Luminosity measurement in ATLAS and CMS

A. Sbrizzi - University of Bologna, Italy

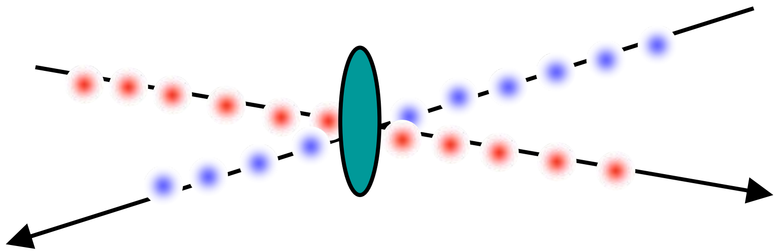
Outline

- Luminosity at LHC
- Measurement strategy
- ATLAS and CMS forward detectors
- Luminosity from QED and QCD processes

The LHC luminosity

The luminosity relates the cross section (σ) of a given process with its event rate (N).

$$L = \frac{N}{\sigma}$$



The luminosity is completely determined by the properties of the colliding proton beams.

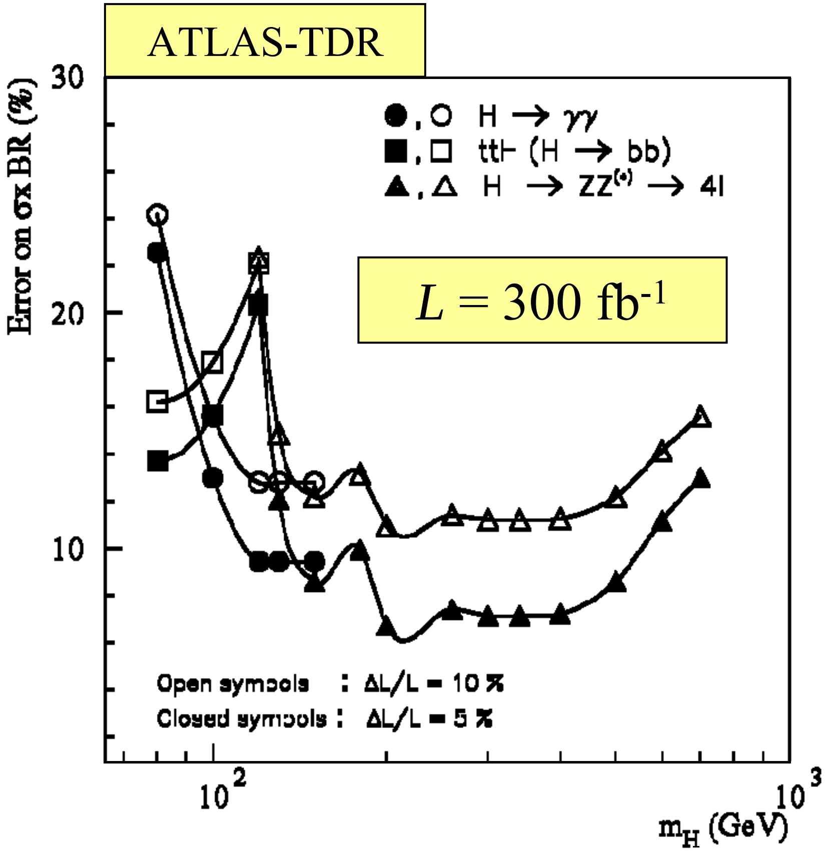
$$L = F\frac{f\sum_{bunches} N_1^i N_2^i}{4\pi\sigma_x\sigma_y}$$

N_1 N_2	Number of protons in colliding bunches
f	Revolution frequency
F	Correction factor for beam crossing angle
σ_x σ_y	Transverse beam dimension at the IP

Importance of measuring the luminosity

Monitor the accelerator performance

Overall normalization of the physics analysis



$$\sigma \times BR = \frac{N_{events}(s^{-1})}{\varepsilon_{\det} \cdot L(cm^{-2}s^{-1})}$$

Systematic uncertainty on L is dominates many analysis.

New physics: deviation of σ×BR from SM predictions.

In the mass range [120, 600] GeV, the Higgs rate can be measured with a precision of 12% (7%) if the luminosity is known to 10% (5%).

The aim is to reach an uncertainty on the luminosity of 2-3 %.

Strategy

Absolute luminosity measurement techiniques

- LHC machine parameters (ΔL = 10%, early stages)
- Optical theorem (L ~10^{27} $cm^{-2}s^{-1}$, ΔL = 2-3%, late 2009)
  - Scintillating fibers in Roman Pots
- Rate of well-calculable physics processes (e.g. W, Z) (L >10^{30} $cm^{-2}s^{-1}$)

Luminosity monitors measuring relative luminosity

- Monitor beam size (Van Der Meer scan) in low luminosity runs, where beam-beam interactions and beam crossing angle effects are suppressed
  - Calorimeter at zero degree (ZDC), Pixel detectors (PLT)
- Measure absolute luminosity in high luminosity runs (L >10^{30} $cm^{-2}s^{-1}$) with calibration constants obtained from low luminosity runs
  - Cherenkov tubes (LUCID), Calorimeters (HF, CASTOR)

Absolute luminosity from optical theorem

Optical theorem

$$\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = \frac{1+\rho^2}{16\pi}\sigma_{tot}^2$$

t is the squared-momentum-transfer.

ρ is a parameter known to good precision (uncertainty of 0.5%).

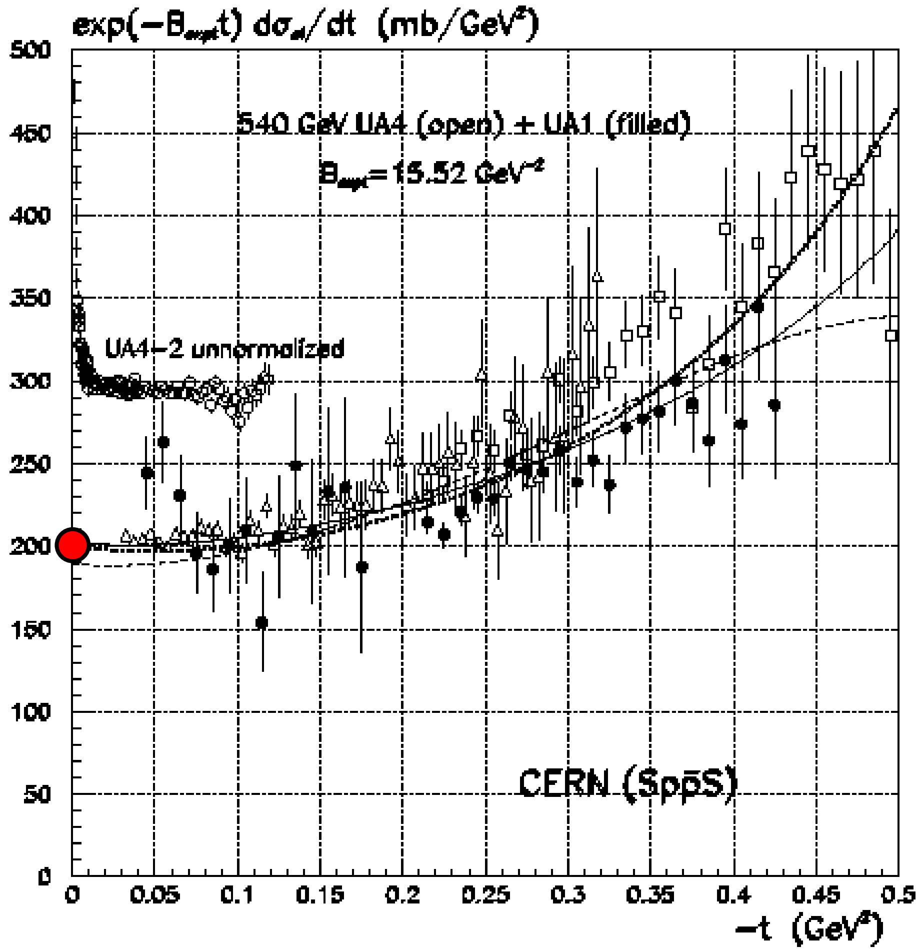
$$\begin{cases} \sigma_{tot} = \dfrac{N_{tot}}{L} \\ \sigma_{el} = \dfrac{N_{el}}{L} \end{cases}$$

$$L = \frac{1+\rho^2}{16\pi} \frac{N_{tot}^{\ 2}}{\left.\dfrac{dN_{el}}{dt}\right|_{t=0}}$$

N_{tot} = total rate from large rapidity detectors ($|\eta| \sim 7$-8)
N_{el} = rate at small angles ($t \sim 0.00065\ \mathrm{GeV}^2 \Leftrightarrow \Theta \sim 3.5\ \mu\mathrm{rad}$) from Roman Pots

The absolute luminosity is obtained from a simultaneous measurement of forward elastic rate (N_{el}) and total rate (N_{tot}) in dedicated low luminosity runs.

Extrapolation of N_{el} down to t=0



Need to be as close as possible to t=0.

With normal LHC settings ($t > 16$ GeV^2), t is not sufficiently small.

Special LHC settings ($t \sim 0.00065$ GeV^2)

Low luminosity (10^{27}) and reduced number of bunches are necessary to reduce beam crossing, beam-beam interactions and event pile-up.

The uncertainty on dN_{el}/dt due to extrapolation down to t=0 is 1-2 %.

