Forward Physics at the Large Hadron Collider

Xavier Rouby

Université catholique de Louvain
Center for Particle Physics and Phenomenology (CP3)

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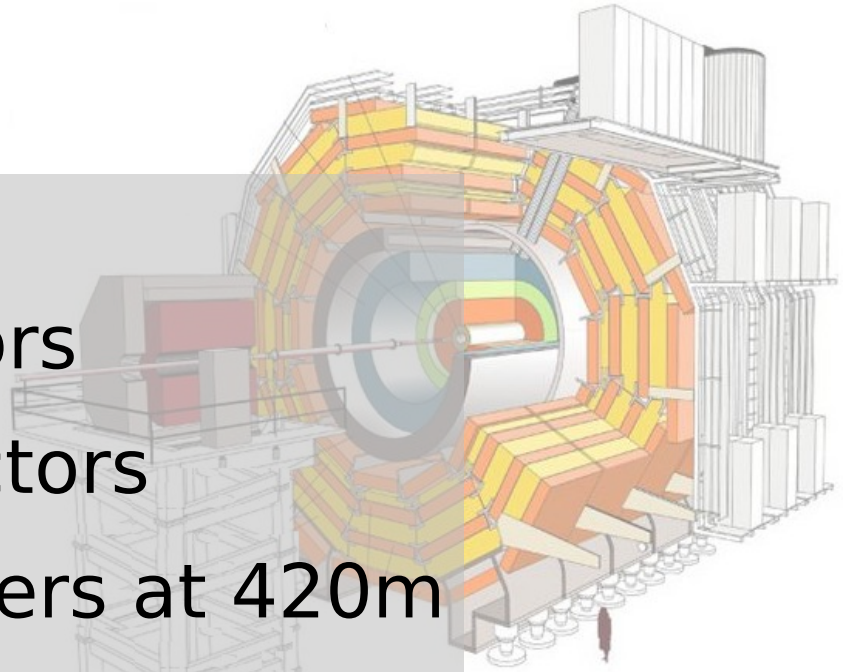
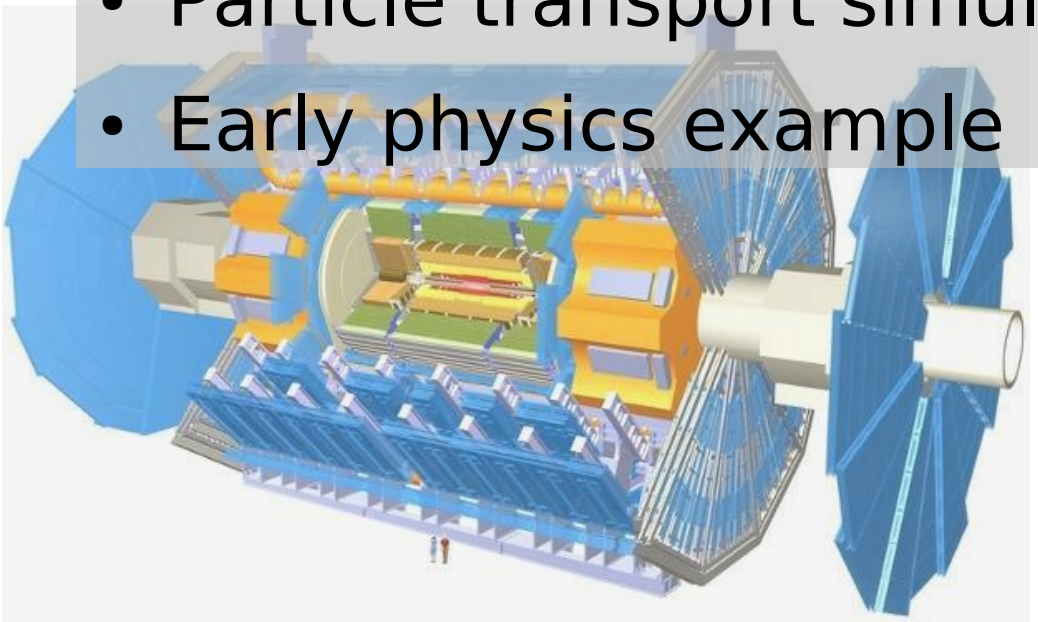
University *of* Glasgow, HEP Thursday seminar

Outline

- Motivations
- CMS forward detectors
- ATLAS forward detectors
- Forward proton taggers at 420m
- Particle transport simulation
- Early physics example



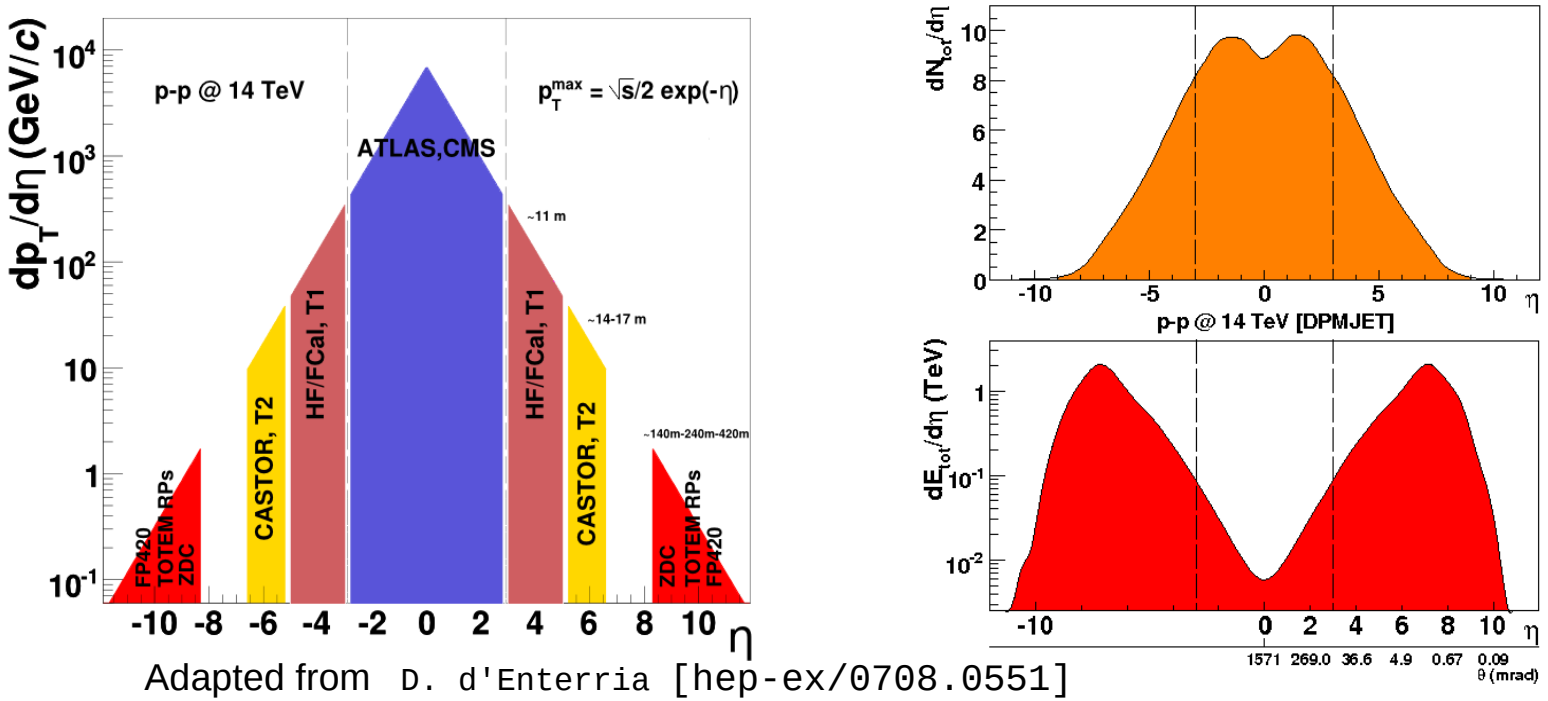


Introduction

Half of full LHC cross section is very soft physics

$$\sigma_{\rm tot}({\rm LHC}) = 111.5 \pm 1.2({\rm stat})^{+4.1}_{-2.1}({\rm syst})\ {\rm mb}$$

COMPETE Coll [PRL 89 (2002) 201801]



Adapted from D. d'Enterria [hep-ex/0708.0551]

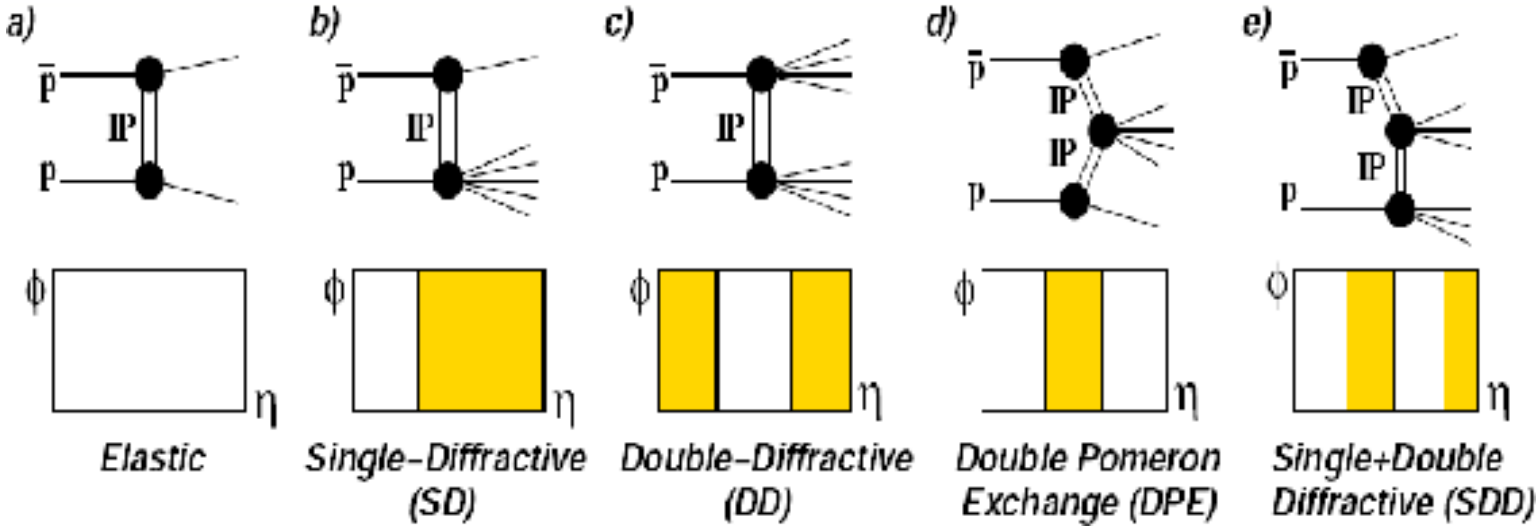
Rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

Pseudo-rapidity $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$

CMS / ATLAS + forward detectors:
largest η coverage ever!

Forward physics

Elastic scattering and diffraction
(including hard scale → pQCD)



Signatures:

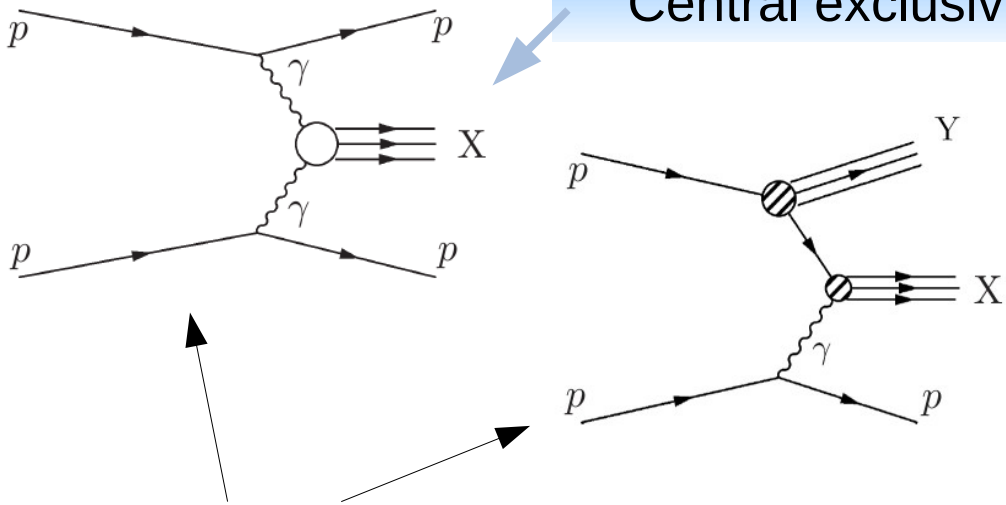
- Large Rapidity Gap
- Forward scattered proton

Central Exclusive Productions

Forward physics

Photon induced physics:
high energy $\gamma\gamma$ and γp interactions

Central exclusive productions

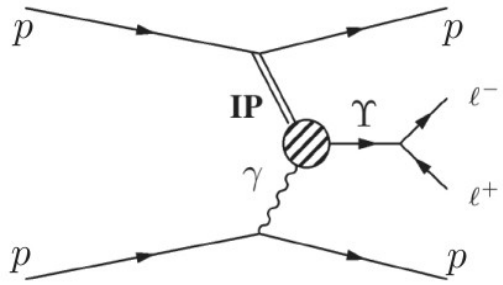


Theoretically well known processes !

High relative luminosity

Signatures:

- Large Rapidity Gap
- Forward scattered proton



Diffractive photoproduction

Forward physics

Low-x QCD : forward jets, DY

→ Constraining proton PDFs at low x ($x \sim 10^{-4}$)

