The TOTEM experiment at LHC

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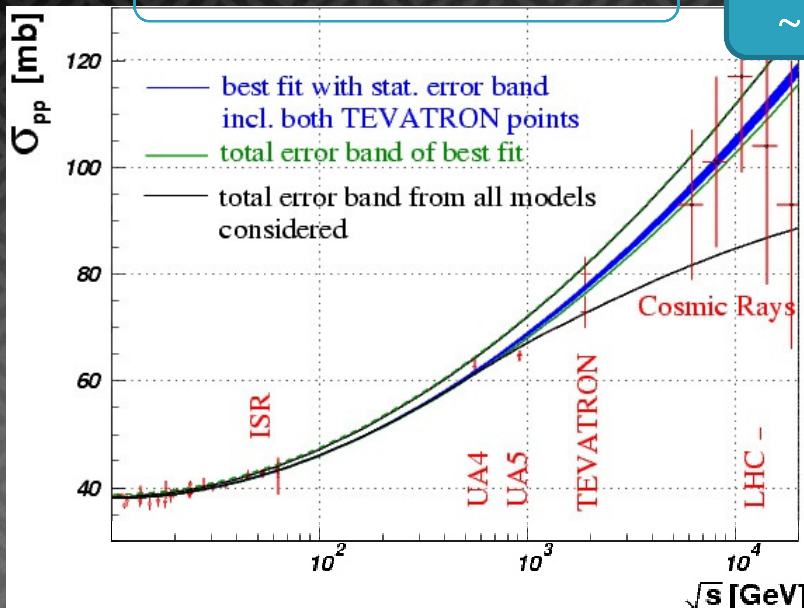
on behalf of the
TOTEM Collaboration

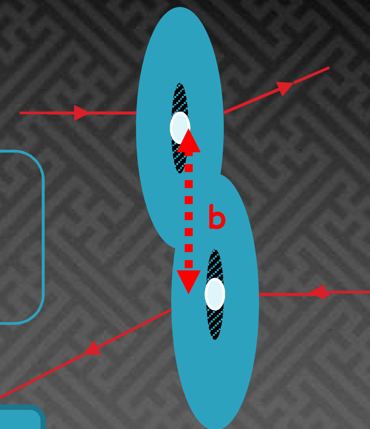
TOTEM Physics Overview

Total cross-section

Ultimately ~1% precision

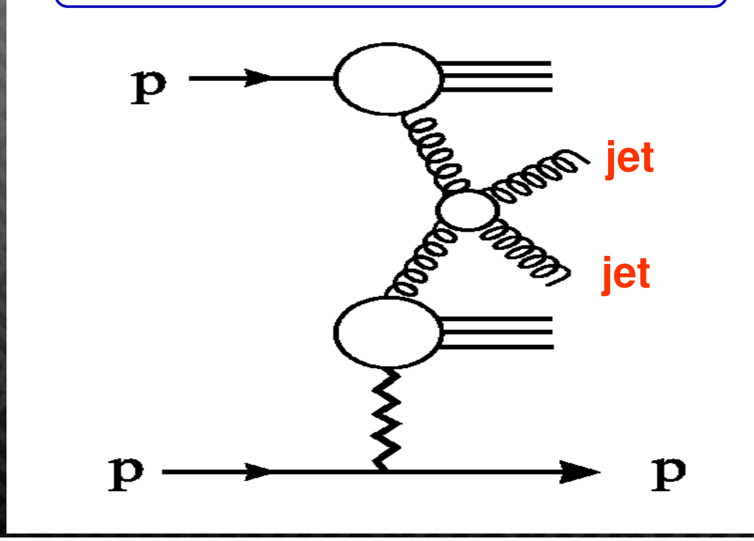


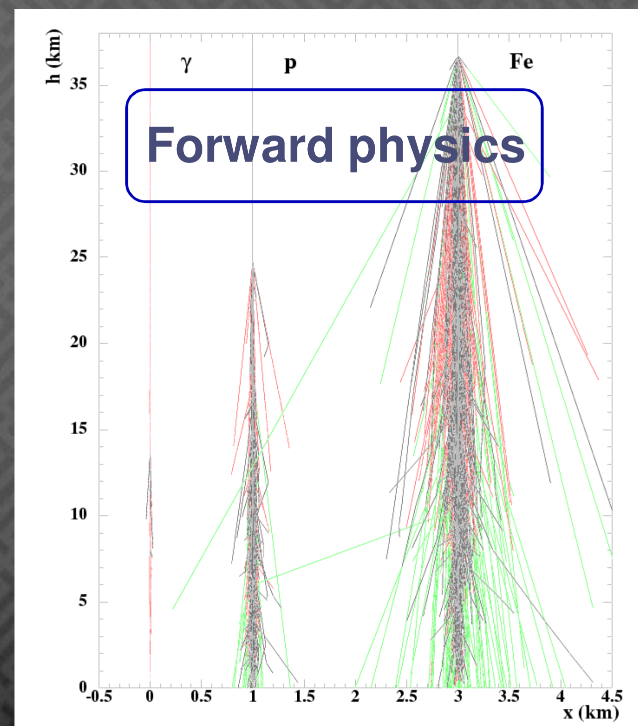
Elastic Scattering



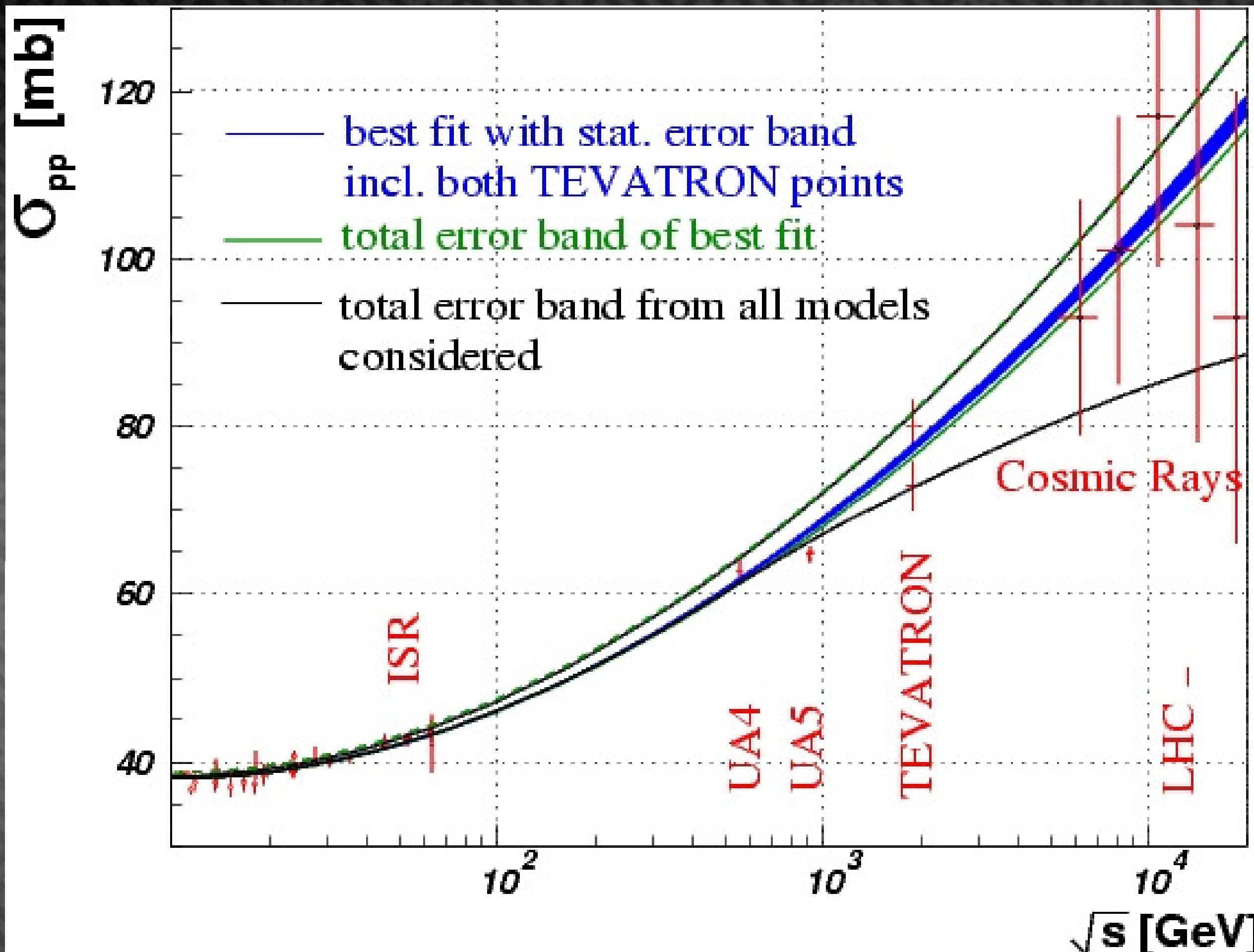
Over a wide *t* range

Diffraction: soft and hard





Physics Motivation (1)



Dispersion relation fit

Best fit σ_{TOT}^{pp} rises as
~ **$\ln^2 s$**

Predictions at 14 TeV:
90-130 mb

- Available data not decisive

- Aim of TOTEM:
~**1%** accuracy

It will distinguish between several models

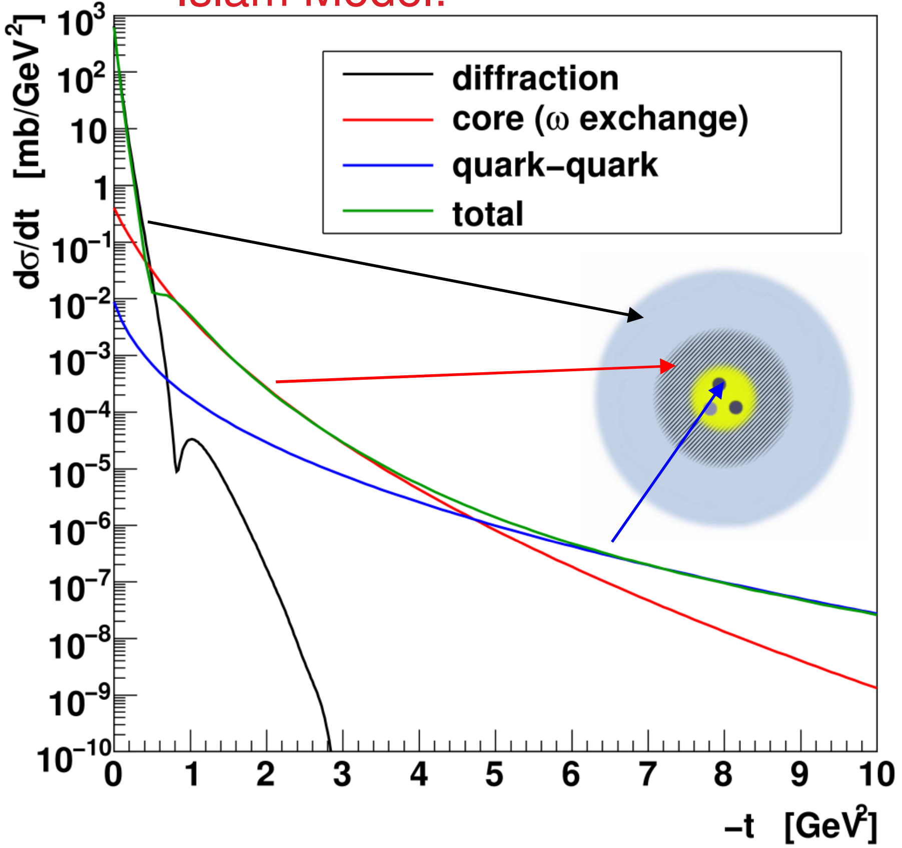
COMPETE Collaboration fits all available hadronic data and predicts:

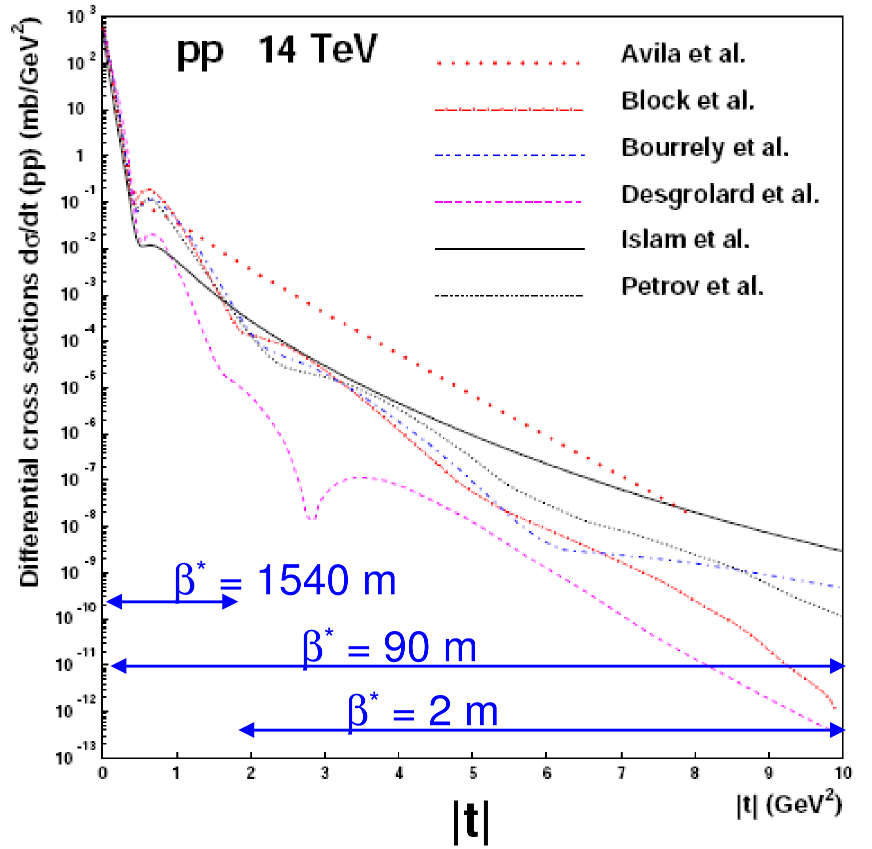
LHC (14TeV): $\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{l} +4.1 \\ -2.1 \end{array}$ mb

[PRL 89 201801 (2002)]

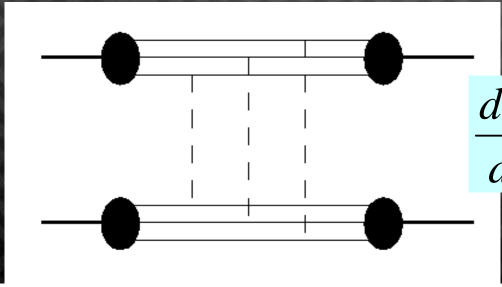
Physics Motivation (2) ...

