Calorimetry Lecture 2

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Outline of Lecture 2

- Specific Calorimeters at the Tevatron and LHC
  - Design Choices and Physics Optimization
- Imperfect Detectors
  - Understanding Potential Limitations
  - A Historical Example

Tevatron Calorimeters

- Main calorimeter parameters were decided ~25 years ago in preparation for Run I (or even earlier for CDF)
  - Readout (and trigger) parameters needed adjustment for Run II detector upgrades due to bunch-crossing time modifications from 3.4 μs in Run I to 396 ns (and once falsely planned for even shorter spacing 132 ns)
  - New tracking (and for D0 a solenoid magnet) introduced new material in front of the calorimeters
  - CDF upgraded plug detectors (same technology used for CMS HCAL), added preshower and installed timing readout to the central EM calorimeter section
- Tevatron detectors have more time between crossings compared to the LHC, **no radiation hardness requirements**, somewhat smaller dynamic range and are optimized for SM
  - Tevatron calorimeters are well understood, operating well and have done amazing things (and still will)

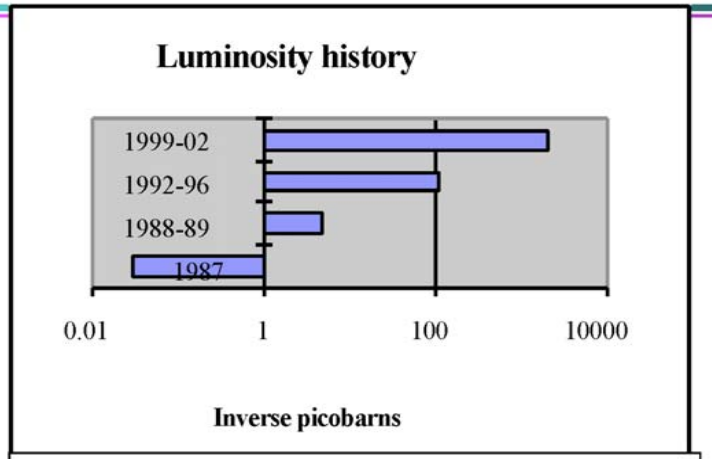
Some Turn-on History

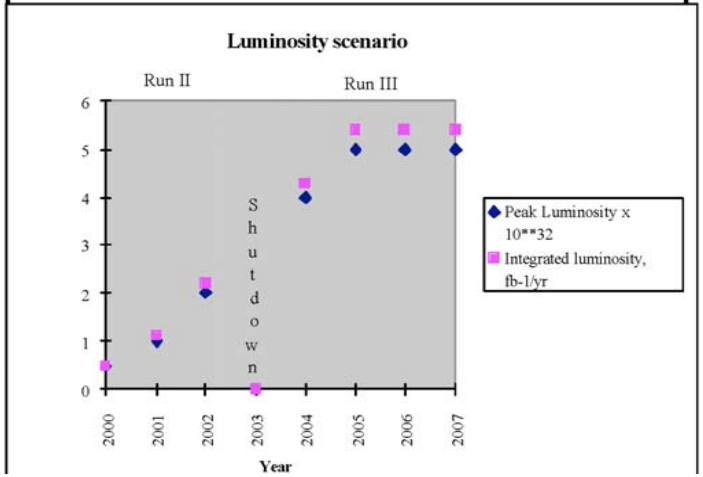
- Things started slowly and expectations (this is a 1999 slide) were still big, overestimating Run II

Many explorations limited by available luminosity ==> Improve this for Run II !

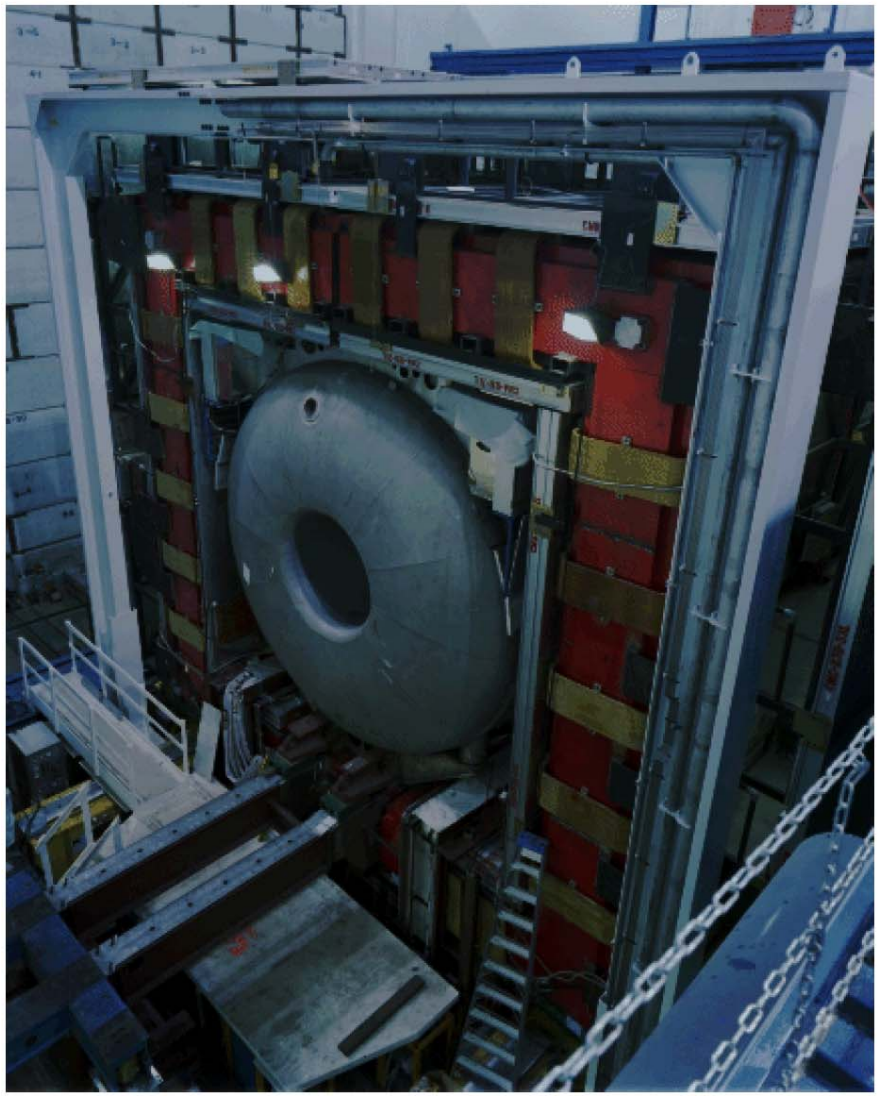
- 1985: first collisions
- 1987: 30 nb^{-1}
- 1988-89: 4.7 pb^{-1}
- 1992-96: Run I 110 pb^{-1}
- 2001-02: Run II 2 fb^{-1}
- 2003-07: Run II >15 fb^{-1}

Possible luminosity evolution:





D0 LAr Calorimeter



D0 liquid Argon calorimeter:

- Conception started in 1983
- Uranium/Liquid Argon em calorimeter
- Copper/Stainless Steel had calorimeter

➔"compensating" $e/\pi \sim 1$ (with 3.4μs integration time)

- 55 000 read-out cells
  - ➔**4 em layers (2, 2, 7, 10 X_0),**
  - ➔**shower-max (EM3): 0.05 x 0.05**
  - ➔**4-5 hadronic layers (FH + CH)**
  - ➔**λ_{int} > 7.2 (total)**
- 5000 semi-projective trigger towers

➔**$\Delta\eta \times \Delta\varphi$ = 0.1x0.1**

- Hermetic :

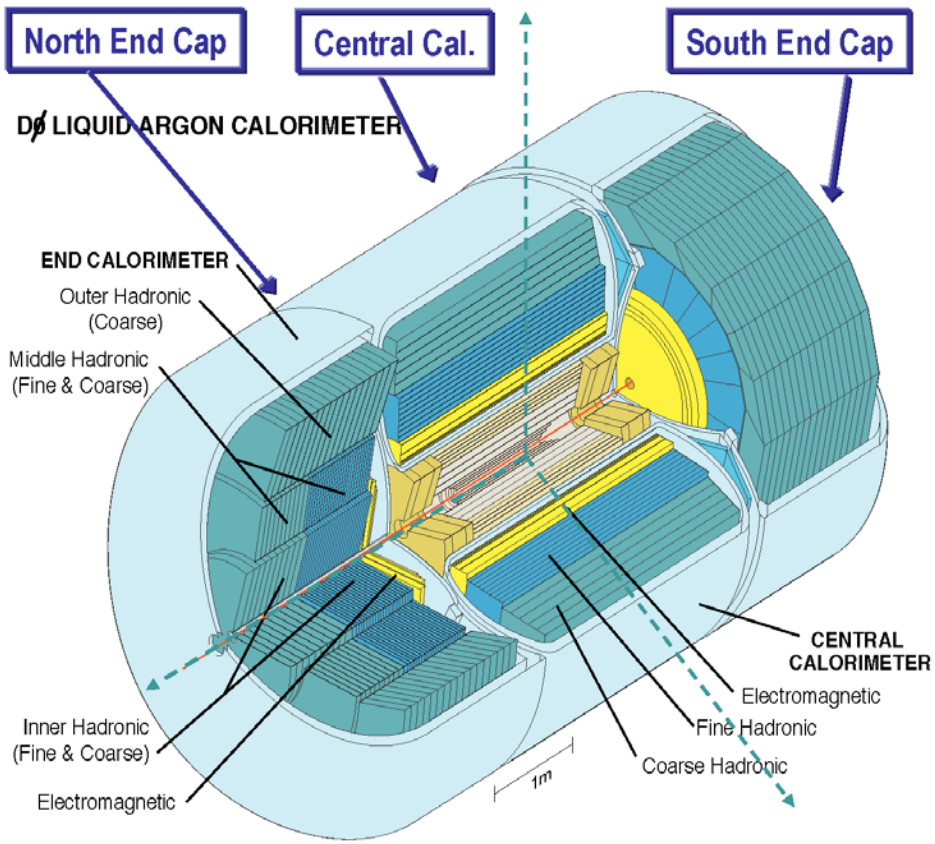
➔**$|\eta| < 4.2$ ($\theta \approx 2^o$),**

- single particle resolution from test beam

e: $\sigma_E/E = 15\% /\sqrt{E} + 0.3\%$

π: $\sigma_E/E = 45\% /\sqrt{E} + 4\%$

D0 LAr Calorimeter



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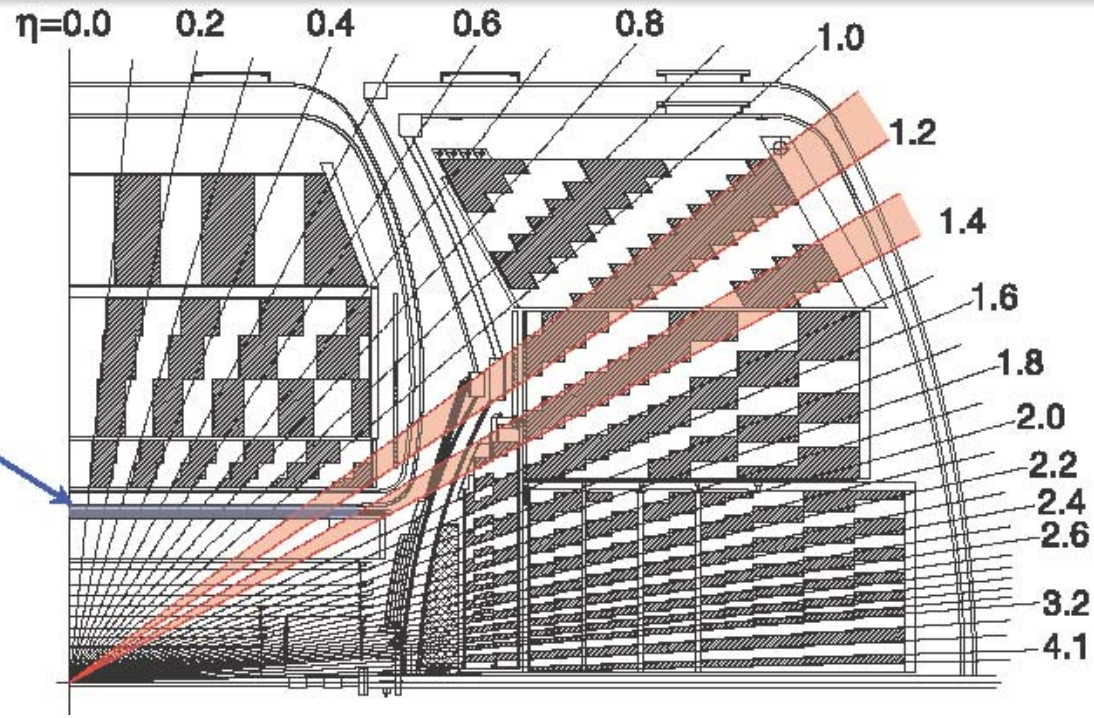
D0 Calorimeter Pseudo-Projective Towers

- Calorimeter cells make up pseudo-projective towers
- Four electromagnetic layers ($\approx 20\ X_0$)
- Three (central) or four (endcaps) finely segmented hadronic layers followed by one coarser hadronic layer. Hadronic depth > 7.2 (8.0) interaction lengths.
- Significant material in front of calorimeter: $\approx 4\ X_0$ (solenoid, preshowers, trackers)

Preshower detector

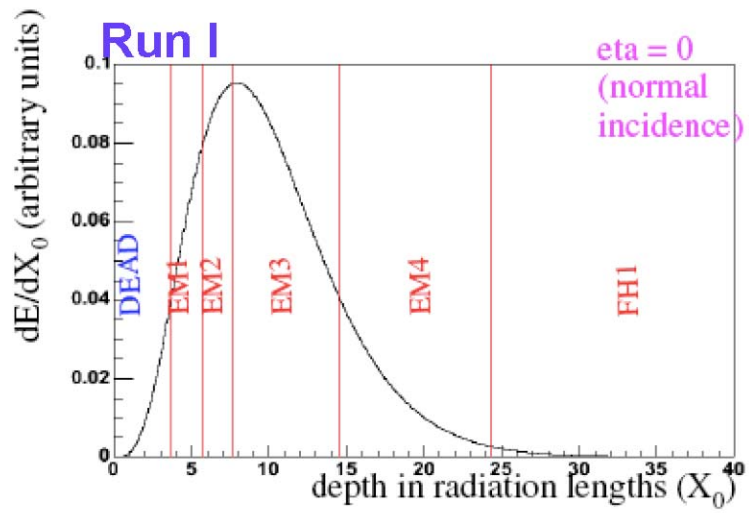
- Scintillating fibers
- Used to improve photon identification

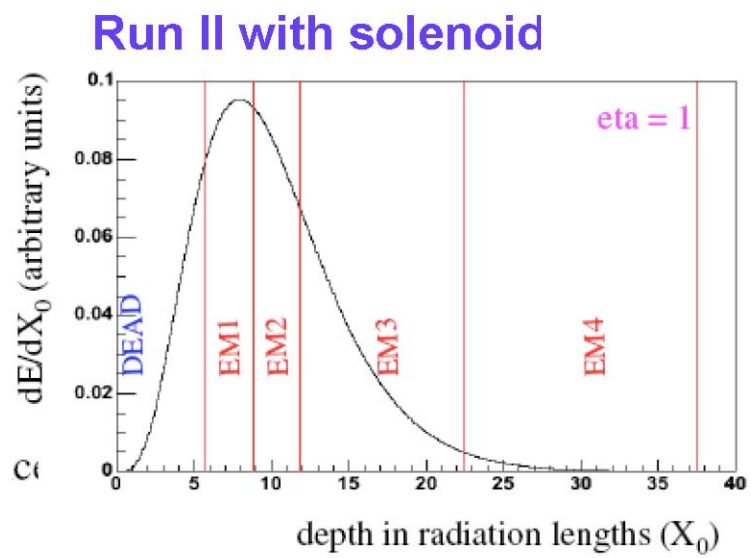


Note, ICD Region

Dead Material In Front of Calorimeter

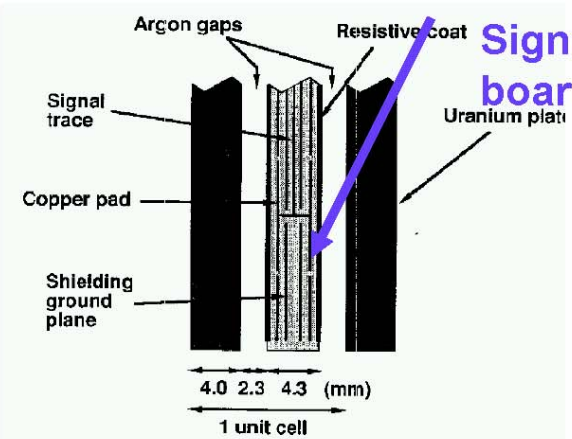
- Fine-Segmentation (0.5x0.5) in EM3 Section lost to the tail of the shower in Run II
  - Reduced power of EM shower ID parameters
  - Reweighted EM1 layer to try to account for dead material and added in preshower energies
  - Result on performance: Raised Energy Resolution Constant Term

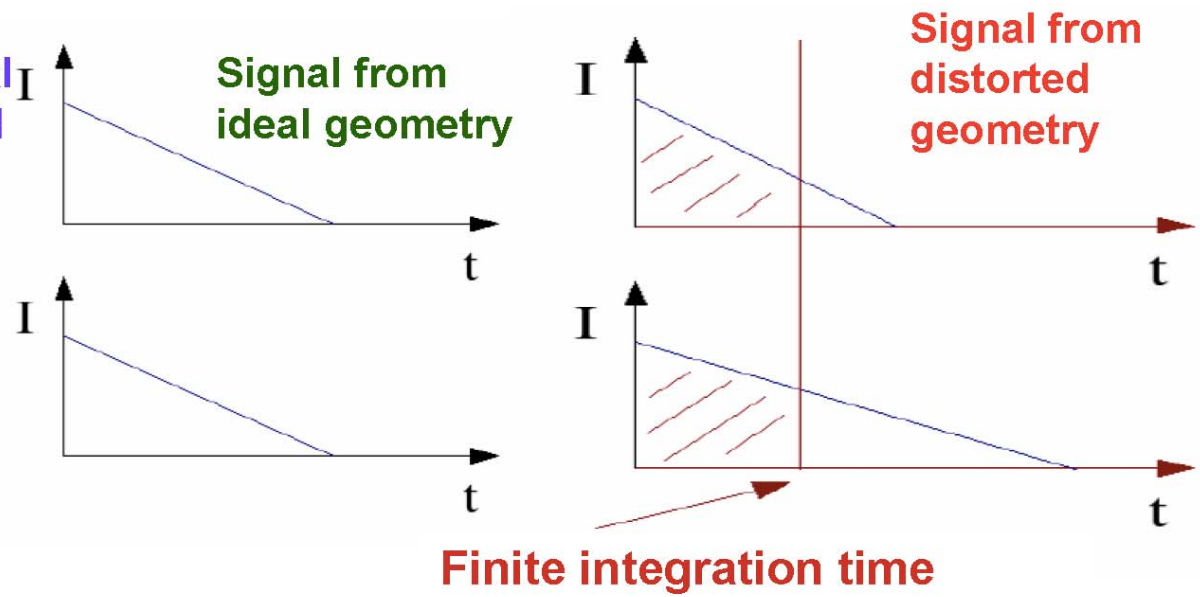




Most Unexpected Changed

- The decrease in charge integration time (and faster pulse shaping – aimed at 132 ns bunch spacing) exposed non-uniformities in the original construction of the LAr gap spacings
  - Jet energy resolution constant term increased to ~8%



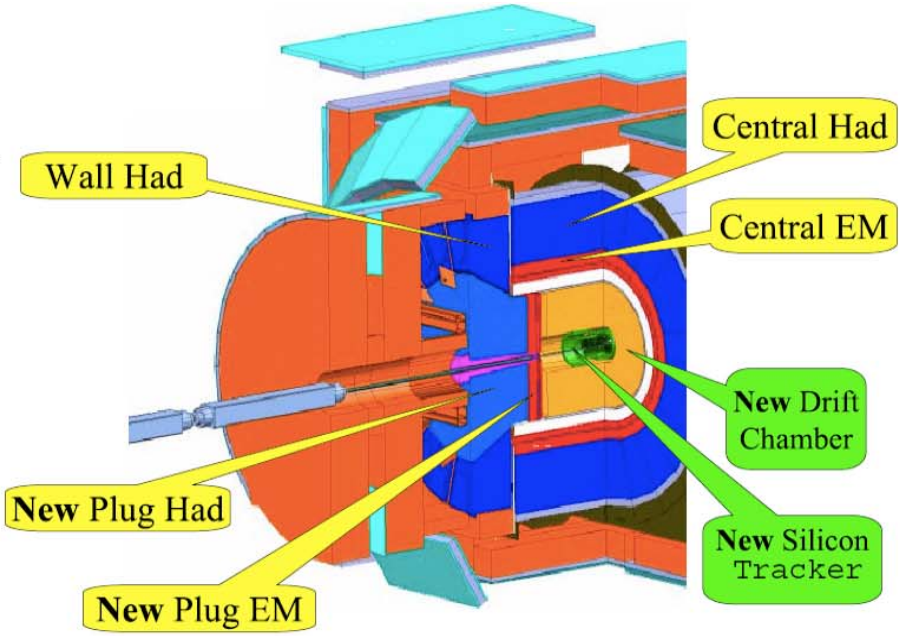


The CDF Calorimeters

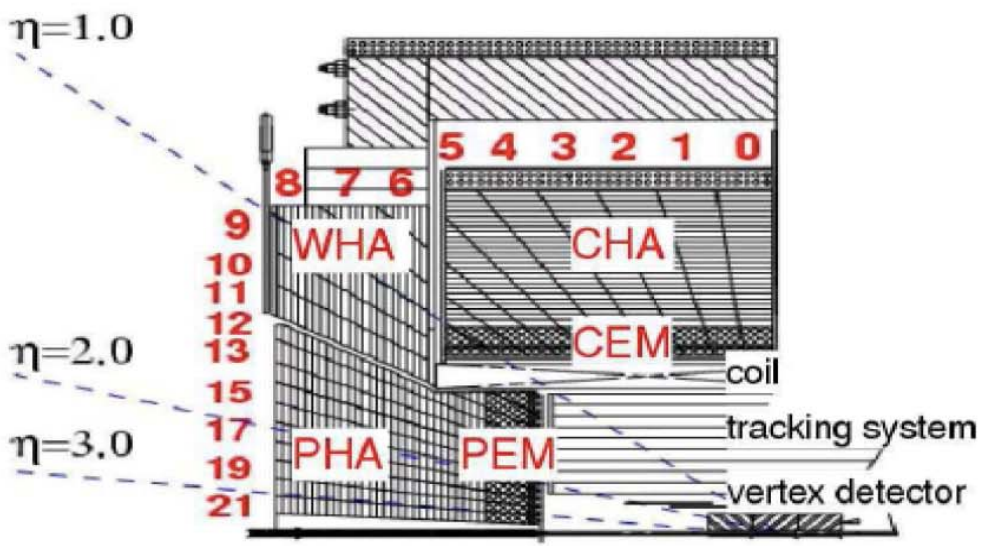
All scintillator-based sampling calorimeters

