The CMS and TOTEM diffractive and forward physics program

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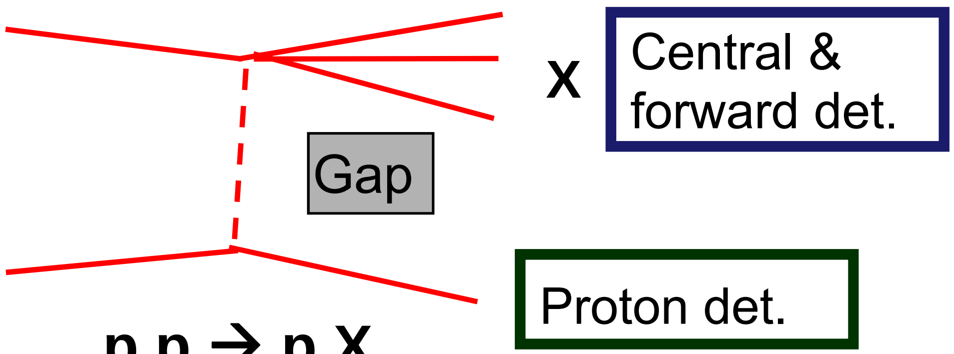
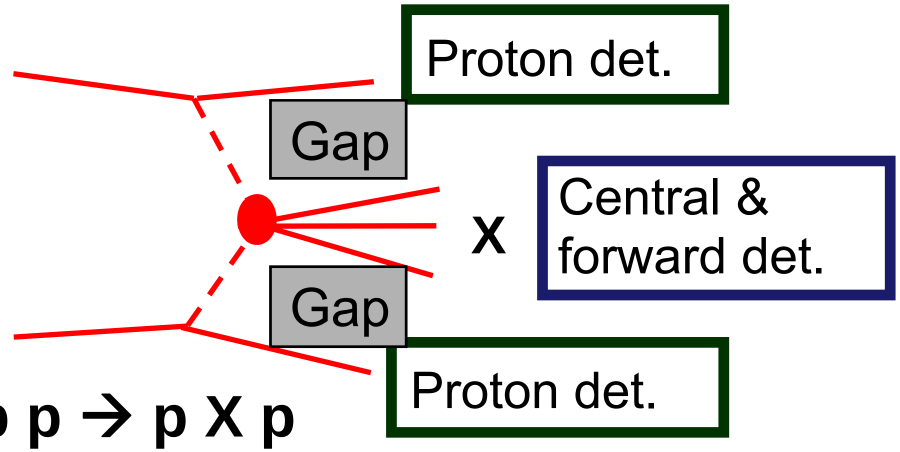
Diffraction: a window to QCD and proton structure

Single Diffraction:



p p → p X

Double Pomeron Exchange or Central Diffraction:



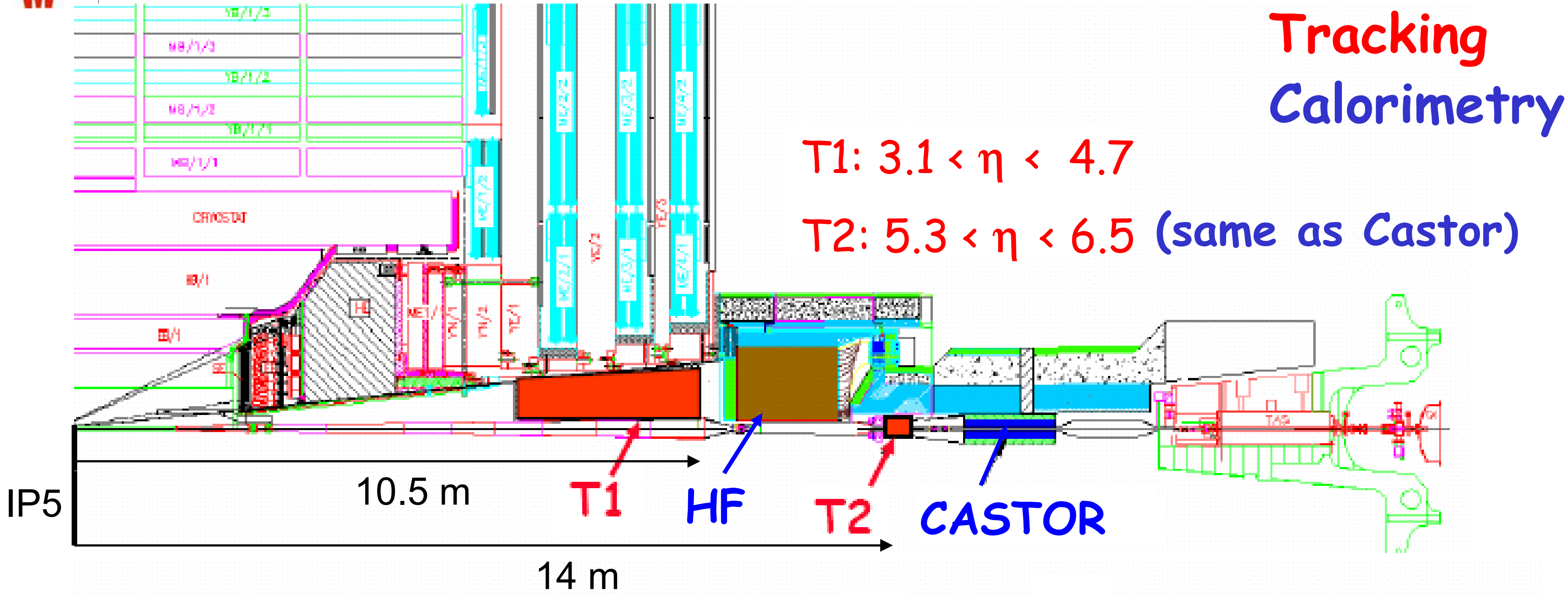
p p → p X p

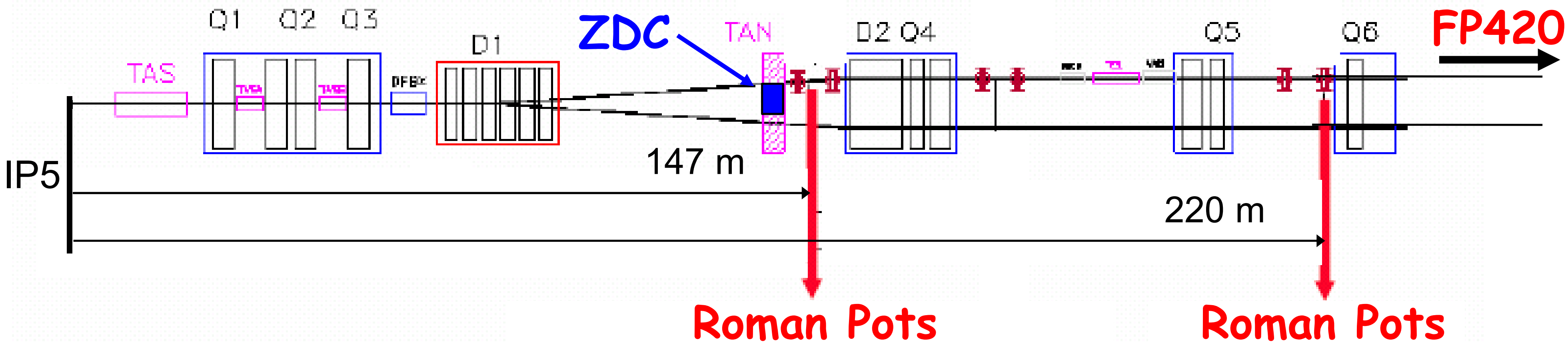
characterized by 2 gluon exchange with vacuum quantum numbers (“Pomeron”)

X = anything : dominated by soft physics
Measurement of inclusive cross sections + their t & M_X dependence → fundamental measurements of non–perturbative QCD at LHC!

X = jets, W, Z, Higgs: hard processes calculable in perturbative QCD
Proton structure (dPDFs & GPDs), high parton density QCD, rapidity gap su probability, new physics in exclusive central diffraction

Experimental apparatus at IP5@LHC

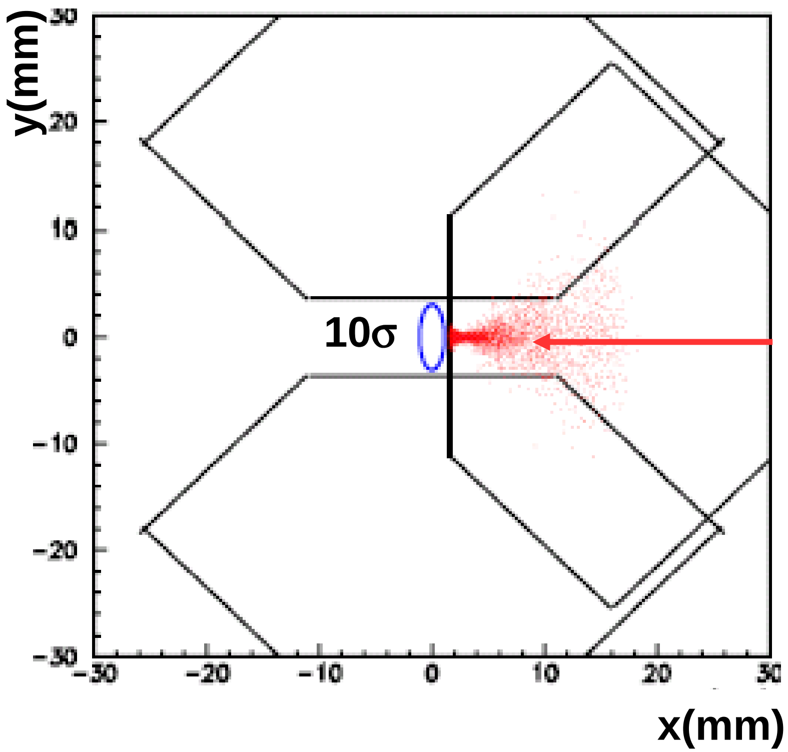




Forward proton measurement: principle

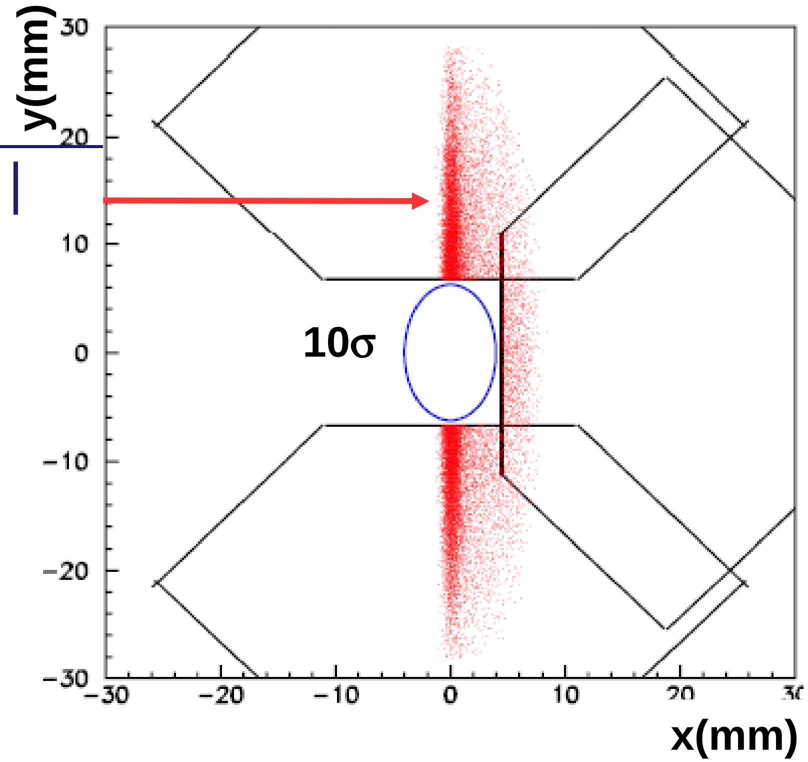
Diffractive protons : hit distribution @ RP220m

high $\mathcal{L}$ (low β*) low $\mathcal{L}$ (high β*)



