

# TOTEM

## experiment at the LHC: status and program

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*INFN-Genova*

*On behalf of the TOTEM collaboration*



# TOTEM collaboration

**CERN, Geneva, Switzerland**

**Università di Genova and Sezione INFN-Genova, Italy**

**Università di Siena and Sezione INFN-Pisa, Italy**

**INFN Sezione di Bari and Politecnico di Bari, Italy**

**University of Helsinki and HIP, Helsinki, Finland**

**Academy of Sciences, Praha, Czech Republic;**

**Estonian Academy of Sciences, Tallinn, Estonia**

**Warsaw University of Technology, Plock, Poland**

**Penn State University, University Park, USA**

**Case Western Reserve University, Cleveland, Ohio, USA**

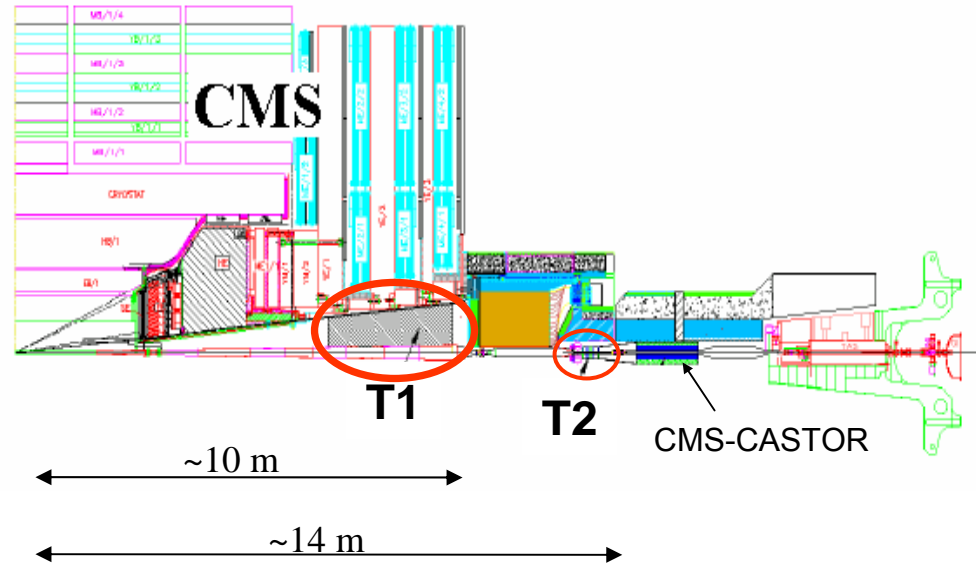
**Brunel University, Uxbridge, UK**

# Physics goals

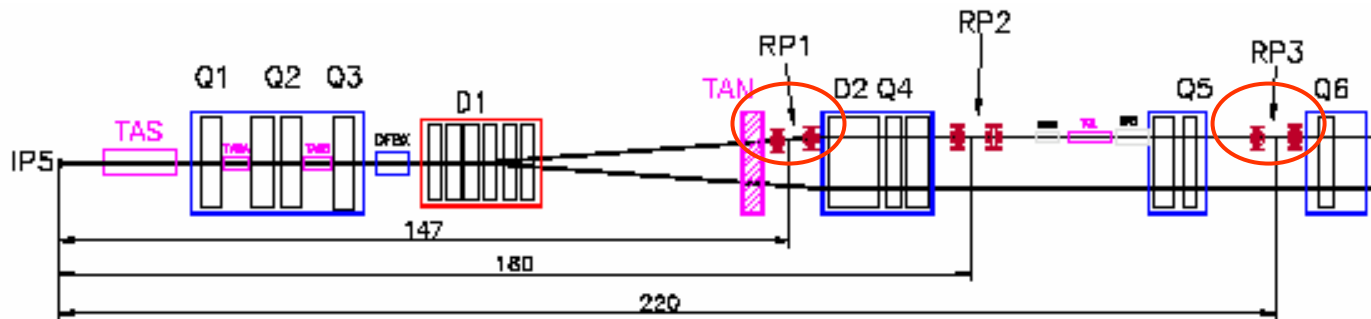
- Measurement of the **total p-p cross-section** at 14 TeV with  $\sim 1\%$  error
- Measurement of the p-p **elastic scattering** in the range  $10^{-3} < -t < 8 \text{ GeV}^2$  ( $-t \sim (p\theta)^2$ )
- **Forward physics**:
  - soft diffraction
  - and with **CMS**
    - SD and DPE production of jets, W, heavy flavors, etc.
    - particle and energy flow in the forward direction
    - central exclusive production
    - low-x physics

# TOTEM detectors

- Inelastic detectors
  - T1 – **CSC** Coverage  $3.1 < |\eta| < 4.7$
  - T2 – **GEM** Coverage  $5.3 < |\eta| < 6.6$
- Leading proton detectors
  - Silicon detectors inside Roman Pots (at 147, 180, 220 m from IP)



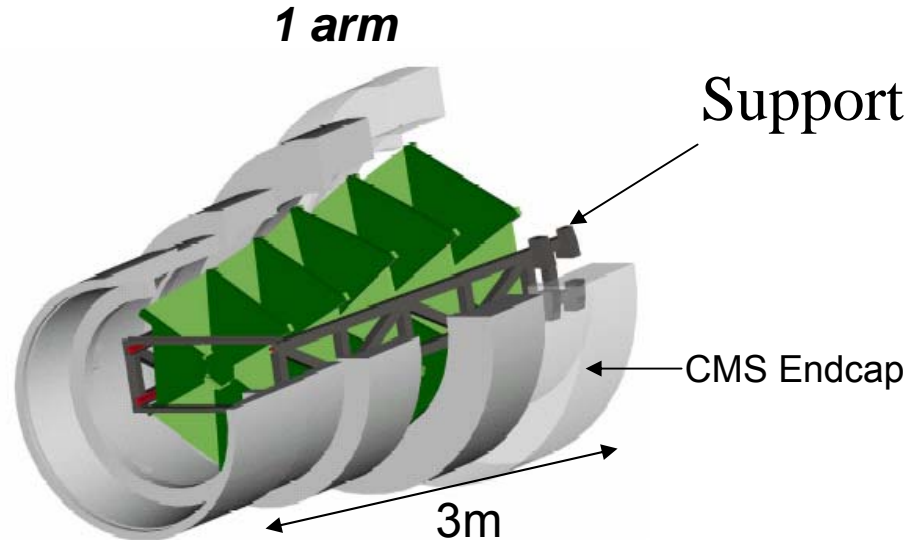
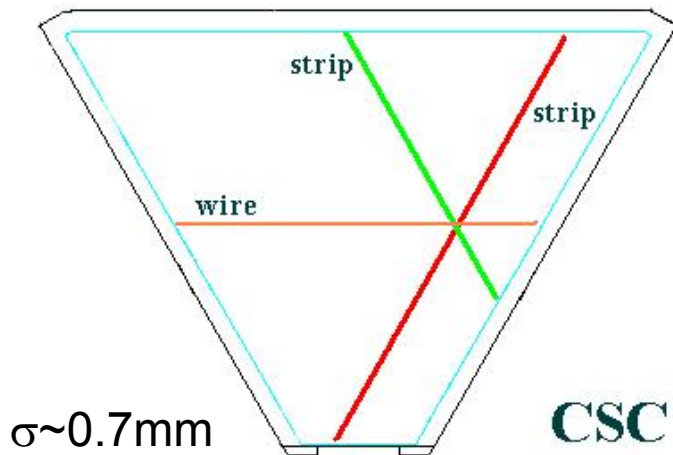
Detectors on both sides.



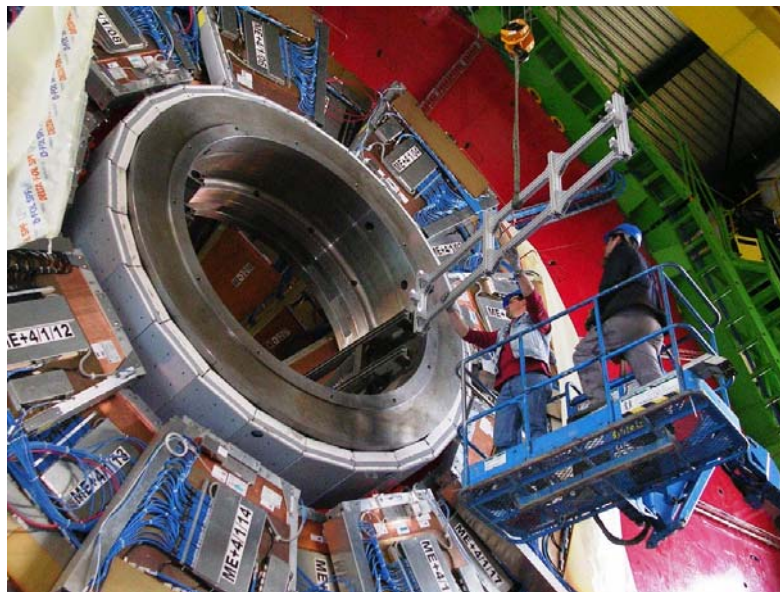
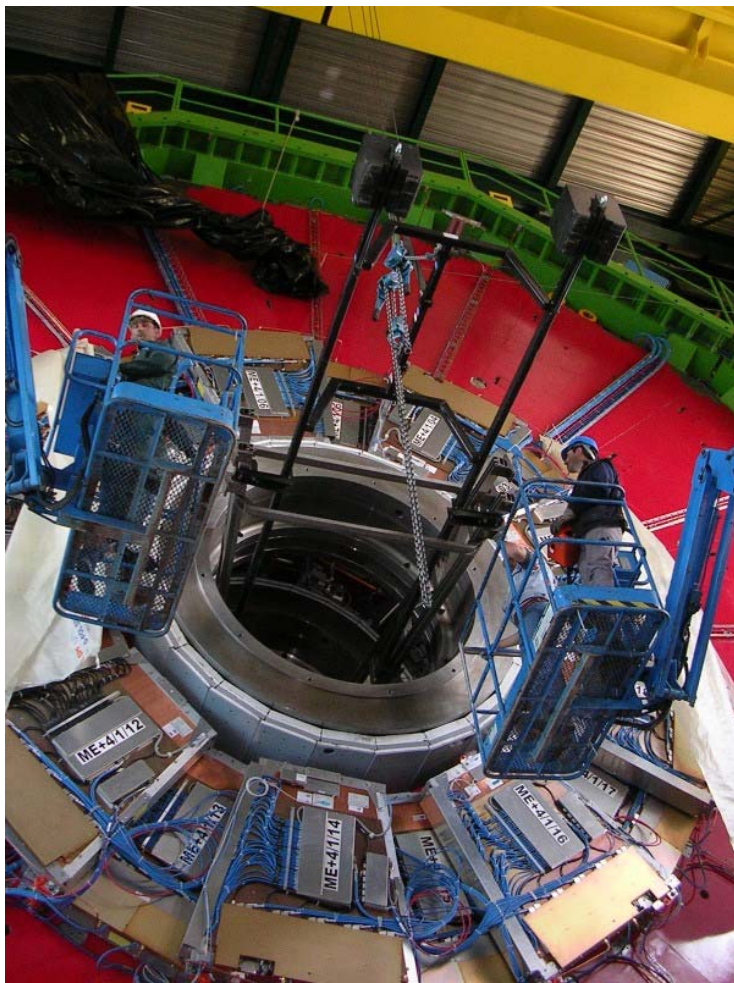
# T1 telescope



- **5 planes with measurement of three coordinates per plane.**
- 3 degrees rotation and overlap between adjacent planes
- **Primary vertex reconstruction**
- Trigger with CSC wires



# T1 support installation

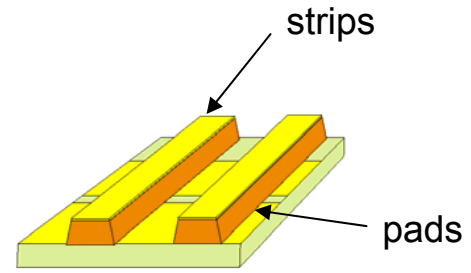
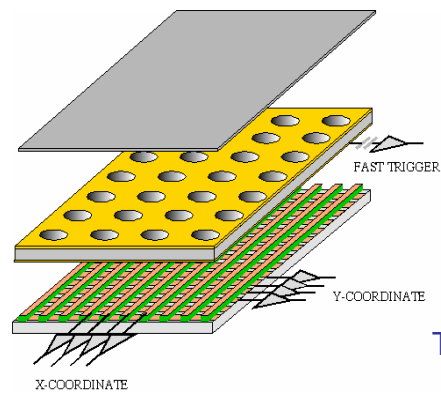