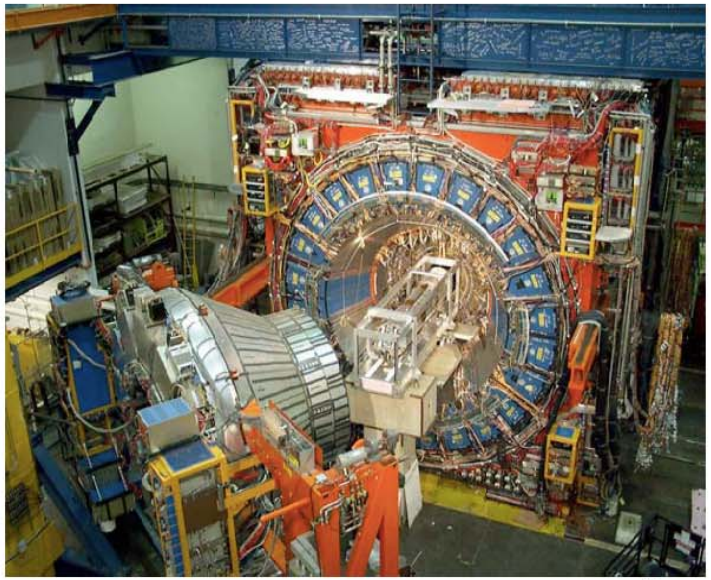
$\|\eta\|$ Range	$\Delta\phi$	$\Delta\eta$
0. - 1.1 (1.2 h)	15°	~ 0.1
1.1 (1.2 h) - 1.8	7.5°	~ 0.1
1.8 - 2.1	7.5°	~ 0.16
2.1 - 3.64	15°	0.2 - 0.6

Table 1.2: CDF II Calorimeter Segmentation



Coarse Granularity in ϕ



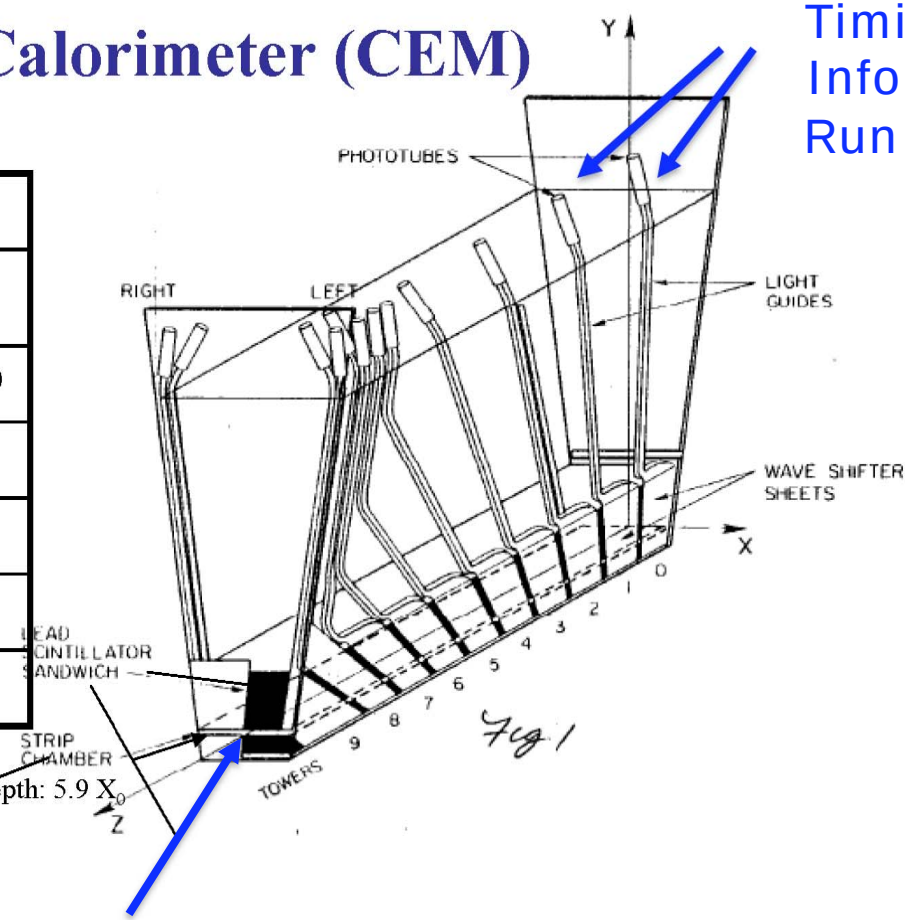


CDF EM Calorimeter

Central Electromagnetic Calorimeter (CEM)

Thickness	**18X_0 , 1l**
Abs. (pb) layer	**1/8" (4.2 mm,0.6 X_0)**
Scint. layer	**5 mm , polystyrene (SCSN-38)**
w.l.s.	**3mm Y7 acrylic sheet**
PMT	**Ham. R580 (1.5")**
light yield	**>100 p.e./GeV/pmt**
resolution	$13.5/\sqrt{E_T}$

Added Timing Info in Run II



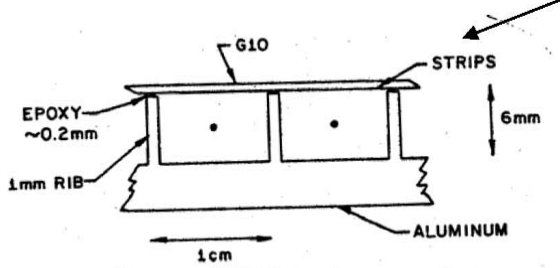


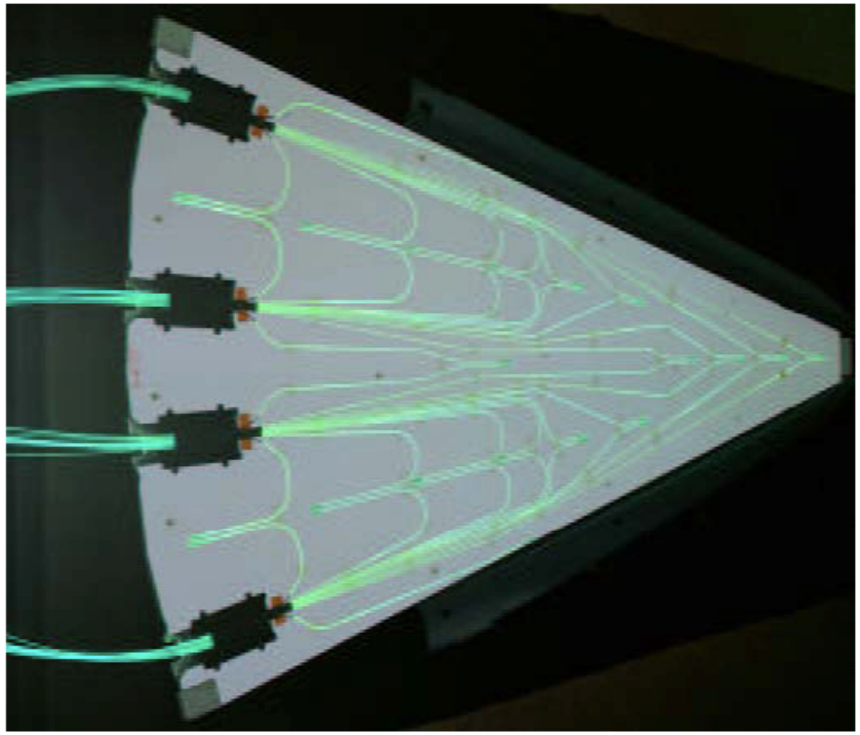
Fig. 3. Prototype strip chamber cross section.

Shower Max Detector (Gas Strip Chamber) at EM Shower Max

CDF Plug Calorimeter

Plug Hadronic Calorimeter (PHA)

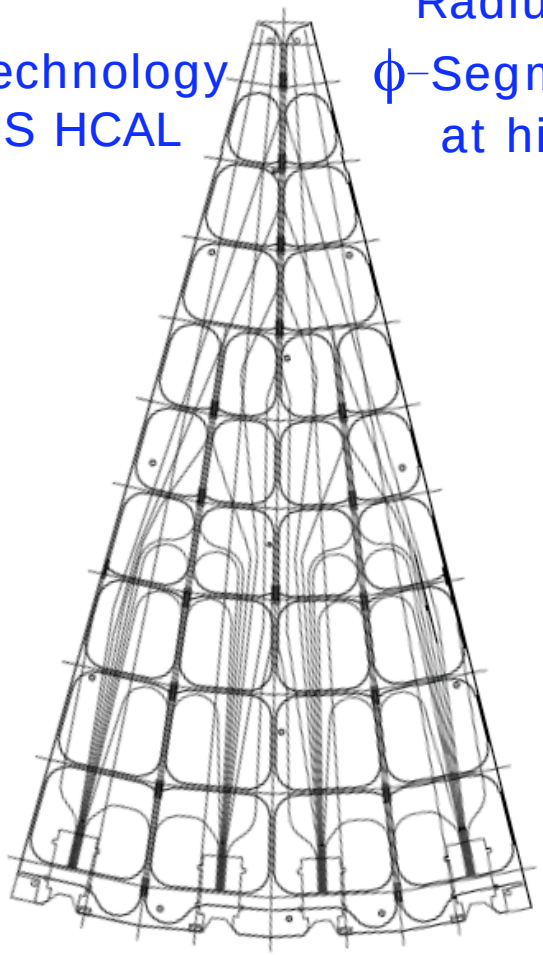
30° Megatiles



Same technology as CMS HCAL

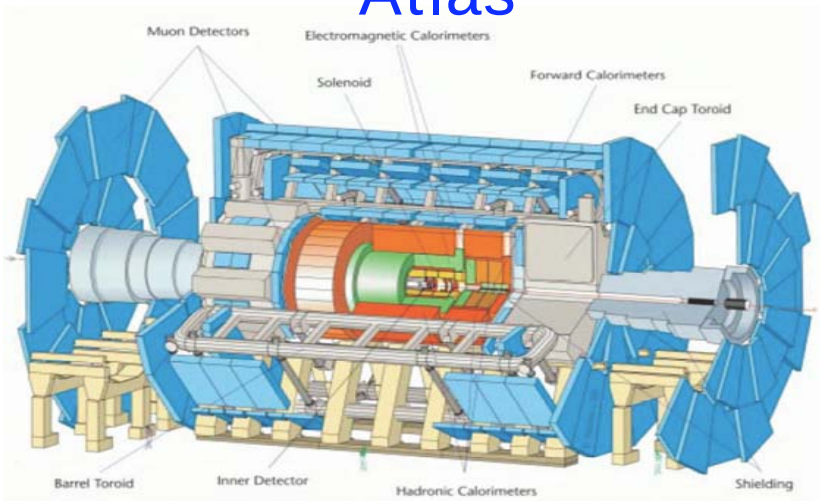
Fiber bending Radius limits

ϕ–Segmentation at high eta

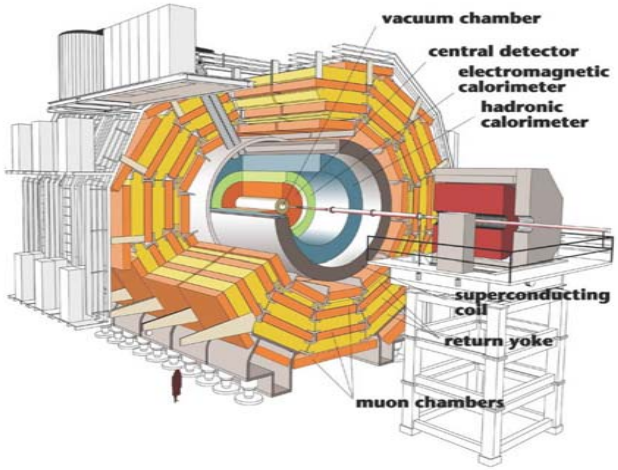


LHC Calorimeters – Lots of Variety!

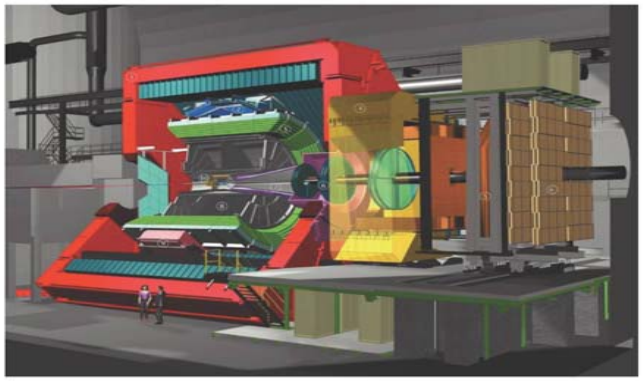
Atlas



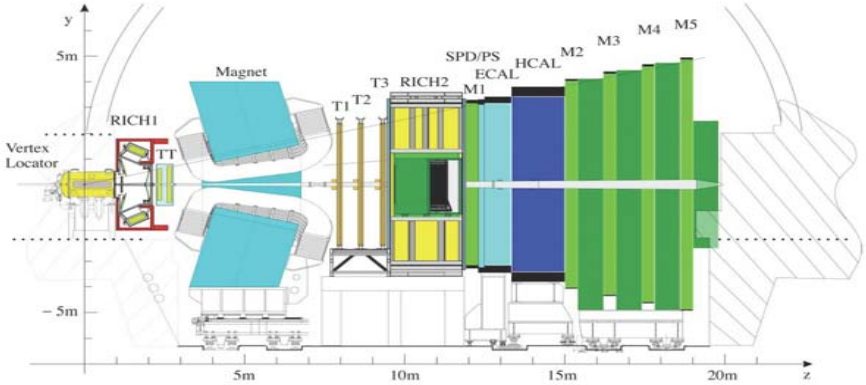
CMS



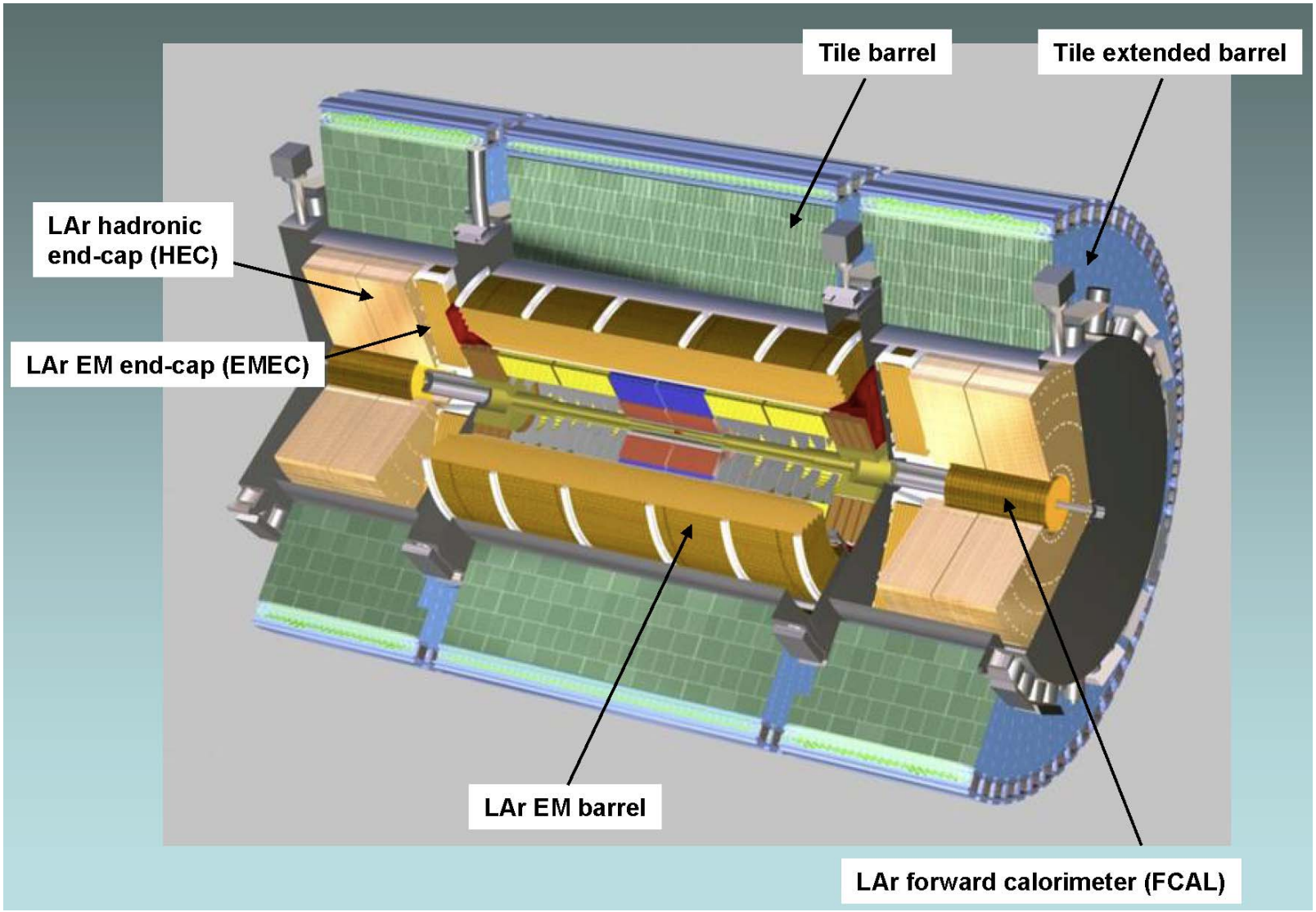
Alice



LHCb

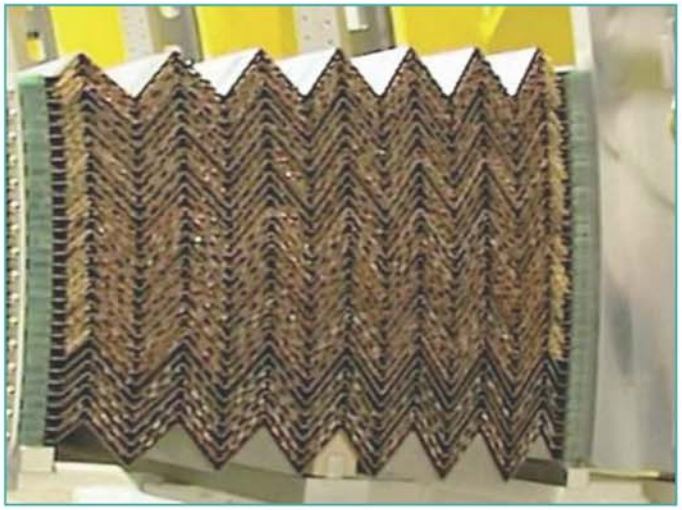


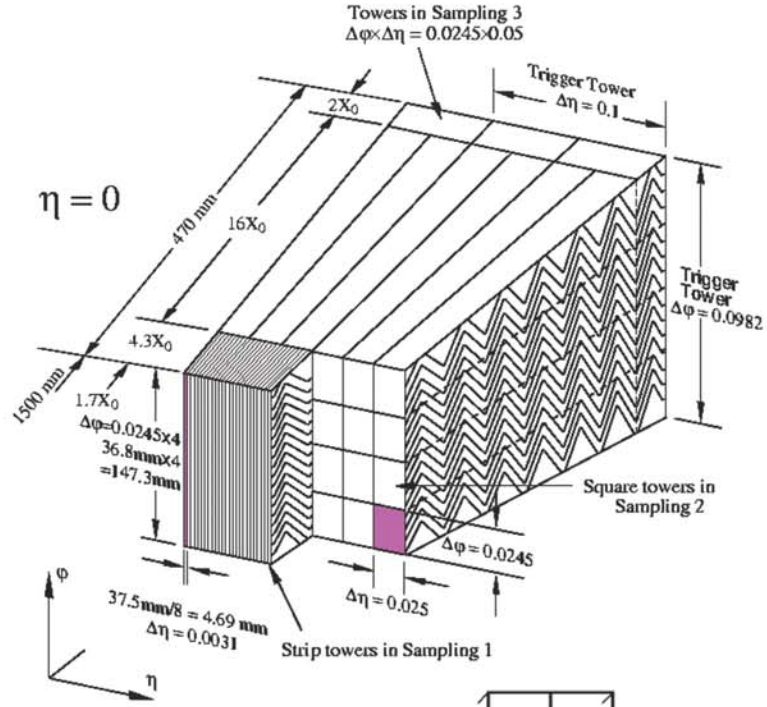
Atlas Calorimeters



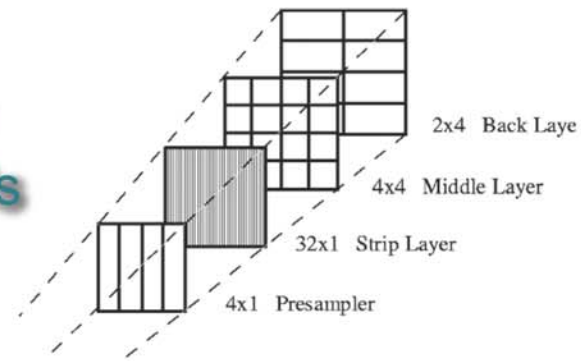
ATLAS Pb/LAr EM

- Length: at least 22 X_0 (47 cm)
- 3 longitudinal layers (+presampler)
- 4 X_0 rejection of π^0 in two photons
- 16 X_0 for shower core
- 2 X_0 evaluation of late showers

