Calorimetry in Particle Physics

Lecture V: Overview of LHC Calorimetry

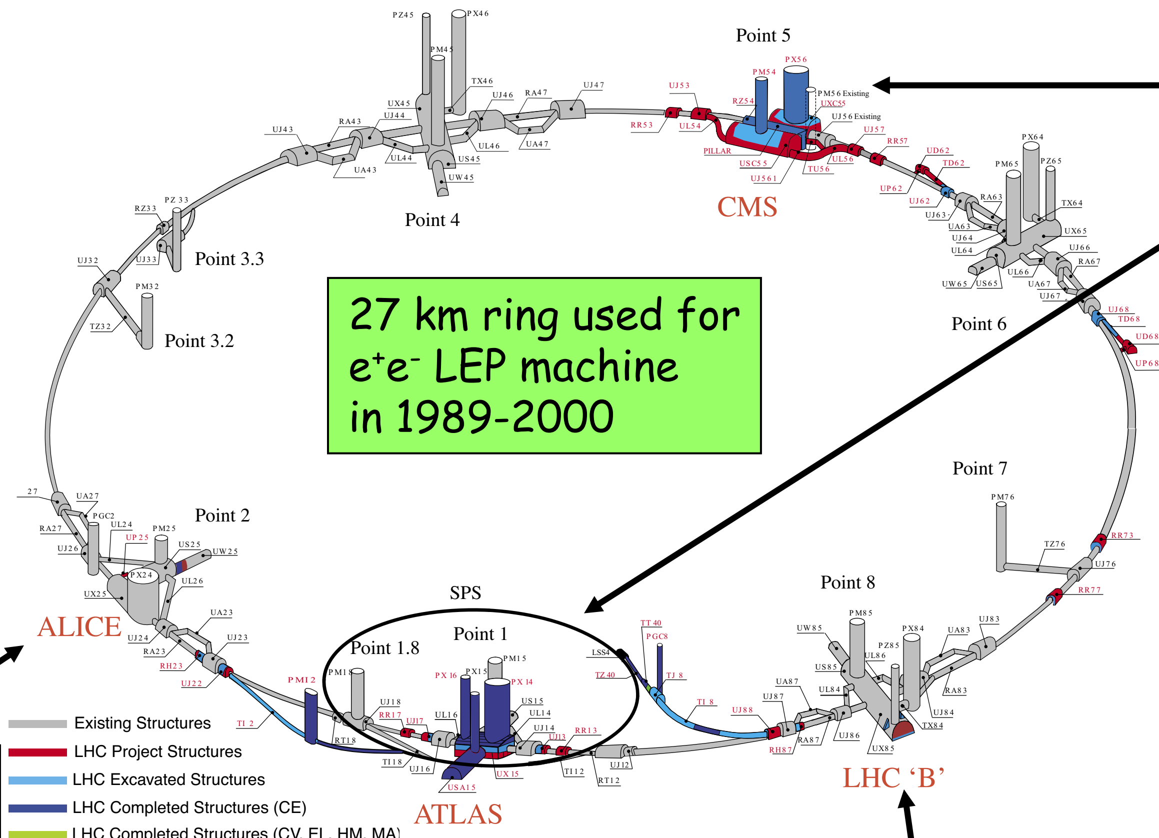
H. Oberlack
MPI für Physik, Munich

CONTENT

- **LHC Project**
- **Calorimetry in LHC 4π pp Detectors**
  - **Physics requirements**
  - **ATLAS calorimeters**
  - **CMS calorimeters**
- **ALICE & LHCb Calorimetry**
- **Conclusions**

- $\sqrt{s}$ = 14 TeV (7 times higher than Tevatron/Fermilab)
  → search for new massive particles up to m ~ 5 TeV

- $L_{design} = 10^{34}$ cm^{-2} s^{-1} (>10^2 higher than Tevatron/Fermilab)
  → search for rare processes with small σ (N = Lσ)



27 km ring used for e^+e^- LEP machine in 1989-2000

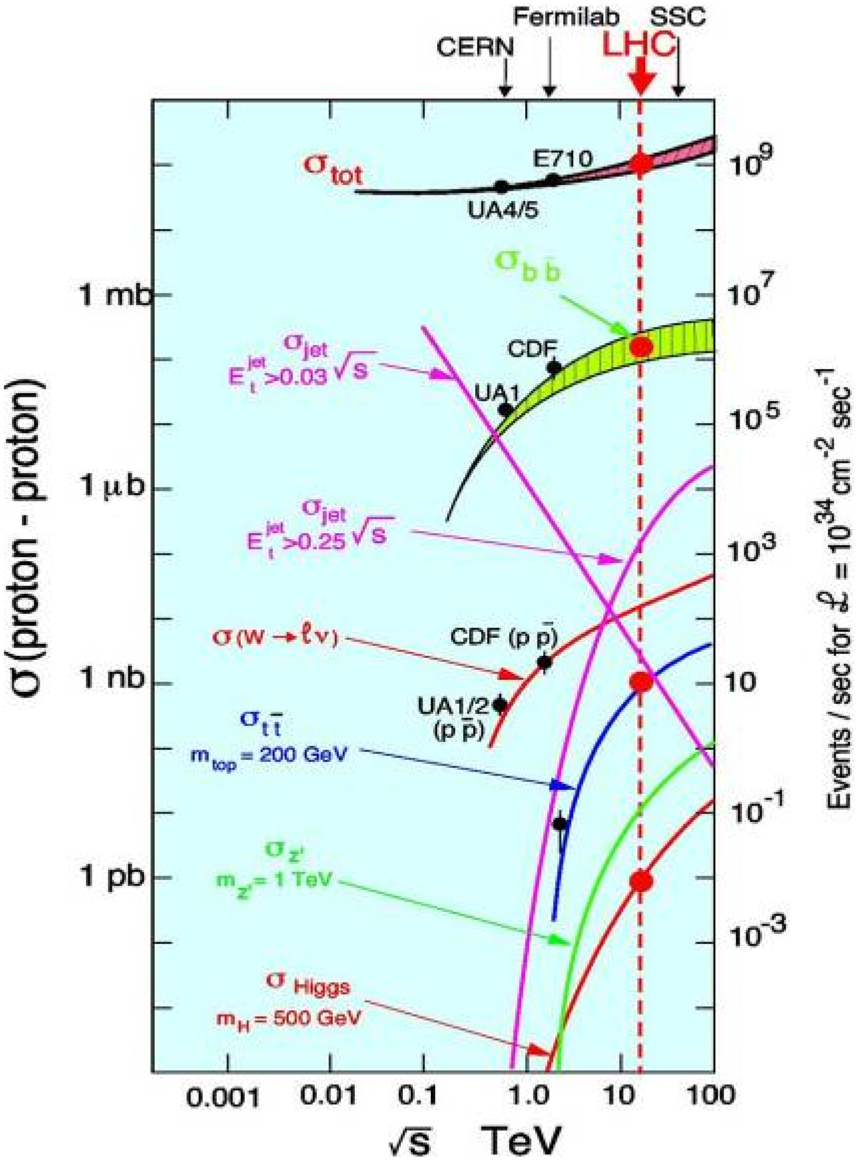
ATLAS and CMS : pp, general purpose

ALICE : heavy ions

LHCb : pp, B-physics

LHC pp Start 2007

Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} s^{-1} at LHC

• Inelastic proton-proton reactions	10^9 / s
• bb pairs • t t pairs	$5\ 10^6$ / s 8 / s
• W → e ν • Z → e e	150 / s 15 / s
• Higgs (150 GeV) • Gluino, Squarks (1 TeV)	0.2 / s 0.03 / s

LHC is a factory for:
top-quarks, b-quarks, W, Z, Higgs, …

Requirements E.m. Calorimeters

- **Most of the requirements come from the H→γγ and the H→4e channels and have driven the calorimeter design.**
  Here e.g. the ATLAS choice, CMS optimized differently.
- **Large acceptance: $|\eta|<3.2$ (precision physics $|\eta|<2.5$)**
- **Energy resolution : → mechanics / electronics calibration**
  - **Stochastic term: $a \leq 10\%$ GeV$^{1/2}$**
  - **Noise term: $b \leq 300$ MeV**
  - **Constant term: $c = 0.7\%$**
- **Linearity: 0.1% or better: → presampler for dead material**
  - **0.02% for high precision measurement, e.g. M_W**
- **Angular resolution: $\sigma(\theta) \approx 50$ mrad $/\sqrt{E}$**
  → lateral / longitudinal segmentation ($\Delta\eta * \Delta\phi = 0.25 * 0.25$)

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- **Particle identification capabilities:**
  - **e / jet,**
  - **γ / jet (in particular γ/π^0 separation for isolated hi-p_T $\pi^0 > 3$)**
- **Time resolution: 100 ps**
- **Large dynamic range : 20 MeV->2TeV → electronic read-out**

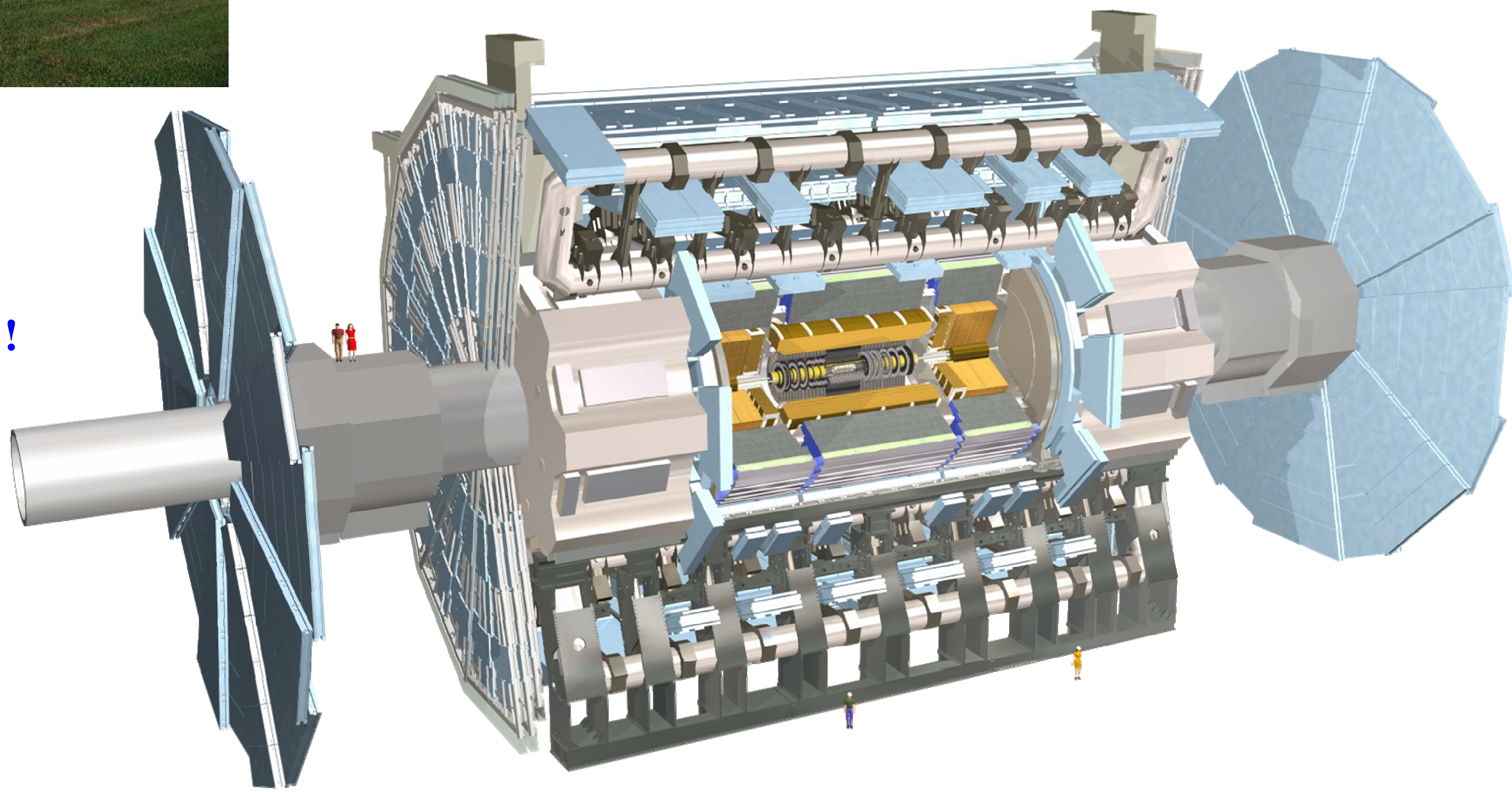
Requirements Hadronic Calorimeters

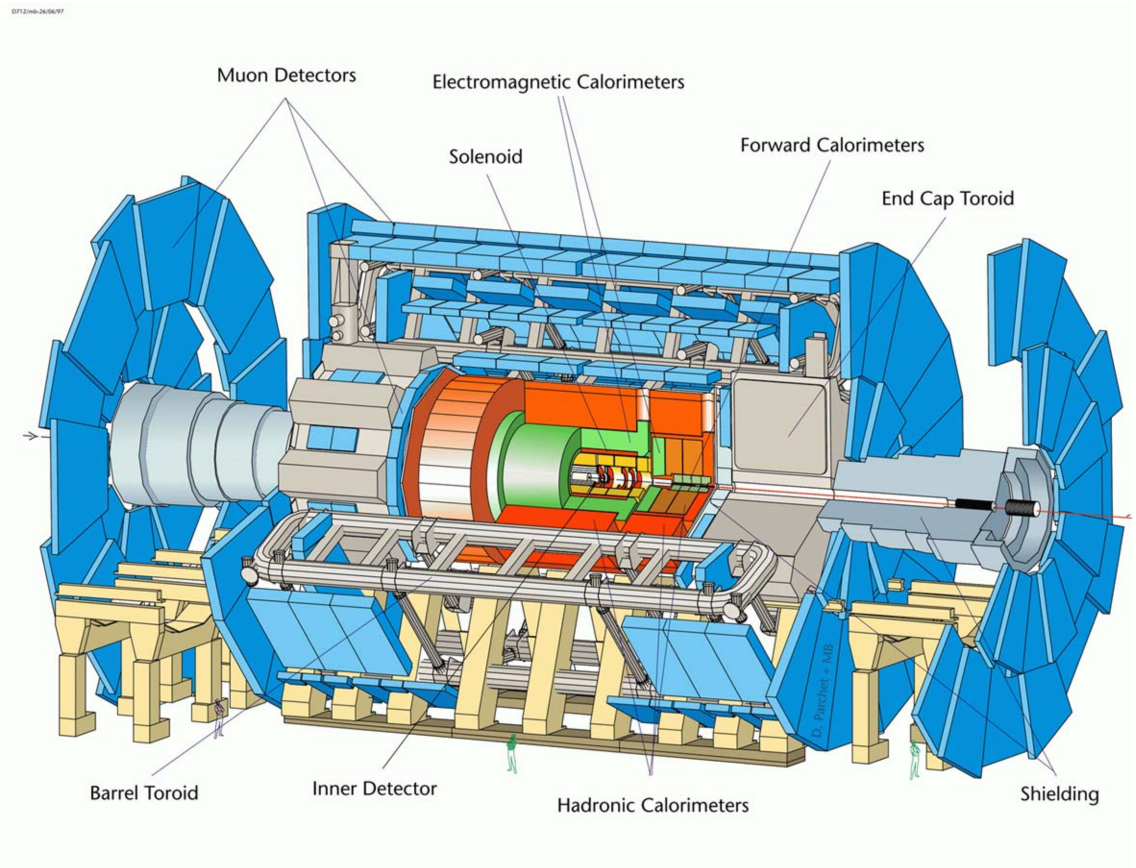
- Hadronic Calorimeters (HCAL) play an essential role in identification and measurement of quarks, gluons, and neutrinos by measuring energy and direction of jets and of missing transverse energy flow in events.
- Jet energy resolution: Stochastic term ~50%, constant term ~2%
- Missing energy forms a crucial signature of new particles, like the supersymmetric partners of quarks and gluons.

  For good missing energy resolution, a hermetic calorimetry coverage up to $|\eta|=5$ is required.
- HCAL will aid in the identification of electrons, photons and muons in conjunction with the tracker, e.m. calorimeter, and muon systems. Need longitudinal and transversal segmentation (e.g. 3-/4-fold longitudinal, $\Delta\eta * \Delta\phi = 0.1 * 0.1$)
- Radiation hard technology for calorimeters in end-cap and forward regions (e.g. expect up to 10**15 n/cm^2-year, 20 Mrad/year)

LHC Detectors are large !

ATLAS
superimposed on the 5 floors of CERN building 40 !

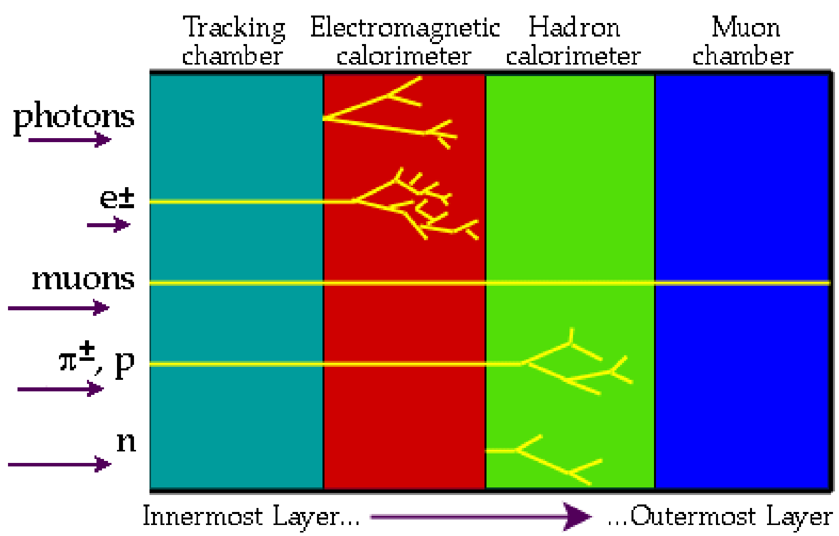




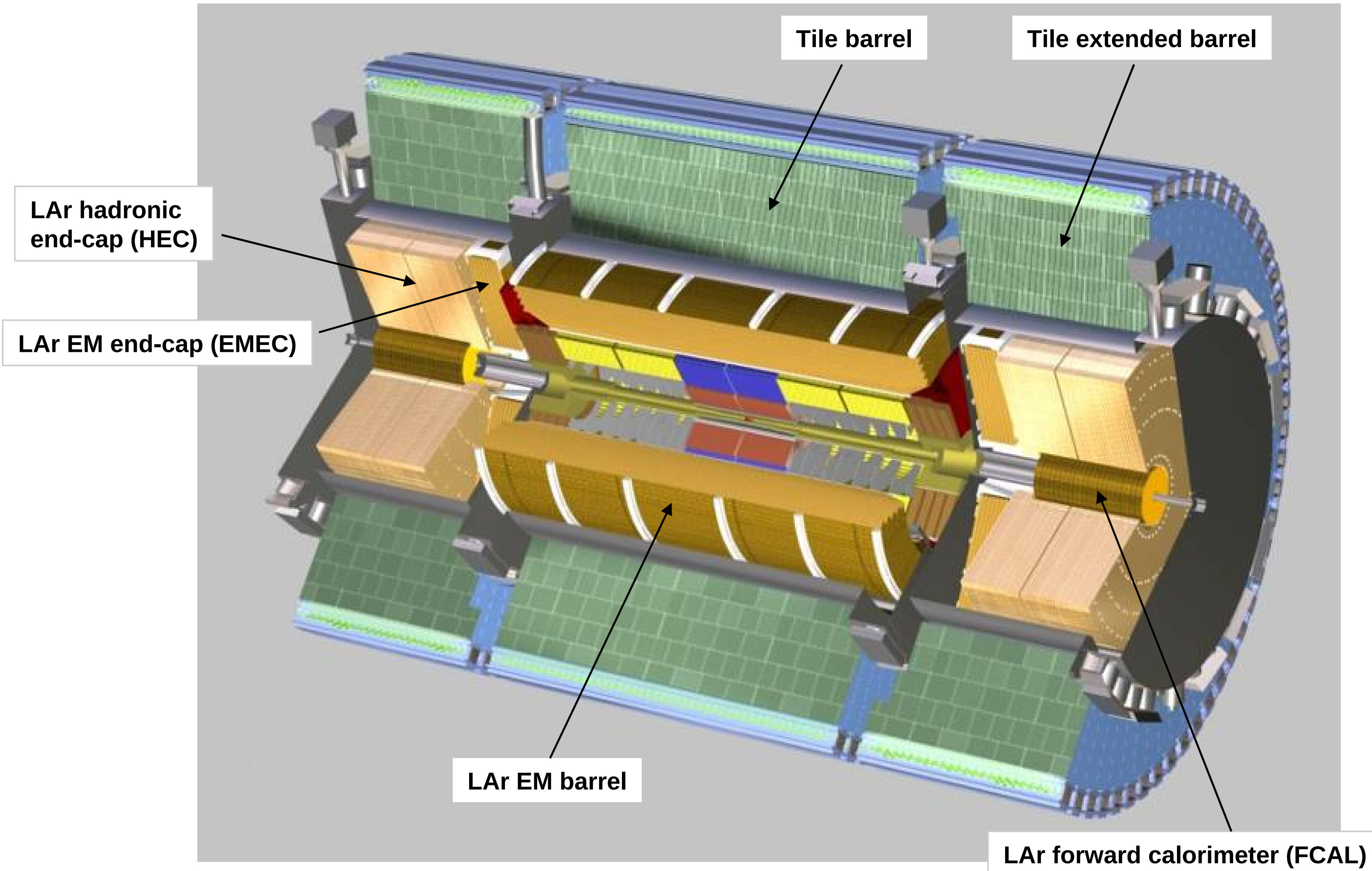
ATLAS Detector

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

- **Tracking (|η|<2.5, B=2T) :**
  - **Si pixels and strips**
  - **Transition Radiation Detector (e/π separation)**
- **Calorimetry (|η|<5) :**
  - **EM : Pb / Liquid Argon (LAr)**
  - **HAD: Fe / scintillator (central), Cu - W / LAr (fwd)**
- **Muon Spectrometer (|η|<2.7) :**
  Air-core toroids with muon chambers