Large rapidity gaps between forward jets

→ HERA and Tevatron observed events with hard scale and LRGs

Validation of cosmic ray generators

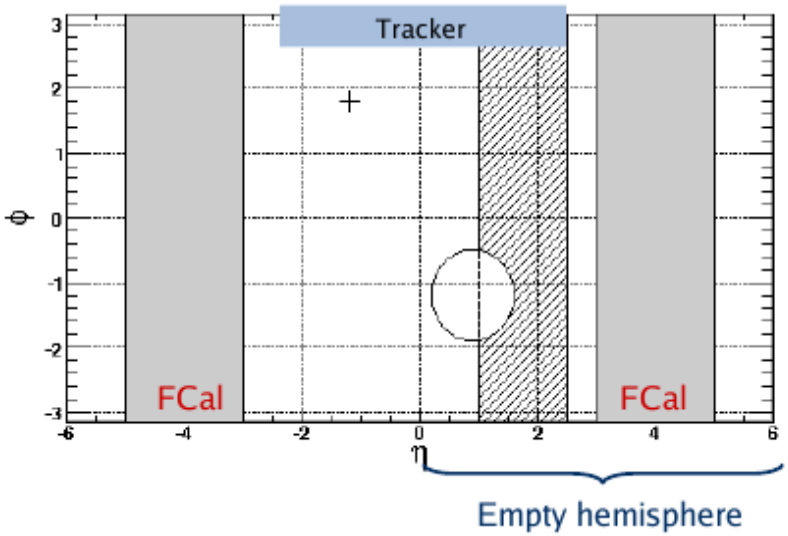
→ LHC pp c.m.s. energy 14 TeV

↔ Fixed target collision energy 100 PeV

Luminosity monitoring or normalization

Tagging γ-interactions

1) Large Rapidity Gaps in forward region of the central detector



e.g. γ p – interactions

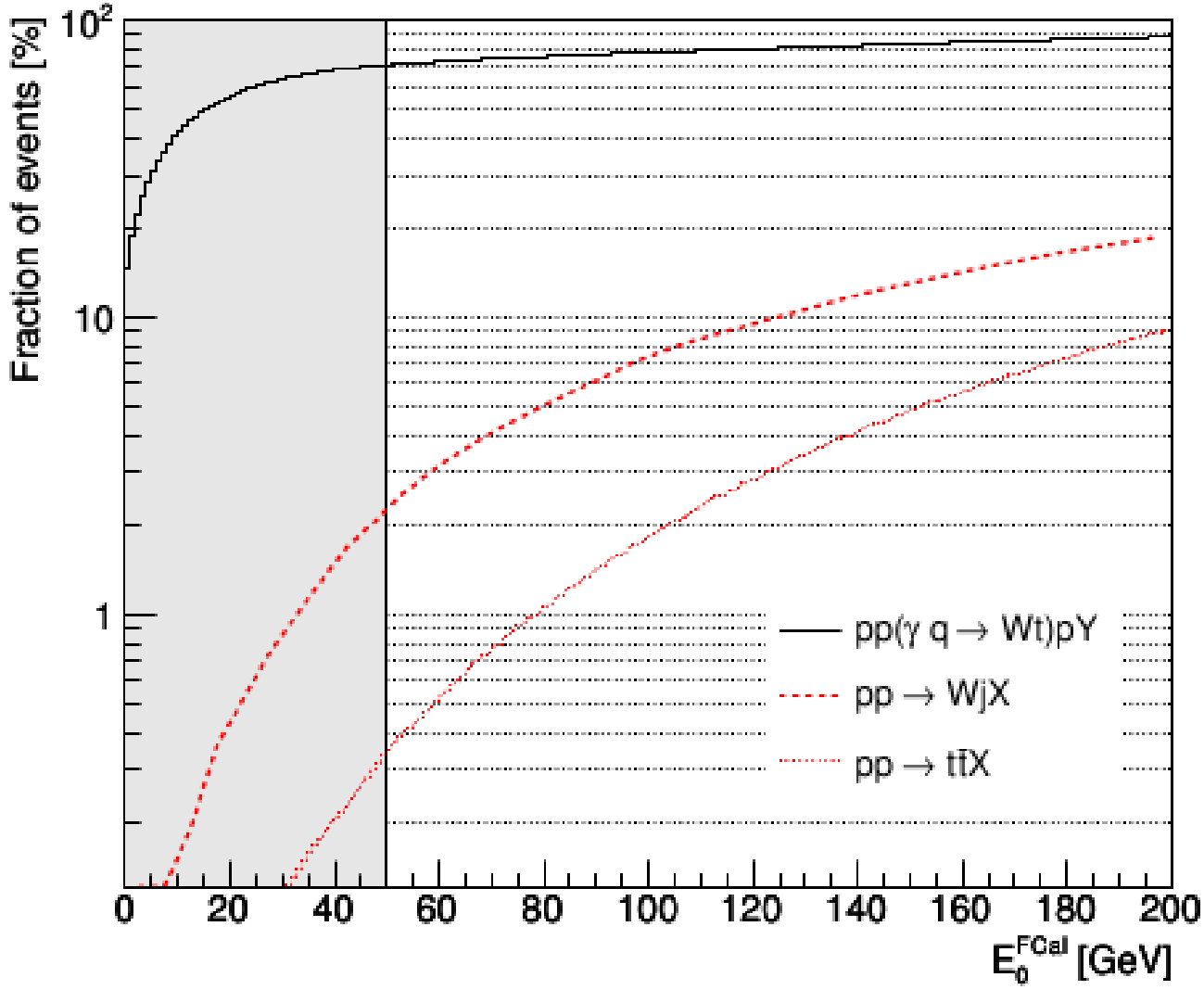
a) choose the « photon-side » minimum of energy in both fwd calos

b) cut on the maximum allowed value for this energy

Rapgap: region devoid of particles

Tagging γ-interactions

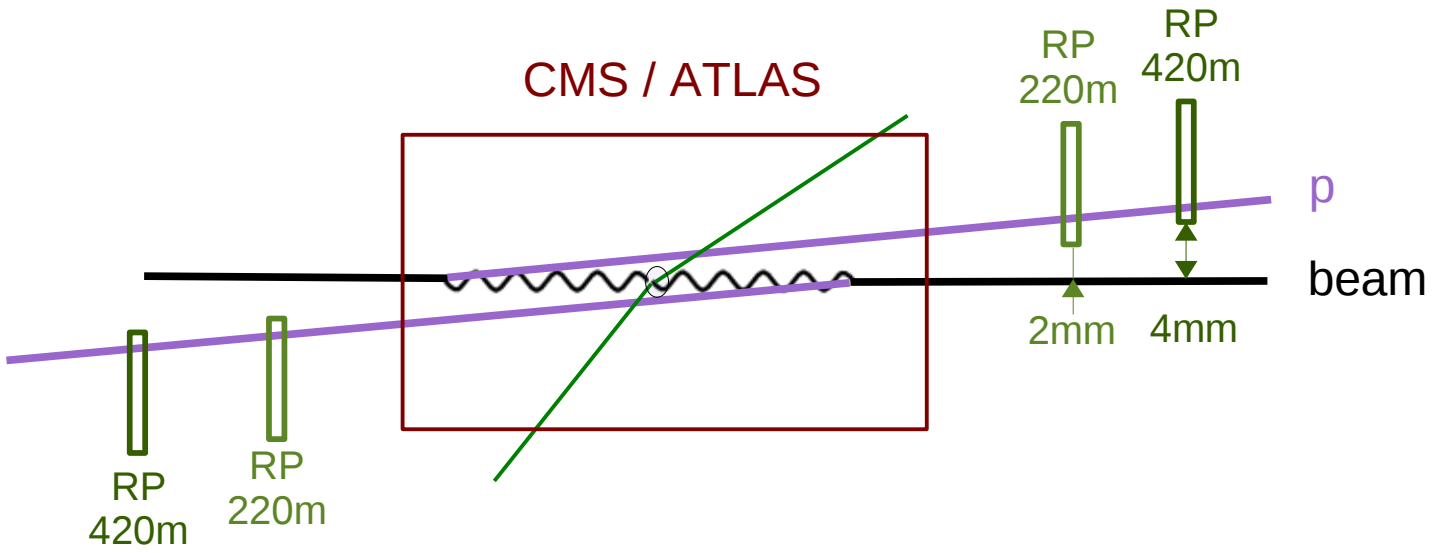
- Large Rapidity Gaps in forward region



S. Ovyn [Photon 2007 proc.], [TOP08 proc.]

Tagging γ-interactions

2) Using very forward proton taggers



a) The proton is scattered elastically

b) It escapes from the central detector with the beam, but with lower energy

c) It is seen by very forward detectors

Need for a realistic simulation of the proton path in the beamline

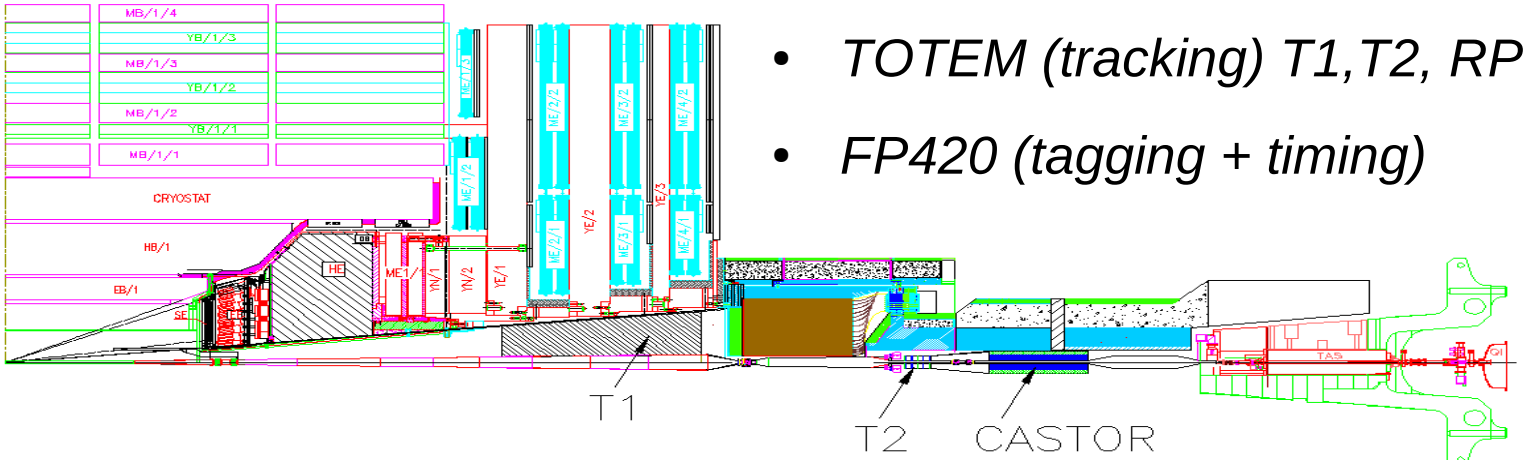
Forward detectors around IP5

Forward detectors around IP5

CMS tracking : $0 < |\eta| < 2.5$

CMS calorimetry : $0 < |\eta| < 5$

- CASTOR (calorimeter)
- ZDC (calorimeter)
- *TOTEM (tracking) T1,T2, RP*
- *FP420 (tagging + timing)*



CMS & TOTEM Coll [CERN/LHCC 2006-039/G-124]

Common physics programme for CMS + TOTEM

Joint data taking → nominal optics

Compatible TOTEM/CMS DAQ for trigger

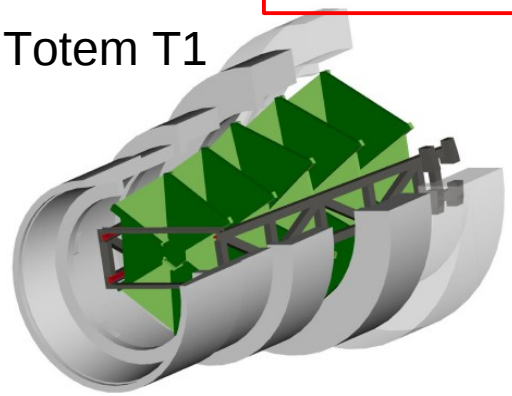
Forward detectors around IP5

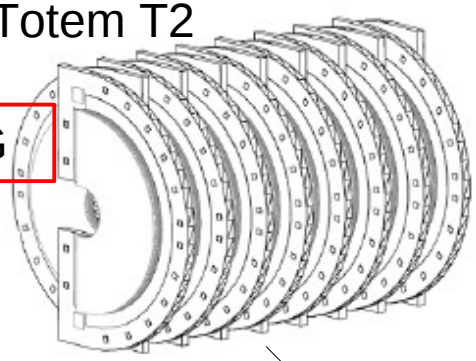
Totem T2

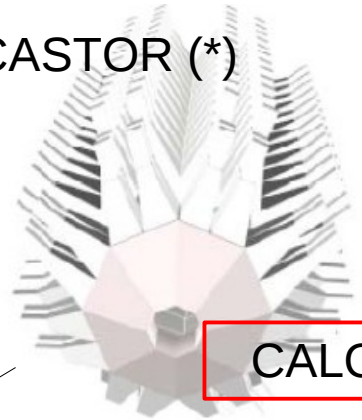
TRACKING

CASTOR (*)

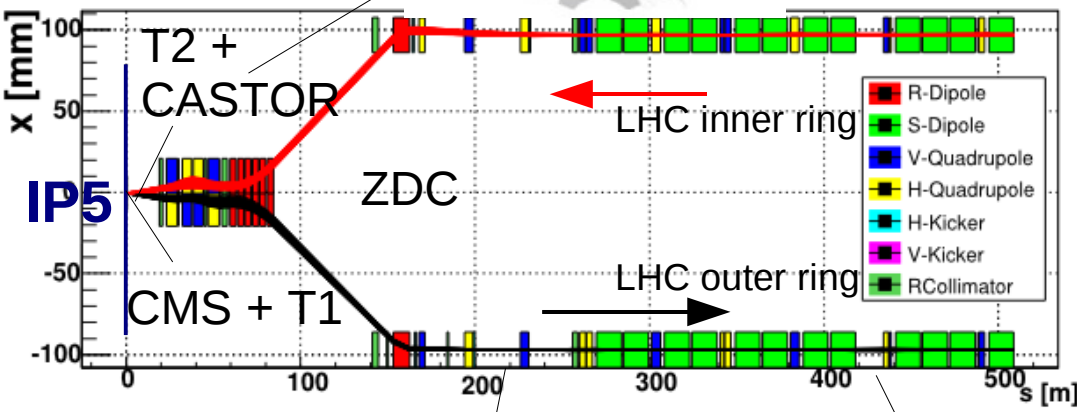
Totem T1



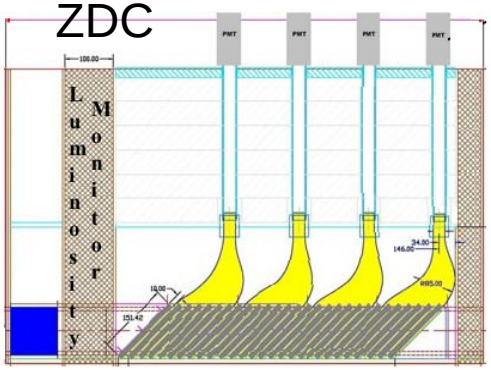




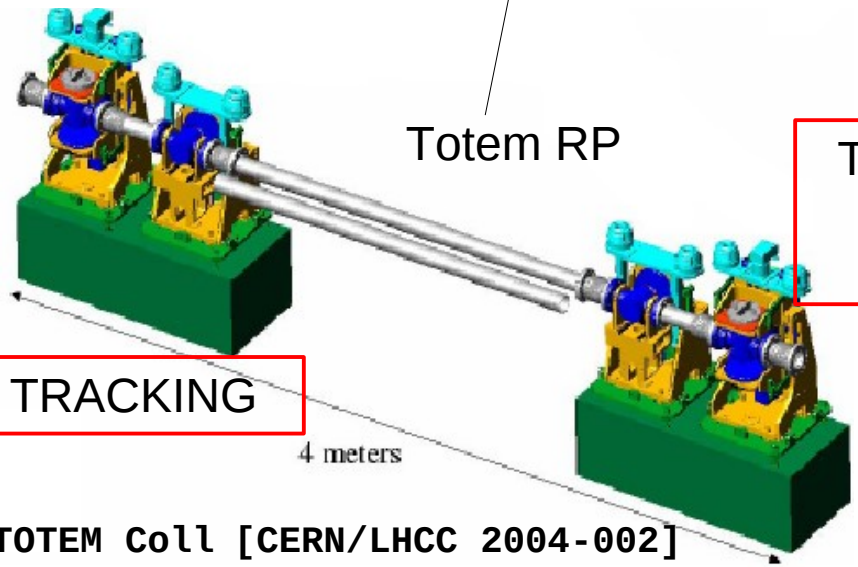
CALORIMETRY



ZDC



CALORIMETRY
neutrals



Totem RP

FP420

TRACKING
&
TIMING

TRACKING

CASTOR:
(*) First one installed in 2008
Second one in 2009 if funded

Physics programme

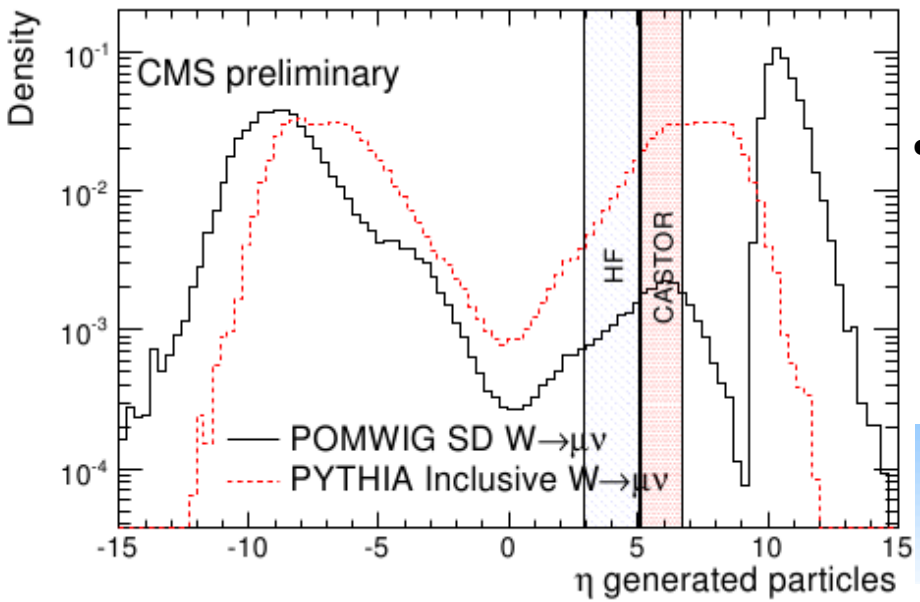
CMS & TOTEM Coll [CERN/LHCC 2006-039]

Possible at various LHC luminosities: already from start-up

Diffraction: SD+DPE

(dijets, W, Z, heavy flavours, SM & MSSM Higgs)

probe of the proton structure at low-x



CMS Coll [PAS DIF 07-002]

- Trigger studies with forward detectors included, as well as pile-up impact
- Hard diffraction program carried out, following HERA and Tevatron

→ Rapidity gap survival probability

→ Diffractive PDF

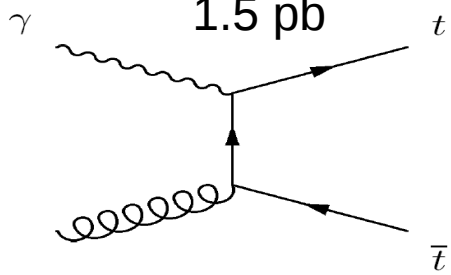
Physics programme

Photon-induced processes

- $\gamma\gamma$: lepton pairs, SUSY, WW and ZZ
- γp: Associated prod of W and H

  or single top ; anomalous top, ...

