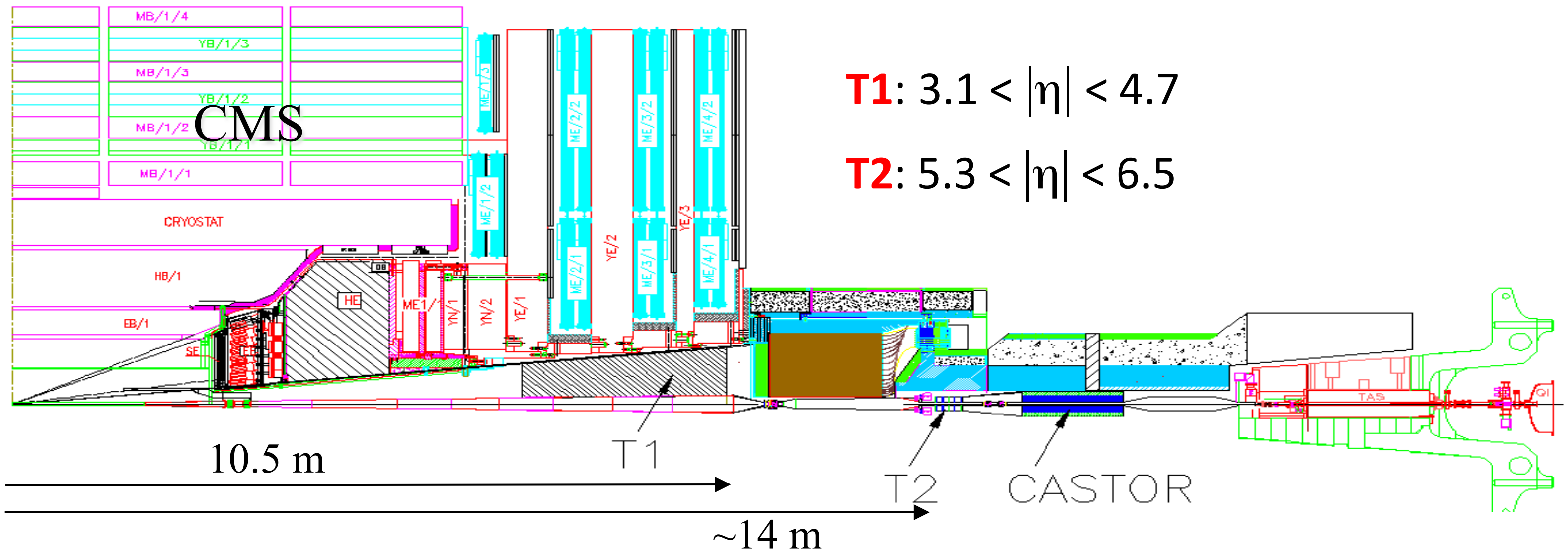
# Proton Proton cross section measurement and diffraction at LHC

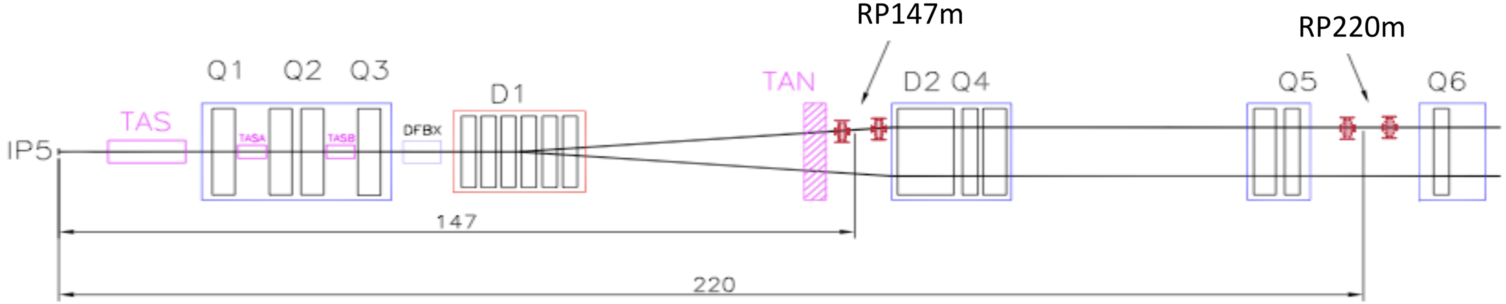
**N.Turini**

# The Totem Detectors

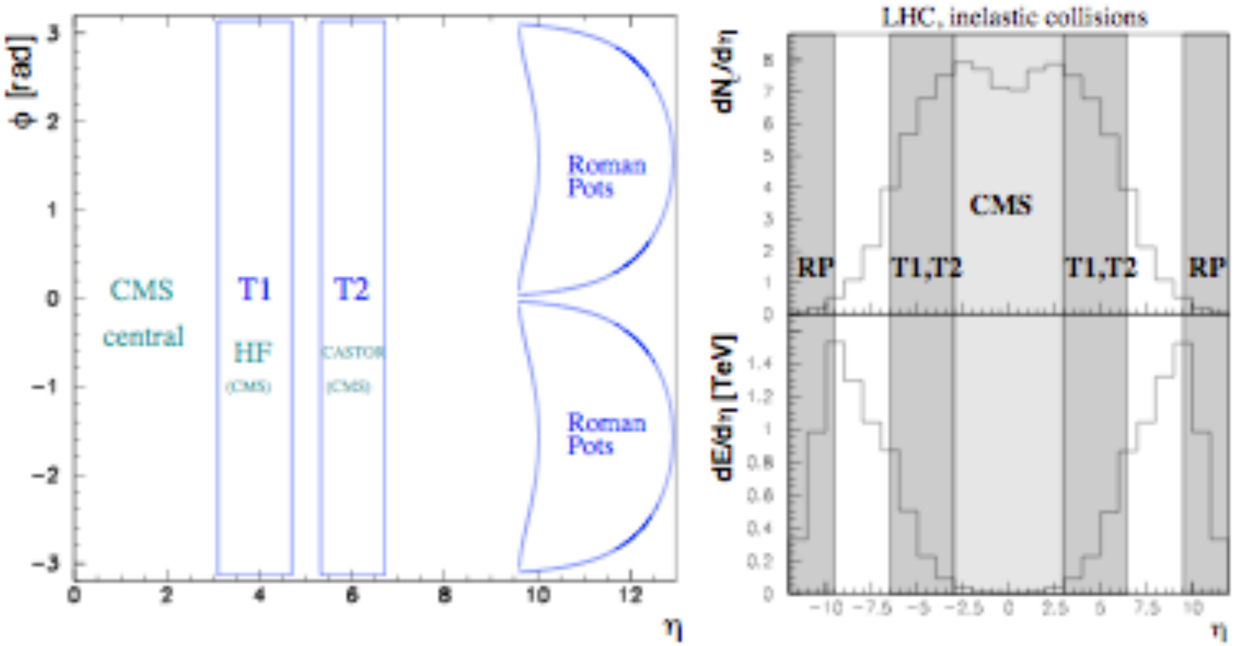
**T1**: $3.1 < |\eta| < 4.7$

**T2**: $5.3 < |\eta| < 6.5$

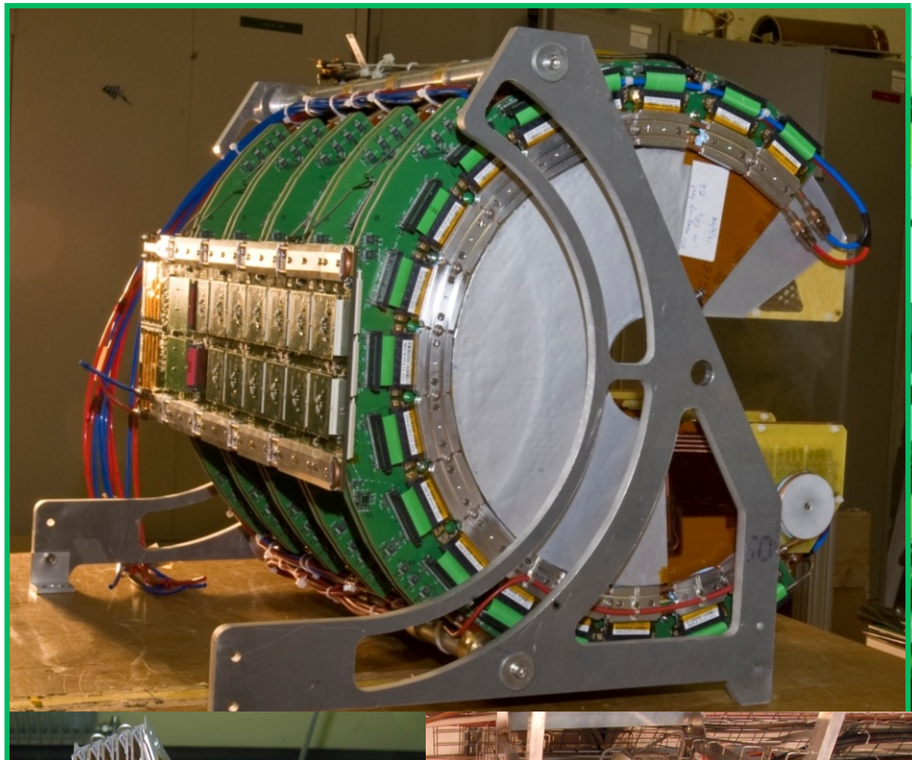


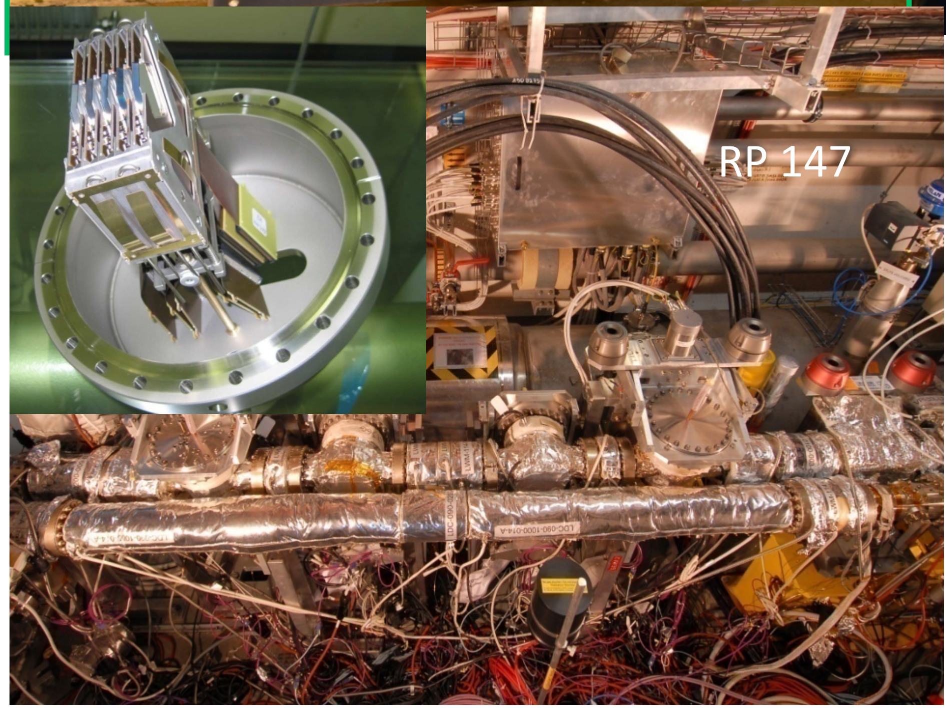



# Totem η coverage




Forward coverage with tracker detectors

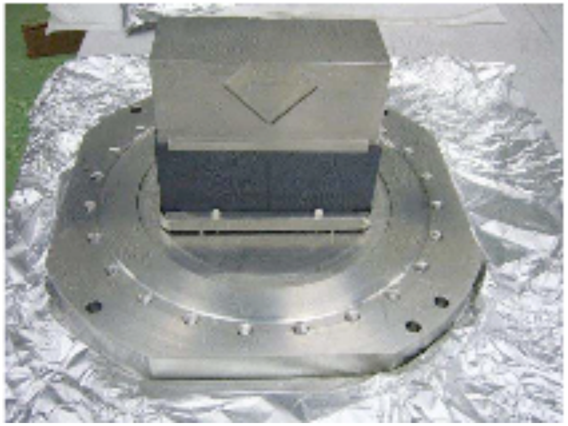


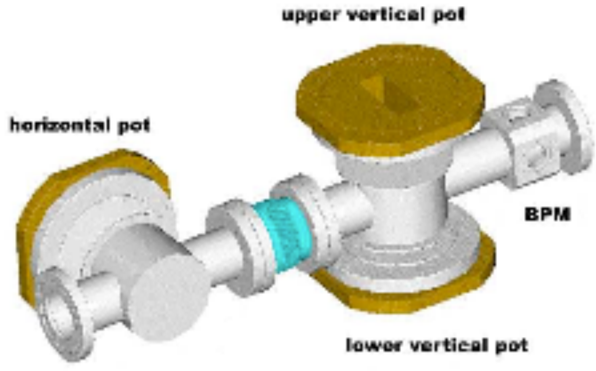


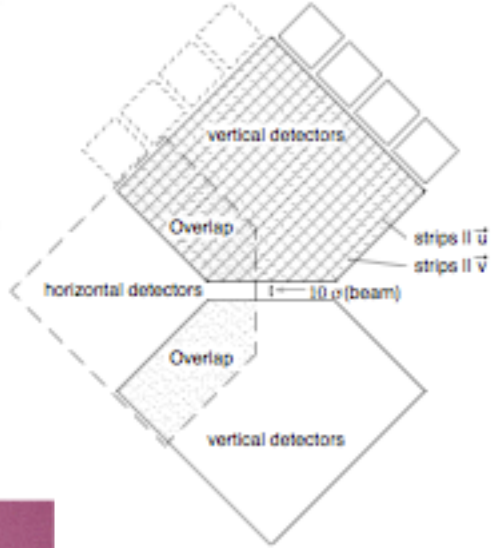

# Detectors

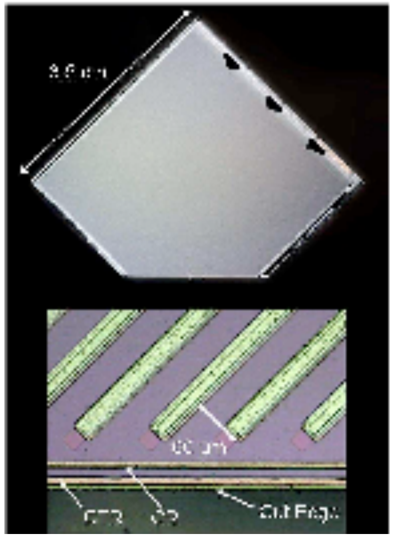
- **T1 and T2 detectors are installed and fully operational**
- **220 m Roman Pot Silicon detectors are fully operational**
- **147 m Roman Pot detectors are installed and tested**

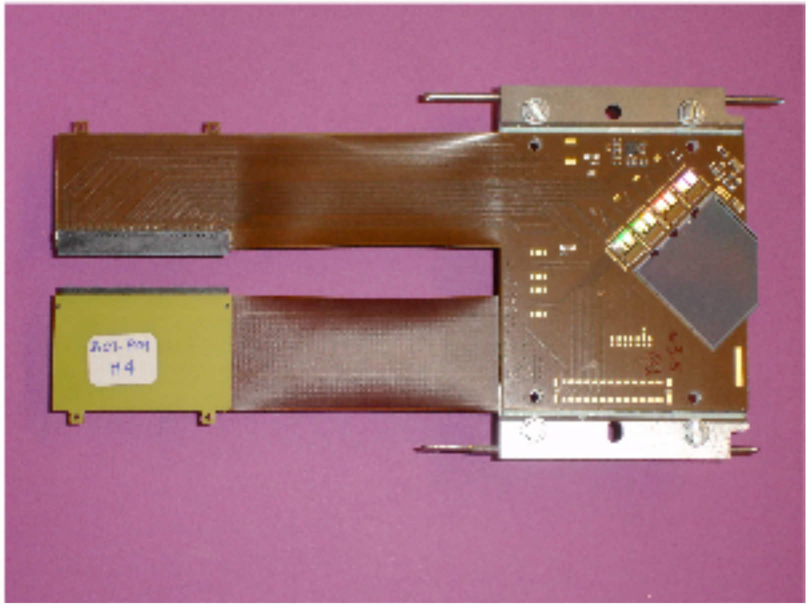
# The Roman Pots

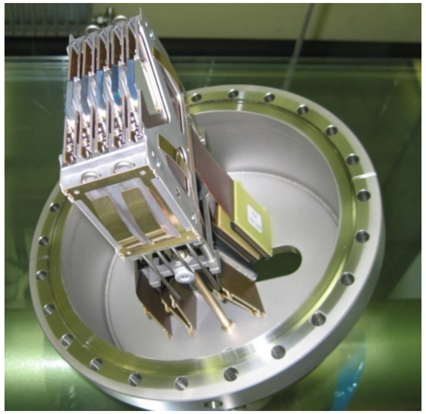




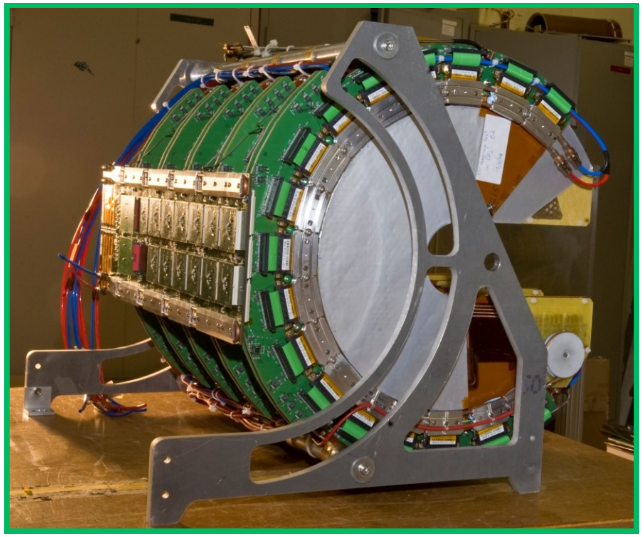





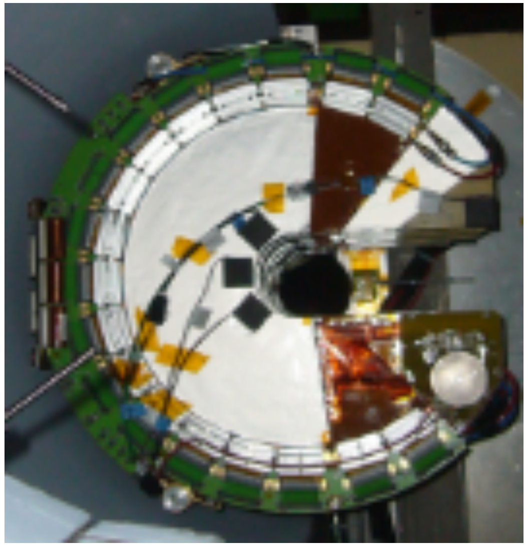


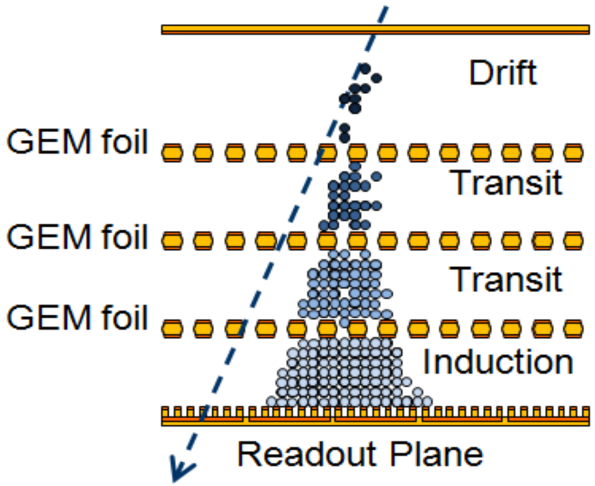
# T2 detector



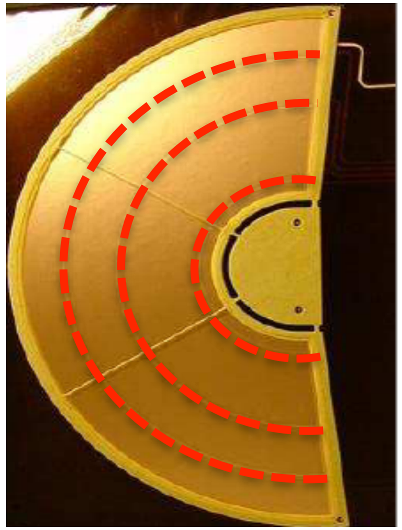
GEM (Gas Electron Multiplier)