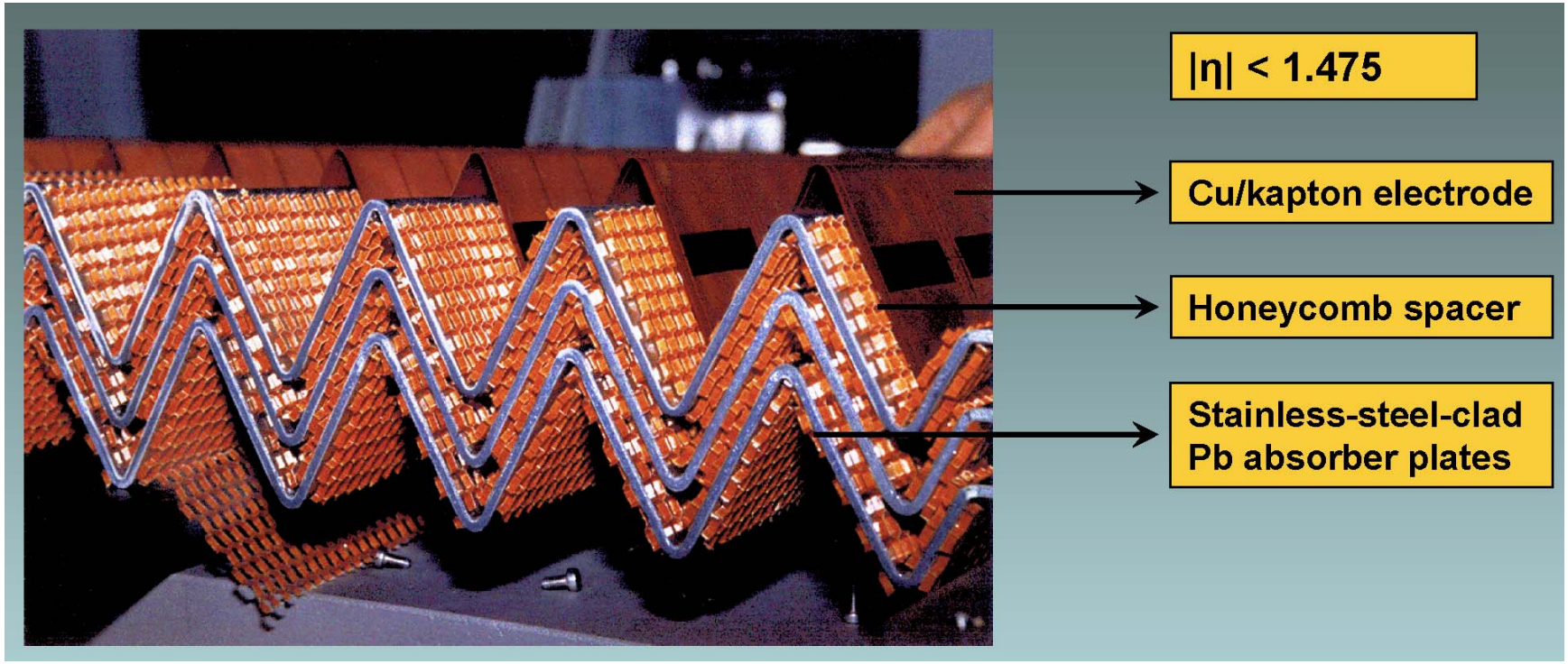




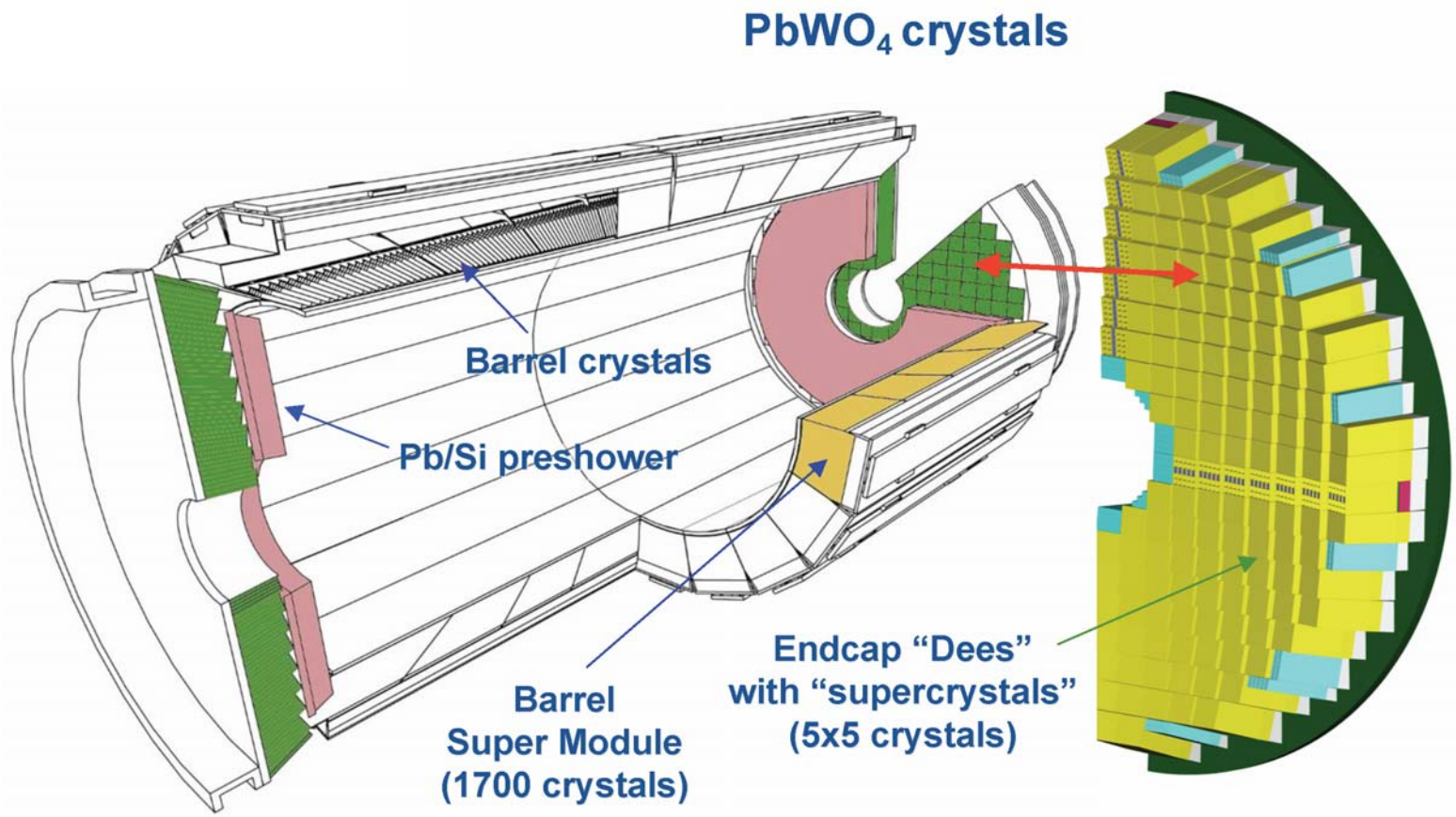
170000 channels



Spacing Held with Honeycomb Structure



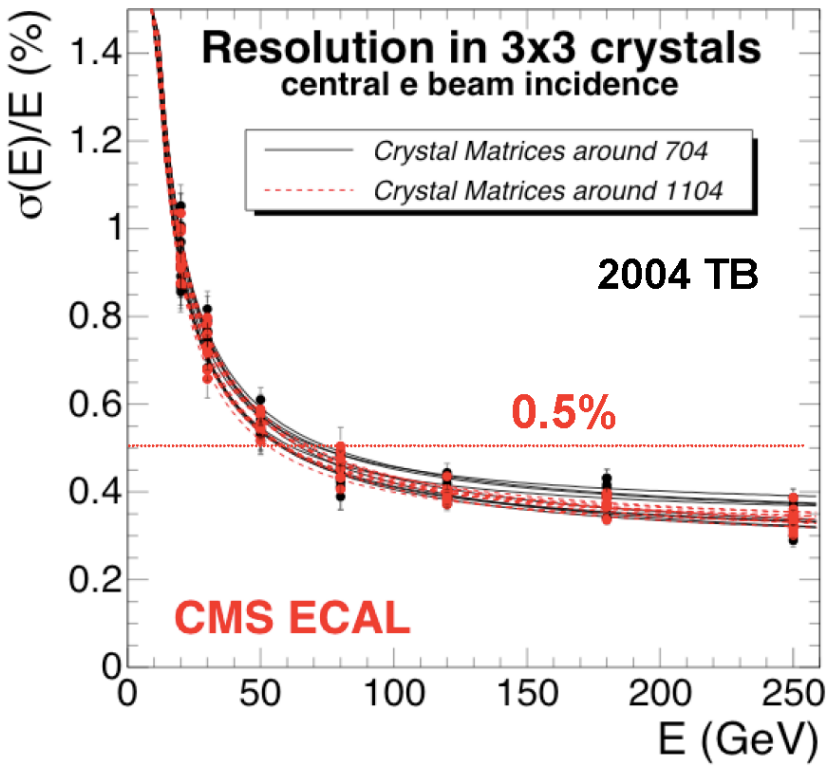
CMS ECAL



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22cm^3$)

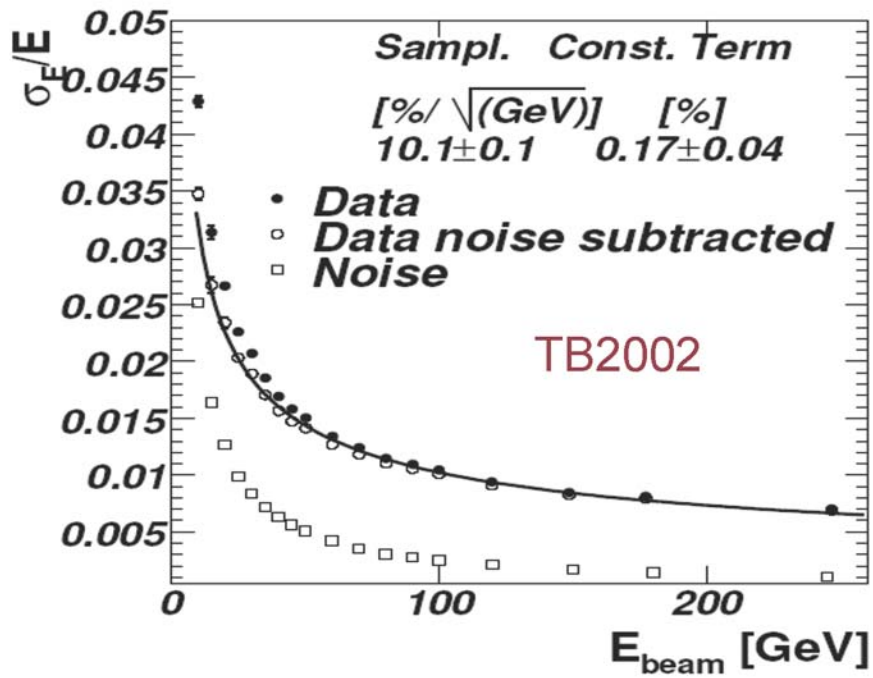
Atlas/CMS ECAL Resolutions



$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

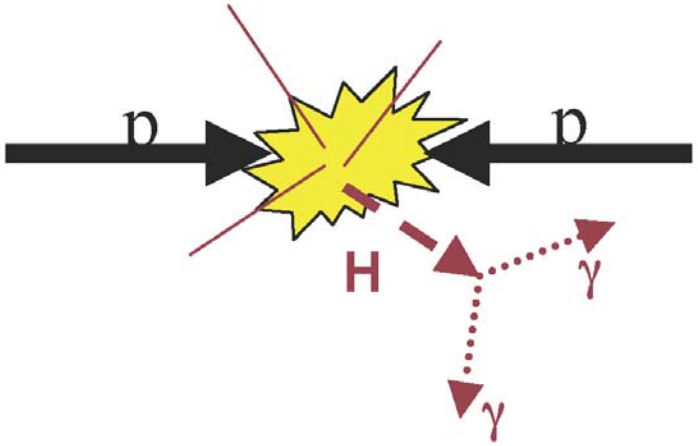
Global Constant Term less than 0.5%

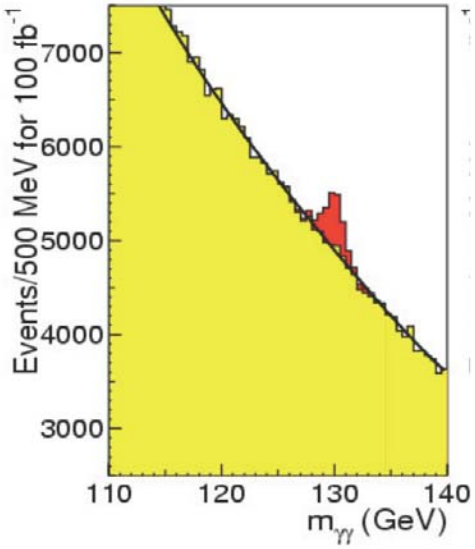
Atlas EM Resolution



Global Constant Term 0.6-0.7%

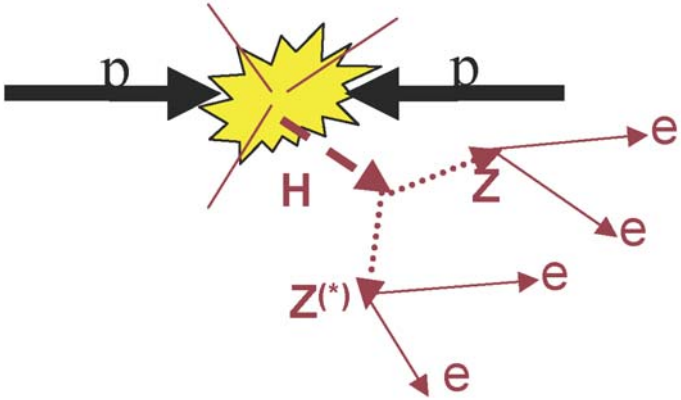
Why ECAL Resolution so critical?





Photons high precision

leptons high precision

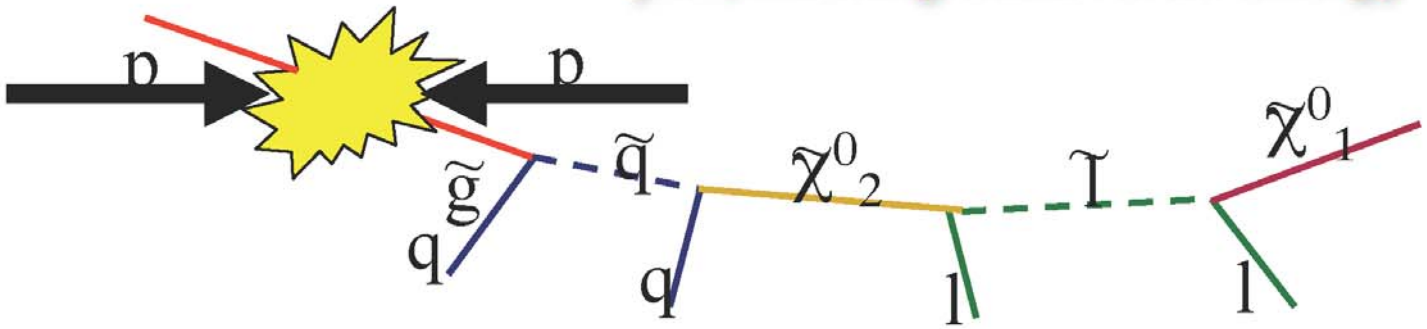


Comparing Atlas/CMS ECAL Designs

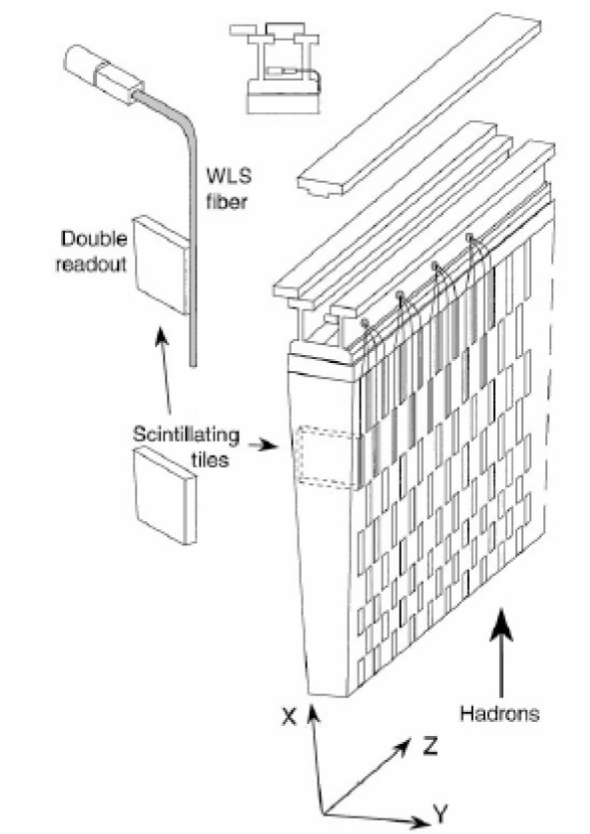
	ATLAS Lead/L. Ar ECAL		CMS PWO Crystal ECAL	
	Barrel	Endcaps	Barrel	Endcaps
# of Channels	110,208	83,744	61,200	14,648
Lateral Segmentation ($\Delta\eta \times \Delta\varphi$)				
Presampler	0.025 x 0.1			
Strip/Preshower	0.003 x 0.1	0.005 x 0.1		32 S /4 crystals
Main Body	0.025 x 0.025		0.0175 x 0.0175	Up to 0.05 x 0.05
Back	0.05 x 0.025			
Longitudinal Segmentation				
Presampler	10 mm L. Ar	2 x 2 mm L. Ar		
Strip/Preshower	~4.3 X_0	~4 X_0		3 X_0
Main Body	~16 X_0	~20 X_0	26 X_0	25 X_0
Back	~2 X_0	~2 X_0		
Designed Energy Resolution				
Stochastic: a	10%	10 - 12%	2.7%	5.7%
Constant: b	0.7%	0.7%	0.55%	0.55%
Noise: C	0.25 GeV	0.25 GeV	0.16 GeV	0.77 GeV

How about jet/MET resolution?

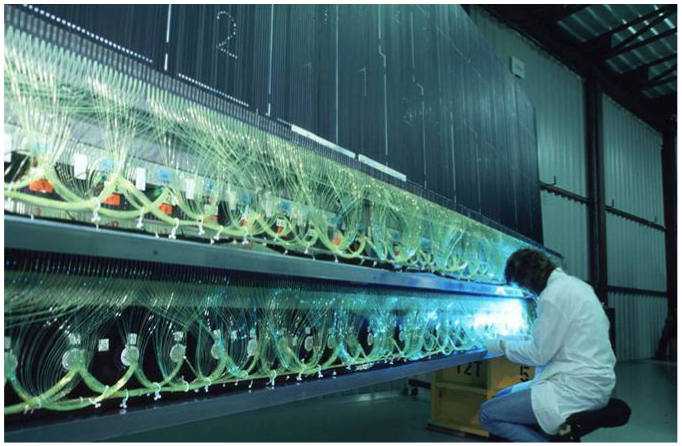
identify complex decay chains by measuring electrons, jets, missing transverse energy



Atlas Tile Calorimeter



Fe/Scint with WLS fiber Readout via PMT



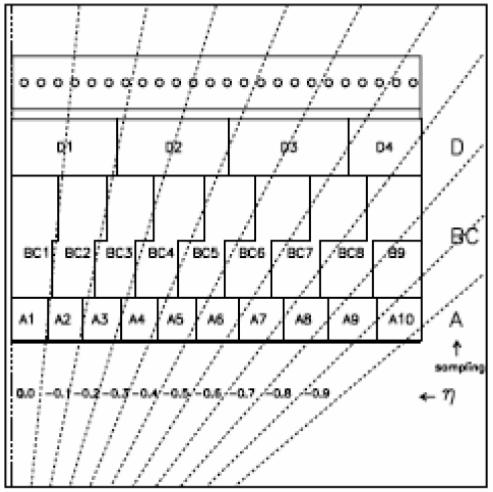


Figure 5-15 Cell geometry of half of a barrel module. The fibres of each cell are routed to one PMT. The PMTs are located in the open circles shown in the girder region.

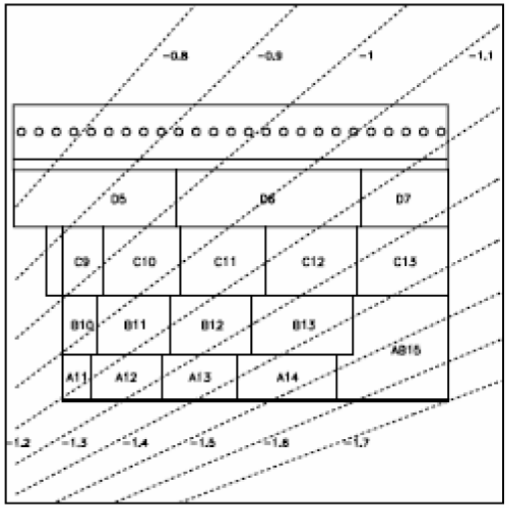
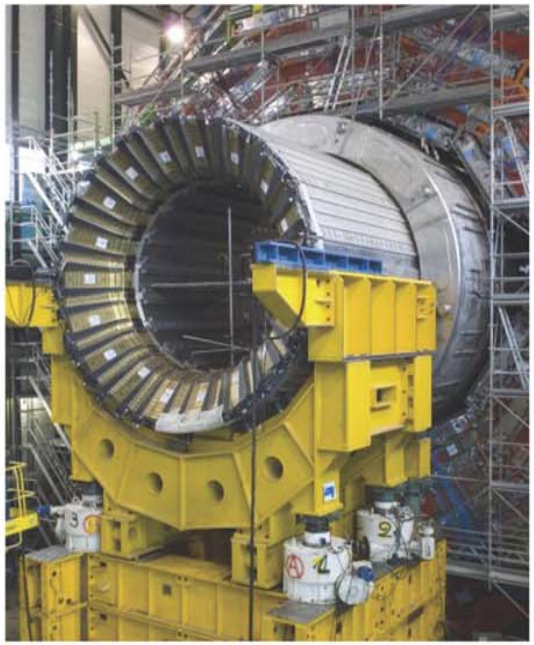
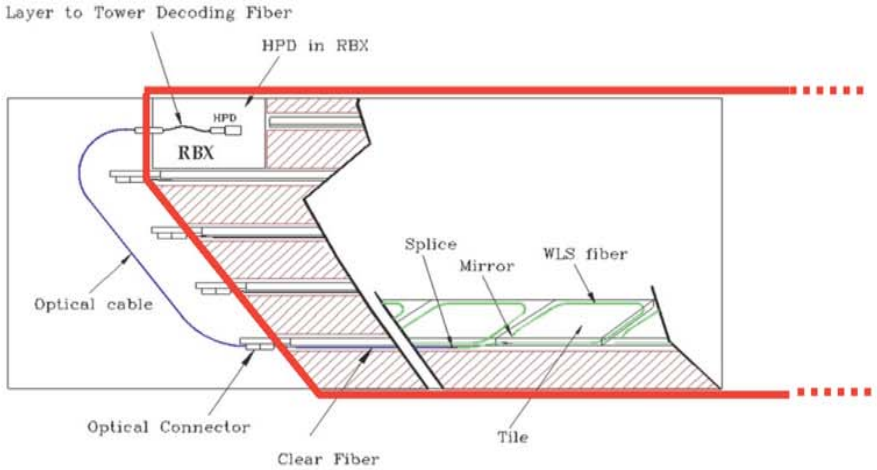
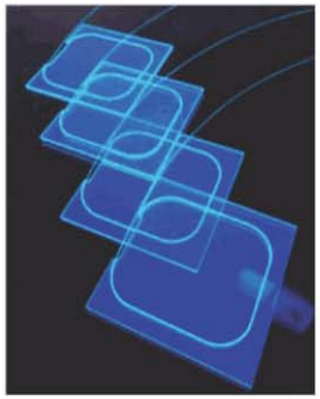


Figure 5-16 Proposed cell geometry for the extended barrel modules (version "a la barrel").

