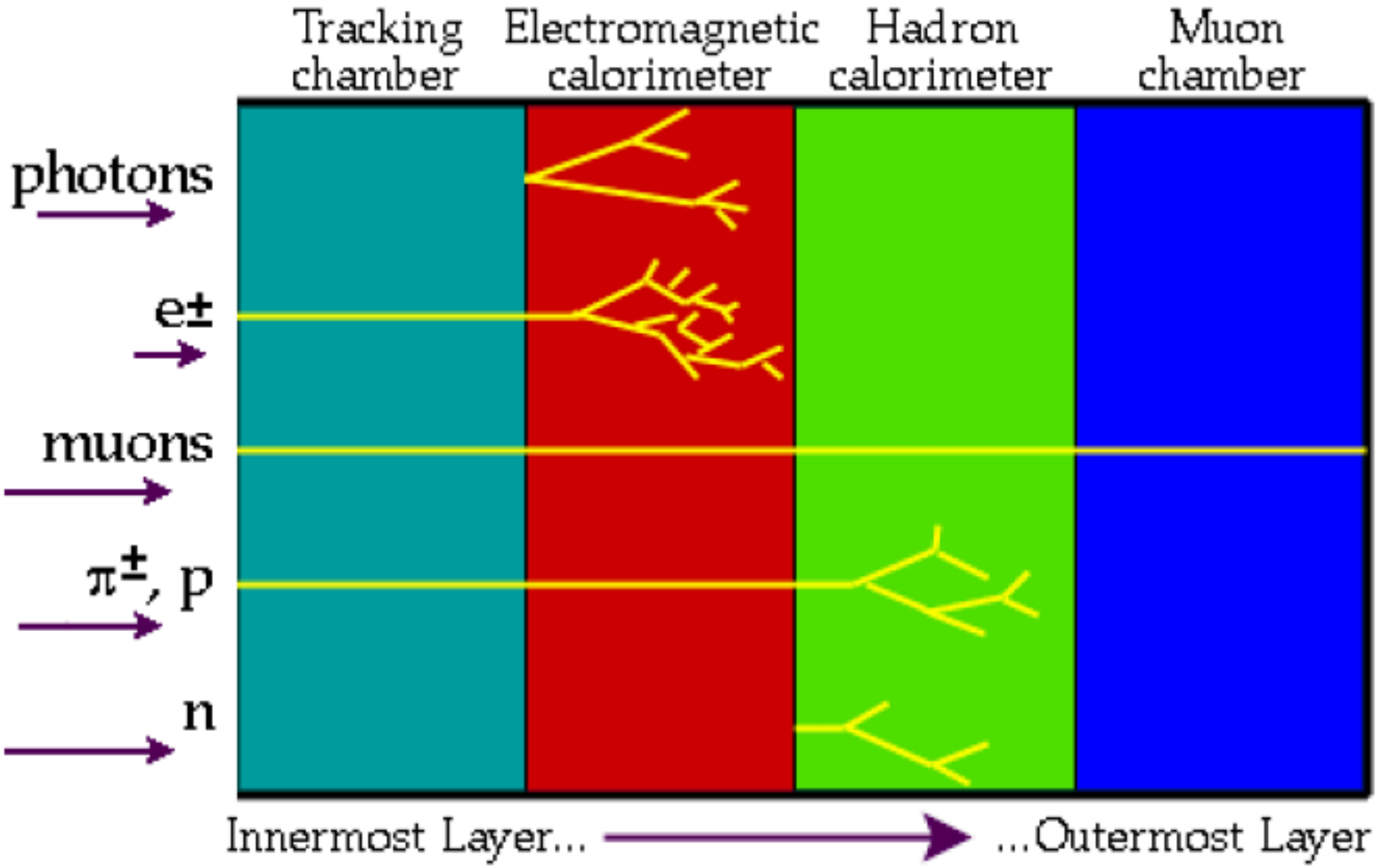
Lecture 8 – Detectors - II

Calorimetry

Considerations for designing a collider detector -- with LHeC as an example

Introduction to Particle Physics - Max Klein – Lecture 8 - Liverpool University 17.3.14