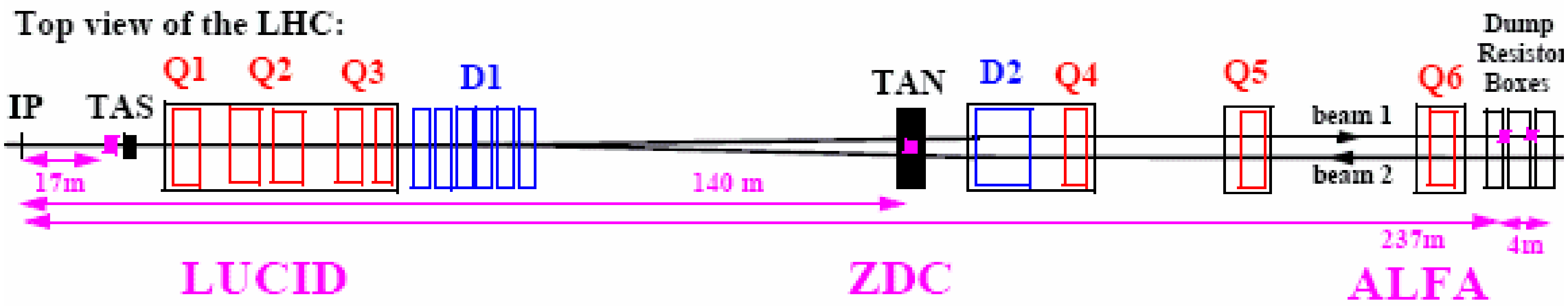
Calibration of luminosity monitors

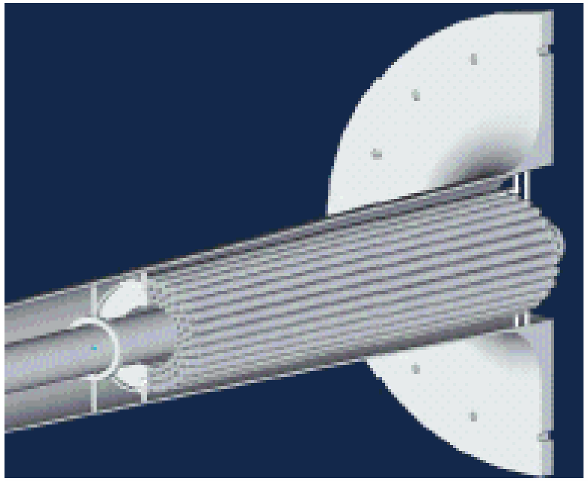
$$L = \frac{\langle M \rangle}{\langle C \rangle \cdot \varepsilon \cdot \sigma_{tot}}$$

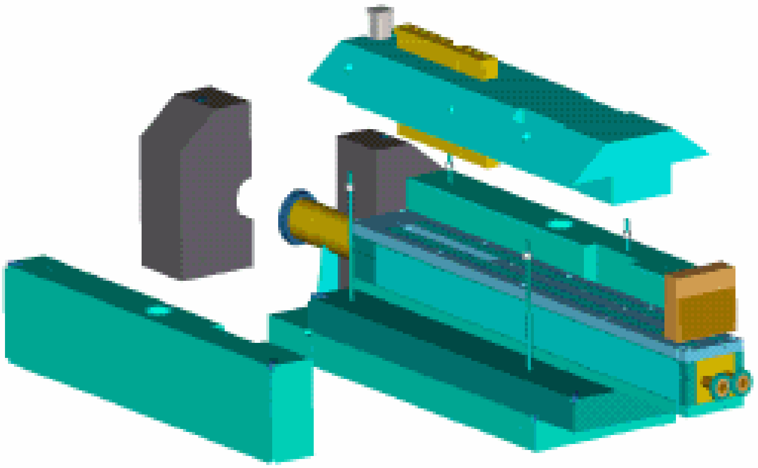
$\langle M \rangle$	Measured number of particles per BX
$\langle C \rangle$	Number of particles per detected interaction
ε	Efficiency for detecting one interaction
σ_{tot}	Total *pp* cross section

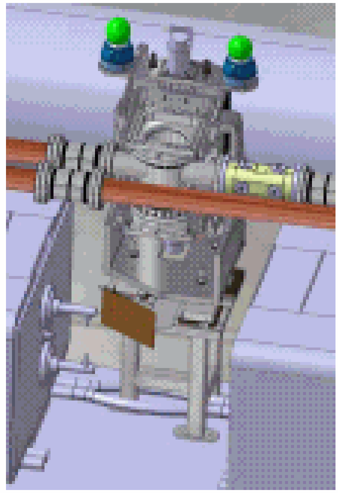
- $\langle C \rangle$ is measured in low luminosity (the probability of >1 interaction per BX is low).
- The product $\varepsilon \times \sigma_{tot}$ is a calibration constant obtained in low luminosity runs, where the monitor runs in parallel with detectors measuring the luminosity (TOTEM, Roman Pot).
- Calculated ε and measured σ_{tot} are used only for consistency check.

ATLAS forward detectors







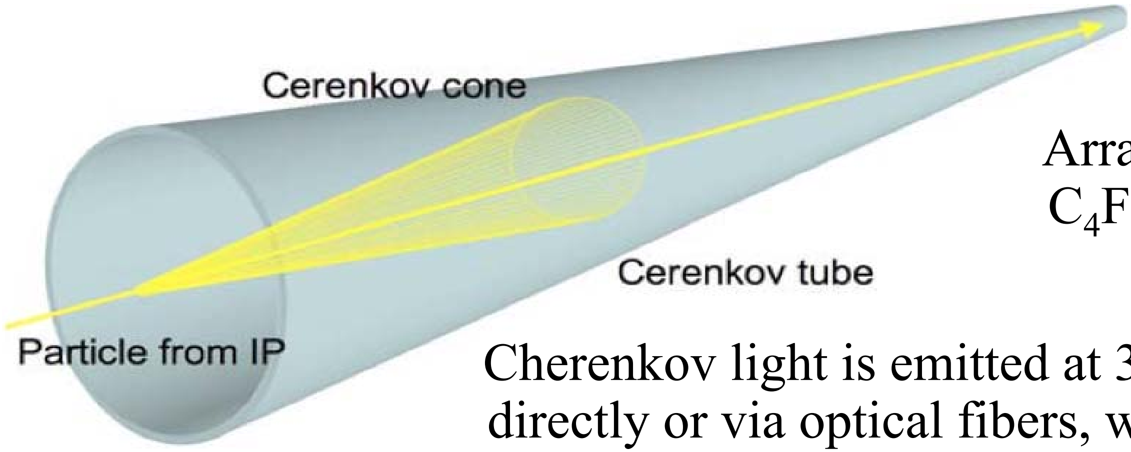


LUminosity measurement with a Cherenkov Integrating Detector

Zero Degree Calorimeter

Absolute Luminosity For Atlas

The LUCID detector

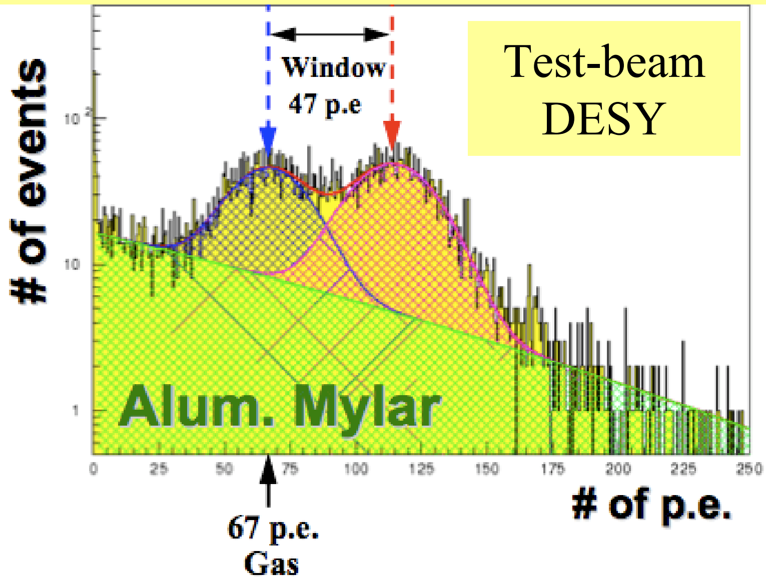


Array of Aluminum tubes filled with C_4F_{10} acting as Cherenkov counters.

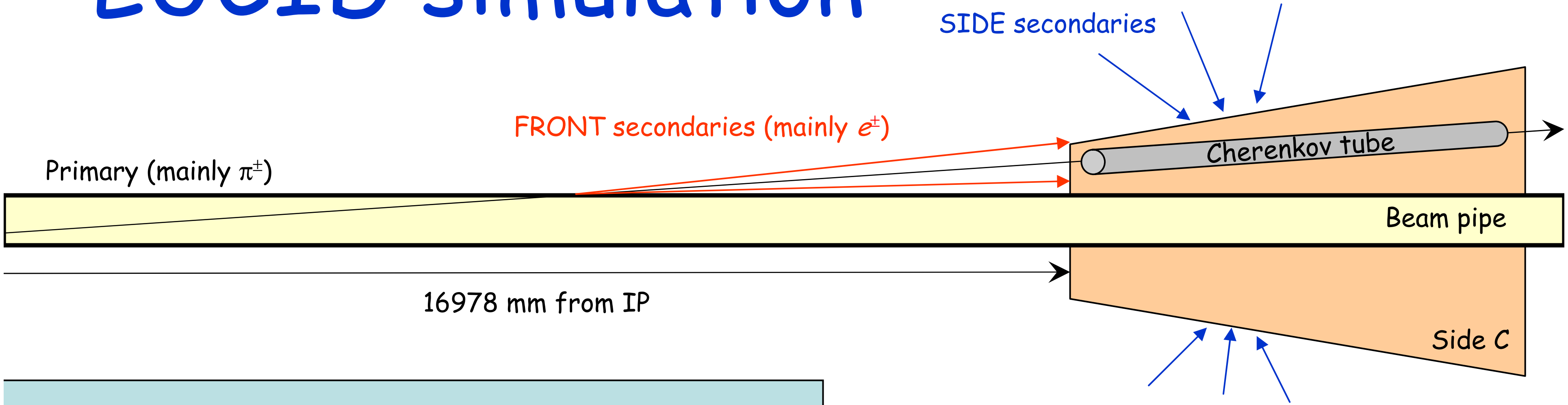
Cherenkov light is emitted at 3° and is read-out after 3 reflections, directly or via optical fibers, with Photo-Multiplier Tubes (PMT).

LUCID can be used to extract the luminosity by counting particles hitting on it.