# T2: telescope

10 triple-GEM planes, to cope with high particle fluxes

$5.3 < |\eta| < 6.6$

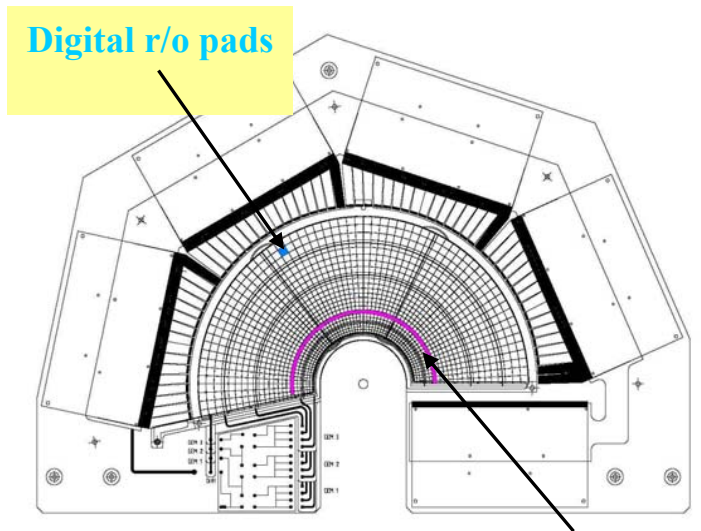
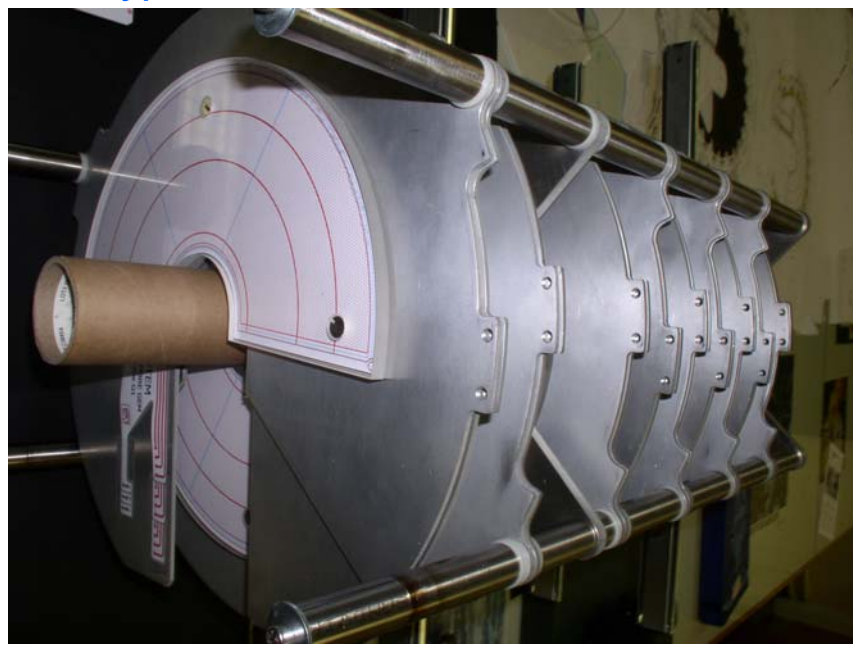
$\sigma_{strip} \sim 70 \mu m$



Double readout layer: **Strips** for radial position, **Pads** for  $\eta, \phi$ .

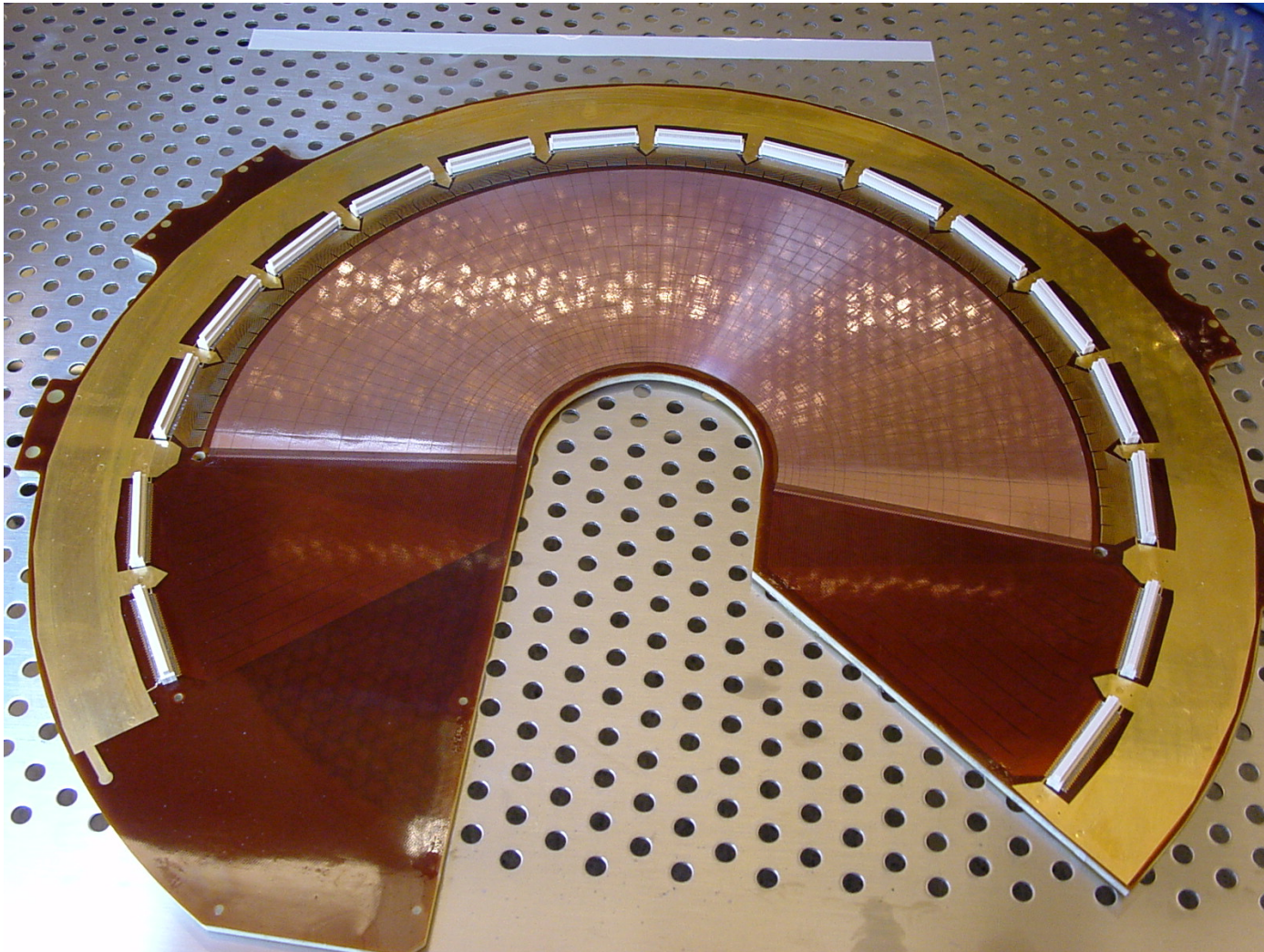
Technology used in COMPASS

## Prototypes



Digital r/o circular strips

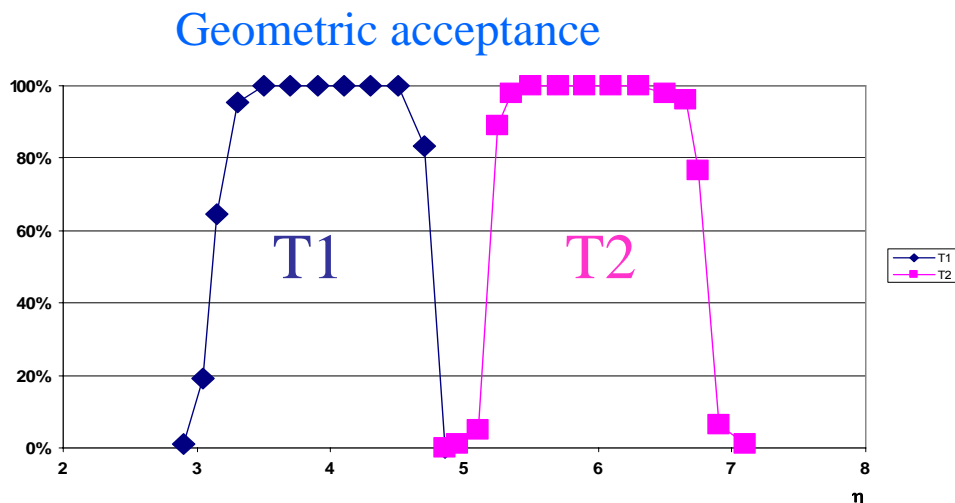
# T2 readout board





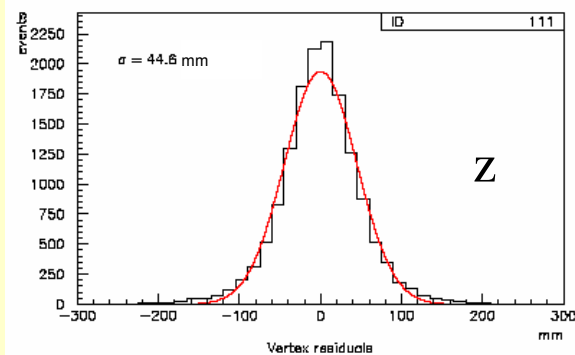
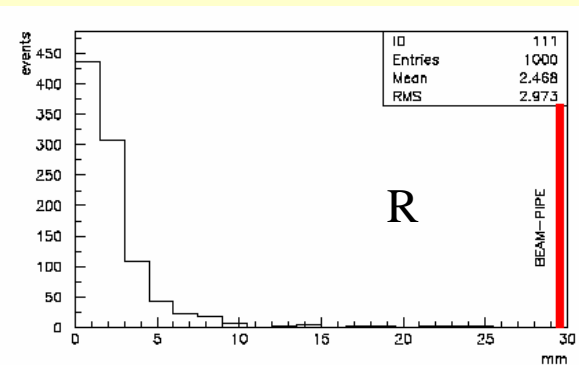
# T1 and T2: simulation and performances

- Reconstructed vertex well inside the beampipe ( $\sigma_r \sim 3\text{mm}$ ) and within  $\pm 5\text{ cm}$  along the beam axis



The primary vertex resolution is sufficient to discriminate beam-beam from beam-gas events.

