Status and Early Physics Program of TOTEM

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on behalf of the

TOTEM Collaboration

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

DIS 2009

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Physics programme

Elastically scattered protons measured

- Total pp cross section at 14TeV with a precision of 1-2%
- Elastic pp scattering, 10^{-3} GeV^2 < –t < 10 GeV^2

Inelastically scattered protons measured

- Soft Single & Central Diffraction (SD, DPE)
- Leading particle & energy flow in forward direction
- Semi–hard + hard Single & Central Diffraction: production of jets, W, heavy flavours...
- Exclusive particle production in Central Diffraction
- Low–x dynamics
- $\gamma\gamma$ & γp physics

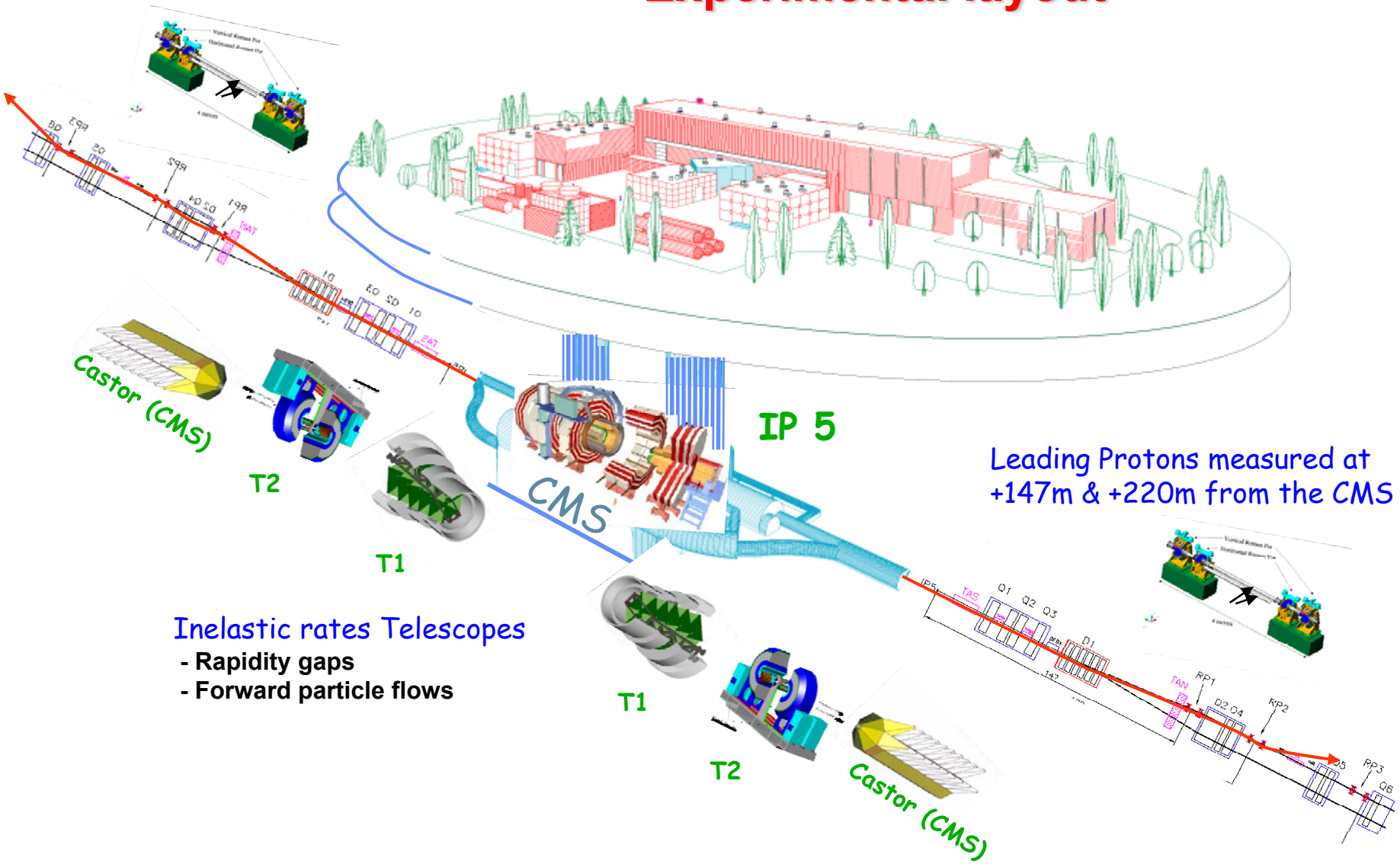
WITH CMS

Physics program for the LHC start

- Diffraction at low/medium luminosity: SD, DPE
- Total cross section with a precision of about 5%
- Multiplicity distributions

Experimental layout

Leading Protons measured at
-220m & -147m from the CMS

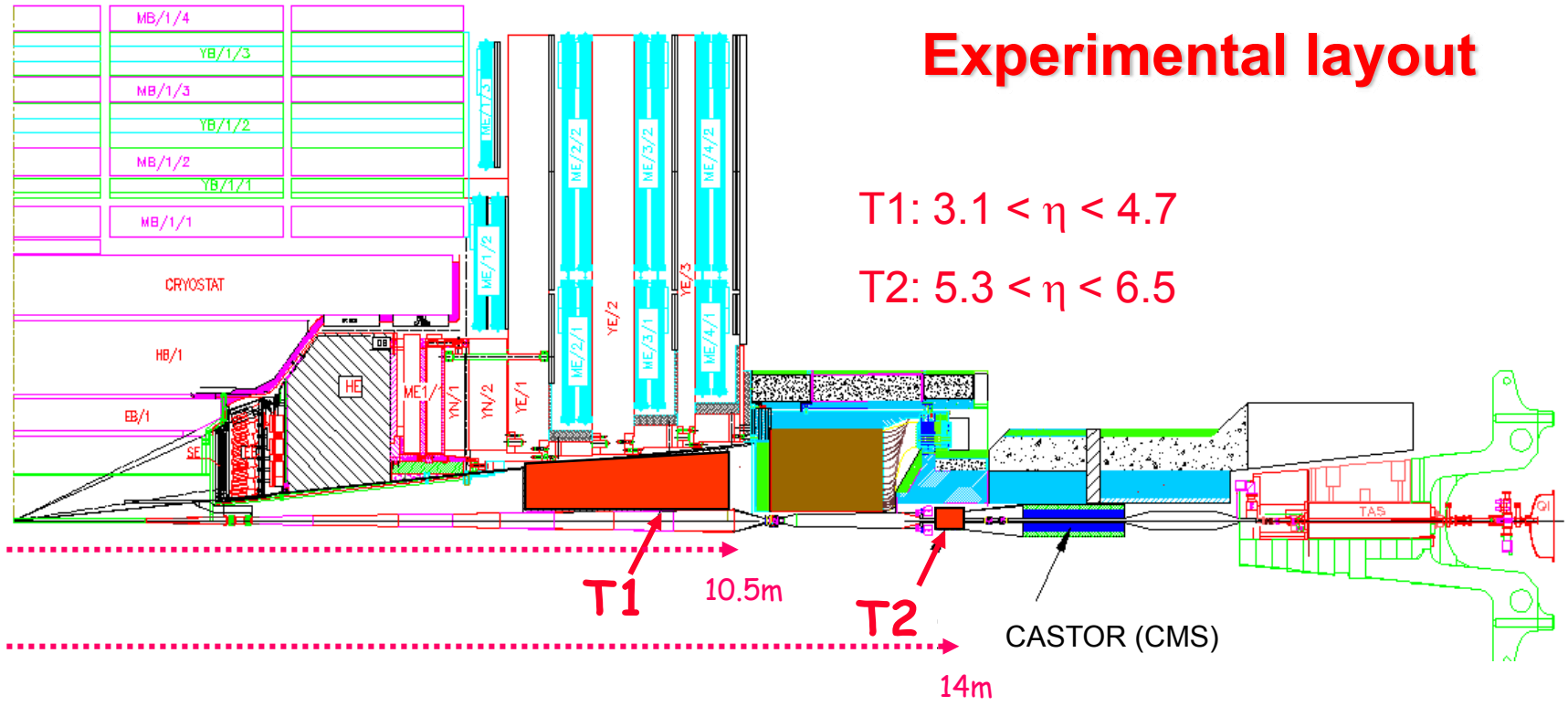


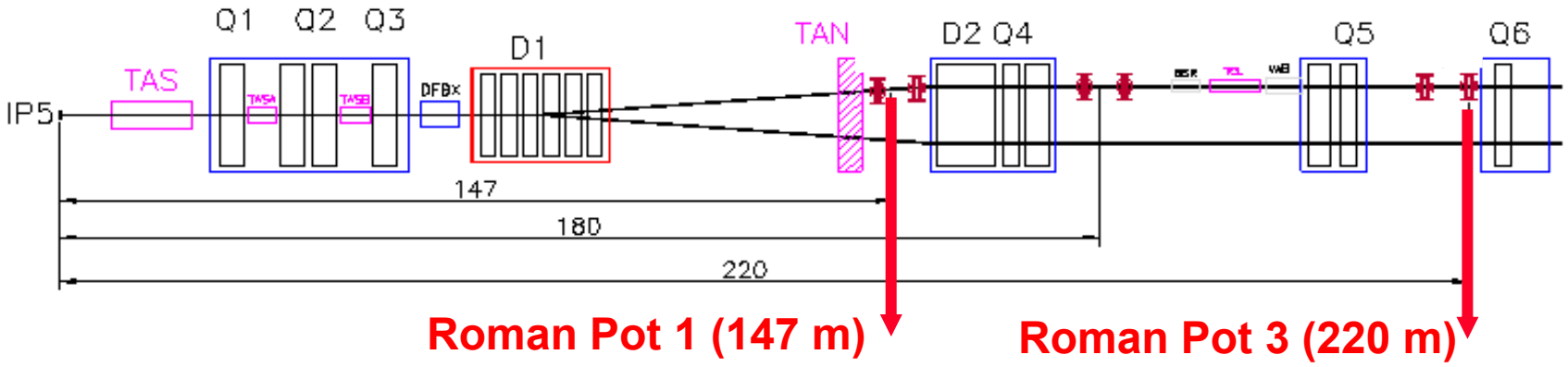
Inelastic rates Telescopes
- **Rapidity gaps**
- **Forward particle flows**

Experimental layout

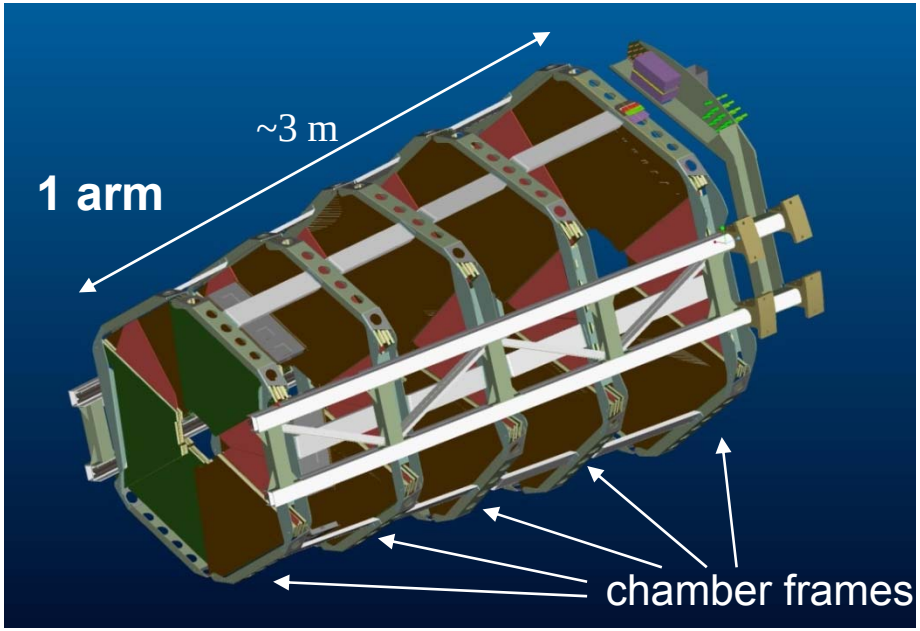
T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5