Top pair 1.5 pb

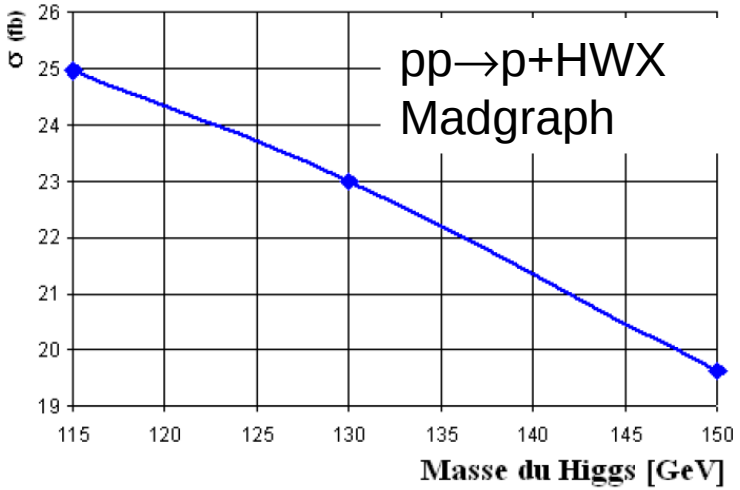


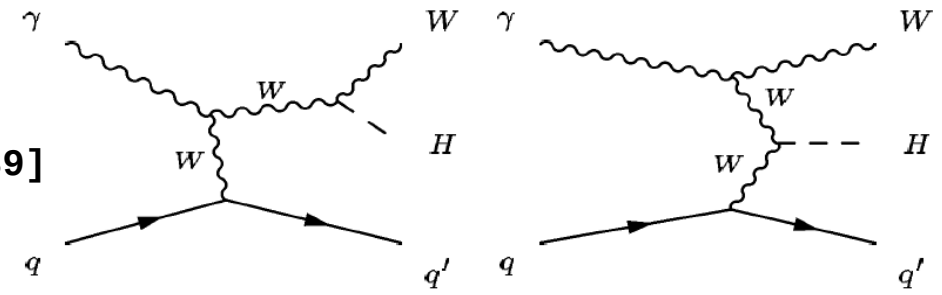
Equivalent Photon Approximation

$$\sigma_{pp} = \int \sigma(W_{\gamma\gamma}) \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} dW_{\gamma\gamma}$$

incoming γ flux

low γ virtuality (typical $q^2 \sim 0.01\,GeV^2$)





CMS & TOTEM Coll [CERN/LHCC 2006-039]

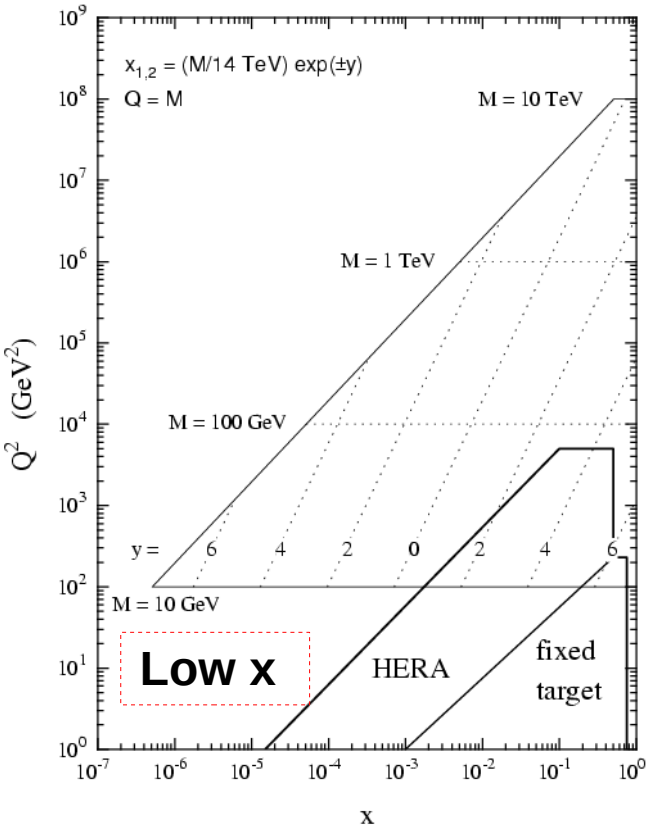
Physics programme

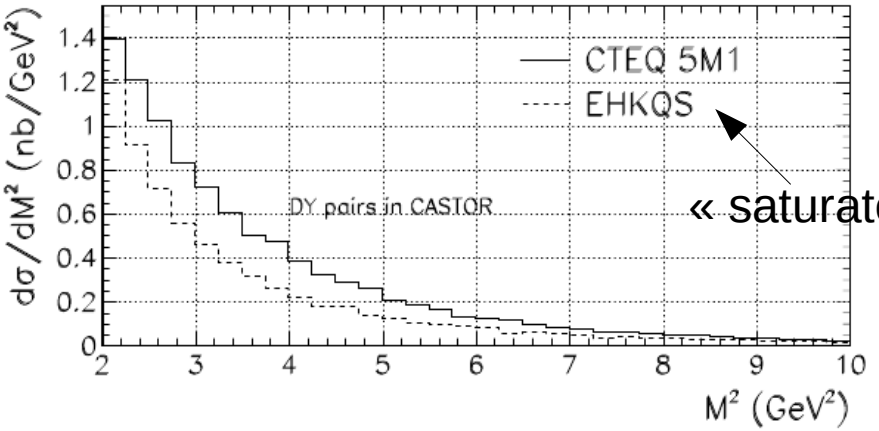
Low-x dynamics:

CMS & TOTEM Coll [CERN/LHCC 2006-039]

Parton saturation, BFKL/CCFM dynamics,
proton structure, multi-parton scattering

- Forward jets & Drell-Yan



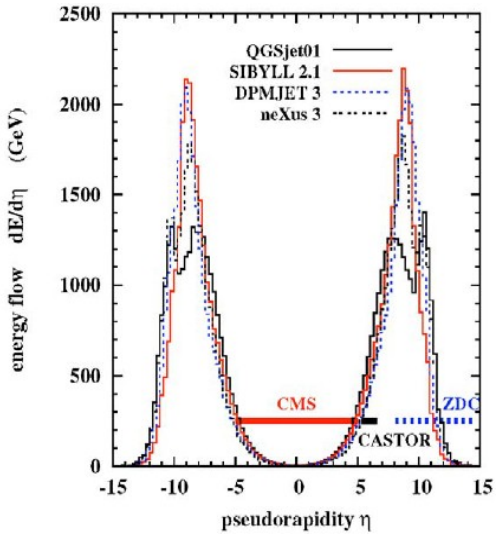


« saturated » pdf

Rapidity gaps

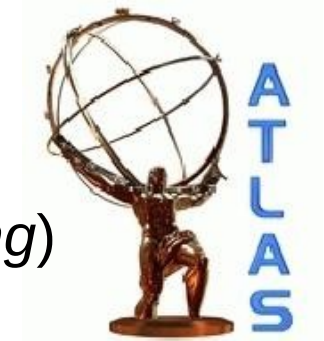
Cosmic rays

Forward energy and particle flows
→ underlying events
→ multiple interactions



Forward detectors around IP1

Forward detectors for ATLAS



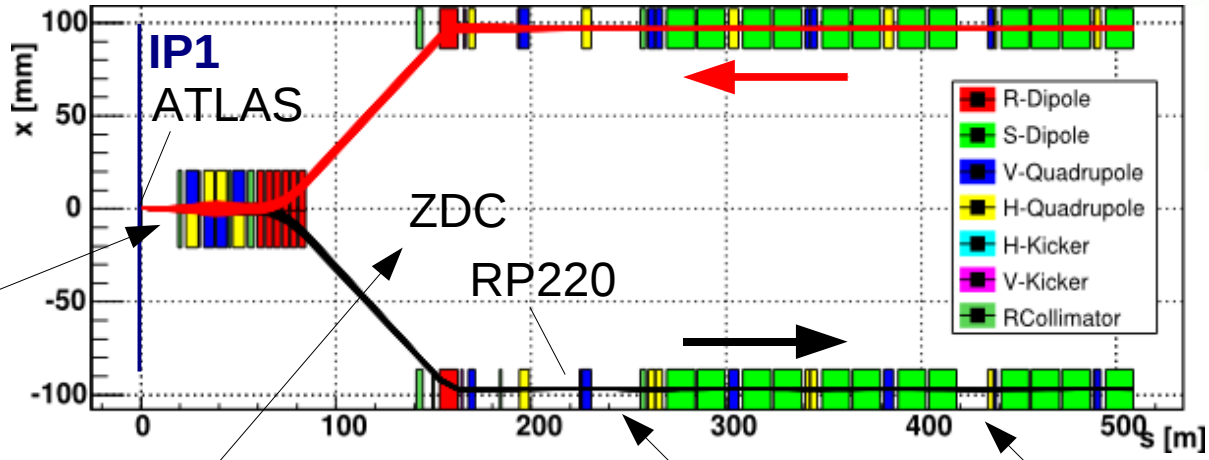
- LUCID: relative luminosity (*cerenkov*)
- ALFA: luminosity normalization, diffraction (*tracking*)
- ZDC: neutrals (*calorimeter*)
- Option: RP220 (*tracking*)
- Option: FP420 (*p tagging*)
- *LHCf (calorimeter)* *Independent experiment*

Luminosity measurement
→ ALFA
→ LUCID

Forward neutrals
→ ZDC

Forward detectors for ATLAS

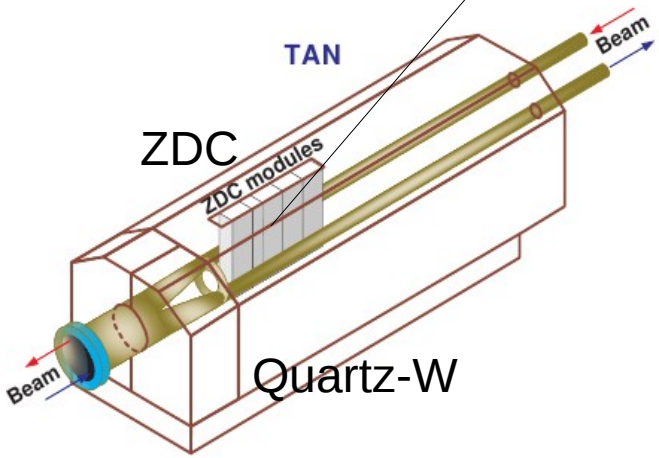
Adapted from
Rouby, de Favereau, Piotrzkowski [JINST 2 P09005]



LUMI

LUCID

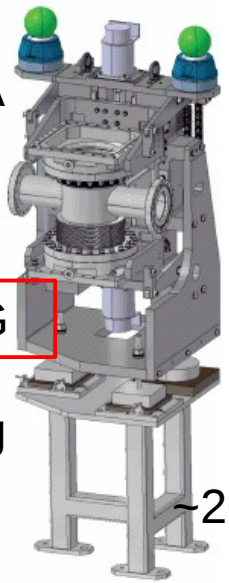
Cerenkov



ZDC

Quartz-W

CALORIMETRY
neutrals



ALFA

TRACKING

Scintillating fibers

~2009

FP420

Si + Cerenkov

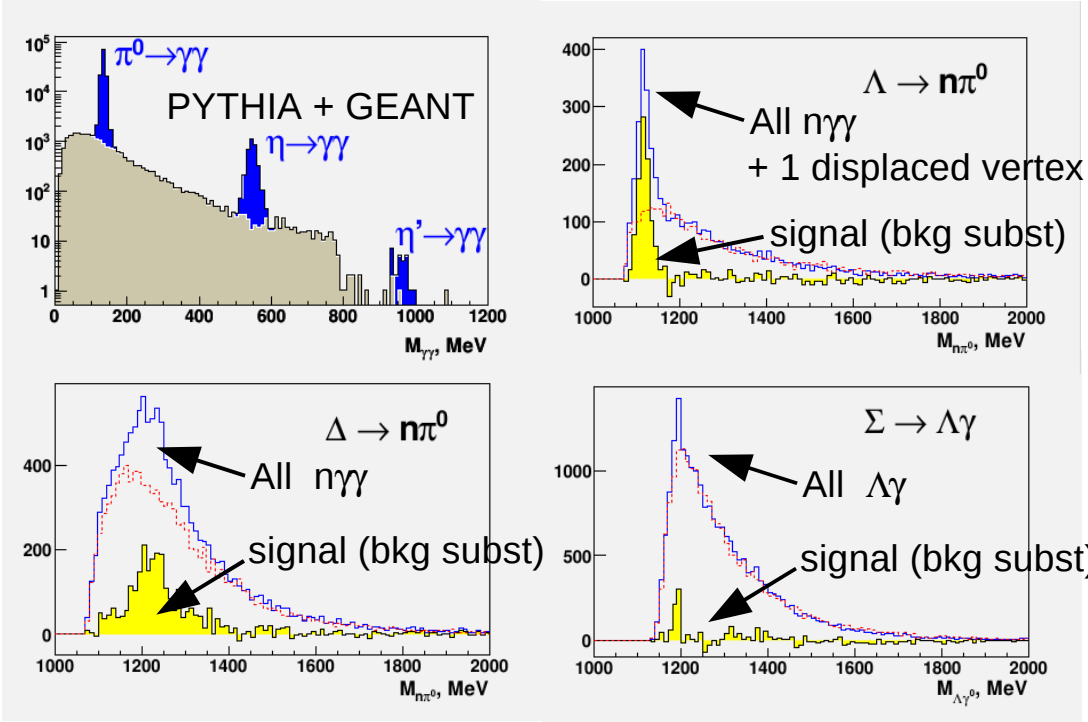
TRACK & TIMING

~2010

ZDC

Zero Degree Calorimeter

Reconstruction of π^0, η, η', Δ, Σ, Λ



- Quartz (fibers) tungsten sampling calo
- $|\eta| > 8.1$ for n & γ ;
- 140 m from IP1

pp programme, but also in AA

ATLAS Coll. [CERN/LHCC/2007-001]

LUCID

LUminosity measurement using a Cerenkov Imaging Detector

- Dedicated luminosity monitors
- Cerenkov counters
- 5.4 < |η| < 6.1 ; 17m from IP1
- 5 rings of 40 tubes (1.5 m long)

Dedicated luminosity monitors

Counts tracks from

minbias,

diffractive events,

...