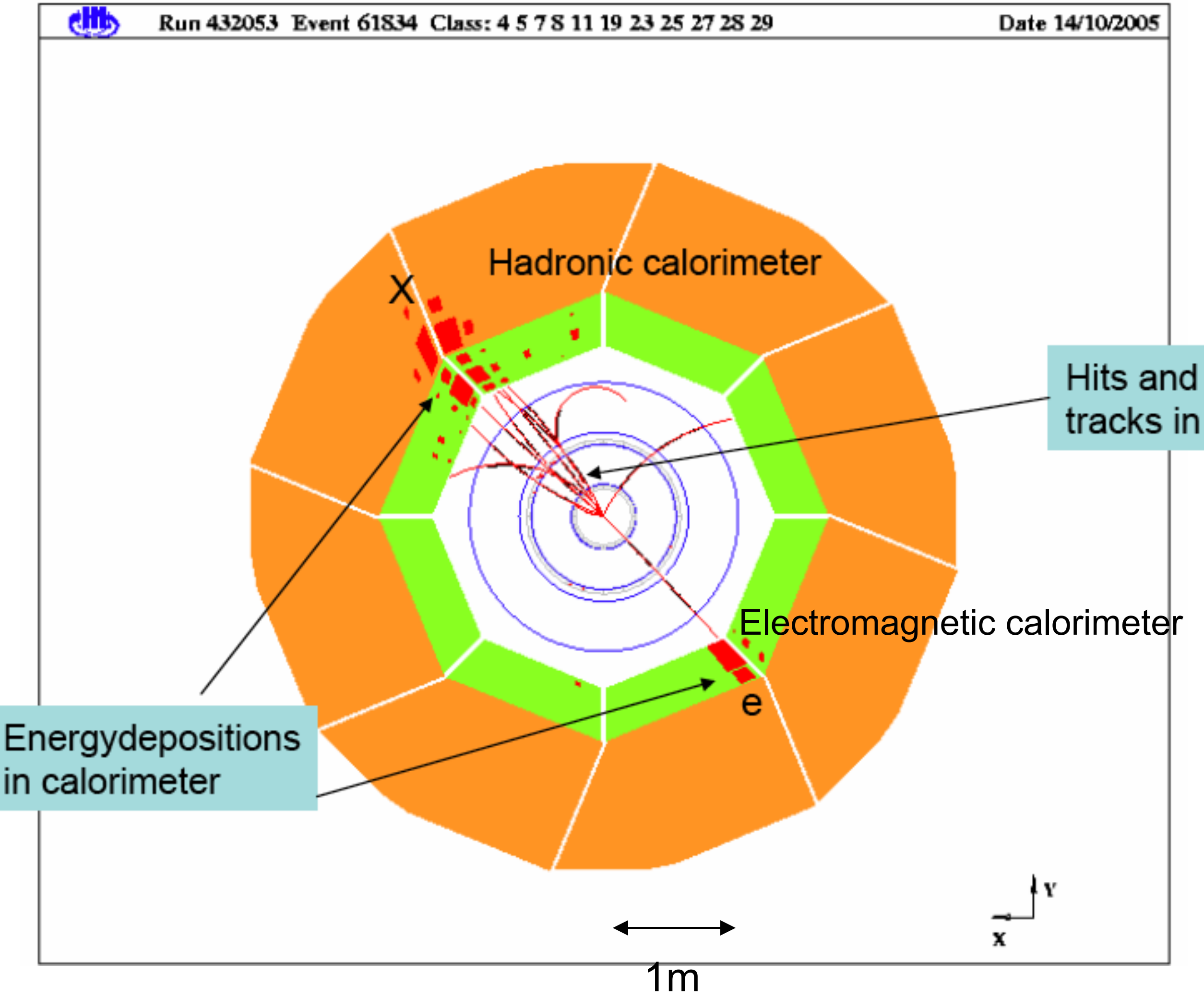
Particle Identification



→ **ν** neutrino carries energy away (“missing E”) **-- Hermetic Detector!**

H1 DIS event in xy view

$$ep \rightarrow e' X$$



Hits and reconstructed tracks in tracker

Energydepositions in calorimeter

Calorimeters

Sensitive to charged and neutral particles

Cascade (showers of particles) N ~ E: $\sigma/E \sim 1/\sqrt{E}$

Longitudinal dimension scales ~ lnE

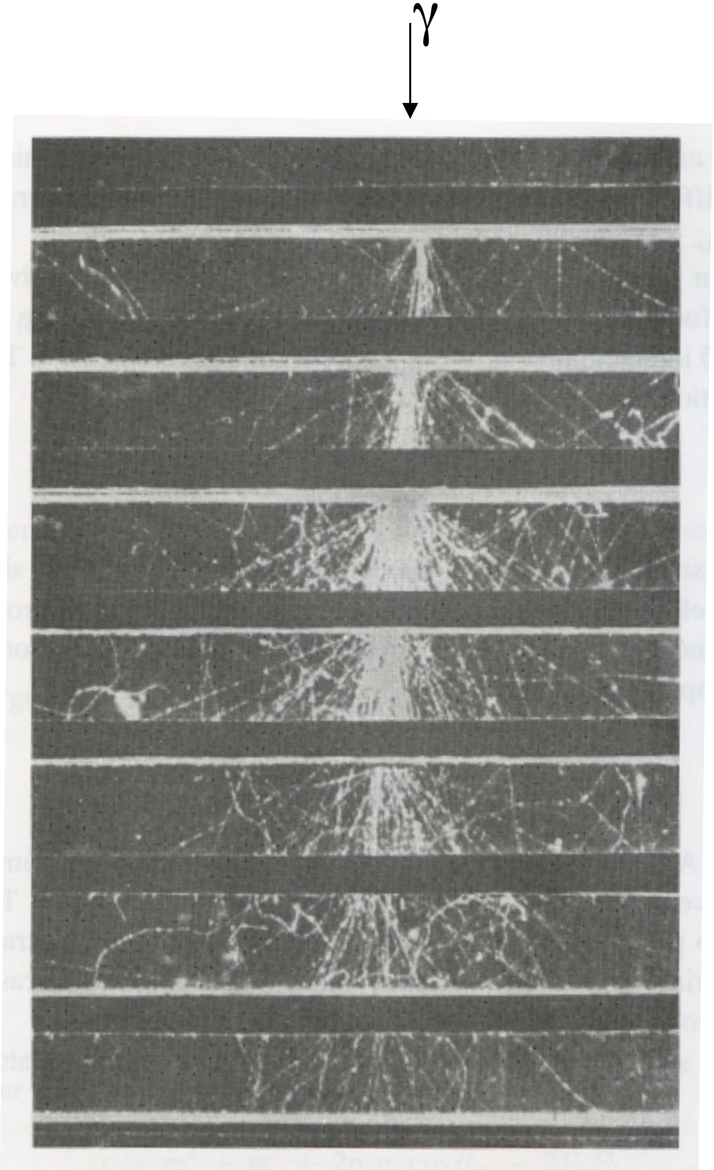
Segmentation: spatial and angular information

Different response to e, h, μ: particle ID

Hermetic coverage to detect neutrinos ("missing E")

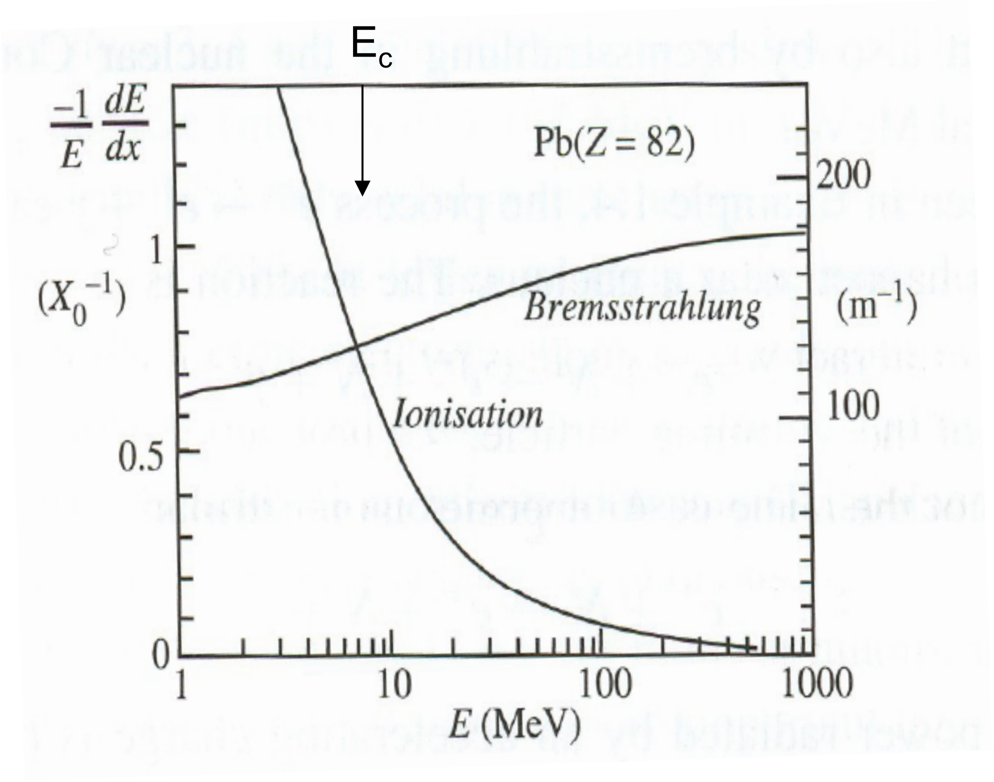
Fast time response: high rates, time measurement