Islam Model:





3-gluon exchange at large |t|:



$$\frac{d\sigma}{dt} \sim t^{-8}$$

Big uncertainties at large |t|:
Models differ by ~ 3 orders of magnitude!

TOTEM will measure the *$10^{-3} < |t| \sim (p\theta)^2 < 10$ GeV²* range with good statistics

... and more

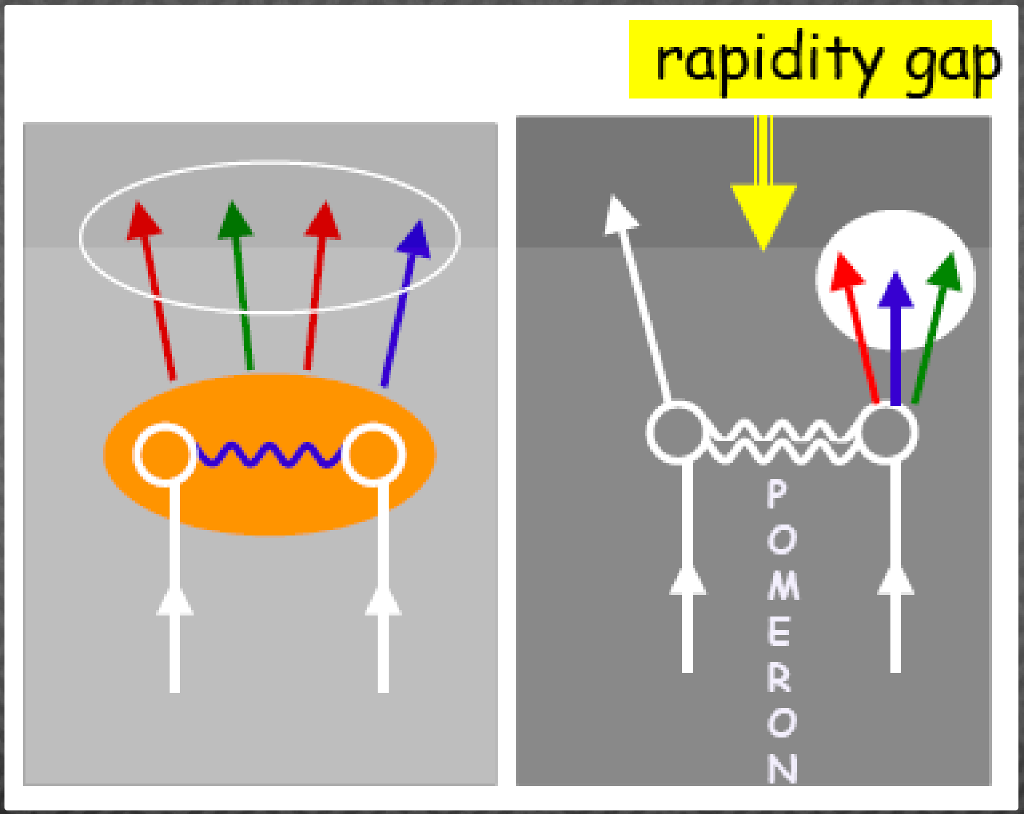
p-p Interactions

η = -ln tg $\theta/2$
$\xi = \Delta p/p$

Non-diffractive	**Diffractive**
Colour exchange	*Colourless exchange with vacuum quantum numbers*
dN / d $\Delta\eta$ = exp (-$\Delta\eta$)	**dN / d $\Delta\eta$ = const**

$\Delta\eta = -\ln \xi$

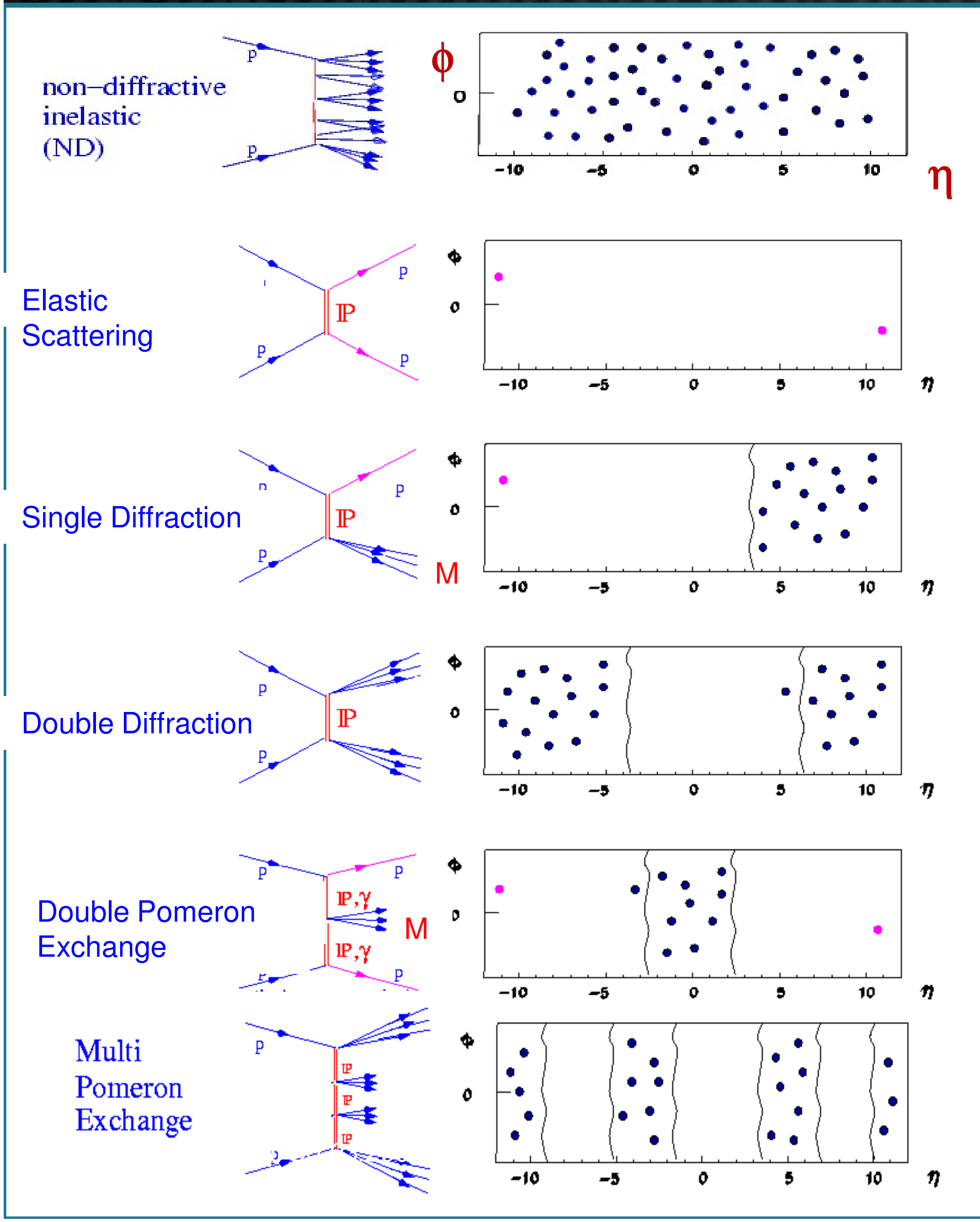
Incident hadrons acquire colour and break apart



Incident hadrons retain their quantum numbers remaining colourless

GOAL: understand the QCD nature of the diffractive exchange

Dominant Event Classes in p-p Collisions



(η = -ln tg θ/2)

~65 mb ~ 58 %

~30 mb

~10 mb

~7 mb ~ 42 %

~1 mb

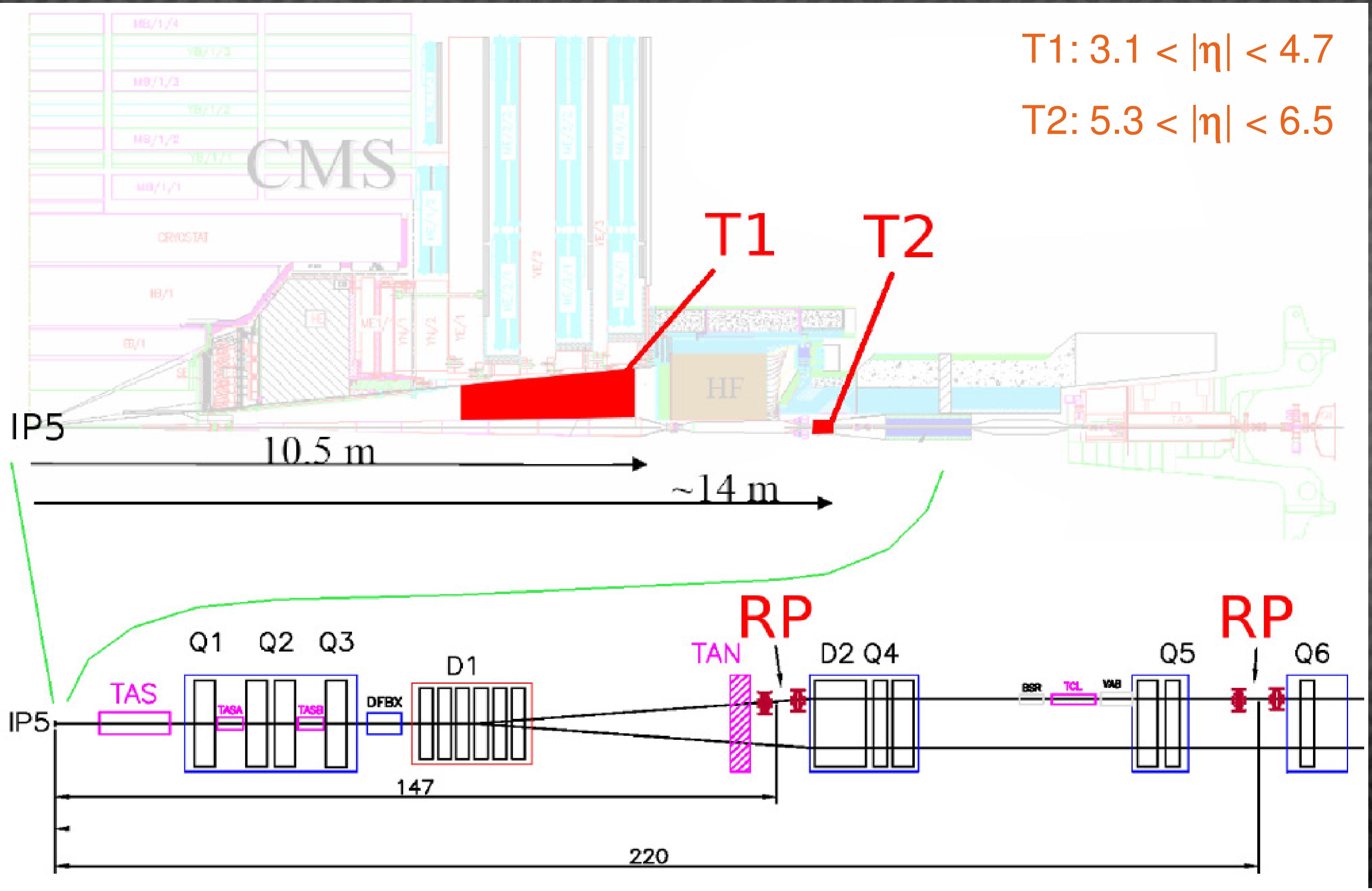
<< 1 mb

Processes with large cross-sections !

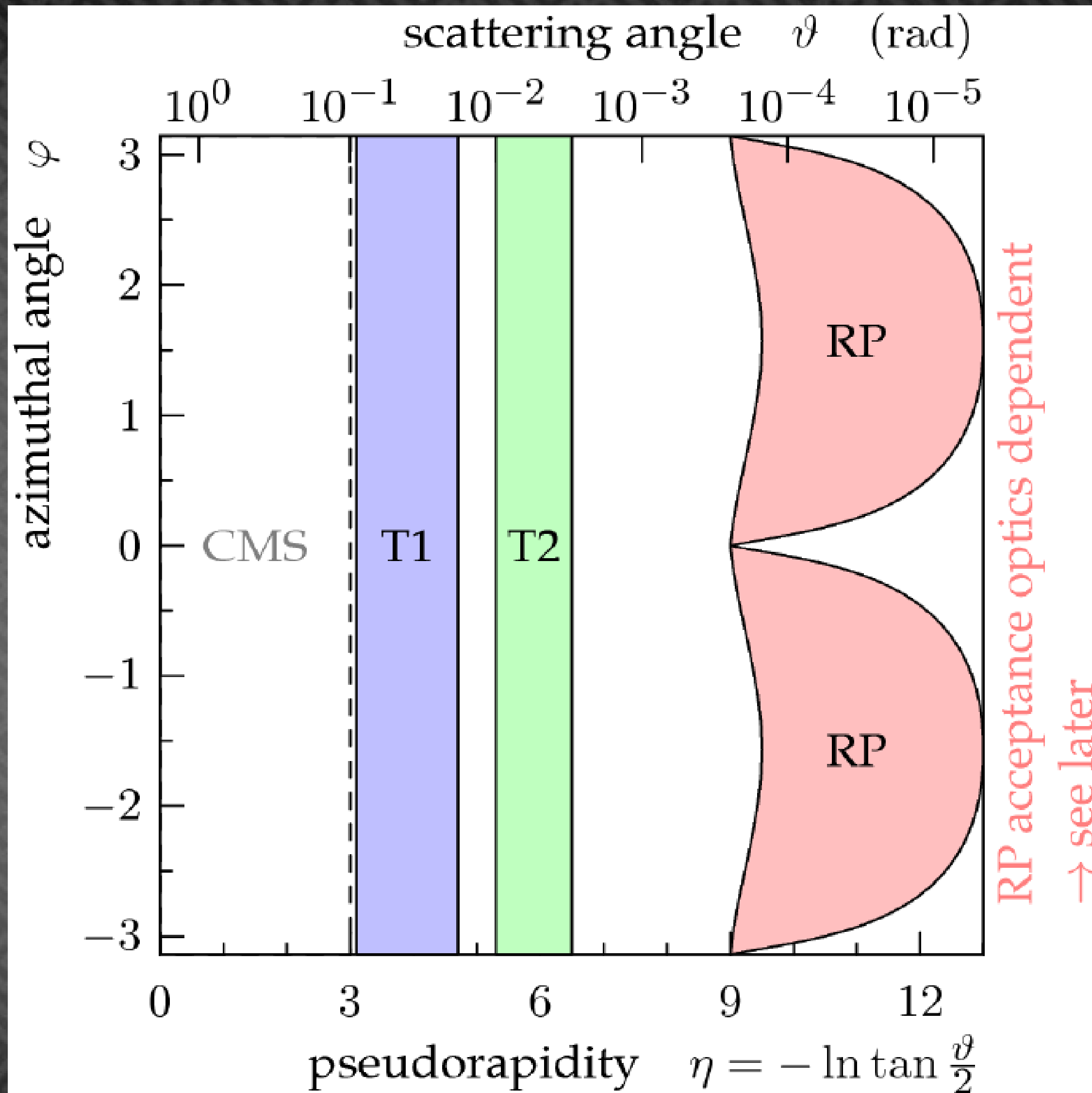
Indicative cross-sections at 14 TeV

TOTEM Experimental Apparatus

- Physics requirements: *forward proton detectors* and *large pseudorapidity coverage*
  ➡ **Roman Pots** & tracking telescopes **T1** and **T2** *(inelastic evts + Vtx reco)*
- *all detectors symmetrically on both sides of IP5*
- *all detectors L1 trigger capable*



