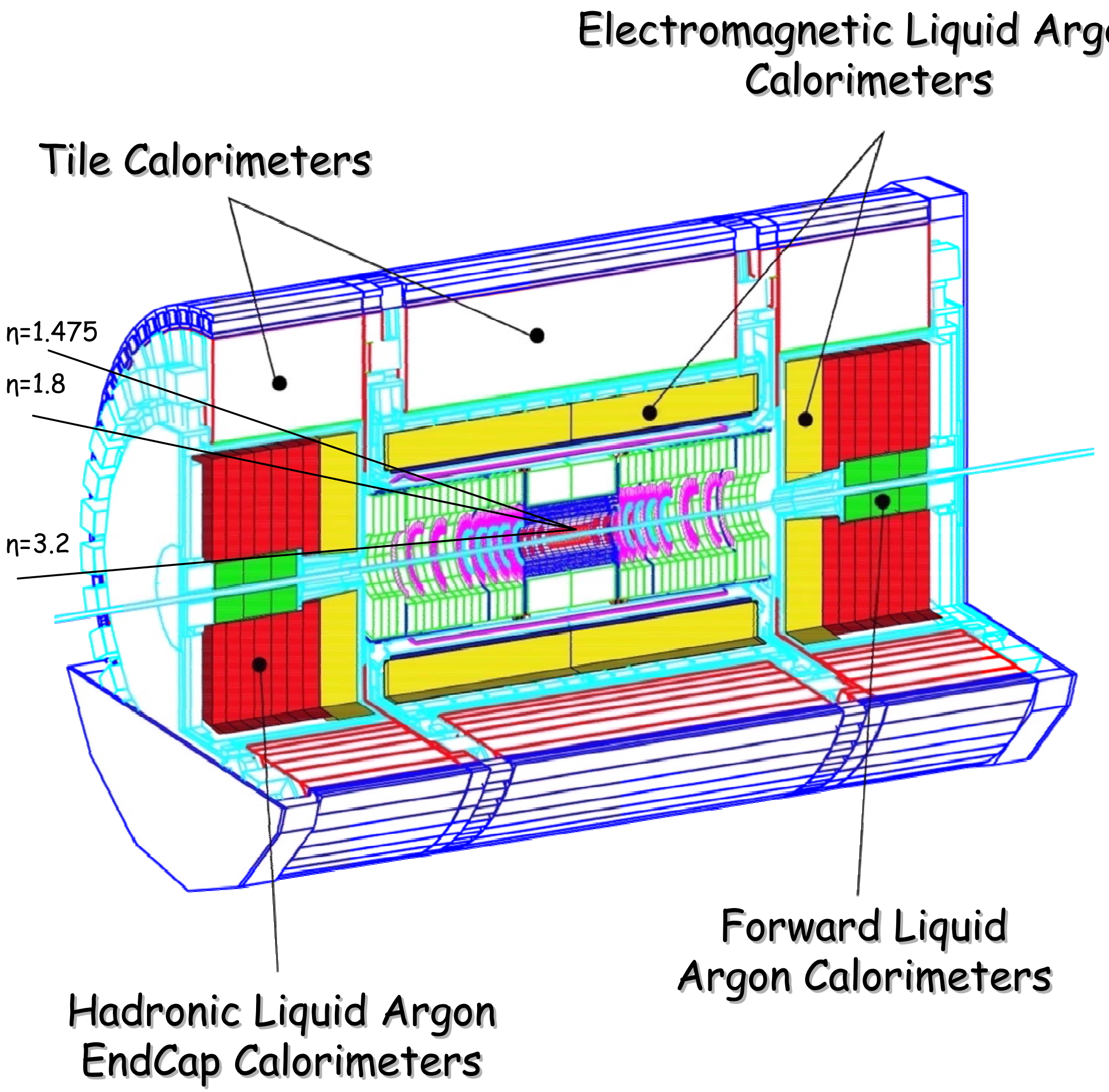
5. Calorimetry

- **Electromagnetic calorimeters**
  - **General considerations**
  - **ATLAS Lar**
  - **CMS crystals**
- **Hadronic calorimetry**
  - **Jets**
  - **Missing Et**

ATLAS Calorimeters



ECAL

Accordion Pb/LAr

$|\eta|<3.2$, 3 samplings

S1: $\Delta\eta x\Delta\phi = 0.025x0.1$

S2: $\Delta\eta x\Delta\phi = 0.025x0.025$

S3: $\Delta\eta x\Delta\phi = 0.05x0.025$

HCAL

Barrel: Fe/Scintillator with WLS fibre readout

3 samplings - $\Delta\eta x\Delta\phi = 0.1x0.1$

Endcap: Fe/LAr

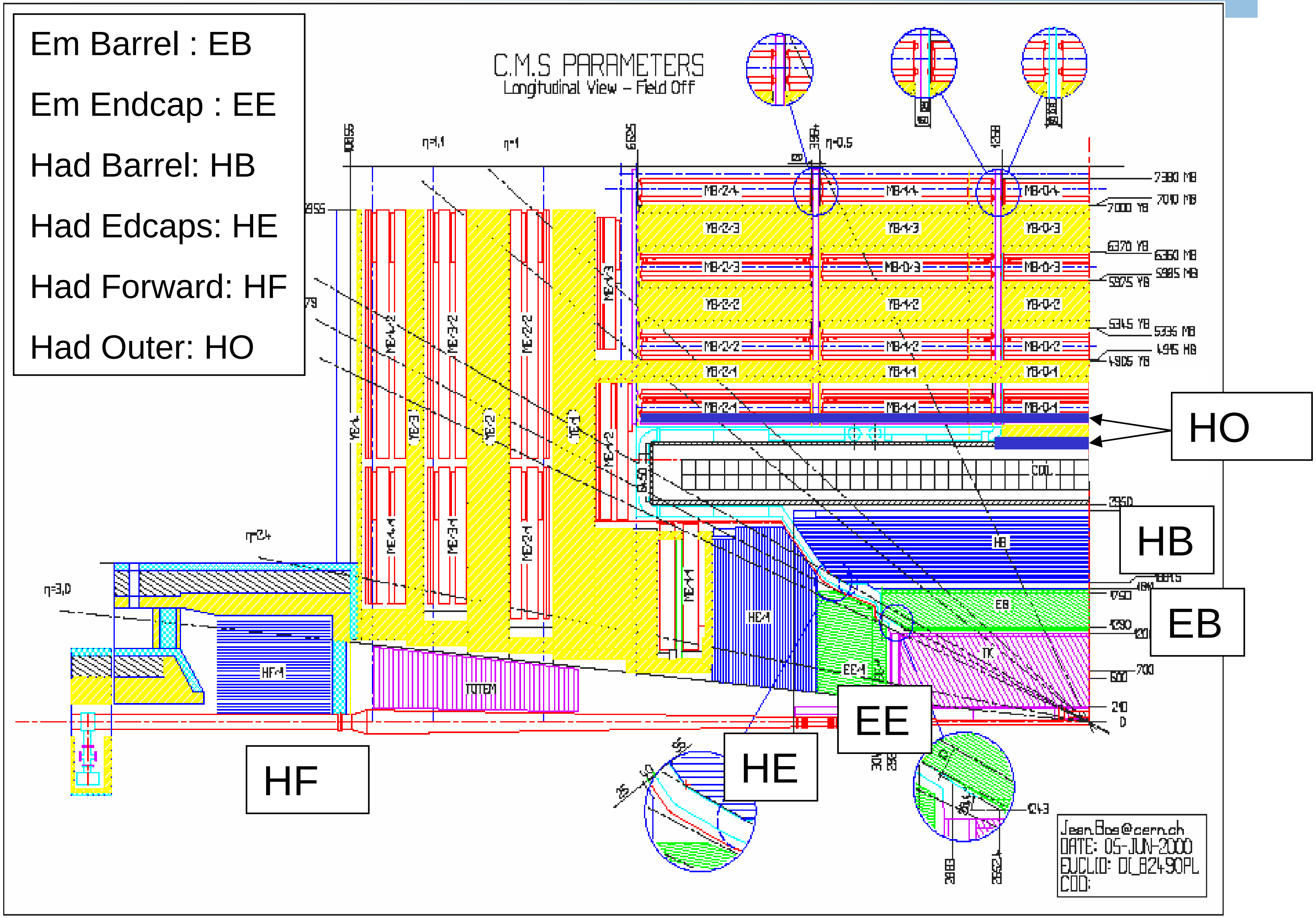
Forward: W/LAr

$3.1<|\eta|<4.9$

$\Delta\eta x\Delta\phi = 0.2x0.2$

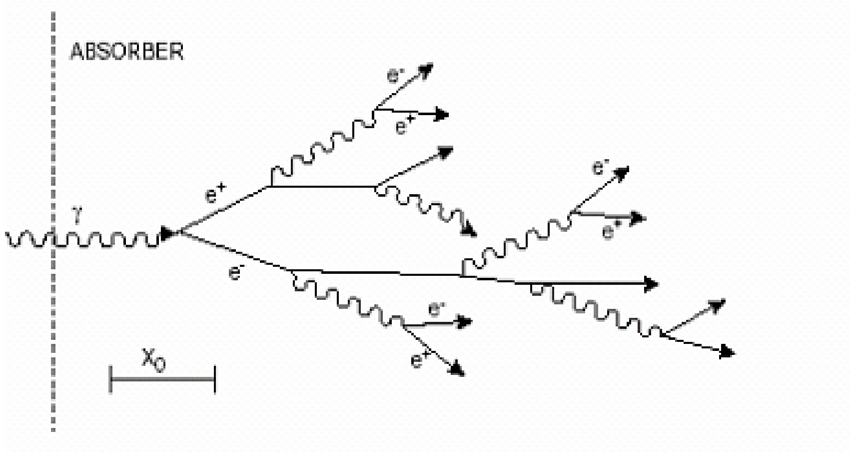
CMS Calorimeters

- Em Barrel : EB
- Em Endcap : EE
- Had Barrel: HB
- Had Edcaps: HE
- Had Forward: HF
- Had Outer: HO



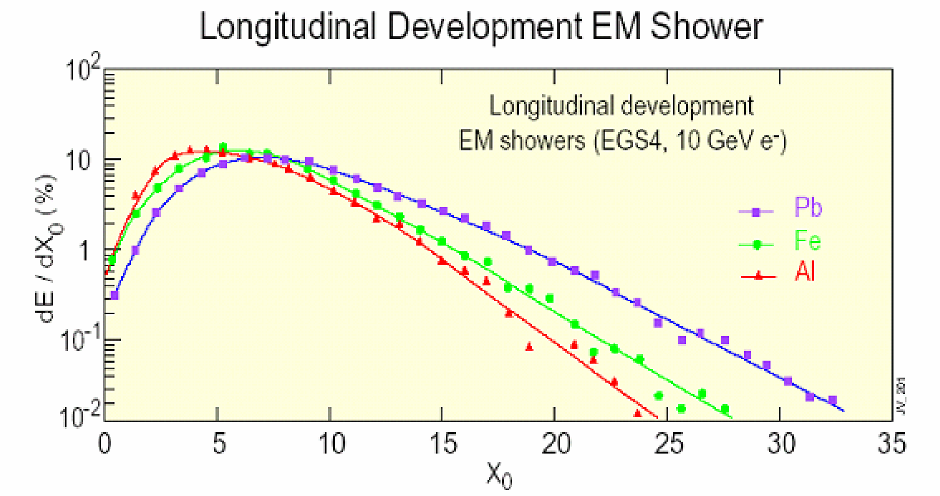
Electromagnetic cascades

A high energy e or γ initiates a cascade of e and γ's via bremsstrahlung and pair production until they fall below critical energy Ec



Characteristic length X_0 ≡radiation length
Shower can be fully measured or *sampled.*

Needs a depth of > 25 X_0 to contain a high energy em shower



Moliere Radius: average lateral deflection of critical energy electrons after 1 X_0
Characteristic of lateral development

Energy Resolution of Calorimeters

Parametrisation of the energy resolution of calorimeters:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \otimes \frac{b}{E} \otimes c$$

symbol ⊕ implies the quadratic sum of the three terms on rhs

'stochastic or sampling' term (coeff. a) accounts for

- the statistical fluctuation in the number of primary signal generating processes

'noise' term (coeff. b) includes

- the energy equivalent of the electronics noise and
- pileup - the fluctuation of energy entering the measurement area from other sources

'constant' term (coeff. c) accounts for

- non-uniformity of signal generation and/or collection
- the cell to cell inter-calibration error
- the fluctuation in the amount of energy leakage
- fluctuation in the e.m. component for hadronic showers

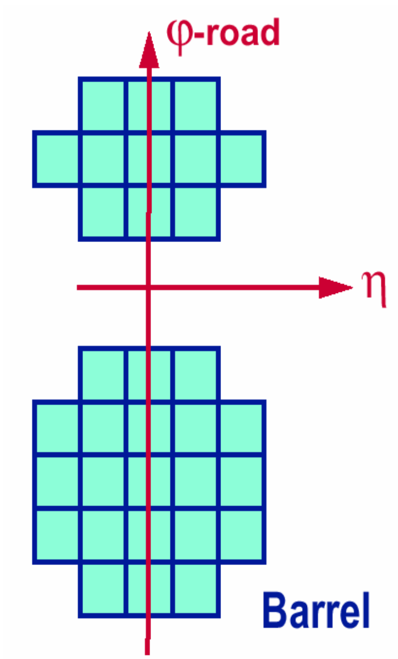
- The tolerable value of the 3 terms depends on the energy range of interest.
- Such parametrisations allow the identification of the causes of resolution degradation.
- Quadratic summation implies independent contributions which may not be the case.

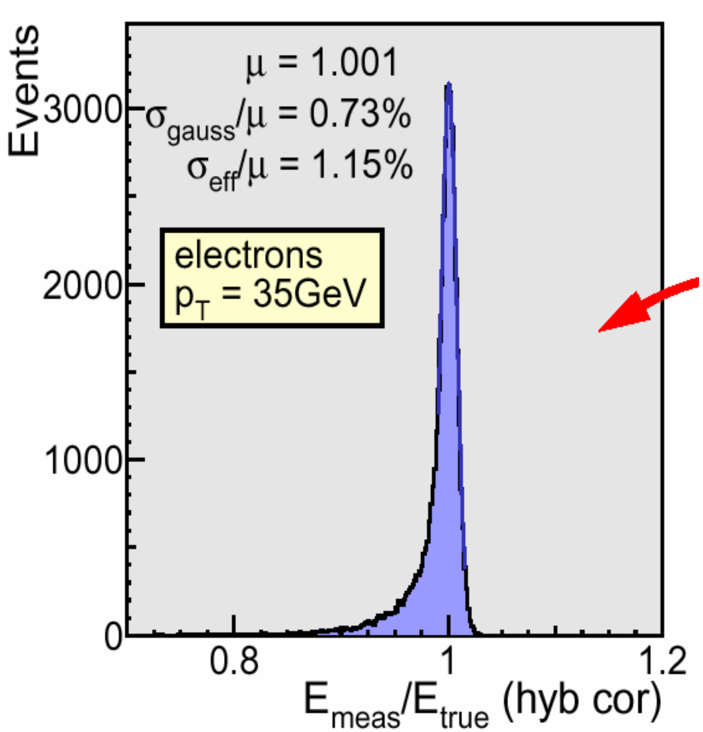
Electron Reconstruction

Reconstruction of electrons that radiate little (and unconverted γs) is simple : **collect energy in an array of 3x3 or 5 x 5 cells** centred on ~ impact point

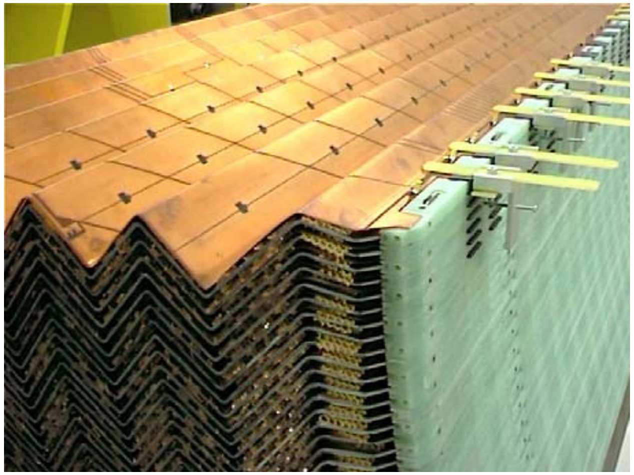
For ‘bremming’ e’s and converting γ’s, challenge is in coping with the combined result of tracker material and the magnetic field

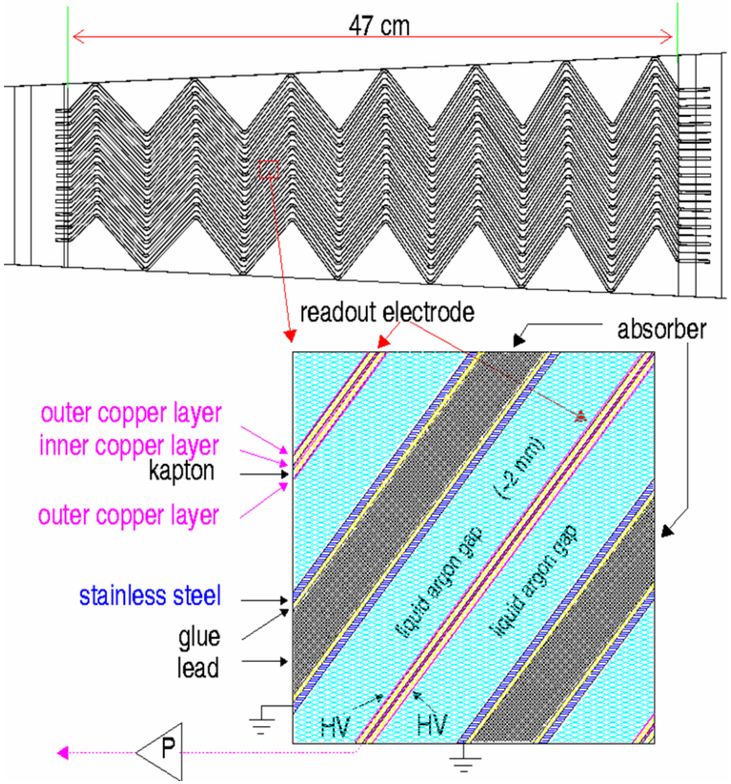
– problem is not energy loss but spraying/spreading of energy



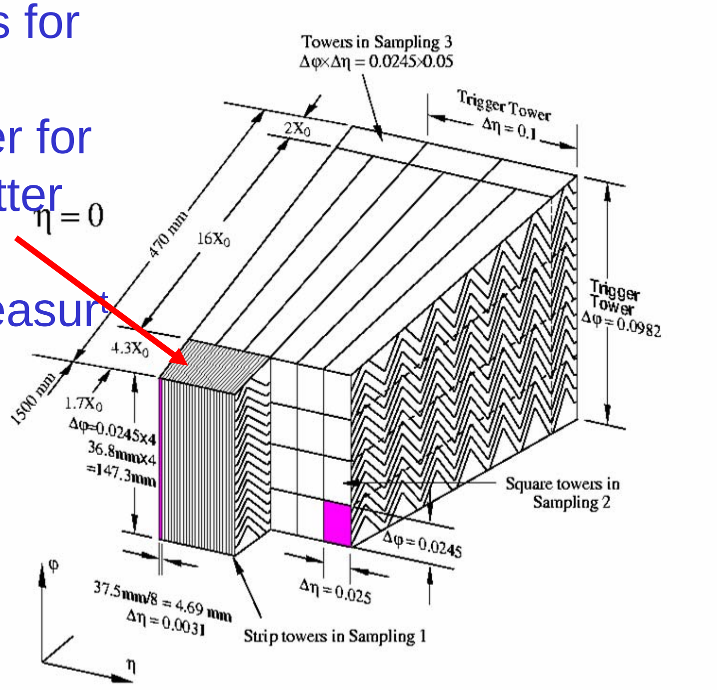


ATLAS: LAr sampling Em Calorimeter



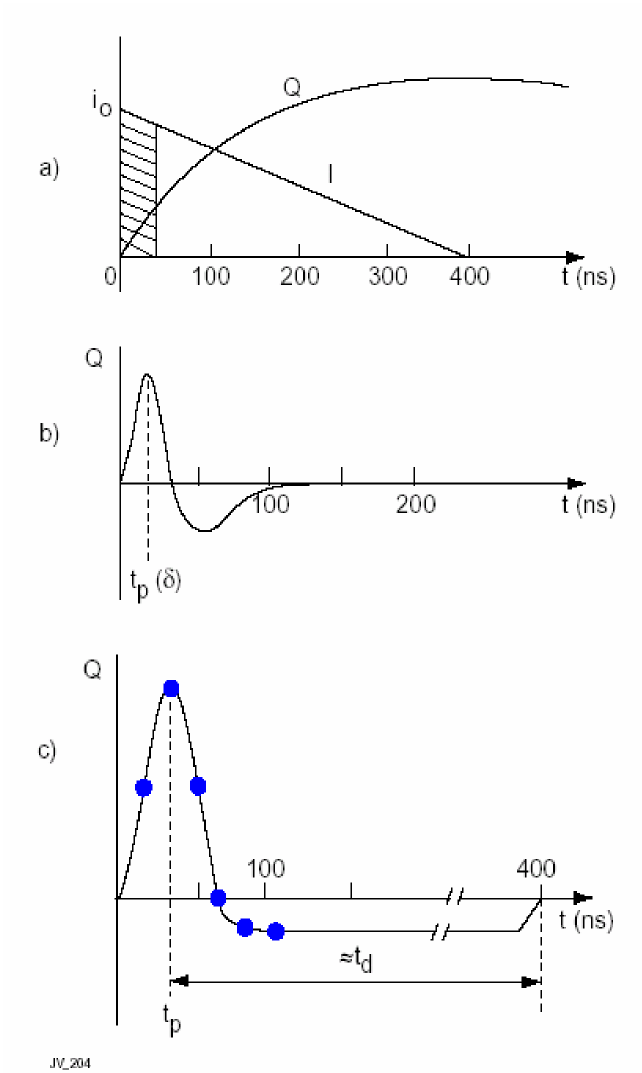


Fine strips for γ/π^0
Presampler for dead matter
and
Angular measur



Accordion geometry benefits :
No cracks in φ
Challenge: constant Ar gap, very precise mechanics
Advantage : good stability

ATLAS LAr Calorimeter: signal shaping

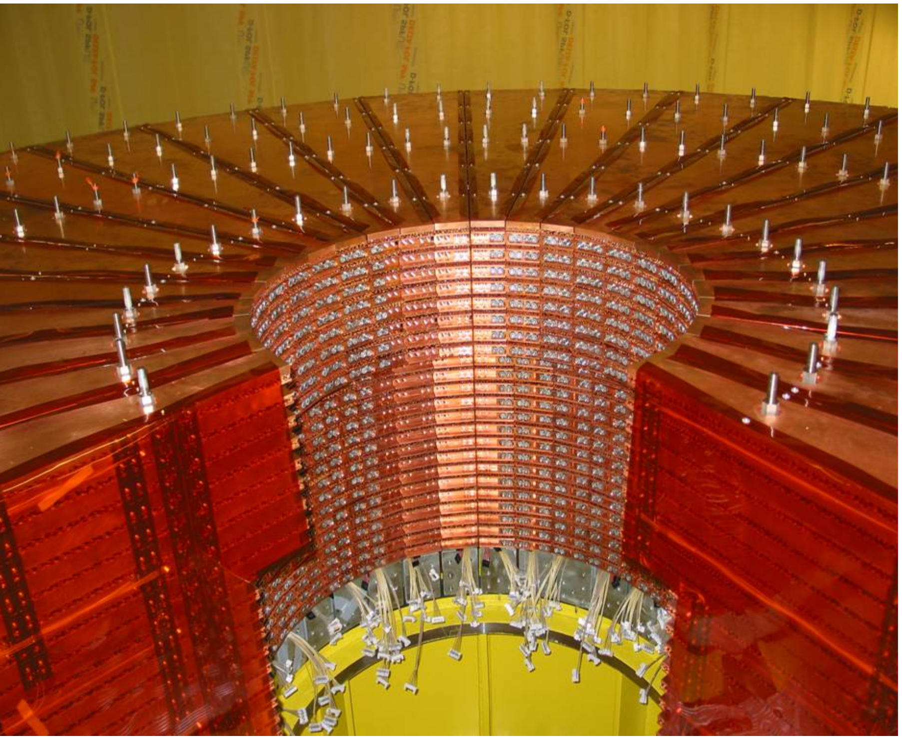


Induced current duration = electron drift time t_d (~450 ns for ATLAS) with a triangular shape