CMS HCAL barrel



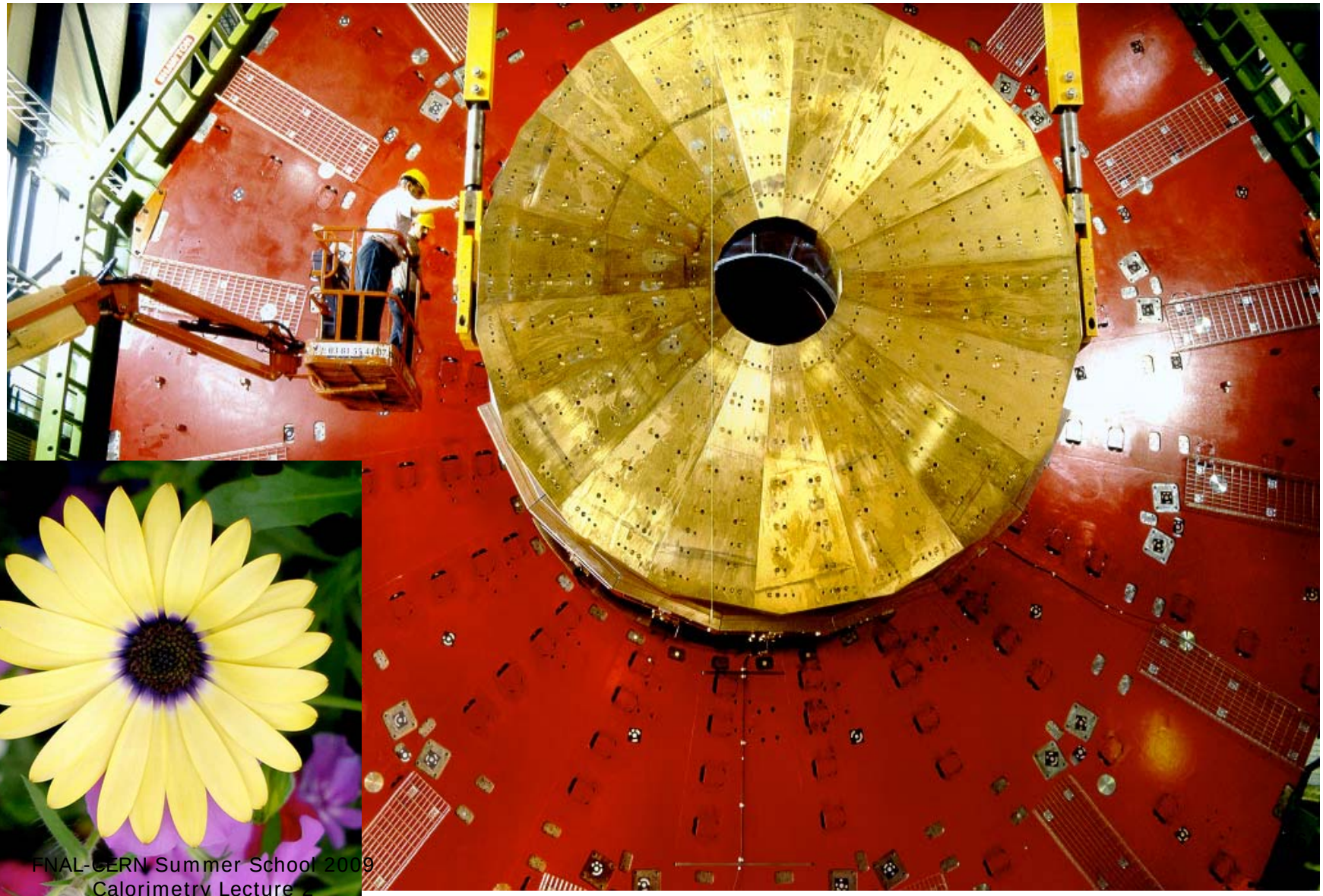




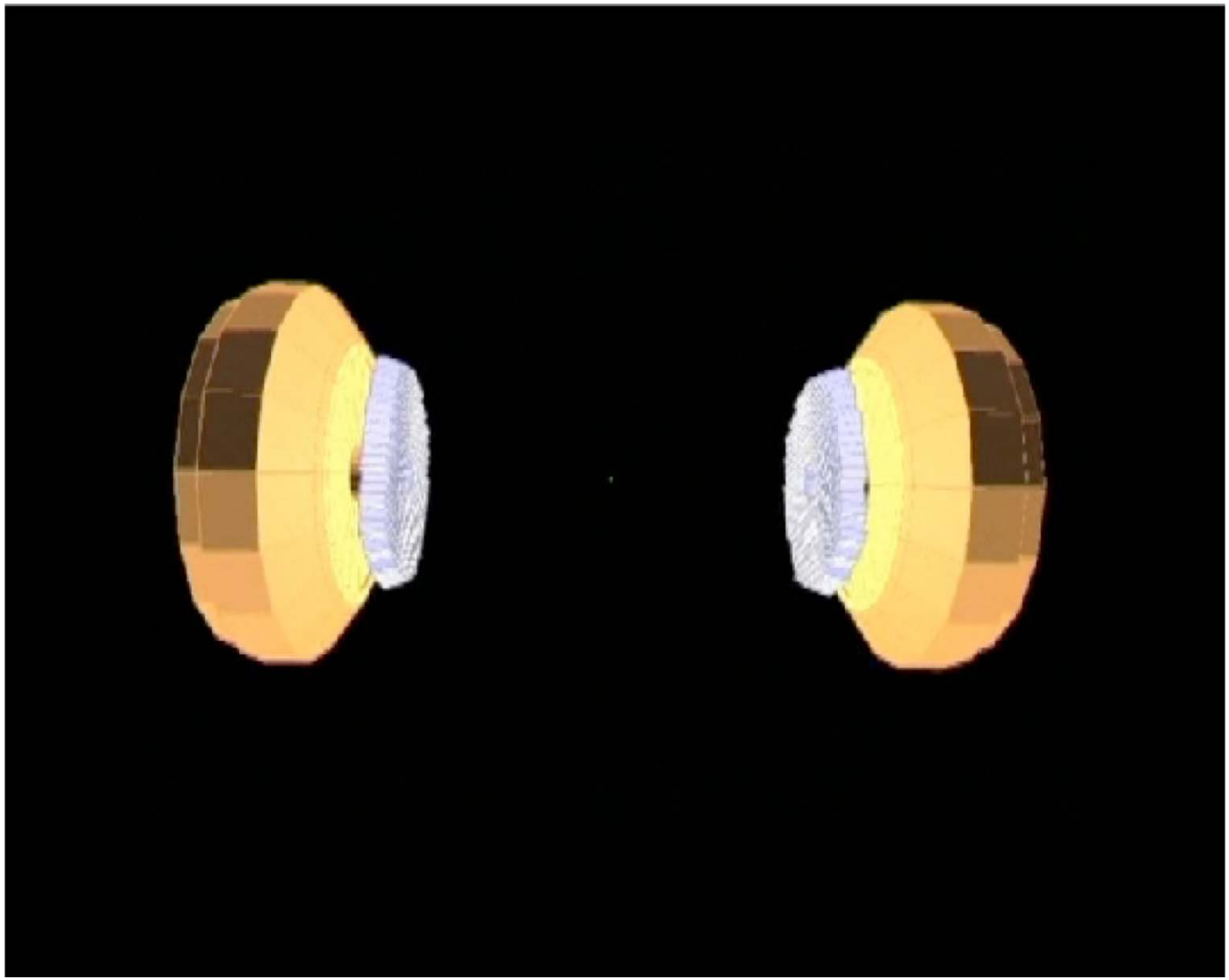
Not all Brass is Expense?

Swords to Plowshares

Swords to Plowshares



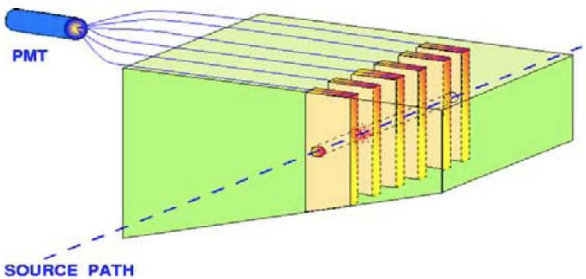
Crystal EM Endcap and Brass HCAL



Comparing Atlas/CMS HCAL Designs

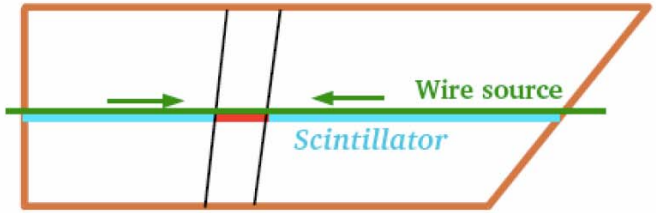
	ATLAS	CMS
Technology		
Barrel / Ext. Barrel	14 mm iron / 3 mm scint.	50 mm brass / 4 mm scint.
End-caps	25 mm (front) - 50 mm (back) copper / 8.5 mm LAr	80 mm brass / 4 mm scint.
Forward	Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr	4.4 mm steel / 0.6 mm quartz
# Channels		
Barrel / Ext. Barrel	9852	2592
End-caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta$ x $\Delta\phi$)		
Barrel / Ext. Barrel	0.1 x 0.1 to 0.2 x 0.1	0.087 x 0.087
End-caps	0.1 x 0.1 to 0.2 x 0.2	0.087 x 0.087 to 0.35 x 0.028
Forward	0.2 x 0.2	0.175 x 0.175
# Longitudinal Samplings		
Barrel / Ext. Barrel	Three	One
End-caps	Four	Two
Forward	Three	Two
Absorption lengths		
Barrel / Ext. Barrel	9.7 - 13.0	5.8 - 10.3 10 - 14 (with Coil / HO)
End-caps	9.7 - 12.5	9.0 - 10.0
Forward	9.5 - 10.5	9.8

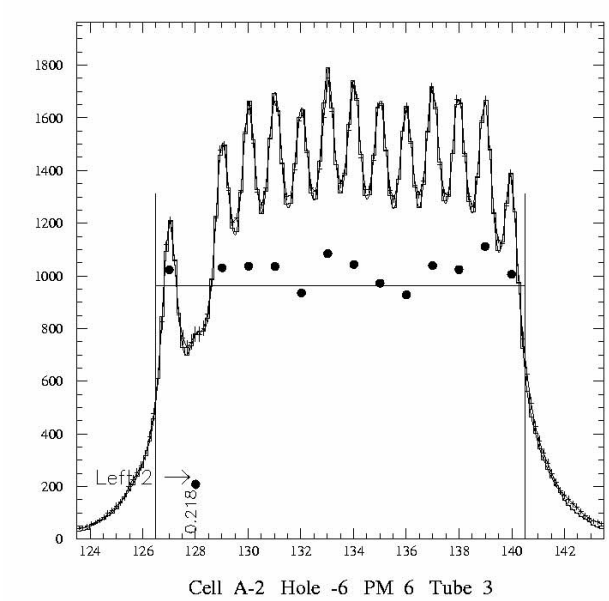
Similar Radioactive Source Calibration

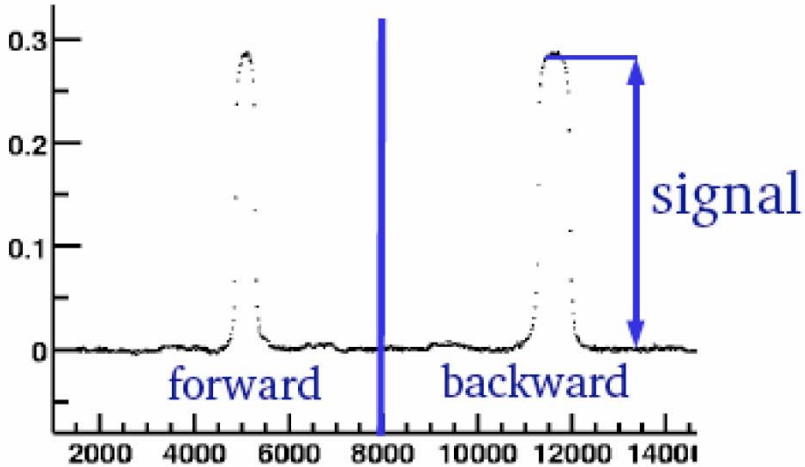


ATLAS Source Path

CMS source path

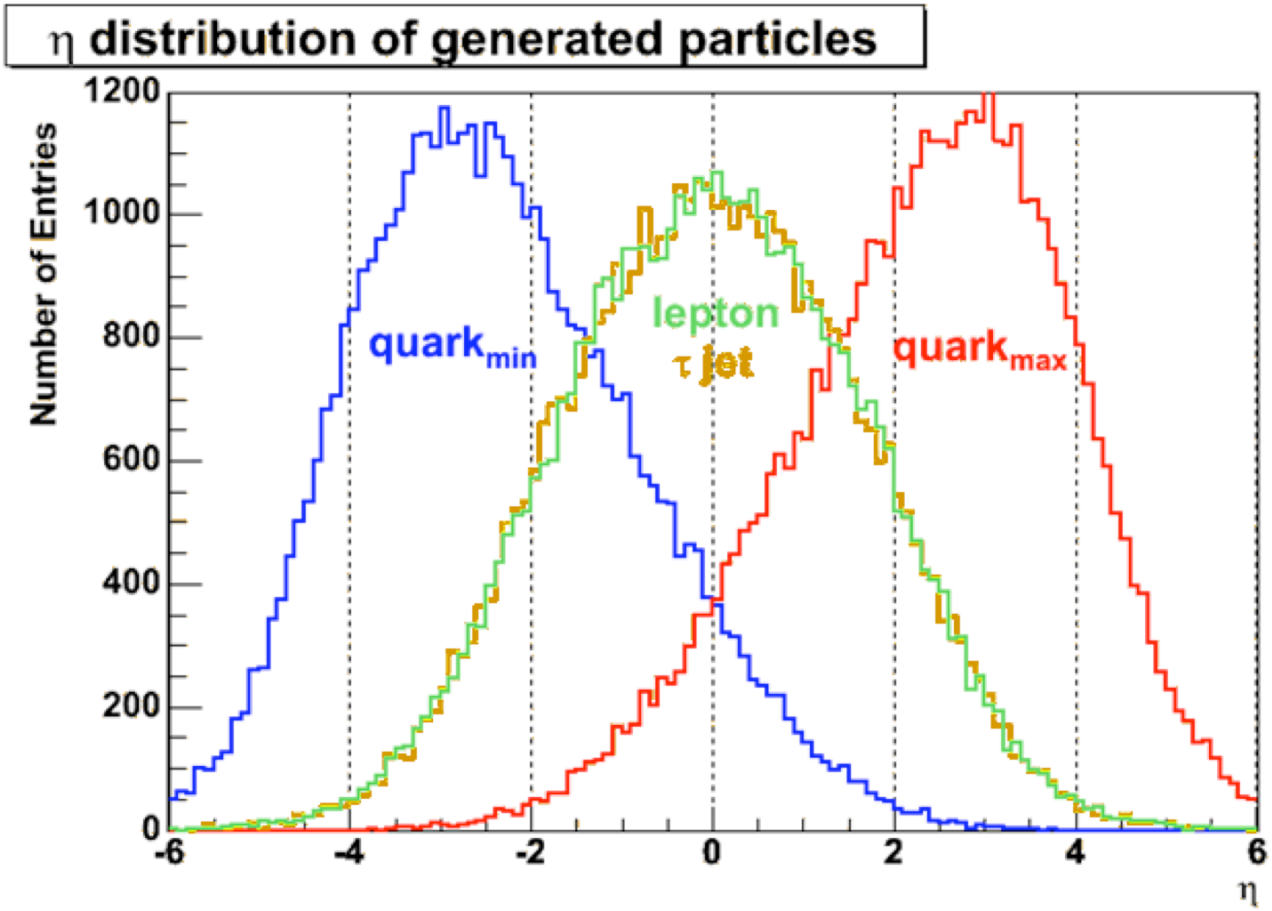






Atlas/CMS Forward Calorimeters

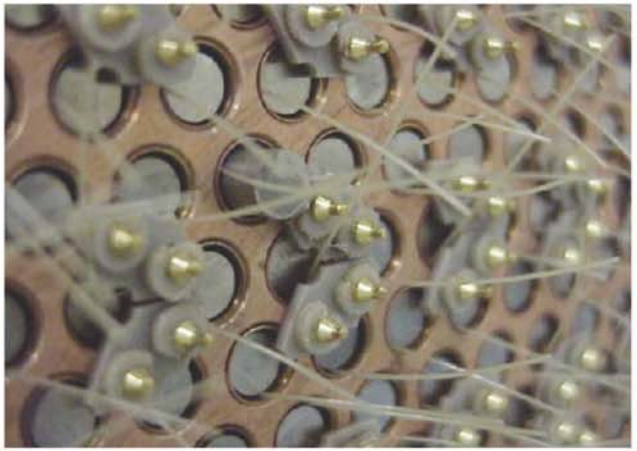
- Very Different Design Approach
  - Weak Boson Fusion Tagging-Jets

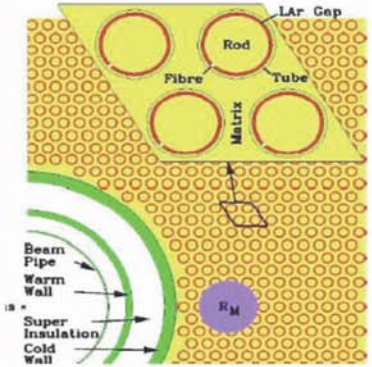


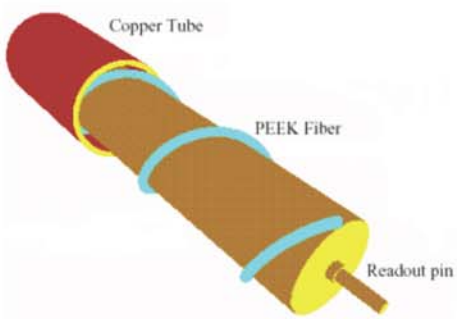
Compact LAr-Cu/LAr-W Calorimeter

ATLAS forward calorimeter

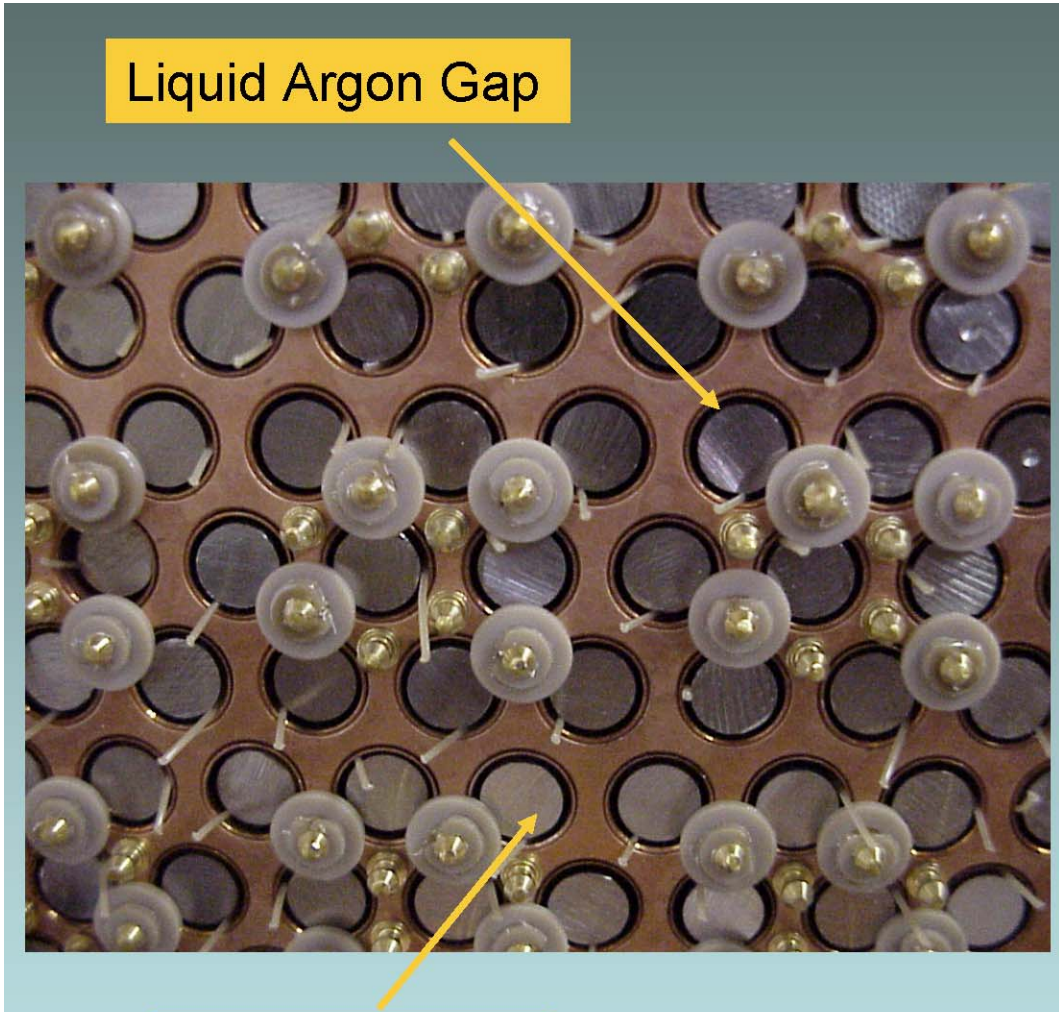
- tubolar structure, very narrow LAr gaps
- 28 X_0 LAr-Cu: electromagnetic
- 2 x 3.7 λ LAr-W: hadronic
- $3.2<|\eta|<4.9$
- Total number of channels: 2822