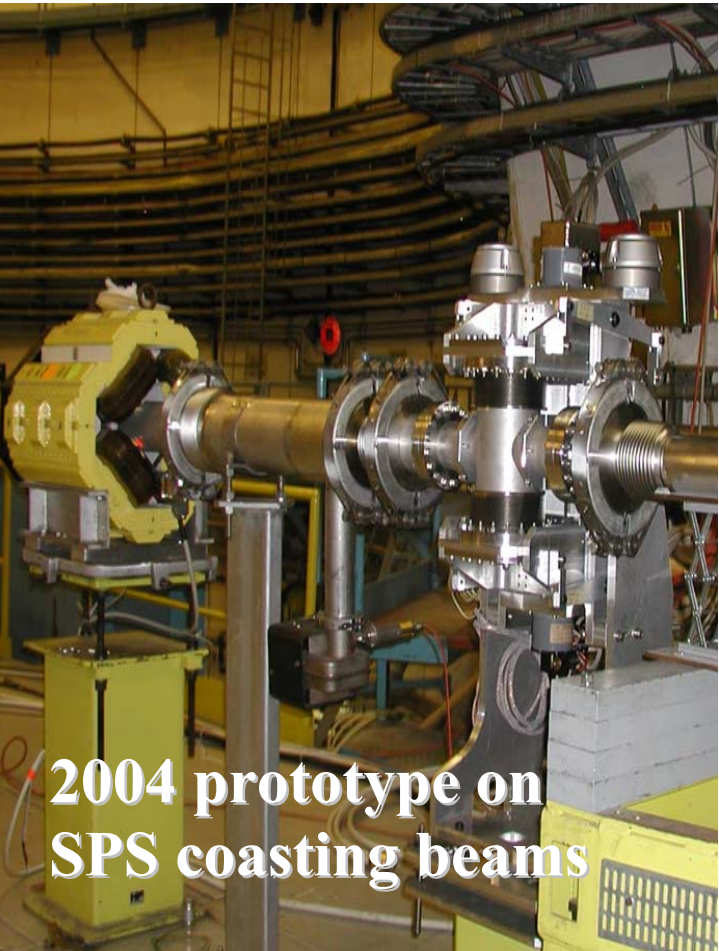
## Primary vertex resolution



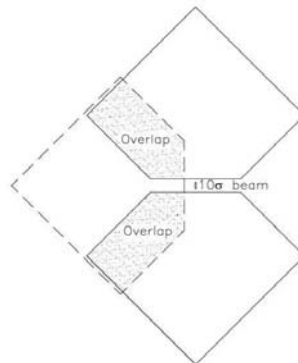
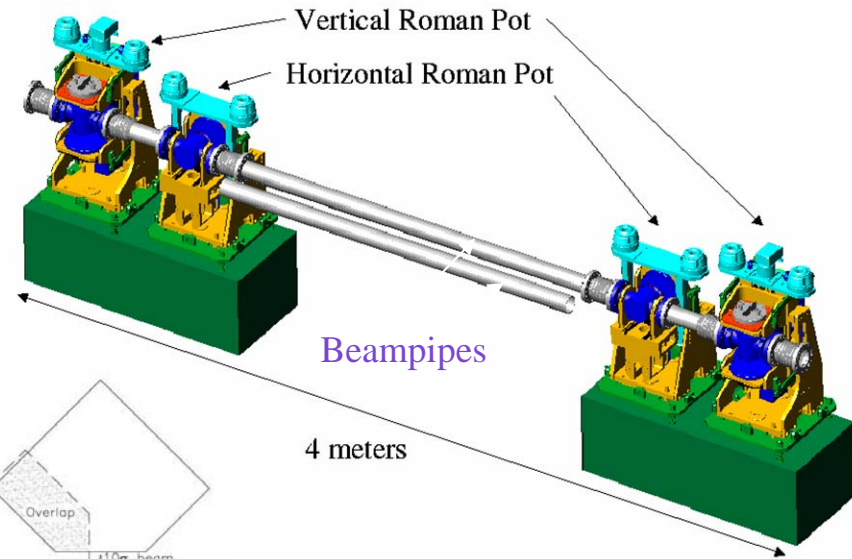
# Roman Pots

Protons at angles of few  $\mu\text{rad}$  with RPs at  $10\sigma + d$  from beam

$$\sigma^{\text{beam}} \sim 80 \mu\text{m at Totem}$$

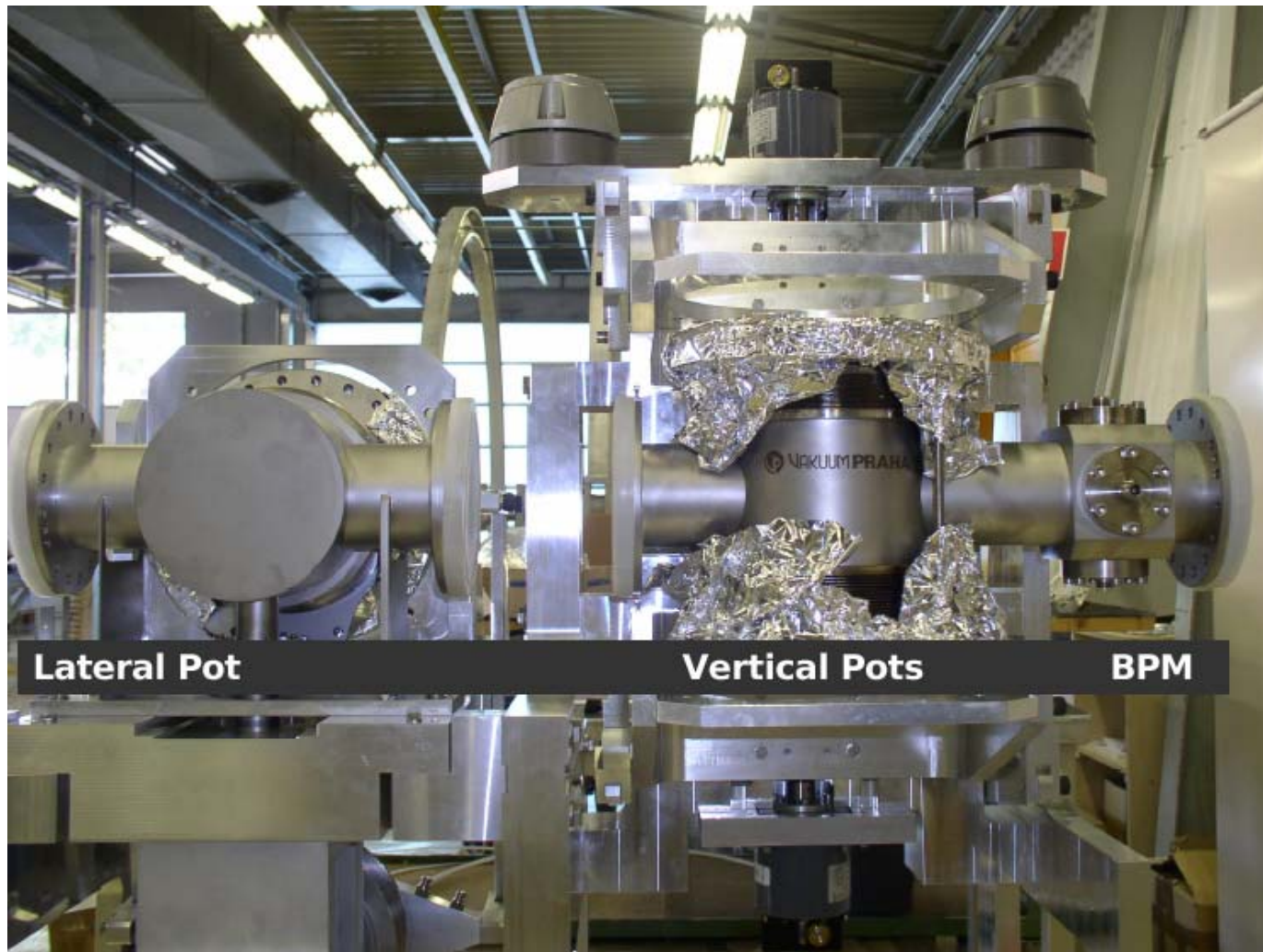


Each **RP station** consists in **2 units** separated by **4m**  
 Each unit has **2 vertical** insertions ('pots') and **1 horizontal**



- 10 planes
- Detector overlapping for tracks alignment

# Roman pots

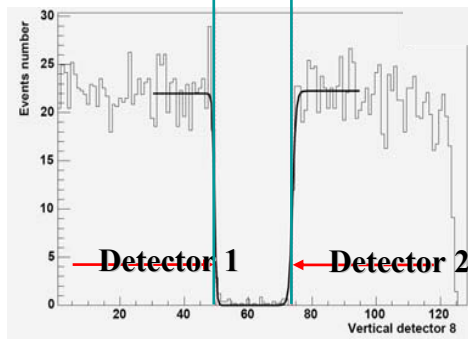
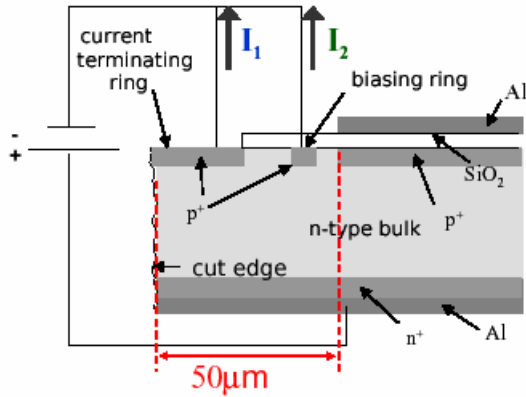


# Leading proton detectors

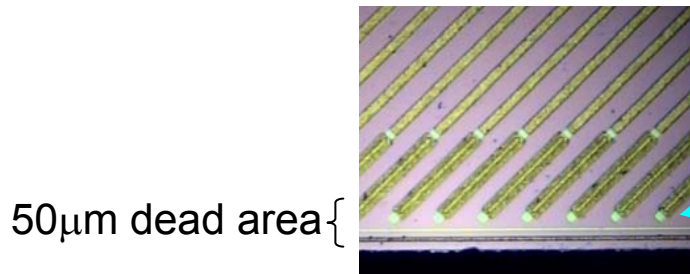


## Current Terminating Structure

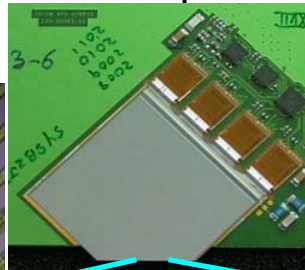
Standard technology with reduced guard rings



Test beam



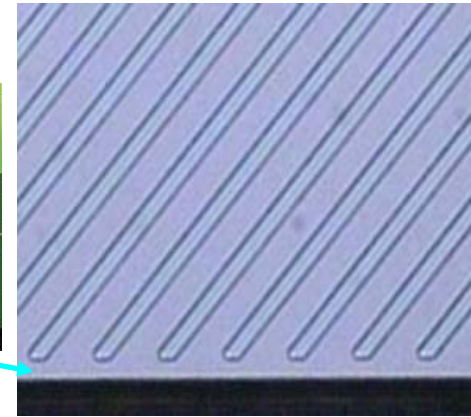
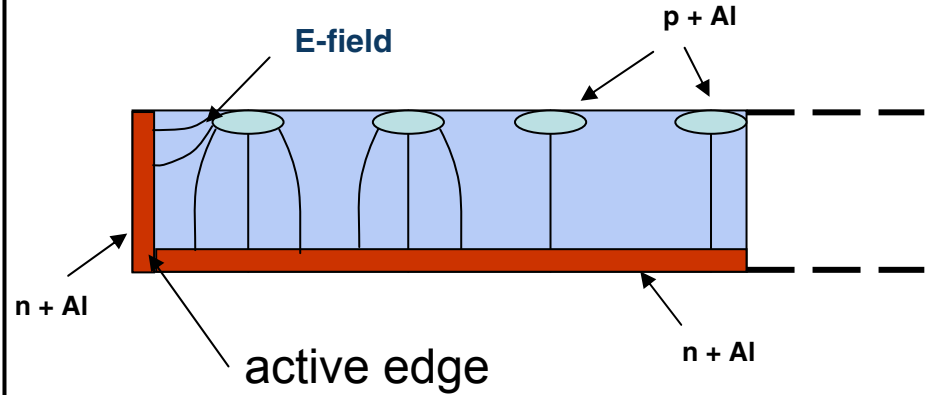
50µm dead area {