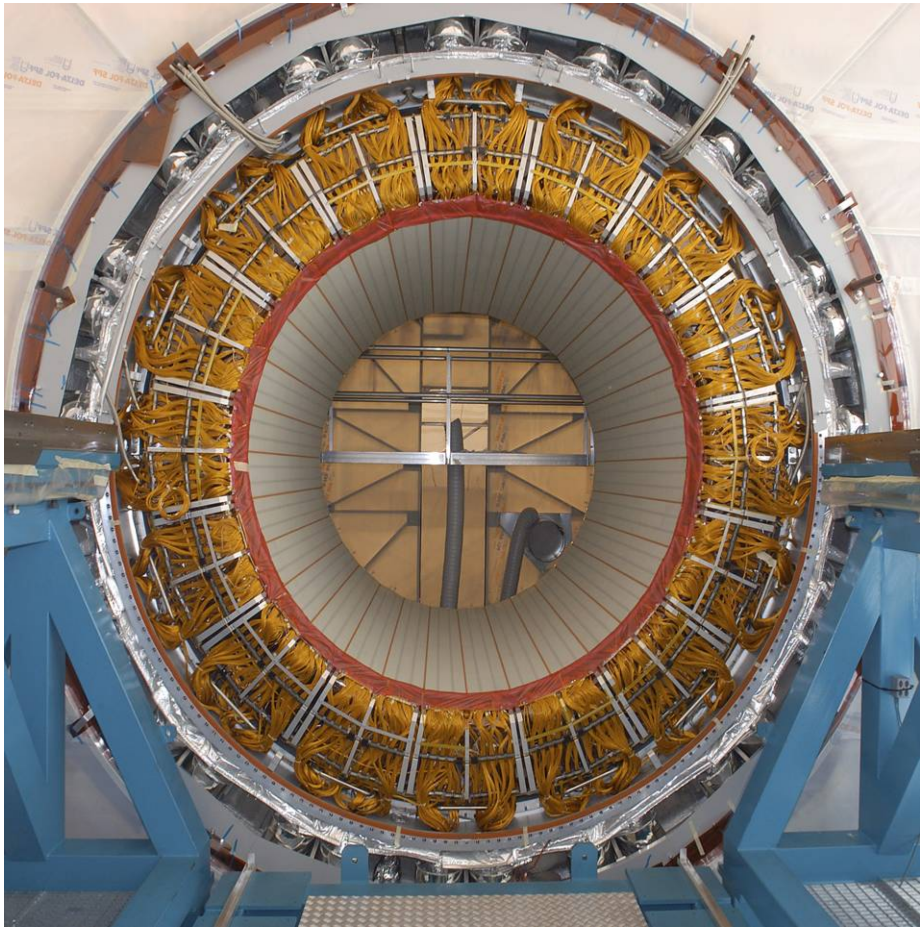
Bipolar preamp-shaper (RC-CR) with zero area to avoid baseline shift by pileup

For $t_p << t_d$ Output response essentially derivative of current pulse .
Max proportional to I_0

ATLAS: LAr Calorimeter



Assembly of the first HEC wheel (horizontal)

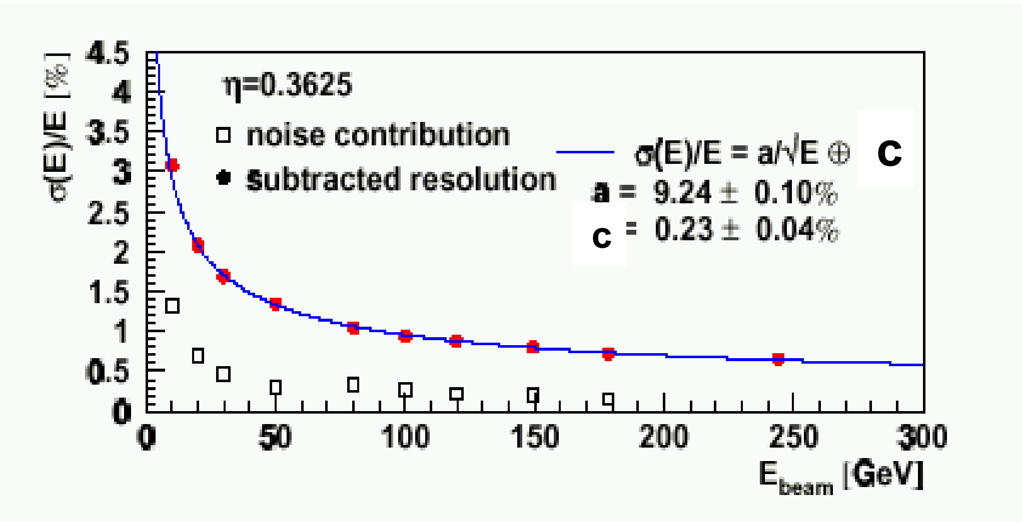


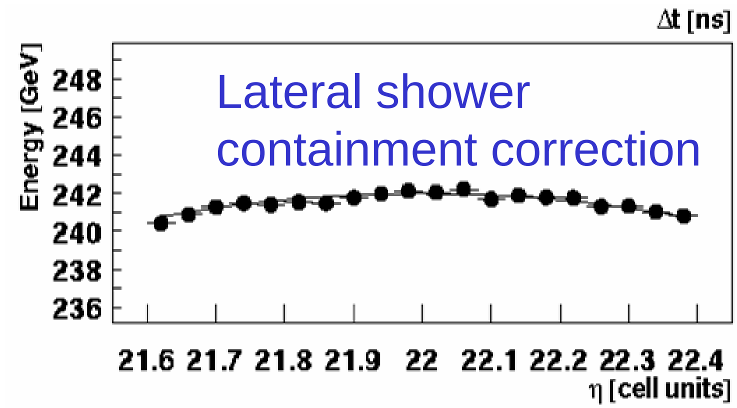
LAr EM half barrel after insertion into the cryostat

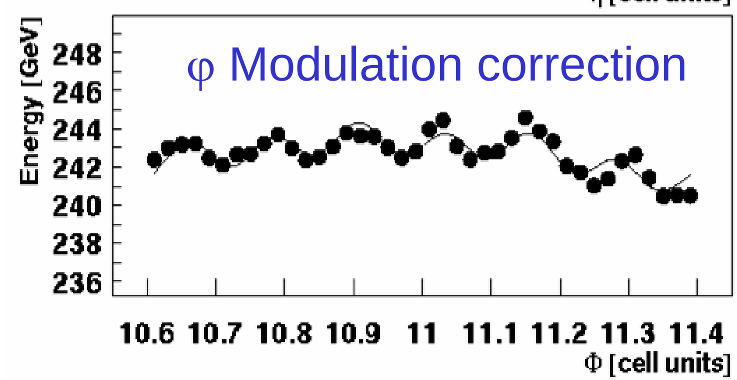
ATLAS : solenoid and LAr in common cryostat

(The ECAL is AFTER the coil)

ATLAS: LAr Calorimeter







Target a = 10%

c = 300 MeV (3x3 cluster)

b < 0.7% (0.5% locally)

CMS : crystal $PbWO_4$ em calorimeter

- Excellent energy resolution (
  - Structural compactness, easy assembly
  - Tower structure, fine transverse granularity

PbWO4

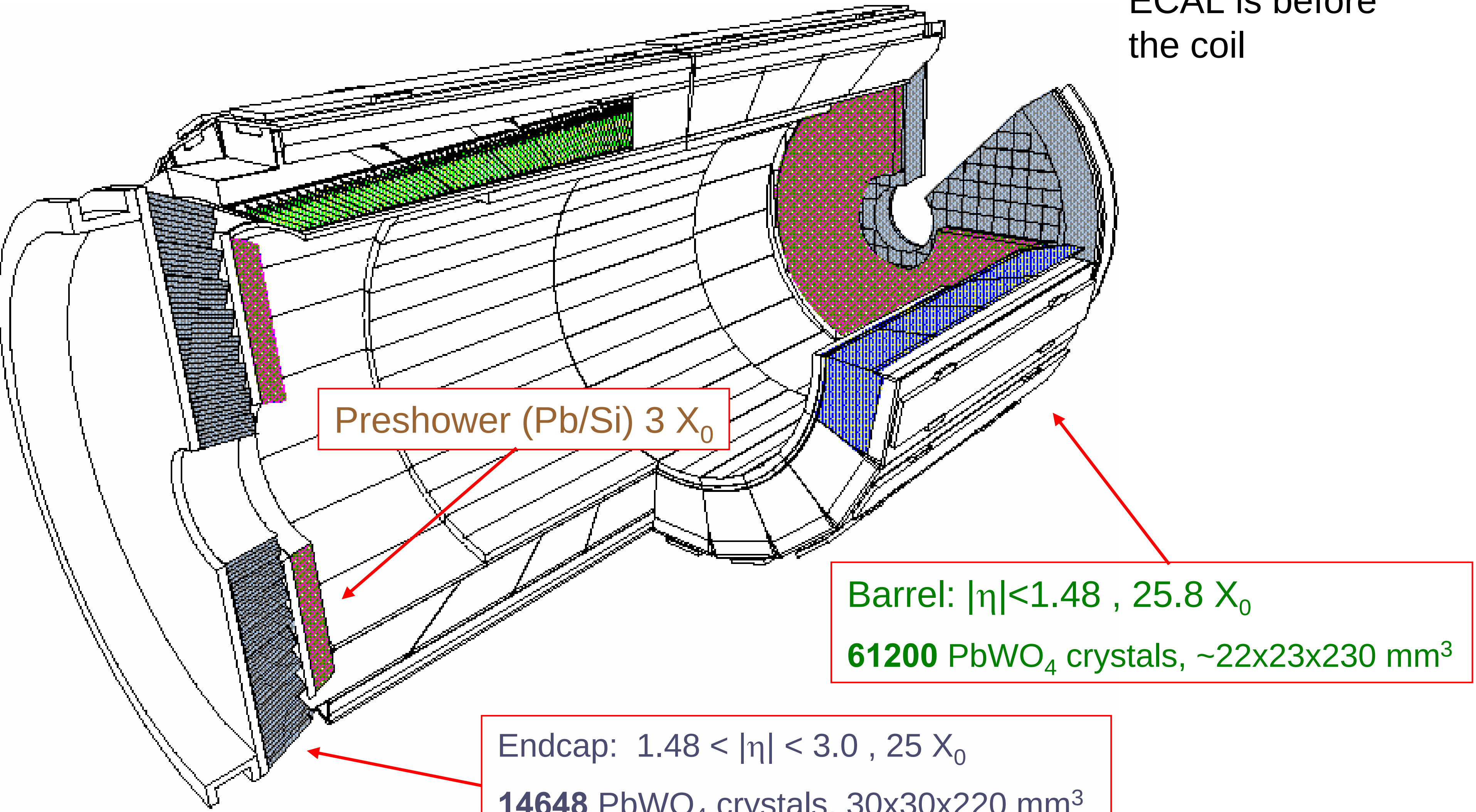
- Fast scintillation
- Small X_0 and R_m
- Intrinsic radiation hardness
- Relatively easy to grow
- Massive production capability

- Low Light Yield
- Strong L.Y. dependence on T
- Small loss of transparency with radiation
- [No longitudinal segmentation], no anglar measurement

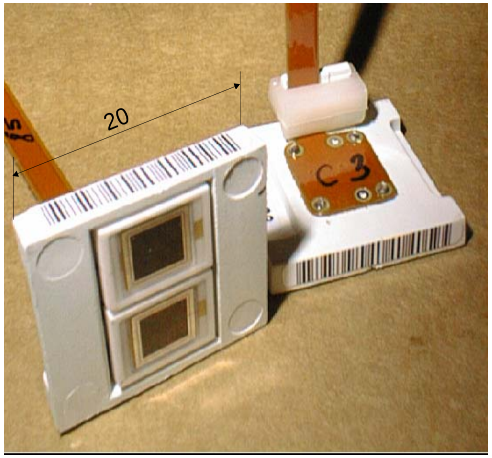
Parameter		Value
Radiation length	cm	0.89
Moliere radius	cm	2.2
Hardness	Moh	4
Refractive index		2.3
Peak emission	nm	440
% of light in 25 ns		80%
Light yield (23 cm)	γ/MeV	100

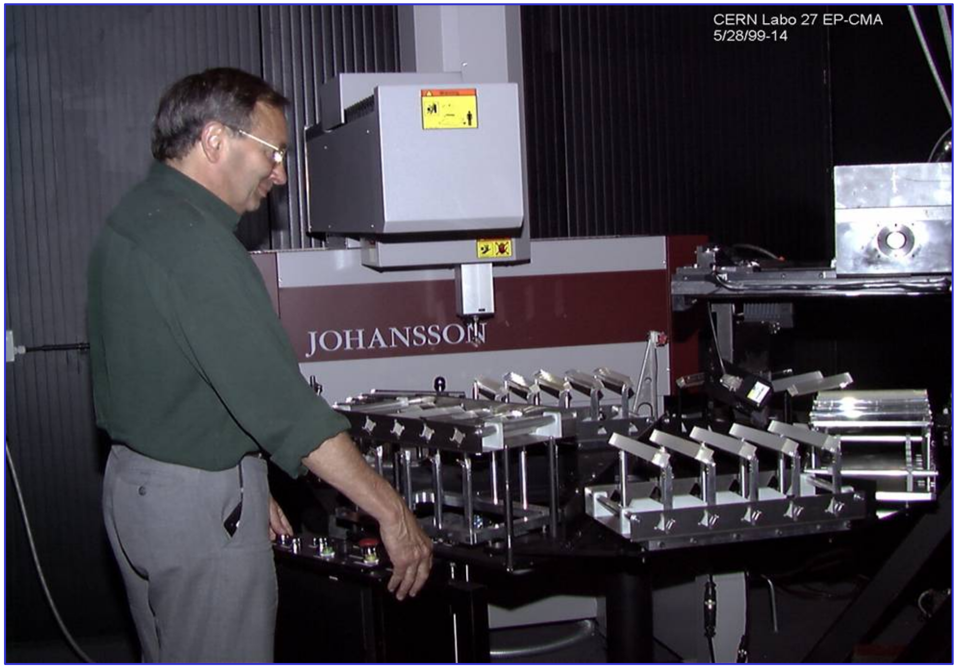
CMS ECAL Structure

ECAL is before the coil

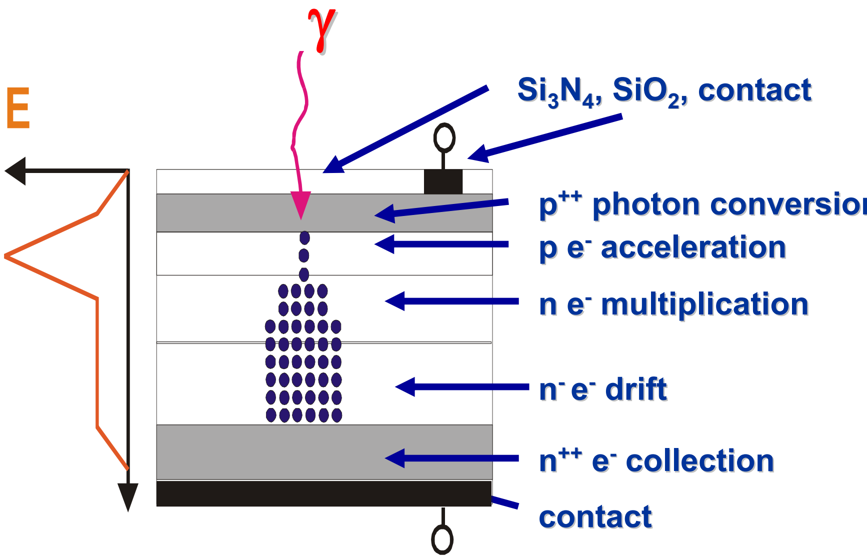


CMS: Crystals & APDs

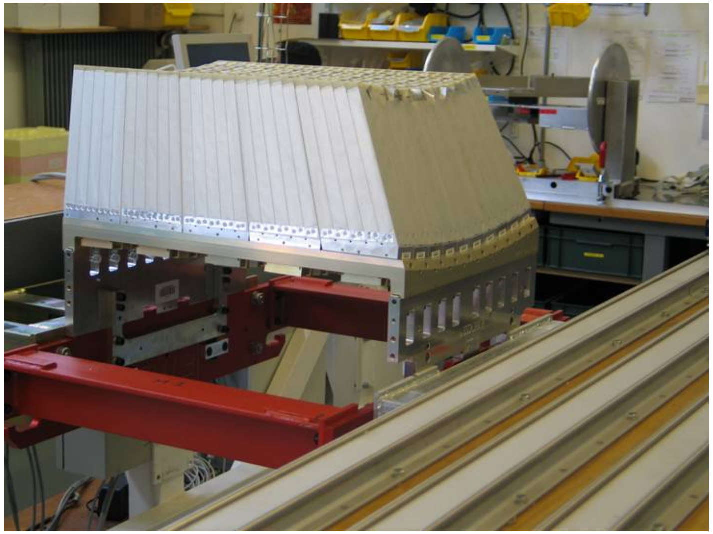


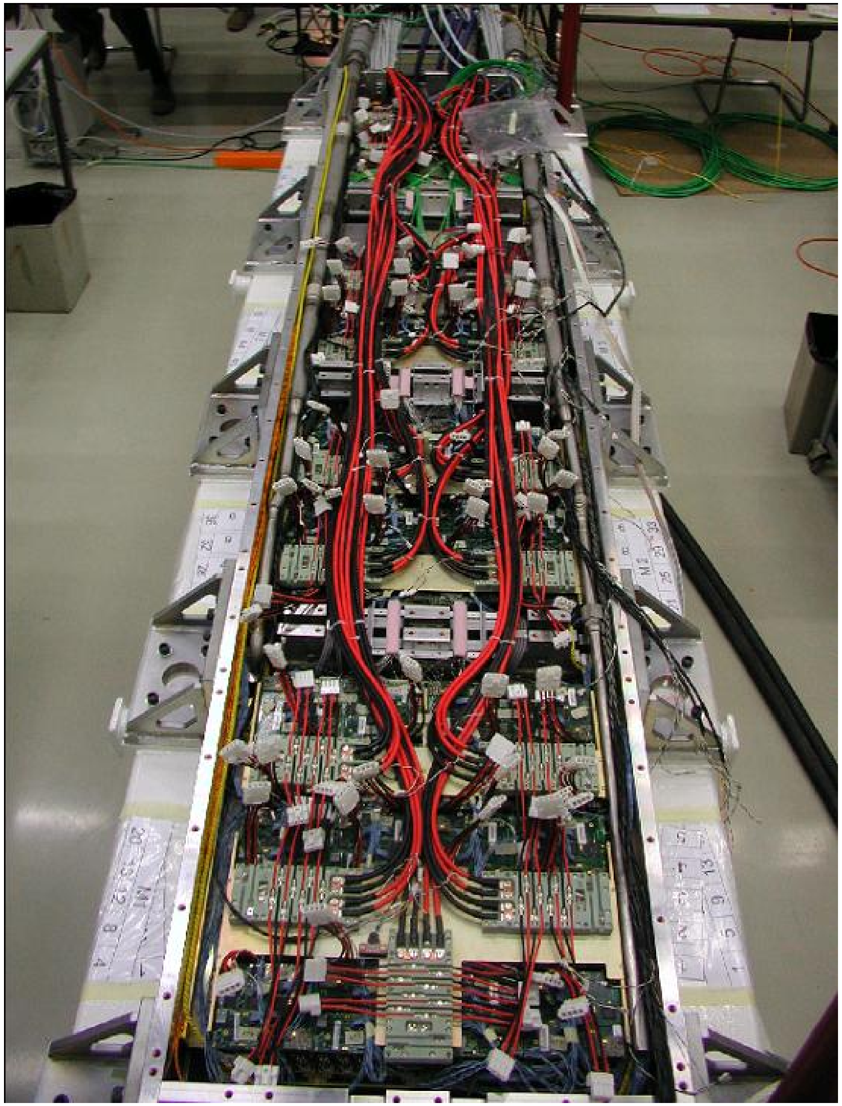


Si Avalanche Photodiodes



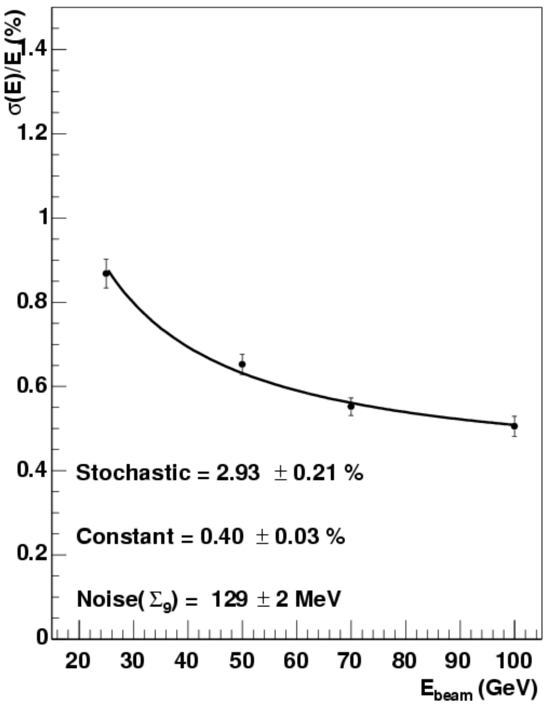
CMS: ECAL Module and Supermodule

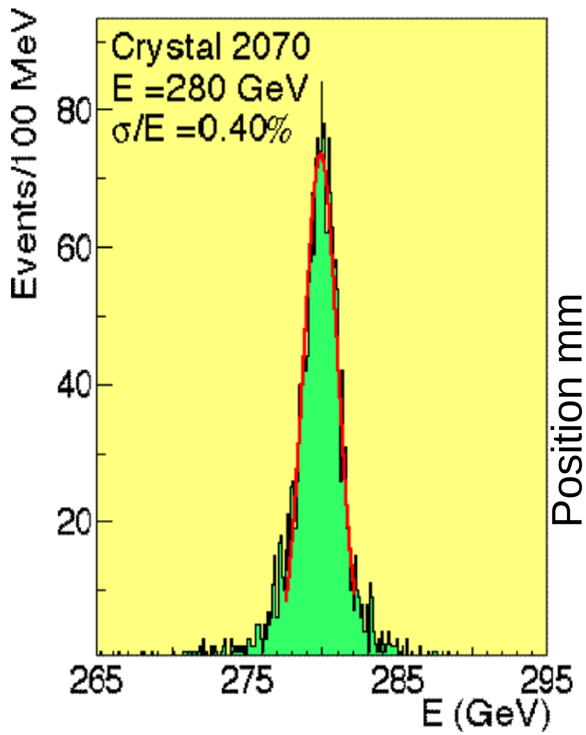


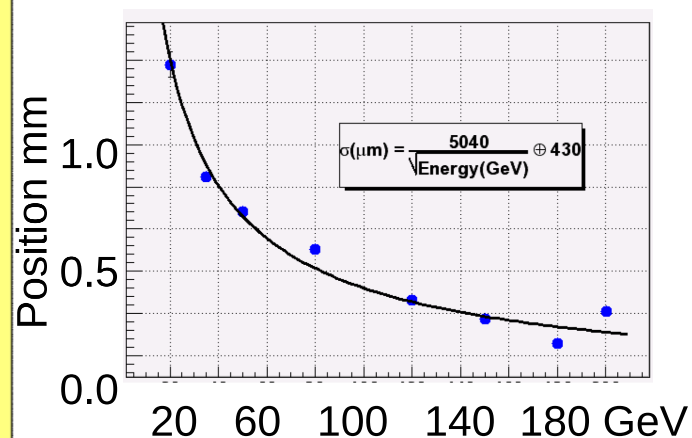


CMS ECAL: Performance

3 x 3 Crystals







$$\sigma_x(E) = \frac{5040}{\sqrt{E}} \oplus 430 \quad (\mu m)$$

Goal

0.85 mm at 50 GeV

CMS ECAL : Need for light monitoring

Colour centres form in PWO under irrad^{n}

Transparency loss depends on dose rate

Equilibrium is reached after a low dose

Partial recovery occurs in a few hours

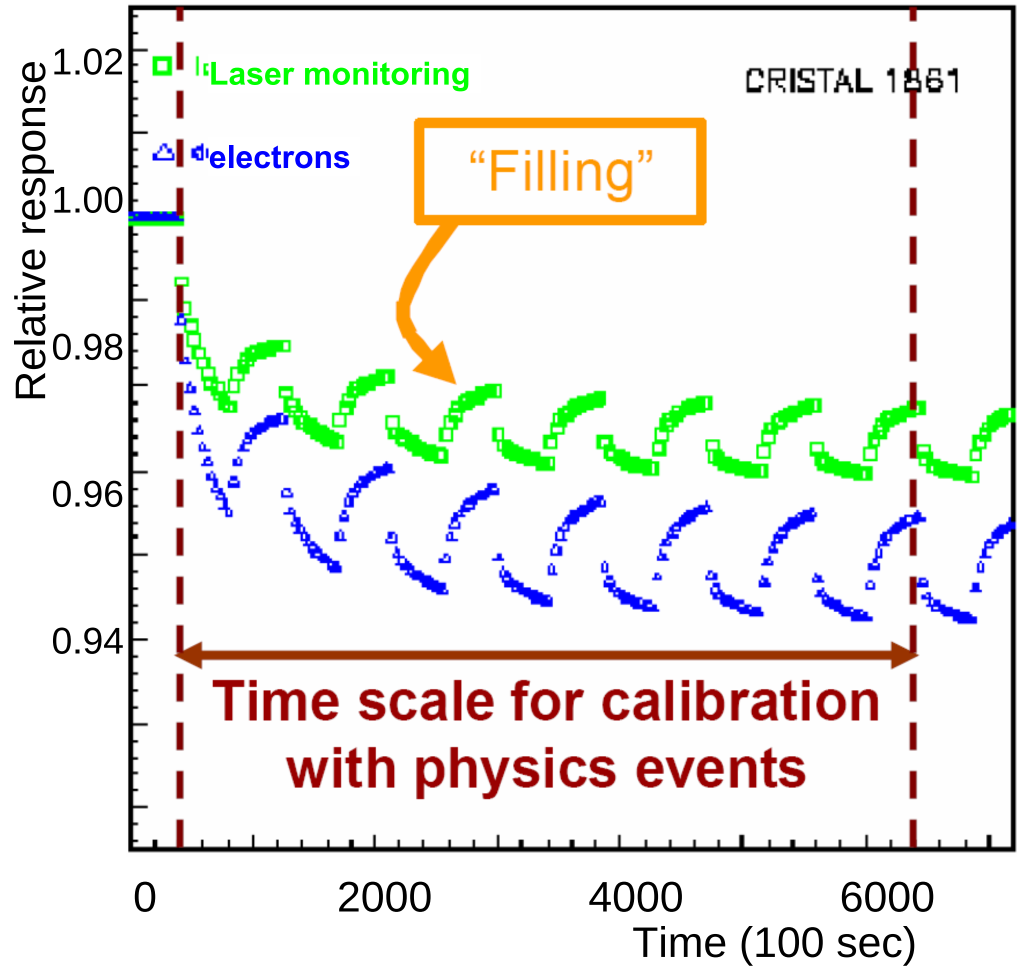
Damage and recovery during LHC cycles tracked with a laser monitoring system