ATLAS Coll. [CERN/LHCC/2007-001]

ALFA

Absolute Luminosity For ATLAS

Roman pots at 237 m from IP1 – tracking with scintillating fibers

Elastic scattering parameters

- 1st) Measurement of luminosity in optimal conditions: goal ~3%
- 2nd) Calibration of lumi monitors

Measurement of the total cross section

Study hard diffraction in nominal optics runs in conjunction with main ATLAS detector and proton taggers possibly after upgrade of ALFA

Luminosity from Coulomb scattering

$$\frac{dN}{dt} = L\pi\left|f_C + f_N\right|^2 \approx L\pi\left|-\frac{2\alpha}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2}\right|^2$$

Elastic rate measurement & Fit of this distribution } Lumi

Luminosity from optical theorem

$$\frac{1}{L} = \frac{1}{16\pi}\frac{\sigma_{tot}^2(1+\rho^2)}{dR_{el}/dt}\bigg|_{t=0}$$

Relies on total cross section

TOTEM @ CMS : also measuring σ_{tot} and calibrating lumi

RP220 : possible radiation hard upgrade of ALFA

R&D program with ATLAS and CMS contribution: FP420

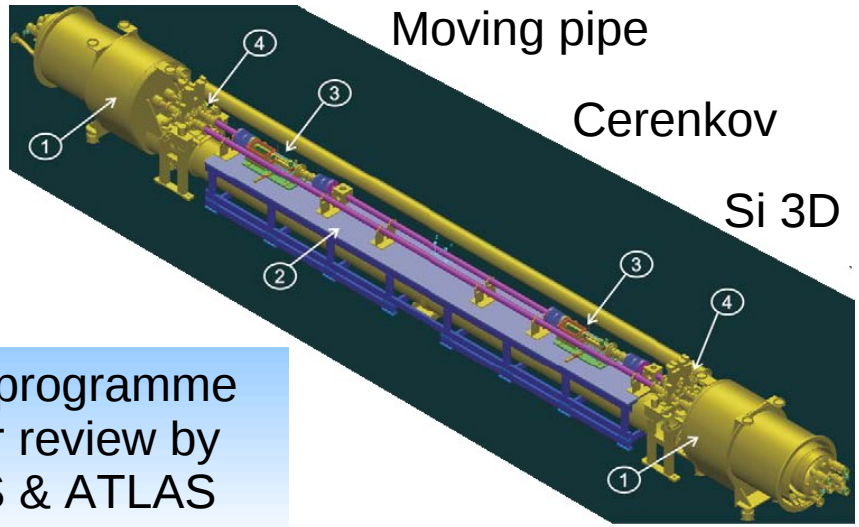
Common R&D: FP420

Proton tagging at 420 m from IP5 or IP1

Common R&D for CMS & ATLAS coll

Installation ~ 2010

Discovery physics



CERN-LHCC-2005-025

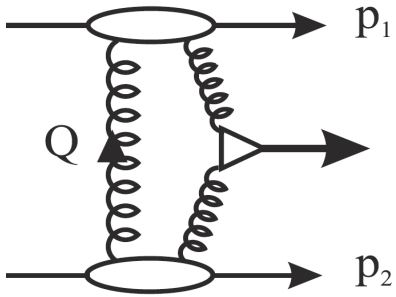
Central Exclusive productions:

Higgs or BSM particles
Higgs production pp → p H p
~ 3 fb (SM)
~ 10-100 fb (MSSM)

R&D programme under review by CMS & ATLAS

Missing mass method

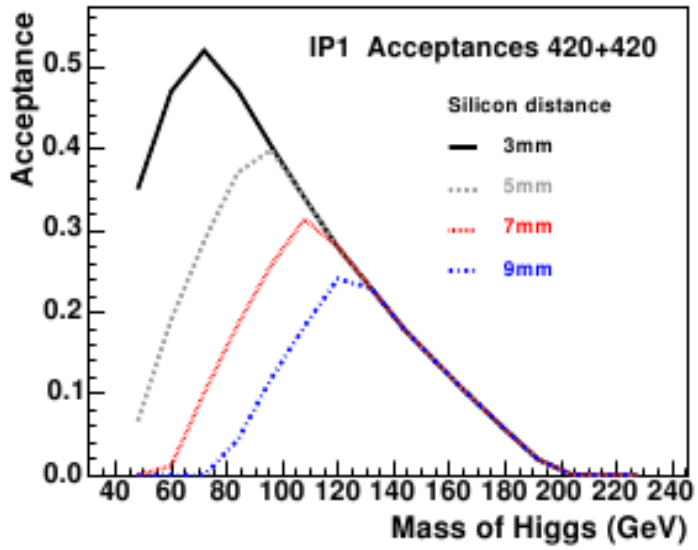
$$M^2 = \xi_1 \xi_2 s$$



p_1 Proton taggers

Central detector

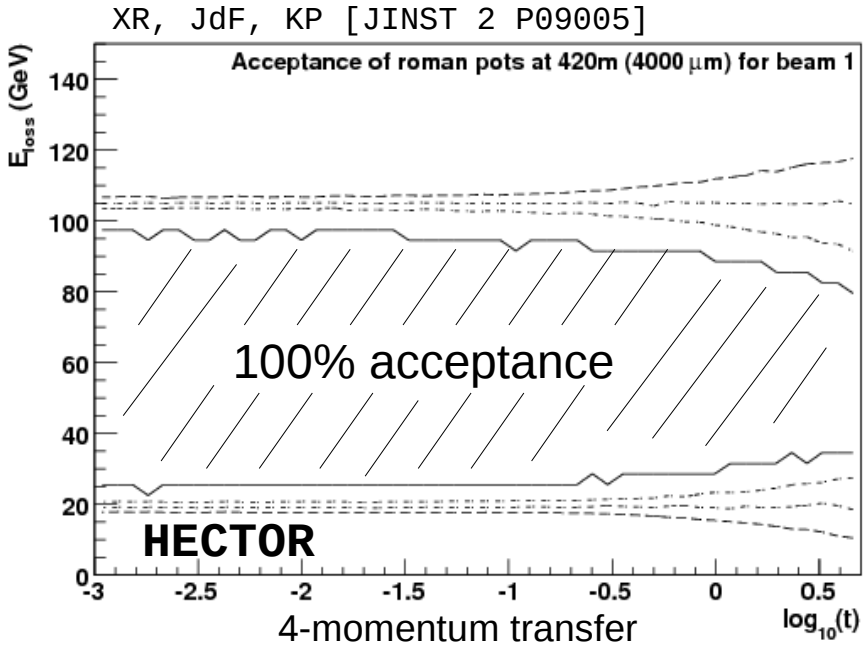
p_2 Proton taggers



Simulation of particle transport in beamlines: Hector and FPtrack

Transport simulation

- Needed for
  - forward detector characterisation
  - signal reconstruction
  - background analysis / rejection



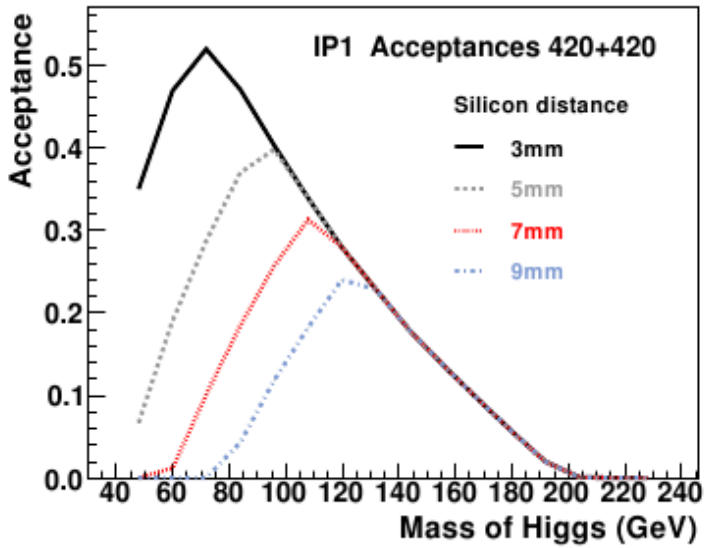
Hector, X. Rouby, J. de Favereau, K. Piotrzkowski

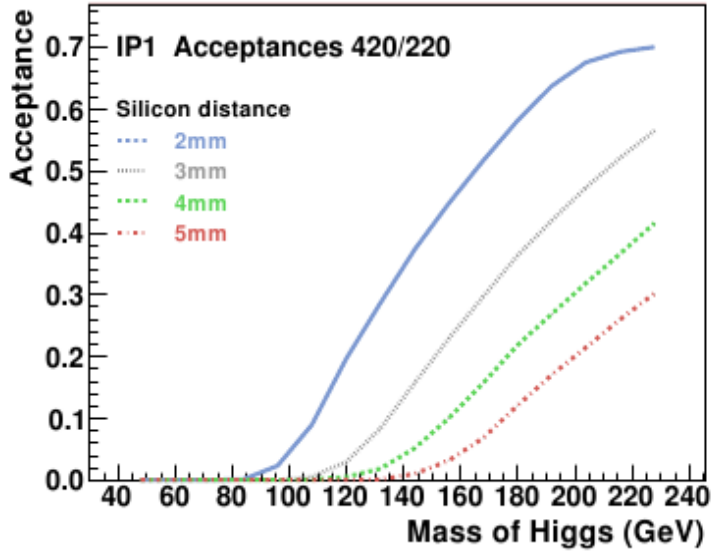
FPtrack, P. Bussey

Transport simulation

FPtrack

Central Exclusive Production pp -> p H p



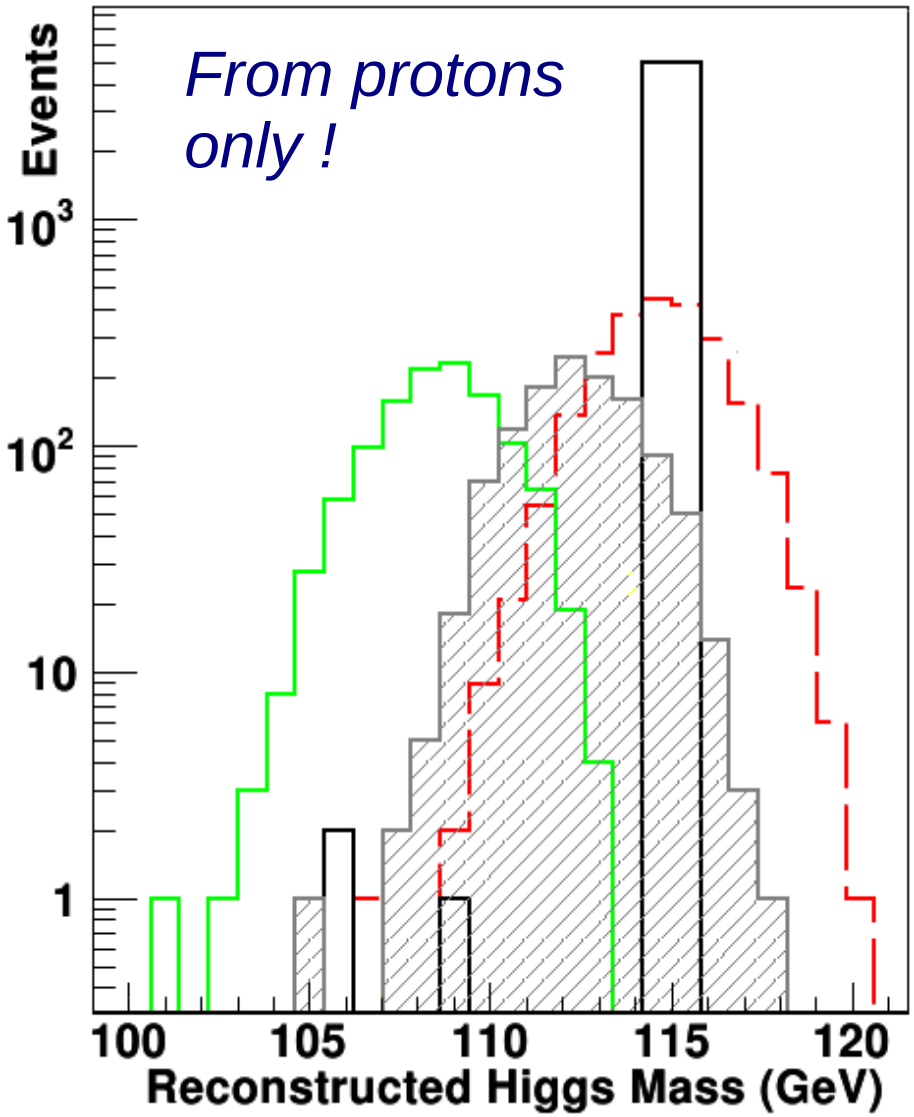


- Characterising CEP Higgs
  - Signal acceptance with respect to the detector position
  - Mass resolution

Transport simulation

$pp(\gamma\gamma \rightarrow H)pp$

Impact of beamline misalignment



Missing mass

- Generator Level
- Bare transport with ideal beamline
- 1 Misaligned quadrupole MQXA.1R5 by 0.5mm
- 1 Misaligned quadrupole + perfect knowledge of beam position at 420m

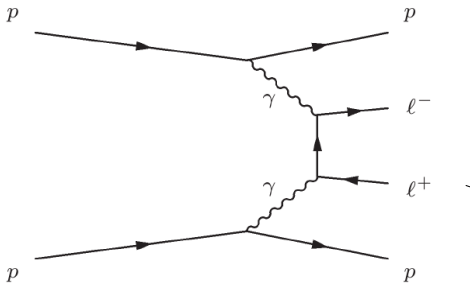
- Clear bias
- Visible beamline aperture effect

Early forward physics

Exclusive dimuons

LHC as a photon collider photon – photon interactions

$pp(\gamma\gamma \to \mu^+\mu^-)pp$



Large well known cross section (QED)

Very clean final state

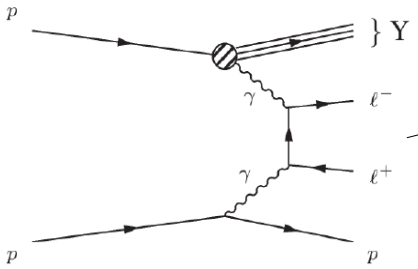
photon-photon (LPAIR)

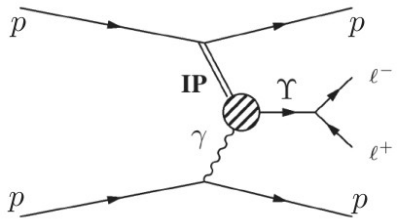
– no cut:
1.47 x 10^8 fb (elastic)

– p_T > 2.5 GeV
74.7 x 10^3 fb (elastic)

– p_T > 2.5 GeV
76.2 x 10^3 fb (inelastic)

Similar final states:





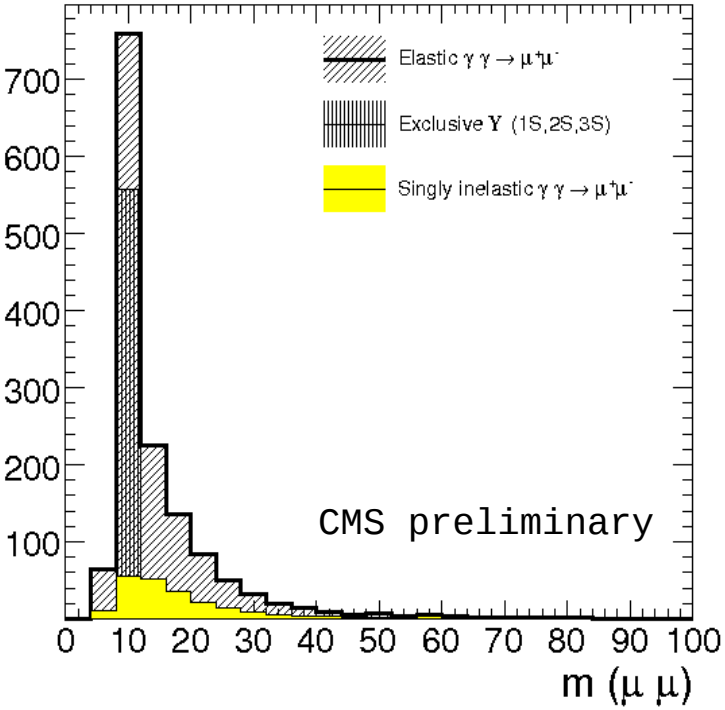
Upsilon (Starlight)

Y(1S) 39 x 10^3 fb
Y(2S) 13 x 10^3 fb
Y(3S) 10 x 10^3 fb

Exclusive Y photoproduction

Exclusive dimuons

JJ Hollar, S Ovyn, X Rouby
CMS PAS DIF-07-001



Overall selection

* p_T and $\Delta\phi$ balance
* calorimetric and tracking exclusivities

« *inelastic* » = one proton dissociates
« *with veto* » = dissociation product seen by one of the forward detectors

$$N_{elastic}(\gamma\gamma \to \mu^+\mu^-) = 709 \pm 27(stat)$$
$$N_{inelastic}(\gamma\gamma \to \mu^+\mu^-) = 636 \pm 25(stat) \pm 121(model)$$

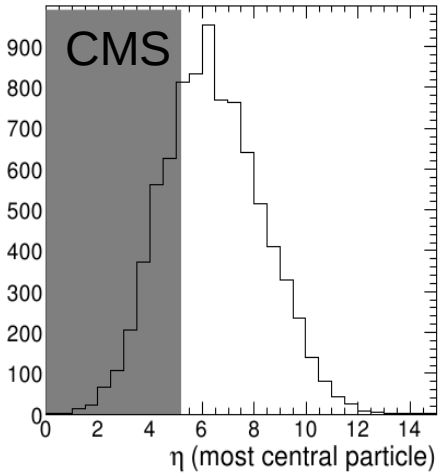
For an integrated luminosity L=100 pb^{-1}, without pile-up