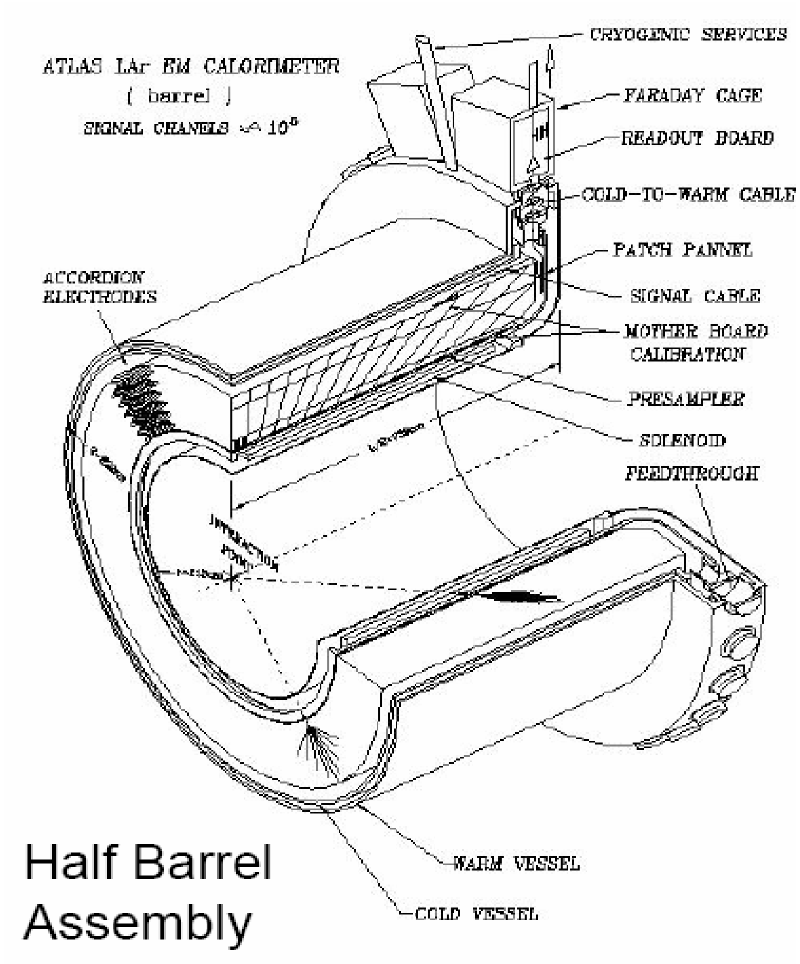


ATLAS LAr and Tile Calorimeters

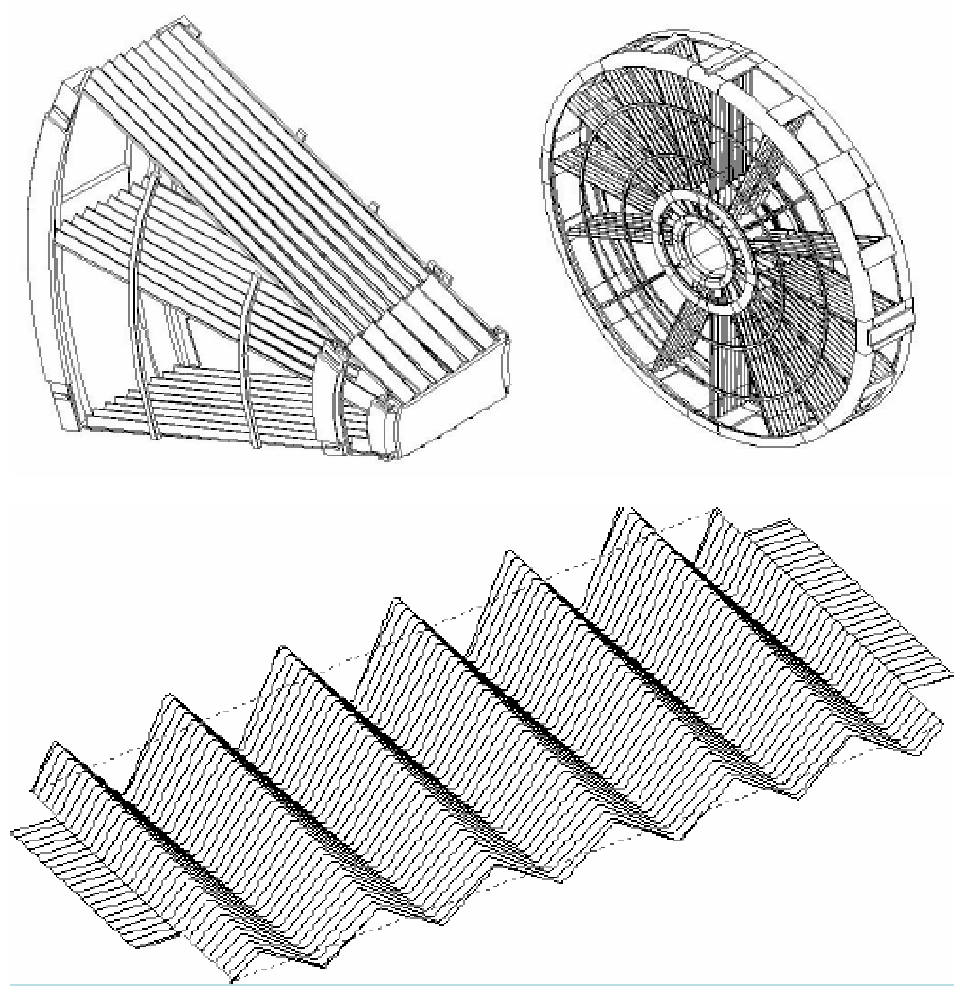


ATLAS E.m. Accordion Calorimeter

Electromagnetic Barrel EMB

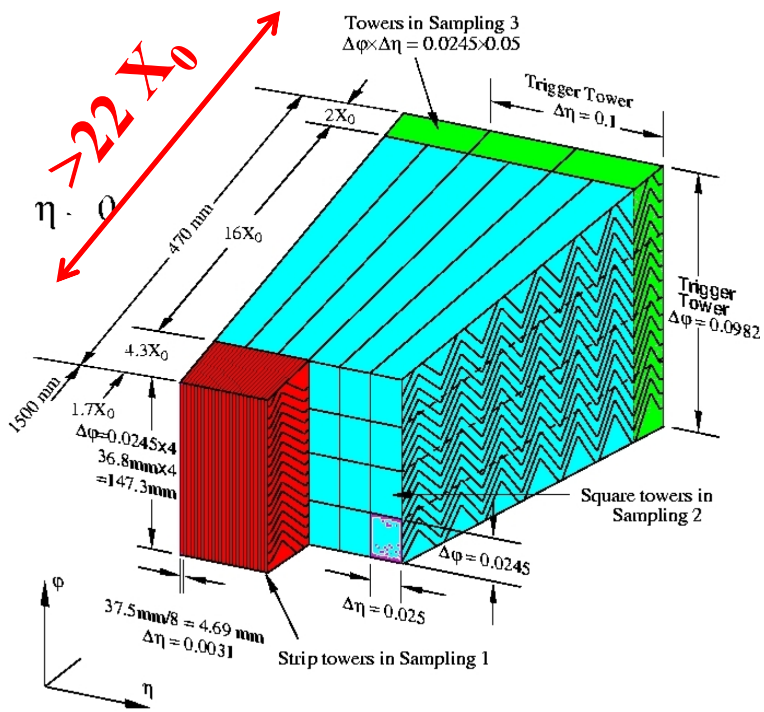


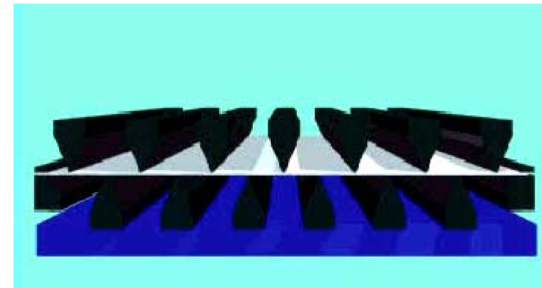
Electromagnetic End-cap EMEC



ATLAS EM Calorimeter

Lead/Liquid argon sampling calorimeter with accordion shape :

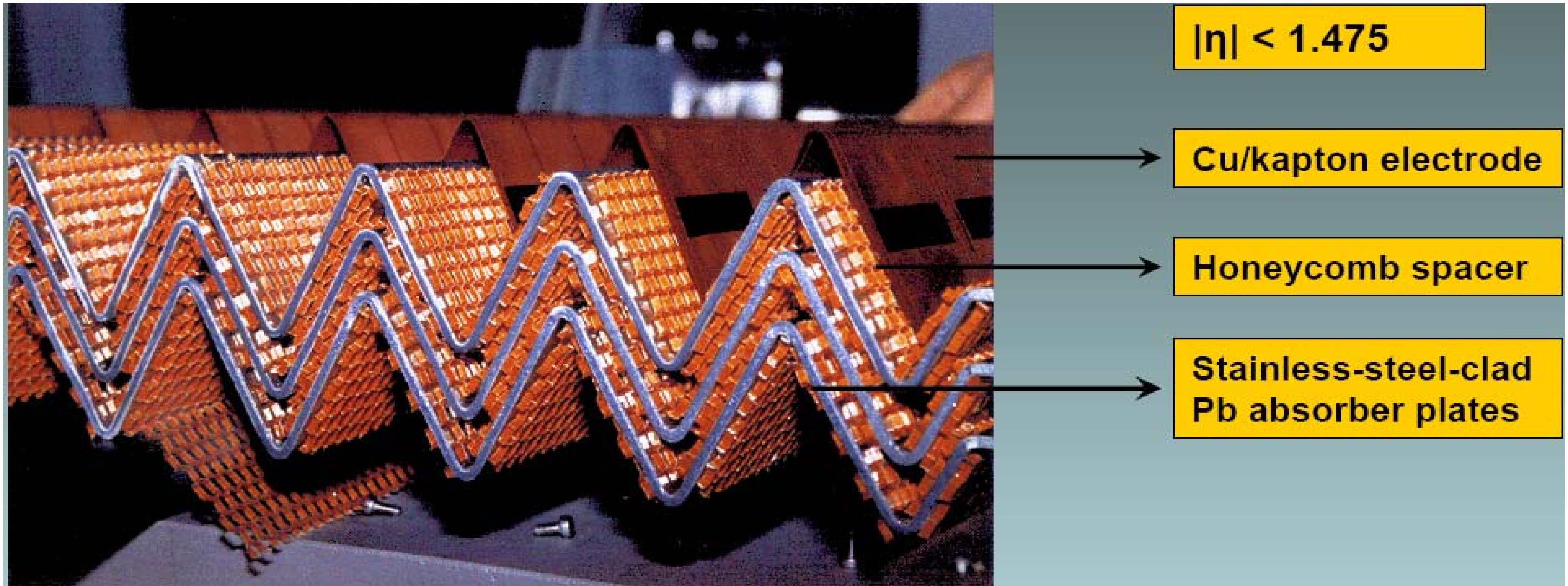




- **Full azimuthal coverage**
- **Rapidity coverage up to 3.2**
- **High granularity (~200000 channels)**
- **Longitudinal segmentation**
- **Presampler for $\eta < 1.8$**

Barrel : gap = 2.1mm @ 2000 V
lead 1.5 (1.1) mm for $\eta < 0.8$ (>0.8)
End-cap : gap varies with radius 3.1->0.9 mm
variable HV by steps

ATLAS EMB Calorimeter



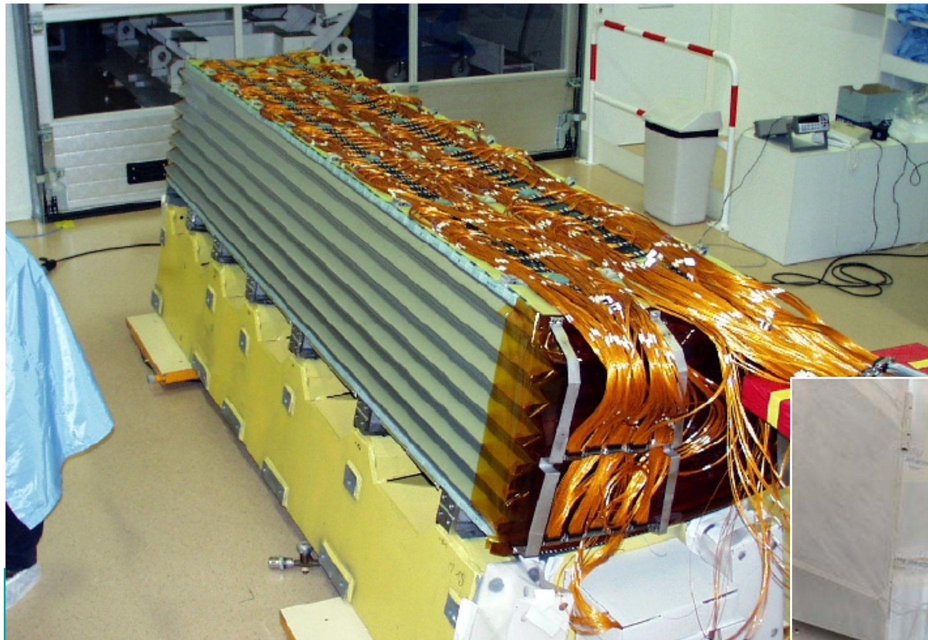
Detector design dictated by physics goals (high energy EM final states)

e.g. $H^0 \rightarrow \gamma\gamma, H^0 \rightarrow ZZ \rightarrow 4e,\ W' \rightarrow e\nu, Z' \rightarrow ee$

Accordion structure chosen to ensure azimuthal uniformity (no cracks)

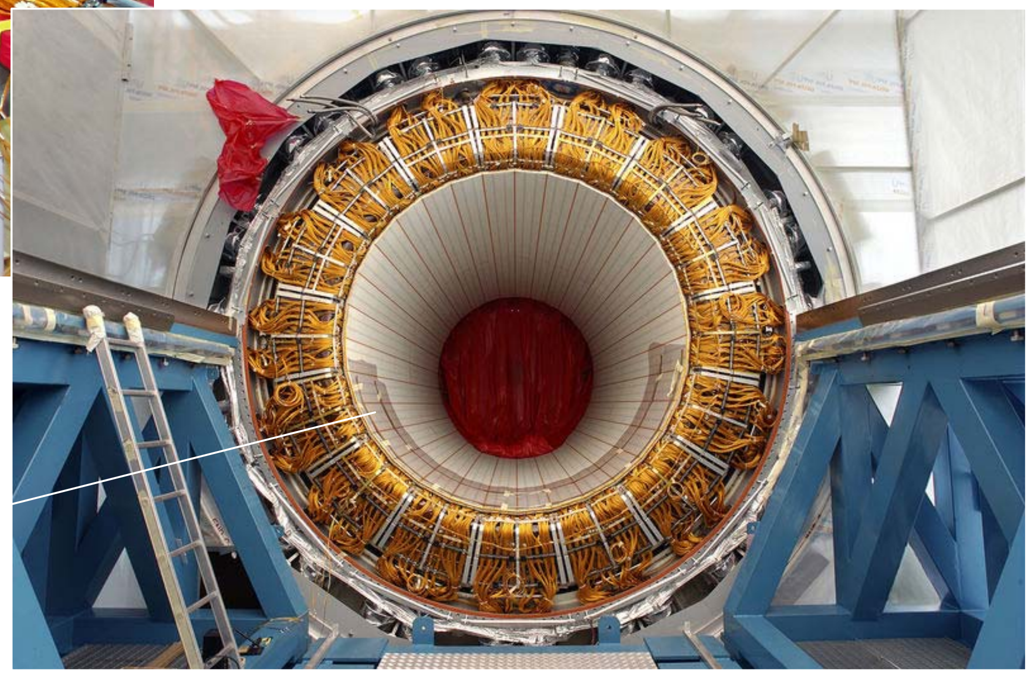
Liquid argon chosen for radiation hardness and speed

ATLAS EMB

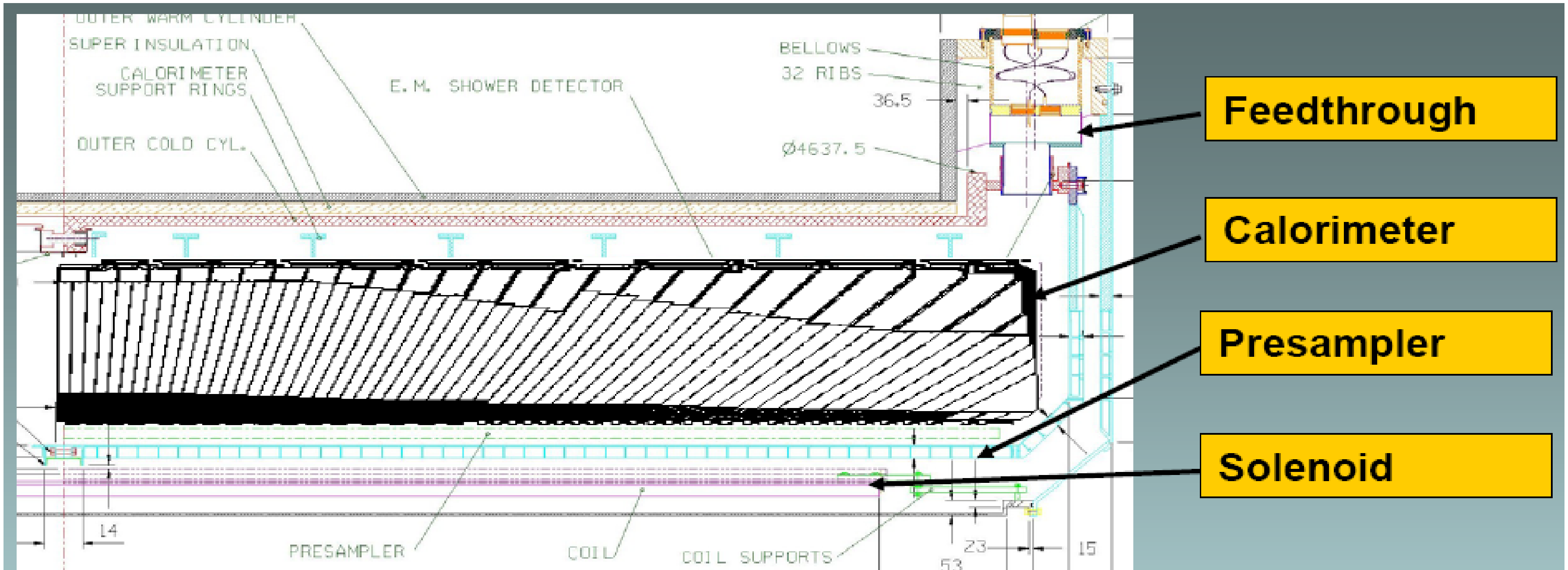


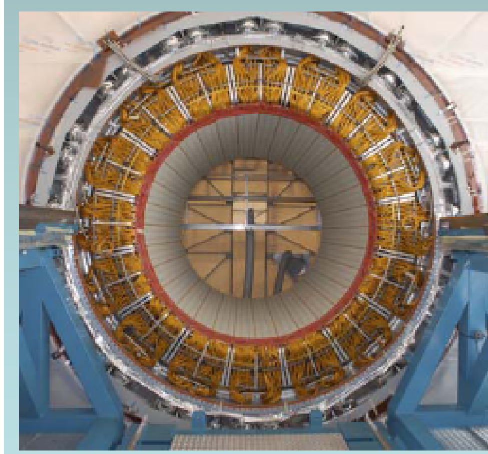
32 modules produced and tested at cold between 2001-2003
Assembly/insertion in cryostat end 2003

Presampler



ATLAS EM Barrel

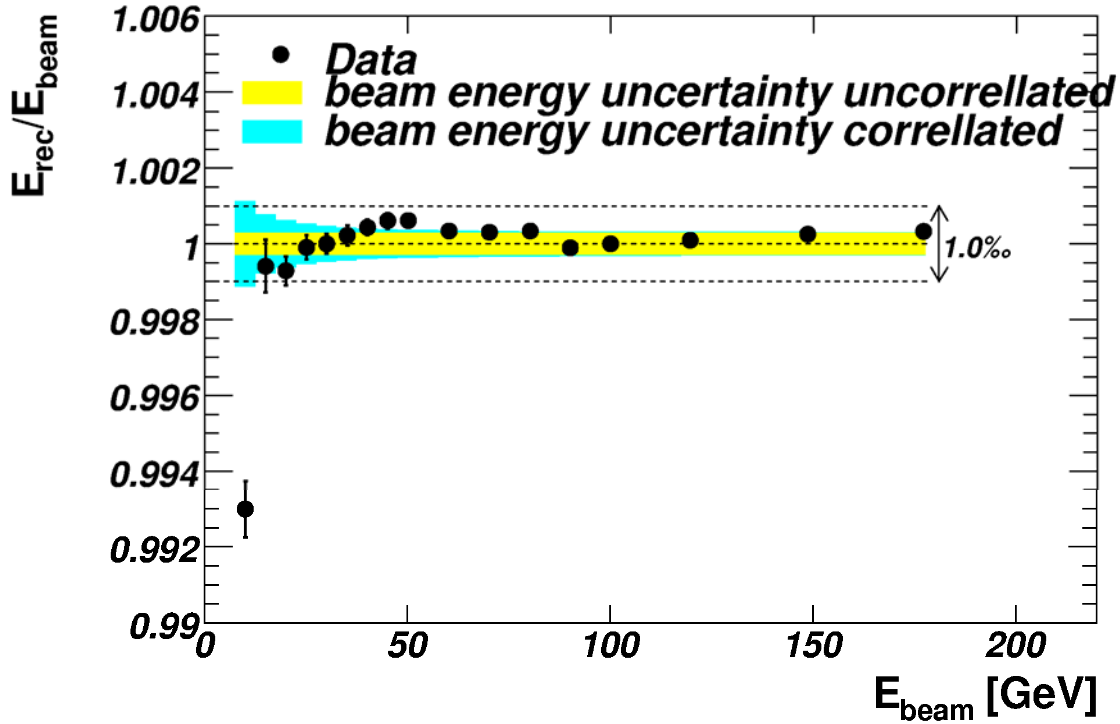




ATLAS EMB Linearity / E-scale

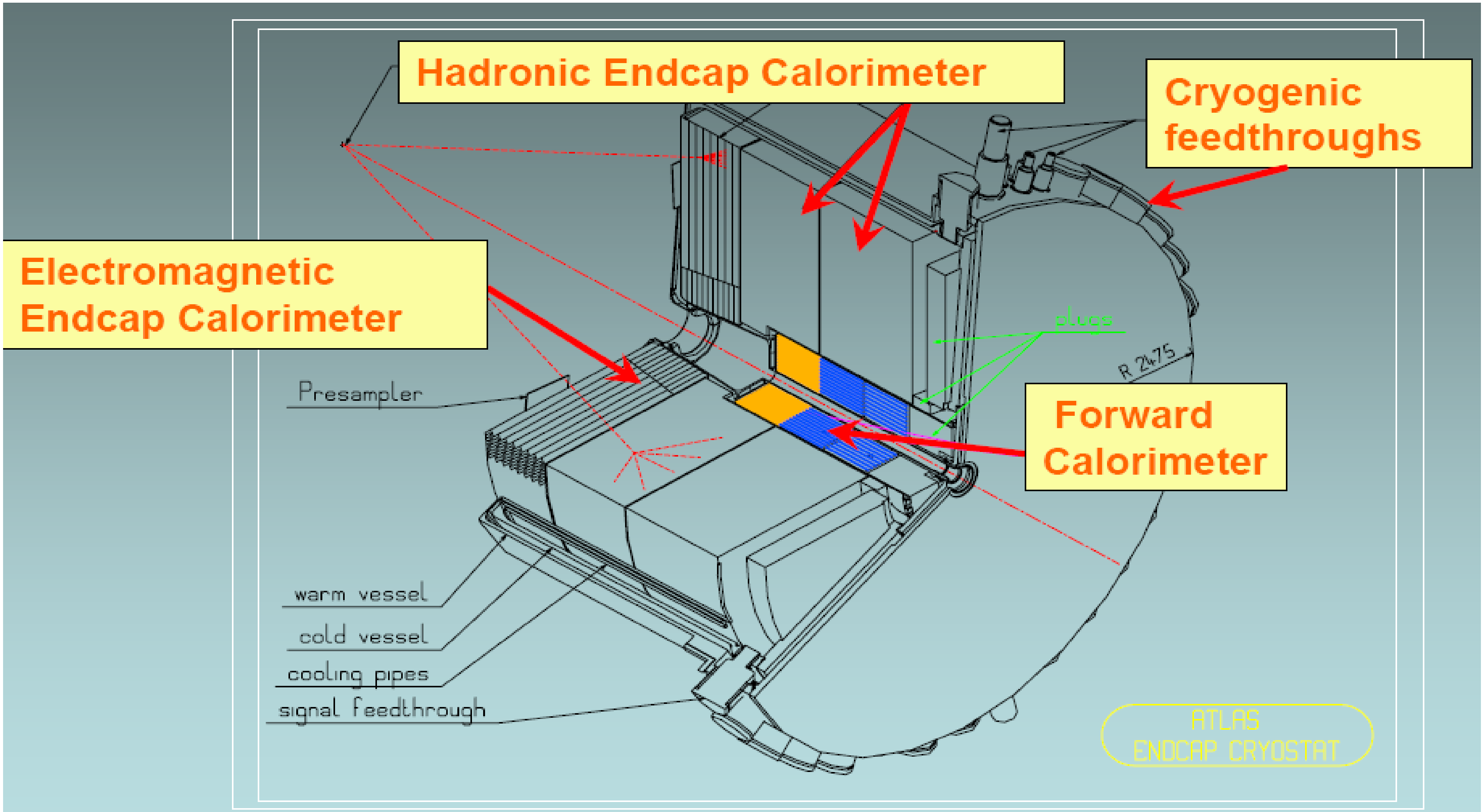
- Needed a dedicated TB set-up in 2002 to measure the beam energy
- e linearity is better than 0.1% in the energy range 20-180 GeV
- Caveats:
  - Check done at one η position
  - Less material than in ATLAS
- Performance adequate for most ATLAS measurements.

