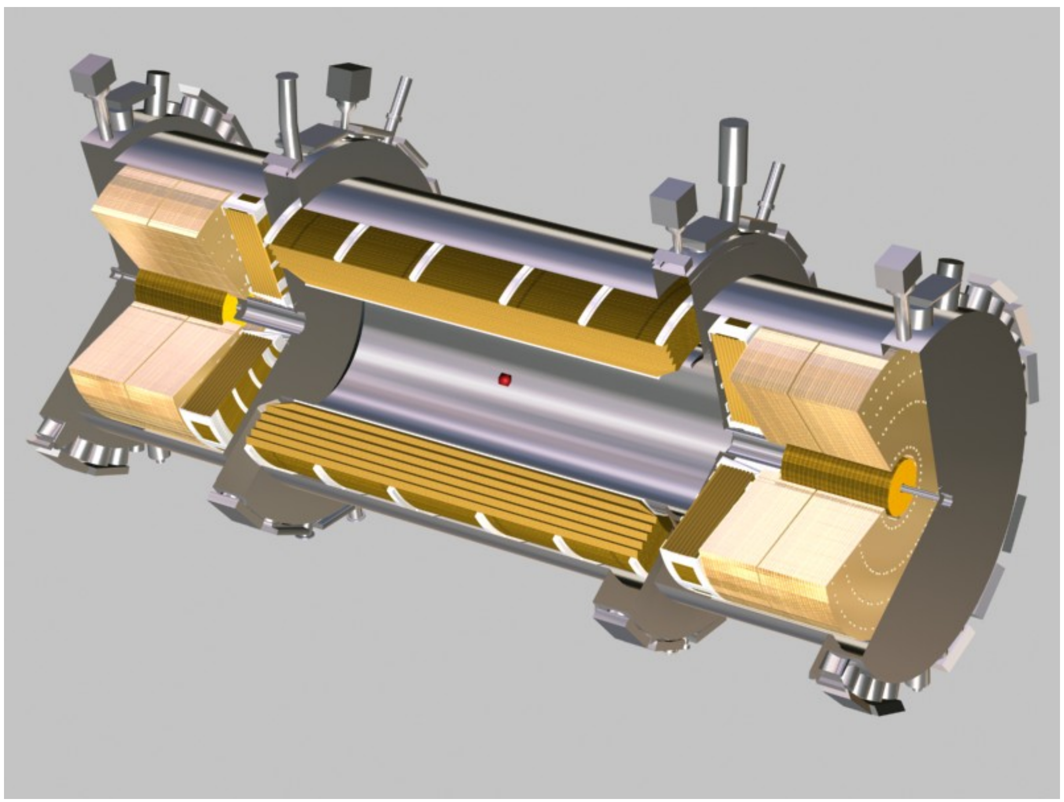
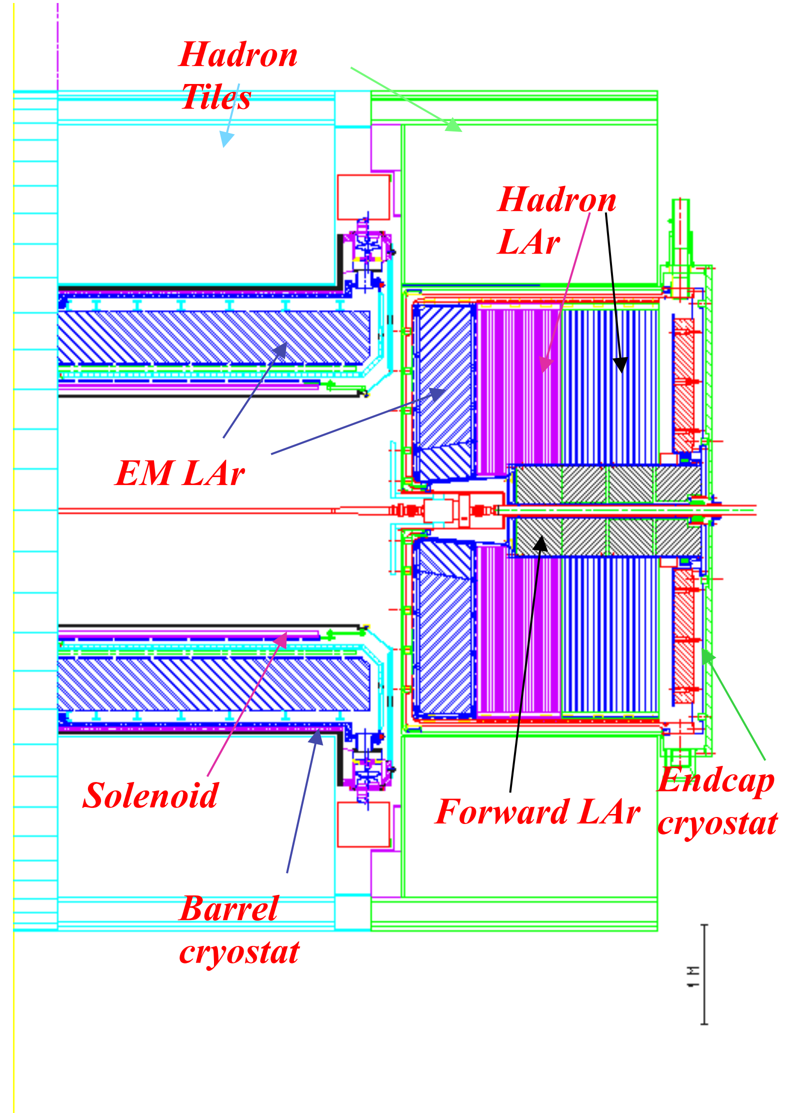
Calorimetry

The LAr calorimetry (pre-samplers, EM, hadronic end-caps, and forward calorimeters)





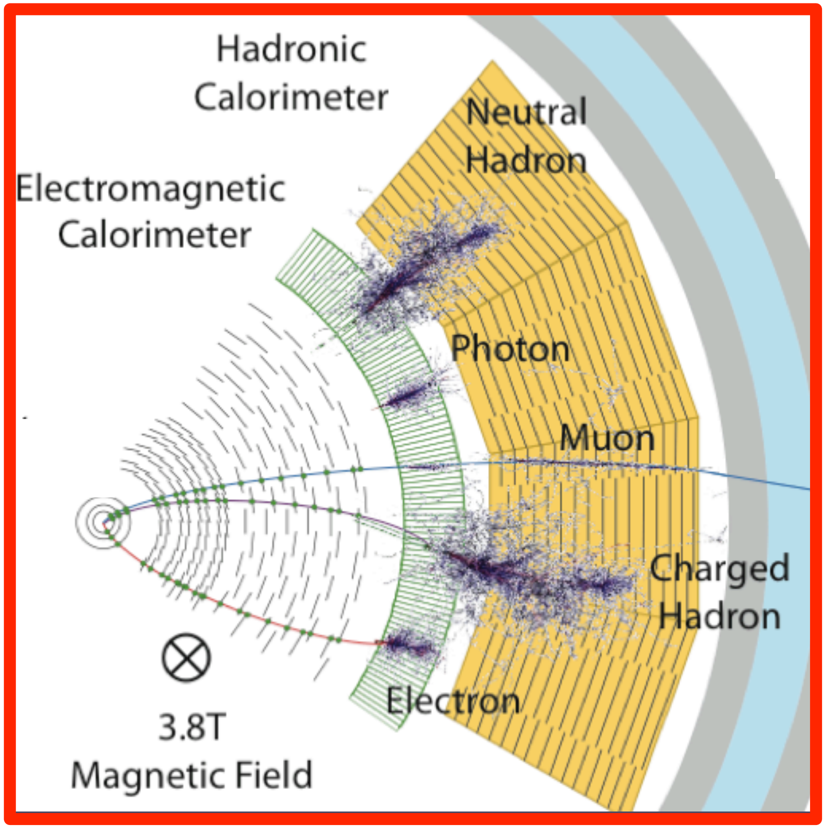
Calorimetry
(based on Bartoletto lectures at CERN)

Particle detection via total absorption
- almost all energy transformed into heat -> calorimeter

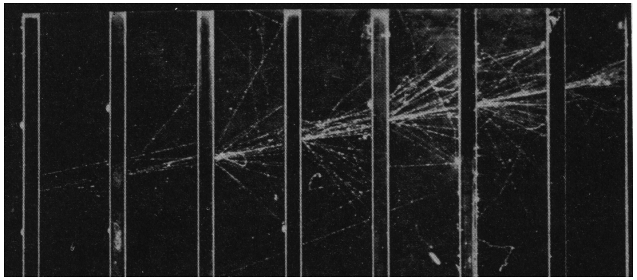
Destructive measurement
- Electromagnetic showers
- Hadronic interactions

Essential for detection of neutral particles
Can identify muons via minimum ionization

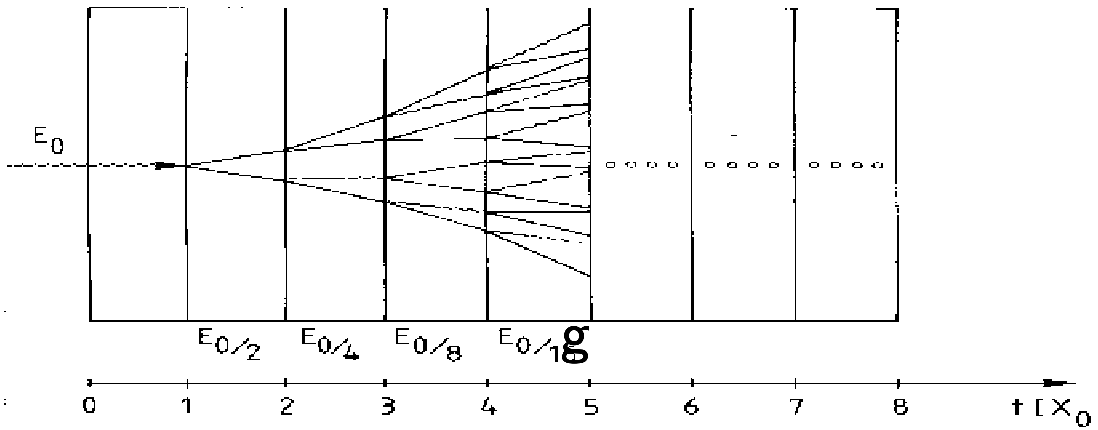
Hermetic calorimeter can detect
ME - missing energy, difference between
collision energy and detected energy
ME – can be due to neutrinos or
new neutral weakly interacting particles



Electromagnetic cascades (showers)



Electron shower in a cloud chamber with lead absorbers



Consider only Bremsstrahlung and pair production.
Assume: $X_0 = l_{pair}$

$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t)<E_c$

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \qquad N^{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2\cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect + absorption.