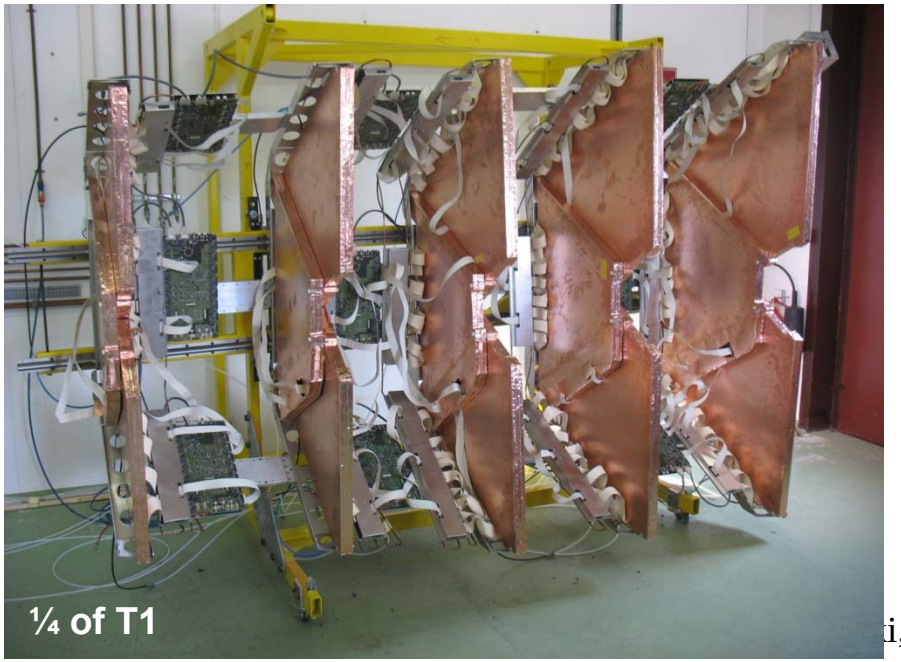
T1 Telescope

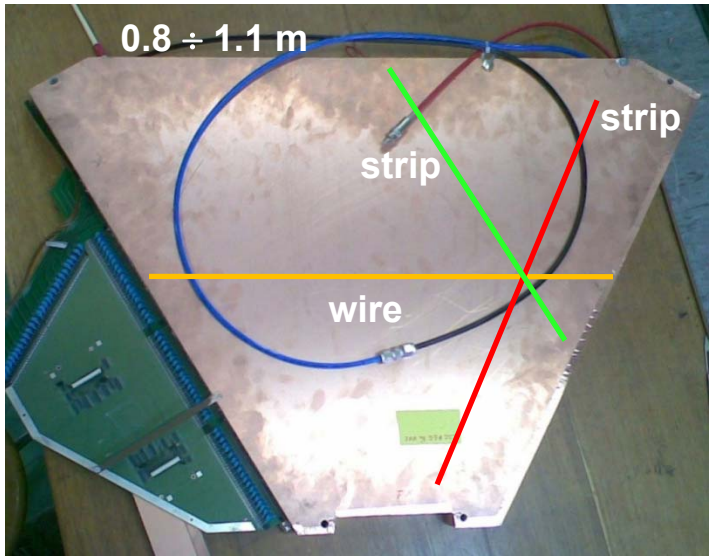


- Cathode Strip Chambers (CSC)
- $3.1 < |\eta| < 4.7$
- 5 planes with measurement of three coordinates per plane, $\sigma \sim 1$ mm
- Primary vertex reconstruction (beam-gas interaction removal)
- Trigger with anode wires
- Connected to VFAT chips
- Successful ageing studies

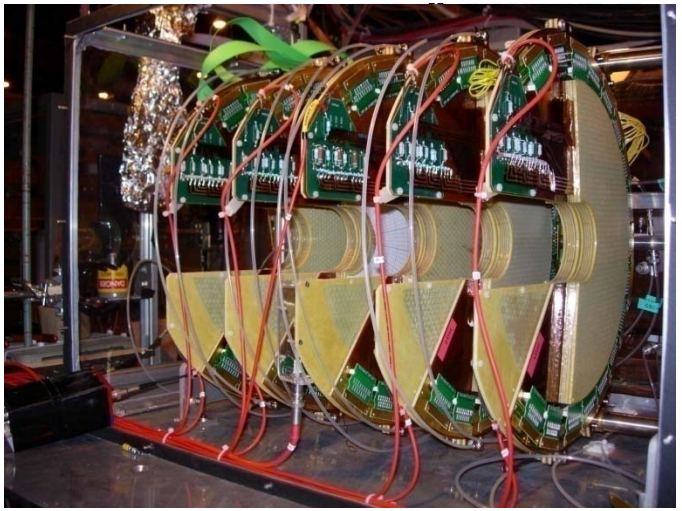
(~ 5 years at $L_{inst}=10^{30}$ cm^{-2}s^{-1})

Installation as soon as possible

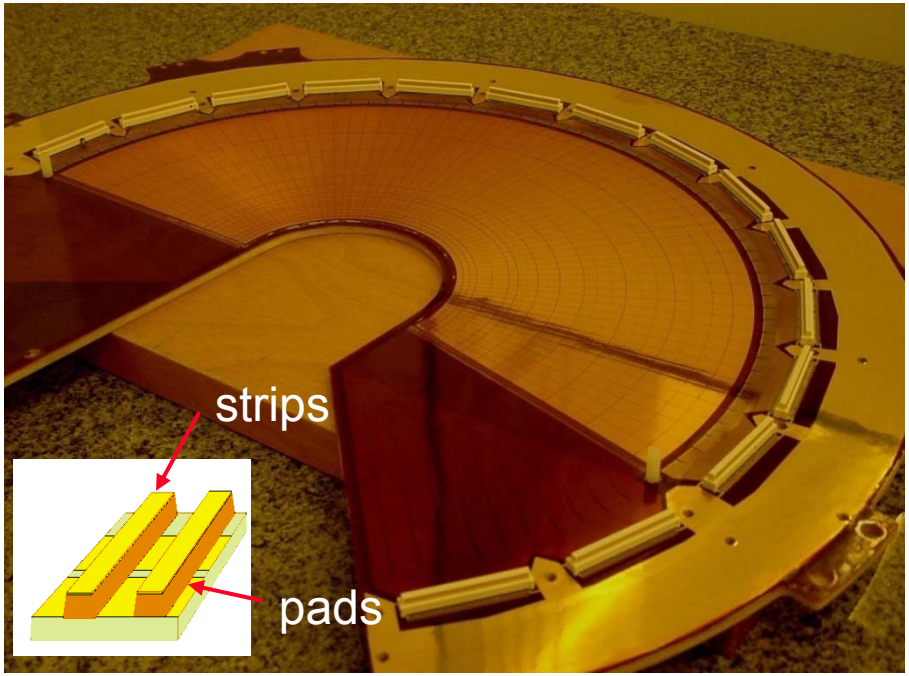




T2 Telescope

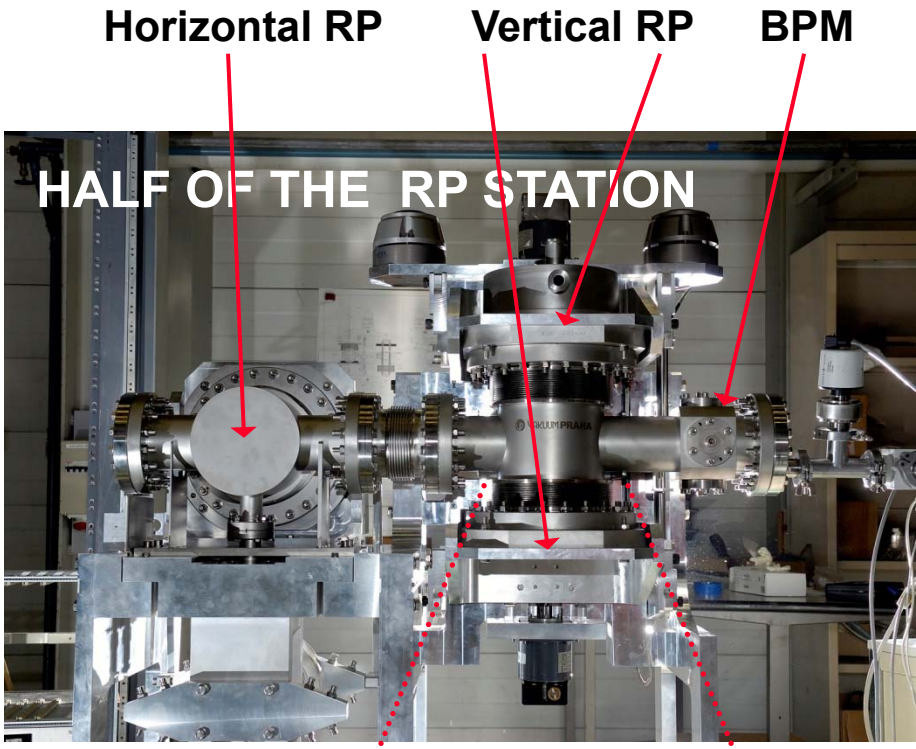


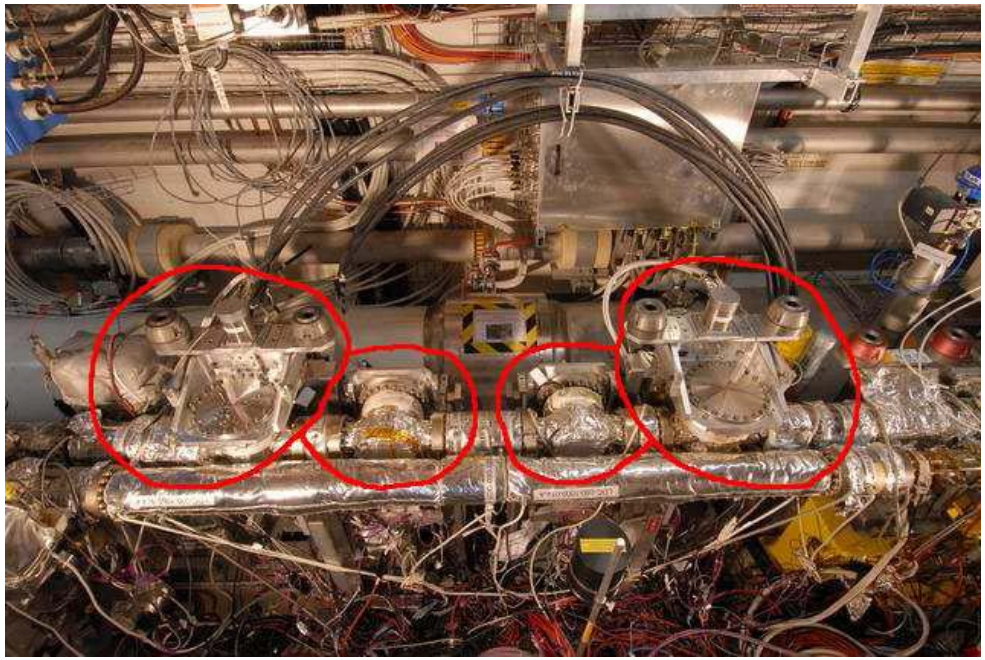
- Gas Electron Multiplier (GEM)
- $5.3 < |\eta| < 6.5$
- 10 half-planes @ 13.5 m from IP5
- Half-plane:
  - 512 strips (width 80 μm, pitch of 400 μm), radial coordinate
  - 65*24=1560 pads (2x2 mm^2 -> 7x7 mm^2), radial and azimuth coord.
  - Resolution: $\sigma(R) \sim 100$ μm, $\sigma(\varphi) \sim 1°$
- Primary vertex reconstruction (beam-gas interaction removal)
- Trigger using (super) pads
- Detectors fully tested in a testbeam with VFAT chips
- Majority of T2 planes installed in LHC, fully done by May