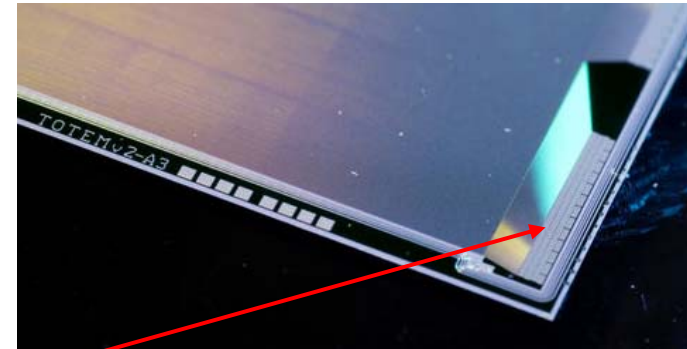
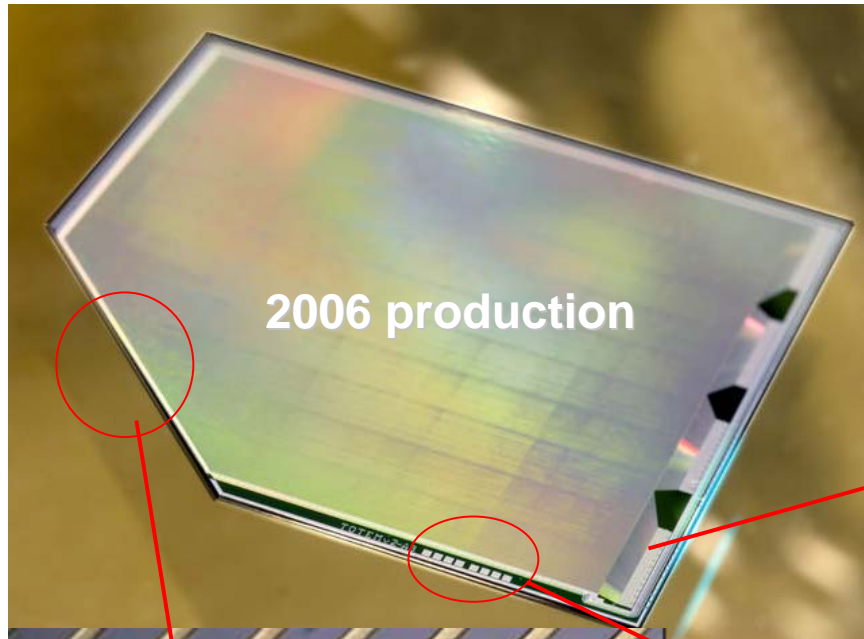
} 10µm dead area

## Planar 3D

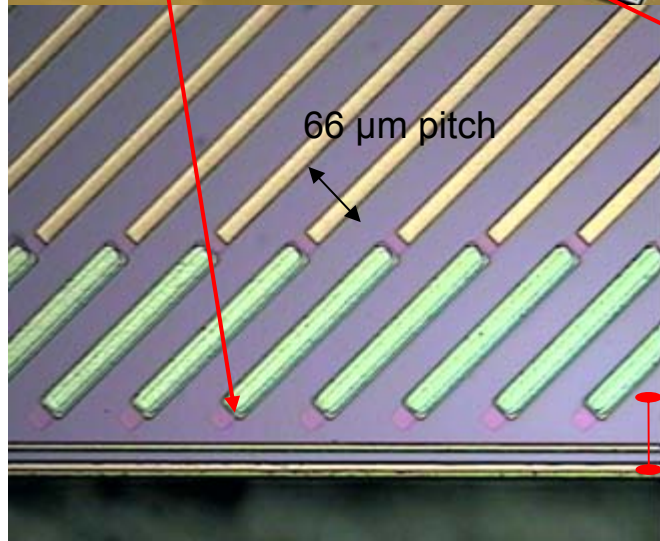
Traditional planar detector with active edge



# Silicon edgeless detectors



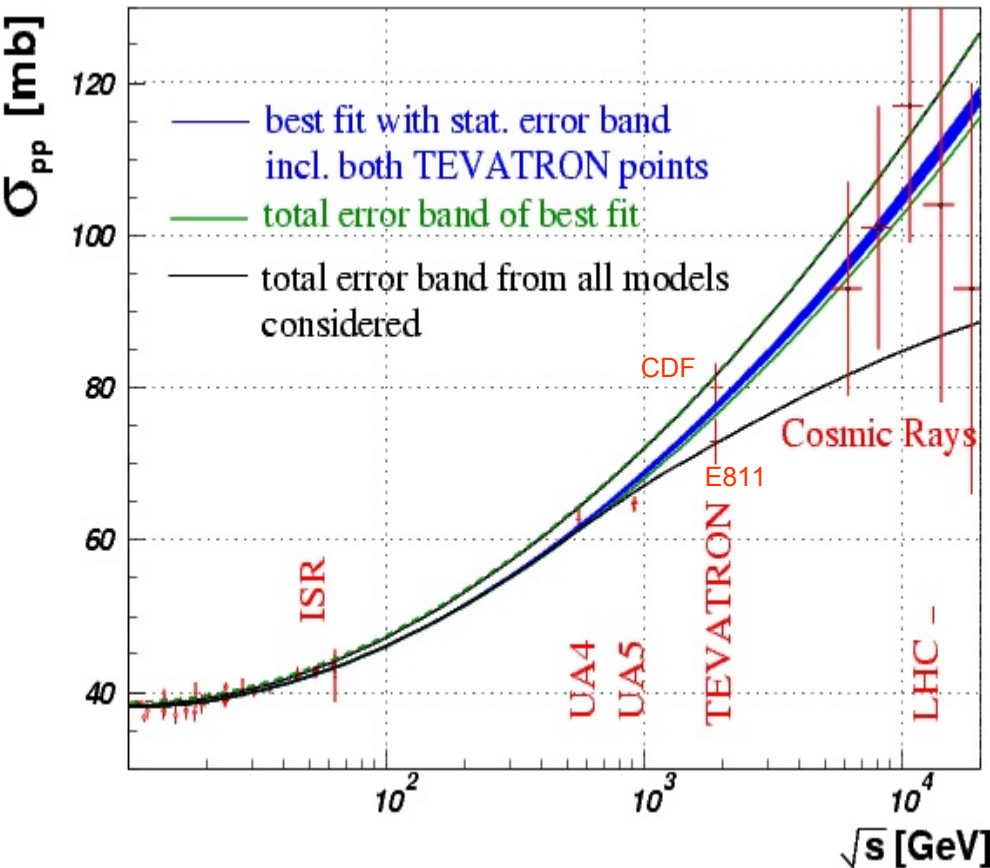
Pitch adapter on detector



50 μm  
dead area



# Total cross-section: experimental results



Previous measurements: PS, ISR, SPS, TEVATRON, Cosmic Rays

$\sigma \sim (\log(s))^\gamma$  with  $\gamma \sim 2$

COMPETE fit predicts at the LHC energy:

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

$$\rho = \frac{\text{Re}(F)}{\text{Im}(F)} = 0.1361 \pm 0.0015^{+0.0058}_{-0.0025}$$

# $\sigma_{tot}$ : experimental method

Luminosity independent measurement using the **Optical theorem**.

$$\left. \begin{aligned}
 L\sigma_{tot}^2 &= \frac{16\pi}{1+\rho^2} \times \frac{dN}{dt} \Big|_{t=0} \\
 L\sigma_{tot} &= N_{elastic} + N_{inelastic}
 \end{aligned} \right\} \Rightarrow \boxed{\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN_{el} / dt) \Big|_{t=0}}{N_{el} + N_{inel}}}$$

$$\left. \begin{aligned}
 &\bullet (dN_{el}/dt)_{t=0} \\
 &\bullet \text{total rate } (N_{el} + N_{inel})
 \end{aligned} \right\} < 1\% \text{ precision}$$

- Measure the **total rate** ( $N_{el}+N_{inel}$ ),  $\sigma_{diff} \sim 18$  mb and min. bias  $\sim 65$  mb, with an expected precision of  **$\sim 0.8\%$**

(running for 1 day at  $L = 1.6 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$ ).

- Extrapolate the elastic cross-section to  $t = 0$ : **systematics dominated:  $\sim 0.5\%$**

(statistical error after 1 day:  $0.07\%$ )

- $\rho = \text{Re } f(0)/\text{Im } f(0)$  unknown; using COMPETE pred.:  **$\sim 0.2\%$**

# TOTEM Optics Conditions

TOTEM needs dedicated short runs at **high- $\beta^*$**  and **low  $\epsilon$**   
**Scattering angles of a few  $\mu\text{rad}$**

**High- $\beta$  optics** for precise measurement of the scattering angle  $\sigma(\theta^*) = \sqrt{\epsilon / \beta^*} \sim 0.3 \mu\text{rad}$

As a consequence **large beam size**  $\sigma(y^*) = \sqrt{\epsilon \beta^*} \sim 0.4 \text{ mm}$

**Reduced number of bunches** ( 43 and 156 ) to avoid interactions further downstream

**Baseline optics  $\beta^*=1540 \text{ m}$** : parallel-to-point focusing in both transverse planes

allows very low- $t$  detection ( $-t \sim 2 \cdot 10^{-3} \text{ GeV}^2$ )

requires special injection optics

probably not available at beginning of LHC

Investigation on  **$\beta^*=90 \text{ m}$**  : parallel-to-point focusing only in vertical plane

$t$  detection down to  $\sim 2 \cdot 10^{-2} \text{ GeV}^2$

achievable by un-squeezing the standard LHC injection optics

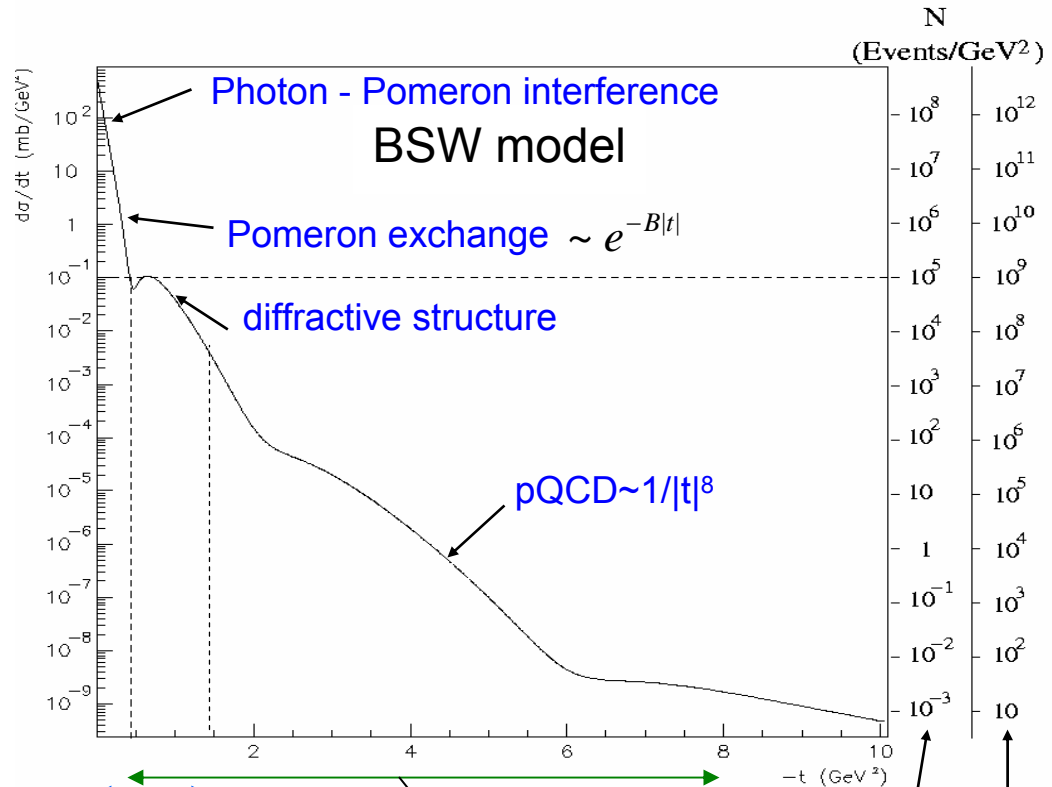
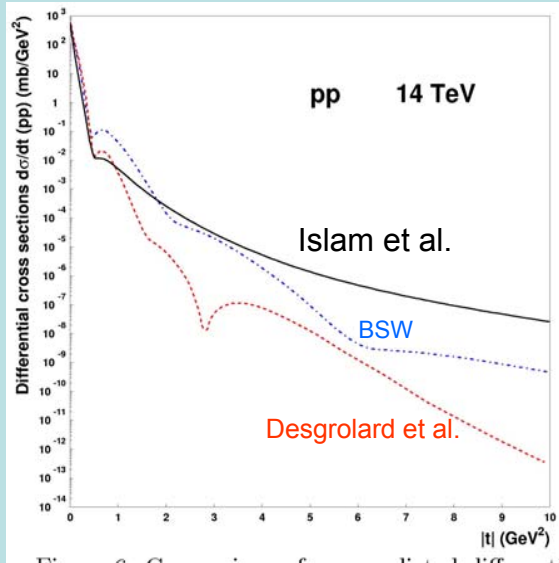


