TOTEM forward measurement: leading protons

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on behalf of the
TOTEM Collaboration
http://totem.web.cern.ch/Totem/

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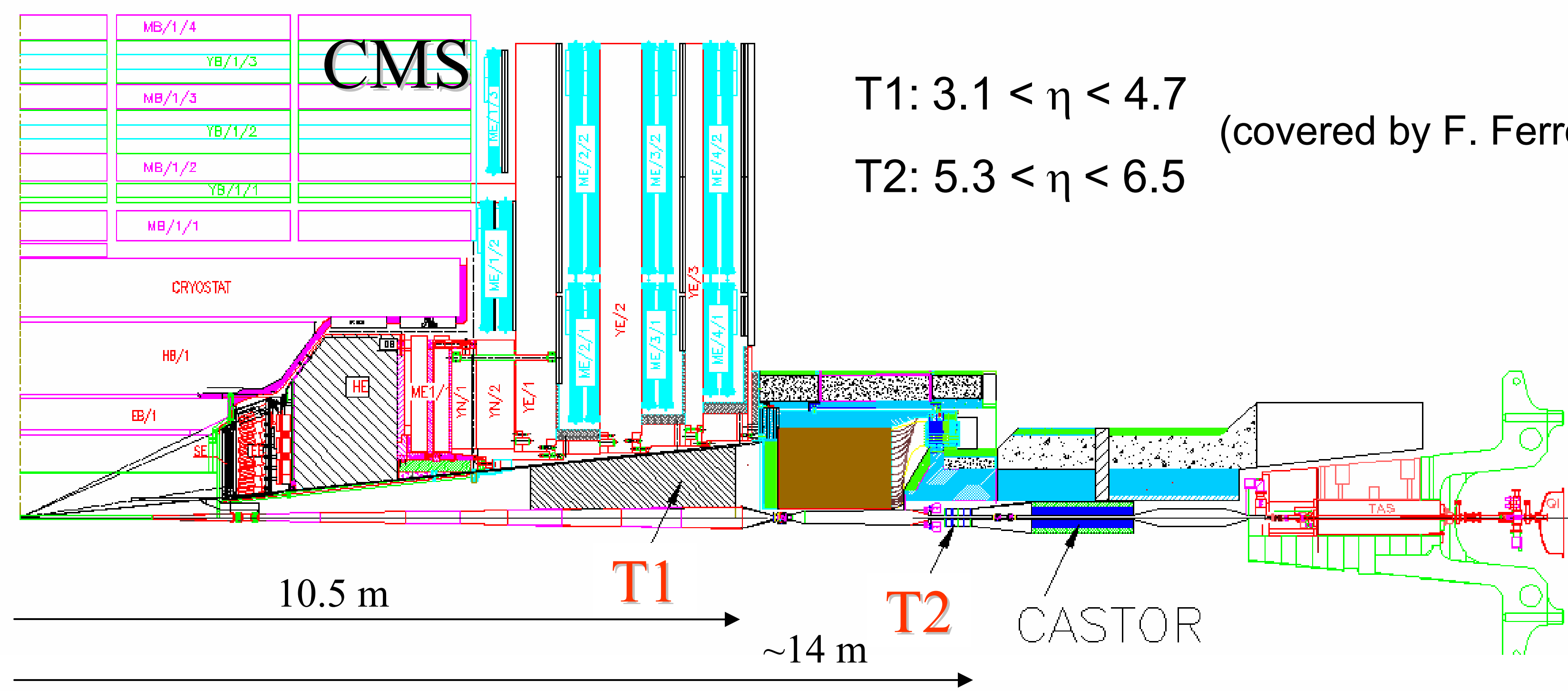
- σ_{tot} (not covered in this talk)
- elastic scattering
- diffraction (together with CMS)

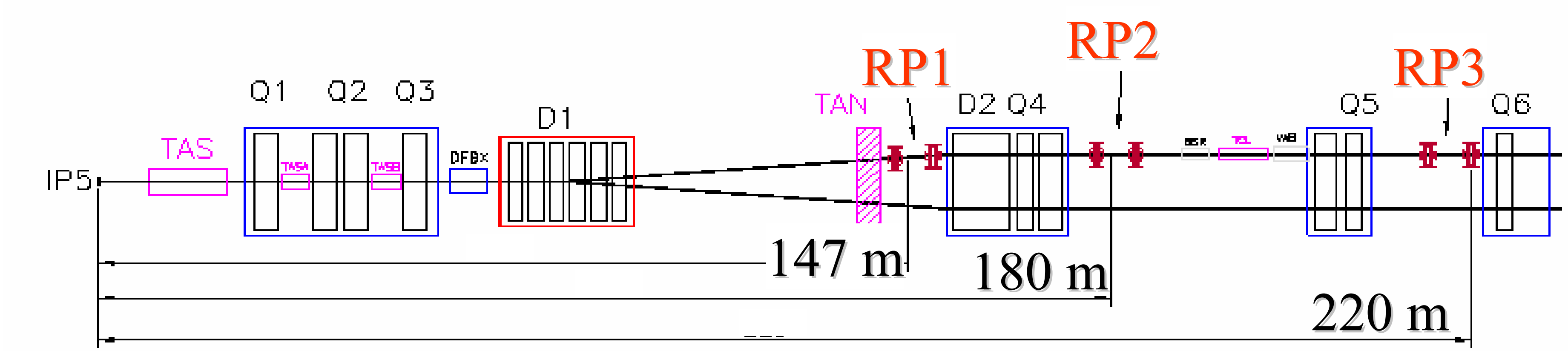
Experimental apparatus

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

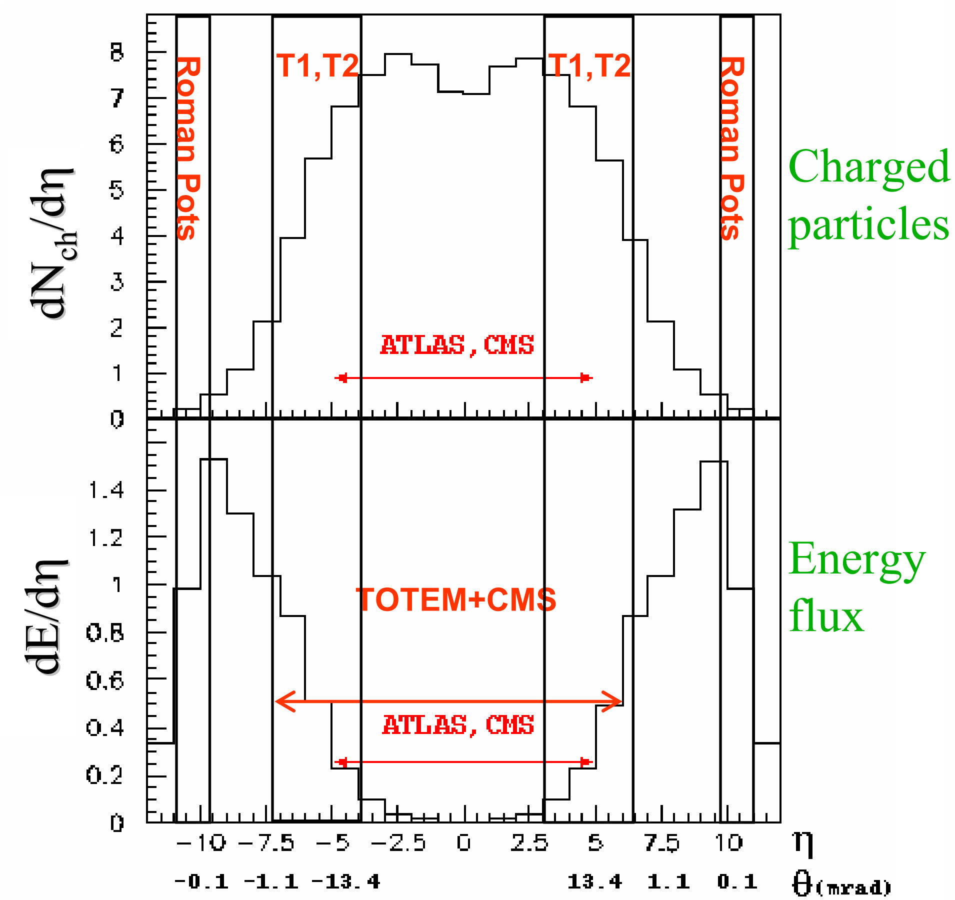
(covered by F. Ferro)

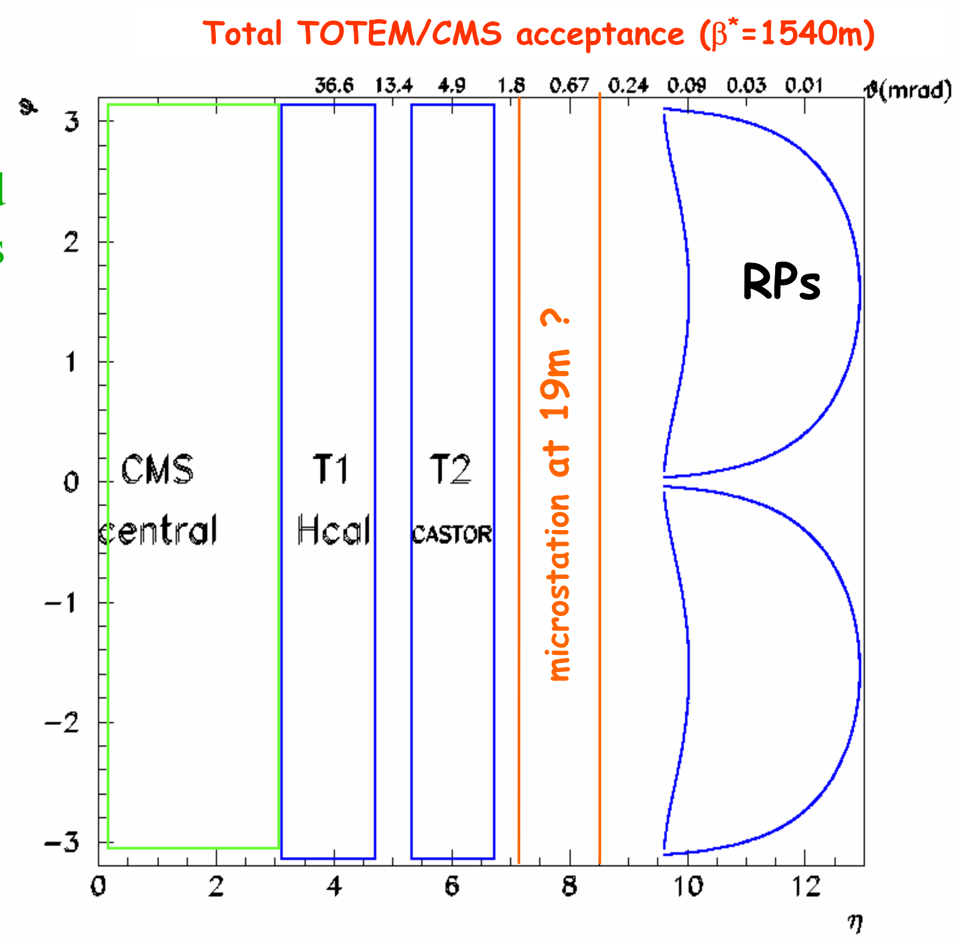




CMS + TOTEM acceptance

CMS+TOTEM: largest acceptance detector ever built at a hadron collider

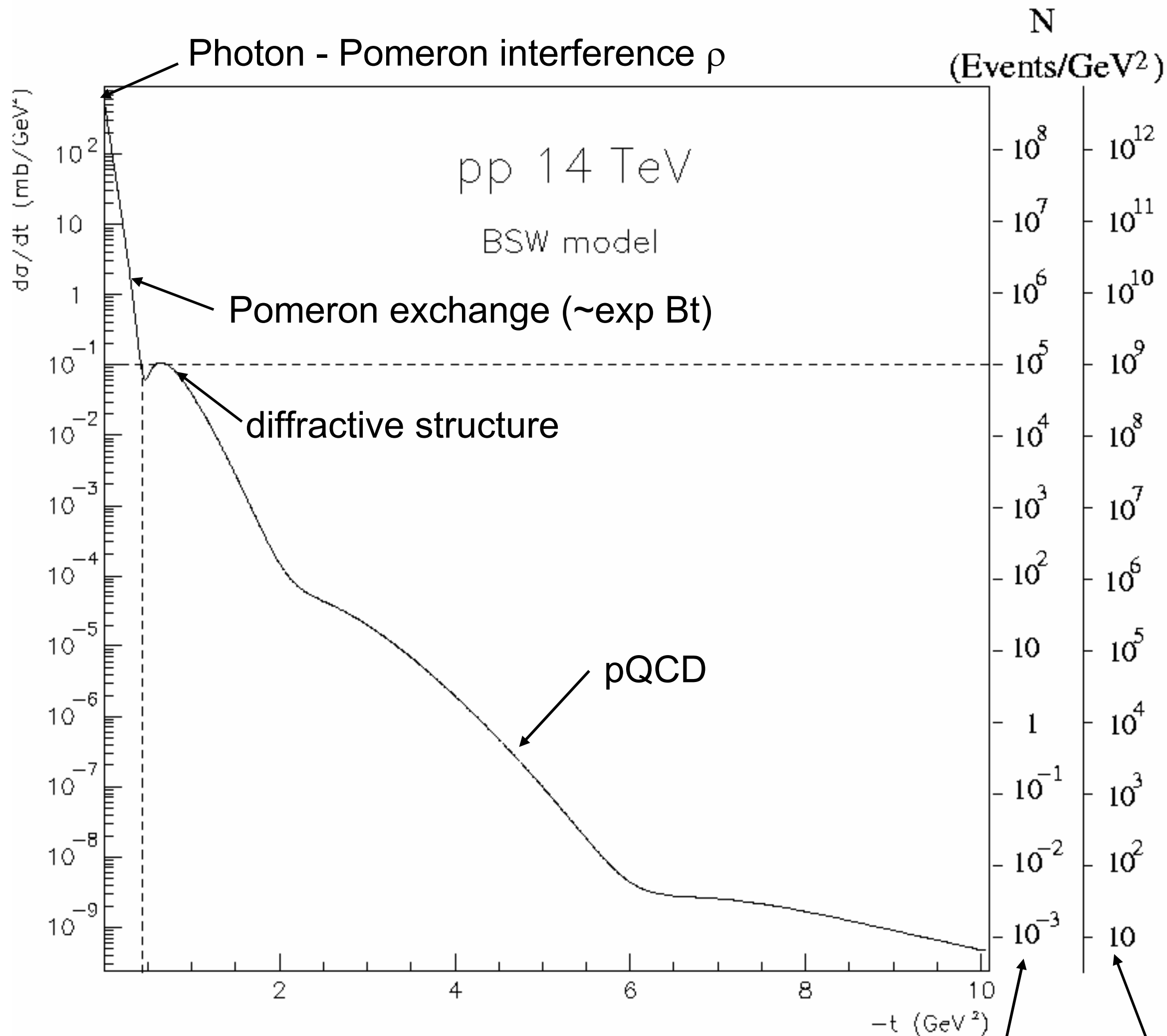




TOTEM Trigger & DAQ are CMS-compatible

(RP's up to 220 m within CMS L1 trigger latency)

Elastic scattering: cross section



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

(β^* = 1540 m & 18 m)

TOTEM beam optics

For σ_{tot} need to measure elastic scattering at very small t ($\sim 10^{-3}$) $\Rightarrow$ measure scattering angles down to a few mrad.