TOTEM Coverage



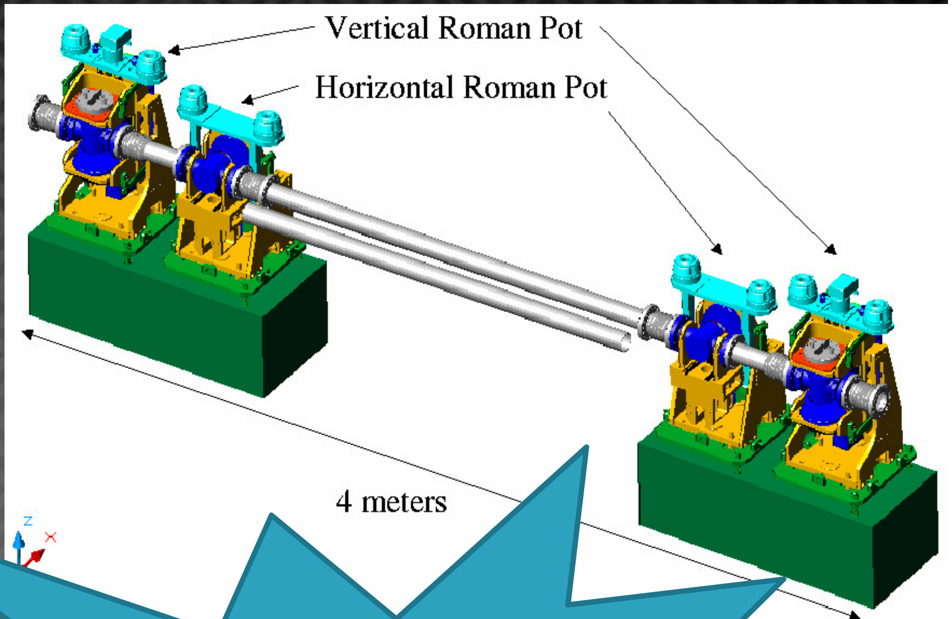
Courtesy by Jan Kaspar

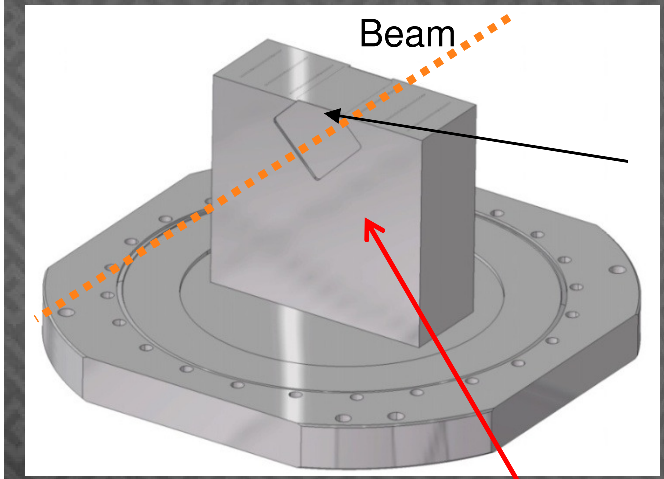
TOTEM Roman Pots

Protons at few µrad angles w. RPs at
$10\sigma + d$ from beam

`Edgeless' detectors to minimize d
(σ^{beam} ~ 80 µm at RP220 w. β^*=1540m)

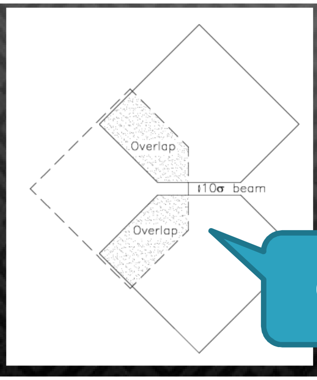
Each RP station has 2 units, 4m apart
Each unit has 2 vertical insertions ('pots') + 1 horizontal

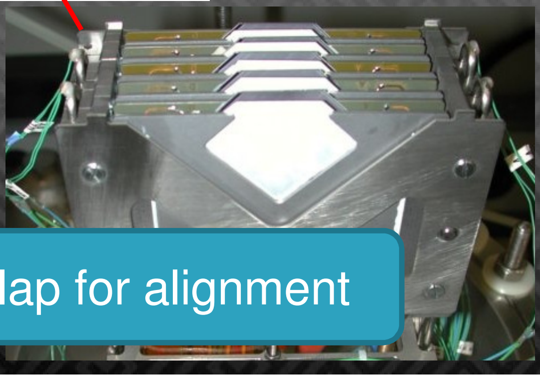




Thin window 150 µm

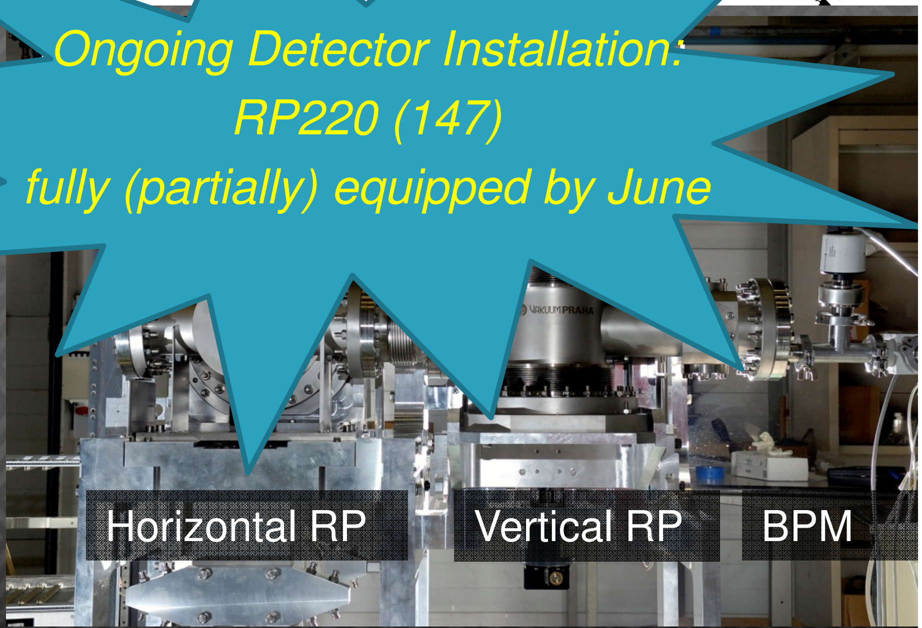
10 silicon detector planes
pitch 66µm



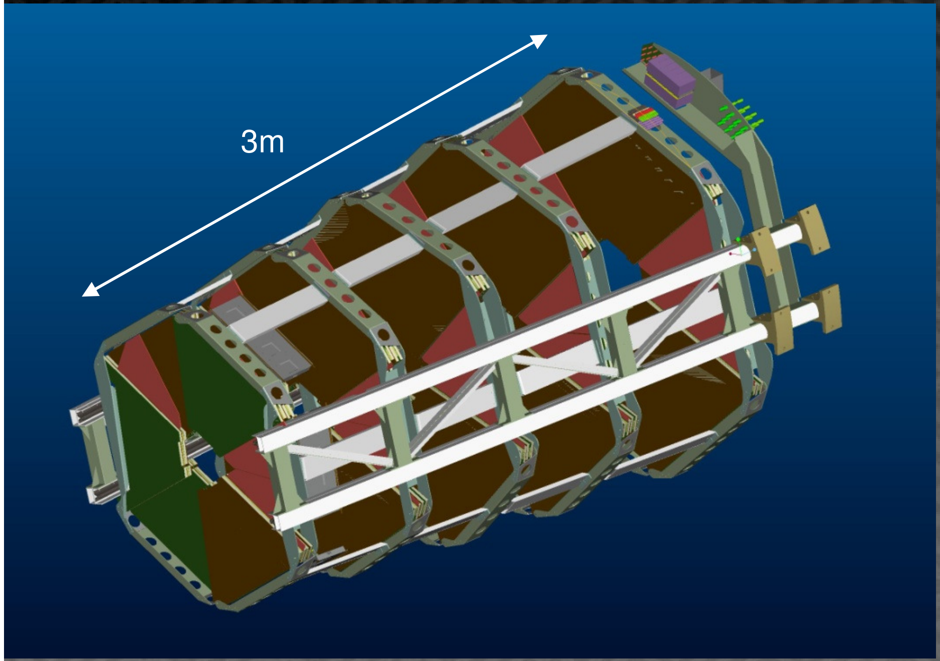


Overlap for alignment

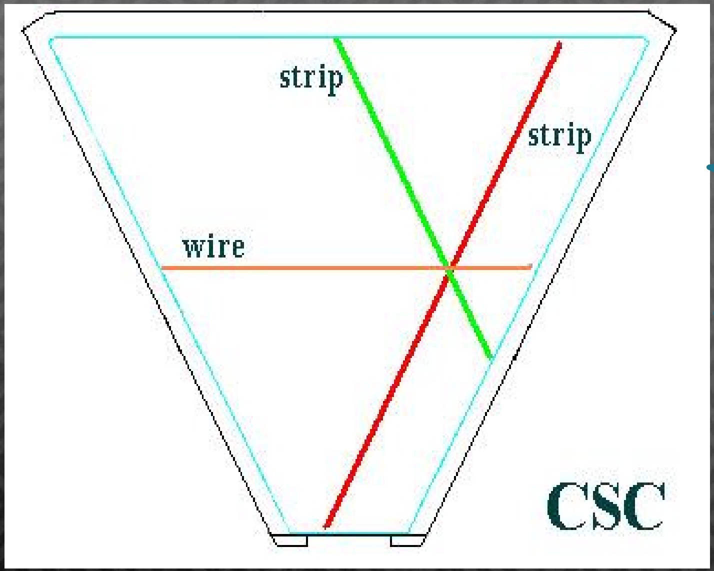
Ongoing Detector Installation:
RP220 (147)
fully (partially) equipped by June



T1 Telescope

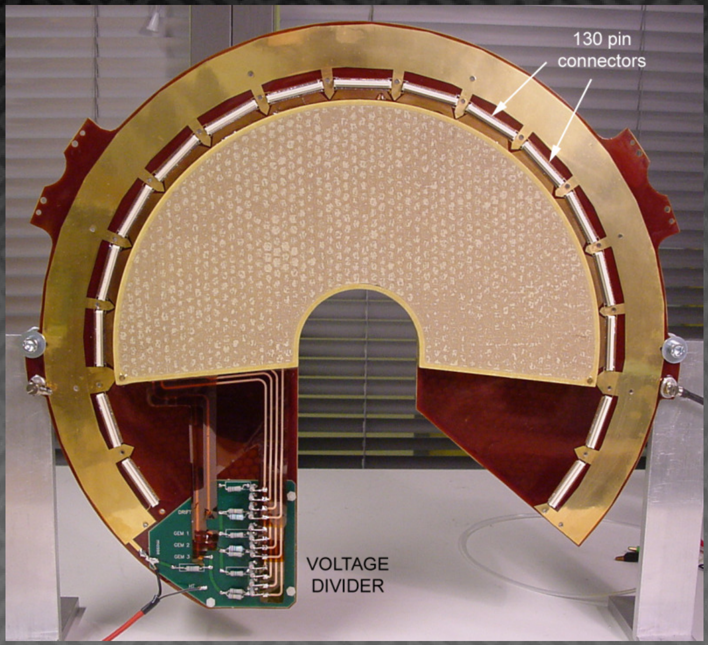


1 station per side of IP5
- each station: 5 planes
- each plane: 6 trapezoidal CSC detectors
- L1 trigger capability
- Cathode Strip Chamber detector
  – 3 coordinates: 2 cathode strips, 1 anode wire
  – Resolution ≈ 1 mm
- Primary Vtx reconstruction to discriminate background (not beam-beam events) for the measurement of N_{inel}
- Multiplicity measurement



Installation foreseen for May/June:
One arm eventually in September

T2 Telescope



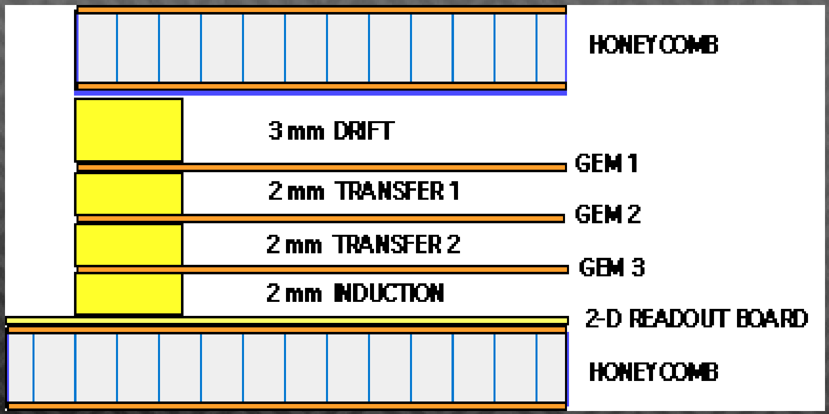
1 station on each side of IP5

- each station: two halves (left/right)
- each half: 10 (5×2 back-to-back mounted) GEM detectors
- L1 trigger capability
- Triple Gas Electron Multiplier detectors