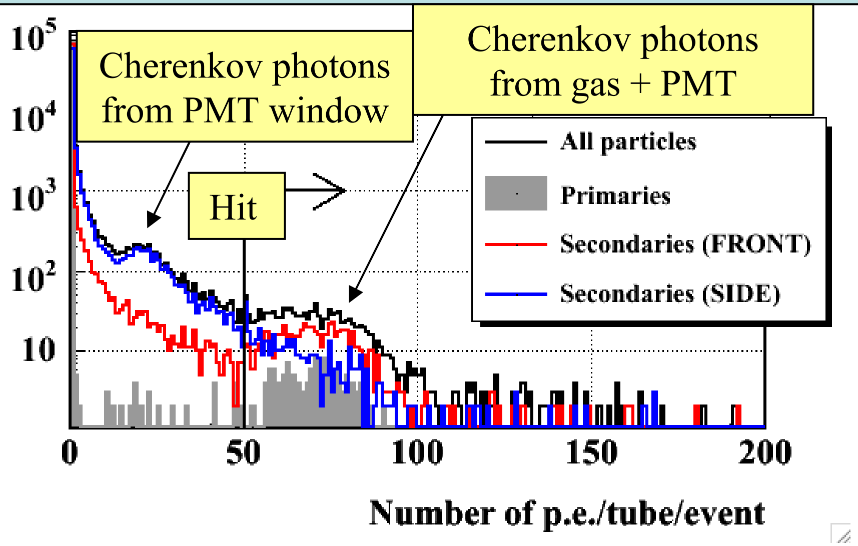
- The Cherenkov threshold (10 MeV for *e* and 2.8 GeV for π) and the pointing geometry to the IP allow for background suppression.
- Background from the PMT is at lower level.
- A good time resolution allows for individual beam crossing detection.



LUCID simulation



1 pp interaction per event ($L < 10^{33}$cm^{-2}s^{-1})



Hit counting

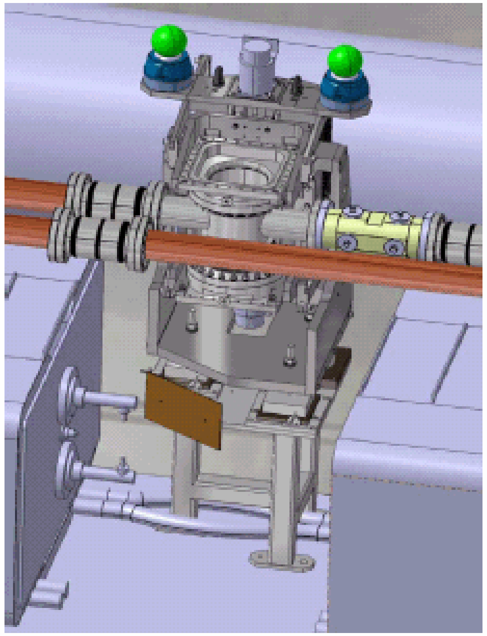
Number of tube having > 50 *p.e.*

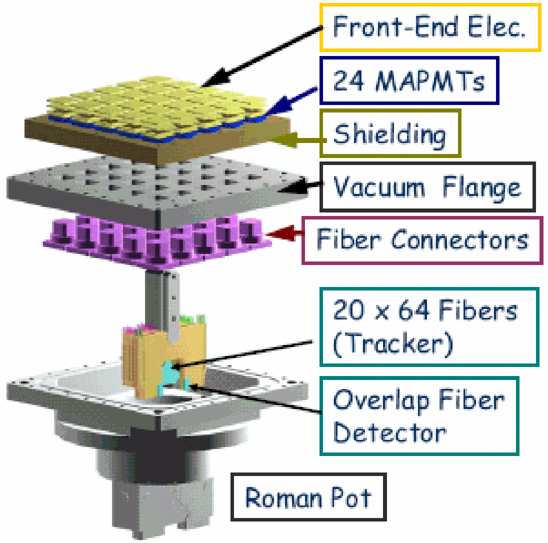
(2% for 1 *pp* interaction)

Particle counting	
[0, 50] *p.e.*	0 particle
[50, 100] *p.e.*	1 particle
[100, 150] *p.e.*	2 particle
…	…

LUCID has been approved for installation in January 2007.

The ALFA detector





Columb interference region

$t \sim 0.00065\ \mathrm{GeV}^2 \Leftrightarrow \theta \sim 3.5\ \mu\mathrm{rad}$

Detector close to beam pipe (1.5 mm) ⇒ Roman Pot.

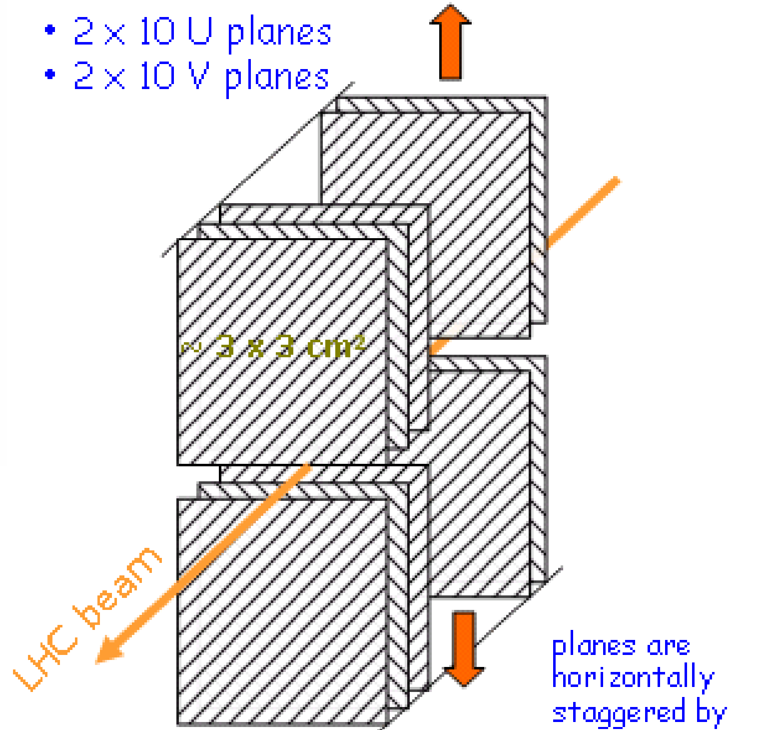
High $\sigma_{x,y}$ (< 120 μm, beam spot at RP), goal 30 μm.

No inactive area.