Calorimeters are "sampling calorimeters":
Several layers of active medium/absorber for optimum energy deposition and measurement



An electromagnetic shower. (From Rossi 1952)

Electromagnetic energy loss - electrons



$$-\frac{dE}{dx} = N \cdot E \cdot \Phi$$

$$N = \frac{\rho N_A}{A}$$

$$\Phi = 4\alpha r_e^2 f(Z)$$

$r_e^2 \sim m_e^{-2}$: muon deposits 2 10^{-5} times less energy than electron by the bremsstrahlung process.

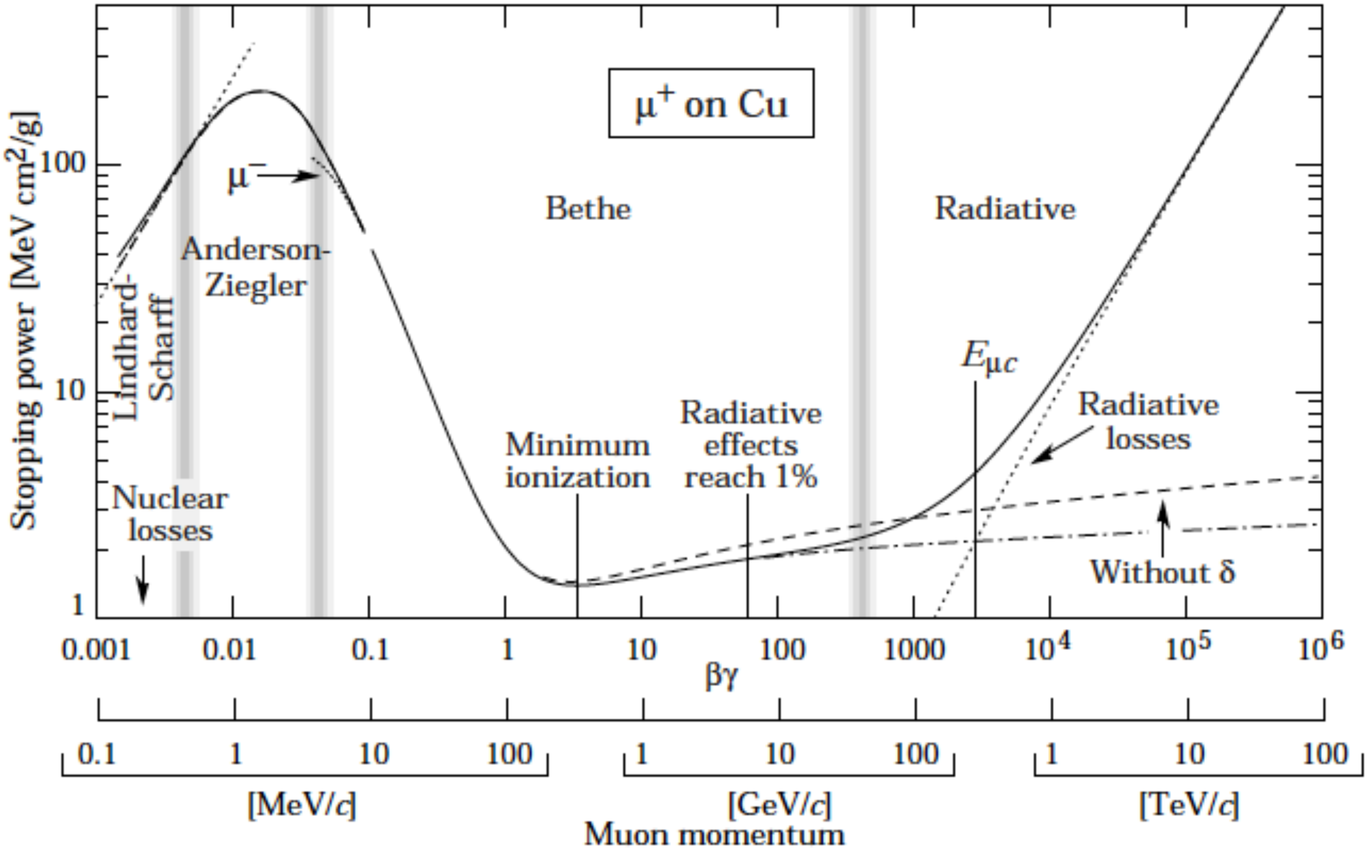
$$-\frac{dE}{dx} \propto E \cdot Z^2$$ Bremsstrahlung

$$-\frac{dE}{dx} \propto \ln(E) \cdot Z$$ Ionisation

$$E_c \approx \frac{800\,MeV}{Z+1.2}$$ critical energy

Bremsstrahlung dominates rather uniform energy loss: high resolution of elm calorimeters

Muon Energy Loss



Critical energy for muons very large.
E_c = 200 GeV in Pb
(~10 MeV for electron)

Muon energy losses for precision measurements and high momenta have to be controlled too

Taken from PDG2010

Radiation Length

$$-\frac{dE}{dx} = E \cdot N \cdot \Phi$$

$$E = E_0 \cdot e^{-x/X_0}$$

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$\frac{1}{X_0} = N\Phi$$

$$\frac{1}{X_0} = 4\alpha r_e^2 \cdot \frac{\rho N_A}{A}\left\{Z^2 (L_{rad} - f(Z)) + Z\, L'_{rad}\right\}$$