2 lasers provide 4 wavelengths: 440/495 nm and 700/800 nm

Light is injected into each crystal

Stability monitored with PN diodes (0.05%)

Simulation for high luminosity at $\eta = 0$ based on test beam results



ECAL Calibration : CMS example

- Precalibration:
  - Lab measurements, **< 5%**
  - cosmics **< 3%**
  - Few SMs in test beam

intercalibration goes directly into constant term
(most of the energy in a single crystal)

In-situ calibration: **at low Lumi**

A) Fast intercalibration using Φ **- symmetry**, **≈2%** **few hours**

B) Use $\mathbf{Z \to e^+e^-}$ for intercalib in η and absolute E scale **few days**

C) When tracker fully operational : E/p from $\mathbf{W \to e\nu}$ **few months**

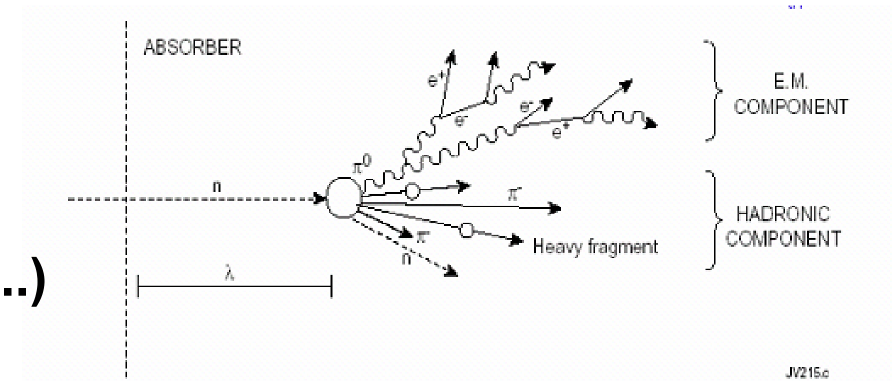
Final goal : **0.5 %**

Laser monitoring:

Correct for variations in crystal transparency due to irradiation

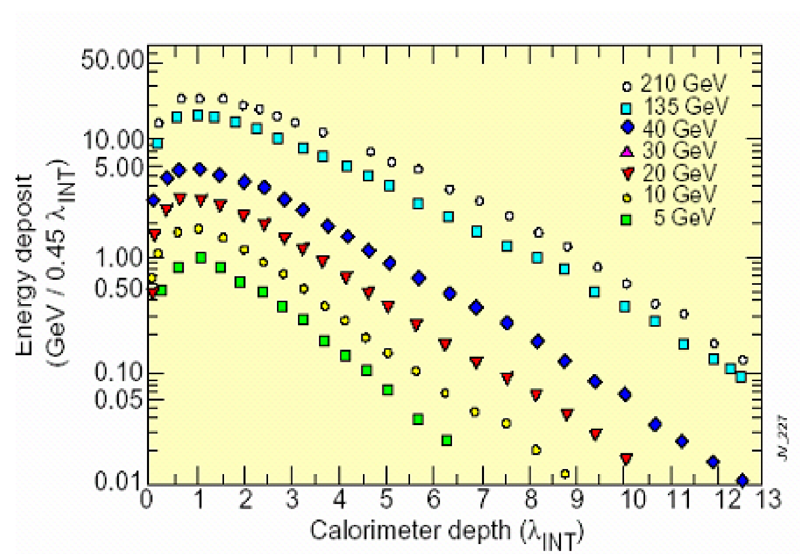
Hadronic cascades

Similar to em shower
but strong interaction responsible
for cascading effect :
Multi-particle production (π^0, $\pi^\pm$, K etc..)
& nuclear break up
until π production threshold



Characteristic length λ
≡nuclear interaction length

About 10 λ necessary to contain 99% of energy of 200 GeV pion

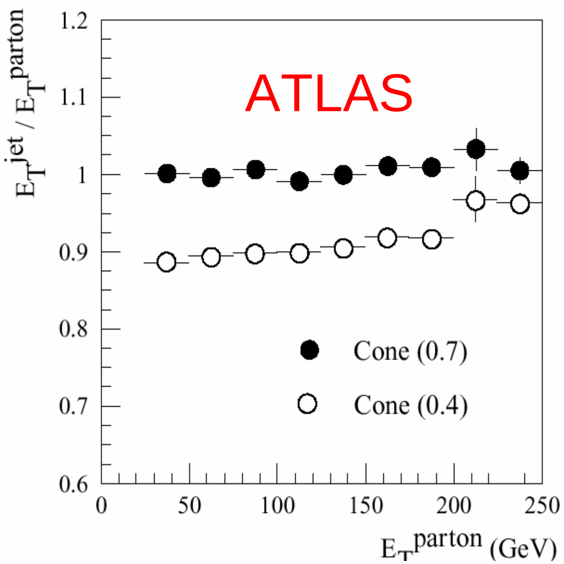


High pt quarks/gluons hadronize giving narrow JETS

Hadronic Calorimetry

- **Hadron calorimeter requirements**
  - Jet energy resolution: limited by jet algorithm, fragmentation, magnetic field and pileup at high luminosity
    - A good figure of merit: width of the jet-jet mass distribution
      - → Low-p_T jets: W, Z → Jet-Jet, e.g. in top decays
      - → High-p_T jets: Z' → Jet Jet (M(Z')~1 TeV)
    - At very high-p_T: need fine lateral granularity (for very collimated jets)
  - Missing transverse energy resolution
    - Gluino and squark production/decay
      - → Forward coverage to $|\eta|<5$
      - → Hermeticity – minimize cracks and dead areas
      - → Absence of tails in energy distribution: more important that a low value in the stochastic term
    - Good forward coverage required to tag processes from vector-boson fusion

Jet Reconstruction

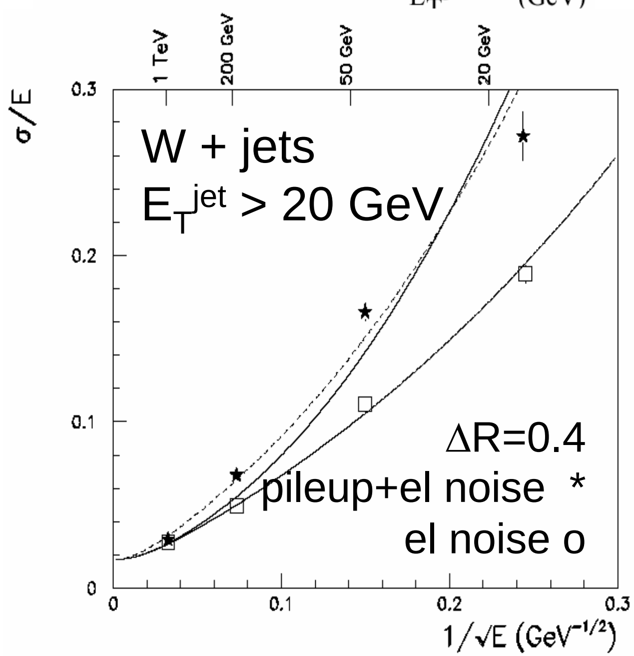


Classical 'cone' algorithm - jet built around a seed

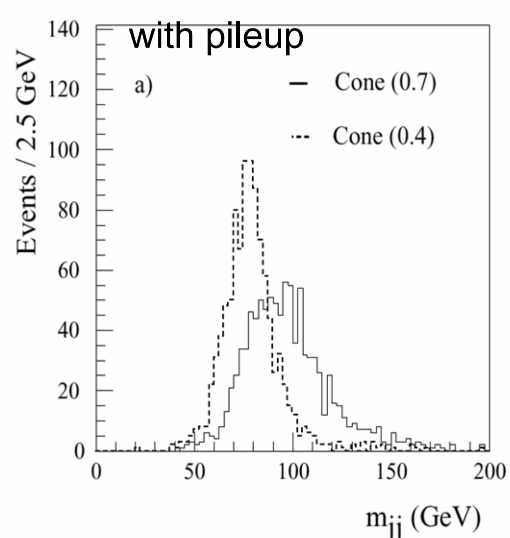
- parameters: E_T^{seed} cut, cone opening radius ΔR

ATLAS: W → jet-jet mass resolution

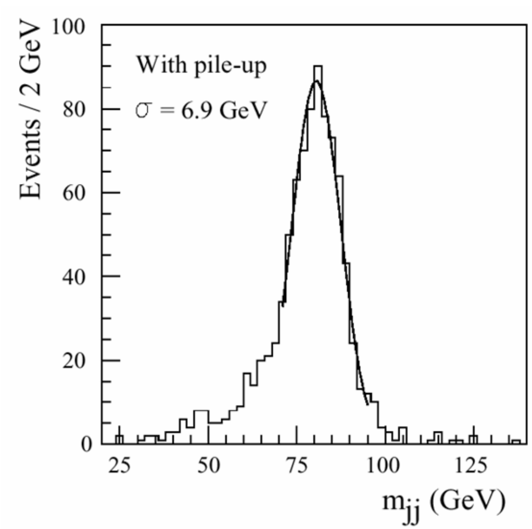
p_T^W(GeV) (GeV)	ΔR	σ_{LoL}	σ_{HiL}
p_T<50	0.4	9.5	13.8
100<p_T<200	0.4	7.7	12.9
200<p_T<700	0.3	5.0	6.9



100<p_T^W<200

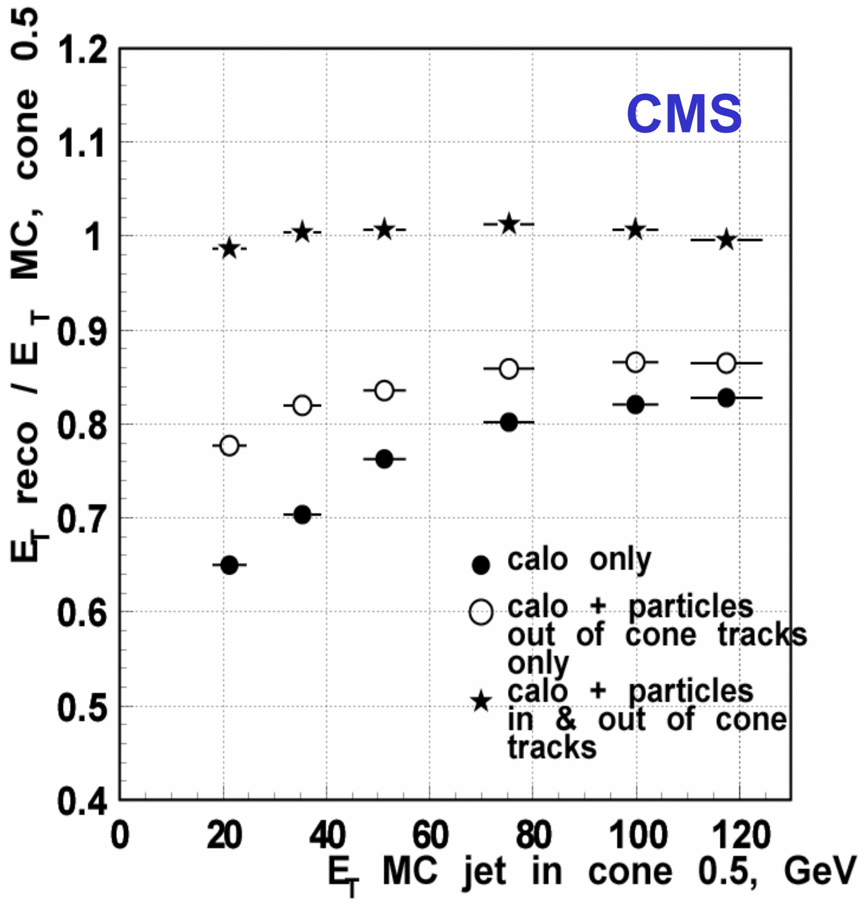


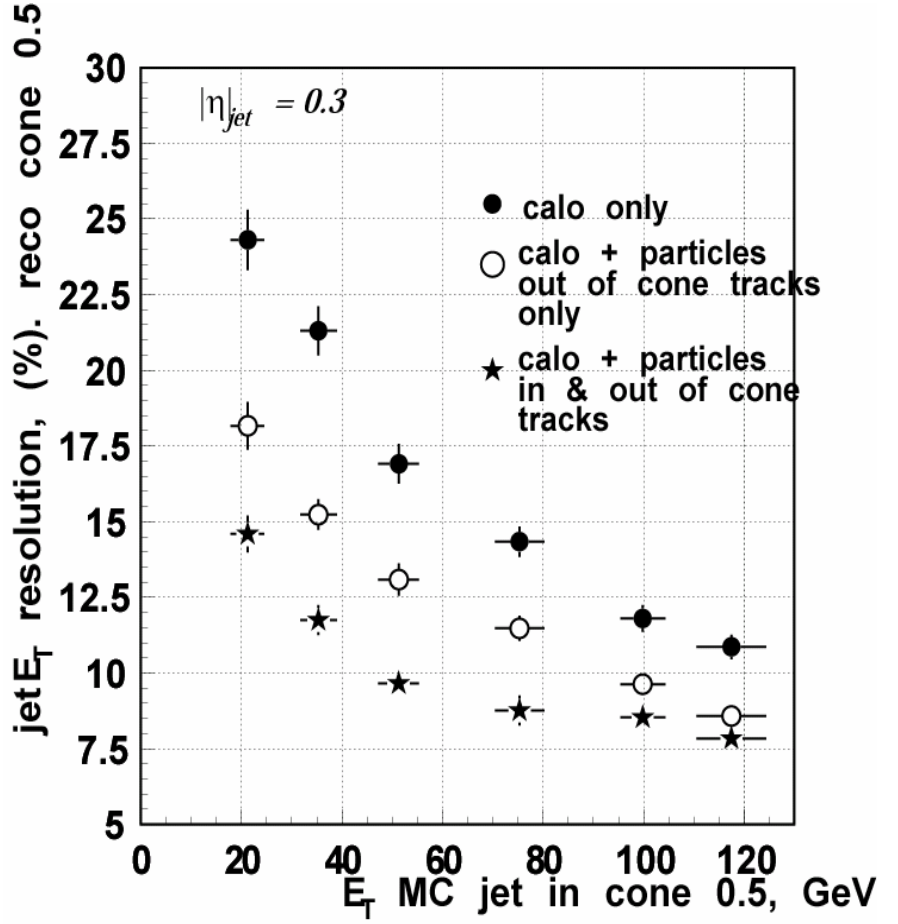
200<p_T^W<700



Jet Energy Measurement: Energy Flow

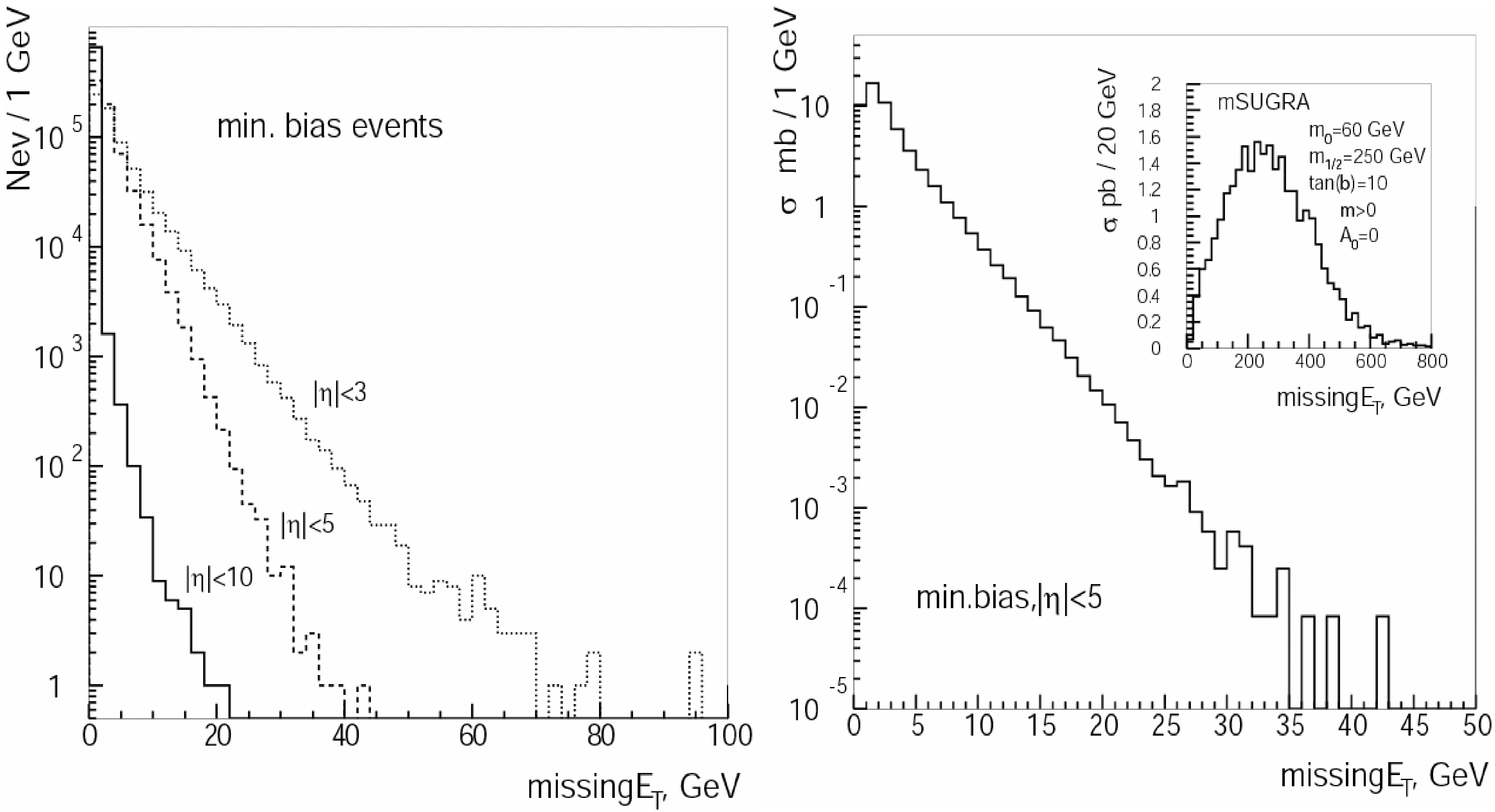
Add energy of charged tracks that bend out of cone (use p meas by tracker)
Replace energy measured in calo for track in cone by p measured in tracker





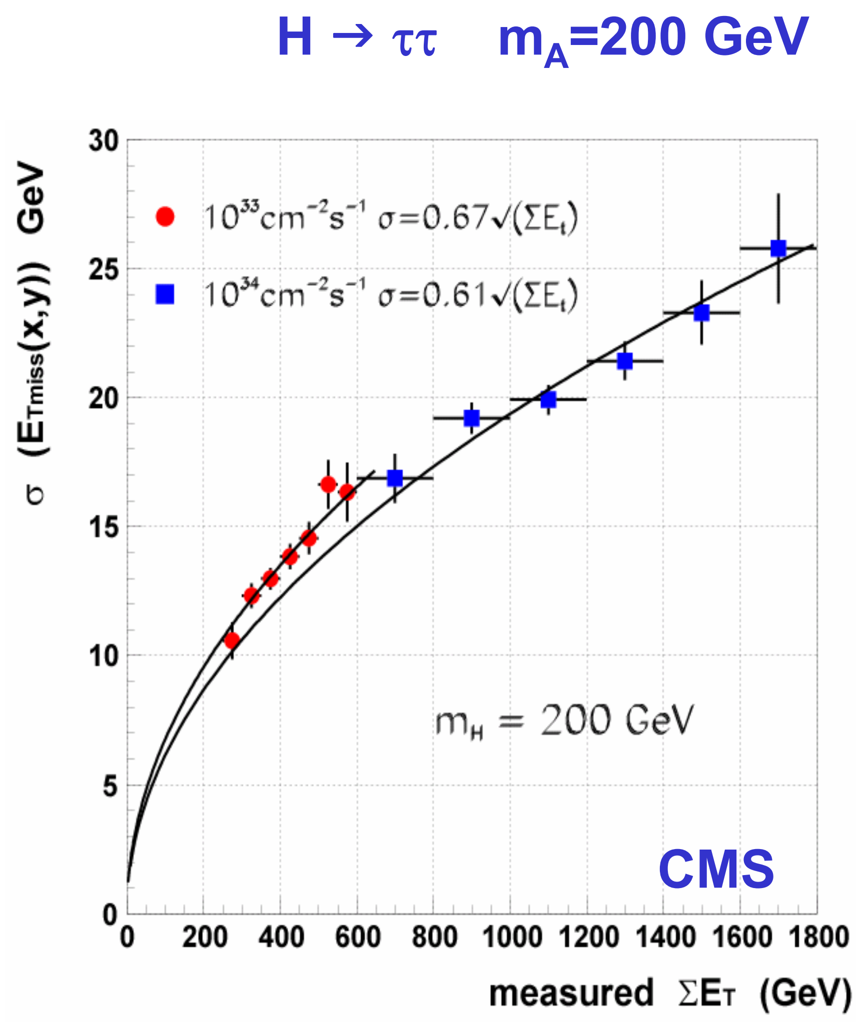
Significant improvement for jets at low E_T

