ATLAS Calorimetry at the Large Hadron Collider

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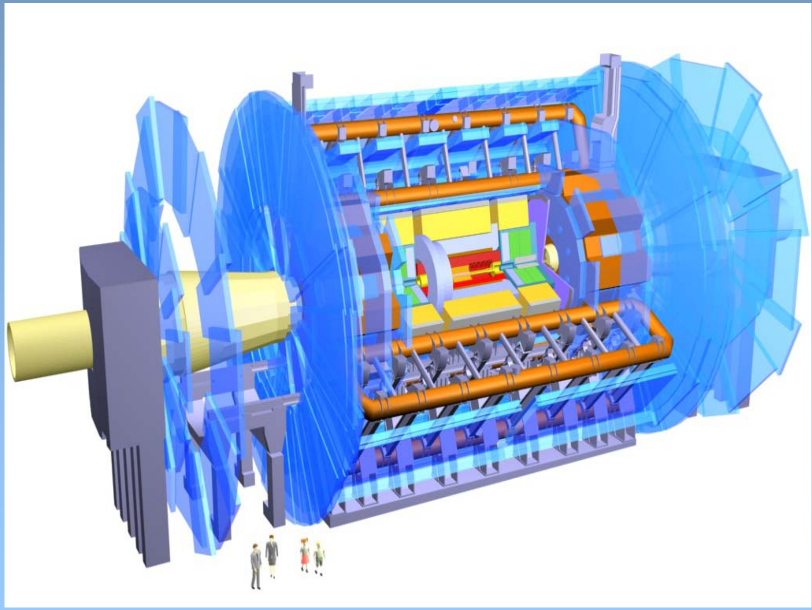
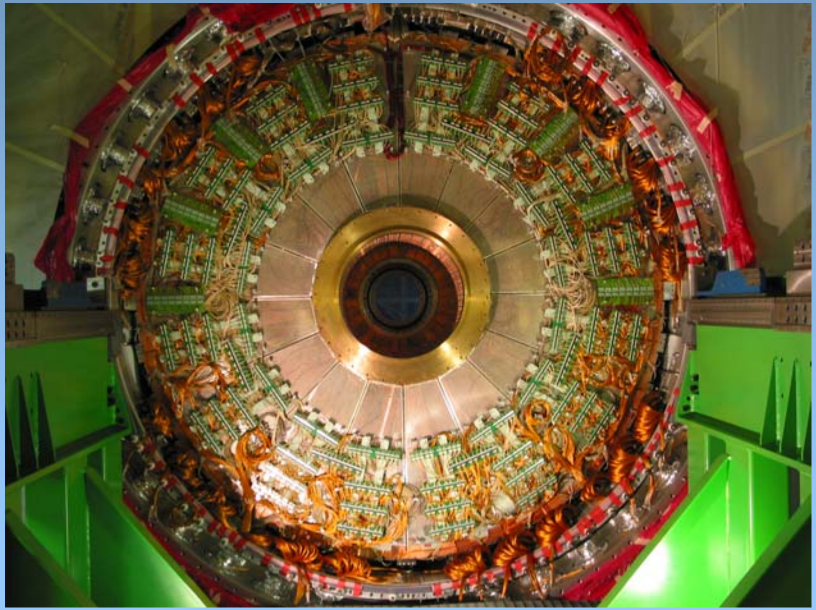
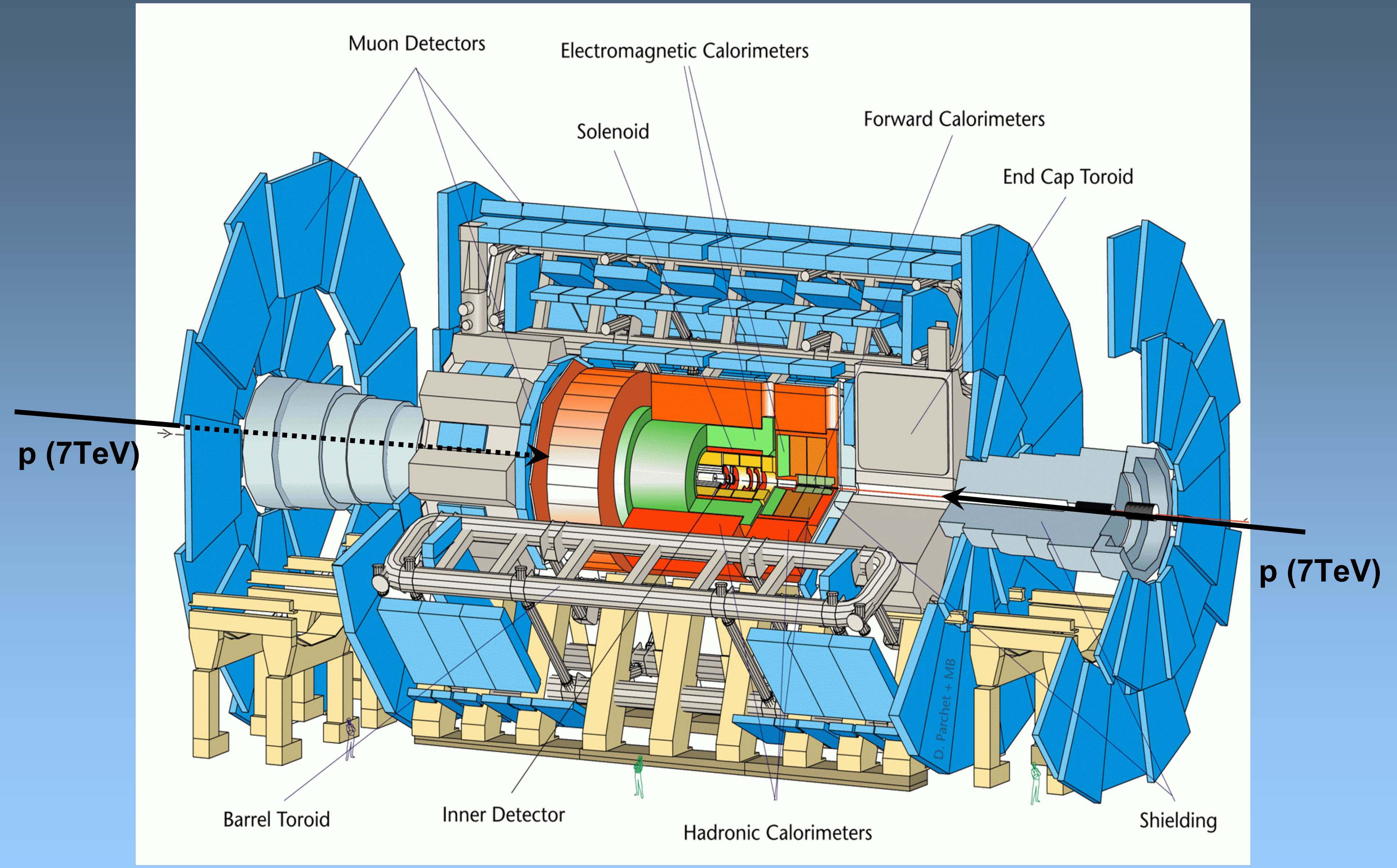
- **Introduction to Calorimetry / Calorimeter Design**
- **The ATLAS Calorimeters**

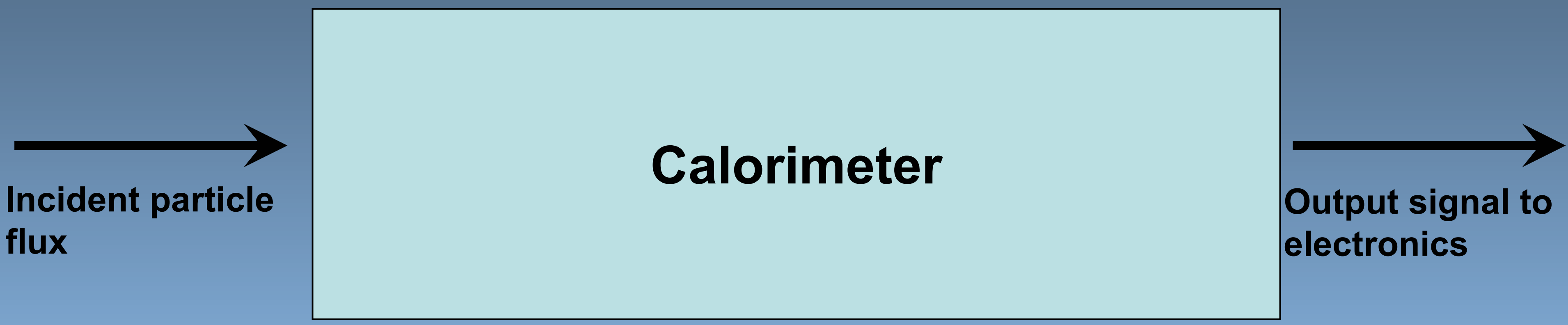




The ATLAS Detector at the Large Hadron Collider



What is a Calorimeter ?



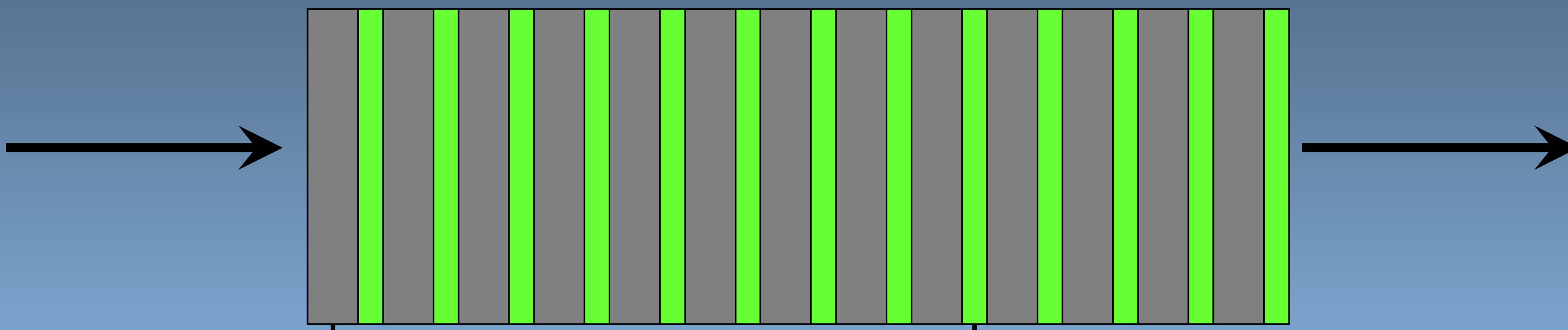
A calorimeter consists of:

Dense absorber material to fully absorb incident particles

Active material to produce an output signal proportional to the input energy

Sampling Calorimeters

Absorber and active materials can be the same (homogeneous calorimeter: e.g. CsI, NaI, Lead glass) or (more commonly) different



absorber (i.e. Pb)

for example:

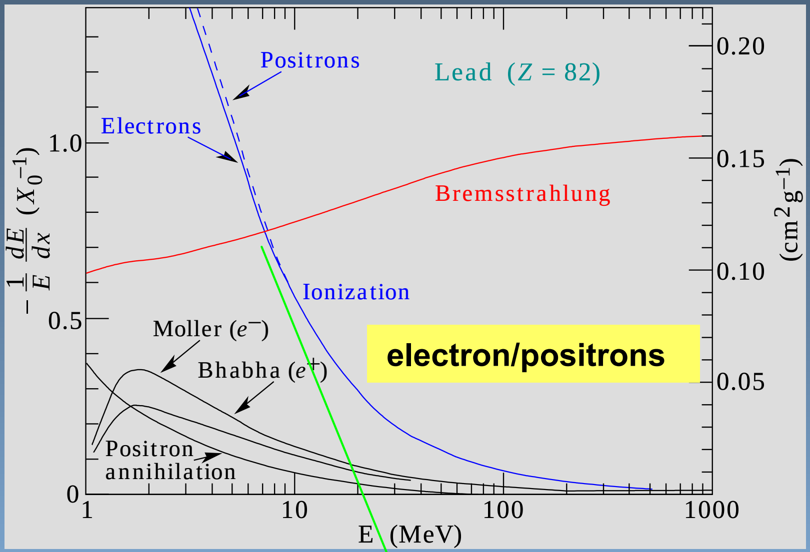
- **Pb (ATLAS EMB,EMEC)**
- **Copper (ATLAS HEC)**
- **Tungsten (ATLAS FCal)**
- **Depleted Uranium (ZEUS)**

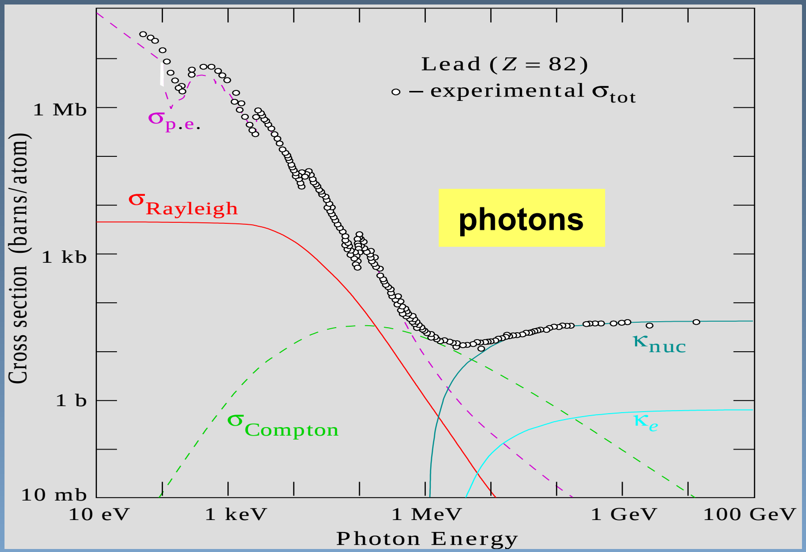
active layer

for example:

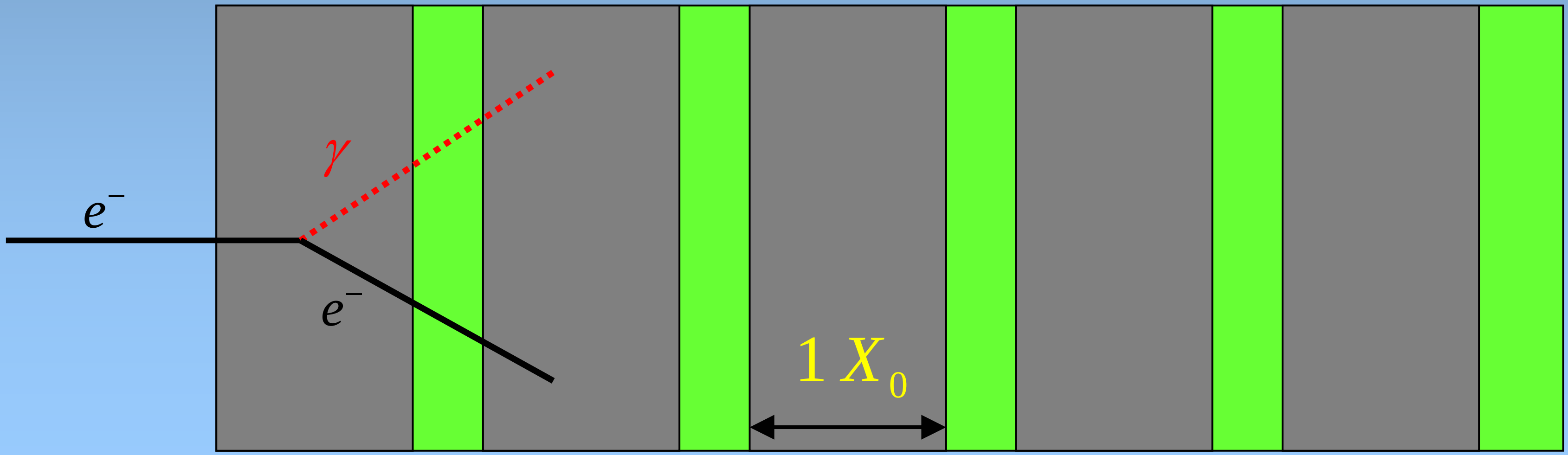
- **Scintillator (light output)**
- **Liquid argon (ionization)**

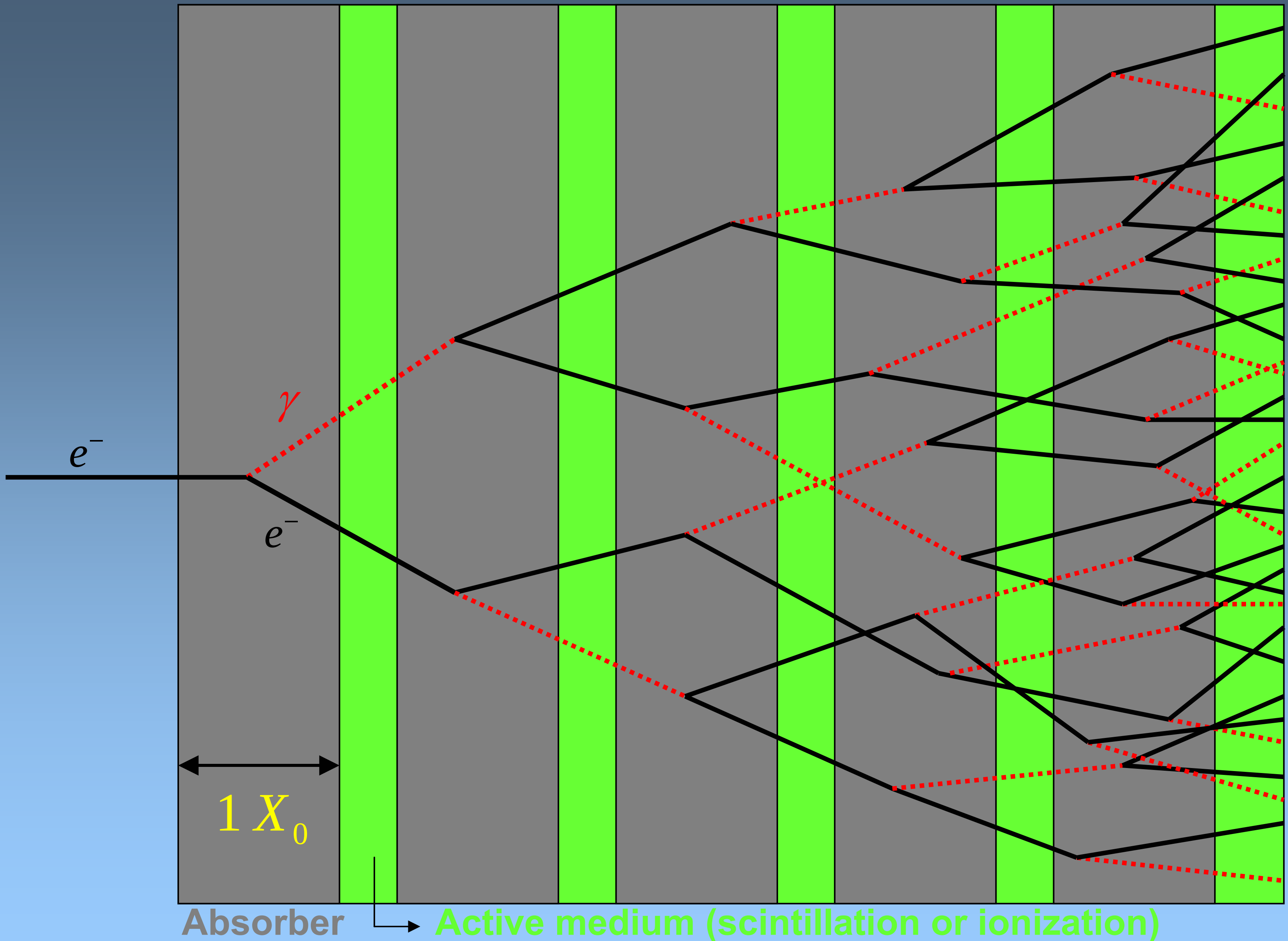
EM Energy Loss vs. Energy (here in Pb) – Electromagnetic Showers





Critical energy E_c **~ 10 MeV**





γ
e^-
e^-
$1\,X_0$
Absorber
Active medium (scintillation or ionization)

How does required detector size scale with energy ?