– double readout: strips (radial) and pads (coarse radial and azimuthal)

– resolution: radial 100 μm, azimuthal 0.8°

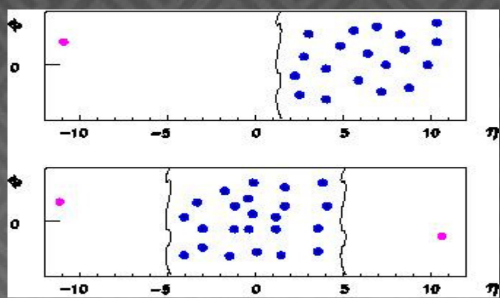
- Vtx reco. + Multiplicity measurement



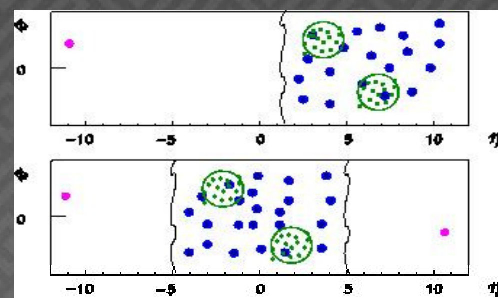
TOTEM Physics and LHC Optics

Feasible physics depends on running scenarios:

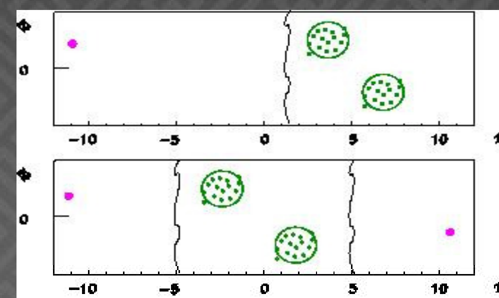
- luminosity
- beam optics (β*)
  - ⇒ acceptance of proton detectors
  - ⇒ precision in the measurement of scattering angle / beam divergence $\propto \sqrt{1/\beta *}$



σ_{tot}(~1%), low t elastic, soft diffraction



σ_{tot}(~5%), low t elastic, (semi)-hard diffraction

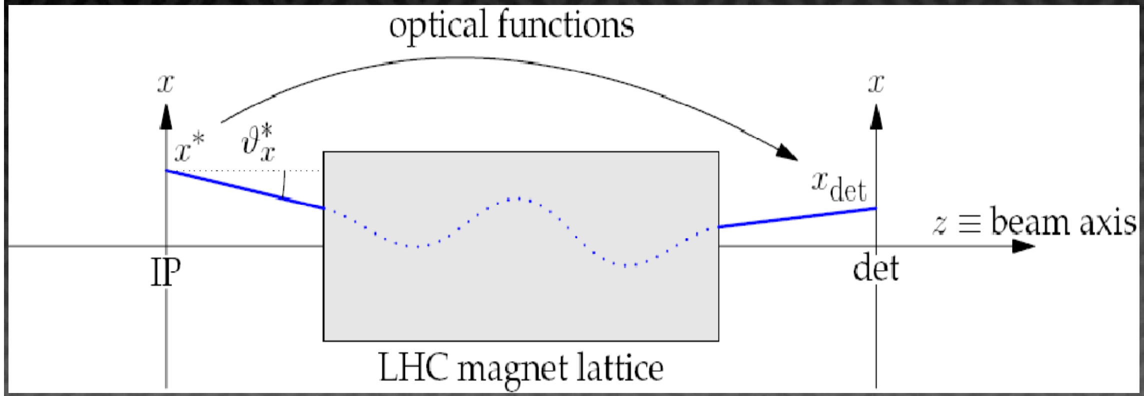


high t elastic, hard diffraction

← cross section | luminosity →

σ	mb	μb		nb	
β* (m)	1540	90	EARLY	2	0.5
$\mathcal{L}$ (cm^{-2} s^{-1})	10^{28}	10^{30}		10^{31}	10^{33}
	TOTEM runs			Standard runs	

Details on Optics



Proton transport equations:

$$x = L_x \theta_x^* + v_x x^* + D\xi$$

$$y = L_y \theta_y^* + v_y y^*$$

Optical functions:

L (effective length); - ***v*** (magnification);

D (machine dispersion)

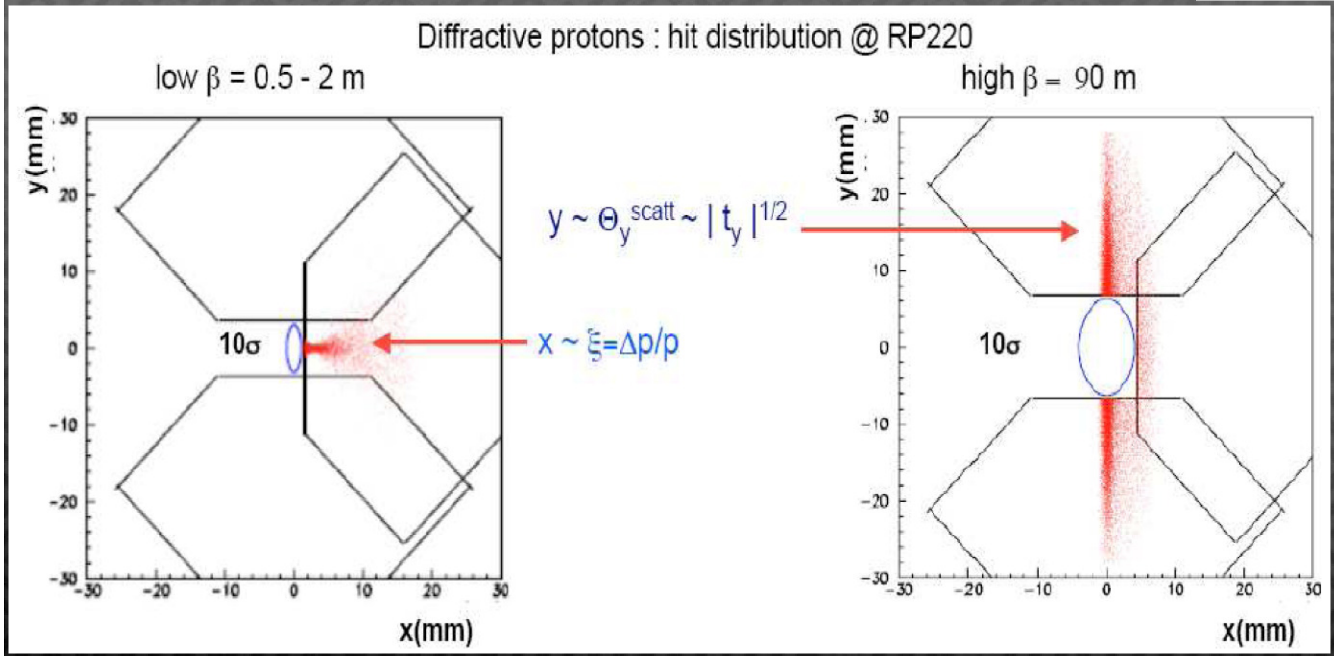
$\xi = \Delta p/p$; $t = t_x + t_y$; $t_i \sim -(p\theta_i^*)^2$

(x^*, y^*): vertex position at IP

(θ_x^*, θ_y^*): emission angle at IP

Describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP.

$\Rightarrow$ **Define t and ξ range (Acceptance)**



Example

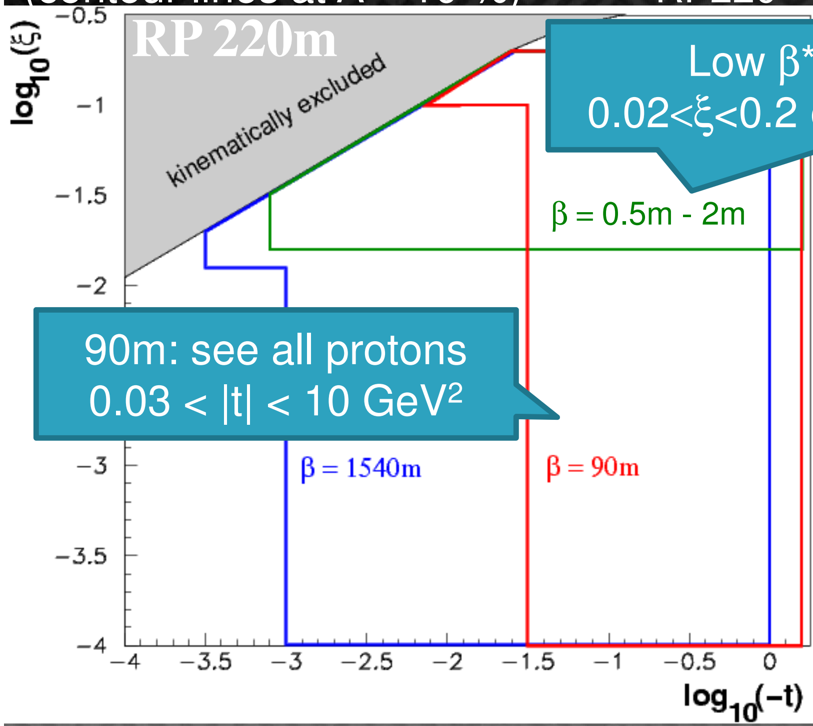
Same sample of diffractive protons at different β*

- low β*: p detected by momentum loss (ξ)

- high β*: p detected by trans. momentum (t_y)

Proton Acceptance

Diffractive Proton Acceptance in (t, ξ):
(contour lines at A = 10 %) RP220



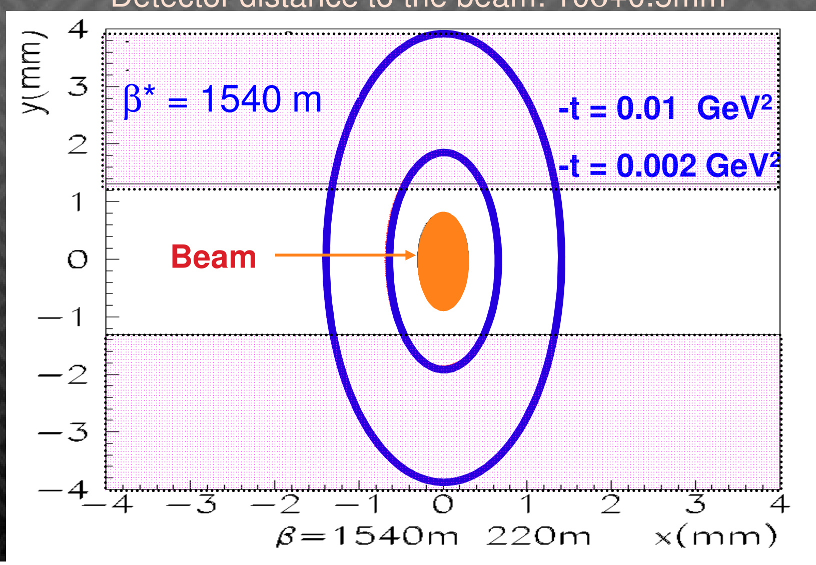
Low β*: see protons
0.02<ξ<0.2 or 2< |t| < 10 GeV²

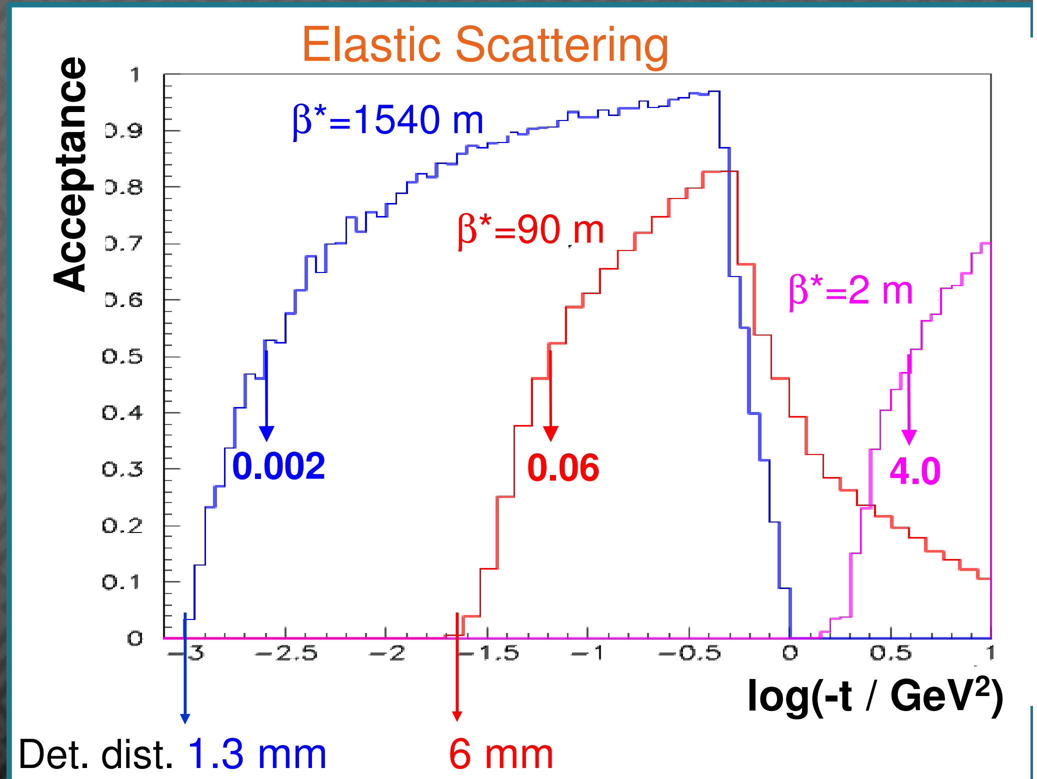
90m: see all protons
0.03 < |t| < 10 GeV²

Optics properties at RP220:

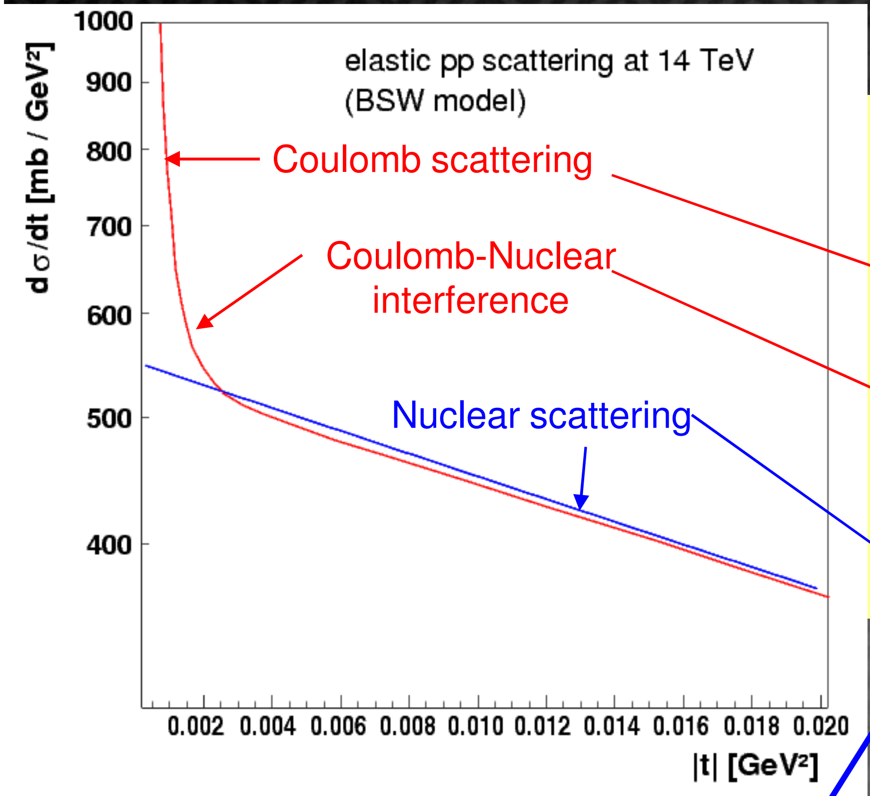
β* = 1540 m	L = 10^{28} – 2 x10^{29}	95% of all p seen; all ξ
β* = 90 m	L = 10^{29} – 3 x10^{30}	65% of all p seen; all ξ
β* = 0.5– 2m	L = 10^{30} – 10^{34}	ξ > 0.02 seen; all t

Detector distance to the beam: 10σ+0.5mm





Total Cross-Section and Elastic Scattering at low |t|



Related by the Optical Theorem:

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2 (\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho - \alpha\phi)\sigma_{tot} G^2(t)}{|t|} e^{-B|t|/2} + \frac{\sigma_{tot}^2 (1+\rho^2)}{16\pi(\hbar c)^2} e^{-B|t|}$$

α = fine structure constant

ϕ = relative Coulomb-nuclear phase

G(t) = nucleon em form factor = $(1 + |t|/0.71)^{-2}$

ρ = Re/Im f(**p**→**p**)

TOTEM Approach:

Measure the exp. slope B in the t-range 0.002 - 0.2 GeV^2 , extrapolate dσ/dt to t=0,
Measure total inelastic and elastic rates (all TOTEM detectors provide L1 triggers):

$$L\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \times \left.\frac{dN_{elastic,nuclear}}{dt}\right|_{t=0}$$

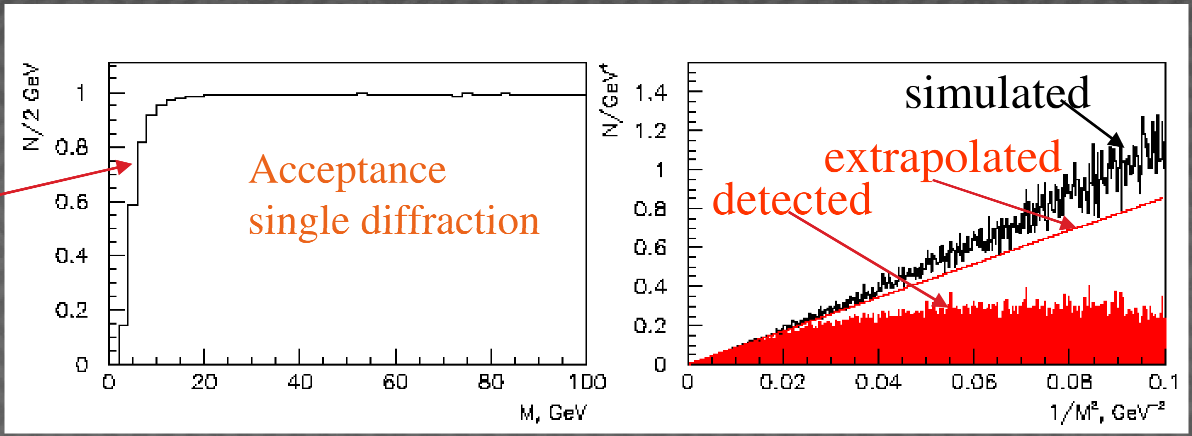
$$L\sigma_{tot} = N_{elastic,nuclear} + N_{inelastic}$$

$$\Rightarrow \quad \sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN_{elastic,nuclear}/dt)|_{t=0}}{N_{elastic,nuclear} + N_{inelastic}}$$

Measurement of the Inelastic Rate

- Inelastic double arm trigger: robust against background, inefficient at small M
- Inelastic single arm trigger: suffers from beam-gas + halo background, best efficiency
- Inelastic triggers and proton (SD, DPE): cleanest trigger, proton inefficiency to be extrapolated
- Trigger on non-colliding bunches to determine beam-gas + halo rates.
- Vertex reconstruction with T1, T2 to suppress background
- Extrapolation of diffractive cross-section to large $1/M^2$ assuming $d\sigma/dM^2 \sim 1/M^2$

Loss at low diffractive masses M



	σ [mb]	trigger loss [mb]	systematic error after extrapolations [mb]
Non-diffractive inelastic	58	0.06	0.06
Single diffractive	14	3	0.6
Double diffractive	7	0.3	0.1
Double Pomeron	1	0.2	0.02
Total	80	3.6	**0.8**

Combined Uncertainty in σ_{tot}

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt|_{t=0}}{N_{el}+N_{inel}}$$

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

	$\beta^* = 90$ m	1540 m
◆ Extrapolation of elastic cross-section to t = 0:	± 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 $(1+\rho^2)$ using full COMPETE error band $\delta\rho/\rho = 33$ %	± 1.2 %	

→ **Total uncertainty in σ_{tot} including correlations in the error propagation:**
$\beta^* = 90$ m : ± 5 %, $\beta^* = 1540$ m : ± (1 ÷ 2) % .

Slightly worse in $\mathcal{L}$ (~ total rate squared!) : ± 7 % (± 2 %).

Precise Measurement with $\beta^* = 1540$ m requires:

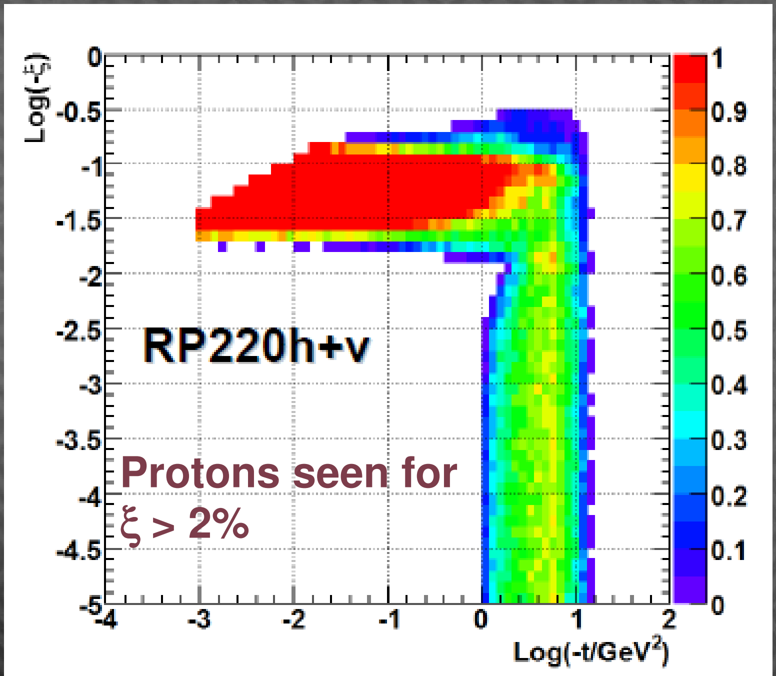
- improved knowledge of optical functions
- alignment precision < 50 μm

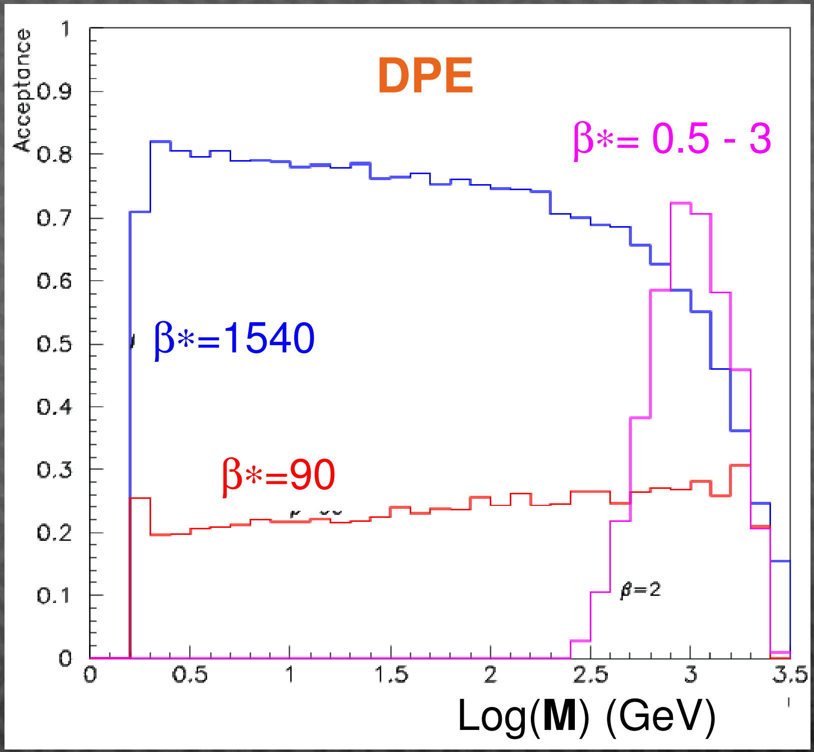
Early Physics with TOTEM *(E_p = 5 TeV & β^* = 3m)*

RP220 Acceptance:

- elastic scattering $1 < |t| < 12$ GeV^2
- diffractive protons $0.02 < \xi < 0.18$
- resolution: $\sigma(\xi) <\sim 6 \cdot 10^{-3}$

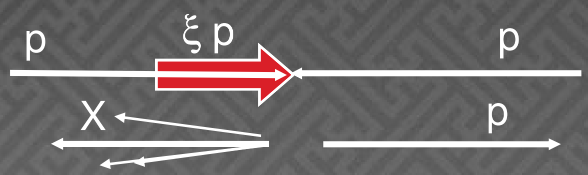
very similar to E_p = 7 TeV !!





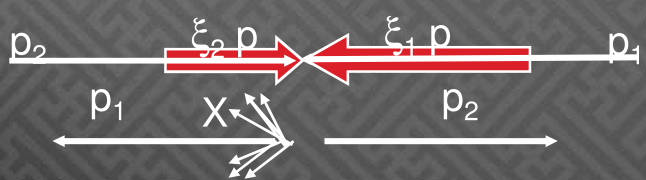
Very first measurements with low β* optics

- <u>Using horizontal RPs</u>
  - $d\sigma^{SD}/dM$ (SD events with high mass)
    - $0.02 < \xi < 0.18 \Rightarrow$ **2 < M < 6 TeV**
    - $\sigma(M)/M$ = 2–4 %

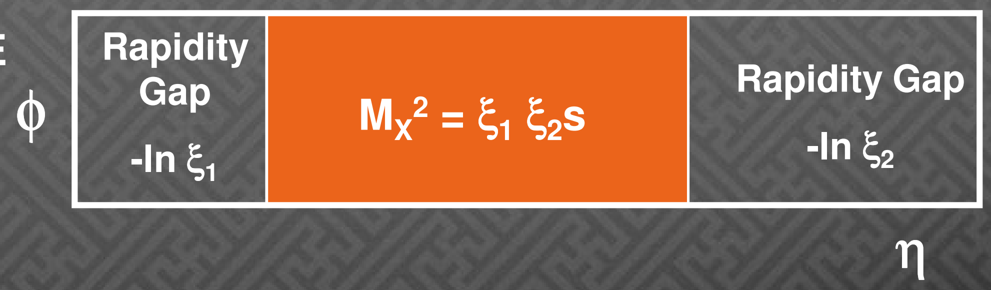


SD

  - $d\sigma^{DPE}/dM$ (DPE high mass)
    - **250 < M < 2500 GeV**
    - $\sigma(M)/M$ = 2.1–3.5 %



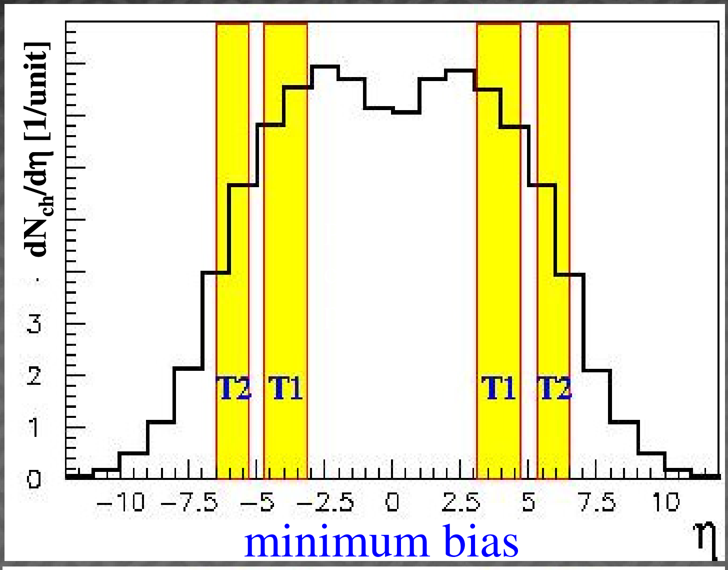
DPE



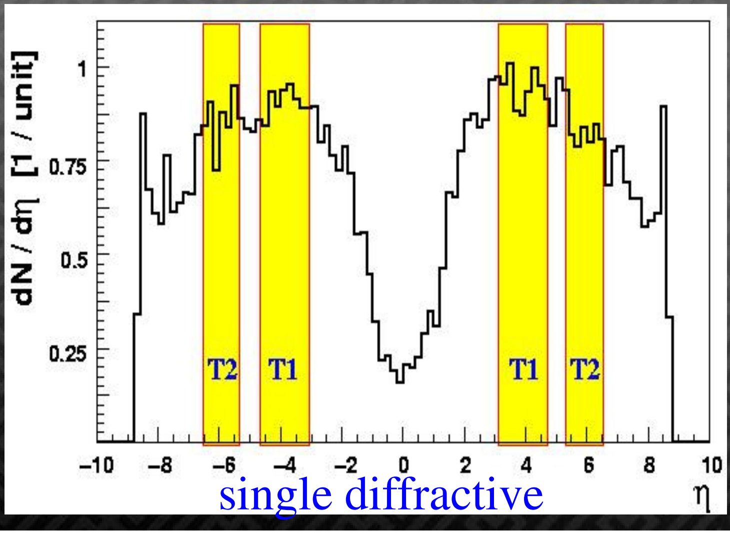
- <u>Using vertical RPs:</u> high t elastic scattering
  - $d\sigma^{Elastic}/dt$ $1 < |t| < 12$ GeV^2 $\sigma(t) \approx 0.2 \cdot \sqrt{|t|}$