Y.T. Tsai Rev.Mod.Phys 46(1974)815

$$\xi = \frac{1 \cdot [gmol^{-1}]}{4\alpha r_e^2 [cm^2] N_A [mol^{-1}]} = 716 gcm^{-2}$$

$$X_0 \approx \frac{A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}} \cdot \frac{716[gcm^{-2}]}{\rho[gcm^{-3}]}$$

X_0 distance over which 1/e of E_0 is lost in bremsstrahlung
also = 7/9 of mean free path of a photon [$\gamma Z \rightarrow Ze^+e^-$]

Energy loss is additive: $\frac{1}{X_0} = \sum_i \frac{f_i}{X_{0,i}}$

For example: Air: f(N)=0.77, f(O_2)=0.22, f(Ar)=0.01, X_0 =0.3km

Absorbers for electromagnetic calorimeters:
Pb: X_0 =0.56 cm, Fe: X_0 = 1.6 cm

Electromagnetic Calorimeter

Radiation length

$$E = E_0 \cdot e^{-x/X_0}$$

$$X_0 = \frac{1}{N\Phi}$$

$$L(95\%) = 20X_0$$

Pb: X_0 =0.56 cm, Fe: X_0 = 1.6 cm

Electromagnetic calorimeters are rather compact. They are placed in between the tracker and the hadronic calorimeter. They thus represent the first stage of the hadronic energy measurement. If space and cost permit, the magnet coil is outside the calorimeters – not possible for LHeC:

20 layers 0.56cm plus LAr gaps: ~40cm

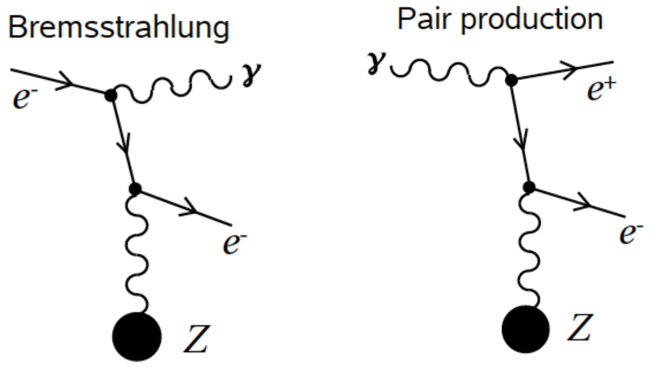
Lateral extension

Shower extends perpendicularly to incident direction due to bremsstrahlung (ϑ~E/m) and multiple scattering

$$\rho_M = \frac{21MeV}{E_c} X_0$$

95% of shower is contained in cone of one Molière radius (1.8cm in lead)

Electron and photon energy loss very similar: $\sigma_\gamma = 7/9\sigma_e$



Hadronic Calorimeter

Hadronic energy loss

Particle production (strong interaction)
$n \sim 20 \ln(E/\mathrm{GeV}) - 18$ secondaries

Nuclear collisions and excitations

Electromagnetic interactions ($\pi^0 \rightarrow \gamma\gamma$)

Ionization, muons, neutrinos

Stronger fluctuation of energy loss
than for electromagnetic interactions.
Thus the resolution is worse.

Fe: $\lambda\rho = 132\ \mathrm{g/cm^2}$ $\lambda = 17\ \mathrm{cm} = 10\ X_0$

The hadronic calorimeters are placed behind electromagnetic ones and used as "tail catchers" of the elm. shower