Calorimeter (use EM as example)

After t radiation lengths (X_0) **total number of particles present is** 2^t

Average energy of a shower particle at depth t is $E(t) = E_0 / 2^t$

Shower has maximum number of particles when $E(t) = E_c$

So, shower maximum appears at

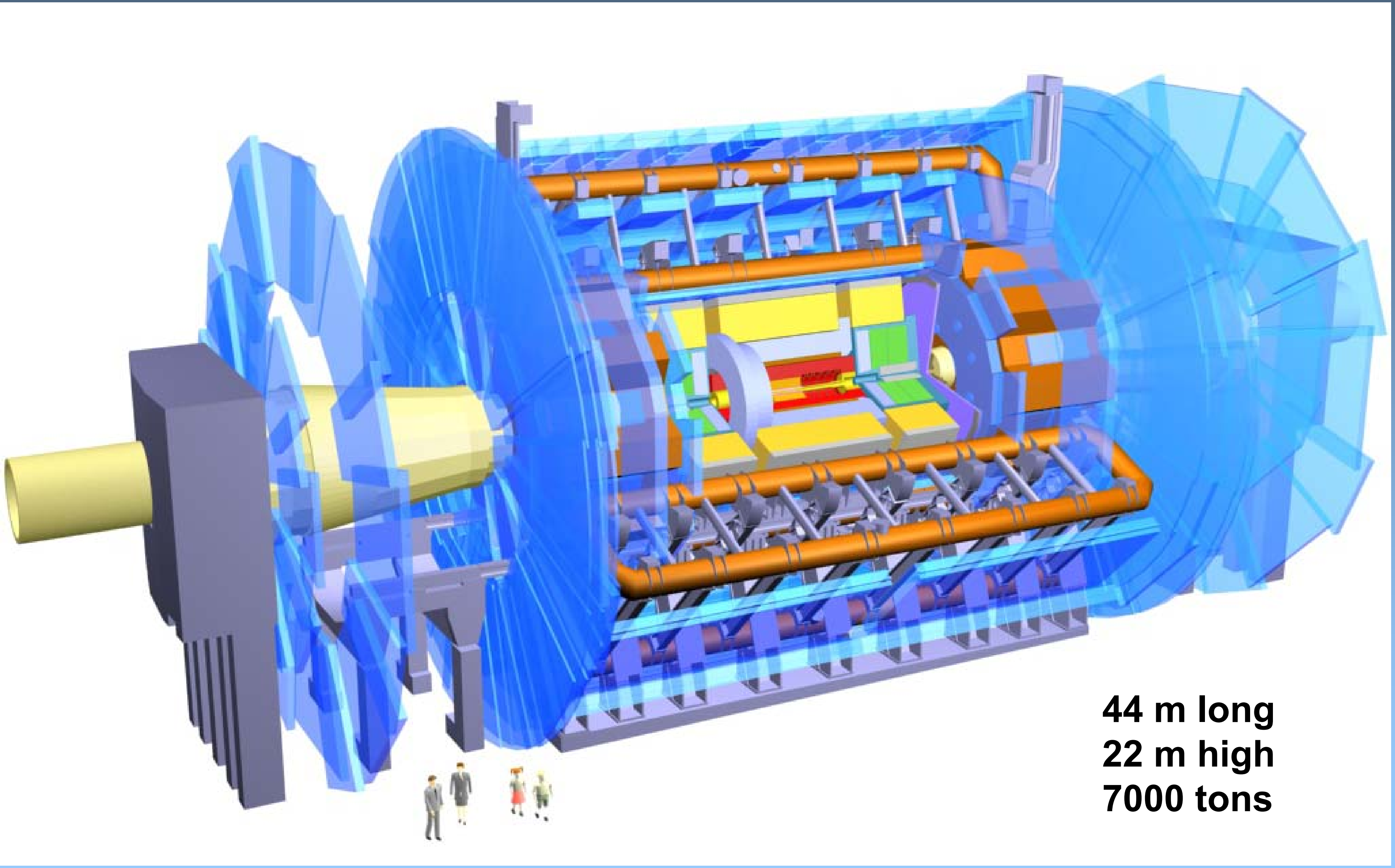
$$t_{\max} = \frac{\ln(E_0 / E_c)}{\ln(2)}$$

As we go to higher and higher energies, calorimetry becomes a more critical part of a detector (relative to tracking)

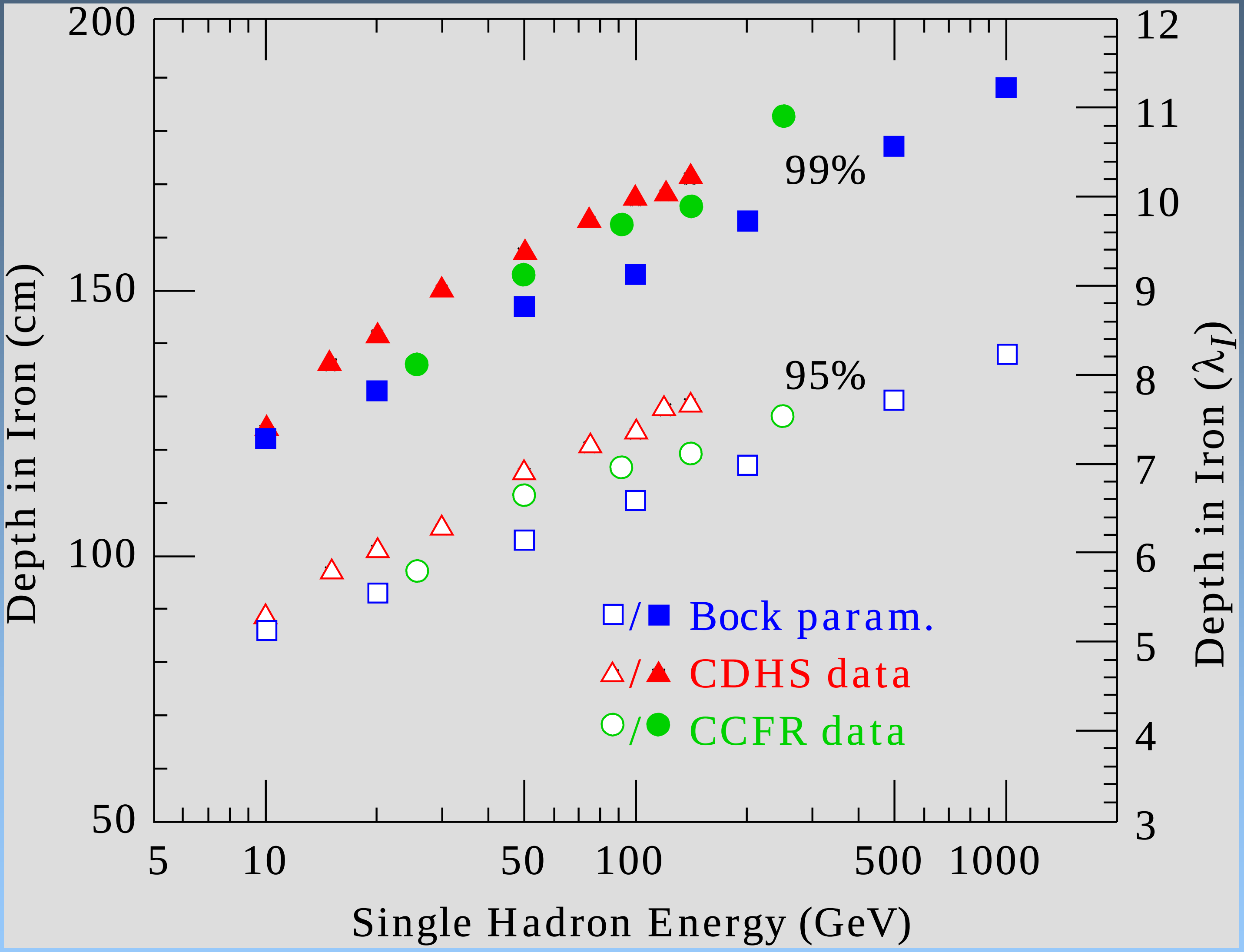
<u>For comparison:</u>

Tracking chambers: for same resolution $\delta p / p$ **required detector size (for same magnetic field) scales with** $\sqrt{E}$

ATLAS Calorimetry at the Large Hadron Collider



Hadronic Energy Containment in Iron



Hadronic Calorimetry

Principle the same as for electromagnetic calorimeters …… BUT

Hadronic interaction length λ_I larger than EM radiation length X_0

→ **Needs to be deeper (denser) than EM calorimeter**

More processes contribute to hadronic shower development than to EM

Process	Percent of Total
Secondary proton ionization	31.6
Electromagnetic cascade	21.0
Nuclear binding energy plus neutrino energy	20.6
Secondary charged pion ionization	8.2
Neutrons with E > 10 MeV	4.9
Neutrons with E < 10 MeV	3.9
Residual nuclear excitation energy	3.7
Z > 1 ionization	2.4
Primary proton ionization	2.3
Other	1.4

!!!!!

Average fractional energy deposition for 10 GeV protons in an Fe-LAr sampling calorimeter

Note that a sizeable fration of the energy deposited in a hadronic shower is electromagnetic (from production and decay of neutral pions $\pi^0 \rightarrow \gamma\gamma$)

Some processes do not lead to an observable signal (e.g. neutrinos)

A calorimeter's response to electromagnetic particles differs from it's response to hadronic particles

↓

e/h ≠ 1 (for non-compensating calorimeters)

Calorimeter Design Criteria

Aspects driven by physics goals

- Signal linearity
- Resolution (energy, position)

Requirements are dictated by resolution required for desired signal (e.g. Higgs discovery)

Aspect driven by experimental conditions

- Radiation tolerance → choice of technology (TileCal vs Liquid Argon)
- Collision frequency → speed of response

Practical aspects

- Cost → Liquid krypton would yield improved resolution, but is more expensive and requires higher purity than liquid argon
- Ease of construction

Energy Resolution of a Sampling Calorimeter

Resolution of a sampling calorimeter typically takes the form:

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

- $\frac{a}{E}$ → noise term
- c → constant term
- $\frac{b}{\sqrt{E}}$ → sampling term

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sampling term

- Choice of absorber
- Choice of active material
- Thickness of sampling layers
- …..

Typically most important in 10-100 GeV energy range

constant term

- depth of detector (X_0, λ_I)
- detector non-uniformities
- cracks
- dead material …….

Dominates at high energy

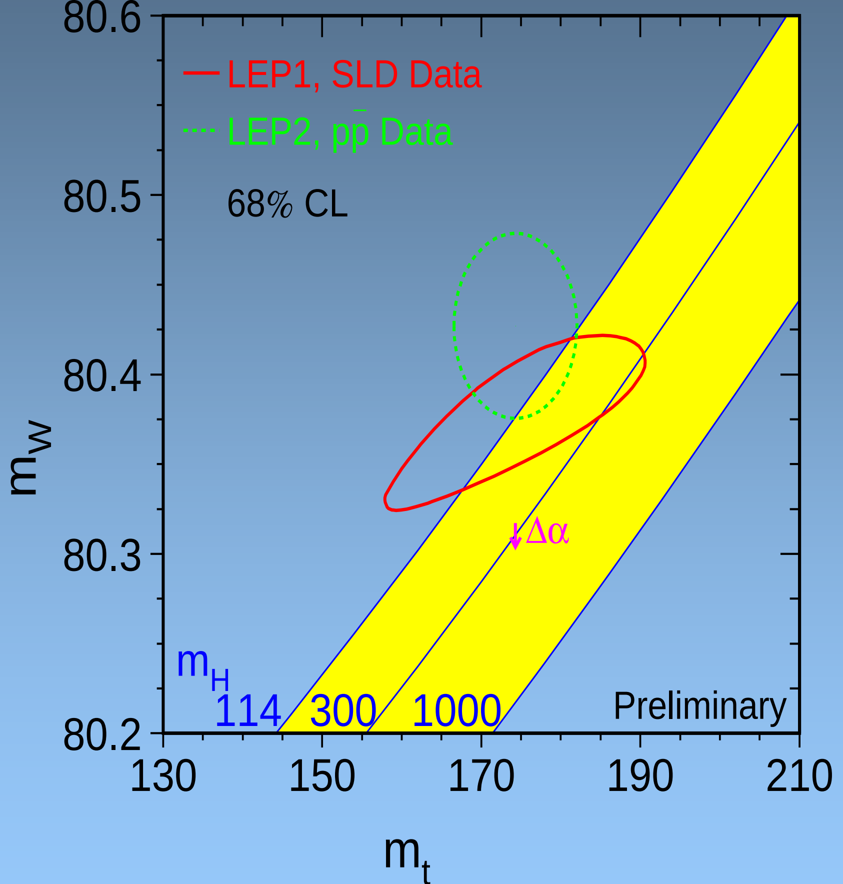
noise term

- electronic noise
- signal pileup

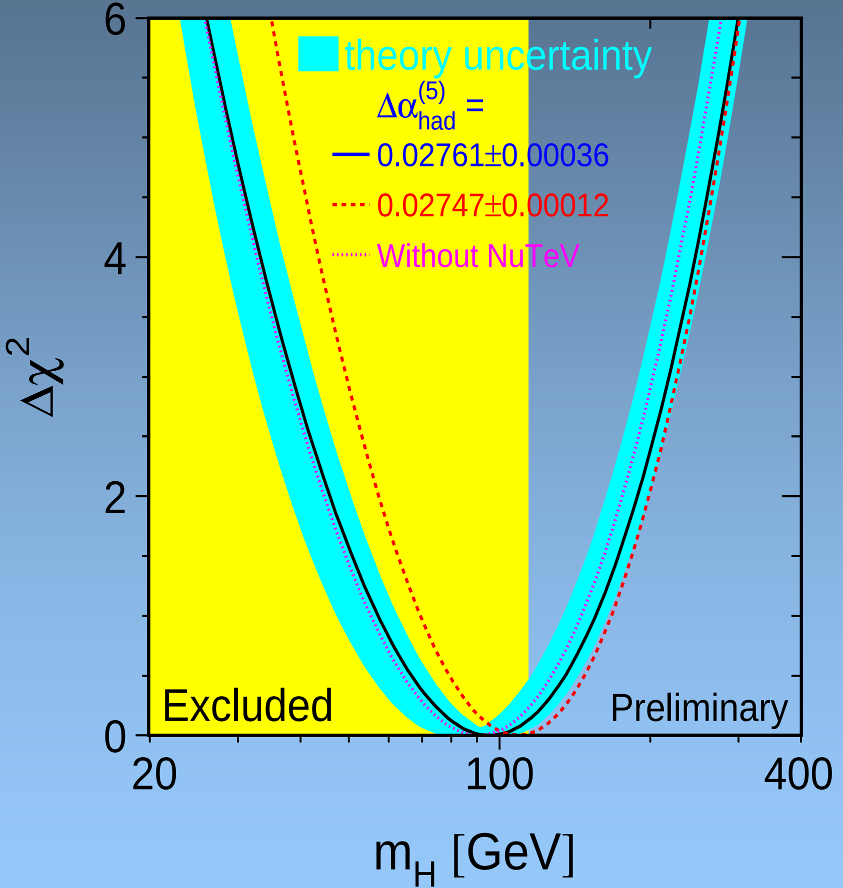
Dominates at low energy

Status of the Search for the Higgs Boson

Discovery of the Higgs bosons is one of the main purposes of the LHC

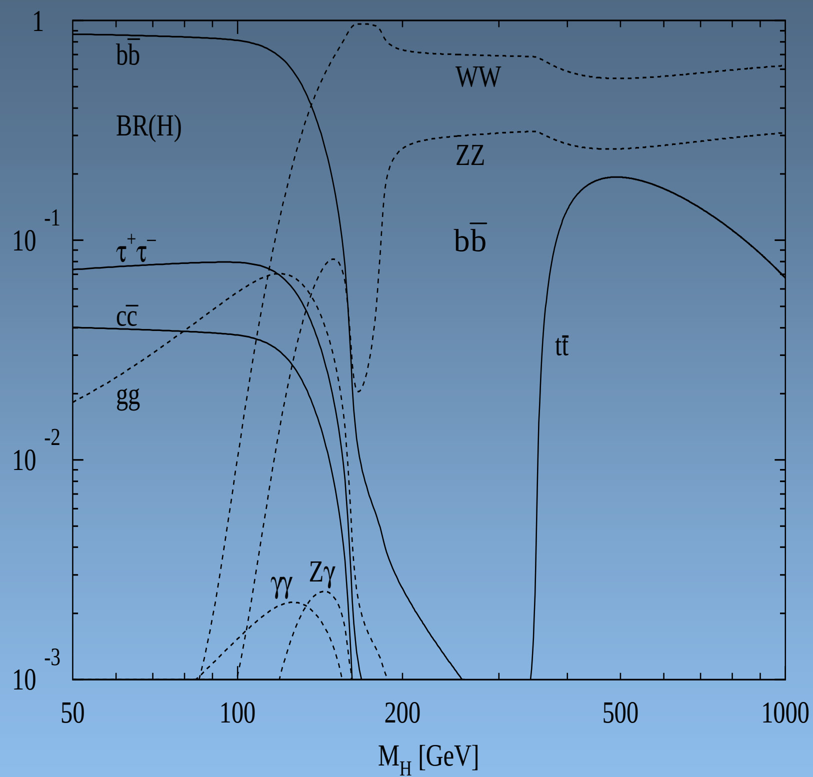


LEP direct search limit > 114 GeV



Current experimental evidence points to a low mass HIggs

Higgs Branching Ratio as a Function of Higgs Mass



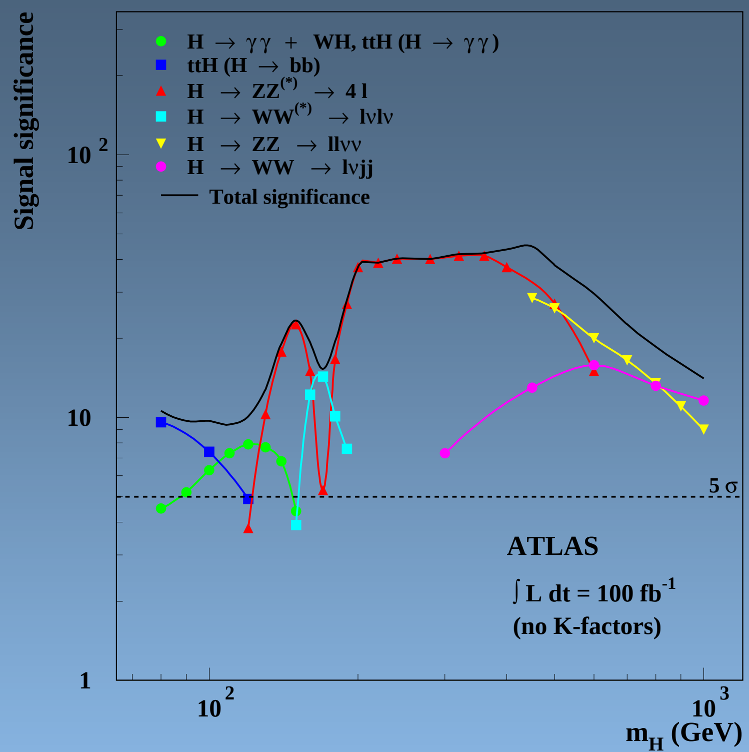
Process	σ	Events / sec	Event / year
$W \to e\nu$	15nb	15	10^8
$Z \to ee$	1.5nb	1.5	10^7
$t\bar{t}$	800pb	0.8	10^7
$b\bar{b}$	500μb	10^5	10^{12}
$\tilde{g}\tilde{g}(M_{\tilde{g}} = 1TeV)$	1pb	10^{-3}	10^4
$H_{SM}(M = 0.8TeV)$	1pb	10^{-3}	10^4
QCDjets $p_T > 200GeV$	100nb	10^2	10^9