The fiber tracker

Concept

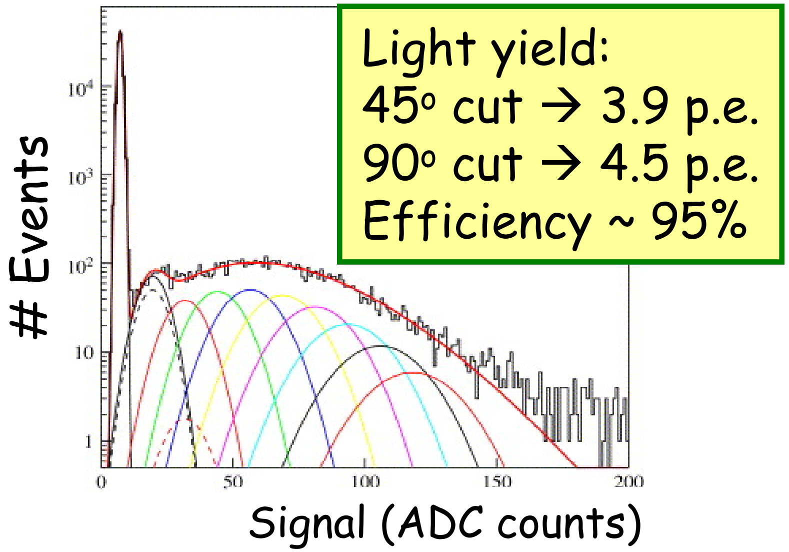
- 2 × 10 U planes
- 2 × 10 V planes

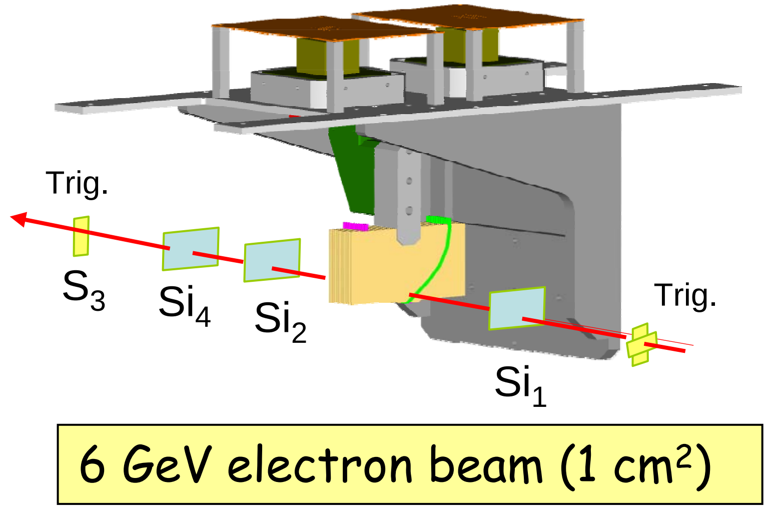


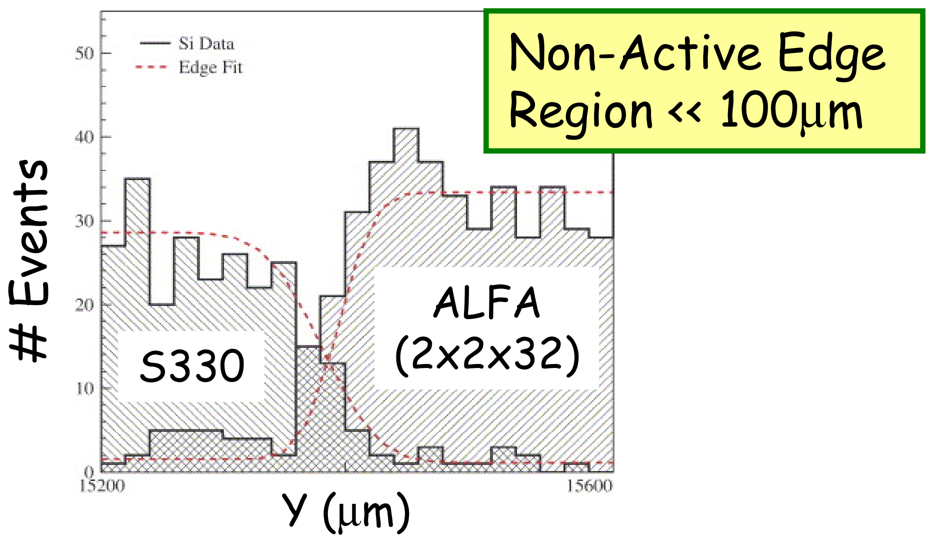
- scintillating fibres
- 0.5 mm² square

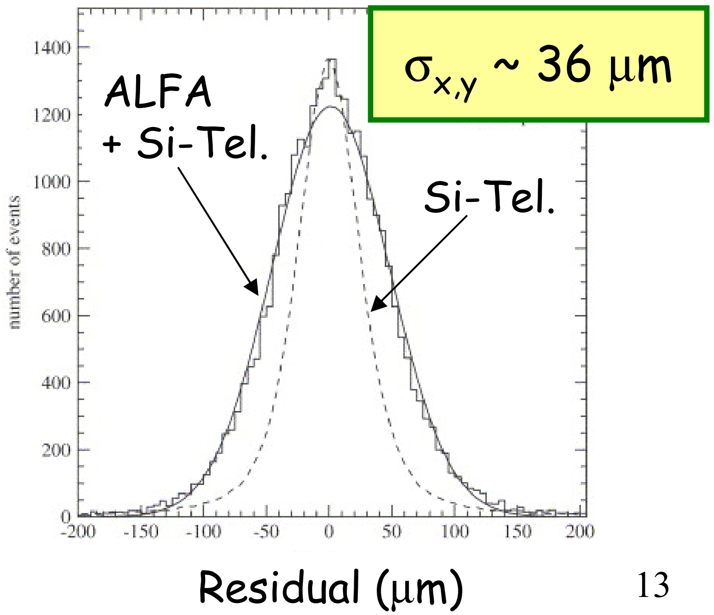
The fibers are read out by MAPMT

ALFA test beam

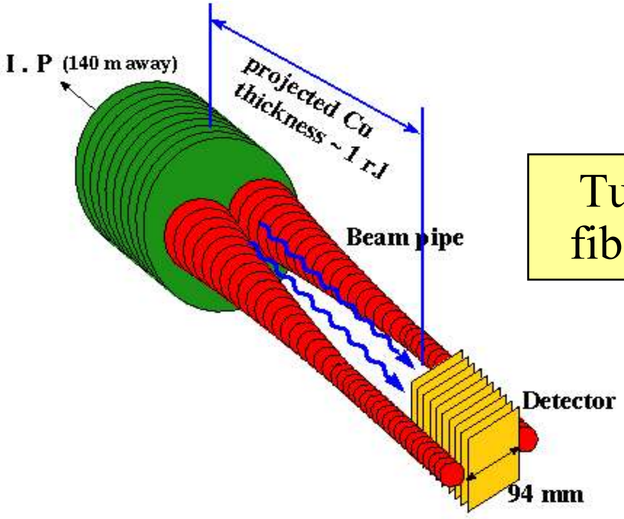




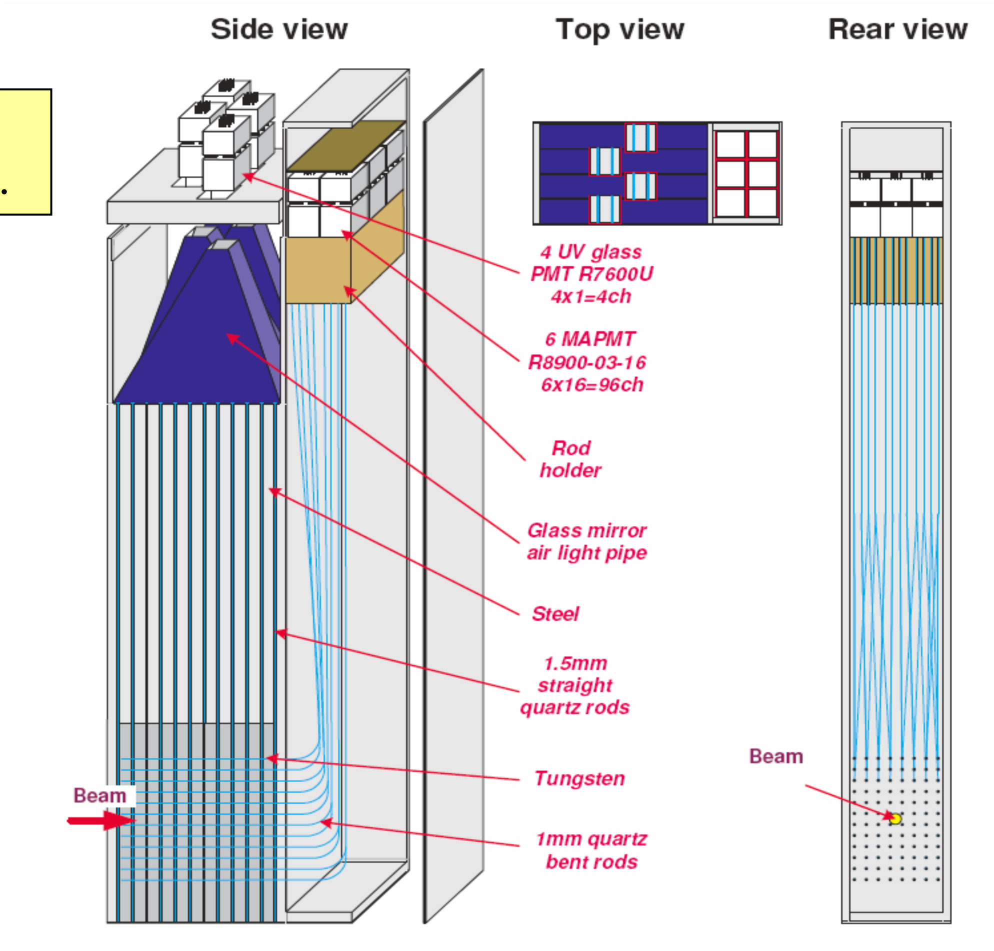




The ZDC detector



Tungsten-quartz fiber calorimeter.



Cherenkov light is collected with straight quartz rods (1.5mm) transverse to the beam.

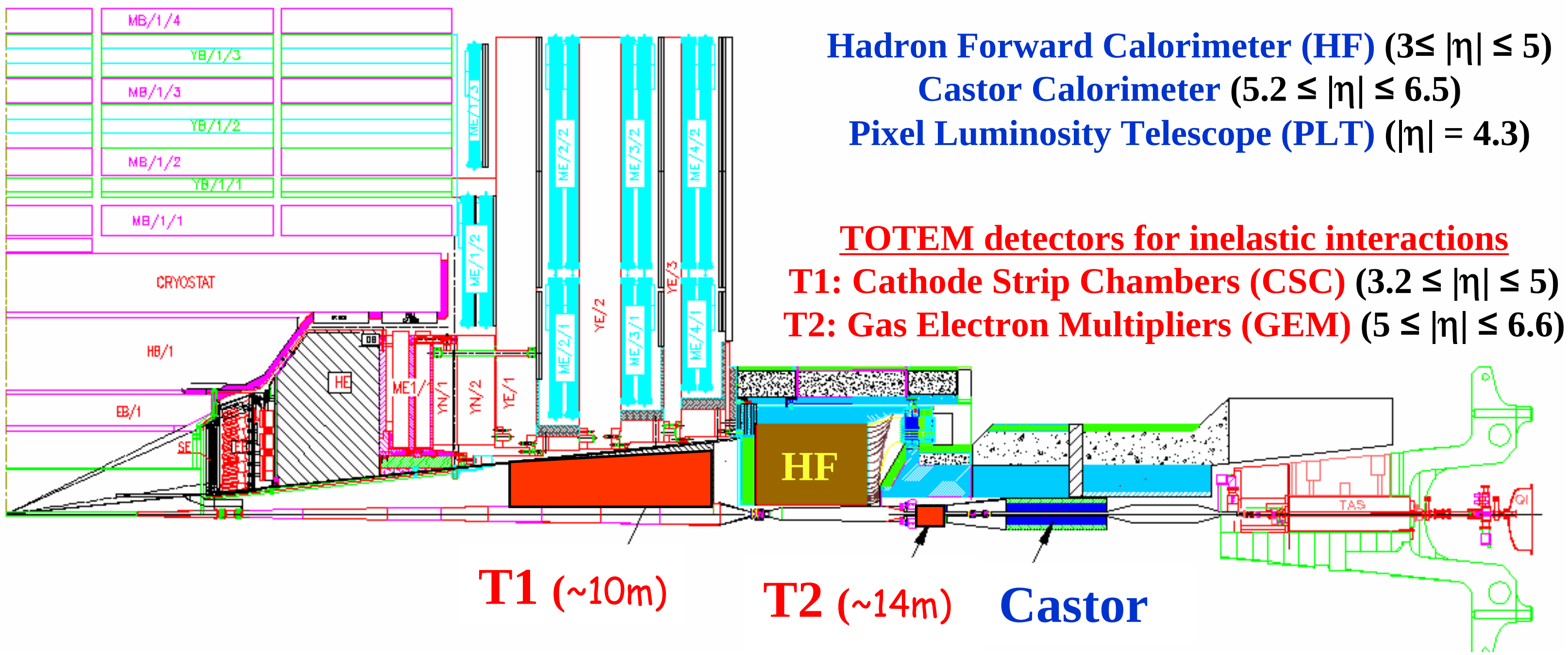
The shower position is measured with bent quartz rods (1mm) parallel to the beam.

It is built to measure the spectator neutrons in heavy-ion interactions, but can also be useful as beam condition monitor.

Good time resolution: single BX detection.