- W mass
  - if one wants to improve over LEP + Tevatron, one needs to know energy scale to ~0.02%
  - Energy scale set by Z → ee
  - Will need combination with tracking detector to extrapolate from Z to W with such precision



Except for E=10 GeV, all energy points are within 0.1%

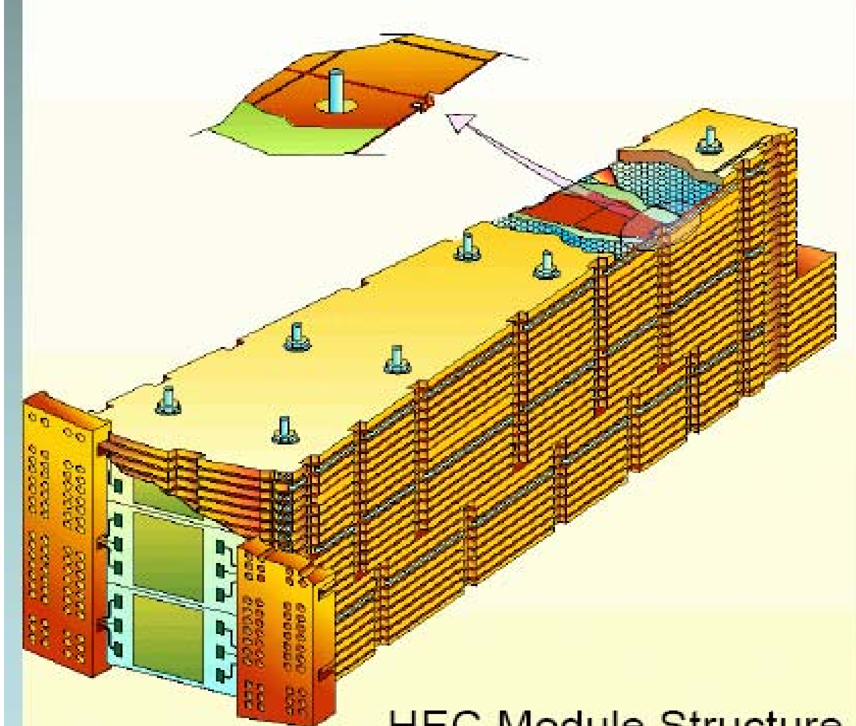
ATLAS LAr End-Cap Calorimeters



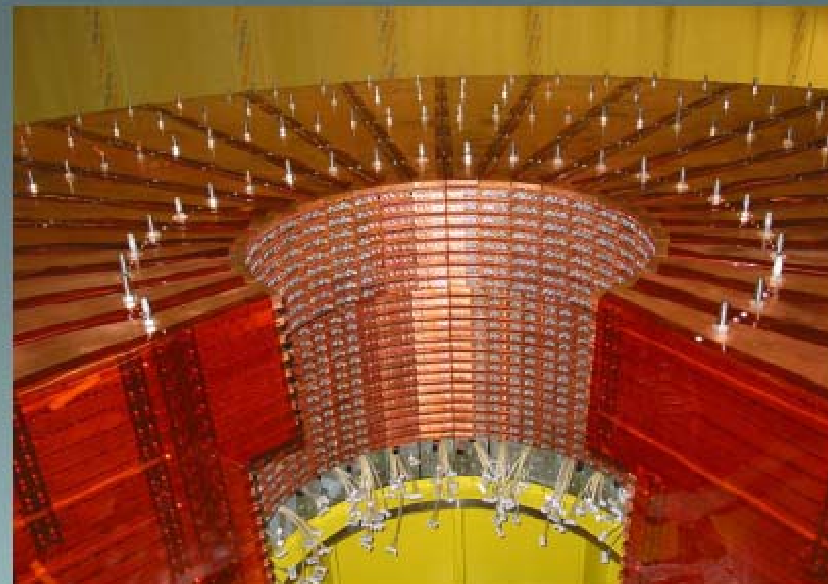
ATLAS Hadronic End-Cap Calorimeter HEC

LAr-Cu sampling calorimeter covering $1.5 < \eta < 3.2$

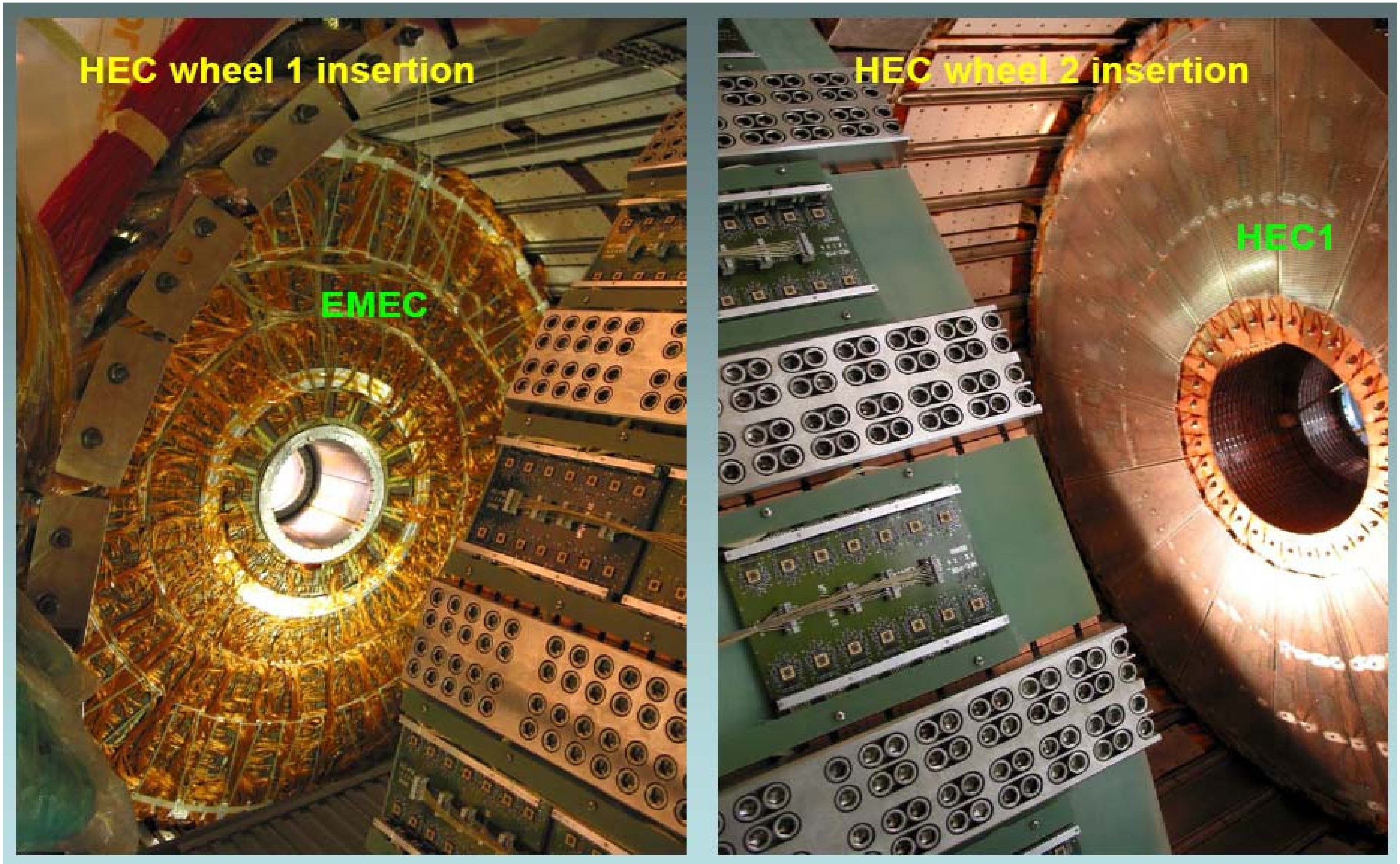
Composed of 2 wheels per end, 32 modules per wheel



HEC Module Structure



ATLAS HEC Insertion into Cryostat

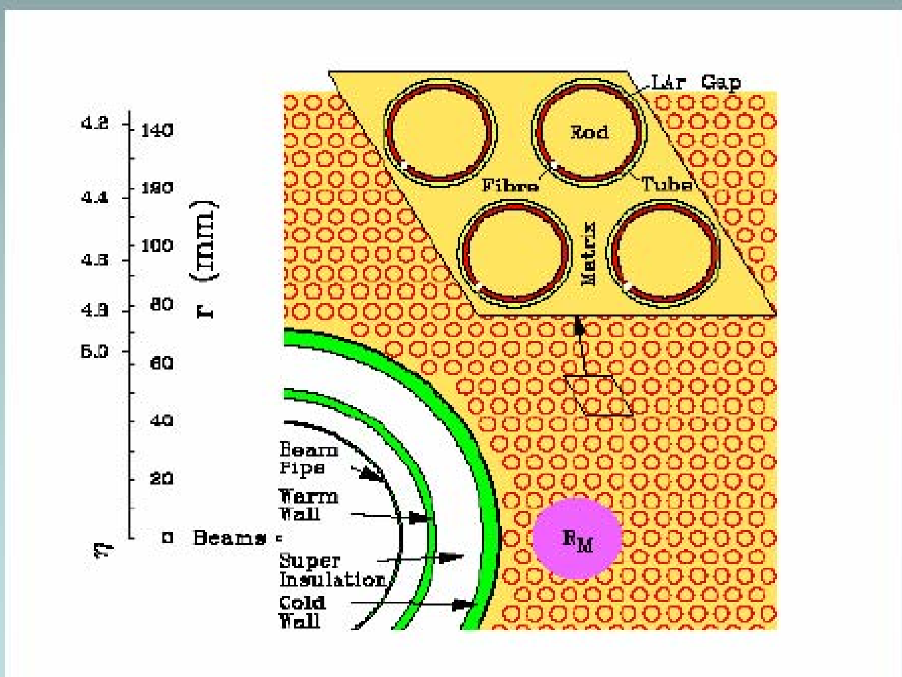


ATLAS Forward Calorimeter FCal

Novel electrode structure → thin annular gaps formed by an tubes in an absorber matrix, which are filled with anode rods of slightly smaller radius

Gap maintained by helically-wound radiation hard plastic fibre (PEEK)

Three modules: 1 EM, 2Hadronic (ease of construction, depth segmentation)

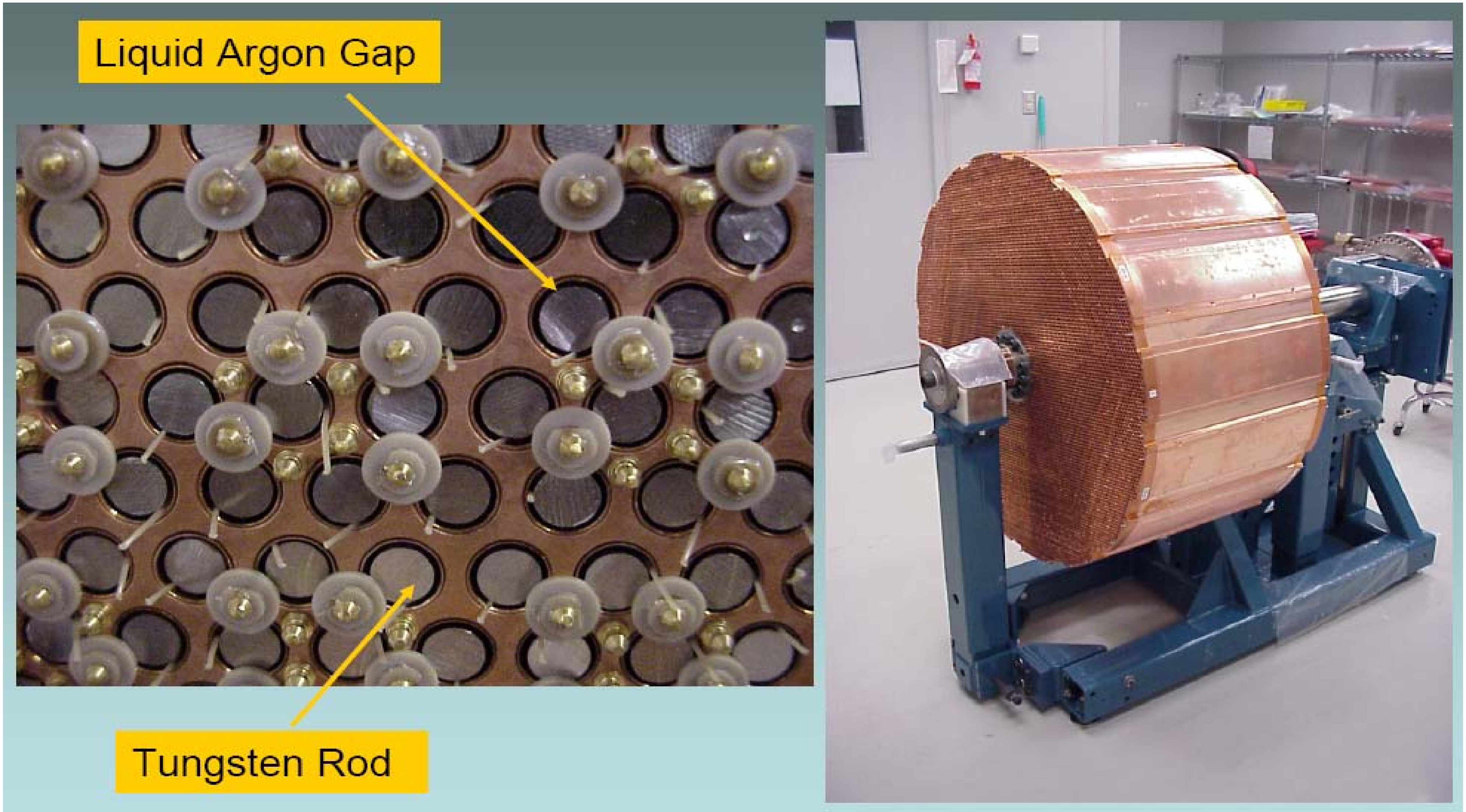


	Type	Absorber	Gap (μm)	Number of Electrodes
FCal1	EM	copper	250	12000
FCal2	HAD	tungsten	375	10000
FCal3	HAD	tungsten	500	8000

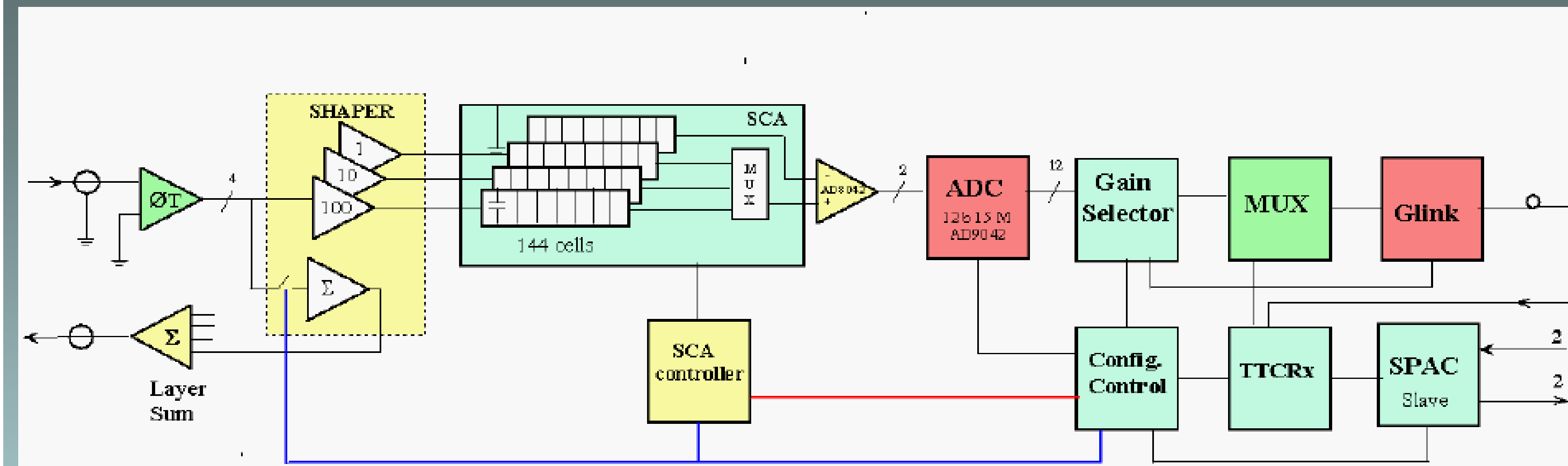
↓

matrix and rods are part of the detector 'absorber' and are composed of the same material

FCal 2/3 Structure and Assembled Module



ATLAS LAr Read-out Electronics

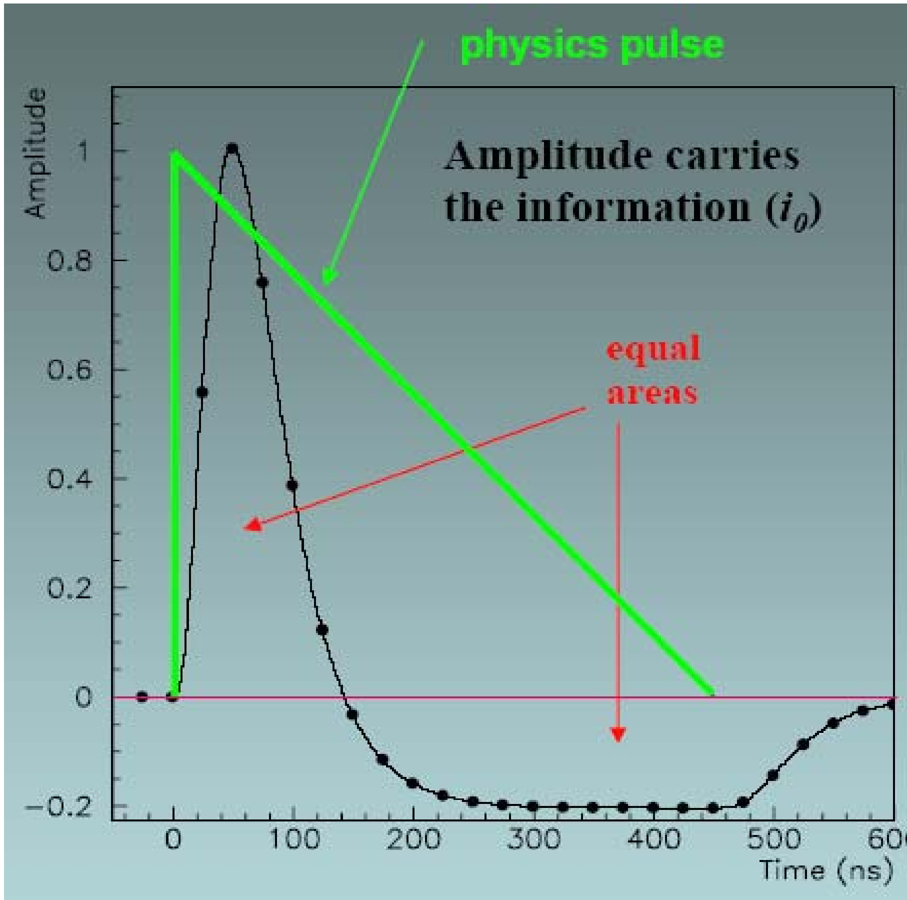


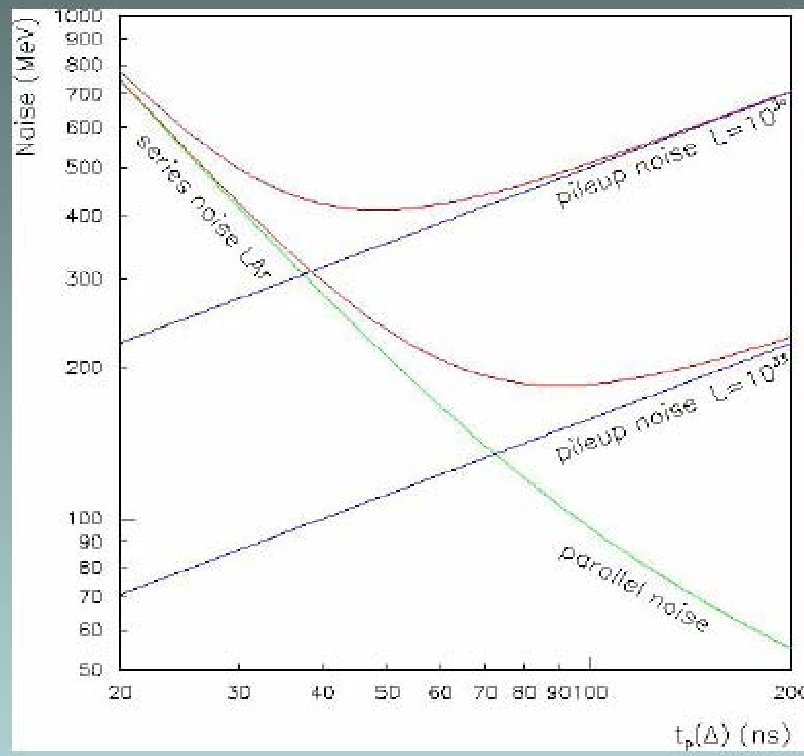
Common readout electronics for all LAr Calorimetry

except for cold (GaAs) preamplifier for Hadronic Endcap Calorimeter

Installation and testing of Front-End Crates currently underway in ATLAS cavern

ATLAS LAr Bipolar Pulse Shaping





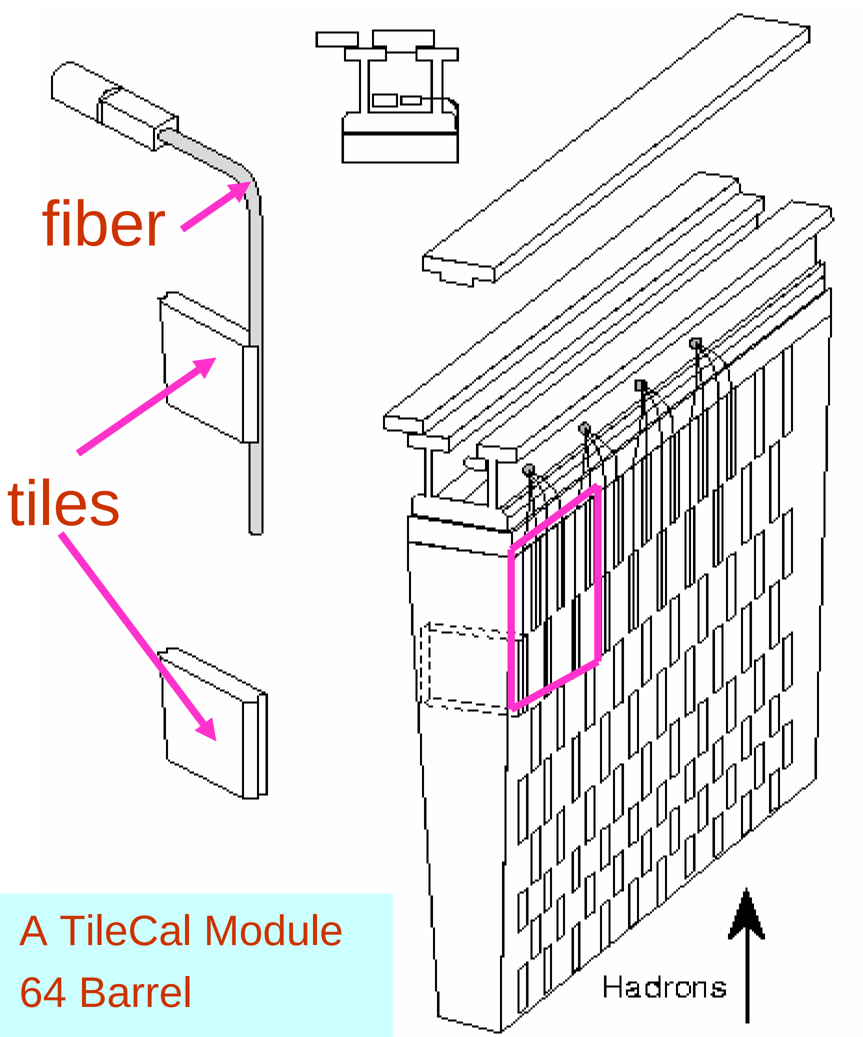
Pulse shape sampled every 25 ns
(eg. once / bunch crossing)

Optimal shaping time is an optimization problem.

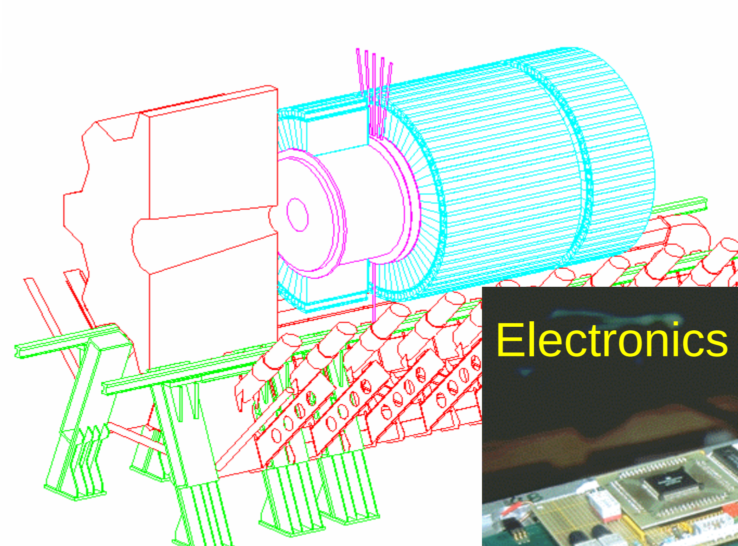
ATLAS LAr Commissioning Plans

- Cold testing of the three cryostats at the surface after detector integration (complete)
- Warm testing (calibration signals, read-out) in the ATLAS cavern
- Cold testing in the ATLAS cavern
- Electronic calibration, noise studies including magnet operation
- Commissioning / integration with trigger / DAQ systems
- Data taking with cosmic rays (begins 2006)
  - LAr Barrel ~June 2006 (cool-down will start next week)
  - LAr End-caps ~Sept 2006
- Commissioning with single beams in summer 2007 (?)
- Commissioning with colliding beams in fall 2007 (?)