In favoured low mass region decay is almost entirely to $b\bar{b}$

QCD background to $H^0 \to b\bar{b}$ too large.
Need to look for cleaner search channel

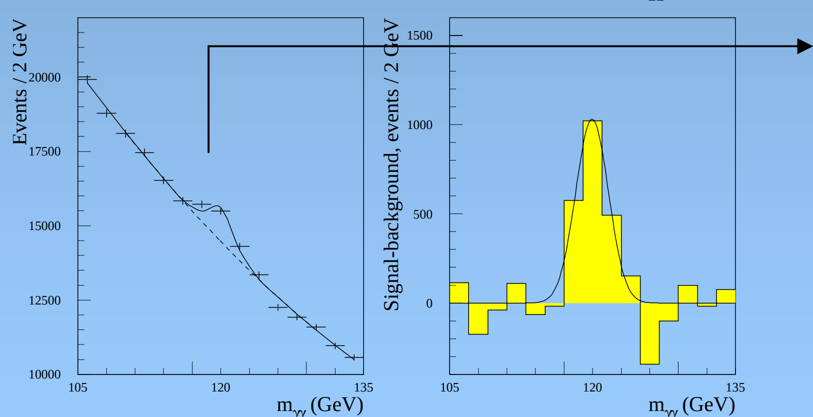
Favoured discovery channel for a light mass Higgs is $H^0 \to \gamma\gamma$

Electromagnetic Energy Resolution



Higgs discovery potential in the favored low-mass region relies on reconstruction of the $H^0 \to \gamma\gamma$ final state

Required resolution on the $H^0 \to \gamma\gamma$ reconstruction represents the most stringent constraint on ATLAS electromagnetic calorimetry

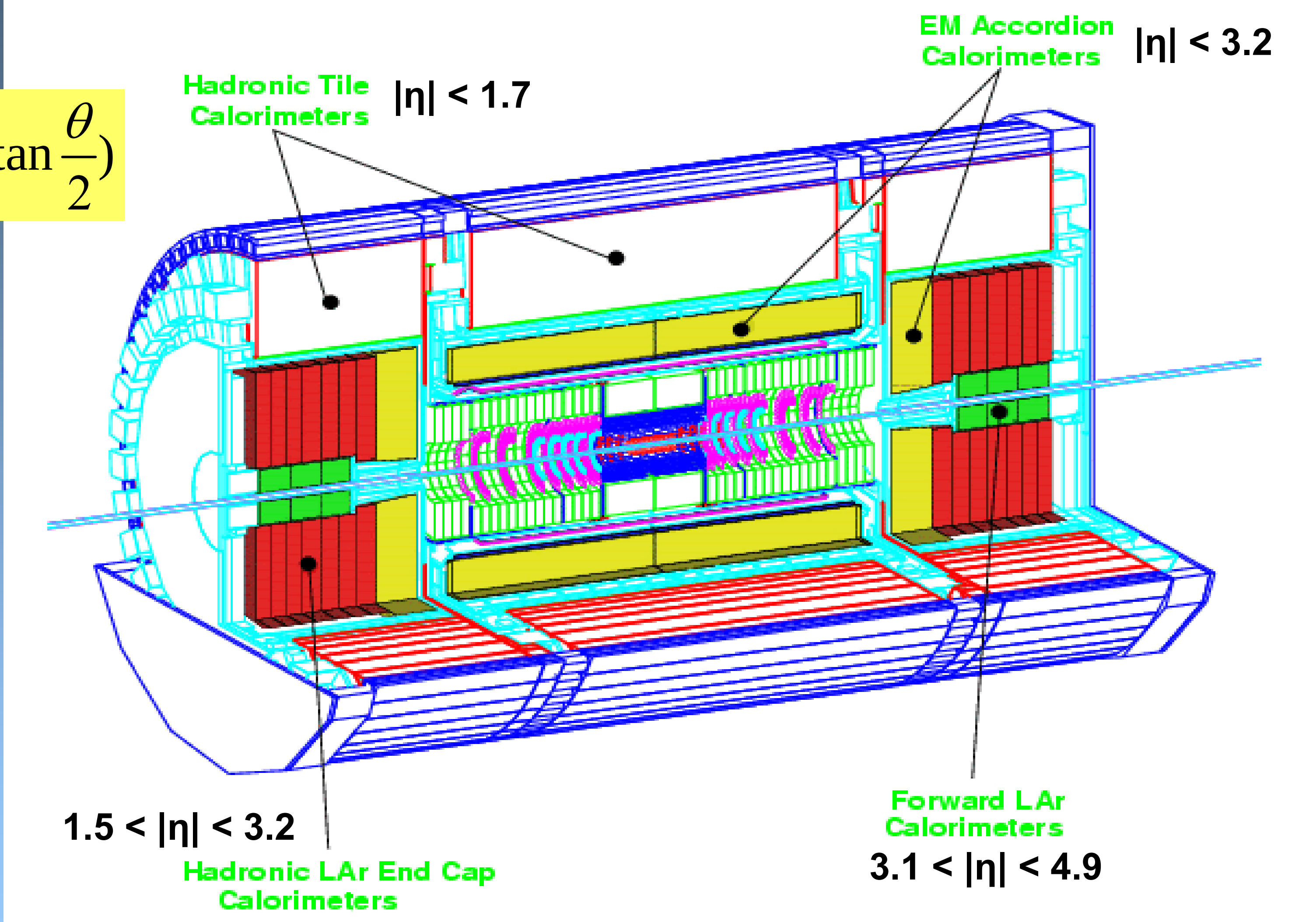


Small signal on significant background. The better the signal resolution, the better the signal to noise ratio

Require good energy resolution AND good position resolution

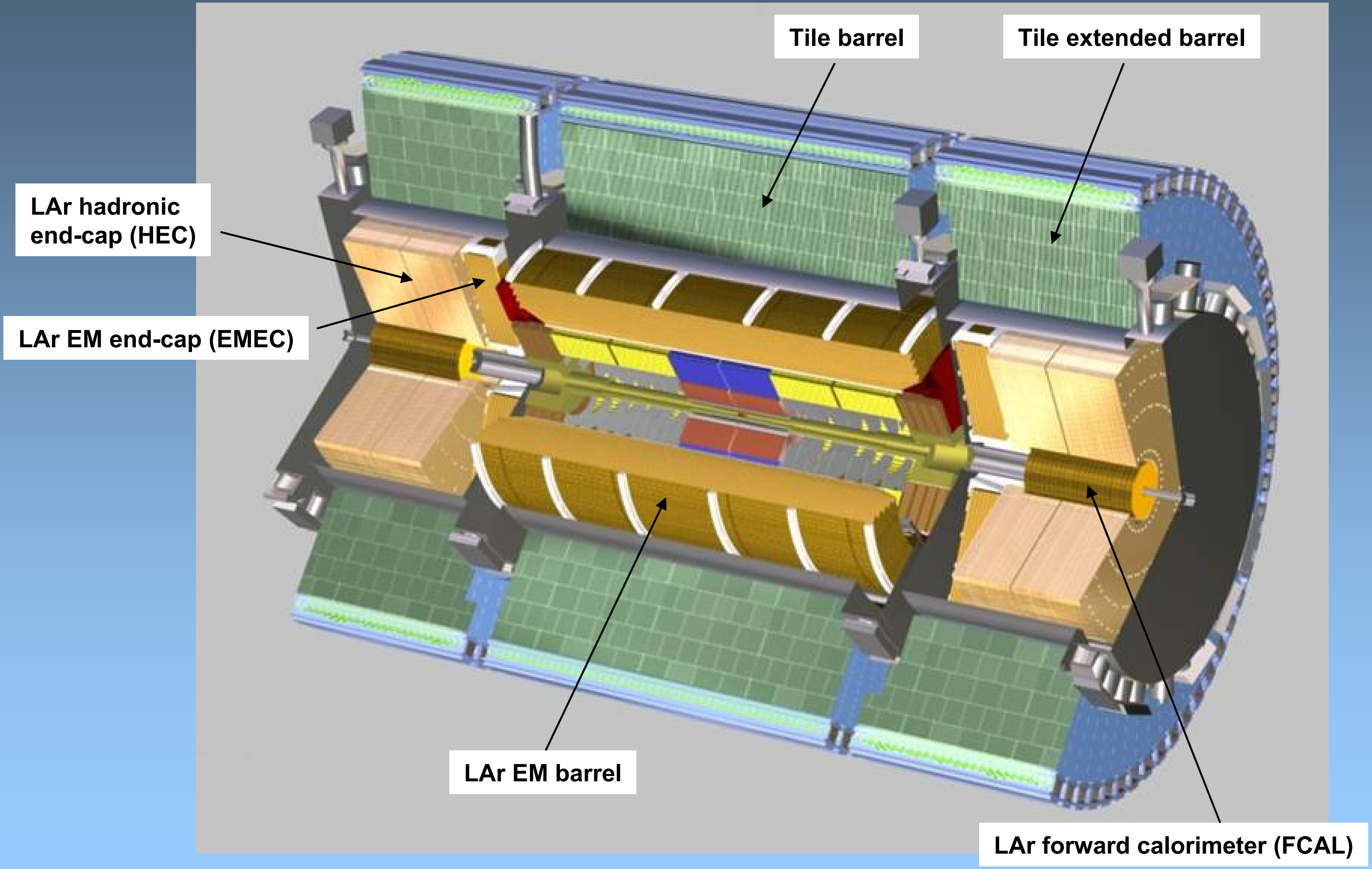
ATLAS Calorimetric Coverage

$$\eta = -\ln(\tan\frac{\theta}{2})$$



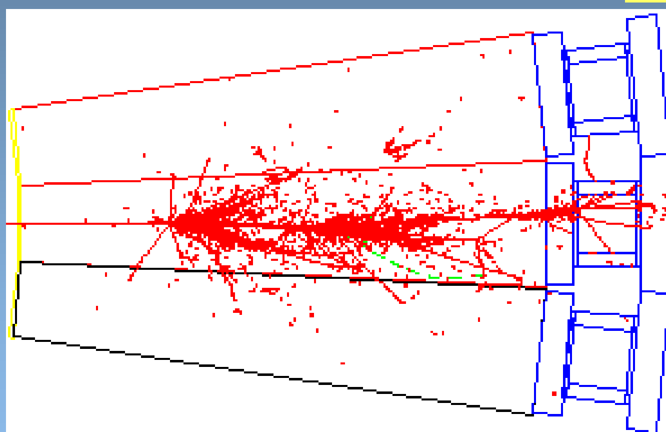
Total mass ~ 4000 tons

The ATLAS Liquid Argon and Tile Calorimeters



The ATLAS Tile Calorimeter

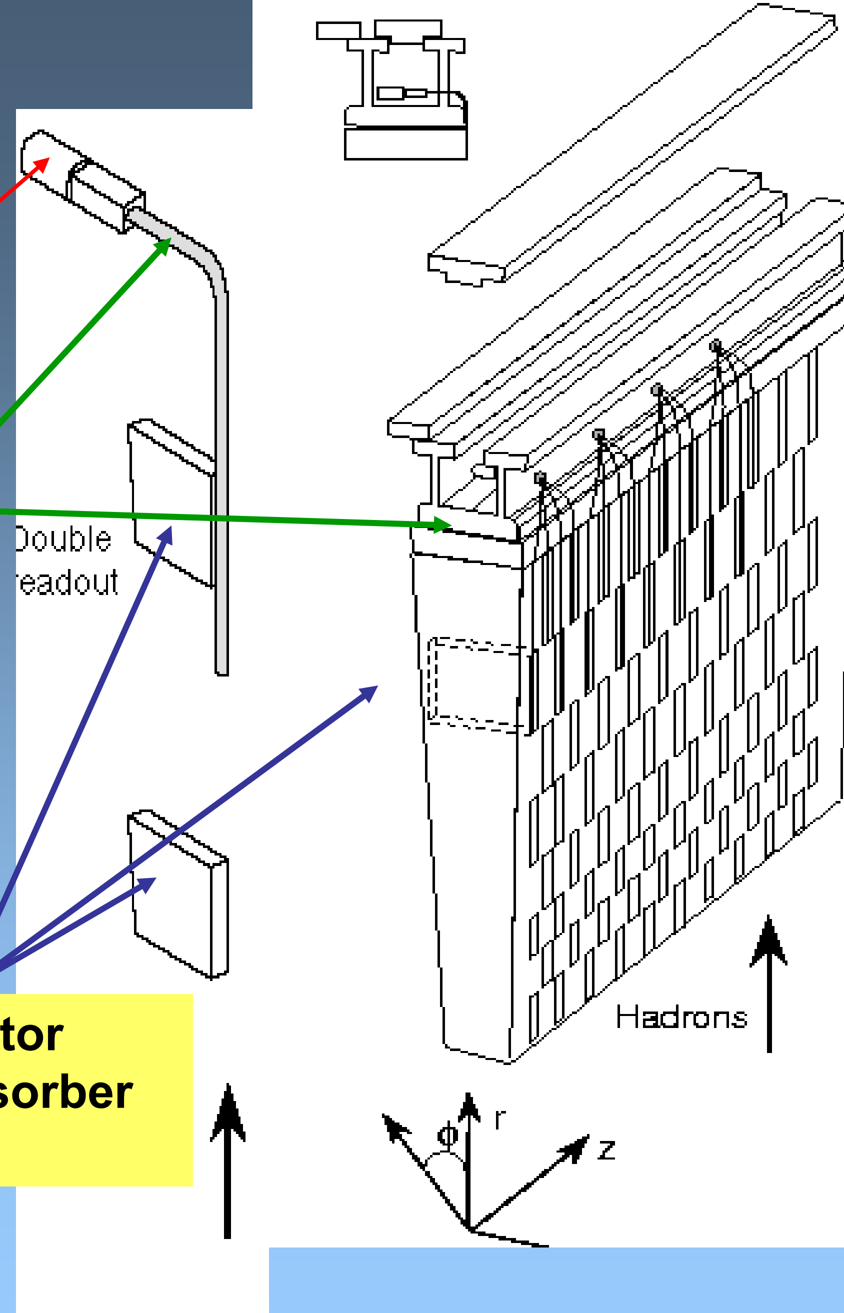
"Conventional" Iron-Scintillating Tile Sampling Calorimeter, but with unconventional mechanical structure



PMT

WLS fiber

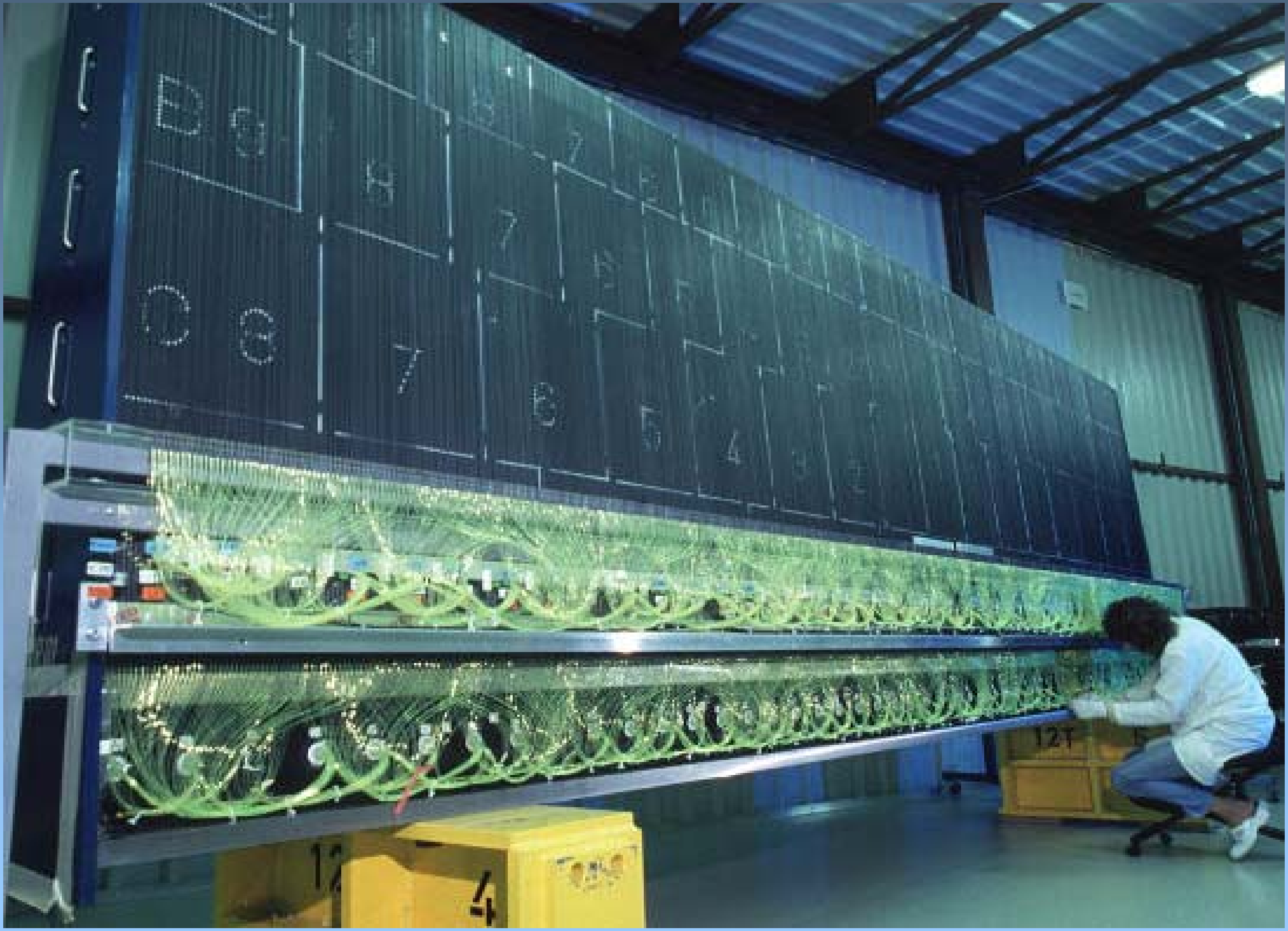
Plastic scintillator inside steel absorber structure