Electromagnetic cascades

Longitudinal shower development: $$\frac{dE}{dt} \propto t^{\alpha} e^{-t}$$

Shower maximum at $$t_{\max} = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$$

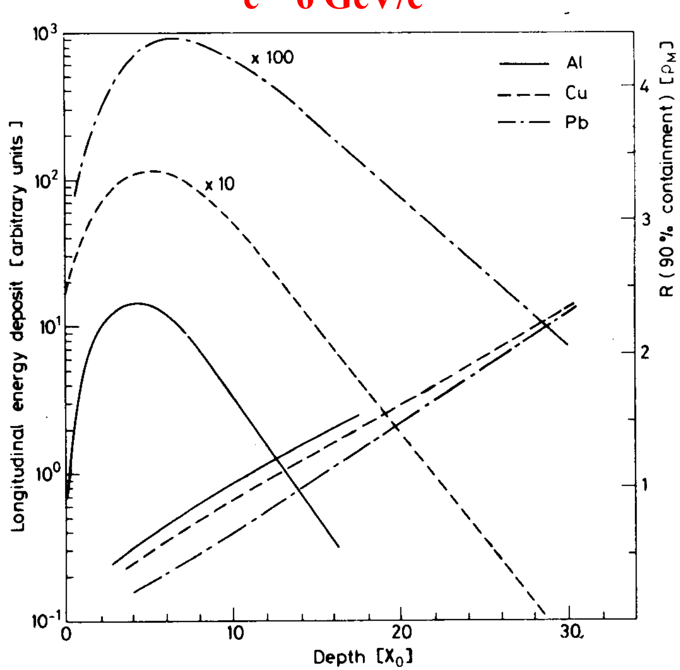
Size of a calorimeter grows logarithmically with E_0

95% containment $$t_{95\%} \approx t_{\max} + 0.08Z + 9.6$$

Transverse shower development: 95% of the shower cone is located in a cylinder with radius 2 R_M

Moliere radius $$R_M = \frac{21\,\text{MeV}}{E_c} X_0 \quad [g/cm^2]$$

e^- 6 GeV/c

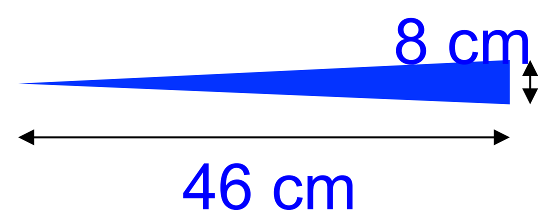


Longitudinal and transverse development scale with X_0, R_M

Example: E_0 = 100 GeV in lead glass

E_c=11.8 MeV ⌧ t_{max} ⌧ 13, $t_{95\%}$ ⌧ 23

X_0 ⌧ 2 cm, $R_M = 1.8 \cdot X_0$ ⌧ 3.6 cm



Electromagnetic shower

- Dominant processes at high energies (E > few MeV) :

- Photons: Pair production

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}}\right) = \frac{7}{9}\frac{A}{N_A X_0}$$

$$I(x) = I_0 e^{-\mu x} \qquad \mu = \frac{7}{9}\frac{\rho}{X_0}$$

μ = attenuation coefficient
X_0 = radiation length in [cm] or [g/cm^2]

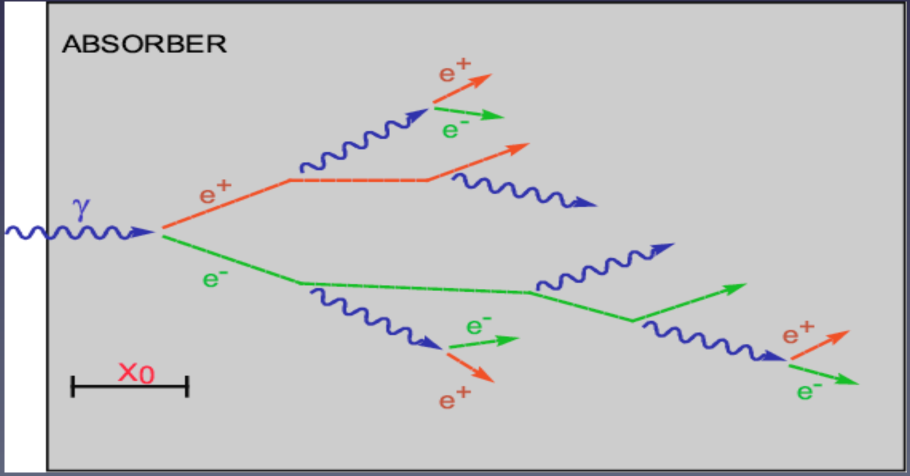
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

- Electrons: Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0}$$

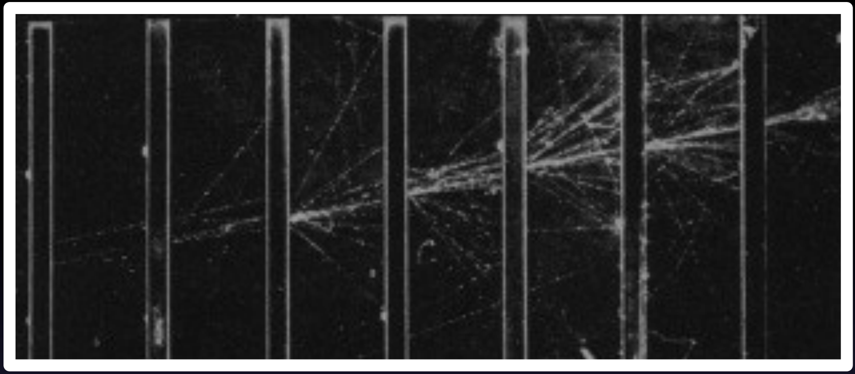
$$E = E_0 e^{-x/X_0}$$

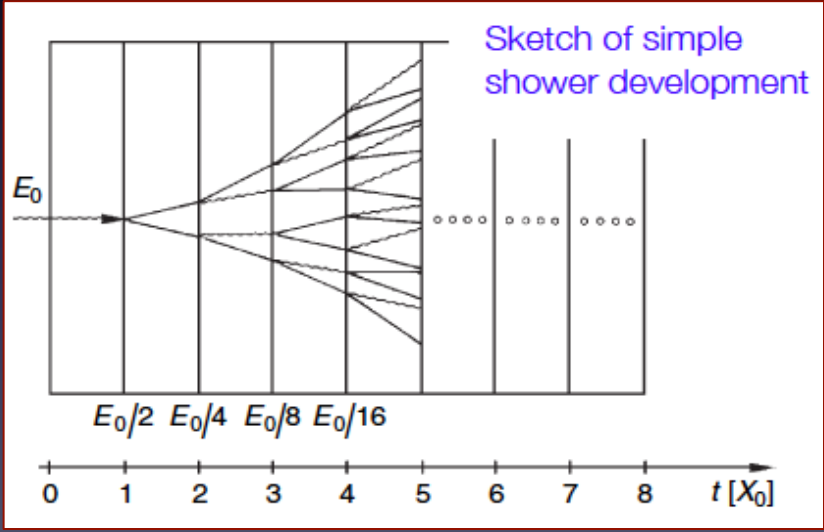
After traversing $x=X_0$ the electron has only 1/e=37% of its initial energy



Analytic shower Model

- Simplified model [Heitler]: shower development governed by X_0
  - e^- loses [1 - 1/e] = 63% of energy in 1 X_0 (Brems.)
  - the mean free path of a γ is 9/7 X_0 (pair prod.)
- Assume:
  - $E > E_c$: no energy loss by ionization/excitation
- Simple shower model:
  - $N(t)=2^t$ particles after $t = x/X_0$ each with energy $E(t)=E_0/2^t$
  - Stops if $E(t) < \mathbf{E_c = E_0 2^{tmax}}$
  - Location of shower maximum at





$$t_{\max} = \frac{\ln(E/Ec)}{\ln 2} \propto \ln \frac{E}{E_c}$$

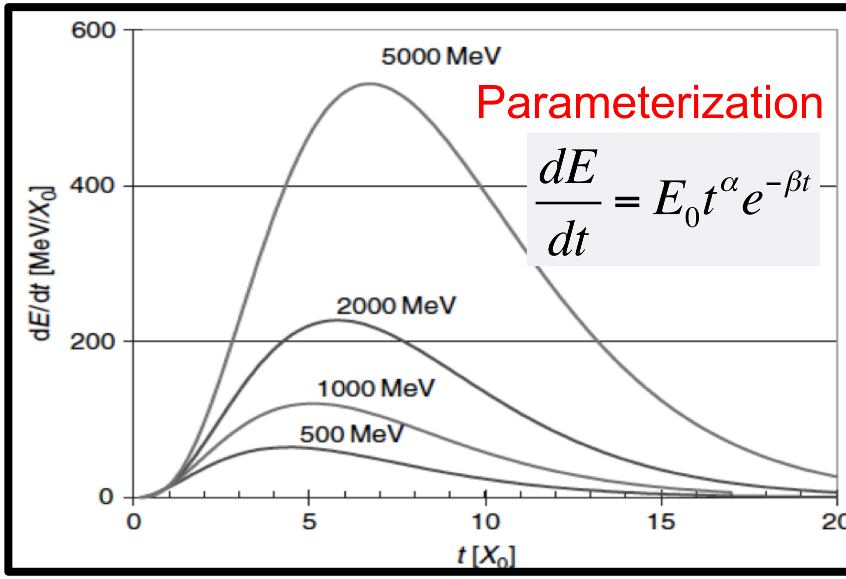
$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_C}$$

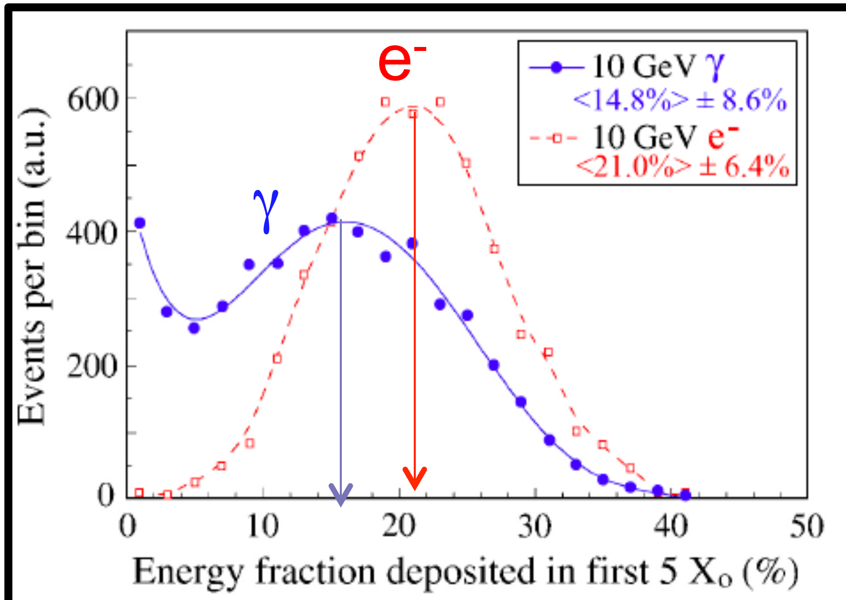
Different shower shape for electron and photon
- due to difference between brehmsstrahlung and conversion

X_0 – radiation length

$$t_{\max} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

$C_{e\gamma}$ = -0.5 for photons
$C_{e\gamma}$ = -1.0 for electrons





Longitudinal shower containment

- Since $t_{max} \approx \ln(E) \rightarrow$ calorimeter thickness must increase as ln(E)
- After shower max showering will stop in ≈ $1X_0$
- To absorb 95% of photons after shower max ≈ $9X_0$ of material are needed
- The energy leakage is mainly due to photons
- A useful expression to indicate 95% shower containment
- A useful expression to indicate 95% shower containment is:

$$L(95\%) = t_{max} + 0.08\,Z + 9.6\ [X_0]$$

$$E_C \approx 10\,MeV \qquad E_0 = 1\ GeV \quad \Rightarrow t_{max} = \ln 100 / \ln 2 \approx 6.6 \qquad N_{max} = 100$$