T1/T2: charged multiplicity

- Measurement of charged multiplicity for different processes
  - Important also for **cosmic ray physics** (e.g. for MC generator validation)
- Identification and measurement of rapidity gaps



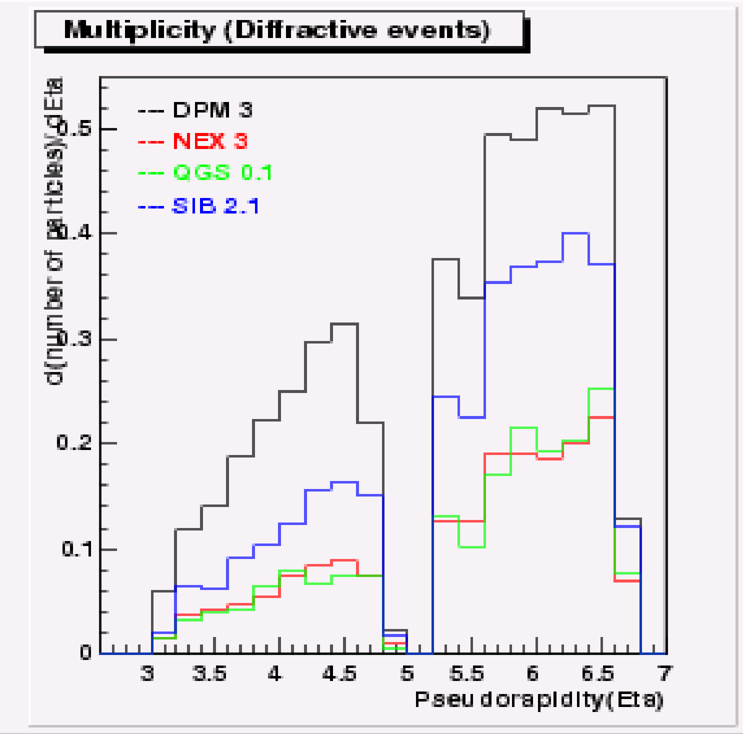
minimum bias



single diffractive

Acceptance:
3.1 < η < 4.7 (T1) & 5.3 < η < 6.5 (T2)

σ(η) = 0.04 – 0.2, no mom. & ϕ info



Conclusions

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

The TOTEM experiment at LHC

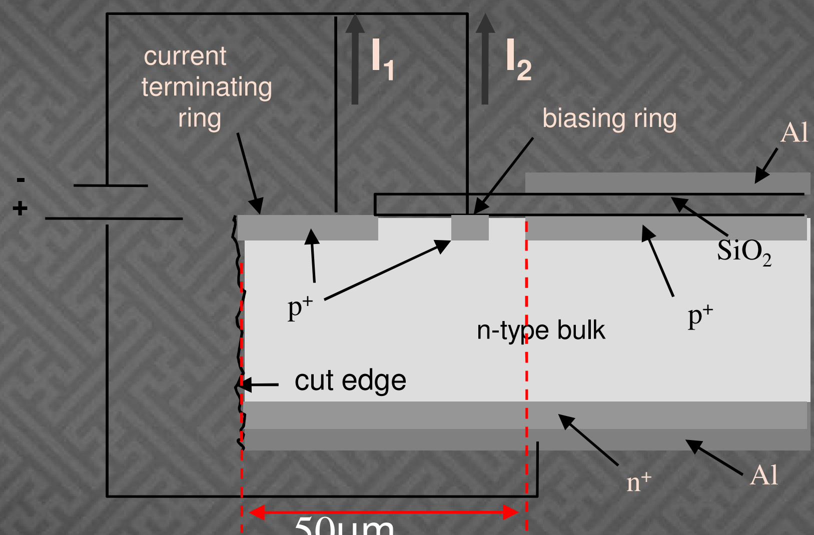
Backup Slides

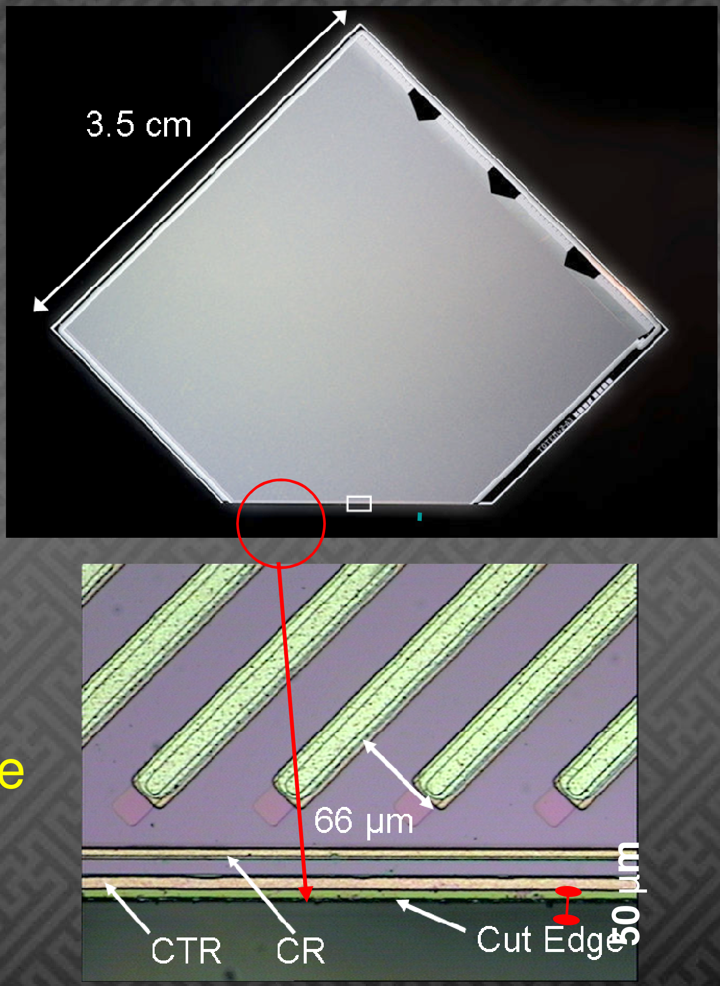
Si CTS edgeless detectors

Proton detection down to $10\sigma_{beam,\perp} + d$ ($\sigma_{beam,\perp}$ = 80 – 600 µm)

To minimize d : detectors with highly reduced inactive edge (”edgeless”)

Planar technology + CTS
(Current Terminating Structure)





Micro-strip Si detectors designed to reduce the inefficiency at the edge.

Inefficient edge ~ 50 µm

Optics and Beam Parameters

Parameters	$\beta^* = 2$ m (standard step in **LHC start-up**)	$\beta^* = 90$ m (early TOTEM optics)	$\beta^* = 1540$ m (final TOTEM optics)
Crossing angle	0.0	0.0	0.0
N of bunches	156	156	43
N of part./bunch	$(4 - 9) \times 10^{10}$	$(4 - 9) \times 10^{10}$	3×10^{10}
Emittance ε_n [μm · rad]	3.75	3.75	1
10 σ_y beam width at RP220 [mm]	~ 3	6.25	0.8
Luminosity [$cm^{-2}\ s^{-1}$]	$(2 - 11) \times 10^{31}$	$(5 - 25) \times 10^{29}$	1.6×10^{28}

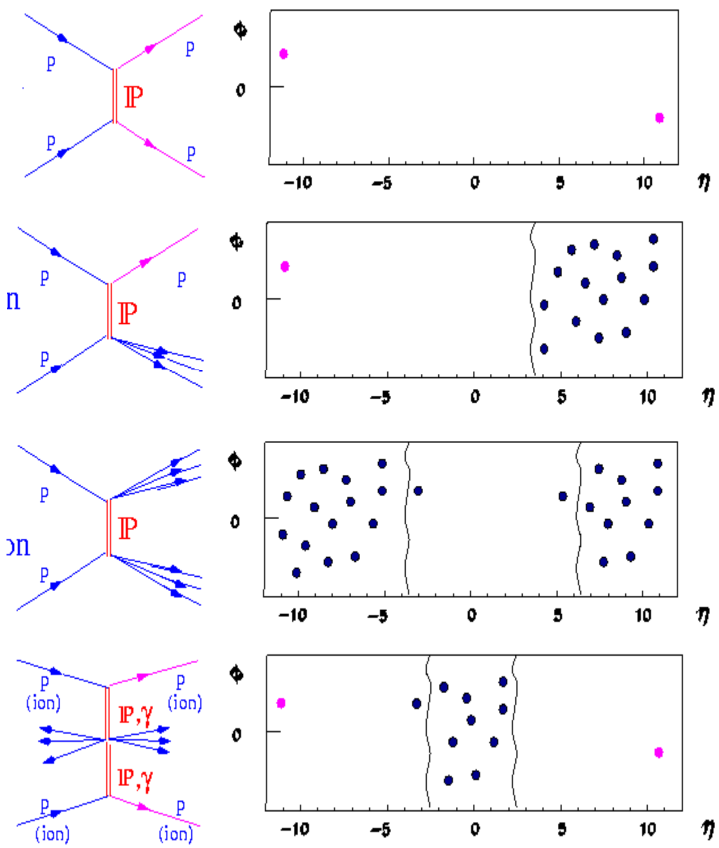
$\beta^* = 90$ m ideal for early running:

- fits well into the **LHC start-up** running scenario;
- uses **standard injection** ($\beta^* = 11$m) → easier to commission than 1540 m optics
- wide beam → ideal for training the RP operation (less sensitive to alignment)

$\beta^* = 90$ m optics proposal submitted to the LHCC and well received.

Level-1 Trigger Schemes

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



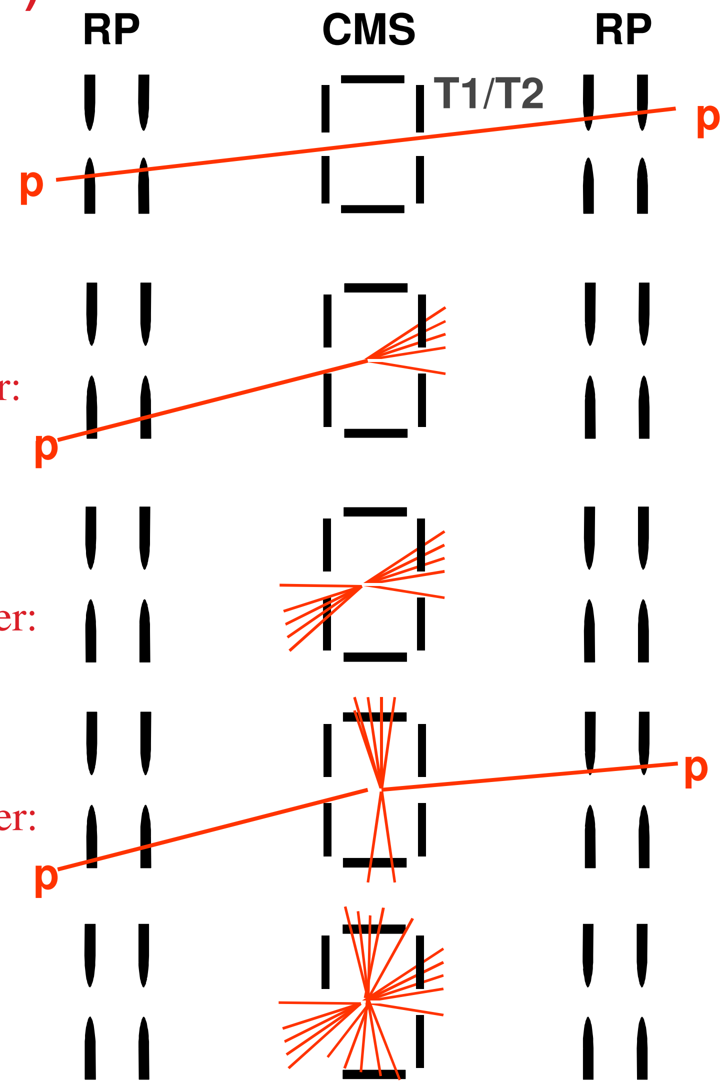
Elastic Trigger:

Single Diffractive Trigger:

Double Diffractive Trigger:

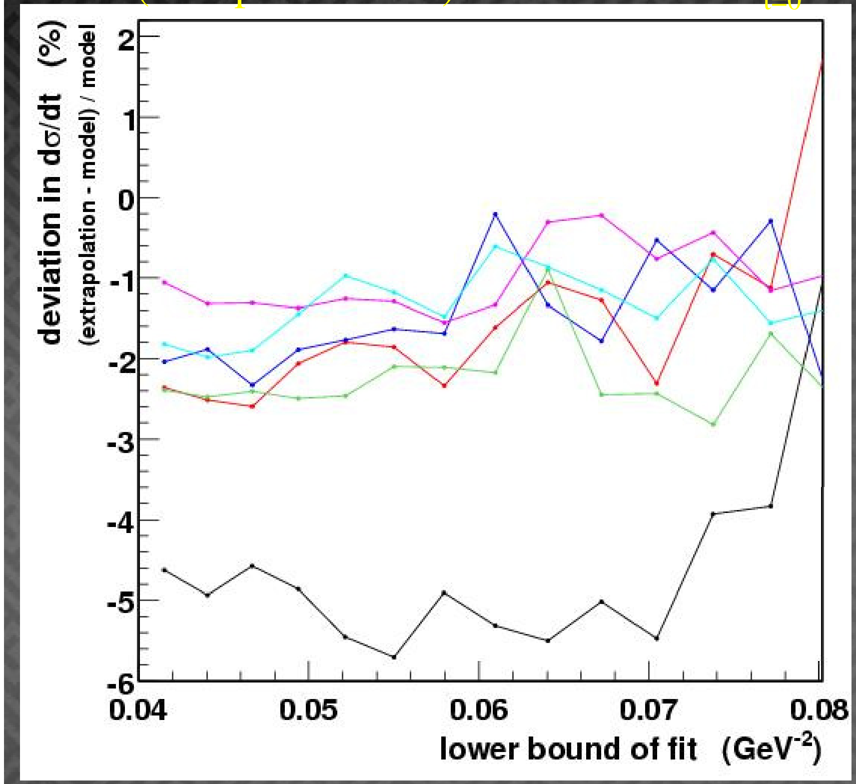
Central Diffractive Trigger:

Minimum Bias Trigger:

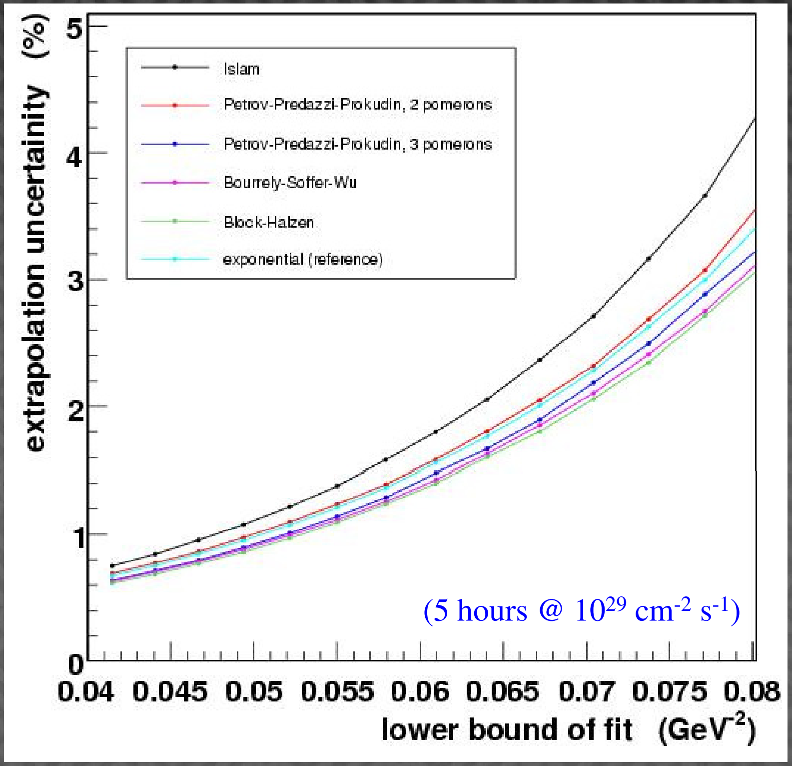


Extrapolation to the Optical Point (t = 0) at β*=90m

(extrapol. - model) / model in $d\sigma/dt\,|_{t=0}$



Statistical extrapolation uncertainty



Common bias due to beam divergence **: – 2 %** (angular spread flattens dN/dt distribution)

Spread between most of the models: **±1%**

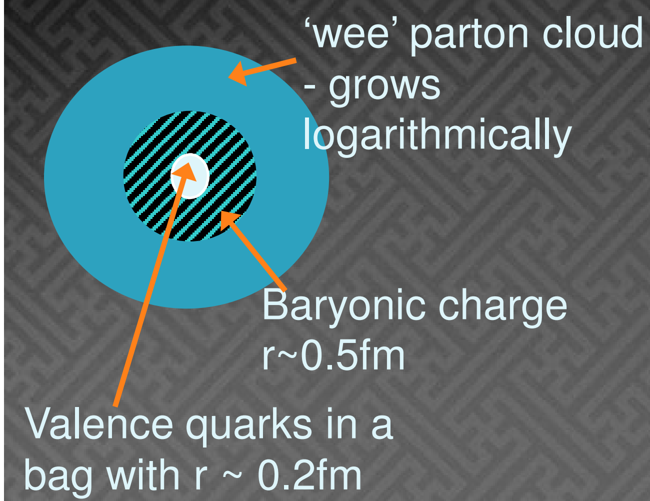
Systematic error due to uncertainty of optical functions: **± 3%**

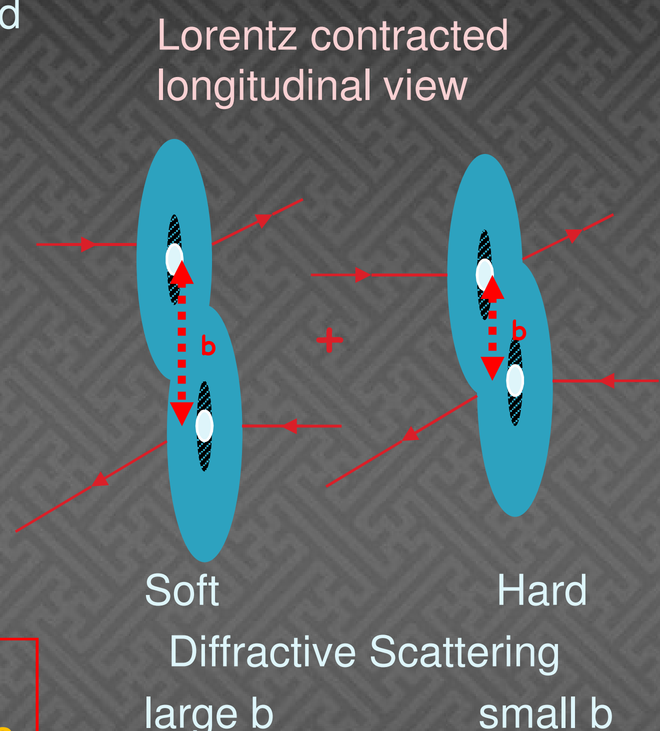
Different parameterizations for extrapolation tested (e.g. const. B, linear continuation of B(t)): negligible impact

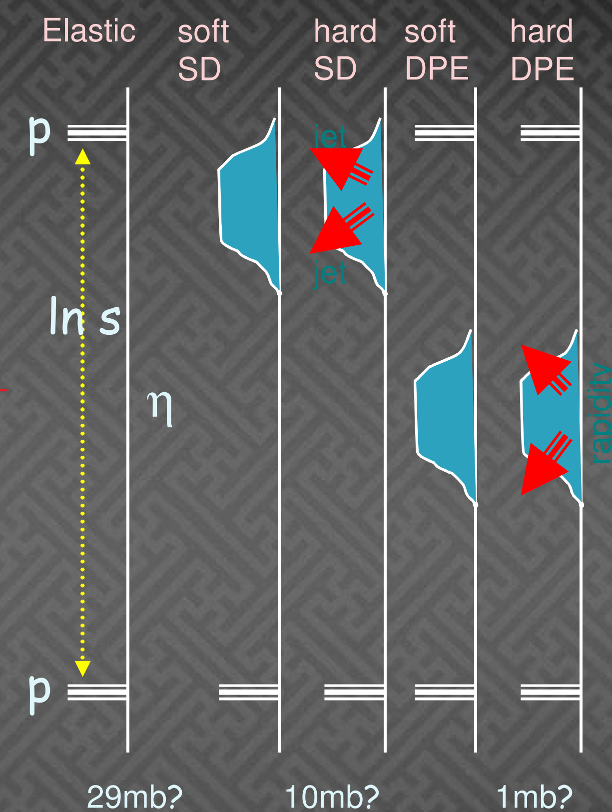
Diffractive scattering is a unique laboratory of confinement & QCD:

A hard scale + protons which remain intact in the scattering process

Forward protons observed, independent of their momentum losses







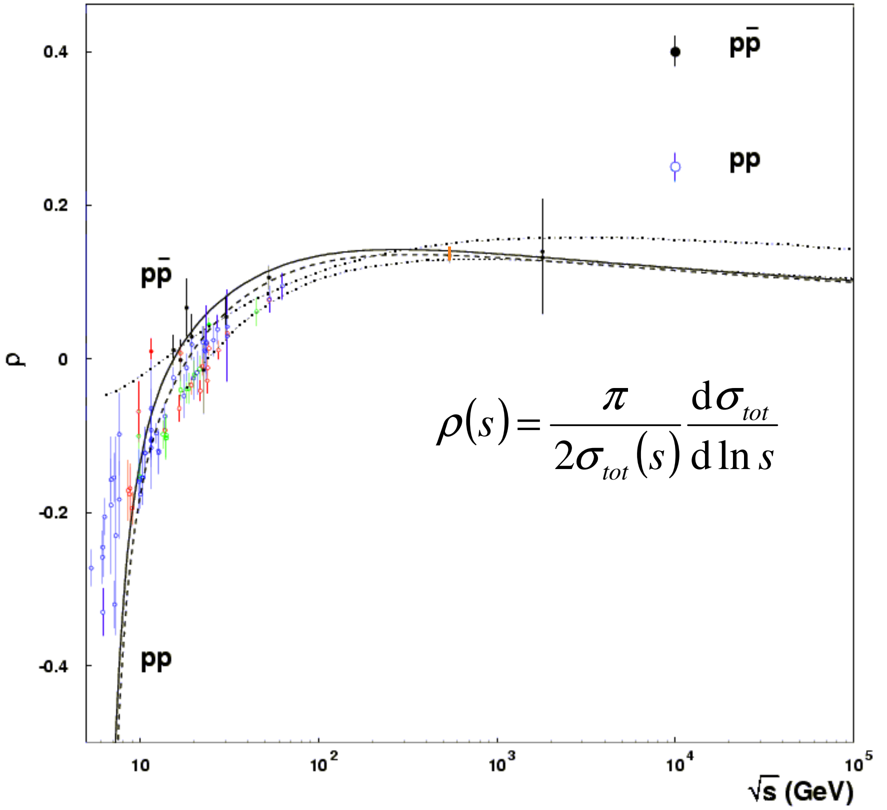
Rapidity gap survival & "underlying" event structures are intimately connected with a geometrical view of the scattering - eikonal approach !

Cross sections are <u>large</u>
Measure σ (M,ξ,t)

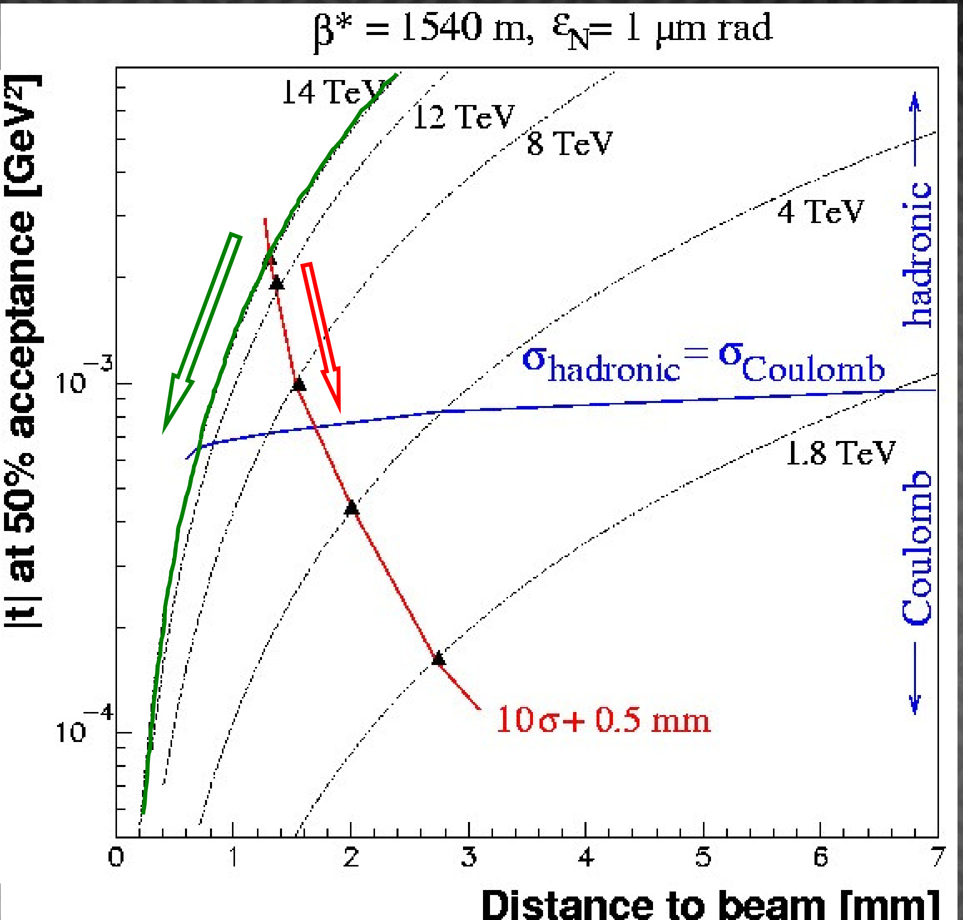
Soft processes:
Coherent interactions
-impact parameter picture.

Hard processes:
Jet momenta correlated with the initial parton momenta.