# Running scenarios

Scenario Physics:	1 low $ t $ elastic, $\sigma_{\text{tot}}$ , min. bias, soft diffraction	2 diffraction	3 large $ t $ elastic	4 soft and semi-hard diffraction (under study)
$\beta^*$ [m]	1540	1540	18	90
N of bunches	43	156	2808	156
N of part. per bunch ( $\times 10^{11}$ )	0.3	0.6 - 1.15	1.15	1.15
Half crossing angle [ $\mu\text{rad}$ ]	0	0	160	0
Transv. norm. emitt. [ $\mu\text{m}$ rad]	1	1 - 3.75	3.75	3.75
RMS beam size at IP [ $\mu\text{m}$ ]	454	454 - 880	95	200
RMS beam diverg. [ $\mu\text{rad}$ ]	0.29	0.29 - 0.57	5.28	2.4
Peak luminosity [ $\text{cm}^{-2} \text{s}^{-1}$ ]	$1.6 \times 10^{28}$	$2.4 \times 10^{29}$	$3.6 \times 10^{32}$	$2 \times 10^{30}$

# Elastic scattering: $d\sigma/dt$

## Different models



$$\beta^* = 1540 \text{ m}$$

$$\mathcal{L} = 1.6 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\beta^* = 18 \text{ m}$$

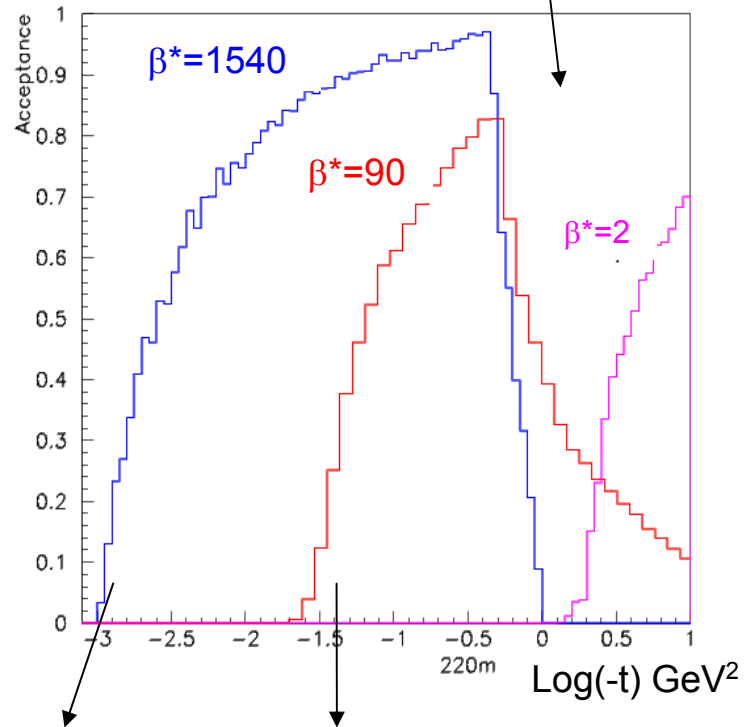
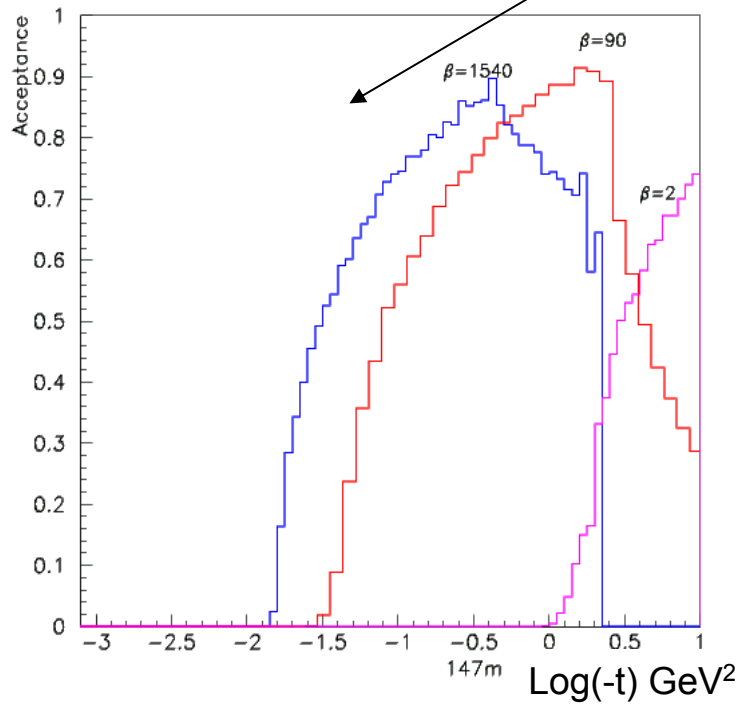
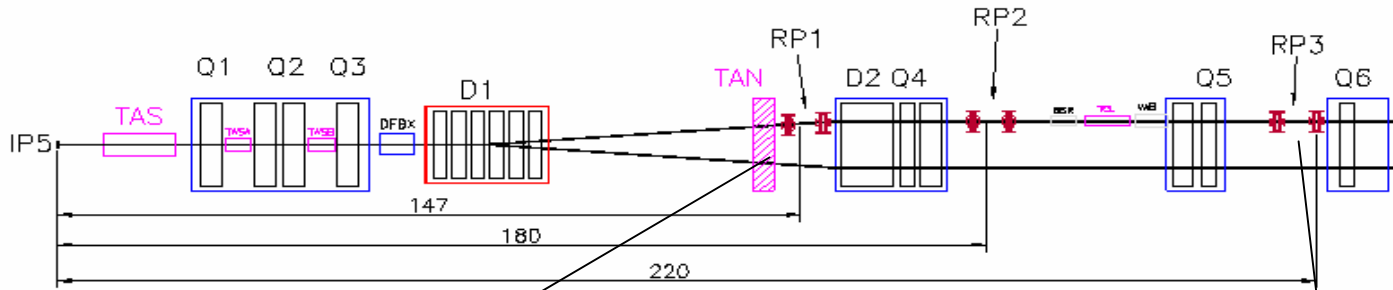
$$\mathcal{L} = 3.6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\int \mathcal{L} dt = 10^{33} \text{ and } 10^{37} \text{ cm}^{-2}$$

(1day @  $10^{28}$  and  $10^{32}$ )

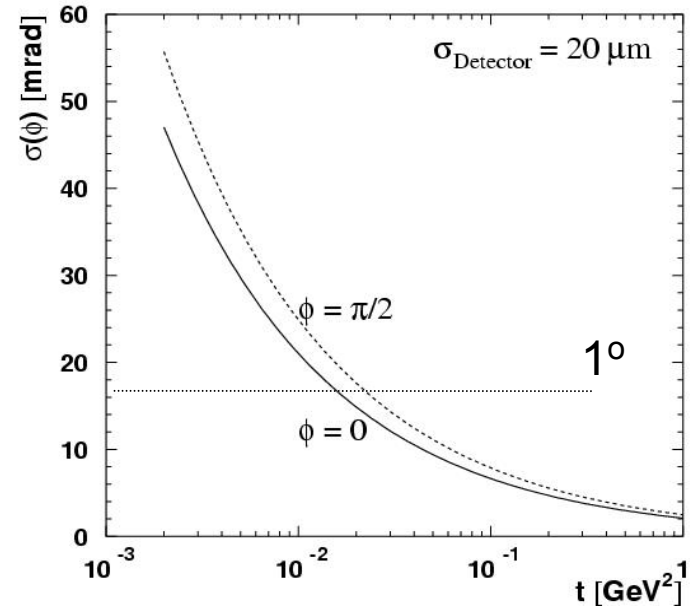
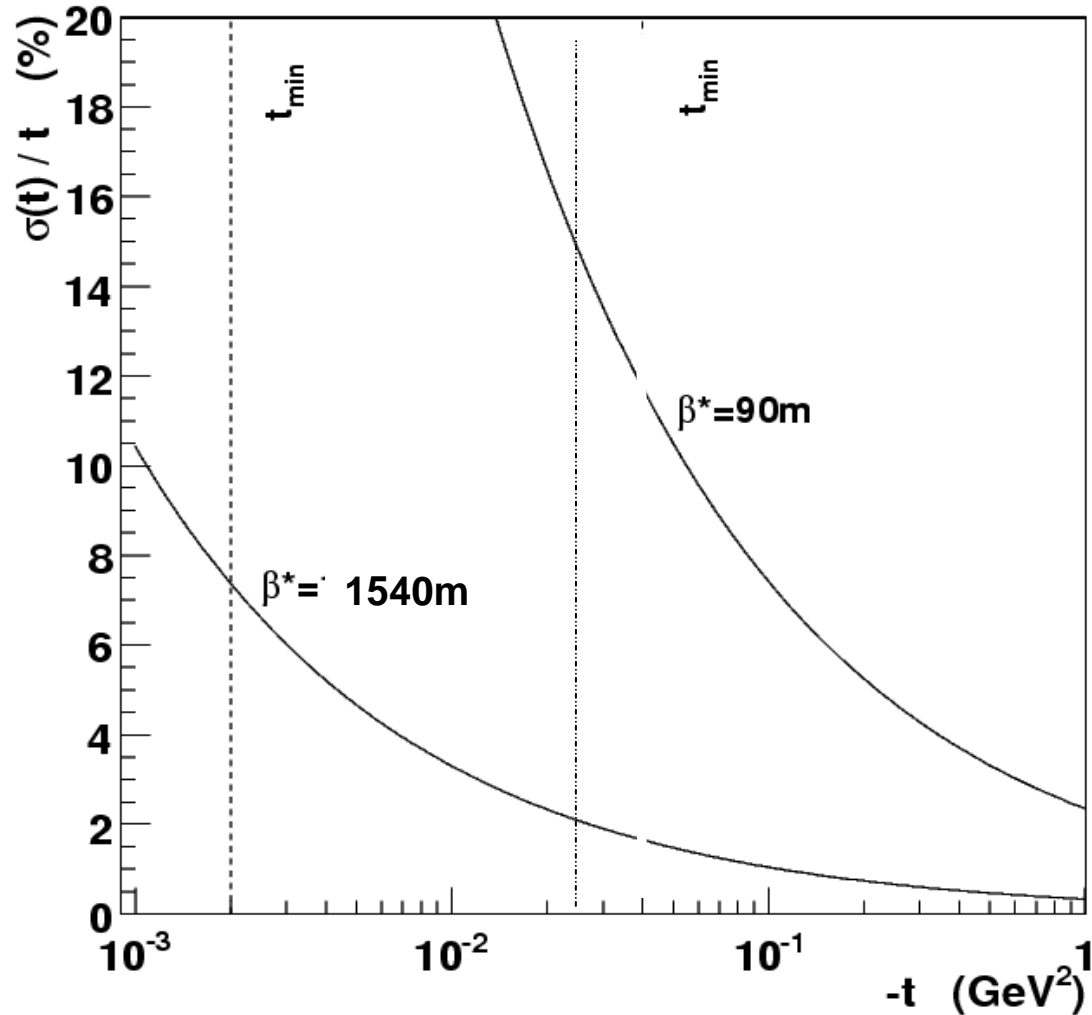
$$t_{\min} \text{ from: } 1.3 \text{ mm} = 10\sigma_{\text{beam}} + 0.5 \text{ mm at } 220 \text{ m RP}$$

# Elastic scattering



Detector distance to the beam: **1.3 mm ( $\beta^*=1540$ )** **6 mm ( $\beta^*=90$ )**

# Elastic scattering resolution



$\phi$  resolution: test collinearity of particles in the 2 arms  $\rightarrow$  background reduction

# Extrapolation to $t=0$

Effect ( $\beta^*=1540$ m)		Uncertainty in Extrapolation
Resolution, statistics (10h@ $10^{28}$ ):	$10^7$ events	0.07 %
Beam energy uncertainty	0.05 %	0.1 %
Beam -- detector alignment	20 $\mu\text{m}$	0.08 %
Angular spread	0.2 $\mu\text{rad}$	0.1 %
<b>Total &lt; 0.5 %</b>		

