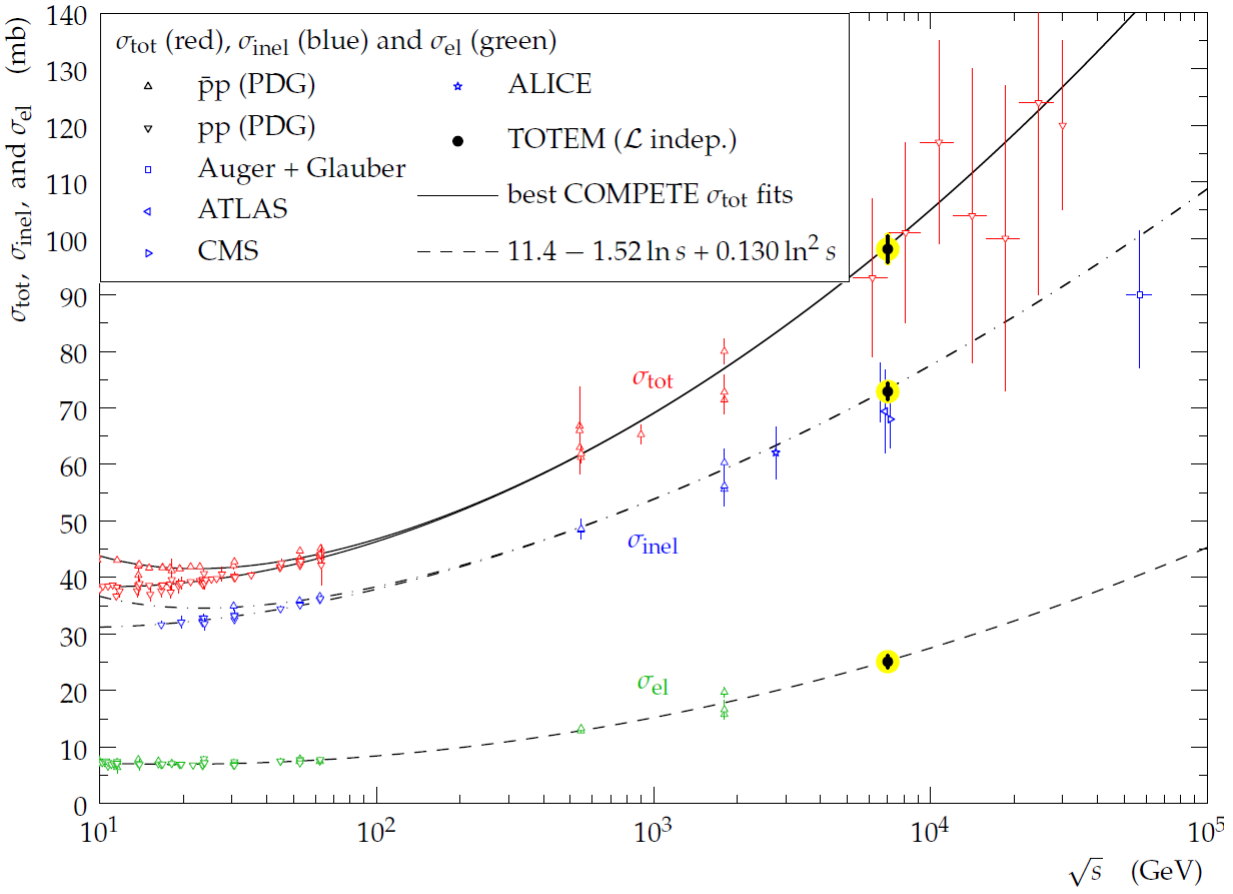
   - **Eliminates dependence on luminosity**

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

$\sigma_{TOT}$ = 98.1 2.5 mb

# Total Cross-Section with the luminosi

**The result of the 4 methods on one plot:**



# Conclusions

- **TOTEM has measured the inelastic and elastic cross sections and the total cross section with the luminosity independent method at √s=7 TeV**
- Very soon these measurements will be repeated at √s=8 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) run
- Several analyses on diffractive physics are going on, results are expected soon

Thank you for you attention !