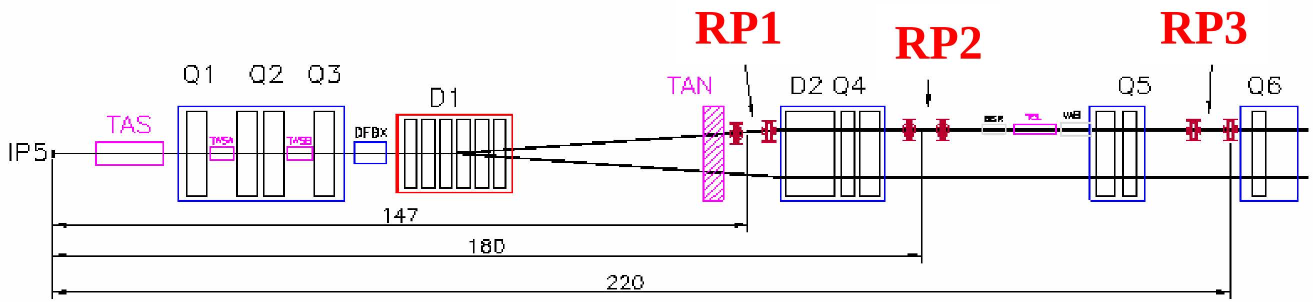
LOI presented in January 2007 (CERN/LHCC/2007-001)

CMS forward detectors



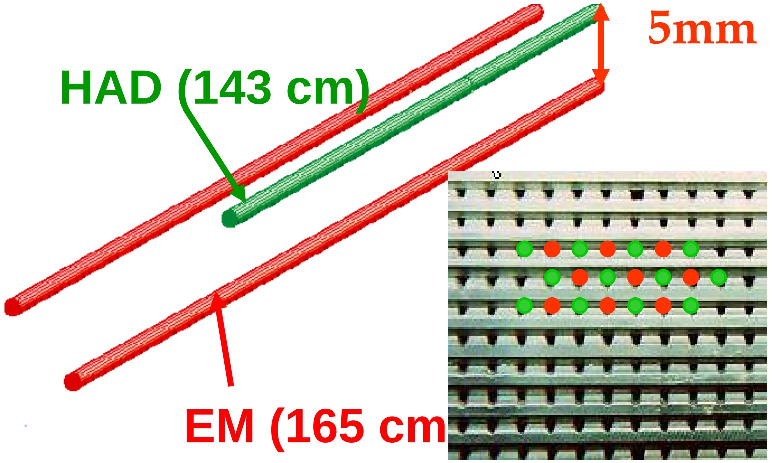
Hadron Forward Calorimeter (HF) (3≤ |η| ≤ 5)
Castor Calorimeter (5.2 ≤ |η| ≤ 6.5)
Pixel Luminosity Telescope (PLT) (|η| = 4.3)

TOTEM detectors for inelastic interactions
T1: Cathode Strip Chambers (CSC) (3.2 ≤ |η| ≤ 5)
T2: Gas Electron Multipliers (GEM) (5 ≤ |η| ≤ 6.6)



TOTEM detectors for elastic interactions
Silicon Strips in Roman Pots (RP)

The Forward Hadron calorimeter (HF)

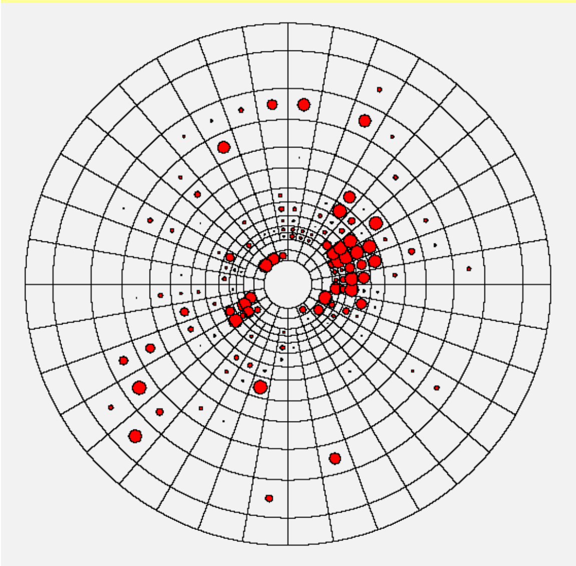


Active detector: embedded radiation hard (>1 Grad/10 years) quartz fibers in steel absorbers.

The Cherenkov light is read-out with PMT at the end of the fibers.

Most of the visible energy is carried by electrons $\Rightarrow$ the shower width is determined by the Moliere radius.

At design luminosity (25 *pp* interactions/BX)



36×12 segments in $(\eta, \varphi) \Rightarrow \Delta\eta\times\Delta\varphi = 0.175\times0.175$

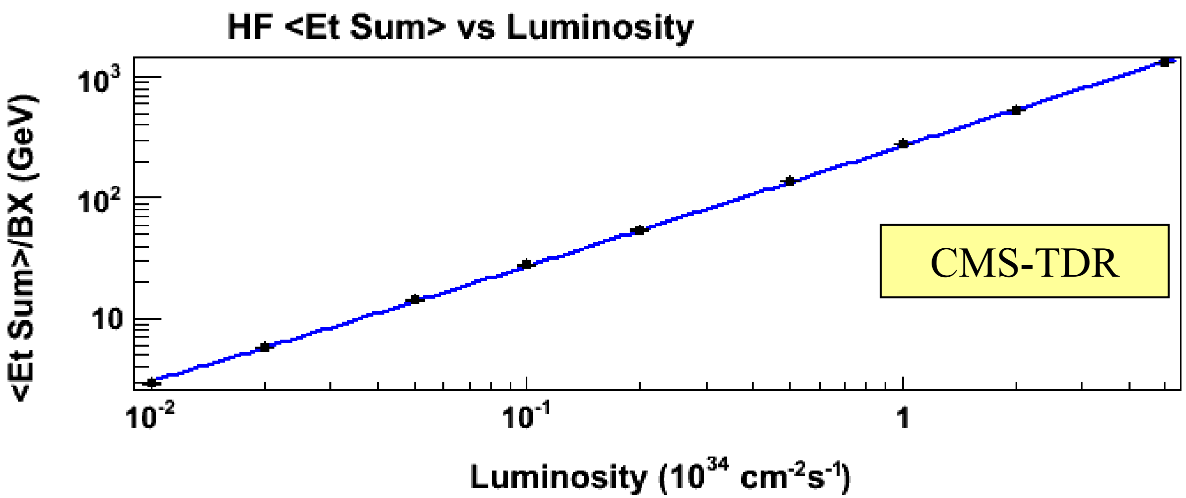
Even at the highest luminosity, the HF is mostly empty.

Luminosity from Zero-Counting method

Assuming that the number of interactions per BX (μ) is Poisson distributed

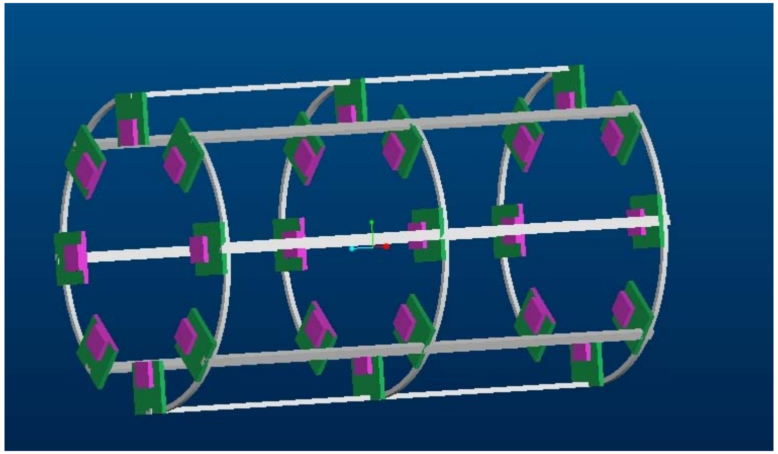
$$P(n,\mu) = \frac{\mu^n e^{-\mu}}{n!} \Rightarrow P(0,\mu) = e^{-\mu} \Rightarrow \mu = -\log[P(0,\mu)]$$

As μ increases, the number of "Zero's" decreases leading to "Zero starvation".
The fraction of zero should be at least 1%, leading to an upper limit on the mean number of interaction to be 4.6.
However, the HF has 864 physical towers, therefore one can make 864 of quasi independent measurements for each BX.



This method uses the linear relationship between the average sum of E_T deposited in the HF and the mean number of interaction per BX.

The Pixel Luminosity Telescope (PLT)



3 planes of 8 diamond sensors ($8 \times 8 mm^2$) bump-bonded to CMS read-out pixels (radiation hard, reduced capacitance ⇒ noise ⇒ fast read-out)

Length: 20 cm, z: ±175 cm, r: 4.5 cm

Small angle pointing telescope (1.56^o)

Signals are 3-fold coincidences, on a bunch by bunch basis (in fast read-out)

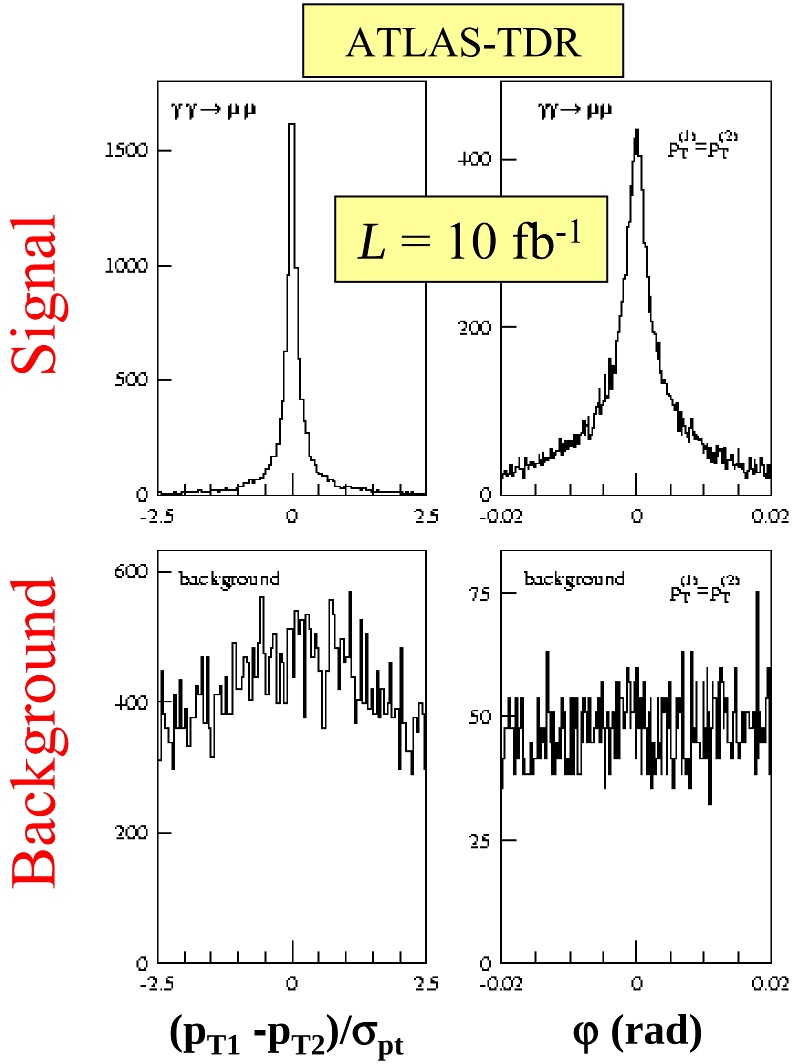
Fast read-out	Full read-out
0, 1, 2, 3, >4 counting	Pulse height
Pixel threshold adjustable	Determination of track origin
Pixel maskable	Determination of IP