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

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

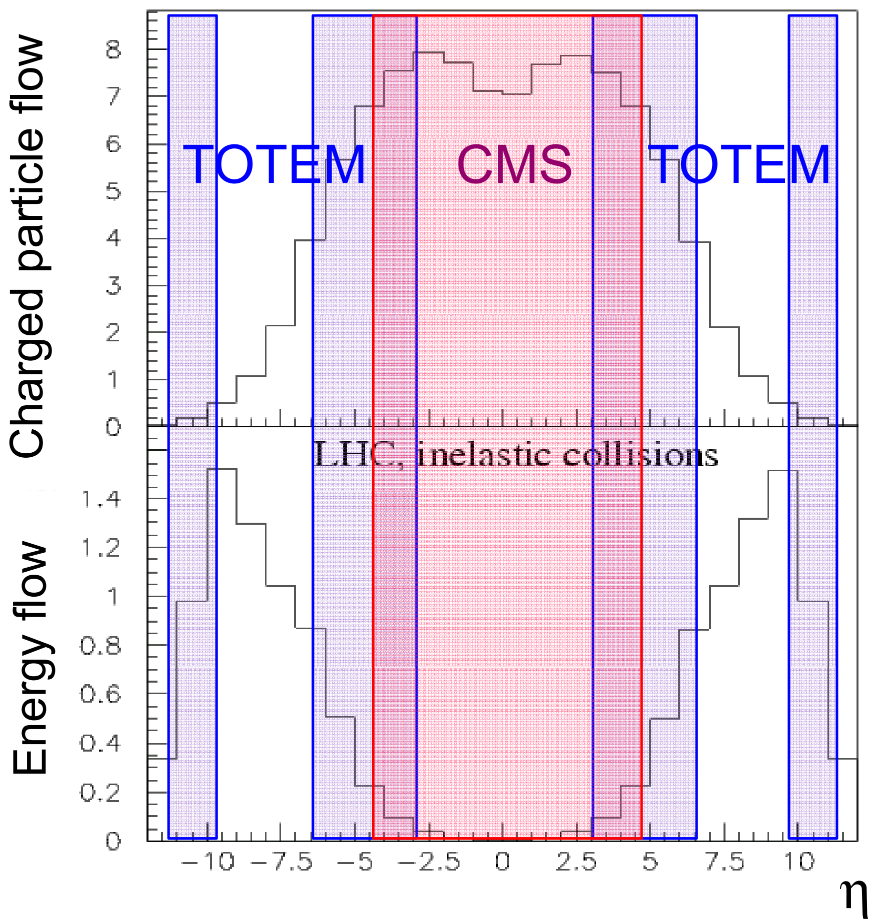


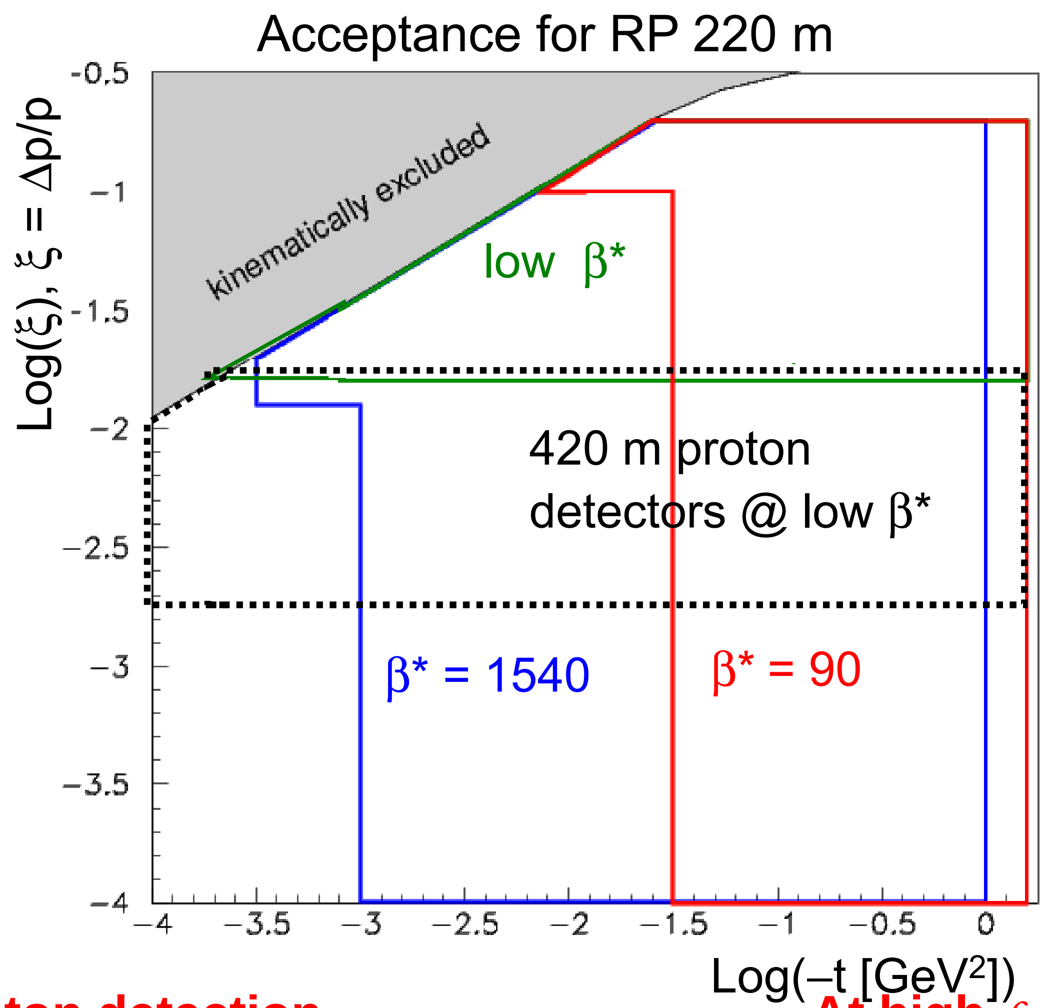
Detect the proton via:

its momentum loss (low β*) **its transverse momentum (high β*)**

CMS/TOTEM combined acceptance

Unique coverage makes a wide range of physics studies possible – from diffraction & proton low-x dynamics to production of SM/MSSM Higgs



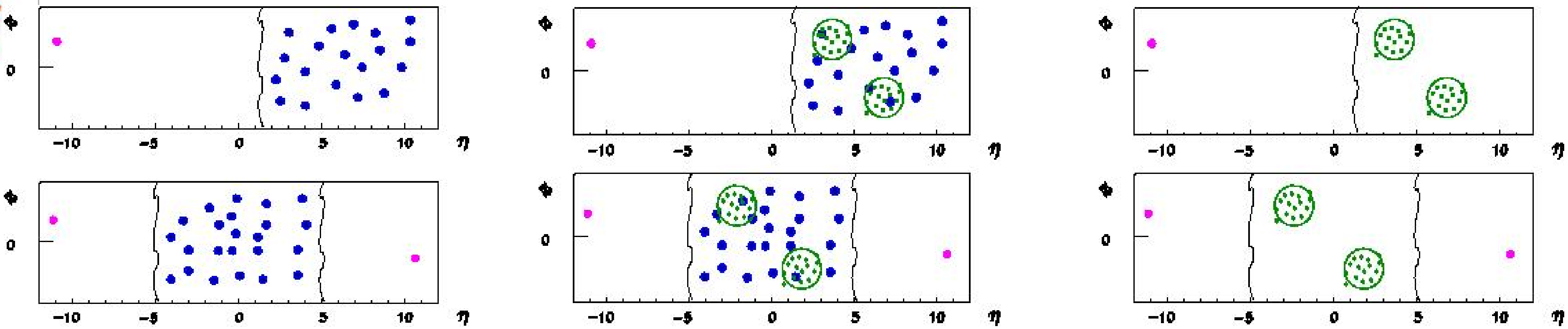


Wide coverage in pseudorapidity & proton detection

At high $\mathcal{L}$

proton detectors @420 m enlarge acceptance to $\xi \sim 2 \cdot 10^{-3}$ For details see B. Cox talk on FP420

Running scenario



pp->pX pp->pXp	pp->pjjX pp->pjjXp	pp->pjj pp->pjjp	(bosons, heavy quarks,Higgs...)

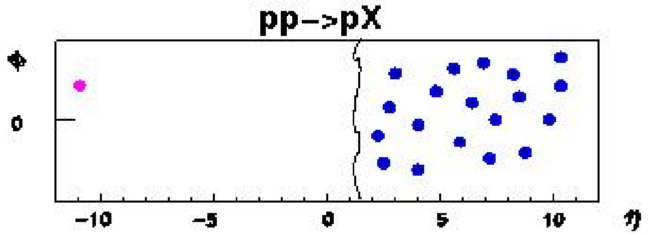
soft diffraction (semi)-hard diffraction hard diffraction

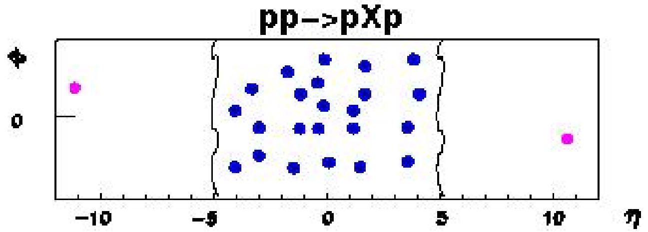
cross section ⟵⟶ luminosity

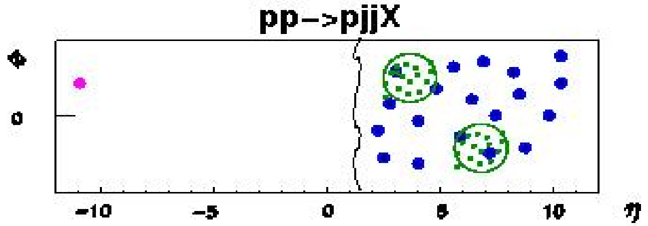
σ	mb	μb	nb	
β^* (m)	1540	90	2	0.5
$\mathcal{L}$ ($cm^{-2}\ s^{-1}$)	10^{28}	10^{30}	10^{32}	10^{34}
	TOTEM runs		Standard runs	

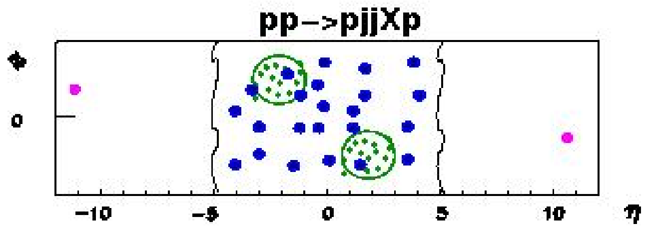
Accessible physics depends on: luminosity
β^* (i.e. proton acceptance)

Triggering on soft & semi-hard diffraction









	σ	Estimated Rates (Hz) [acceptance corrected] $L = 10^{30}\ cm^{-2}s^{-1}$, $\beta^* = 90$ m	$L = 10^{32}\ cm^{-2}s^{-1}$, $\beta^* = 2$ m
1p T1/T2	14 mb	6000	$1.4 \cdot 10^5$
2p T1/T2	1 mb	200	$3.5 \cdot 10^3$
1p T1/T2 jet(s)	1μb (p_T^{jet}>20 GeV)	0.2	
	30nb (p_T^{jet}>50 GeV)	0.01	0.5
2p T1/T2 jet(s)	60nb (p_T^{jet}>20 GeV)	$7 \cdot 10^{-3}$	
	1.5 nb (p_T^{jet}>50 GeV)		0.03

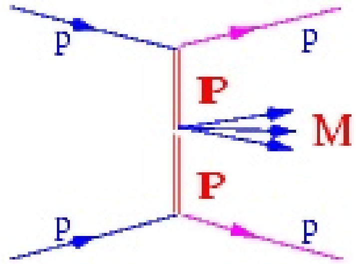
Diffraction at low luminosity: soft central diffraction

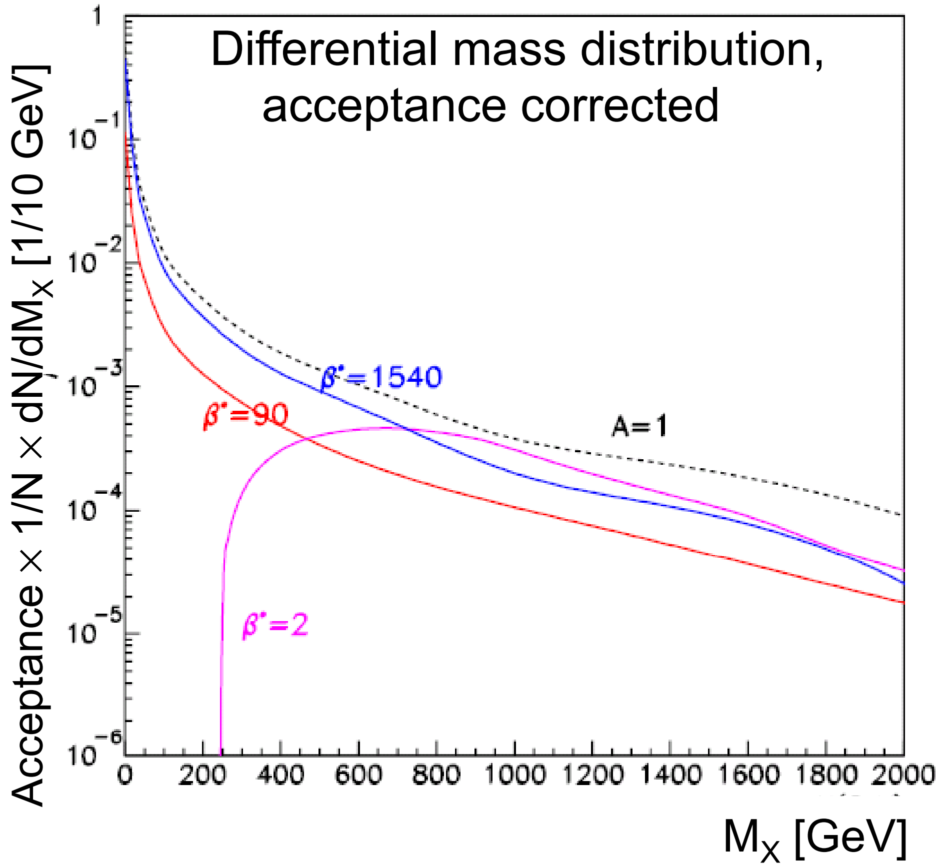
Study of mass distribution via the 2 protons $M_X = \sqrt{\xi_1 \xi_2 s}$