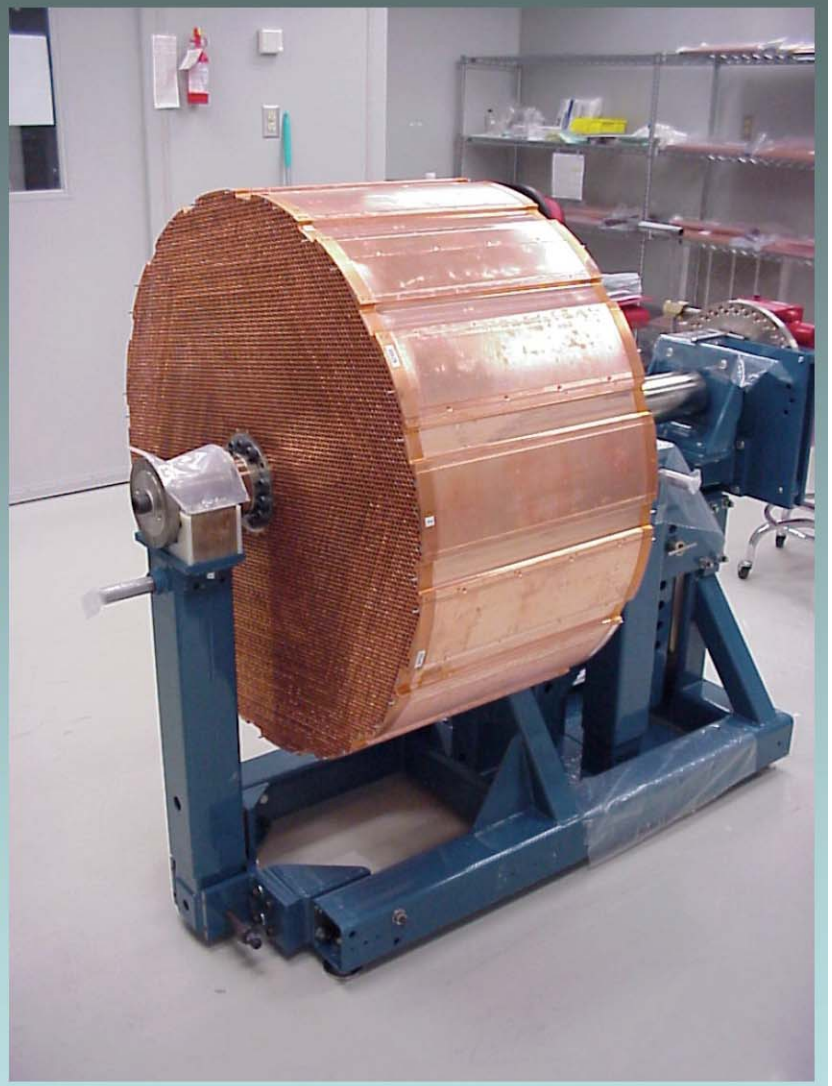




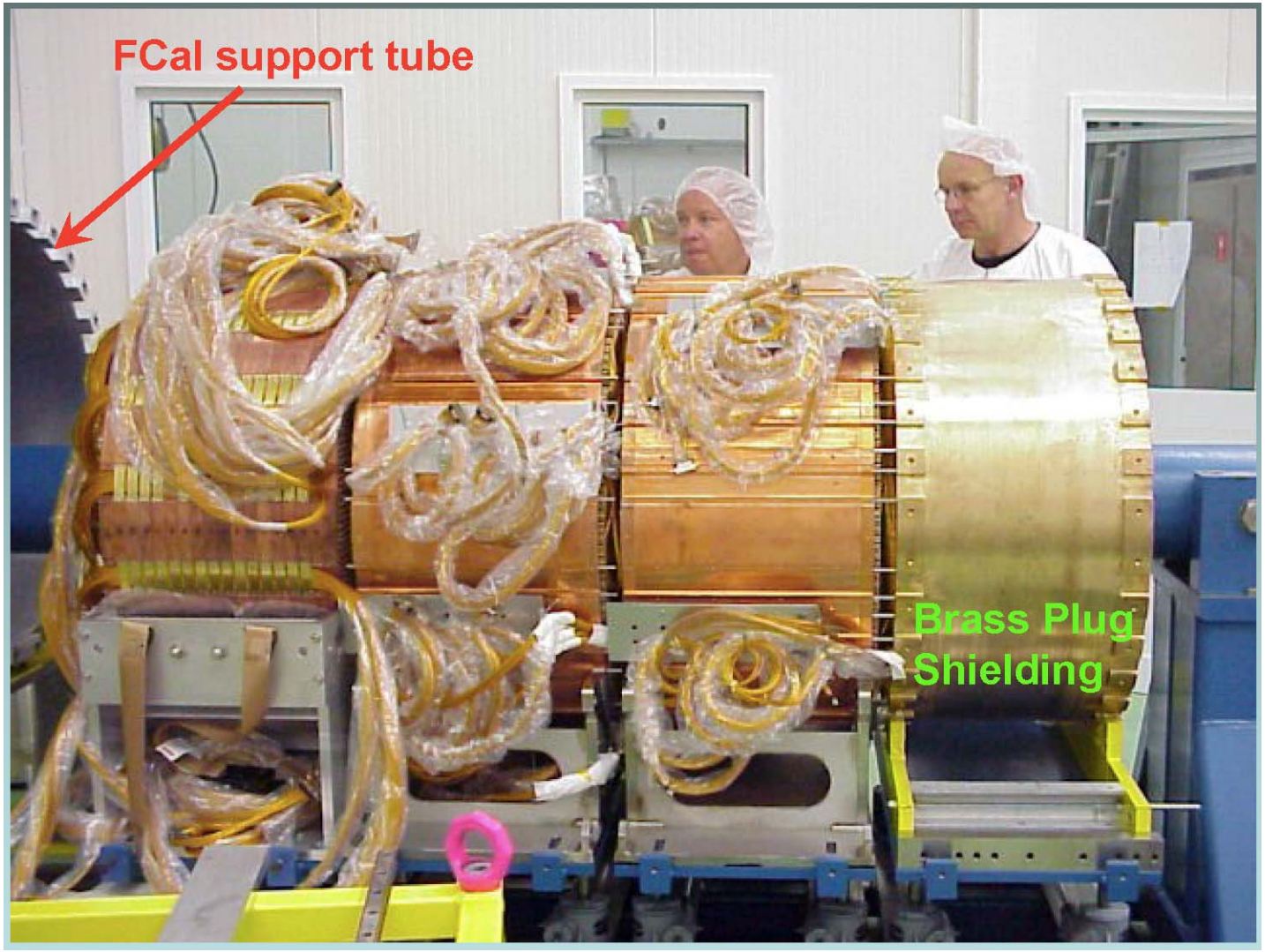


Compact size





Complete Assembly

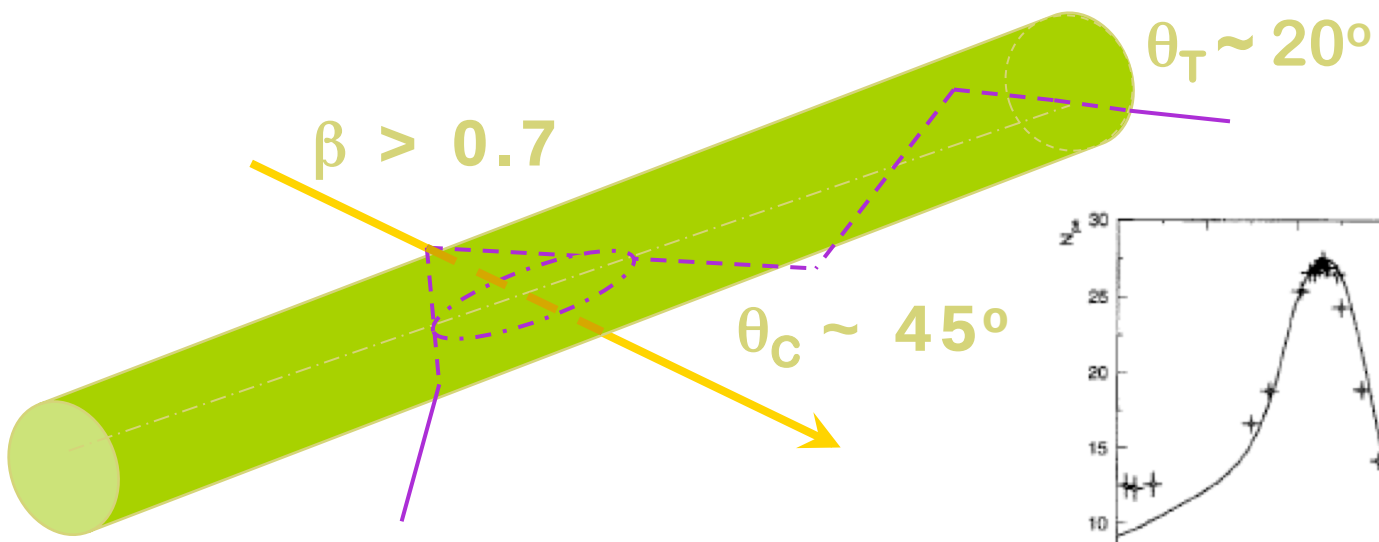


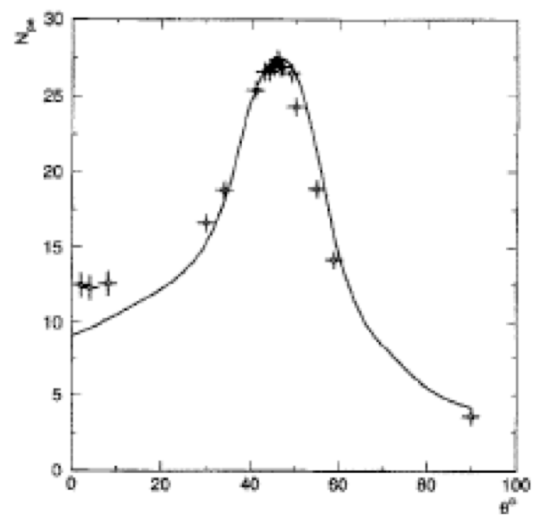
CMS Forward Calorimeter

- Quartz fibers are manually inserted in slots between iron plates

Cherenkov Light from Quartz Fibers

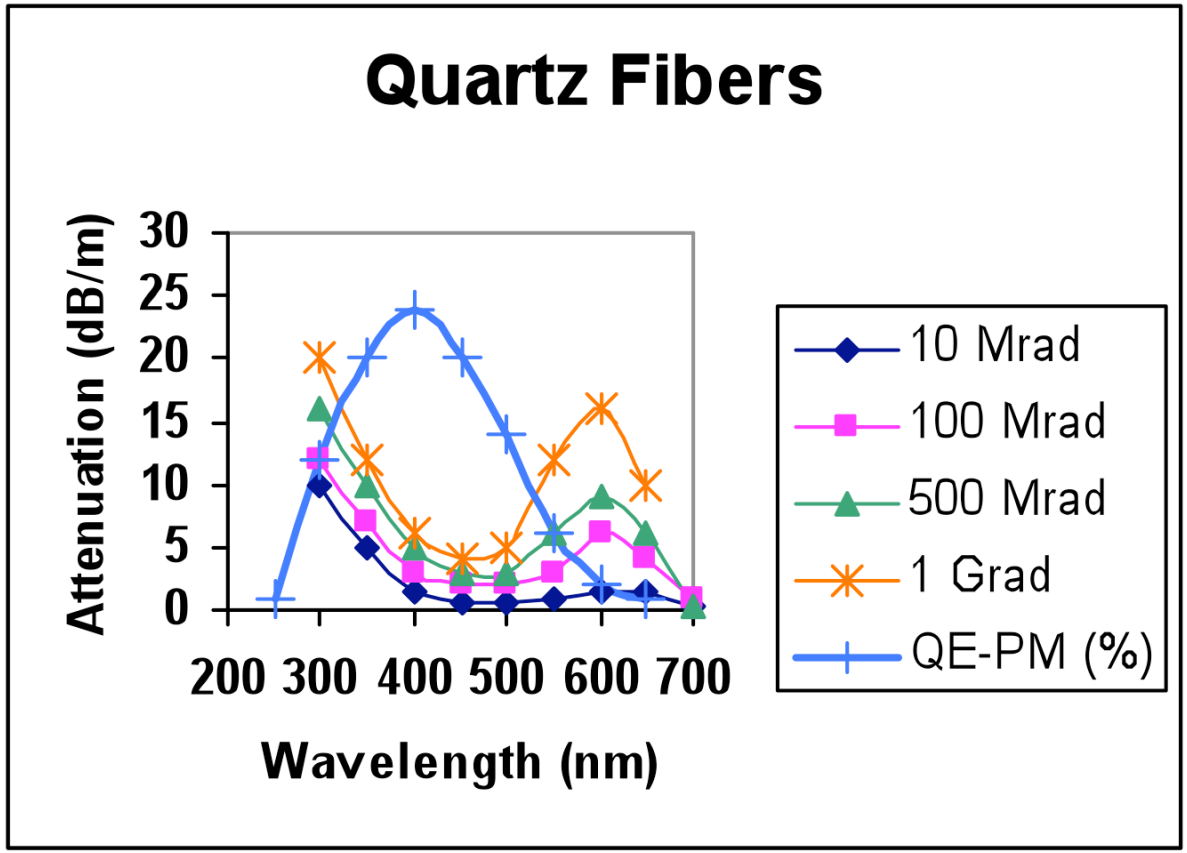
- In quartz ($n=1.45\approx\sqrt{2}$) charged particles with $\beta > 1/n$ (0.7) emit Cherenkov light (Threshold 0.2 MeV for e, 400 MeV for p)
- Cherenkov angle θ_c such that $\cos\theta_c = (\beta n)^{-1}$ (~45° for $\beta=1$)
- Optical fibers only trap light emitted within the numerical aperture of the fiber θ_T (~20° with axis of fiber)





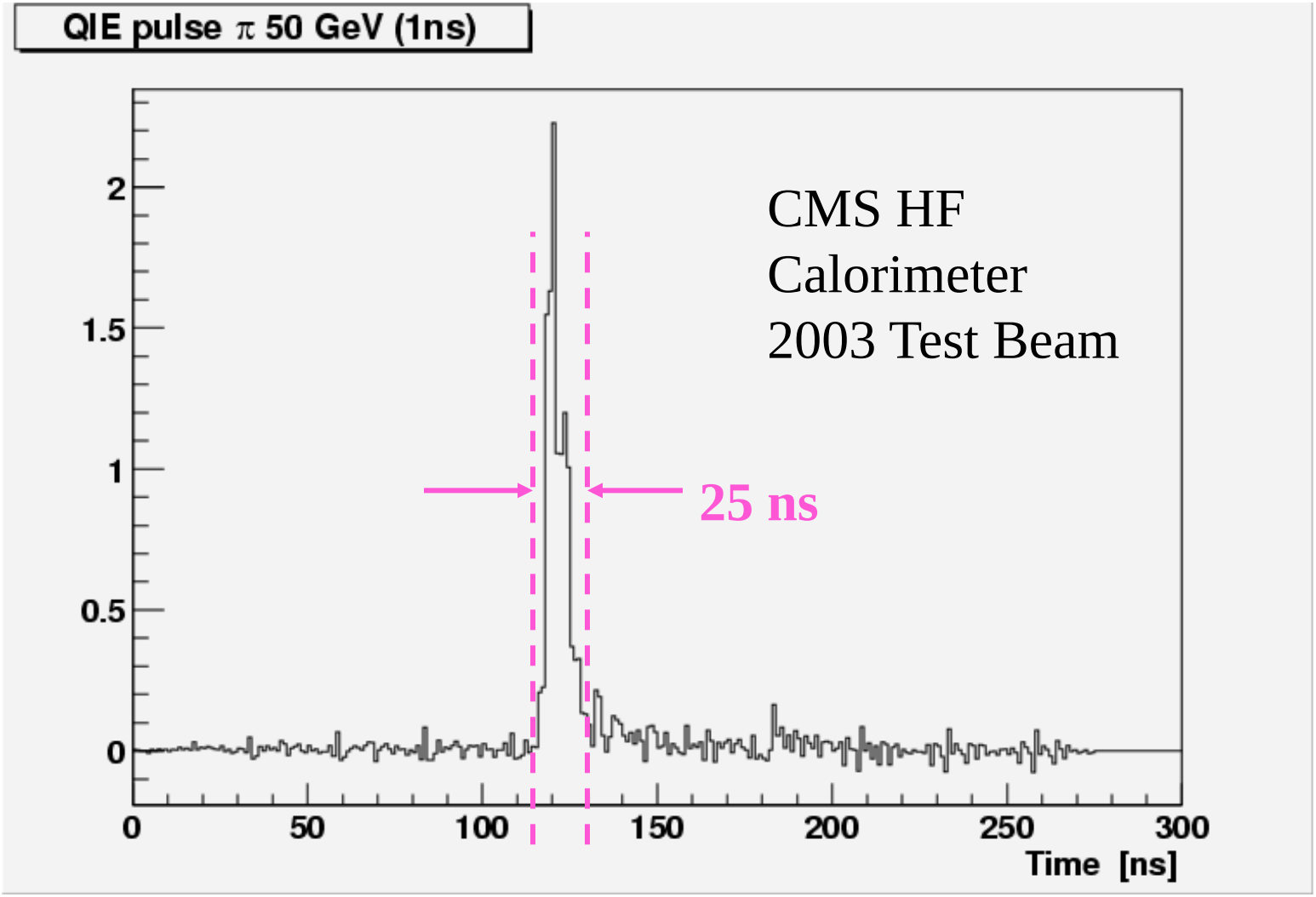
Note, co-linear radiating particles do not produce captured light

Radiation Hardness

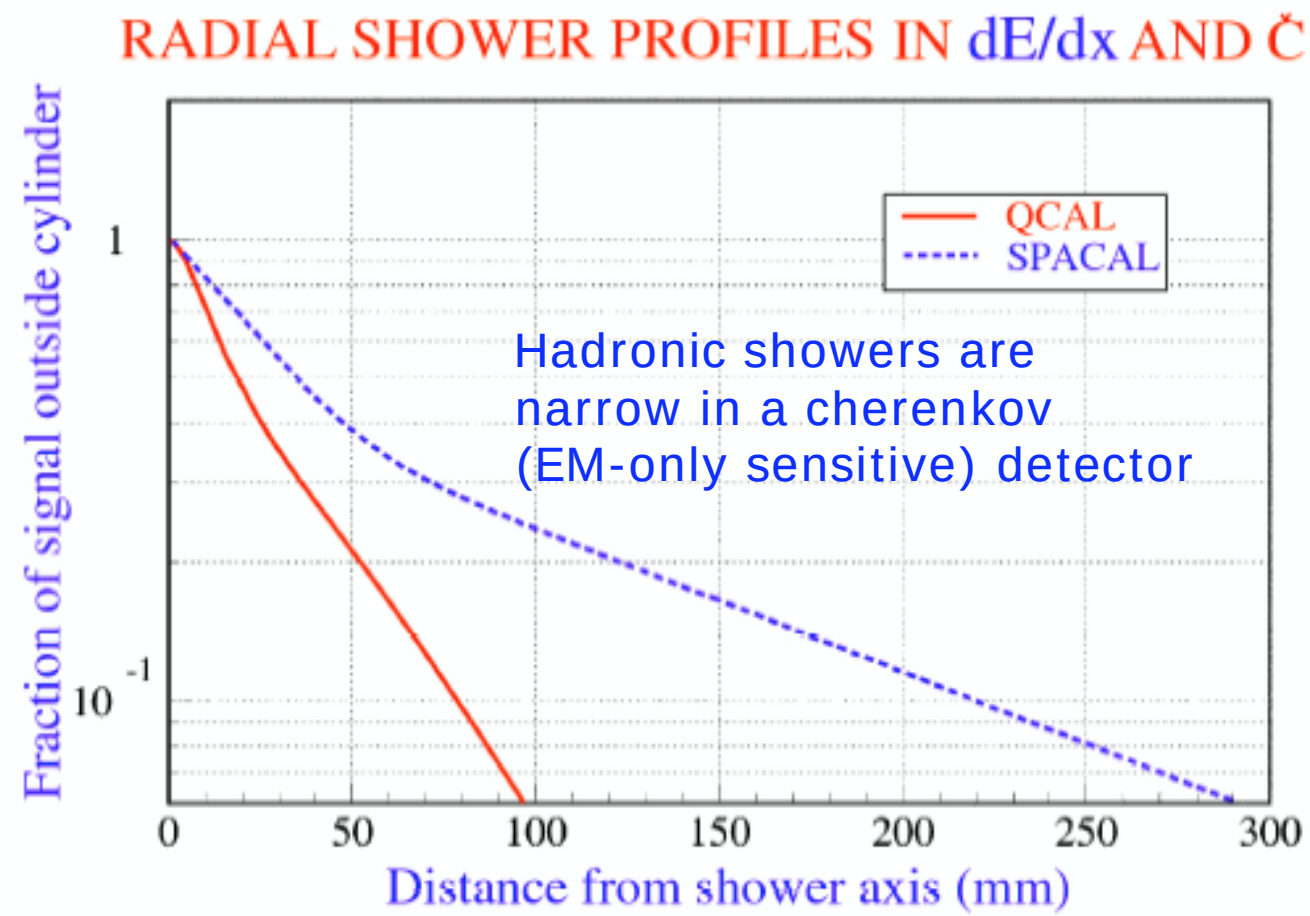


Typical spectral response of QF shows reduced radiation damage effects in the region around maximum (420 nm) of PMT sensitivity (Quantum Efficiency); this is an important asset of quartz-fiber calorimetry.