10 planes around the beam pipe
14 meters from IP



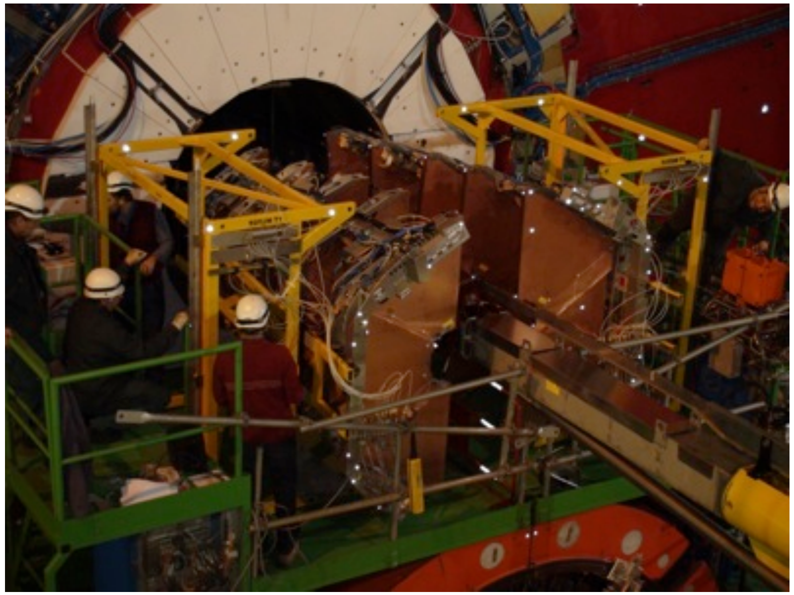



http://gdd.web.cern.ch/GDD
/



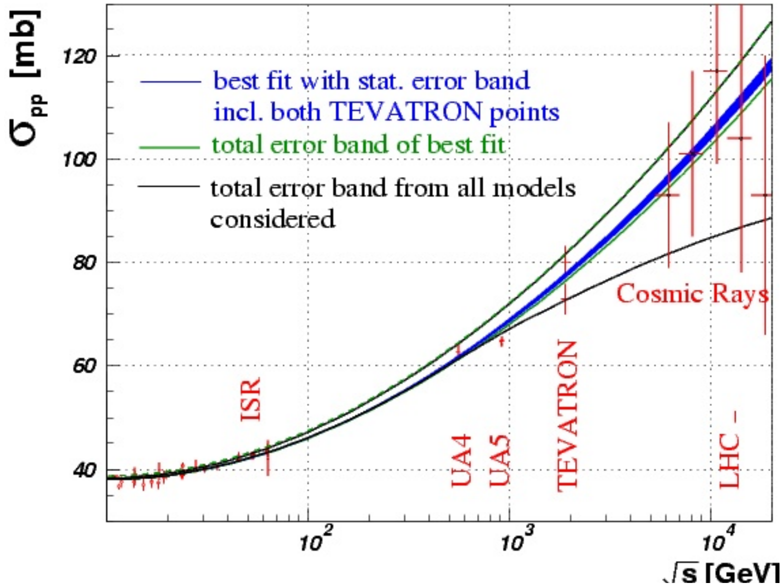
# T1 detector

CSC (Catod Strip Chambers)
5 planes each quarter
~ 7 meters from IP

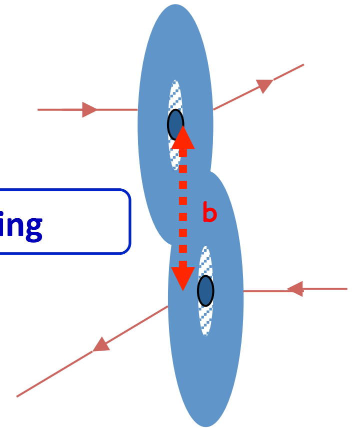


# TOTEM Physics Overview

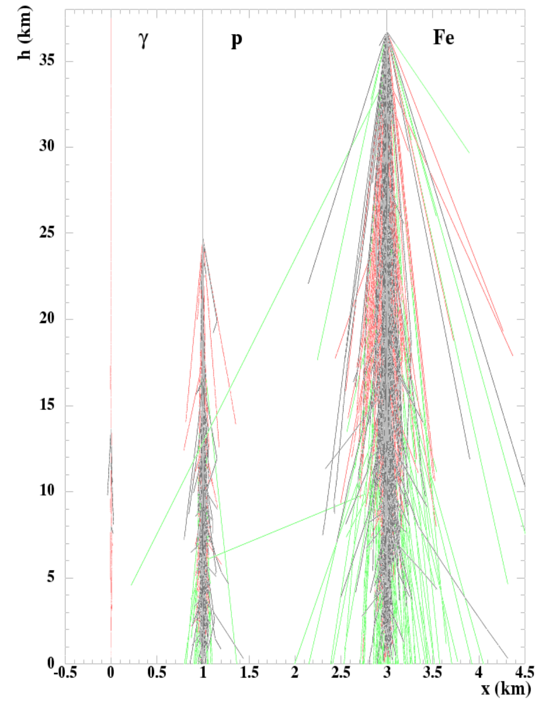
**Total cross-section**



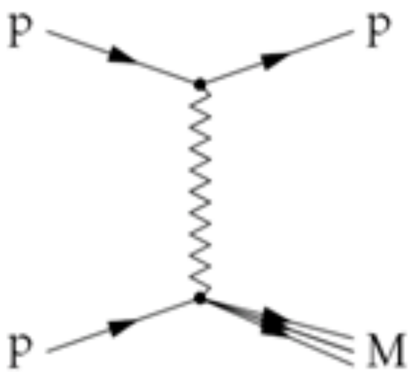

**Elastic Scattering**

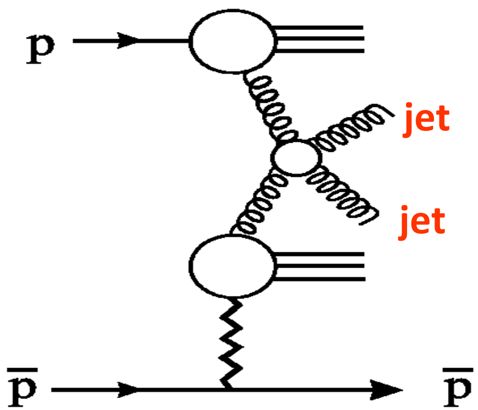



**Forward physics**



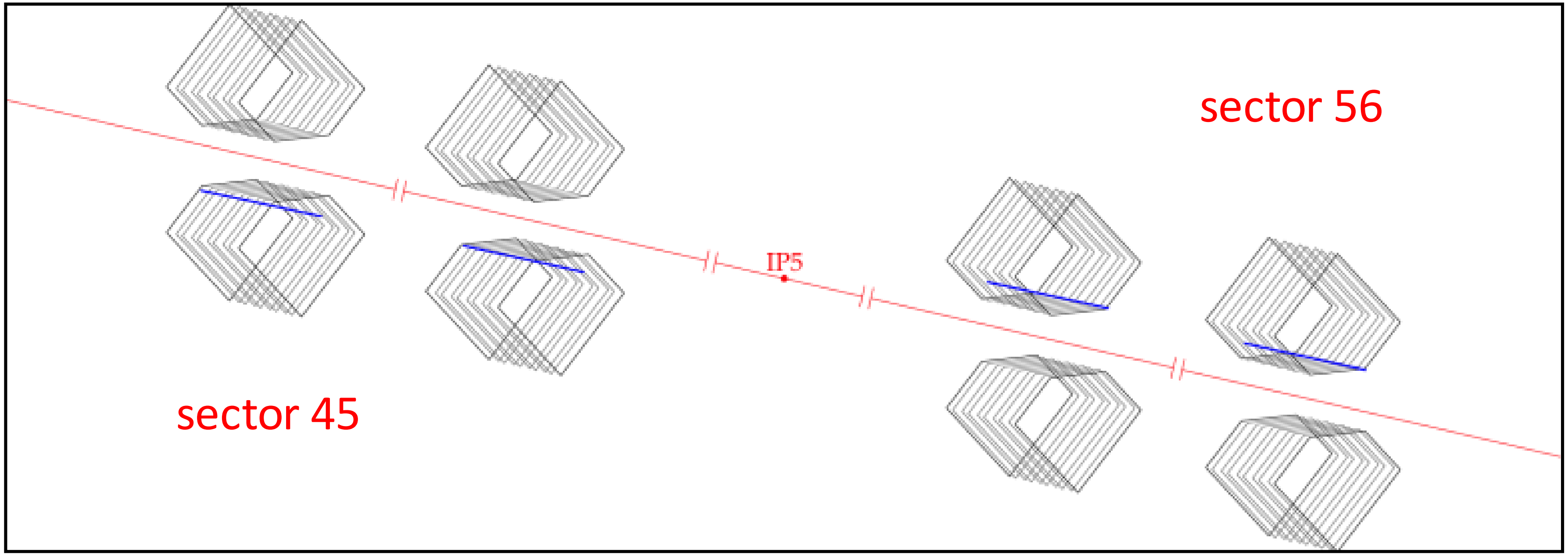

**Diffraction: soft (and hard with CMS)**



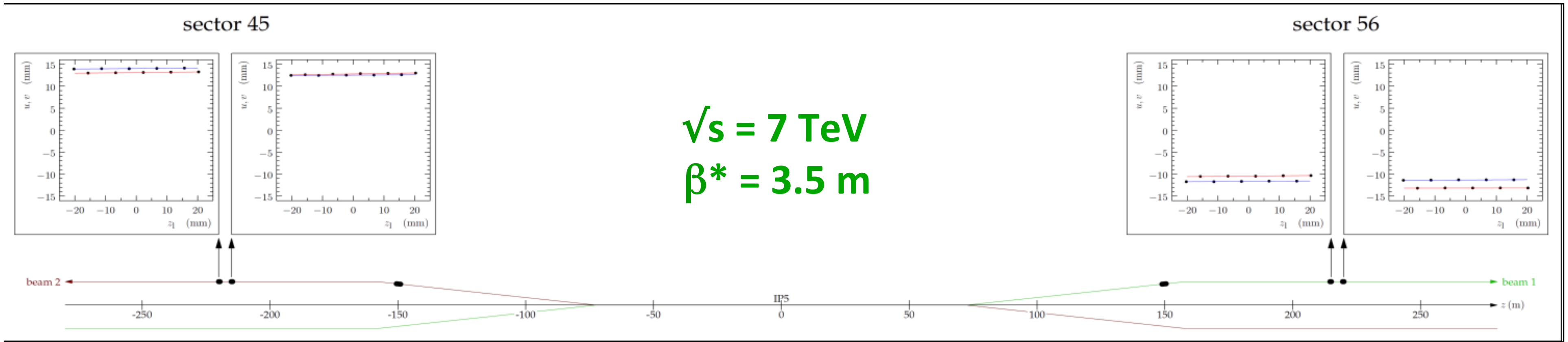



# 2010 Data from Runs with RPs at 25σ (1.5nb$^{-1}$)

## First p-p Elastic Scattering Event Candidates [LPCC July 2010]




Event scanning and constraining analysis procedure



# pp Interactions

**Non-diffractive**

Colour exchange

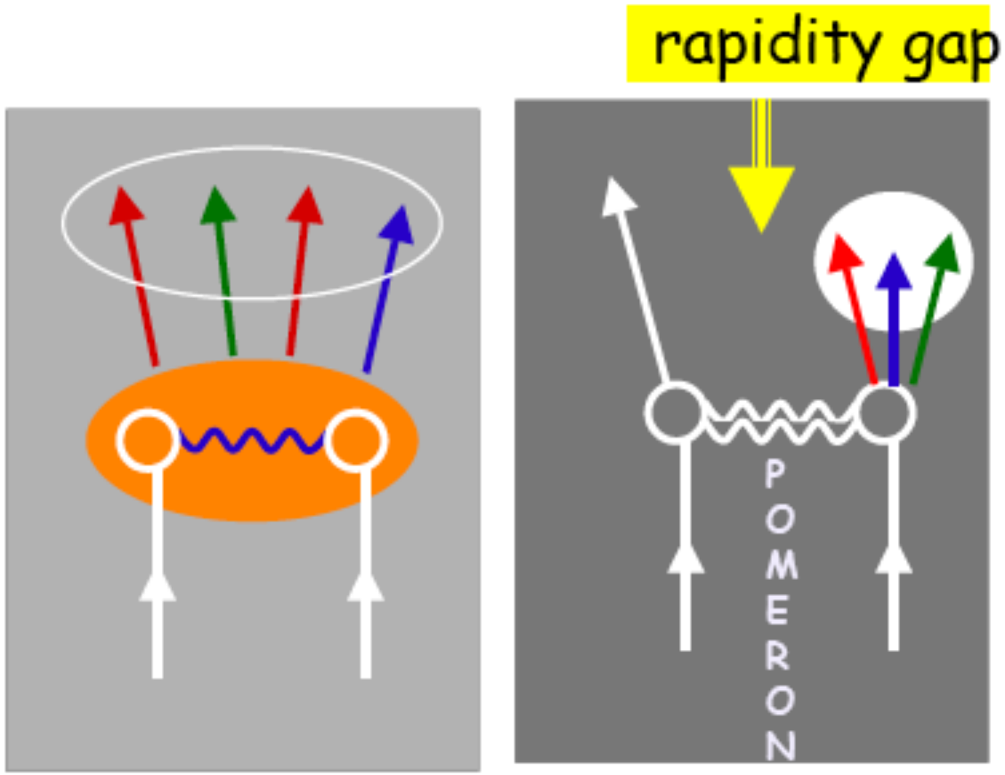
**dN / d Δη = exp (-Δη)**

**Diffractive**

Colourless exchange with vacuum quantum numbers

**dN / d Δη = const**

Incident hadrons acquire colour and break apart

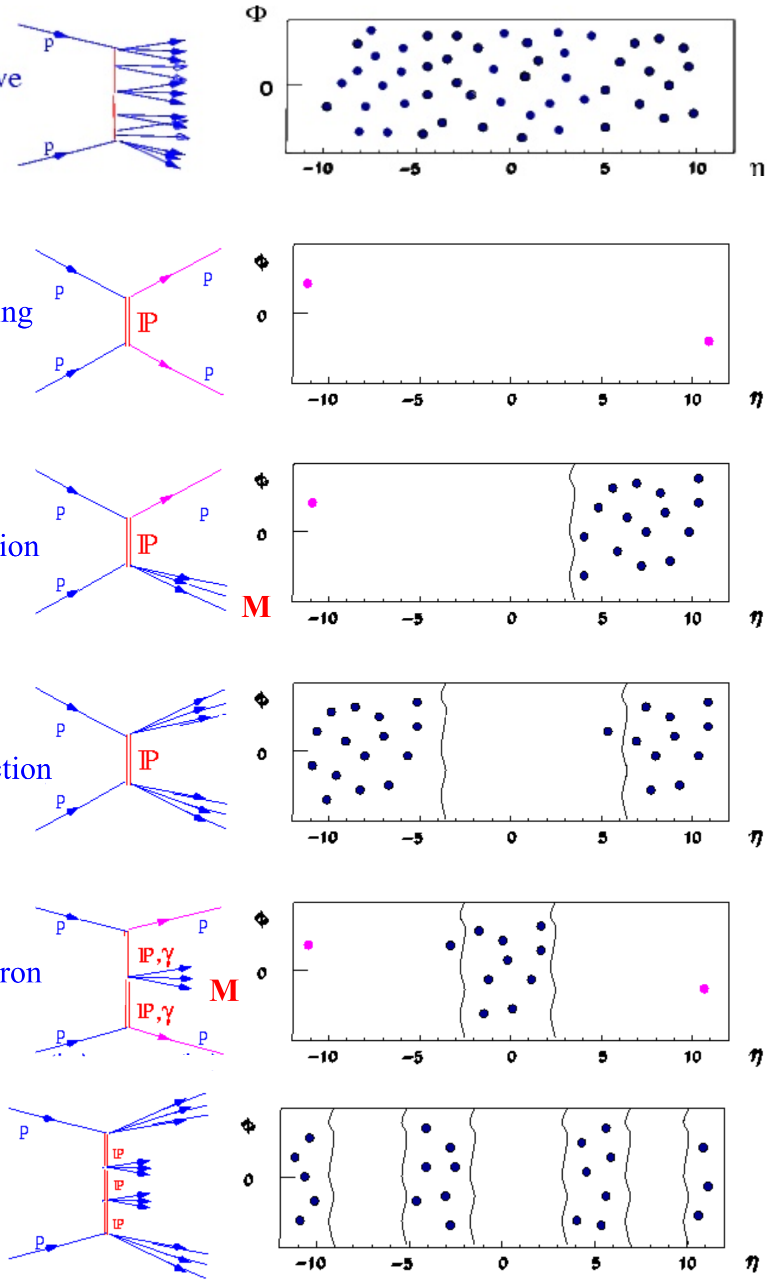



Incident hadrons retain their quantum numbers remaining colourless

GOAL: understand the QCD nature of the diffractive exchange

# Inelastic and Diffractive Processes ($\eta = -\ln tg\ \theta/2$)

All the drawings show soft interactions.
In case of hard interactions there should be jets, which fall in the same rapidity intervals.