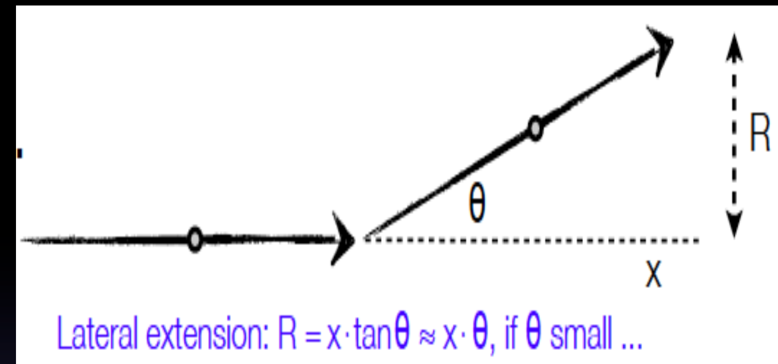
$$E_0 = 100\ GeV \quad \Rightarrow t_{max} = \ln 10{,}000 / \ln 2 \approx 9.9 \qquad N_{max} = 10{,}000$$

	Scint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

Lateral development of EM shower

- **Opening angle:**
  - **bremsstrahlung and pair production**

$$\langle\theta^2\rangle \approx \left(\frac{m_e c^2}{E_e}\right)^2$$



  - multiple coulomb scattering [**Molière** theory]

$$\langle\theta\rangle = \frac{E_s}{E_e}\sqrt{\frac{x}{X_0}} \quad \text{where} \quad E_s = \sqrt{\frac{4\pi}{\alpha}}\left(m_e c^2\right) = 21.2 MeV$$

- Main contribution from low energy e^- as $\langle\boldsymbol{\theta}\rangle \sim 1/E_e$, i.e. for e^- with $E < E_c$

- **Molière** Radius

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21.2 MeV}{E_c} X_0$$

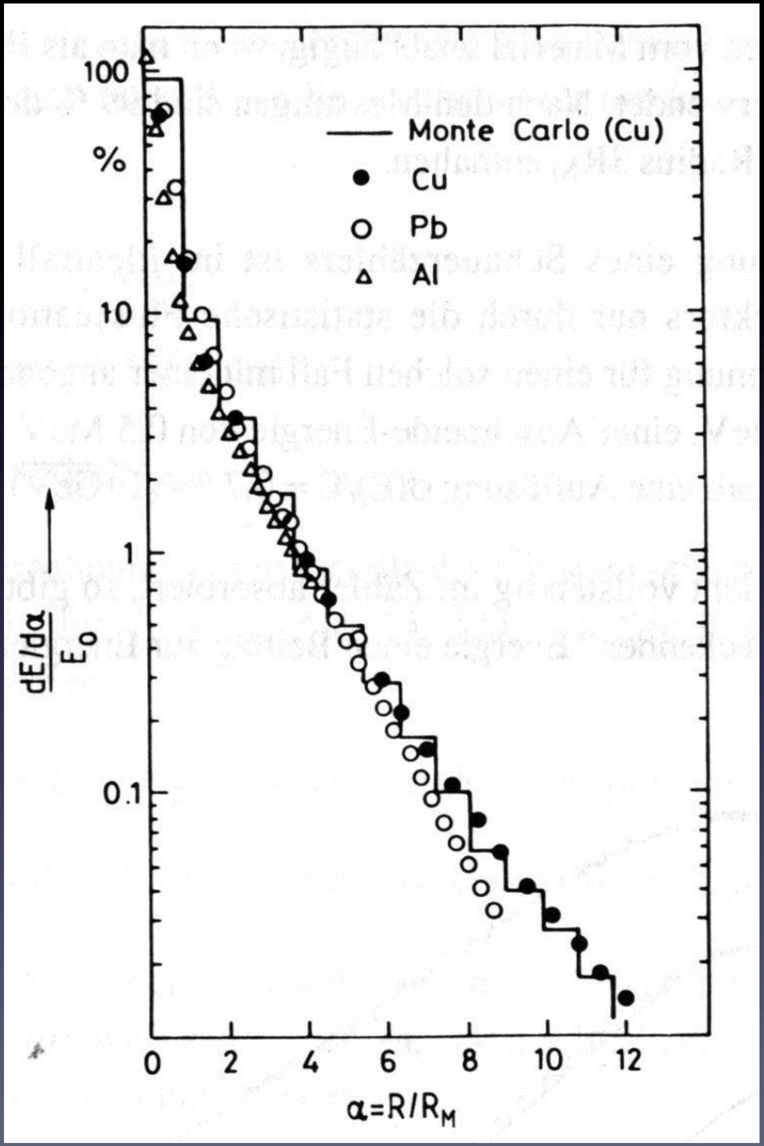
- Assuming the approximate range of electrons to be X_0 yields $\langle\boldsymbol{\theta}\rangle \approx 21.2$ **MeV/E_e** → lateral extension: $R = \langle\boldsymbol{\theta}\rangle X$

Lateral development of EM shower

- Inner part is due to Coulomb's scattering of electron and positron
- Outer part is due to low energy γ produced in Compton's scattering, photo-electric effect etc.
  - Predominant part after shower max especially in high Z absorbers

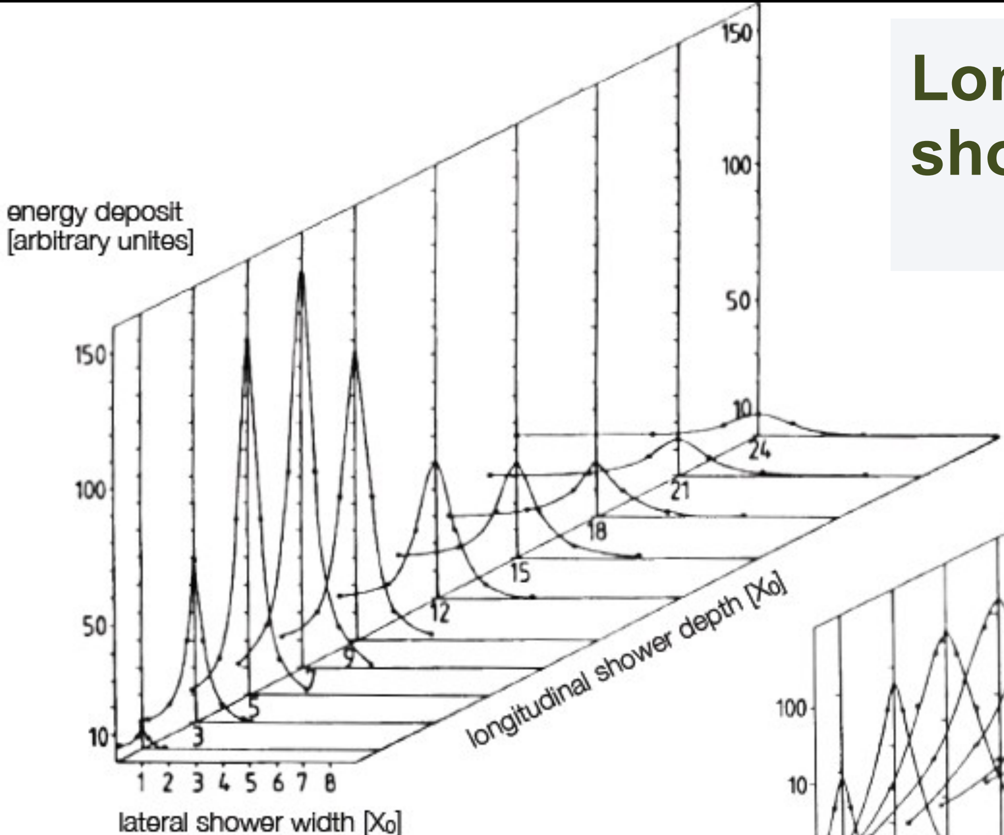
$$\frac{dE}{dr} = \alpha e^{-r/RM} + \beta e^{-r/\lambda_{\min}}$$

- The shower gets wider at larger depth
- An infinite cylinder of radius $2R_M$ contains 95% of the shower