ξ measured directly ($\sigma(\xi) \sim 1.6 \cdot 10^{-3}$ @ $\beta^* = 90$ m) or

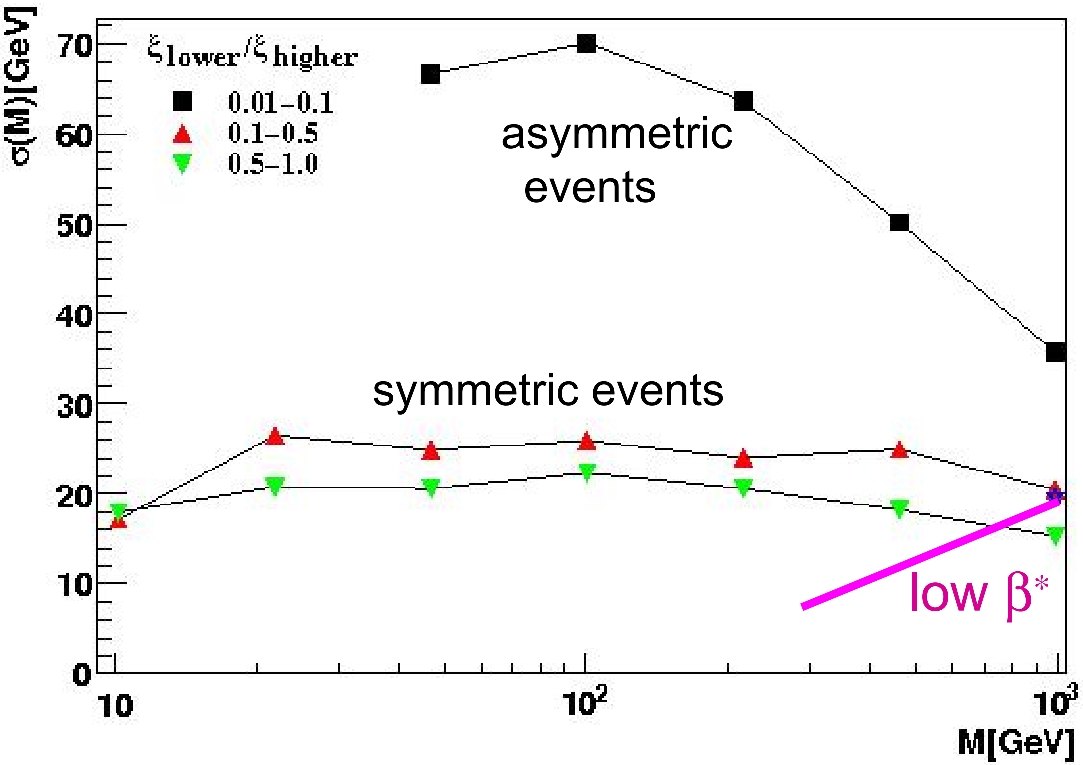
– with rapidity gap $\Delta\eta = -\ln\xi$ $\sigma(\xi)/\xi \sim 80$ %

– with calorimeters $\xi = \Sigma_i E^T_i e^{\pm\eta_i} / \sqrt{s}$ $\sigma(\xi)/\xi \sim 100$ %



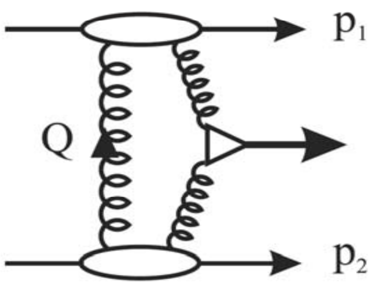


Mass resolution, $\beta^* = 90$ m, RP@220 m



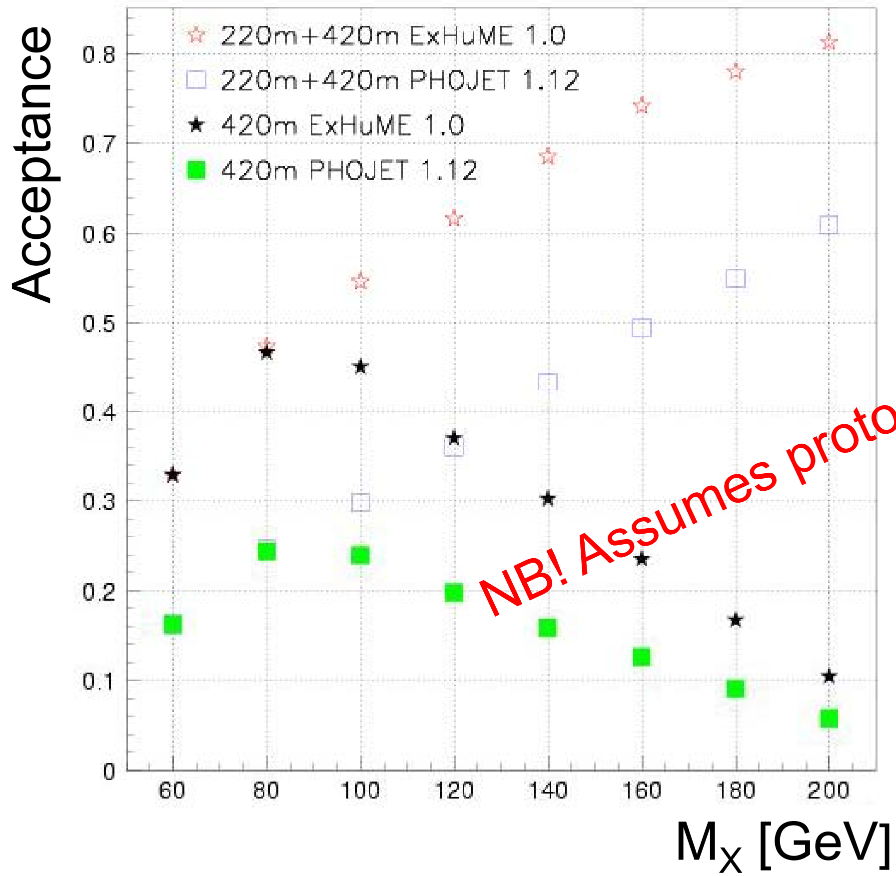
Diffraction at high luminosity: central exclusive production

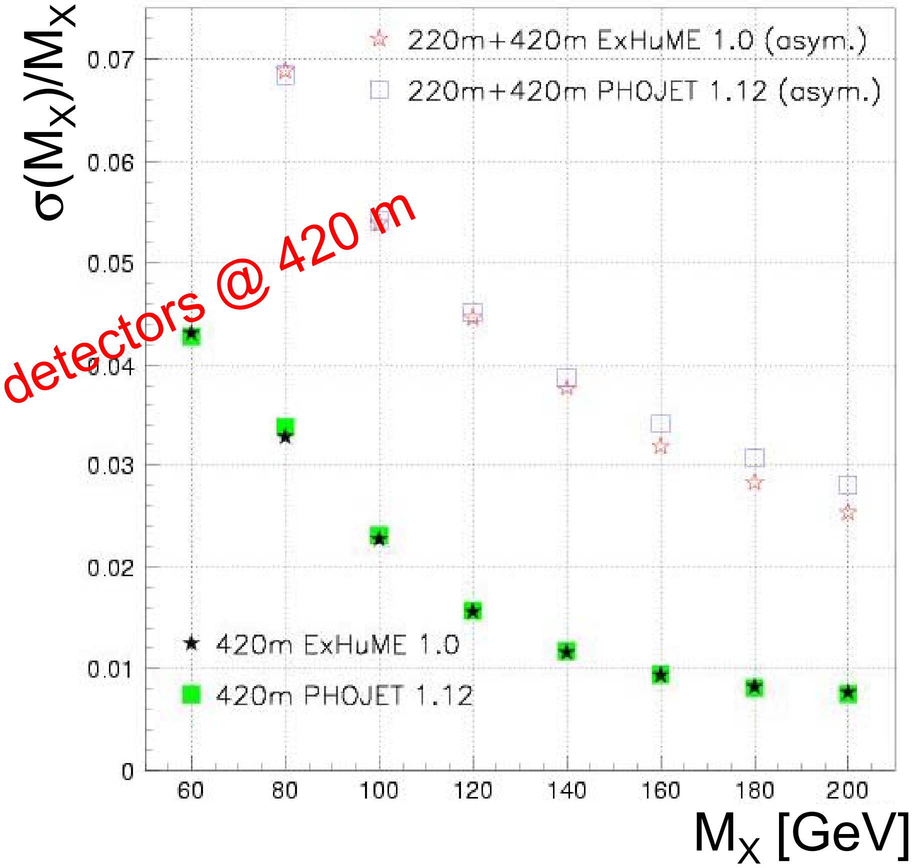
New physics searches e.g. σ (pp → p H(120 GeV)[→bb] p) ~ 3 fb *(KMR)*



J^{PC} selection (0^{++}...) → qq background heavily suppressed
Selection: 2 protons + 2 b-jets with consistent mass values
Experimental issues: trigger efficiency & pileup background

σ in some MSSM scenarios much larger, H → WW if H heavier





NB! Assumes proton detectors @ 420 m

Diffraction at high luminosity: triggering on diffraction

dedicated diffractive trigger stream foreseen at L1 & HLT (1 kHz & 1 Hz)

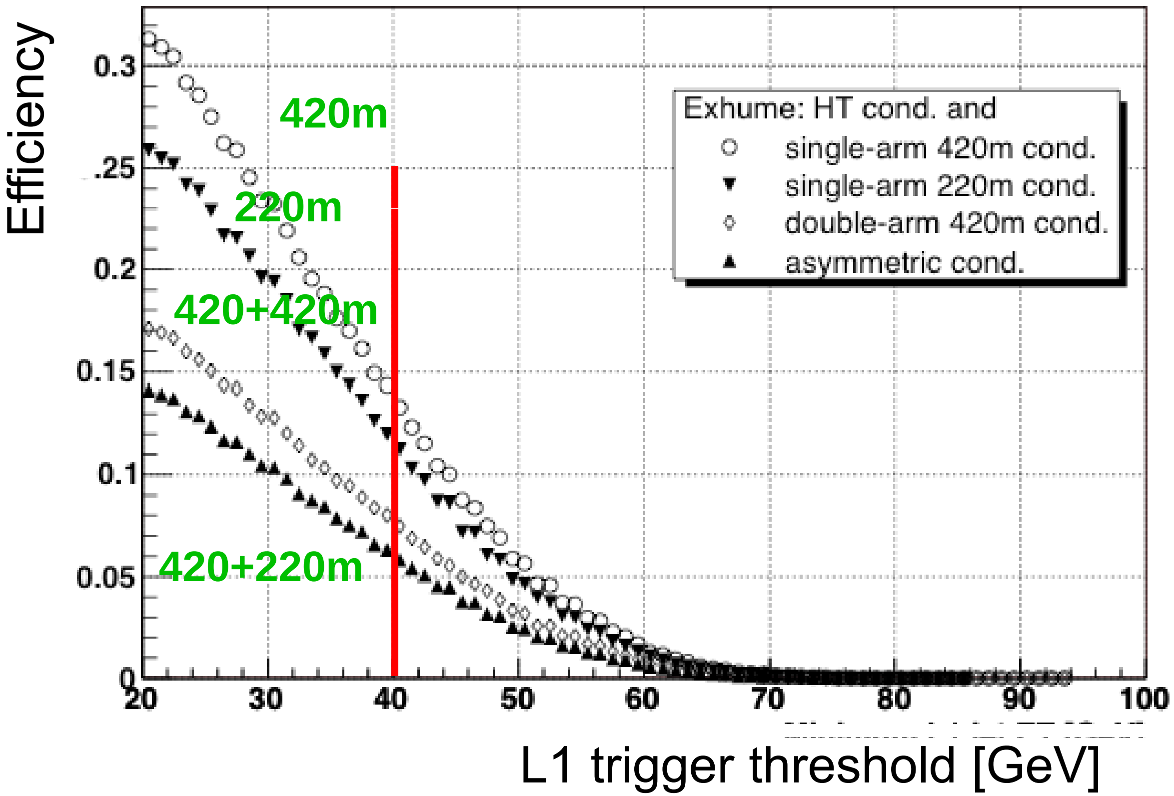
standard trigger thresholds too high for diffraction at nominal optics → use information from fwd detectors to lower particular trigger thresholds

L1:

- jet E_T > 40 GeV (↔ standard 2–jet threshold: ~100 GeV @ $\mathcal{L} = 2 \cdot 10^{33}\ cm^{-2}s^{-1}$)
- 1 (or 2) arm RP@220 m
- diffractive topology (fwd rap gaps, jet–proton hemisphere correlation …)