Interaction or absorption length

$$\lambda = \frac{A}{N_A \rho \sigma}$$

$$\sigma = \pi \cdot r_A^2$$

$$V_A = \frac{4\pi}{3} r_A^3 = A \frac{4\pi}{3} r_p^3$$

$$r_A = r_p \cdot A^{1/3}$$

$$\lambda = 35 \frac{g}{cm^2} \cdot \frac{A^{1/3}}{\rho}$$

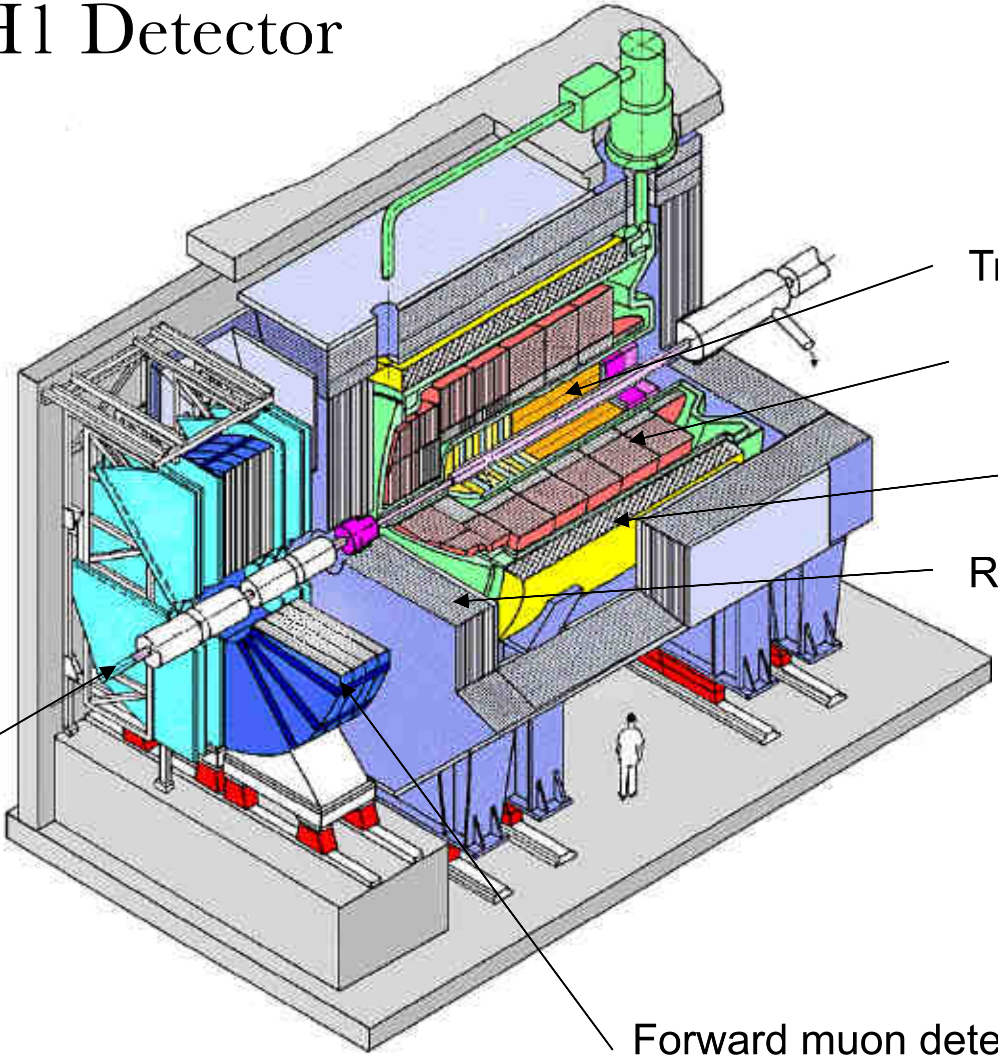
95% of secondaries are confined in 1 λ

A shower is absorbed fully after 7 λ

ATLAS

Scintillator tile – Fe Calorimeter ($7\lambda = 1.1\mathrm{m}$)