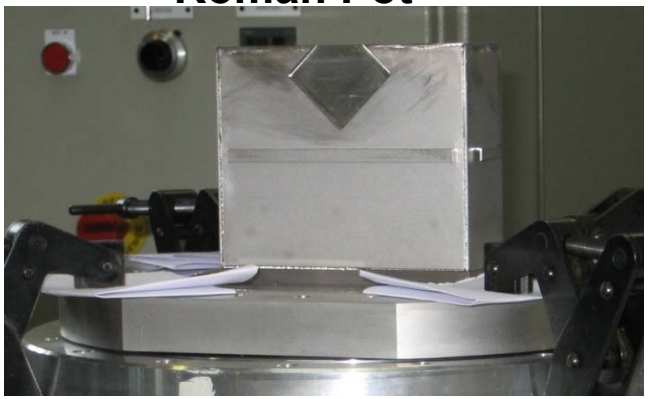
Roman Pots

- 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 of the beam
- All RP stations installed in the LHC





Roman Pot



Roman Pot detectors

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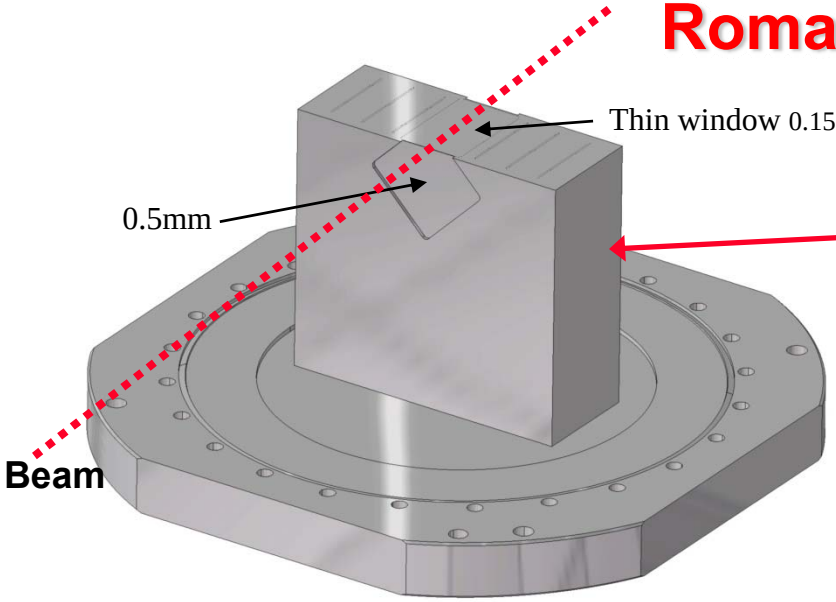

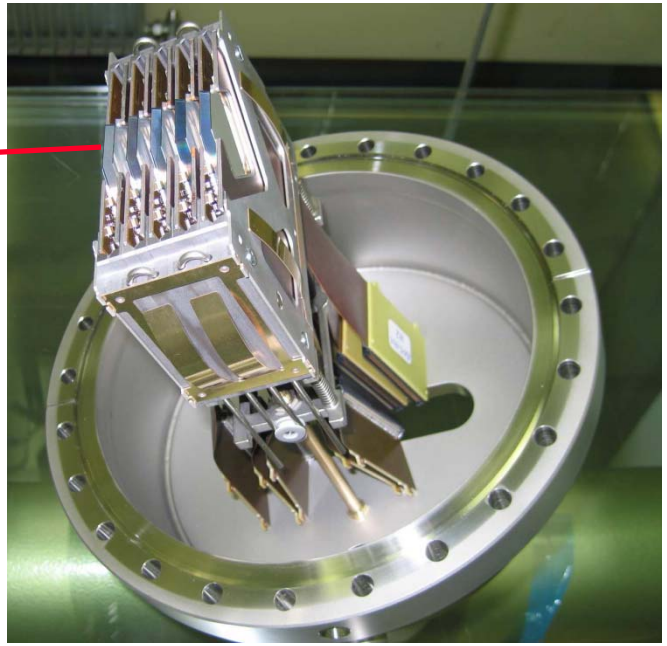

10 planes of edgeless detectors

- Leading proton detection at distances down to 10×σ(beam) + d
- Need “edgeless” detectors that are efficient up to the physical edge to minimize “d”
- σ(beam) ≈ 0.1–0.6 mm (optics dep.)

β^* [m]	$\lvert t_{\min}\rvert$ [GeV^2]	$\lvert\Delta t/t_{\min}\rvert$ $d = 50\,\mu$m	$\lvert\Delta t/t_{\min}\rvert$ $d = 500\,\mu$m
0.5	4.93	1.8 %	18.3 %
2	1.70	3.0 %	32.1 %
90	$30.3 \cdot 10^{-3}$	1.5 %	16.0 %
1535	$0.69 \cdot 10^{-3}$	10.2 %	124 %

Si Edgeless Detectors for RP

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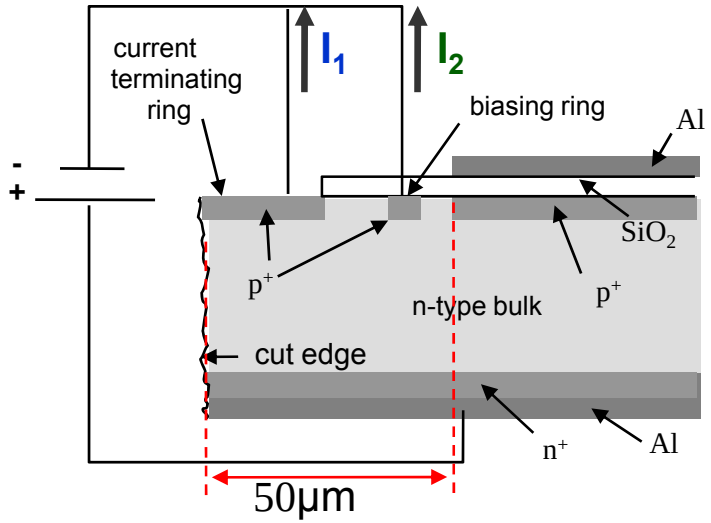
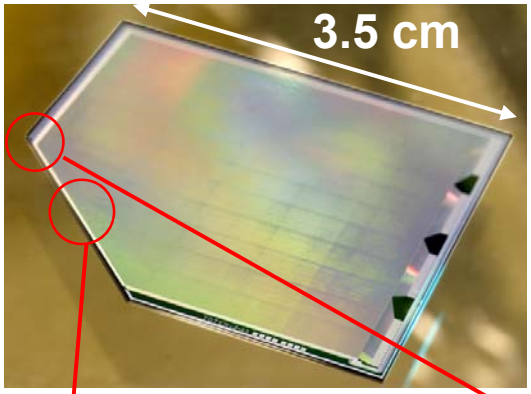
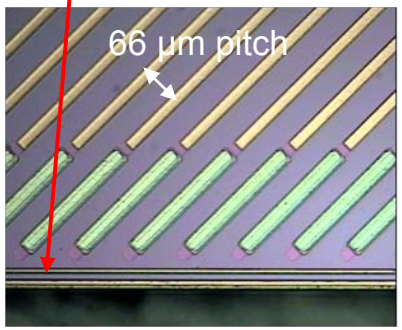
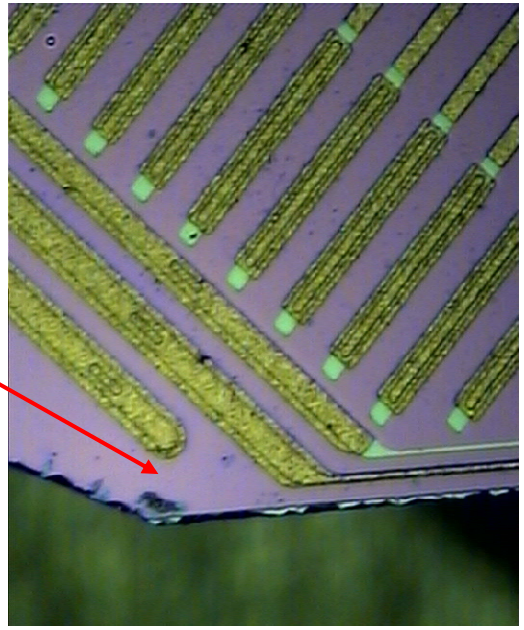
Planar technology with CTS (Current Terminating Structure)



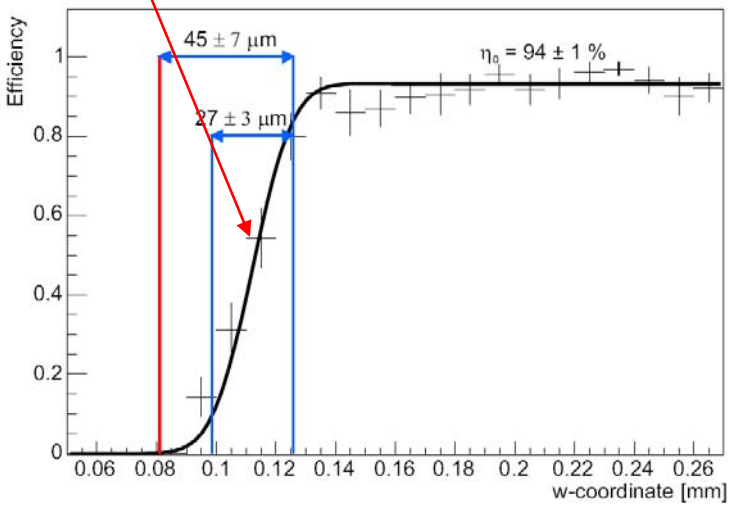






50 μm dead area

- **AC coupled microstrips made in planar technology with novel guard-ring design and biasing scheme**
- **Readout with VFAT chips**
- **Leakage current : 60 nA at 200 V (excellent)**
- **All produced**
- **Installation ongoing: RP220 (147) fully (partially) equipped by June**



LHC Optics

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Proton position at RP (x^*, y^*) is a function of position (x^*, y^*) and divergence (Θ_x^*, Θ_y^*) at IP:

$$y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^*$$

$$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \qquad \xi = \Delta p/p$$ **– momentum loss**

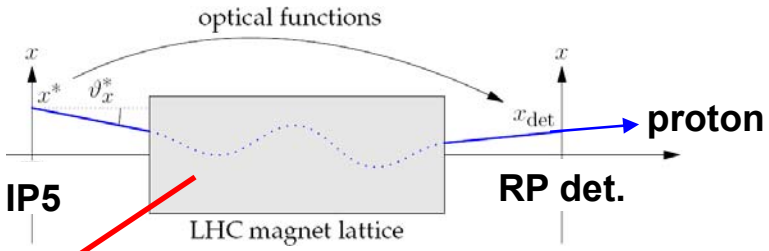
Beam size and beam divergence at IP5 and at RP

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

$\sigma(\Theta_x) = \sqrt{\dfrac{\varepsilon}{\beta_x}}$ beam divergence at IP5 limits the angle measurement precision

Proton acceptance is determined by

- optical functions, mainly L_x, L_y, D_x
- beam size σ_x, σ_y at RP
- internal LHC apertures