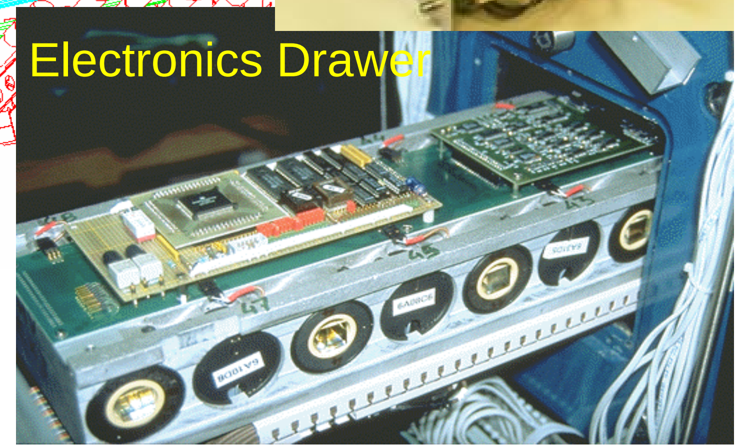
ATLAS TileCal Detector



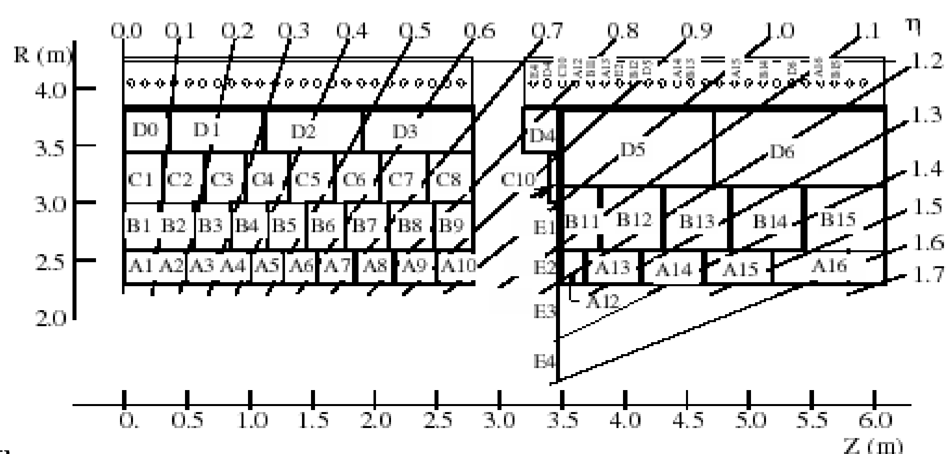
A TileCal Module
64 Barrel
2x64 Ext. Barrel



Finger LVPS

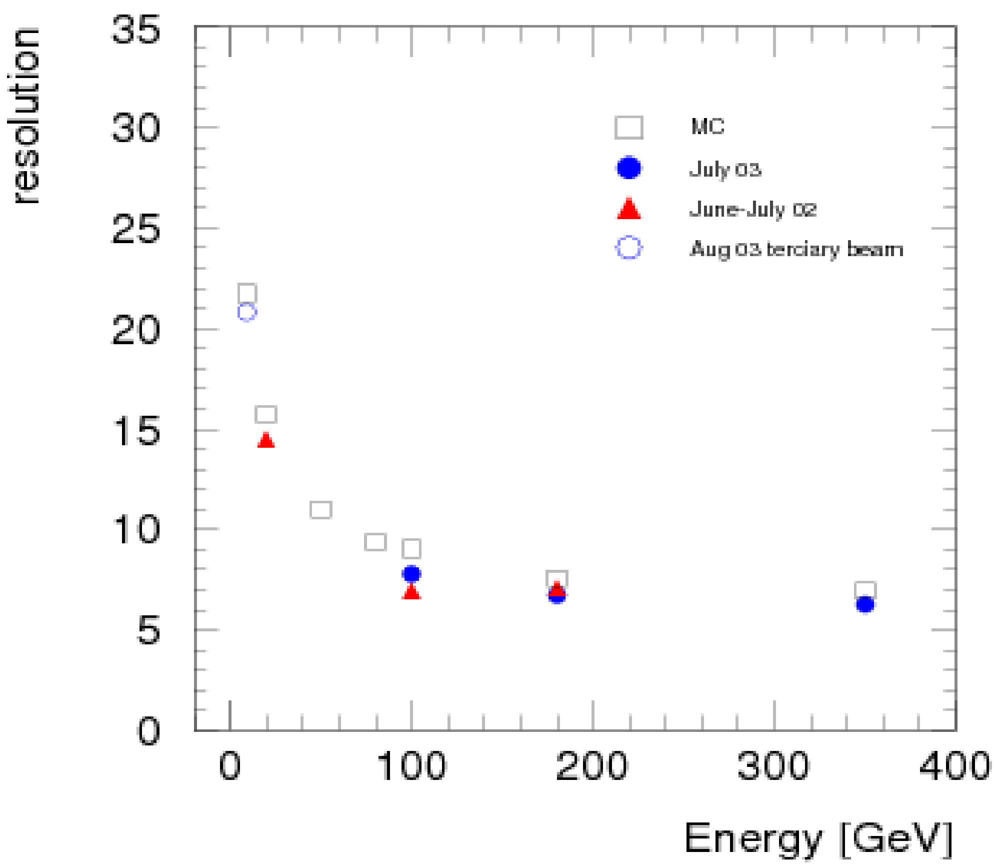


TILECAL CELLS



ATLAS TileCal Performance for Pions

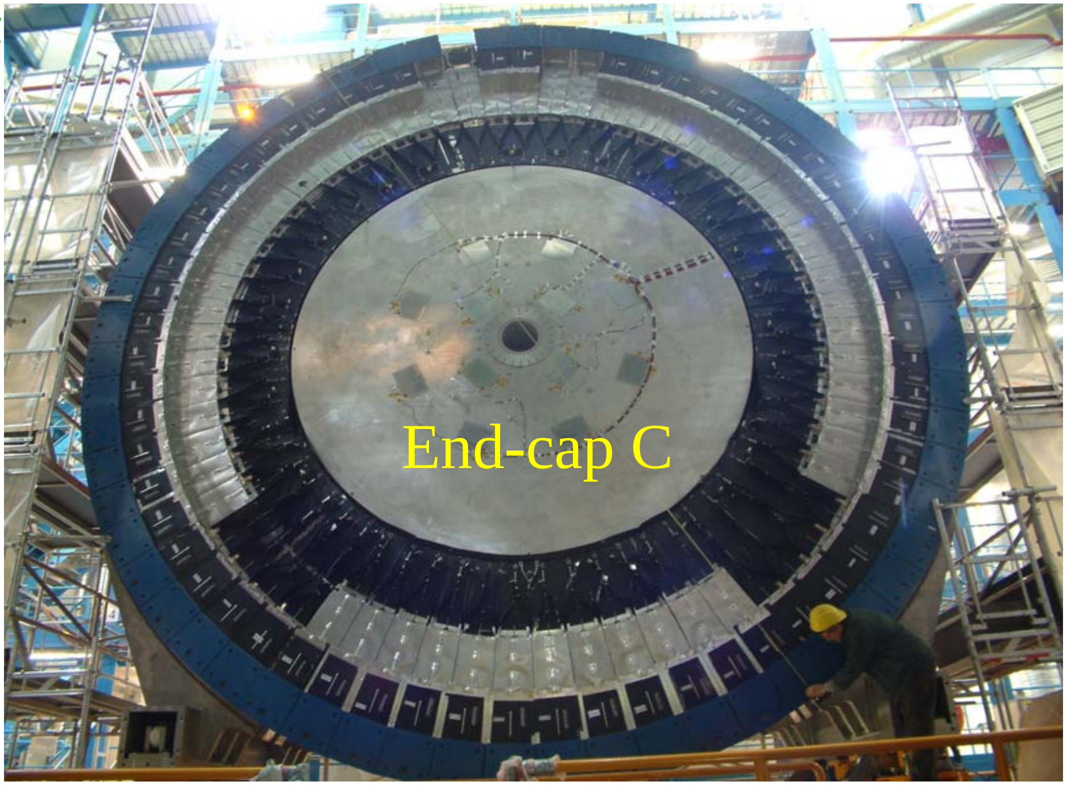
- **Testbeam results:**
  - linearity studies show e/h=1.36
  - uniformity of response over several modules at the level of 1.5%



Good agreement with latest G4 MC (4.7.1 QGSP)

ATLAS Calorimeter Installation Status

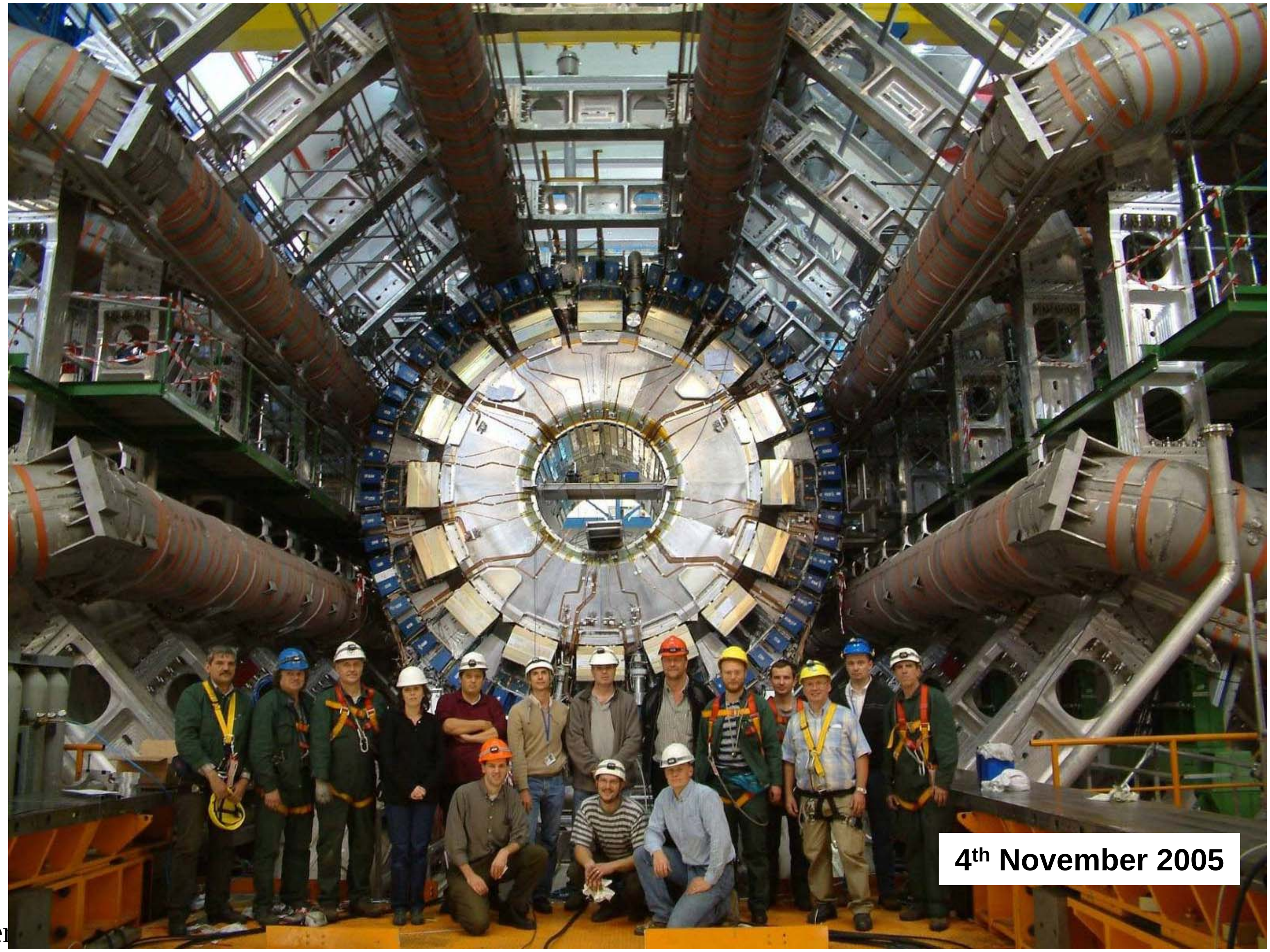
- Barrel part of the calorimeter (Tile + LAr cryostat) is at its final position.
  - Tile FE electronics in the modules certified.
  - LAr electronics being inst



- End-cap C (Tile with gap scintillators + LAr cryostat) in its garage position
  FE electronics certified.
- End-cap A being lowered
  - Tile bottom 1/3 lowered.
  - LAr cryostat will be lowered week after Easter.

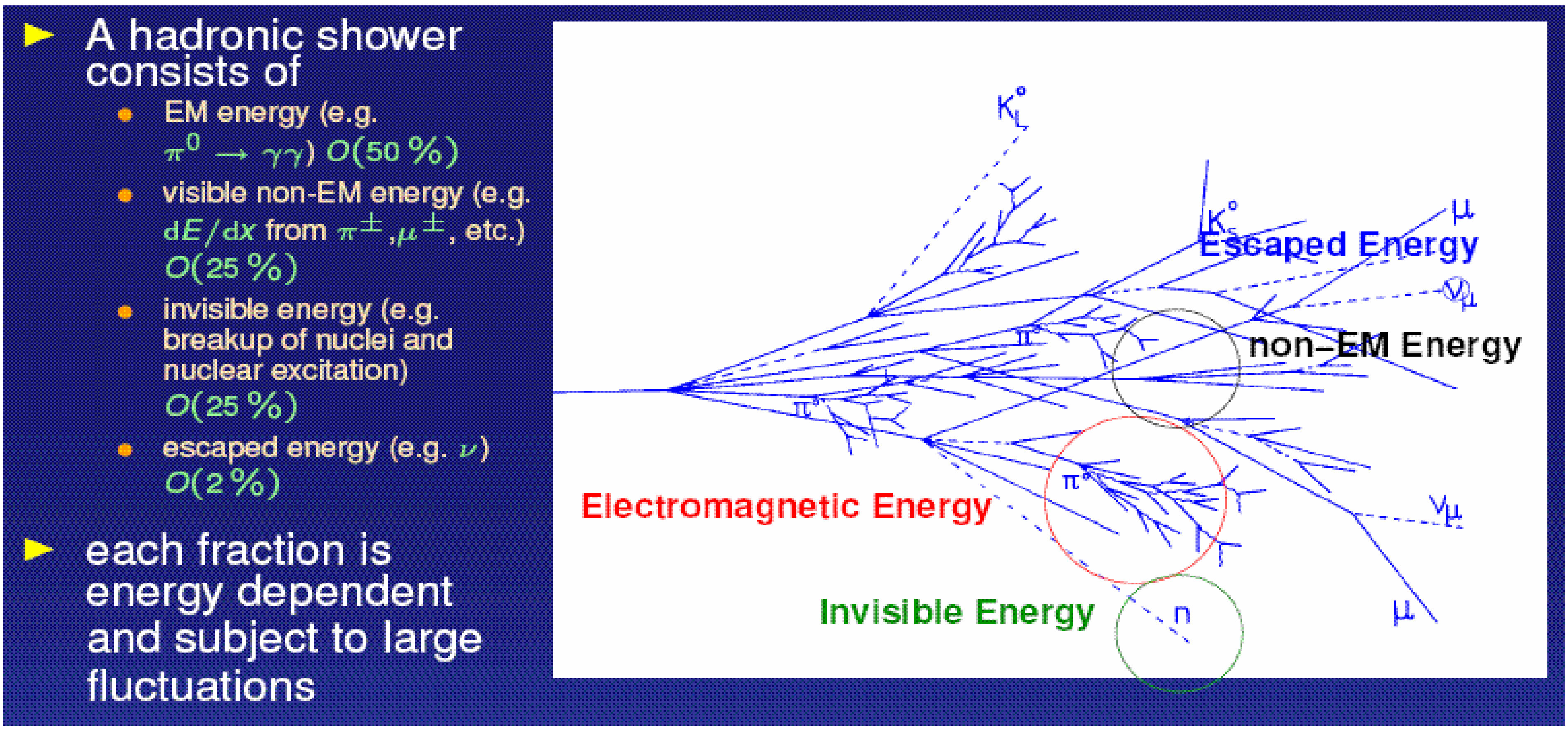
ATLAS Barrel Calorimeter at IP

(LAr and Tile calorimeters, including central solenoid) moved on air pads into its final position at the centre of the ATLAS detector



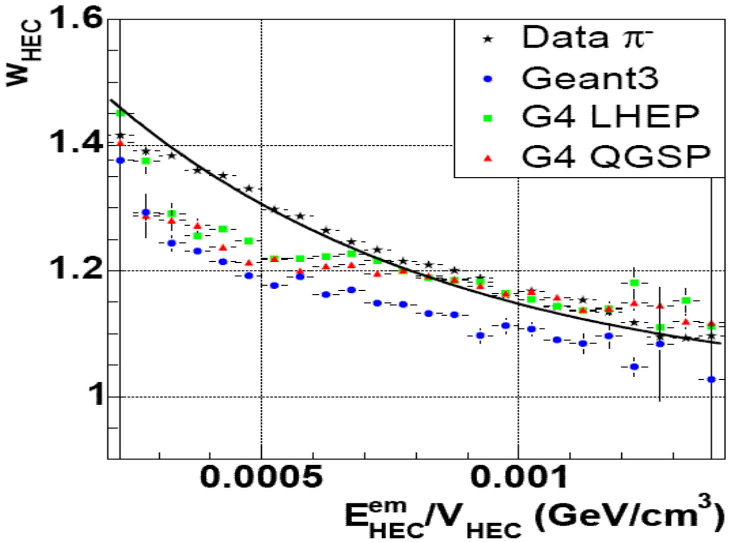
ATLAS Hadronic Calibration: Concept

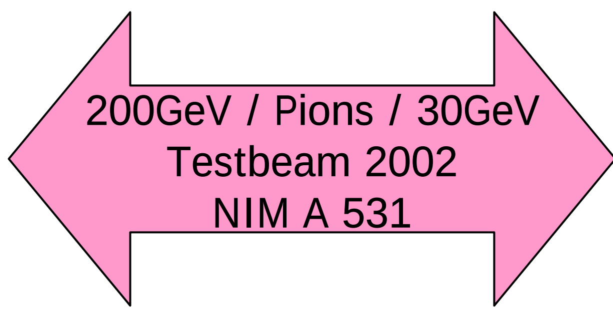
- **Goal is to obtain for each calo cell optimum estimate of deposited energy:**
  'local calibration'
- **Start with em scale**
- **Weighting approach:**
  Energy density in individual cell yields good estimate of em fraction

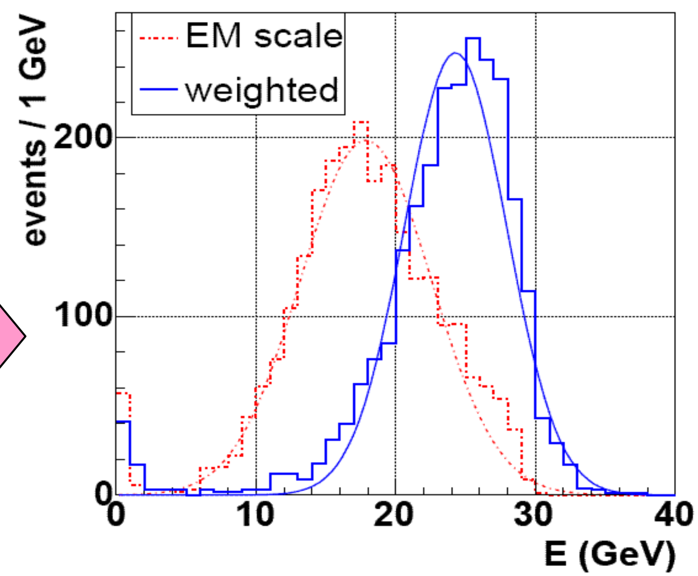


ATLAS Hadronic Calibration: Concept

- E.m. topo cluster: Use general cluster moments to get probability for a cluster to be almost pure e.m. type: Assign e.m. scale.
- Dead material corrections: Use correlations with layer/cell deposits in neighbouring topo clusters.
- Energy corrections step by step and uncorrelated: if problems in situ (simulation ↔ data) have better chance to identify source of problem.
- Validation of MC using testbeam data is a vital step in the procedure!



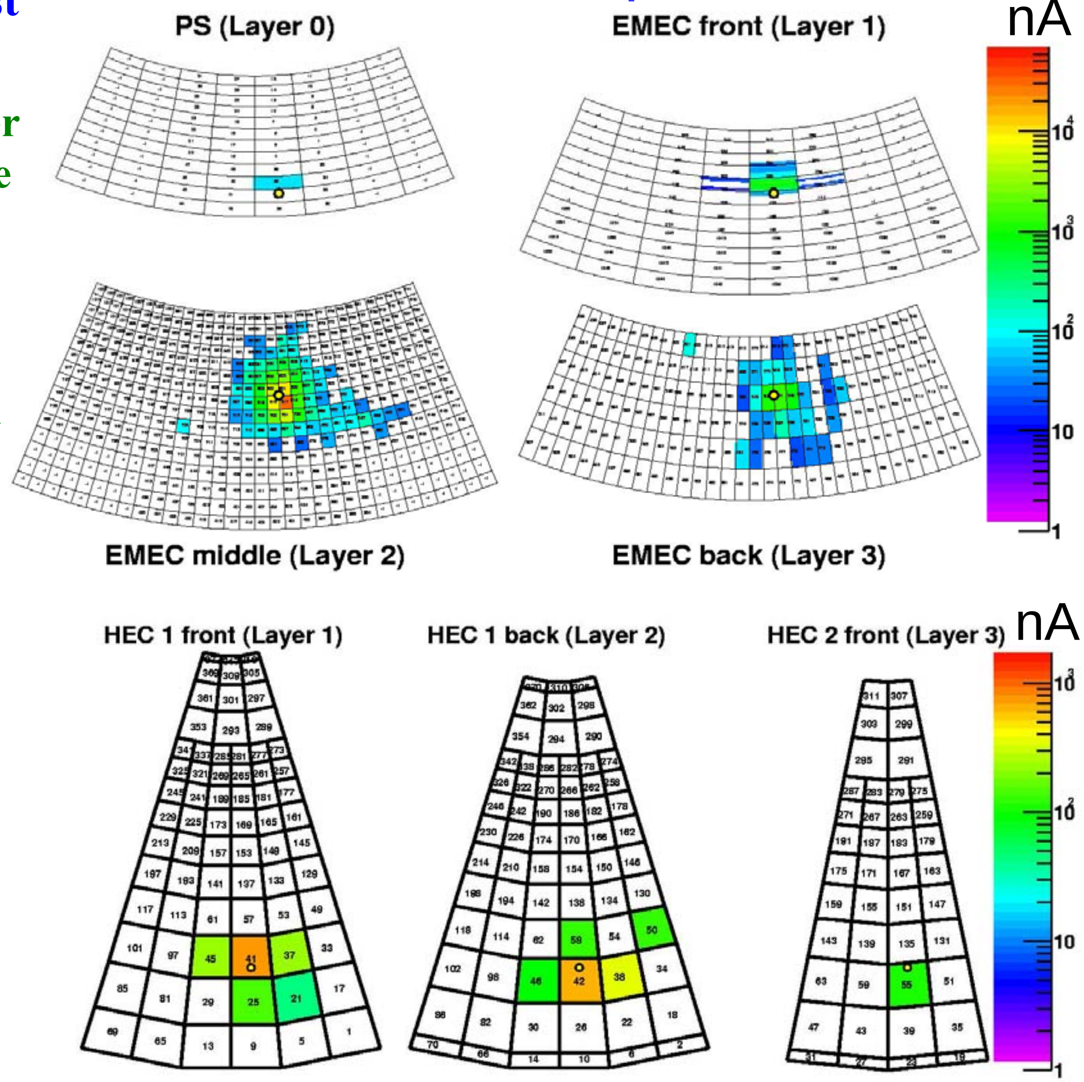




Clustering

- **Cell-based topological nearest neighbor cluster algorithm**
  - clusters are formed per layer using neighbours (that share at least one corner)
  - $E_{seed} > 4\sigma_{noise}$
  - $|E_{cell}| > 2\sigma_{noise}$
  - include neighbour cells with $|E_{cell}| > 3\sigma_{noise}$