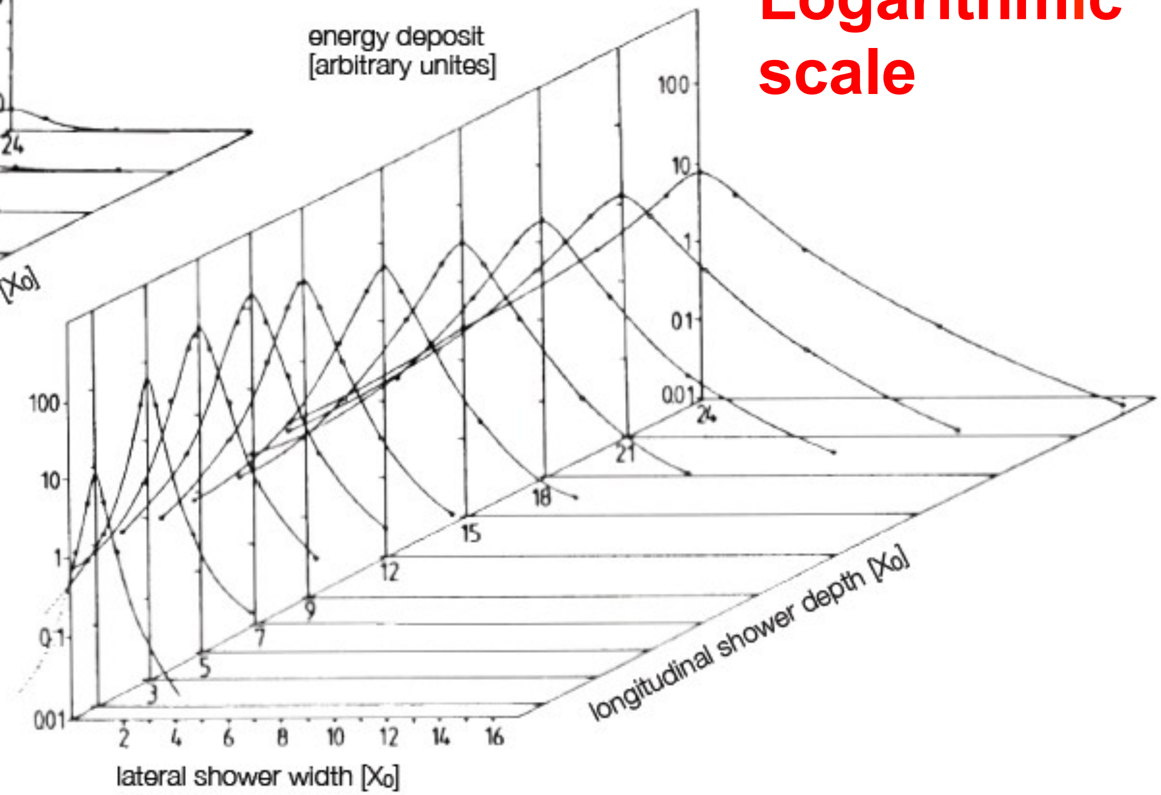


3D EM Shower development

Longitudinal and transfer EM shower profile of 6 GeV e^- in Pb

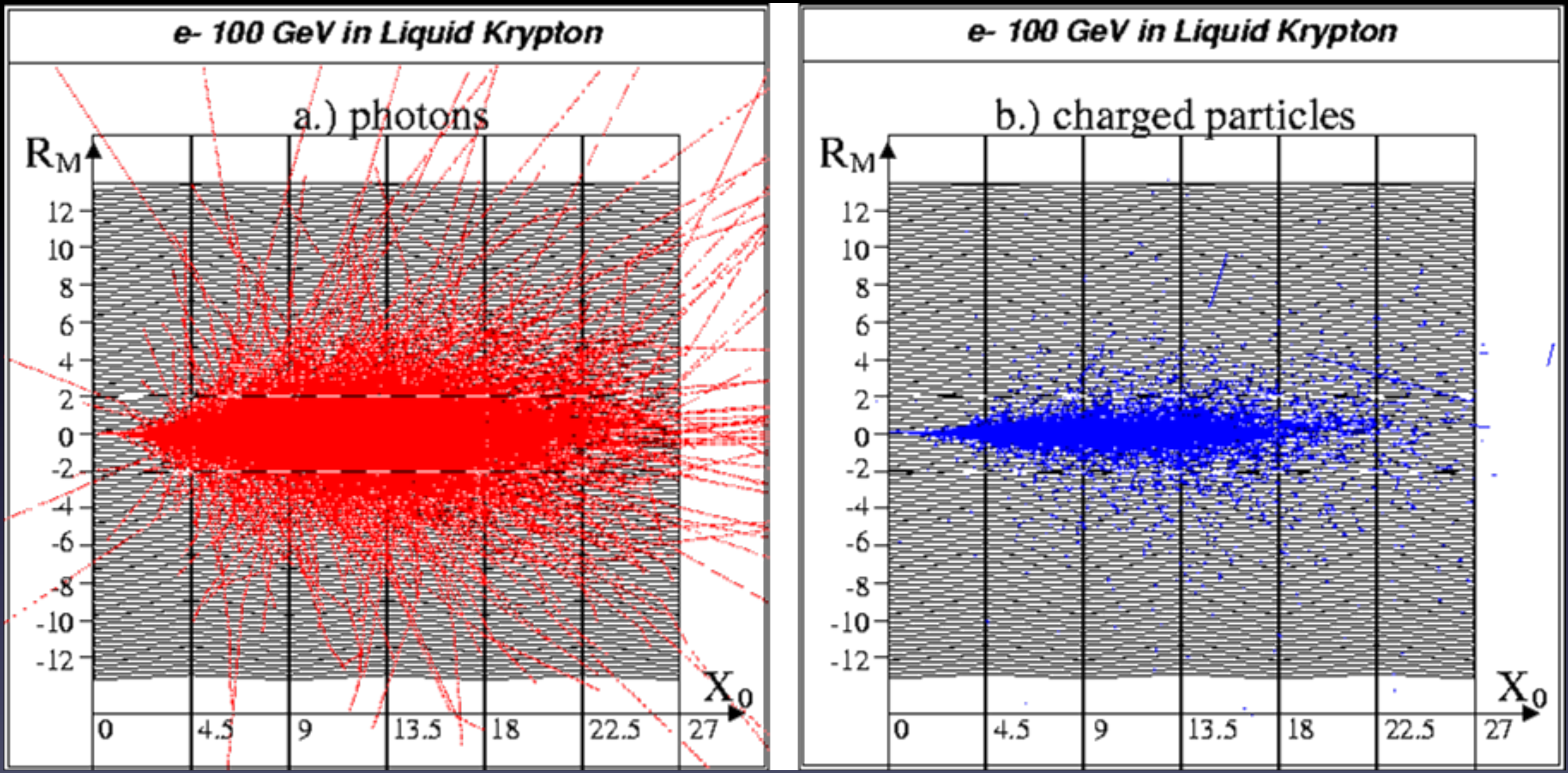


Linear scale



Logarithmic scale

EM shower development in liquid krypton (Z=36, A=84)



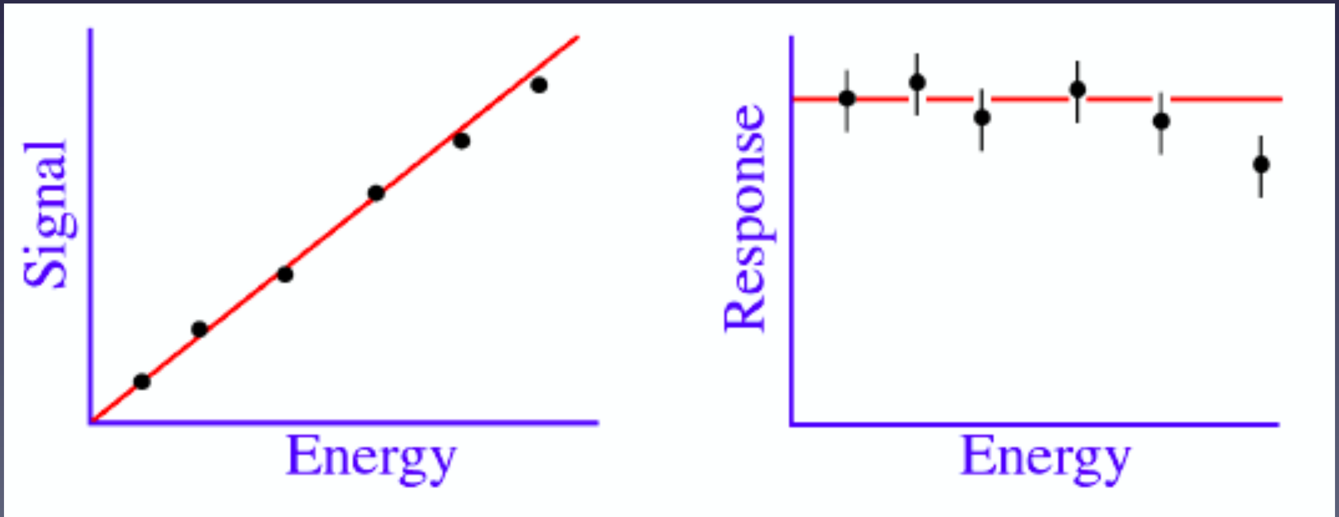
GEANT simulation of a 100 GeV electron shower in the NA48 liquid Krypton calorimeter (D.Schinzel)

Discussion: Explain why they are different

Energy Measurement

How we determine the energy of a particle from the shower?

- Detector response → Linearity
  - The average calorimeter signal vs. the energy of the particle
  - Homogenous and sampling calorimeters
  - Compensation (for hadronic showers)
- Detector resolution → Fluctuations
  - Event to event variations of the signal
  - What limits the accuracy at different energies?



Signal per unit of deposited energy

EM calorimeters are linear

Hadronic calorimeters are not linear

Sources of Non Linearity

- **Instrumental effects**
  - **saturation of gas detectors, scintillators, photo-detectors, electronics**
- **Response varies with something that varies with energy**
- **Examples:**
  - **Deposited energy "counts" differently, depending on depth and depth increases with energy**
- **Leakage (increases with energy)**

Signal linearity for electromagnetic showers

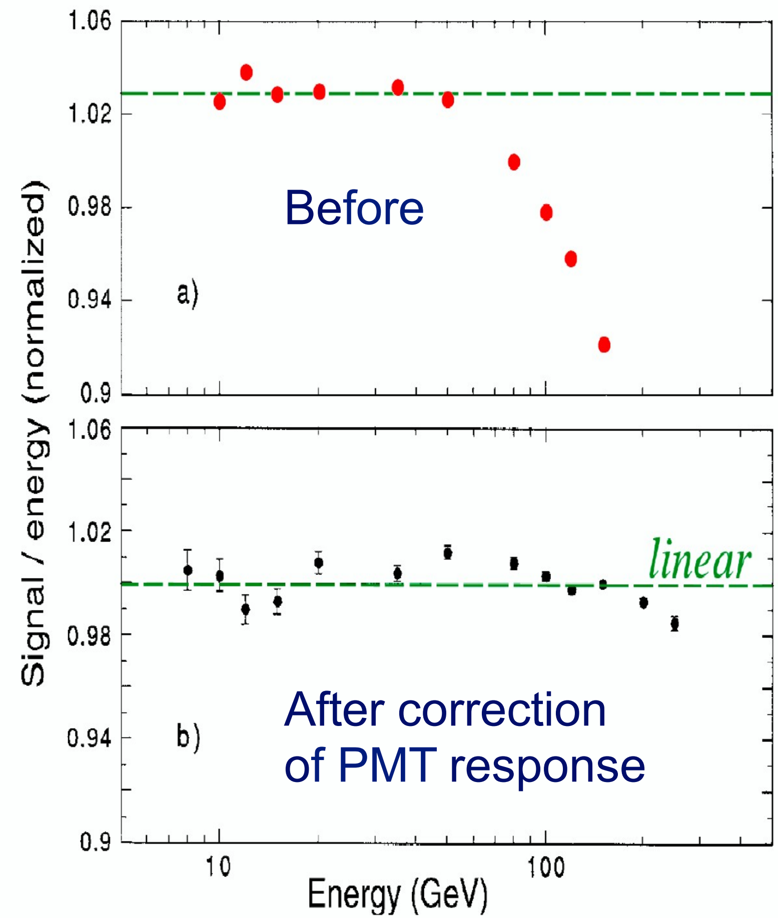


FIG. 3.1. The em calorimeter response as a function of energy, measured with the QFCAL calorimeter, before (*a*) and after (*b*) precautions were taken against PMT saturation effects. Data from [Akc 97].