| | |
|---|---|
| non–diffractive inelastic (ND) | ~60 mb |
| Elastic Scattering | ~25 mb |
| Single Diffraction | ~10 mb |
| Double Diffraction | ~5 mb |
| Double Pomeron Exchange | ~1 mb |
| Multi Pomeron Exchange | << 1 mb |

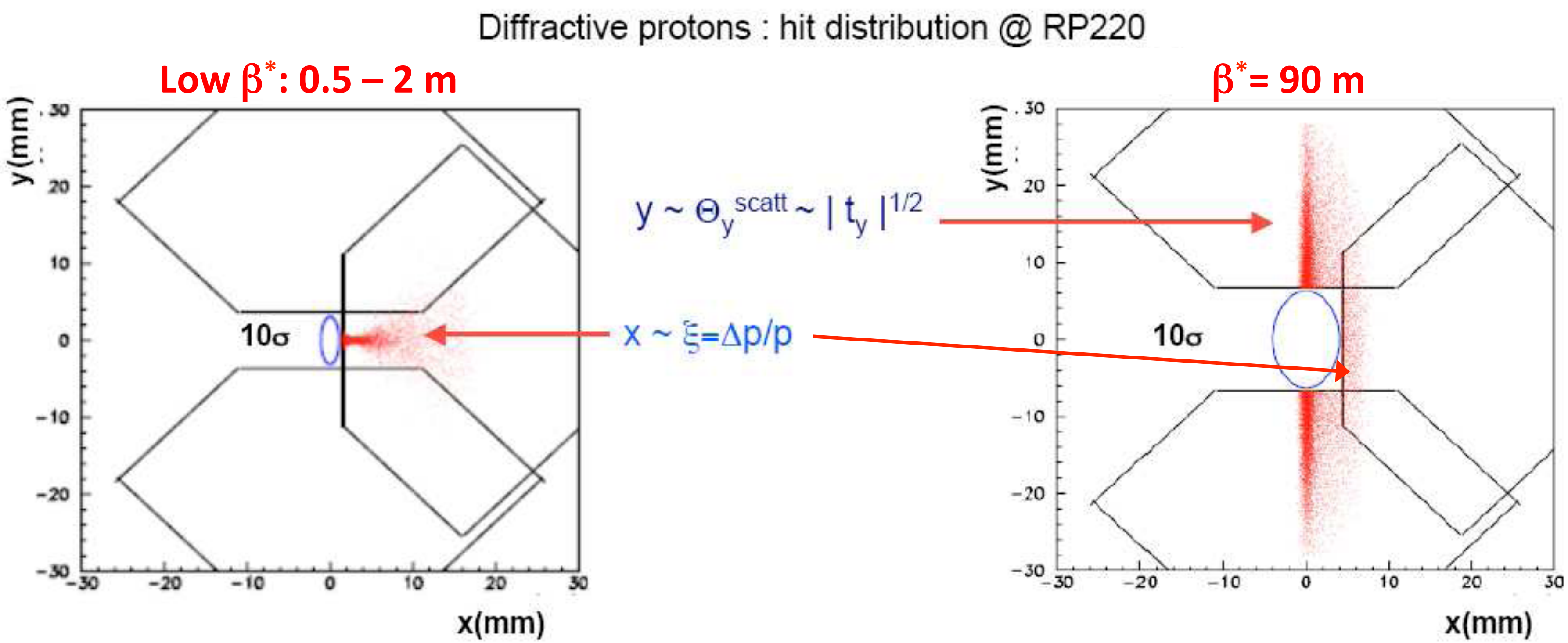
Measure $\sigma$ (M,ξ,t)

Diffractive scattering is a unique laboratory of confinement & QCD:
A hard scale + hadrons which remain intact in the scattering process.

# Diffractive forward protons @ RPs

$$
\begin{aligned}
y(s) &= v_y(s)\cdot y^* + L_y(s)\cdot \Theta_y^* \\
x(s) &= v_x(s)\cdot x^* + L_x(s)\cdot \Theta_x^* + \xi\cdot \boxed{D(s)}
\end{aligned}
$$

Dispersion shifts diffractive protons in the horizontal direction

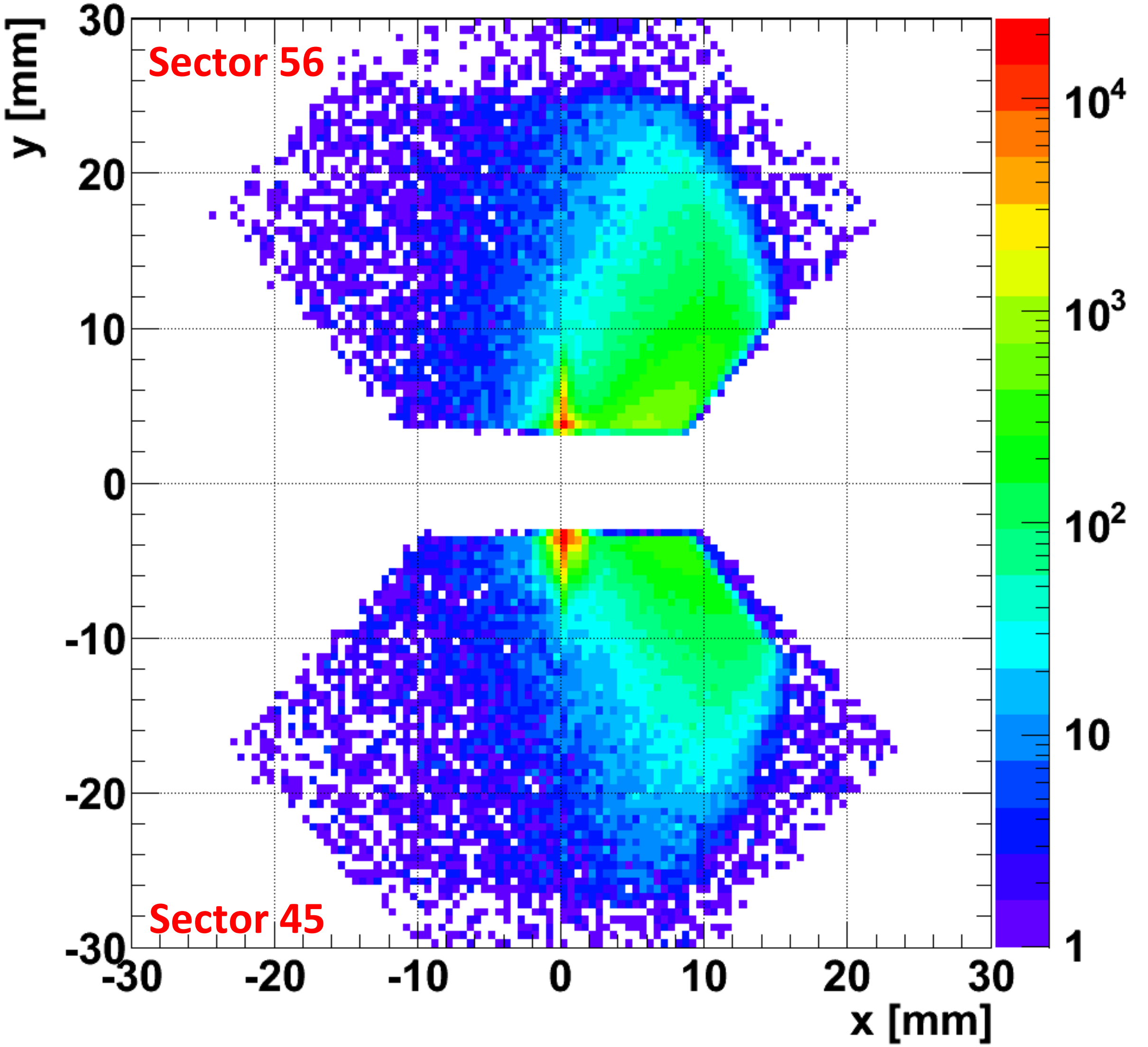


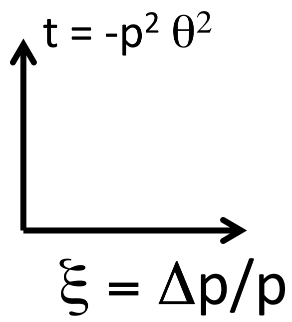

- For low-$\beta^*$ optics $L_x$, $L_y$ are low
- $v_x$, $v_y$ are not critical because of small IP beam size

- $L_x$=0, $L_y$ is large
- beam $\sigma$ = 212 µm → $v_x$, $v_y$ important (deterioration of rec. resolution)

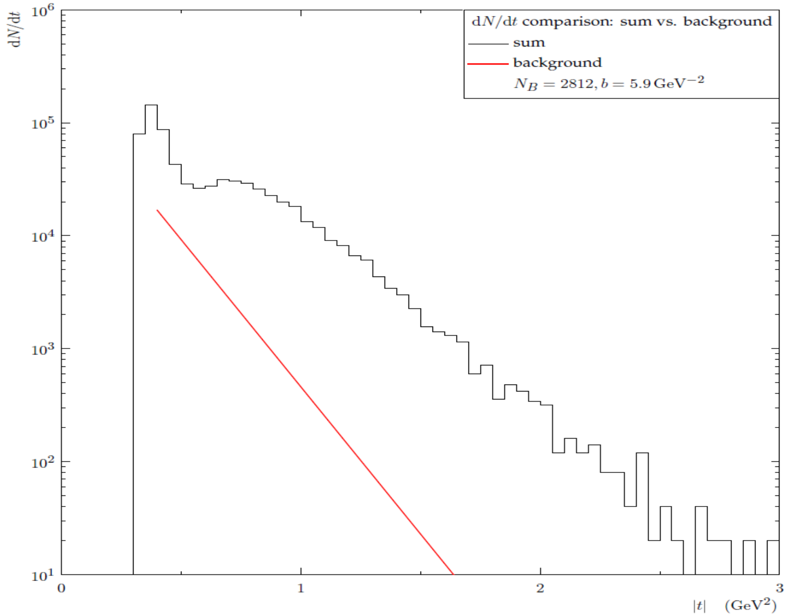
# P-P Elastic Cross Section measurement

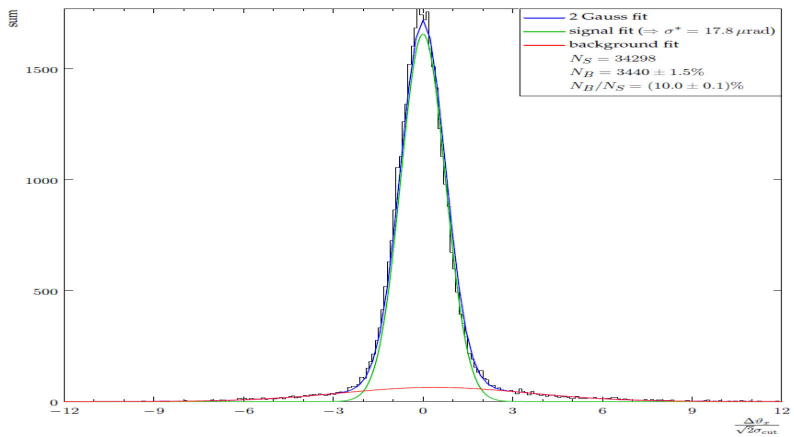
$\sqrt{s}$ = 7 TeV
$\beta^*$ = 3.5 m

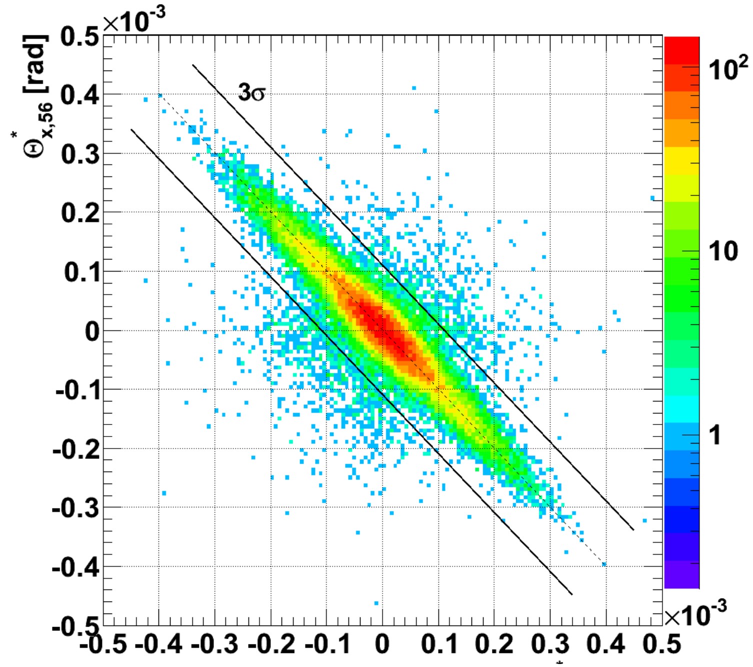


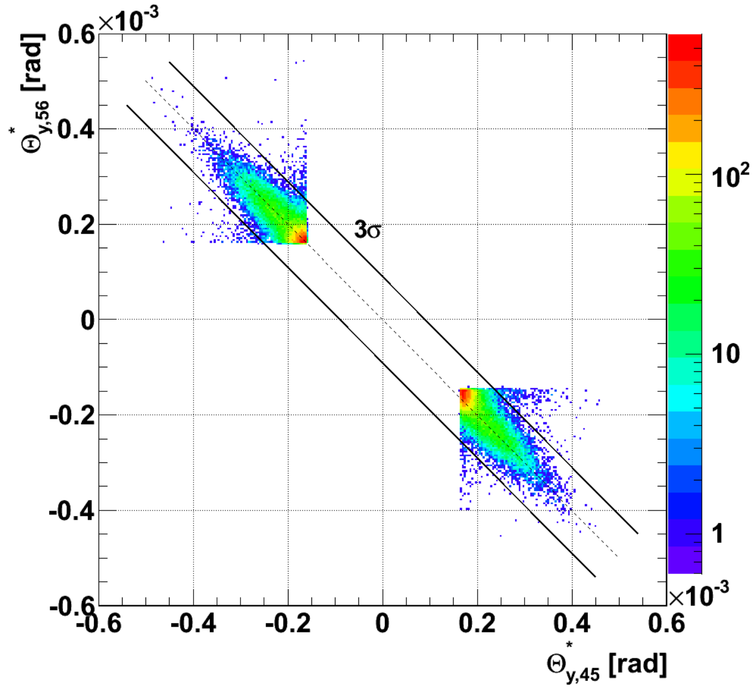



# Kinematics correlations and background subtraction

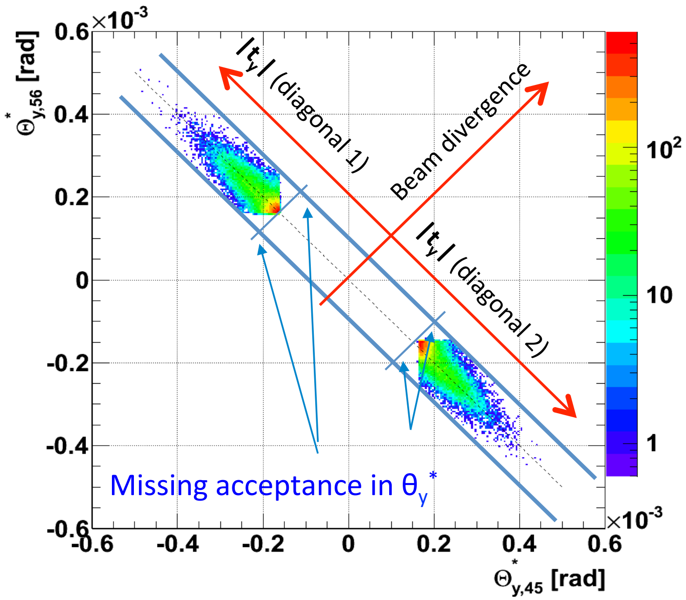


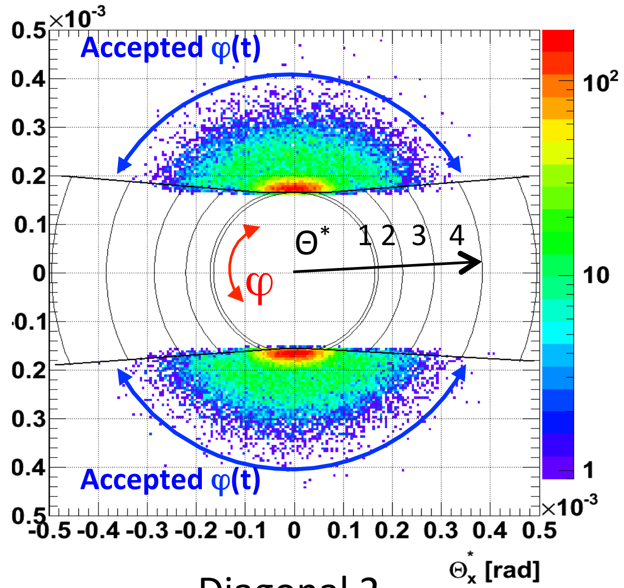



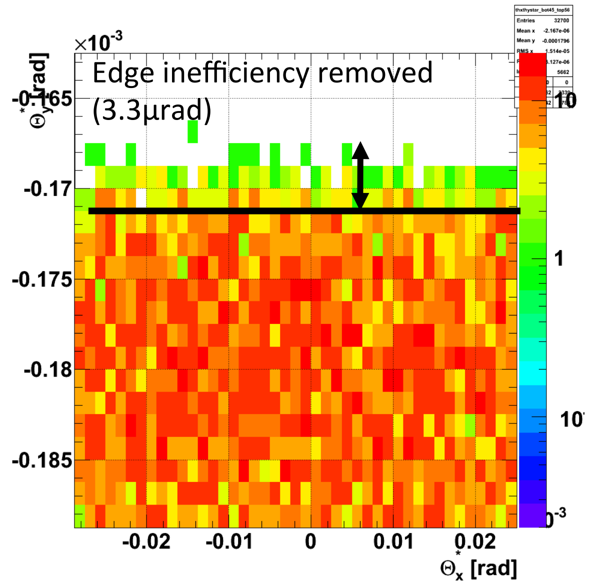



# Acceptance corrections



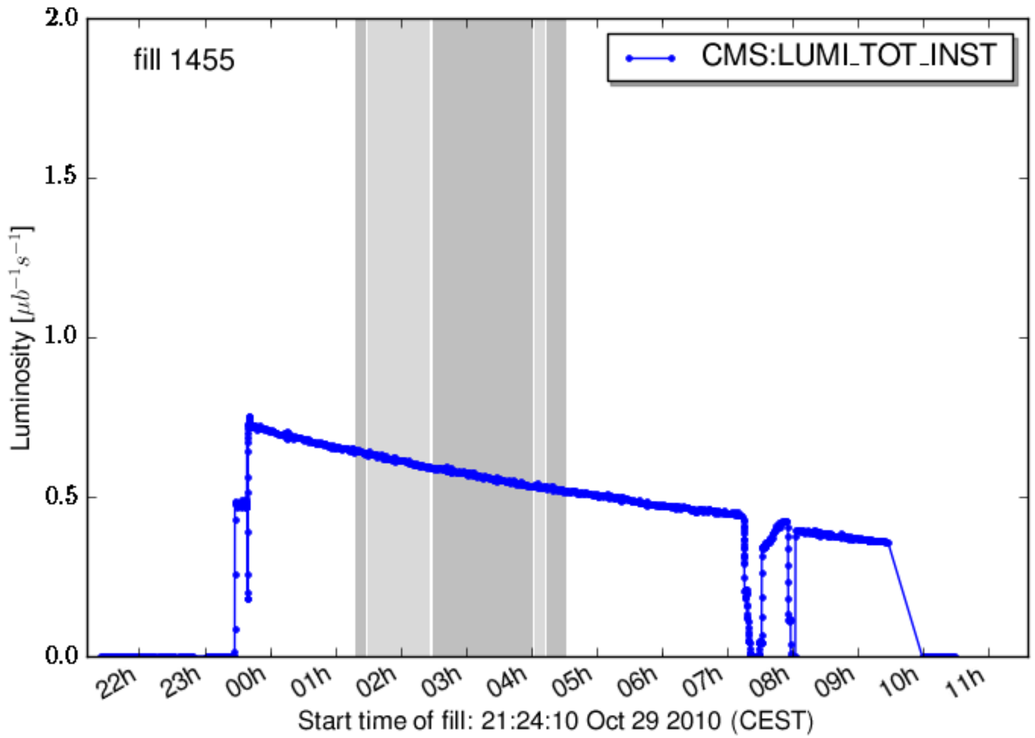




Correction of $\theta_y^*$ dist. for missing 'corners' of acceptance

Correction for missing φ accept.:
Correction = 2π / accepted φ(t)
Near edge region to be removed