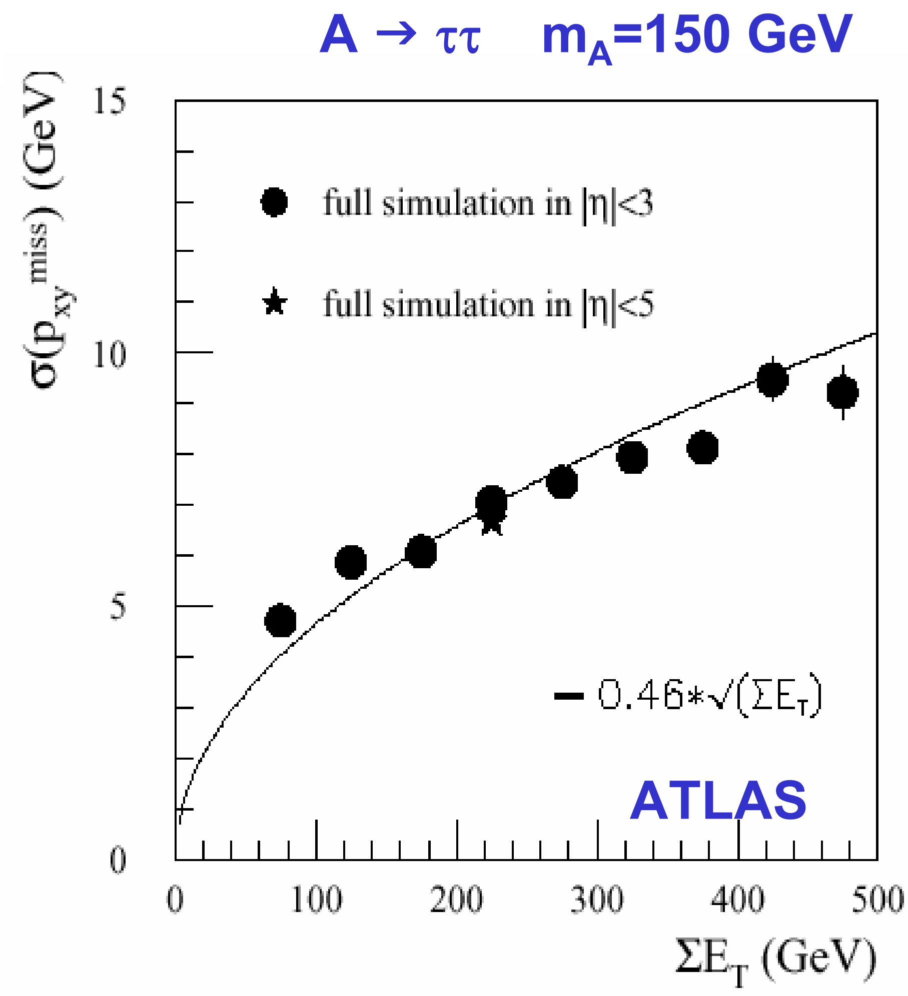
Missing E_T



Require Calorimetry coverage $|\eta| > 5$

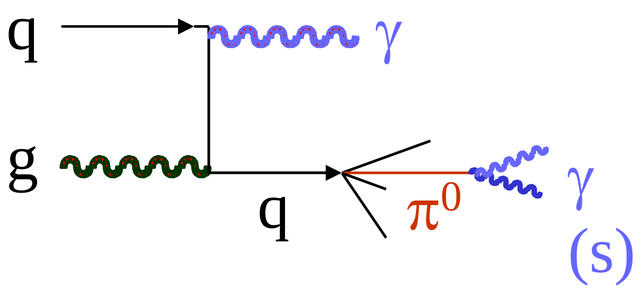
Missing E_T resolution





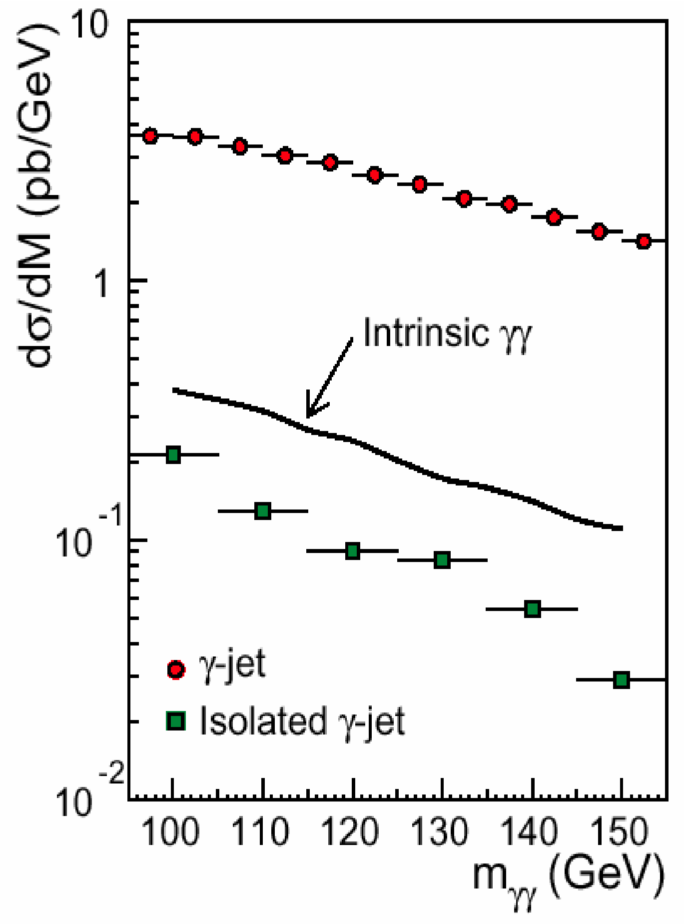
γ-Jet Rejection I

For H → γγ Large Reducible Background from γ-jet and jet-jet



$$\frac{\sigma_{jj}}{\sigma(H \to \gamma\gamma)} \sim 10^8$$

⇨ need large γ-jet separation (essentially γ-π^0 separation) to reject jets faking photons



γ-Jet Rejection

Cuts (ATLAS)

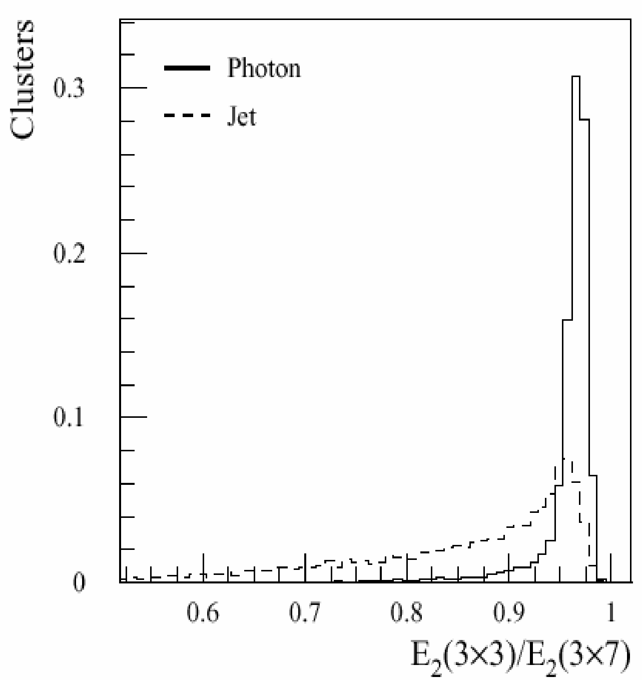
$E_{T\gamma1}, E_{T\gamma2} > 40, 25$ GeV with $|\eta| < 2.5$

$E_{H1}/E_{em} < f_{cut}$ (little/no had activity)

$E_{em2}^{3x3} / E_{em2}^{7x7}$ (shower size)

Shower width in η

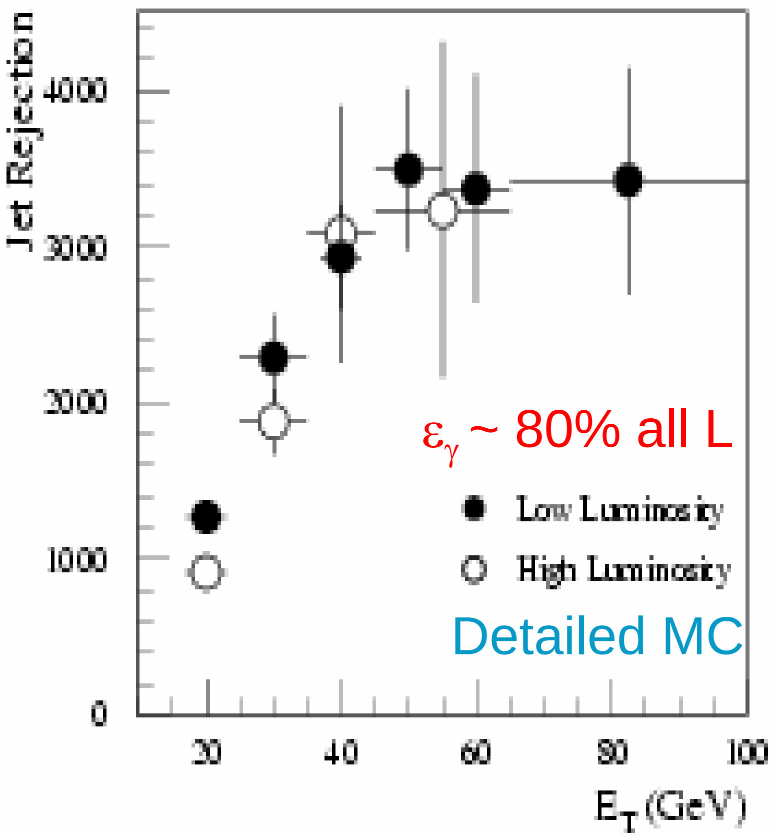
Track Veto (no chrg trk $p_T > p_{Tcut}$)



ATLAS EM calorimeter

4 mm η-strips in first compartment

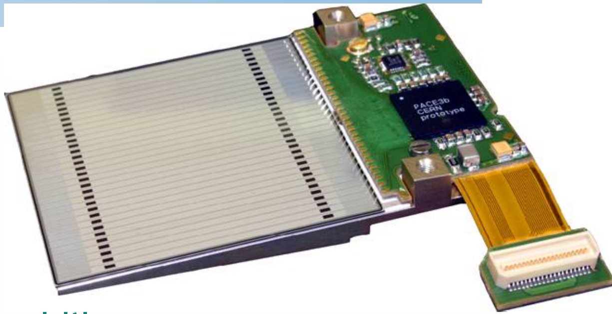
3 longitudinal segments



⇨ (γ–jet + jet-jet) < 40% $\gamma\gamma$

$\gamma - \pi^0$ Separation

Isolated π^0's - detect presence of 2 em showers.

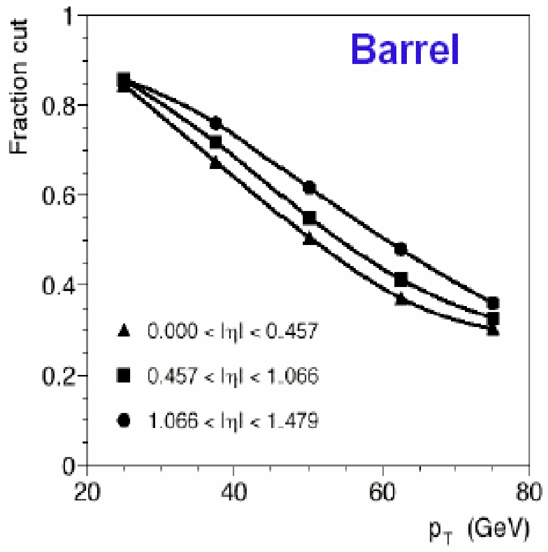


CMSPreshower module

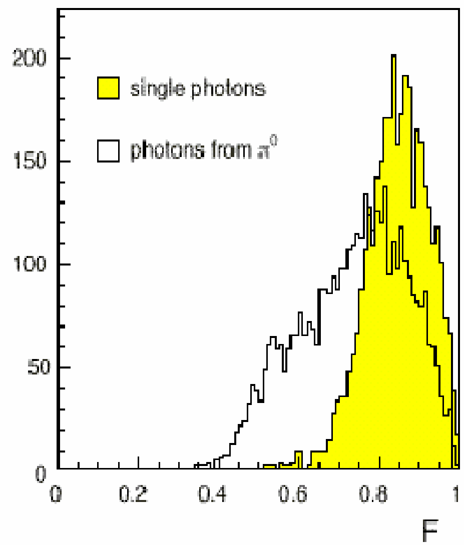
CMS Barrel

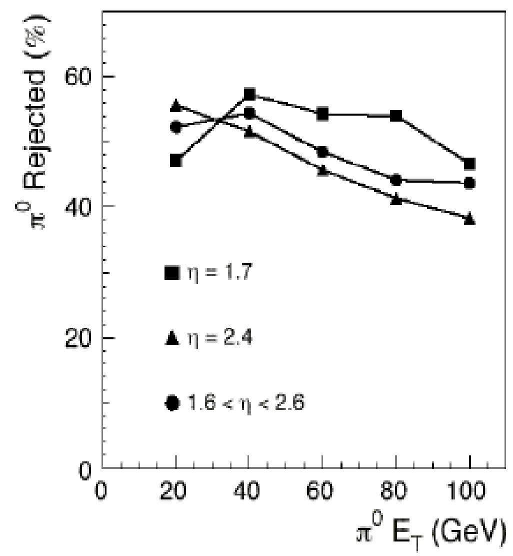
- use fine transverse crystal granularity (2.2×2.2 cm²)
- Compare energy deposited by single γ and π^0 in 3×3 crystal array

variables - 9-energies, x and y position, and a pair measuring the shower width



Endcap





CMS Endcap

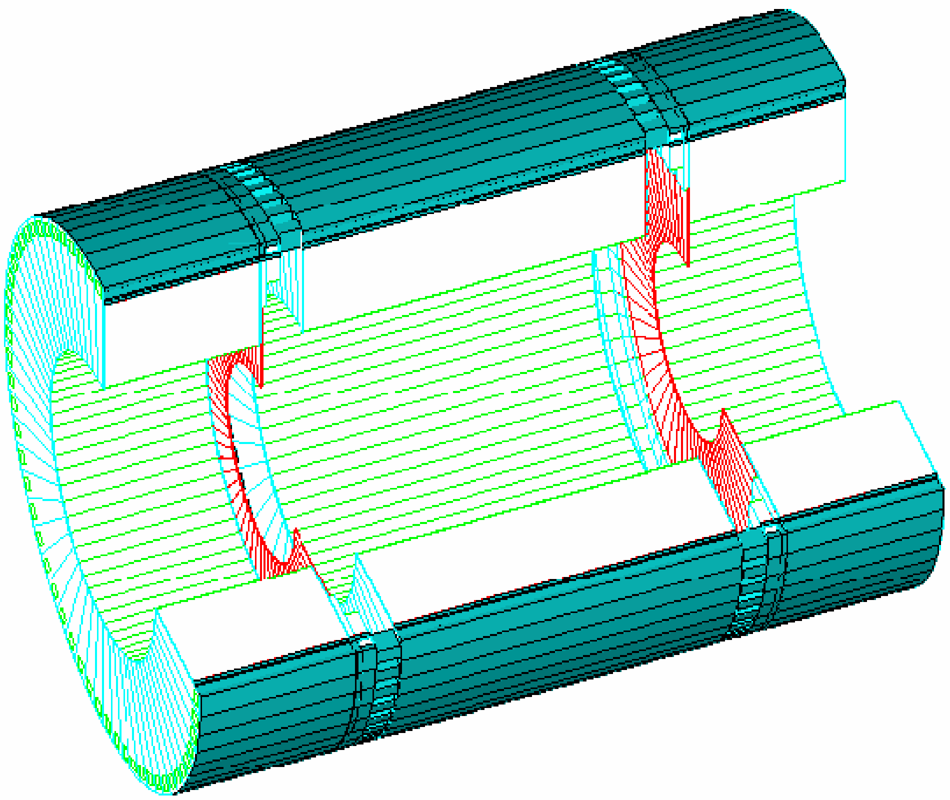
- use preshower - two planes of Si strips with fine pitch (≈2mm)

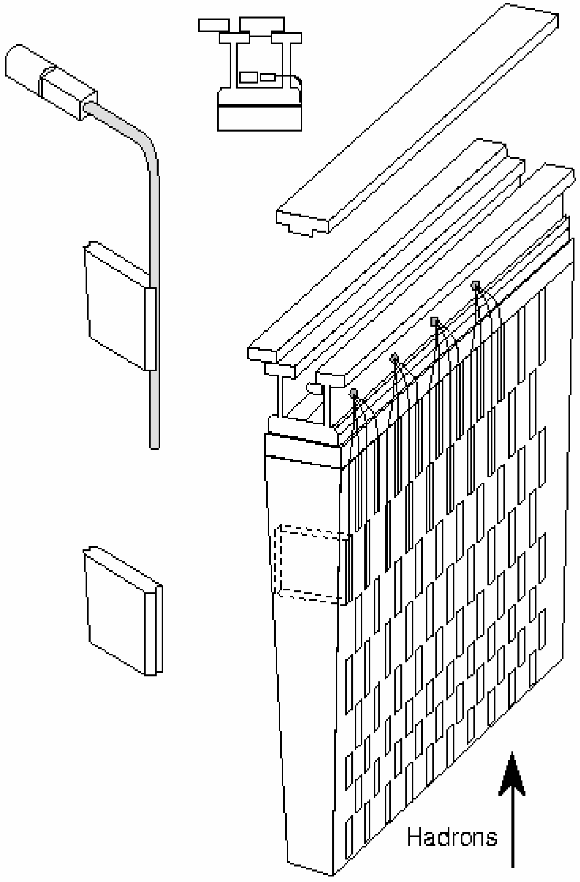
compare signal (summed in 1,2 or 3 adjacent strips with the total signal in 21 adjacent strips centred on strip with highest signal

ATLAS: Tilecal

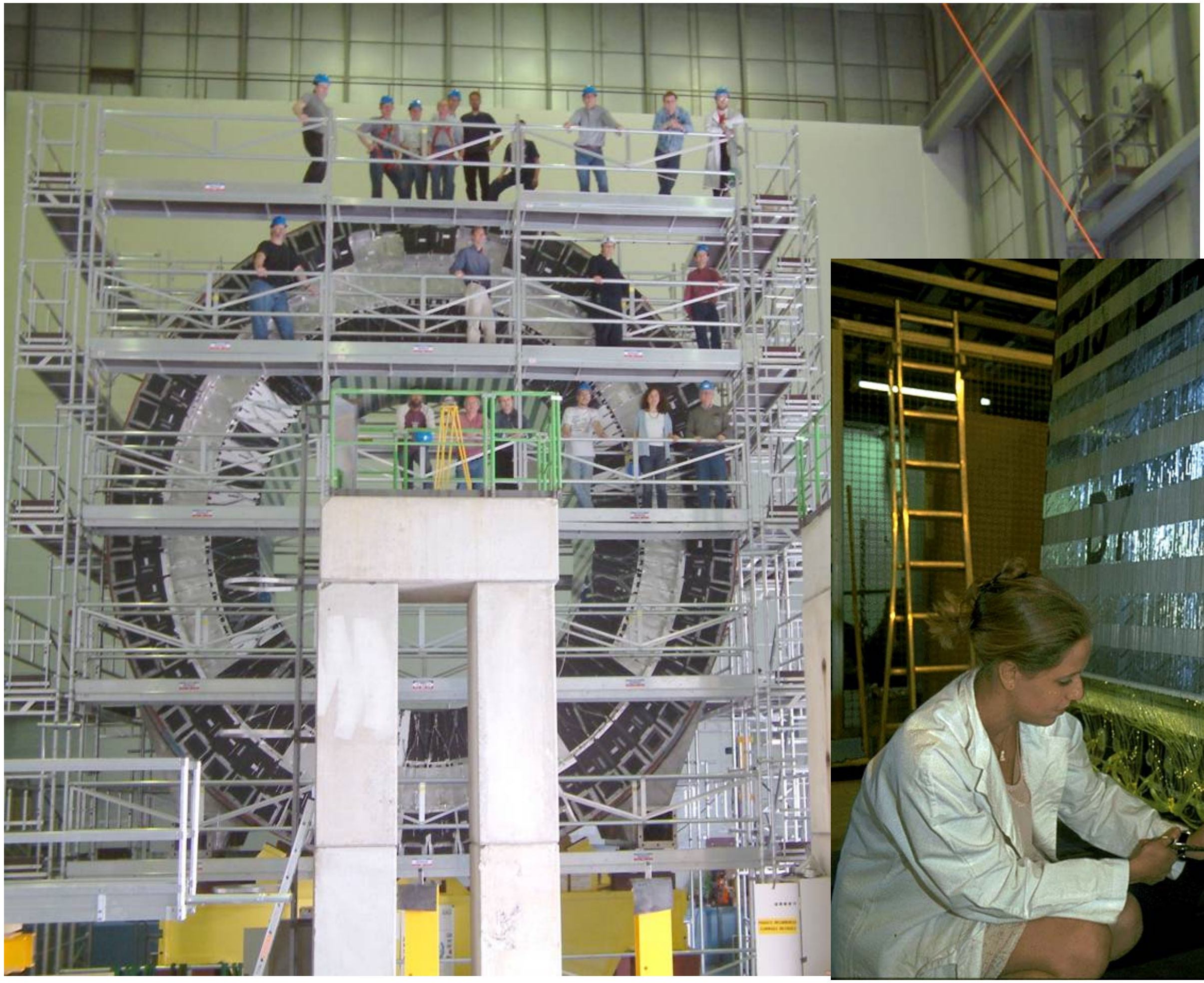
Fe absorber with scintillator tile readout with

$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$, 3 longitudinal samplings, $|\eta| < 1.7$





ATLAS: Tilecal Assembly



ATLAS: Calorimeter Performance

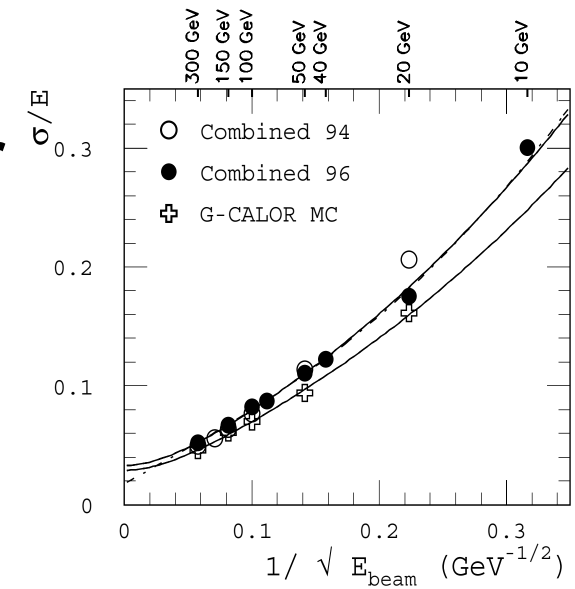
Combined Test:

EM LAr and Hadronic Tile Calorimeter

π Energy Resolution

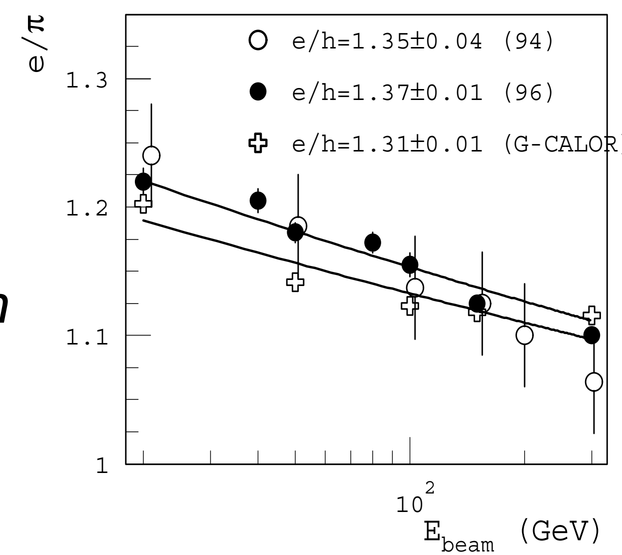
$$\sigma / E = a / \sqrt{E} \oplus b \oplus c / E$$

	a (%GeV$^{1/2}$)	b (%)	c (GeV)
Data	69.8 ± 0.2	3.3 ± 0.2	1.8± 0.1
G-CALOR	61.7 ± 0.1	2.9 ± 0.3	1.5 fixed



e/π ratio Degree of non-compensation *e/h*

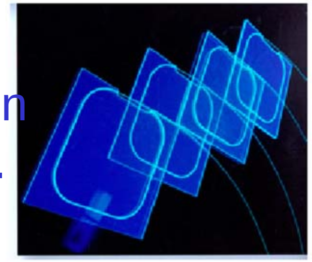
$$e/\pi = \frac{e/h}{1+(e/h-1)\cdot F(\pi^0)}, F(\pi^0) = 0.11 \cdot \ln E$$