# Backup part

# Luminosity calibration

**TOTEM is able to determine the CMS luminosity:**

- Elastic and inelastic rates are used

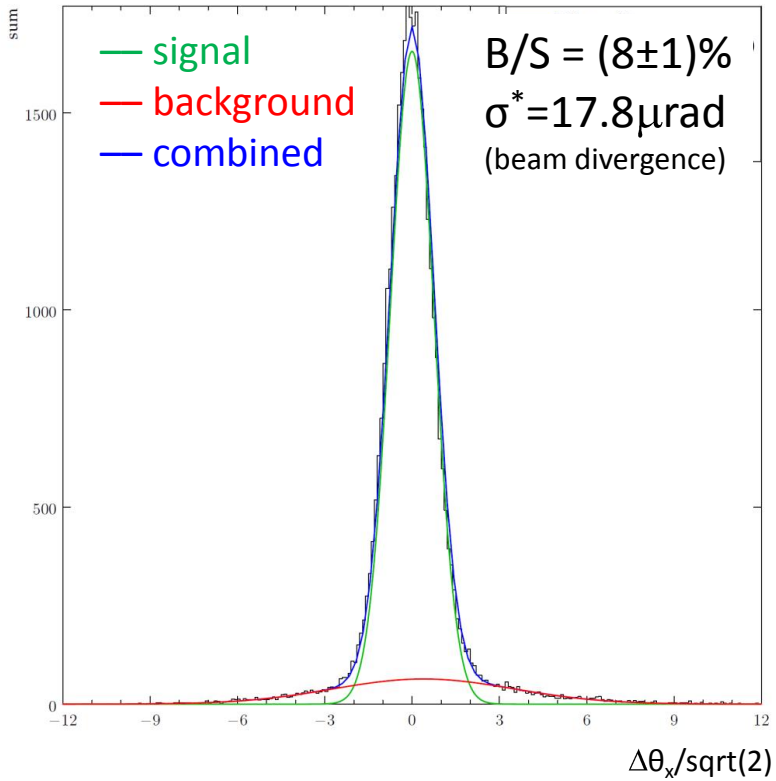
$$L = \frac{1+\rho^2}{16\pi\, c^2} \cdot \frac{(N_{EL} + N_{INEL})^2}{dN_{EL}/dt\big|_{t=0}}$$

**Obtained luminosity values**

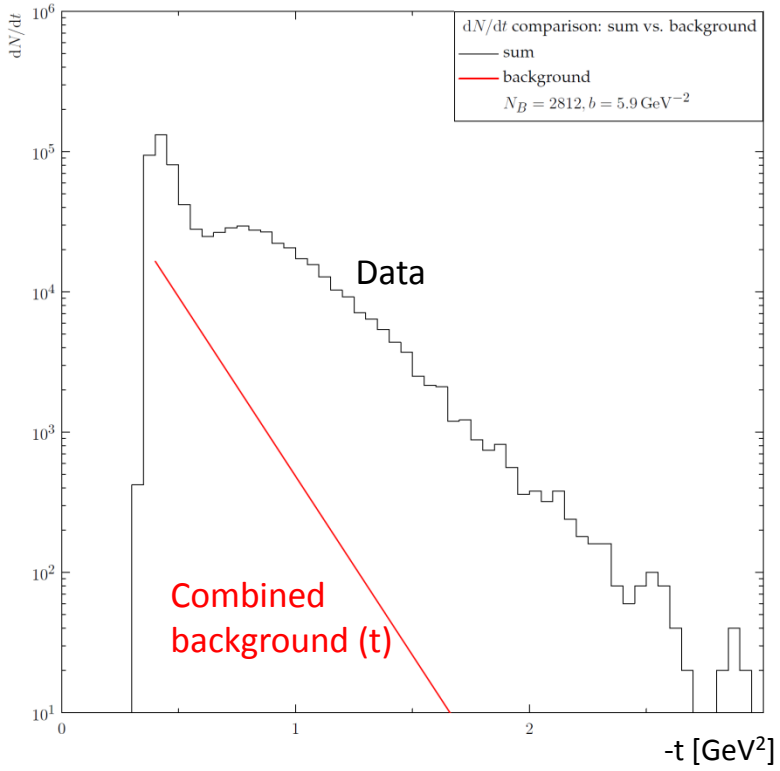
October data : $L_{CMS} = 82.8\,\mu b^{-1} \pm 4\%$ $L_{TOTEM} = 84.2\,\mu b^{-1} \pm 3.8\%$

June data : $L_{CMS} = 1.65\,\mu b^{-1} \pm 4\%$ $L_{TOTEM} = 1.655\,\mu b^{-1} \pm 4.5\%$