Proton trajectory:

$y(s) = L_y(s)\, \theta_y^* + v_y(s)\, y^*$, $\quad L(s) = [\beta(s) \times \beta^*]^{1/2} \sin \mu(s)$

$x(s) = L_x(s)\, \theta_x^* + v_x(s)\, x^* + D_x(s)\, \xi$, $\quad v(s) = [\beta(s) / \beta^*]^{1/2} \cos \mu(s)$

- Maximise $L_x(s)$, $L_y(s)$ at RP location
- Minimise $v_x(s)$, $v_y(s)$ at RP location (parallel-to-point focussing: v=0)

$\Rightarrow$ High-β^* optics: for TOTEM β^* = 1540 m ($v_x \approx 0$, $v_y \approx 0$ at 220 m)

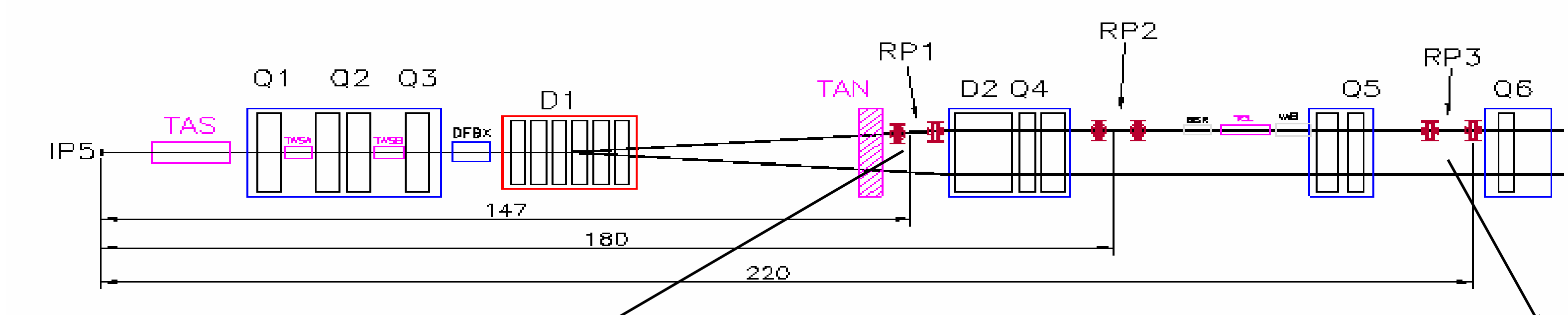
Consequences:

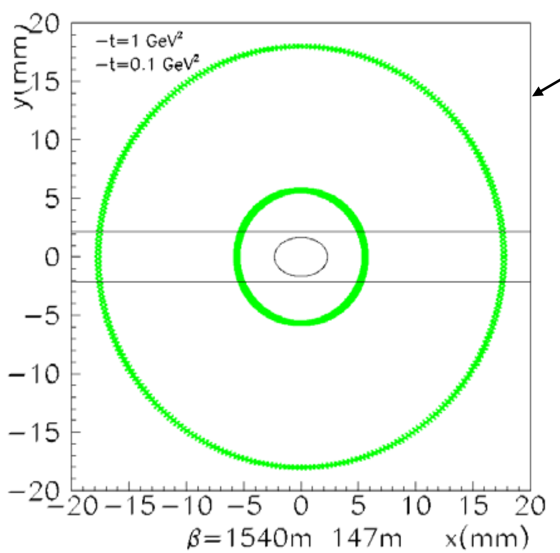
- **low angular spread at IP:** $\sigma(\theta^*_{x,y}) = \sqrt{\varepsilon / \beta^*} \approx 0.3\ \mu$rad
- **large beam size at IP:** $\sigma^*_{x,y} = \sqrt{\varepsilon\, \beta^*} \approx 0.4$ mm

(if $\varepsilon_N = 1\ \mu$m rad)

$\Rightarrow$ **Reduced # of bunches (43 & 156) to avoid parasitical interactions downstream.**

$\mathcal{L}_{TOTEM} = 1.6 \times 10^{28}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ & $2.4 \times 10^{29}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

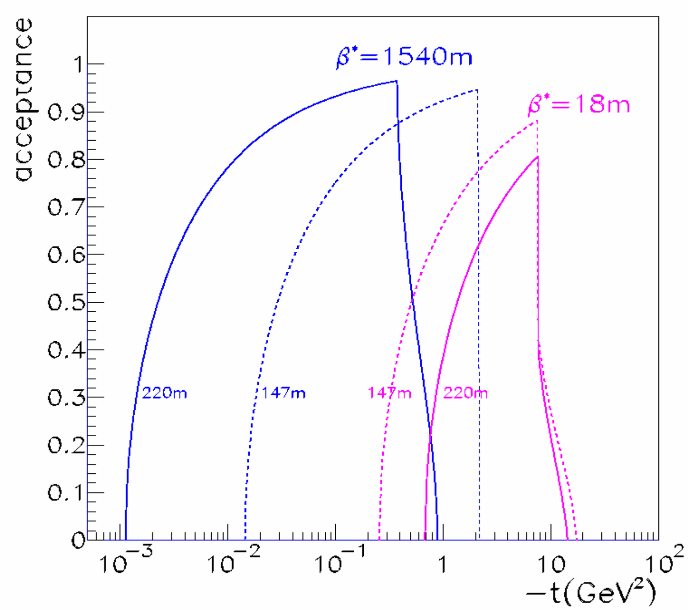


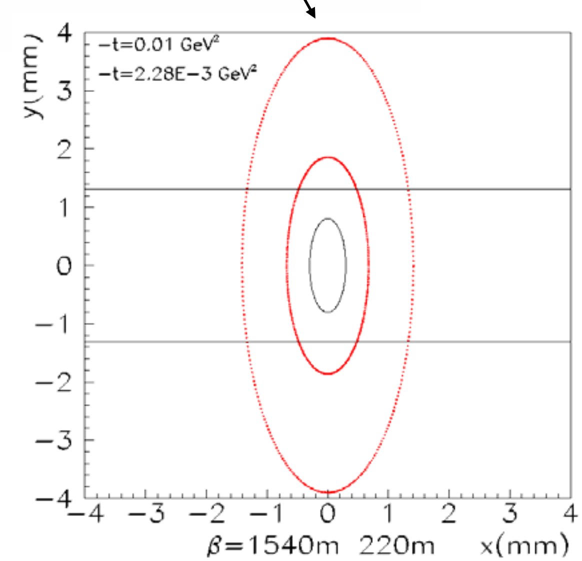


Elastic scattering

$\beta^* = 1540$ m

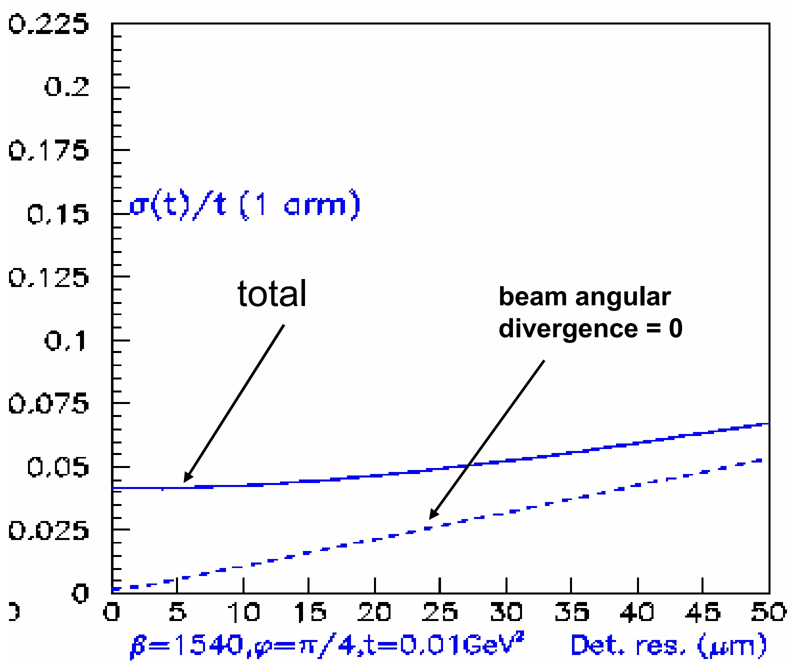
acceptance



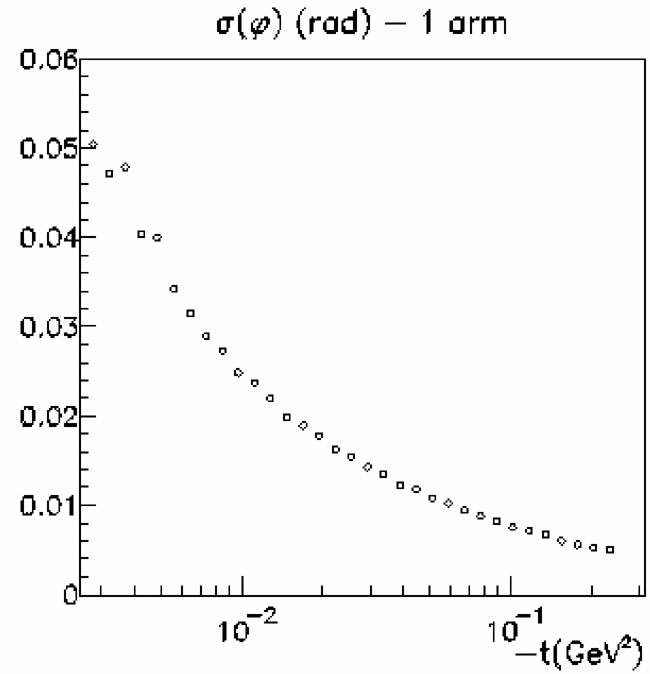


Leading protons: t & ϕ resolution

$\sigma(t)/t$ vs detector resolution



ϕ resolution vs t

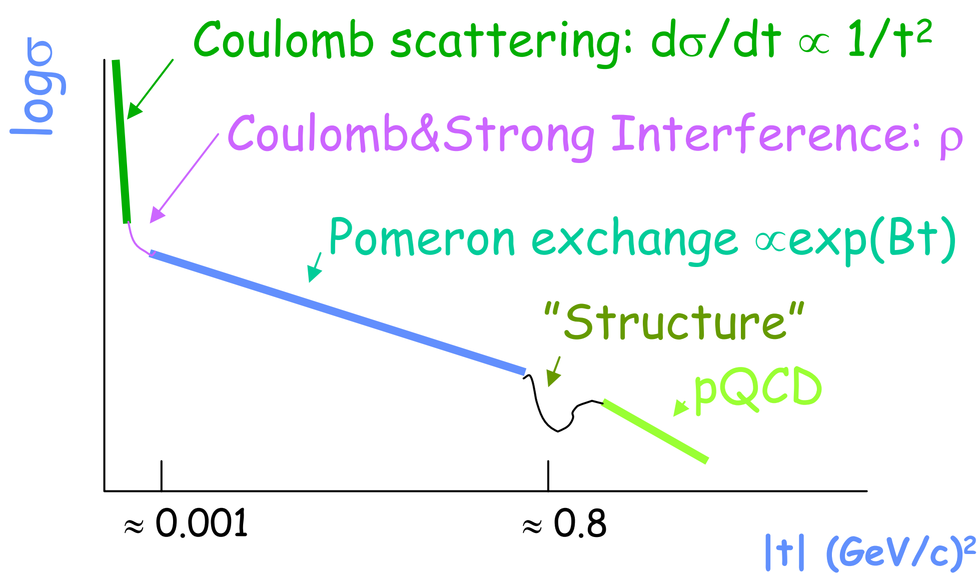


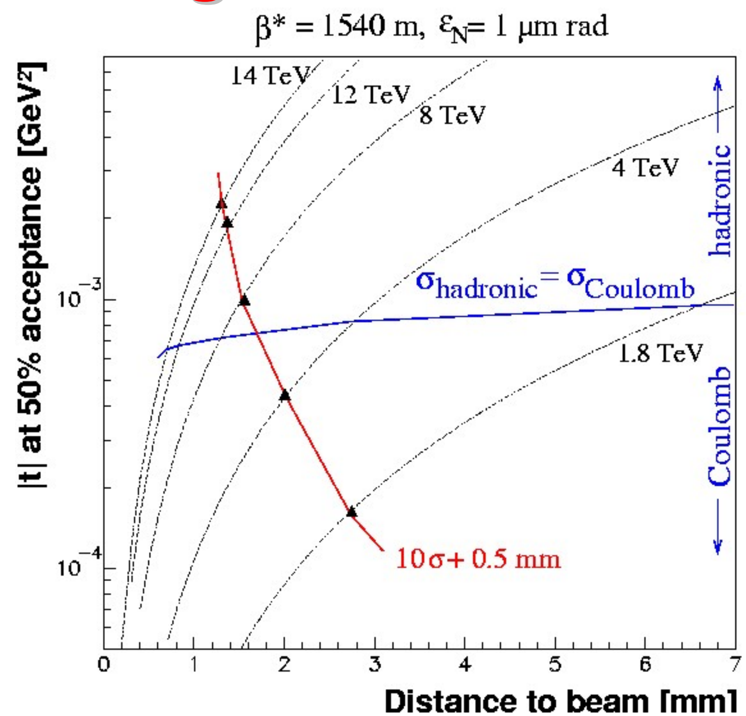
Test collinearity of protons with 2 arms
$\Rightarrow$ Background reduction

All plots based on LHC6.4 optics using MADX. Beam approach $10\sigma_{beam}$ + 0.5 mm. All relevant smearings at IP & RP locations taken into account.

Use ϕ correlation for DPE selection

Elastic scattering



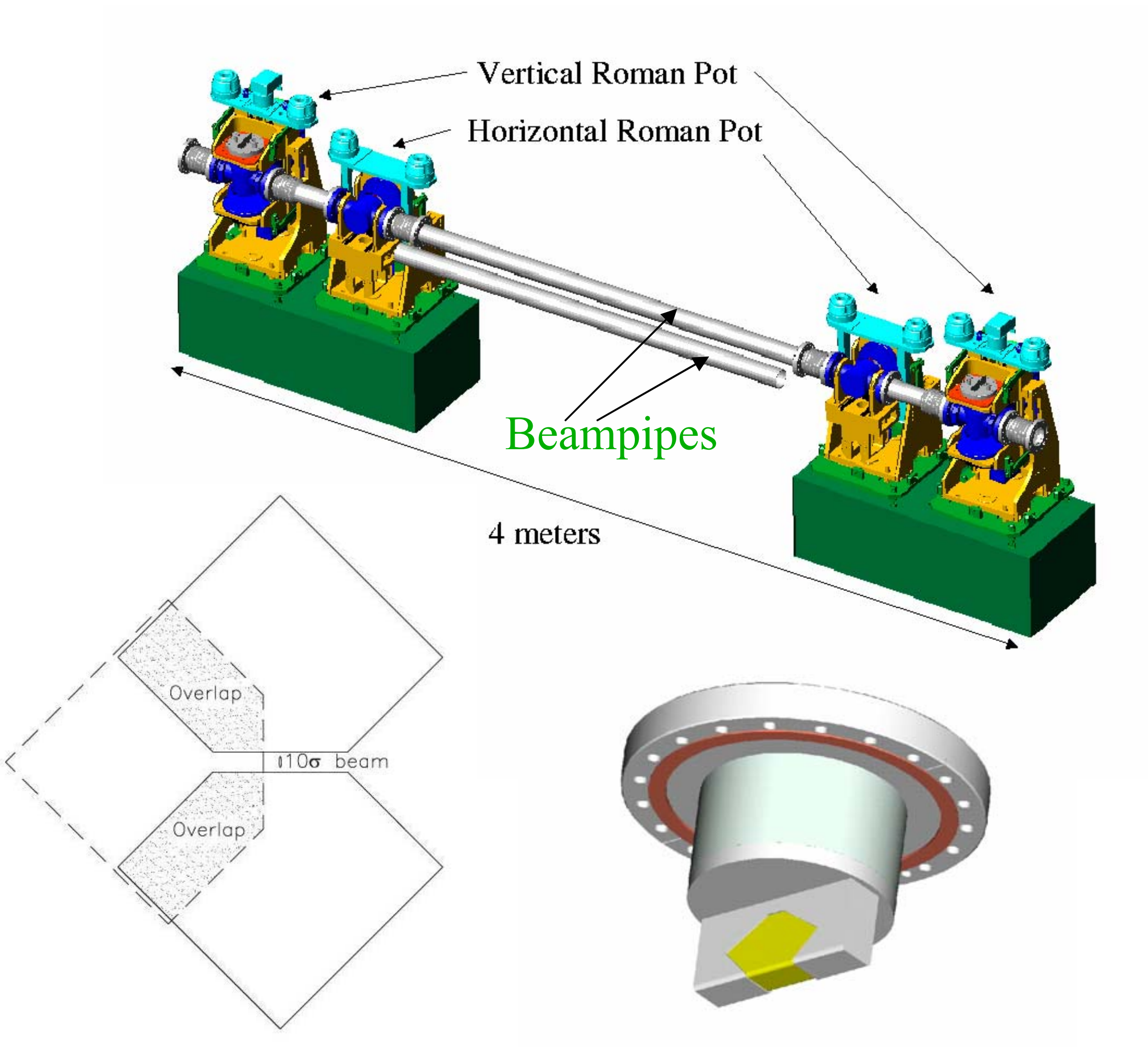


Region	$|t|$ [GeV]^2	Running Scenario
Coulomb region	$\leq 5\times10^{-4}$	[lower s, RP's closer to beam]
Interference, ρ meas.	$5\times10^{-4} \div 5\times10^{-3}$	[as above], standard β* = 1540 m
Pomeron exchange	$5\times10^{-3} \div 0.1$	β* = 1540 m
Diffractive structure	$0.1 \div 1$	β* = 1540 m, 200 - 400 m (?)
Large $|t|$ – perturb. QCD	$1 \div 10$	β* = 18 m