H1 Detector



Tracker

Liquid Argon Calorimeter

Coil

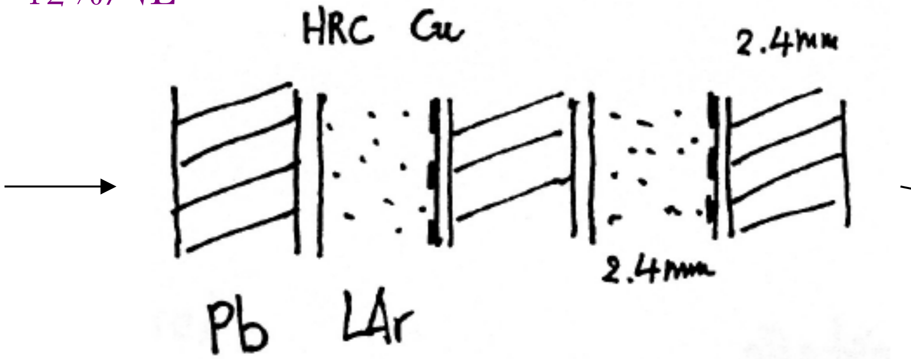
Return Iron/ μ Detector

beam line

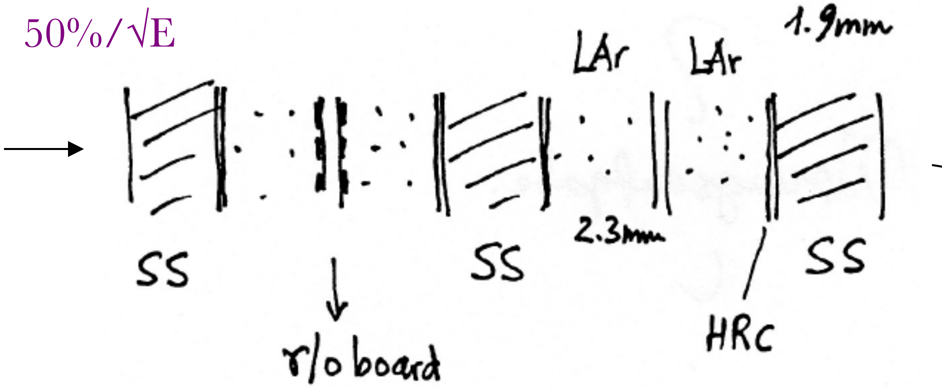
Forward muon detector

H1 Liquid Argon (LAr) Calorimeter

elm.
$25X_0$
$12\%/\sqrt{E}$



Hadr.
7λ
$50\%/\sqrt{E}$

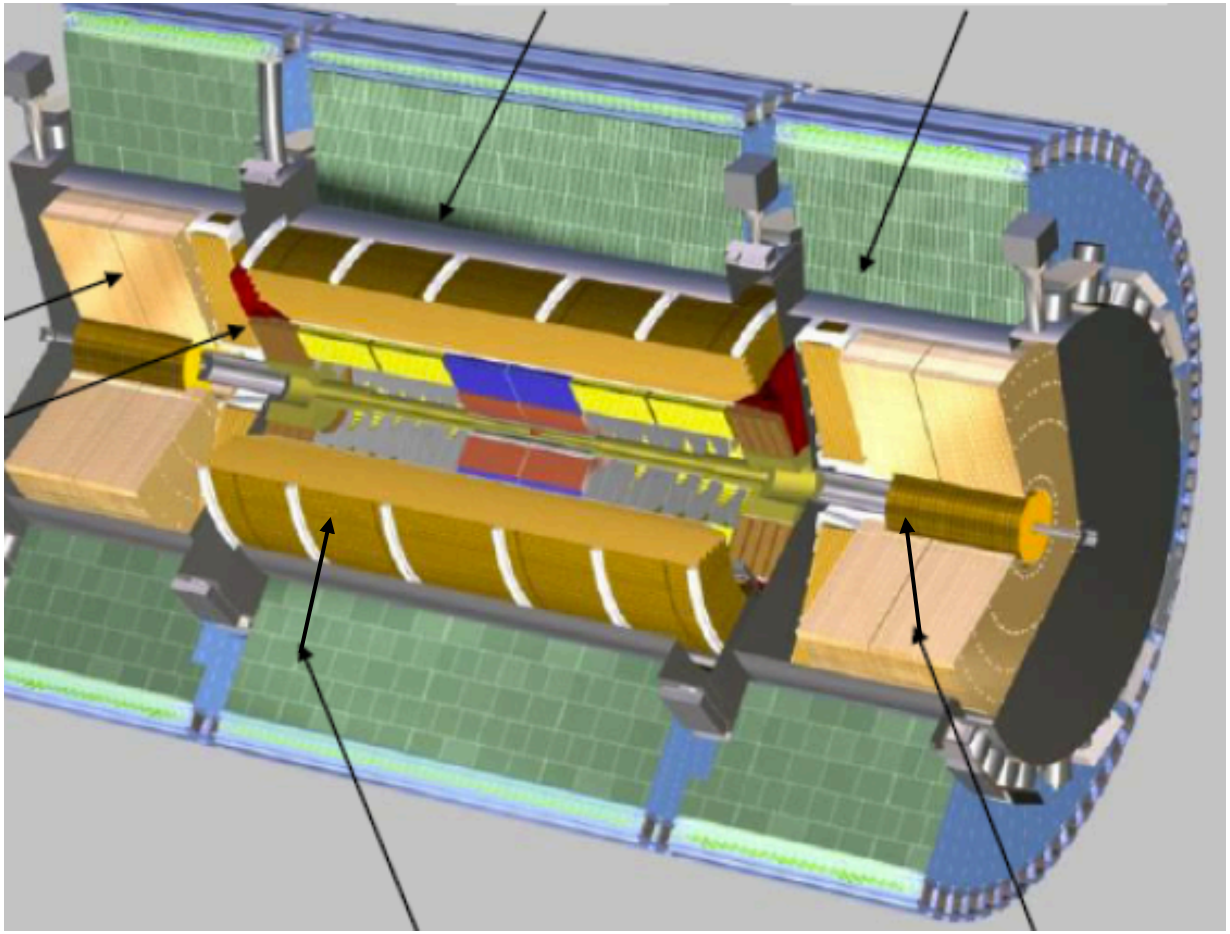


Pb: G10|Lead\G10, SS: stainless steel

HRC: high resistive coating (10MΩ/area)

Photograph after deassembly, October 2007

ATLAS Calorimeters



Tile barrel and extended barrel

LAr

hadronic

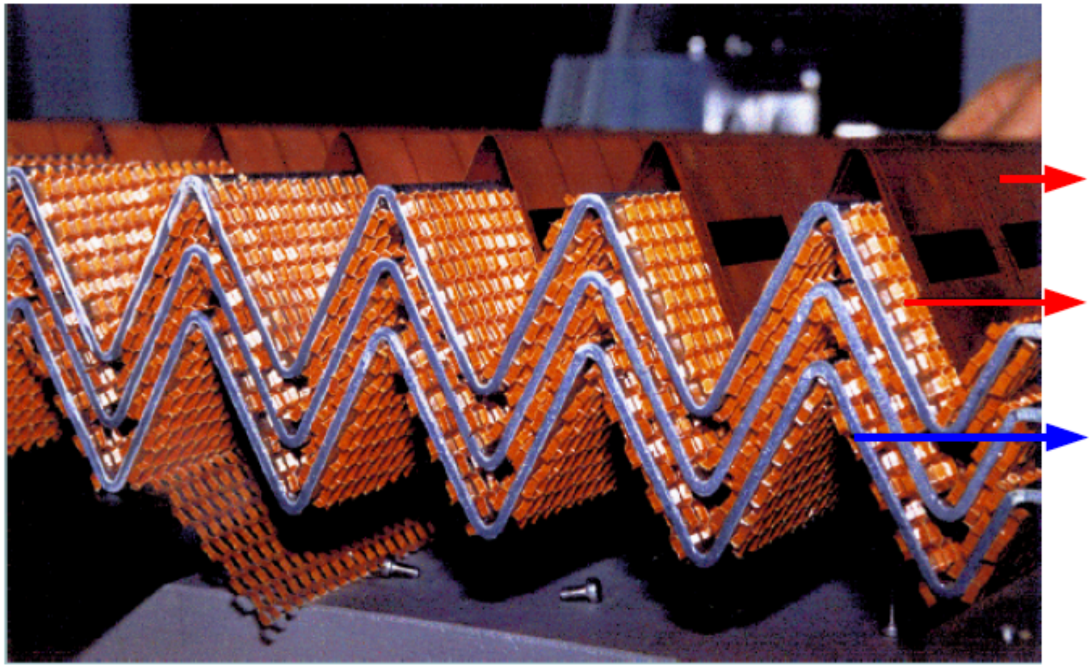
electromagn.