# Background and resolution determination β*=3.5m




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



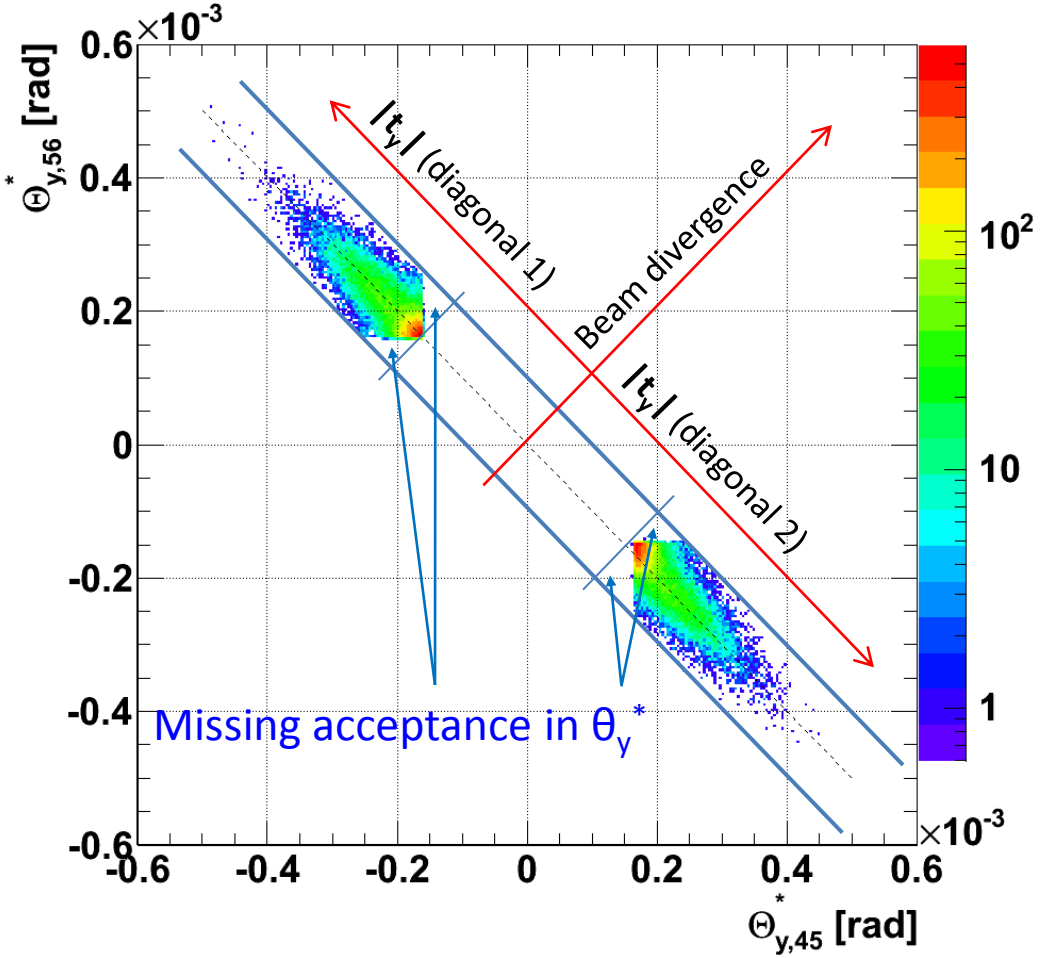

**Signal vs. background (t)**

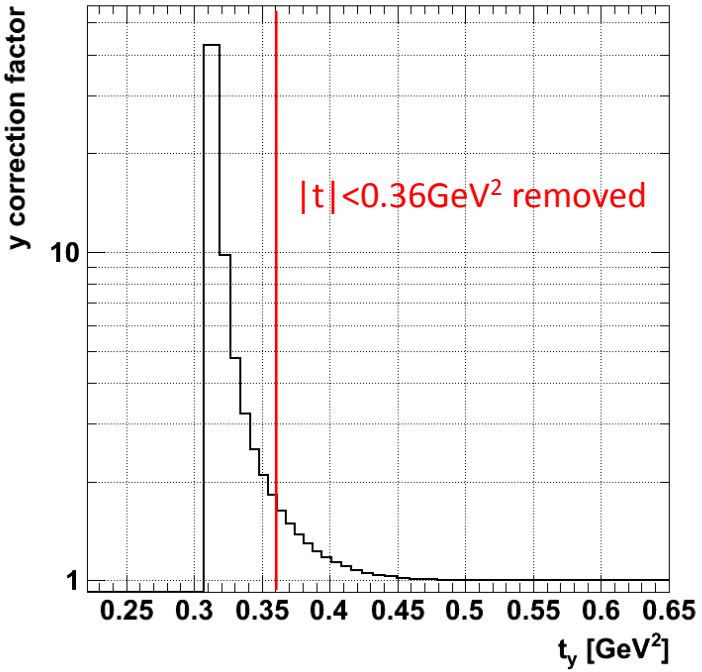
**$\sigma^*$ → t-reconstruction resolution:**

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

|t|=0.4GeV²: B/S = (11±2)%
|t|=0.5GeV²: B/S = (19±3)%
|t|=1.5GeV²: B/S = (0.8±0.3)%