Leading proton detectors: Roman pots

Measurement of very small p scattering angles (few μrad):

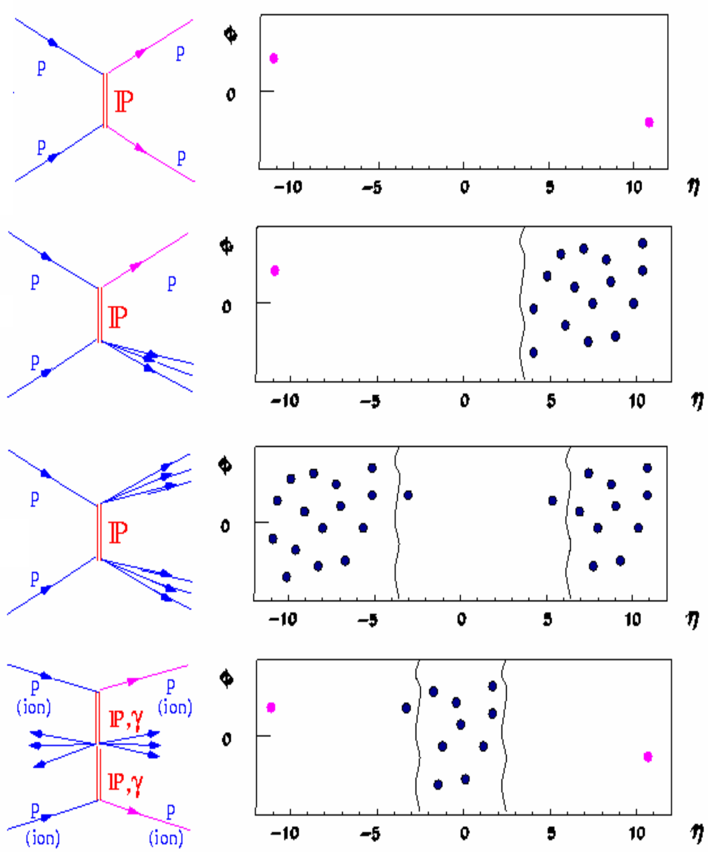
Leading proton detectors in RPs approach beam to 10 σ + 0.5 mm ≈ 1.5 mm



2004 prototype

Level-1 trigger schemes

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



Elastic Trigger:
Signal: 500 Hz
Background: 20 Hz

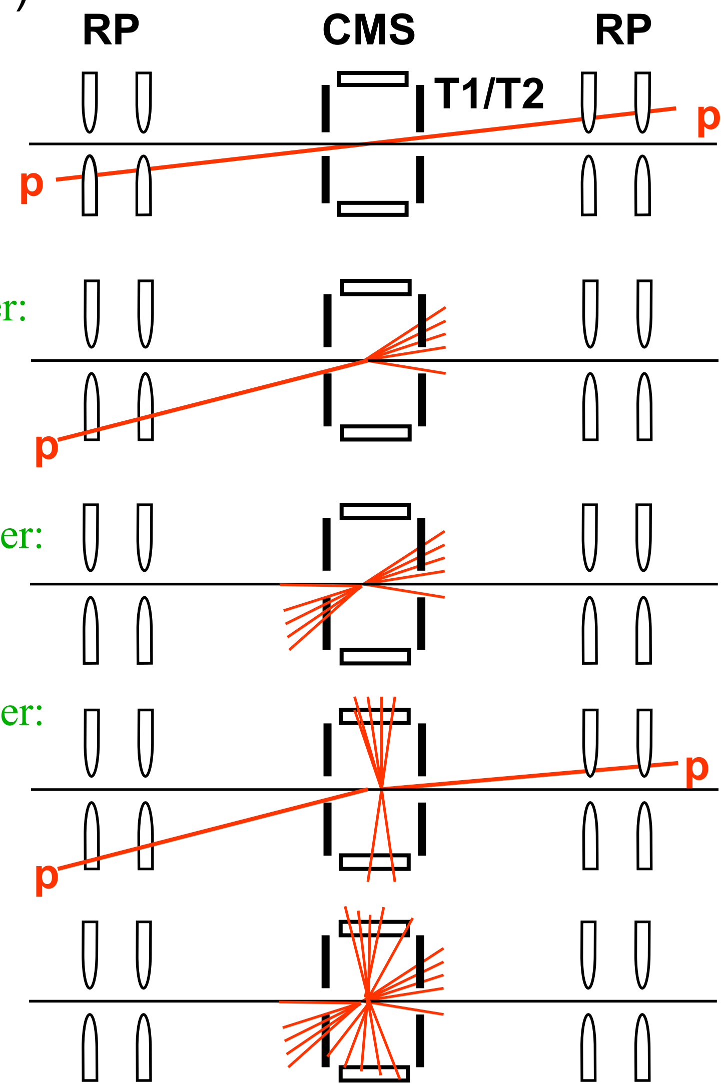
Single Diffractive Trigger:
Signal: 200 Hz
Background: < 1 Hz ?
(using vertex reconstruction in T1/T2)

Double Diffractive Trigger:
Signal: 100 Hz

Central Diffractive Trigger:
Signal: 10 Hz
Background: 2 Hz

Minimum Bias Trigger:
Signal: 1 kHz

Backgrounds under study!

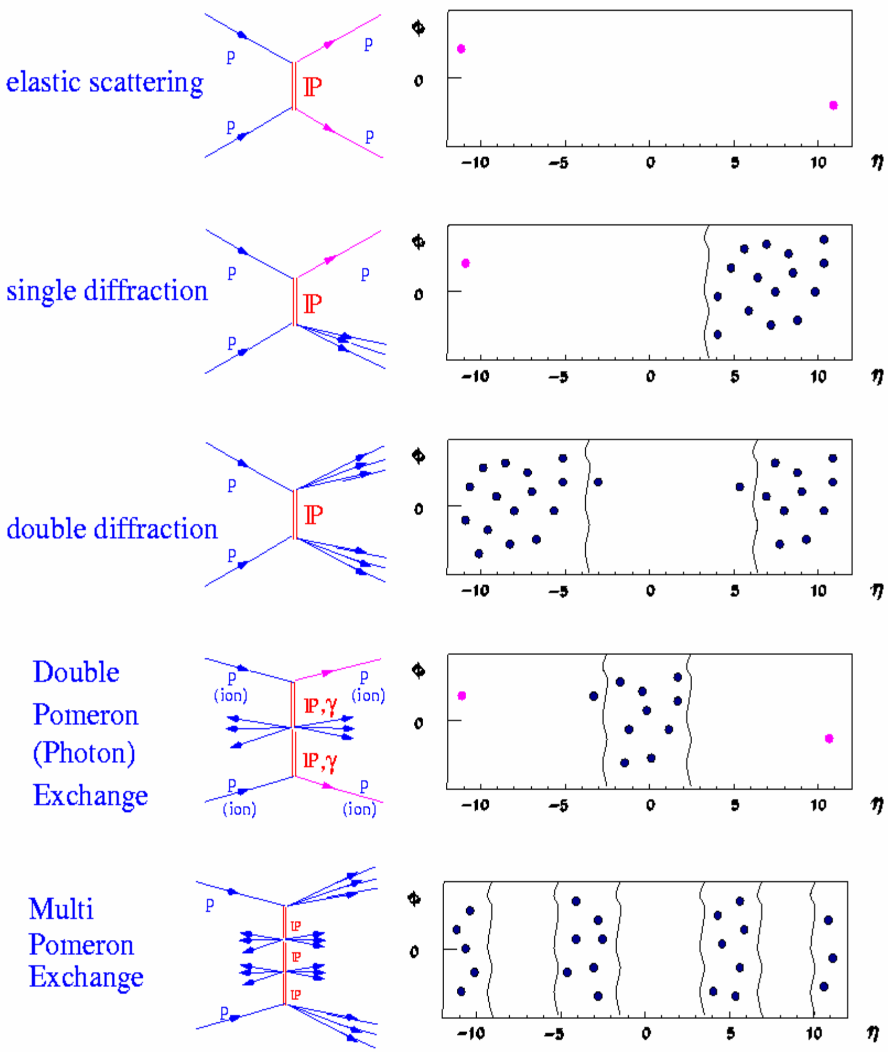


Running scenarios

Scenario (goal)	1 low |t| elastic, σ_{tot} , min. bias	2 diffr. phys., large p_T phen.		3 intermediate |t|, hard diffract.	4 large |t| elastic
β^* [m]	1540	1540		200 – 400 (?)	18
N of bunches	43	156		936	2808
Half crossing angle [μrad]	0	0		100 - 200	160
Transv. norm. emitt. [μm rad]	1	1	3.75	3.75	3.75
N of part. per bunch	0.3×10^{11}	0.6×10^{11}	1.15×10^{11}	1.15×10^{11}	1.15×10^{11}
RMS beam size at IP [μm]	454	454	880	317 - 448	95
RMS beam diverg. [μrad]	0.29	0.29	0.57	1.6 - 1.1	5.28
Peak luminos. [cm^{-2} s^{-1}]	1.6×10^{28}	2.4×10^{29}		$(1 - 0.5) \times 10^{31}$	3.6×10^{32}

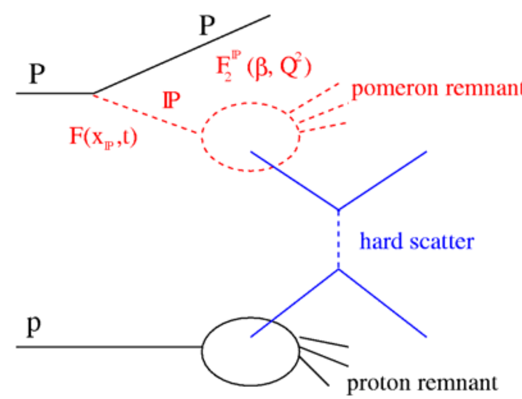
$\beta^* = 0.5$ m & $\mathcal{L} = (10^{32} \div 10^{34})$ cm^{-2} s^{-1} not yet part of TOTEM program but under study.

Diffraction at LHC:



pp scattering at highest energy

Soft & Hard Diffraction



$\xi < 0.1 \Rightarrow$ O(1) TeV "gluon beams"

e.g. Structure of the Pomeron $F(\beta,Q^2)$

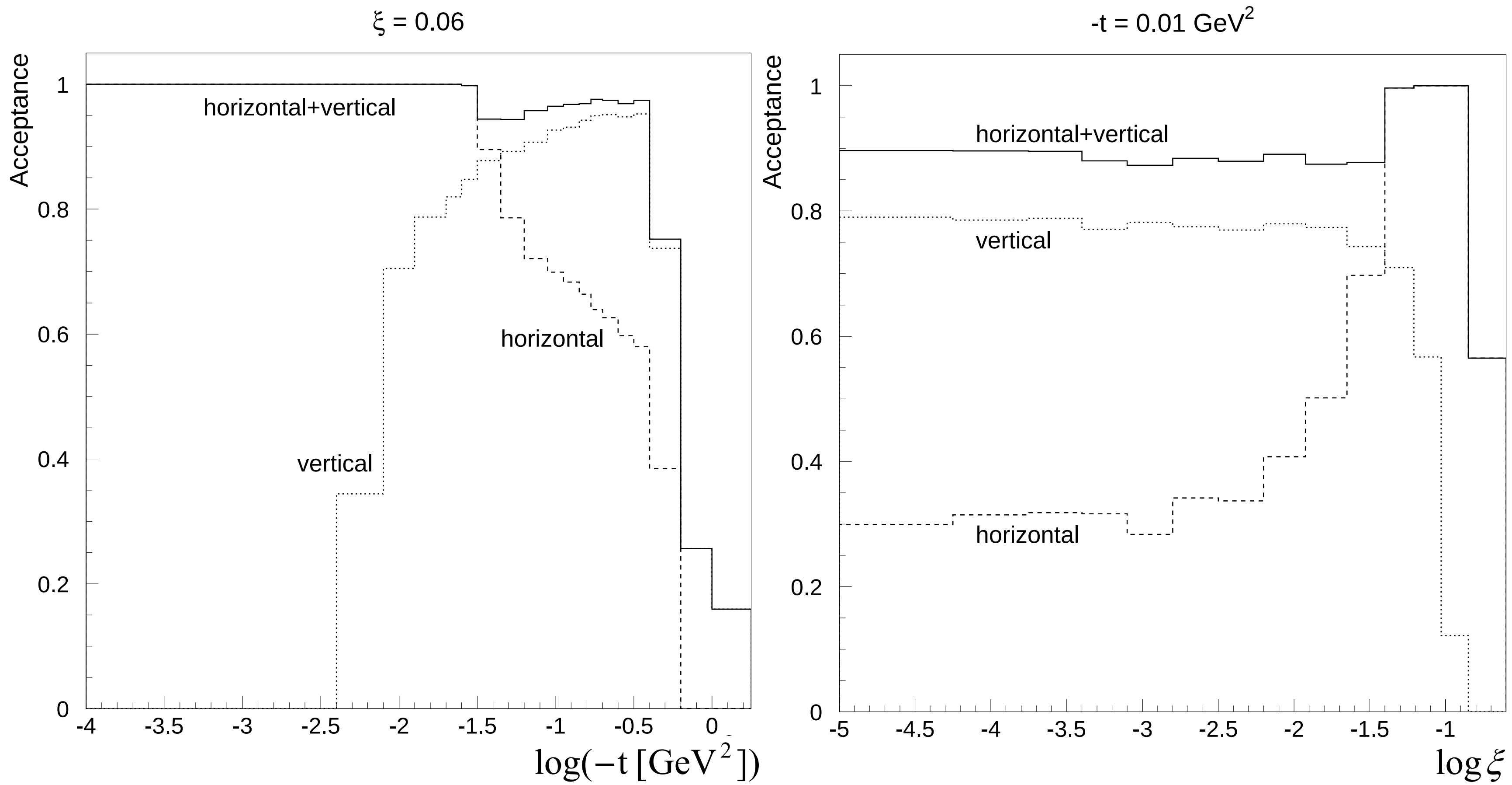
β down to ~ 10^{-3} & Q^2 ~10^4 GeV^2

Diffraction dynamics?