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

Total cross section

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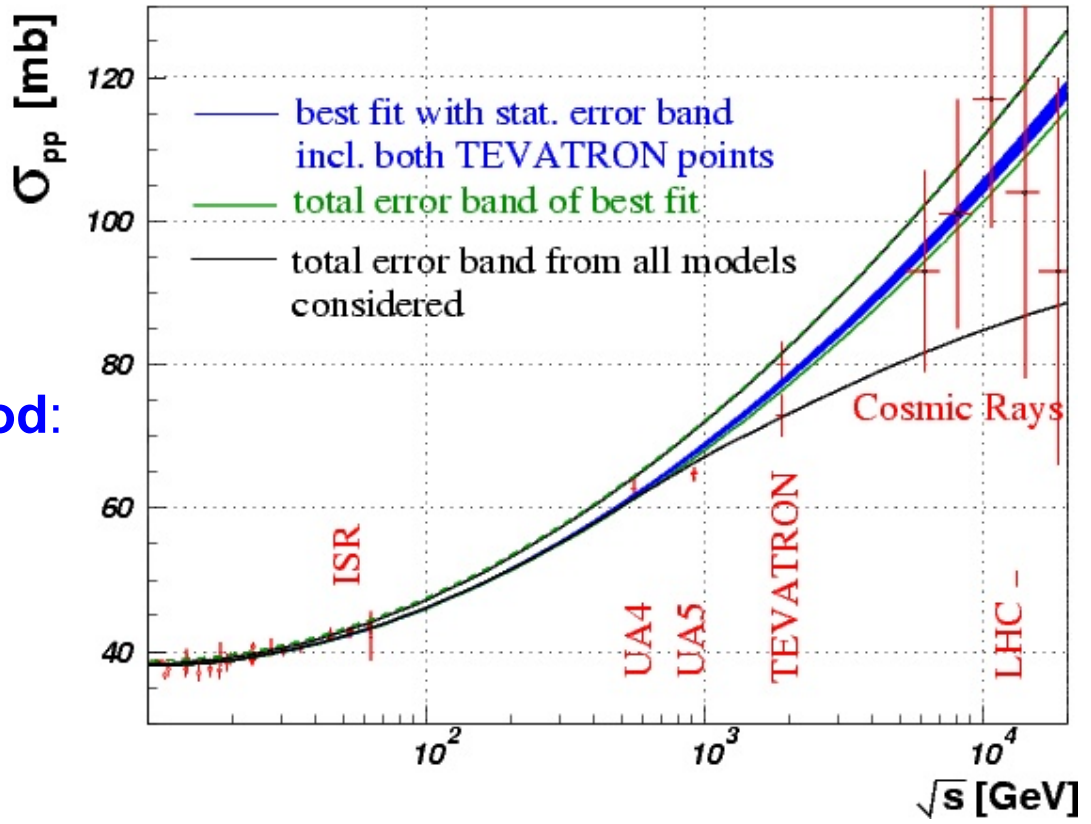
Disagreement E811–CDF: 2.6 σ

Best combined fit by COMPETE:

$$\sigma_{tot} = 111.5 \pm 1.2\ ^{+4.1}_{-2.1}\ \text{mb}$$

Models vary within (at least) $^{+10}_{-20}$ %



Luminosity independent method:

$$\sigma_T = \frac{8\pi}{p\sqrt{s}} \mathrm{Im}F(s,t)|_{t=0}$$ Optical Theorem

$$\Downarrow$$

$$L\sigma_T^2 = \frac{16\pi}{1+\rho^2} \times \left.\frac{dN_{el}}{dt}\right|_{t=0}, \quad \rho = \left.\frac{\mathrm{Re}F}{\mathrm{Im}F}\right|_{t=0}$$

$$L\sigma_T = N_{el} + N_{inel}$$

$$\Downarrow$$

$$\sigma_T = \frac{16\pi}{1+\rho^2} \times \frac{(dN_{el}/dt)|_{t=0}}{N_{el} + N_{inel}}$$

- Elastic rate N_{el}
- Extrapolation to the optical point t=0

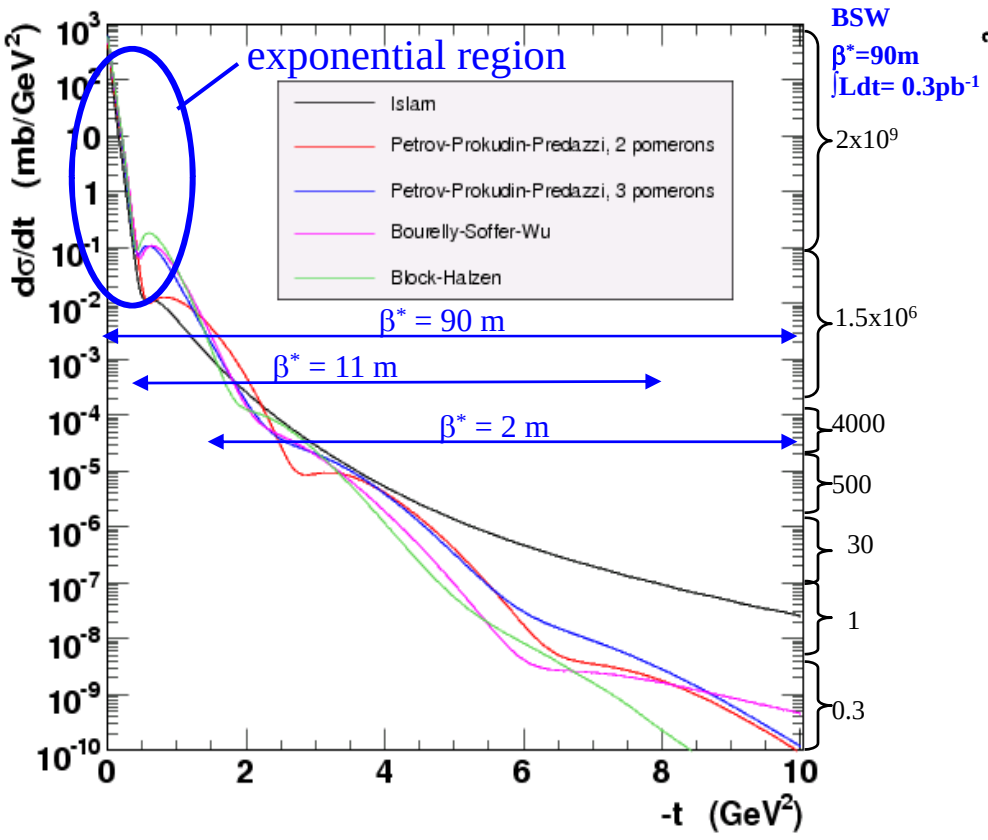
} **Depend on optics**

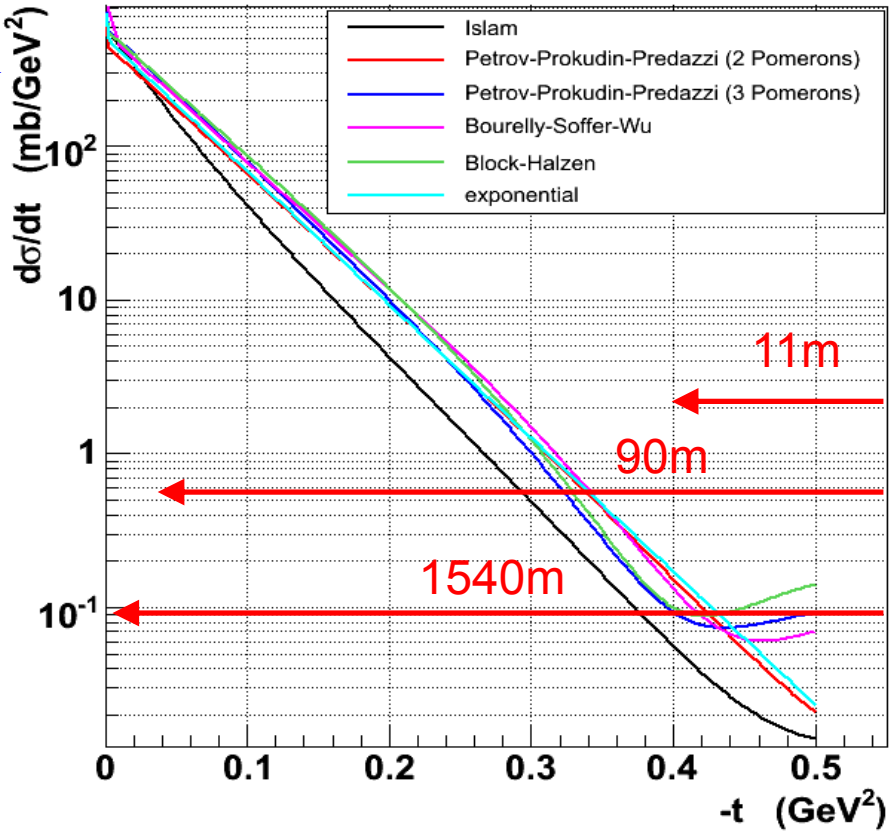
- Inelastic rate N_{inel}
- ρ - COMPETE extrapolation

$$t \cong -p^2\Theta^2$$

$$\rho = 0.1361 \pm 0.0015\ ^{+0.0058}_{-0.0025}$$

Elastic scattering, exponential part





High β* optics needed to measure the total pp cross-section

Early optics:

β*=90m (un-squeezing of existing injection optics, $|t| > 3 \cdot 10^{-2}$ GeV^2)

Target optics:

β*=1540m (difficult to have at the beginning – requires special injection optics)

acceptance at very low $|t| > 2 \cdot 10^{-3}$ GeV^2

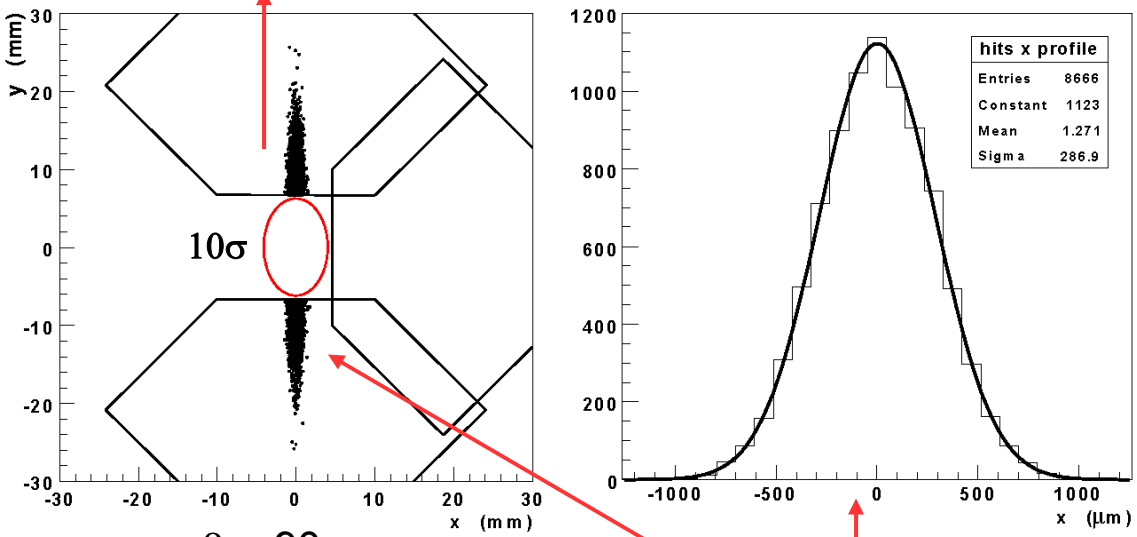
Elastic rate measurement (β^* = 90 m optics)

- Earliest possible high β^* optics
- |t|-acceptance down to 0.03 GeV^2 , covering well the exponential region of dσ/dt;
- Typical luminosity L ~ 10^{28} – 10^{29} cm^{-2} s^{-1}
- **parallel–to–point focusing** only in **vertical** plane @ 220 m
- **no emmission-angle dependence** in **horizontal** displacement
- Thick beam usefull for commissioning of RP detectors

elastic → $\begin{cases} y(220) = L_y \cdot \Theta_y^* \\ x(220) = v_x(s) \cdot x^* \end{cases}$