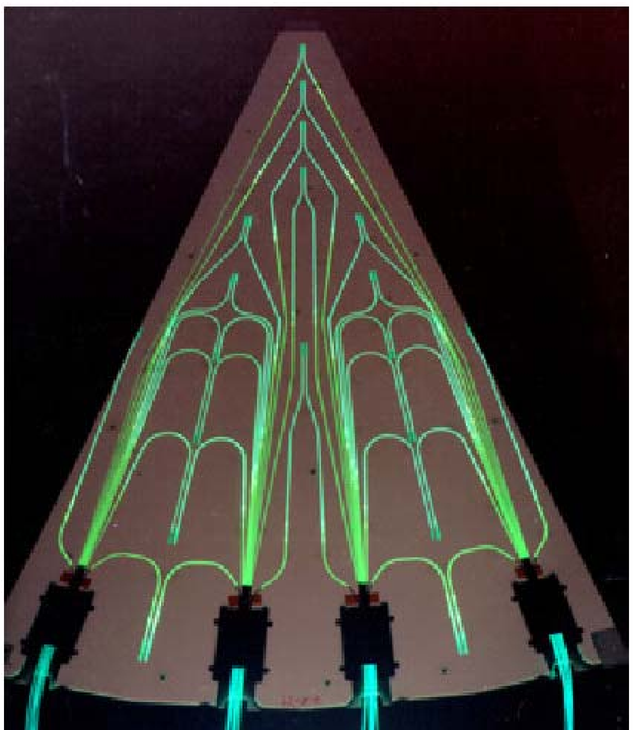


CMS HCAL

Routing of clear fibres to optical disconnects

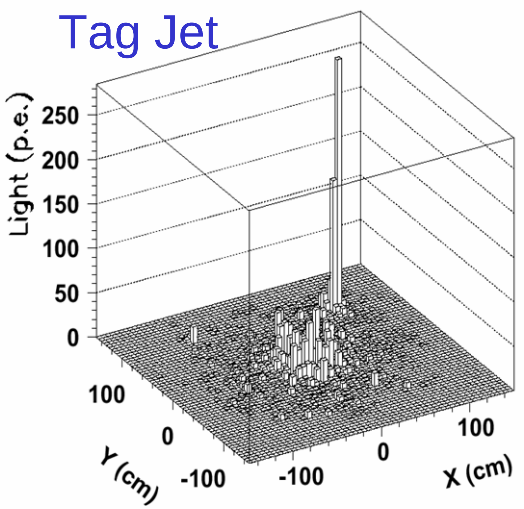
WLS fibres Embedded in plastic scint. plates

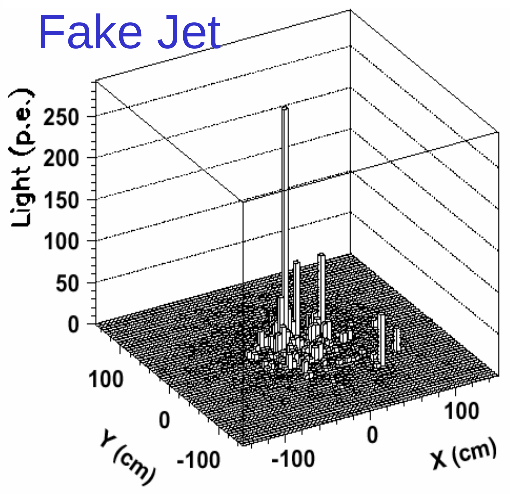


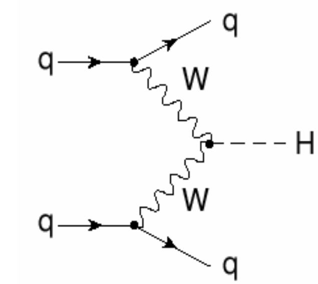


Central Region (|η|<3) : Brass/Scintillator with WLS fibre readout, projective geometry, granularity $\Delta\eta \times \Delta\phi = 0.0875 \times 0.0875$

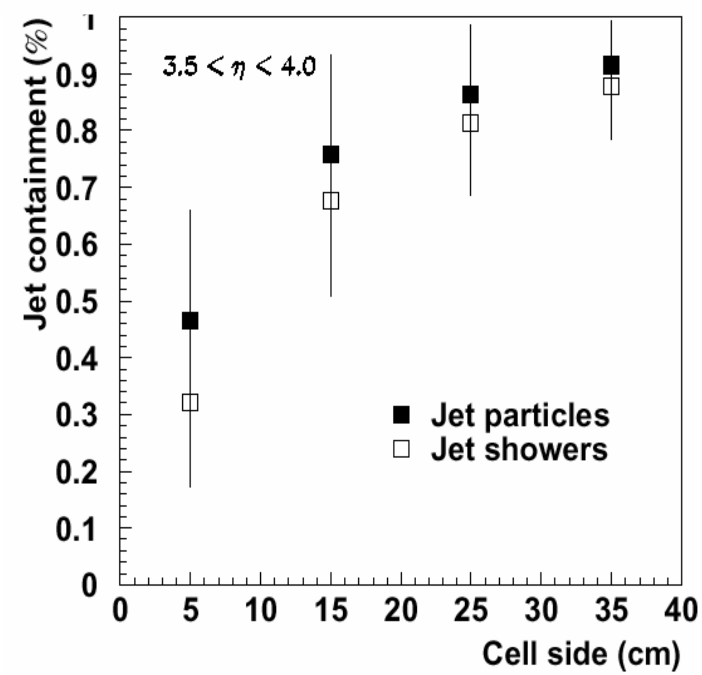
Forward Jet Tagging

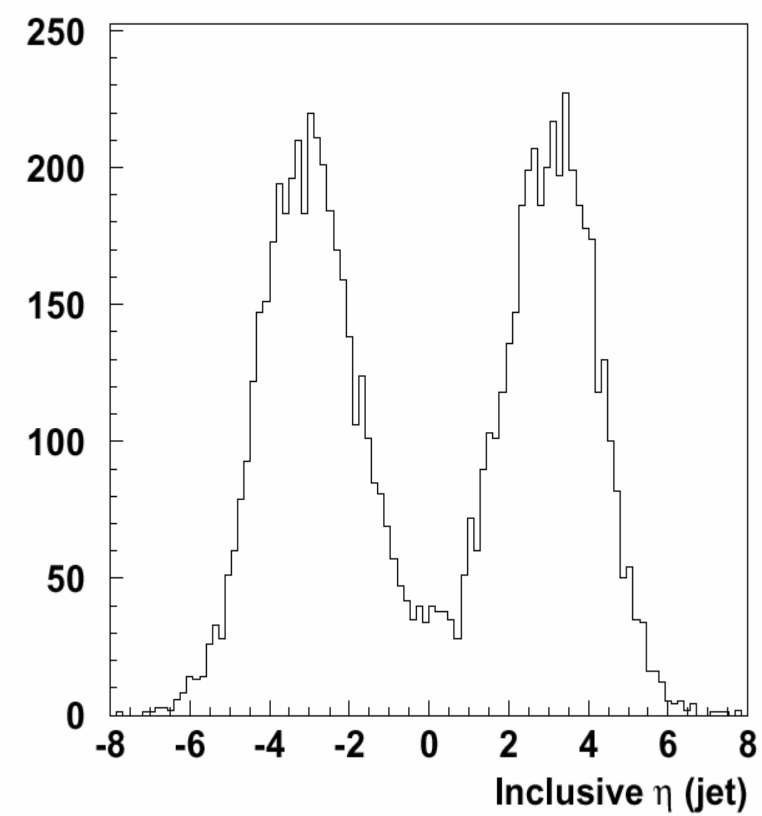




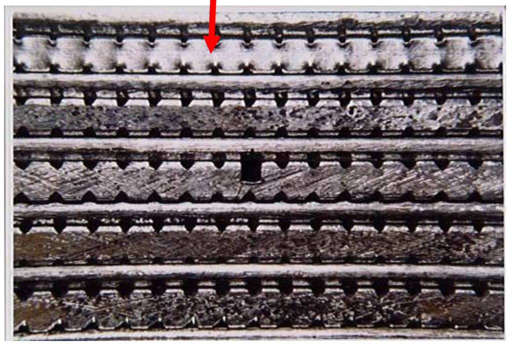


Tagging Jets





CMS: Very Forward Calorimeter



Fibres insertion
in HF wedges

Forward Region (3<|η|<5): Fe/Quartz Fibre, Cerenkov light

6. Tracking

- **ATLAS and CMS have chosen different options**
  - **CMS: 10-14 points, but extremely precise (< 30 μm) in Rϕ and low occupancy measurements (all silicon)**
  - **ATLAS: fewer (4) “clean” points at small radius (<50 cm), followed by ~ 40 points with smaller precision (50 μm) and larger occupancy (TRT straw tubes)**

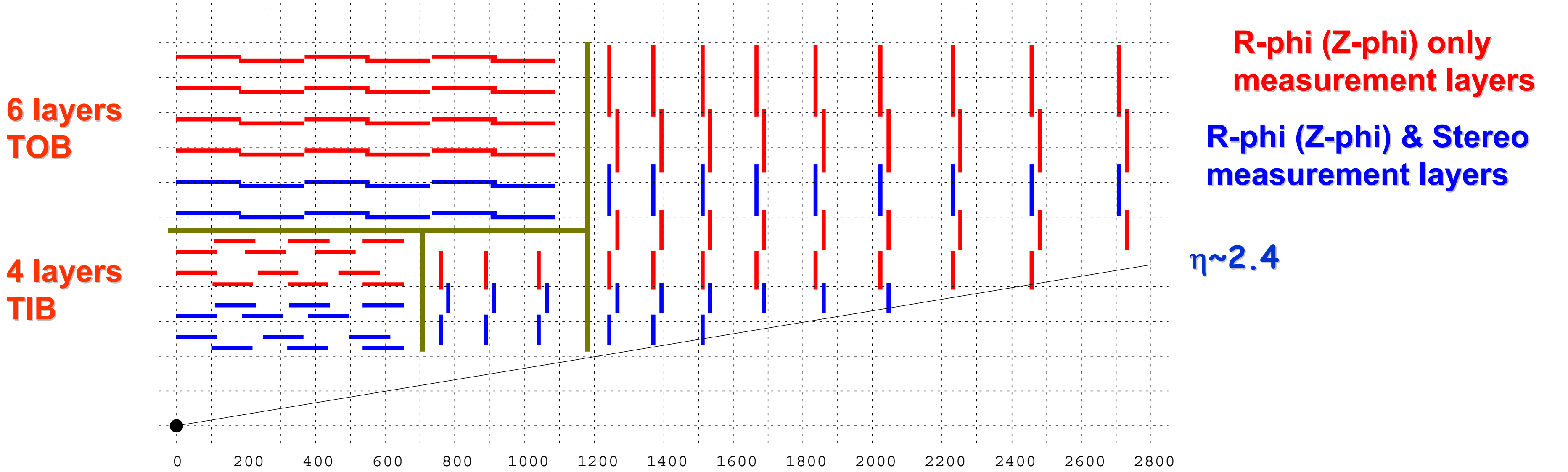
- **Both have 3 layers of pixels between 4cm and ~25 cm**

- **Silicon ST and pixels must be run at low Temperature (-10ºC) to avoid long term deterioration by radiation.**
  - **This induces large material budget (cooling pipes and ledges)**

CMS Tracking

- **Few, very precise and clean measurements layers.**
  - **2-3 Silicon Pixel & 10-14 Silicon Strip Measurement Layers**

Radius ~ 110cm, Length ~ 270cm



210 m^2 of Si strips

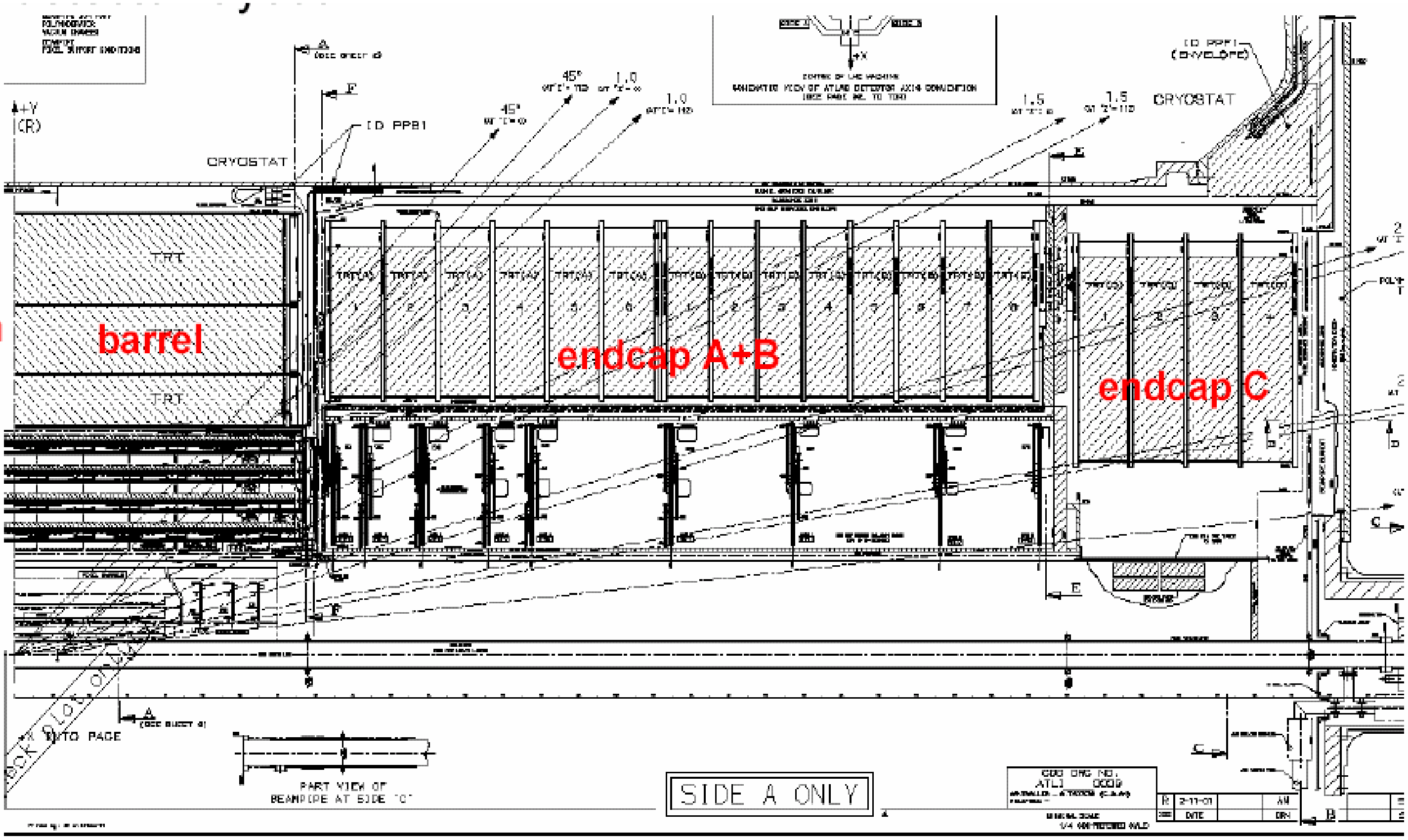
P.Bloch IMFP05

ATLAS Tracker Layout

TRT
r=55-105cm

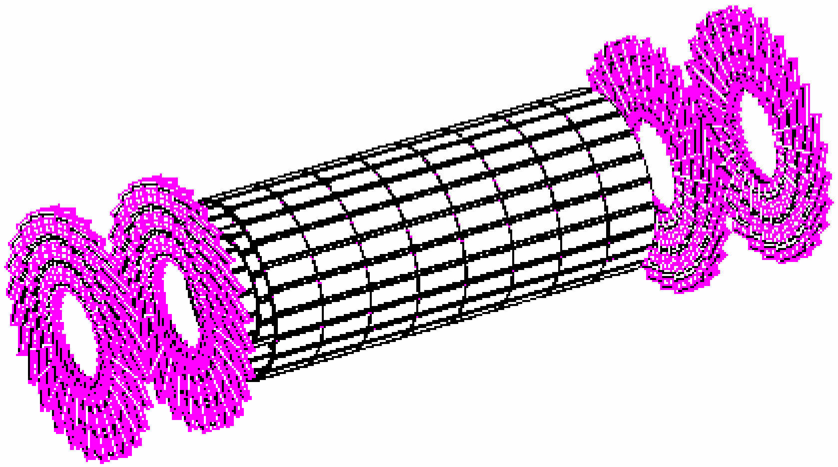
SCT
r=25-50cm

Pixels
r=5-25cm

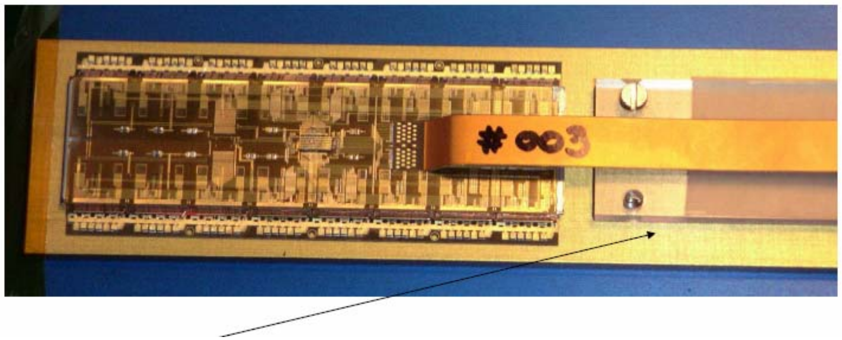


b identification

- **Pixel detectors**
  - **Both ATLAS and CMS**
    - **Very close to beam pipe (first point at 4cm) Different scenario for High luminosity**
  - **Small pixel size (150μm). Occupancy: 10^{-4}. Resolution: ~20μm.**



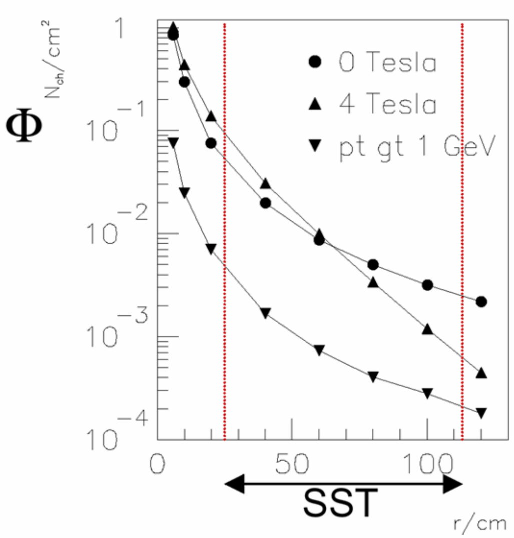
Module with DSM ROC on a module handle



- **Pixels are essential for HLT and Pattern .Recognition**

CMS Tracking Requirements

- **Efficiency: need low, ~few % occupancy; Resolution**



Twelve hits; 4T field
spatial resolution: (pitch/ √12)
Radius: 110 cm
→momentum resolution:

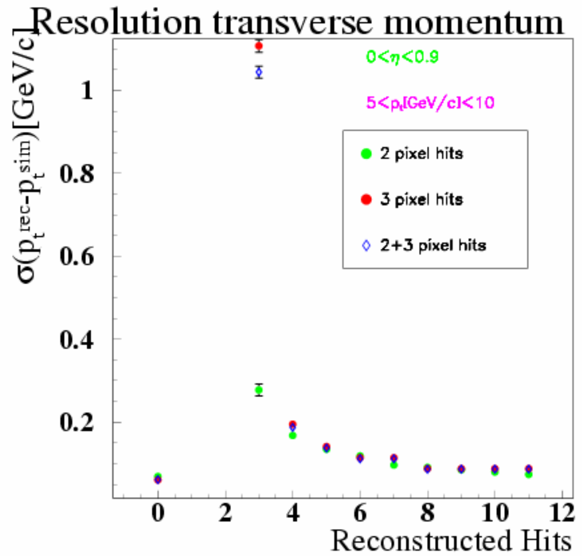
$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100\,\mu m}\right)^{1} \left(\frac{1.1m}{L}\right)^{2} \left(\frac{4T}{B}\right)^{1} \left(\frac{p}{1Tev}\right)$$

→Need pitch ~100μm.

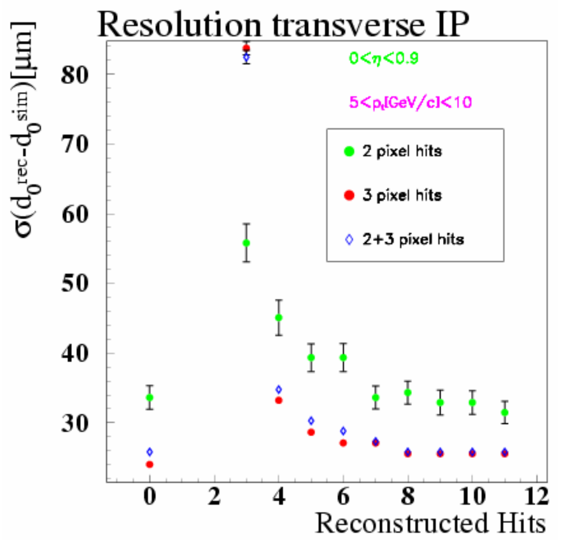
small radii: need cell size < 1cm²
+ fast (~25ns) shaping time
condition is relaxed at large radii

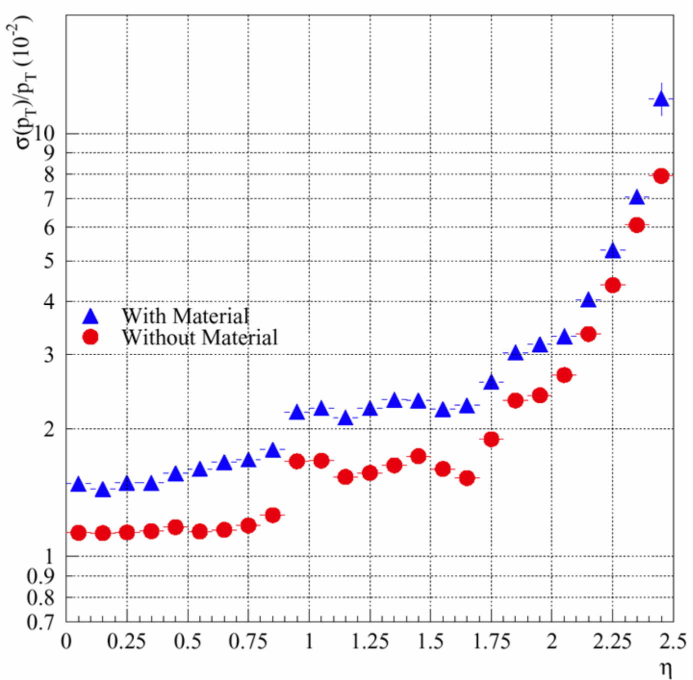
- **Strip size**
  - Strip length: 10cm (inner layers) to 20cm (outer layers).
  - Pitch: 80μm (inner layers) to 200μm (outer layers)

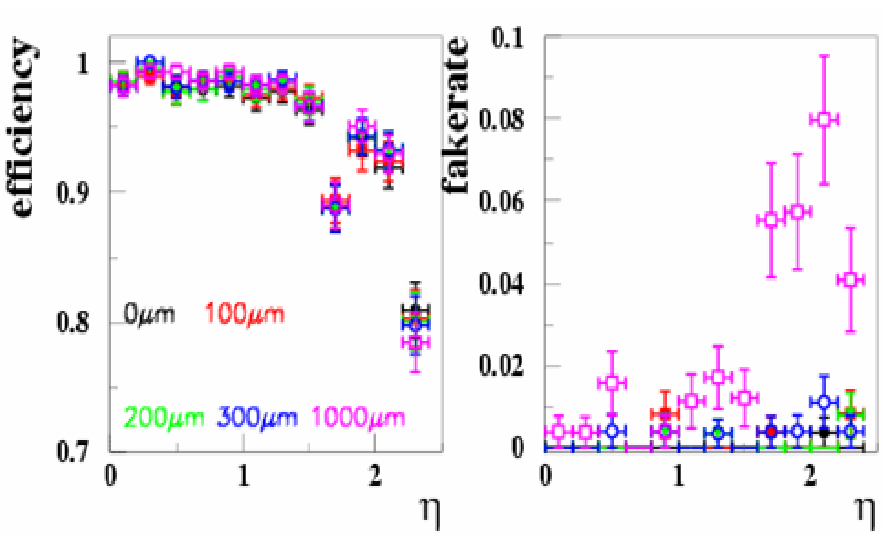
CMS Tracker performance



Most of the performance already with ~4-5 hits (useful for HLT)