Exclusive final states ?

Rapidity gap physics - multigaps!

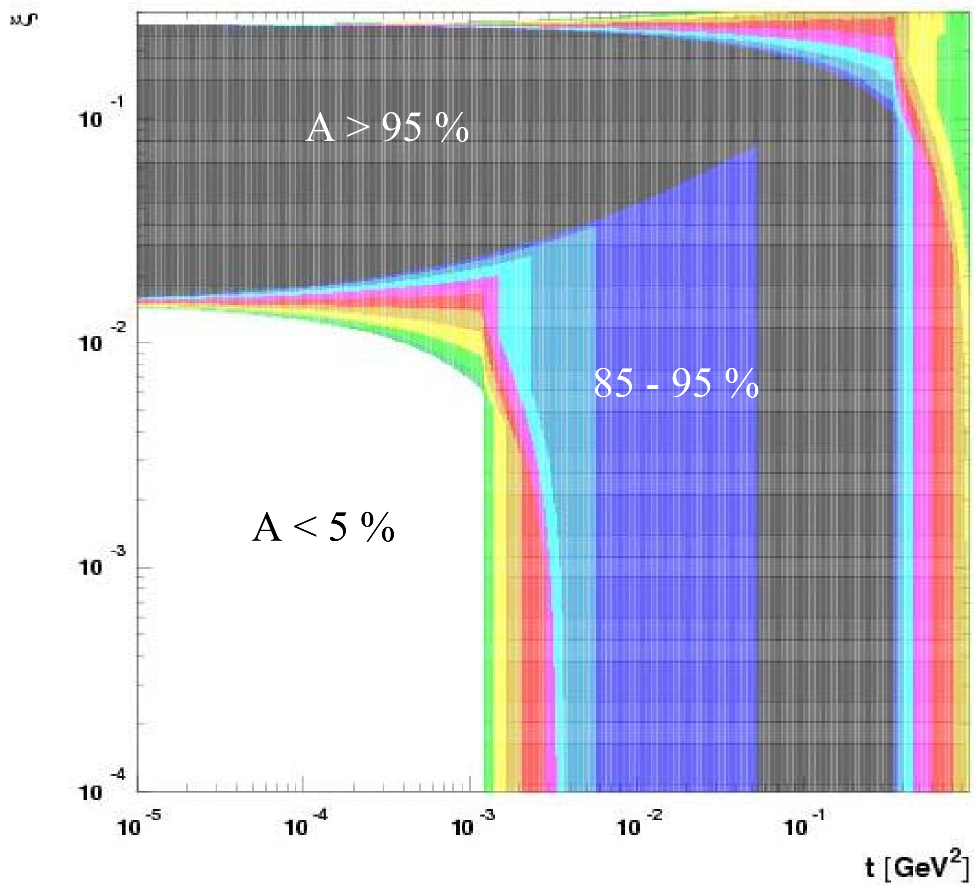
Leading protons at high β*: acceptance



Horizontal & Vertical detectors are complementary:

Horizontal – good acceptance at large ξ
Vertical – good acceptance at small ξ + some t (& large ξ + larger t)

Leading protons at high β*: acceptance



β* = 1540 m
RP at 220 m

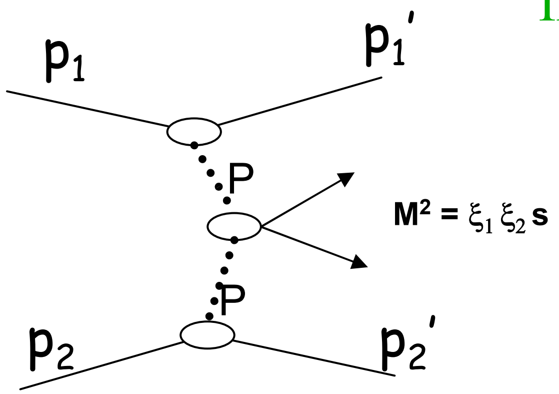
~ 90% of all diffractive protons are seen in the Roman Pots

Luminosity 10^{28}-10^{29}cm^{-2}s^{-1} (few days or a week)

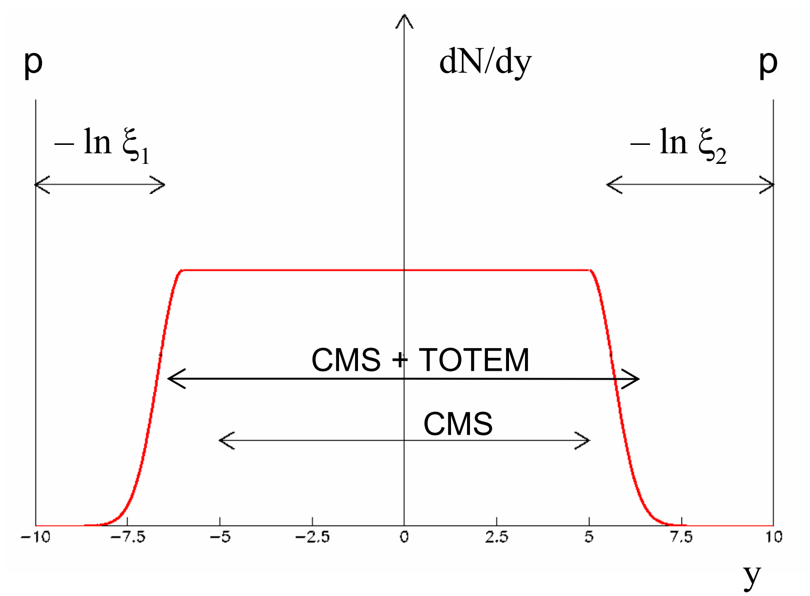
proton momentum can be measured with a resolution of few 10^{-3}

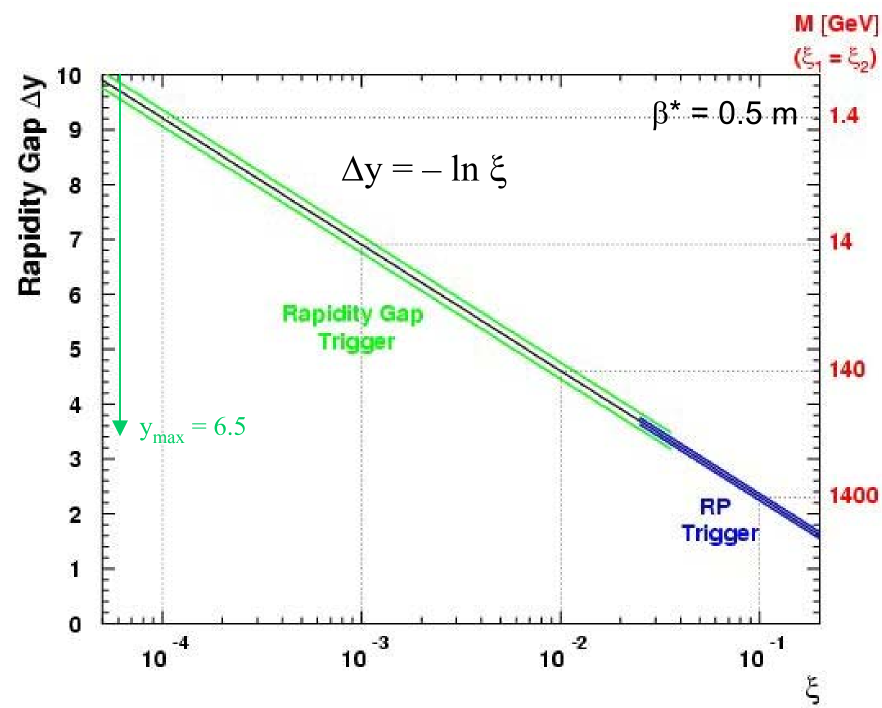
Prospects for Double Pomeron Exchange

In collaboration with CMS



$\beta^* = 1540$ m:	$\sigma_\xi = 0.5\%$	$\mathcal{L} \leq 2.4 \times 10^{29}$ cm^{-2} s^{-1}
$\beta^* = 200 \div 400$ m:	$\sigma_\xi \sim 1$ ‰	$\mathcal{L} \leq 10^{31}$ cm^{-2} s^{-1}
$\beta^* = 0.5$ m:	$\sigma_\xi \sim 1$ ‰	$\mathcal{L} > 10^{31}$ cm^{-2} s^{-1}

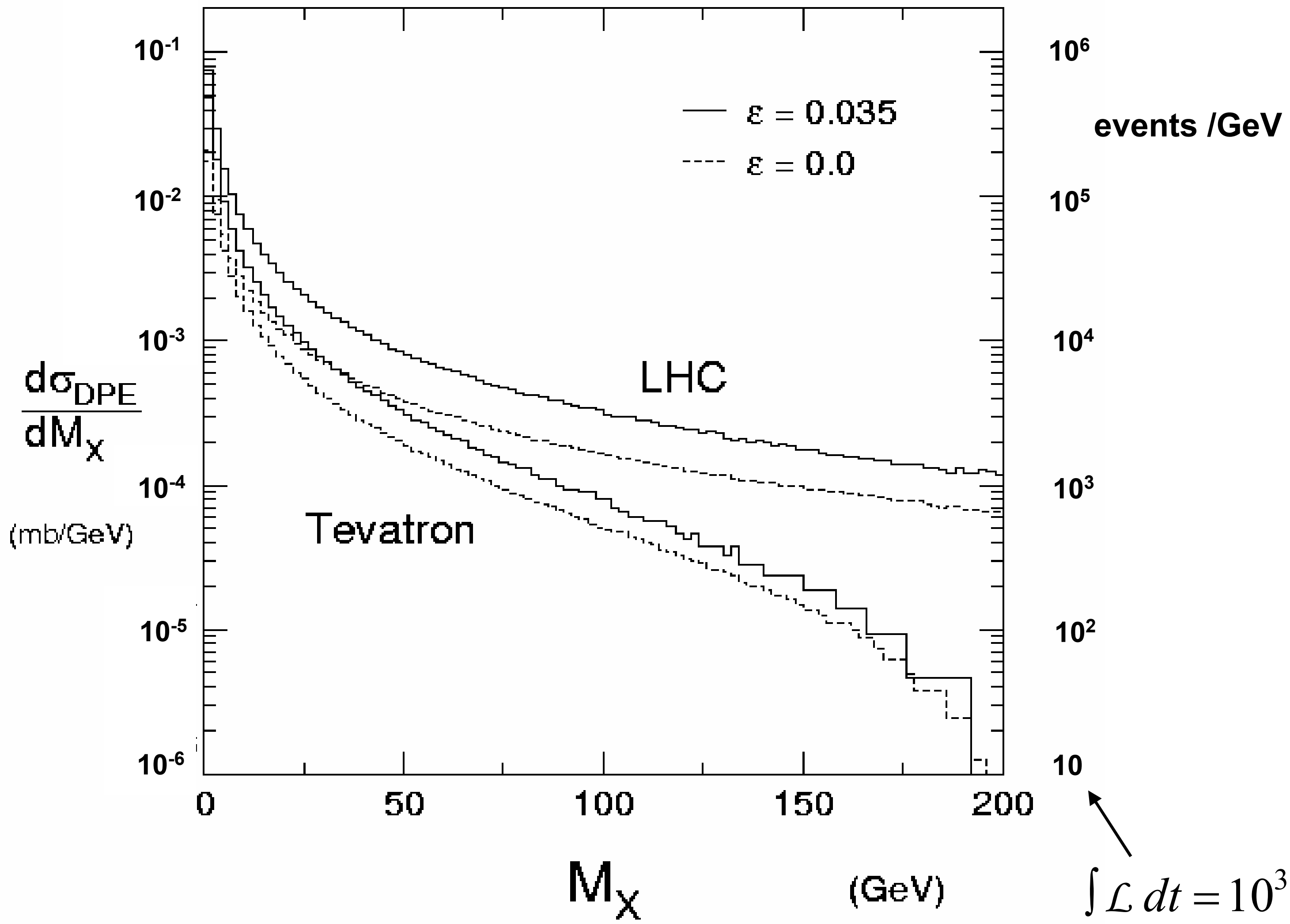




Trigger via Roman Pots $\xi > 2.5 \times 10^{-2}$

Trigger via rapidity gap $\xi < 2.5 \times 10^{-2}$

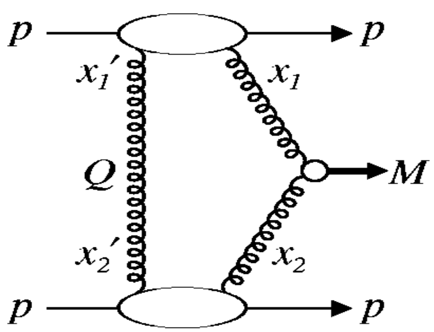
Double Pomeron exchange: cross section



$\int \mathcal{L}\, dt = 10^{37}\,\mathrm{cm}^{-2}$

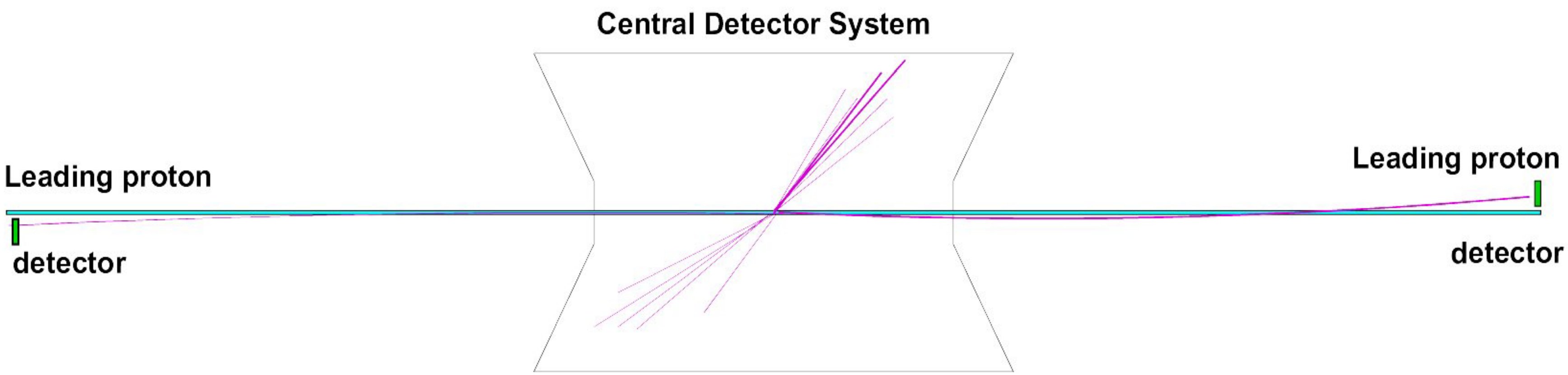
(β^* = 200-400 m)

Exclusive production by DPE



Advantage: selection rules: $J^{PC} = 0^{++}, 2^{++}, \ldots \Rightarrow$ reduced background, determination of quantum numbers.
Good proton ϕ resolution: determine parity: $P = (-1)^J \Leftrightarrow d\sigma/d\phi \sim 1 + \cos 2\phi$
Good central mass resolution (via protons for large masses) $\Rightarrow$ further reduction of backgrounds

Measure leading protons accurately with RP detectors using the accelerator as a spectrometer & impose 4-vector conservation



Experimental signature: 1 leading proton with small momentum loss /side + a central system. Large rapidity gaps between protons & central system.