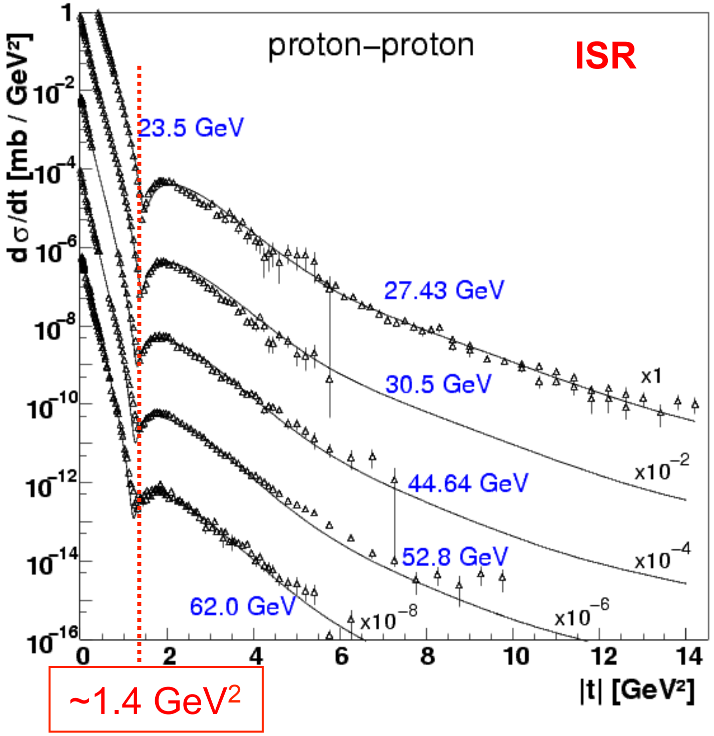
# Luminosity

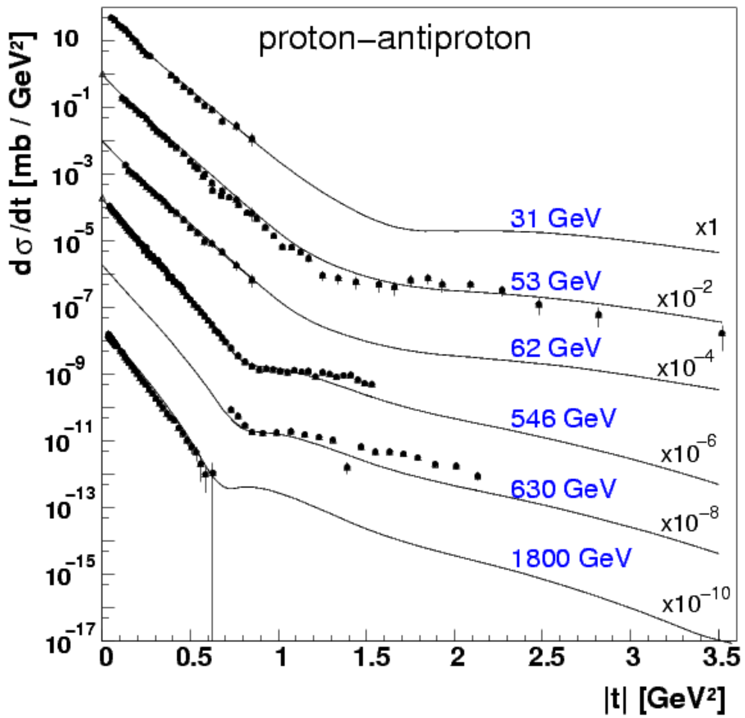
The data where taken in a special run oct 30 2010.
The 220m pots where inserted at 7σ from the beam.
β*=3.5m



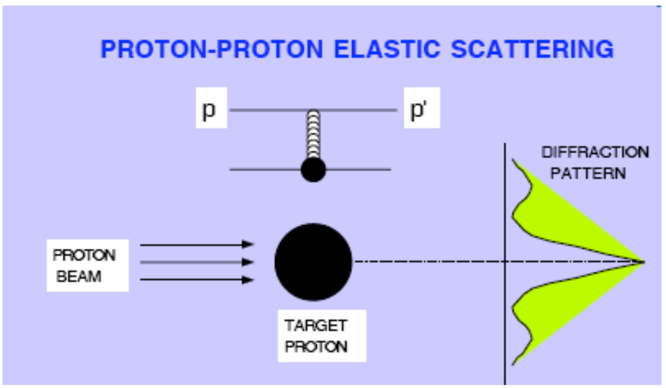

| Time | Events | Eff. DAQ | Eff. trigger | Luminosity |
|---|---|---|---|---|
| Oct 30 2010 | $5.48*10^6$ | 0.99 | 0.995 | 6.187 $nb^{-1}$ |

# Elastic scattering – from ISR to Tevatron



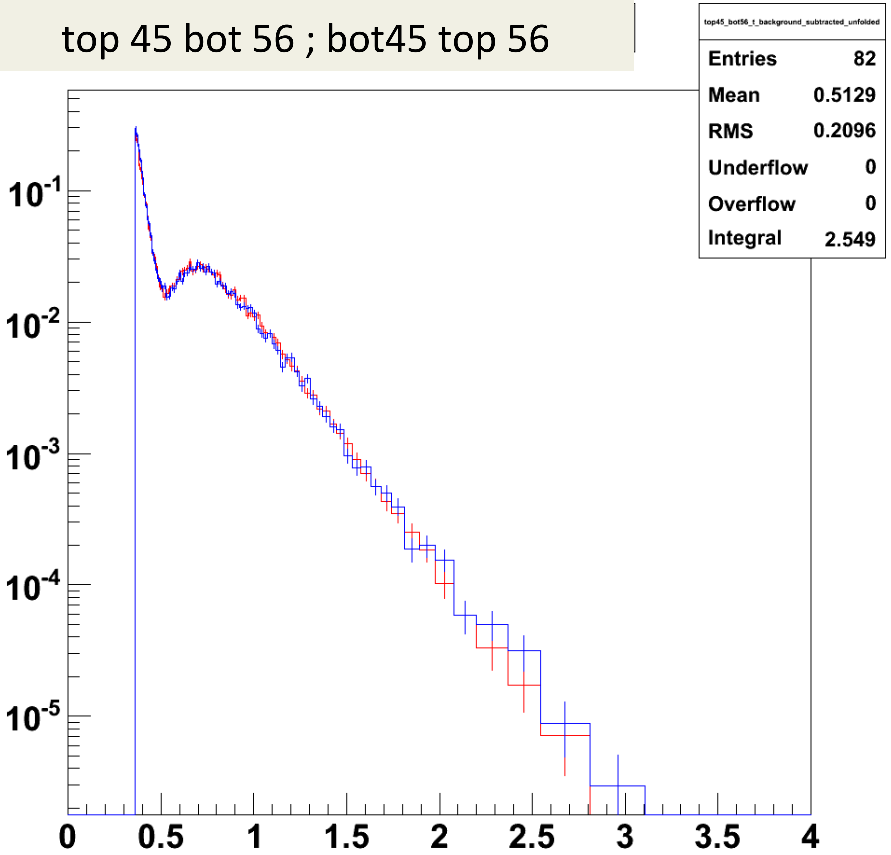

Diffractive minimum: analogous to Fraunhofer diffraction: $|t| \sim p^2\, \theta^2$



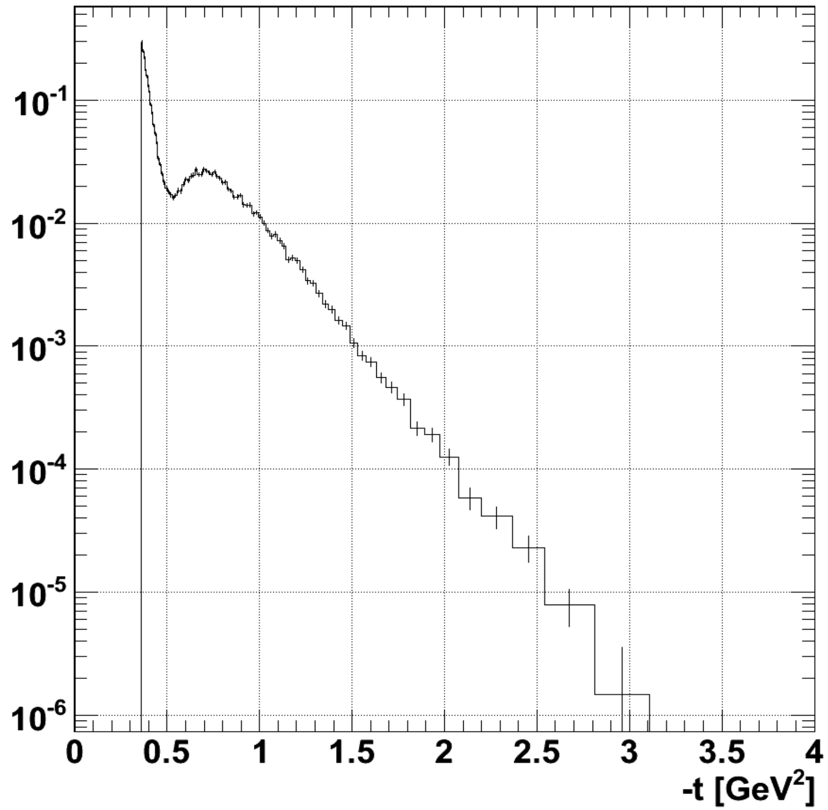

- exponential slope B at low |t| increases
- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from $\sigma_{tot}$)
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, $\bar{p}p$
  → different mix of processes