EM Calorimeter configurations

Total absorption

- Electrons and photons stop in calorimeter
- Scintillation proportional to energy of electron
- Usually non-organic scintillator (BGO, $PbWO_{4,\ldots}$) or liquid Xe
- Advantage: Excellent energy resolution

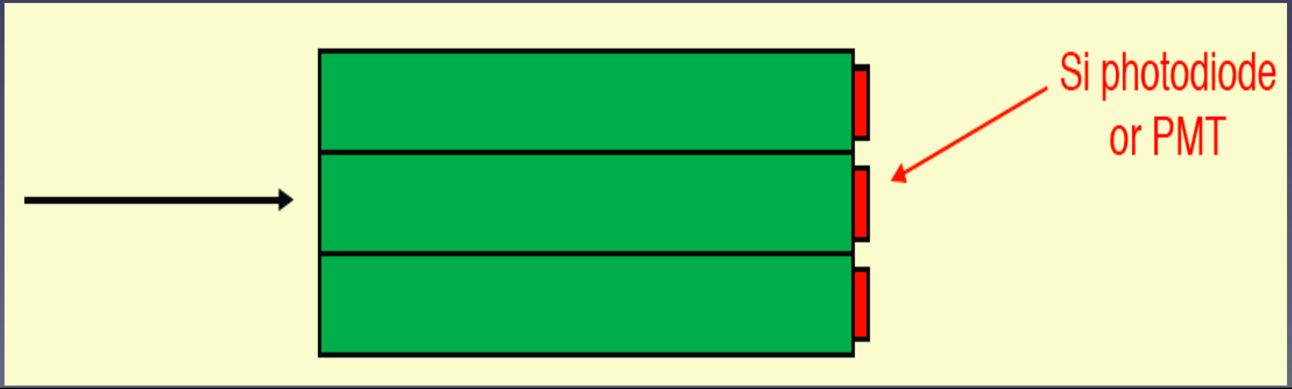
  see all charged particles in the shower (but for shower leakage) best statistical precision

  -> uniform response, good linearity
- Disadvantages:

  cost and limited segmentation

If W is the mean energy required to produce a signal (eg an e^--ion pair in a noble liquid or a 'visible' photon in a crystal)

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}$$



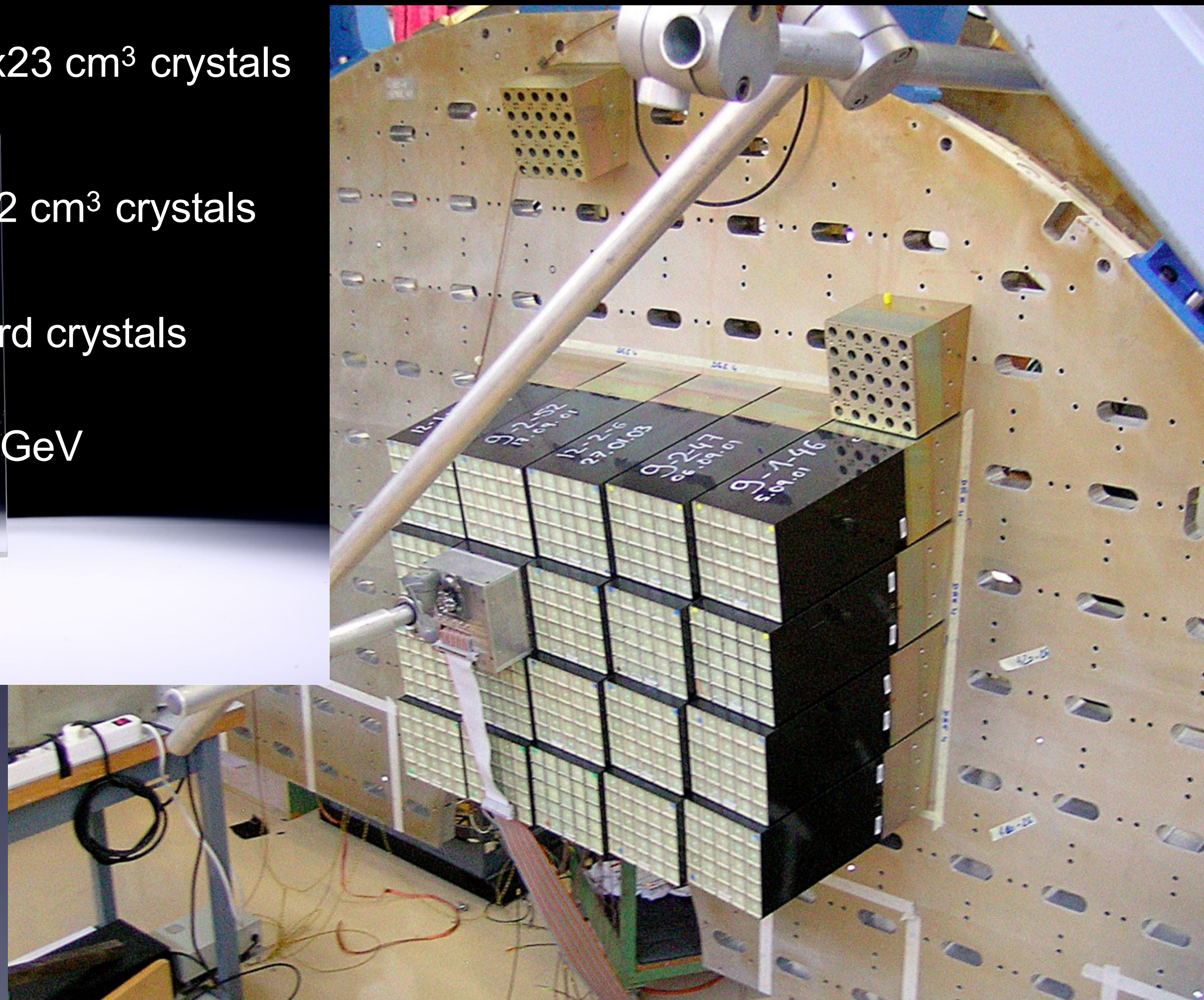
Homogenous calorimeters

Barrel: 62K 2.2x2.2x23 cm^3 crystals

Endcap: 15K 3x3x22 cm^3 crystals

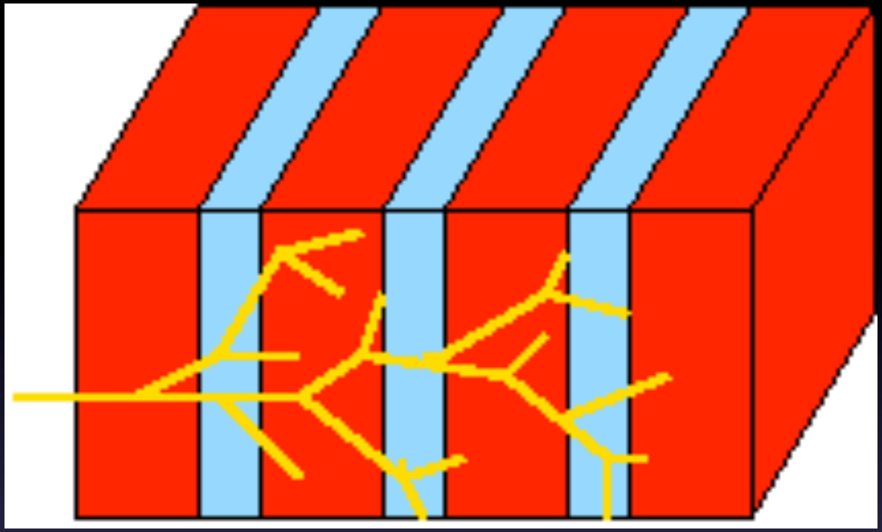
$PbWO_4$ radiation hard crystals

1% resolution at 30 GeV



EM Calorimeter configurations

- Sampling Calorimeter
  - One material to induce showering (high Z)
  - Another to detect particles (typically by counting number of charged tracks)
  - Many layers sandwiched together
  - Resolution $\propto E^{-1/2}$
- Advantages
  - Depth segmentation
  - Spatial segmentation
- Disadvantages:
  - Only part of shower seen, less precise
- Examples
  - ATLAS ECAL
  - Most HCALs