Possibilities of ρ measurement



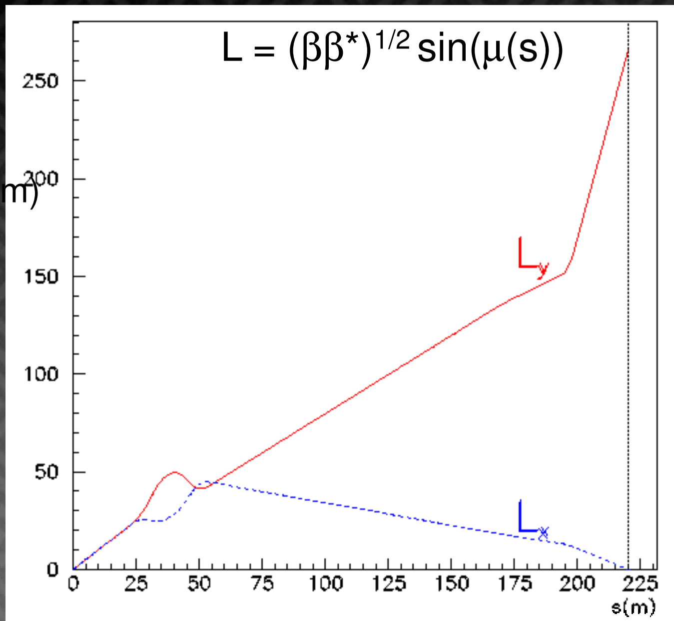
$$\rho(s) = \frac{\pi}{2\sigma_{tot}(s)} \frac{d\sigma_{tot}}{d\ln s}$$



Try to reach the Coulomb region and measure interference:

- move the detectors closer to the beam than 10 σ + 0.5 mm
- run at lower energy @ √s < 8 TeV

Optical Functions ($\beta^* = 90$ m)



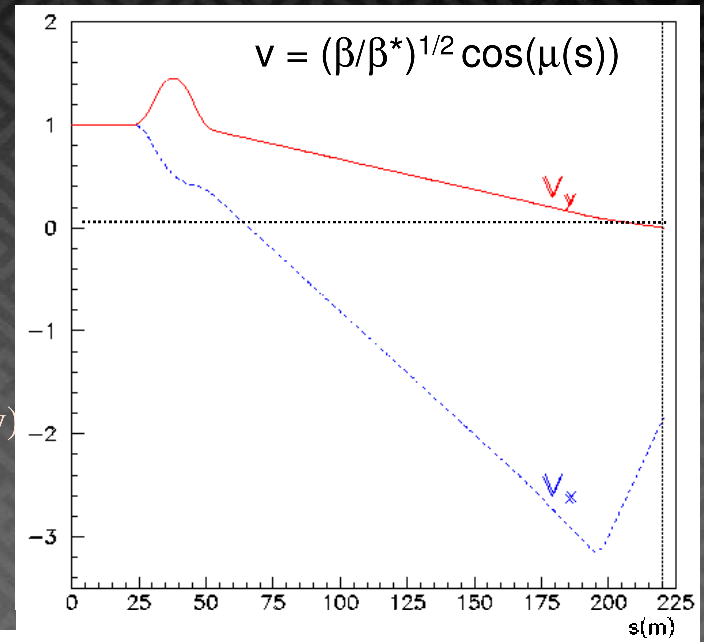
Idea:

L_y large L_x=0

v_y = 0

$\mu_y(220) = \pi/2$ $\mu_x(220) = \pi$

(parallel-to-point focussing on y)



$x = L_x\theta_x^* + v_x x^* + D\xi$

$y = L_y\theta_y^* + v_y y^*$

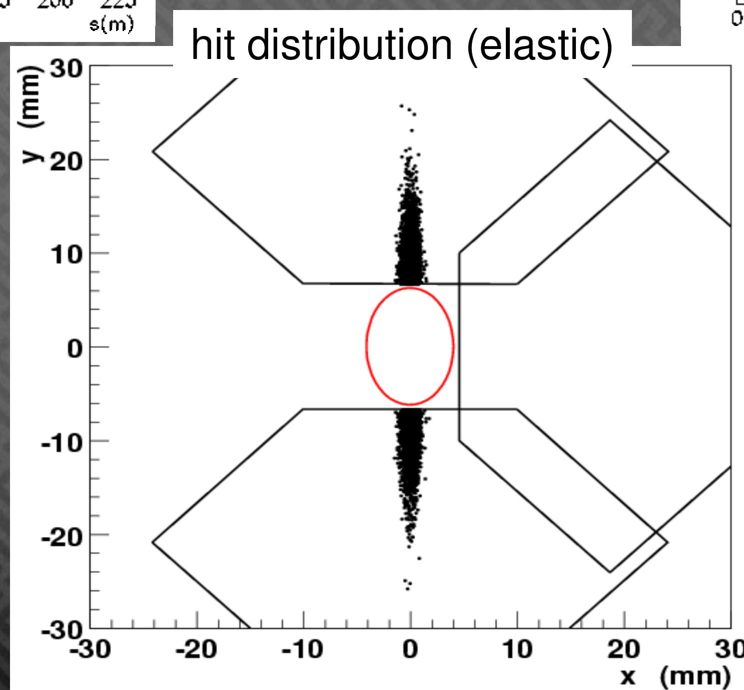
$\xi = \Delta p/p$

(x^*, y^*): vertex position at IP

(θ_x^*, θ_y^*): emission angle at IP

$t = t_x + t_y$

$t_i \sim -(p\theta_i^*)^2$



Optical functions:

- L (effective length)
- v (magnification)

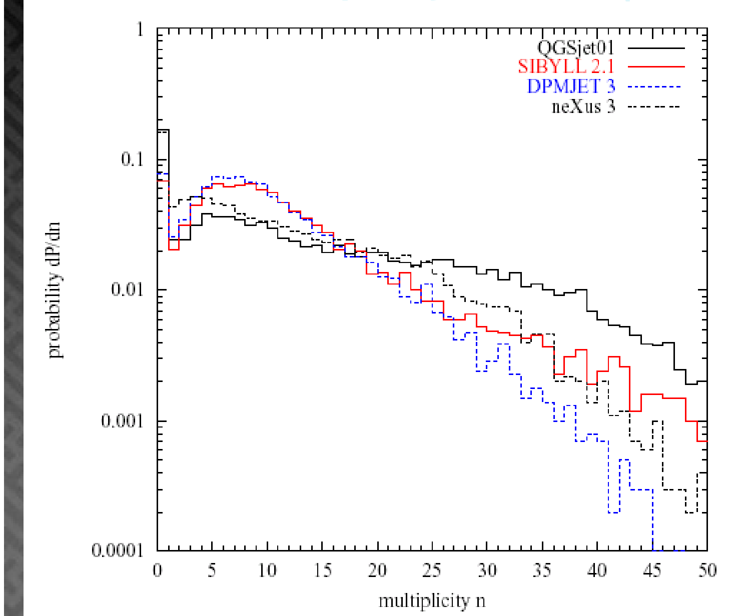
defined by β (betatron function) and μ (phase advance);

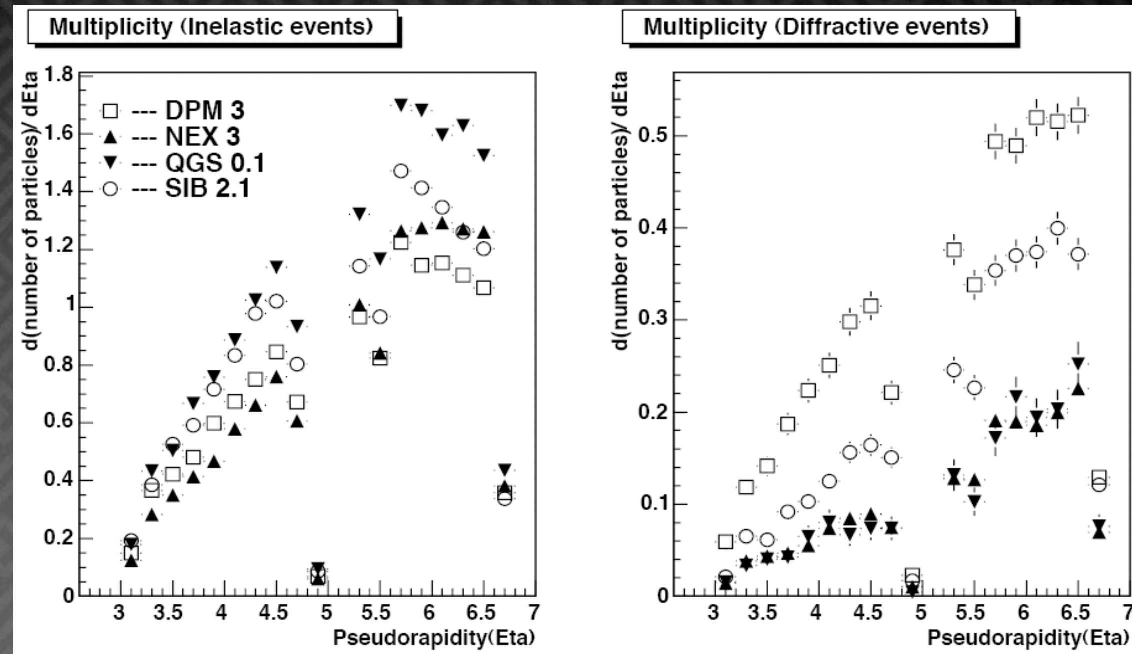
- D (machine dispersion)

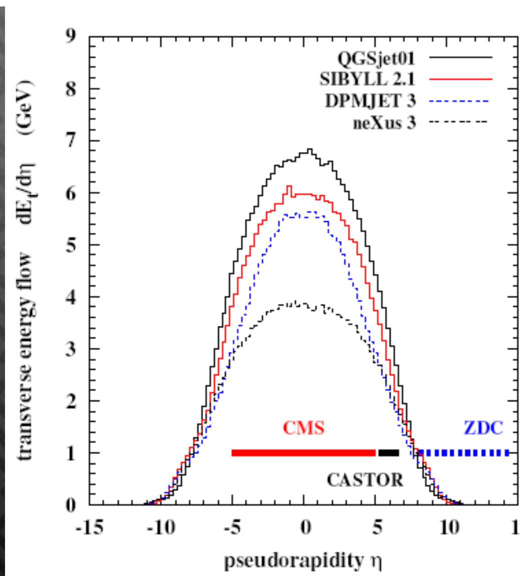
$\Rightarrow$ describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP

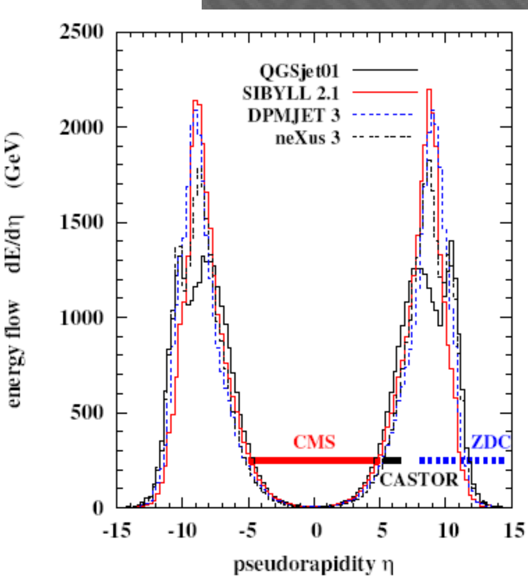
Forward Physics: VHE Cosmic Ray Connection

Total multiplicity in T2 (5<η<7)









p-p collisions @ LHC as predicted by generators tipically used to model hadronic showers generated by VHE CR

Interpreting cosmic ray data depends on hadronic simulation programs.
Forward region poorly known/constr.
Models differ by factor 2 or more.
Need forward particle/energy measurements e.g. dN/dη, dE/dη…

Machine Induced Background

T1/T2 Detectors:

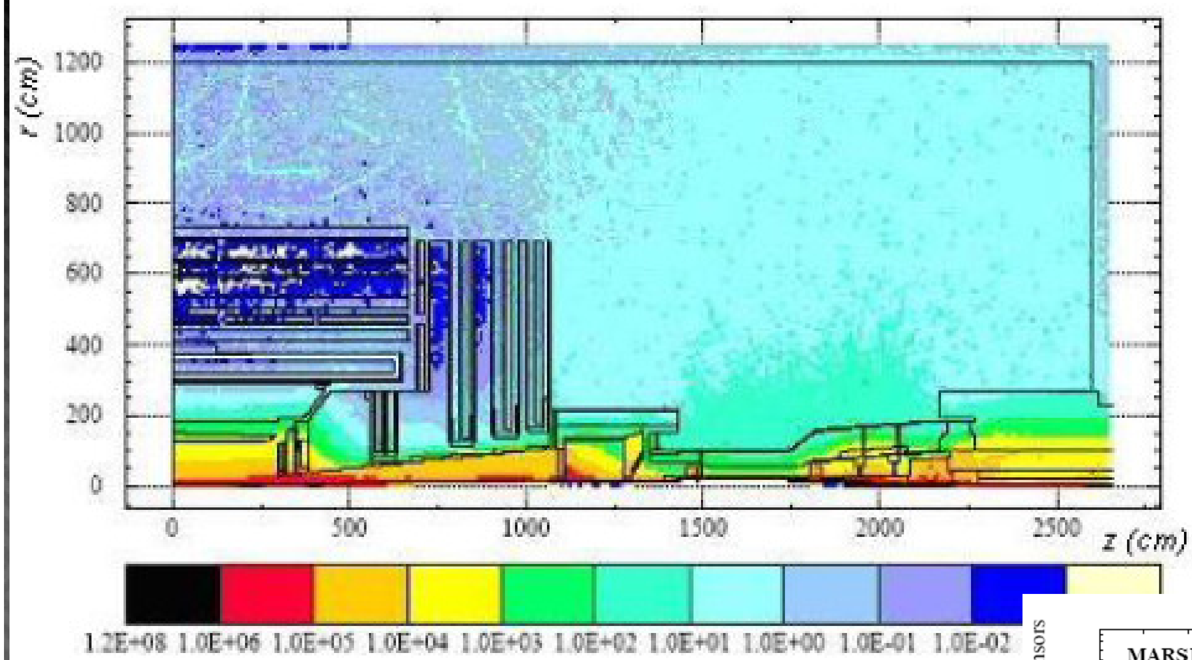
- **beam-gas interactions**: prel. ext. ~ 14 Hz per beam;
  ~ 19 KHz for MB events (σMB = 80 mb, L = 2.4 $\cdot 10^{29}$ cm^{-2} s^{-1})
  ⇒ reduced by vertex reconstruction
- **muon halo** (expected to be very small, not yet quantified)

Roman Pot Detectors:

- **beam halo** (protons out of design orbit): ext. (β^* = 1540m) ~ $12 \cdot 10^{-4}$/bunch
  ⇒ reduced by requiring coincidence between RP arms
- **beam-gas interactions**: ext. (β^* = 1540m) ~ $3 \cdot 10^{-4}$/bunch after cuts
  ⇒ reduced with cuts on track angles and multiplicities
- **p-p collision (at IP) background**: ext (β^* = 1540m) ~ $(0.4 \div 2) \cdot 10^{-4}$/bunch after cuts
  ⇒ reduced with cuts on track angles and hit multiplicities

Tot. elast. evts ~ 3 KHz (L = 10^{29} cm^{-2} s^{-1}); prel. expt. S/B ~ $(0.6 \div 0.7) \cdot 10^3$

Expected Radiation Dose in CMS/TOTEM



(b) Radiation Dose (rad)

In 1 year @

$L_{inst} = 10^{34}\ cm^{-2}s^{-1}$

At RPs locations =>