# Proton Proton Elastic Cross Section

top 45 bot 56 ; bot45 top 56

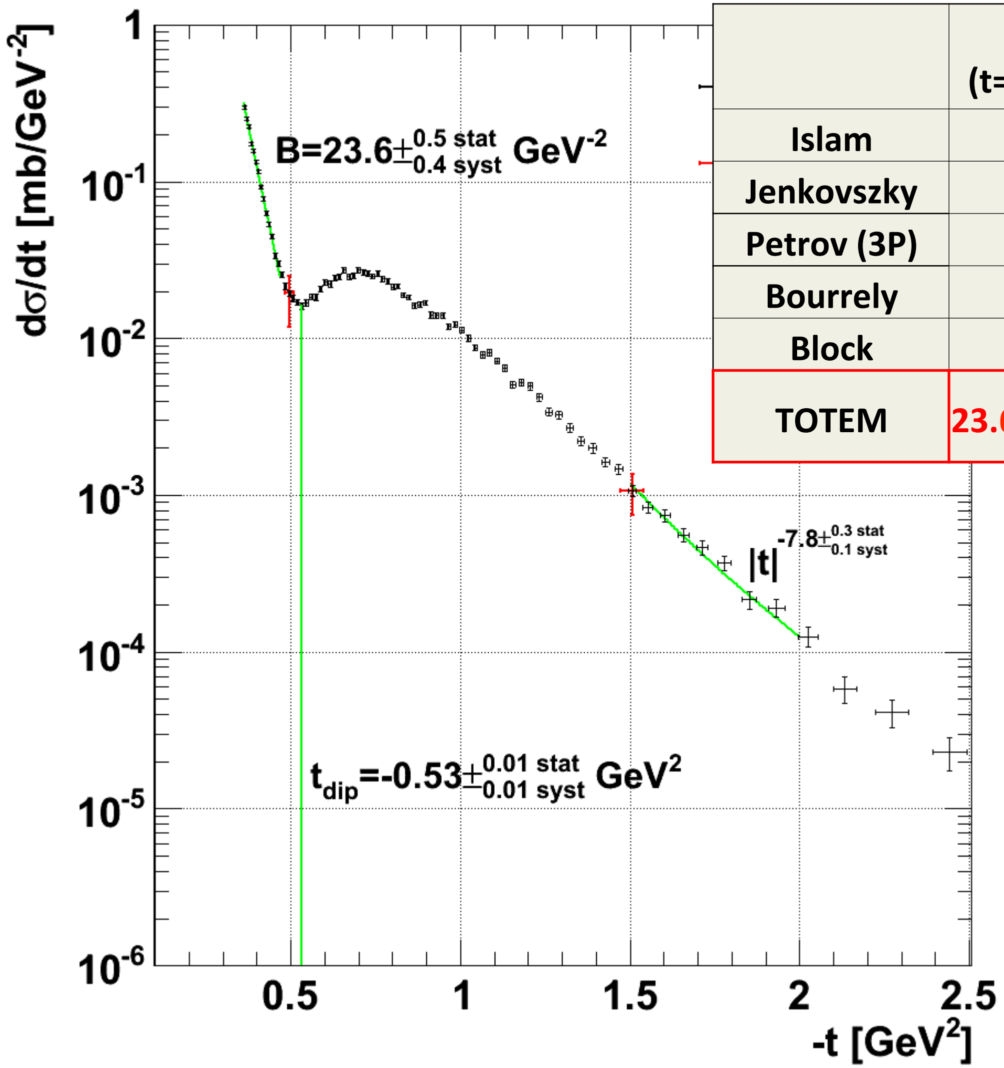



2 diagonals: 2 different experiments, but not 2 independent experiments



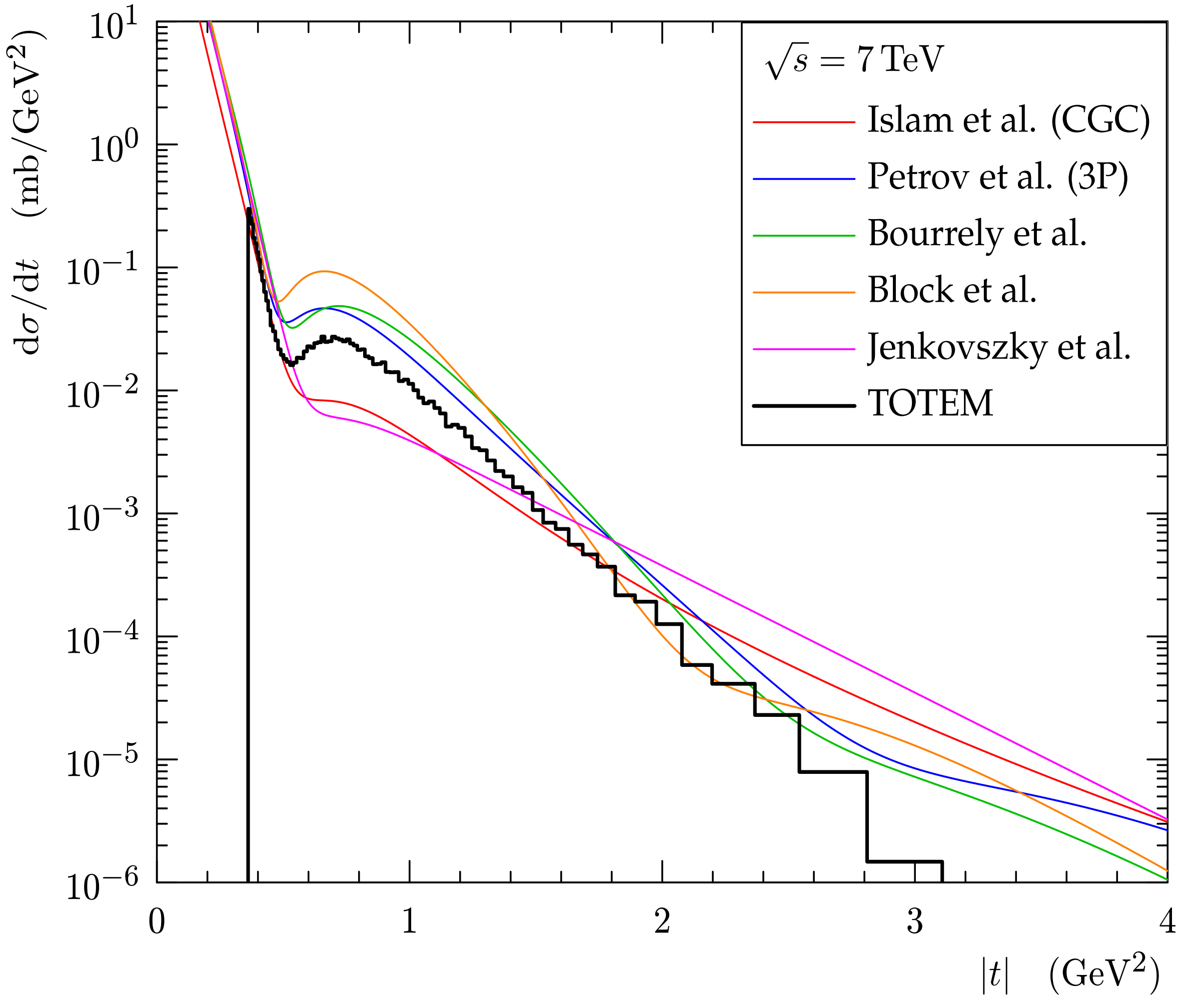

Global elastic differential cross section

# P-P Cross Section and Models Comparison

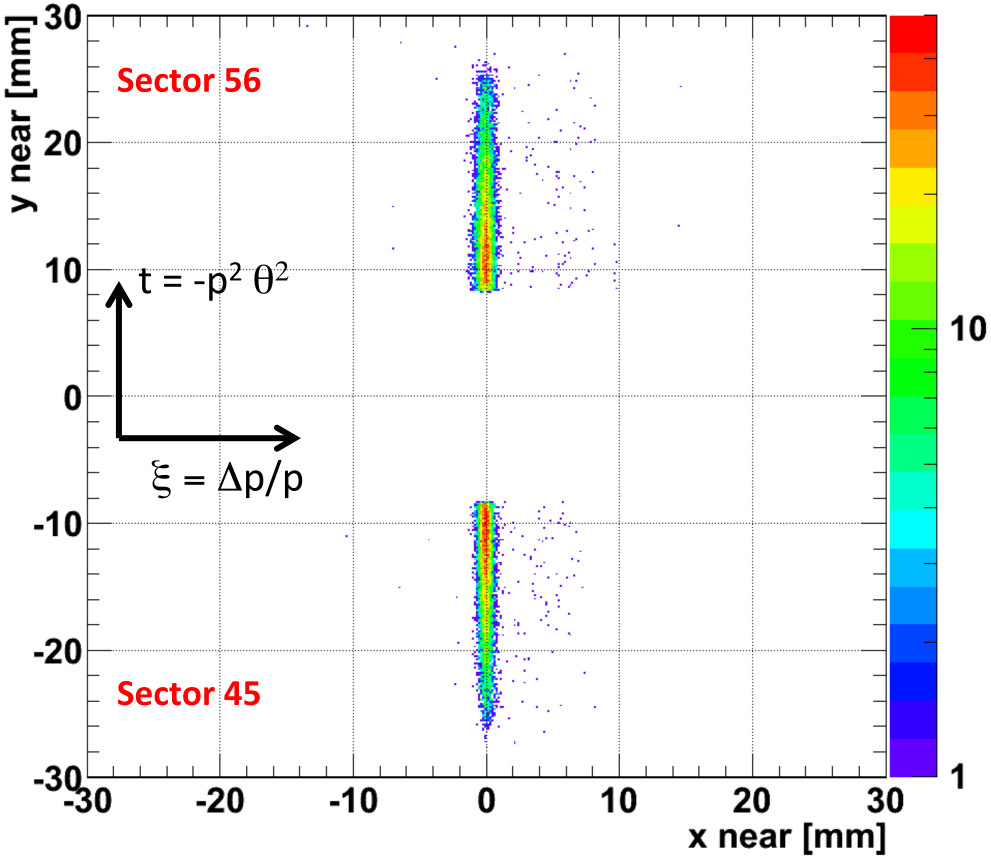



| | B (t=-0.4 GeV²) | $t_{DIP}$ | $t^{-x}$ [1.5–2 GeV²] |
|---|---|---|---|
| Islam | 19.9 | 0.65 | 5.0 |
| Jenkovszky | 20.1 | 0.72 | 4.2 |
| Petrov (3P) | 22.7 | 0.52 | 7.0 |
| Bourrely | 21.7 | 0.54 | 8.4 |
| Block | 24.4 | 0.48 | 10.4 |
| TOTEM | 23.6 ± 0.5 ± 0.4 | 0.53 ± 0.01 ± 0.01 | 7.8 ± 0.3 ± 0.1 |

# P-P Cross Section and Models Comparison



# Low t elastic cross section measurement




Protons x-y Raw distribution

$\beta^* = 90m$

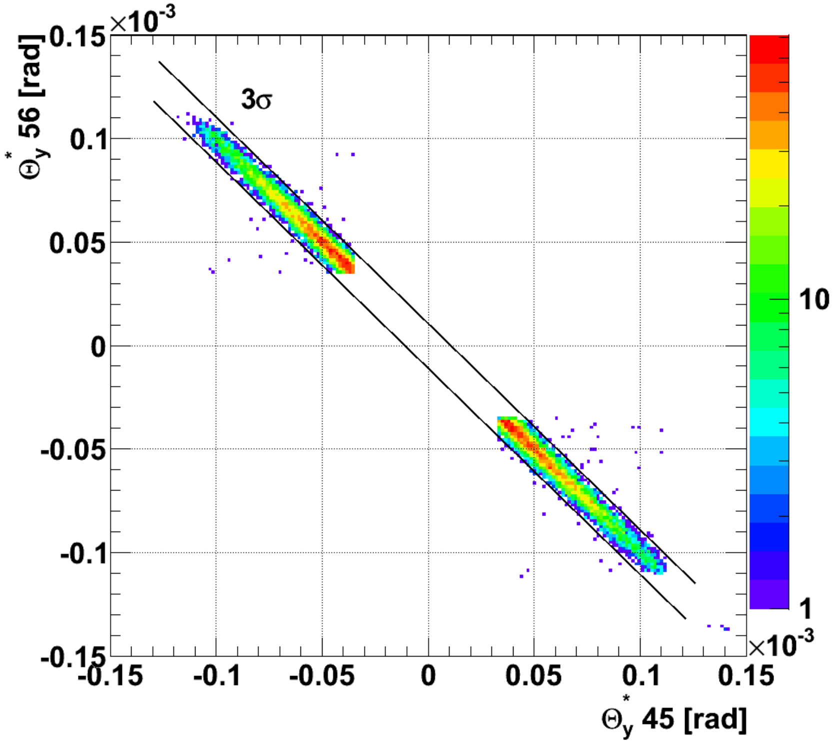
$L_y \sim 260$ m

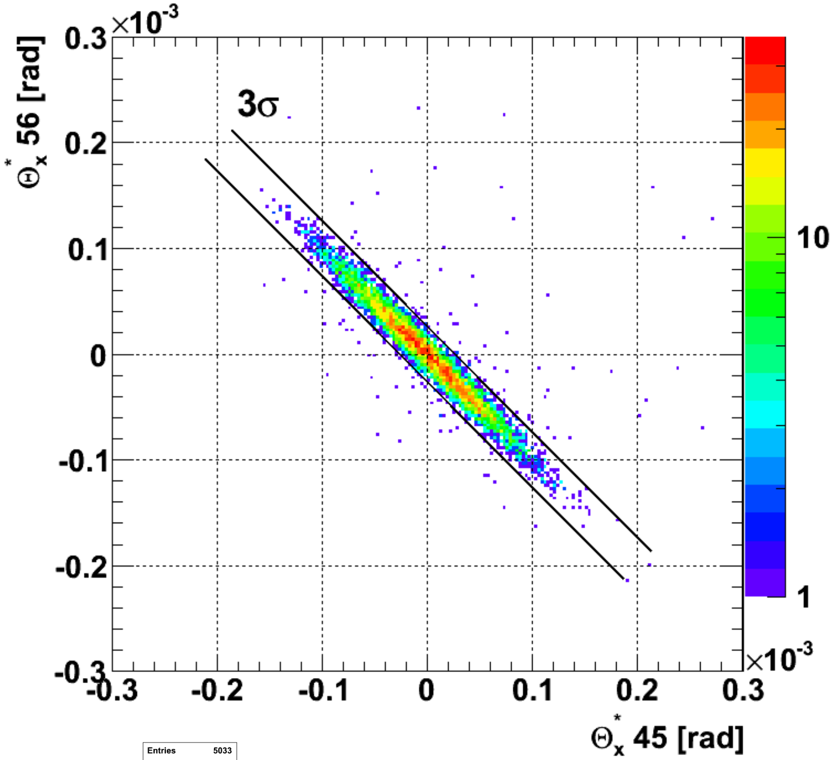
$L_x \sim$ 0-3 m

**Integrated luminosity : 1.65 $\mu barn^{-1}$**

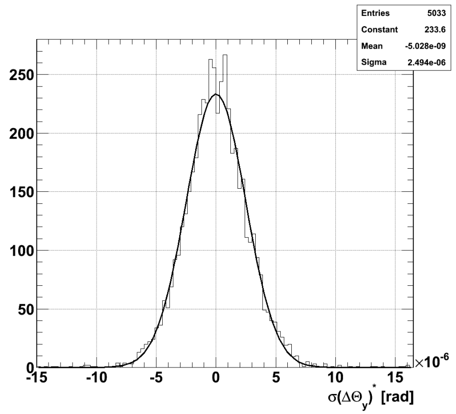
**Inel. pile-up ~ 0.005 ev/bx**

# $\Theta_x$ and $\Theta_y$ correlations of both arms




$\theta^*_y$ resolution (very large Ly) in agreement with beam divergence




$\theta^*_x$ 'resolution' includes also the detector and the vertex spread in plot above, but vertex effect vanishes when computing $\theta$ with elastic constraint

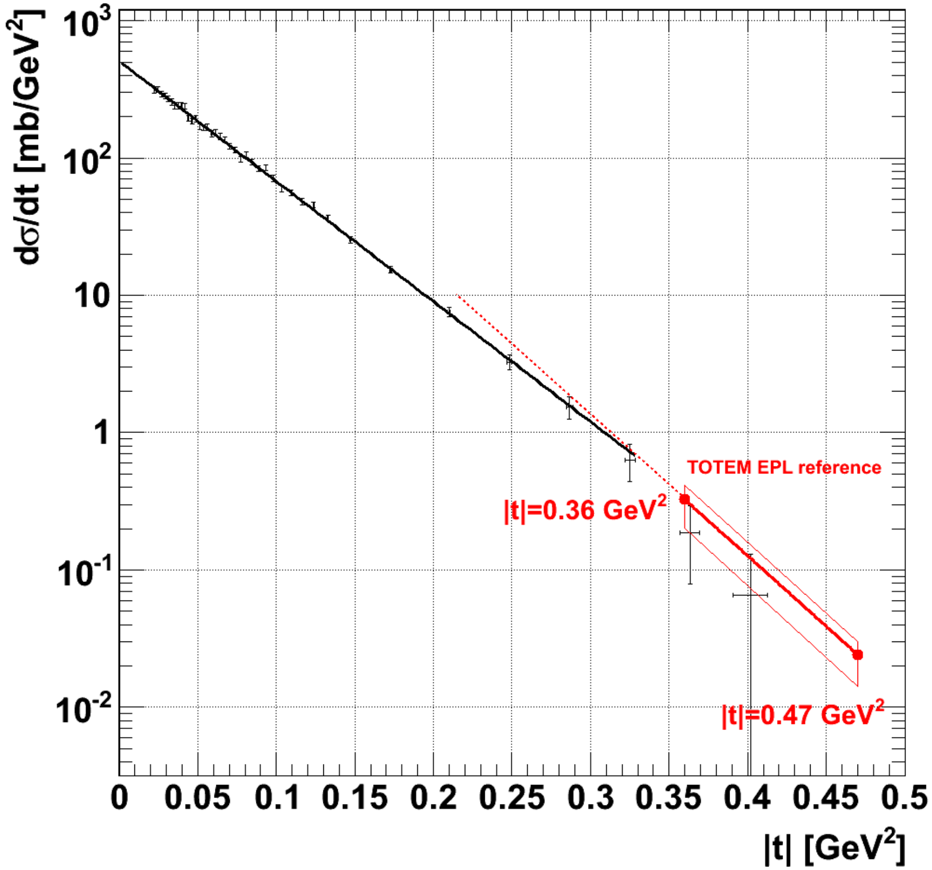
# Elastic differential cross section

**Exponential slope:**

$$B\Big|_{t=0} = 20.1\,\mathrm{GeV}^{-2}$$

**Extrapolation to t = 0:**

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = 5.037\times10^{2}\,\mathrm{mb}\,/\,\mathrm{GeV}^{2}$$




## Integral Elastic Cross-Section

$$\sigma_{EL} = 8.3\,\mathrm{mb}^{(\mathrm{extrapol.})} + 16.5\,\mathrm{mb}^{(\mathrm{measured})} = 24.8\,\mathrm{mb}$$

# Cross-Section Formulae

Optical Theorem:

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

Using luminosity from CMS:

$$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt}$$

ρ from COMPETE fit:

$$\rho = 0.14^{+0.01}_{-0.08}$$

$$\sigma_{TOT} = \sqrt{19.20\,\text{mb}\,\text{GeV}^2 \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}}$$

$$\sigma_{TOT} = \sigma_{EL} + \sigma_{INEL}$$

# TOTEM: pp Total Cross-Section

Elastic exponential slope: $B\big|_{t=0} = (20.1 \pm 0.2^{(stat)} \pm 0.3^{(syst)})\ \text{GeV}^{-2}$

Elastic diff. cross-section at optical point: $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = (503.7 \pm 1.5^{(stat)} \pm 26.7^{(syst)})\,\text{mb / GeV}^2$

Optical Theorem, $\rho = 0.14^{+0.01}_{-0.08}$

## Total Cross-Section

$$\sigma_T = \left(98.3 \pm 0.2^{(\text{stat})} \pm 2.7^{(\text{syst})} \quad \begin{bmatrix} +0.8 \\ -0.2 \end{bmatrix}^{(\text{syst from } \rho)}\right)\ \text{mb}$$

# TOTEM: pp Inelastic Cross-Section

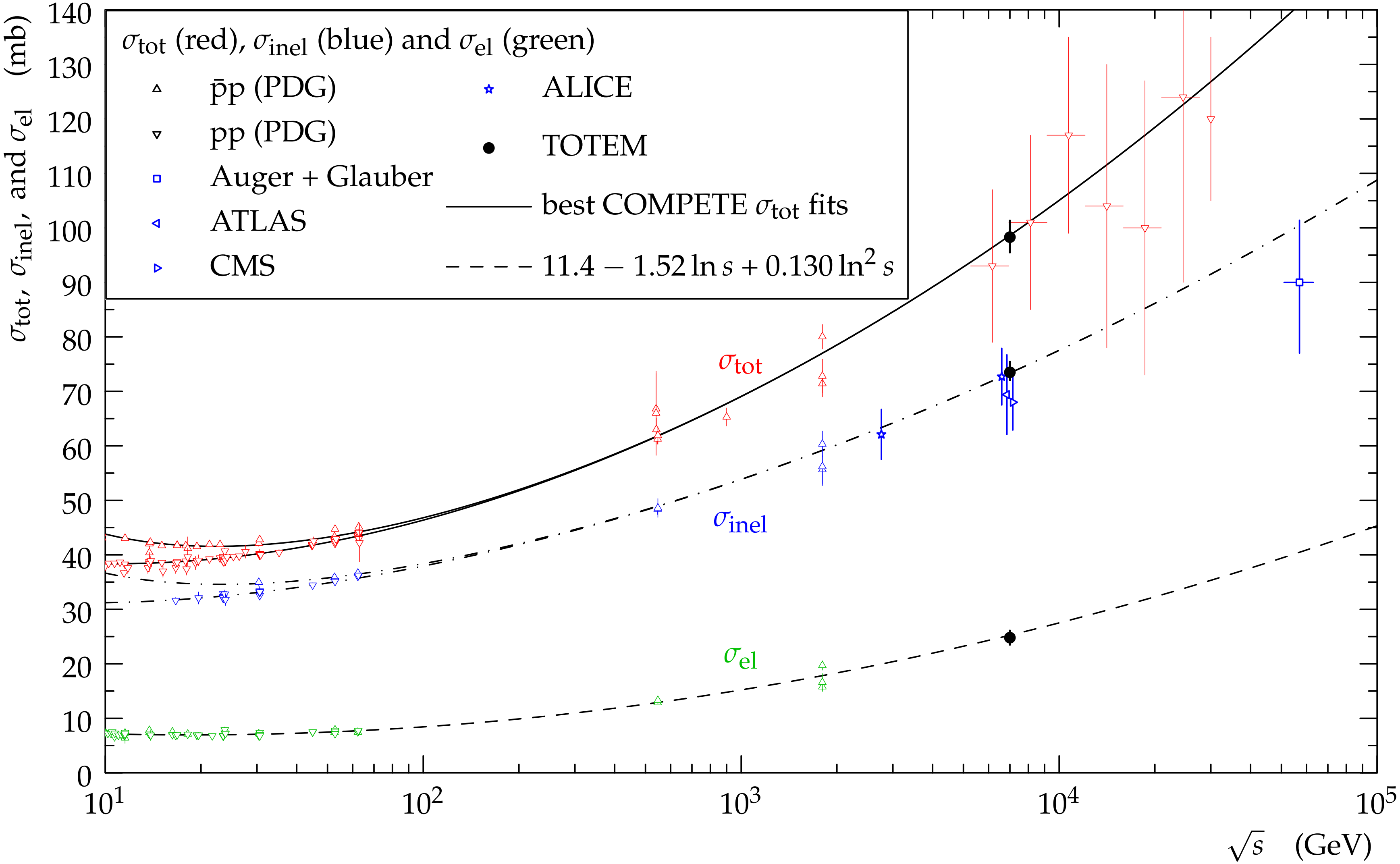
$\sigma_{el} = \left(24.8 \pm 0.2^{(stat)} \pm 1.2^{(syst)}\right)$ mb $\quad \sigma_T = \left(98.3 \pm 0.2^{(stat)} \pm 2.7^{(syst)} \begin{bmatrix} +0.8 \\ -0.2 \end{bmatrix}^{(syst\ from\ \rho)}\right)$ mb

## Inelastic Cross-Section

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

$\sigma_{inel}$ (CMS) = $(68.0 \pm 2.0^{(syst)} \pm 2.4^{(lumi)} \pm 4.0^{(extrap)})$ mb
$\sigma_{inel}$ (ATLAS) = $(69.4 \pm 2.4^{(exp)} \pm 6.9^{(extrap)})$ mb
$\sigma_{inel}$ (ALICE) = $(72.7 \pm 1.1^{(mod)} \pm 5.1^{(lumi)})$ mb

# Total, Elastic, Inelastic Cross-Section



# pp Cross-Sections @LHC: 4 Methods
## (& Luminosity calibration)

1. Low_L(CMS) + Elastic + Optical T.
   - depends on CMS luminosity for low-L bunches & elastic efficiencies & ρ

2. High_L(CMS) + Elastic + Optical T.
   - checks the CMS luminosity for high-L vs low-L bunches

3. High_L(CMS) + Elastic + Inelastic
   - minimizes dependence on elastic efficiencies and no dependence on ρ

4. (L-independent) + Elastic + Inelastic + Optical T.
   - eliminates dependence on luminosity

# 1. Low_L(CMS) + Elastic + Optical T.

June'11 data : RP 10σ ; L: bunches 1-2·$10^{10}$ p

- $$\sigma^2_{TOT} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$
- **$\sigma_{TOT}$ = 98.3 mb ± [2.0(lum) 0.5(syst) $^{0.8}_{0.15}$ (ρ)] mb**
- $\sigma_{EL} = \int d\sigma_{EL}/dt = 24.8$ mb
- $\sigma_{INEL} = \sigma_{TOT} - \sigma_{EL} = 73.5$ mb

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# 2. High_L(CMS) + Elastic + Optical T.