Cherenkov Light is Intrinsically Fast



Sharper Shower Profiles



Energy Resolution of Cherenkov Detectors

$$\frac{\sigma(E)}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

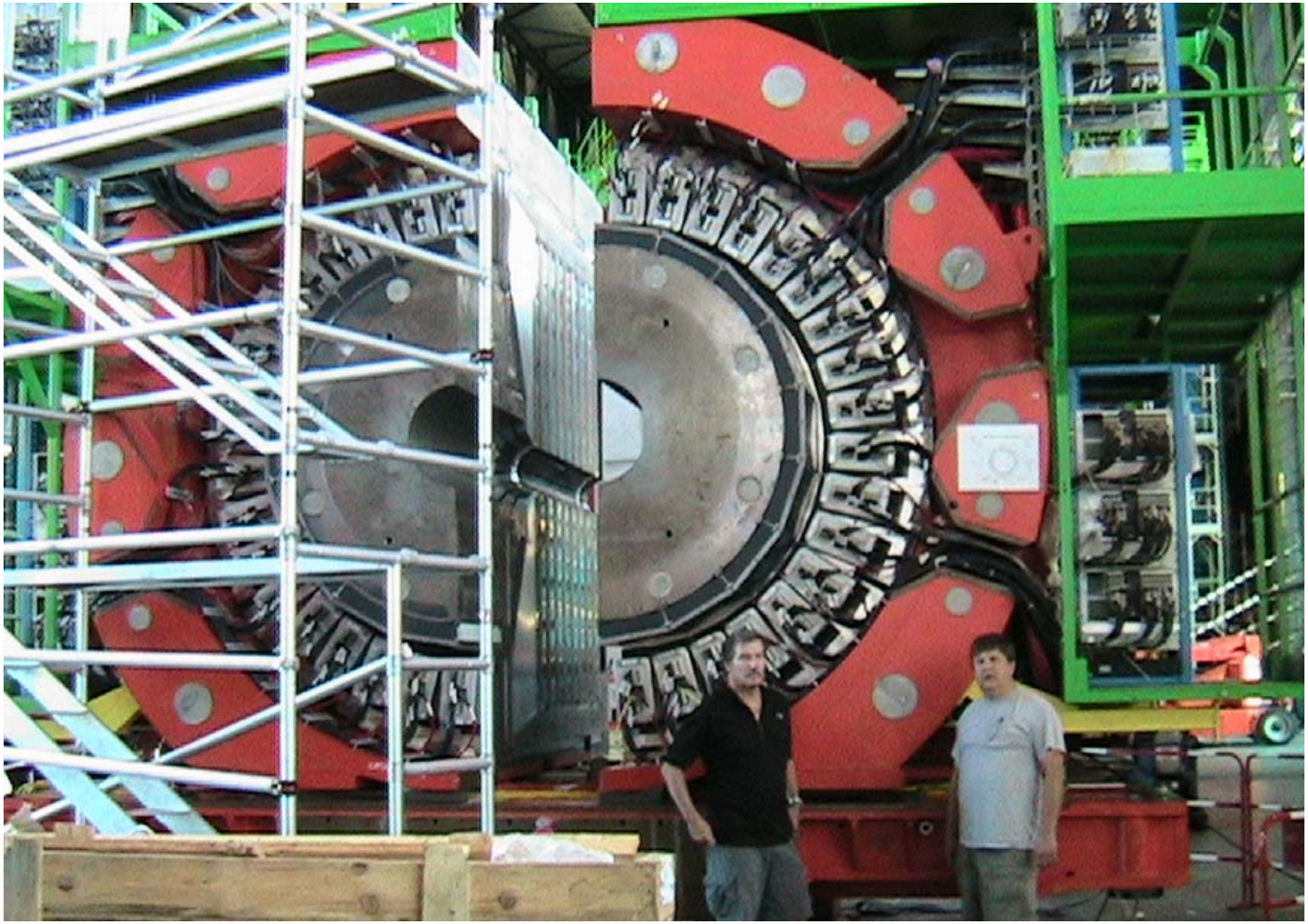
N **-** Noise, etc

C **-** Constant term (calibration, nonlinearity)

S **–** Statistical fluctuations

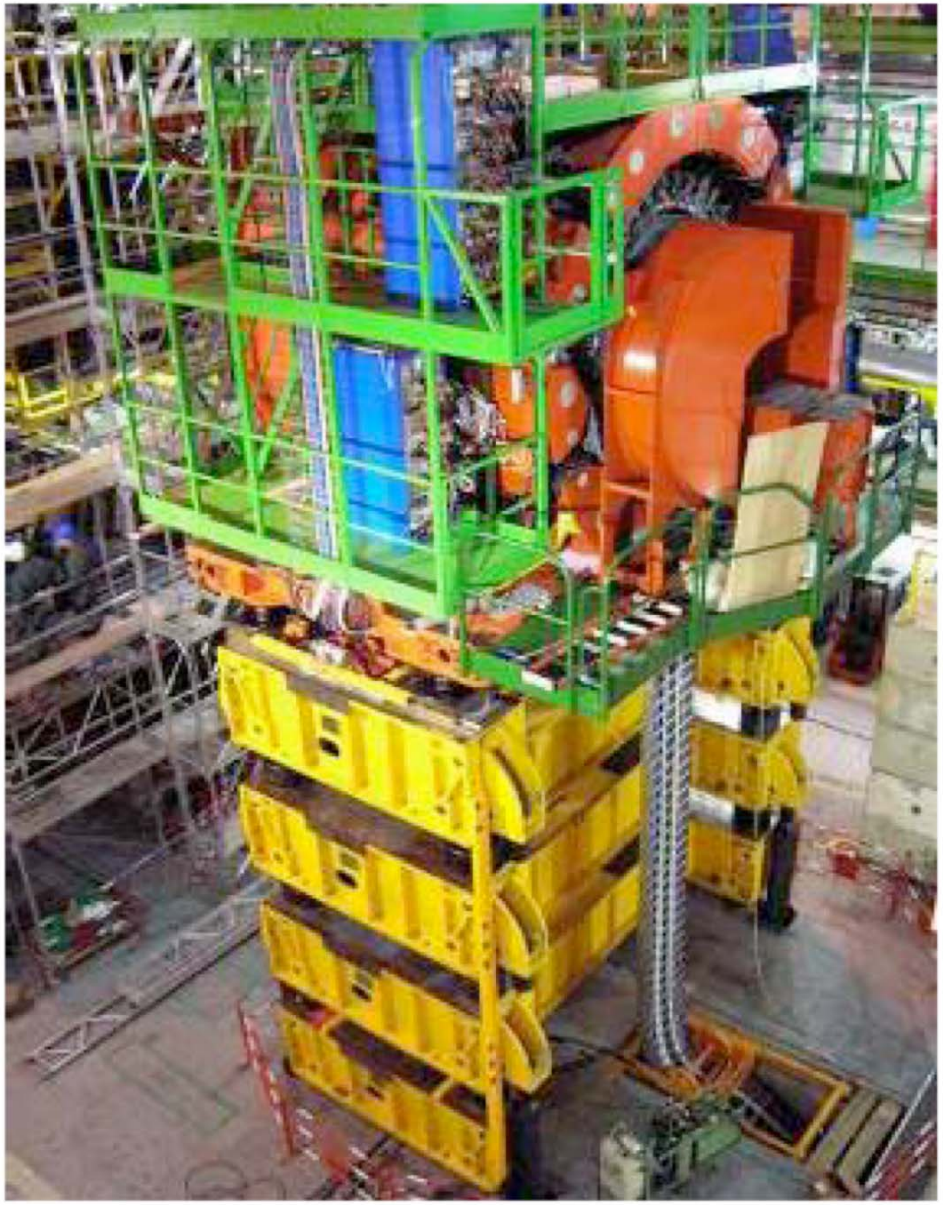
- Electromagnetic energy resolution is **dominated by photoelectron statistics** and can be expressed in the customary form. The stochastic term S = 198% and the constant term C = 9%.
- Hadronic energy resolution is largely determined by the fluctuations in the neutral pion production in showers, and when it is expressed as in the EM case, S = 280% and C = 11%.
- Highly non-compensating: e/h ~ 5
- Light yield ~ 0.3 pe/GeV
- Uniformity (transverse) ± 10%
- Precision in η ~ 0.03 and in ϕ ~ 0.03 rad

Not So Compact (11.2 m from Int. Point)

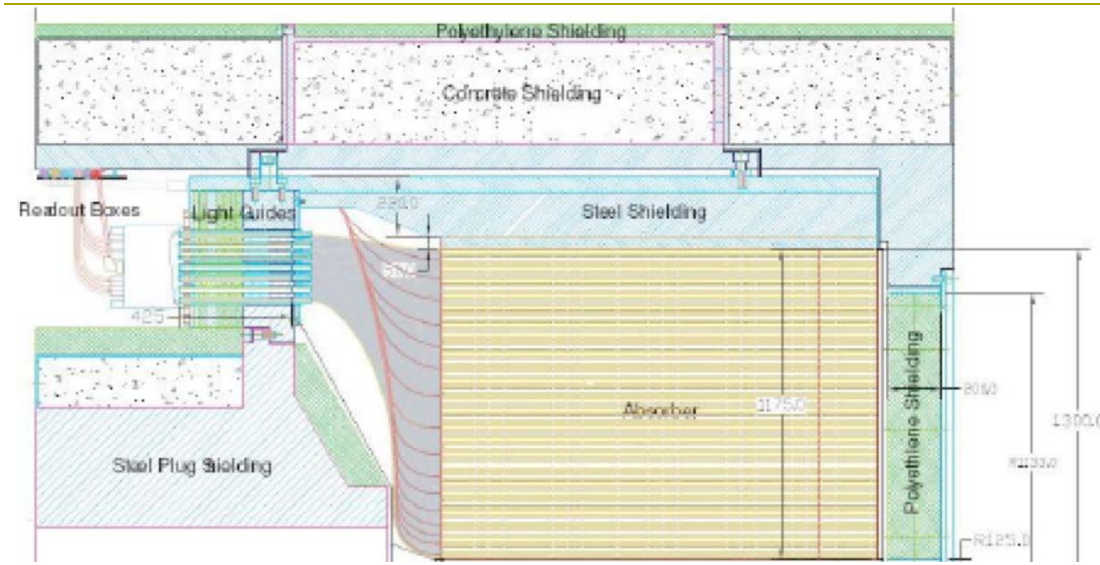


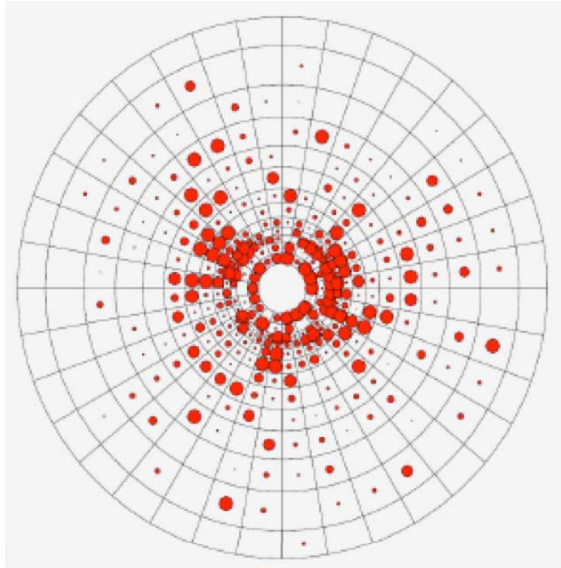
Needs to be Raised to Beam Level

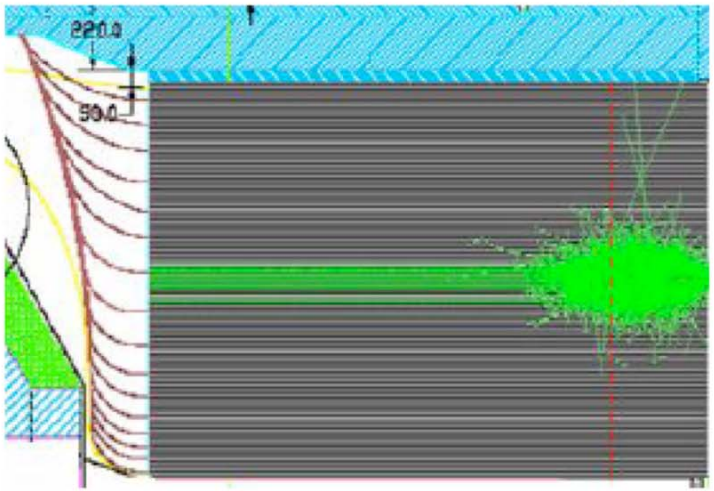
- Assembly is raised to beam level when being used
- And is lowered and stored in garages when CMS needs to be opened
  - One detector located on each side of the interaction region (11.2 meters from IP)



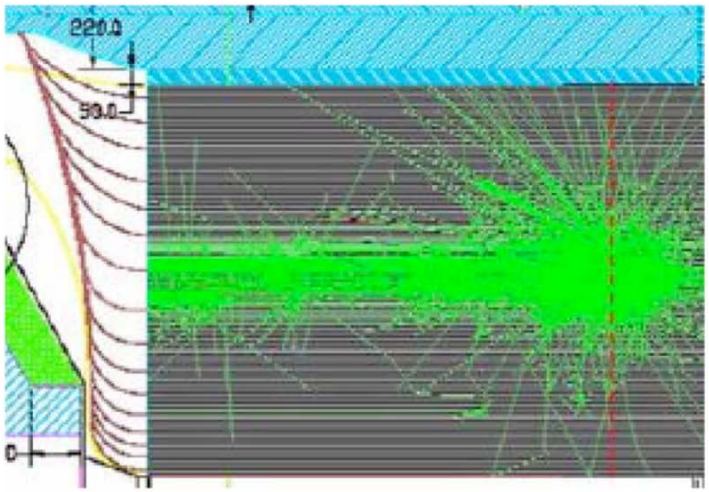
Electron and Jet Longitudinal Profiles







100 GeV electron shower

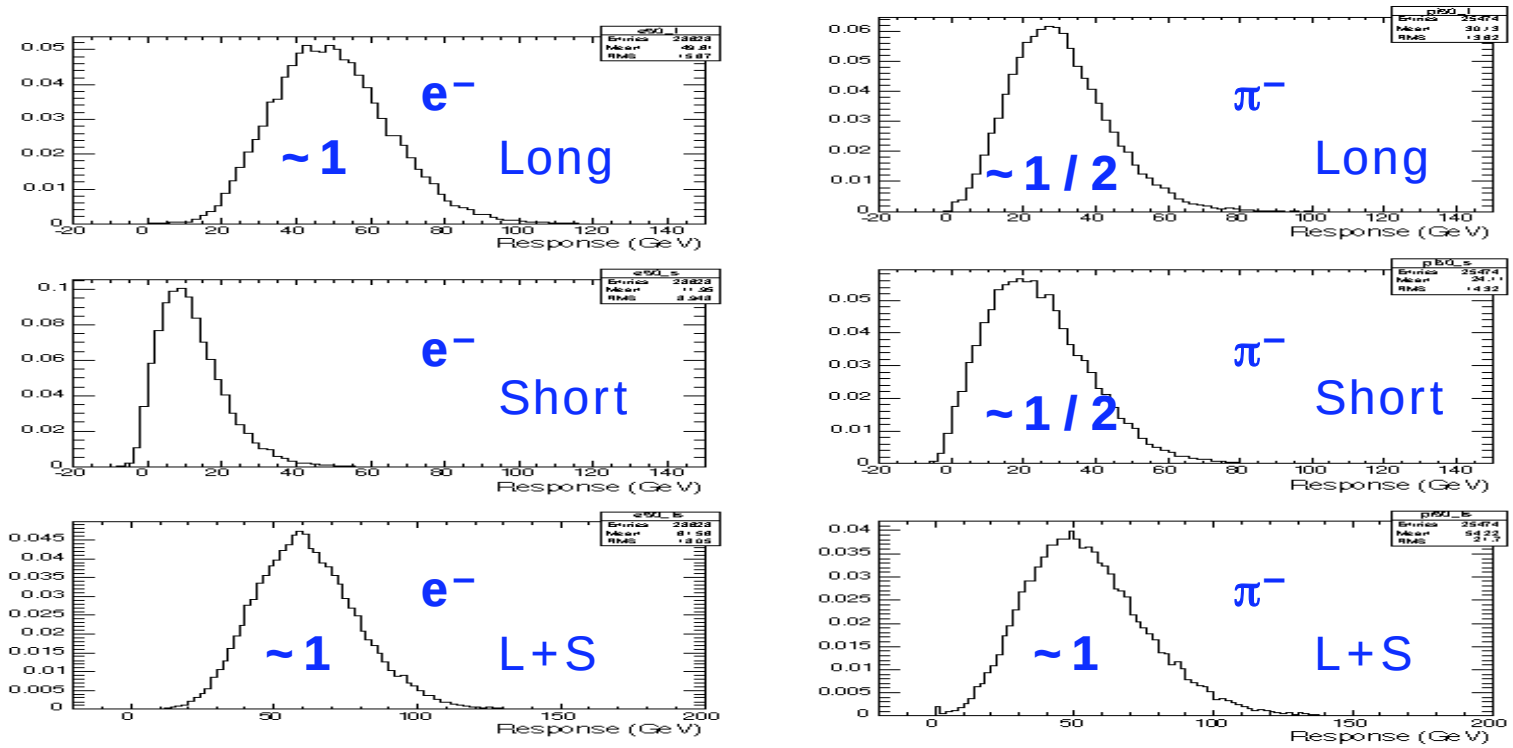


100 GeV proton shower

⇐ JET

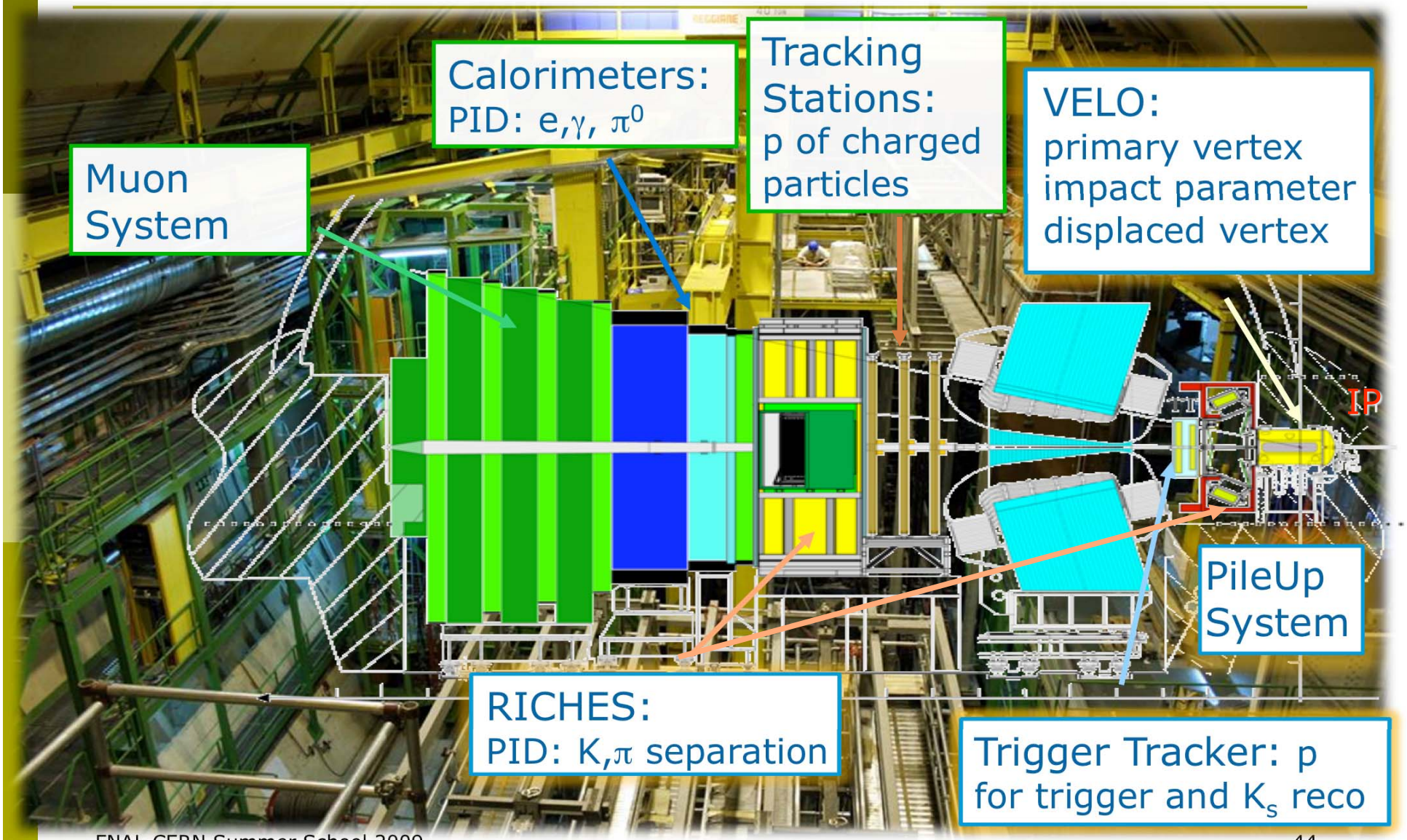
Hardware Compensation

- Cherenkov calorimeter has two fiber lengths (Long and Short) which are readout separately
  - They are designed to give hardware e/h compensation at ~50-150 GeV