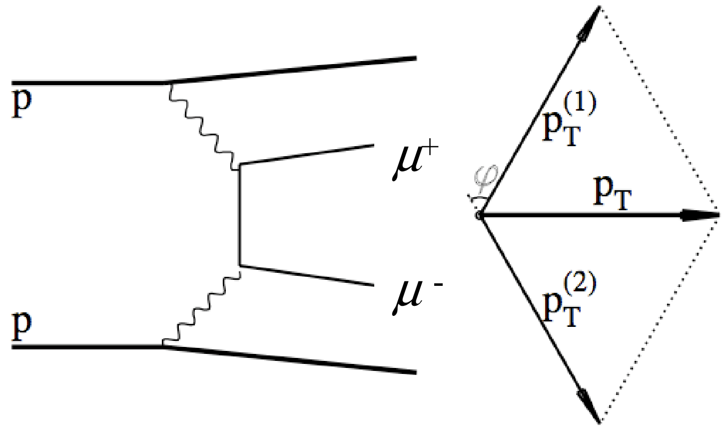
The PLT is a beam condition monitor (not yet approved).

Luminosity from physics signals

- Well-known QED processes are commonly used to measure the luminosity in e^+e^- colliders (Bhabha scattering) and *ep* colliders (*ep* bremsstrahlung).
- In *pp* colliders, QED processes have in general a low cross section.
- However, at high luminosity, the occurence of well-calculable physics decays becomes relevant and can be used to estimate luminosity
  - lepton pair production from double photon exchange (QED)
  - leptonic W and Z decays (QCD)

QED: Muons from double γ exchange





$\sigma_{\mu\mu} \sim$ 1pb (~ 0.01 Hz at $L = 10^{34}$ cm^{-2} s^{-1})
$m_{\mu\mu} \sim$ GeV, $p_T(\mu\mu) \sim 0$
$p_T(\mu) > 6$ GeV, $|\eta(\mu)|<2.5$

Background from Drell-Yan and semileptonic heavy quark decays is suppressed with offline cuts on φ and $(p_{T1}-p_{T2})$ (17%).

$\Delta L/L = 2\%$

Electron channel also possible, but additional dipole magnet should be installed.

QCD: leptonic W and Z decays

$$pp \rightarrow W \rightarrow \ell \nu$$

$$pp \rightarrow Z \rightarrow \ell^+ \ell^-$$

Clean signature of leptonic final state.
High rate: O (10 Hz) at $L = 10^{34}$ cm^{-2} s^{-1}.
$\Delta L/L$ = 1% in 20 min.

The increasing precision of the QCD calculation of W and Z production cross section makes the counting of the W and Z leptonic decays an attractive means to measure the luminosity at the LHC (ref. G. Polesello)

$$L = \frac{N_{W/Z} - N_{background}}{A \cdot \varepsilon \cdot \sigma_{W/Z}}$$

$N_{W/Z}$	Number of identified bosons
$N_{background}$	Number of background events
A	Geometrical acceptance
ε	Reconstruction efficiency
$\sigma_{W/Z}$	Theoretical cross section

Largest uncertainies: theoretical estimate of $\sigma_{W,Z}$ and detector modelling.

Uncertainty on luminosity from W/Z decays

In *pp* collision, $\sigma_{W,Z}$ is the convolution of the PDF and the partonic cross section

$$\sigma_{W/Z} = \sum_{i,j} \int dx_i dx_j f_1(x_i) f_2(x_j) \hat{\sigma}_{ij \to W/Z}(S_{max} x_i x_j)$$

- The partonic cross section is known at NNLO at 1% level (PRD 094008)
- The PDF contribution controversial (commonly set at 3%) (hep-ph/0307219)
- Currently available tools are NLO + parton shower (see also CMS 2004/056)
- Uncertainty on background simulation to be studied
  - QCD and heavy quarks (difficult to simulate, real data needed)
  - Leptonic decays of top quark pairs
  - $W \to \tau \to l$ decays
- Uncertainty on acceptance determination at 2% level (hep-ph/0405130)
  - Variation of NLO QCD scale 1%
  - PDF contribution 1%
  - Improvement are expected by better fixing PDF by looking at W/Z data
  - EW effect of multiple photon radiation to be studied

Conclusions

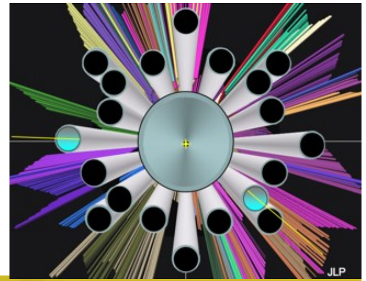
- ATLAS and CMS measure the luminosity with several different detectors
- Absolute luminosity measured at low luminosity is used to calibrate luminosity monitors working at higher luminosity

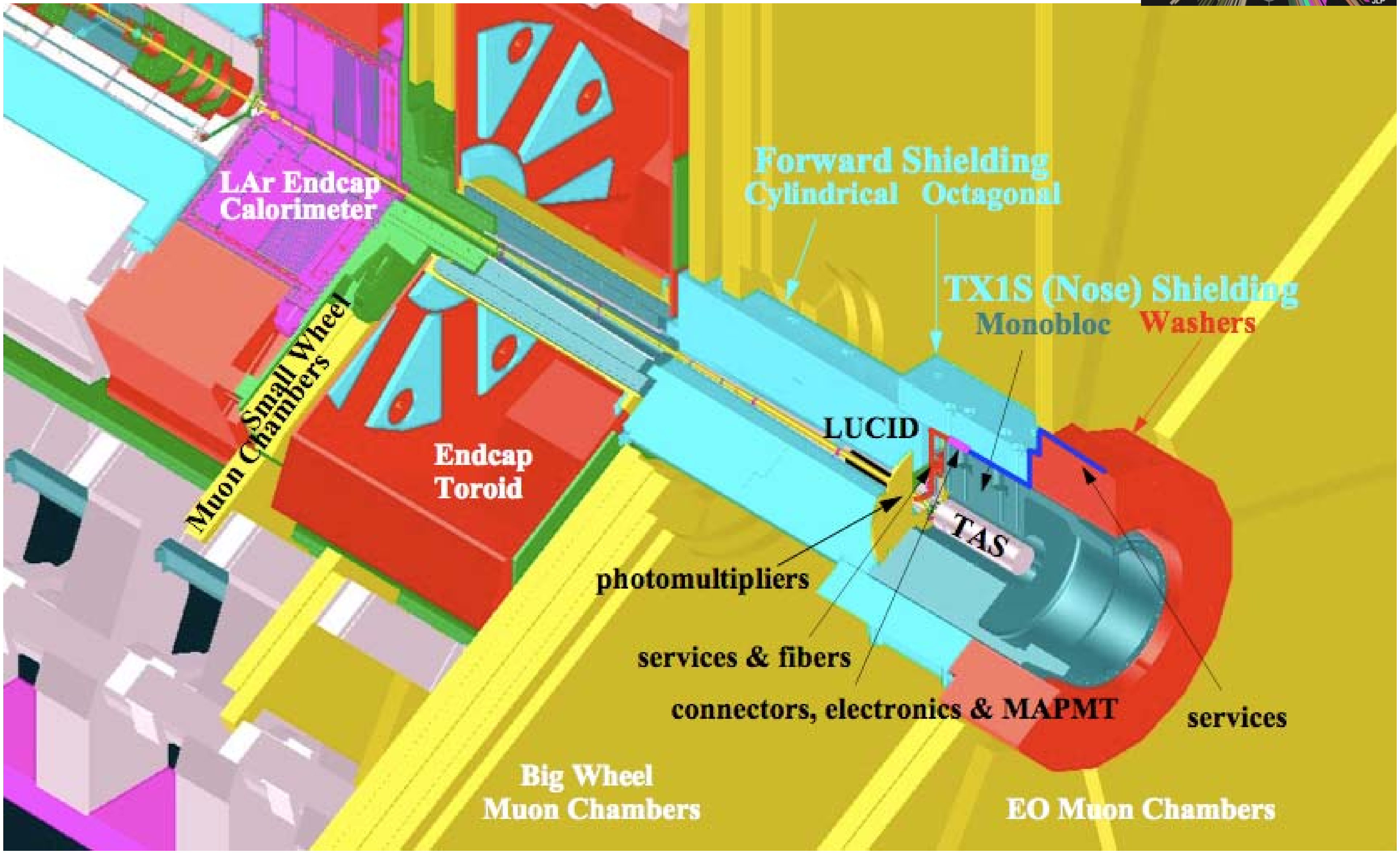
At early stages, LHC parameters will be used to estimate luminosity (ΔL=10%).
Later, the aim is the reach a precision at 2-3% level.