Exclusive production by DPE: examples

Particle	σ_{excl}	Decay channel	BR	Rate at 2.4×10^{29} cm^{-2} s^{-1} $\beta^* = 1540$ m (no acceptance / analysis cuts)	Rate at 10^{31} cm^{-2} s^{-1} $\beta^* = 200\text{-}400$m
χ_{c0} (3.4 GeV)	3 μb [KMRS]	$\gamma\, J/\psi \rightarrow \gamma\, \mu^+\mu^-$ $\pi^+\pi^- K^+K^-$	6×10^{-4} 0.018	1.5 / h 46 / h	62 / h 1900 / h
χ_{b0} (9.9 GeV)	4 nb [KMRS]	$\gamma\, \Upsilon \rightarrow \gamma\, \mu^+\mu^-$	10^{-3}?	0.08 / d	3.5 / d
H (120 GeV)	0.1 ÷ 10 fb assume 3 fb	$b\bar{b}$	0.68	0.02 / y	1 / y

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

- modify optics locally (increase dispersion at 220 m),
- move detectors closer to the beam (if possible),
- install additional Roman Pots in cryogenic region of LHC (further from IP)

Running scenario examples

Luminosity $2 \cdot 10^{29}$ cm $^{-2}$ s $^{-1}$

Data taking for soft diffraction : 20 mb ⟶ 4 kHz ⟶ $4 \cdot 10^{8}$ events / 1 eff. Day

Double Pomeron : 1 mb ⟶ $2 \cdot 10^{7}$ events / 1 eff. Day

Precise study of soft diffraction phenomena

Luminosity 10^{31} cm $^{-2}$ s $^{-1}$

A one week run (4 10^{5} s) ⟶ 4 10^{36} cm $^{-2}$ ⟶ 4000 evts / nb

Double Pomeron exchange

High masses order of TeV

χ_c ⟶ 10^{6-7} events before decay

χ_b ⟶ 10^{3-4} events before decay

Large pt di jets ⟶ coplanar dijet pair with only 2 accompanying protons

Single diffraction with high pt jets and leptons

Study of rapidity gaps with identified protons

Leading proton physics with TOTEM: high & intermediate β^*

Standalone running:

- σ_{tot} with 1 % uncertainty

$\rightarrow \beta^* = 1540$ m

- elastic scattering $d\sigma/dt$ for 10^{-3} GeV^2 < t < 10 GeV^2

$\rightarrow \beta^* = 1540$ m & $\beta^* = 18$ m

Common running with CMS:

- precise study of soft diffraction (~ 90 % of diffractive protons measured)

$\rightarrow \beta^* = 1540$ m

- study of hard diffraction & exclusive DPE

$\rightarrow \beta^* = 200$-$400$ m

TOTEM TDR submitted to LHCC 01/2004 LHCC 2004-002/TOTEM TDR 1

Common CMS/TOTEM physics TDR to be submitted early 2005

Leading proton studies at low β^*

Main motivation: DPE & exclusive new particle production

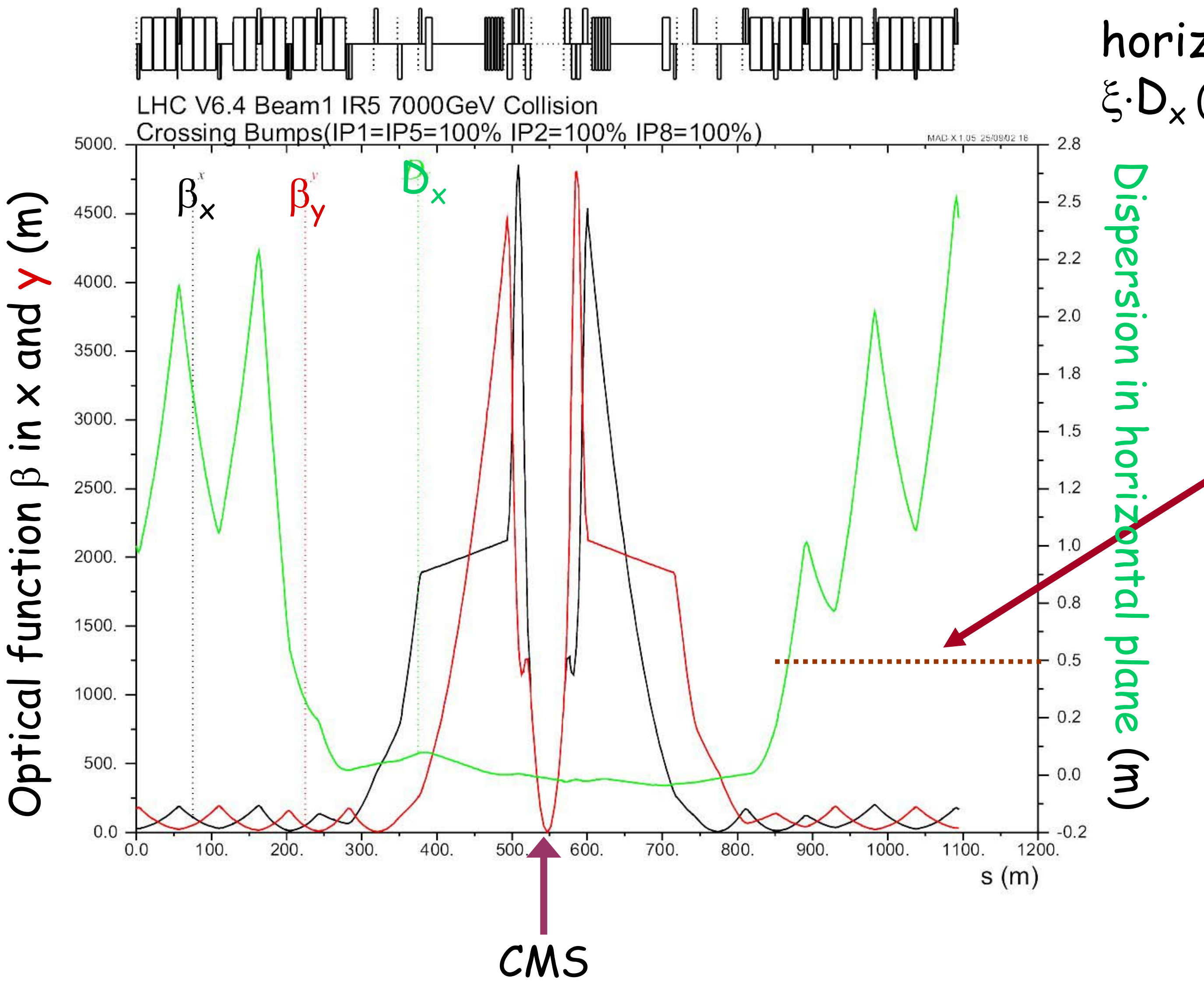
- $\mathcal{L}$ > few $\cdot 10^{32}$ cm^{-2} s^{-1} for cross sections of ~ fb (like Higgs)
- measure both protons to reduce background from non-exclusive
- measure final state in central detector to reduce gg background

Challenges:

- M ~ 100 GeV $\Rightarrow$ need acceptance down to ξ's of a few ‰
- pileup events destroy rapidity gaps $\Rightarrow$ $\mathcal{L}$ < few $\cdot 10^{33}$ cm^{-2} s^{-1}
- sufficently good mass resolution from protons only to overcome reduced cross section w.r.t. standard channels

A study made by the Helsinki group in TOTEM.

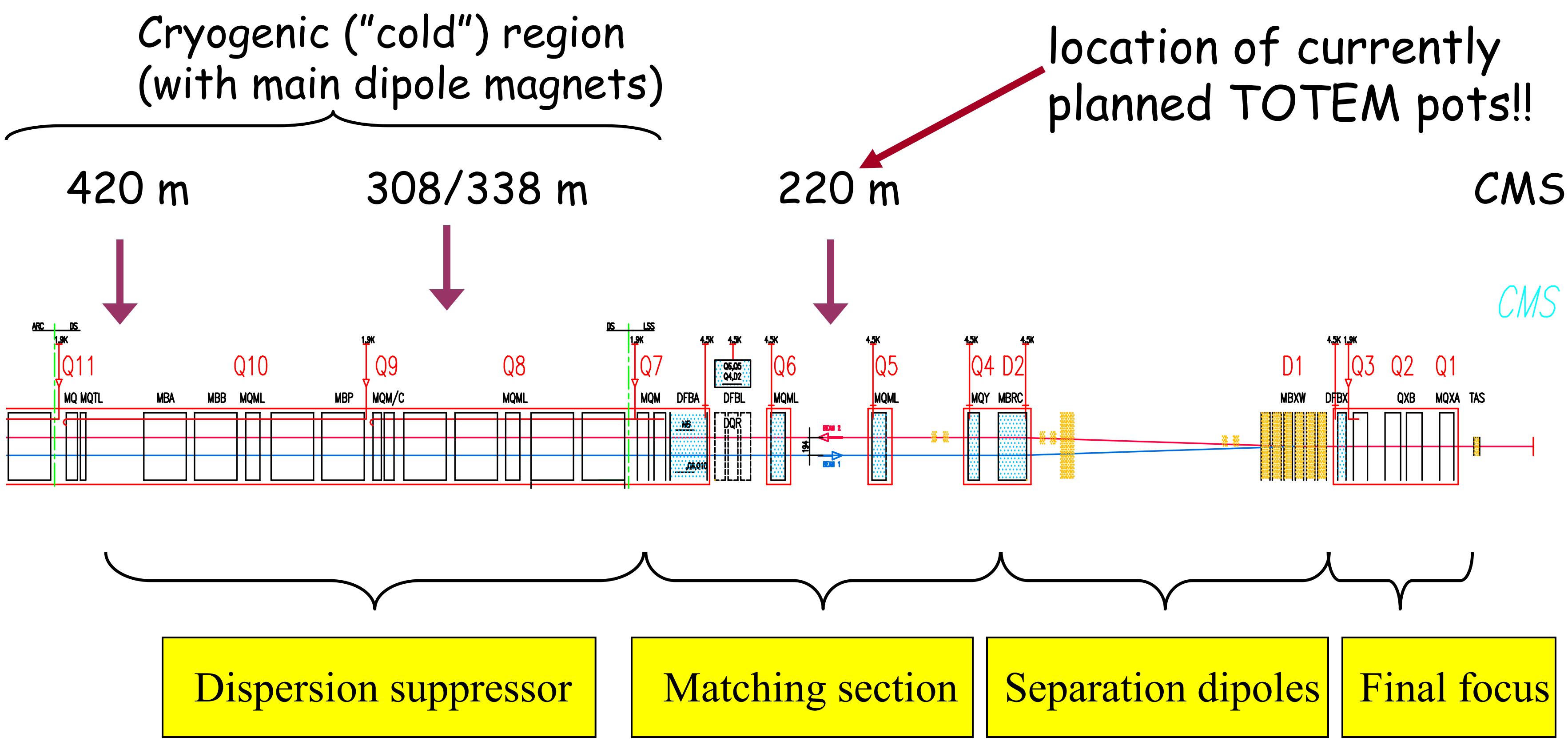
Dispersion function - low β* optics (CMS IR)



horizontal offset = $\xi \cdot D_x$ (ξ = momentum loss)

To get 2.5 mm offset from a $\xi \sim 0.5$ % proton $\Rightarrow$ dispersion $\geq$ 0.5 m $\Rightarrow$ proton taggers located > 250 m from IP i.e. in "cryogenic section" of LHC.

Studied proton detector locations



Leading proton acceptance & resolution studies

- pp $\rightarrow$ p + X + p simulated using PHOJET1.12
- Protons tracked through LHC6.2 optics using MAD8

Simulated experimental leading proton uncertainties:

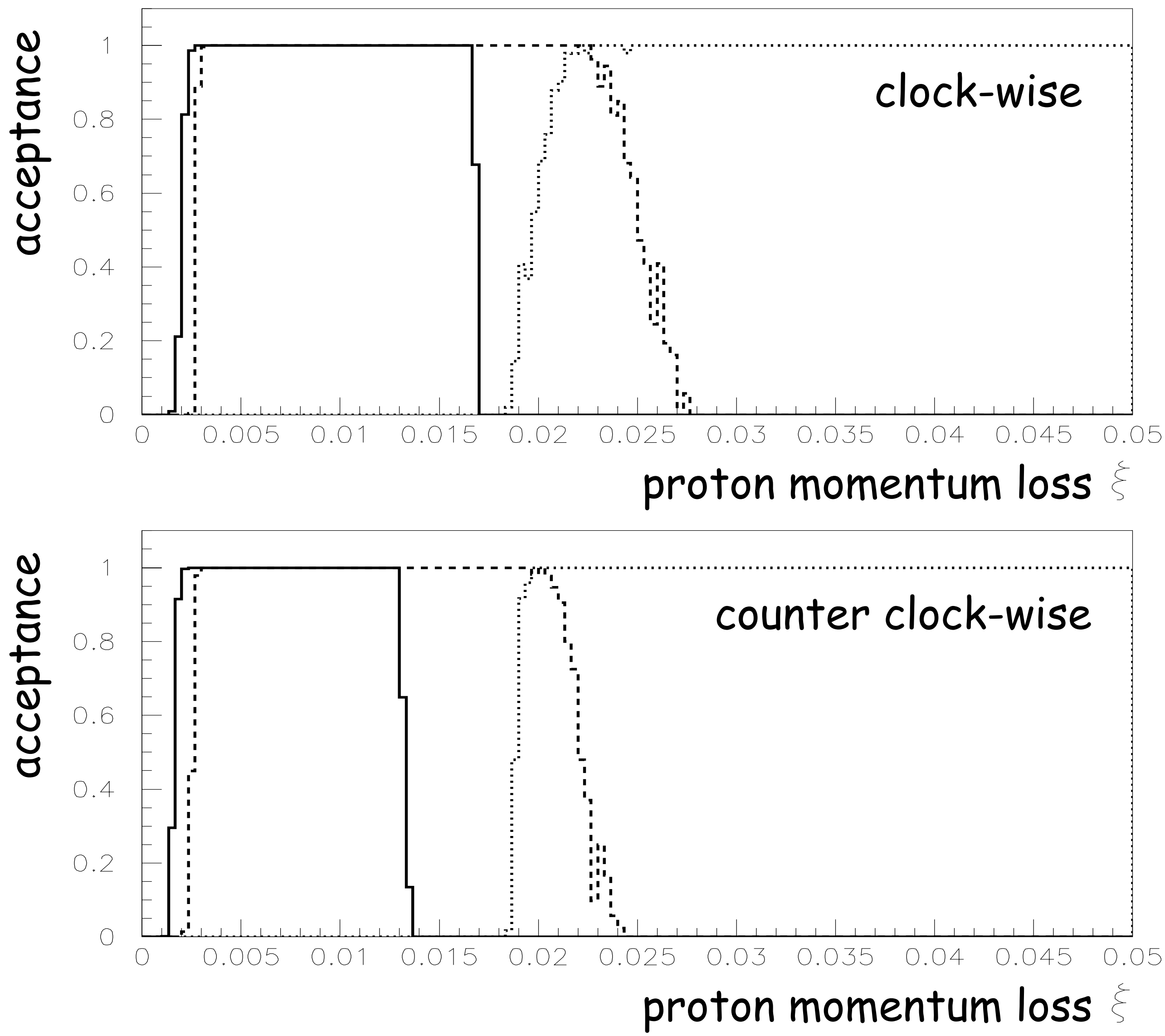
- Initial conditions at interaction point
  - Transverse vertex position ($\sigma_{x,y}$ = 16 μm)
  - Beam energy spread (σ_E = 10^{-4})
  - Beam divergence (σ_θ = 30 μrad)

T. Mäki, MSc (eng.)thesis;
HIP-2003-11/EXP

- Conditions at detector location
  - Position resolution of detector ($\sigma_{x,y}$ = 10 μm)
  - Resolution of beam position determination ($\sigma_{x,y}$ = 5 μm)

Also systematic offsets at detector locations has been studied.