Elastically scattered protons @ RP 220, β^* = 90

$y \sim \Theta_y^{scatt} \sim \sqrt{|t_y|}$



β = 90 m

$x = v_x \cdot x^*$

Usefull for BPMs calibration

Inelastic event rate N_{inel}

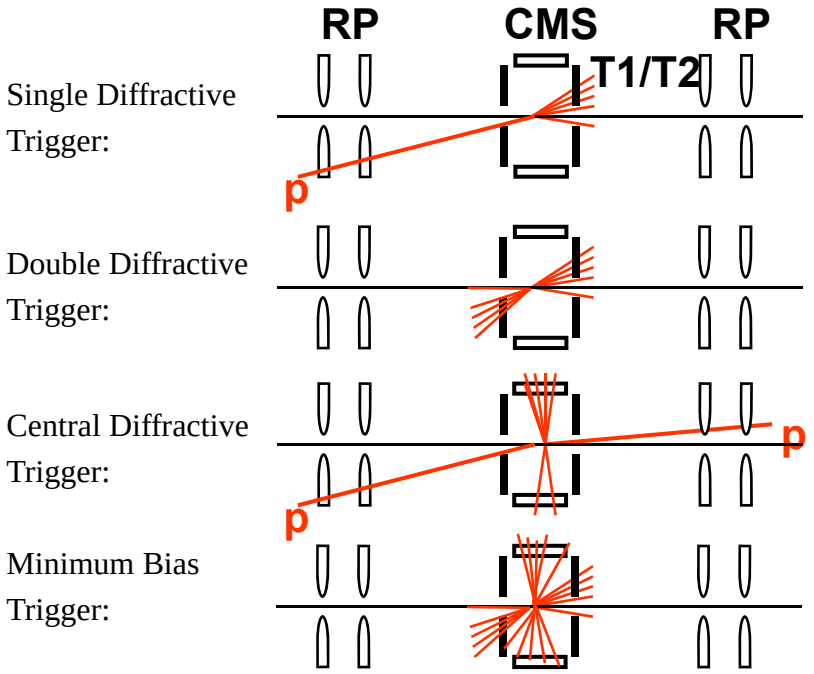
T1&T2 + RP provide fully inclusive trigger:

primary vertex reconstruction to discriminate against beam-gas interactions

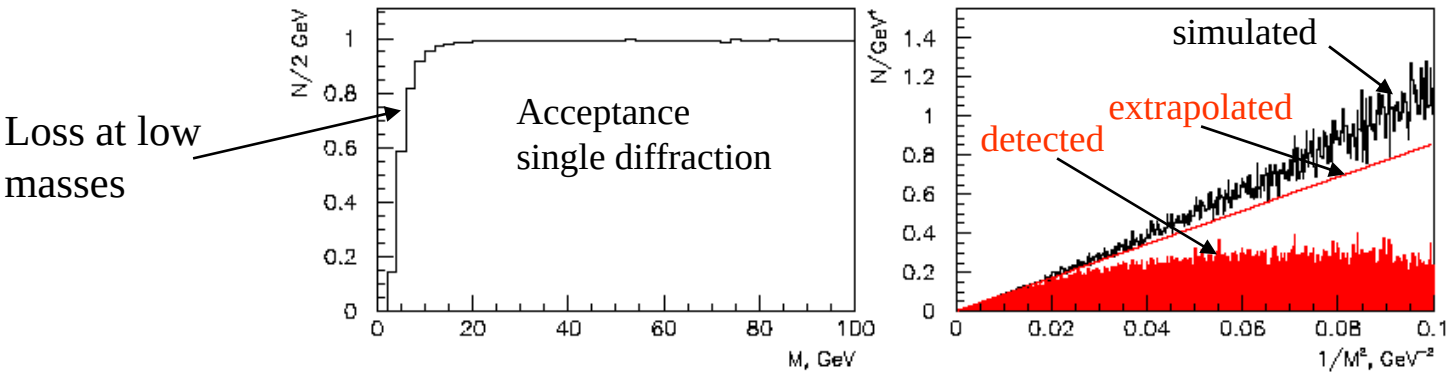
TOTEM Trigger efficiency:

SD: 82 %,

NSD > 99 % !



Extrapolation of SD cross-section to large $1/M^2$ using $d\sigma/dM^2 \sim 1/M^2$.



Combined uncertainty in σ_{tot}

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

	β^* = 90 m	1540 m
• **Extrapolation of elastic cross-section to t = 0:** (Smearing effects due to beam divergence, statistical errors, uncertainty of effective length L_{eff}, RP alignment, model dependent deviations)	± 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+ ρ^2):**	± 1.2 %	
Total uncertainty in σ_{tot} :	± 5%	± 1÷2 %
Total uncertainty in L :	± 7 %	± 2 %

β^* = 90 m required for early σ_{tot} measurement during the first year of LHC running at 10 TeV

Diffractive forward protons @ RPs

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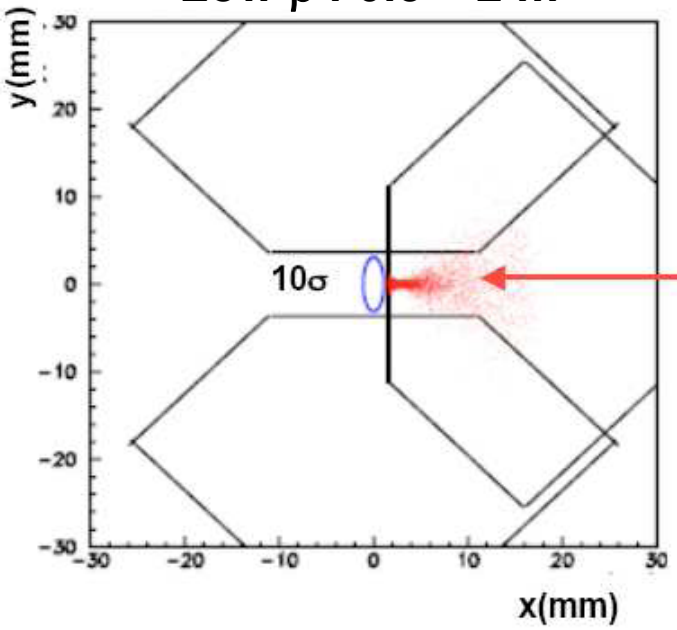
$$y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^*$$
$$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s)$$

Dispersion shifts diffractive protons in the horizontal direction

Diffractive protons : hit distribution @ RP220

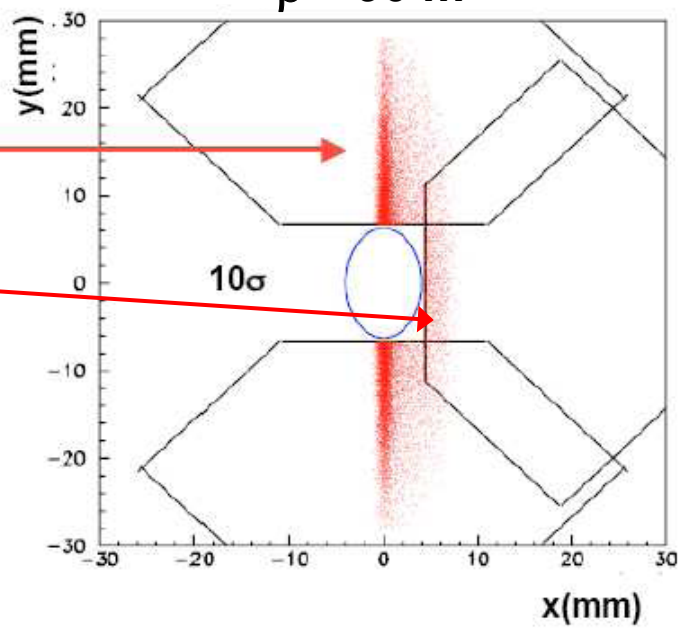
Low β*: 0.5 – 2 m



$y \sim \Theta_y^{scatt} \sim |t_y|^{1/2}$

$x \sim \xi = \Delta p/p$

β*= 90 m



- For low-β* 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 high
- beam σ = 212 μm → v_x, v_y important (deterioration of rec. resolution)

TOTEM diffractive protons' acceptance

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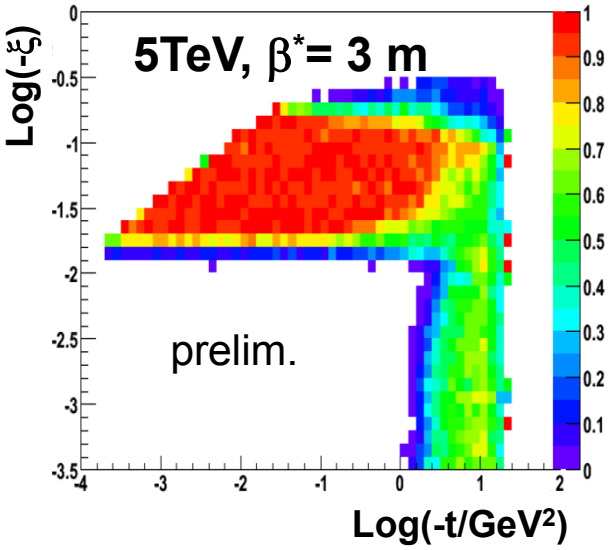

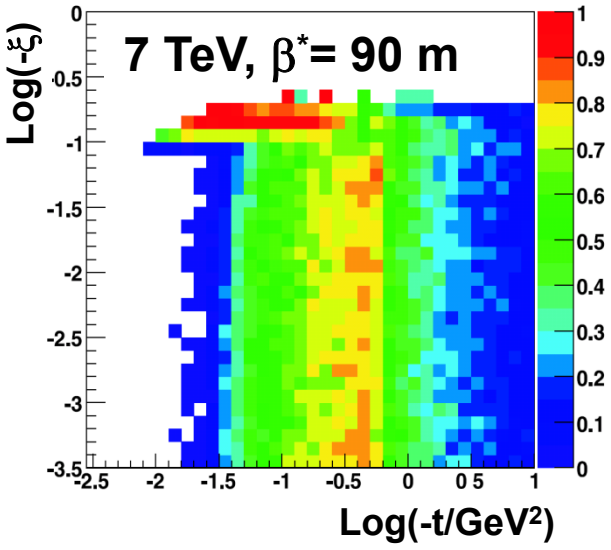

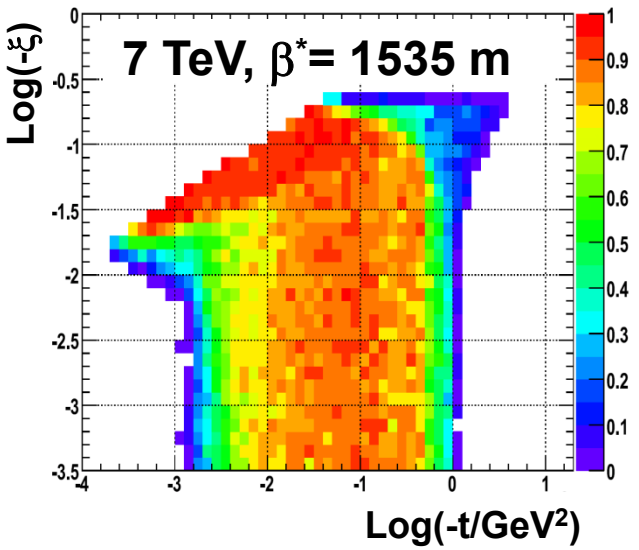

low β^*

low β^* : 0.5 – 2 m, $L \approx 10^{33}$ cm^{-2}s^{-1}
early running: E = 5TeV, β^* = 3 m

elastic acceptance
2 GeV^2 < -t < 10 GeV^2

resolution
$\sigma(\Theta)$ = 16 – 30 μrad
$\sigma(\xi) = 1 – 6 \cdot 10^{-3}$

-ξ > 2 % seen

(hard) diffraction, high |t| elastic scattering

β^* = 90 m

$L \approx 10^{30}$ cm^{-2}s^{-1}

elastic acceptance
$3 \cdot 10^{-2}$ GeV^2 < -t_y < 10 GeV^2

resolution
$\sigma(\Theta)$ = 1.7 μrad
$\sigma(\xi) = 6 – 15 \cdot 10^{-3}$

all ξ seen, universal optics

diffraction, mid |t| elastic scattering, total cross-section

β^* = 1535 m

$L \approx 10^{28} – 10^{29}$ cm^{-2}s^{-1}

elastic acceptance
$2 \cdot 10^{-3}$ GeV^2 < -t_y < 0.5 GeV^2

resolution
$\sigma(\Theta)$ = 0.3 μrad
$\sigma(\xi) = 2 – 10 \cdot 10^{-3}$

all ξ seen

total cross-section, low |t| elastic scattering

Early measurements with RPs (+ T1 & T2)