HLT (more process dependent):
e.g. 420 m proton detectors, mass constraint, b-tagging..

bench mark process: central exclusive H(120 GeV) → bb
L1: ~ 12 %
HLT: ~ 7 %
additional ~ 10 % efficiency @ L1 with a 1 jet + 1 μ (40 GeV, 3 GeV) trigger



Diffraction at high luminosity: reducing pileup background

At high luminosity, non-diffractive events overlaid by soft diffractive events mimic hard diffractive events ("pileup background")

Pileup event probability with single proton in RP@220m (420m) ~ 6 % (2 %) → probability for fake central diffractive signal caused by pileup protons

lumi	$\langle N^{PU} \rangle$	420+420	220+220	220+420	Total
$1 \cdot 10^{33}$	3.5	0.003	0.019	0.014	0.032
$2 \cdot 10^{33}$	7.0	0.008	0.052	0.037	0.084
$5 \cdot 10^{33}$	17.5	0.033	0.205	0.153	0.300
$7 \cdot 10^{33}$	25.0	0.063	0.280	0.246	0.417
$1 \cdot 10^{34}$	35.0	0.101	0.480	0.380	0.620

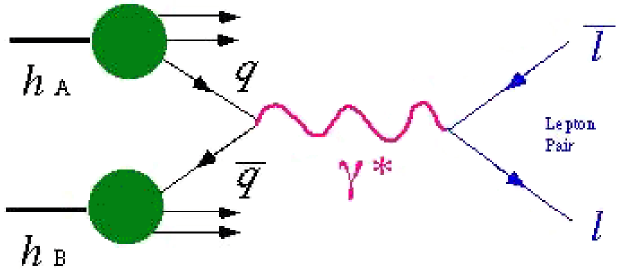
Pileup background reduction:

- correlation ξ & mass measured with central detector & proton detectors
- fast timing detectors to distinguish proton origin & hard scattering vertex from each other (R&D project)

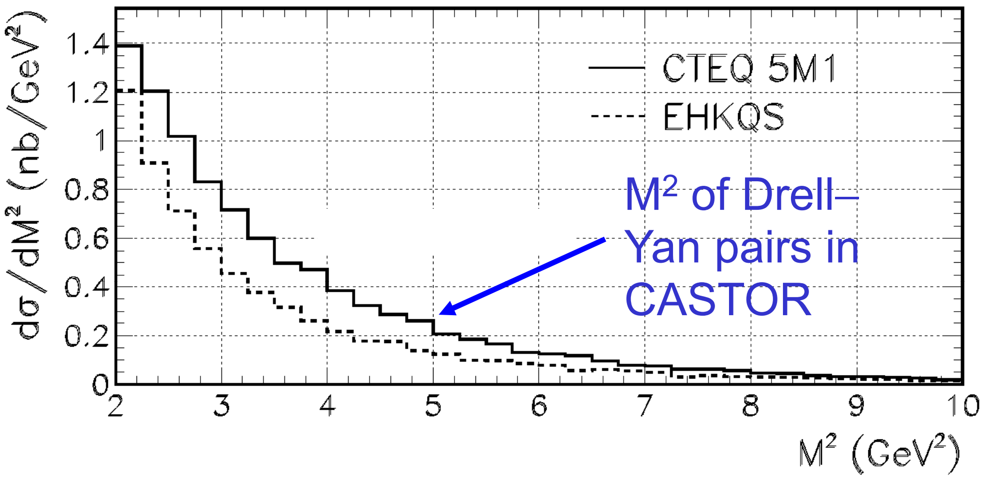
pileup background depends on LHC diffractive proton spectrum
→ rapidity gap survival probability

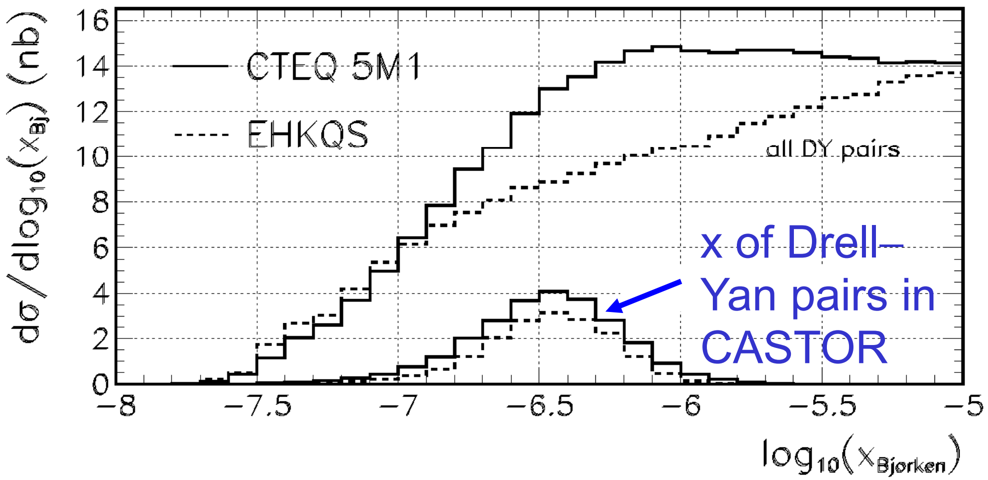
Low–x physics

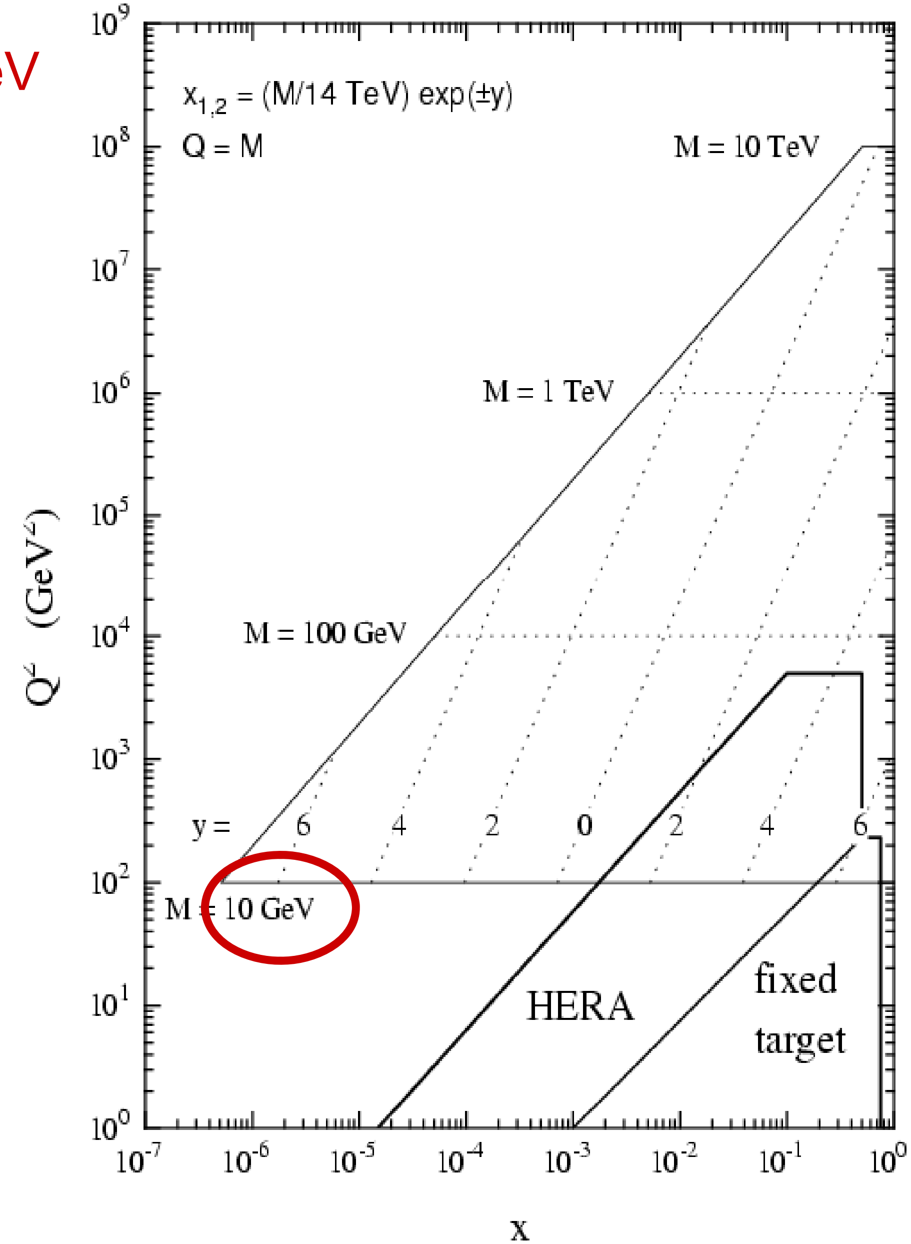
high √s @ LHC allows access to quark & gluon densities for small Bjorken–x values: fwd Drell-Yan (jets) sensitive to quarks (gluons)



η > 5 & M < 10 GeV
⇒ x ~ 10^{-6}–10^{-7}
T2 + CASTOR !!





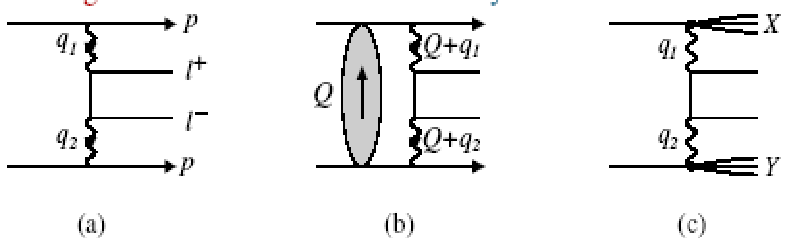


Forward physics

– Forward particle & energy flow: validation of hadronic air shower models, possible new phenomena…
– Study of underlying event
– γγ & γp mediated processes: e.g. exclusive dilepton production

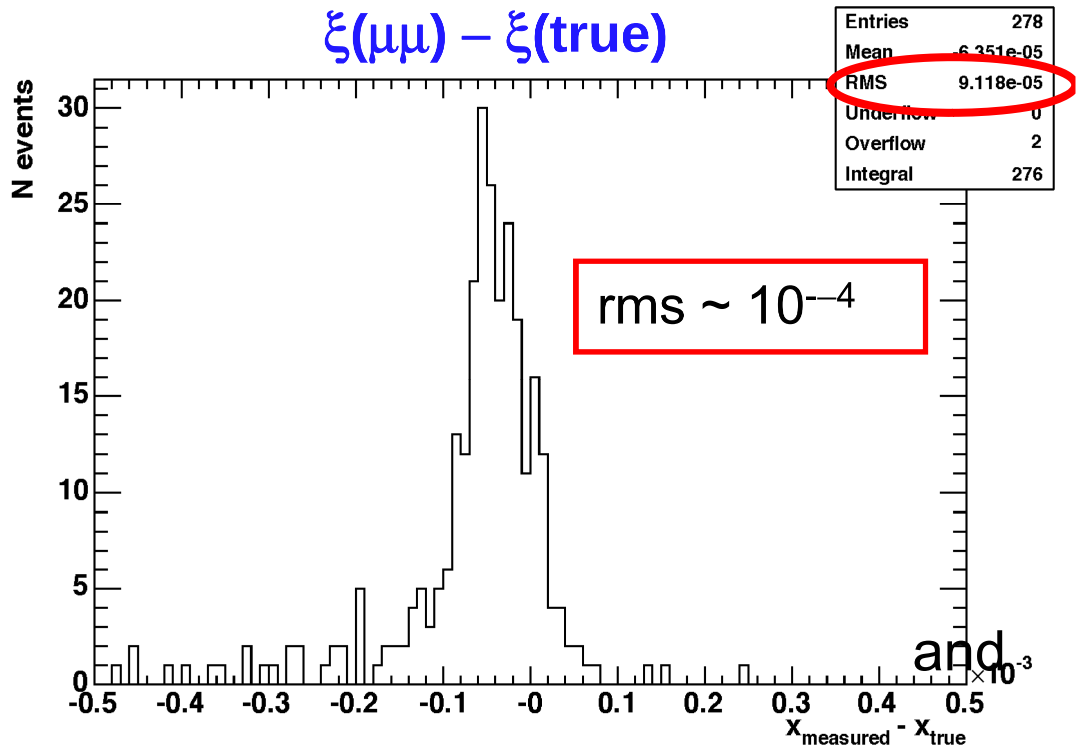
- QED process (a) production σ precisely known

event generator LPAIR based on ME by Vermaseren



- Hadronic corrections [(b) (c)] small.