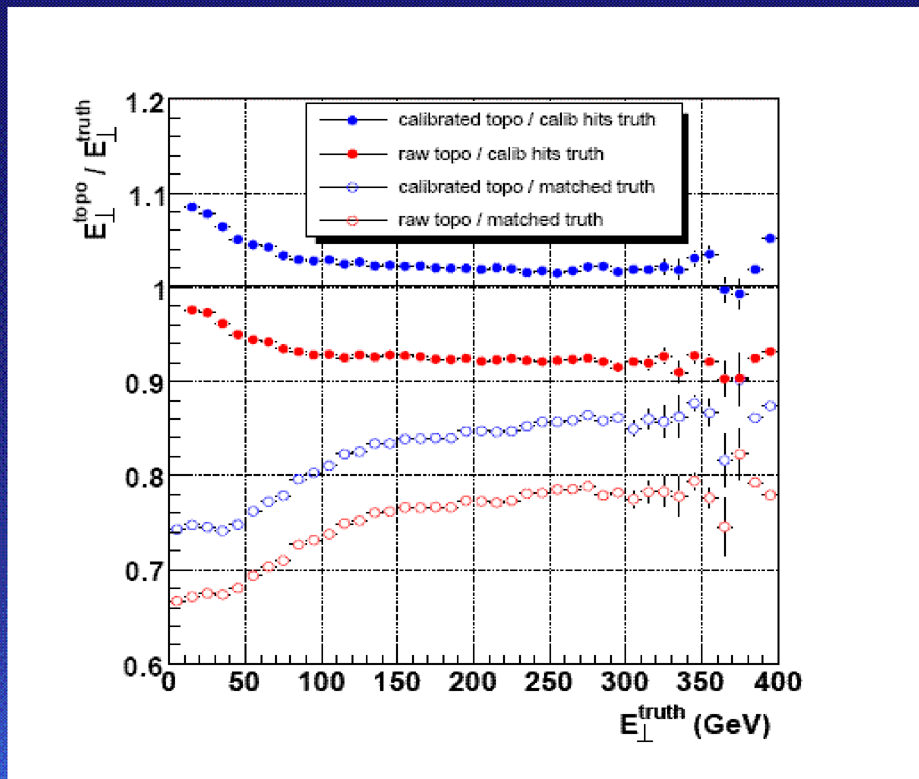
180 GeV pion

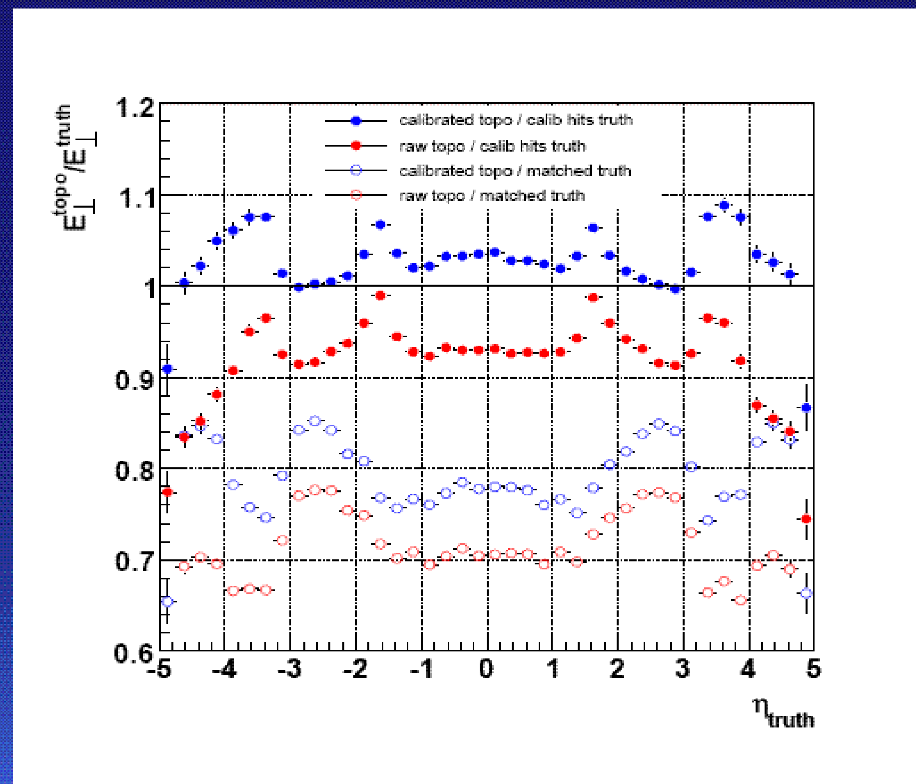


Apply single pion weights to jets

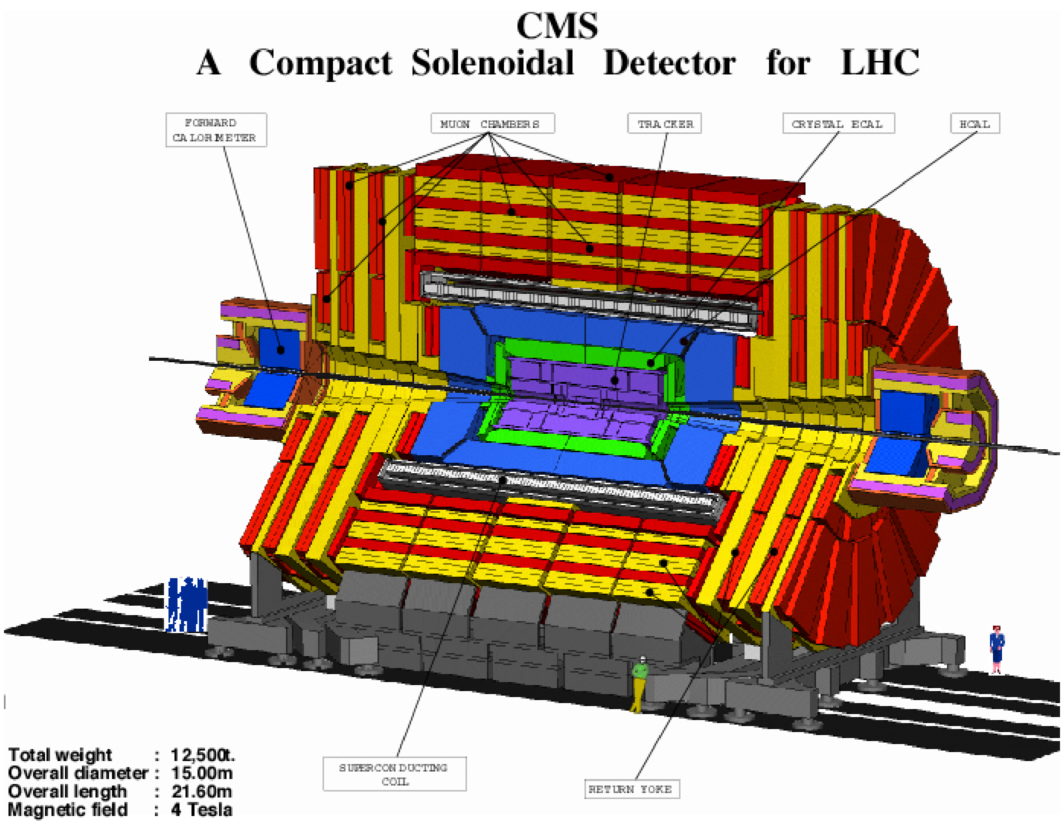
- ratios of $E_\perp$ for the matched jets as function of $E_\perp^{truth}$ (left) and η^{truth} (right) for
  - calibrated topo jets over the calibration hit truth (full blue dots)
  - raw topo jets over the calibration hit truth (full red dots)
  - calibrated topo jets over the matched particle truth (open blue dots)
  - raw topo jets over the matched particle truth (open red dots)

Still ongoing: get weights from jets directly and compare!



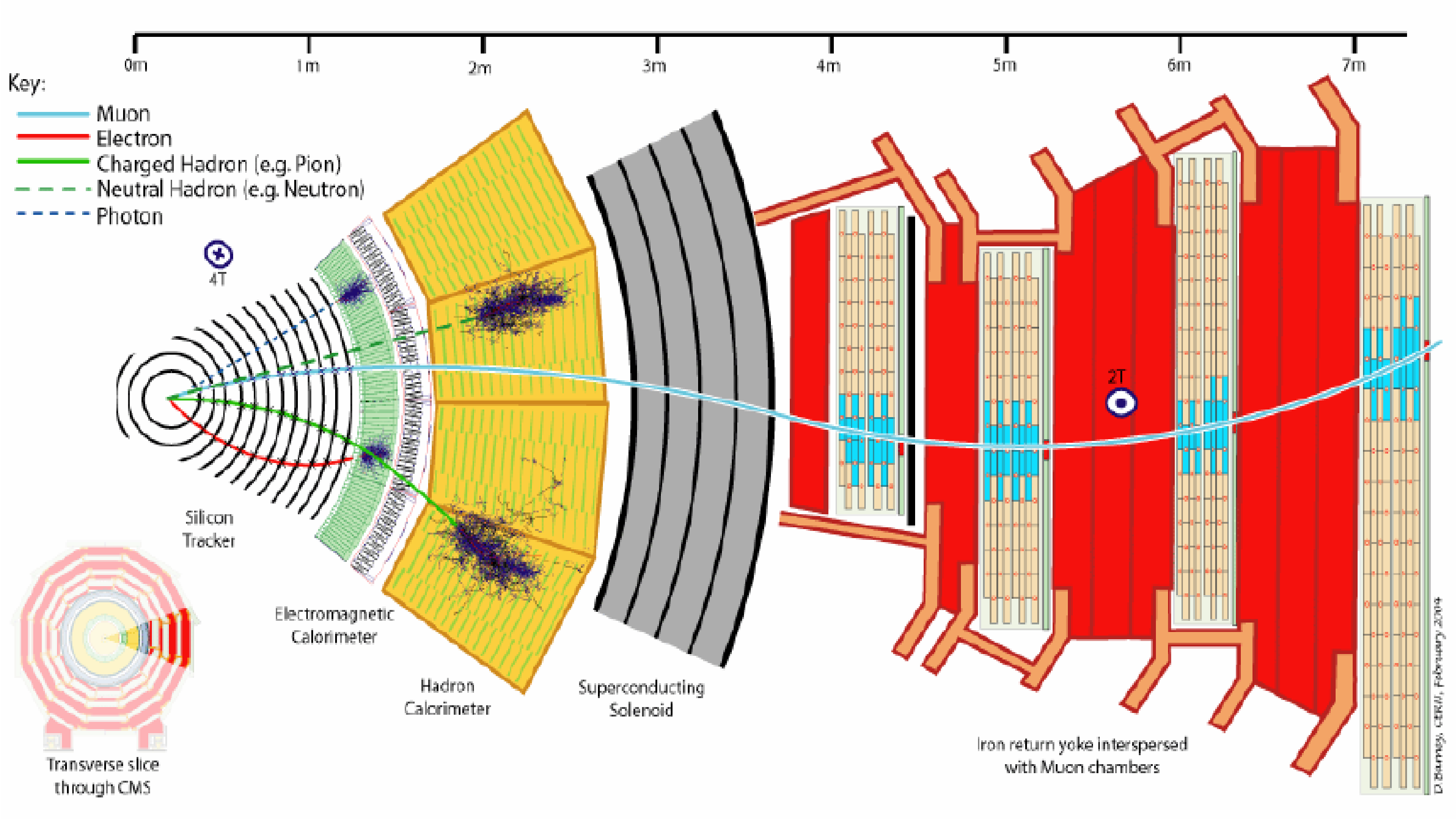


CMS Detector

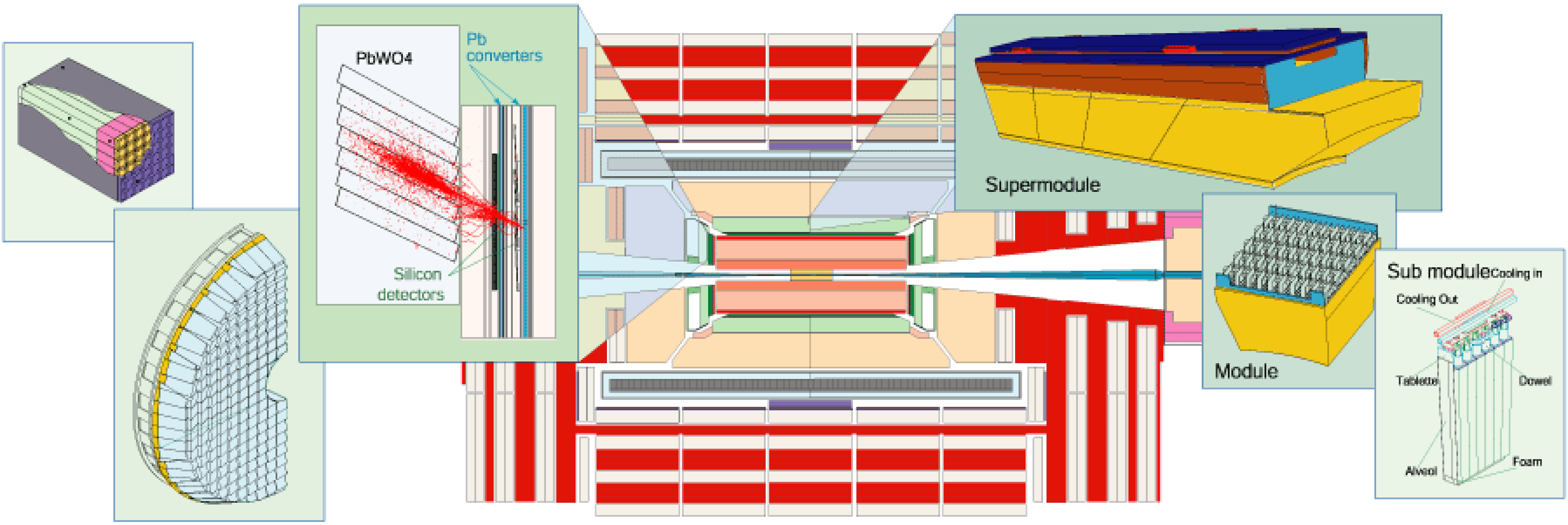


- Solenoidal magnetic field (4T) in inner tracking detector and in calorimeters.
  - Momentum measurement in ID
  - Muon measurement
- ID: High resolution semiconductor detectors: 9,7 Mio. channels, 210 m^2
- ECAL: Energy measurement in Lead –Tungstate crystals (excellent E-resolution for Photons)
- HCAL: Hermetic coverage to $|\eta|=5$

CMS Detector

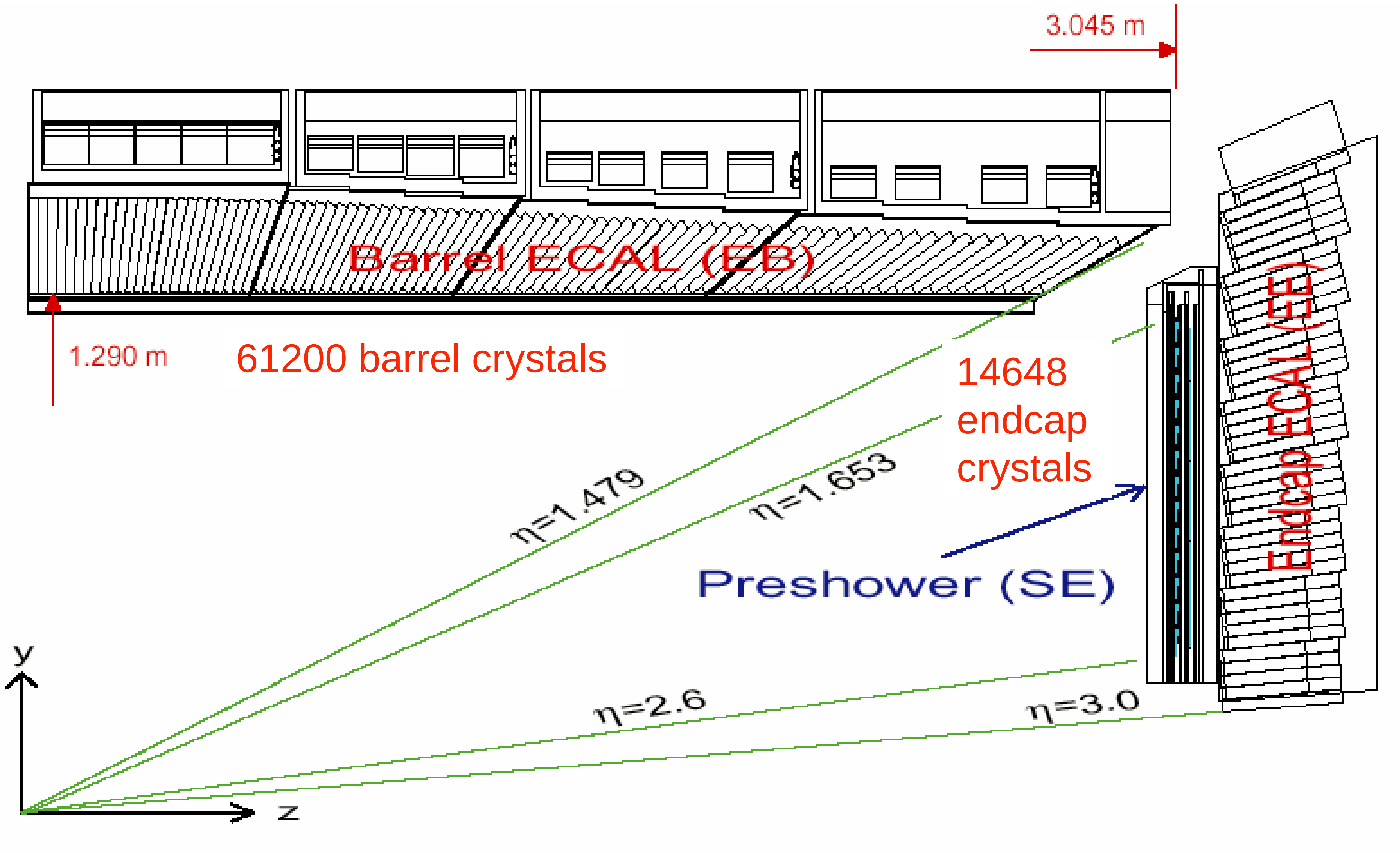


CMS E.m. Calorimeter: ECAL

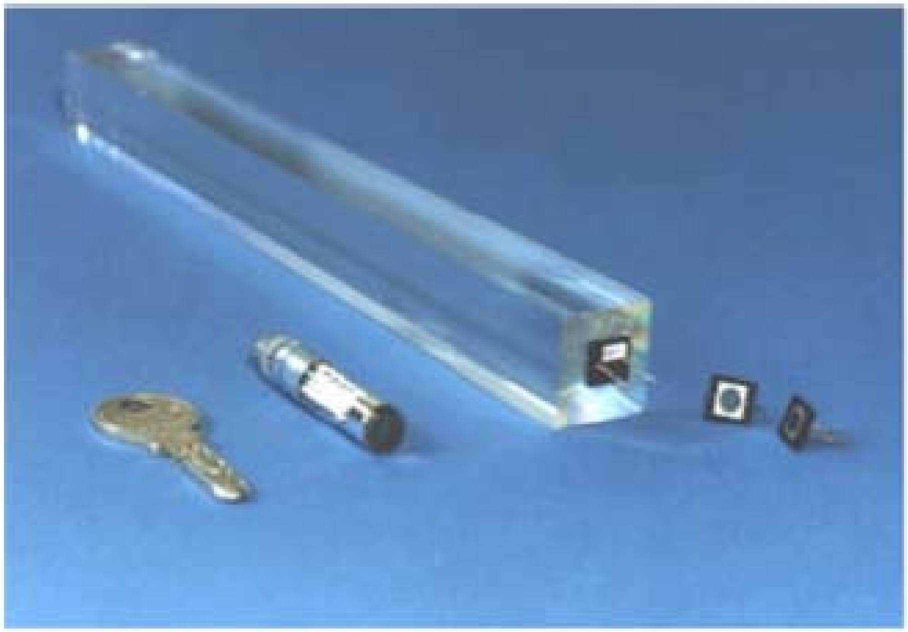


- **Principal design objective: Construct a very high performance e.m. calorimeter of scintillating crystal calorimeter ($PbWO_4$ lead-tungstate).**
- **Excellent e.m. energy resolution (stochastic term ~3%) since almost all of the energy of electrons and photons is deposited within the crystals.**
- **Lead tungstate crystals: high density, small Moliere radius, low X_0.**
- **High-resolution crystal calorimeter chosen to enhance the $H\rightarrow\gamma\gamma$ discovery potential at the initially lower luminosities at the LHC**

CMS ECAL


3.045 m
Barrel ECAL (EB)
1.290 m
61200 barrel crystals
14648 endcap crystals
Endcap ECAL (EE)
η=1.479
η=1.653
Preshower (SE)
η=2.6
η=3.0
y
z

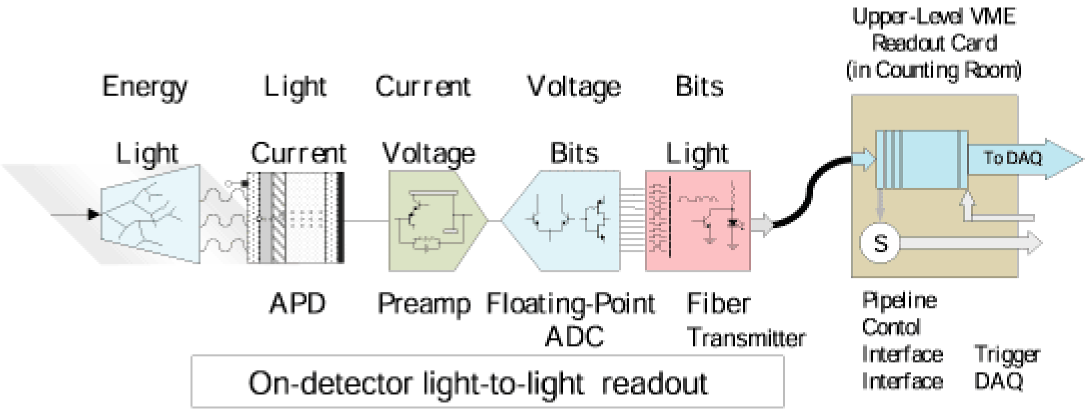
CMS ECAL $PbWO_4$ Crystals

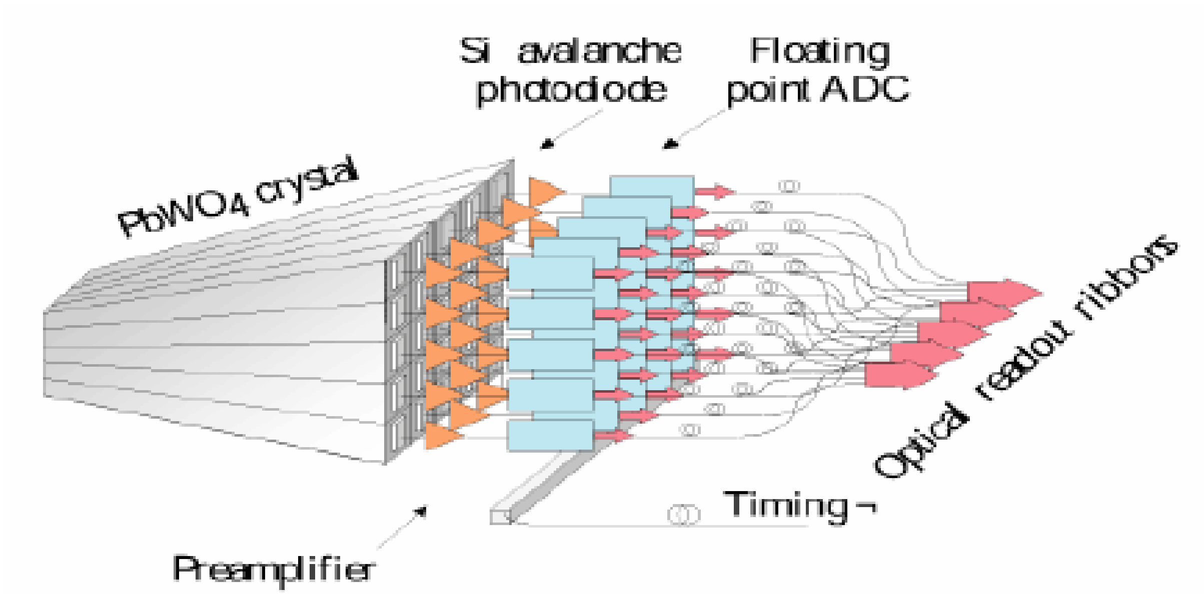


Properties of $PbWO_4$

- **Fast scintillating material**
- **High density and small radiation length**
  - **In CMS 26 X_0 = 23 cm**
- **Small Moliere radius**
- **Radiation hard**

CMS ECAL Readout



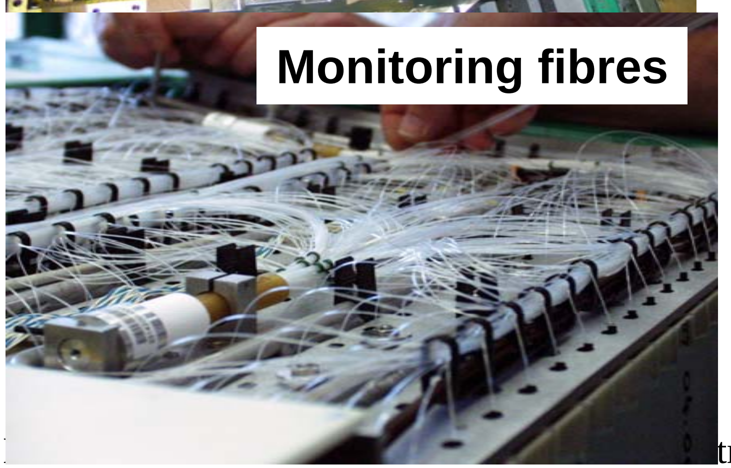


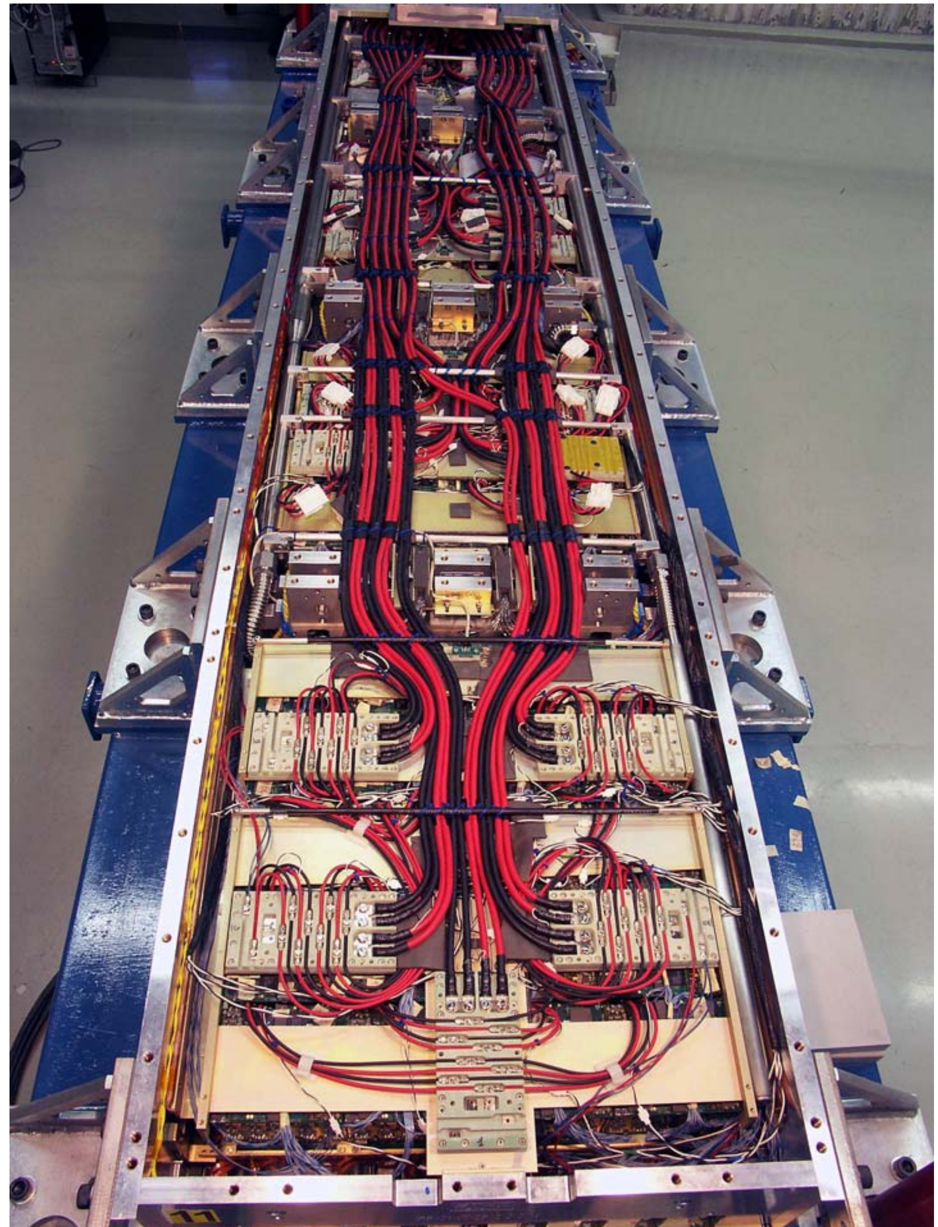
To avoid the design and construction of a very large quantity of radiation-hard electronics, the data are transported from the on-detector electronics immediately after the digitization step, to the counting room by fiberoptic links.