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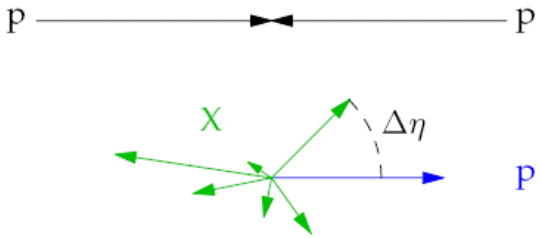
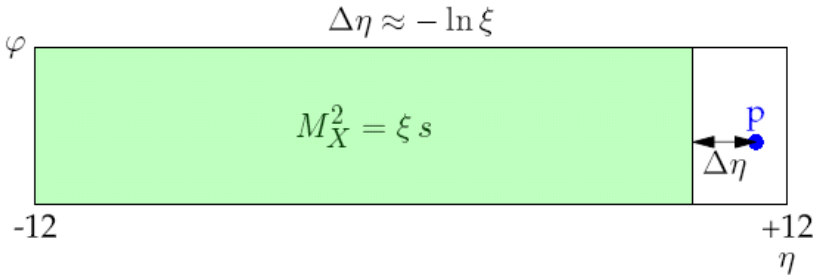
p = 5 TeV, β* = 3m
Acceptance: 0.02 < -ξ < 0.18, ξ = Δp/p
Resolution: σ(ξ) ~ 1 – 6 · 10^{-3}, σ(Θ*) ~ 15 μrad

$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}$$

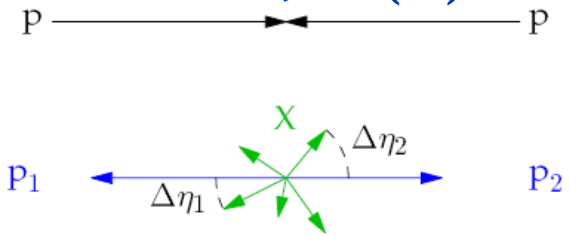
- **Measure ξ**
- **Compare with rap. gap Δη = -lnξ**
- **Cross-section σ (ξ,t)**

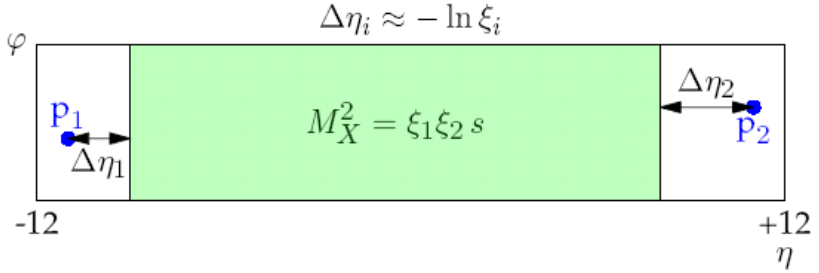
- **Single Diffraction (SD), horizontal RPs:**
  $d\sigma^{SD}/dM$ at high masses,
  1.4 < M < 4.2 TeV, σ(M)/M = 2 – 4 %





- **Double Pomeron Exchange (DPE), horizontal RPs:**
  d σ^{DPE}/dM at high masses,
  0.2 < M < 1.8 TeV, σ(M)/M < 2 – 4 %





- **Elastic Scattering, vertical RPs:**
  d σ^{ES}/dt for 2 < |t| < 10 GeV^2, σ(t)/t ~ 0.2/√|t|

Early measurements T1 & T2

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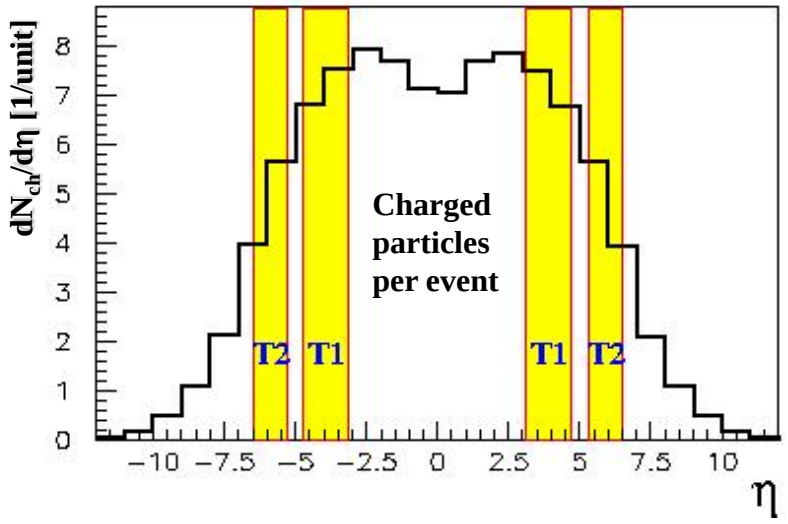
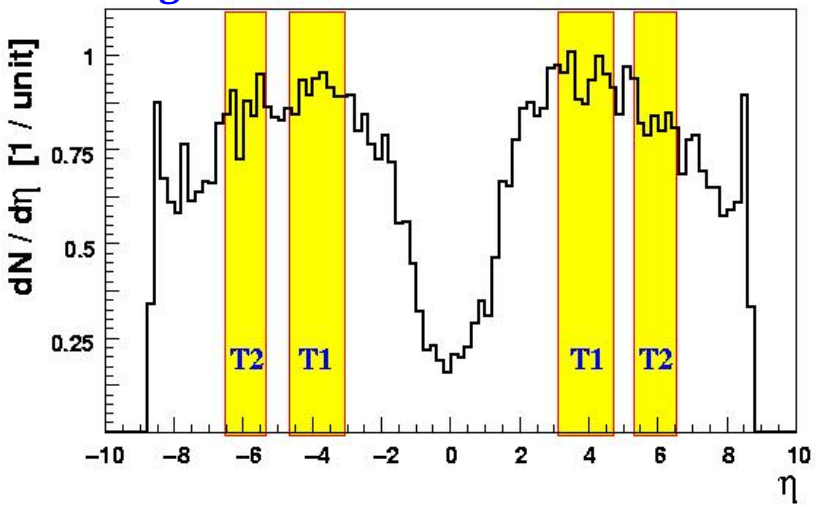
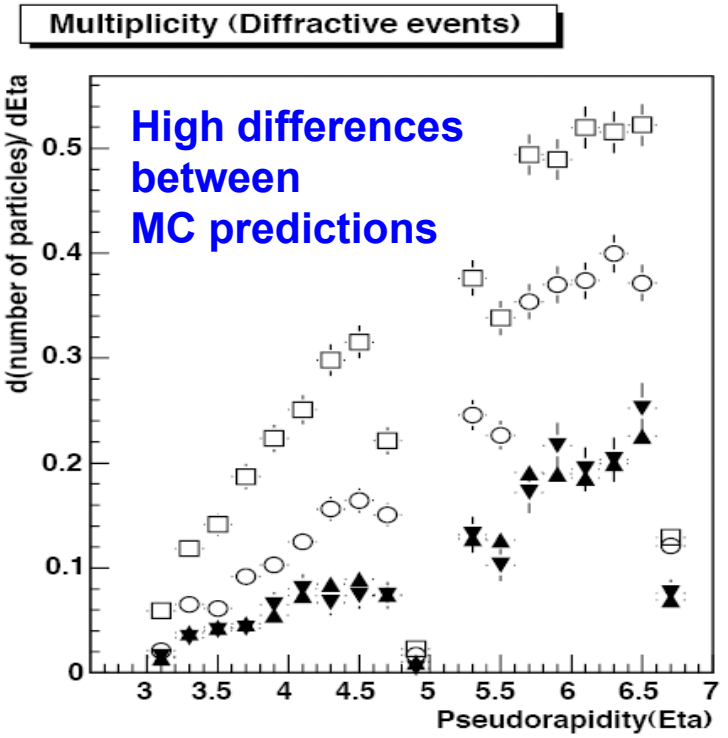
non-diffractive minimum bias events



single-diffractive events



- Rapidity gap studies (topologies of diffractive events)
- Charged multiplicity studies (essential for minimum bias and cosmic ray MC generators tuning / validation)



Outlook: Detection of Diffractive Protons in IR3

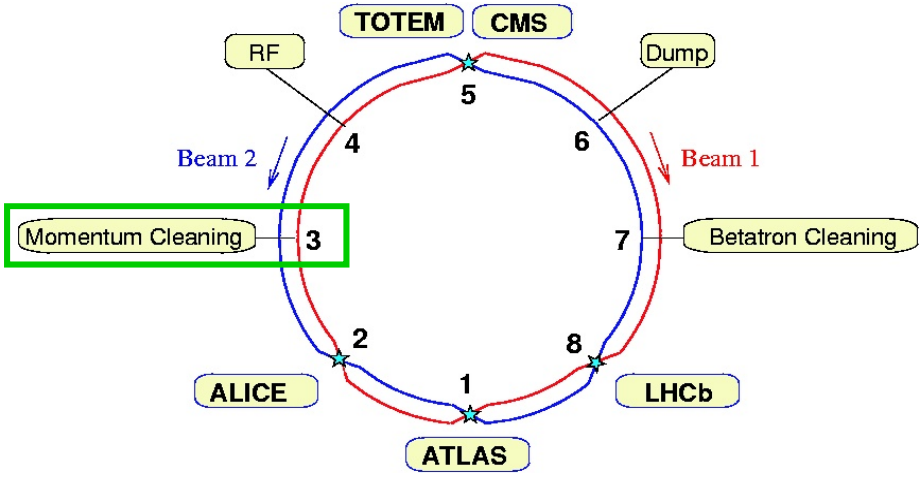
TOTEM

Good acceptance and momentum resolution for diffractive protons needs:

large dispersion D (few m) (x=ξ·D)
small beam width σ(<1 mm)

Available in Momentum Cleaning Region IR3!

A combined collimator-detector device can be placed there.

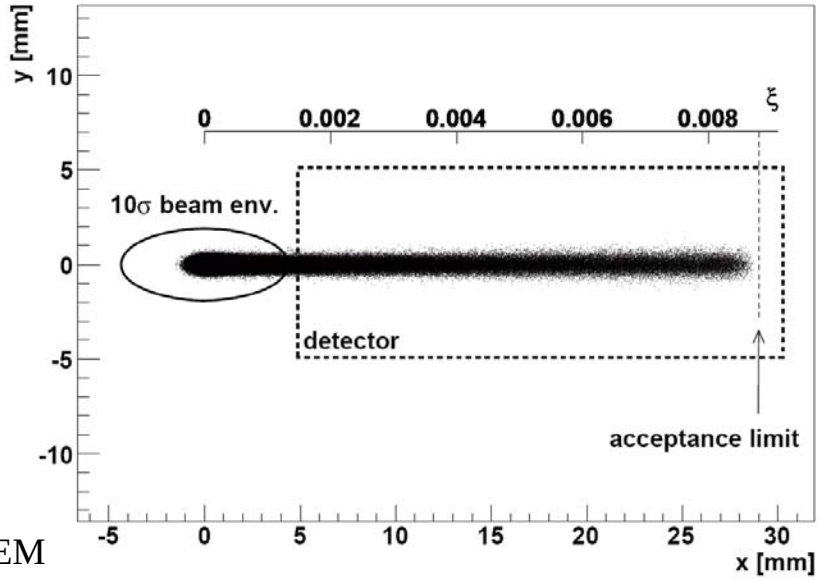


Advantage for machine protection:

- **collimator downstream of detectors absorbs possible showers**
- **Warm region!**

- **Detect diffractive protons from all interaction points.**
- **~3MHz diffractive proton rate hitting Q6 magnet found (~5MHz quench limit)**
  - **magnet protection possibly needed at L=10^{34}**

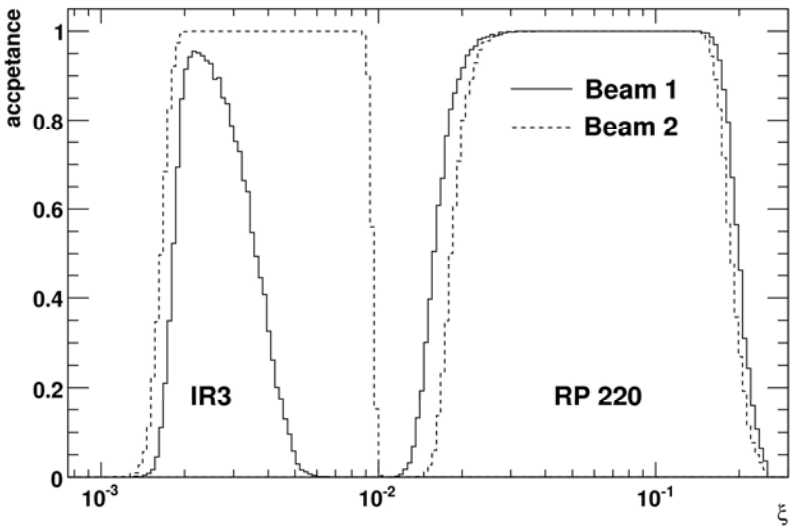
IP 3 hit distribution in a plane transverse to Beam 2 for DPE events @ IP5