Calibration process for luminosity and energy scale of proton detectors



Allows proton ξ value reconstruction with a 10^{-4} resolution < beam energy spread
Striking signature: acoplanarity angle between leptons

CMS 2008 diffractive & forward program

First analysis in 2008 most likely based on large rapidity gap selection Even if RP@220 m available need time to understand the data …

Concentrate first analysis on data samples where pileup negligible

Developing rapidity gap trigger with forward calorimeters (HF, CASTOR…)

Program:

"Rediscover" hard diffraction a la Tevatron, for example:

- measure fraction of W, Z, dijet and heavy flavour production with large rapidity gap
- observe jet-gap-jet and multi-gap topologies

Forward physics with CASTOR

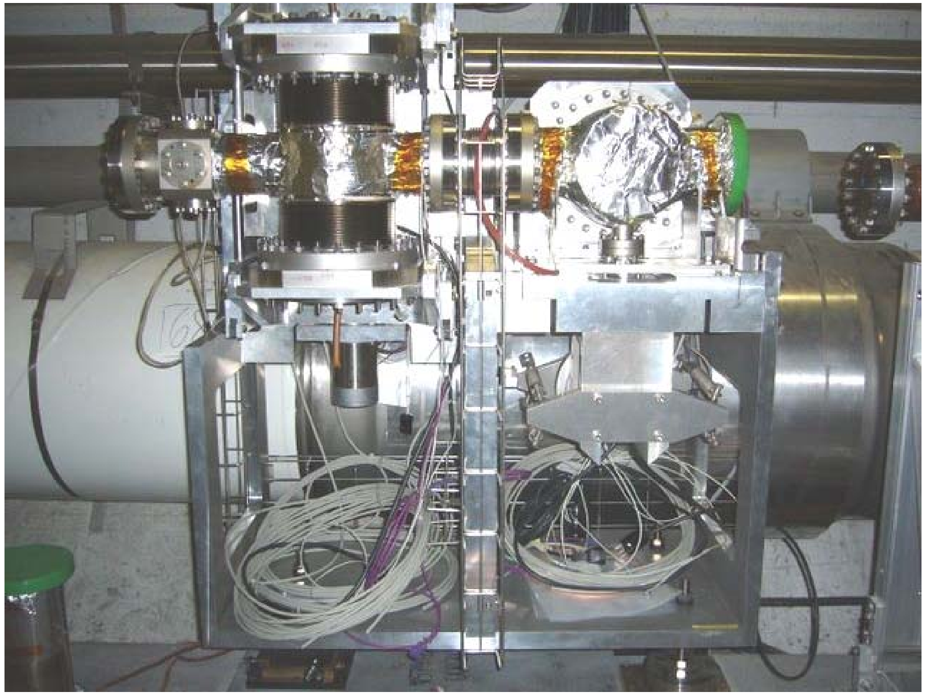
- measure forward energy flow, multiplicity, jets & Drell-Yan electrons

$\gamma\gamma$ & γp interactions, for example

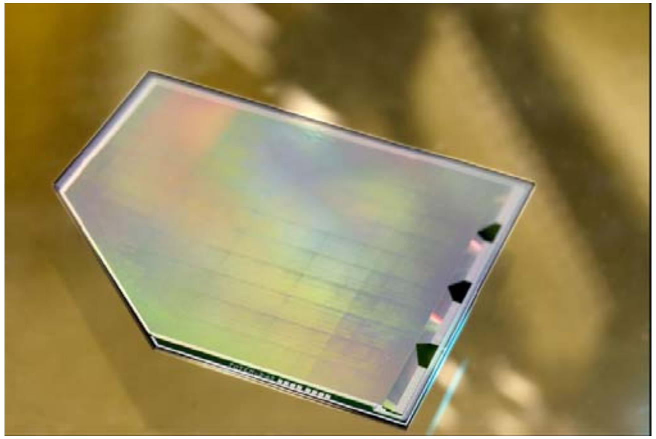
- observe exclusive di-lepton production

TOTEM Detectors: Roman Pots

2 RP220 m stations installed into LHC in May-June, remaining by end of summer

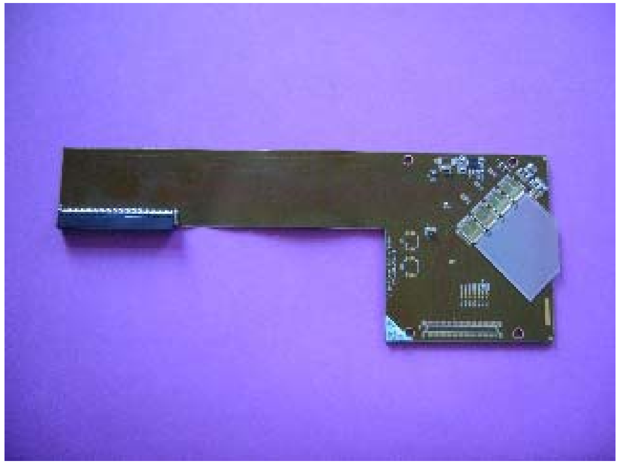


Si edgeless detector



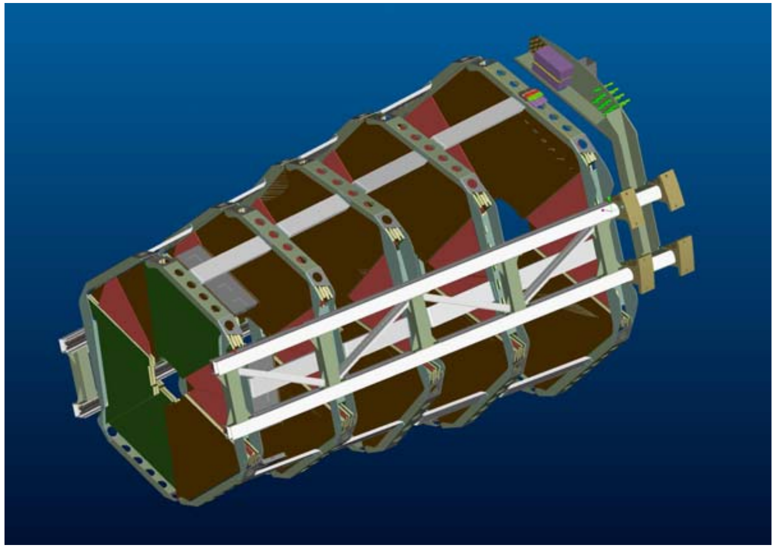
First edgeless Si detectors mounted with final VFAT hybrid successfully working with source & in test beam → all detector assemblies ready for mounting by April 2008.

VFAT hybrid with detector

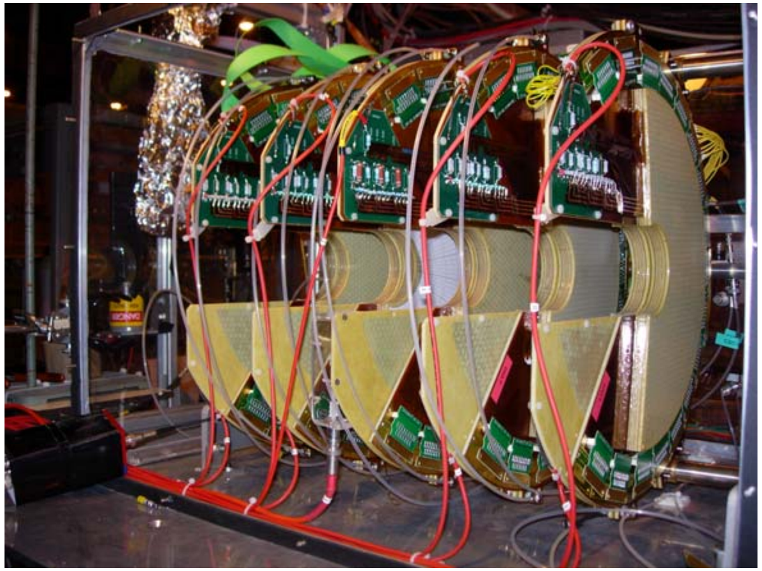


TOTEM detectors: T1 & T2

T1 Telescope



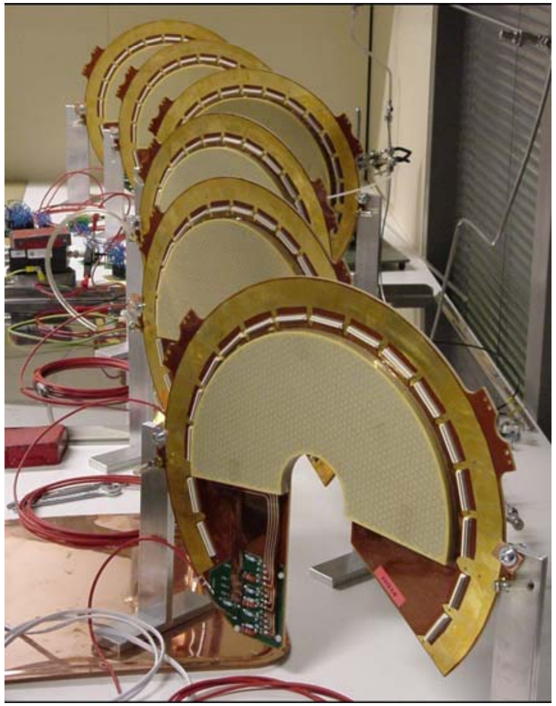
T2 Telescope



testbeam setup

Mechanical frames and CSC detectors in production; tests in progress. During 2007 complete CSC production. Plan to have two half-telescopes ready for mounting in April 2008.

All necessary GEM's produced (> half tested upto gains of 80000). Energy resolution 20-30 %. The 4 half-telescopes should be ready for mounting in April 2008.



Optics & beam parameters

Parameters	β^* = 2 m (standard step in LHC start-up)	β^* = 90 m (early TOTEM optics)	β^* = 1540 m (final TOTEM optics)
Crossing angle	0.0	0.0	0.0
N of bunches	156	156	43
N of part./bunch	$(4 - 9) \cdot 10^{10}$	$(4 - 9) \cdot 10^{10}$	$3 \cdot 10^{10}$
Emittance [μm · rad]	3.75	3.75	1
10 · vertical beam width at RP220 [mm]	~ 3	6.25	1.3
Luminosity [$cm^{-2}\ s^{-1}$]	$(2 - 11) \cdot 10^{31}$	$(5 - 25) \cdot 10^{29}$	$1.6 \cdot 10^{28}$

β^* = 90 m ideal for early running:

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

β^* = 90 m optics proposal submitted to LHCC & well received.

β^* = 90 m optics

Optics optimized for elastic & diffractive scattering

Proton coordinates w.r.t. beam in the RP at 220 m:

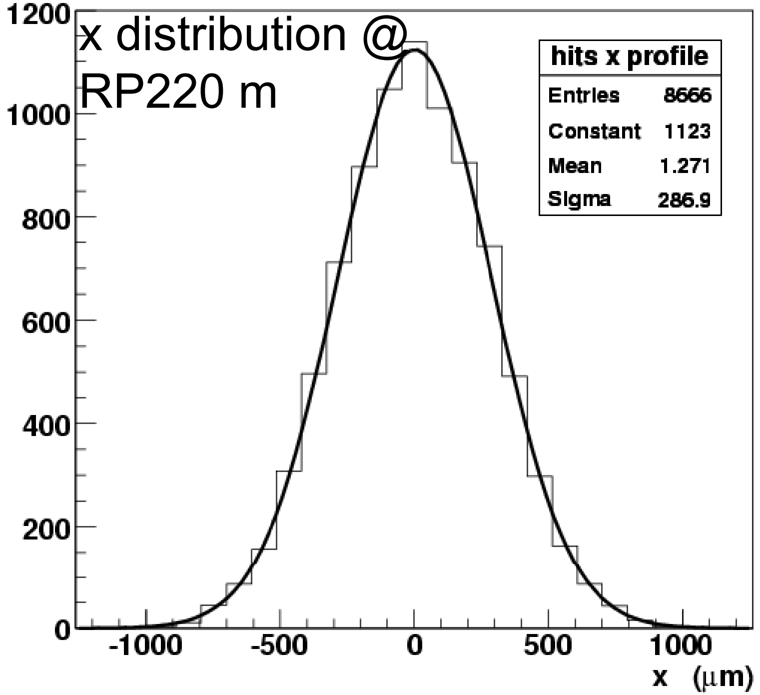
$$y = L_y\theta_y^* + v_y y^*$$

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

(x^*,y^*):vertex position
(θ_x^*,θ_y^*):emission angle
$\xi = \Delta p/p$

L_y = 265 m (large) v_y = 0
vertical parallel-to-point focusing
→ optimum sensitivity to θ_y^*
i.e. to t (azimuthal symmetry)

L_x = 0 v_x = – 2 D = 23 mm
elimination of θ_x^* dependence
→ enhanced sensitivity to x in diffractive events,
→ horizontal vertex measurement in elastic events



x distribution @ RP220 m for elastic events → measurement of horizontal vertex distribution @ IP