Exclusive dimuons

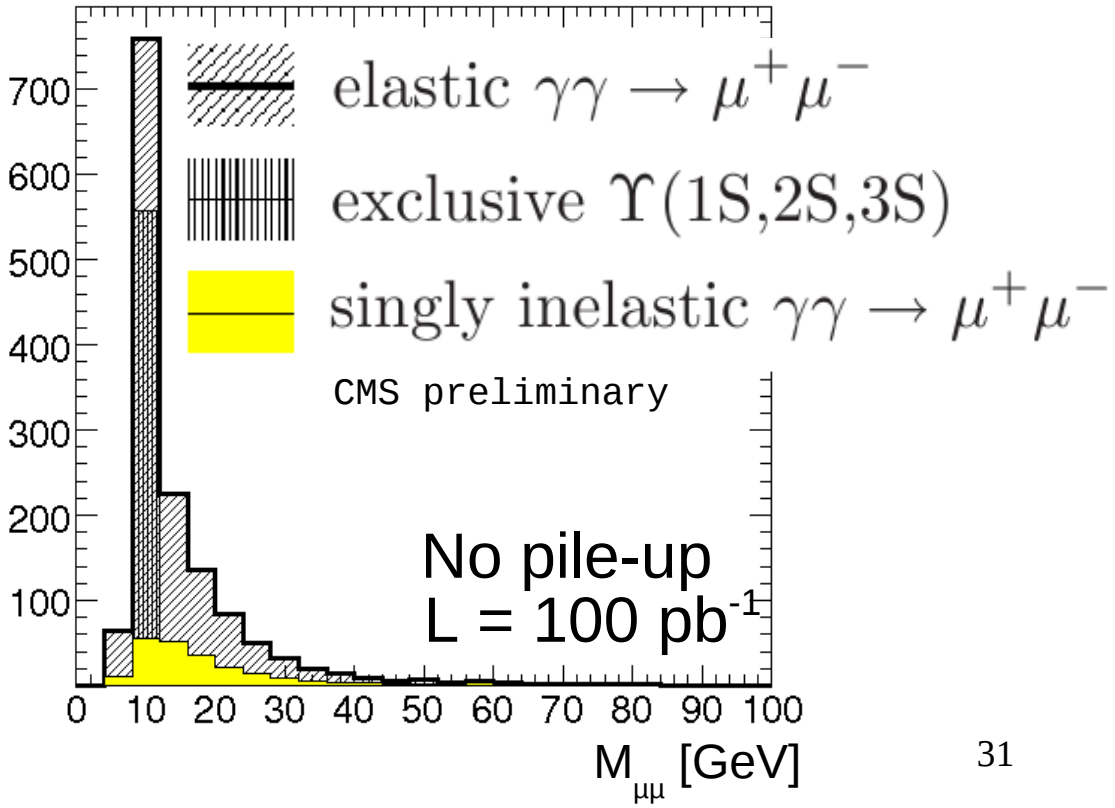
After 100 pb^{-1} :

CMS Coll. [CMS PAS DIF-07-001]

$$N_{elastic}(\gamma\gamma \to \mu^+\mu^-) = 709 \pm 27(stat)$$
$$N_{inelastic}(\gamma\gamma \to \mu^+\mu^-) = 636 \pm 25(stat) \pm 121(model)$$



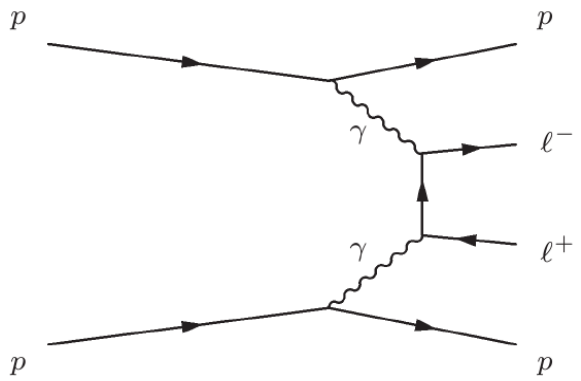
$$N^{w/veto}_{inelastic}(\gamma\gamma \to \mu^+\mu^-) = 223 \pm 15(stat) \pm 42(model)$$



Using CASTOR & ZDC to veto inelastic events

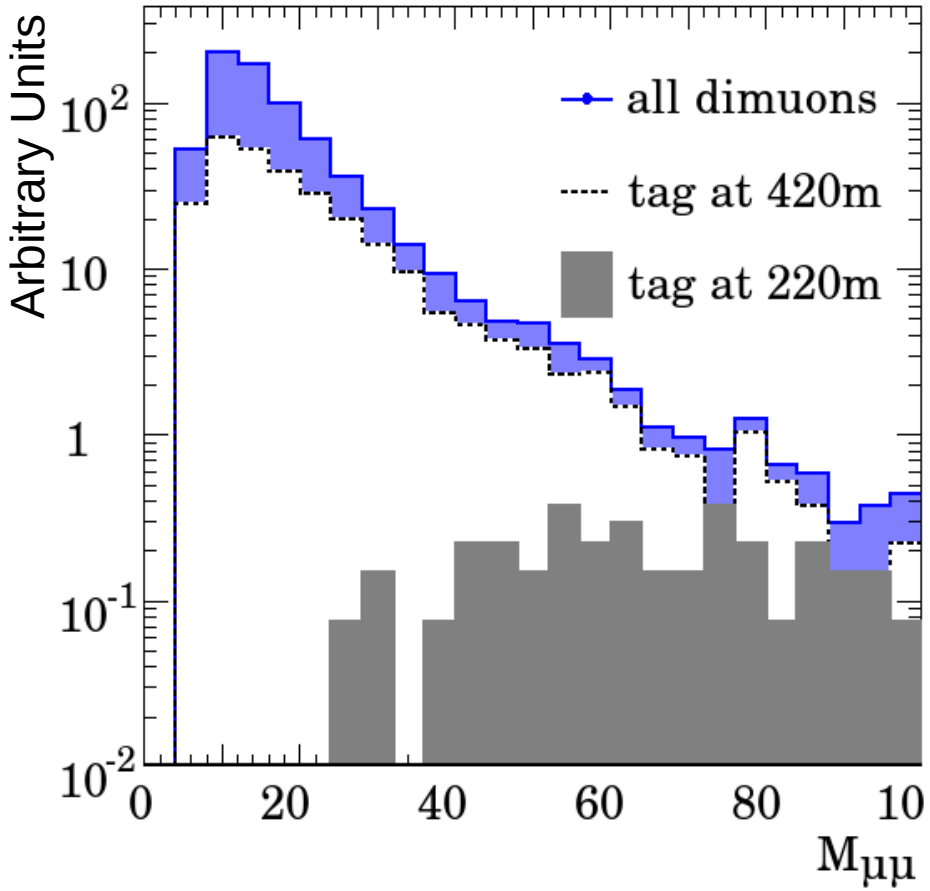
- **Luminosity normalization ~ 4%**
- **Forward detector calibration**

Exclusive dimuons



1) Measuring both muons in central detector

2) Tagging at least one proton

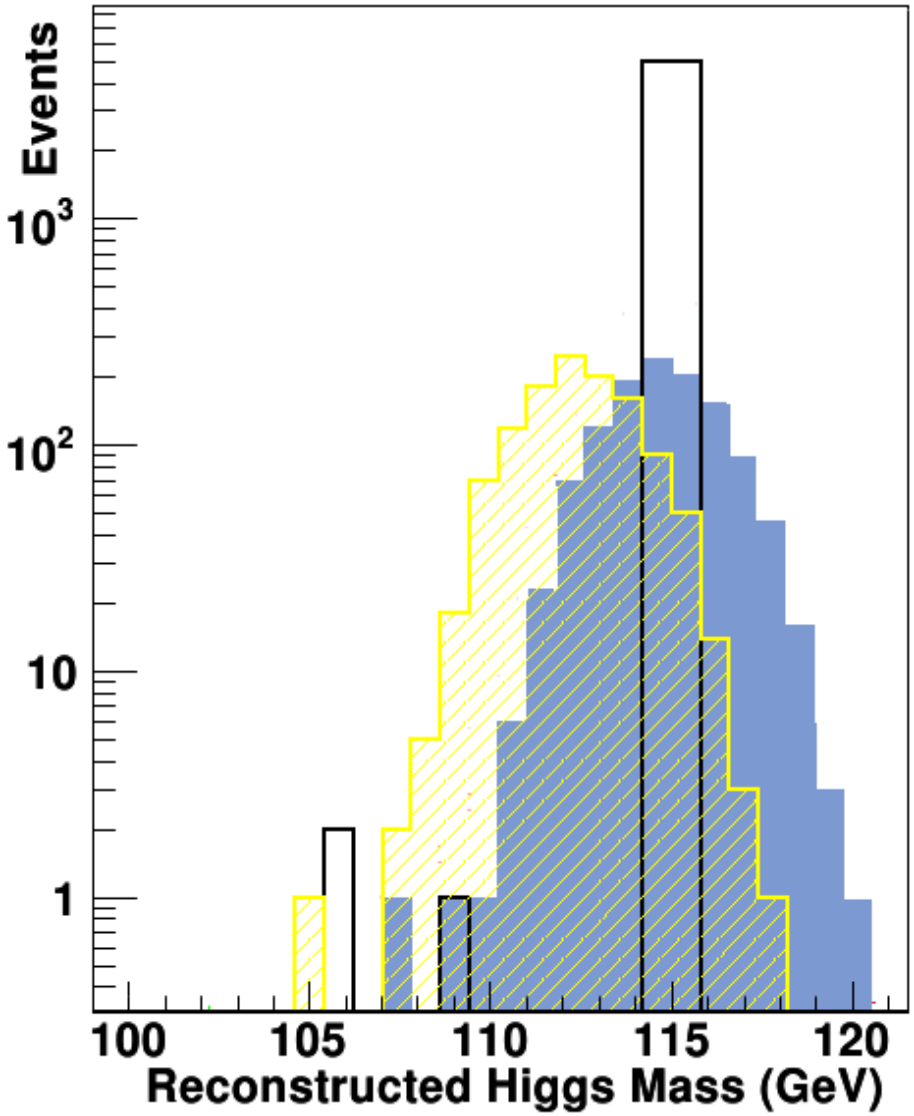


Most of the selected exclusive muon pairs have a proton within forward detector acceptance !

Transport simulation

$pp(\gamma\gamma \rightarrow H)pp$

Impact of beamline misalignment



Missing mass

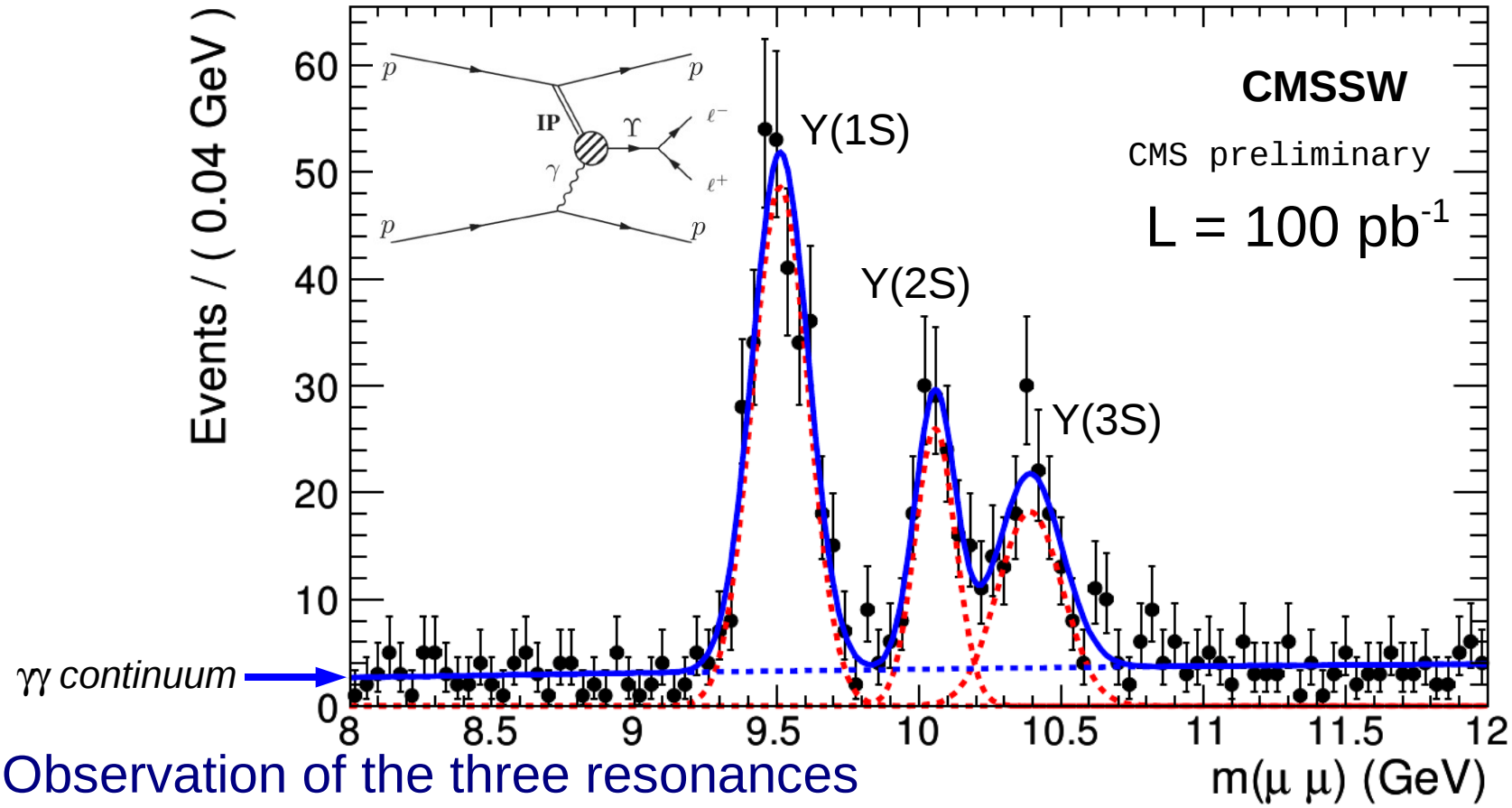
- Generator level
- 1 Misaligned quadrupole + perfect knowledge of beam position at 420m
- Using dimuon data for FP420 calibration

No more bias

Calibration based here on 700 dimuon events ($100pb^{-1}$)

Upsilon: measurement

Selection of the dimuon pairs as for $\gamma\gamma$ events



CMS Coll. [CMS PAS DIF-07-001]

Observation of the three resonances

- cross section measurement
- low p_T track calibration
- detector alignment
- sensitivity to t distribution slope

Conclusions

ATLAS / CMS + forward detectors:
largest η coverage ever

Dedicated instrumentation:
CMS : CASTOR/ZDC + TOTEM + FP420
ATLAS: LUCID/ZDC/ALFA +RP220/FP420

Many different fields covered by forward physics:

- low-x QCD
- exclusive QED
- Higgs/SUSY/BSM

Some References

Forward Physics

at the LHC : D. d'Enterria [hep-ex/0708.0551], X. Rouby [CMS CR-2008/020]
at IP5 : CMS & TOTEM Coll [CERN/LHCC 2006-039/G-124]
at IP1 : ATLAS Collaboration [CERN/LHCC 2007-001],
ATLAS Collaboration [CERN/LHCC 2008-004]
FP420 : M. G. Albrow et al. [CERN/LHCC 2005-025], ...