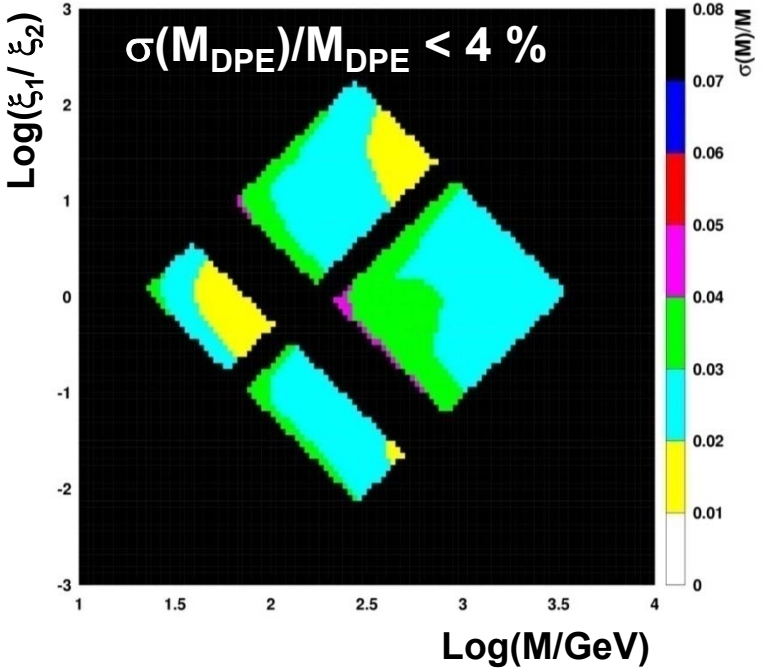


Proton Acceptance of a "Combined IP3 + RP220 TOTEM" Experiment

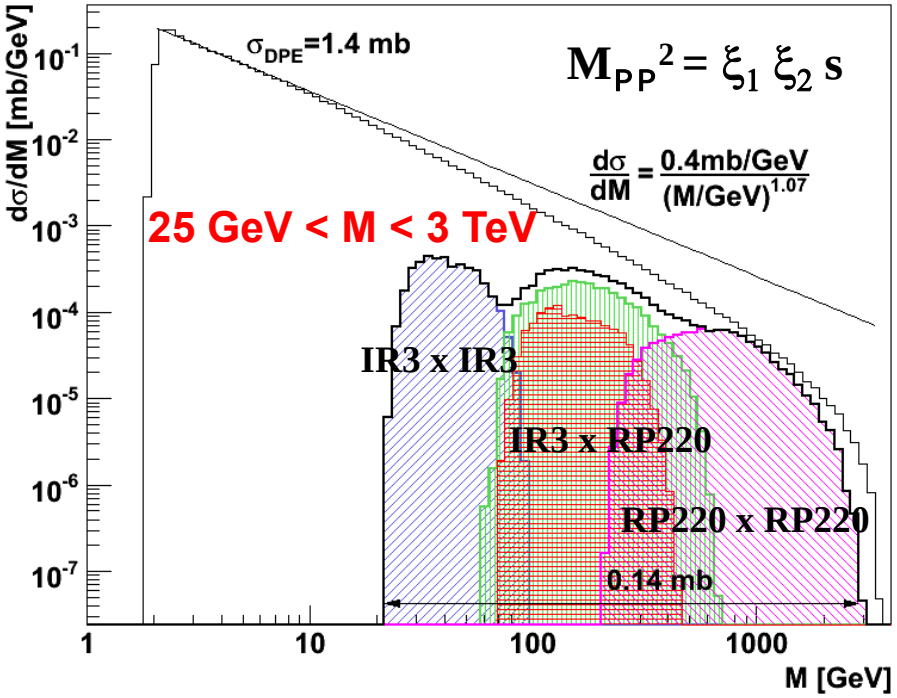
TOTEM

ξ–aceptance, β*=0.5 m, p=7 TeV





DPE Mass Spectrum with Detector Acceptance



- Nearly **full M_{DPE}-range** avaliable at low β^* and high $\mathcal{L}$
- **Luminosity calibration** for all LHC experiments:
  - After absolute σ_{tot} & $\mathcal{L}$ measurements with TOTEM
  - Use low-mass DPE with both protons detected in IR3 as a "standard candle"
  - Identify interaction point by time difference between the 2 protons

Summary

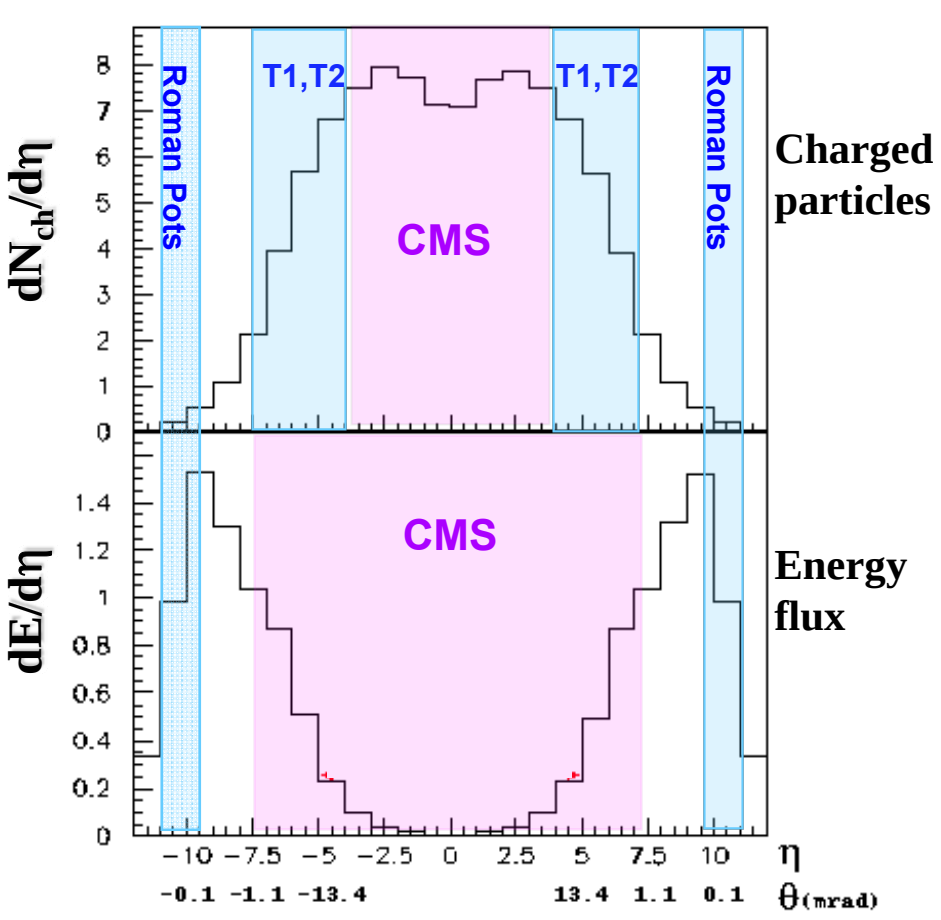
- **TOTEM** will be **ready** for data taking at the LHC restart and will run under all beam conditions.
- Measurement of **total pp cross-section** (and L) with a precision of **1-2%** (**2%**) with $\beta^* = 1540$ m (dedicated runs).
- Measurement of **elastic scattering** in the range **$10^{-3} < |t| < 10$ GeV^2**
- Early measurements
  - low β^*:
    - study of SD and DPE at high masses
    - elastic scattering at high |t|
    - measurement of forward charged multiplicity
  - $\beta^* = 90$ m:
    - first measurement of σ_{tot} (and L) with a precision of **~ 5%** (**~ 7%**)
    - elastic scattering in a wide |t| range
    - inclusive studies of diffractive processes
    - measurement of forward charged multiplicity
- Later: common CMS/TOTEM Physics Programme

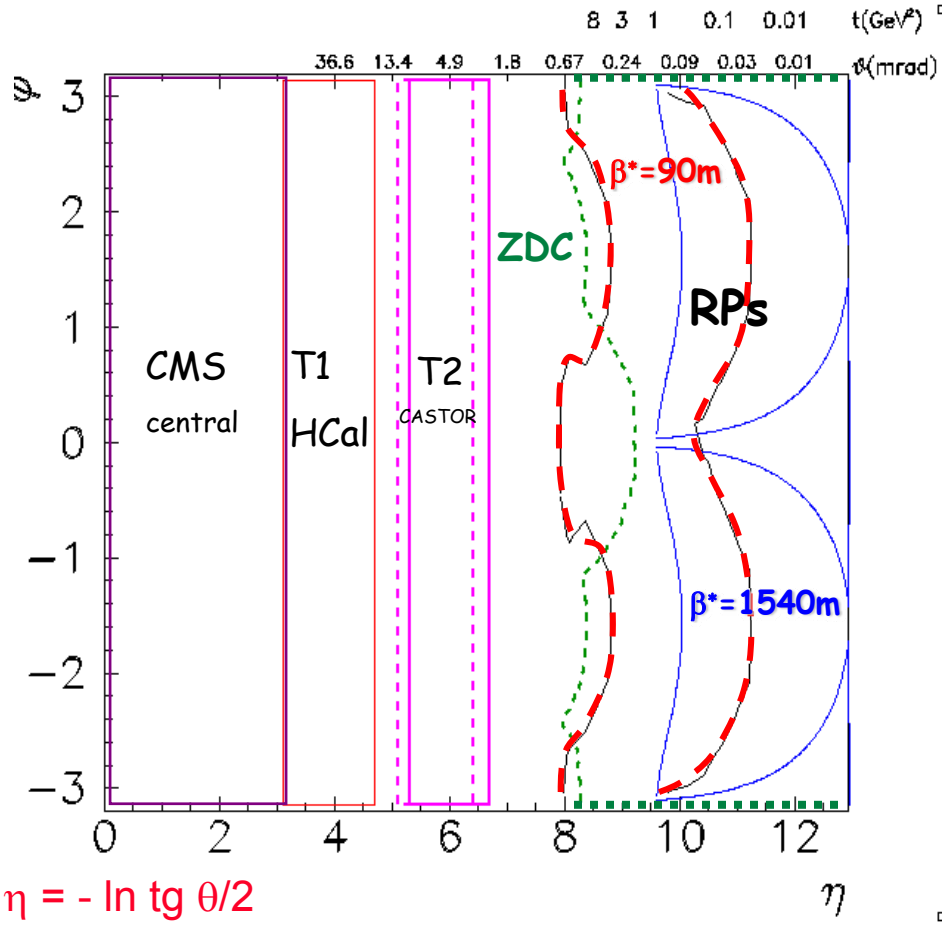
CMS + TOTEM: Acceptance

TOTEM

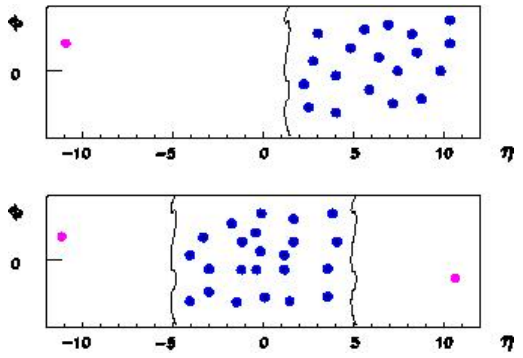
largest acceptance detector ever built at a hadron collider

90% (65%) of all diffractive protons are detected for $\beta^* = 1540$ (90) m



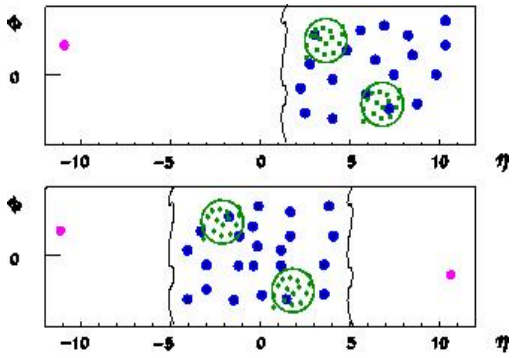


CMS + TOTEM running scenarios



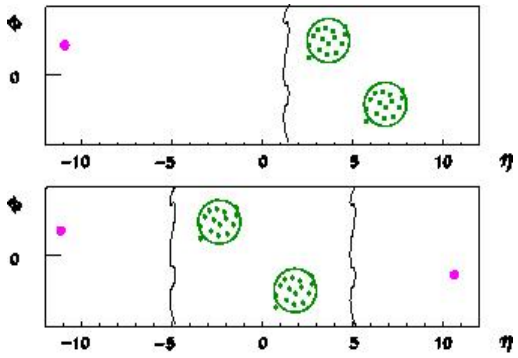
pp->pX
pp->pXp

soft diffraction



pp->pjjX
pp->pjjXp

(semi)-hard diffraction



pp->pjj (bosons, heavy
pp->pjjp quarks,Higgs...)