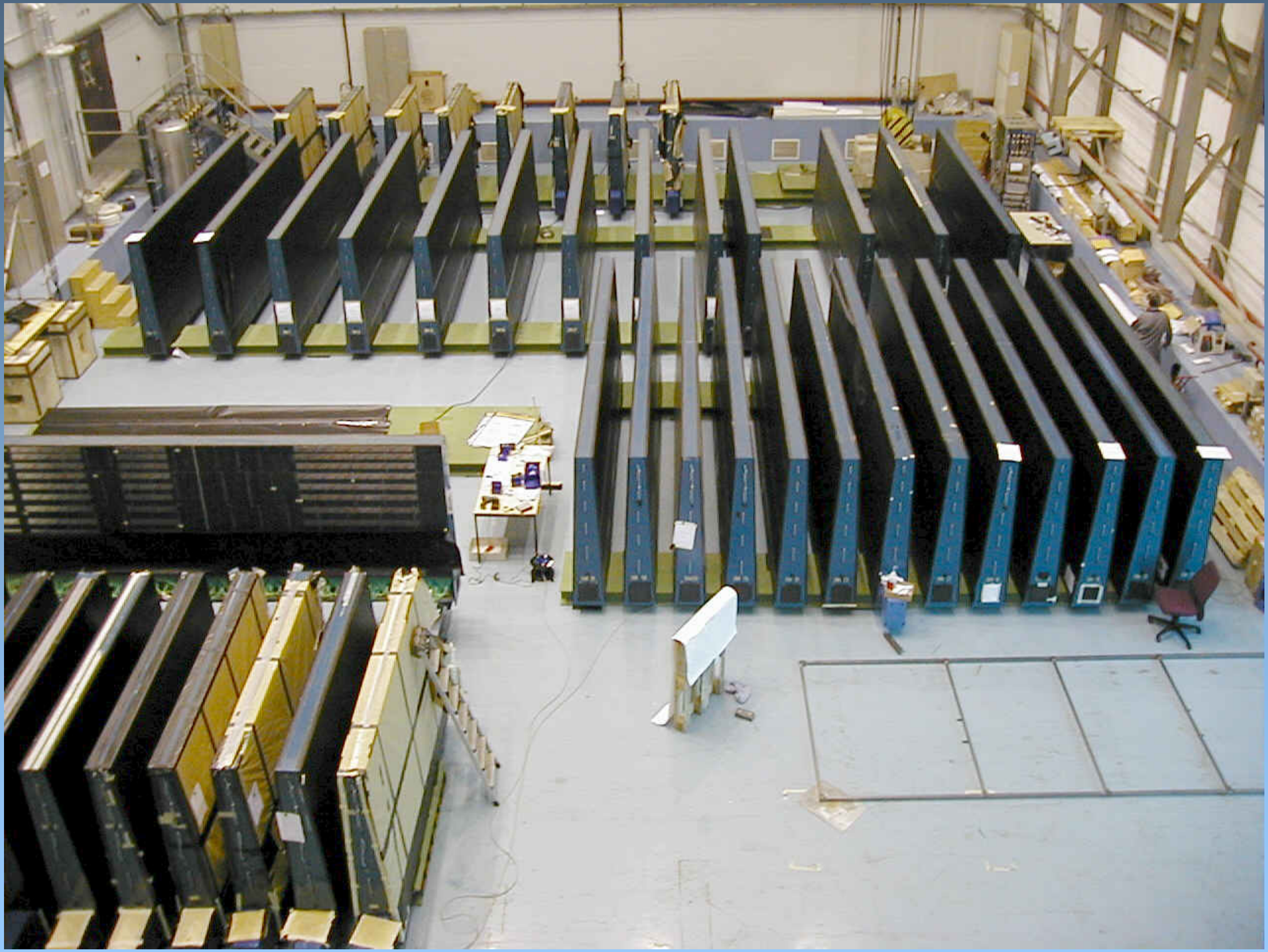
Tile Calorimeter Construction

- Iron cutting
- sub-module assembly
- tile manufacturing
- tile insertion

One TileCal Barrel Module



TileCal Modules Before Assembly



TileCal Barrel Preassembly (April 2003)

Final assembly of TileCal detector is done in the ATLAS Cavern

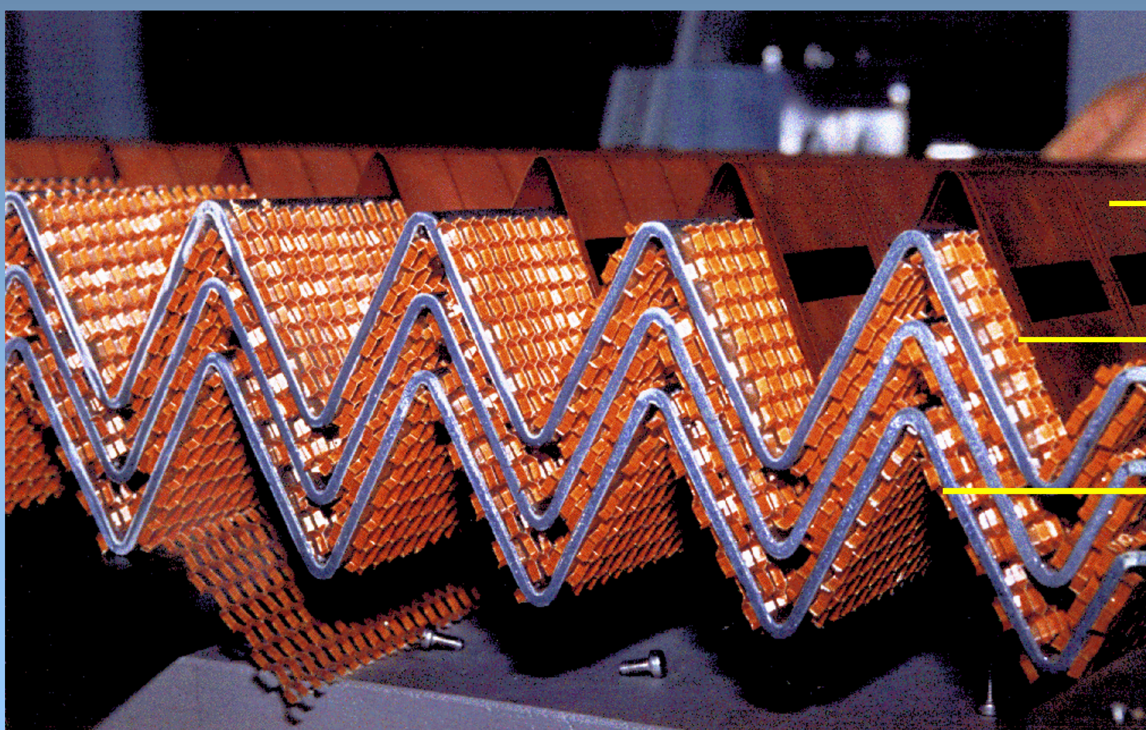
ATLAS Electromagnetic Barrel Calorimeter

Detector design dictated by physics goals:

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



$|\eta| < 1.475$

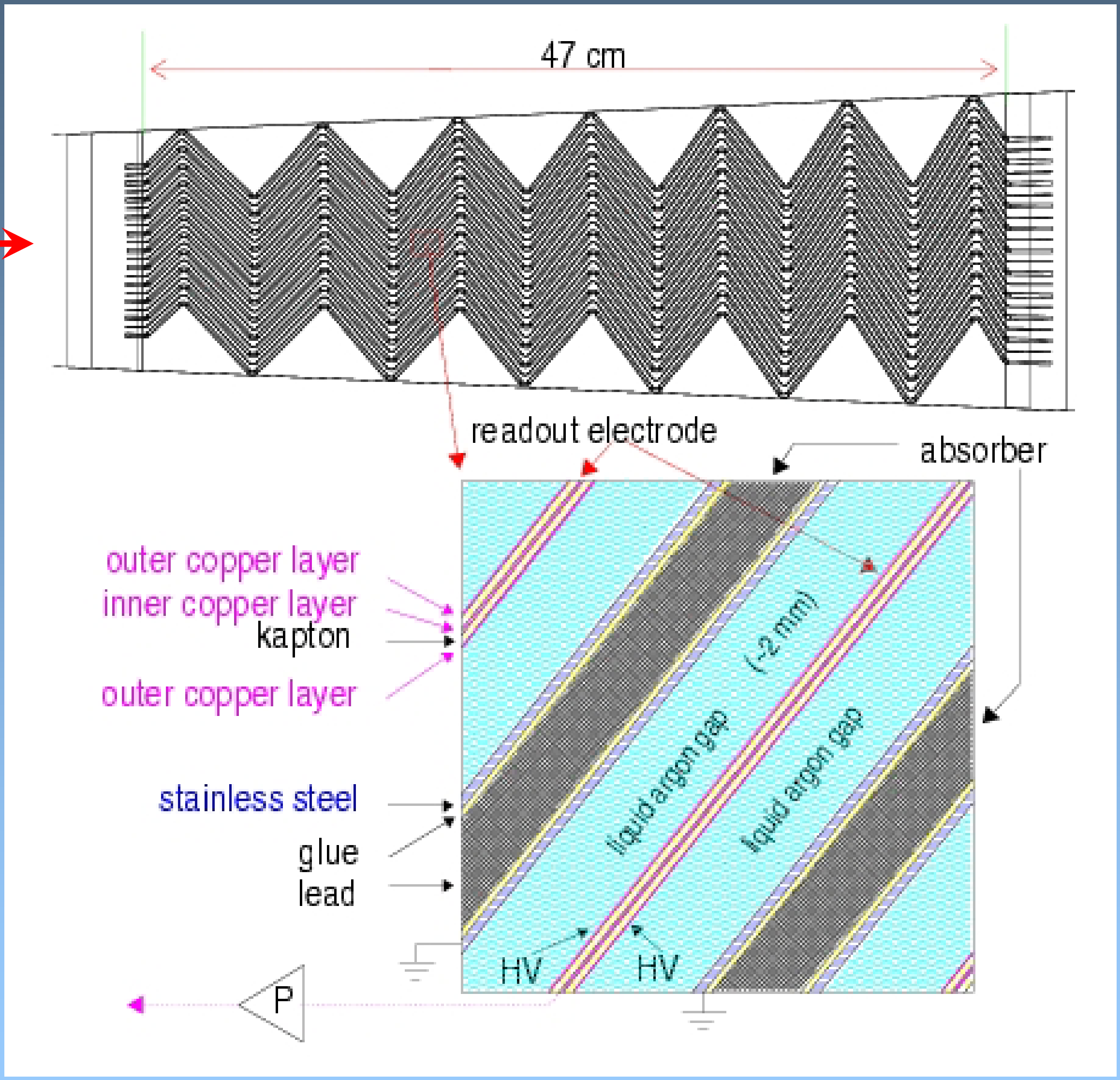
Copper/kapton electrode

Honeycomb spacer to maintain LAr gap

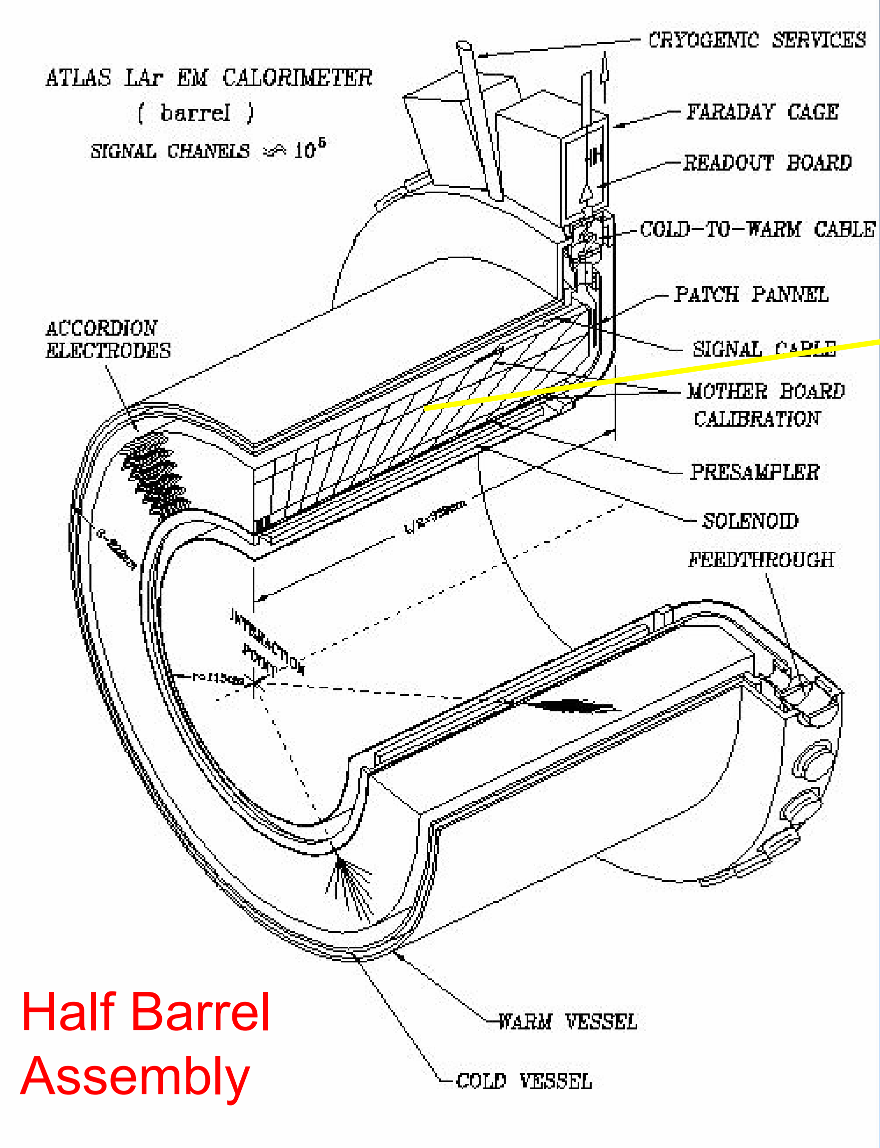
Stainless-steel-clad Pb absorber plates

LAr Gap Structure in Accordion EMB Calorimeter

Particle from interaction point

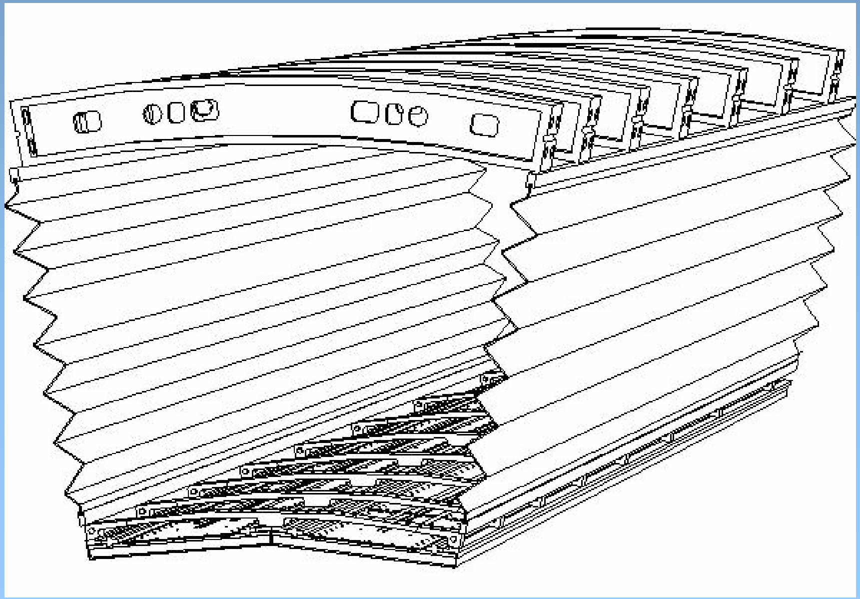


ATLAS EMB Calorimeter (Half Barrel}

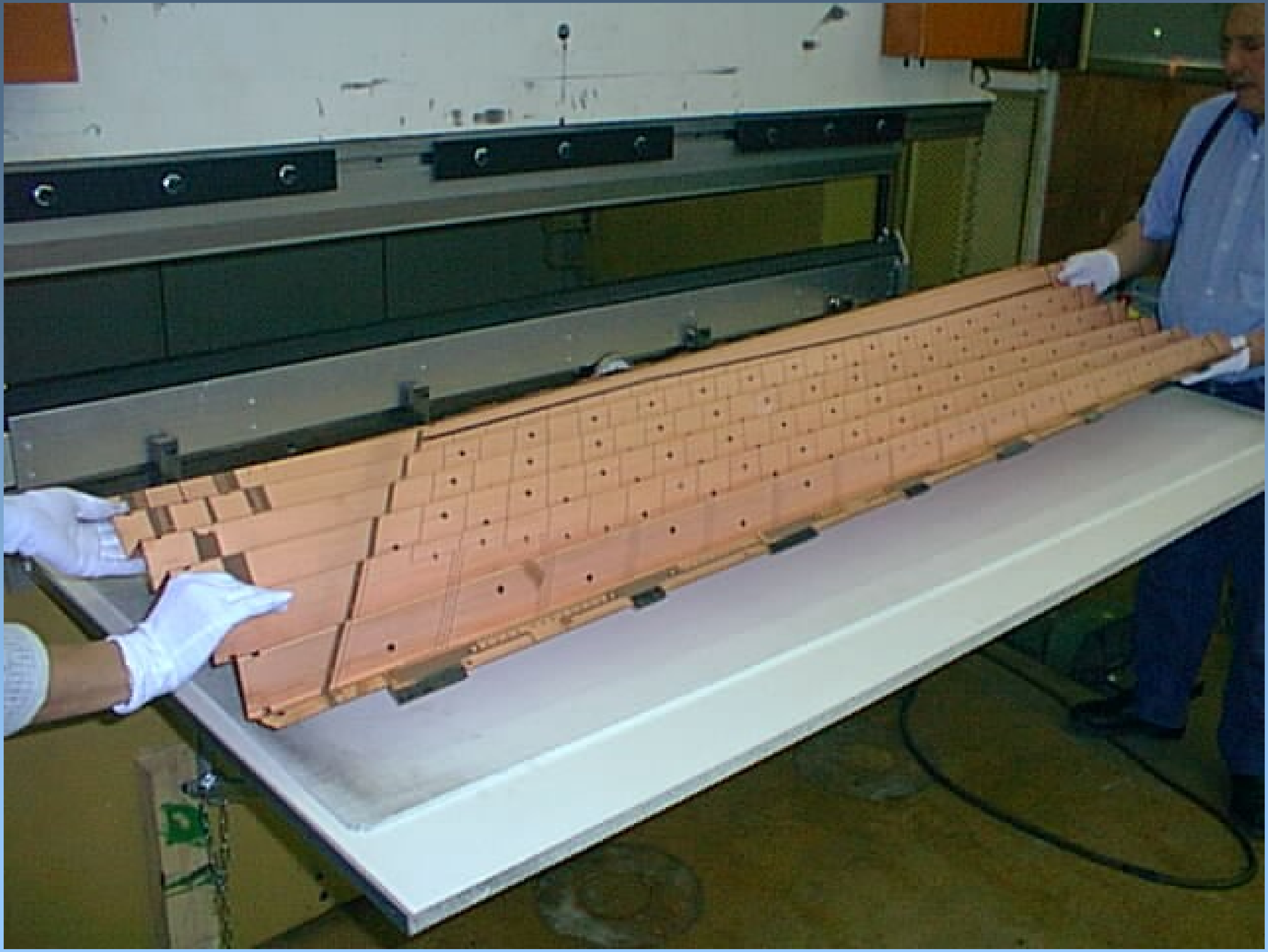


Half Barrel Assembly

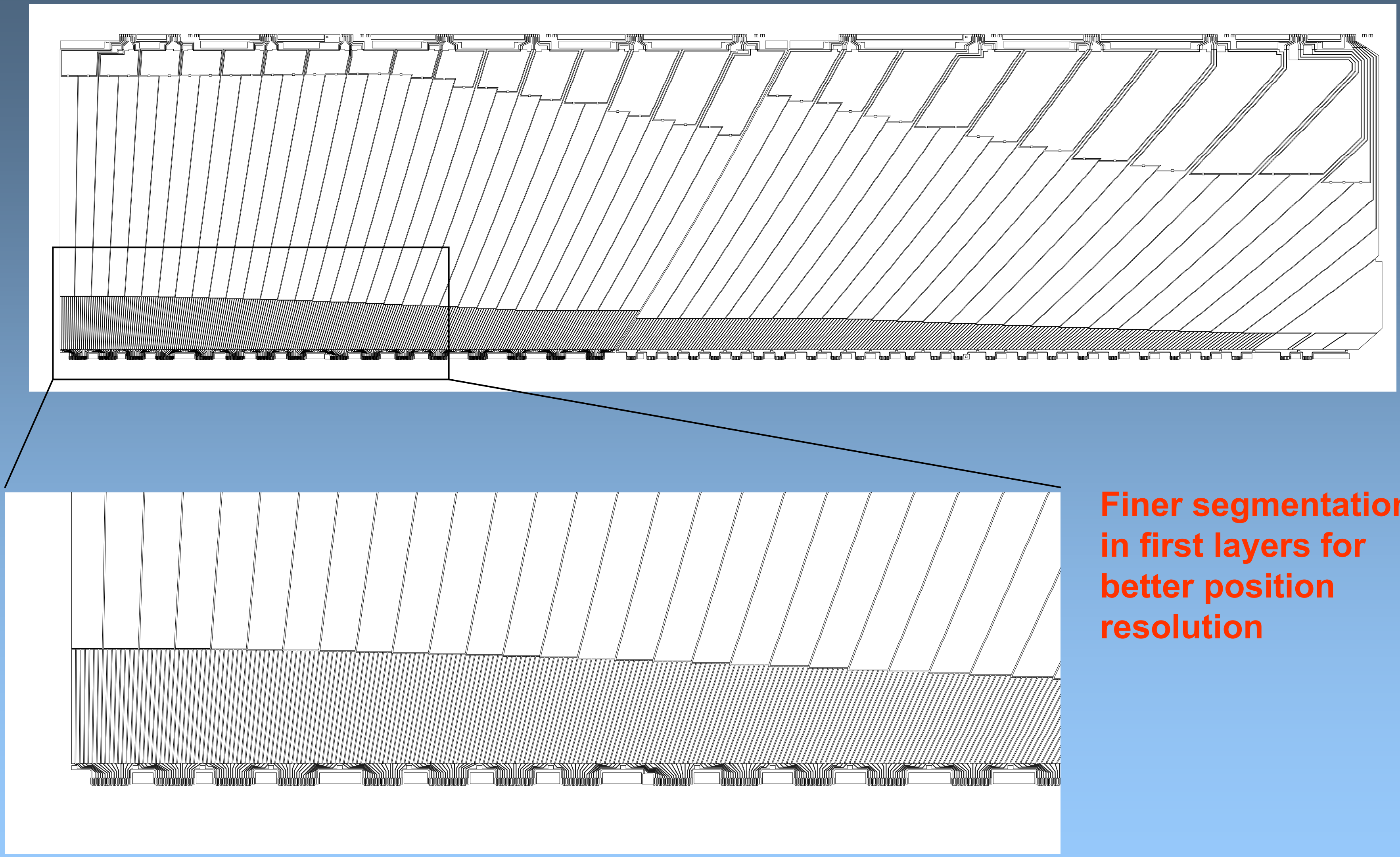
Note η segmentation of readout



Readout segmentation of accordian electrodes (in η)