Leading proton acceptance



Detector locations at

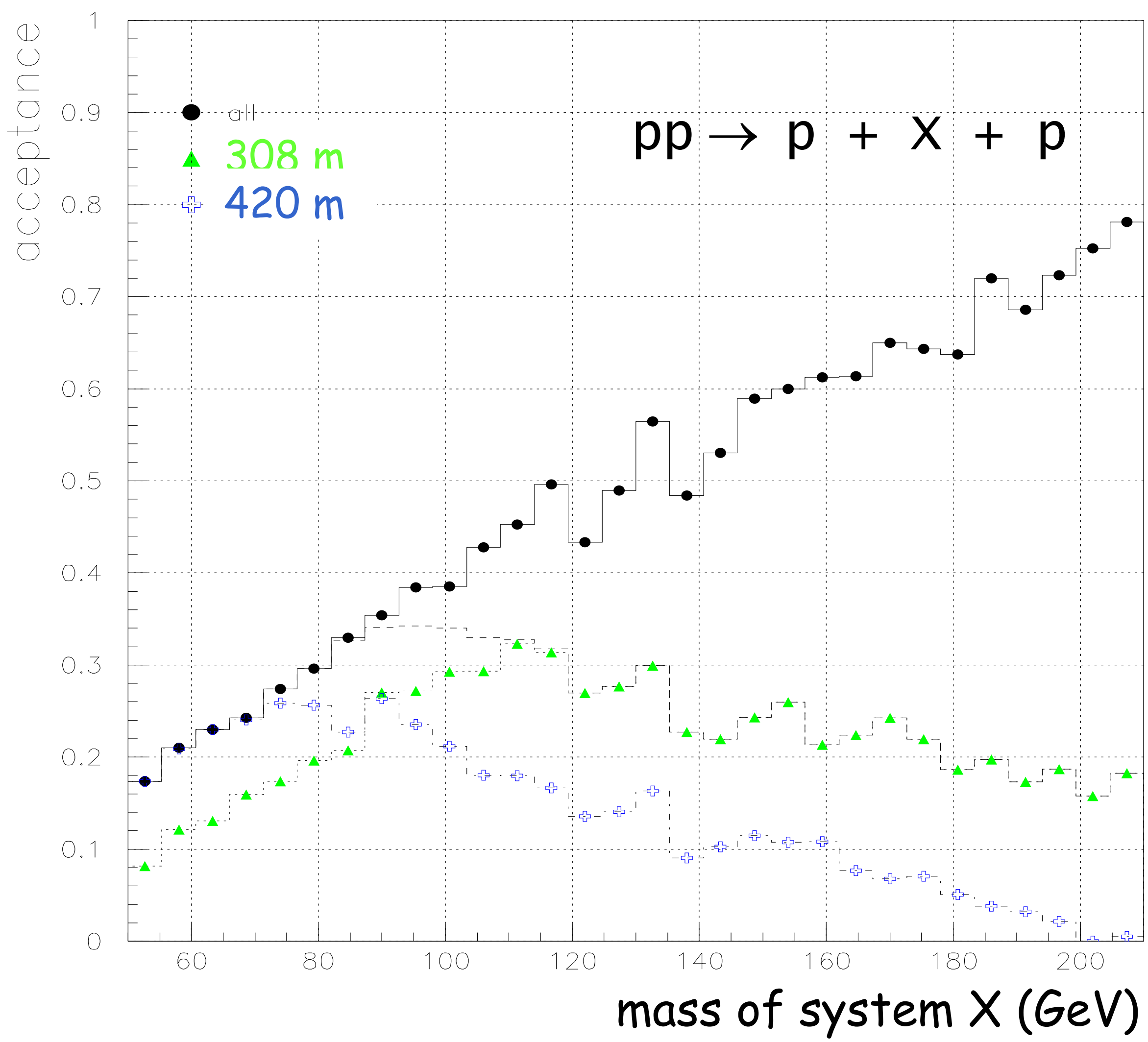
- 220 m (dotted)
- 308/338 m (dashed)
- 420 m (solid)

Optimistic assumption on approach:

$10 * \sigma_{beam} + 0.1$ mm

$\Rightarrow$ <u>acceptance down to 0.2 %</u>

Mass acceptance central system

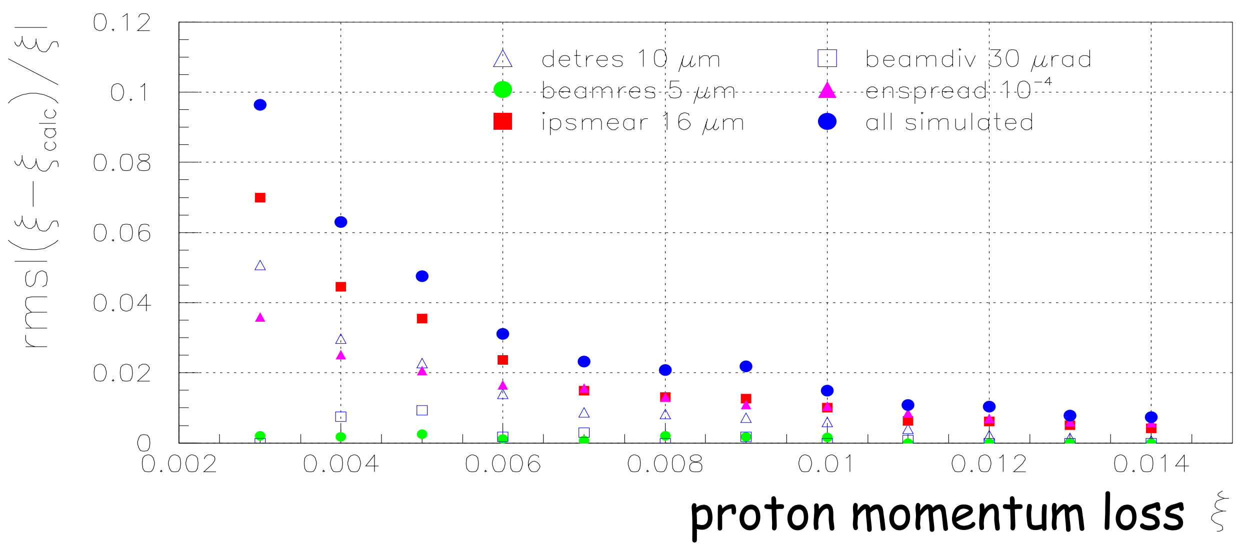


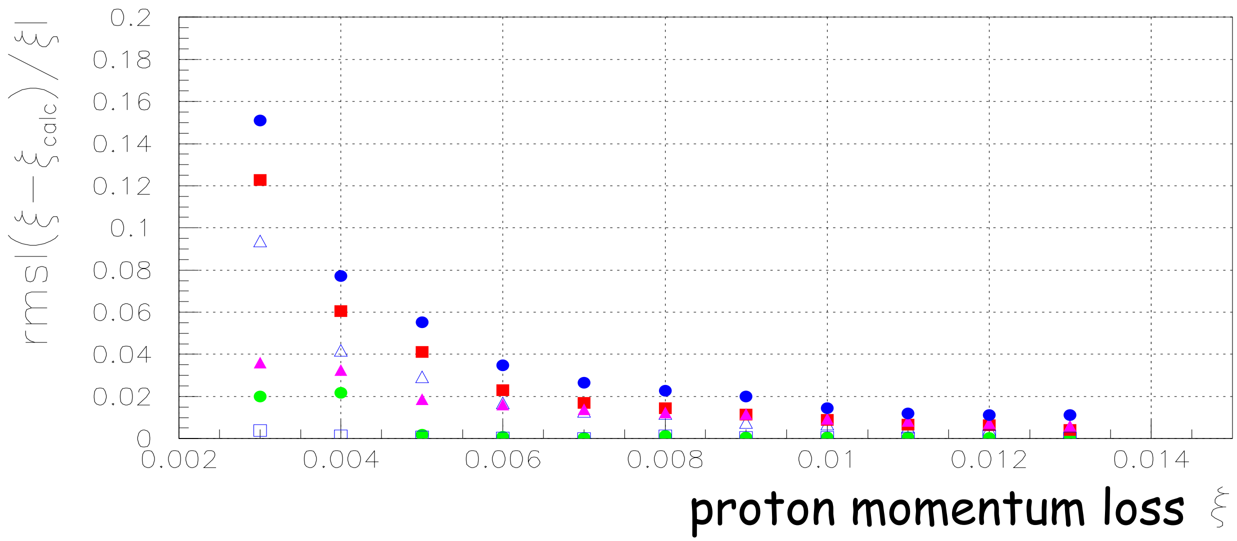
both protons seen with ~ 45 % efficiency at a mass of 120 GeV

acceptance still at masses around 60 GeV

(caveat: PHOJET limits ξ to 0.25 so acceptances somewhat over-estimated)

Momentum loss resolution at 420 m

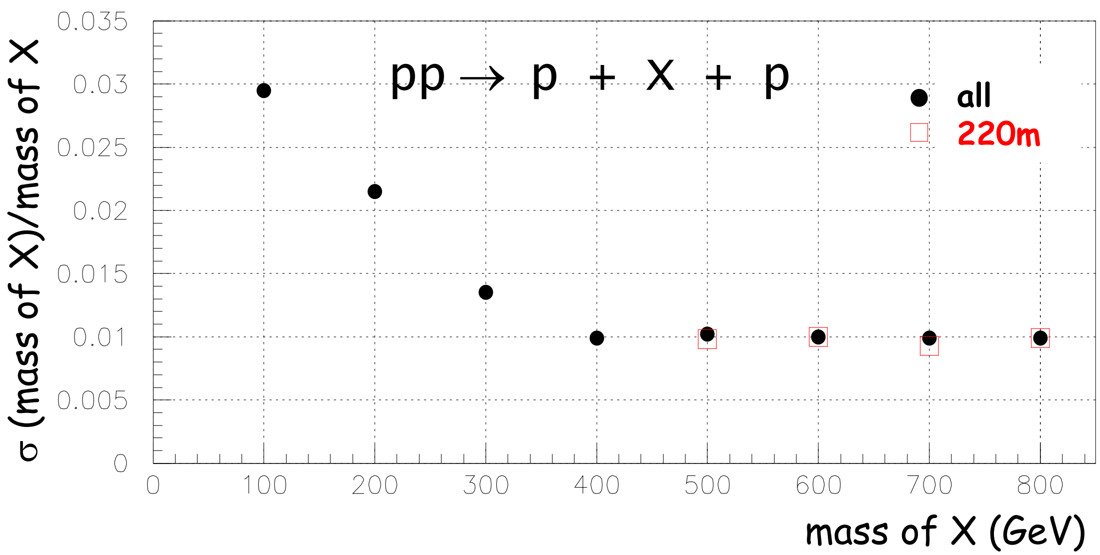


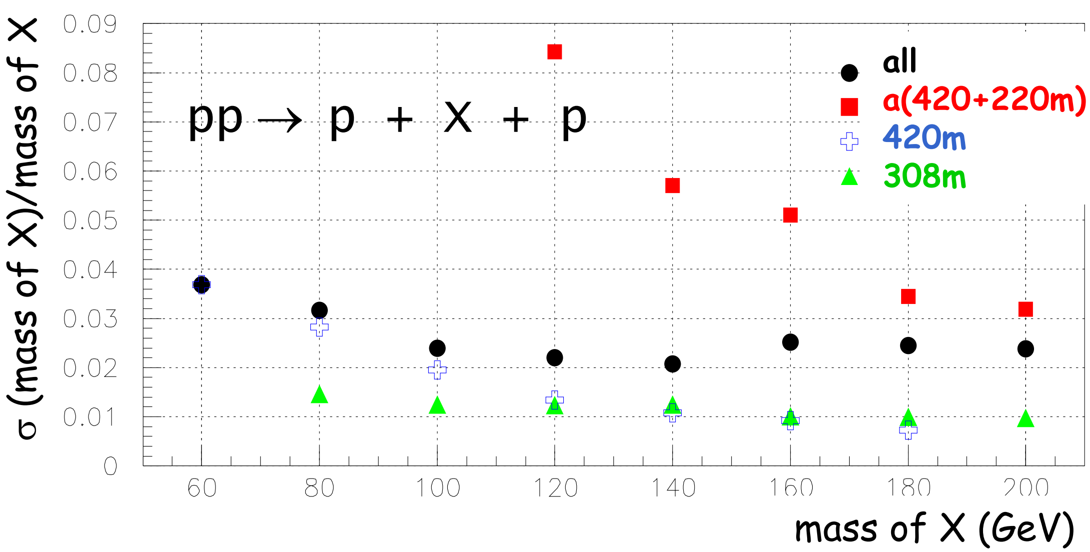


Resolution improves with increasing momentum loss

Dominant source: transverse vertex position (at small momentum loss) and beam energy spread (at large momentum loss, 420 m)/detector resolution (at large momentum loss, 215 m & 308/338 m)

Mass resolution of central system





Resolutions for separate locations and all combination ("naive" combination)

- resolution ranges from ~ 4 % at low masses to ~ 1 % at high mass

- optimal resolution ~ 1 % for symmetric pairs (i.e. $\xi_1 \approx \xi_2$)

NB! a(420+215m) = $\xi_1 >> \xi_2$ or $\xi_1 << \xi_2$

NB! Some effects are anticorrelated for ξ_1 & ξ_2 (e.g. transverse vertex position) $\Rightarrow$ $\sigma(M)/M < \frac{1}{2}\sqrt{\Sigma_i \sigma(\xi_i)/\xi_i}$

Triggering diffractive events at low β^*

Constraints on triggering diffractive events:

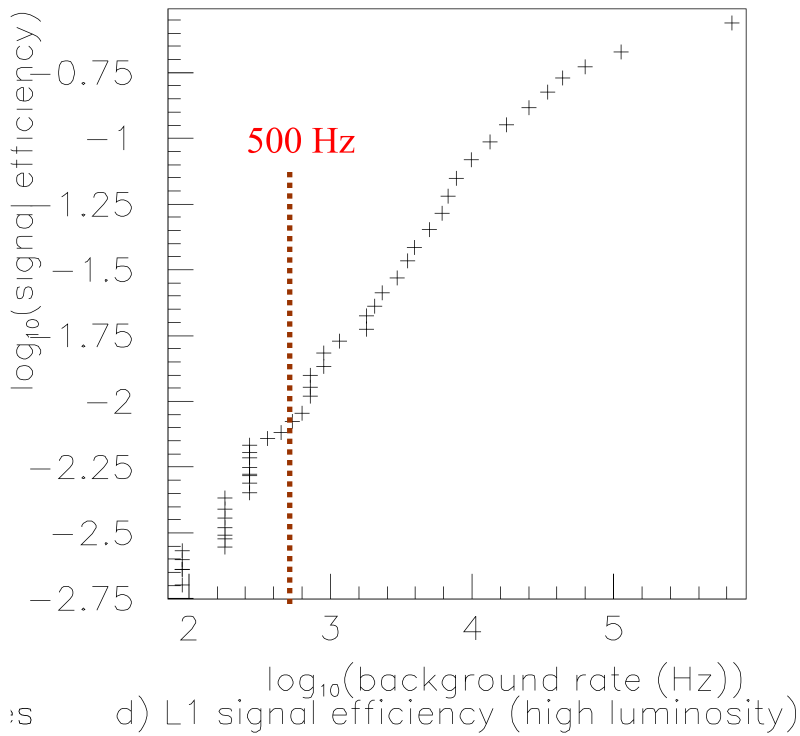
- At level 1 leading proton info available only from detectors < 220 m from IP (CMS trigger latency, ATLAS worse!!) + asymmetric events have bad mass resolution $\Rightarrow$ for new particle masses $\leq \sim 180$ GeV, level 1 trigger must be based on central detector info only !!
- Level 1 trigger based on calorimetry & muon chambers only.
- E_T threshold of inclusive jet trigger is too high to be useful.
- Pileup will destroy some rapidity gaps (~2(20) inelastic events at $10^{33}(10^{34})$ cm^{-2} s^{-1}) + cause accidental 2 leading proton events (SD+SD)
- Allowed level 1 trigger rate for a special diffractive new particle trigger could be ~500 Hz (?)(out of 100 kHz, no prescaling!!)