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

Accessible physics depends on luminosity & β*

Prospects for Diffractive and Forward Physics at the LHC, CERN/LHCC 2006-039/G-124

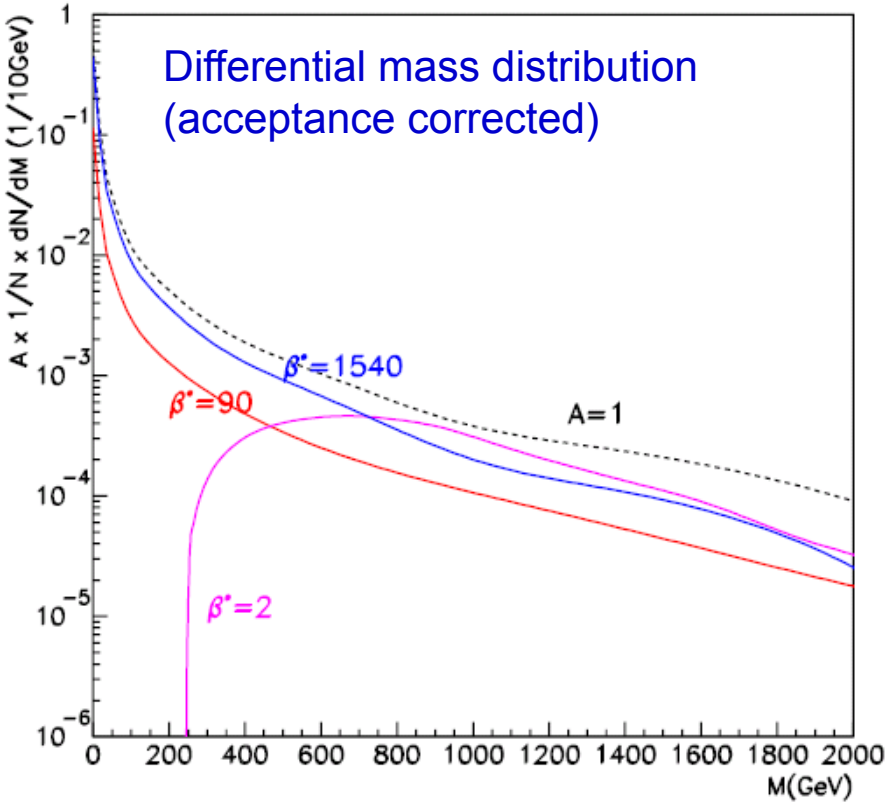
Differential mass distribution in DPE

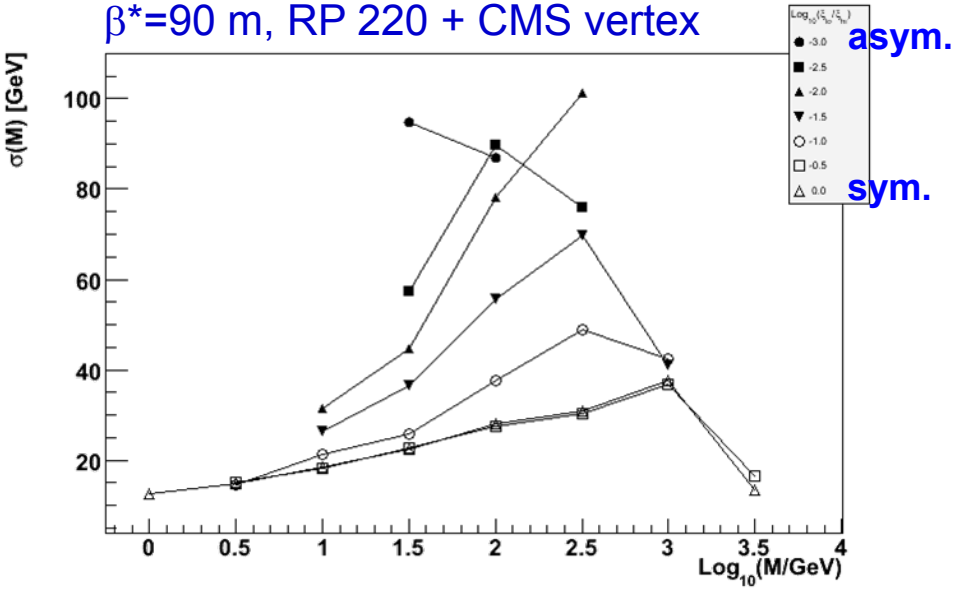
- **Study of mass distributions via the 2 protons**
  - **Trigger with 2p+T1/T2: rate ~200Hz @ β^*=90m, L=10^{30}cm^{-2}s^{-1}**
  - **TOTEM trigger rate limit ~2kHz**

low/medium luminosity

- **ξ measured directly (TOTEM) or**
  - **With rapidity gap $\Delta\eta$=-ln ξ**
  - **With calorimeters $\xi = \sum_i E_T^i e^{\mp\eta_i} / \sqrt{s}$**

} (TOTEM+CMS)





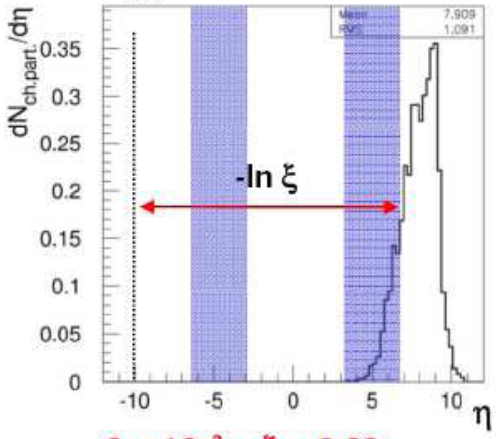
Pseudorapidity Distributions for SD

TOTEM

$\xi = \Delta p / p$

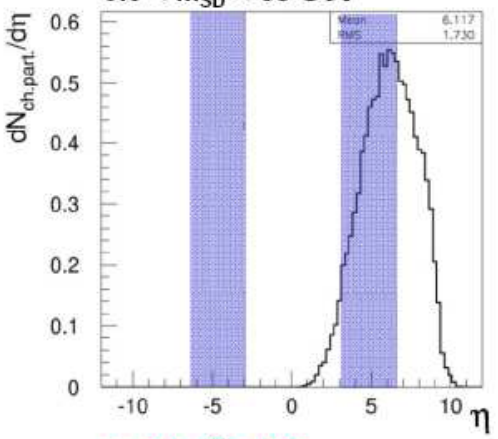
$\xi < 5 \times 10^{-7}$

M_{SD} < 9.9 GeV



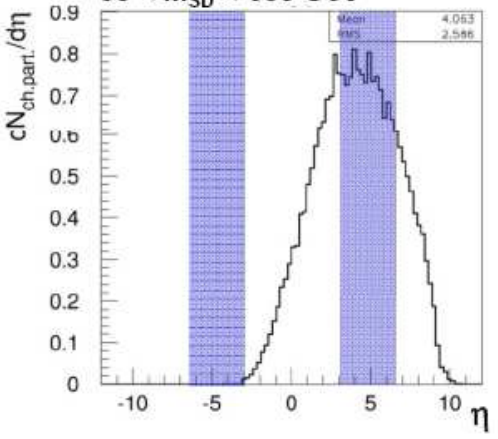
$5 \times 10^{-7} < \xi < 2 \times 10^{-5}$

9.9 < M_{SD} < 63 GeV



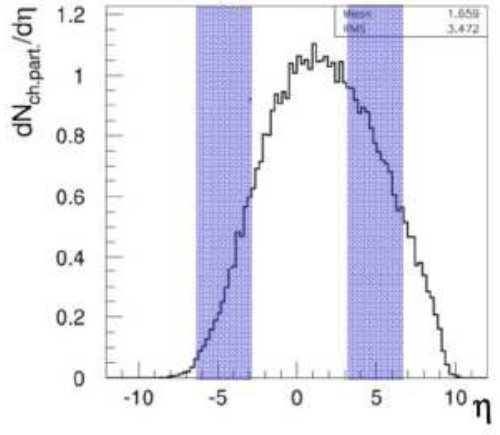
$2 \times 10^{-5} < \xi < 2 \times 10^{-3}$

63 < M_{SD} < 630 GeV



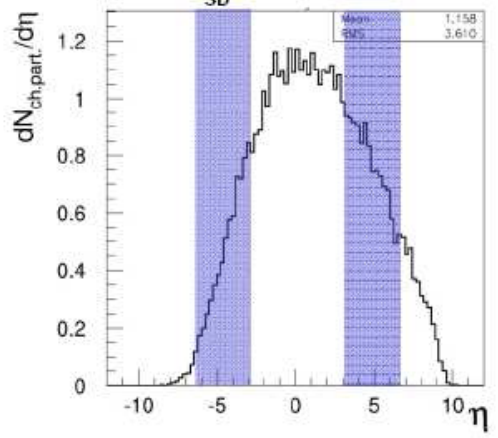
$2 \times 10^{-3} < \xi < 0.02$

0.63 < M_{SD} < 2.0 TeV



$0.02 < \xi < 0.2$

2.0 < M_{SD} < 6.3 TeV



Running Scenarios

Scenario Physics:	1 low |t| elastic, σ_{tot} (@ ~1%), MB, soft diffr.	2 low/large |t| elastic, σ_{tot} (@ ~5%), MB, soft/semi-h. diffr.	3 large |t| elastic, hard diffraction
β^* [m]	1540	90	2 ÷ 0.5
N of bunches	43 ÷ 156	156	936 ÷ 2808
Bunch spacing [ns]	2025 ÷ 525	525	25
N of part. per bunch	(0.6 ÷ 1.15) x 10^{11}	1.15 x 10^{11}	1.15 x 10^{11}
Half crossing angle [μrad]	0	0	92
Transv. norm. emitt. ε_n [μm rad]	1	3.75	3.75
RMS beam size at IP [μm]	450	213	32
RMS beam diverg. at IP [μrad]	0.3	2.3	16
Peak Luminosity [cm^{-2} s^{-1}]	10^{28} ÷ 2 x 10^{29}	3 x 10^{30}	10^{33}

← Cross section
Luminosity →

β^* (m)	1540	90	2	0.5
L (cm^{-2} s^{-1})	10^{29}	10^{30}	10^{32}	10^{33}
	TOTEM runs		Standard runs	

Accessible physics depends on luminosity & β^*

beam ang. spread at IP: $\sigma_{\theta^*} = \sqrt{(\varepsilon / \beta^*)}$

beam size at IP: $\sigma^* = \sqrt{(\varepsilon \beta^*)}$

- Optimal β^* = 1540m optics requires special injection optics: probably NOT available at the beginning of LHC
- Early β^* = 90m optics achievable using the standard LHC injection optics