CMS ECAL Status

- **Crystals**
  49000 barrel crystals (80%) delivered
- **Bare Supermodules**
  25 (out of 36) bare SMs assembled.
- **Photodetectors** :
  All 130k APDs and 11000 VPTs (~70%) delivered
- **Electronics** :
  Most on-board electronics in-hand, Off-detector electronics in good shape.
- **'Dressed' Supermodules (equipped with electronics, cabling)**
  - **Good results from first fully 'dressed' SM in Oct-04 Beam test.**
  - **7 (out of 36) SMs dressed**
  - **3 dressing lines operational. 3 SMs being dressed now.**
  - **Finalize 1 SM/week.**
- **SM installation in several phases**
  One half (18 SM) in Aug-06, several in Oct-06, completion in May-07.
- **Concern**
  Crystals: delivery defines ECAL critical path.

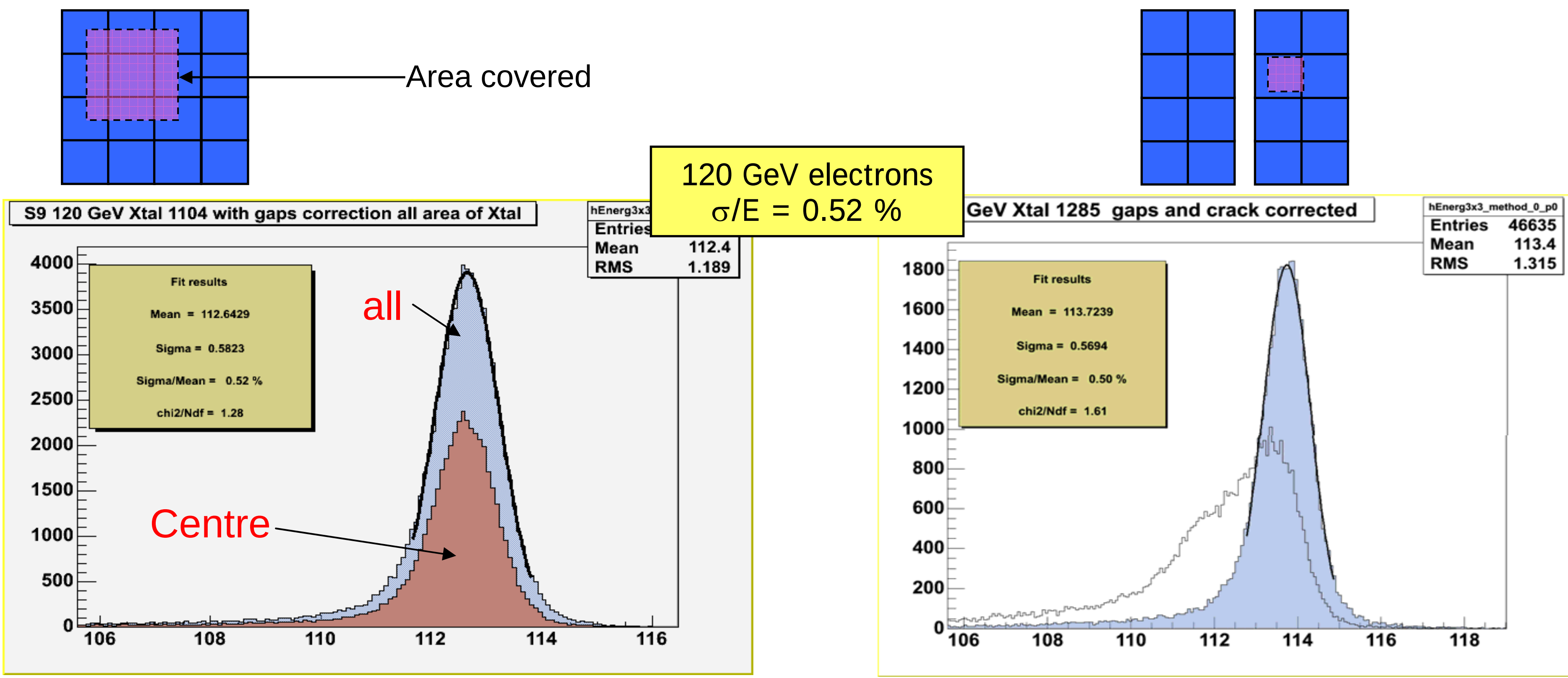
CMS ECAL Supermodule Assembly





CMS ECAL: Energy resolution over large areas

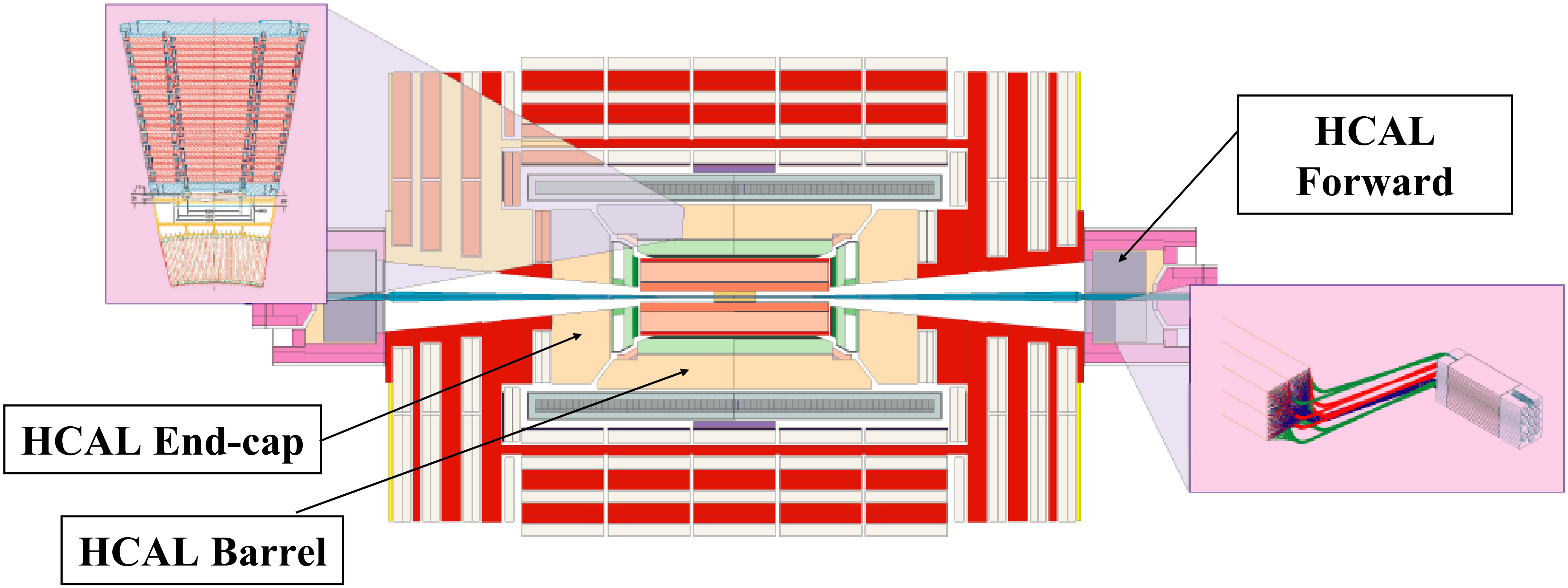
- Corrections for “local containment” (not hitting the crystals in the middle) work as well as previous results and Monte-Carlo studies suggest
- Also corrections for losses close to 6 mm inter-module voids



CMS ECAL: Inter-Calibration of Crystals

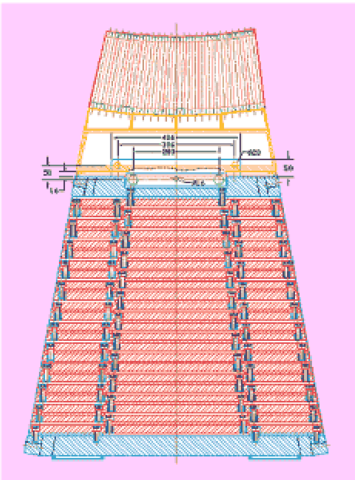
- **Inter-Calibration known to 4.4% from laboratory measurements (Light Yield, Light Transmission, APD response)**
- **Target precision (~0.5%) makes the job hard, not just quantitatively but qualitatively**
  - **More and more effects become no longer negligible as the target precision is increased**
- **Essential issue is inter-calibration**
  - **In both time and space: energy reconstructed at $\eta = 0.5$ last Tuesday, must give the same response as energy reconstructed $\eta = -1.3$ next Friday**
- **During inter-calibrate with physics events everything must remain constant (or be corrected by independent measurement) $\Rightarrow$ laser monitoring**
  - **So it must not take too long. Target: couple of months (one year ?)**

CMS Hadronic Calorimeter System HCAL

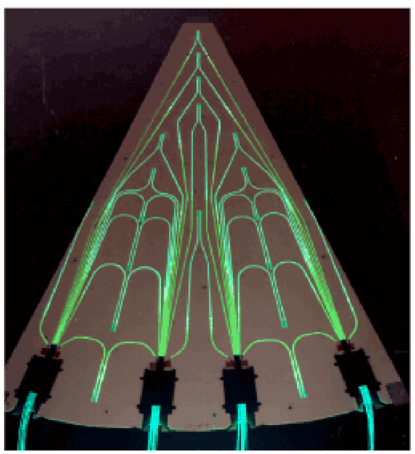


- Hadronic barrel and end-cap calorimeters are sampling calorimeters with 50 mm thick copper absorber plates interleaved with 4 mm thick scintillator sheets.
- Forward calorimeters are sampling calorimeters with steel absorbers and scintillating fibers for read-out.

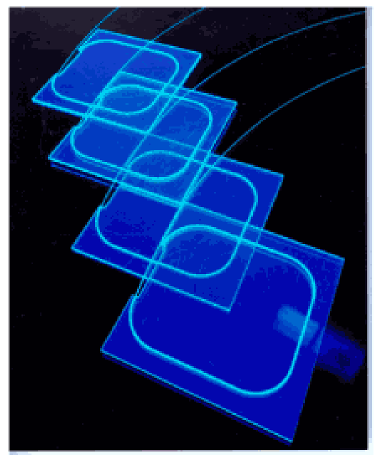
CMS HCAL Barrel / End-cap



- Copper as absorber material because of density.
- Barrel HCAL constructed of two half-barrels each of 4.3 m length.
- End-cap HCAL consist of two large structures at each end of the barrel within the region of high magnetic field.
- Barrel HCAL inside the coil not sufficiently thick, additional scintillation layers placed just outside the magnet coil.
- Full depth of the combined barrel detectors ~11 λ.



- Megatiles large sheets of plastic scintillator
- Subdivided into tiles of size $\Delta\eta \times \Delta\phi = 0.87 \times 0.87$
- Scintillation signals from megatiles detected using waveshifting fibers.
- Fibre diameter ~1 mm.



- Light emission from tiles in the blue-violet (410-425 nm).
- Light wavelength shifted via fibers to green (490 nm).
- Green light transported via clear fiber waveguides to connectors at the ends of the megatiles.

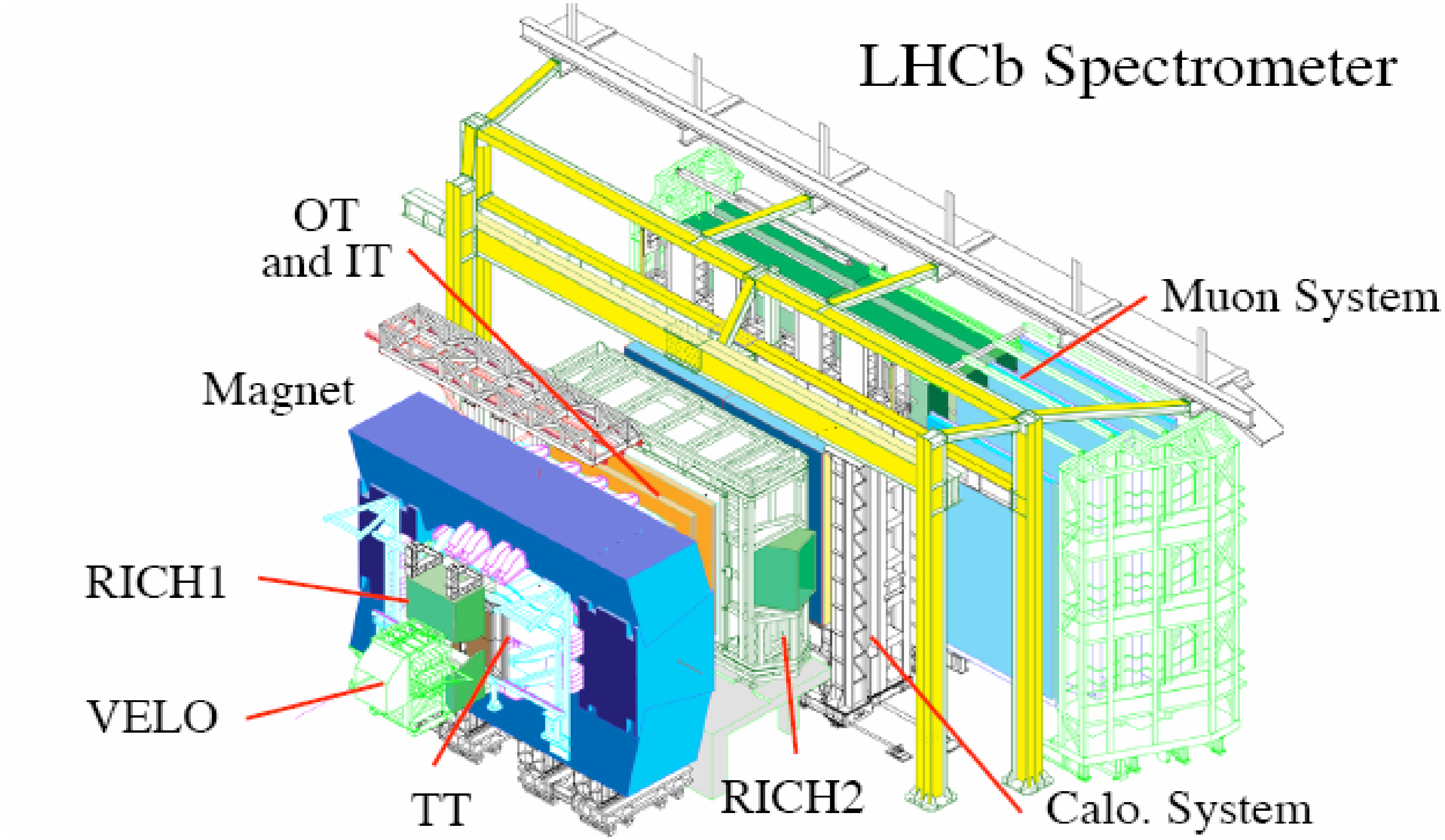
CMS HCAL Forward

HF in Bat. 186: Start 'burn-in' of both HF in mid-2005
The two HF are the first elements to be lowered into UX

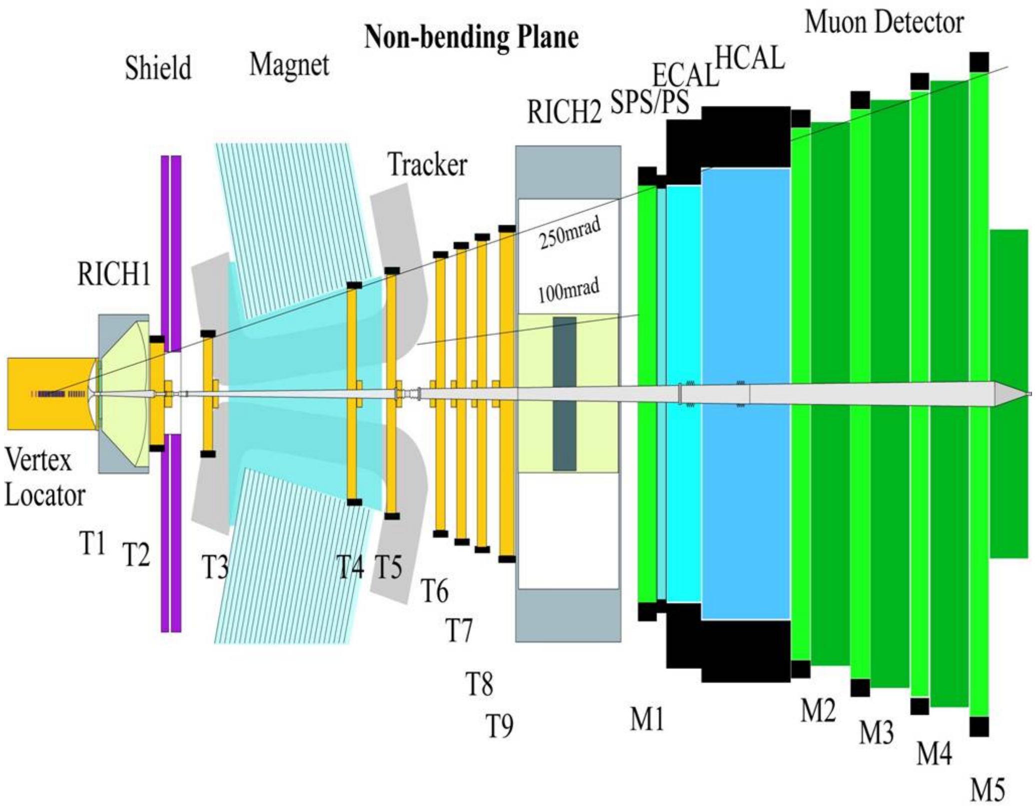
CMS HCAL Status

- **Assembly and Installation**
  - **Absorbers and optics of all HCAL complete. 2nd HF being mounted.**
- **Electronics :**
  - **Almost all HPDs and HF_PMTs delivered.**
  - **Installation of readout boxes in progress.**
  - **Off-detector: Expect to produce and burn-in all 270 HTR cards by end of summer.**
- **Source Inter-calibration**
  - **Carrying out HB, HE and HF inter-calibrations in 2005/06 before lowering into UX5**
- **Test Beam 2004**
  - **Results using low energy beam have been used to tune G4 simulation.**
  - **Need Test beam in 2006 to carry out combined final ECAL+HCAL measurements**

LHCb Detector



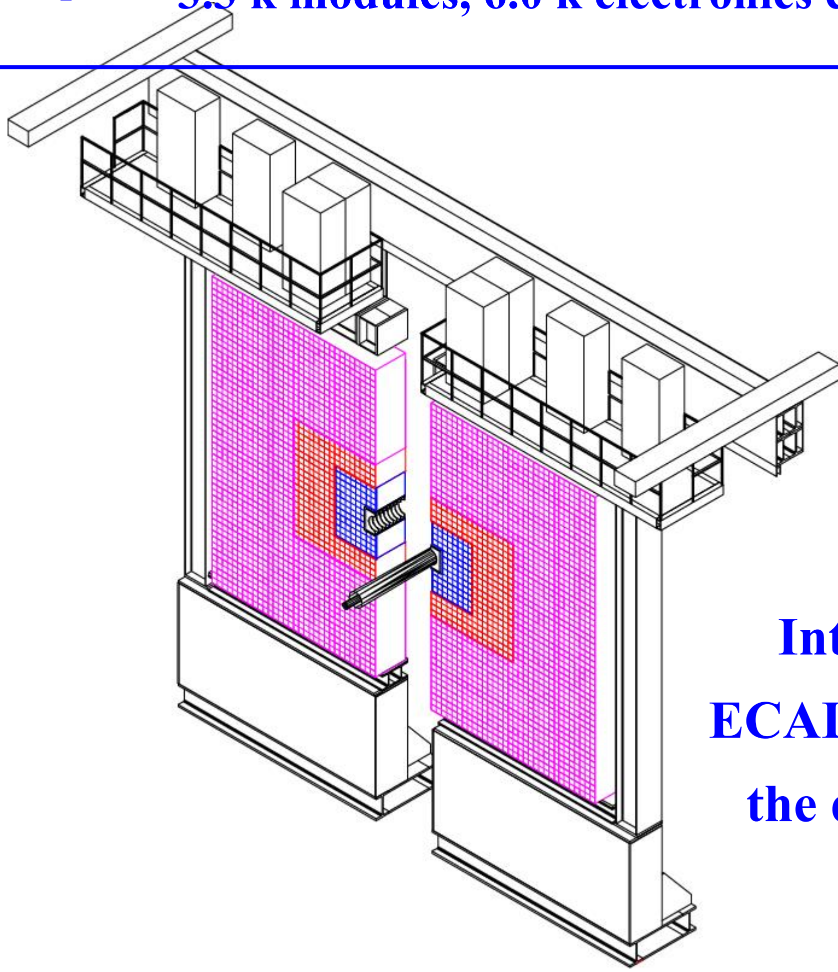
LHCb Detector



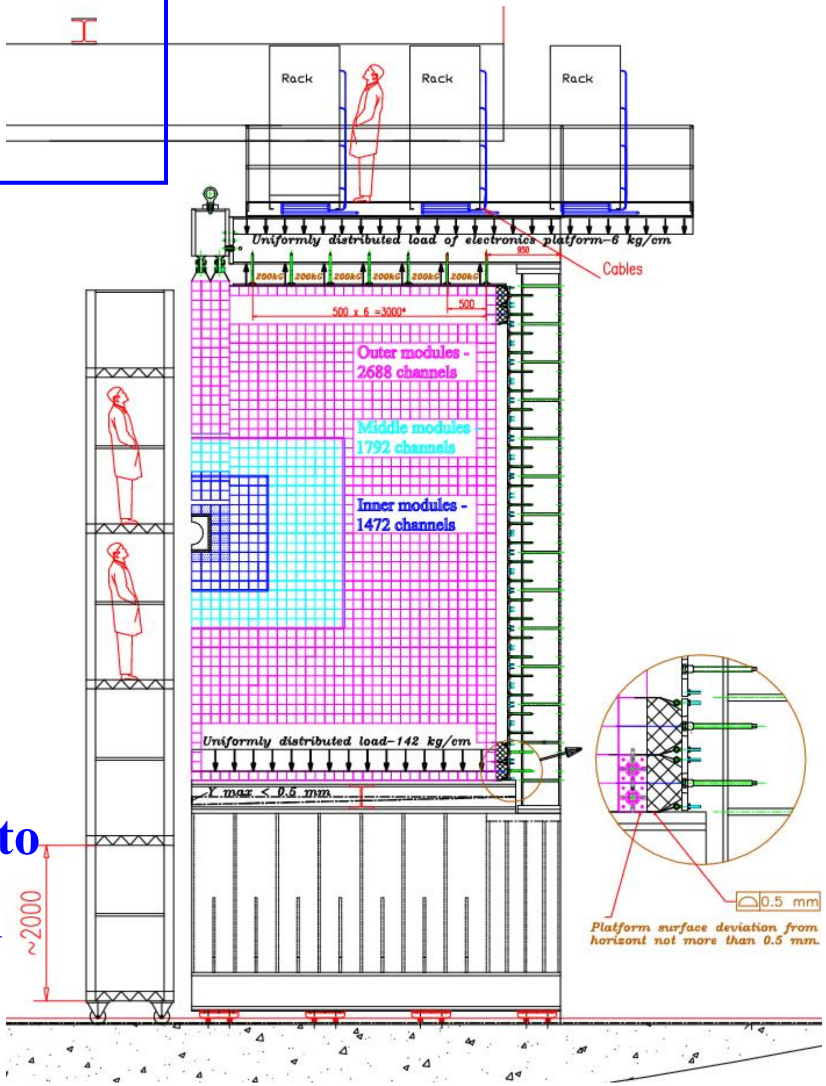
- **Experiment to investigate**
  CP-violationin B-Meson system
- **High event rates expected:**
  10^{12} bb-pairs / year @ L =10^{32}
- **Important precision measurements**