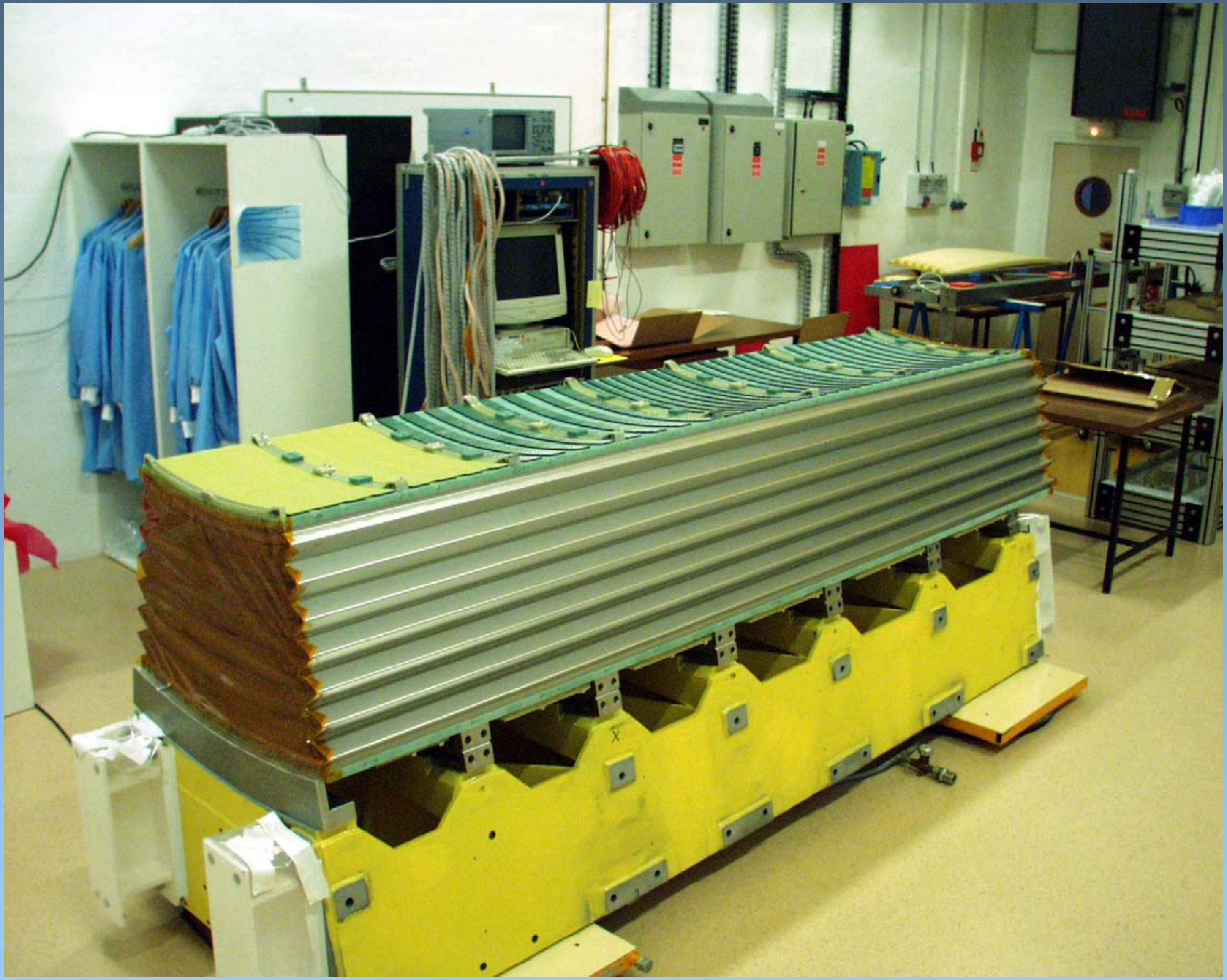


Readout segmentation of accordian electrodes (in η)



Finer segmentation in first layers for better position resolution

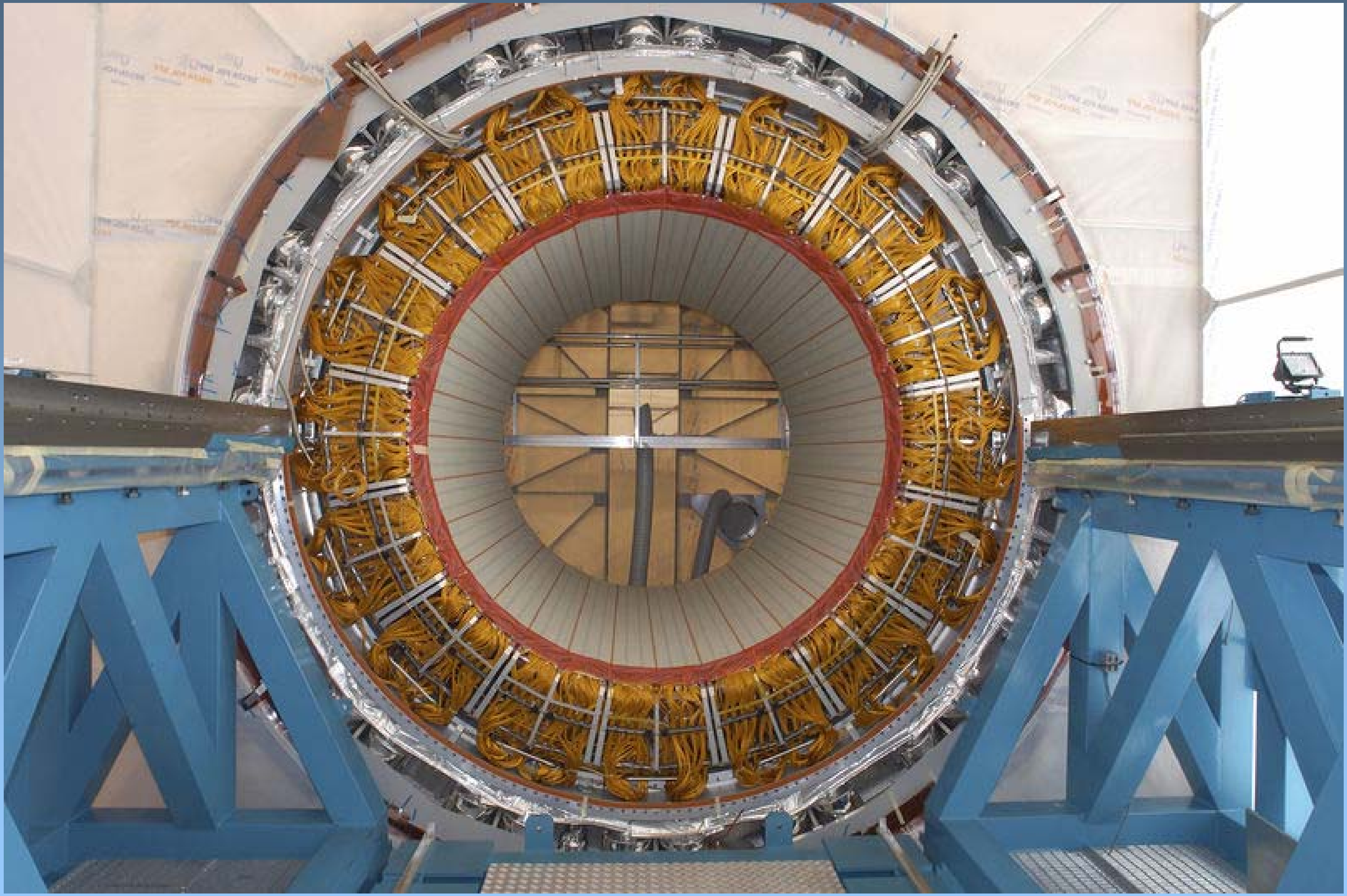
Stacked Electromagnetic Barrel Calorimeter Module



Installation of EMB Half-Barrel Module

EMB Half-Barrel Wheel on Insertion Stand

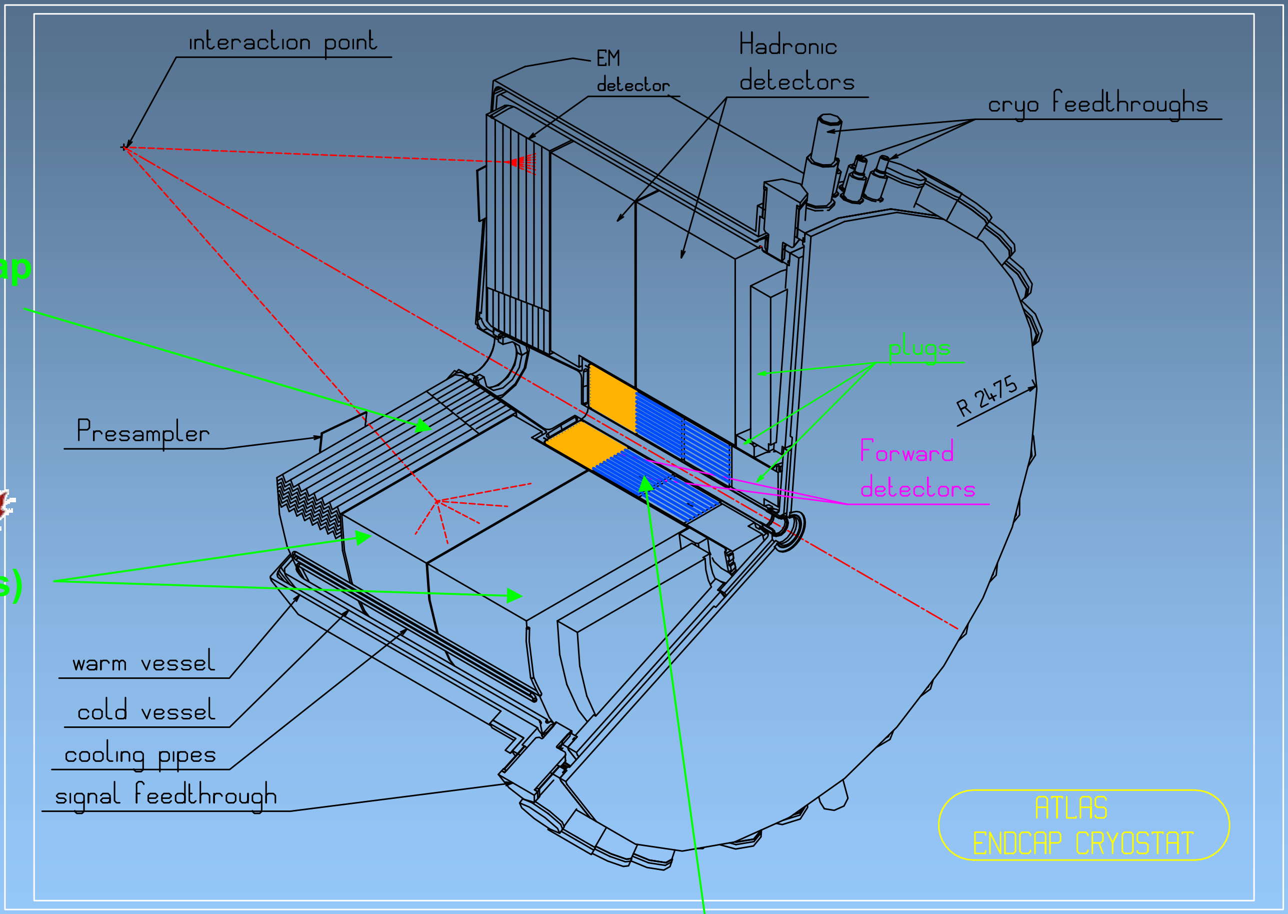
ATLAS EBM Calorimeter Installed in Barrel Cryostat



The ATLAS Endcap Calorimeter

Electomagetic Endcap Calorimeter (EMEC)

Hadronic Endcap Calorimeter (2 Wheels)



Forward Calorimeter

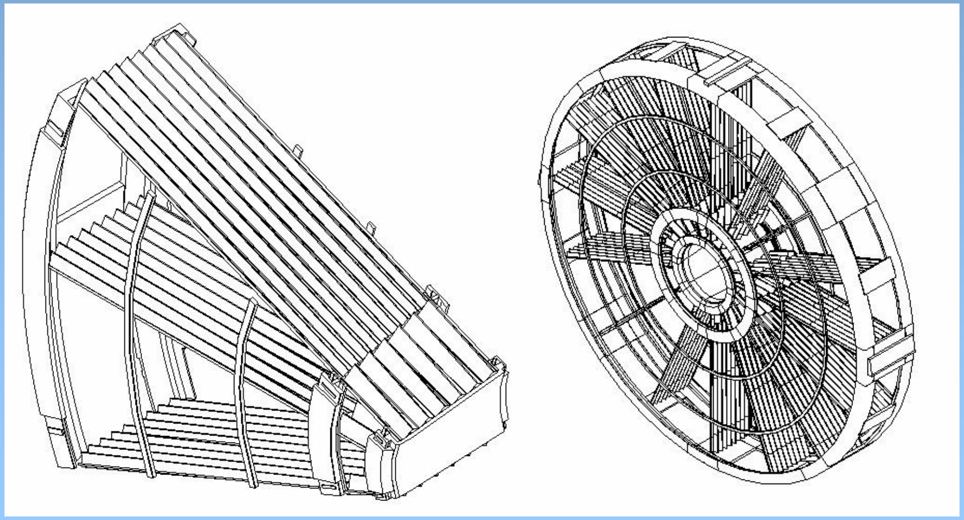
Electomagnetic Endcap Calorimeter (EMEC)

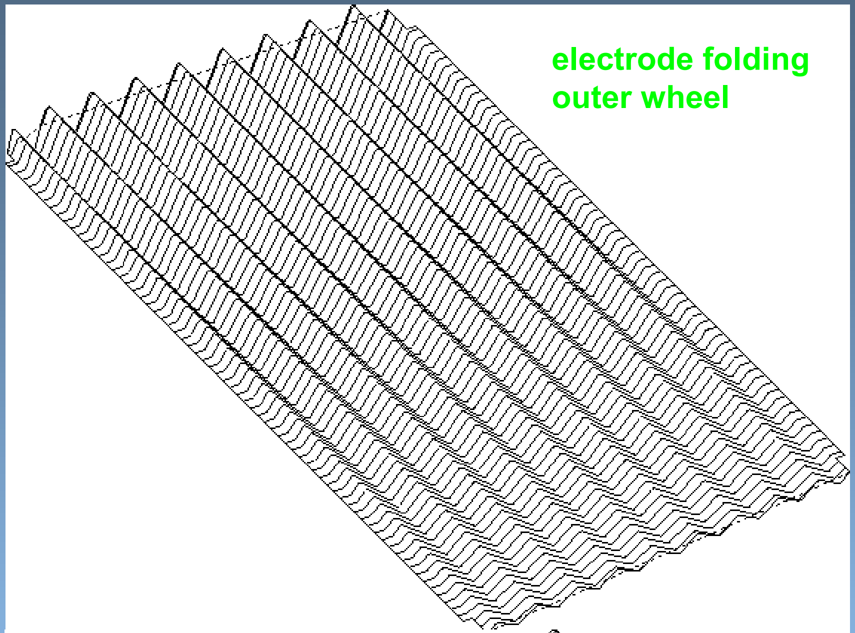
1.375 < |η| < 3.2

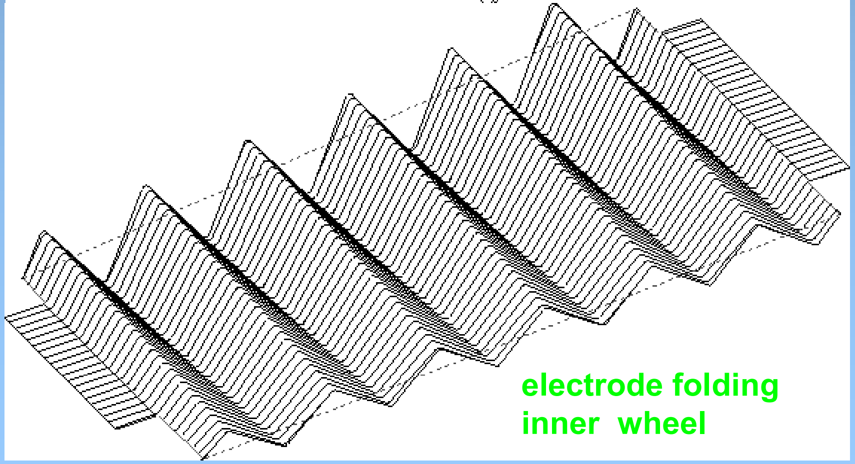
Accordion structure chose here as well. Design is more complicated as folding amplitude is a function of radius