endcaps

Central barrel electromagnetic

Forward calorimeter

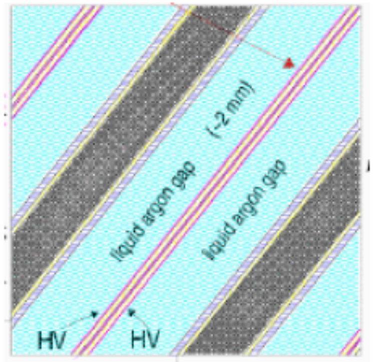
ATLAS LAr Electromagnetic Calorimeter



Cu electrodes at +HV

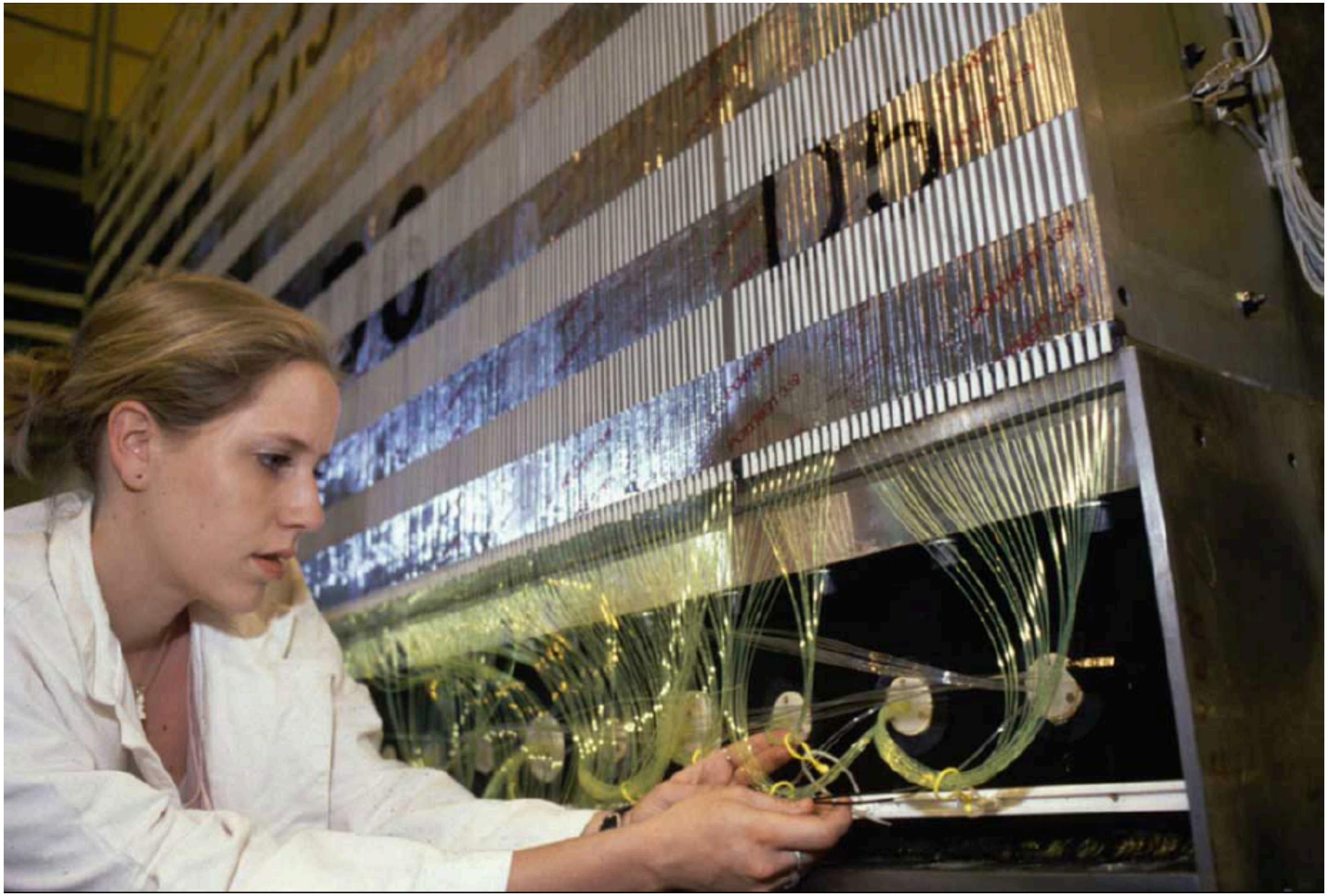
Spacers define LAr gap
2 × 2 mm

2 mm Pb absorber
clad in stainless steel.



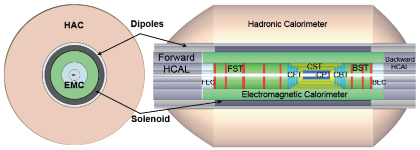
D.Pitzl

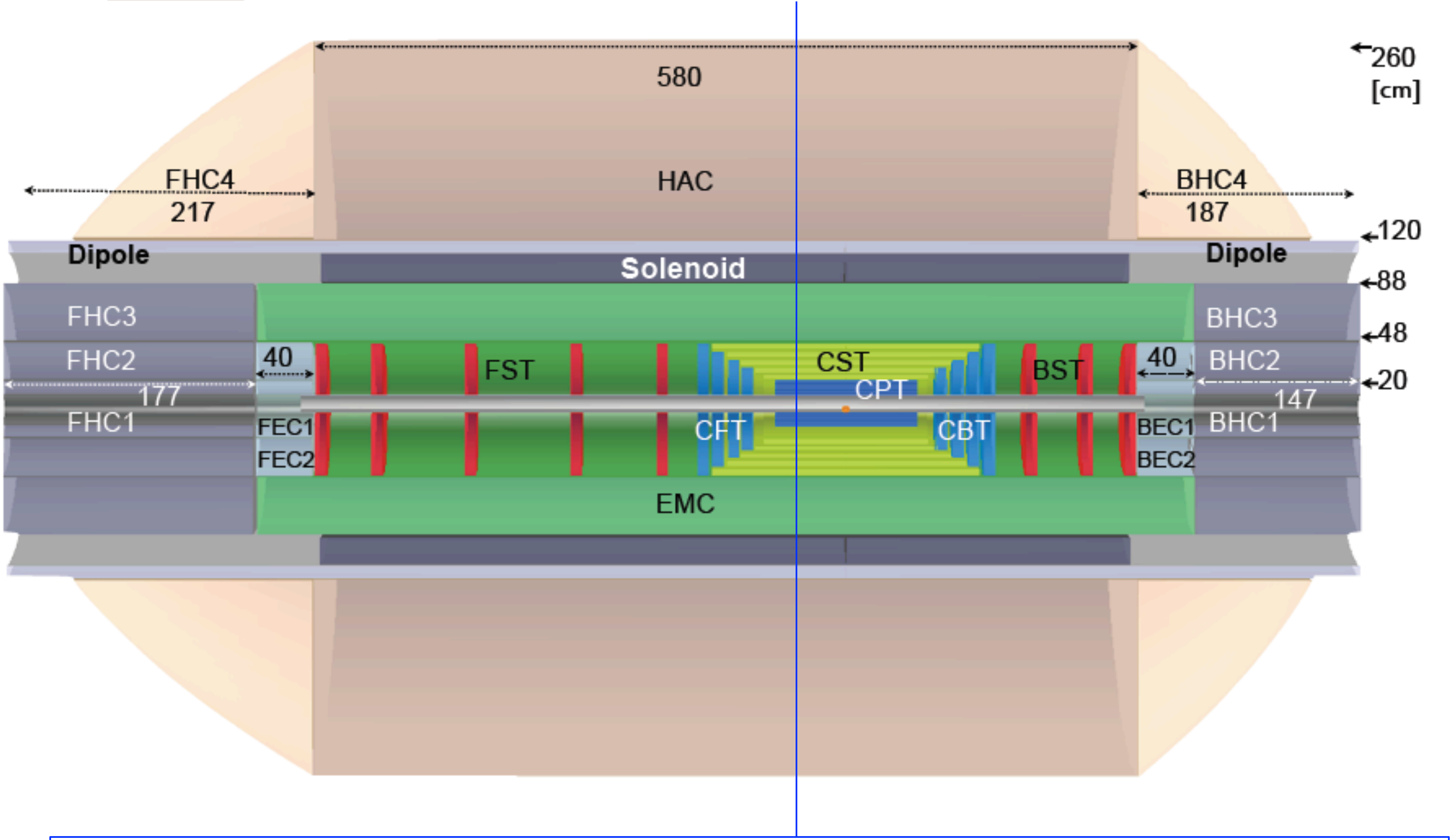
ATLAS Scintillator Tile Hadronic Calorimeter



Scintillator and Fe absorber, read out perpendicular to beam axis

LHeC Detector*)





Central silicon tracker: 48cm, EMC: D=40cm, Solenoid: R=1m, HAC: D=140cm

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*) from LHeC design report 2012