- At high luminosity, W and Z decays offer an alternative way to estimate luminosity
  - Studies of Monte Carlo simulations are ongoing in order to reduce the uncertainty to the minimum theoretical value (2%)

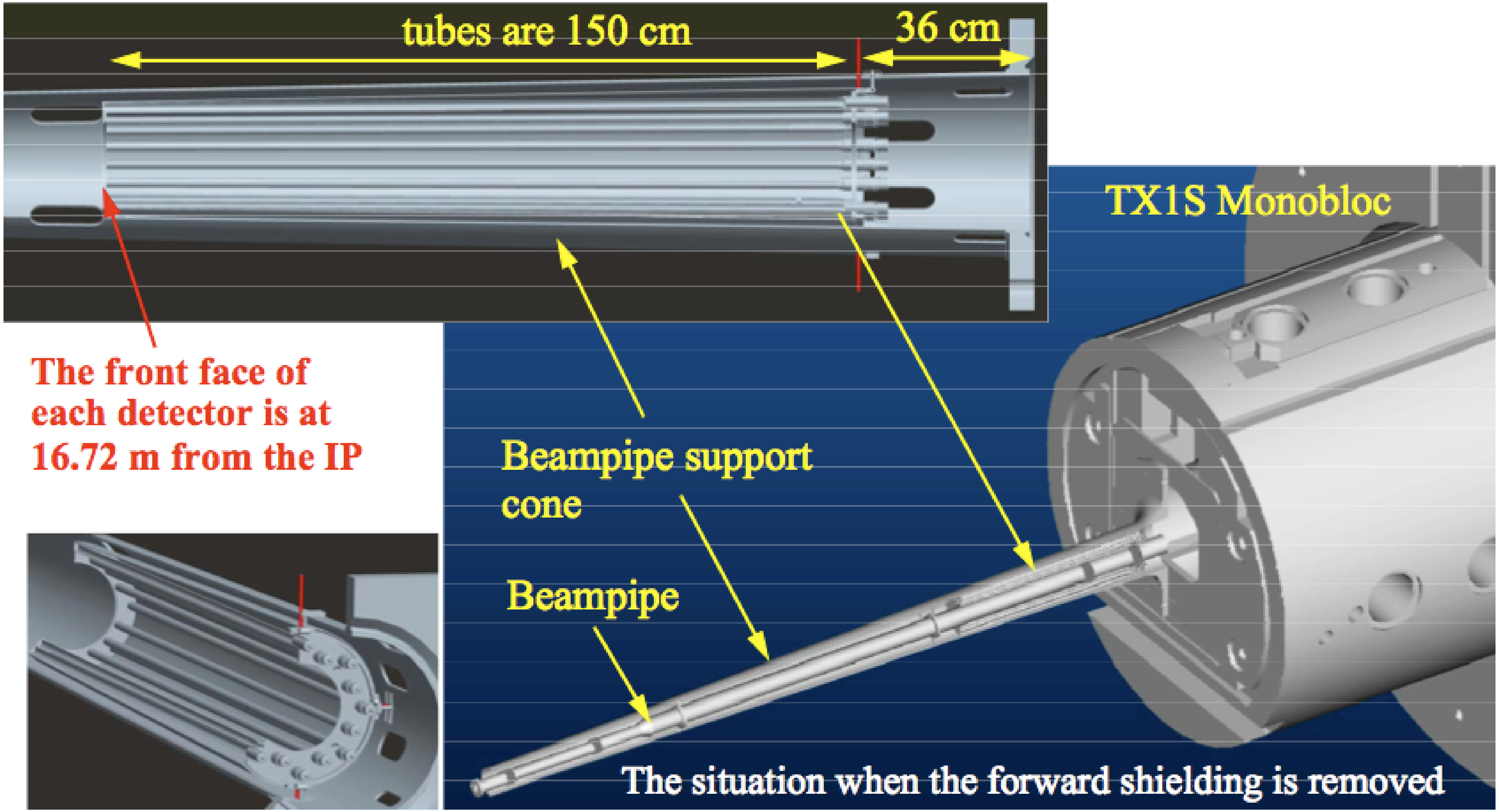
Back-up slides

Location of LUCID

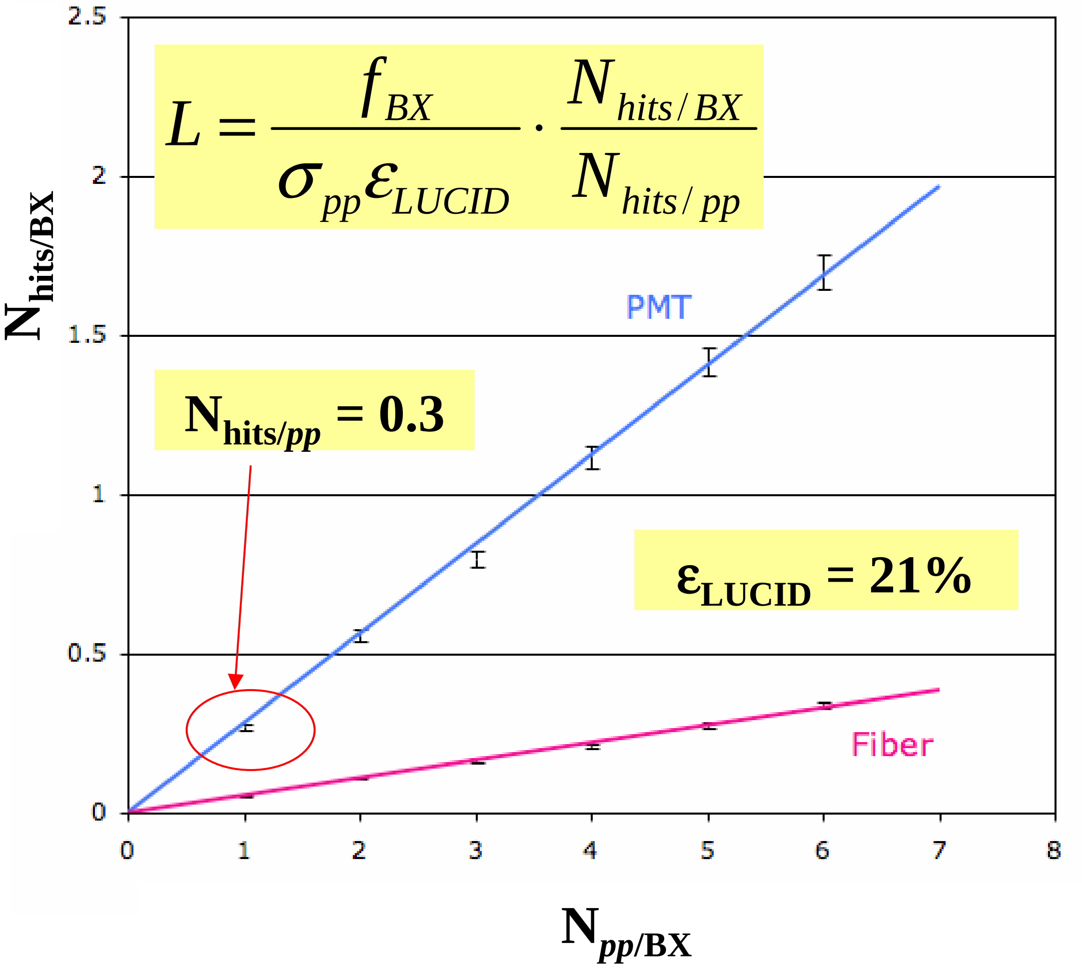




The LUCID detector

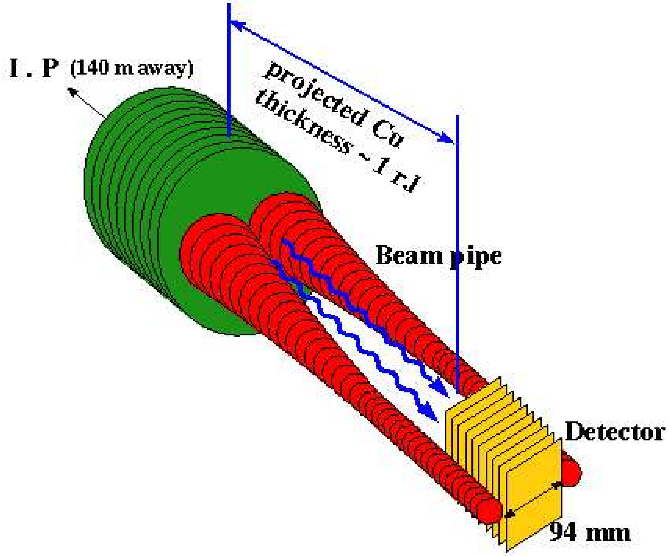


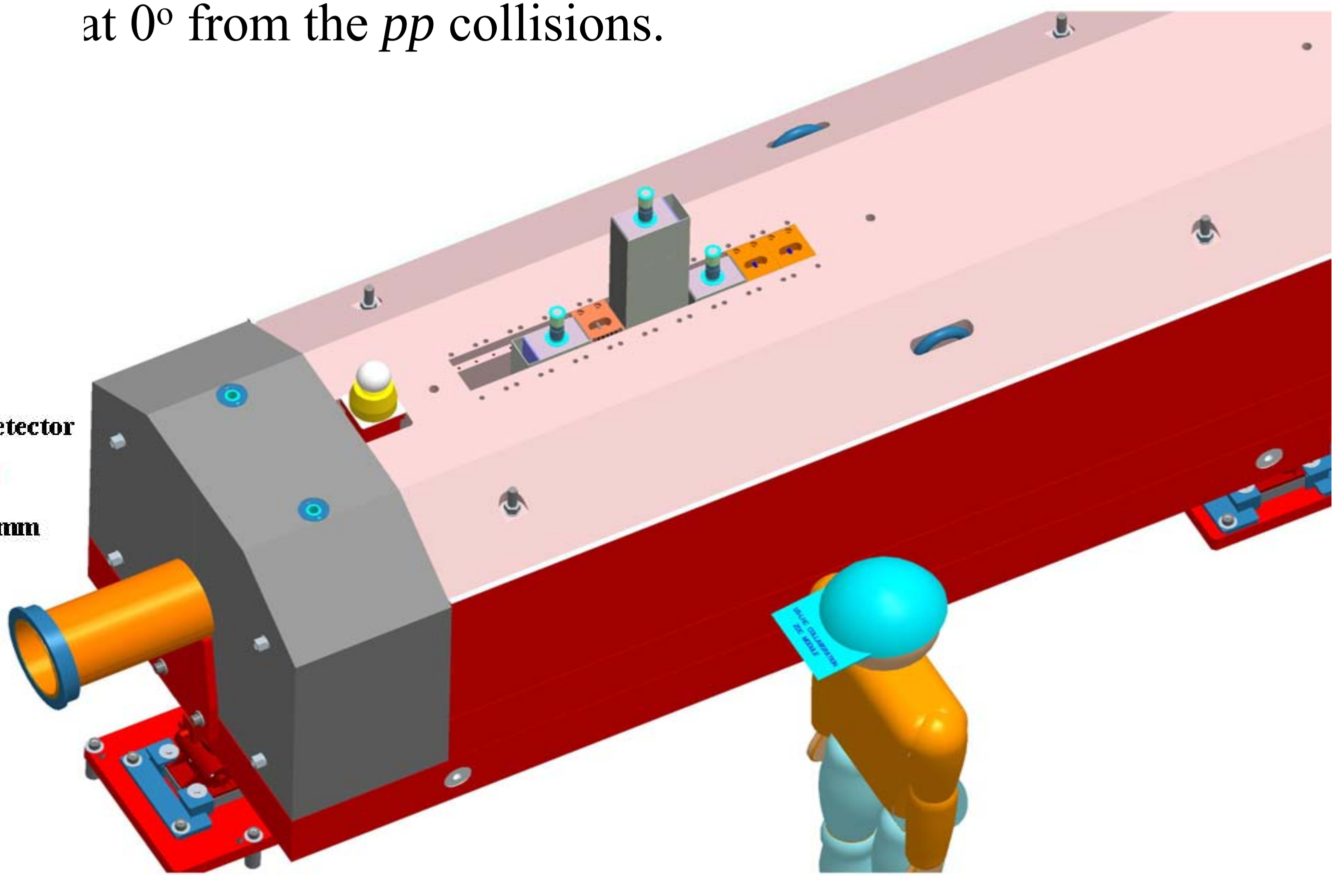
LUCID at higher luminosity



The ZDC location

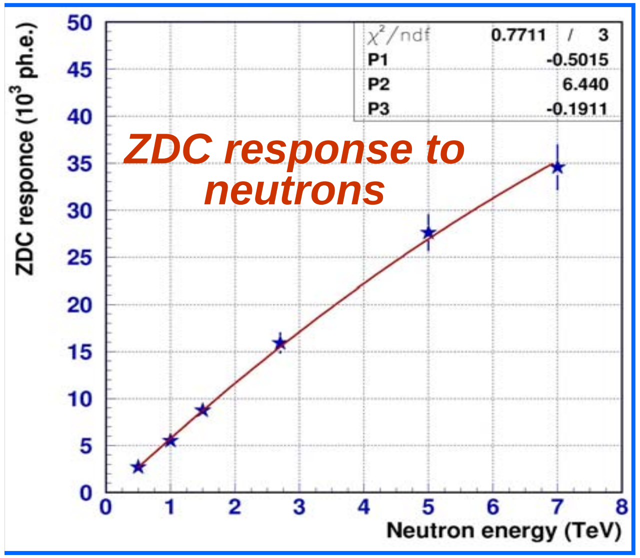