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




**Correction error ($t_y$):**

0.31 GeV$^2$ : 30%

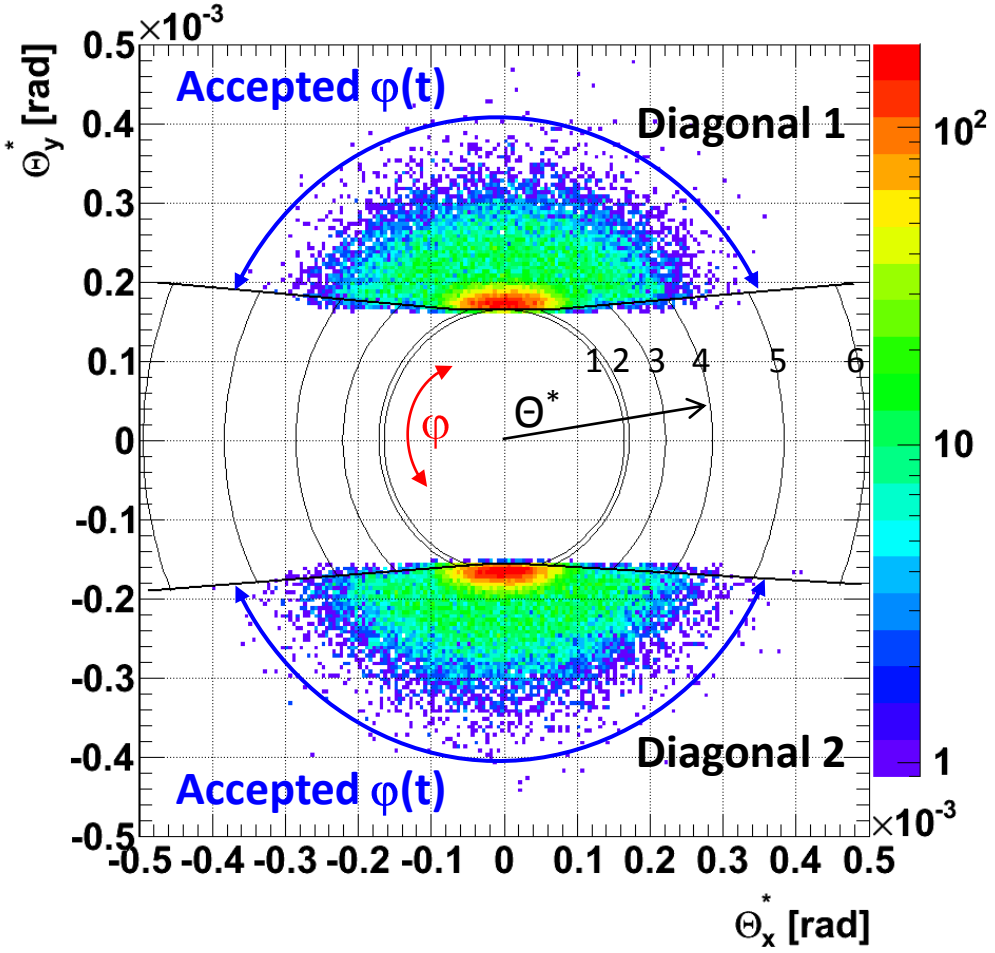
0.33 GeV$^2$ : 11%

0.35 GeV$^2$ : 2%

0.4 GeV$^2$ : 0.8%

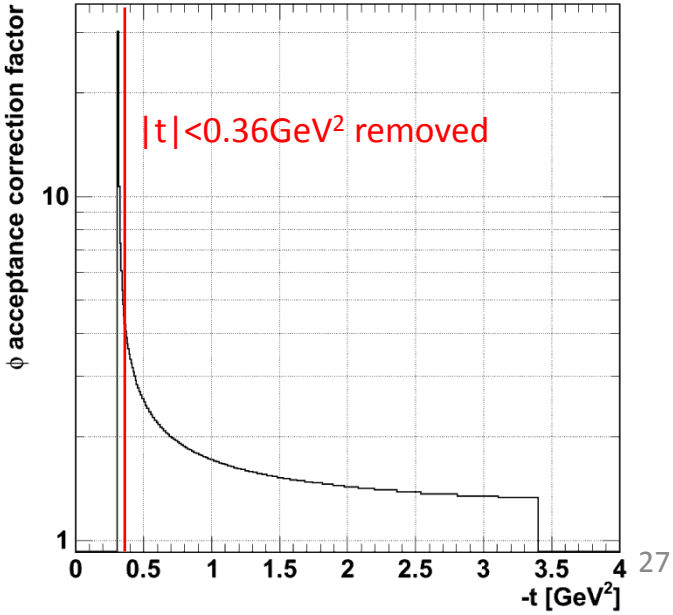
0.5 GeV$^2$ : 0.1%

# 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**