Photon Physics

K. Piotrzkowski, Phys. Rev. D63 (2001) 071502, hep-ex/0009065.
K. Piotrzkowski et al, High energy photon interactions at the LHC,
to be submitted to EPJ
S. Ovyn, Photon 2007, TOP 2008 proceedings

Particle transport software

Hector : Rouby, de Favereau, Piotrzkowski [JINST 2 P09005],
arXiv:0707.1198v2 [physics.acc-ph]
FPTrack : P. Bussey, http://ppewww.physics.gla.ac.uk/~bussey/FPTRACK

Early Measurements at LHC

Exclusive production of leptons in CMS:
J. Hollar, S. Ovyn, X. Rouby, [CMS PAS DIF-07-001], [CMS AN-2007/032]

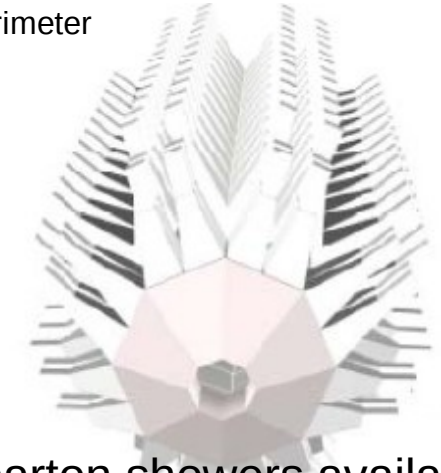
Single diffractive production of W:
M. Arneodo, A. Vilela Pereira, [CMS PAS DIF-07-002], [CMS AN-2007/033]

Back-up slides

CASTOR

Centauro And Strange Object Research

- Quartz tungsten sampling calorimeter
- 5.25 < |η| < 6.5
- 14.38m from IP
- 0.65m long cylinder
- 0.36m diameter
- Separate EM + HAD units



enhances CMS hermiticity

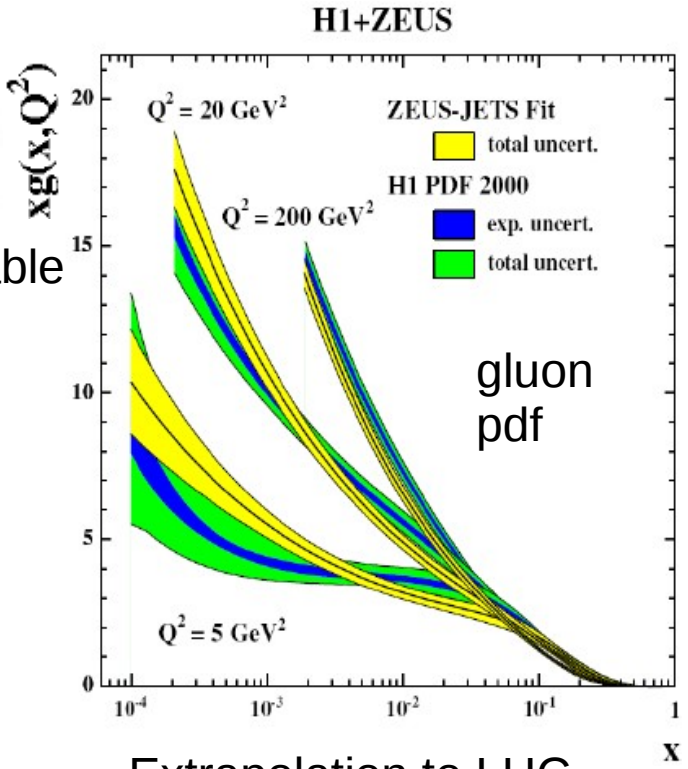
Access to low-x

→ multiple descriptions of parton showers available
→ distinction possible with CASTOR ?
→ study of underlying events

Constraining cosmic ray MC models

Drell Yann events

Forward jets ; Energy flow ; rap-gap veto



gluon pdf

Extrapolation to LHC ranges ?

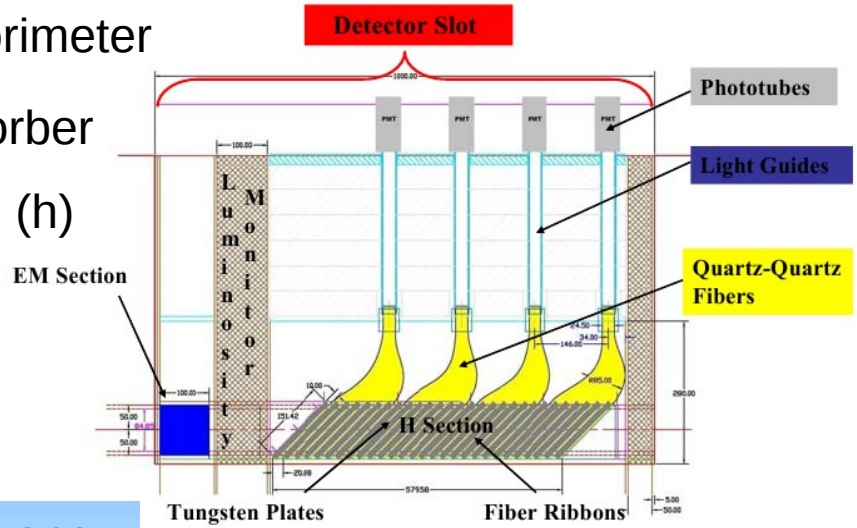
1 CASTOR installed in 2008
a second one later if fundings are ok

Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

ZDC

Zero Degree Calorimeter

- Quartz (fibers) tungsten sampling calorimeter
  - 140m from IP in TAN neutral absorber
  - 1000mm (l) x 96mm (w) x 607mm (h)
- |η| > 8.1 neutrons ; photons
- Separate EM + HAD sections



Contribution to the evaluation of rapidity gaps
- pomeron induced physics
- veto condition for proton dissociation

Energy flow in forward region

Forward physics

Complementary measurement for
- luminosity calibration of online monitors
- beam crossing angle

Accelerator physics

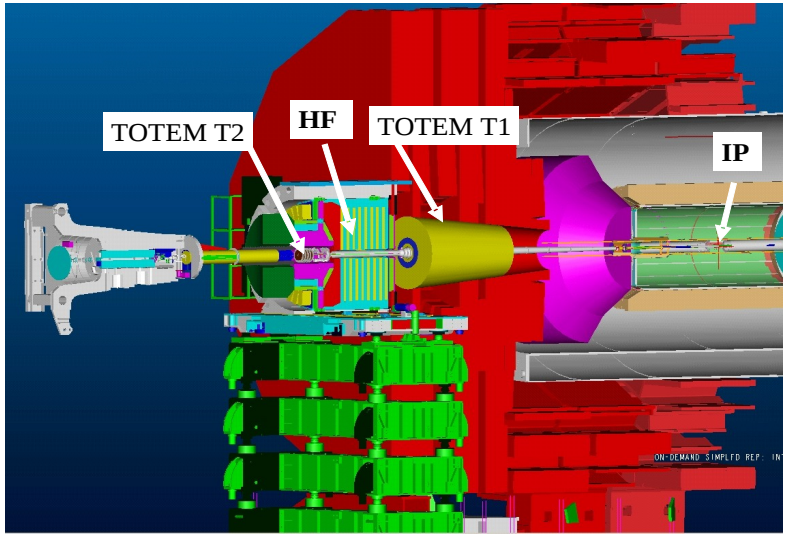
Cosmic ray physics
Heavy ion physics

Already installed

Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

TOTEM

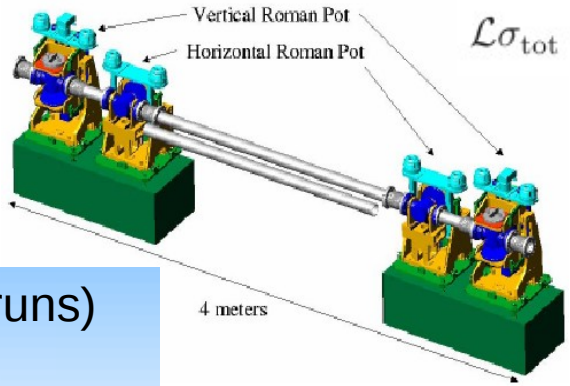
TOTEM: T1 $3.1 < \eta < 4.7$
TOTEM T2 $5.3 < \eta < 6.7$
RP : $100 < \xi < 1000$



Totem T1 : in front of HF, 7.5m from IP, Cathode Strip Chambers, 2.8m long, 5 planes of CSC

Totem T2 : in front of CASTOR, 13.6m from IP, Gas Electron Multiplier sensors

Totem RP: Roman Pots at (147&149)m and (216&220)m, edgeless Si microstrip



$$\mathcal{L}\sigma_{\rm tot} = N_{\rm el} + N_{\rm inel}$$

- Total LHC cross section (dedicated LHC runs)
- Luminosity normalization
- Diffraction programme

$$Im\big[f(\theta = 0)\big] = \frac{q}{4\pi}\sigma_{\rm tot}$$

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

Backup
- CASTOR
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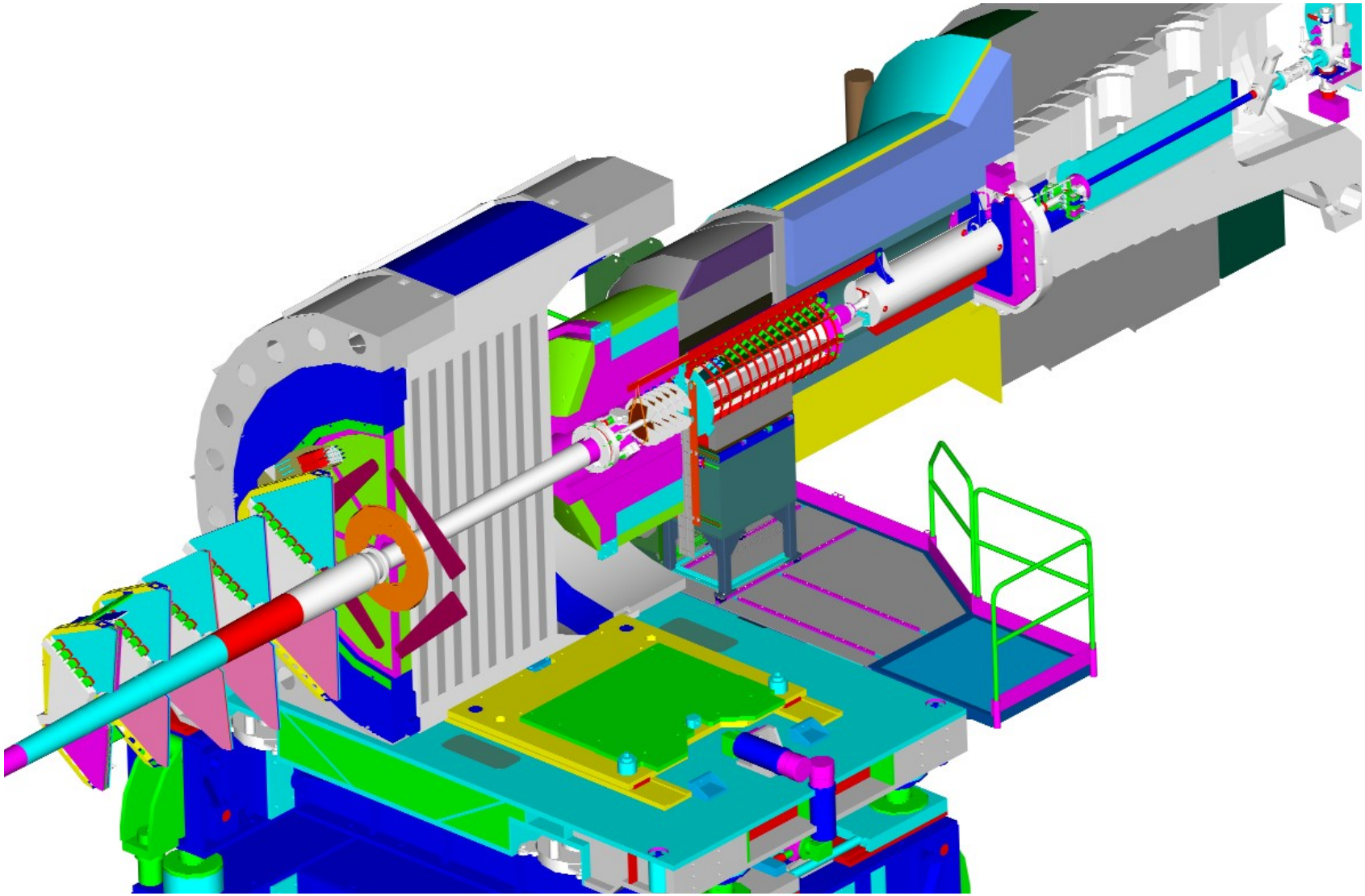
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

CASTOR + TOTEM



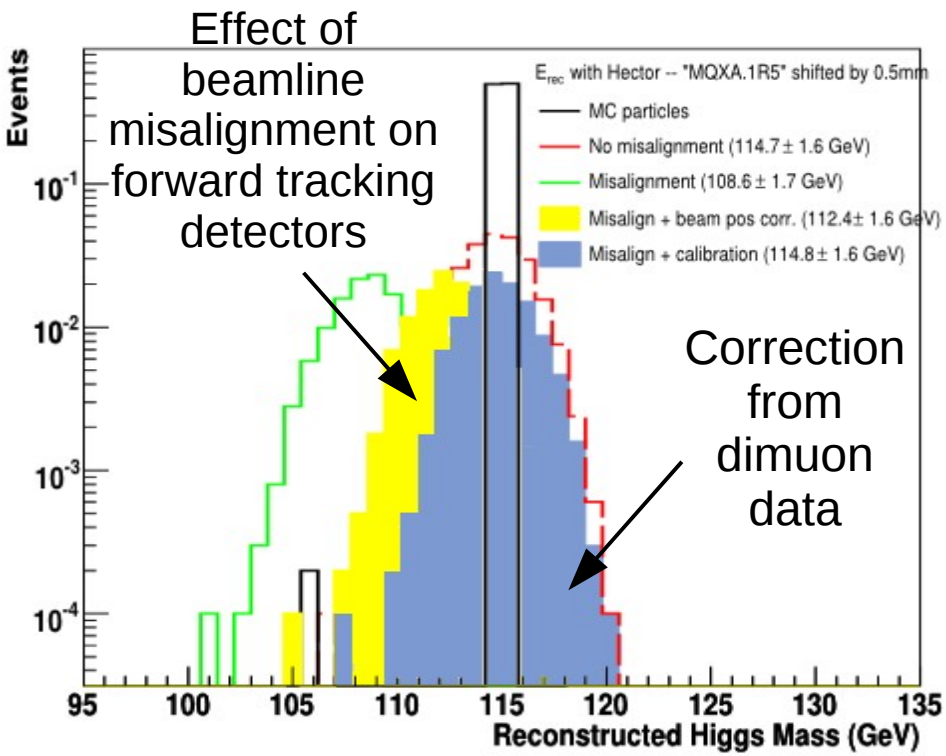
Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

Exclusive dimuons

- Applications
  - Luminosity normalization: offline calibration of lumi monitors
    - Low reducible background
    - Irreductible (inelastic) background manageable
  - Forward detector calibration+ alignment

Rouby, de Favereau, Piotrzkowski
[JINST 2 P09005]

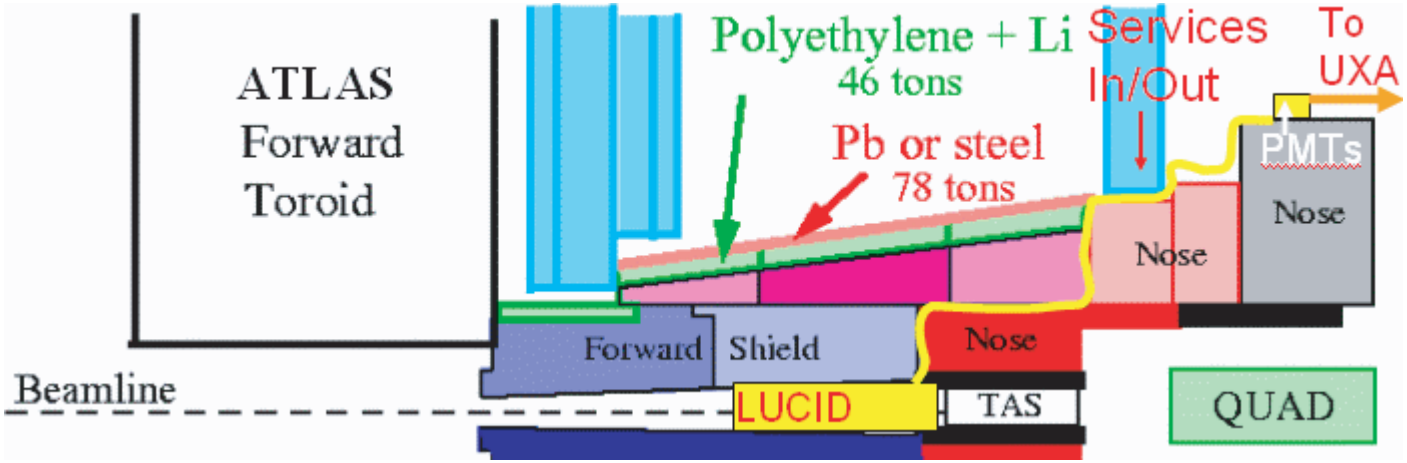
$$pp(\gamma\gamma \to H)pp$$



Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

LUCID

- LUminosity measurement using a Cerenkov Imaging Detector
  - Dedicated luminosity monitors
  - Cerenkov counters
  - 5.4 < |η| < 6.1 ; 17m from IP1
  - 5 rings of 40 tubes (1.5 m long)
  - Counts tracks from minbias, diffractive events, ...