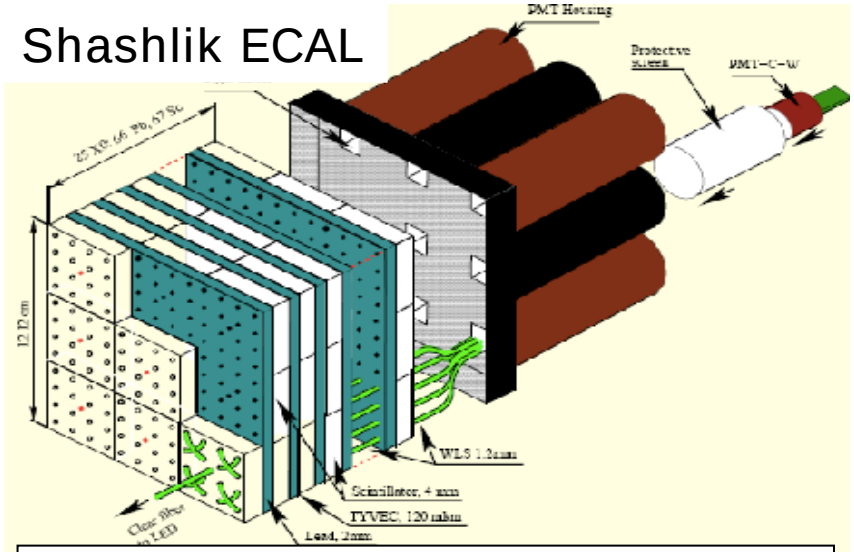
Total = L+S, EM = L−S, HAD = 2S

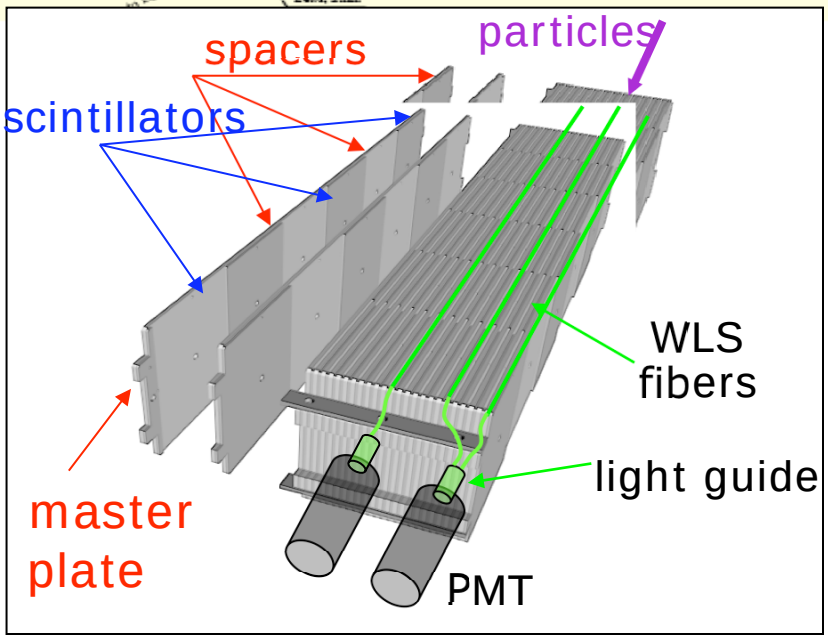
LHCb Calorimeters



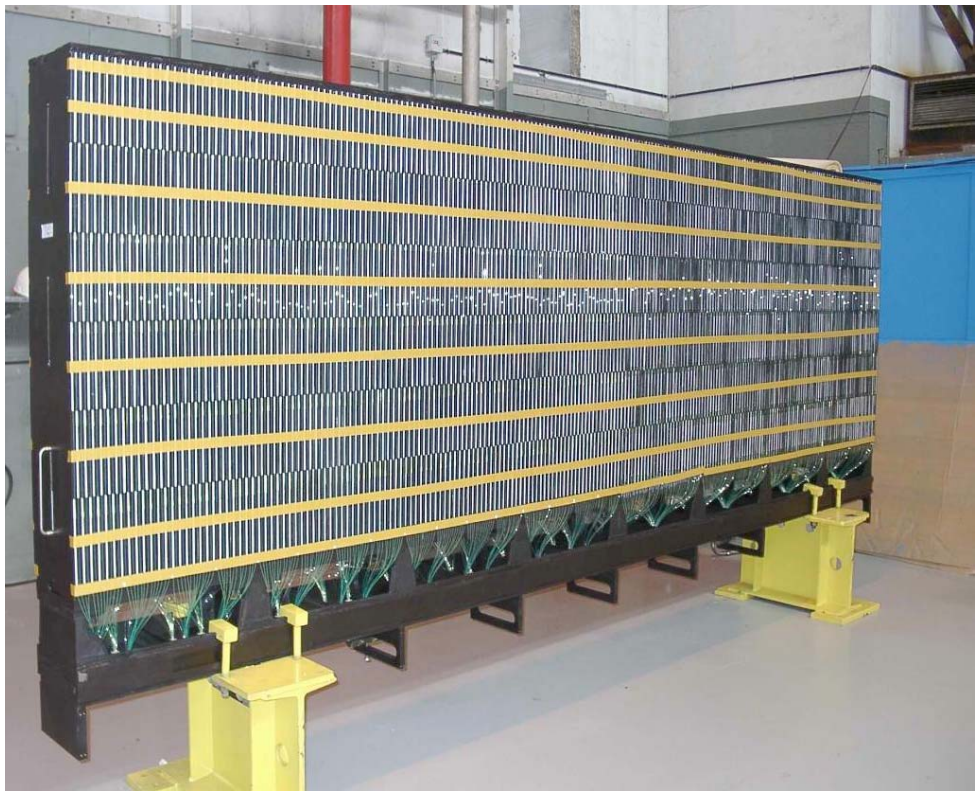
Wall Structures

Shashlik ECAL





LHCb HCAL



Module standing on end showing 6 longitudinal compartments

Master plates	6 mm
Spacers	4 mm
Scintillator	3 mm
Sampling:	
longitudinal	20 cm
lateral	2 cm

6 longitudinal sections (5.6 λ_I) (high energy showers not fully contained – but does not spoil the trigger operation)

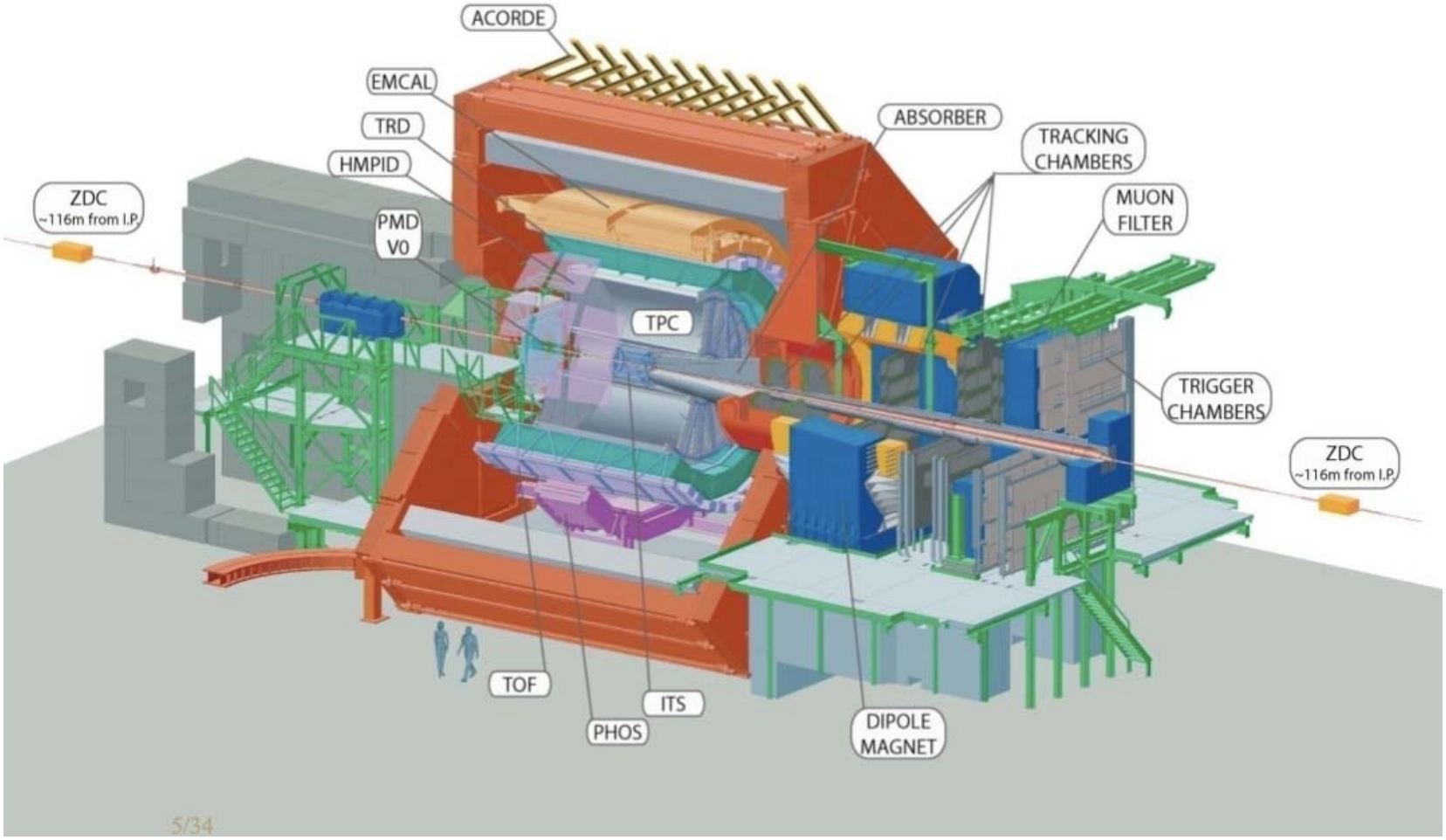
HCAL Resolution:

$$\frac{\sigma}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\%$$

ECAL Resolution:

$$\frac{\sigma_E}{E} = \frac{(9.4 \pm 0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\% \oplus ((145 \pm 13)\ \mathrm{MeV})/E$$

ALICE EMCAL and PHOS

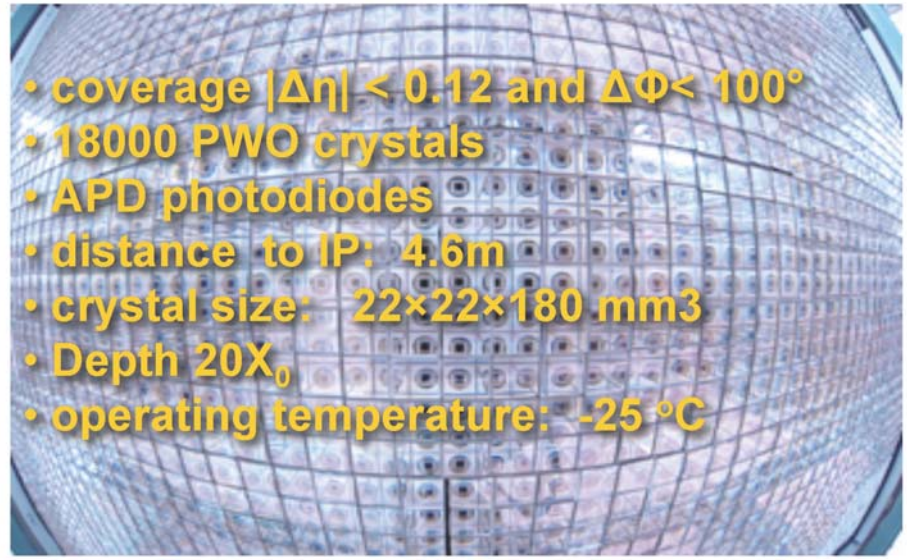


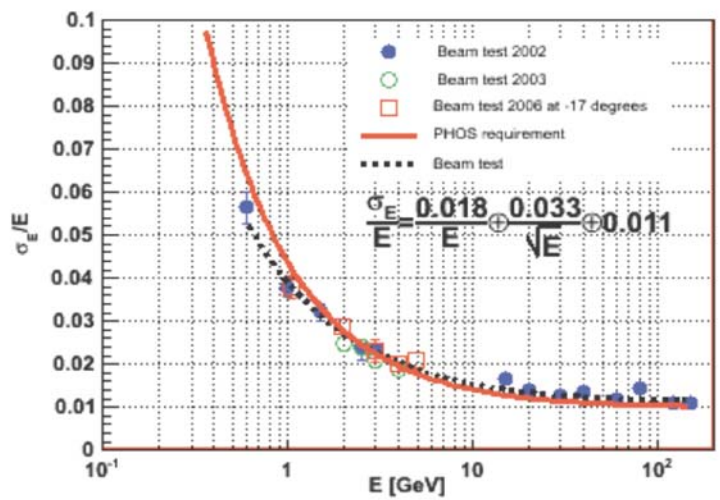
Alice PHOS with $PbW0_4$ Crystals

ALICE PHOS

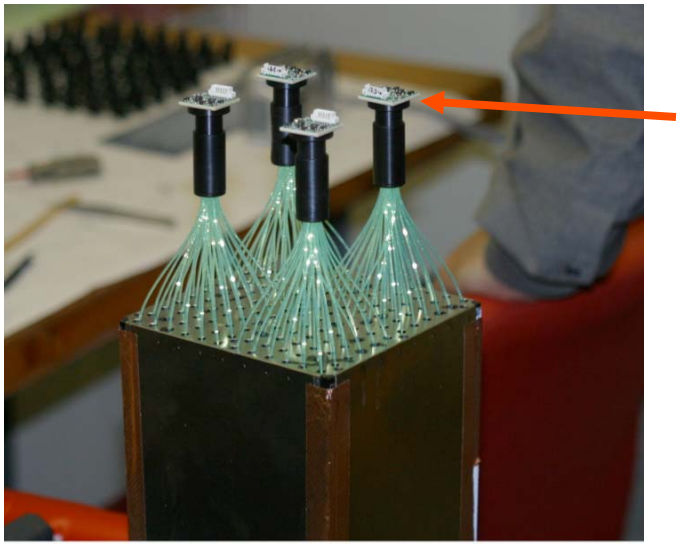
To measure γ, π^0 and η
from 0.5 to 100 GeV

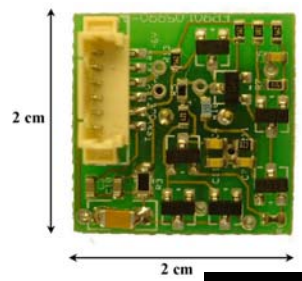
1 module installed
2 more in first long shut down
completed in 2010

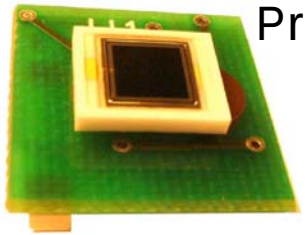




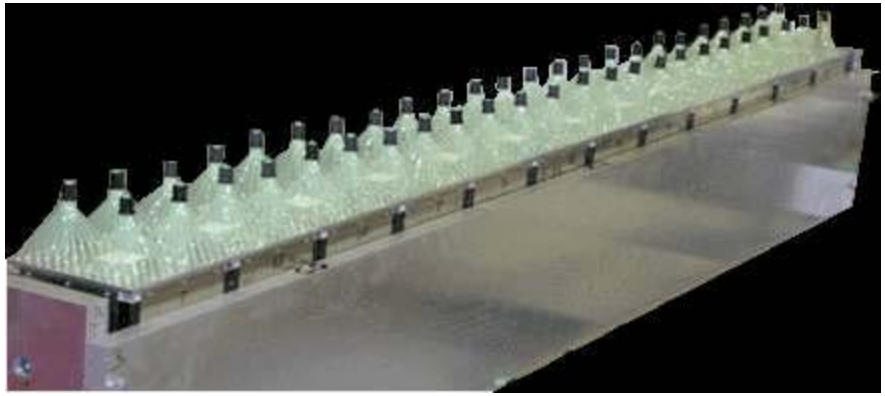
Alice EMCAL with Shashlik







Preamplifier + APD



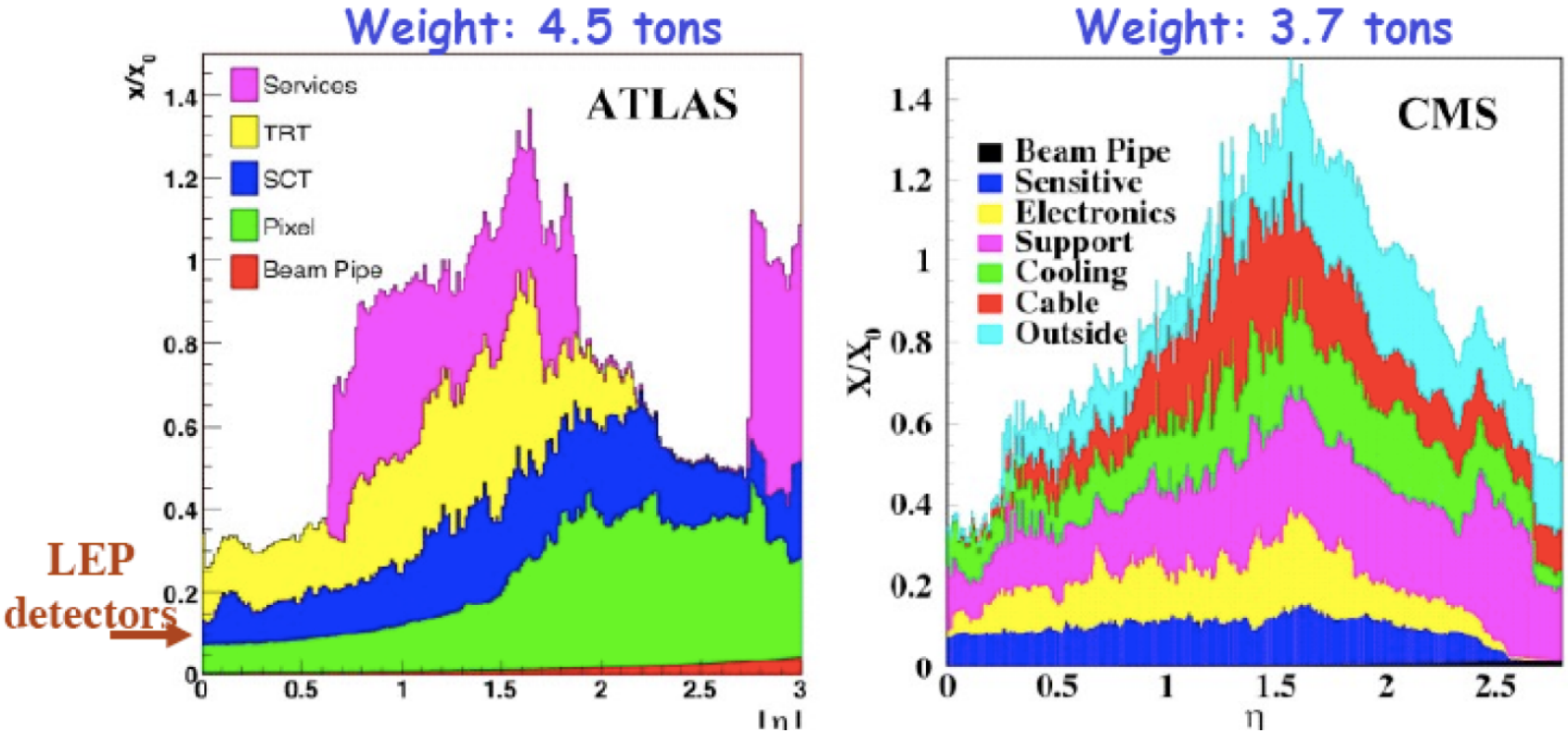
- 4 6x6 cm^2 towers/module
- WLS fiber readout on 1cm grid
- 5x5 mm^2 Hamamatsu S8148 APD
- ~4.5 photo-electrons/MeV
- Operated at nominal M=30
- Fullscale Energy = 250 GeV

- $\delta\eta = \delta\phi = 0.014$
- 20.1 X_0
- Pb:Sc = 1.44 : 1.76 mm

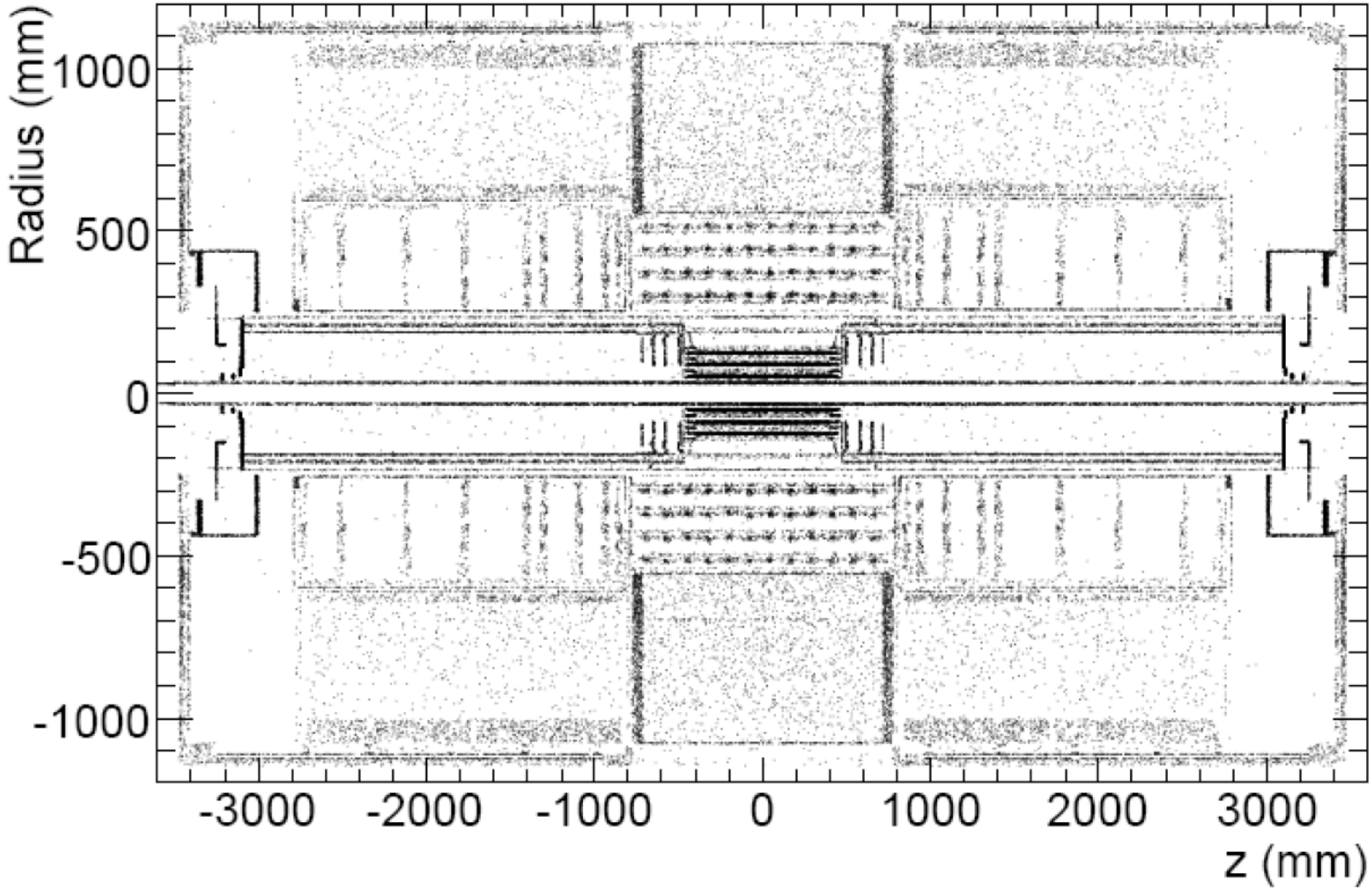
RETURNING TO ISSUES OF IMPERFECT DETECTORS