October'11 data : RP 6.5/5.5/4.8σ ; L: bunches $7\cdot 10^{10}$ p

- $\sigma_{TOT}^2 = \dfrac{16\pi(\hbar c)^2}{1+\rho^2}\cdot \left.\dfrac{d\sigma_{EL}}{dt}\right|_{t=0}$
- **$\sigma_{TOT}$ = 98.2 mb ± [2.0(lum) 1.0(syst) $^{0.8}_{0.15}$ (ρ)] mb**
- $\sigma_{EL} = \int d\sigma_{EL}/dt = 25.3$ mb
- $\sigma_{INEL} = \sigma_{TOT} - \sigma_{EL} = 73.0$ mb

**LHCC - Preliminary**

# 3. High_L(CMS) + Elastic + Inelastic

October'11 data : RP 6.5/5.5/4.8σ ; L: bunches $7 \cdot 10^{10}$ p

- $\sigma_{EL} = \int d\sigma_{EL}/dt = 25.3$ mb
- $\sigma_{INEL} = L^{-1} \cdot N_{INEL} = 73.4$ mb
- $\sigma_{TOT} = \sigma_{EL} + \sigma_{INEL}$
- **$\sigma_{TOT}$ = 98.7 mb ± [3.9(lum) 2.0(syst) ] mb**

**LHCC - Preliminary**

# 4. Elastic + Inelastic + Optical T.

October'11 data : RP 6.5/5.5/4.8σ ; L: bunches $7 \cdot 10^{10}$ p

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

- **$\sigma_{TOT}$ = 97.8 mb ± [2.4(syst) $^{1.6}_{0.3}$ (ρ)] mb**

**LHCC - Preliminary**

# pp Total Cross-Sections @LHC √s=7TeV

1. $\sigma_{TOT} = 98.3 \text{ mb} \pm ^{2.2}_{2.0} \text{ mb}$
2. $\sigma_{TOT} = 98.2 \text{ mb} \pm ^{2.4}_{2.2} \text{ mb}$
3. $\sigma_{TOT} = 98.7 \text{ mb} \pm 4.4 \text{ mb}$
4. $\sigma_{TOT} = 97.8 \text{ mb} \pm ^{2.9}_{2.4} \text{ mb}$

LHCC - Preliminary

# pp Total Cross-Sections @LHC √s=7TeV

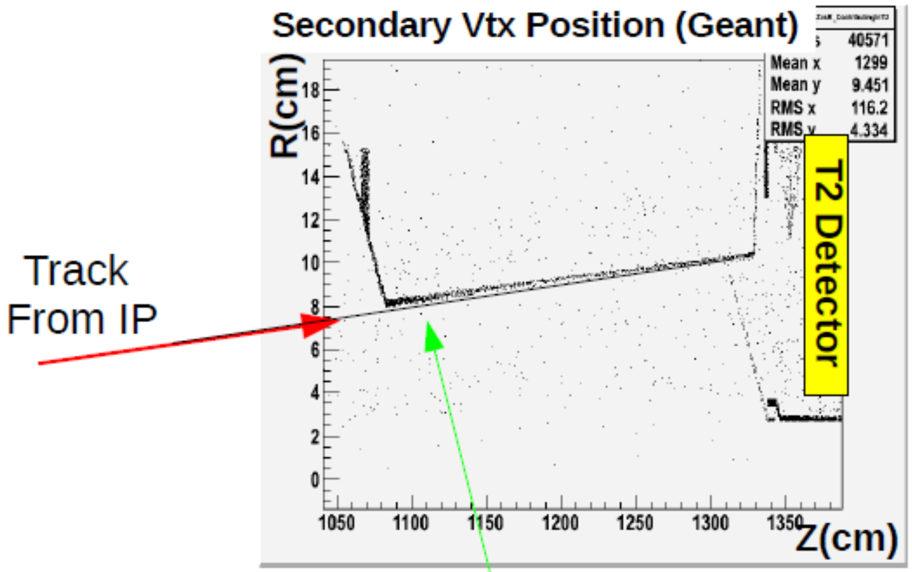
$$\sigma_{TOT} = 98.25 \text{ mb} \pm^{2.1}_{1.9} \text{ mb}$$

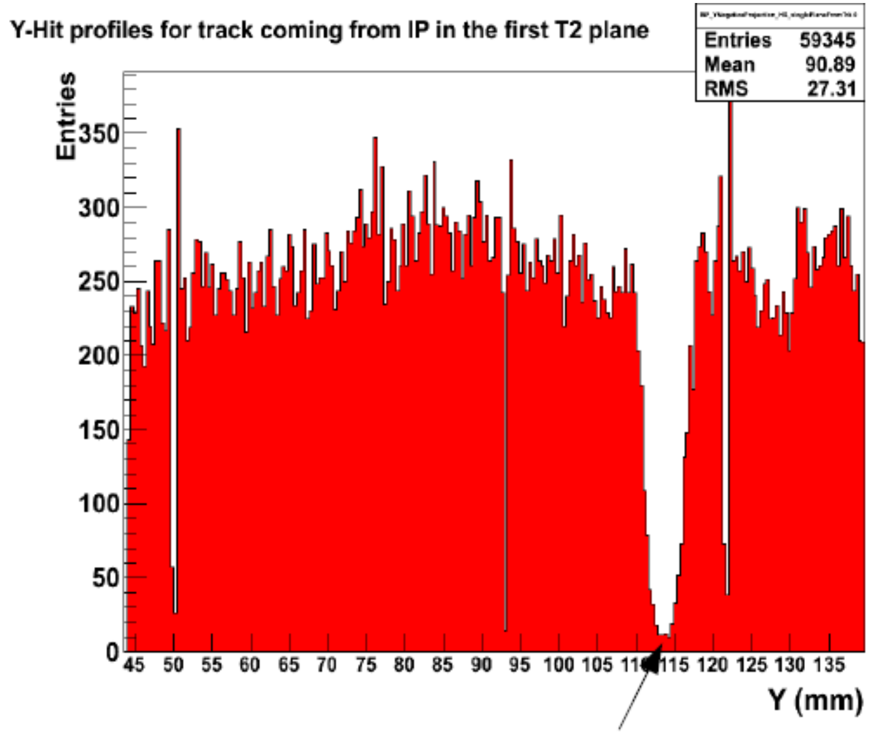
LHCC - Preliminary

# Charged particle dN/dη measurement in the pseudorapidity range 5.3< η<6.4

- In 2011 the T2 detector has been used to evaluate the charged tracks density.
- The runs used for this purpose where low luminosity runs to avoid the pileup.
- The detector sit after a large amount of material from the vacuum chamber and most of the analysis work has been devoted on the evaluation of the fraction of primary tracks.

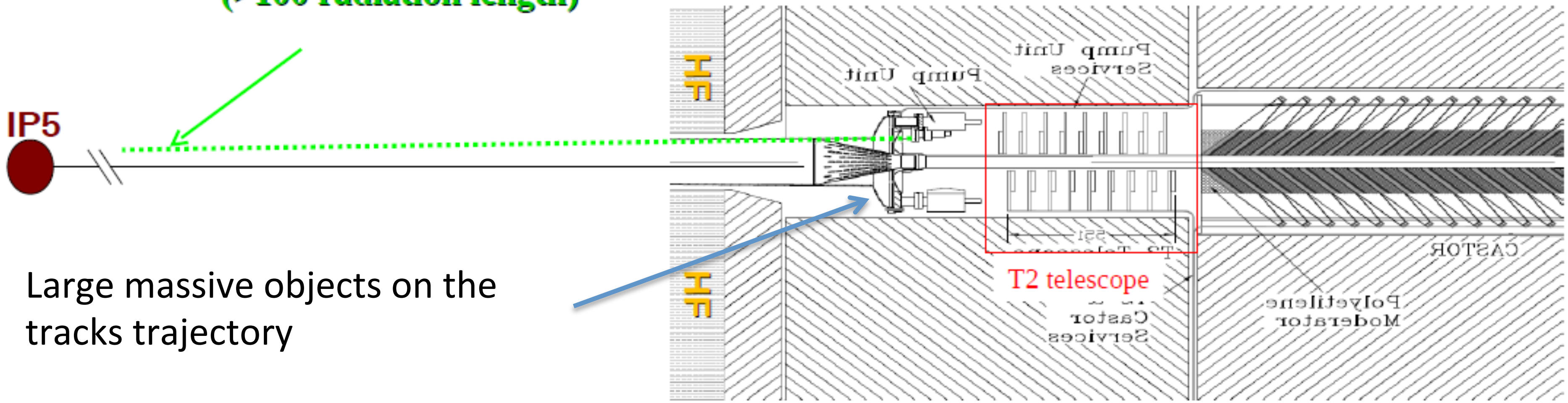
## Vacuum chamber shadow, and secondary particles production



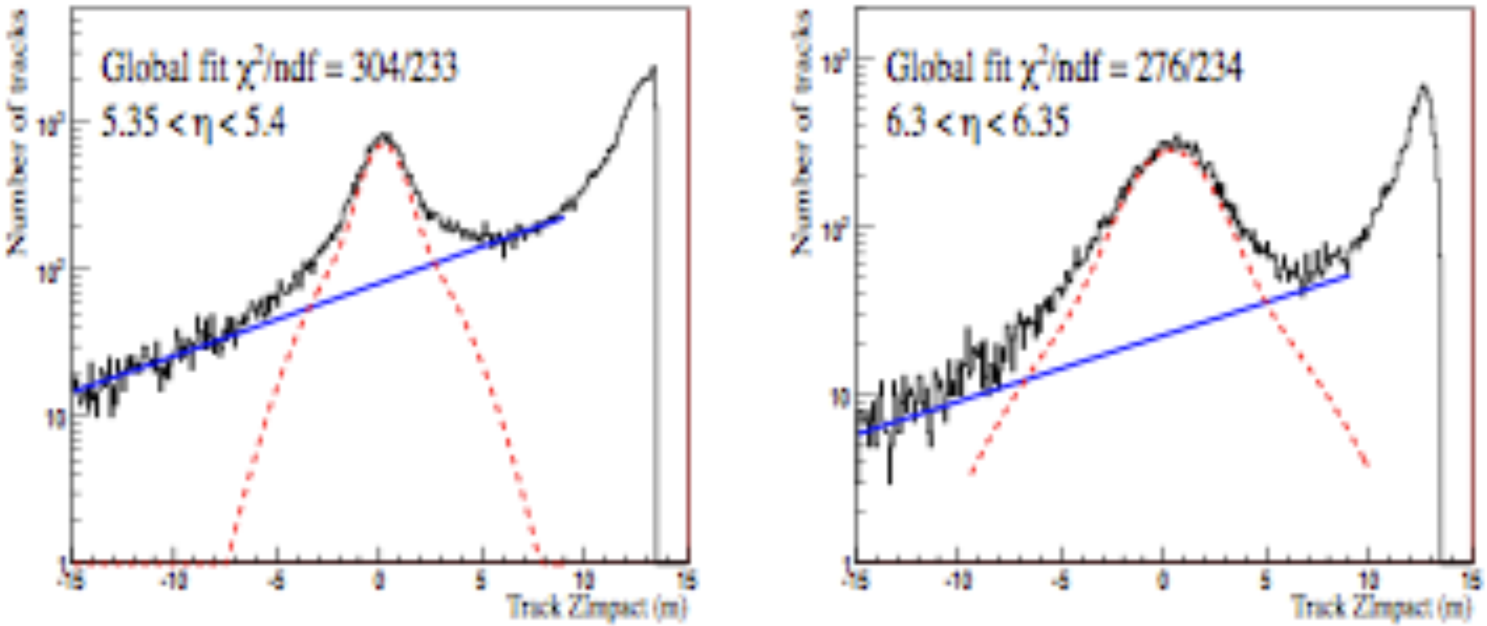

The beam pipe shadows the particle flux in a specific angle corresponding to η~5.54

**BeamPipe cone at η~5.54 (>100 radiation length)**

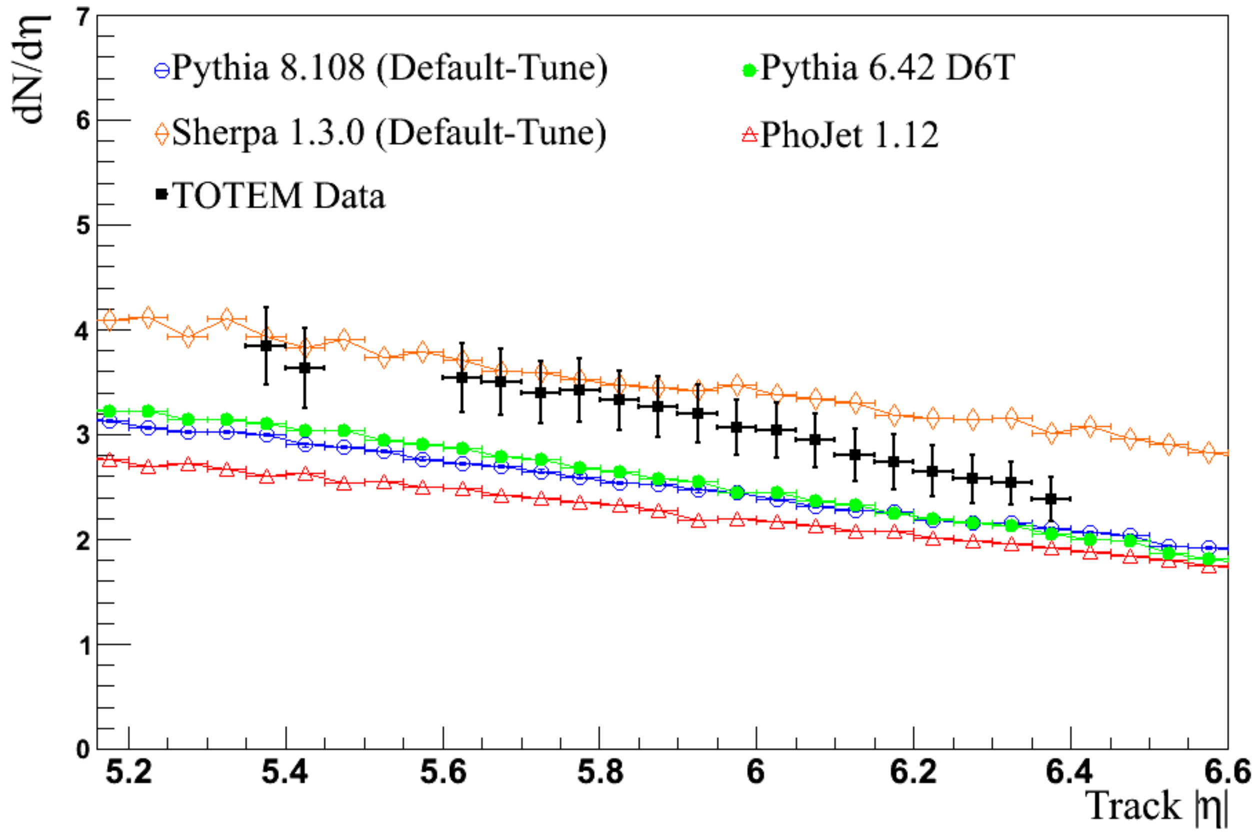



Large massive objects on the tracks trajectory

# Secondary tracks evaluation

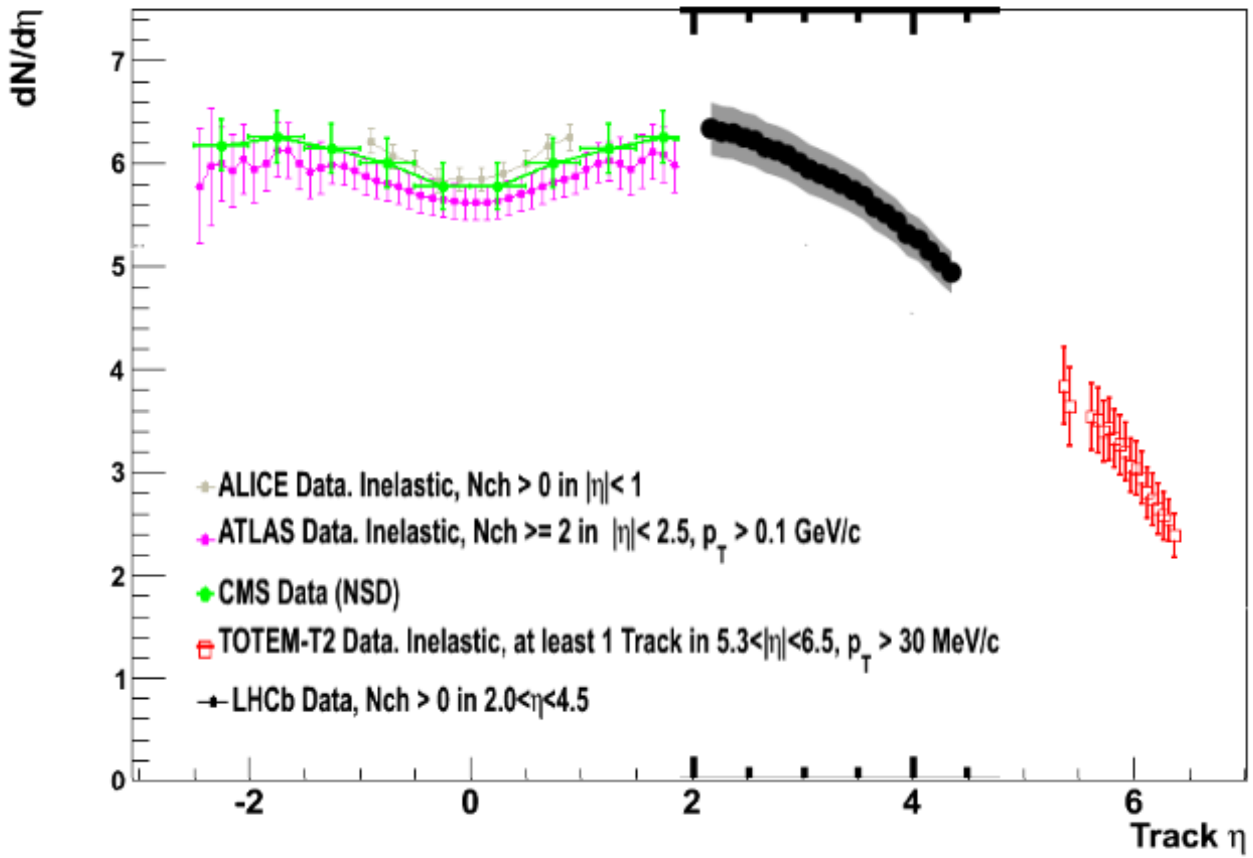


# Charged particle dN/dη



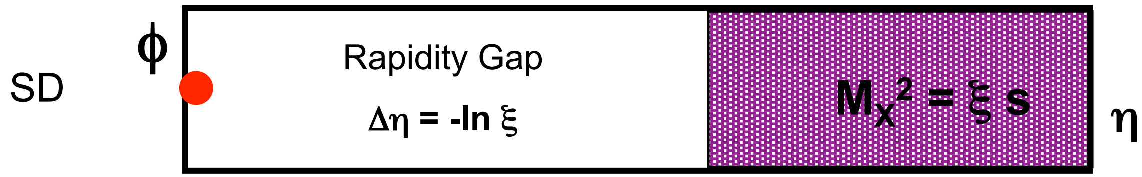
# Track density compared with central measurements