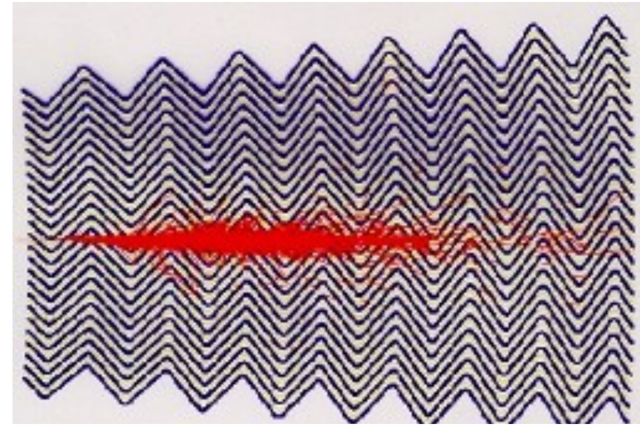


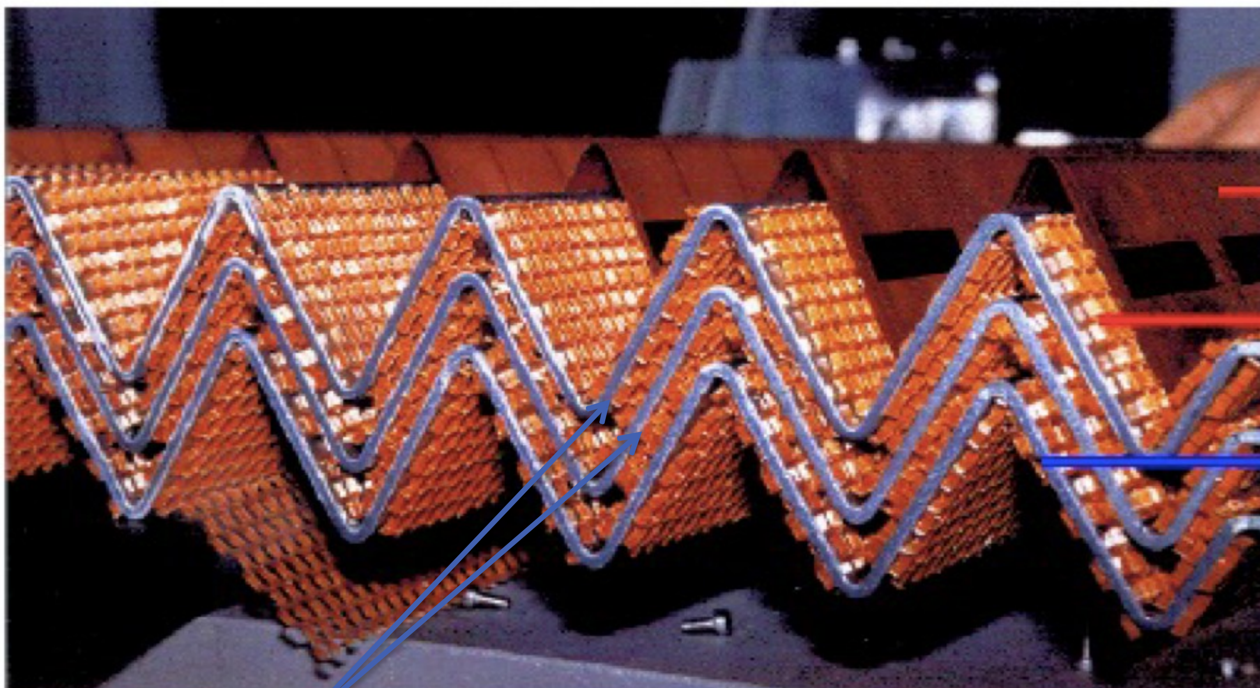
- Sampling fraction

$$f_{sampling} = \frac{E_{visible}}{E_{deposited}}$$

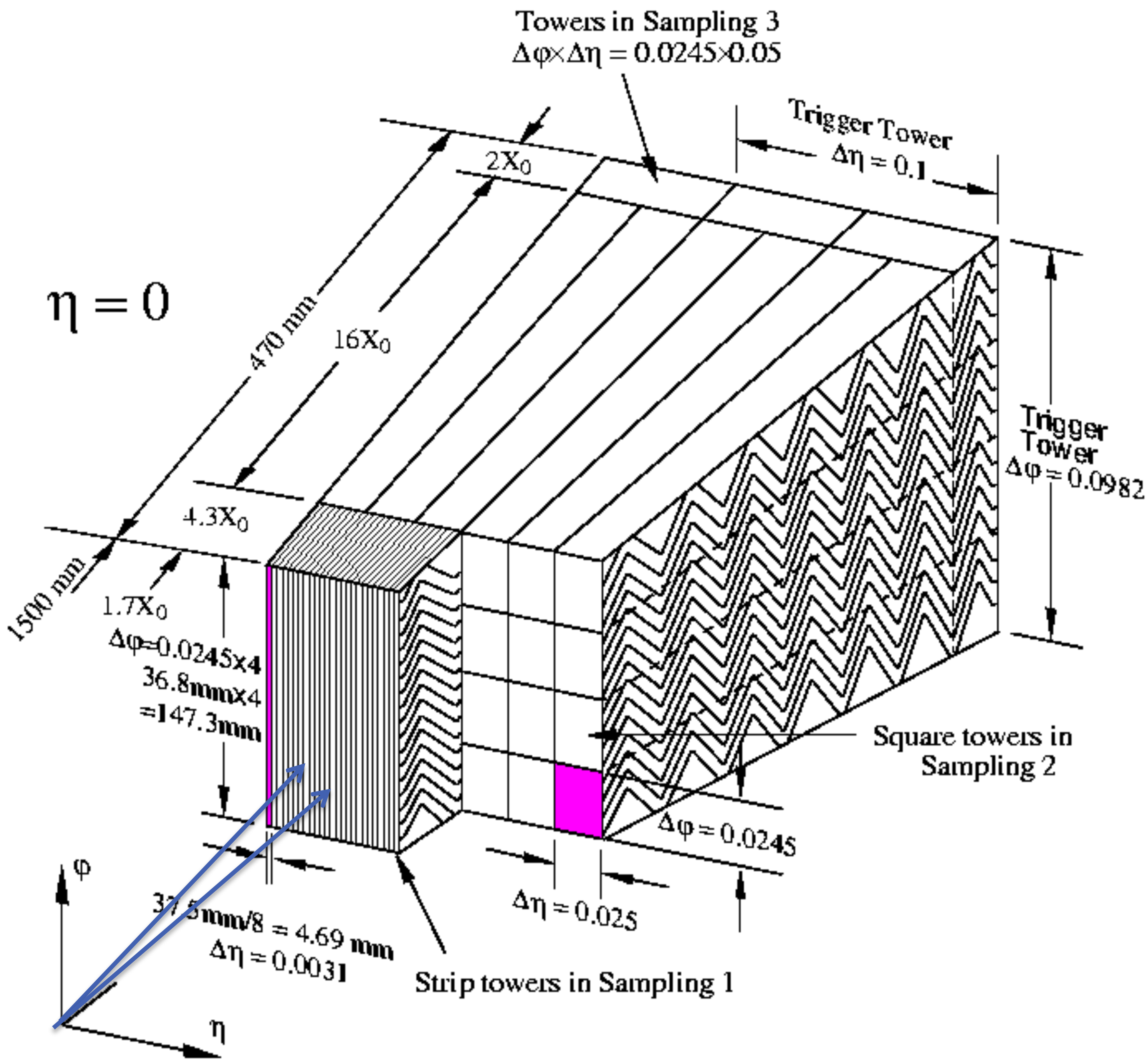
ATLAS Liquid Argon ECAL

~220,000 individual readout channels
multiplexed into towers for trigger



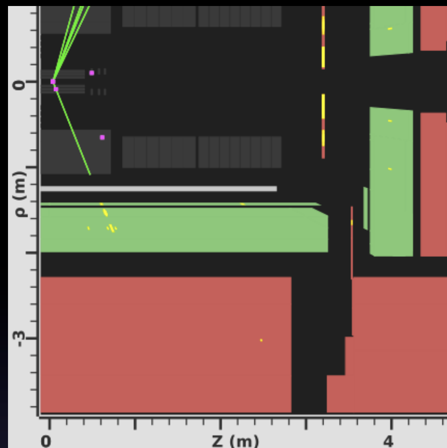


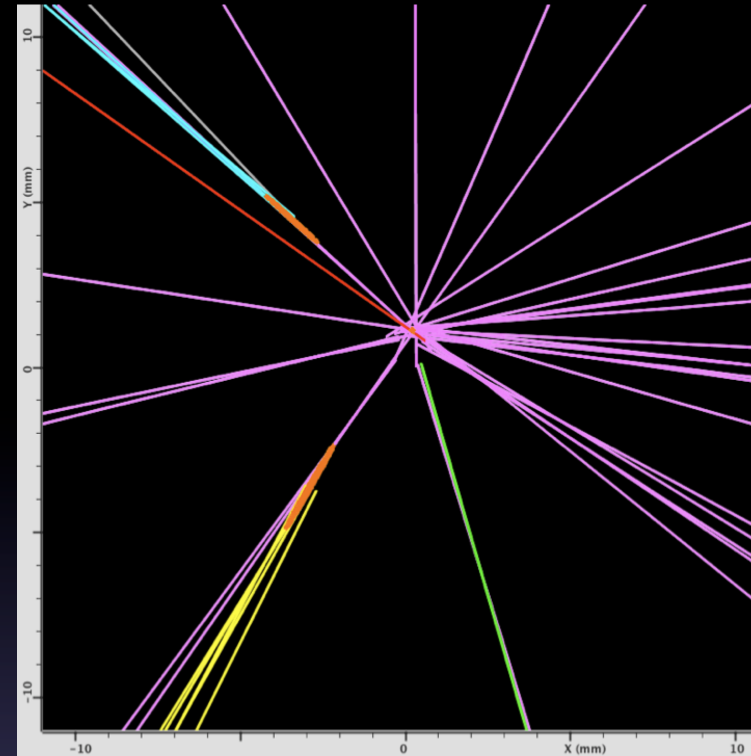
$\eta = 0$

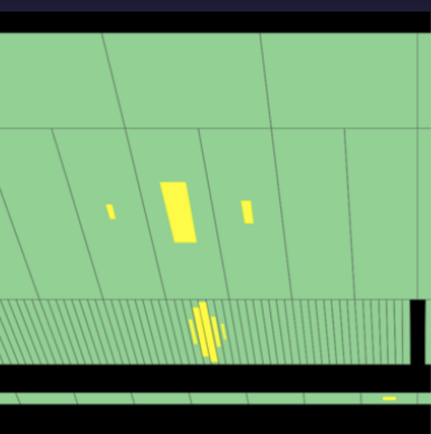


Towers in Sampling 3
Δφ×Δη = 0.0245×0.05
Trigger Tower
Δη = 0.1
2X0
16X0
470 mm
4.3X0
1500 mm
1.7X0
Δφ=0.0245x4
36.8mmx4
=147.3mm
Trigger Tower
Δφ = 0.0982
Square towers in Sampling 2
Δφ = 0.0245
Δη = 0.025
5mm/8 = 4.69 mm
Δη = 0.0031
Strip towers in Sampling 1
φ
η

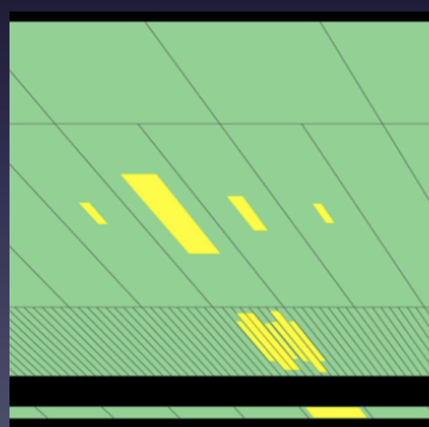
Signatures





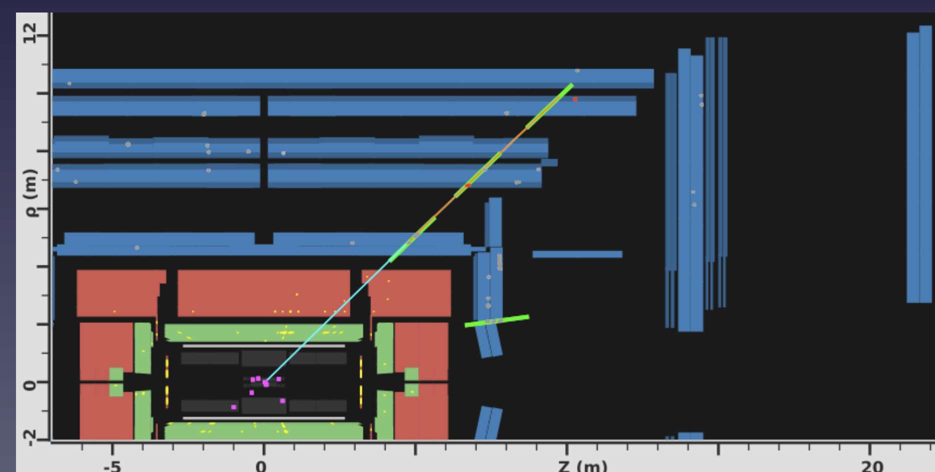


photon



π^0

muon



Energy resolution

- Ideally, if all shower particles counted

$$E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$$

- In practice

$$\sigma_E = a\sqrt{E} \oplus bE \oplus c \qquad \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- a: stochastic term
  - intrinsic statistical shower fluctuations
  - sampling fluctuations
  - signal quantum fluctuations (e.g. photo-electron statistics)
- b: constant term
  - inhomogeneities (hardware or calibration)
  - imperfections in calorimeter construction (dimensional variations, etc.)
  - non-linearity of readout electronics
  - fluctuations in longitudinal energy containment (leakage can also be ~ E-1/4)
  - fluctuations in energy lost in dead material before or within the calorimeter
- c: noise term
  - readout electronic noise
  - Radio-activity, pile-up fluctuations

Effects on energy resolution

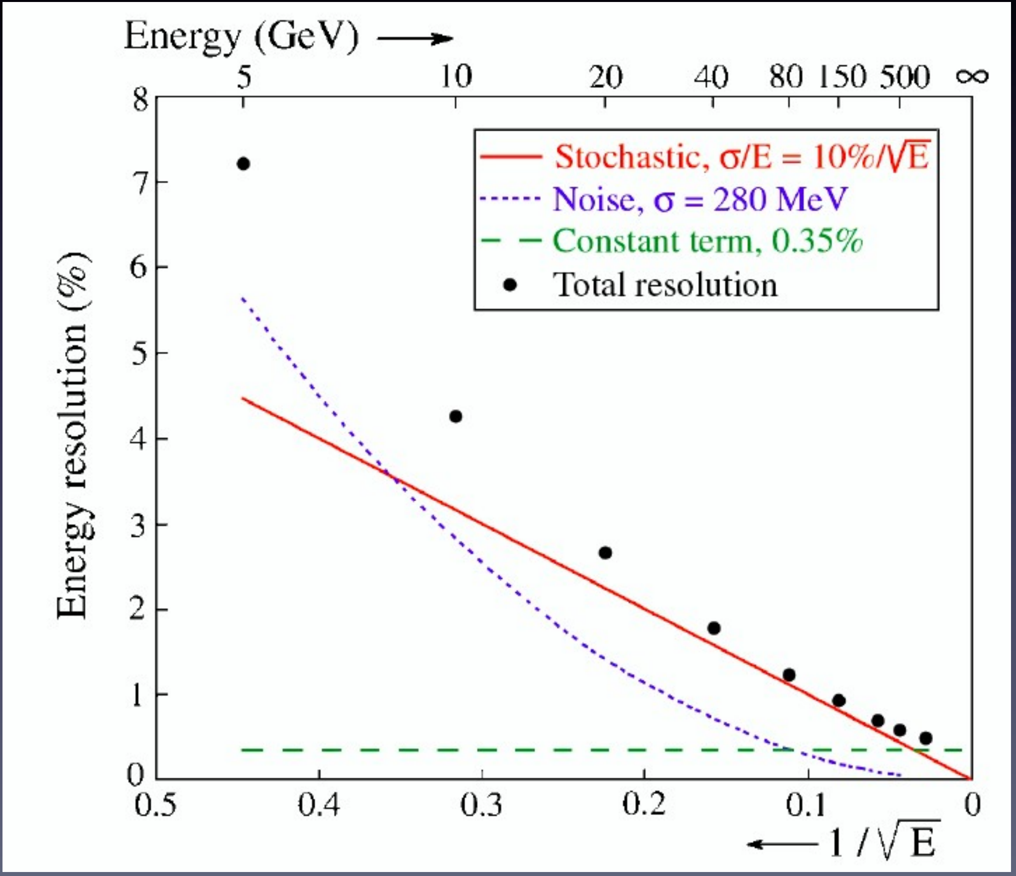
Different effects have different energy dependence