The ZDC is placed at the junction where the two beam pipes of the LHC become one, at 0° from the *pp* collisions.

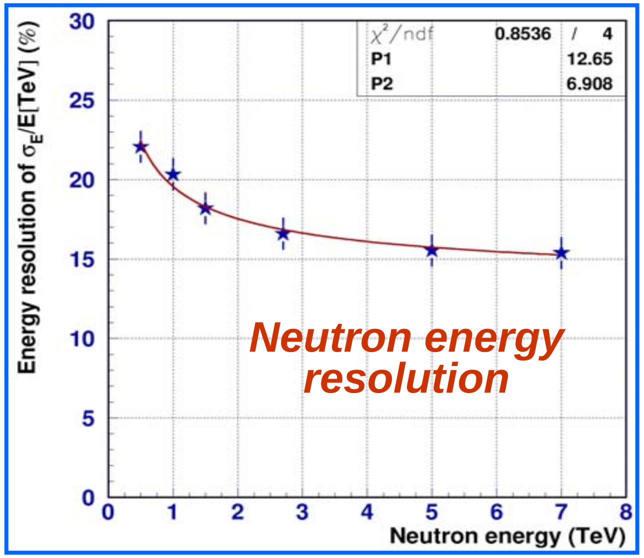


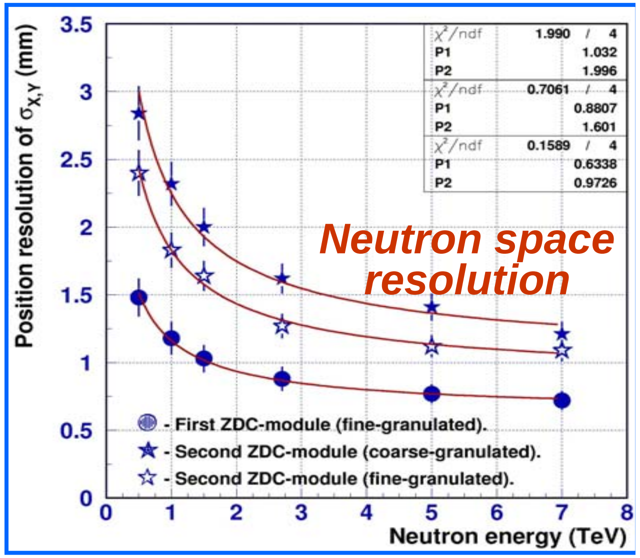


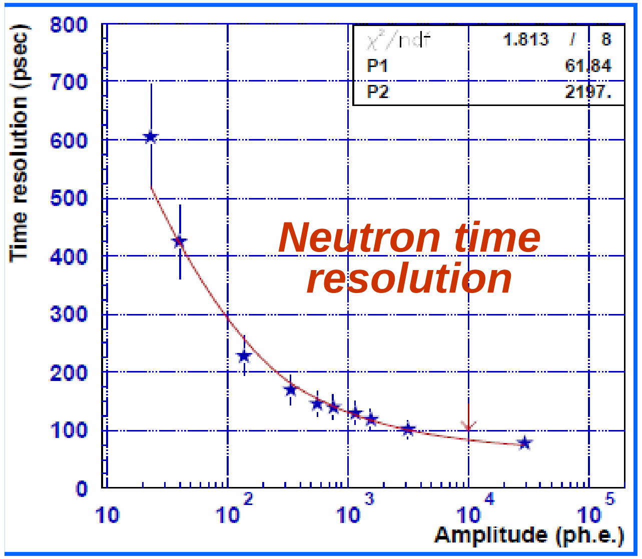
It is located in the shielding unit that protect the magnets from radiation, measuring neutral particle production (n, γ, π^0).

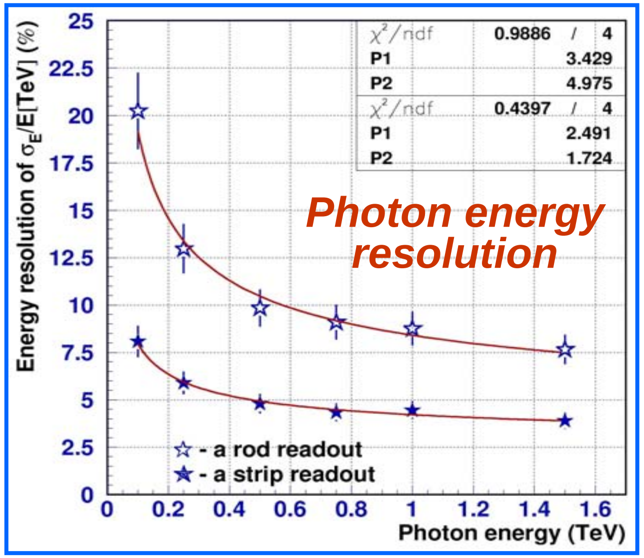
The ZDC test-beam performance

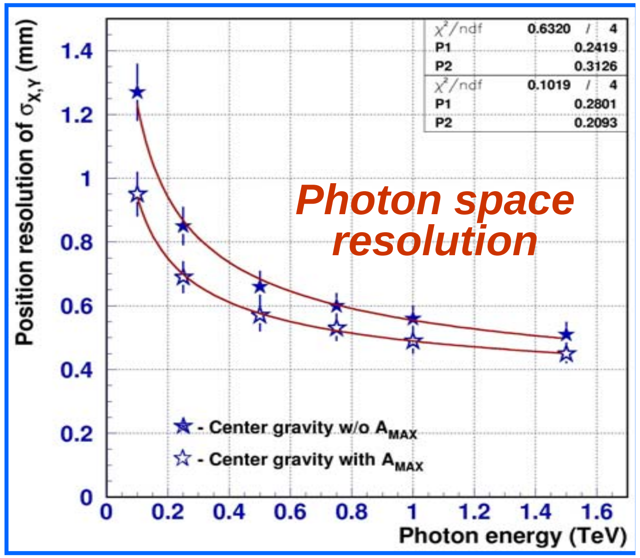






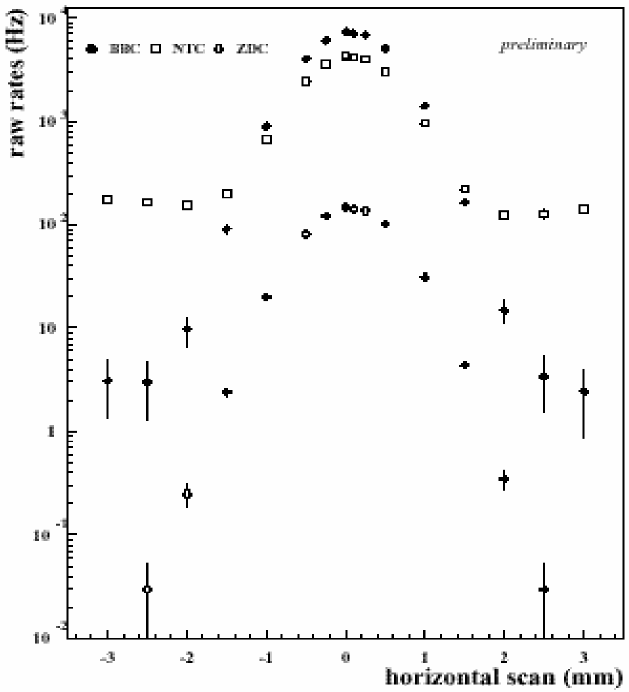






ZDC as a beam monitor

beam position monitor



crossing angle monitor