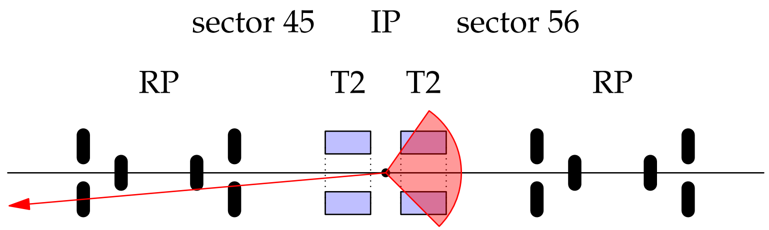
dN/dη data from ALICE, ATLAS, CMS, LHCb, TOTEM

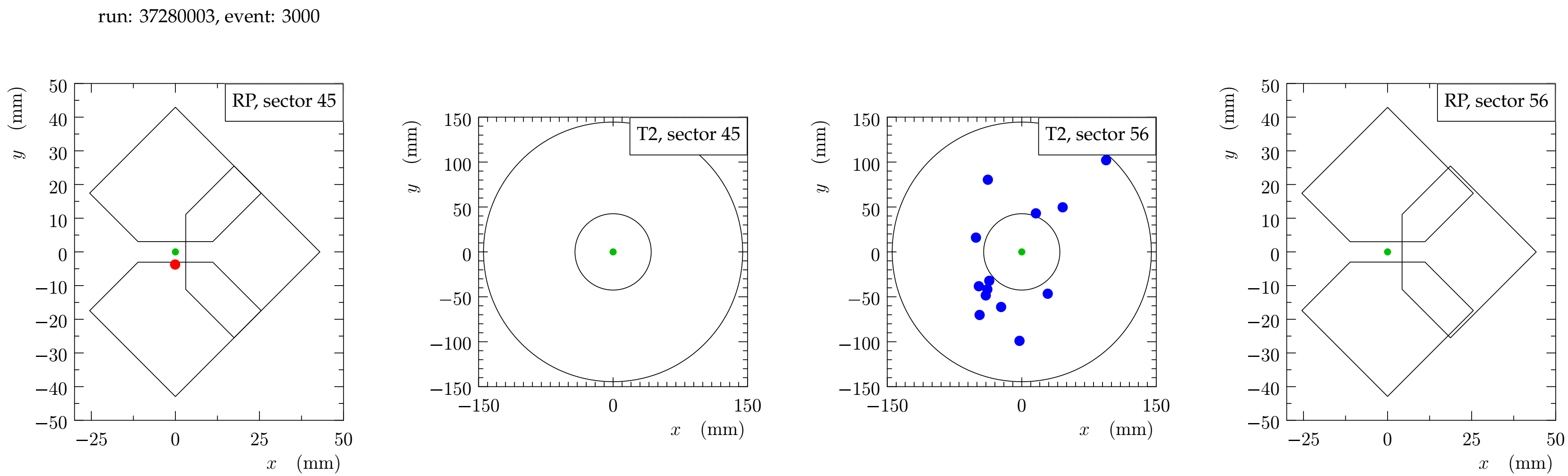


# Single diffraction low ξ

Correlation between leading proton and forward detector T2

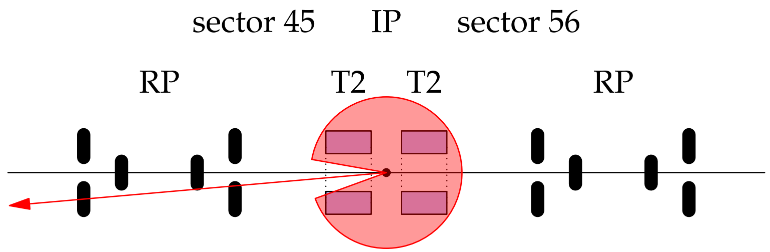


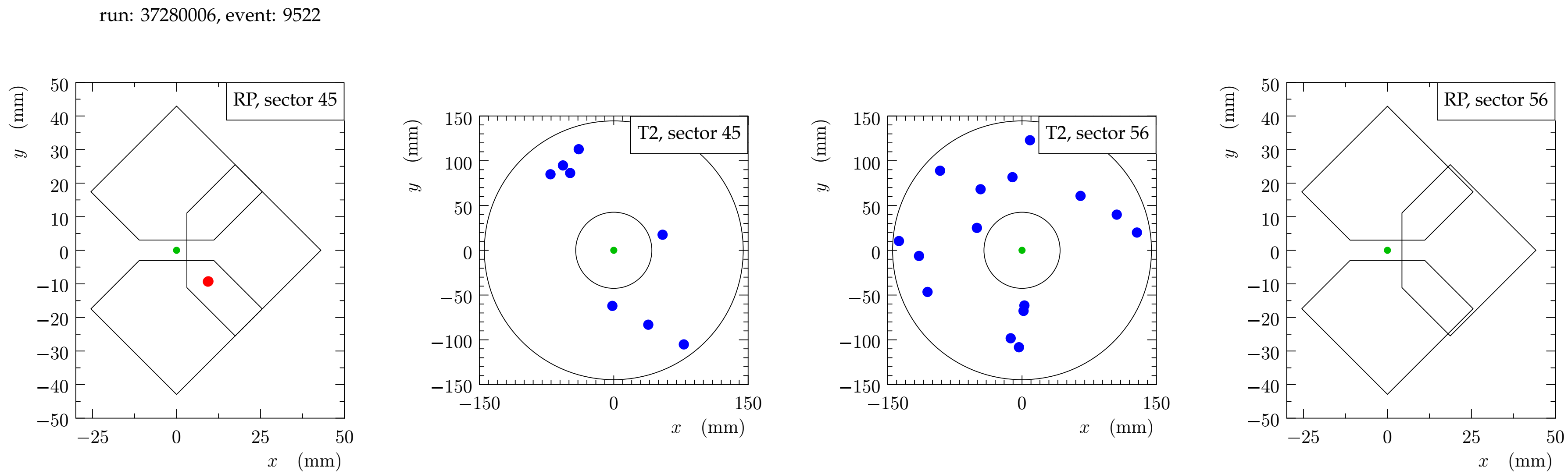



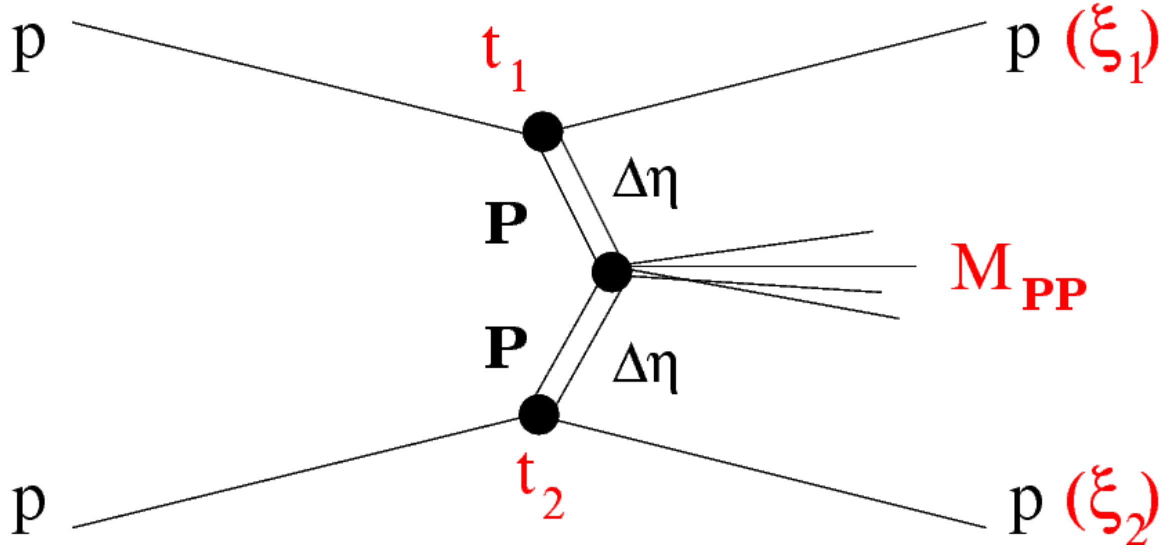
# Single diffraction large ξ

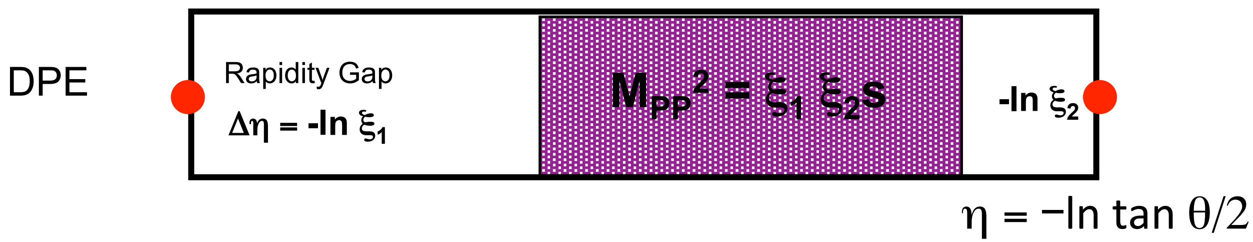
correlation between leading proton and forward detector T2

# Double Pomeron Exchange (DPE)

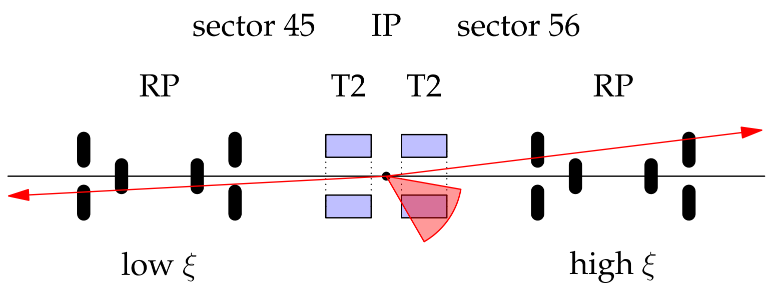


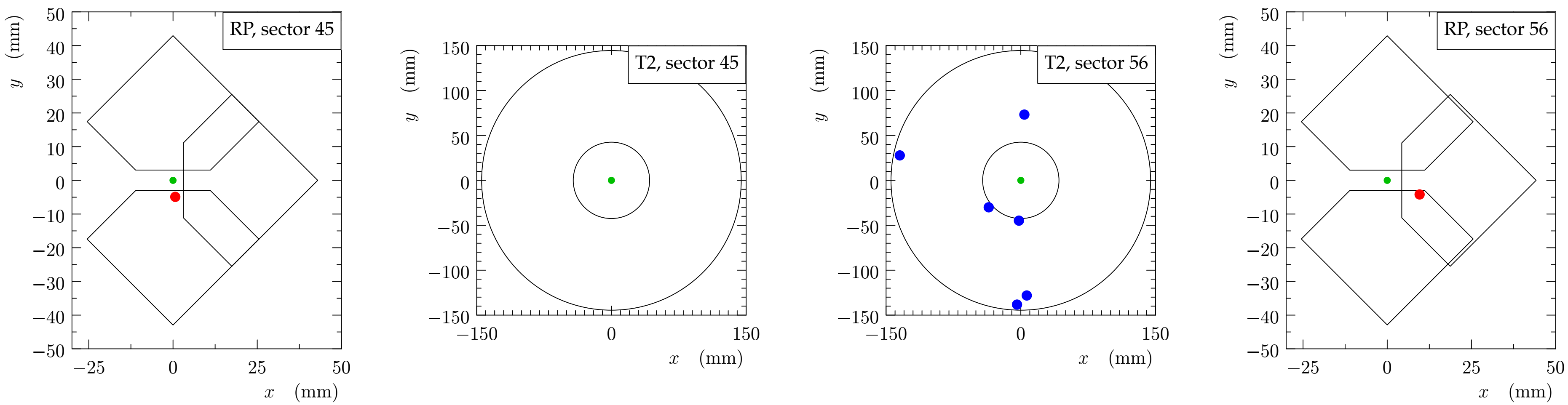

Use the LHC as a Pomeron-Pomeron (Gluon - Gluon) Collider - GGC

# Double Pomeron Exchange (DPE)

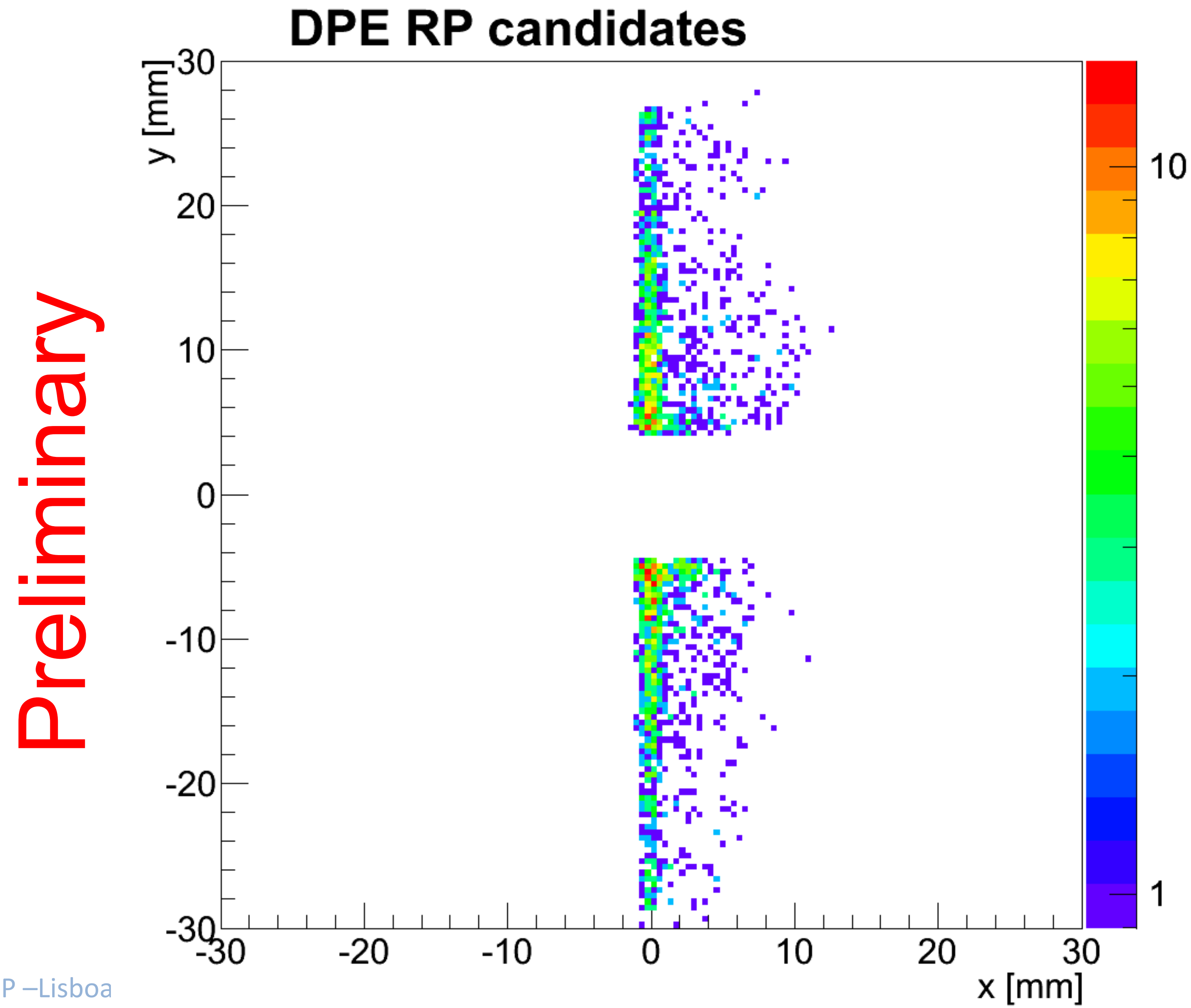
correlation between leading protons and forward detector T2