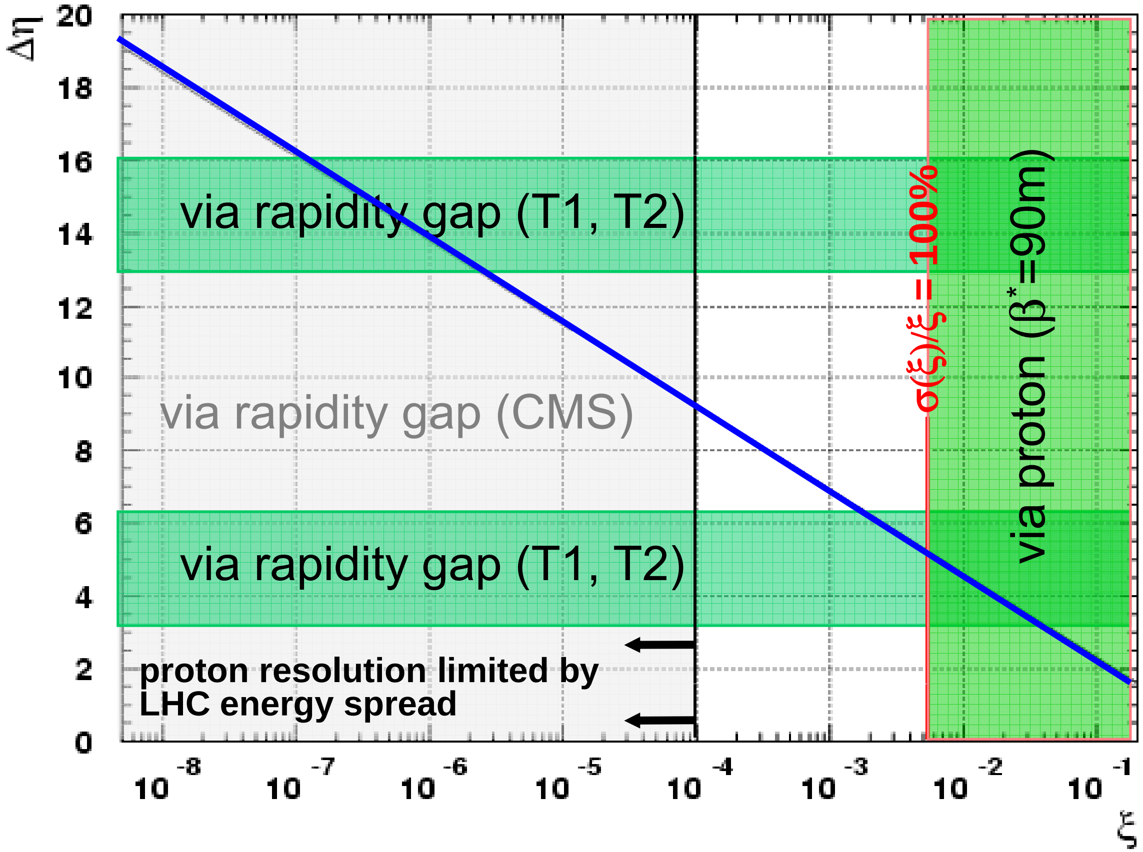
Luminosity estimate together with beam parameters if horizontal-vertical beam symmetry assumed

Beam position measurement to ~1 μm every minute

TOTEM 2008 physics program

For early runs: optics with β^* = 90 m requested from LHCC

- Optics commissioning fits well into LHC startup planning
- Typical running time: several periods of a few days
- Total pp cross section within ± 5%
- Luminosity within ± 7%
- Soft diffraction with ξ–independent proton acceptance (~ 65%)



Summary

CMS and TOTEM diffractive and forward physics program

CMS+TOTEM provides unique pseudo-rapidity coverage
Integral part of normal data taking both at nominal & special optics

Low Luminosity (< 10^{32} $cm^{-2}s^{-1}$): nominal & special optics

- Single & central diffractive cross sections (inclusive & with jets, rapidity gap studies)
- Low–x physics
- Forward Drell-Yan & forward inclusive jets
- Validation of Hadronic Air Shower Models

Running with TOTEM optics: large proton acceptance

No pileup

Increasing Luminosity (> 10^{32} $cm^{-2}s^{-1}$): nominal optics

- Single & central diffraction with hard scale (dijets, W, Z, heavy quarks) ⇒ dPDF's, GPD's, rapidity gap survival probability
- $\gamma\gamma$ & γp physics

Pileup not negligible: important background source

High Luminosity (> 10^{33} $cm^{-2}s^{-1}$) : nominal optics

- Characterise Higgs/new physics in central diffraction?

Need additional proton detectors

TOTEM

CMS

Content of common physics document

Includes important experimental issues in measuring forward and diffractive physics but not an exhaustive physics study

- Detailed studies of acceptance & resolution of forward proton detectors
- Trigger
- Background
- Reconstruction of kinematical variables

Several processes studied in detail

An important milestone for collaboration between the 2 experiments

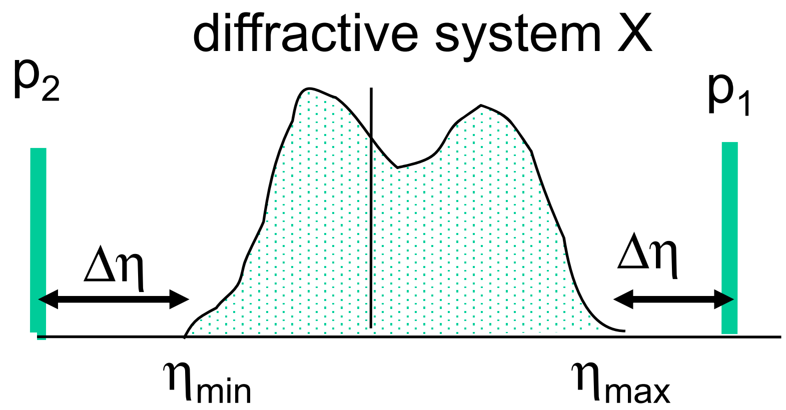
Running scenarios

Physics:	low |t| elastic, σ_{tot}, min bias	large |t| elastic	Soft diffraction	Soft & semi-hard diffraction
β^*[m]	1540 (90)	18, 2, 0.5	1540	90
N of bunches	43	2808	156	156
N of part. per bunch (x 10^{11})	0.3	1.15	(0.6 - 1.15)	1.15
Half crossing angle [μrad]	0	160	0	0
Transv. norm. emitt. [μm rad]	1 (3.75)	3.75	1 - 3.75	3.75
RMS beam size at IP [μm]	454 (200)	95	454 - 880	200
RMS beam diverg. [μrad]	0.29 (2.3)	5.28	0.29 - 0.57	2.3
Peak luminosity [cm^{-2} s^{-1}]	1.6 (7.3) x 10^{28}	3.6 x 10^{32}	2.4 x 10^{29}	2 x 10^{30}

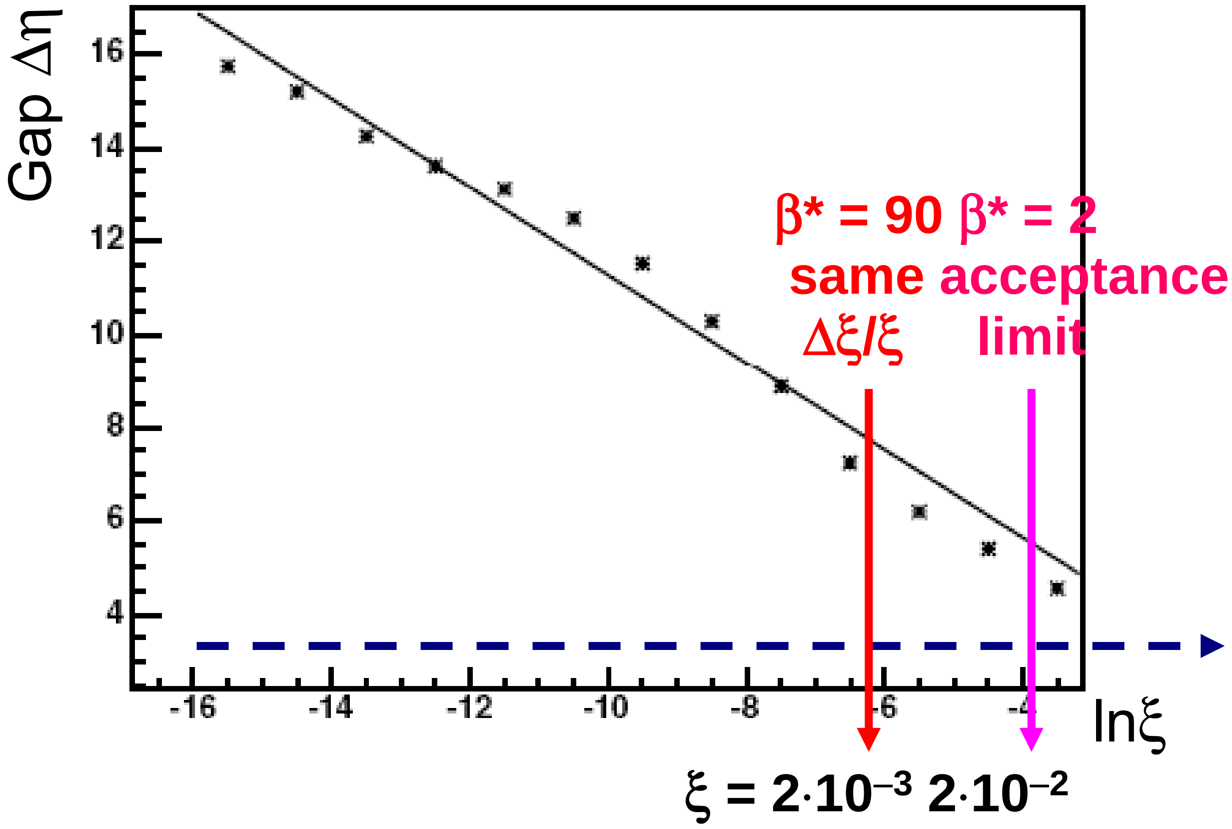
Diffraction at low luminosity: rapidity gaps

Measure ξ via rapidity gap: $\Delta\eta = -\ln\xi$

Achieved resolution: $\sigma(\xi)/\xi \sim 80\ \%$

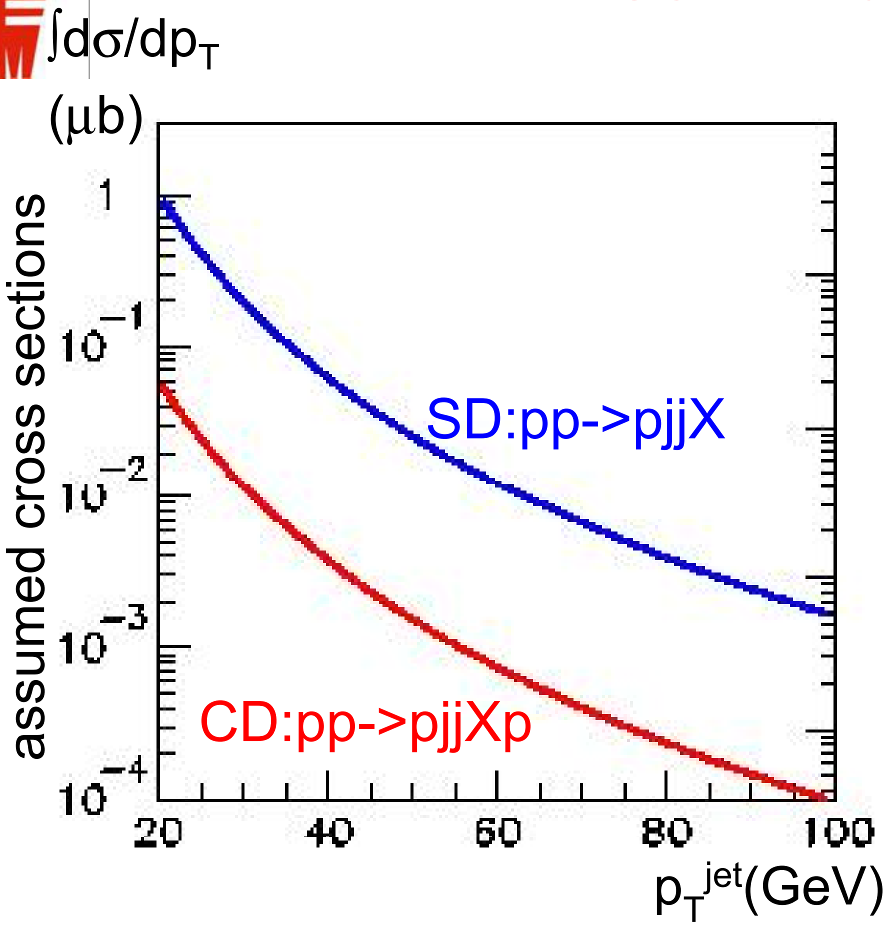


Gap vs ln (ξ) T1+T2+Calorimeters



Gap measurement limit due to acceptance of T2

Diffraction at medium luminosity: semi-hard diffraction



Measure cross sections & their t, M_X, p_T^{jet} dependence

Event topology: exclusive vs inclusive jet production

→ access to dPDF's and rapidity gap survival probability

N event collected
[acceptance included]