Theoretical models uncertainties:

$\beta^*=1540$  m < 0.1%

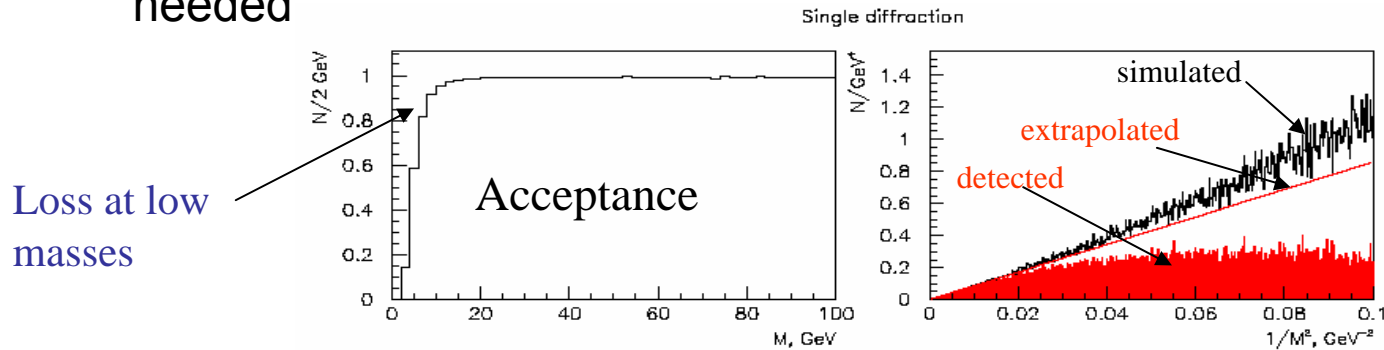
$\beta^*=90$  m  $\sim$  0.5%

At  $\beta^*=90$  m a smaller contribution from systematic effects is expected

# Inelastic and total cross section

Inelastic event selection:

- trigger from T1 or T2 (*double arm o single arm*)
- Vertex reconstruction (to eliminate beam-gas bkg.)
- 2.8 mb lost because of acceptance in diffractive events. Extrapolation needed



Pythia generator

Losses	$\sigma(\text{mb})$	Double arm	Single arm	Uncertainty after extrapolation
Minimum bias	58	0.3	0.06	0.06
2 x single diffractive	14	-	2.5	0.6
Double diffractive	7	2.8	0.3	0.1
Double Pomeron	1	-	-	0.02
Elastic Scattering	30	-	-	0.1

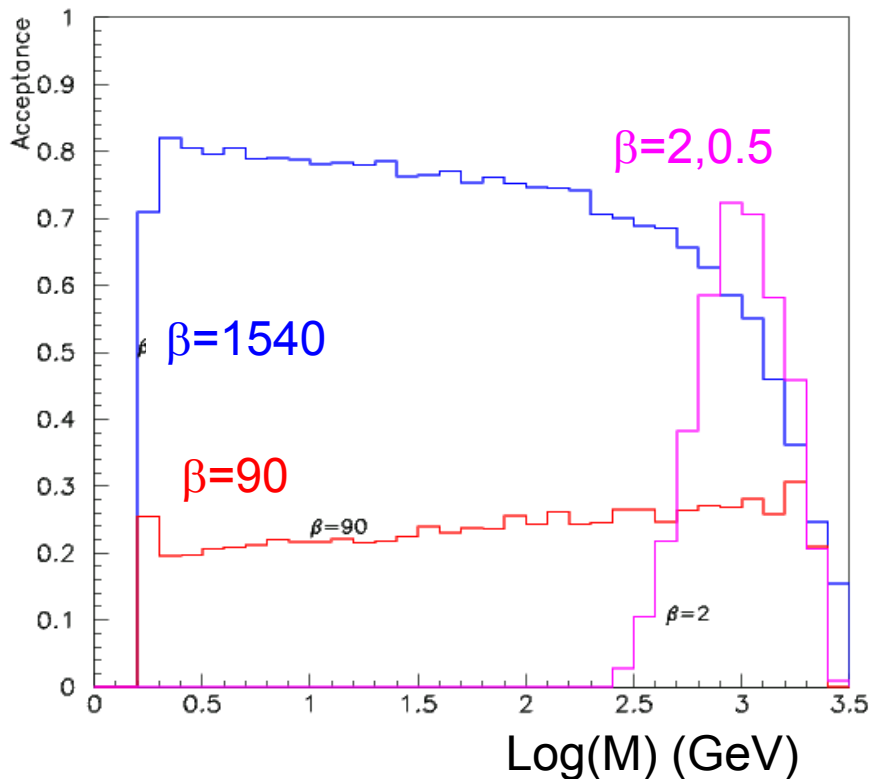
$$\frac{\Delta\sigma_{tot}}{\sigma_{tot}} \approx \sqrt{0.008^2 + 0.005^2} \approx 0.01$$



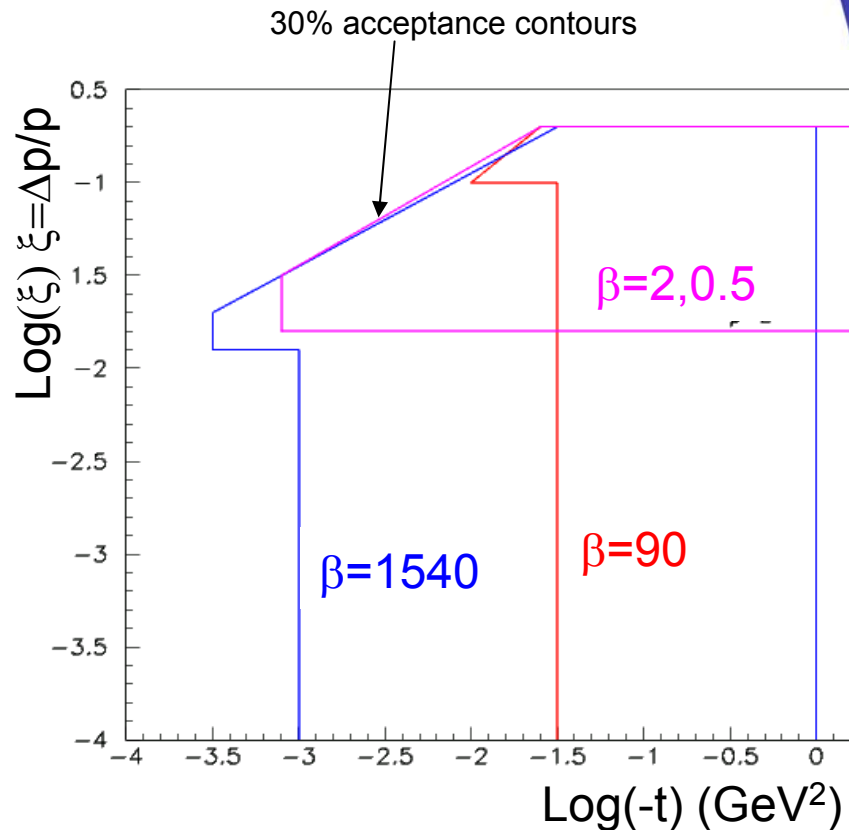
# Diffraction protons



RP at 220 m



diff. protons detected



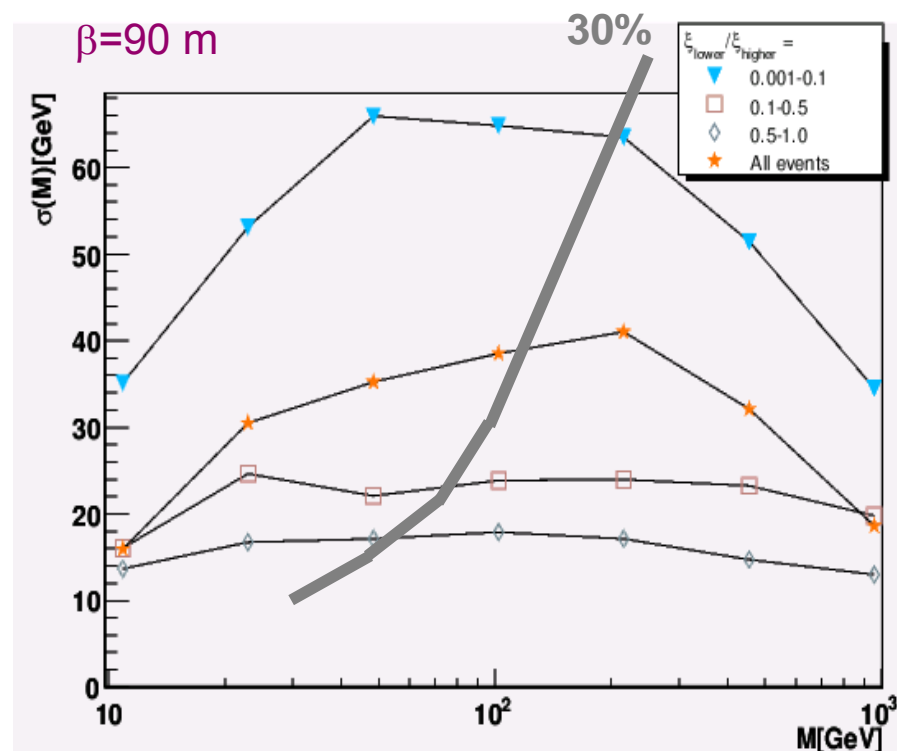
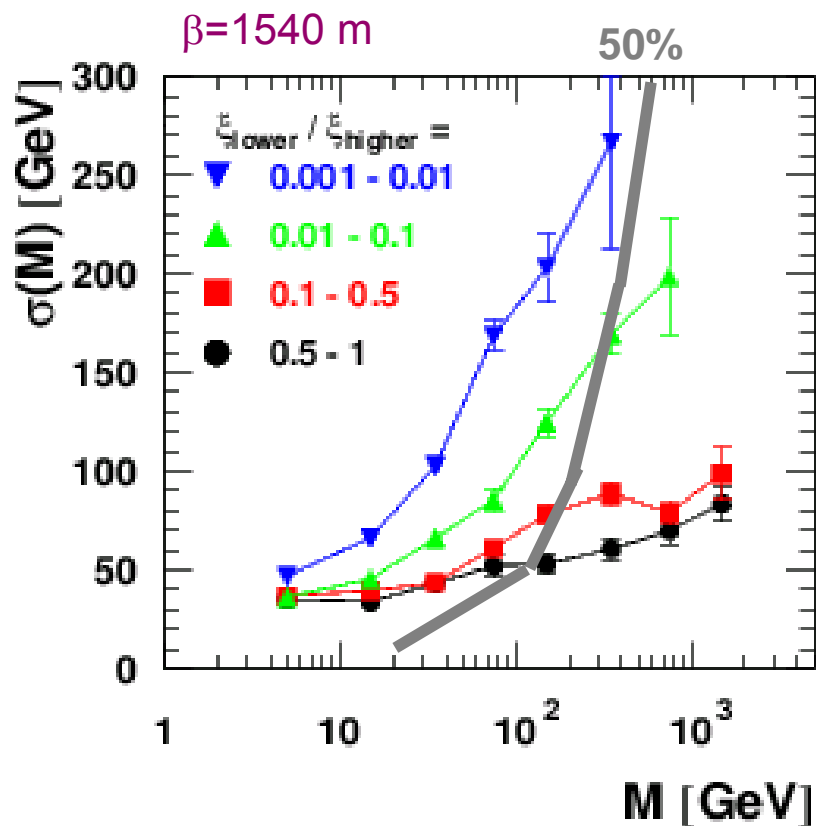
1-arm	2-arm
(incl. SD)	(incl. DPE)
~50%	~30%
~90%	~80%