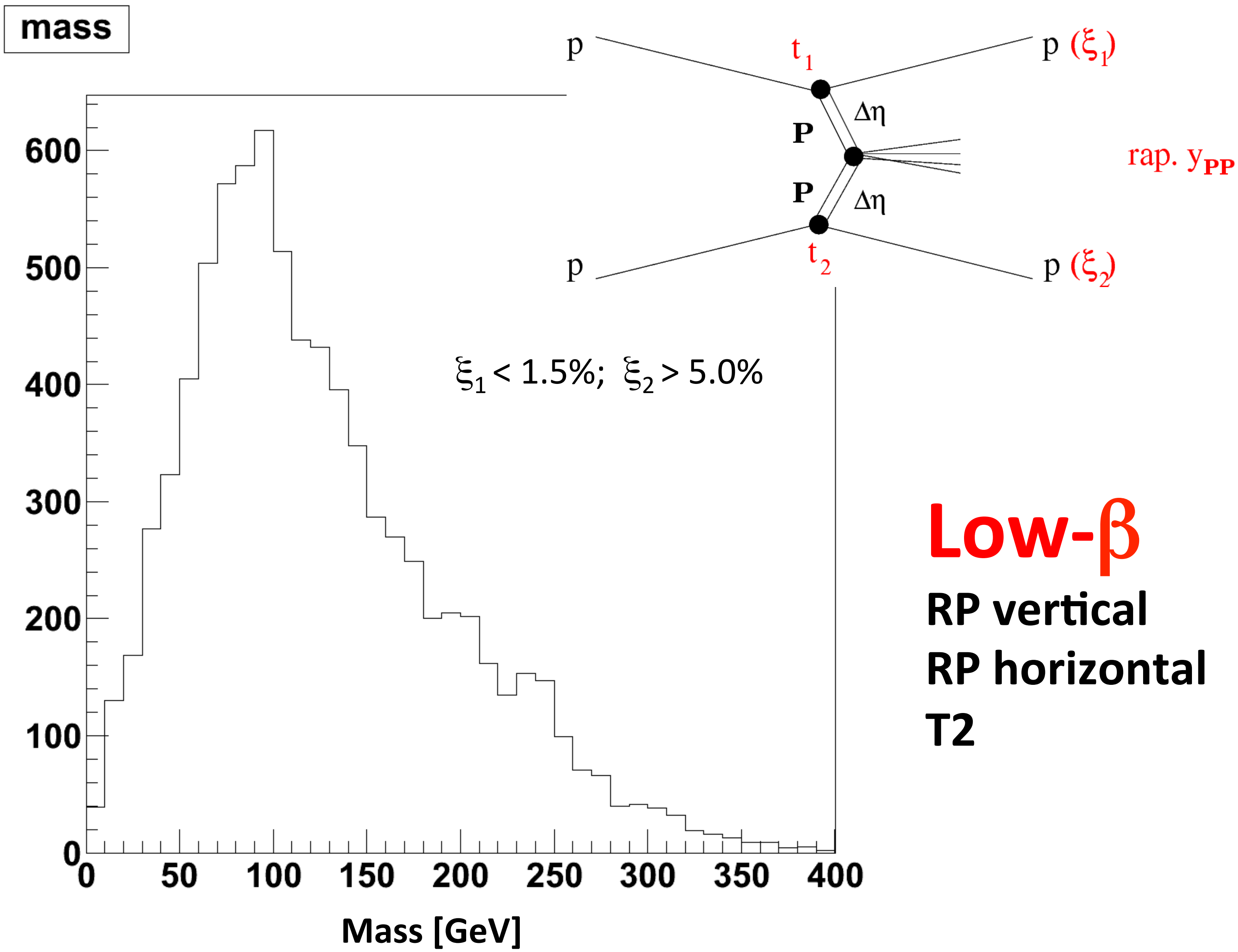

run: 37220007, event: 9904



# Data Oct'11: DPE (as logic complement to the elastic tag)



# Example of DPE Mass Reconstruction




**Low-β**

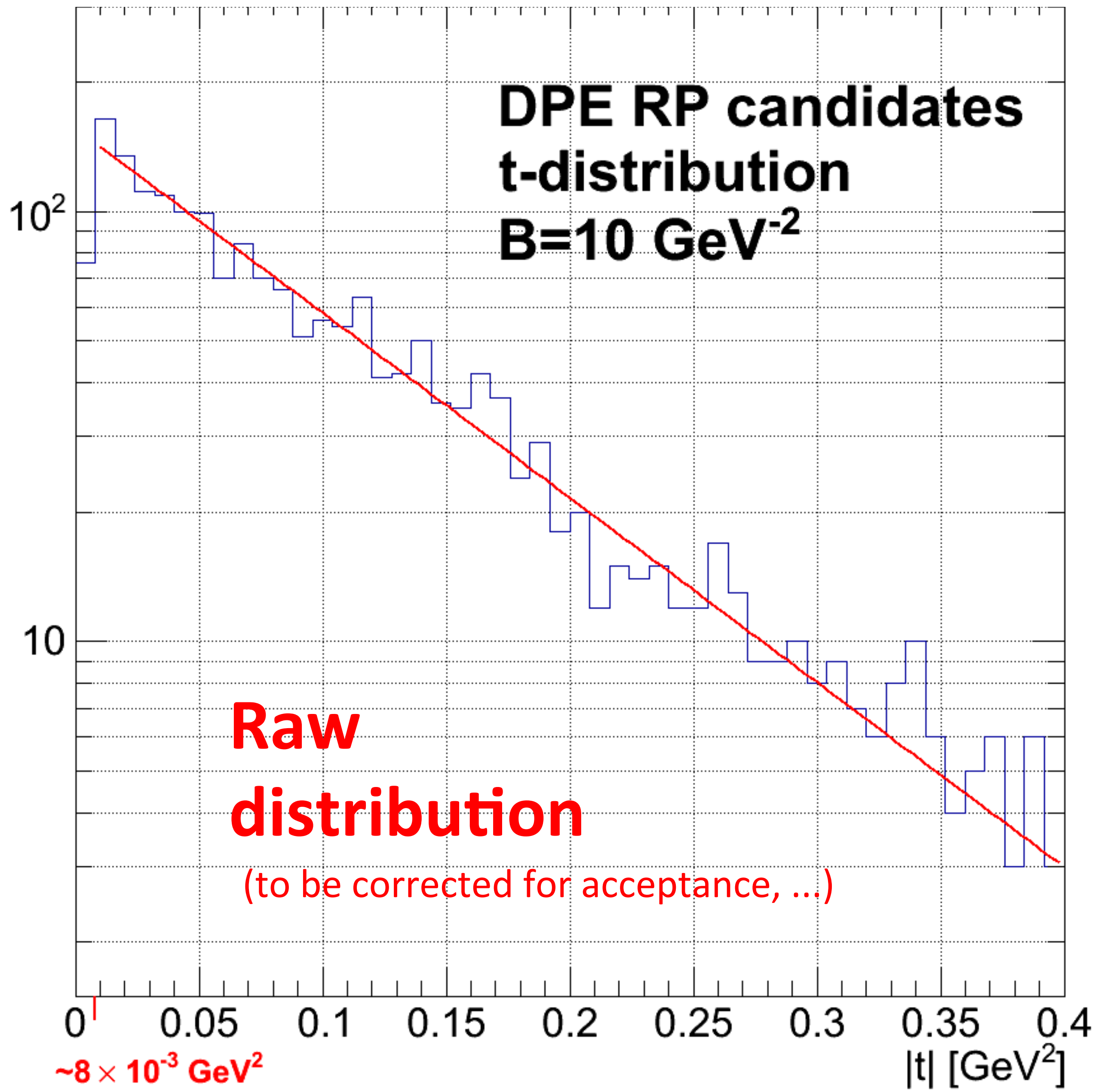
**RP vertical**

**RP horizontal**

**T2**

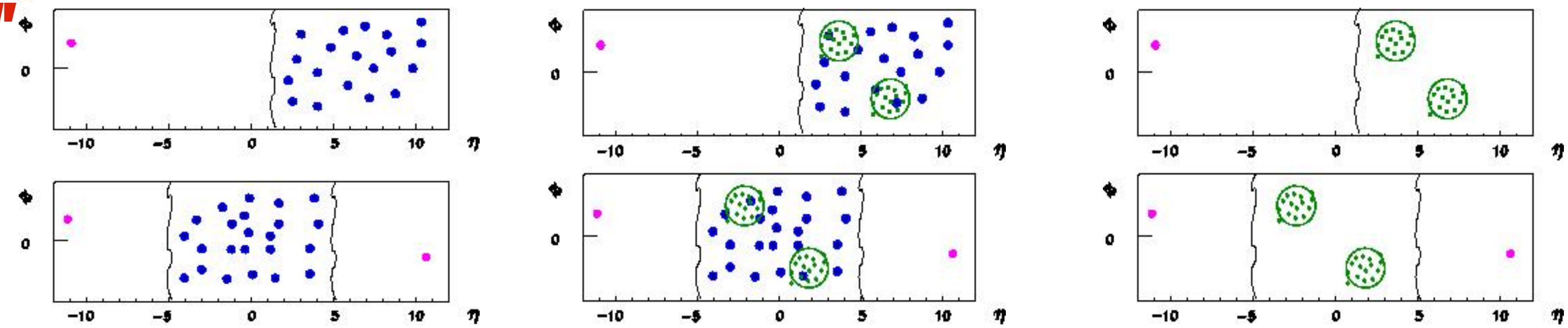
# Data Oct'11: DPE Cross-Section

Preliminary




Distribution integrated on ξ

# TOTEM + CMS running scenarios




| pp->pX<br>pp->pXp | pp->pjjX<br>pp->pjjXp | pp->pjj (bosons, heavy<br>pp->pjjp quarks,Higgs...) |
|---|---|---|
| soft diffraction | (semi)-hard diffraction | hard diffraction |

← Cross section ———————— Luminosity →

| | | | | | |
|---|---|---|---|---|---|
| β (m) | 1540 | 90 | 2 | 0.5 | |
| L ($cm^{-2}$ $s^{-1}$) | $10^{29}$ | $10^{30}$ | $10^{32}$ | | $10^{34}$ |
| | TOTEM LHC runs | | | Standard LHC runs | |

# Conclusions

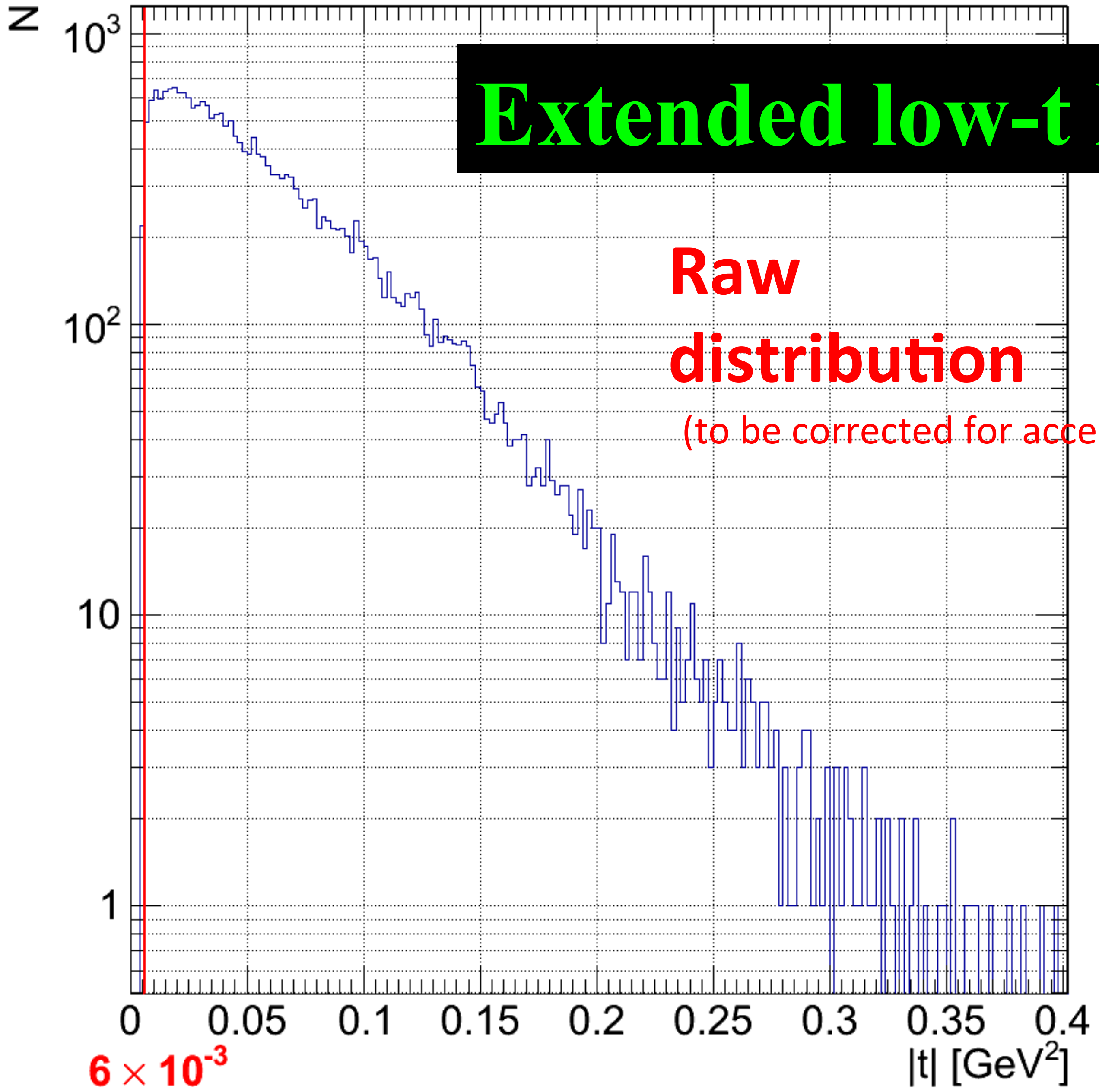
- The TOTEM experiment has performed the total and elastic P-P cross section at 7 TeV measurement using the Roman Pots placed at 220m from IP5.
- The measurement is done using the CMS estimation of Luminosity
- The inelastic cross section is currently under evaluation directly using the inelastic detector T1 and T2 and is in agreement with the value estimated by subtraction
- The direct measurement of the total cross section using the luminosity independent method is finalized.
- The inelastic detector allowed us to estimate the charged track density at large pseudorapidity values.
- A new trigger has been deployed to trigger directly CMS from 220m RP and new physics scenarios are now open.

# Backup

# Data Oct'11: Elastic Differential Cross-Section

**Extended low-t limit**

Preliminary




**Raw distribution**

(to be corrected for acceptance, ...)

# Systematics and Statistics

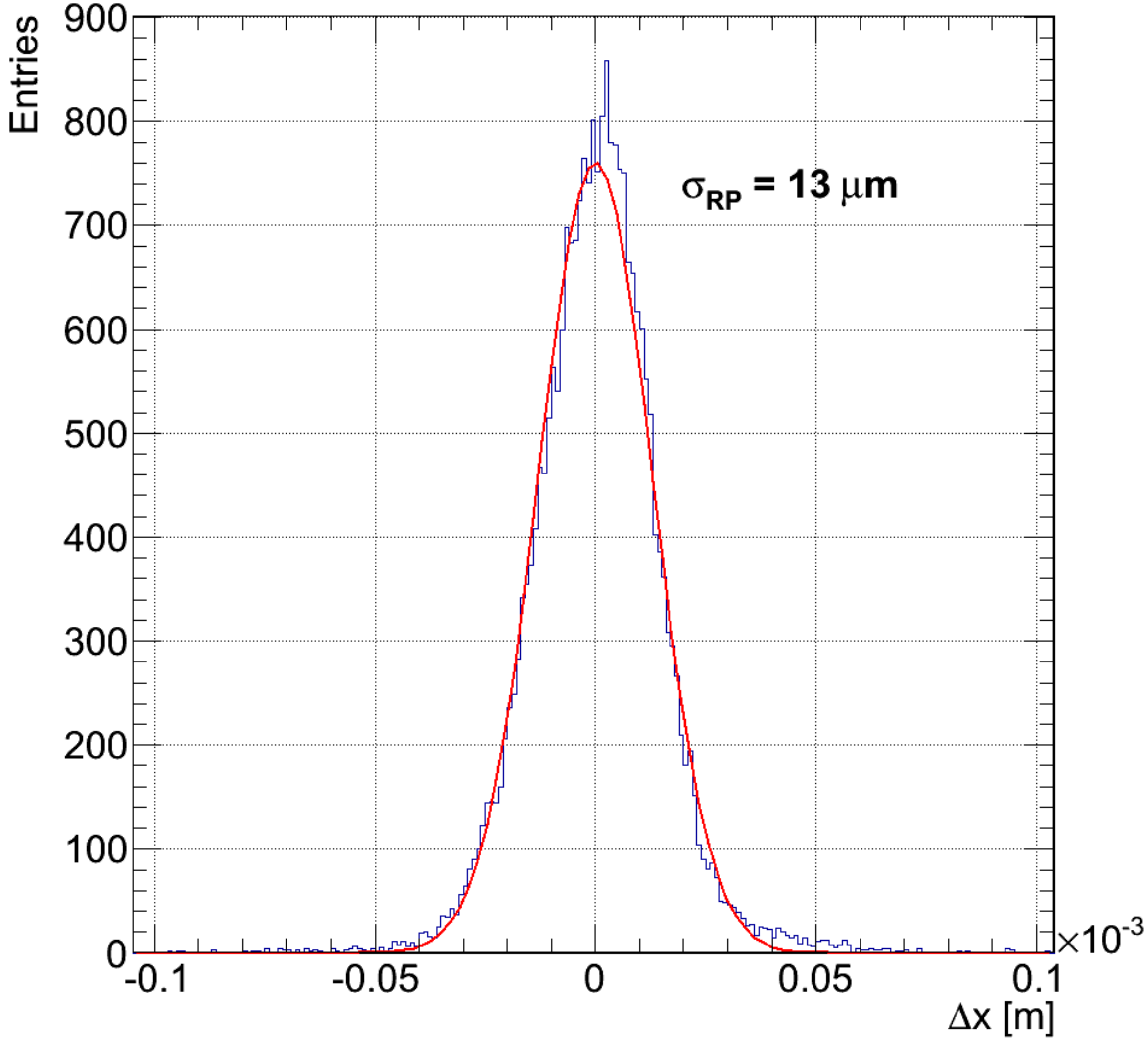
- t : ±[0.6:1.8]%$^{\text{syst optics}}$ ± <1%$^{\text{align.}}$ ±[3.4:11.9]%$^{\text{stat}}$ (before unfolding)
- $d\sigma/dt$ : ±4%$^{\text{syst lumin}}$; ±1%$^{\text{syst (acc.+eff.+backg.+tag)}}$ ±0.7%$^{\text{syst unfold.}}$
- B : ±1%$^{\text{stat}}$ ±1%$^{\text{syst from t}}$ ±0.7%$^{\text{syst from unfolding}}$
- $d\sigma/dt_{(t=0)}$ : ± 0.3%$^{\text{stat}}$ ±0.3%$^{\text{syst (optics)}}$ ±4%$^{\text{syst lumin}}$ ±1%$^{\text{syst (acc.+eff.+backg.+tag)}}$
- $\int d\sigma/dt$ : ±4%$^{\text{syst lumin}}$ ±1%$^{\text{syst (acc.+eff.+backg.+tag)}}$ ±0.8%$^{\text{stat extrap.}}$

- $\sigma_{TOT}$ : (+0.8% -0.2%)$^{\text{syst }\rho}$ ± 0.2%$^{\text{stat}}$ ±2.7%$^{\text{syst}}$ = (+2.8%-2.7%)$^{\text{syst}}$ ± 0.2%$^{\text{stat}}$
- $\sigma_{EL}$ : ±5%$^{\text{syst}}$ ±0.8%$^{\text{stat}}$
- $\sigma_{INEL}$ : (+2.4%-1.8%)$^{\text{syst}}$ ± 0.8%$^{\text{stat}}$

# Data Oct'11: Elastic + DPE

Resolution

Preliminary



# Inelastic cross section measured by T2

$$\sigma_{\text{inelastic, T2 visible}} = 69.3 \pm 0.1\ (\text{stat}) \pm 1.0\ (\text{syst}) \pm 2.8\ (\text{lumi})\ \text{mb}$$

$$\sigma_{\text{inelastic}} = 73.4 \pm 0.1\ (\text{stat}) \pm 1.9\ (\text{syst}) \pm 2.9\ (\text{lumi})\ \text{mb}$$