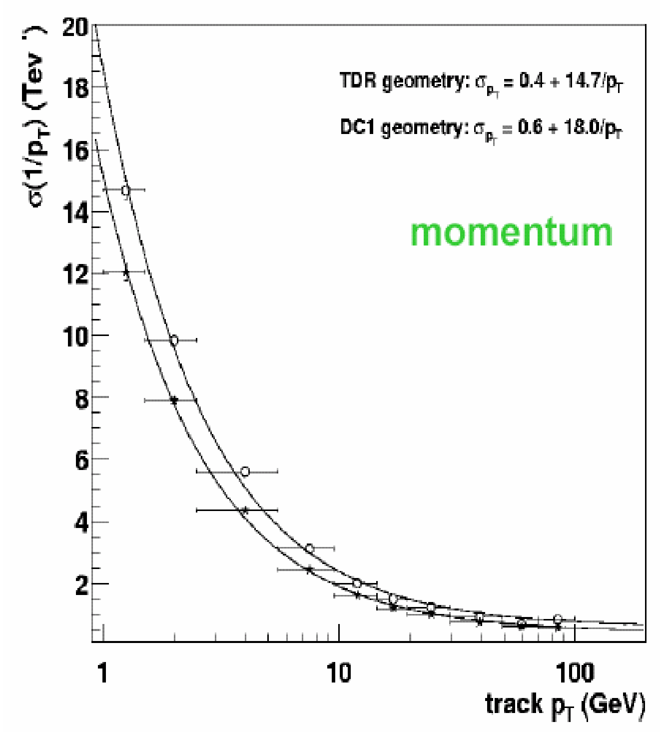


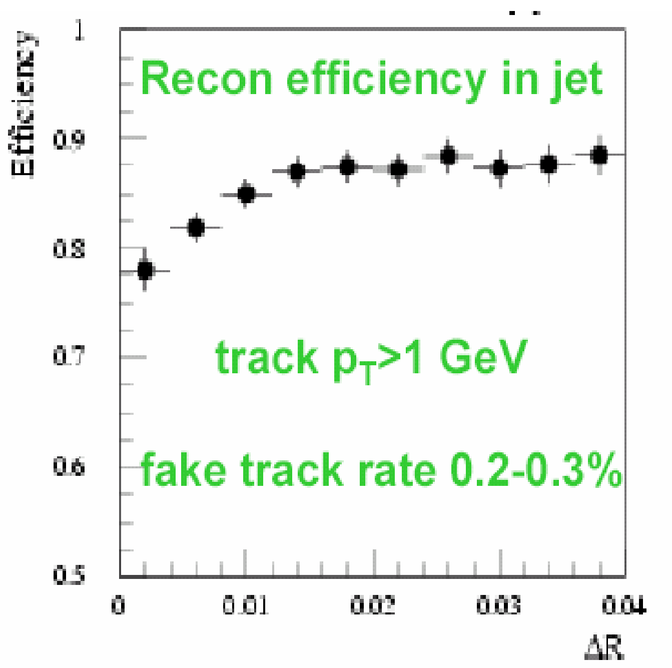




P.Bl

ATLAS Tracker Performance

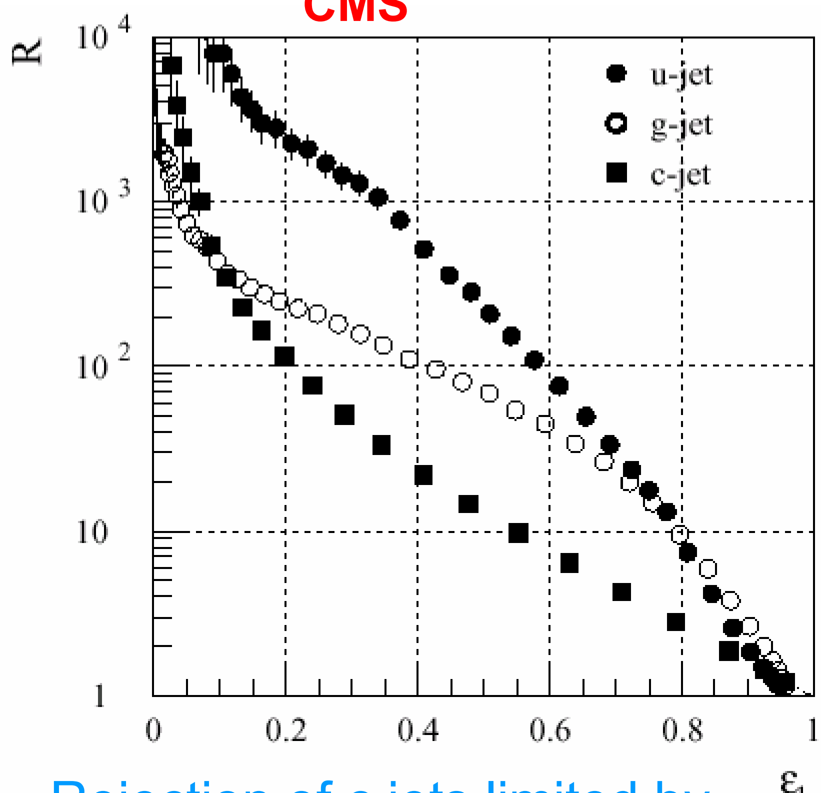




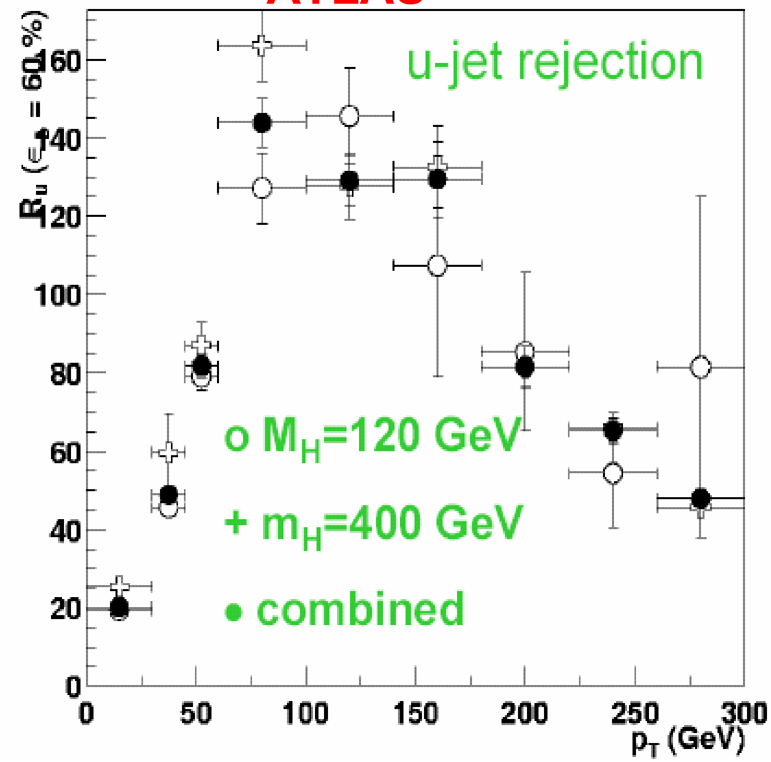
$\sigma(p_T)/p_T \sim 0.6+18p_T$ %
(p_T in TeV)

b jet identification

CMS



ATLAS



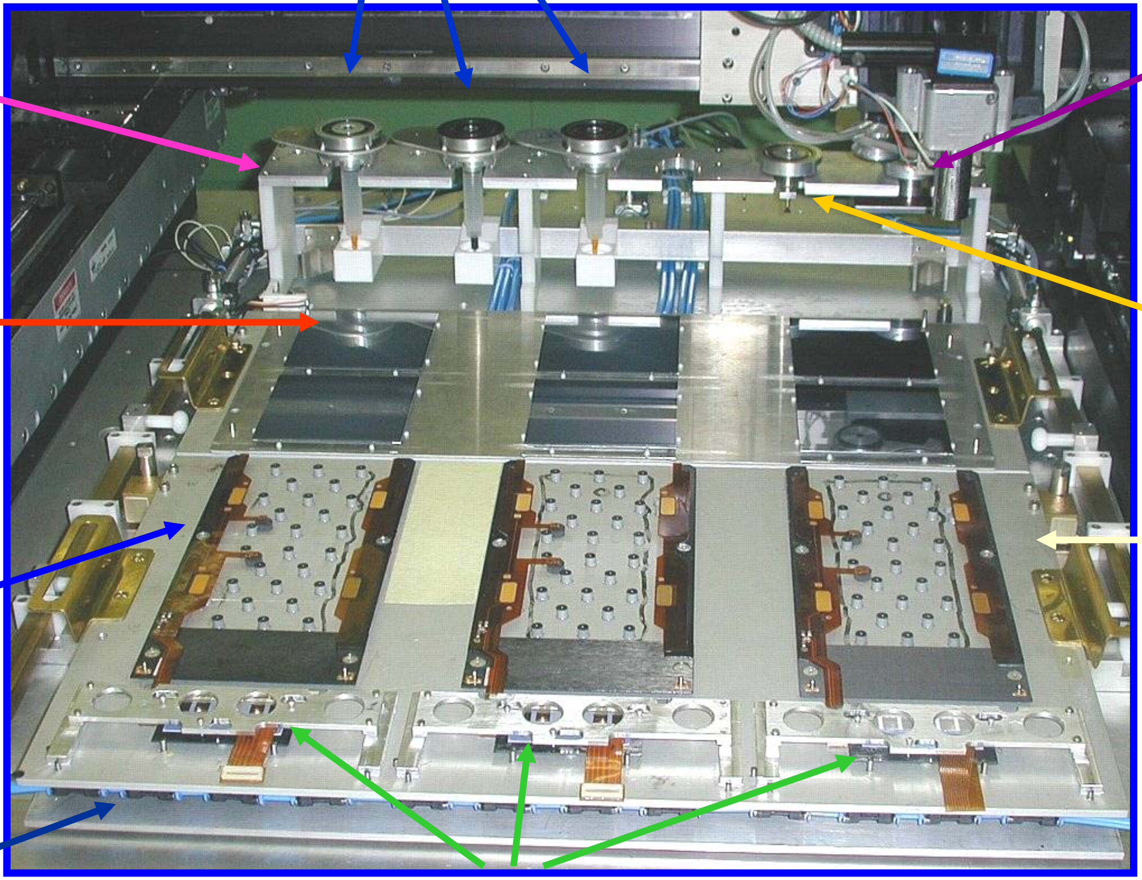
Rejection of c jets limited by τ_c
Rejection of g jets limited by g-splitting:
@ kinematics of M_H=400 GeV,
BR($g \to cc$)=6%
BR($g \to bb$)=4%

Significant dependence on jet p_T:

- Balance between multiple scattering (low p_T) and pattern recognition effects (high p_T)
  - Very dense jets at high energy
  - Best rejection around 100 GeV
  - Little intrinsic dependence on boson mass

P.Bloch IMFP05

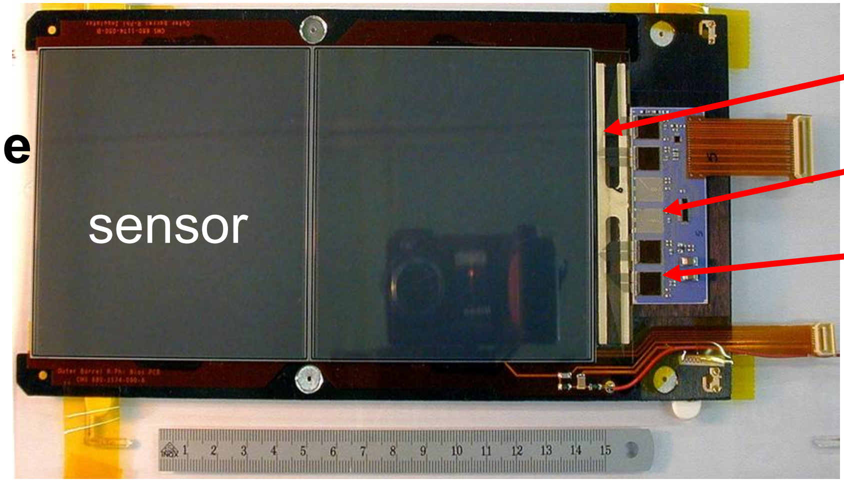
CMS Tracker Production: Automation



P.Bloch IMFP05

CMS Tracker: Some Components

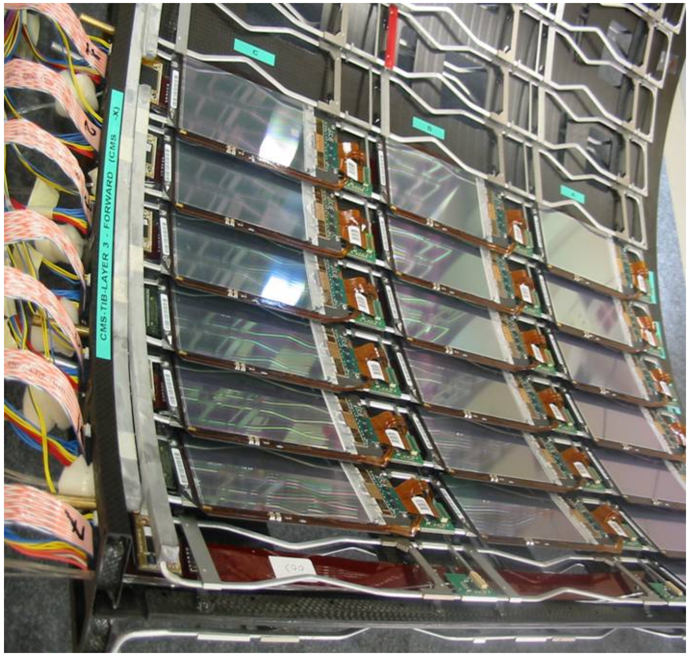
Si Strip Module



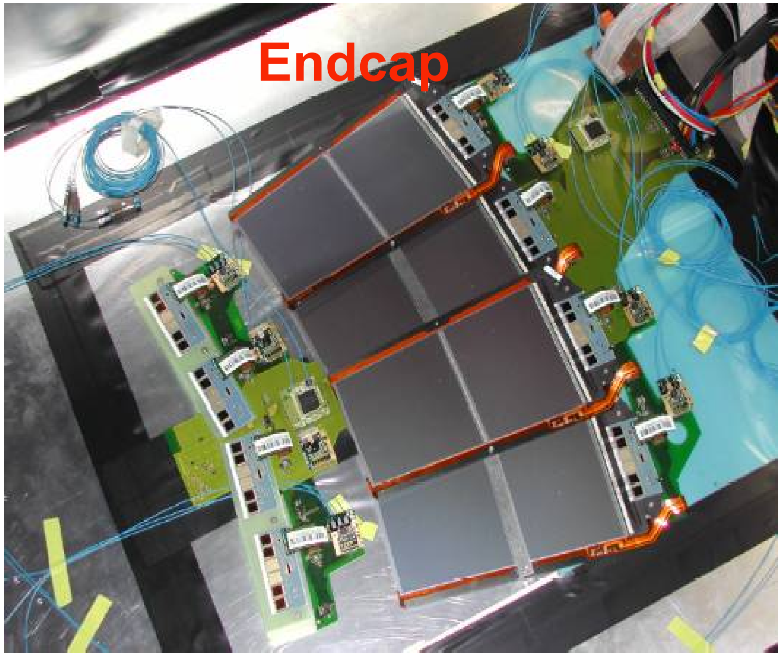
Pitch adaptor

Hybrid

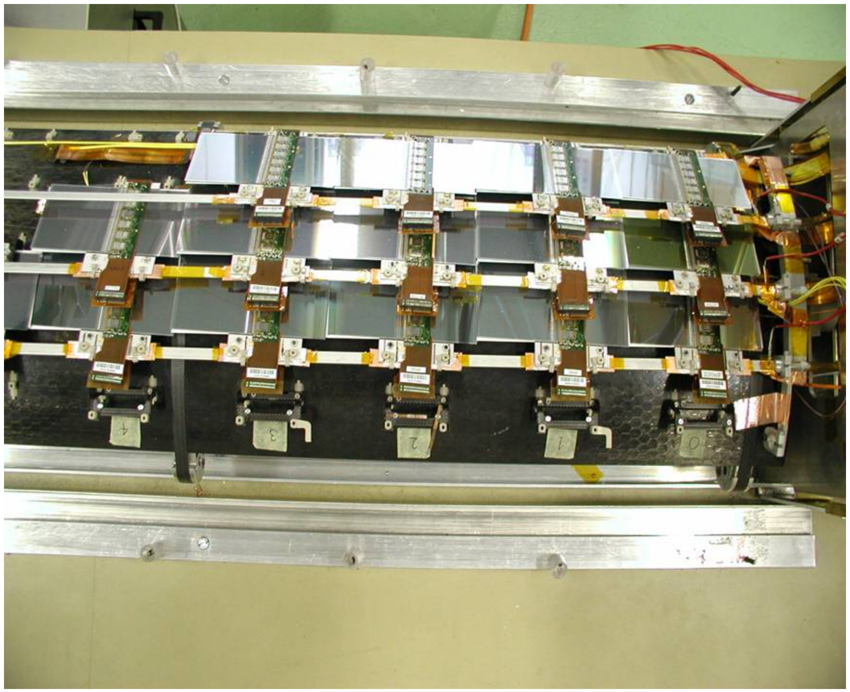
APV25



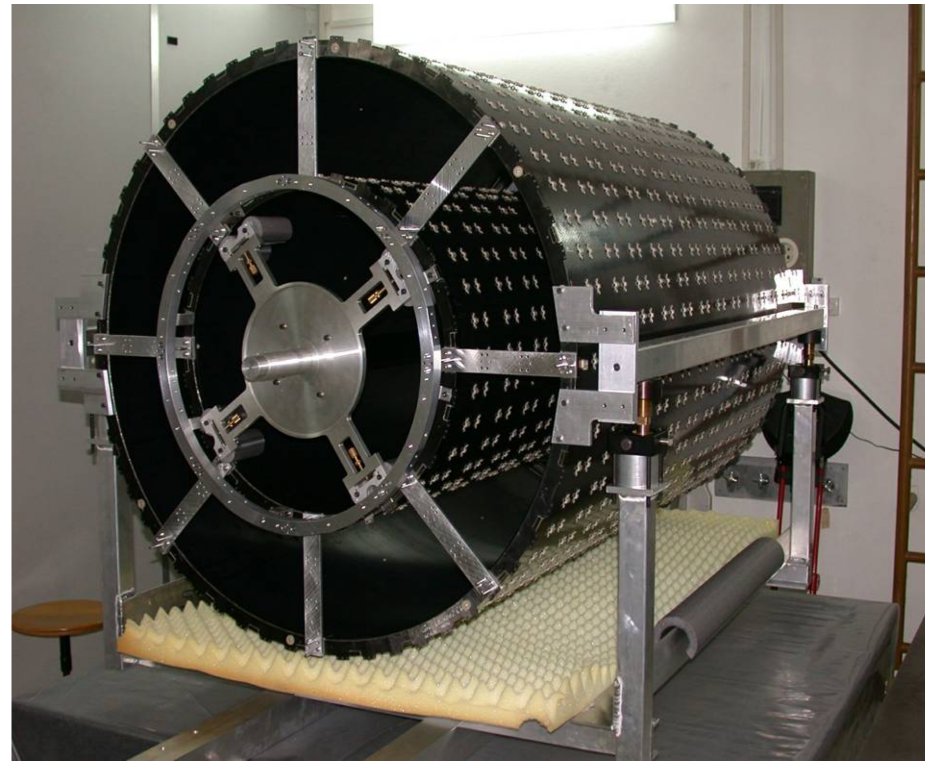
Barrel TIB



ATLAS Tracker: Some Components

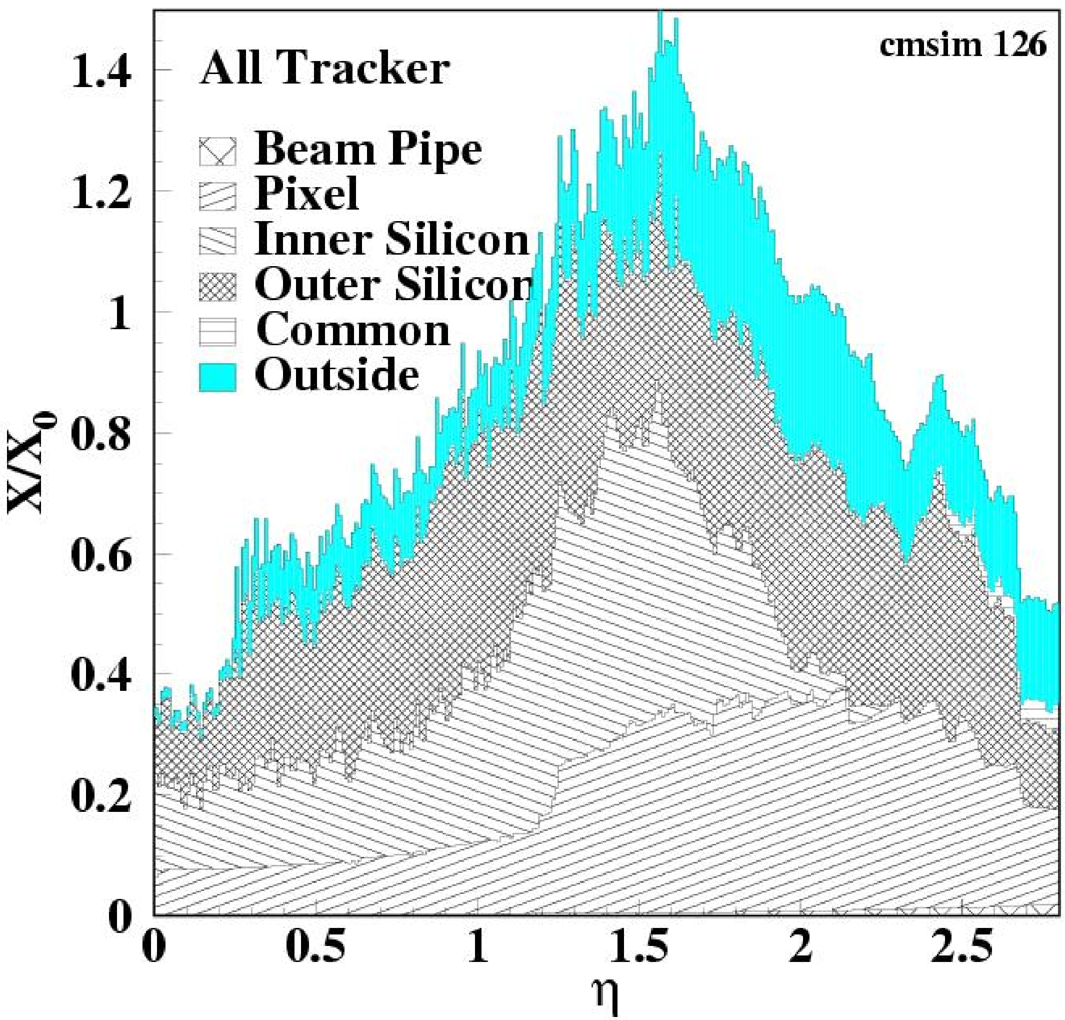


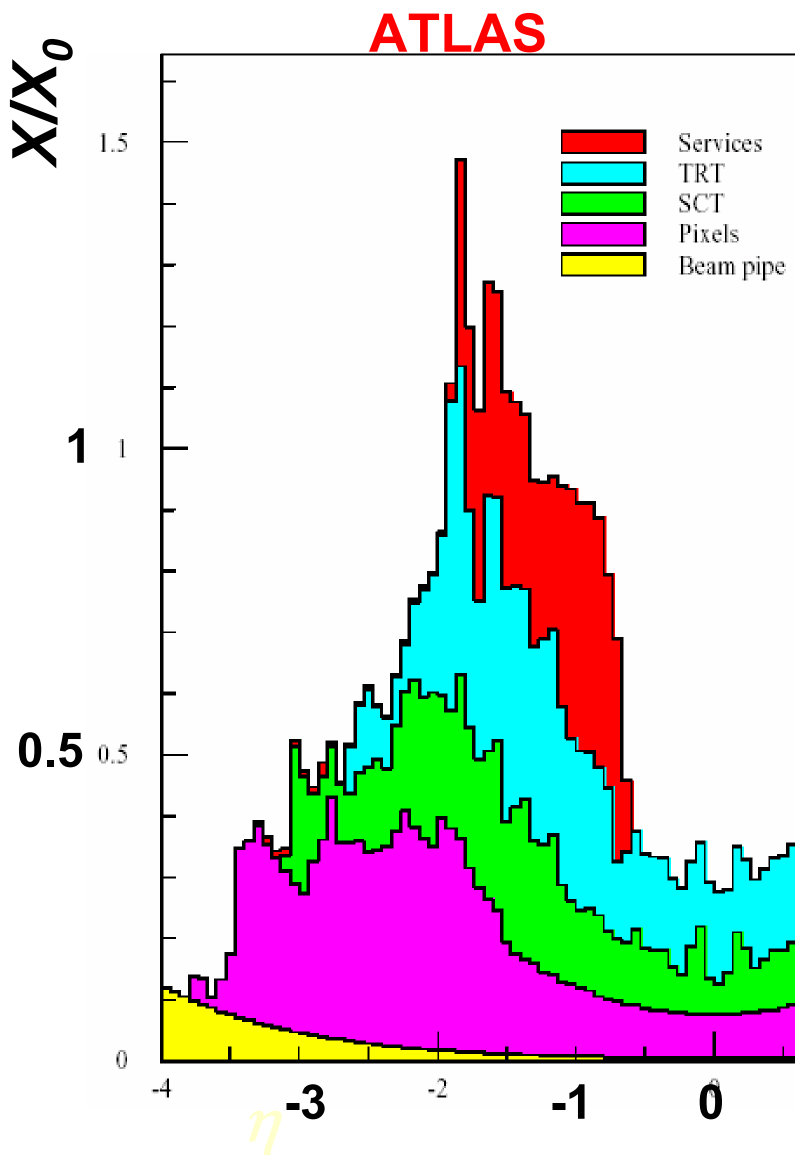
SCT barrel system test



Two of the SCT barrel support structures

The black point: material in Trackers





7. Trigger and DAQ

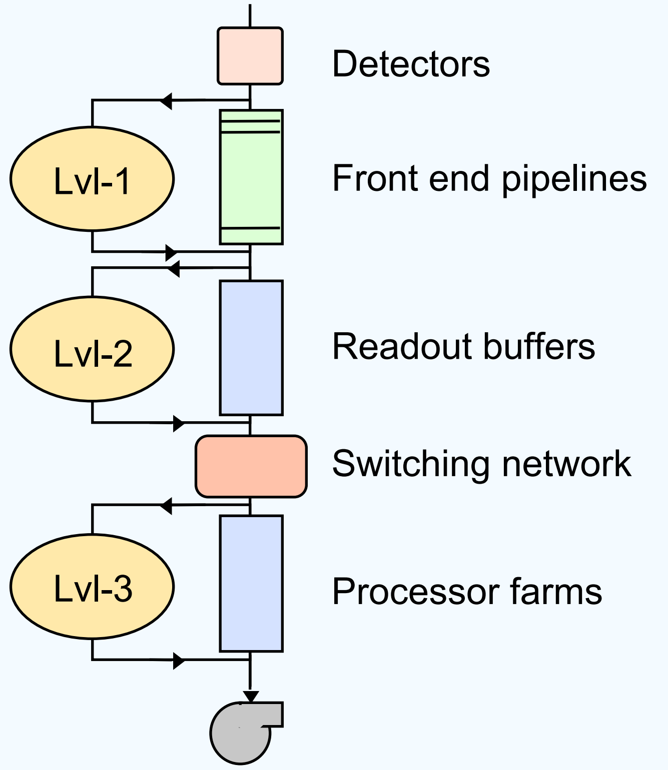
- **Challenge**
- **ATLAS and CMS different strategies**