# Central mass resolution (with protons)

## Sample of DPE events

$$M = \sqrt{\xi_1 \xi_2 s}$$

Mass resolution in DPE depends on  $\xi_{\text{lead}}/\xi_{\text{Nlead}}$  ratio







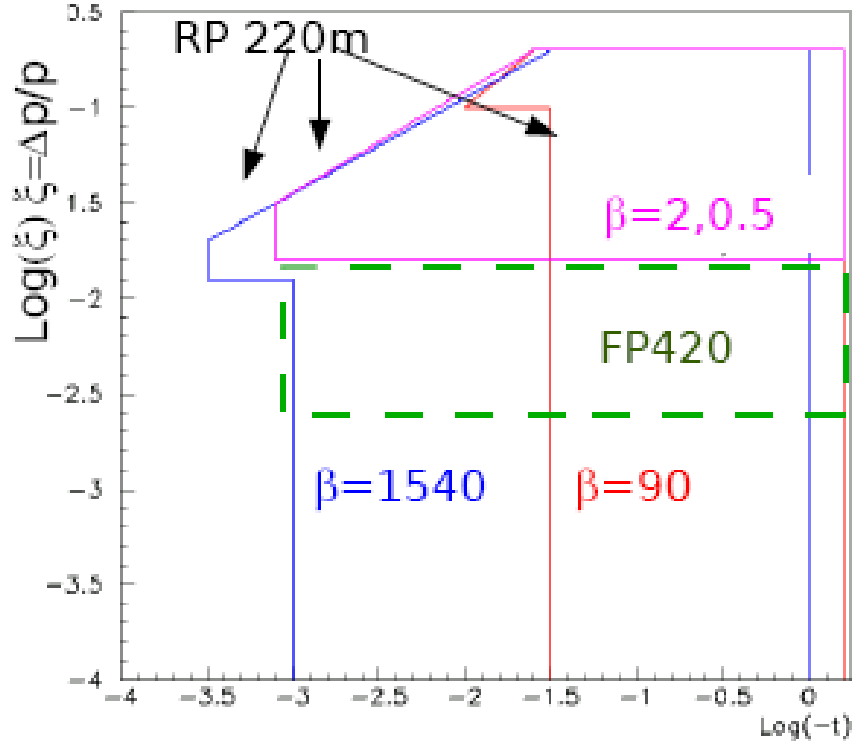
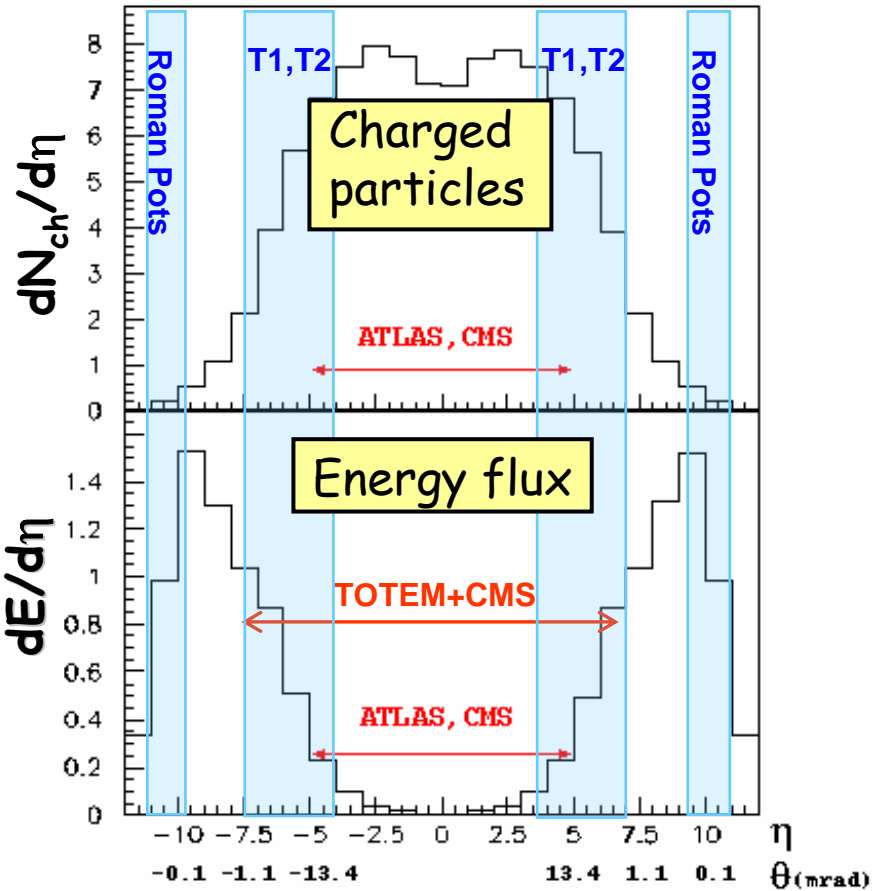
# TOTEM + CMS

Largest acceptance detector ever built at a hadron collider

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

$10^7$  min bias events, incl. all diffractive processes, in 1 day with  $\beta^* = 1540$  m

The document describing the common physics program is foreseen for fall





# CMS-TOTEM common physics menu

## Low Luminosity ( $<10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ): low and high $\beta^*$

- Measure inclusive SD and DPE cross sections and  $t$ ,  $M_x$  dependence
- Rapidity Gap selection
- Forward Drell-Yan
- Validation of Cosmic Ray generators

Running with TOTEM optics: large proton acceptance

No pile-up

## High Luminosity ( $> 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ) : low $\beta^*$ (routine CMS data taking)

- Measure SD and DPE in presence of hard scale (dijets, vector bosons, heavy quarks): dPDF, GPD
- $\gamma\gamma$  and  $\gamma p$  physics

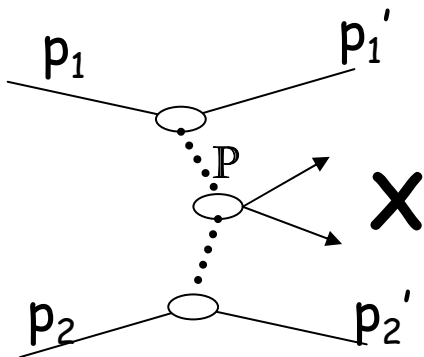
Pile-up not negligible:  
main source of background

## $> 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

- Discover the SM or MSSM Higgs in central exclusive production

Need additional forward proton detector

# CMS/TOTEM:DPE (1)



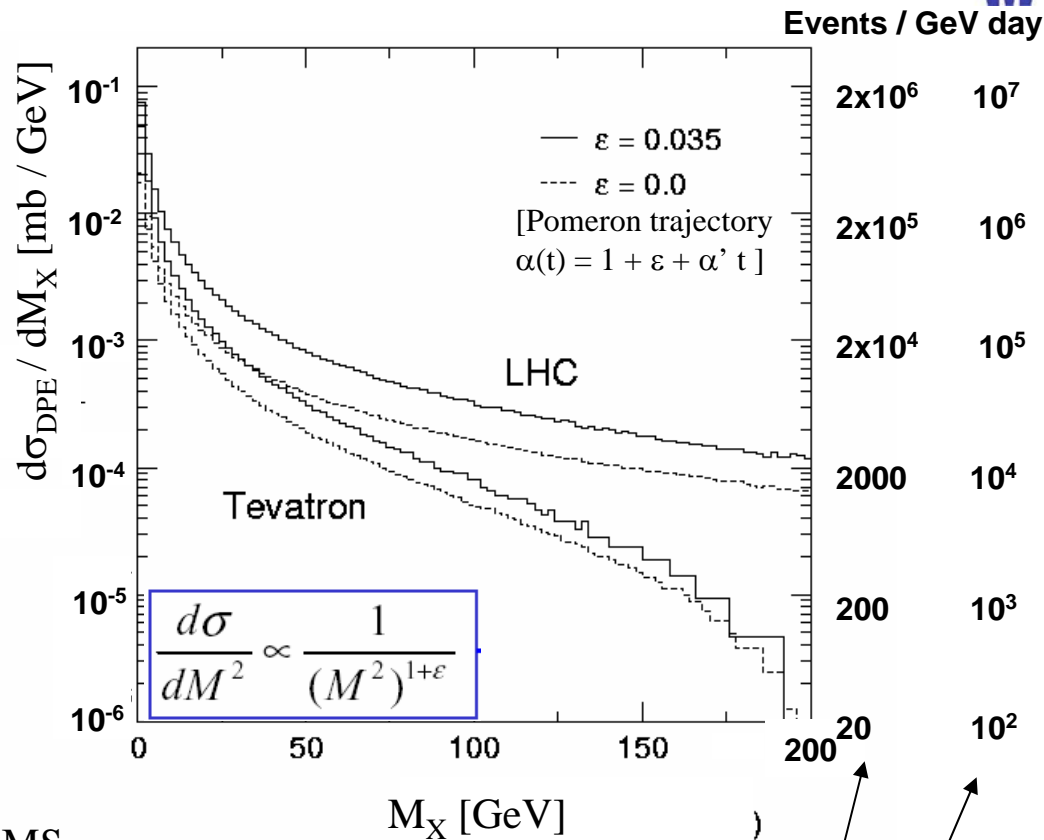
Measure > 90% of leading protons with RPs and diffractive system 'X' with T1, T2 and CMS.

CMS/TOTEM: both protons tagged

Masses within reach:  $\sqrt{\xi_1 \xi_2} \leq 0.1$

$\Rightarrow M = \sqrt{\xi_1 \xi_2} s \leq 1.4 \text{ TeV}$

- Threshold scan for New Physics
- Triggered by leading proton and seen in CMS
- Central production of states X:  
X =  $\chi_c$ ,  $\chi_b$ , Higgs, dijets, SUSY particles, ...



$L (\text{cm}^{-2} \text{s}^{-1}) = 2 \cdot 10^{29} \quad 10^{30}$   
 $\beta^* (\text{m}) = 1540 \quad 90$



# CMS/TOTEM: DPE (2)

Advantage: selection rules:  $J^P = 0^+, 2^+, 4^+$ ;  $C = +1$

⇒ reduced background, determination of quantum numbers.

Good  $\phi$  resolution in TOTEM: determine parity:  $P = (-1)^{J+1} \Leftrightarrow d\sigma/d\phi \sim 1 \pm \cos 2\phi$

## LHC (CMS+TOTEM):

Particle	$\sigma_{\text{excl}}$	Decay channel	BR	Rate at $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$	Rate at $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
$\chi_{c0}$ (3.4 GeV)	3 $\mu\text{b}$ [KMRS]	$\gamma J/\psi \rightarrow \gamma \mu^+ \mu^-$ $\pi^+ \pi^- K^+ K^-$	$6 \times 10^{-4}$ 0.018	65 / h 1900 / h	2 / s 54 / s
$\chi_{b0}$ (9.9 GeV)	4 nb [KMRS]	$\gamma Y \rightarrow \gamma \mu^+ \mu^-$	$\leq 10^{-3}$	$\leq 3$ / d	$\leq 300$ / d
H (SM) (120 GeV)	1 ÷ 10 fb assume 3 fb	$b\bar{b}$	0.68	1 / y	100 / y (after cuts: 11/y)

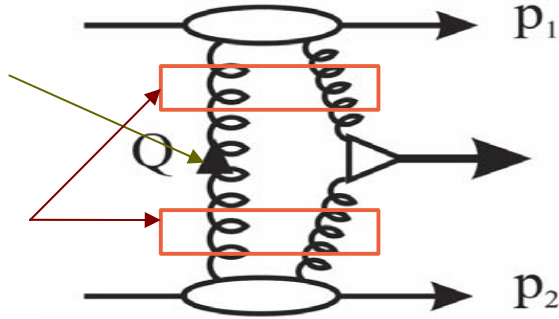
**Higgs** needs  $L \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , i.e. a running scenario for  $\beta^* = 0.5 \text{ m}$ :

- trigger problems in the presence of overlapping events
- install additional Roman Pots in cold LHC region (420 m) at a later stage

# CMS/TOTEM: light SM/MSSM Higgs in central exclusive production

shields color charge of other 2 gluons

Vacuum quantum numbers "Double Pomeron Exchange"