Constructed as an inner and outer wheel

"spanish fan" geometry

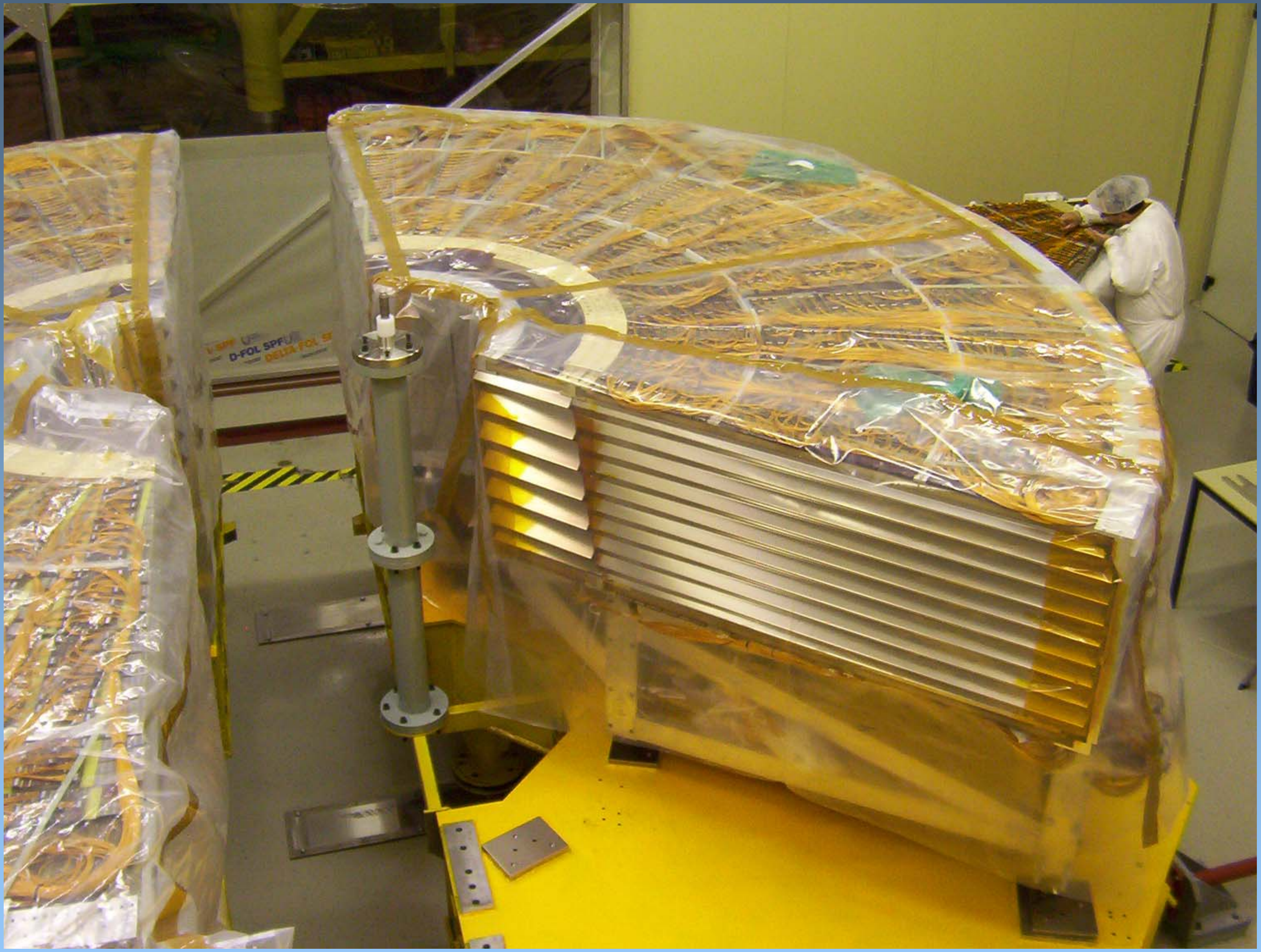






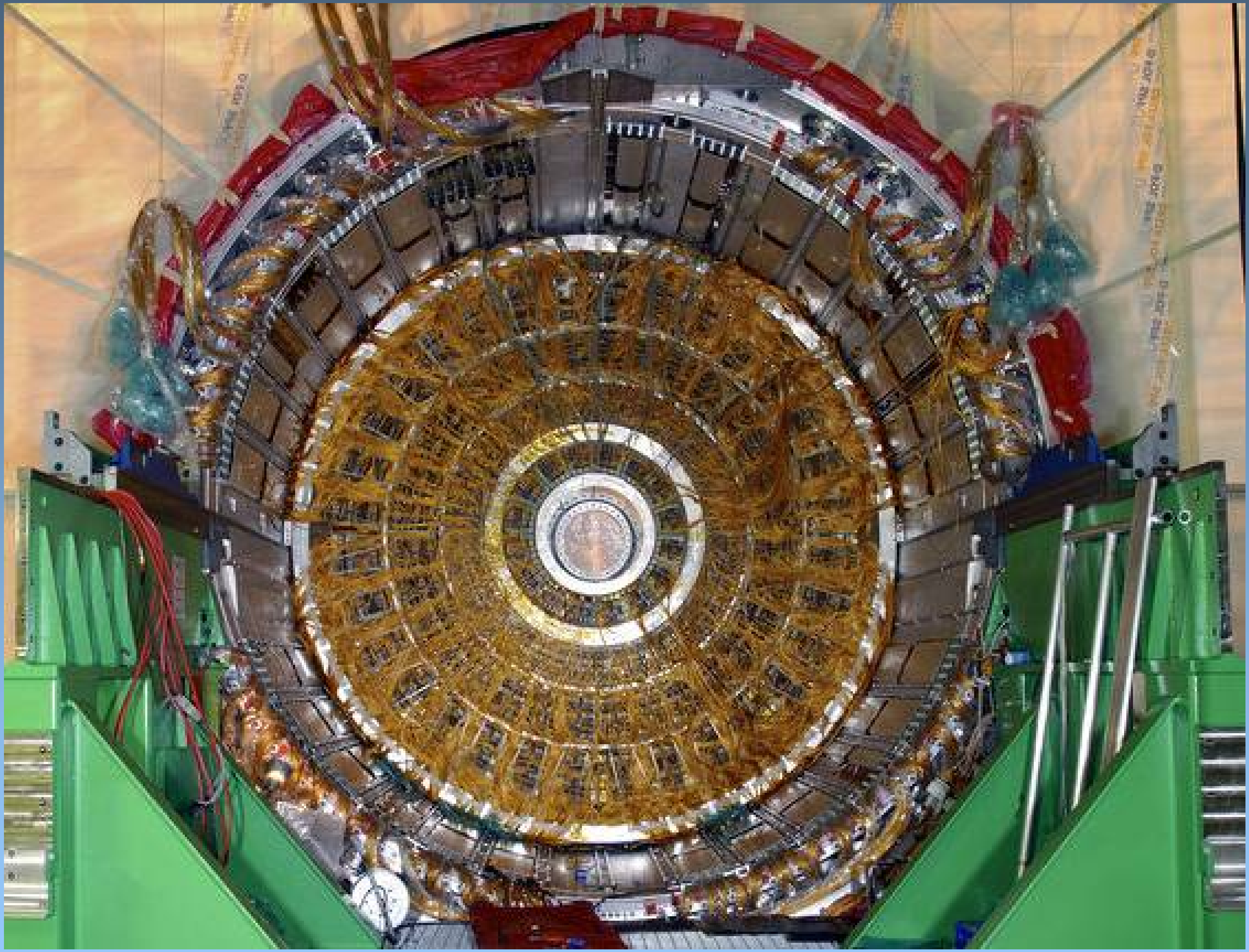
Construction of 1/8 Sector of EMEC

Construction of an EMEC Wheel



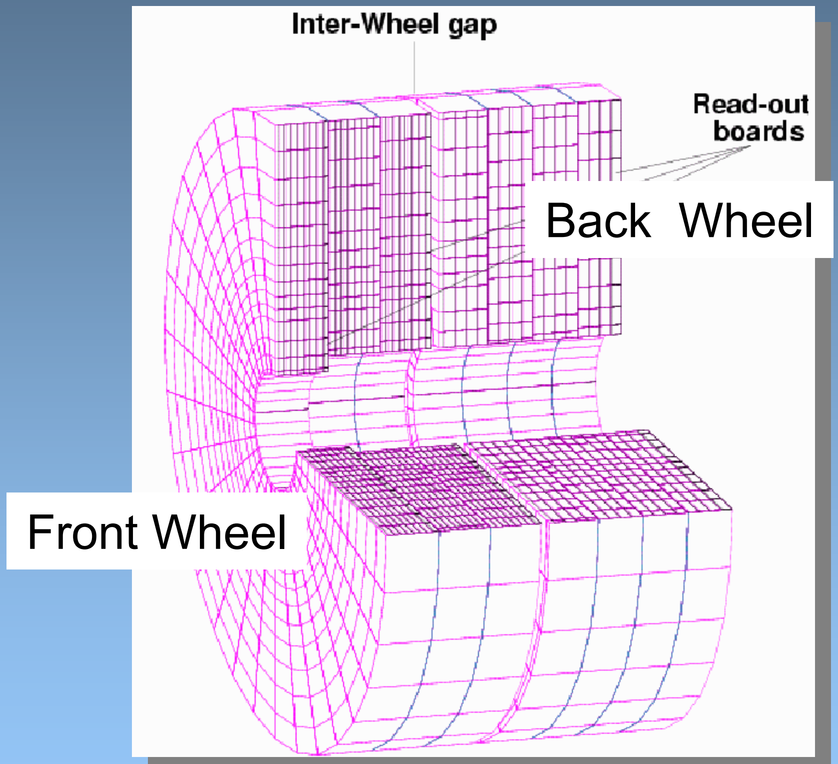
Inner and outer wheels visible

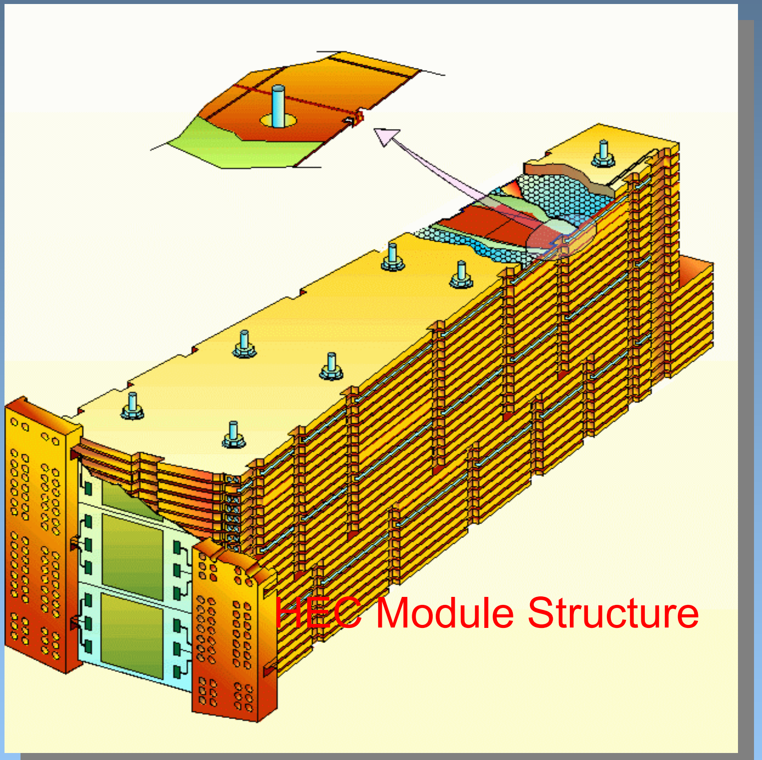
Endcap C EMEC Installed and Cabled



ATLAS Hadronic Endcap Calorimter (HEC)

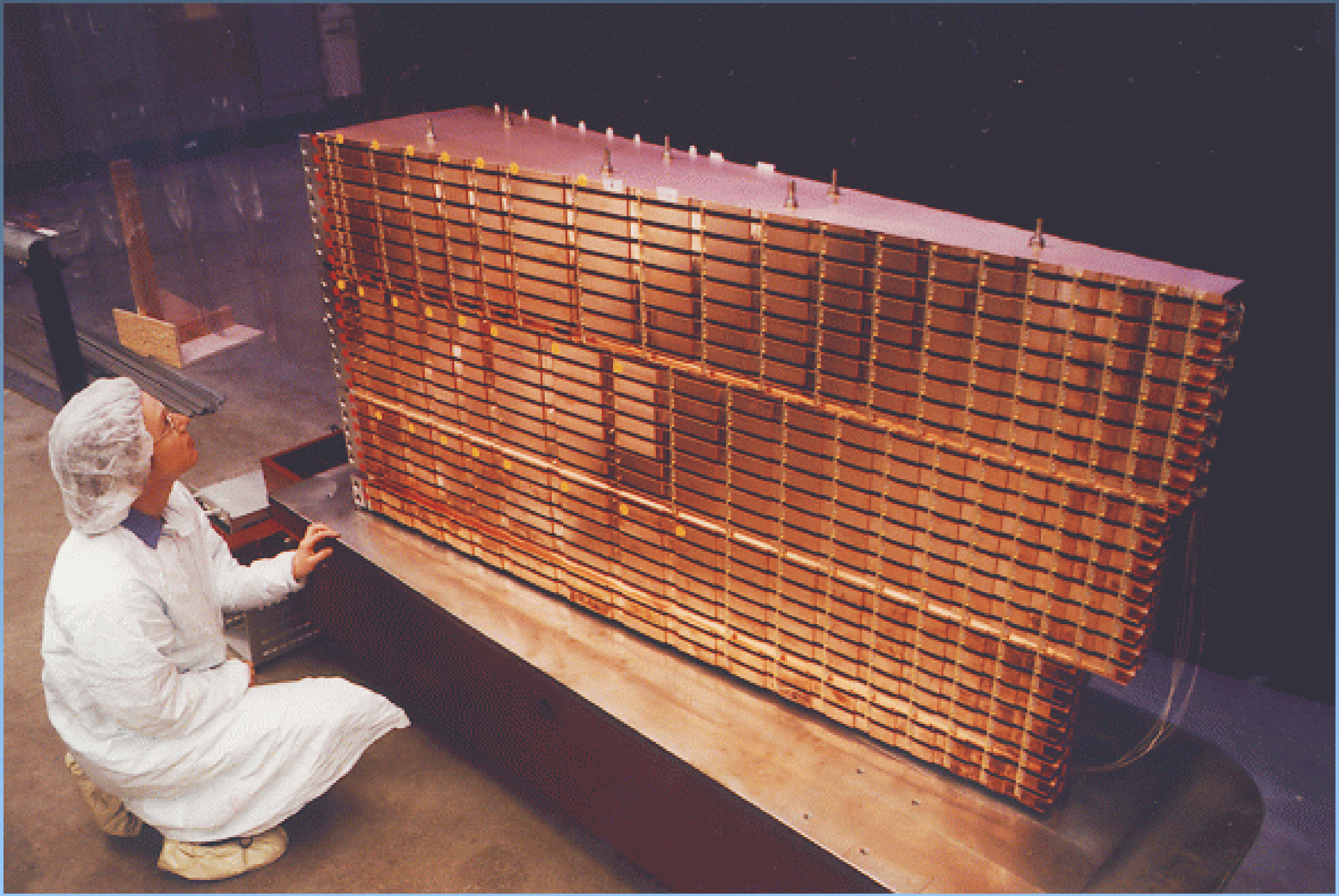
LAr-Cu sampling calorimeter covering 1.5 < η < 3.2



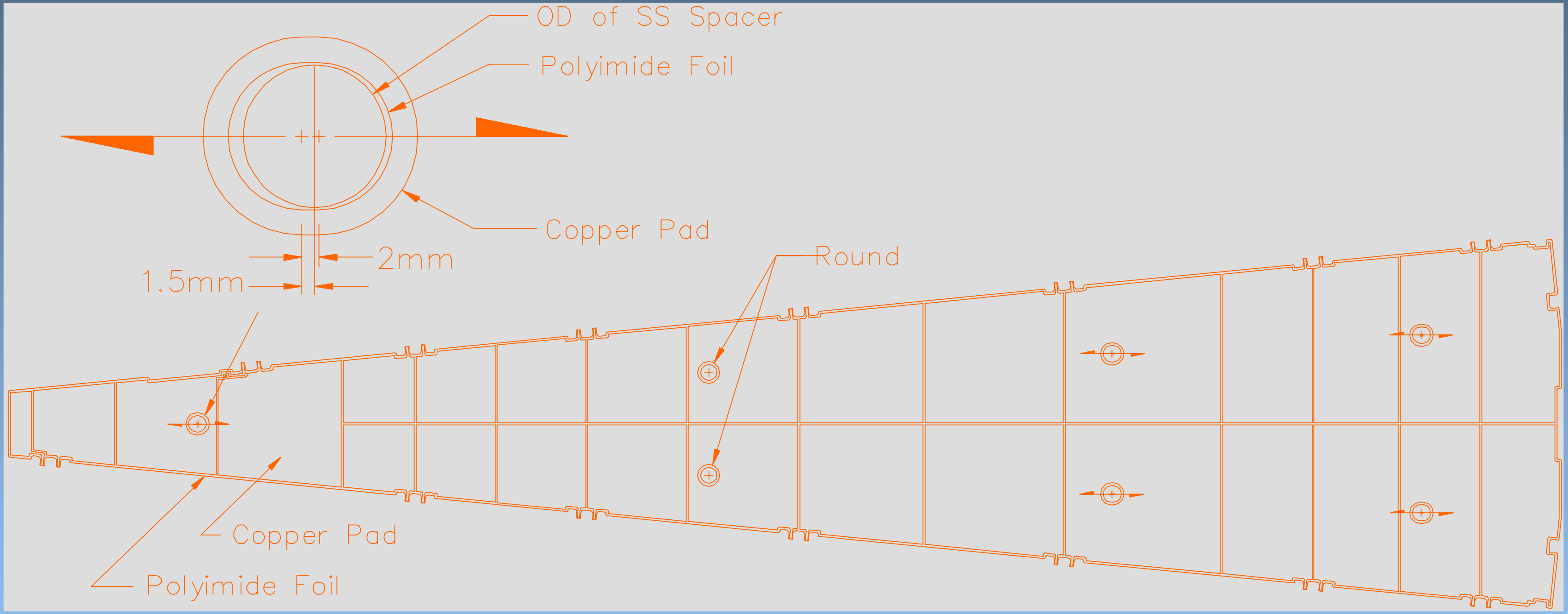


Composed of 2 wheels per end, 32 modules per wheel

HEC Module

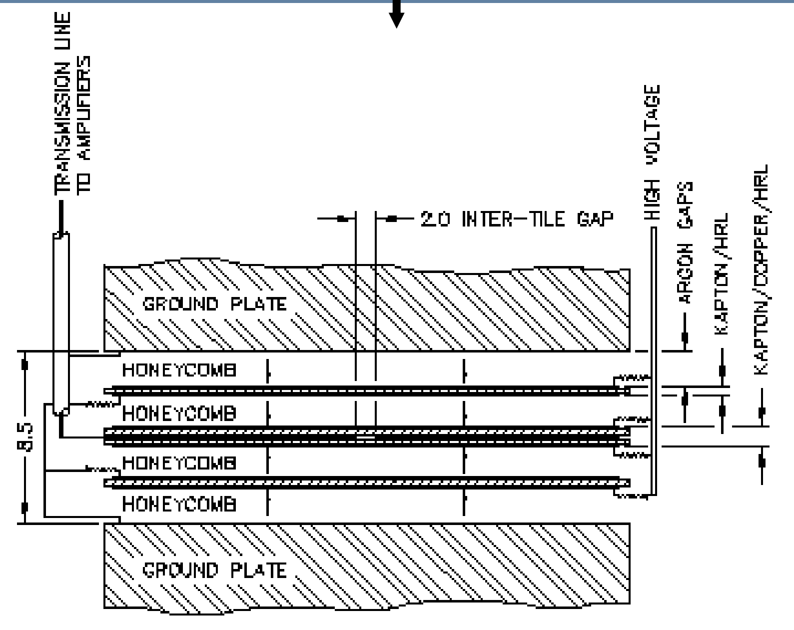


HEC Readout Granularity



HEC Readout Electrode Structure

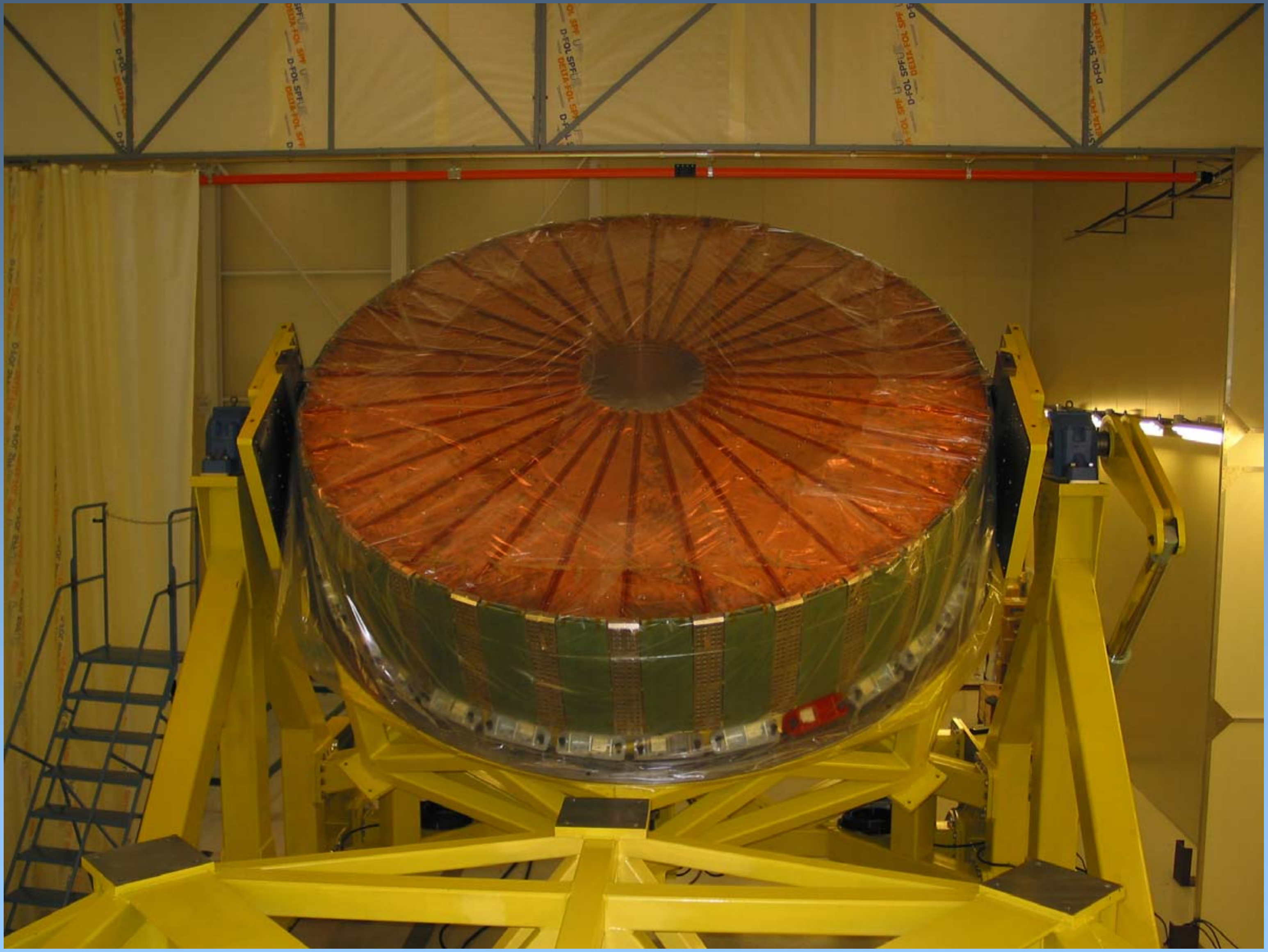
- The read-out structure is electrostatic transformer:
  - Small gap avoids ion build-up
  - Same behaviour as a 4 mm gap with lower HV (2 kV instead of 4 kV)