Trigger/DAQ requirements/challenges

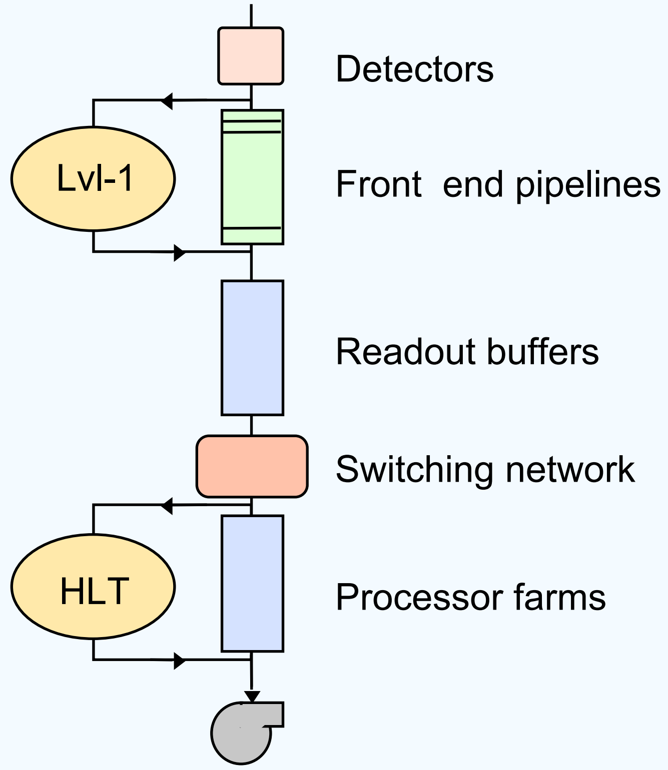
- **N (channels) ~ O(10^7); ≈20 interactions every 25 ns**
  - **need huge number of connections**
  - **need information super-highway**
- **Calorimeter information should correspond to tracker info**
  - **need to synchronize detector elements to (better than) 25 ns**
- **In some cases: detector signal/time of Flight > 25 ns**
  - **integrate more than one bunch crossing's worth of information**
  - **need to identify bunch crossing...**
- **Can store data at ~ (1-2)x10^2 Hz**
  - **need to reject most interactions**
- **It's On-Line (cannot go back and recover events)**
  - **need to monitor selection**

Online Selection Flow in pp

- **Level-1 trigger: reduce 40 MHz to 10^5 Hz**
  - **This step is always there**
  - **Upstream: still need to get to 10^2 Hz; in 1 or 2 extra steps**



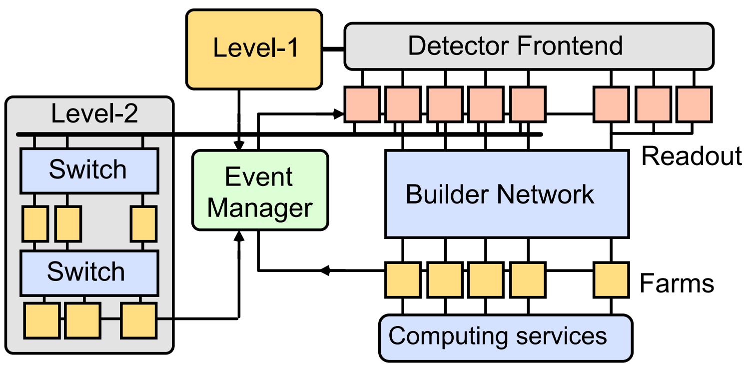
ATLAS: 3 physical levels

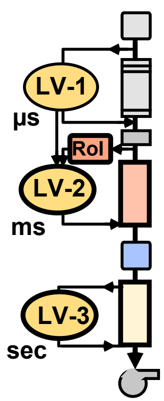


CMS: 2 physical levels

Three physical entities

- Additional processing in LV-2: reduce network bandwidth requirements





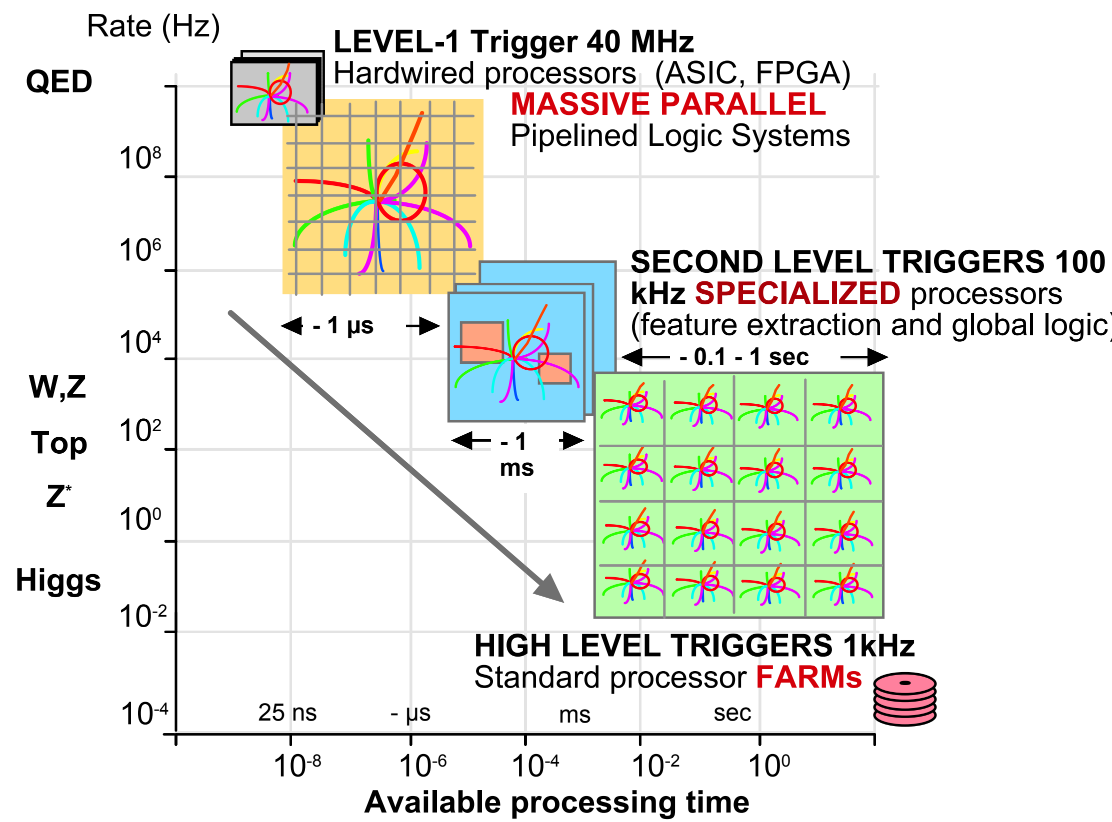
40 MHz

10^5 Hz

10^3 Hz

10 Gb/s

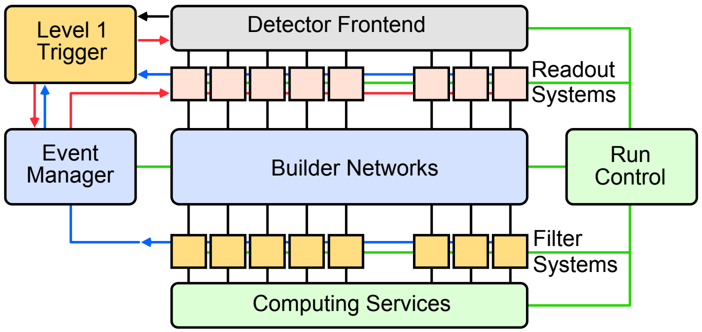
10^2 Hz

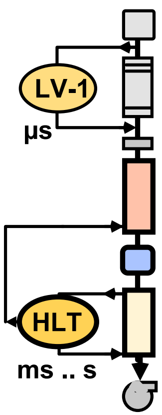


- Investments in control logic and specialized processors

P.Bloch IMFP05

Two physical entities



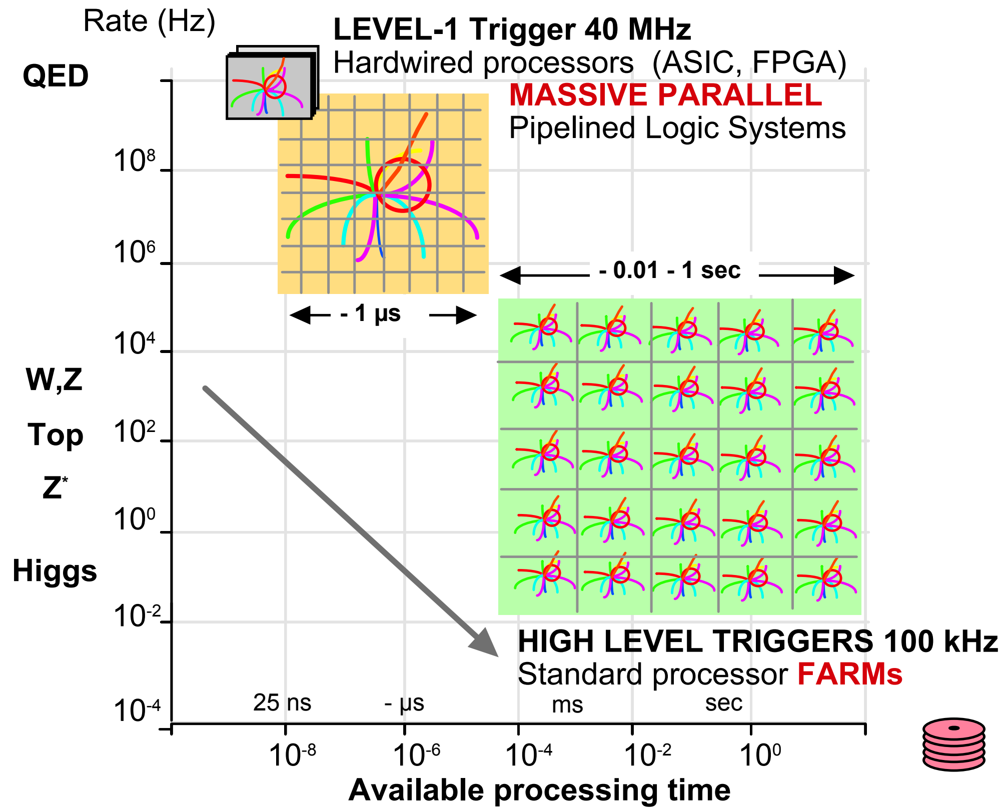


40 MHz

10^5 Hz

1000 Gb/s

10^2 Hz

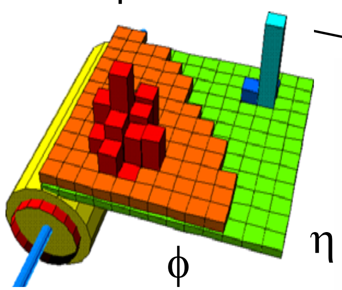


- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

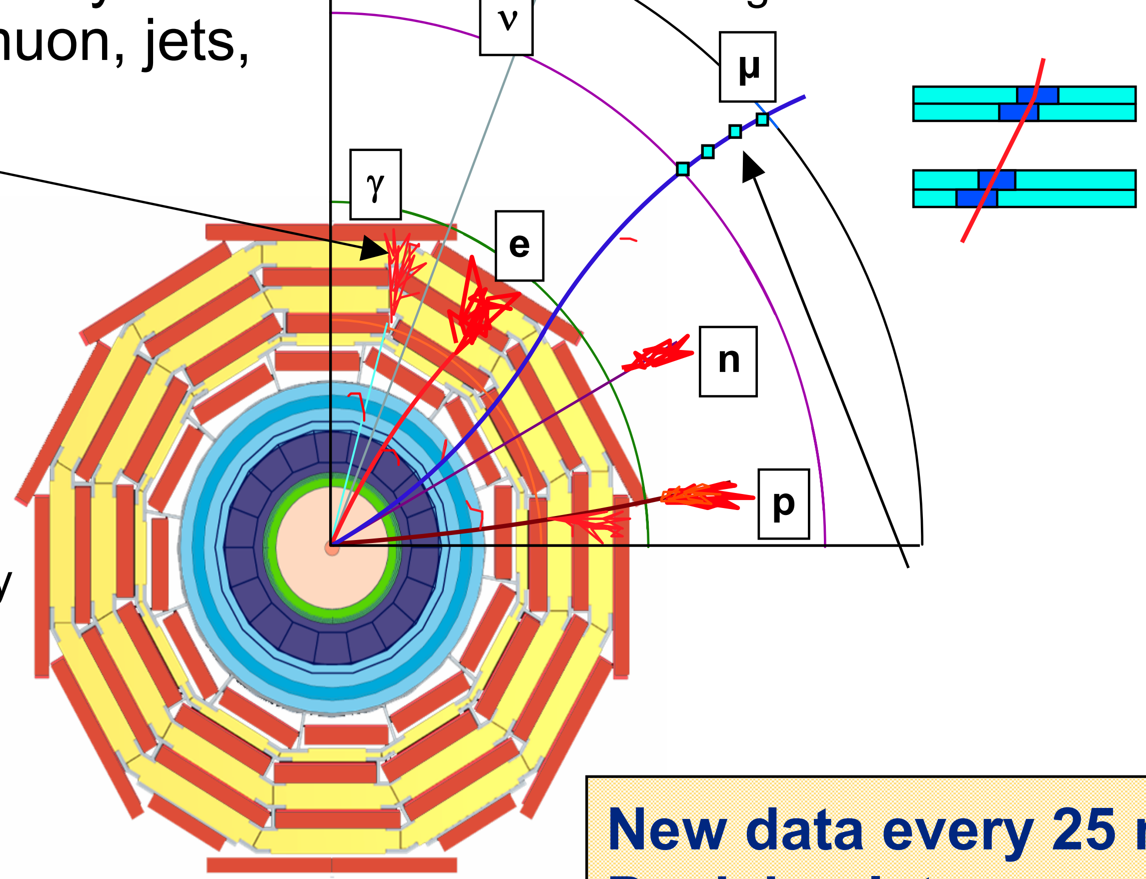
-Investments in bandwidth and commercial processors

Level-1 Trigger

Use prompt data (calorimetry and muons) to identify:
High p_T electron, muon, jets, missing E_T



MUON System
Segment and track finding



CALORIMETERs
Cluster finding and energy deposition evaluation
+ isolation

New data every 25 ns
Decision latency ~ μs

Level-1 Isolated Trigger

Trigger Primitive Generator

Fine grain Flag Max of ( )

Pixel Processor

E_t cut + Max ( ) > Threshold

AND

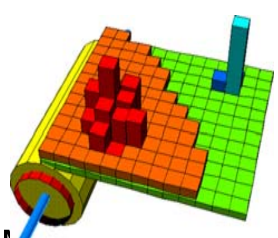
Longitudinal cut (H/E) / < 0.05

AND

Neighbors longitudinal cut / < 2 GeV

AND

One of (, , ,)

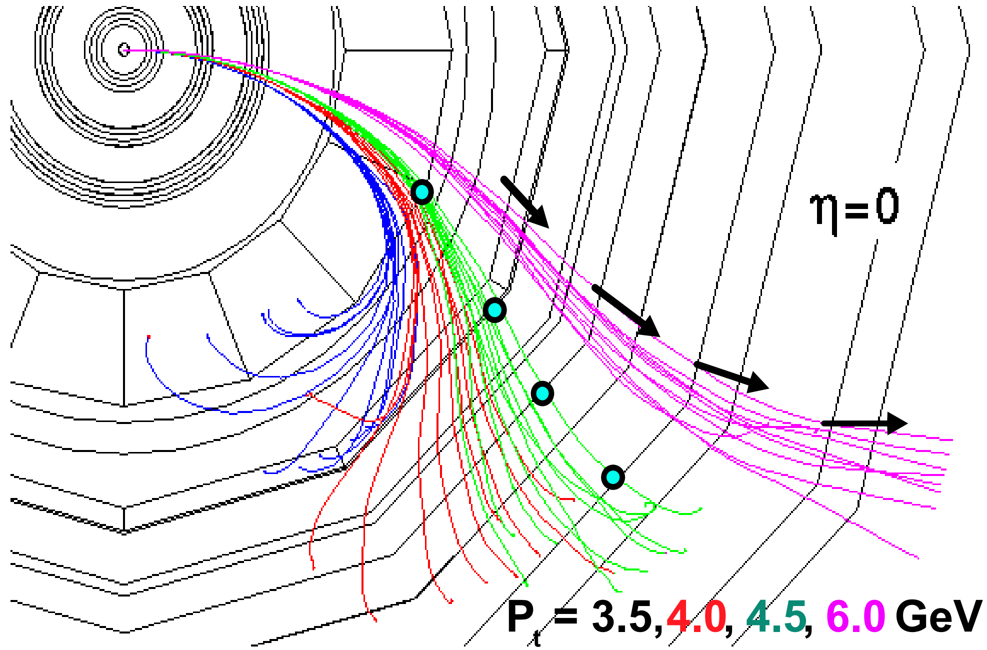


ISOLATED ELECTRON

Level-1 Muon Trigger

Trigger based on tracks in external muon detectors that point to interaction region

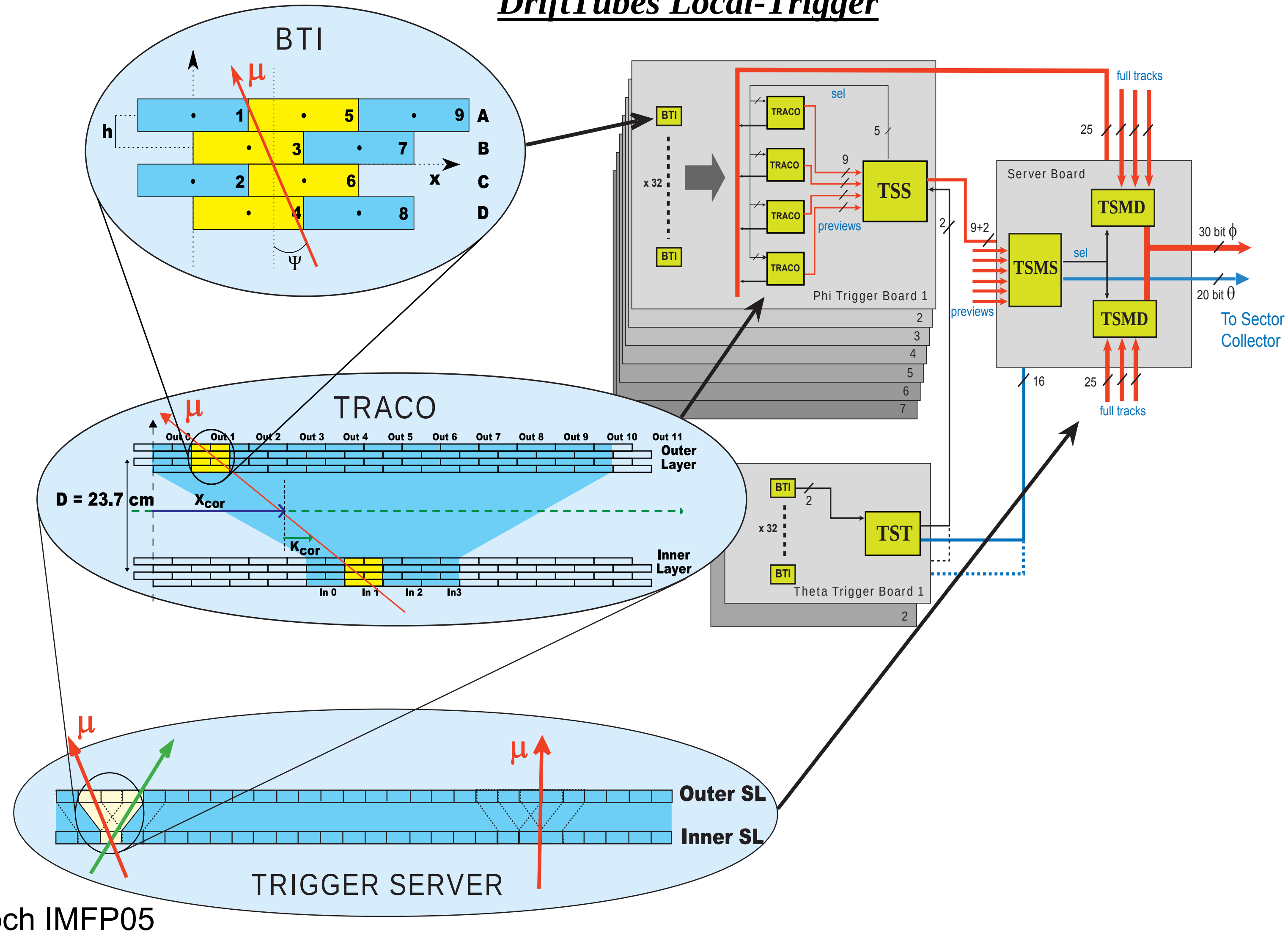
- Low-p_T muon tracks don't point to vertex
  - Multiple scattering
  - Magnetic deflection
- Two detector layers
  - Coincidence in "road"



Detectors:
RPC (pattern recognition)
DT(track segment)