Dimensions of the LHeC Detector

$$\frac{\delta p_T}{p_T^2} = \frac{\Delta}{0.3BL^2} \cdot f$$

$$CST : \frac{\delta p_T}{p_T^2} := 5 \cdot 10^{-4} GeV^{-1}$$

$$B = 3.5T, \Delta \approx 10\mu m, N = 9, L = 0.4m$$

Tracker: Silicon only, compact, D=50cm

$$L = 5.7m$$

$$R = 0.96m$$

$$B = 3.5T$$

$$E \propto R^2 L \cdot B^2$$

$$E(LHeC) \approx 80MJ, [J = Nm]$$

$$prize \sim \frac{1}{2}(E / MJ)^{0.66}$$

Locate **solenoid** between EMC and HAC:
Cost [and joins dipole for beam bending]

$$E = E_0 \cdot e^{-x/X_0}$$

$$X_0 = \frac{1}{N\Phi}$$

$$L(95\%) = 20X_0$$

$$X_0(Pb) = 0.56cm$$

EMC: LAr-Pb: D=40cm

$$\lambda = 35\frac{g}{cm^2} \cdot \frac{A^{1/3}}{\rho}$$

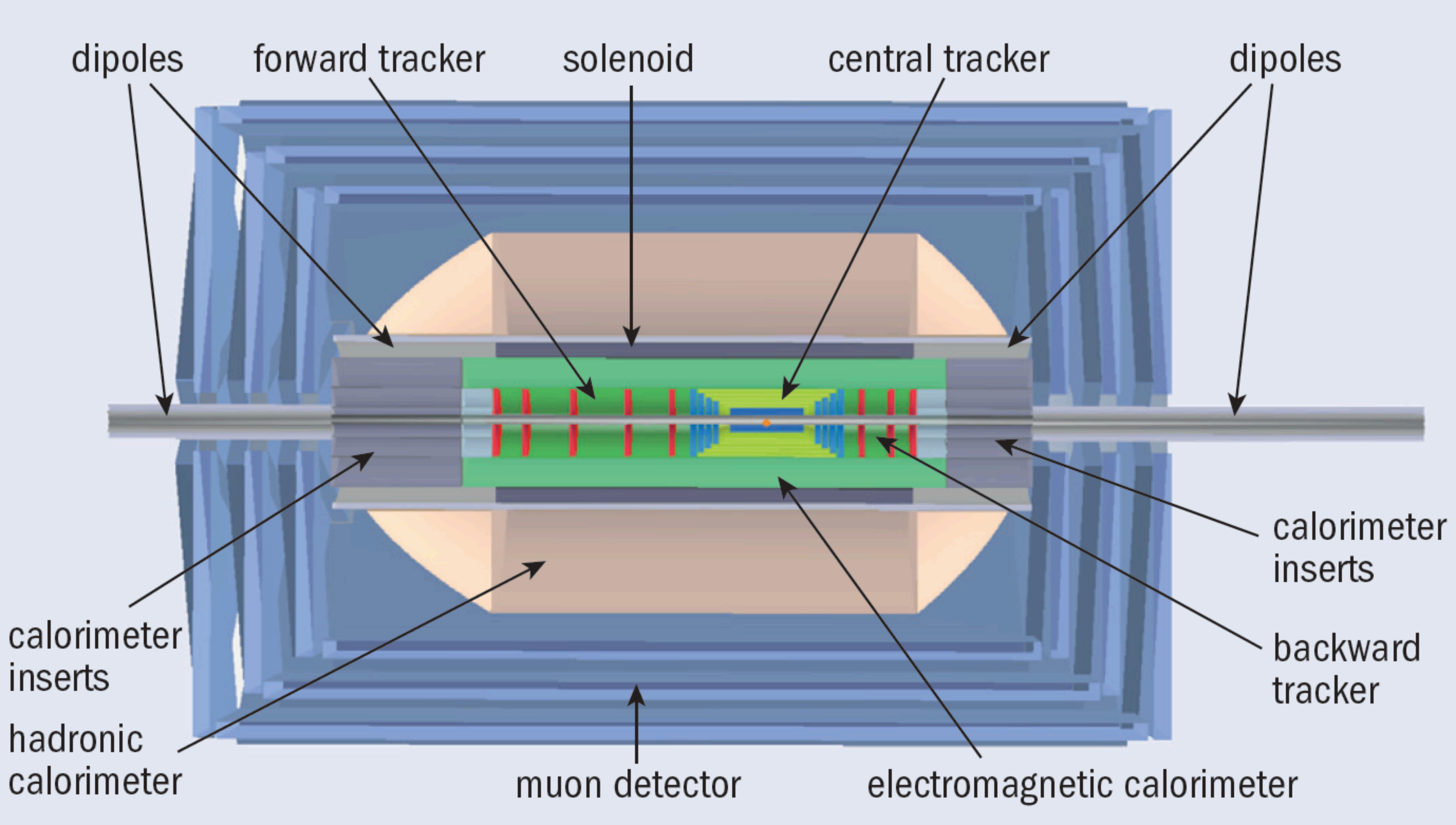
$$\lambda(Fe) = 17cm$$

$$L(95\%) = 7\lambda$$

HAC: Sc-Fe: D=140cm

The LHeC detector is surrounded by a muon detector system, conceptionally for muon identification only. There are forward and backward detectors as part of the central detector, and there are further apart detectors for tagging p,n in p beam direction and e,γ in e beam direction (“backwards”)

LHeC Detector Design Concept



Muon detector: ID with few detector planes, no momentum measurement – unlike ATLAS

Detector - Summary

1. The requirement to select often rare events (“trigger”) has replaced the photographic methods.
2. The physics of heavy quarks has boosted the development of Silicon track detectors.
3. Energies are measured in “sampling calorimeters” – in multilayers of absorber and active material.
4. Modern collider detectors have a common structure: tracker, ecal., hcal., solenoid, muon detector.
5. The (xy) dimension of a tracker is determined by the required momentum resolution (B,Δ,L).
6. An electromagnetic calorimeter absorbs 95% of the shower energy in 20 radiation lengths (X_0).
7. The em. energy loss mechanism is primarily bremsstrahlung and the energy resolution ~10%/√E.
8. A hadronic calorimeter absorbs a hadron shower completely after 7 absorption lengths (λ).
9. Due to the more stochastic nature of hadron interactions and the complexity of the hadron energy loss processes, the energy resolution is ~40%/√E. The “HCAL” catches the elm. shower tail.
10. Calorimetry has to be hermetic (4π) acceptance in order to reconstuct the energy balance (ν’s MET).
11. Muons penetrate the whole calorimeter and can thus be identified and their momentum reconstructed.

Detectors have to fulfill further demands as from trigger complexity, readout speed and data volume…