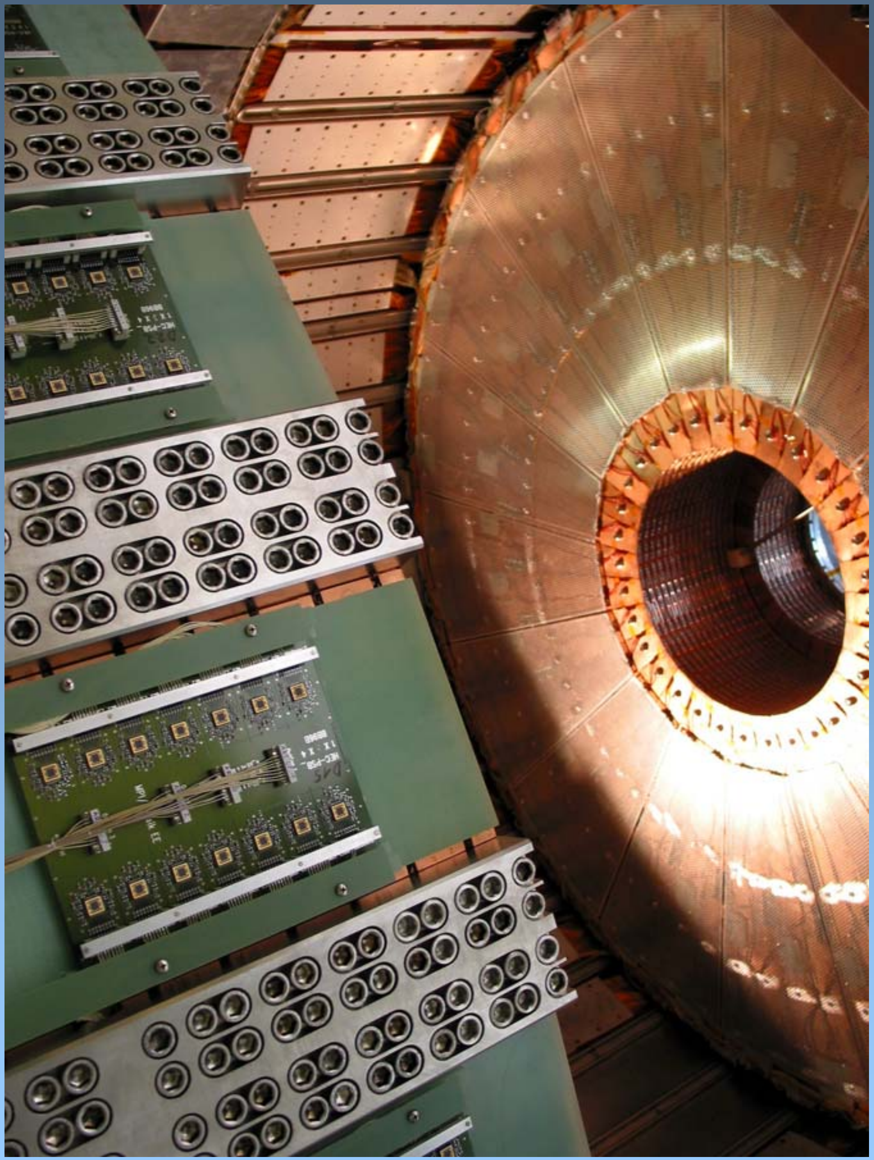
- Robust against H.V. shorts

HEC Module Assembly into HEC Wheel

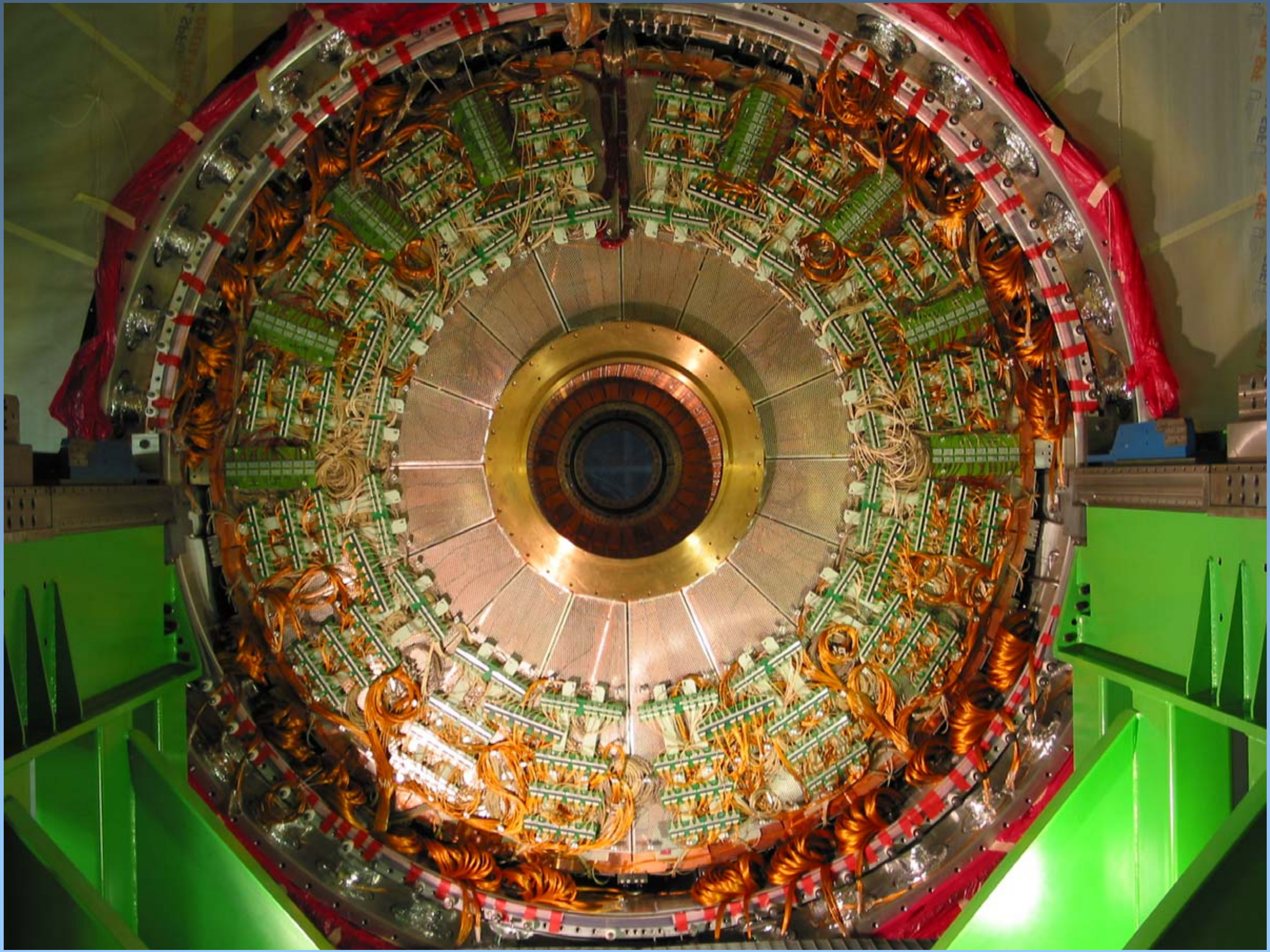
Rotation of HEC Wheel to Vertical (HEC Rotator)



HEC Storage and Insertion into Endcap Cryostat



Endcap C Hadronic Endcap Calorimeter Installed and Cabled

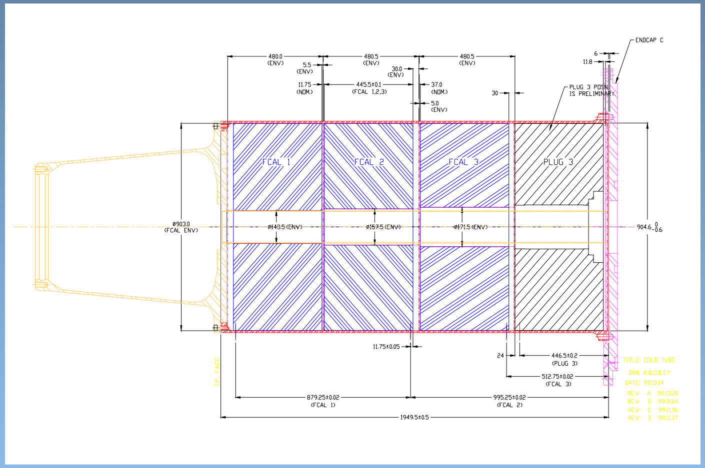


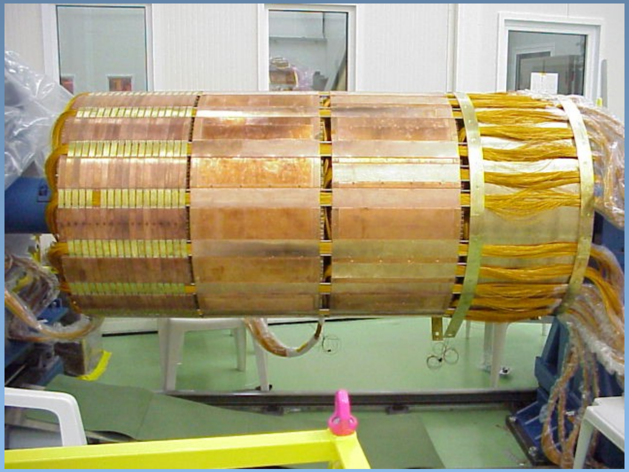
ATLAS Forward Calorimeter

Provides calorimetric hermiticity: covers $3.1 < \eta < 4.9$

Important for determination of missing transverse energy (signature of supersymmetry and other possible new physics scenarios).

Require liquid argon calorimeter with very thin gaps





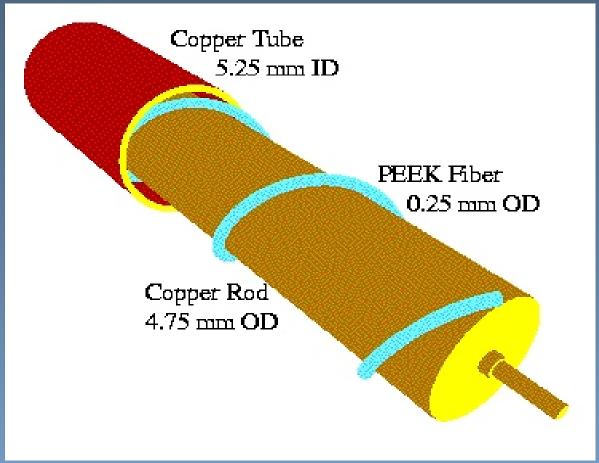
Novel detector design – tubular electrodes in an absorber matrix

- **one copper module (copper electrodes, copper absorber)**
- **two hadronic modules (tungsten electrodes, tungsten absorber)**
- **one uninstrumented brass plug (prevents punch through to muon system)**

Forward Calorimeter Design Concept

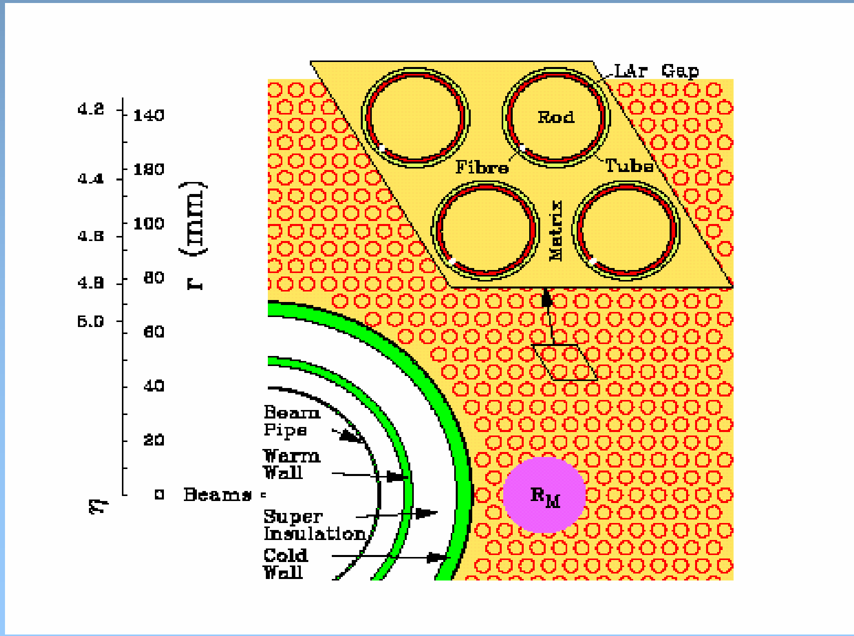
Tubular electrode structure allows for very narrow LAr gaps:

- **FCal1: 250 µm ~ 12K electrodes**
- **FCal2: 375 µm ~ 10K electrodes**
- **FCal3: 500 µm ~ 8K electrodes**

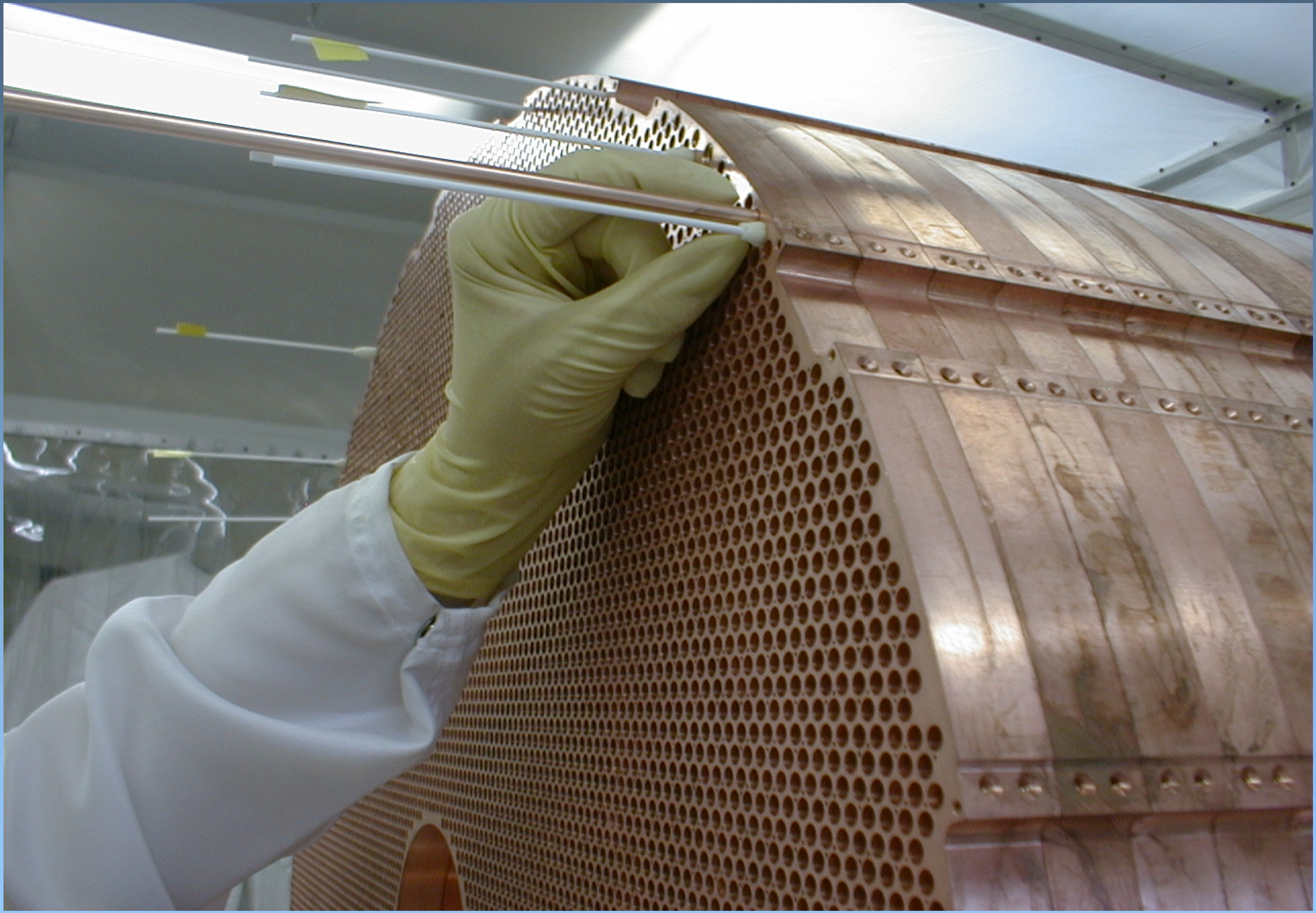


Absorber formed by material matrix containing the electrodes as well as by the electrode rods

- **FCal1 matrix: 18 copper plates**
- **FCal2 matrix: tungsten slugs**
- **FCal3 matrix: tungsten slugs**