- Sampling fluctuations $\sigma/E \sim E^{-1/2}$
- shower leakage $\sigma/E \sim E^{-1/4}$
- electronic noise $\sigma/E \sim E^{-1}$
- structural non-uniformities: $\sigma/E = \text{constant}$

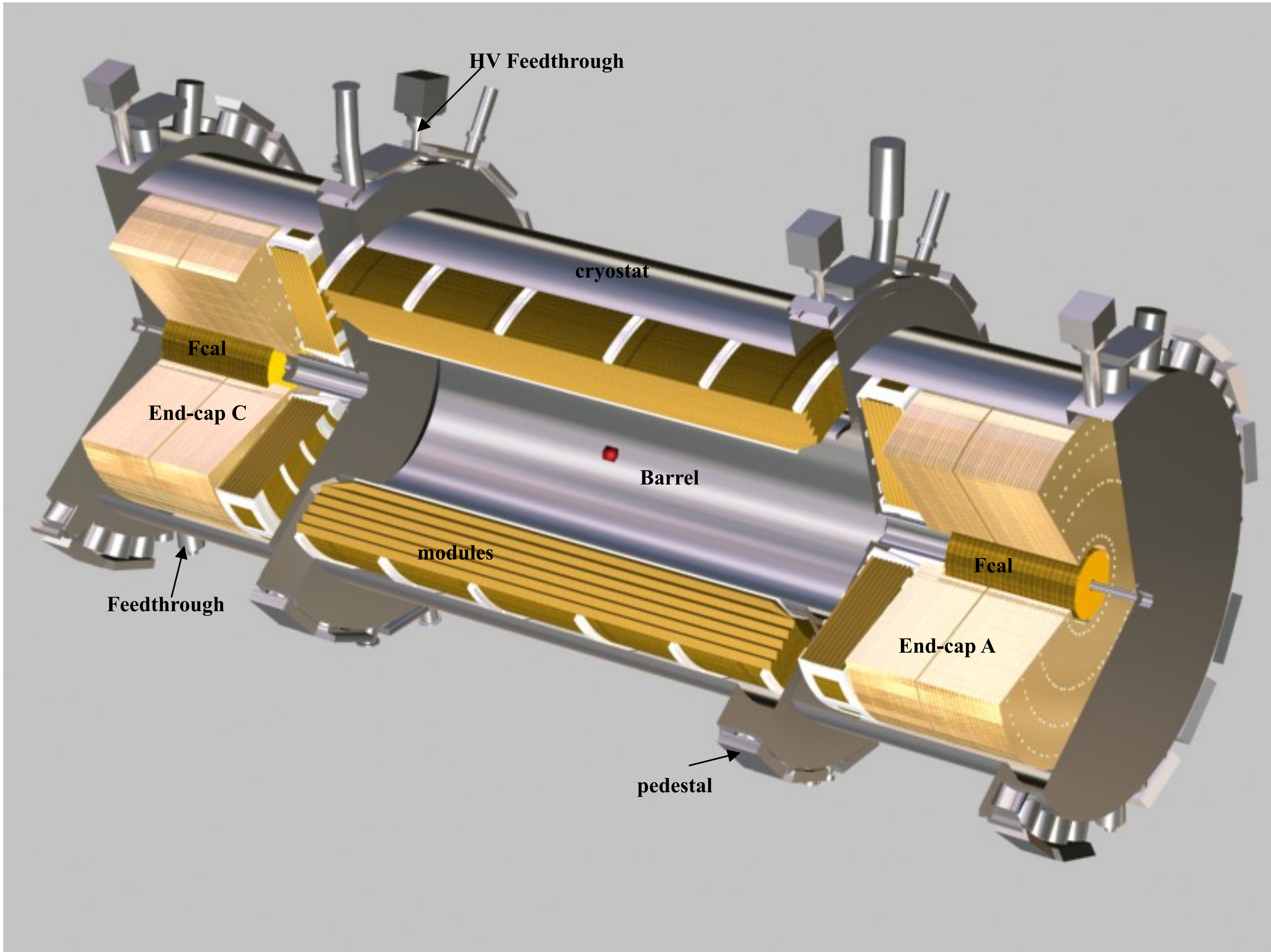
- $\sigma^2_{tot} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 + \sigma^2_4 + \ldots$

ATLAS EM calorimeter

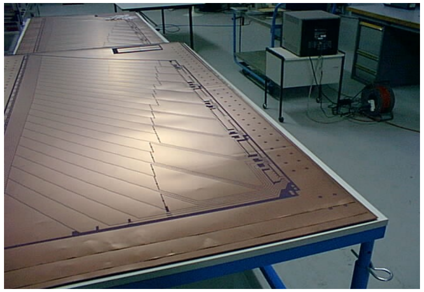
$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{170 MeV}{E} \oplus 0.7\%$$



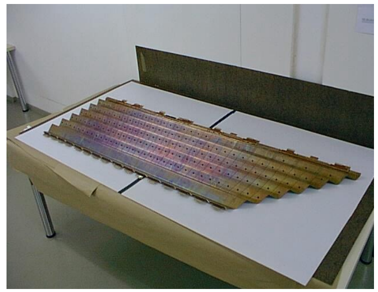
Picture Book of US ATLAS Liquid Argon Calorimeter Construction


HV Feedthrough
cryostat
Fcal
End-cap C
Barrel
modules
Feedthrough
Fcal
End-cap A
pedestal