MinBias (E_T > 30 GeV) ~ 0.22 mb $\Rightarrow$ $10^3/10^4$ suppression at $10^{33}/10^{34}$ cm^{-2} s^{-1}

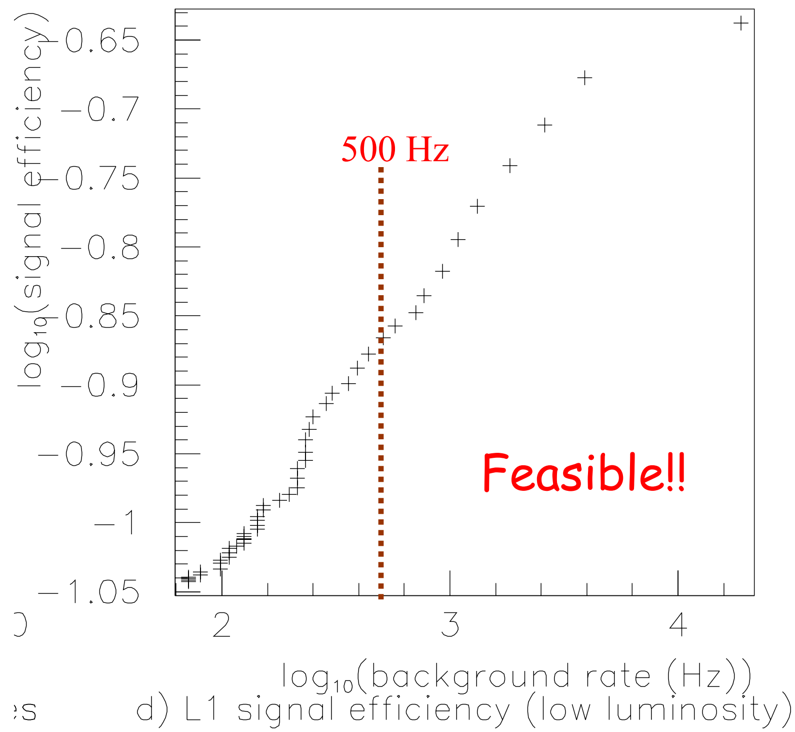
Case study for a 120 GeV Higgs using topological variables (forward E_T, jet E_T's, η's & ϕ-angles) of the 2-jet final state with a "CMS-like" L1 calorimetry trigger.

Preliminary results on L1 triggering of a 120 GeV Higgs

"High" luminosity ($10^{34} cm^{-2} s^{-1}$)



"Low" luminosity ($10^{33} cm^{-2} s^{-1}$)



Efficiency includes "usefulness" cuts (protons & b-jets seen) !!

Will be repeated with complete CMS trigger simulation !!

Improvements should be possible by using also T2 & CASTOR !!

Leading proton studies at low β^*

For sufficient acceptance for M $\leq$ 200 GeV

- increase dispersion locally & use currently planned Roman pots
  - no L1 problem anymore
  - technical feasibility & performances unstudied
- install additional Roman pots in the cryogenic region of LHC
  - ~1 % mass resolution obtainable for symmetric events ($\xi_1 \approx \xi_2$)
  - feasible L1 triggering scheme?
  - technical feasibility?
  - alignment procedure?

Topics for ”the tagged protons at LHC” project

• Implementation of leading proton acceptance & resolution in general simulation frame works (like OSCAR of CMS).

• Focus feasibility studies on $\beta^* = 0.5$ m:

1. increase dispersion locally & use currently planned Roman pots

   - technical feasibility
   - once optics exist ⇒ performance studies

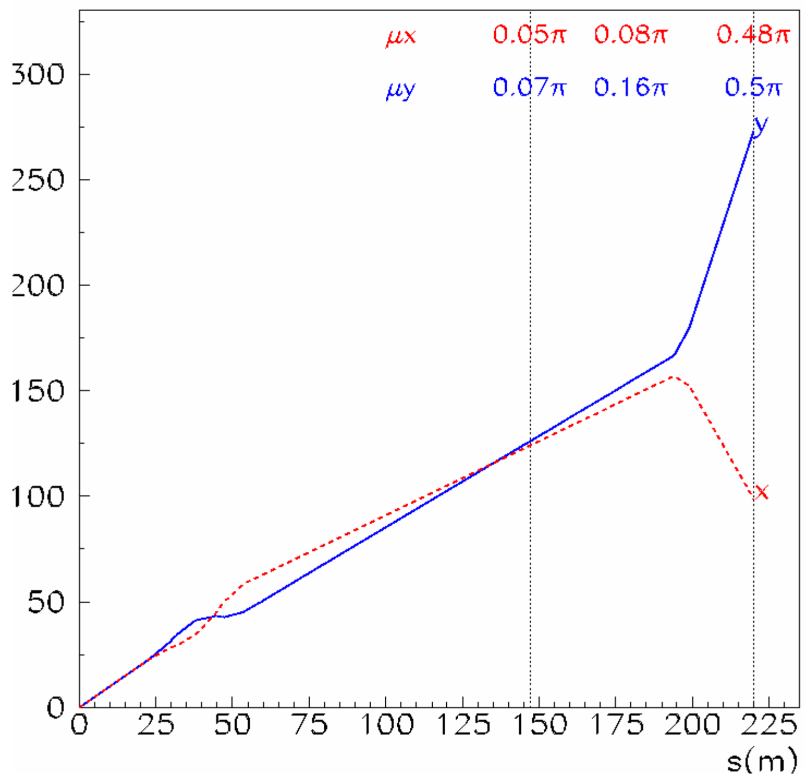
2. additional Roman pots in the cryogenic region of LHC

   - L1 triggering scheme
   - technical feasibility
   - alignment & stability procedure

3. AOA

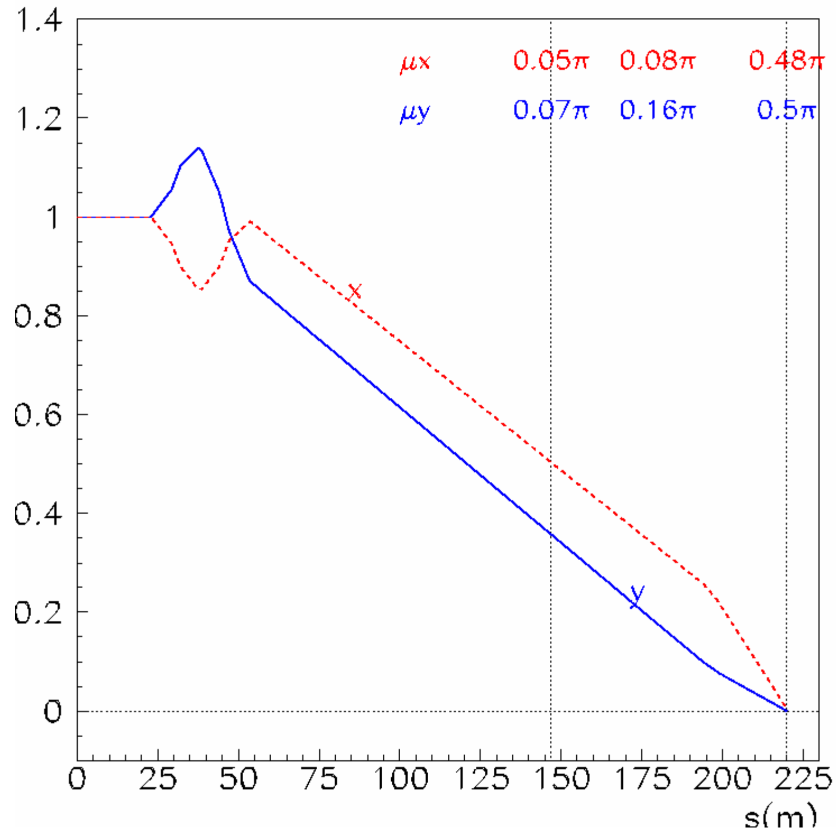
⇒ the significance of some specific exclusive DPE processes (e.g. 120 GeV Higgs) for some initial LHC luminosity (e.g. 30 fb^{-1})

High β optics: lattice functions



$$v = (\beta/\beta^*)^{1/2} \cos \mu(s)$$

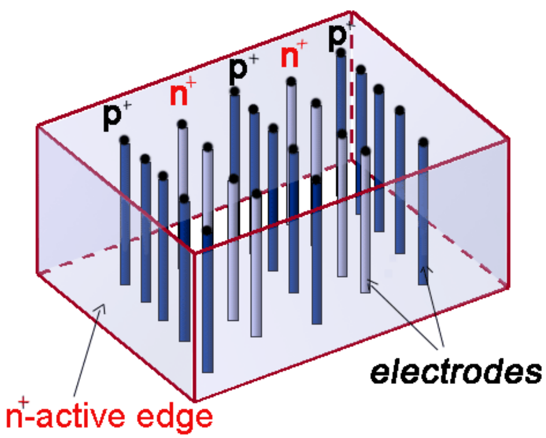
$$L = (\beta\beta^*)^{1/2} \sin \mu(s)$$



Leading proton detectors: sensors

Need full efficiency as close to sensor edge as possible; adequate resolution ~ 20 μm

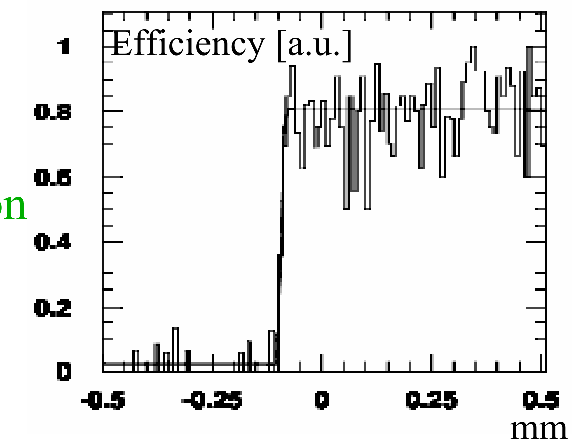
3D Si Detectors:



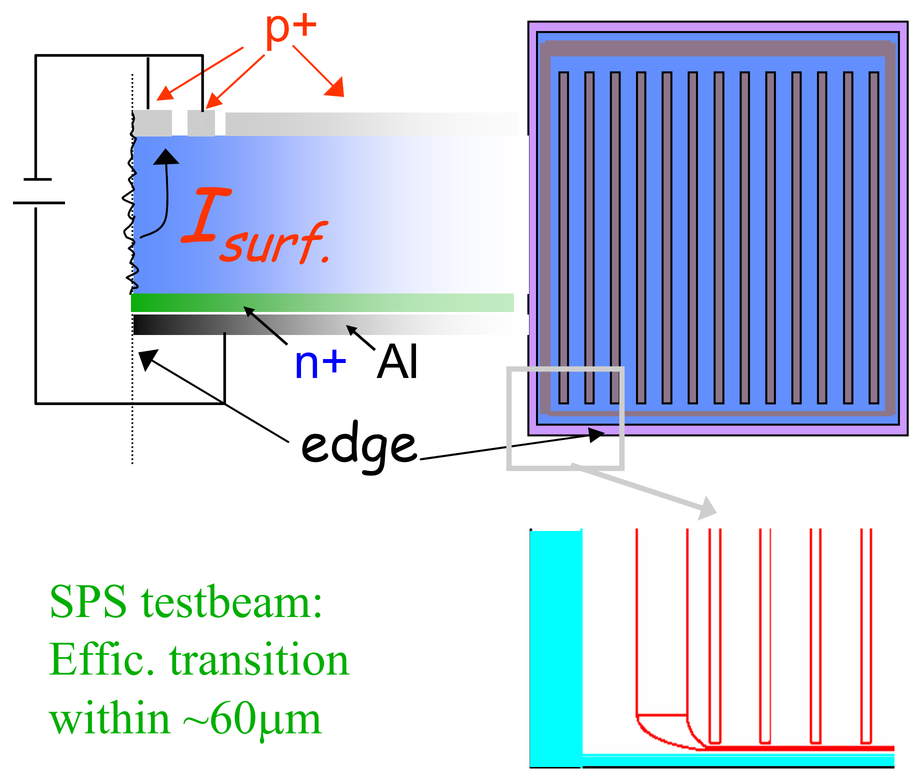
Electrodes processed through the *bulk*.

The edge is itself an electrode.

SPS testbeam:
Effic. transition
within ~15μm

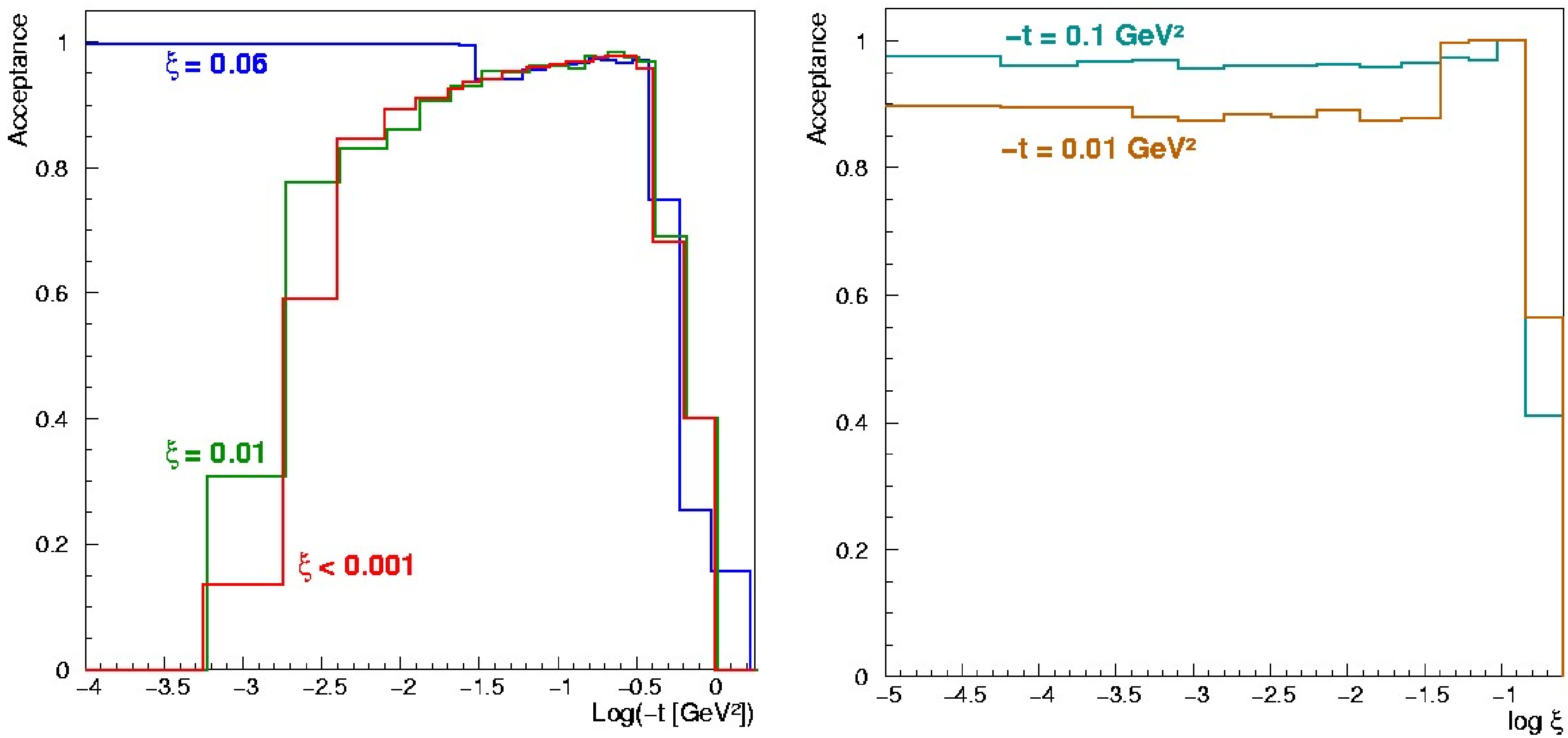


Planar Si with reduced current-terminating guard structure (only ~70 μm):