LHCb ECAL

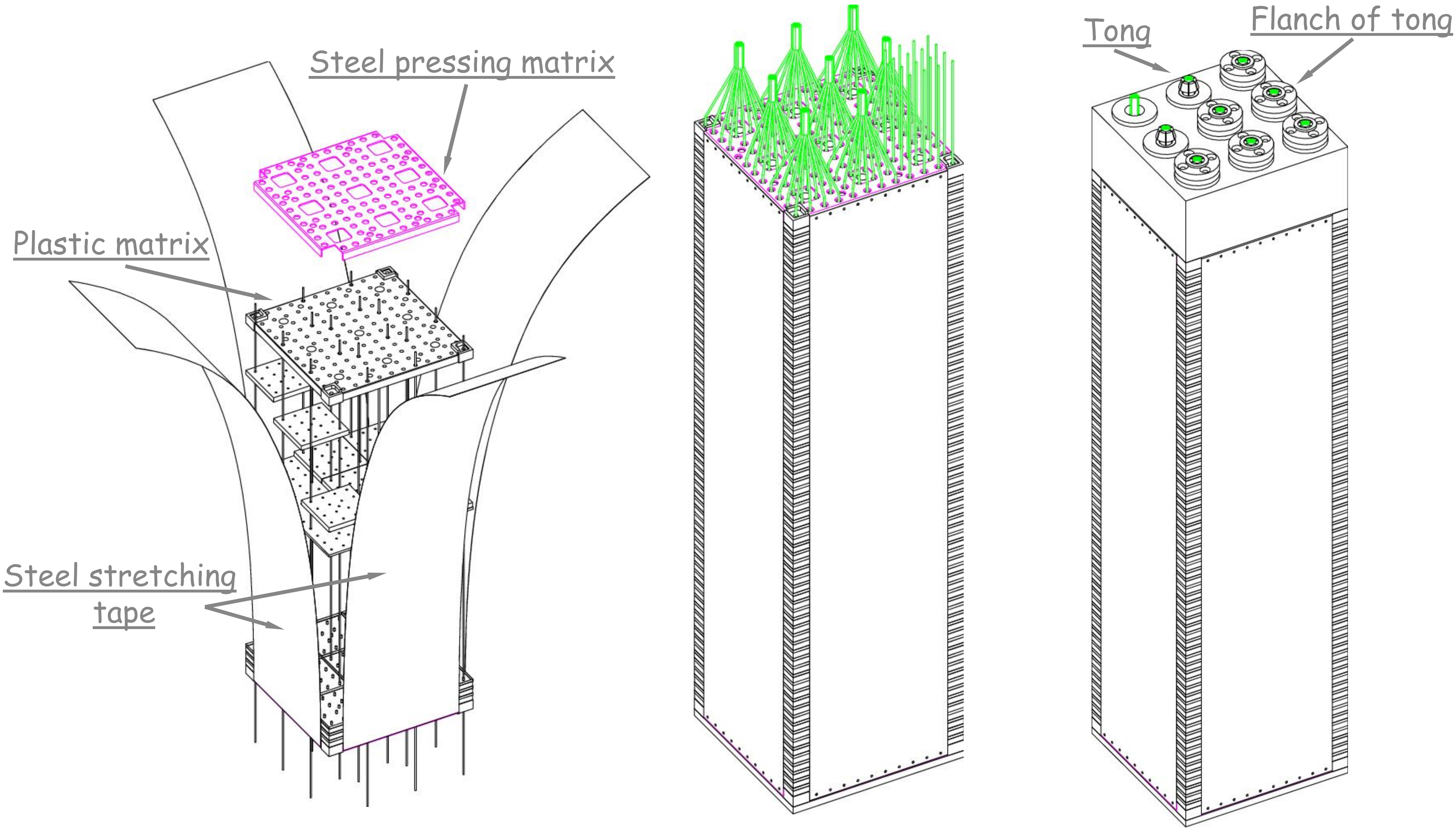
- Shashlik type technology
- 3 regions with different cell size
- 3.3 k modules, 6.0 k electronics channels



Integration of ECAL modules into the detector wall

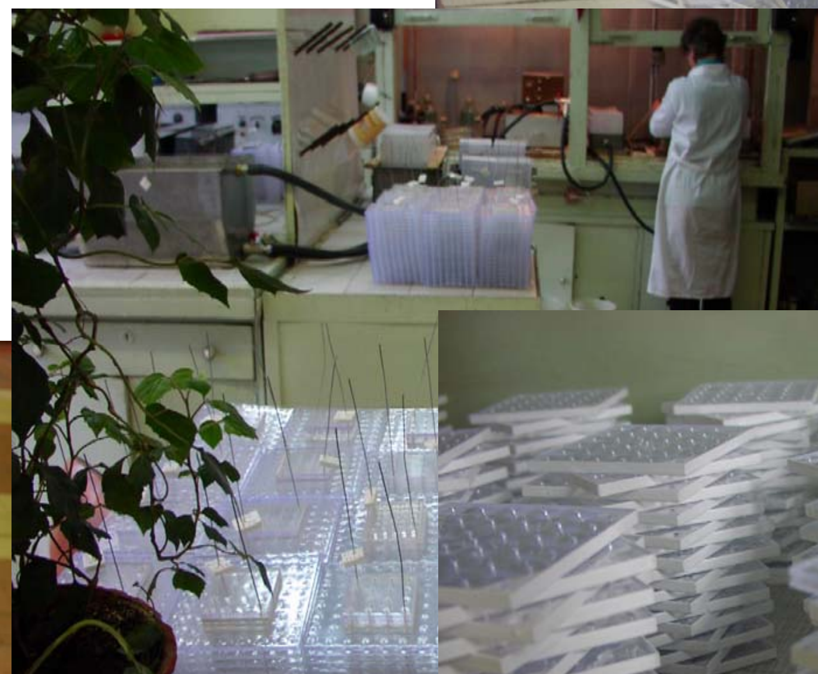


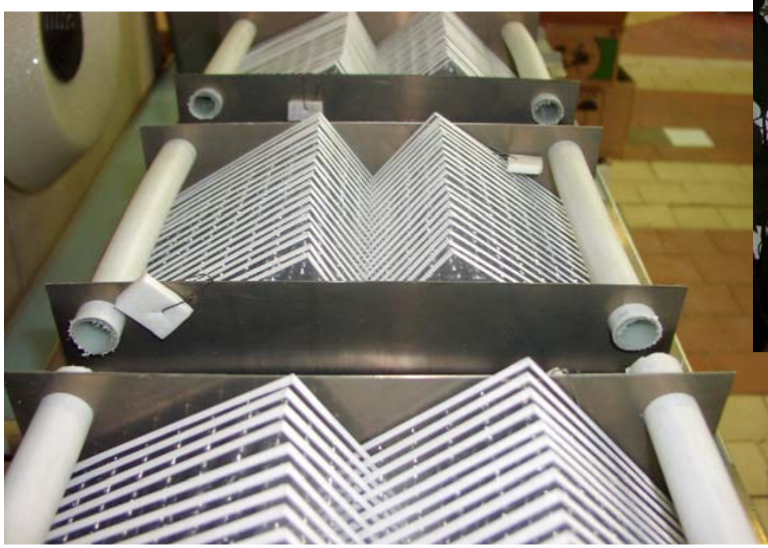
LHCb ECAL: Stack assembly



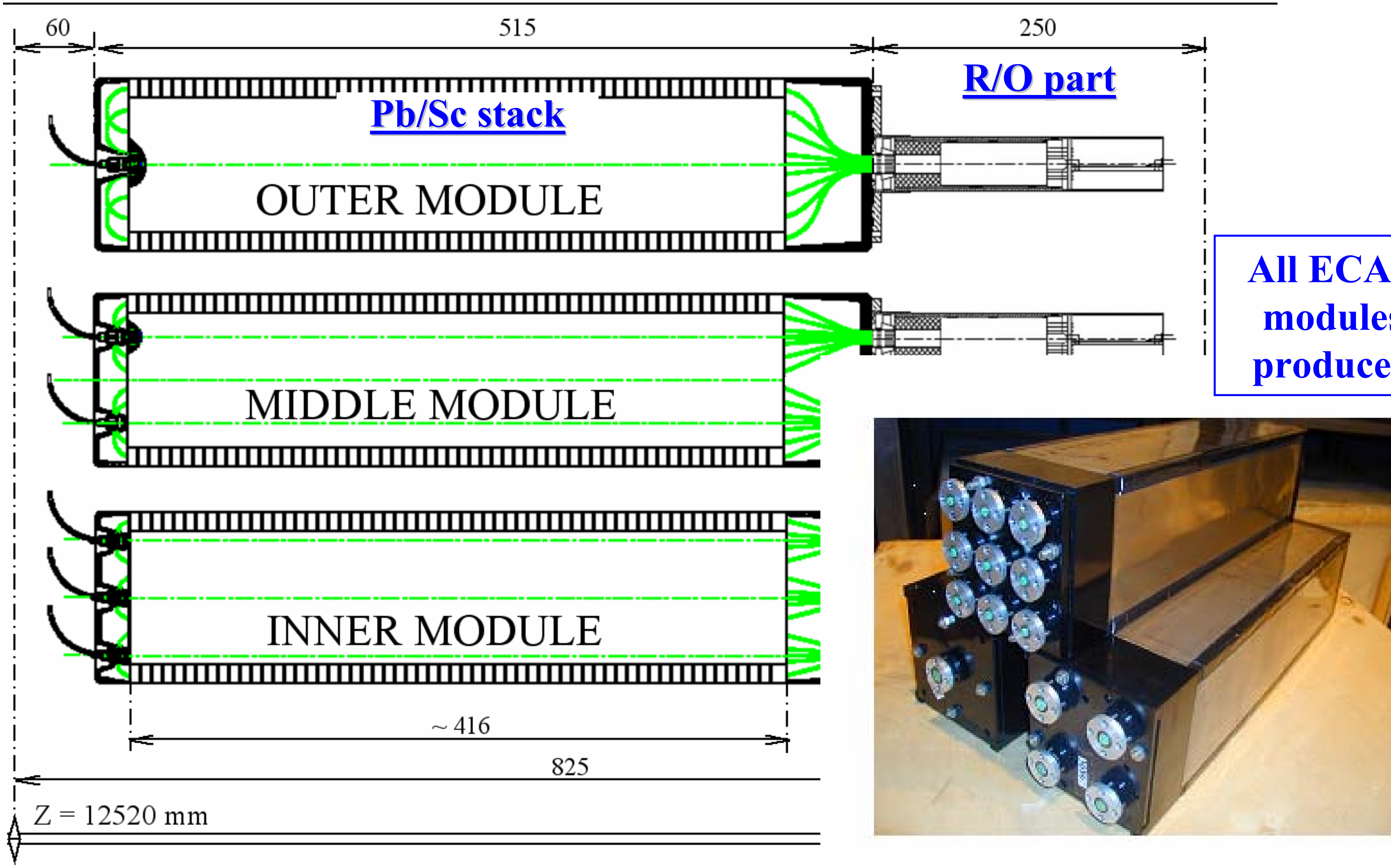
LHCb ECAL Module: Tile Production

- Tiles are produced with injection moulding technique under high pressure
- Chemical treatment of tile edges
- Light reflection from tile edges ~90%
- In total 450 K tiles produced
- Production rate up to 800 tiles
- with treated edges /day
- Tile-to-tile spread: r.m.s.<2.5%



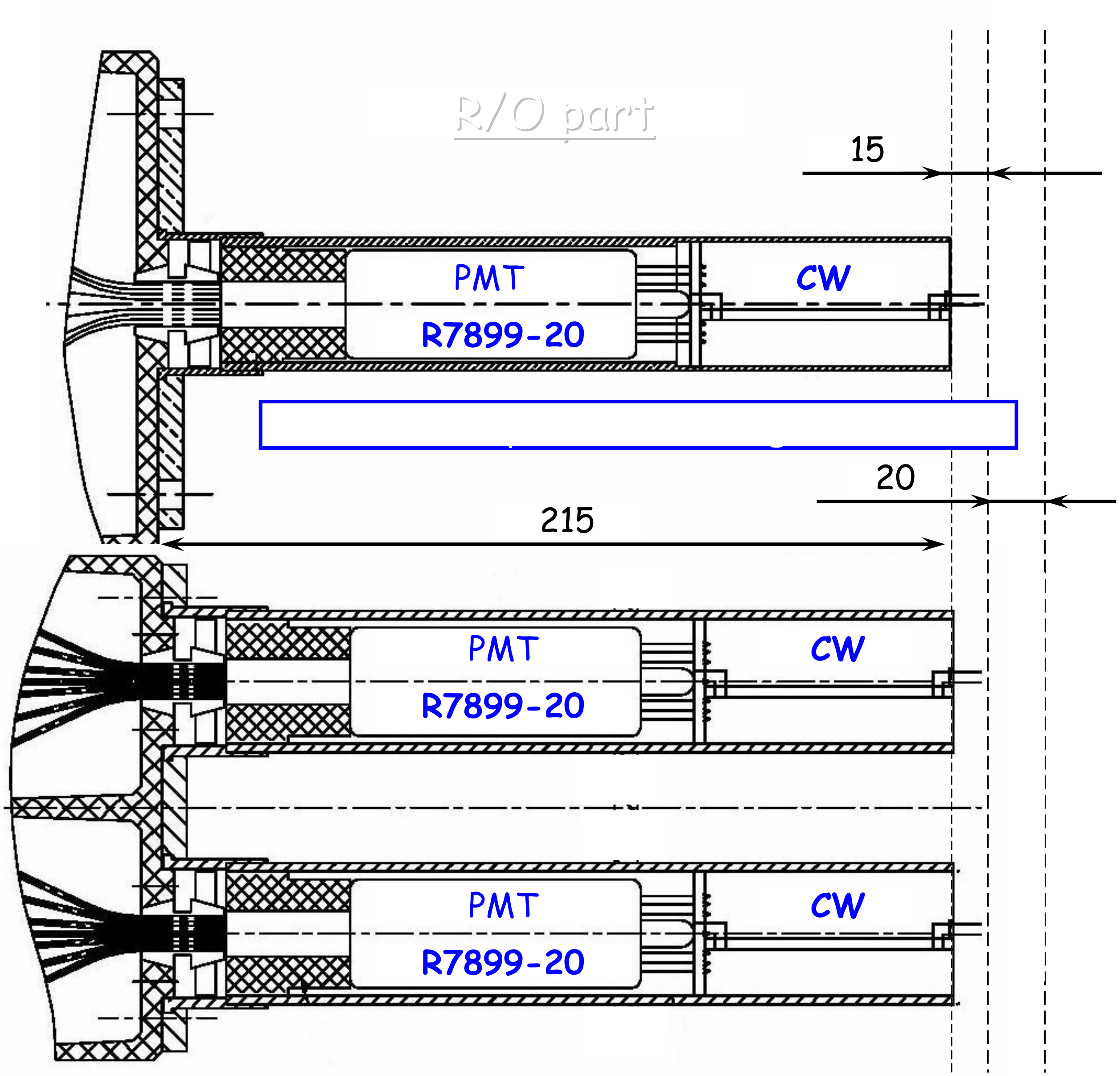


LHCb ECAL Module



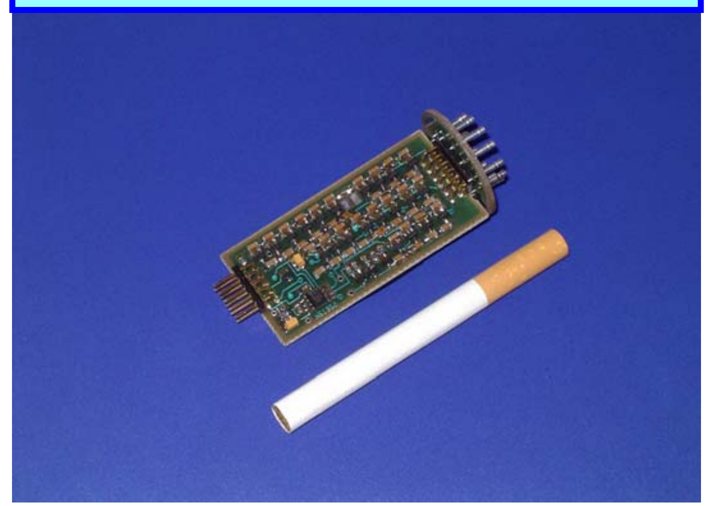
All ECAL modules produced

LHCb ECAL Module: Read-out Part



PMT R7899-20

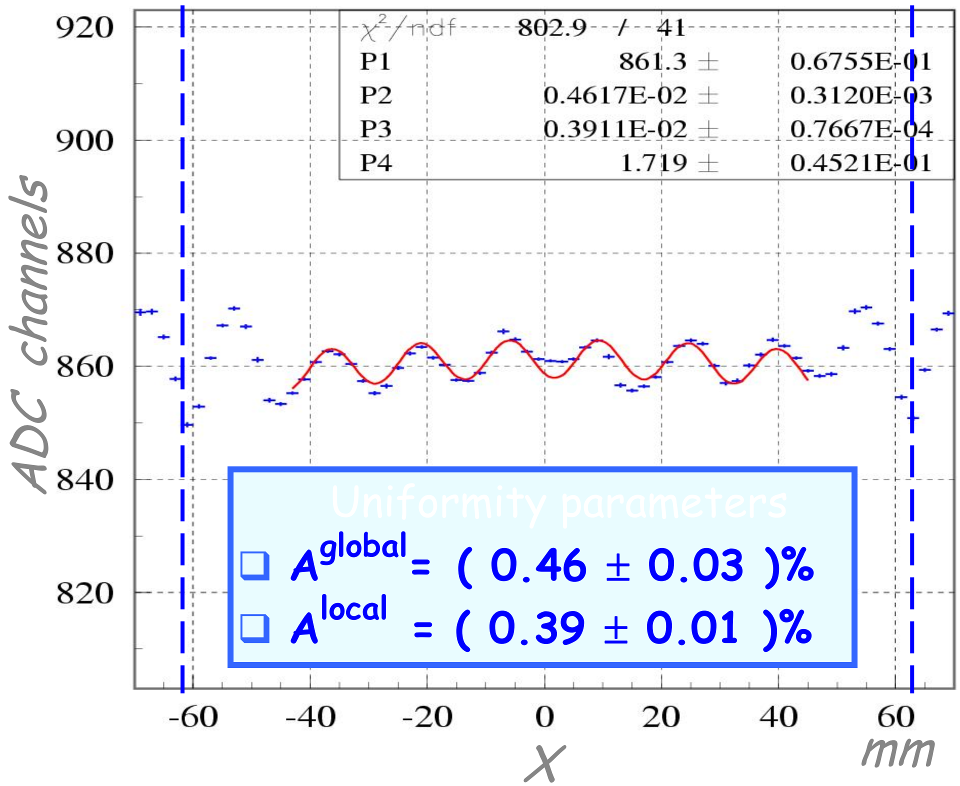
Base: Cockcroft-Walton multiplier



LHCb ECAL: Module Performance

Uniformity

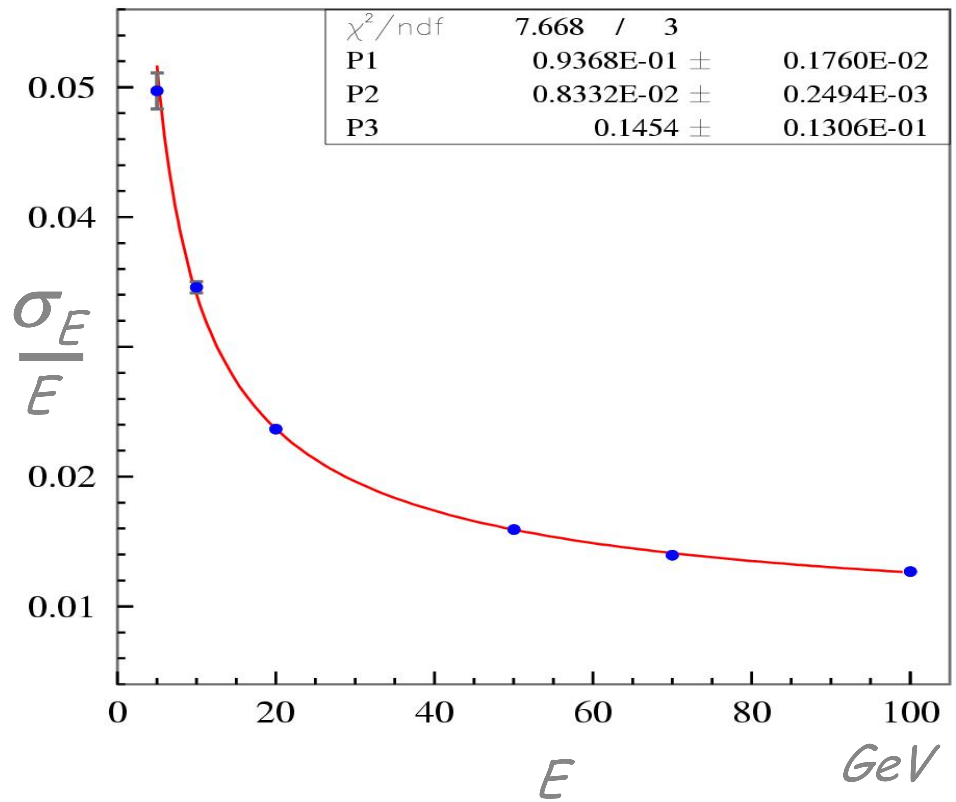
Transversal scan of ECAL module with 50 *GeV* e^- beam



- ±1.3% for perpendicular e-beam
- ±0.6% for e-beam at 200 mrad

Energy resolution

ECAL module energy resolution: e^- beam



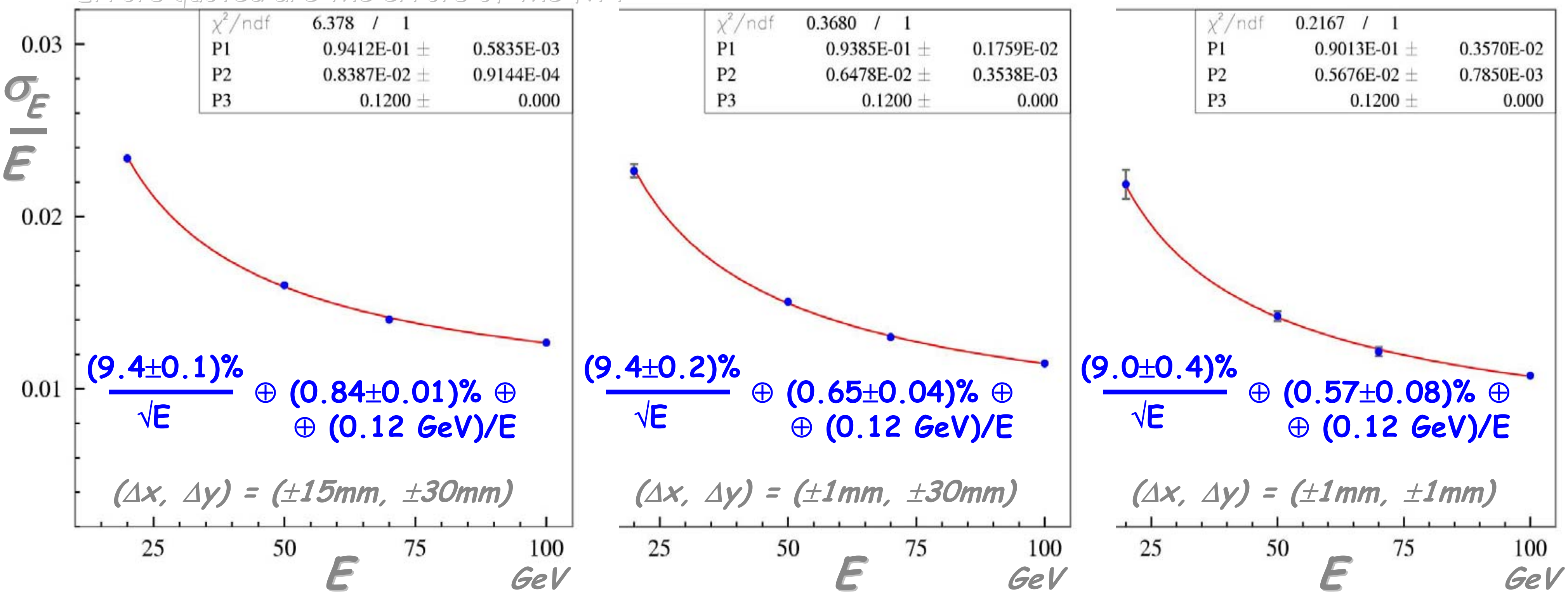
Required energy resolution: $\frac{10\%}{\sqrt{E}} \oplus 1\%$