CMS Level-1 Muon Trigger: DT

DriftTubes Local-Trigger



P.Bloch IMFP05

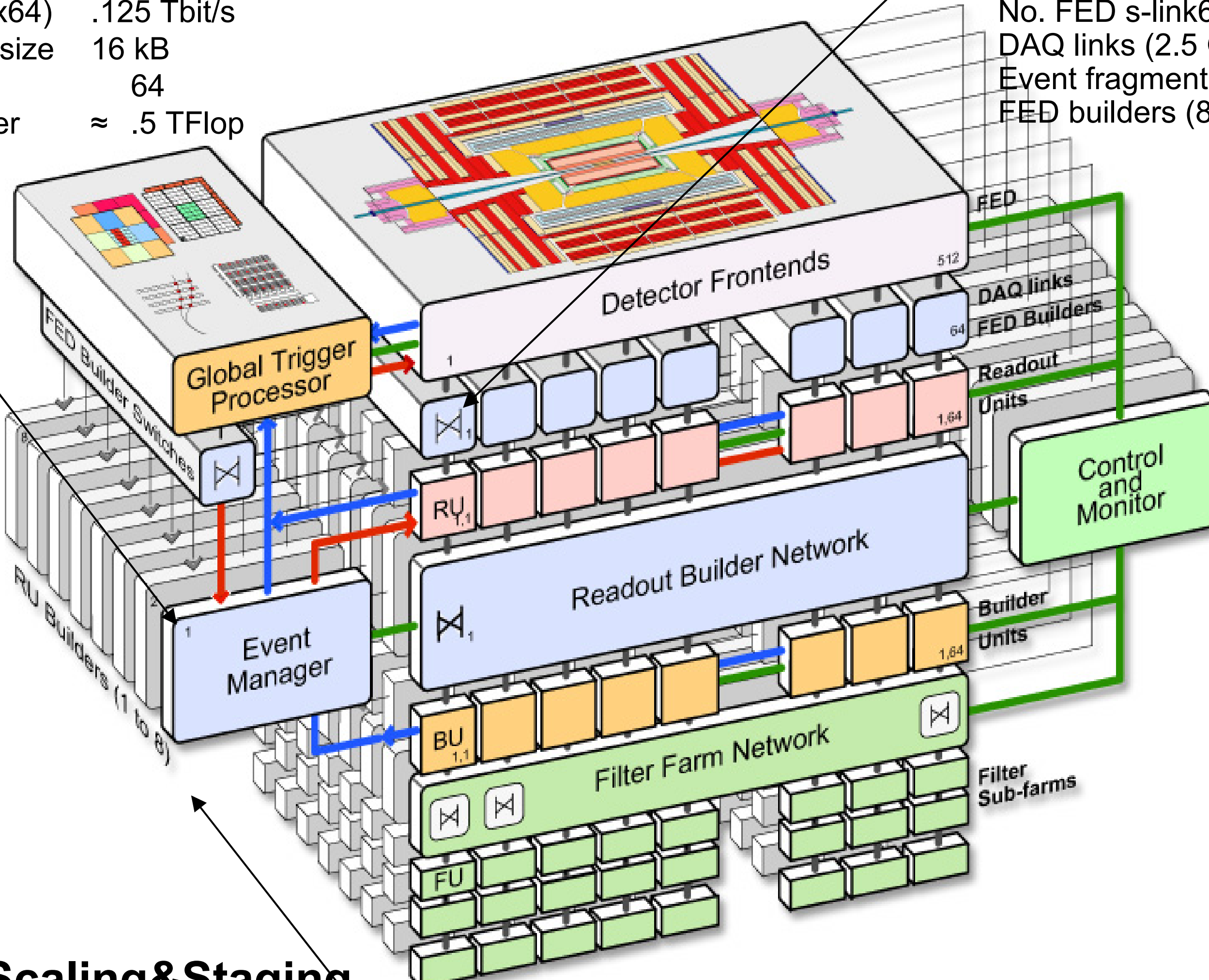
3D-EVB: DAQ architecture

DAQ unit (1/8th full system):

Lv-1 max. trigger rate	12.5 kHz
RU Builder (64x64)	.125 Tbit/s
Event fragment size	16 kB
RU/BU systems	64
Event filter power	≈ .5 TFlop

Data to surface:

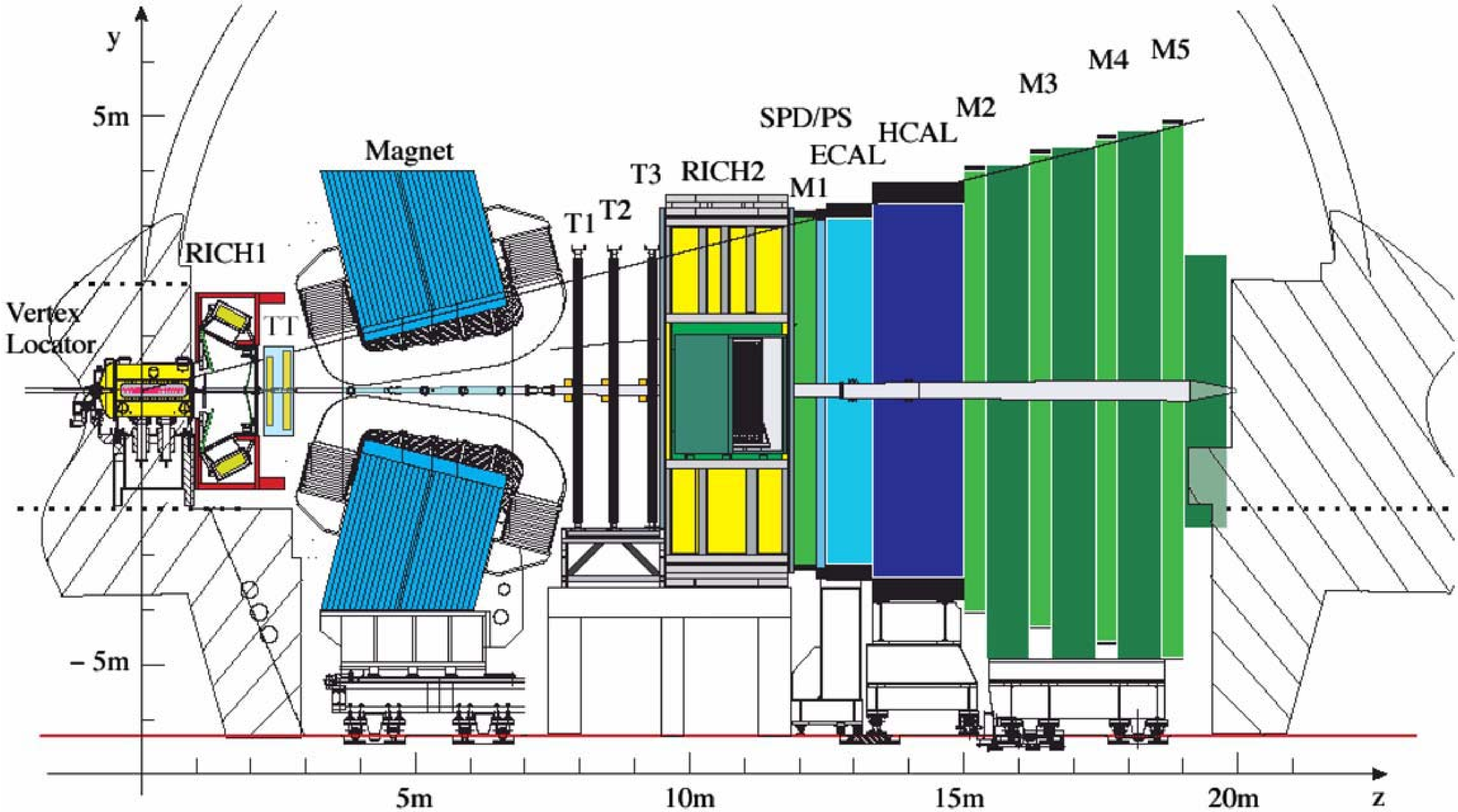
Average event size		1 Mbyte
No. FED s-link64 ports	>	512
DAQ links (2.5 Gb/s)		512+512
Event fragment size		2 kB
FED builders (8x8)	≈	64+64



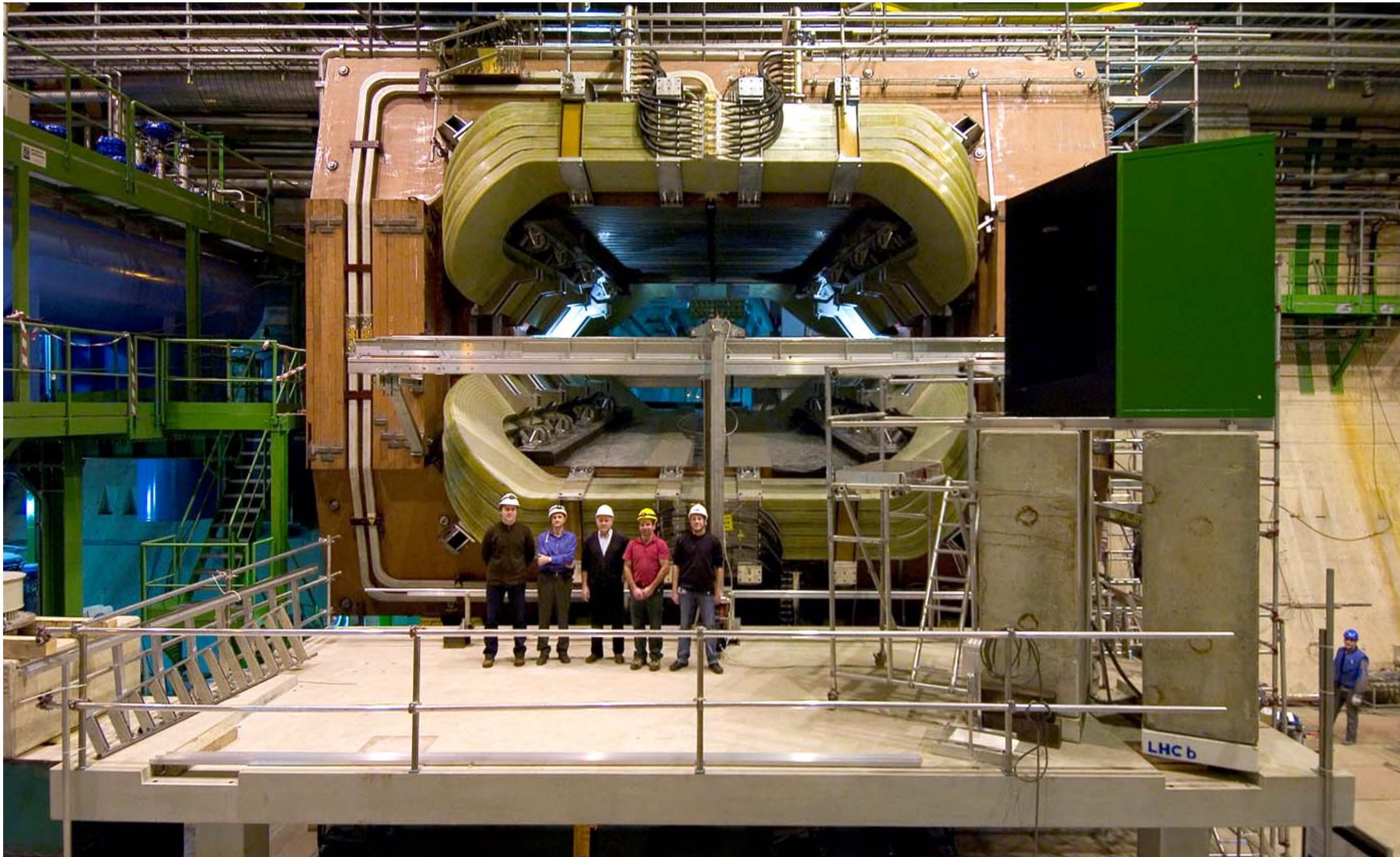
DAQ Scaling&Staging

P.Bloch IMFP05

8. LHCb experiment

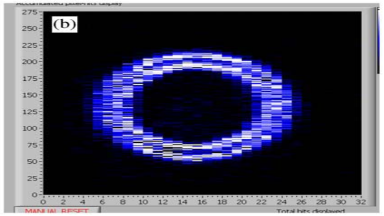


LHCB magnet



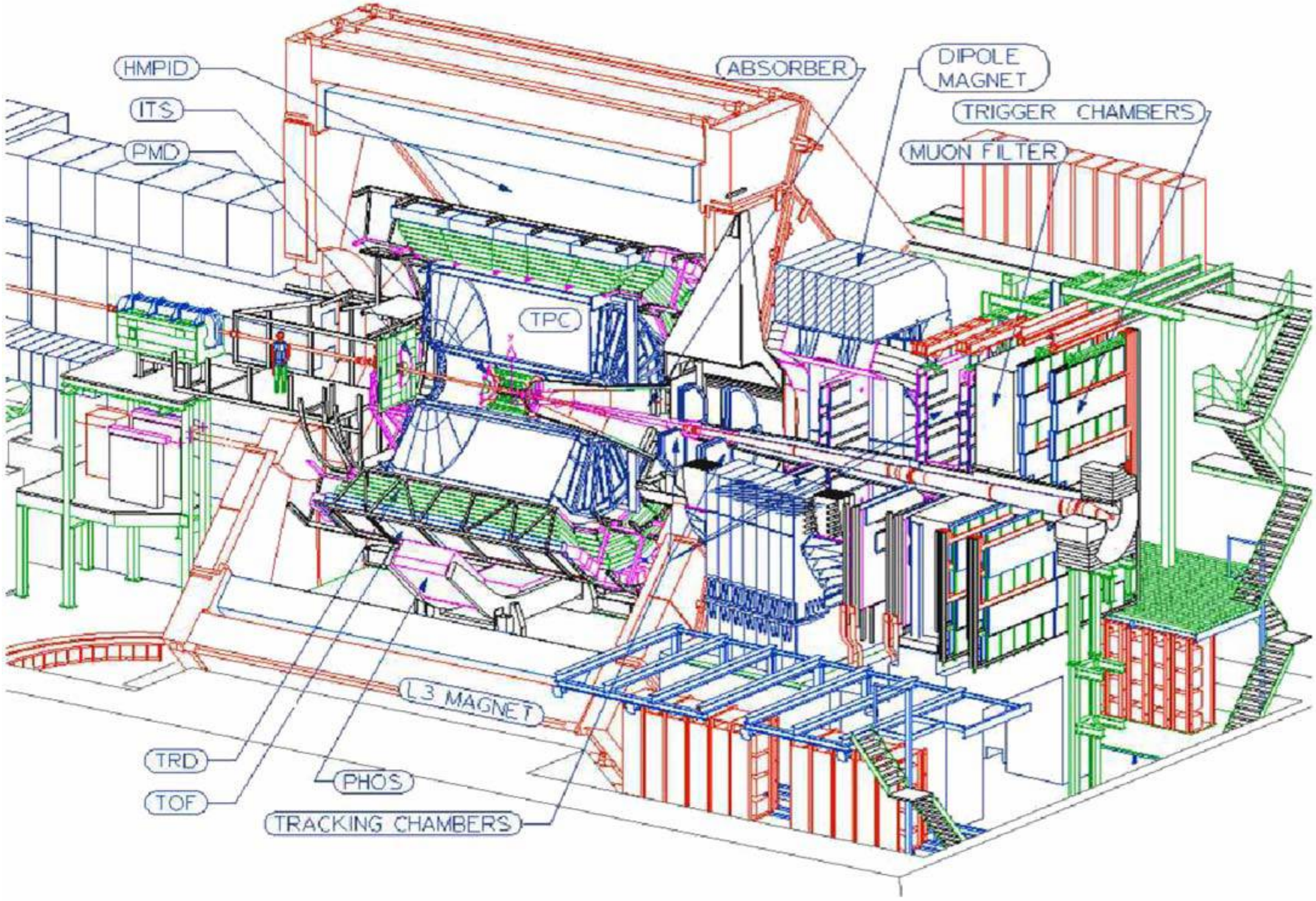
LHCb

- **Dedicated B physics experiment L = 10^{32} cm^{-2} s^{-1}**
- **Detector**
  - **21 layers Silicon microstrip detector (Vertex)**
  - **Straw tubes tracking detector**
  - **RICHs for particle ID;**
    - **aerogel , C4F10 and CF4 gas radiators**
    - **Read by HPDs (1000 single photon pixels in 80mm diam. tube)**
  - **Em calorimeter (Shashlik lead scintillator sampling) with Sci Preshower**
  - **Hadron Calorimeter (tile, similar to ATLAS design)**
  - **Muon stations with MWPC**

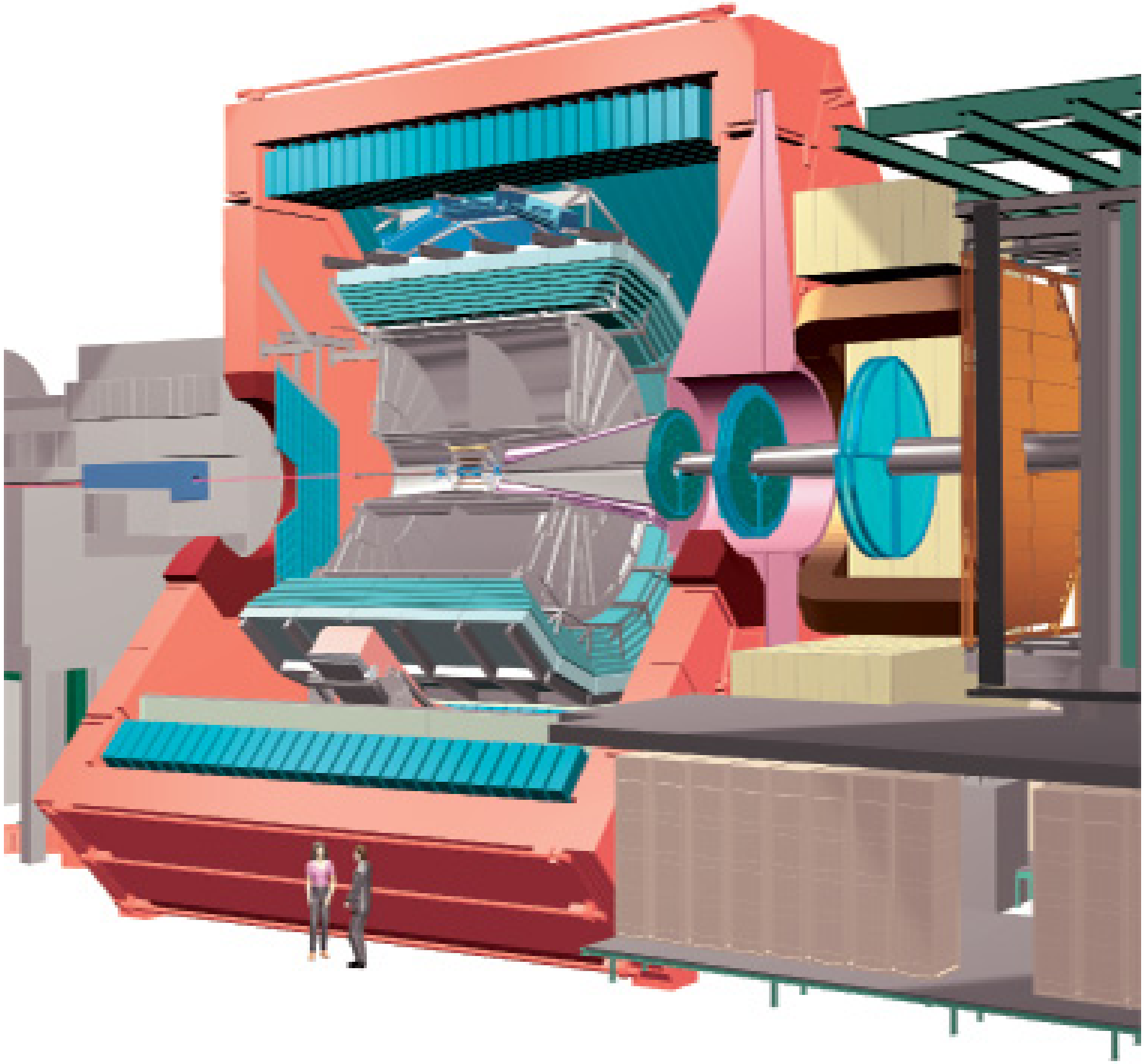


ALICE

- **Dedicated Ion experiment**

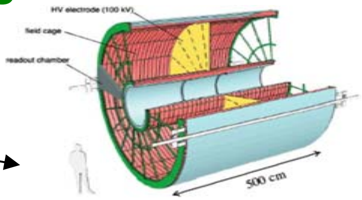


ALICE



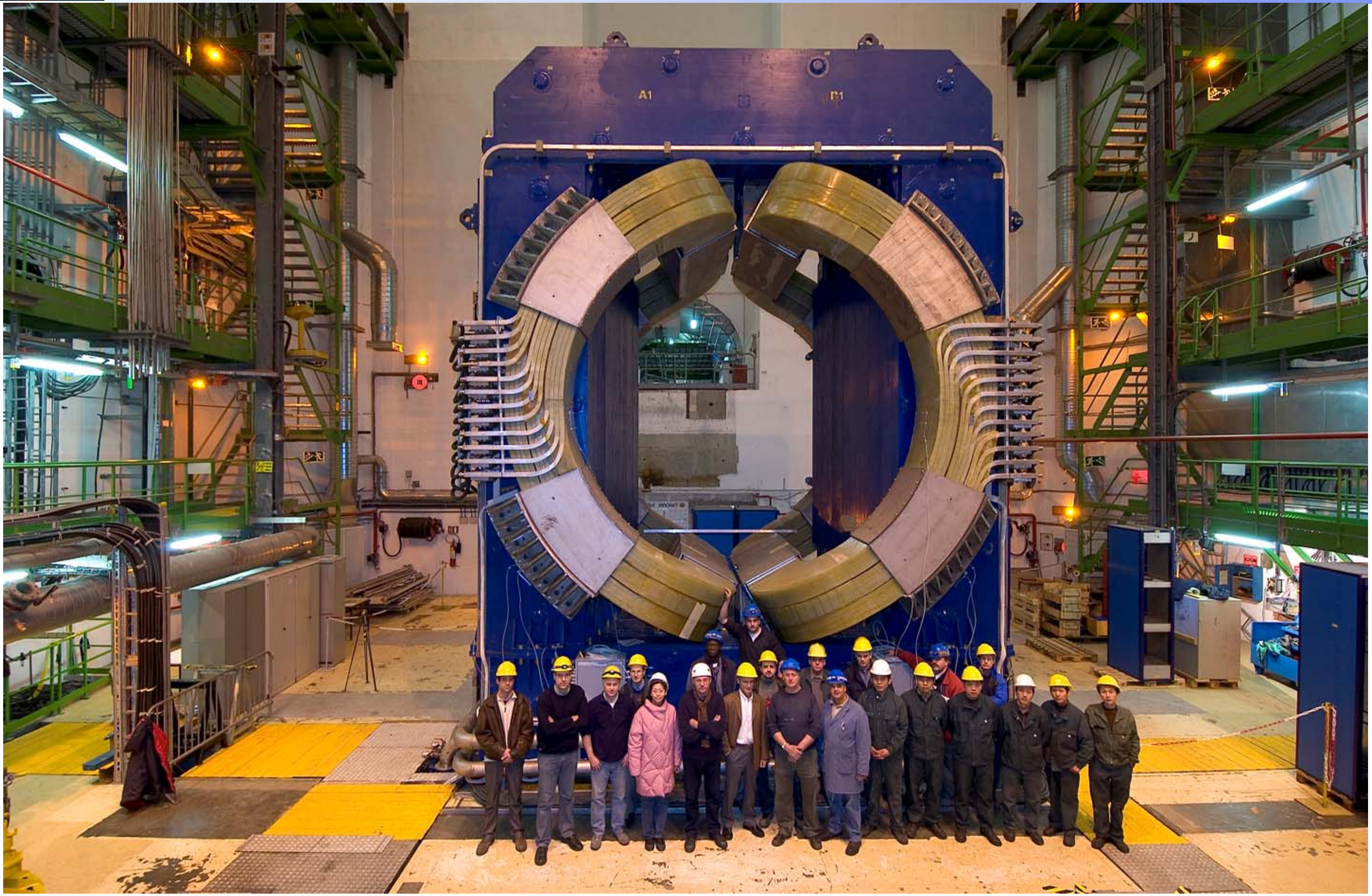
ALICE

- **Central part for hadrons, e, γ $\theta = [45^o, 135^o]$, full azimuth**
  - **Embedded in L3 magnet**
  - **Tracking:**
    - **ITC silicon pixels, drift and strip Si detectors**
    - **Large TPC**



  - **Particle ID**
    - **TOF (TOFPID)**
    - **RICH (HMPID) (partial azimuth)**
    - **TRD**
    - **Single arm calorimeter (PHOS) (partial azimuth)**
  - **Zero Degree calorimeters ZDC and Particle Multiplicity Detector**
- **Forward Muon Spectrometer**

ALICE forward Magnet



Summary

- It was a long way from the initial ideas to the detectors construction.
  - Many today's achievements seemed pure dreams 15 yrs ago !
- A set of unprecedented challenges
  - From the rate of events, to the selectivity, to the hostility of the environment and the need for very high resolutions and acceptances, a very difficult job
- Simulation says that ATLAS and CMS will probe the Physics that the LHC will deliver very effectively
- Current issues: calibration, alignment, initial run scenarii etc…
  - Installation and commissioning of the detector.
  - And then: control and monitor…