SPS testbeam:
Effic. transition
within ~60μm

Diffraction at high β*: Acceptance

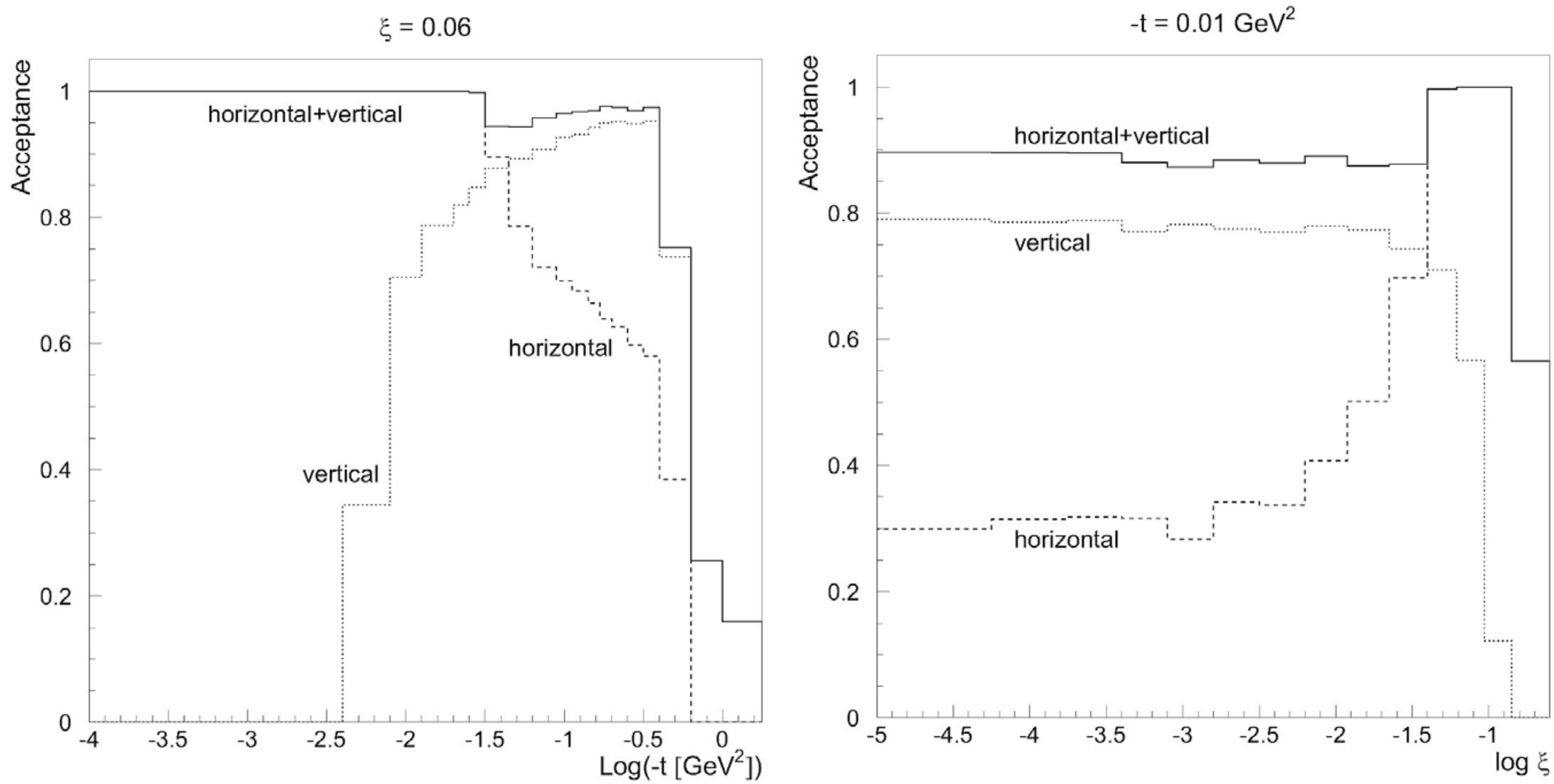


>90% of all diffractive protons are seen in the Roman Pots

Luminosity 10^{28}-10^{30}cm^{-2}s^{-1} (few days or weeks)

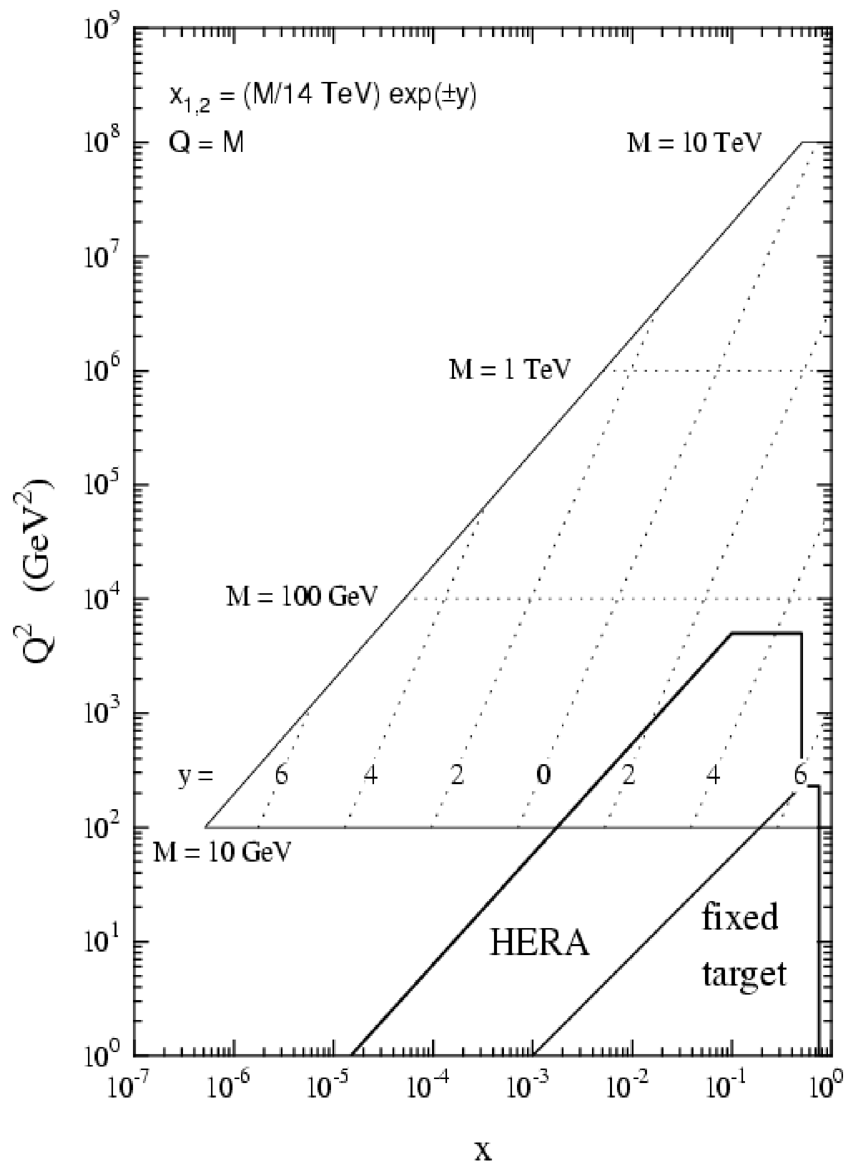
proton momentum can be measured with a resolution of few 10^{-3}

Leading protons at high β*: acceptance



Horizontal & Vertical detectors are complementary:

Horizontal – good acceptance at large ξ
Vertical – good acceptance at small ξ + some t (& large ξ + larger t)



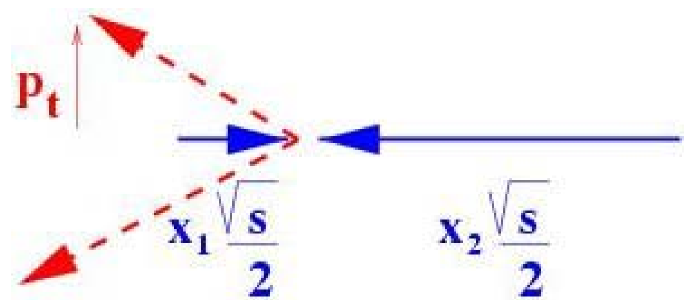
LHC: due to the high energy small values of Bjorken-x

For rapidities above 5 and masses below 10 GeV

⇒ x down to $10^{-6} \div 10^{-7}$

Possible with T2 in TOTEM (calorimeter, tracker):

$5 < \eta < 6.7$

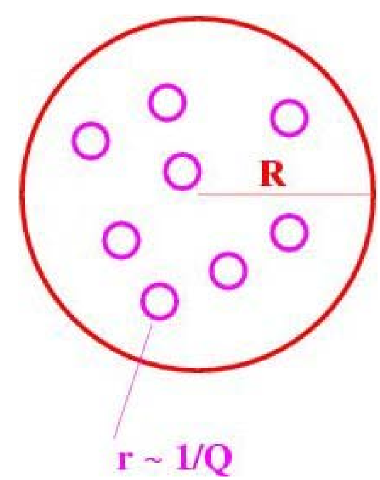


$$x_1 x_2 > \frac{4 p_t^2}{s}$$

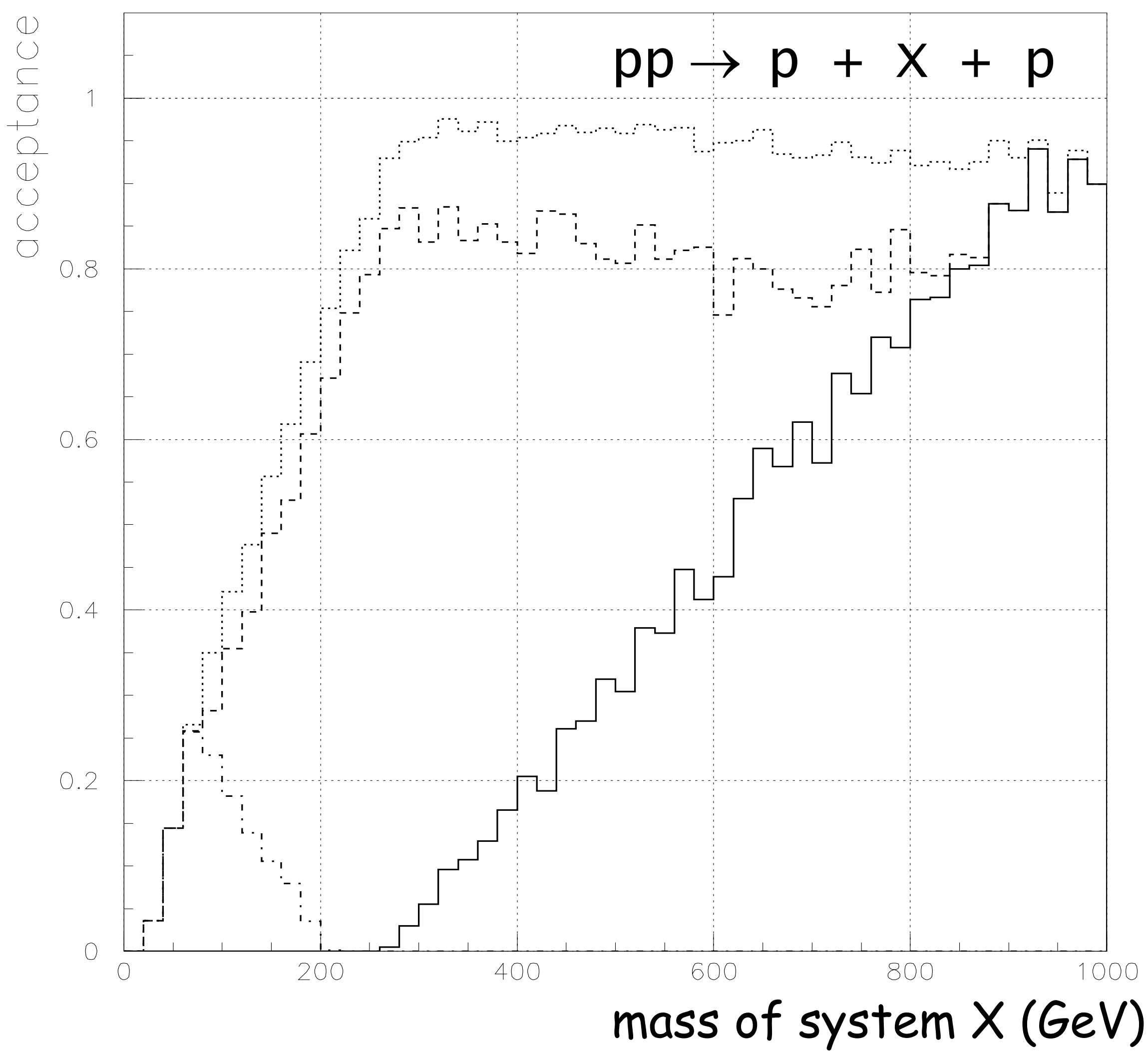
Proton structure at low-x:
Parton saturation effects?

$$\frac{\alpha_s}{Q^2} x g\left(x, Q^2\right) > \pi R^2$$

Saturation or growing proton?



Mass acceptance central system



Combined acceptance of

- all locations (dotted)
- 420 m + 220 m (dashed)
- 220 m alone (solid)
- 420 m alone (dash-dotted)

Level 1 Trigger Case Study for a 120 GeV Higgs

V.Bergholm, MSc(eng.) thesis;

- $pp \rightarrow p + H(\rightarrow bb) + p$ kinematics simulated using PHOJET1.12 (PYTHIA 6.205)
- Background sample from PYTHIA (Dijets with hard scattering $p_T > 30$ GeV with $\sigma = 0.18$ mb)
- Superposition of MinBias events
- Simplified CMS Level 1 calorimeter trigger simulation ⇒ granularity (calo regions), E_T smearing, lost particle rejection ⇒ calo region based jet reconstruction with min $E_T = 35$ GeV.
- "Usefulness" cuts (protons & b-quarks seen) on signal ($\varepsilon \sim 45$ %)
- Signal characteristics: 2 jets of same E_T back-to-back in phi + forward rapidity gaps

No validation yet against official CMS level 1 trigger simulation

Efficiency Budget - Diffractive Higgs Events

Exclusive diffractive Higgs events (M_H= 120 GeV)

- Both protons within acceptance of proton taggers (~ 45 %)
- Both b-jets within Tracker acceptance ($|\eta|<2.5$) (~ 85 %)

(need b-tag to reduce gg background)

- Br ($H \rightarrow bb$) (in SM ~ 68 %)
- Efficiency of b-tagging, ε_b ($\varepsilon_b^2 = (0.77)^2$ ~ 60 %?)
- Level 1 trigger efficiency at $10^{33} cm^{-2} s^{-1}$ (~ 35 %?)

Total exclusive diffractive Higgs efficiency: (~ 5.5 %?)

Improvements possible?: b-tag efficiency & Level 1 trigger efficiency (include other trigger detectors: T2, CASTOR ...)