Material in front of Atlas/CMS ECALs

Amount of material in ATLAS and CMS inner trackers



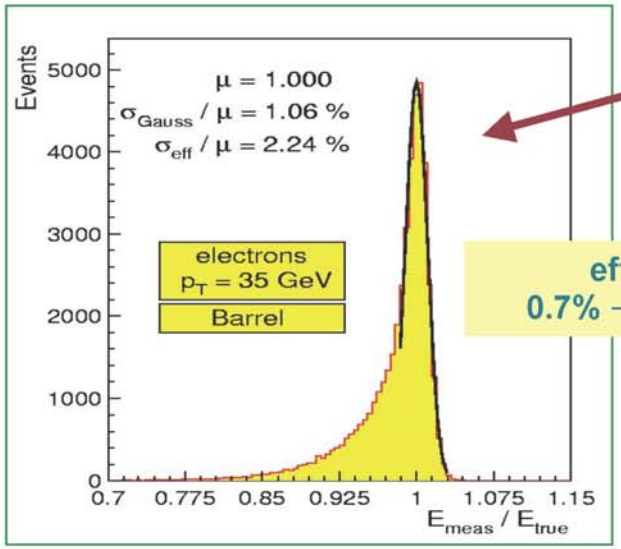
Photon Conversion Image of Material



Electrons are affected too

Effects of material in front

CMS

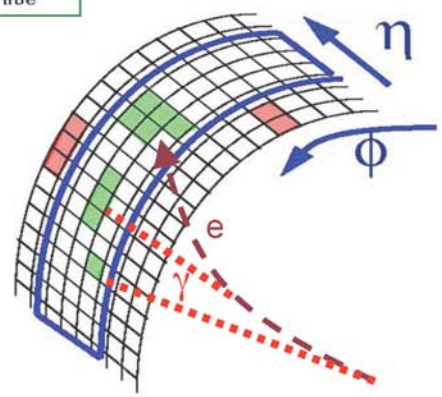


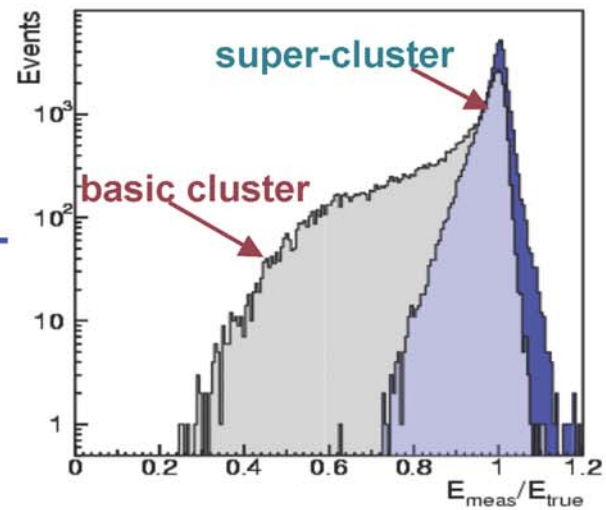
50% electrons undergo

non-negligible bremsstrahlung

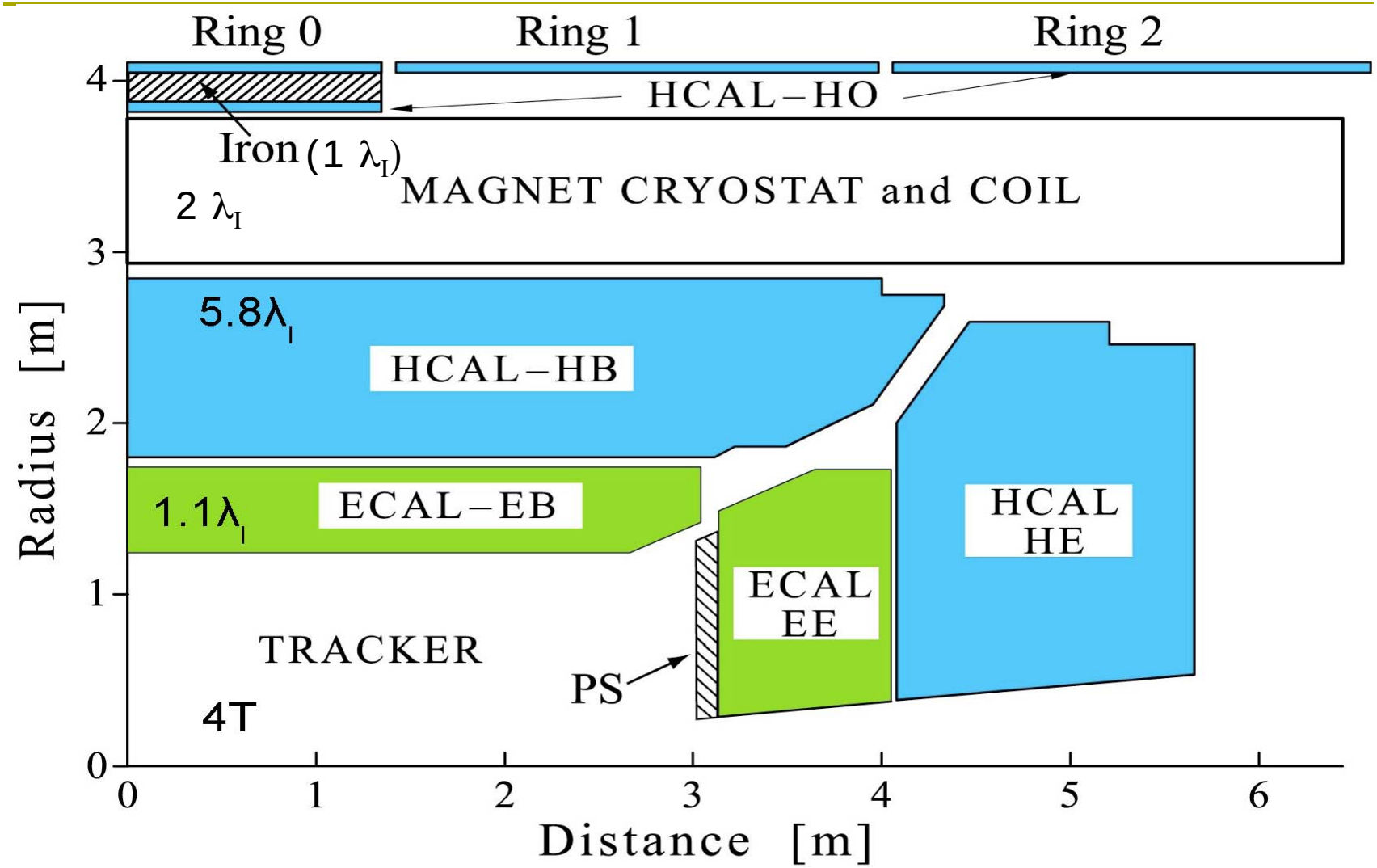
effect on resolution at p_T 35 GeV:
0.7% → 1.06% (gauss) → 2.2 % (effective)

dynamic clustering algorithms (superclusters) can resum photon energies



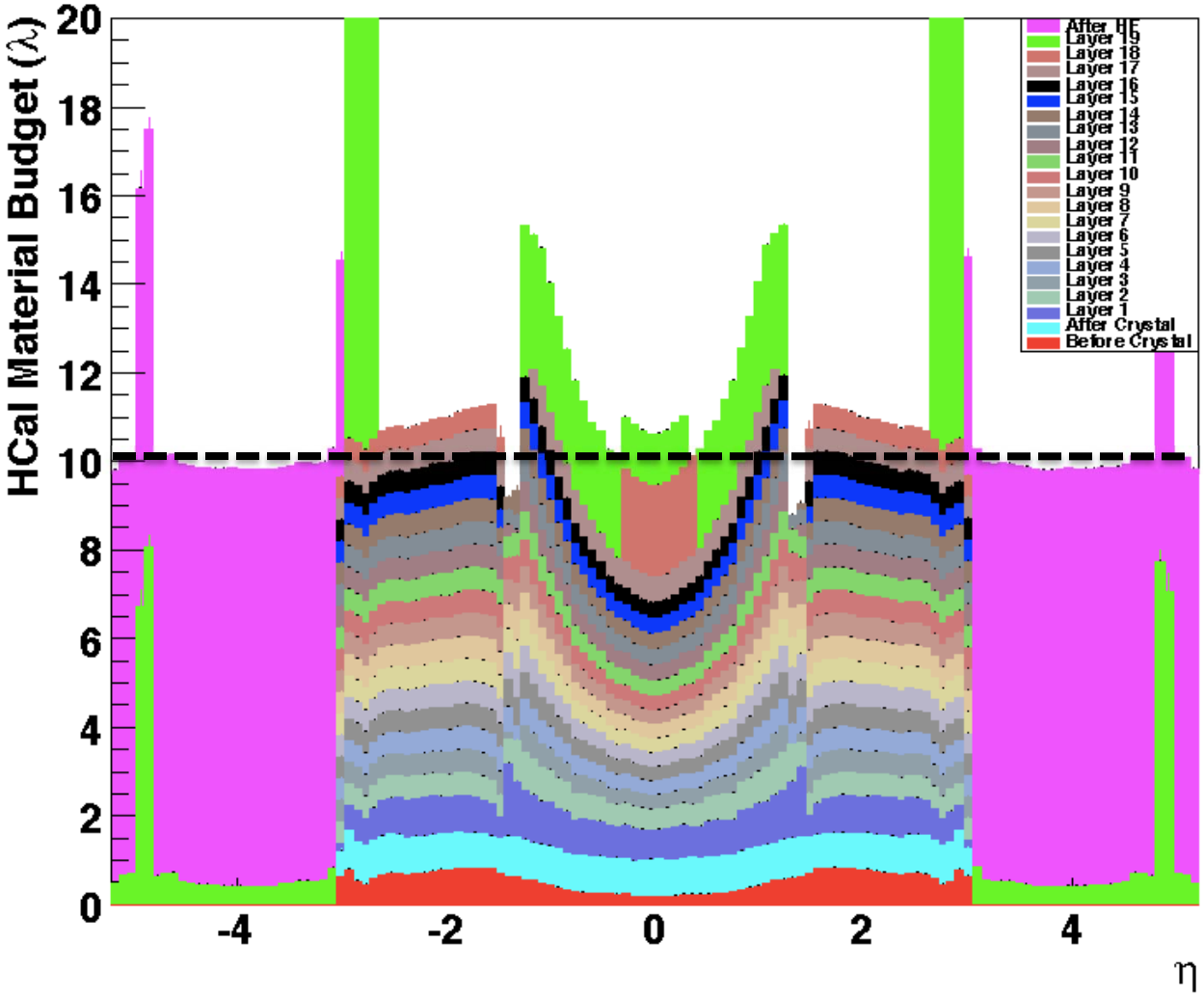


CMS Calorimeters

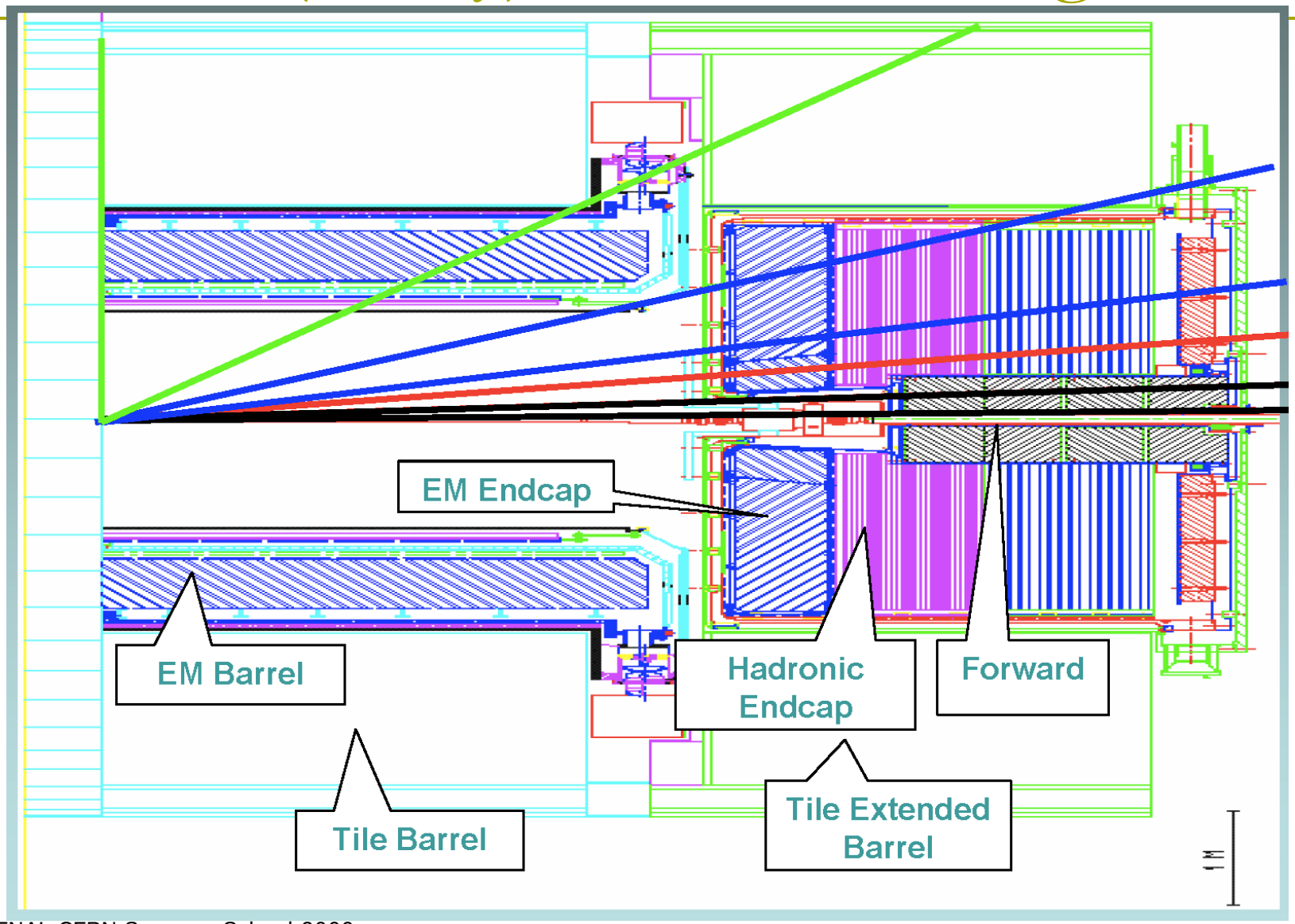


Note, setting energy scale for tail catcher can be tricky because of e/π response energy dependence

Barrel Geometry and Tail Catchers



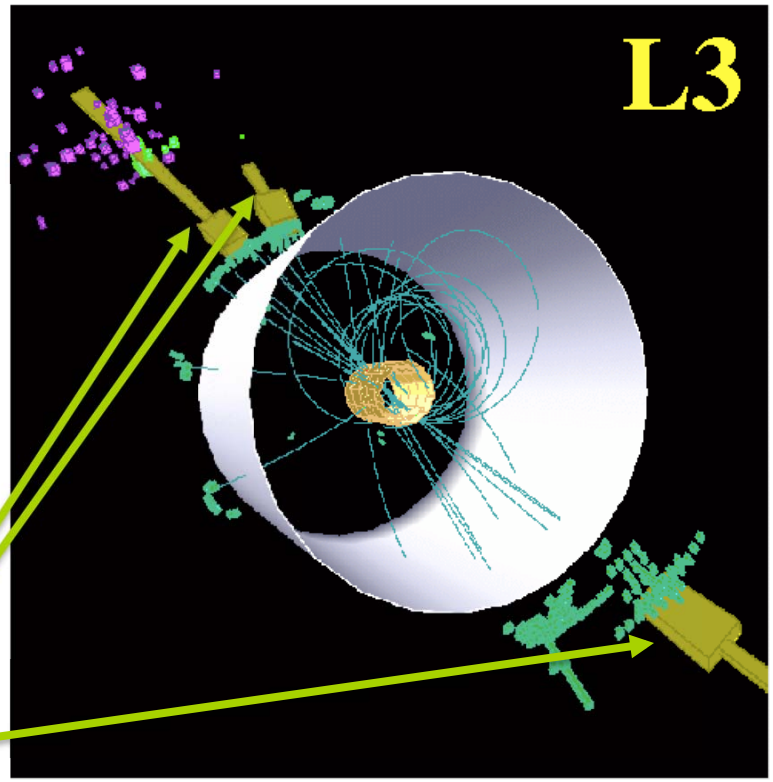
Atlas (Many) Transition Regions



Transition Regions

most significant Hνν candidate

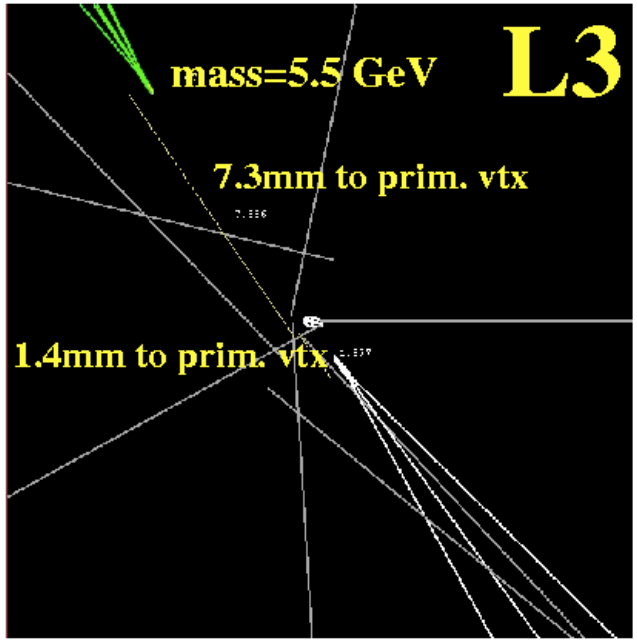
√s=206.3 GeV
Jet Energies ≈60 GeV each,
and ~90 GeV Missing Energy



SPACAL hits

measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view



L3 Higgs search

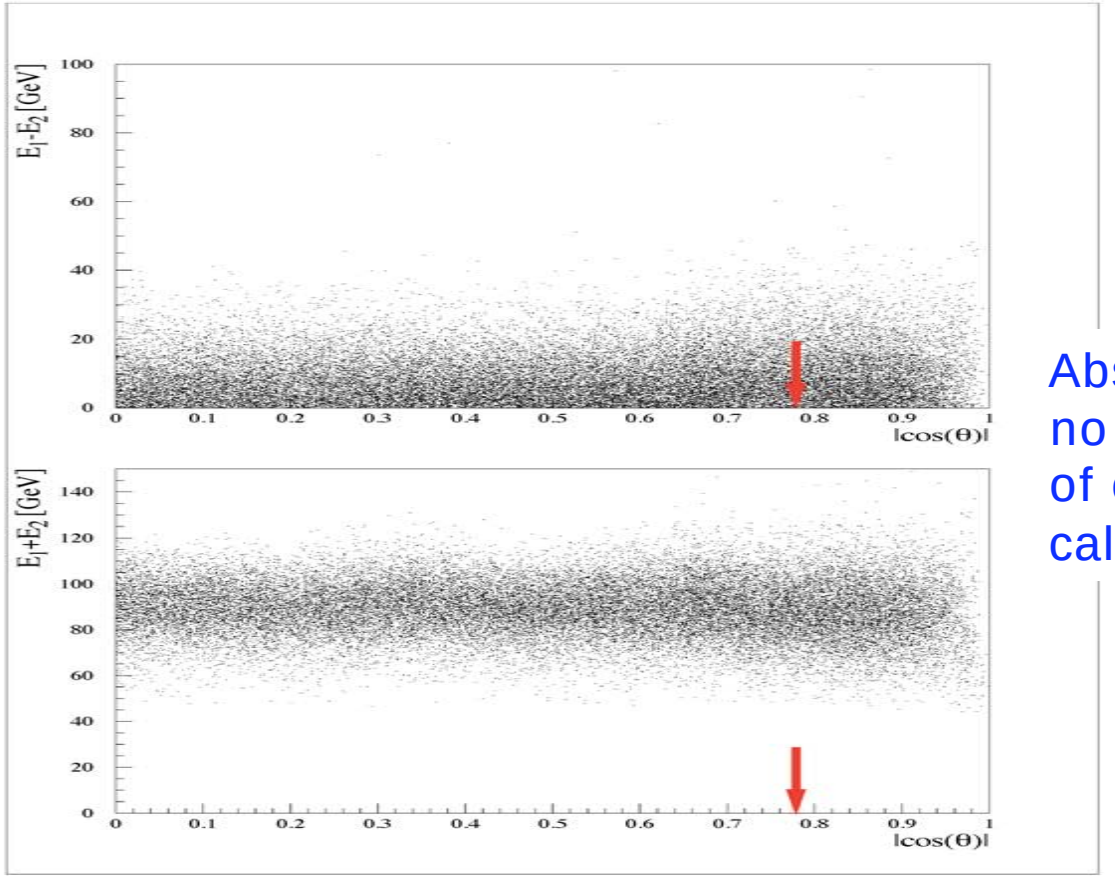
Instrumented Cracks?

Sent to Groups: CMS (1960 people with e-mail)
00/11/03 - 18:51:46

Dear Colleagues,
Today was the open session of the LEPC. The LEP Higgs Working Group made a clear recommendation for a further run in 2001 at 208 GeV with 200 pb-1 per experiment. Combining all experiments an excess of events of 2.9 sigma is reported for a Higgs mass at 115 GeV.
There is one new candidate from L3 in the channel H nu nu, with both jets in the instrumented cracks between barrel and end caps.
There is no goldplated event in H ll. The most significant 4 jet events come all from ALEPH, but they found no new events since the LEP fest.
If the effect is real a further run with 200 pb-1 per experiment in 2001 would enable to establish a combined 5 sigma effect.
This evening the LEPC in the closed session had a lively discussion.
I understand the LEPC is not so convinced on the scientific evidence.
They will probably make a neutral statement, allowing the Research board to decide anything.
The research Board meets next Tuesday. At the end the DG decides...
The 4 LHC spokespersons have requested to meet with CERN management.
Obviously the LHC community is worried, whilst the LEP community pushes for further run... not simple. A large number belongs to both communities!
Have a nice week-end!

Jet Measurements

Z Calibration Data in 2000



Absolutely no evidence of cracks in calorimeter

Missing energy event has $\cos\theta_{thrust} = 0.77$ where the jet energy resolution is 13%.

L3 Higgs search