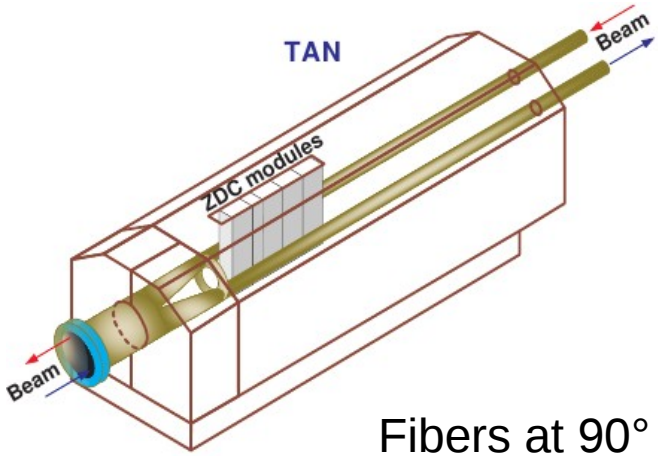


ATLAS Collab. [CERN-LHCC/2004-010]

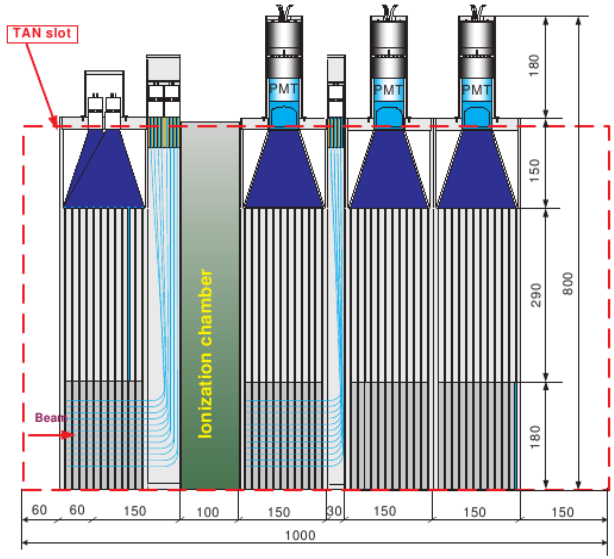
ZDC

Zero Degree Calorimeter

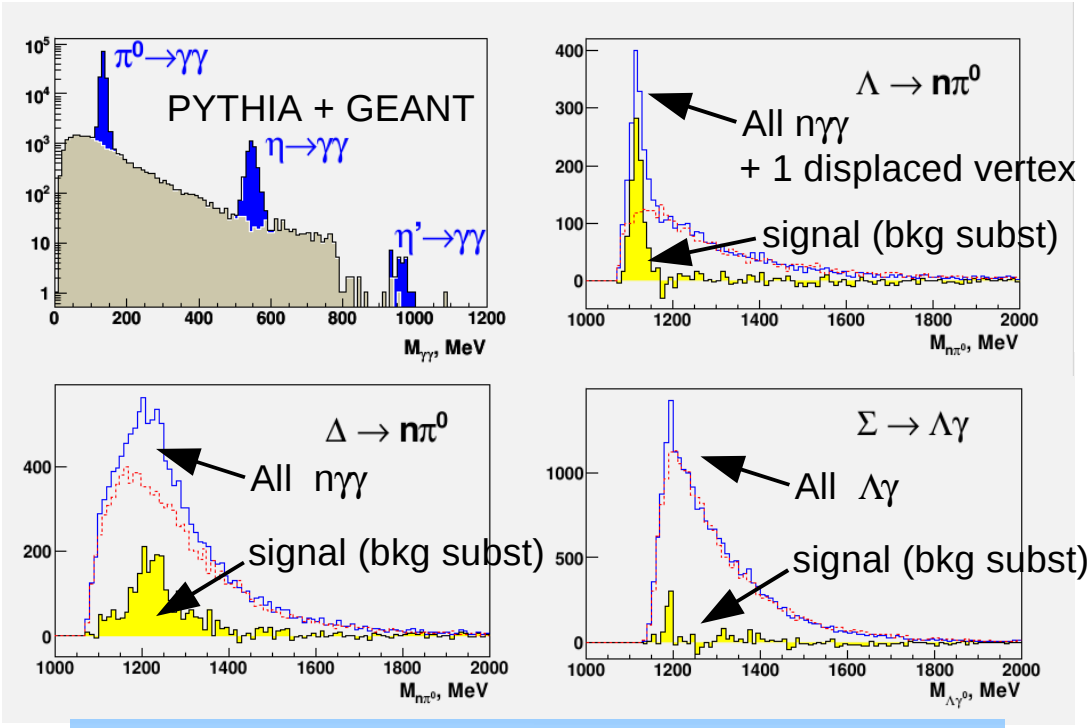
- Quartz (fibers) tungsten sampling calorimeter
- |η| > 8.1 neutrons & photons
  - 140 m from IP in neutral absorber
  - 850 mm (l) x 91mm (w) x 620mm (h)



Fibers at 90°



EM + HAD



Reconstruction of π^0, Λ, ...

pp programme, but also in AA

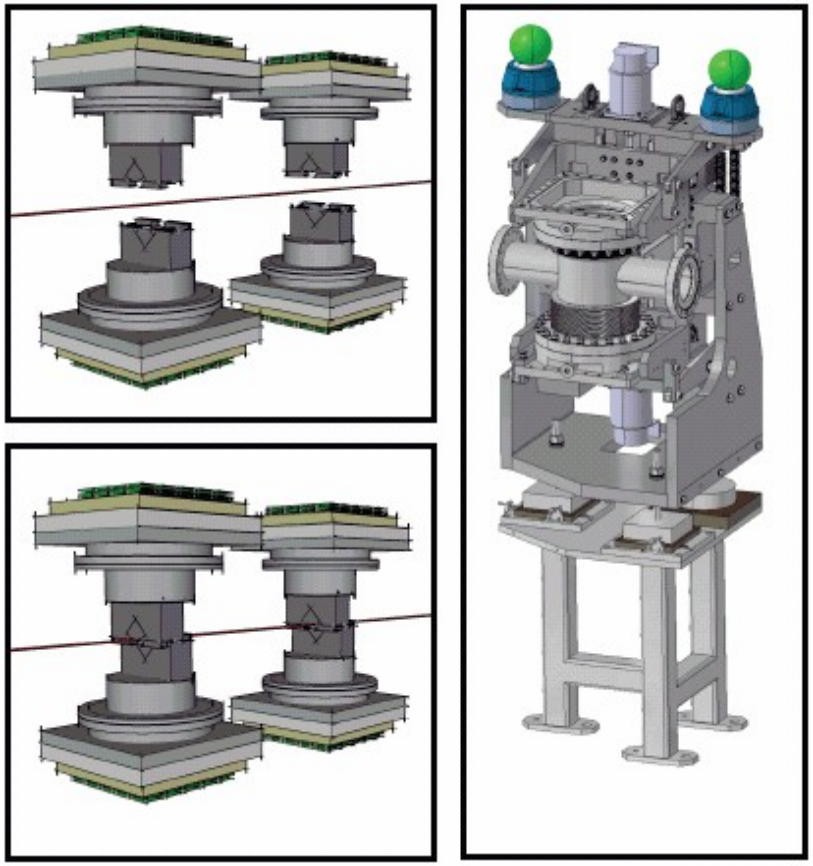
ATLAS Coll. [CERN/LHCC/2007-001]

Status : approved (2007)

Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

ALFA

Absolute Luminosity For ATLAS



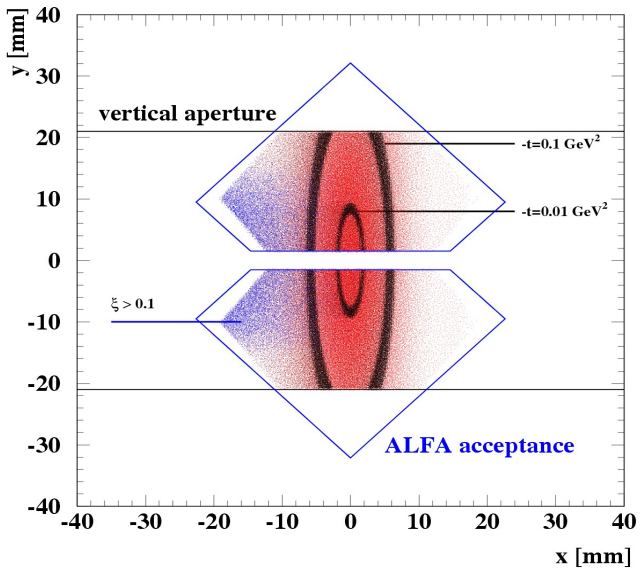
Roman pots

237m from IP1

tracking with scintillating fibers

elastic scattering parameters

- 1st) Measurement of luminosity in optimal conditions: goal ~3%
- 2nd) Calibration of lumi monitors
- Single Diffractive events

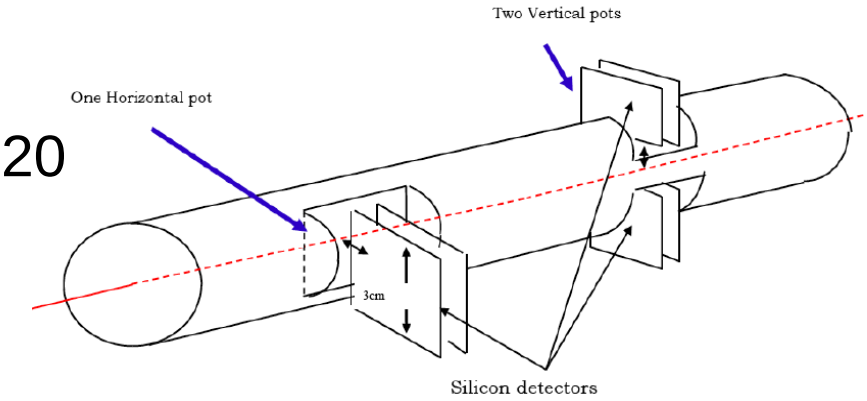


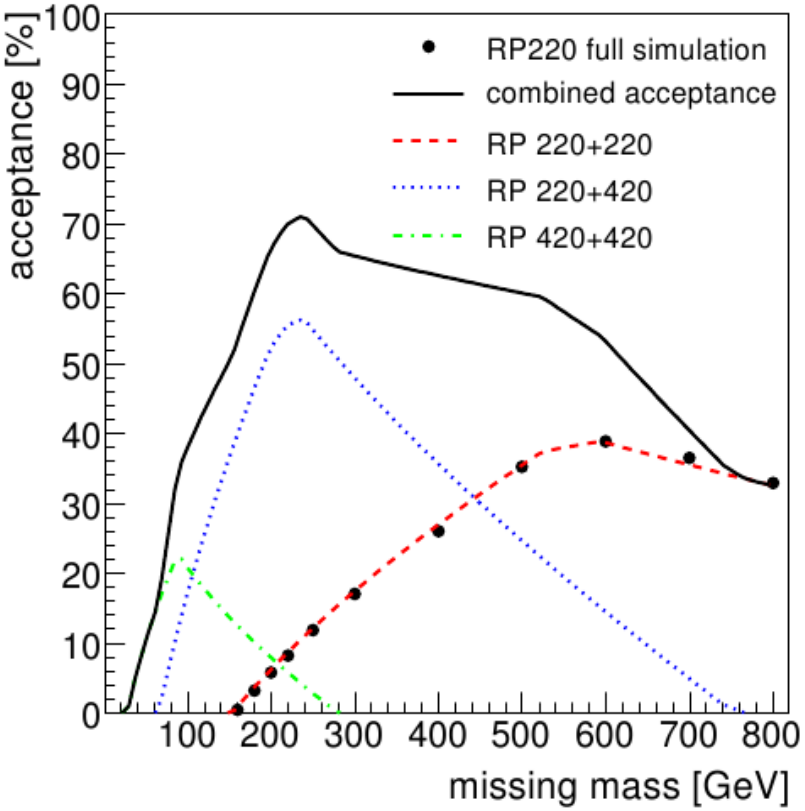
Lumi calibration:
Runs with dedicated LHC optics

Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

Option : RP220

- Roman pots at 216+224 m from IP1
- Movable beampipe at 224m for timing detectors
- RP similar to TOTEM
- Same technology as for FP420





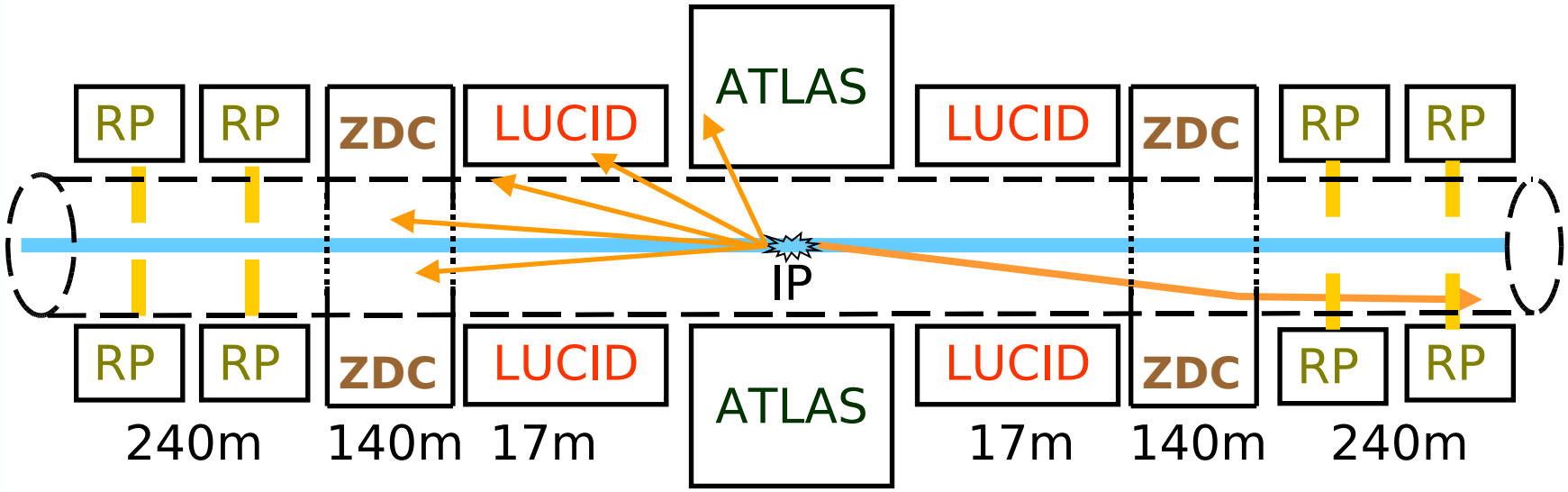
Missing mass method:

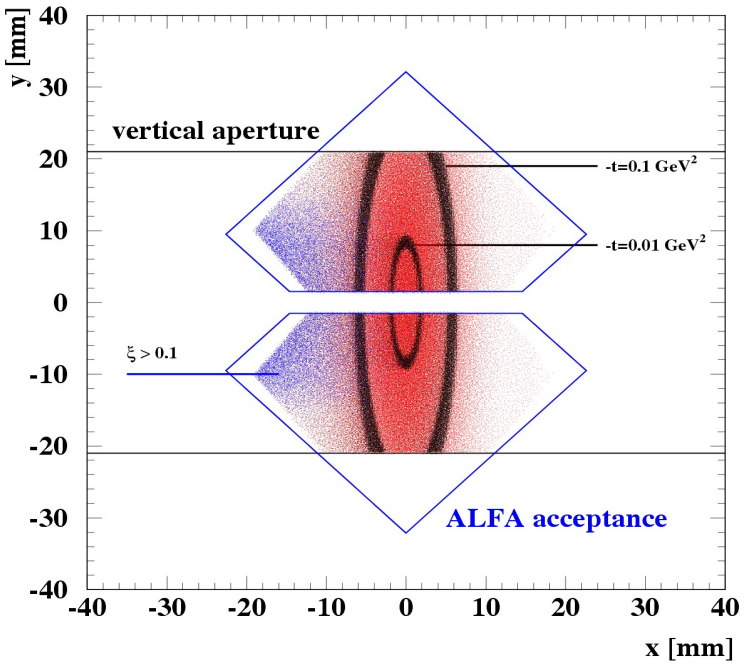
measuring the momentum loss of both final state protons ξ_1 and ξ_2 gives an access to the central system mass