$\beta^* = 90$ m $\int \mathcal{L}\, dt = 0.3$ pb^{-1}

SD:	p_T>20 GeV	6x10^4
CD:	"	2000

$\beta^* = 2$ m $\int \mathcal{L}\, dt = 100$ pb^{-1}

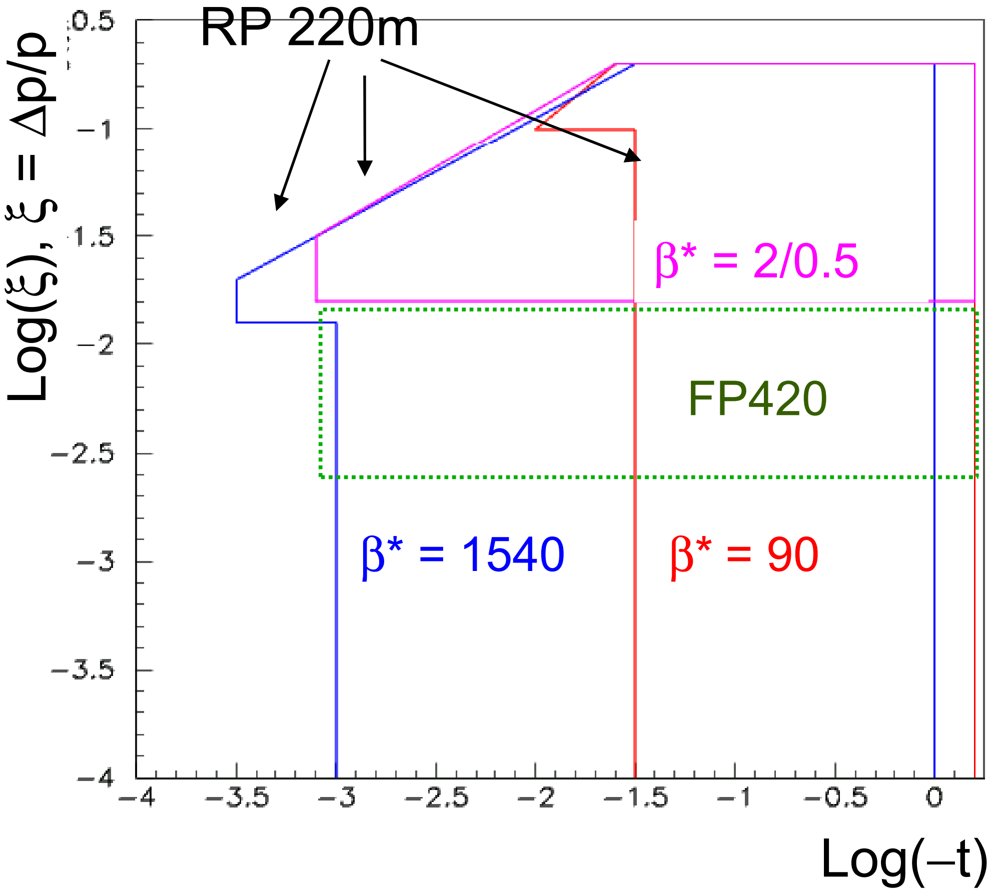
SD:	p_T>50 GeV	5x10^5
CD:	"	3x10^4

In case of jet activity ξ also determined from calorimeter info:

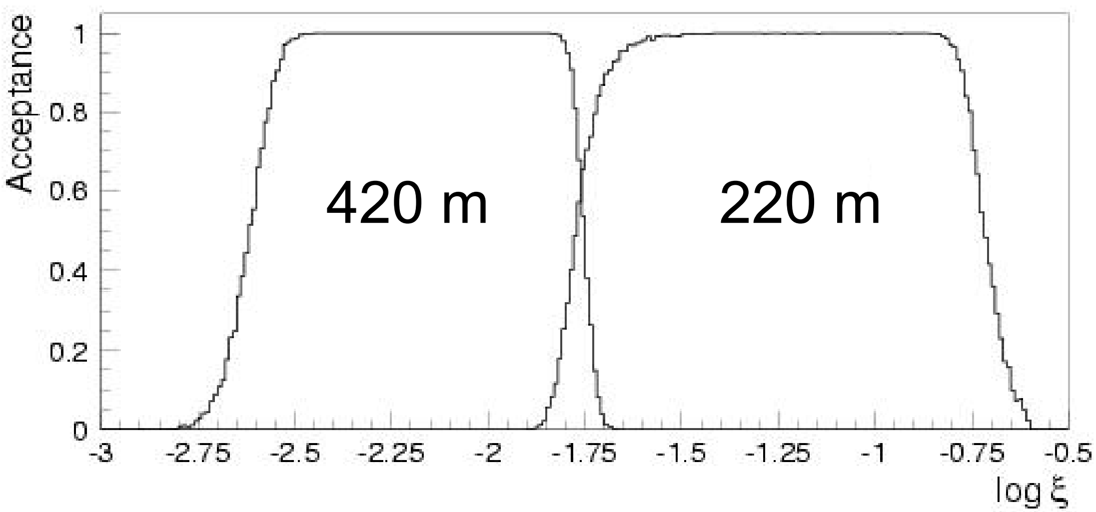
$\xi^{\pm} = \Sigma_i E_T^i e^{\pm\eta_i} / \sqrt{s}$

$\sigma(\xi)/\xi \sim 40$ %

Forward proton measurement: acceptance (@220 m & 420 m)



β*= 0.5 – 2 m



Proton detectors at 420 m would enlarge acceptance range down to ξ = 0.002 at high luminosity (= low β*).

Forward proton measurement: momentum resolution (β^* = 90 m)

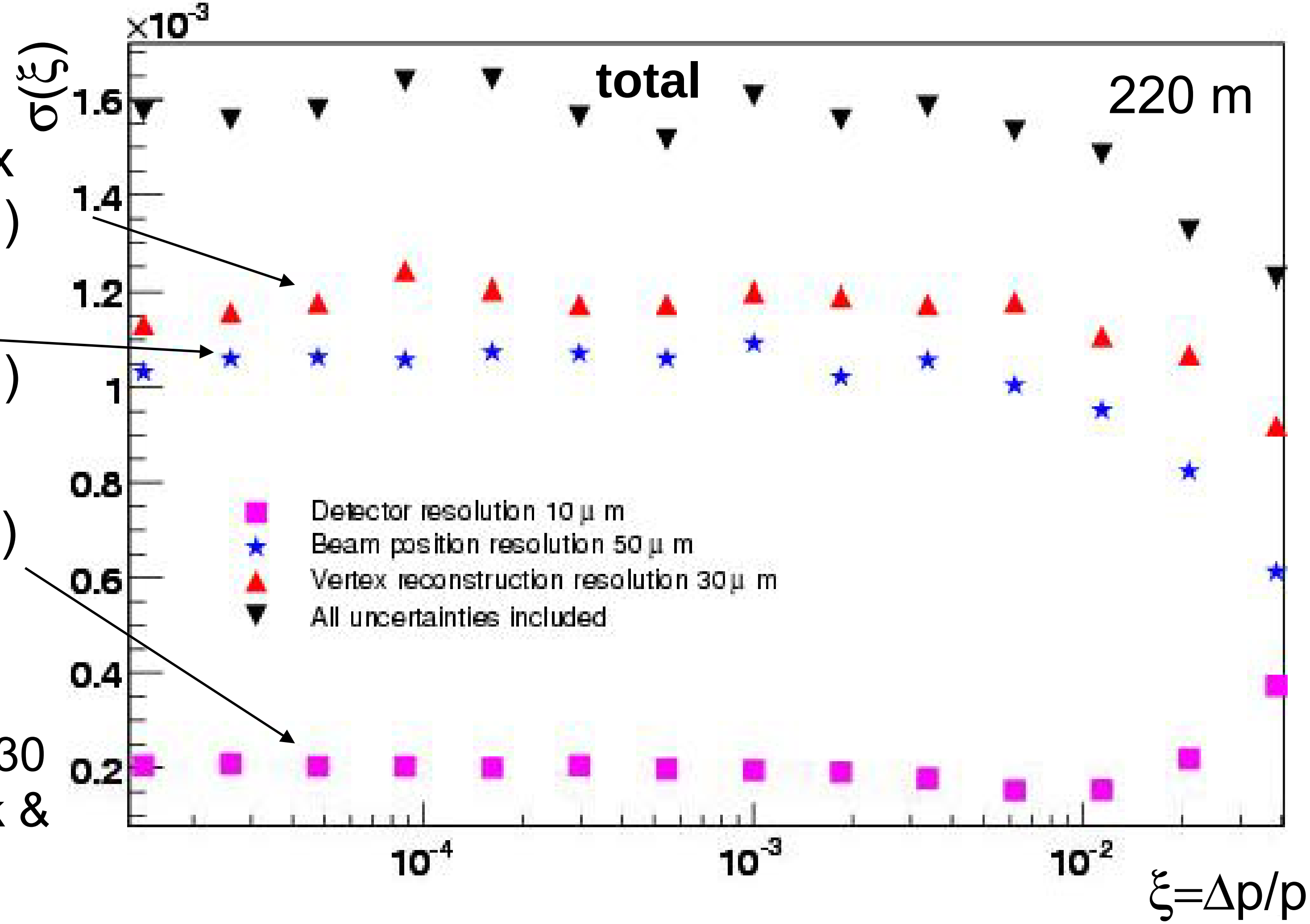
Individual contribution to the resolution:

Transverse vertex resolution (30 μm)

Beam position resolution (50 μm)

Detector resolution (10 μm)

Final state dependent; 30 μm for light quark & gluon jets



Forward proton measurement: momentum resolution (β* = 2/0.5 m)

Individual contribution to the resolution:

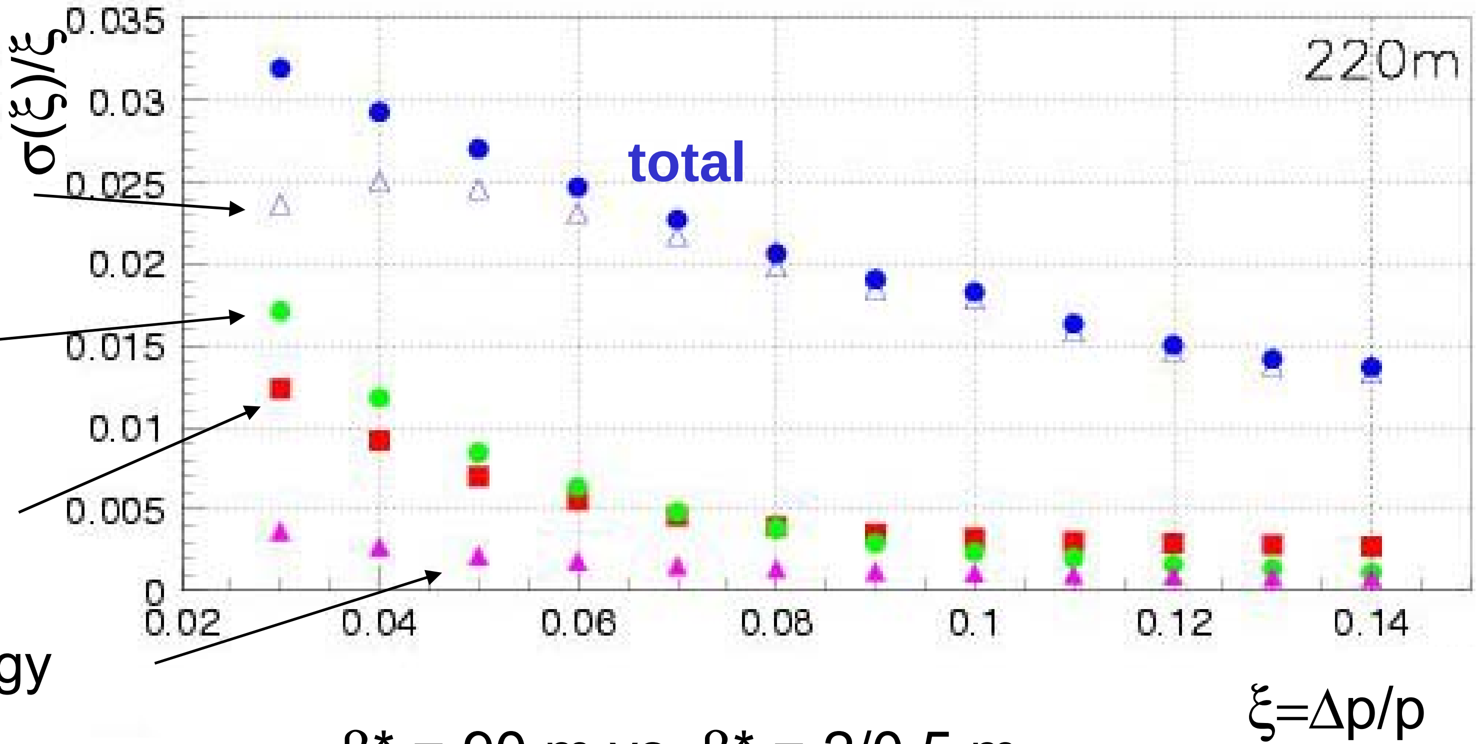
Detector resolution (10 μm)

Beam position resolution (50 μm)

Transverse vertex resolution (10 μm)

Relative beam energy spread ($1.1 \cdot 10^{-4}$)

Very little final state dependence since transverse IP size is small.