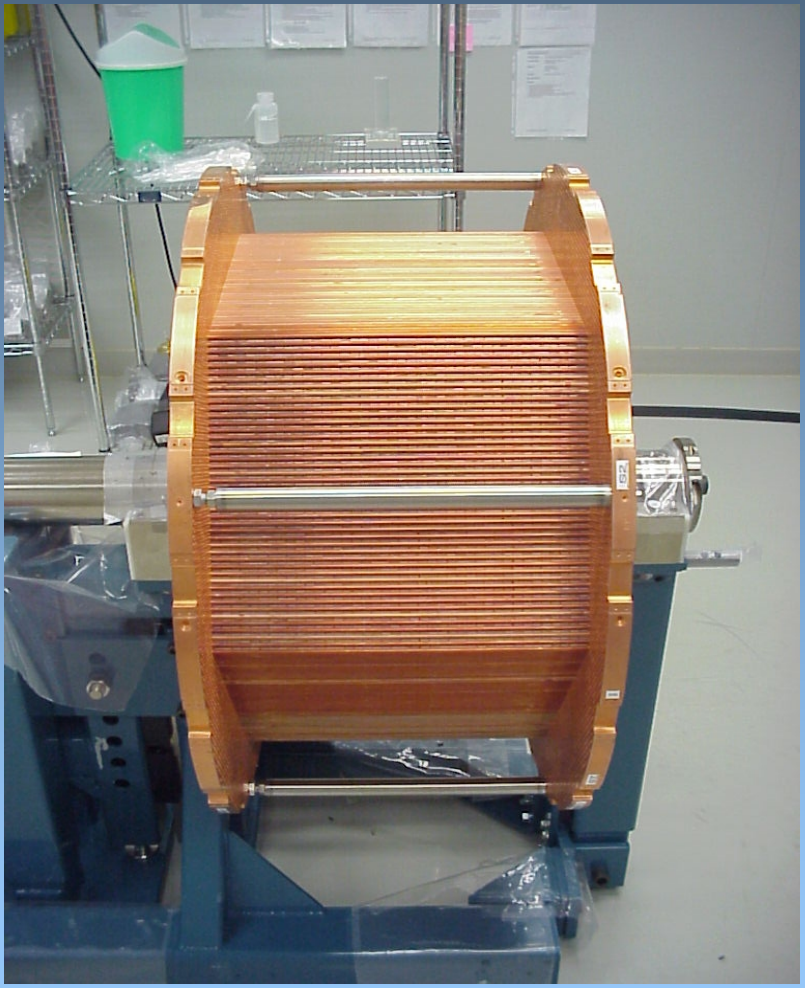
FCal1 Structure / Assembly



Insertion of FCal1 electrode tube

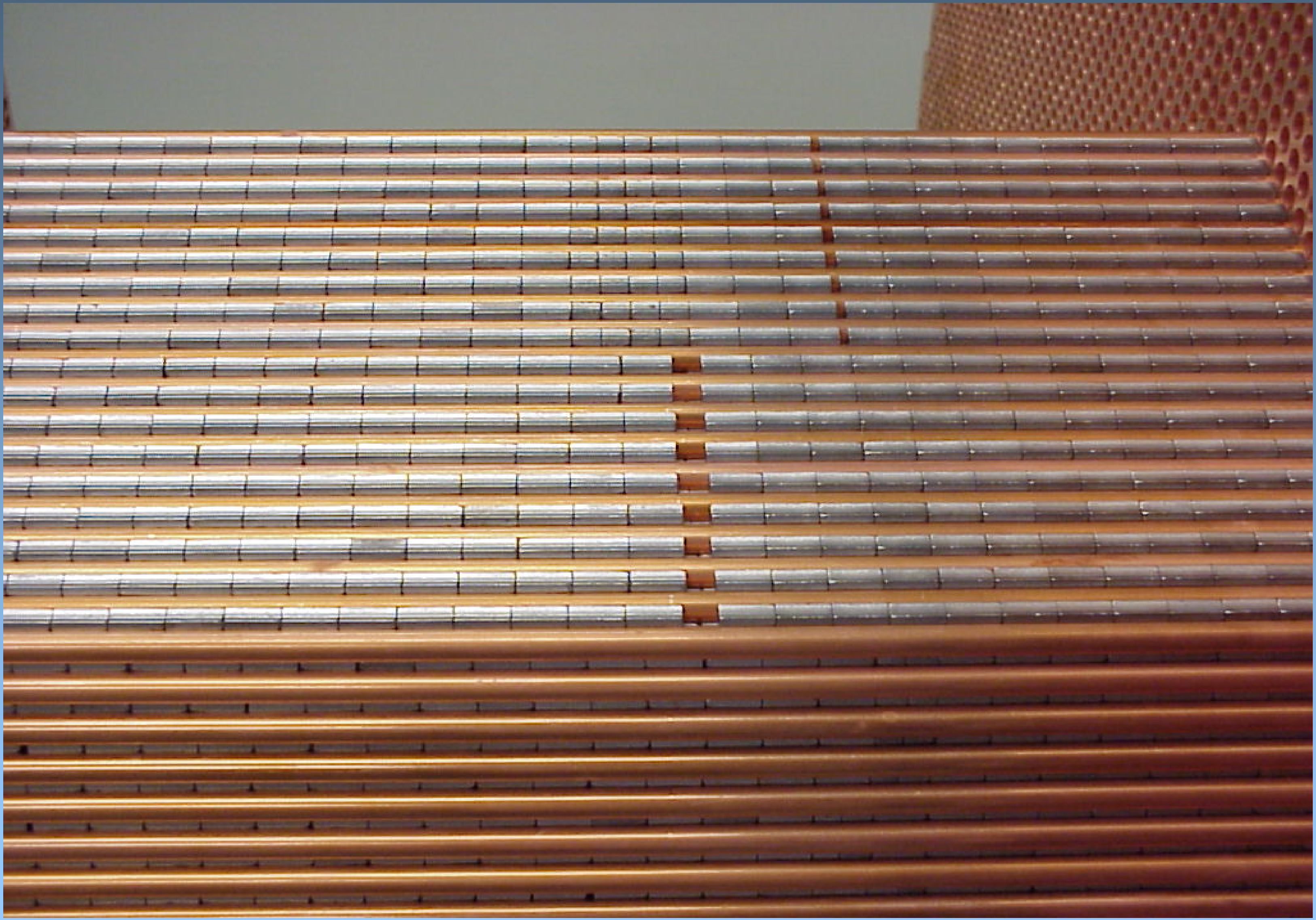
FCal2/3 Structure and Assembly

Endplate and inner absorber assembly



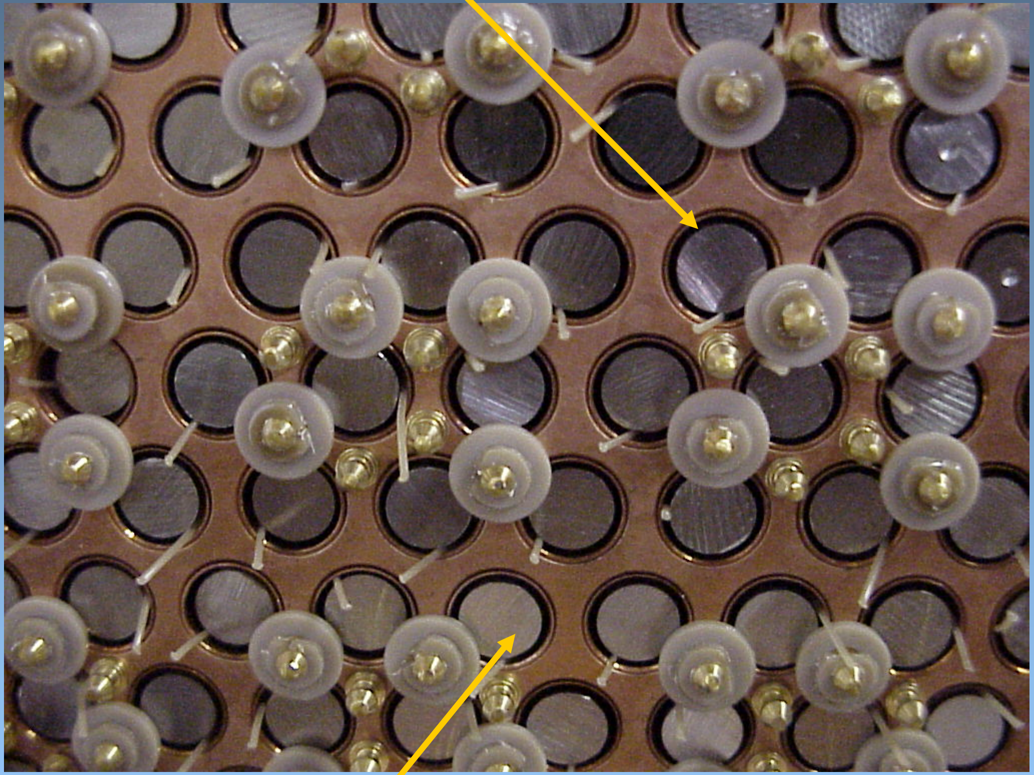
During matrix stacking (tubes and slugs)

Matrix Stacking of Hadronic FCal Module

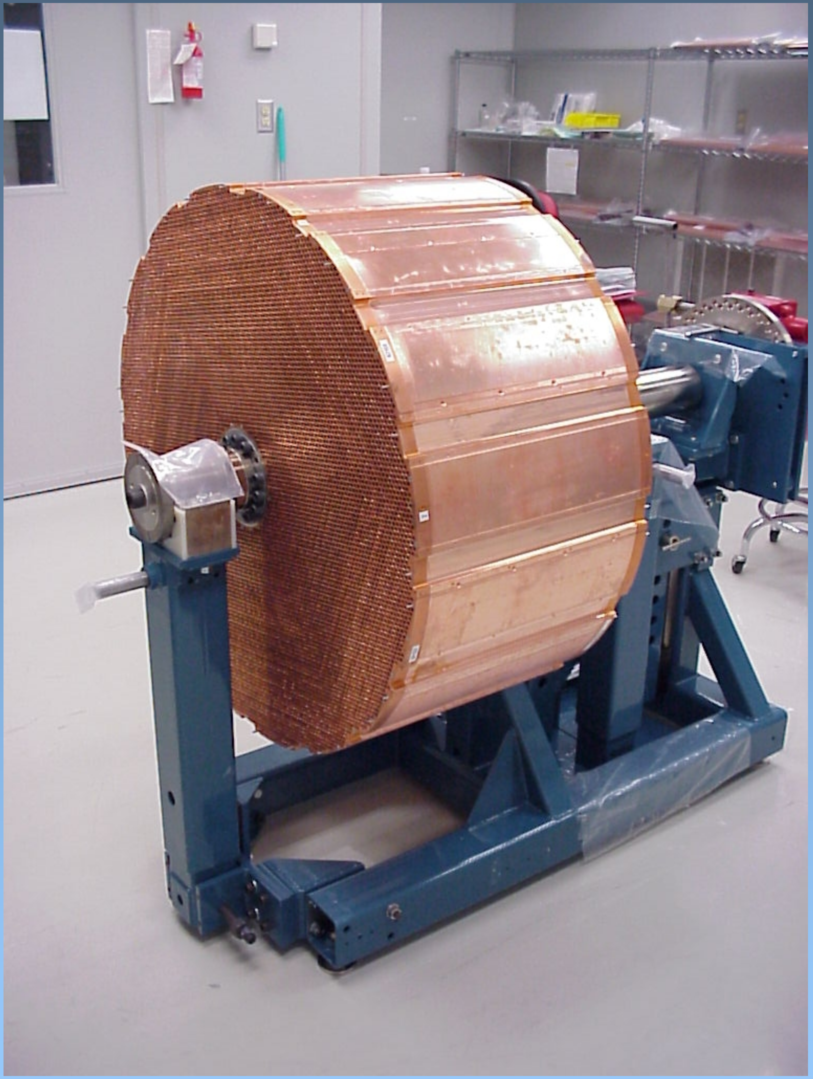


FCal2/3 Structure and Assembled Module

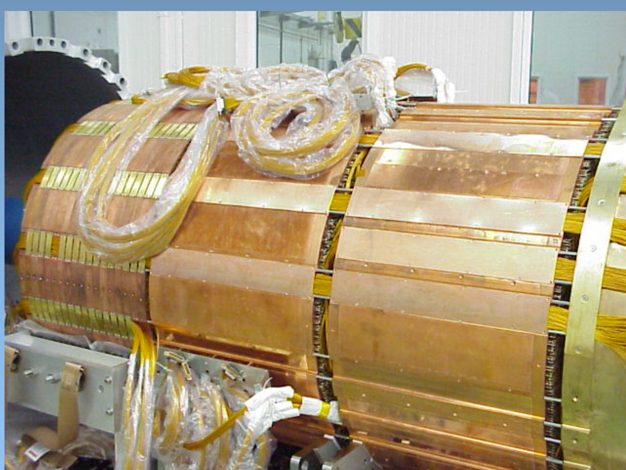
Liquid Argon Gap

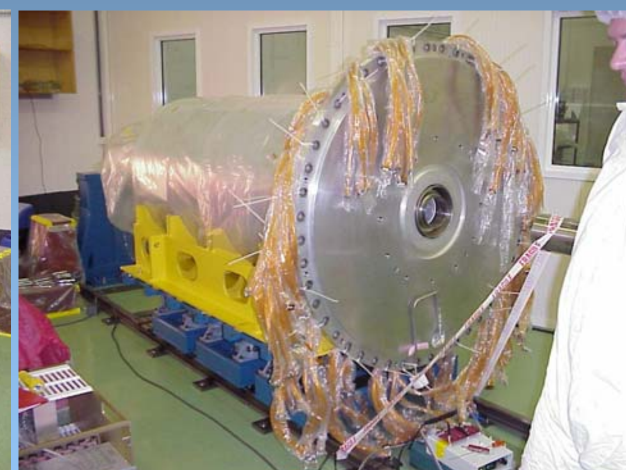


Tungsten Rod



Forward Calorimeter Modules and Final Assembly

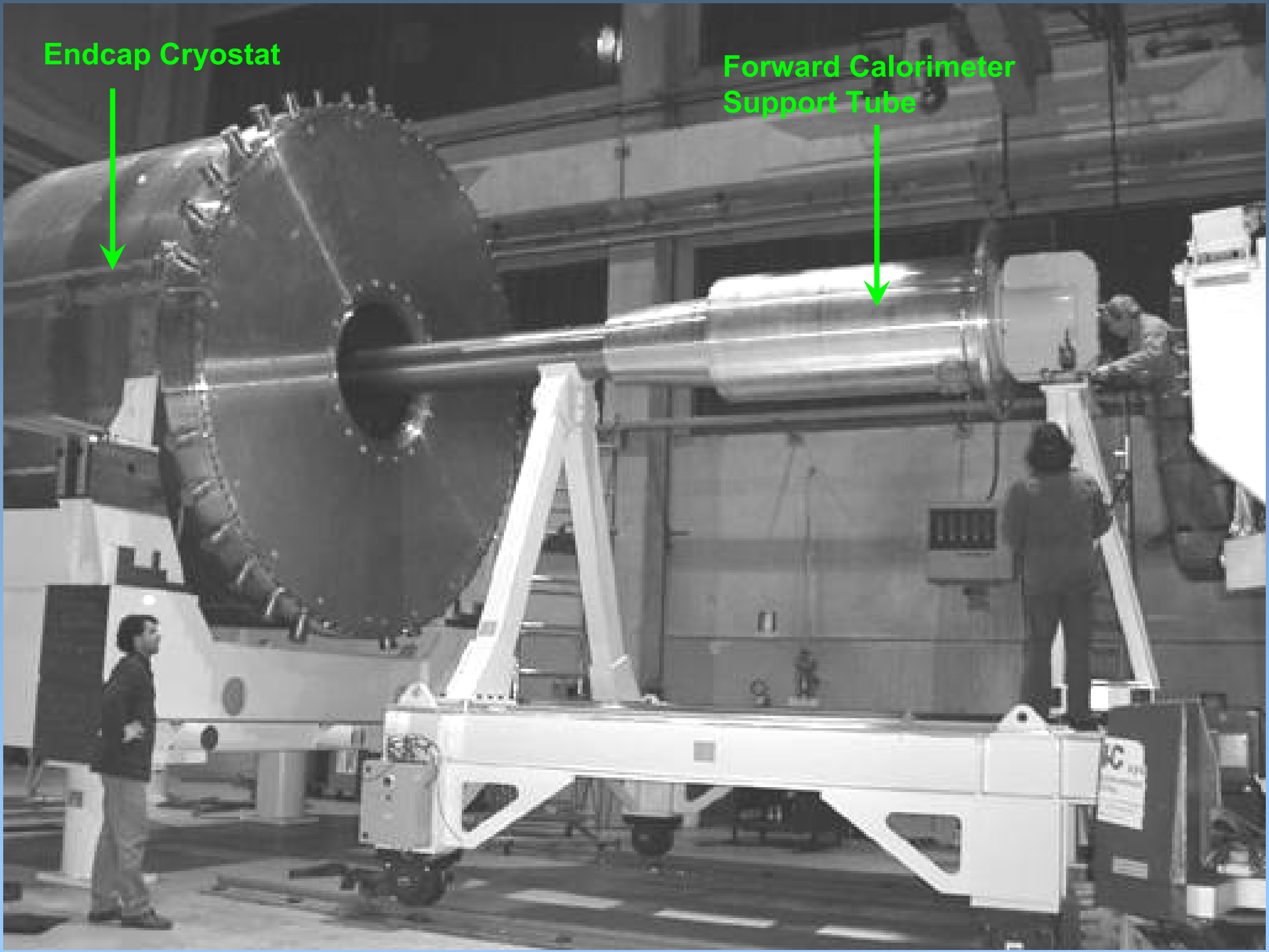




First Integrated FCal ready for delivery to ATLAS

Final assembly of the second FCal will begin this spring. Modules are completed

The ATLAS Endcap Calorimeters



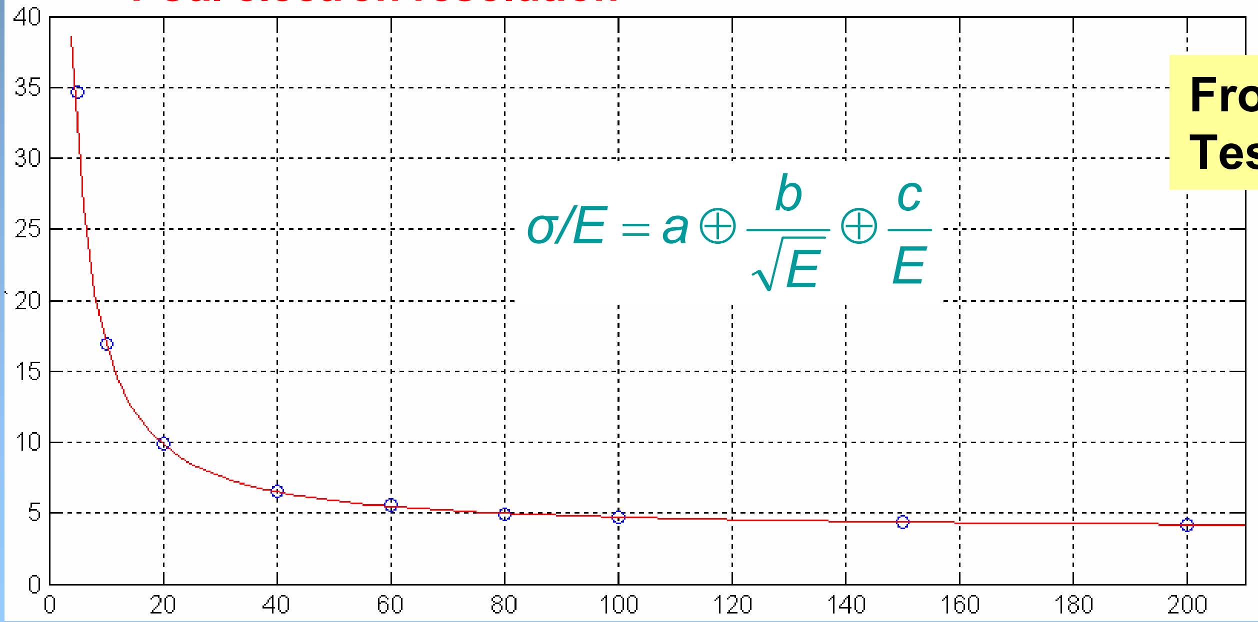
Calorimeter Testbeams

Beam tests of calorimeter prototypes and production module are a critical part of calorimeter development and construction.

EMEC, HEC testbeams are covered in next two talks

Still to come (summer 2004)

- **HEC/EMEC/FCal Combined Testbeam 2004**
- **ATLAS Barrel Testbeam (Full slice through ATLAS barrel, including tracking)**



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

From the 2003 FCal Testbeam

a=(3.76±0.06)%,
b=(24.5±0.84) √GeV %,
c=(145.5±1.6) GeV%

Exceeds design goal