$pp \rightarrow pHp$

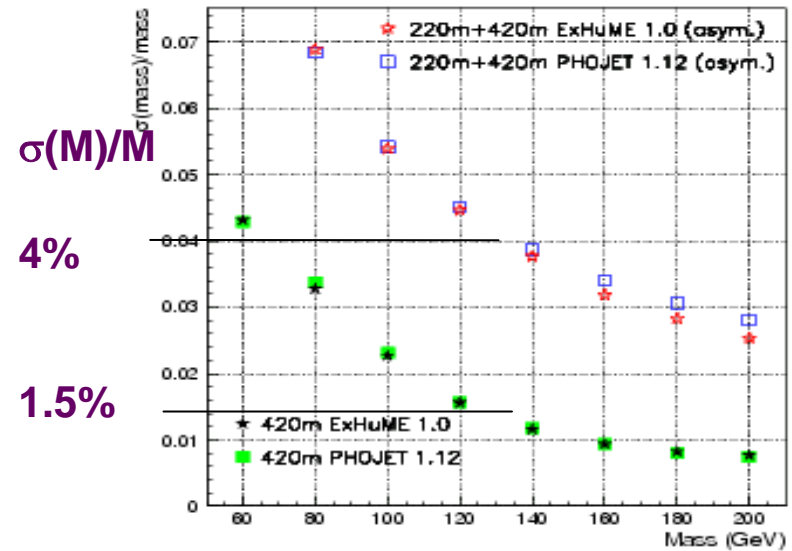
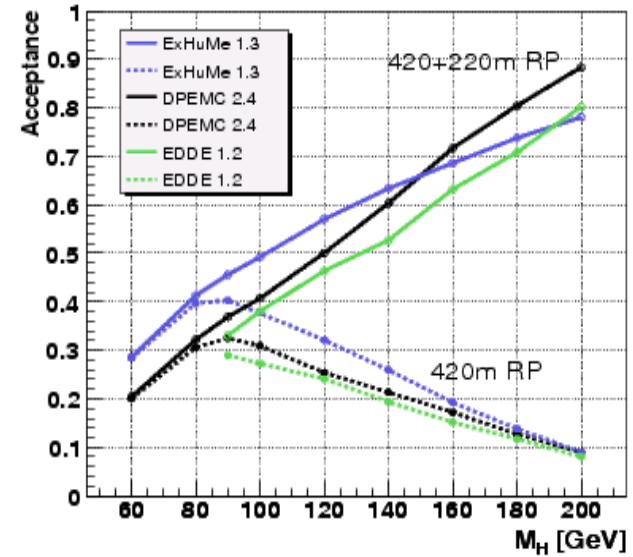
Extensive study of theoretical models & MC generators

$H \rightarrow b\bar{b}$   $M_H = 120$  GeV only few events expected in  $30\text{fb}^{-1}$  and  $S/B \sim 0.1-1$

$H \rightarrow WW$   $M_H > 130$  GeV  $N_{ev} \sim 3-6$  for  $30\text{fb}^{-1}$

Background and pile-up studies in progress

Cross-section is expected to be orders of magnitude higher in MSSM model for high  $\tan\beta$



$\sigma(M)/M$

4%

1.5%

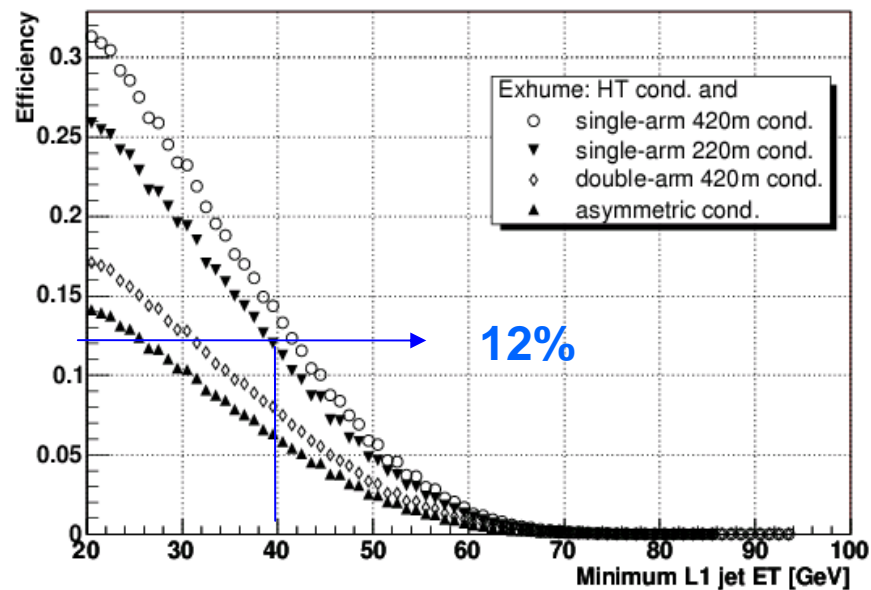
# Trigger studies (low $\beta^*$ )

Trigger is an important **limiting factor** to select diffractive events (“low” pT processes)

CMS trigger bandwidth limits: L1 : O(1) kHz ; HLT : O (1) Hz

**Combinations of TOTEM RP with the standard CMS trigger conditions (jets, muons) : it is possible to lower the jet/muon thresholds substantially and stay in the limits**

The CMS trigger menus now foresee 1% of the trigger on L1 and HLT for a dedicated diffractive trigger stream



Example for Central Exclusive Production:  
 $H(120) \rightarrow b \bar{b}$

2-jets ( $E_T > 40 \text{ GeV}$ ) & single-arm RP 220m

M. Grothe et al., proceedings HERA-LHC workshop '05,  
and CMS Note 2006/054 & TOTEM Note 2006/01

# Low luminosity: soft DPE and SD

**Trigger** (special optics):

DPE : 2 proton trigger  
 (anti collinearity condition) +T1/T2  
 SD : 1 p + T1/T2 opposite

- Measure cross sections,  $t$ ,  $M$  dependence

- Measure the central Mass via:  
 proton(s)

rap-gap relation

calorimeters  $\xi_p = (\sum_i E_i^T e^{\pm n_i})/\sqrt{s}$   $\sigma(\xi)/\xi \sim 40\%$

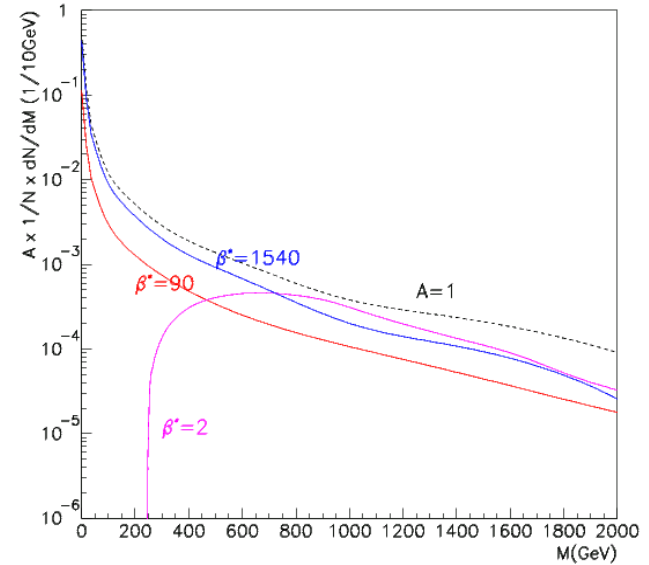
- Transition from soft to semi-hard scale:  
 in the soft sample, “contamination”  
 of (low  $p_T$ )-dijets events

$\beta=90$  m in  $0.3\text{pb}^{-1}$

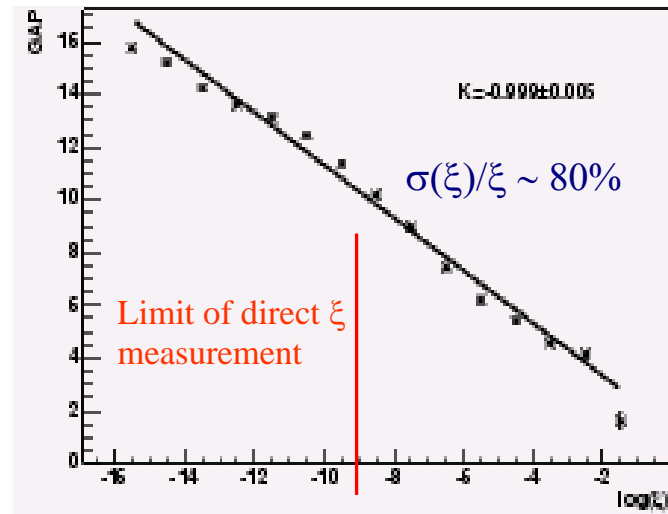
~10M events of inclusive DPE/SD

~1K events of DPE-dijets (low  $p_T$ )

~10K events of SD-dijets “



GAP (T1/T2/Calorimeter) vs  $\ln(\xi)$

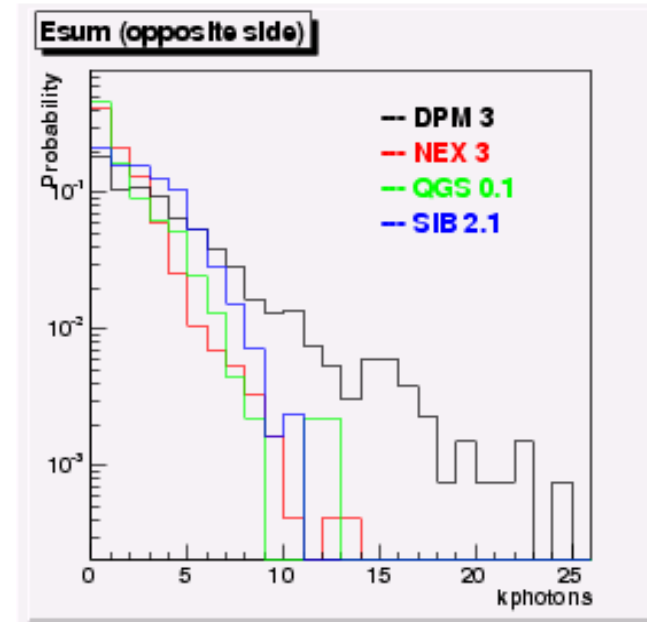
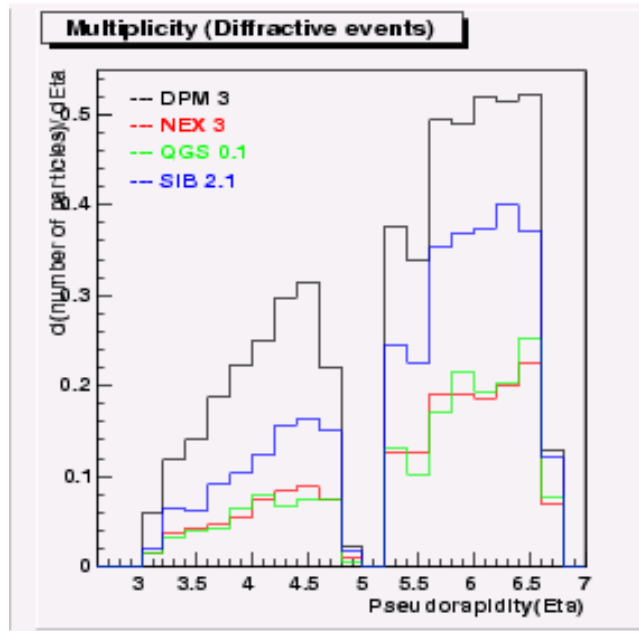


# Cosmic rays connection

- Interpreting cosmic ray data depends on hadronic simulation programs
- Forward region poorly known/constrained
- Models differ up to a factor 2 or more

Need forward particle/energy measurements: LHC center-of-mass energy corresponds to  $E_{\text{lab}} = 10^{17}$  eV

Achievable at low luminosity using T1/T2/Castor





# Summary

TOTEM will be ready for data-taking at the LHC start:

Measure **total pp cross-section (and luminosity)** with a precision of **1 %**  
with  $\beta^* = 1540$  m  
(Possible early measurement with  $\beta^* = 90$  m)

Measure **elastic scattering** in the range  $10^{-3} < t < 10 \text{ GeV}^2$

In collaboration with CMS:

**soft diffraction**

**semi-hard diffraction ( $p_T > 10 \text{ GeV}$ )**

**hard diffraction**

**Exclusive Double Pomeron Exchange**

**Studies of forward particle production**