<u>β* = 90 m vs. β* = 2/0.5 m</u>

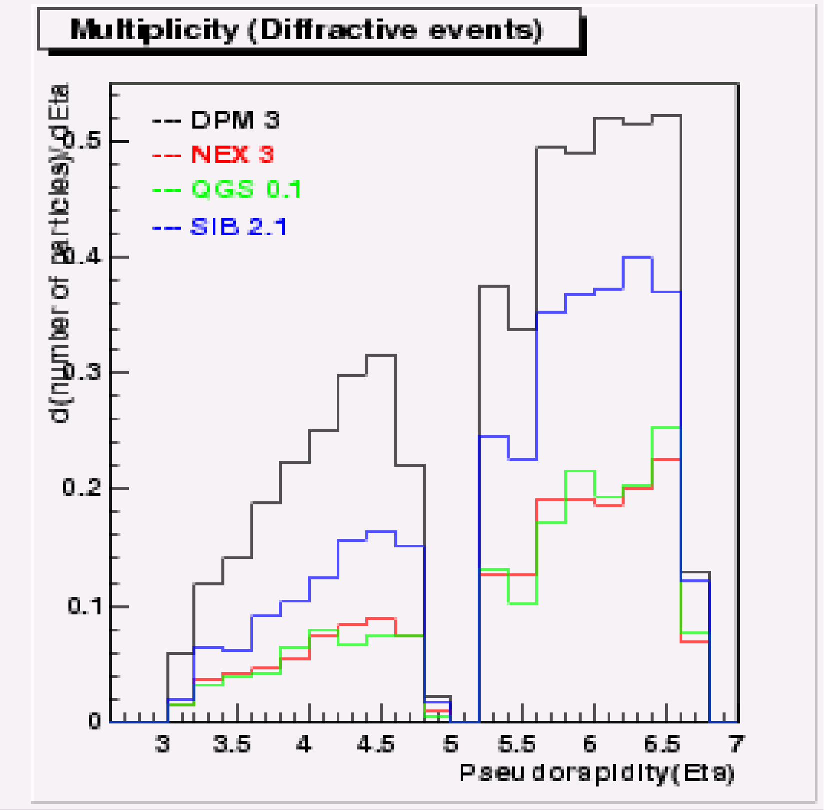
Better σ(ξ)/ξ for β* = 2/0.5 m & larger luminosity but limited ξ acceptance (ξ > 0.02)

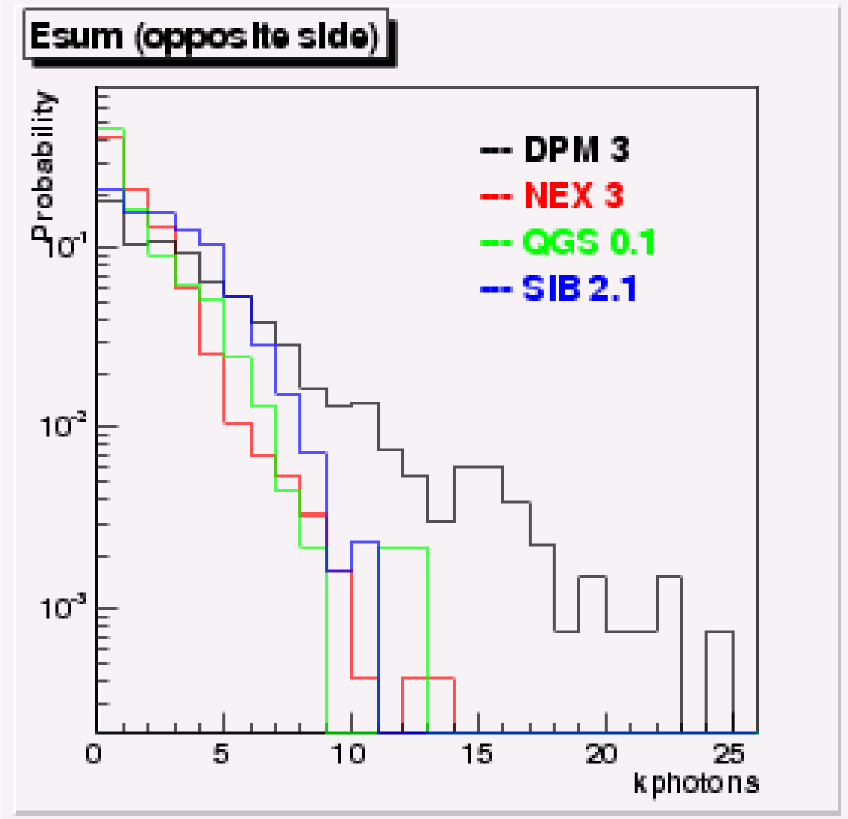
Cosmic ray connection

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

Need forward particle/energy measurements at high center-of-mass energy
(LHC ↔ $E_{lab}=10^{17}$ eV)

Achievable at low luminosity using T1/T2/HF/Castor





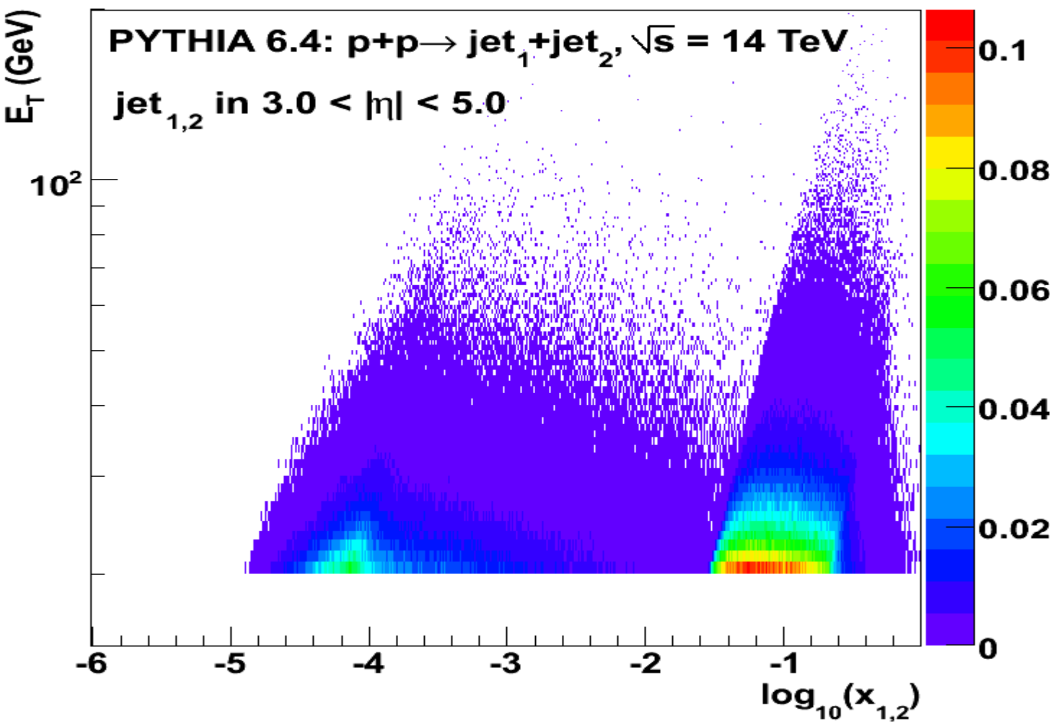
Low-x physics: forward jets

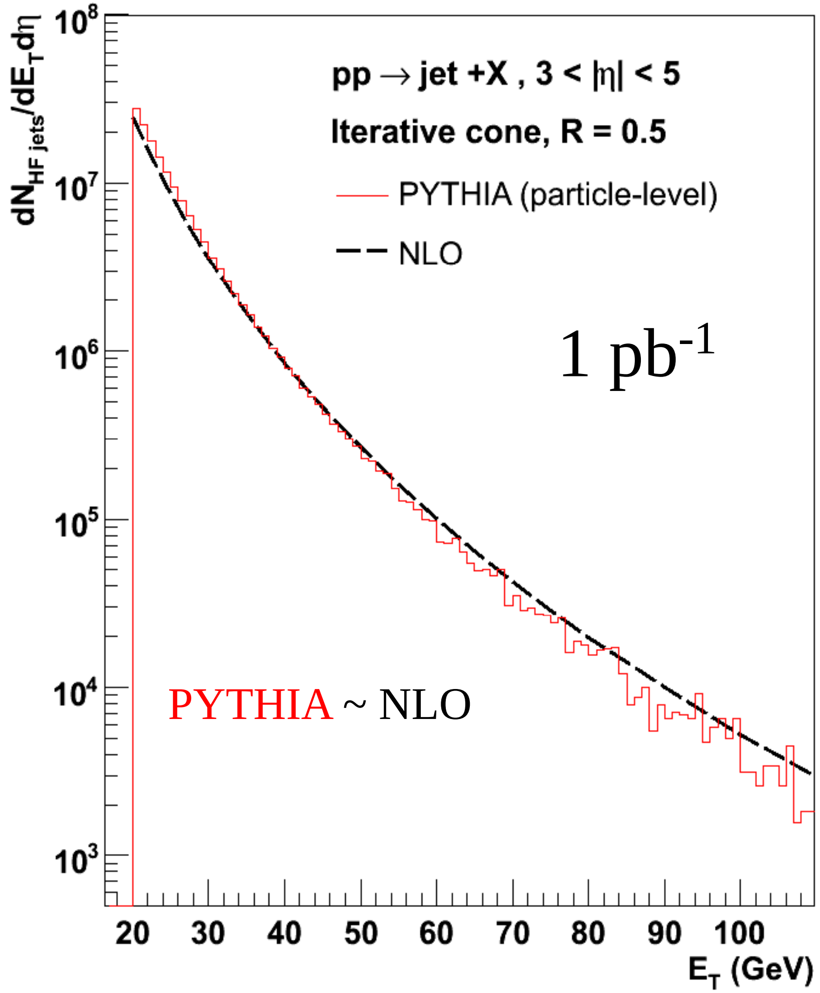
Inclusive forward "low-E_T" jet

(E_T ~20-100 GeV) production:

$$p + p \rightarrow jet1 + jet2 + X$$

Sensitive to gluons with: $x_2 \sim 10^{-4}$, $x_1 \sim 10^{-1}$

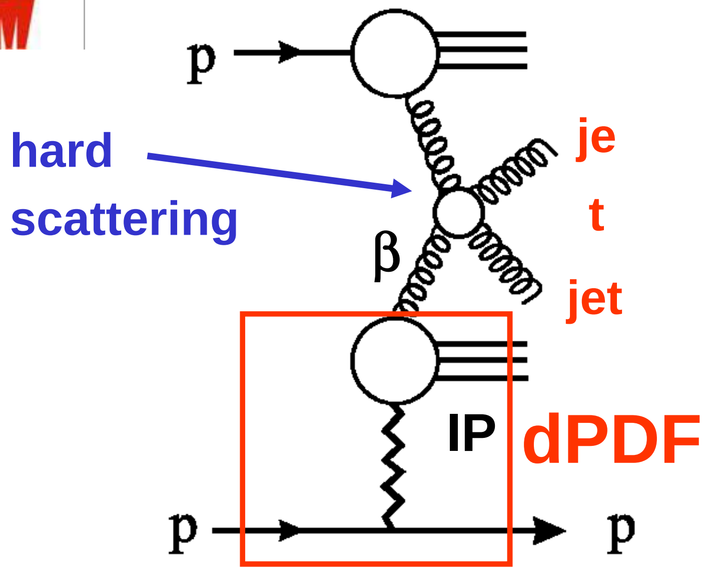




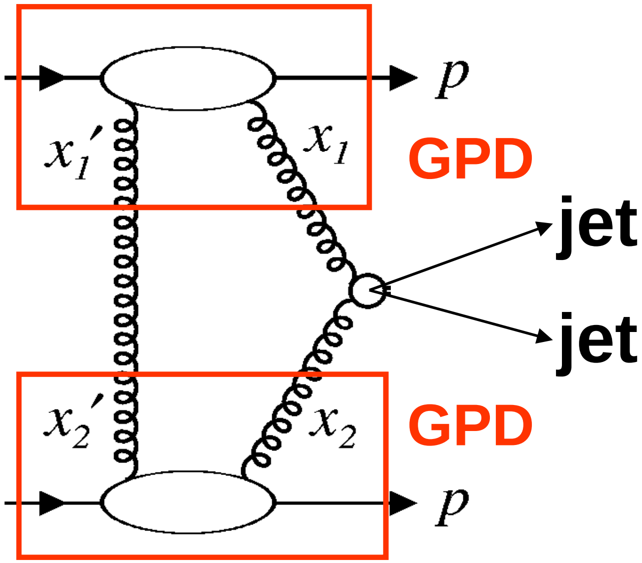
Large expected yields

(~10^7 at ~20 GeV) !

Diffractive PDF's and GPD's



- **Diffractive PDFs:**
  probability to find a parton of given x under condition that proton stays intact – sensitive to low-x partons in proton, complementary to standard PDFs



- **Generalised Parton Distributions (GPD)**
  quantify correlations between parton momenta in the proton
  t-dependence sensitive to parton distribution in transverse plane

  When x'=x, GPDs are proportional to the *square* of the usual PDFs