LHCb ECAL: Module Performance

Energy resolution: constant term

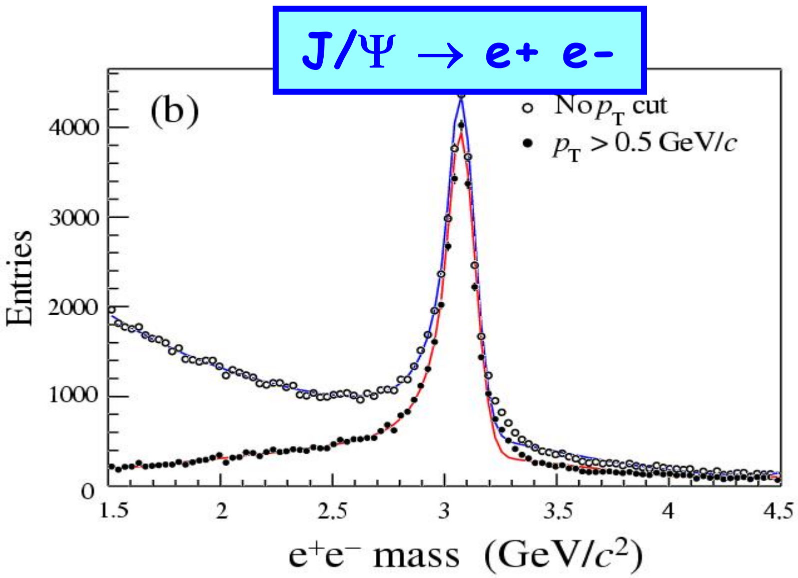
Contribution from the lateral non-uniformity

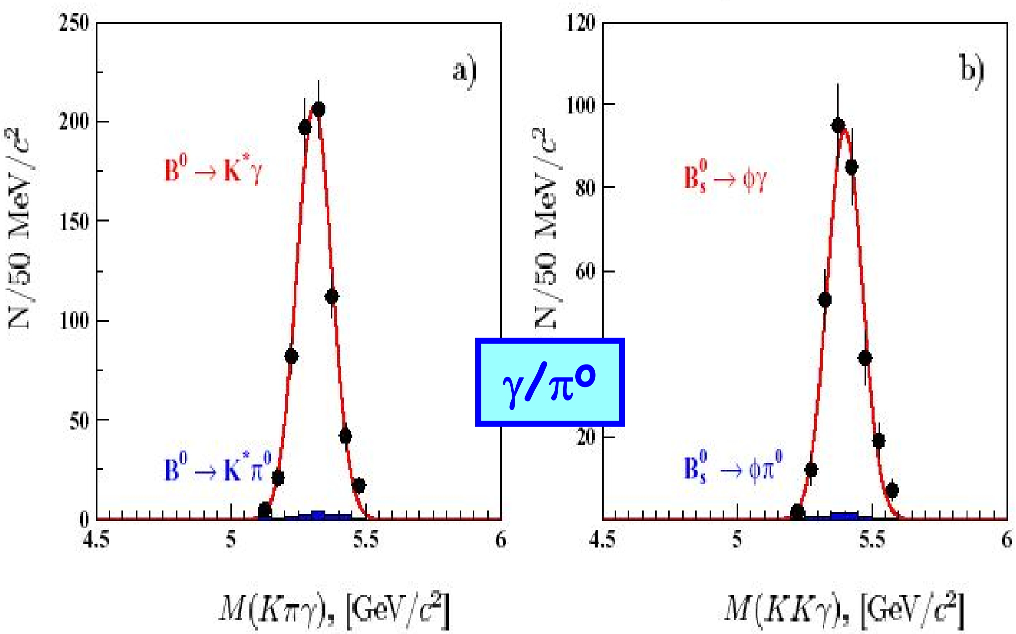
Errors quoted are the errors of the fit !

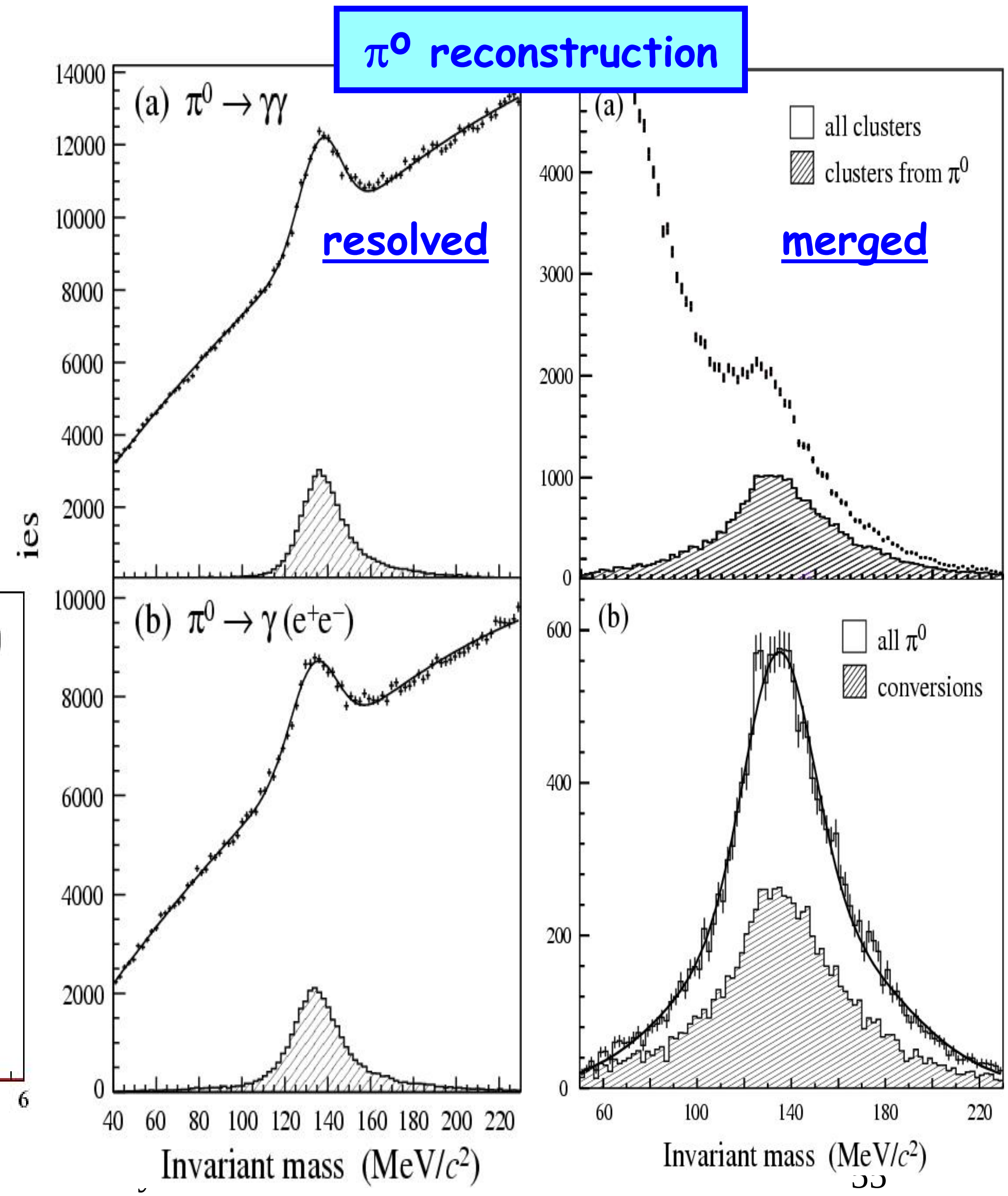


~Half of the constant term value comes from lateral non-uniformity of response

LHCb ECAL: Physics





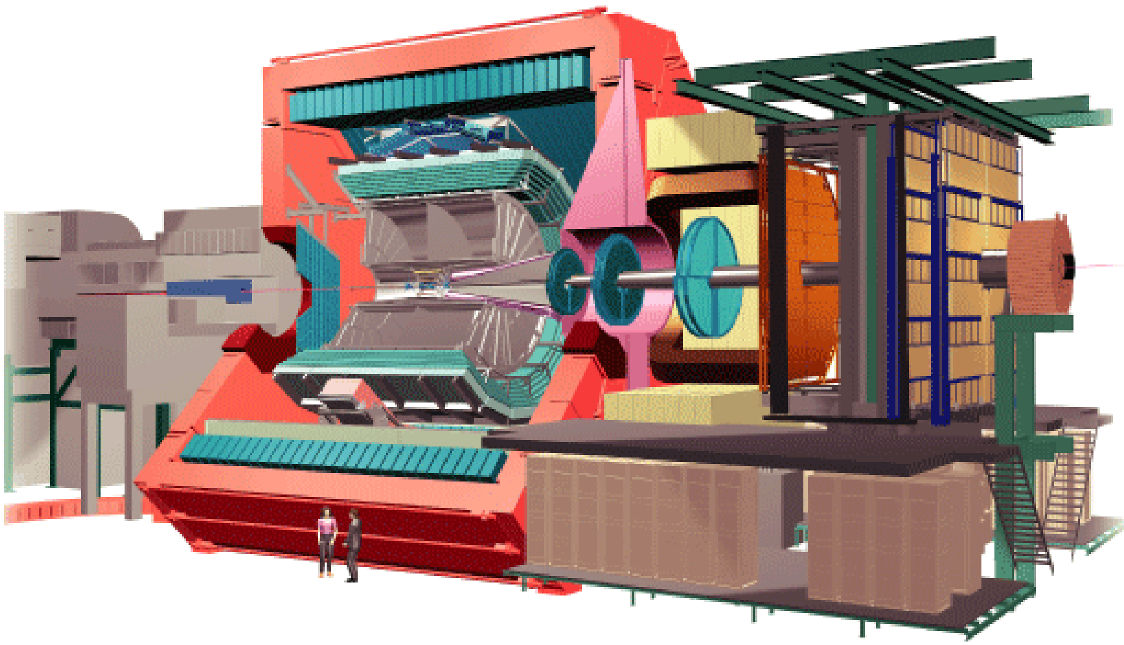


LHCb Calorimeter Installation in IP8

E-cal

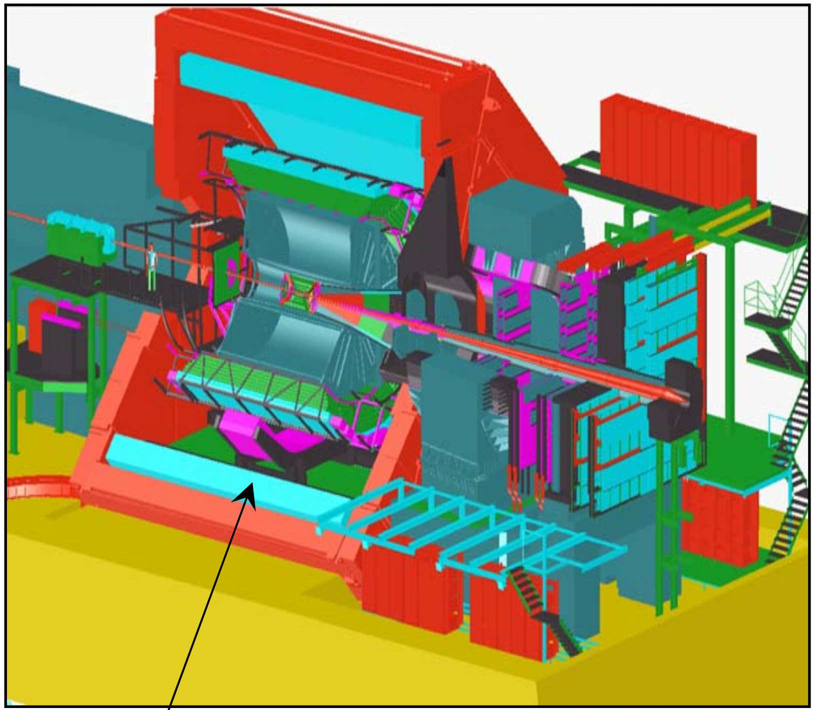
H-cal

ALICE



- **The ALICE Collaboration is building a dedicated heavy-ion detector to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies.**
- **Aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.**

ALICE PHOS



PHOS (PHOton Spectrometer) is a high resolution electromagnetic calorimeter consisting of 17920 detection channels based on lead-tungstate crystals(PWO).

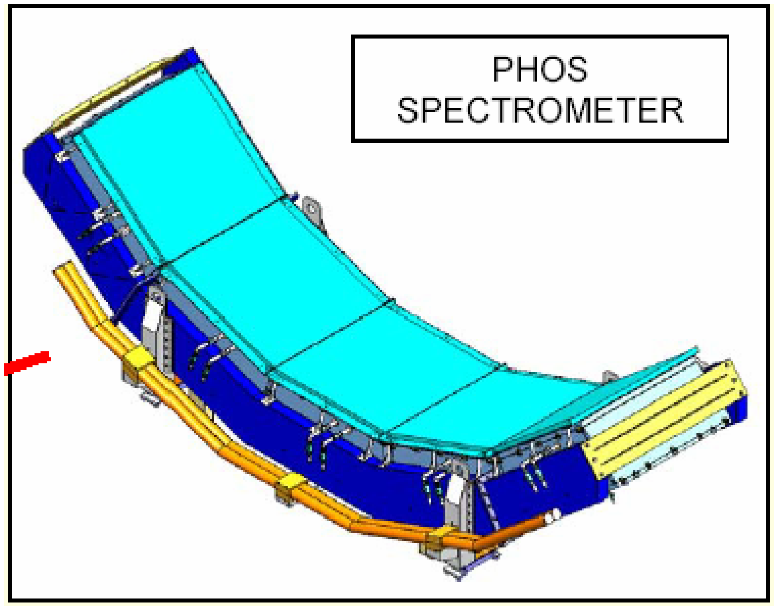
PHOS tasks to investigate:

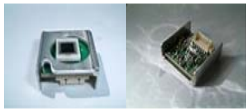
- Initial phase of collision of heavy nuclei via direct single photons and diphotons,
- Jet-quenching as probe of deconfinement, studied via high p_T γ and π^0,
- Signals of chiral-symmetry restoration.

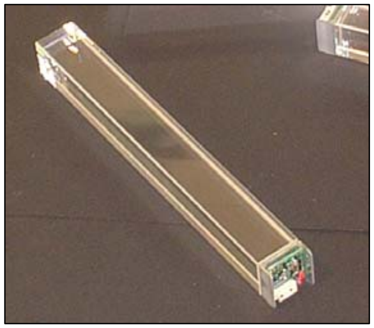
PHOS technical data:

- 17920 lead-tungstate crystals
- distance to IP 4400 mm
- coverage in η -0.12;+0.12
- coverage in azimuth 100°
- crystal size 22x22x180 mm^3
- depth in radiation length 20
- modularity 5 modules
- total area $8m^2$
- total crystal weight 12.5 t
- operating temperature -25 °C
- photoreadout APD

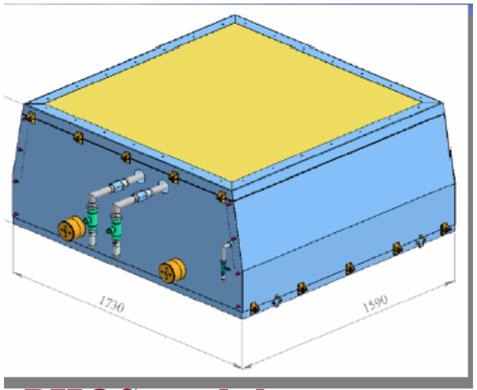
ALICE PHOS



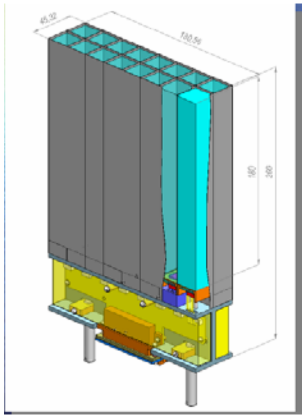




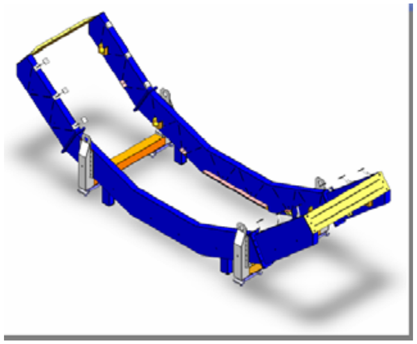
Crystal detector unit



PHOS module
Working temperature: -25 °C



Strip unit of 16 detector units



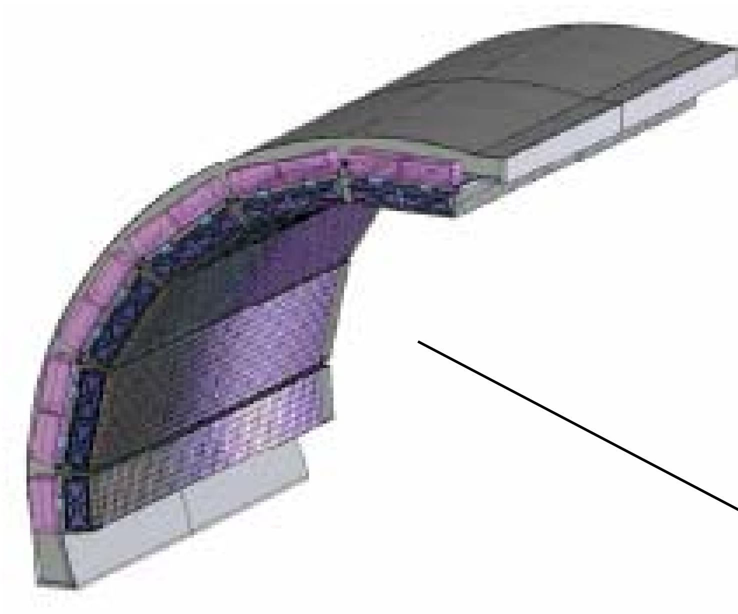
PHOS Cradle

Modular structure

➢ **5 independent *modules* each of 3584 *crystal detector units:***

✓ ***PWO crystal+ APD+ preamp.***

ALICE EMCal



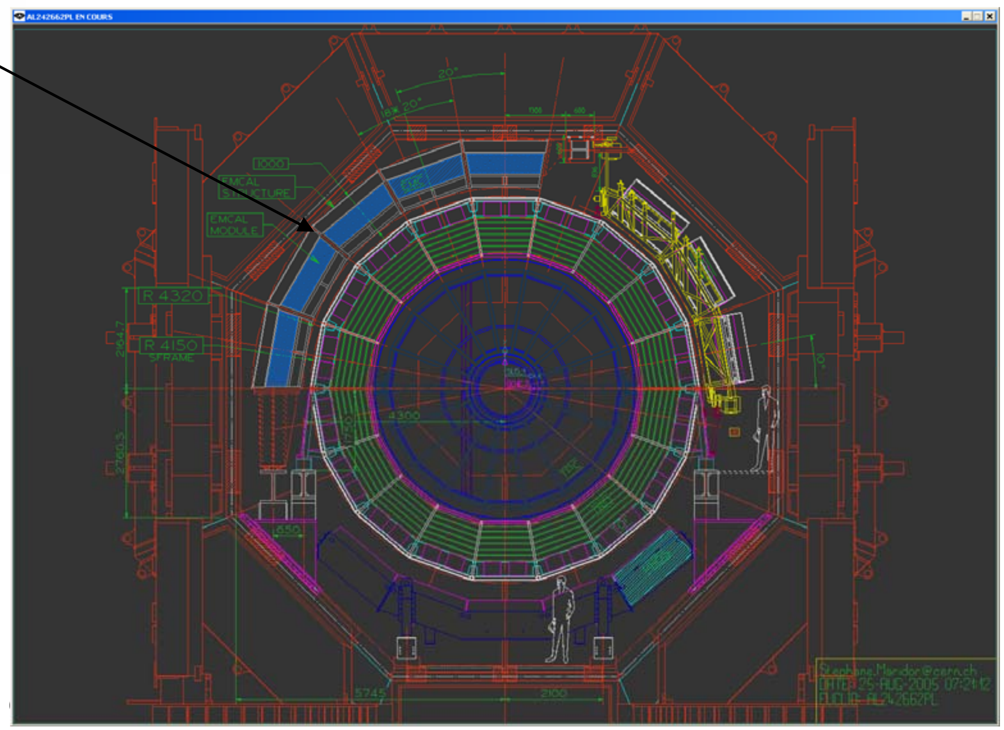
Lead-scintillator sampling calorimeter

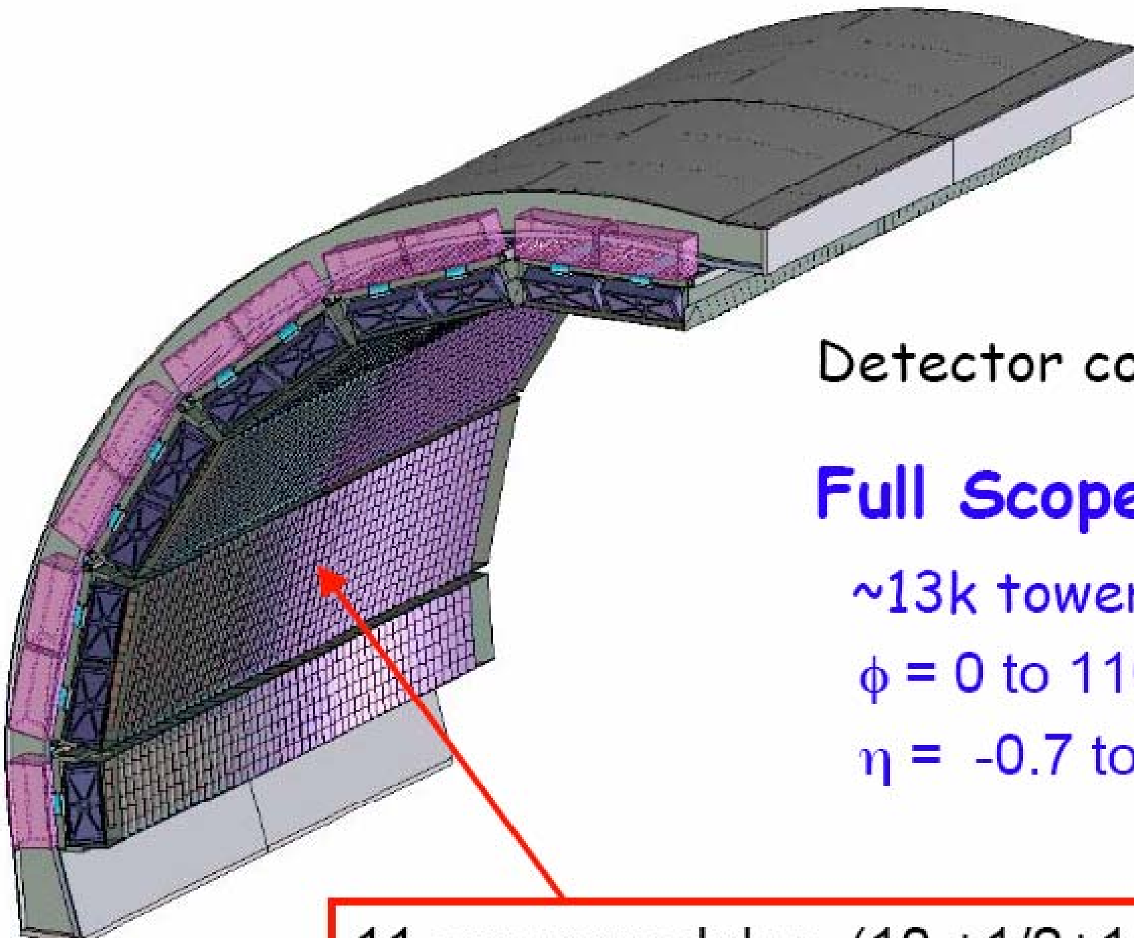
$|\eta|<0.7$, $\Delta\phi=110^o$

Shashlik geometry, APD photosensor

PHOS Readout electronics

~13K towers ($\Delta\eta x \Delta\phi \sim 0.014x0.014$)





11 super modules (10 +1/2+1/2)

Detector concept defined

Full Scope:

~13k towers

ϕ = 0 to 110°

η = -0.7 to 0.7

LHC Start-up for Physics

I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

IV. 25ns operation II
- Push towards nominal performance

CONCLUSIONS ON LHC CALORIMETERS

- **LHC calorimeters are designed to cover a wide range of novel physics searches.**
- **They employ sophisticated, mature as well as newly developped techniques.**
- **Radiation hardness sets high requirements.**
- **Quality control during production is a must. It has rigorously been implemented in most cases, e.g. failure rates in the final calorimeters of ~0.1 % have been achieved.**
- **LHC collaborations try to have calorimeters ready for the start-up of the LHC machine in 2007.**
- **In some cases the efforts will have to be increased to cope with this deadline.**