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

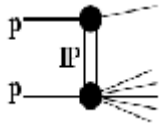
Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

Single diffraction





$pp \rightarrow pX$

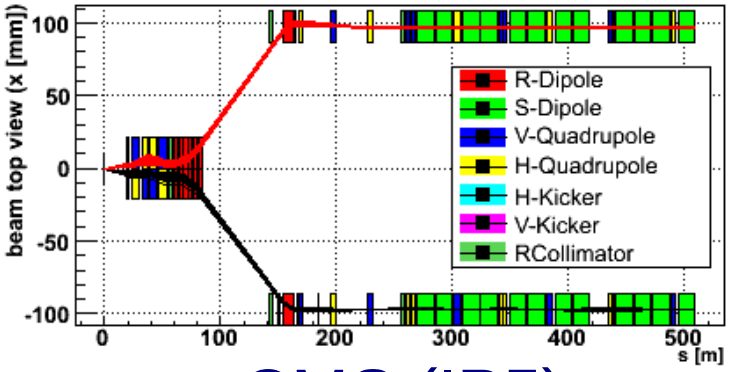


The X system is accessible by ATLAS + forward detectors

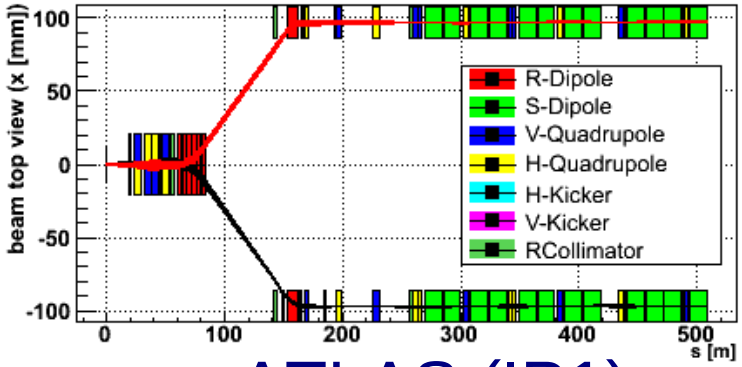
The forward proton is measured by RP/ALFA/FP420

Backup
- CASTOR
- ZDC (CMS)
- TOTEM
- dimuons
- LUCID
- ZDC (ATLAS)
- ALFA (ATLAS)
- RP220
- SD

HECTOR: implementation

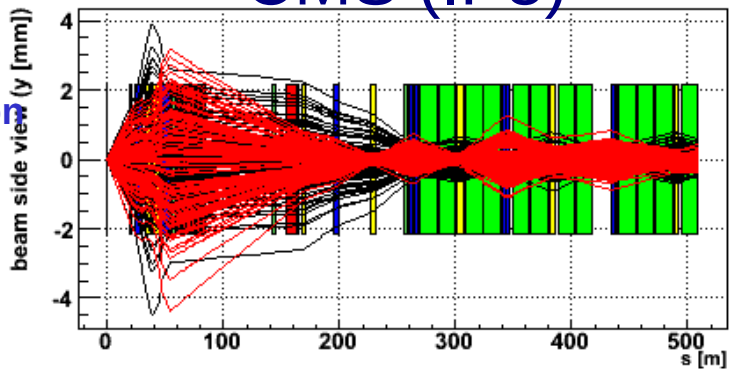


top

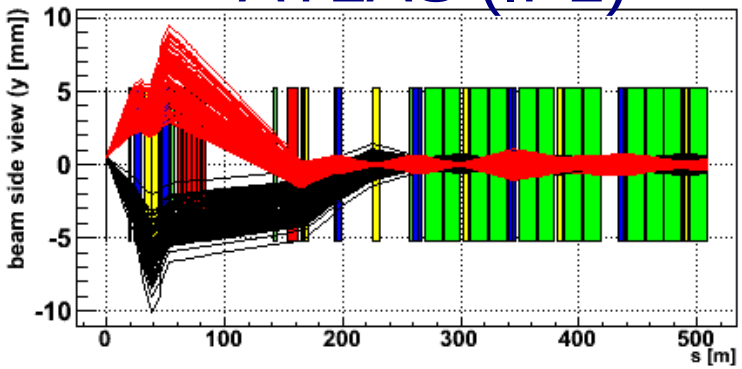


CMS (IP5)

ATLAS (IP1)



side



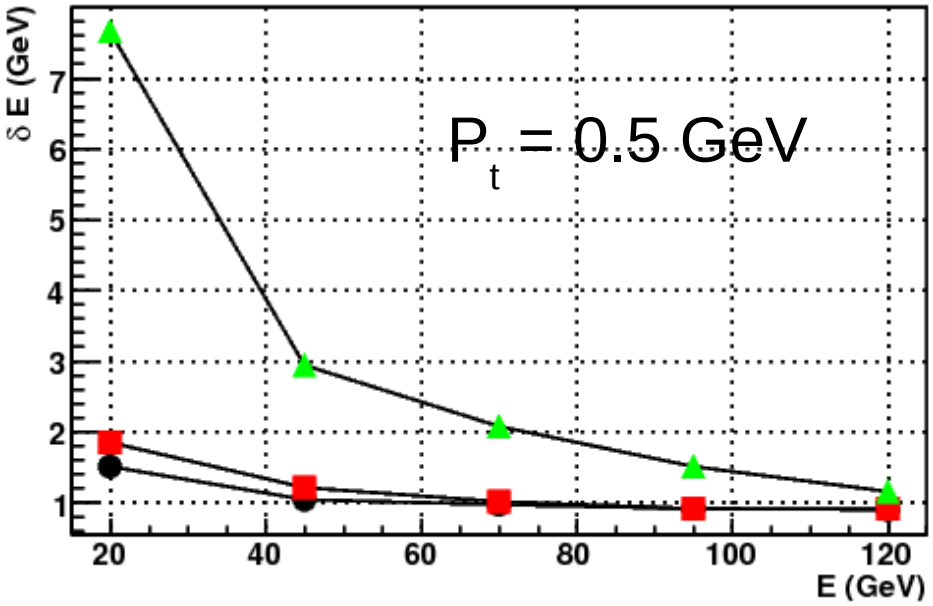
Horizontal crossing plane

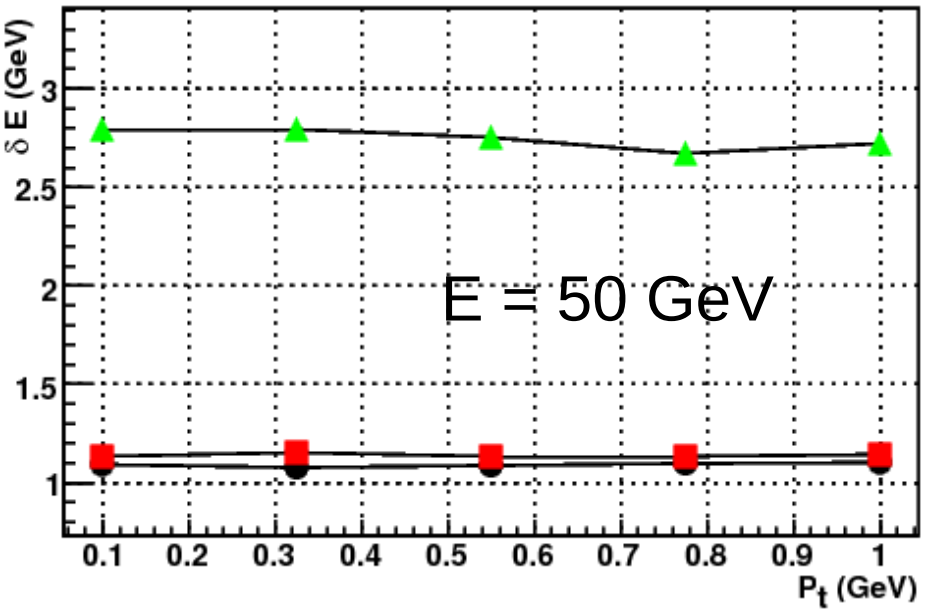
Vertical crossing plane

Input Needed:

- effective field strength / length
- magnet position / aperture

Reconstruction





Forward detectors at 420m + 428m

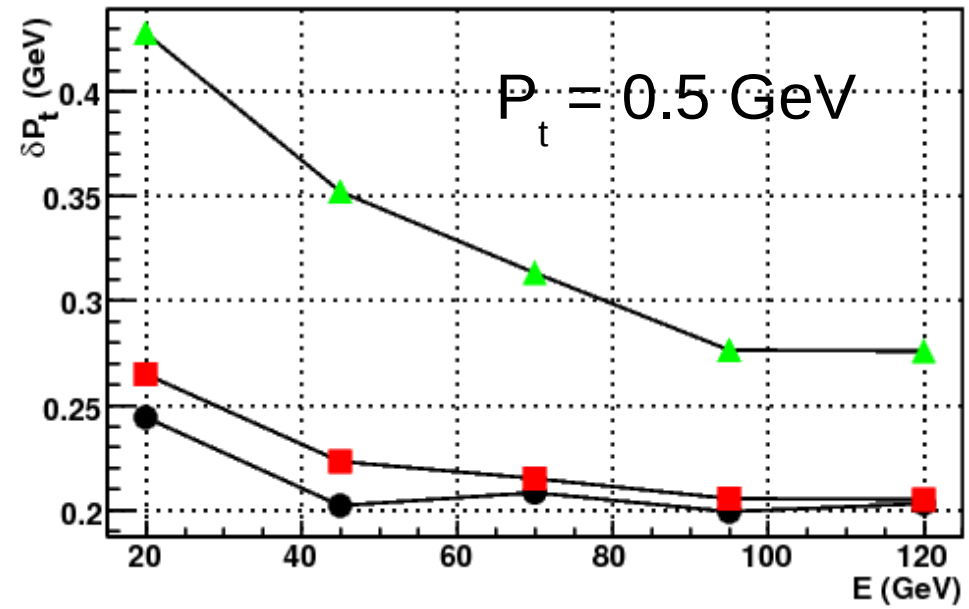
Energy Resolution

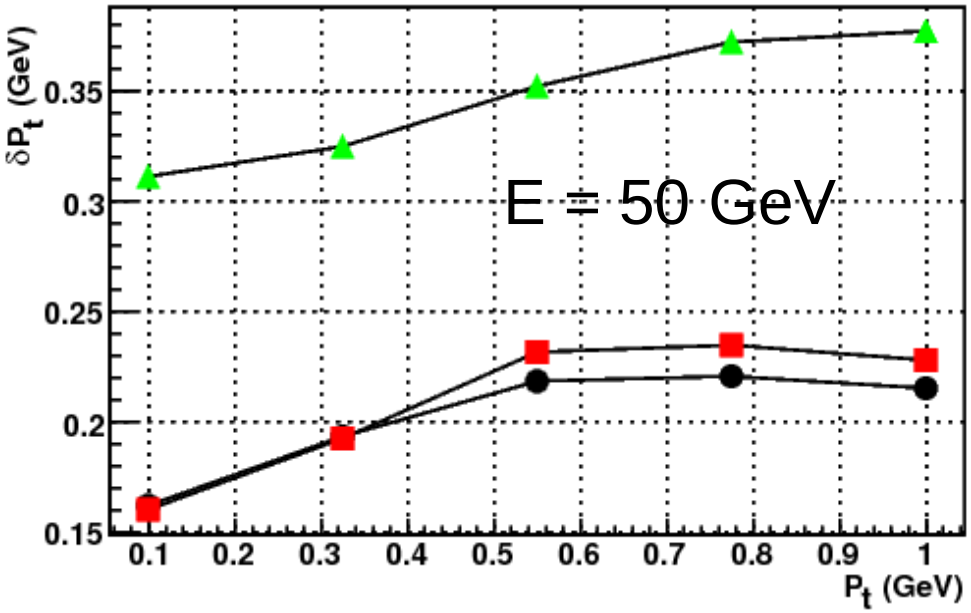
$$P_t \simeq \sqrt{Q^2}$$

Detector resolution

- 30 μm
- 5 μm
- perfect

Reconstruction





Forward detectors at 420m + 428m

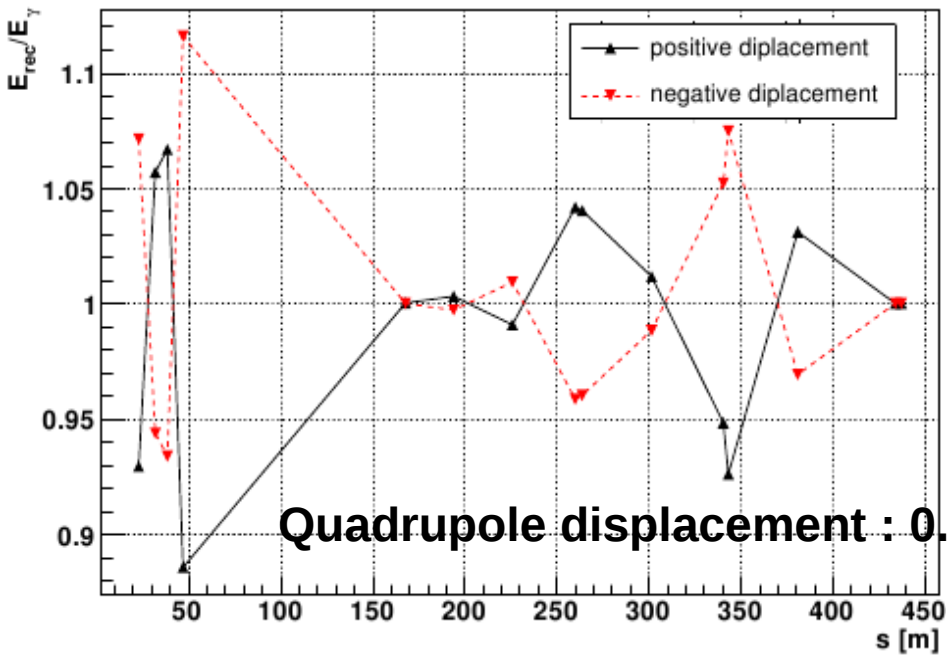
P_T Resolution

$$P_t \simeq \sqrt{Q^2}$$

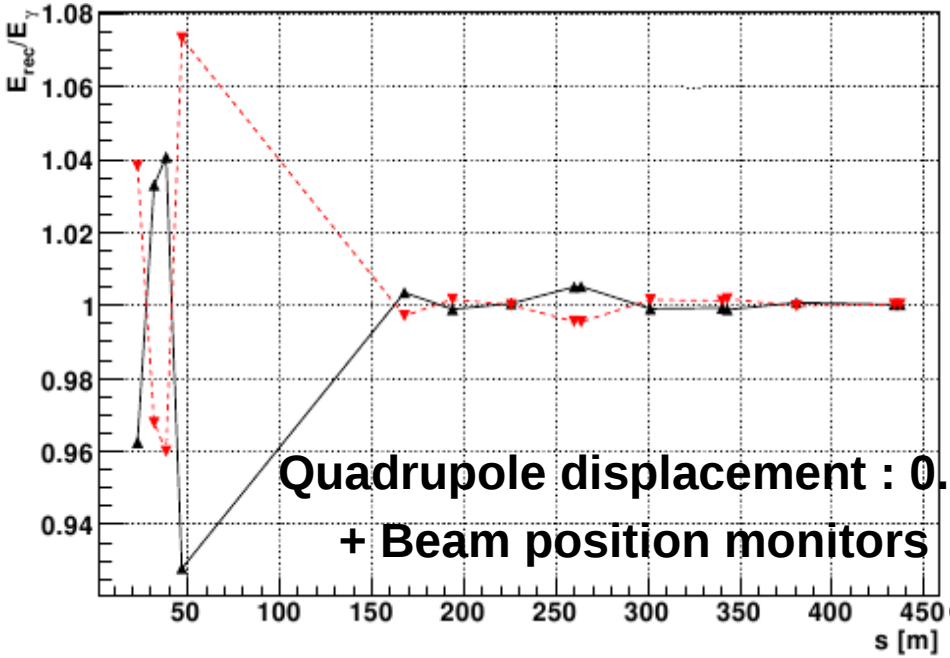
Detector resolution

- 30 µm
- 5 µm
- perfect

Misalignment of the beamline



Quadrupole displacement : 0.5 mm



Quadrupole displacement : 0.5 mm
+ Beam position monitors

E_{loss} = 100 GeV

Assumes :
ideal beamline BUT 1 displaced quadrupole

Impact on reconstructed energy

Also assumes :
perfect knowledge of beamline position at 420m