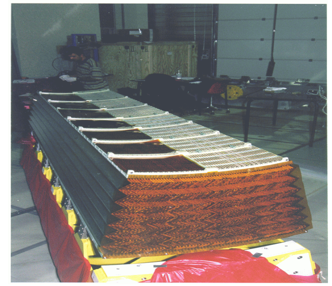
Electromagnetic module



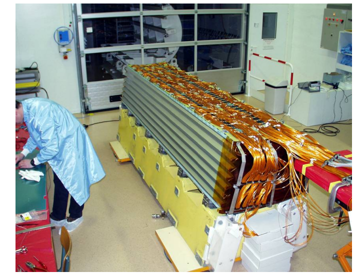
Electrode



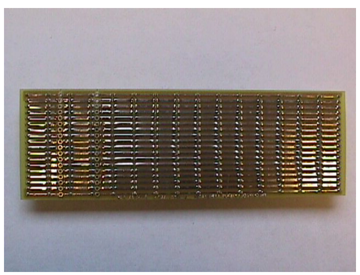
Electrode bending

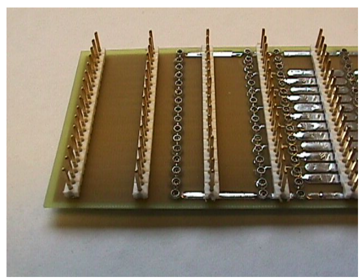


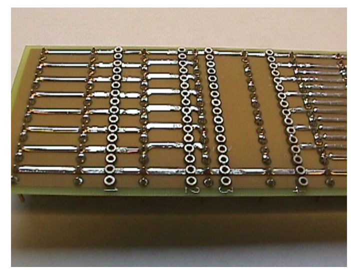
Module assembly



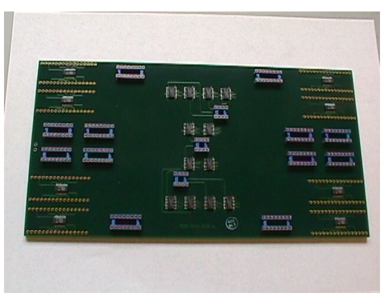
Completed module



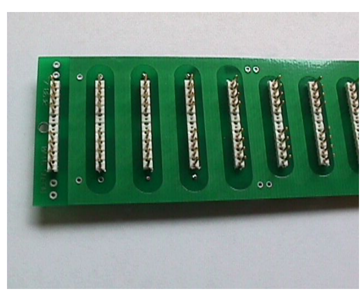




Summing boards

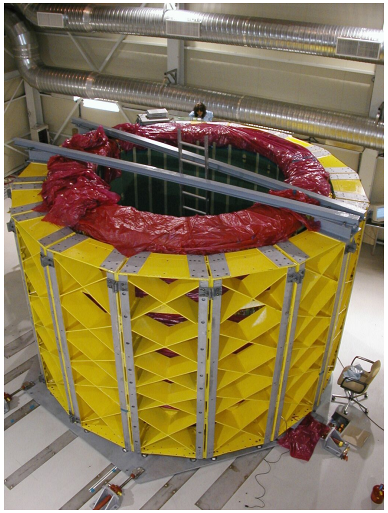


Mother boards

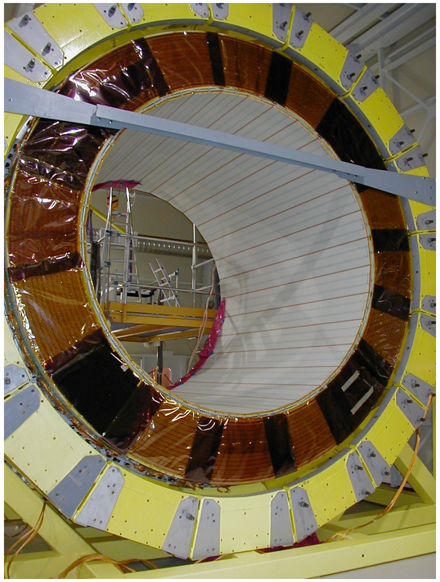


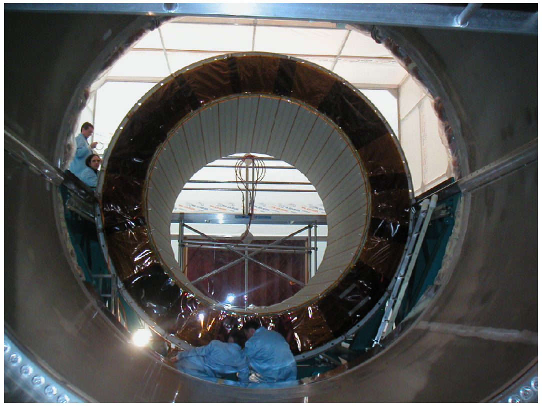
HV boards

Electromagnetic modules



Half-barrel wheel assembly
16 modules

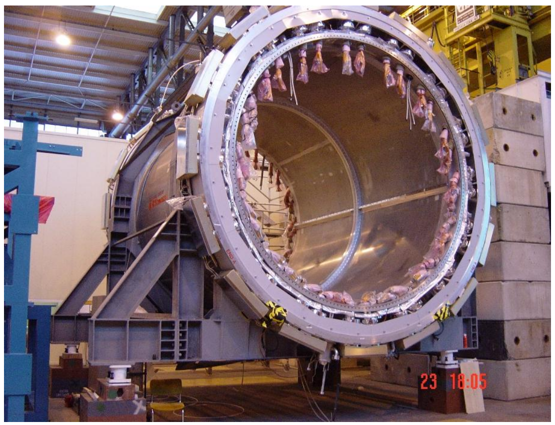




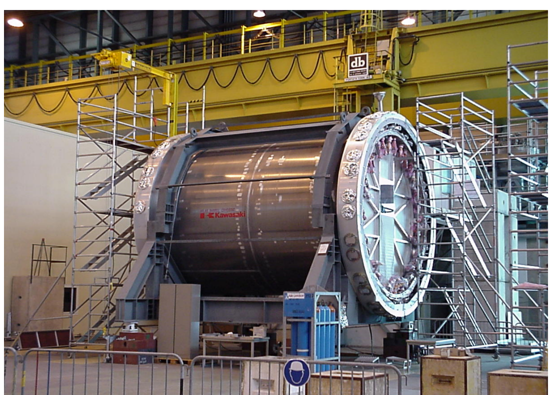
Installation into the cryostat

Cryostat

Construction



Feedthrough assembly

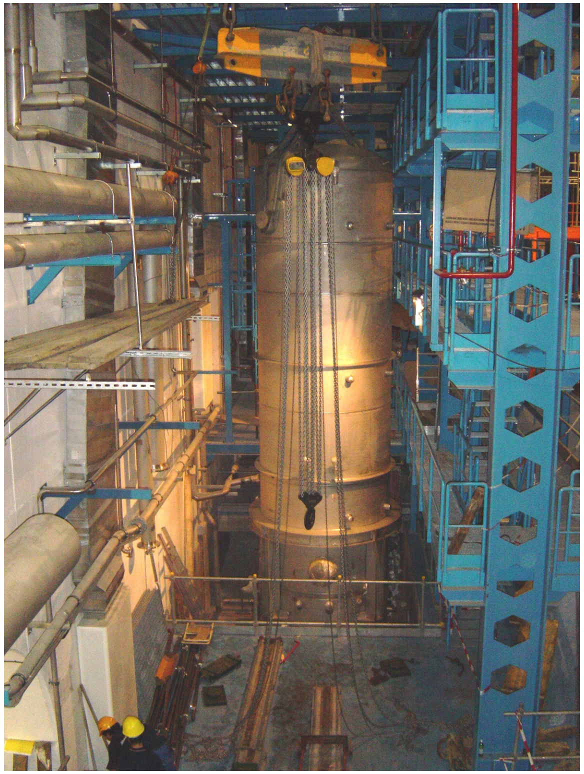


Testing

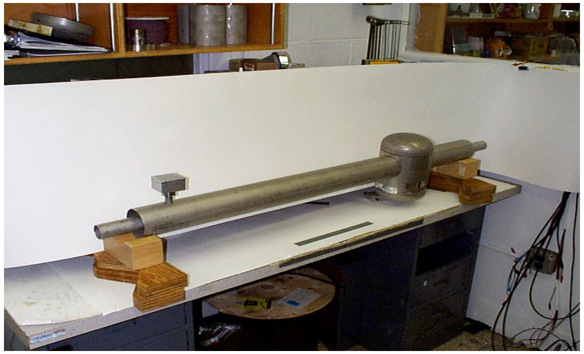
Transport

Integration

Cryogenics components

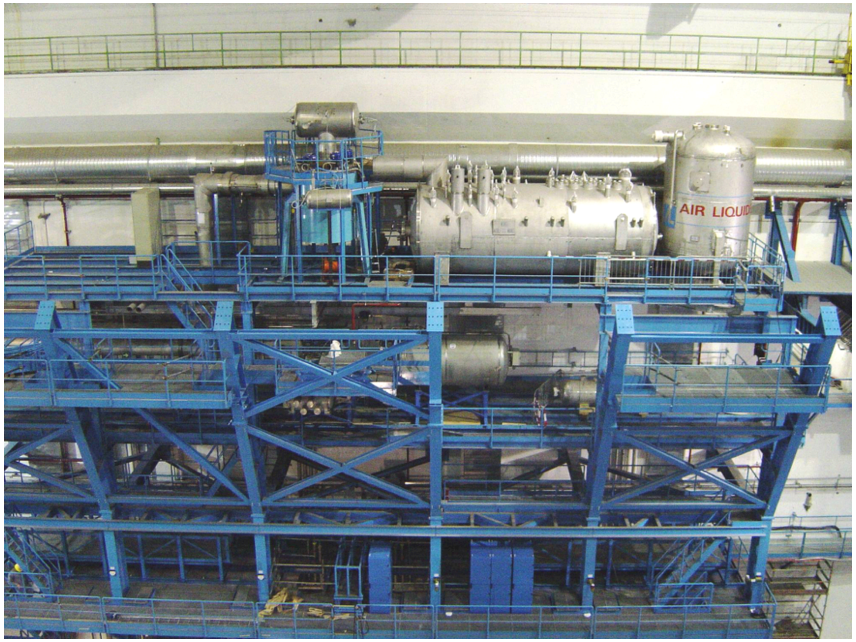


Separation Dewar



Quality meter

Proximity piping



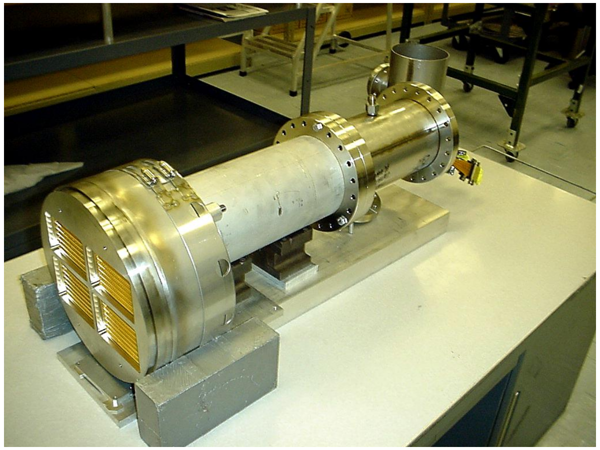
Cryogenics in SH1

Helium main refrigerator compressor station

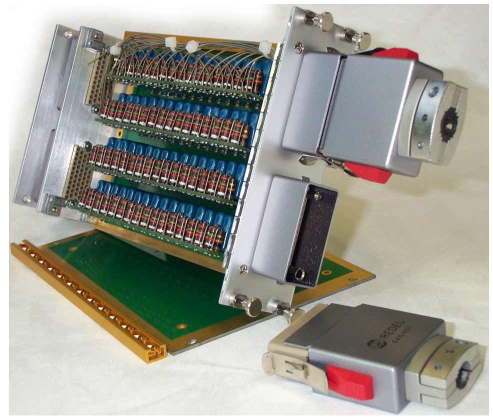
Helium shield refrigerator compressor station

Nitrogen refrigerator compressor station

Feedthroughs



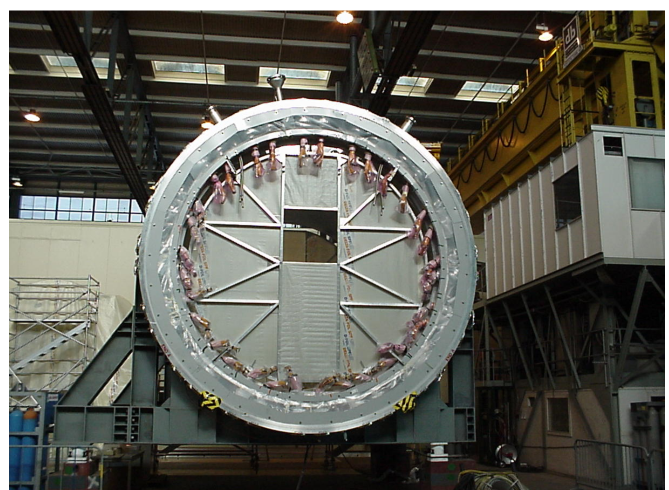
Signal Feedthrough



HV filter box

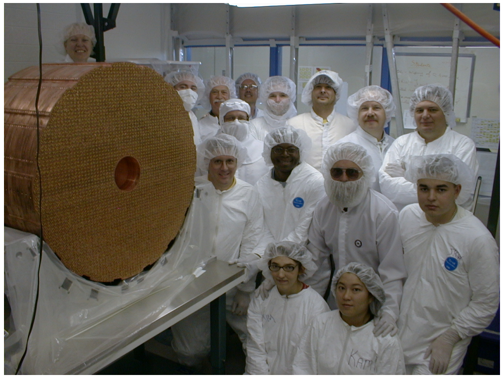
HV Feedthrough

Signal Feedthrough –ready for installation



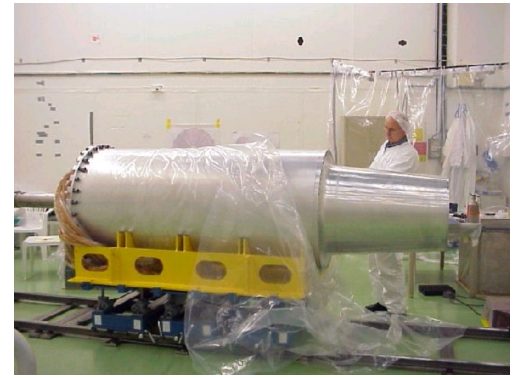
Feedthrough's installation completed

Forward Calorimeter

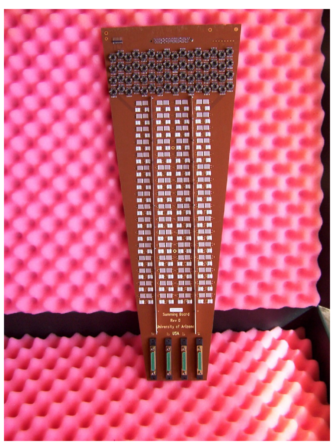


First module

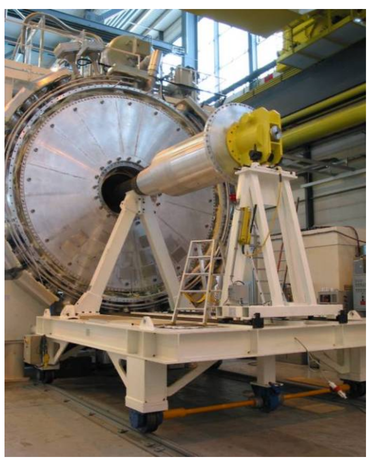
Module assembly



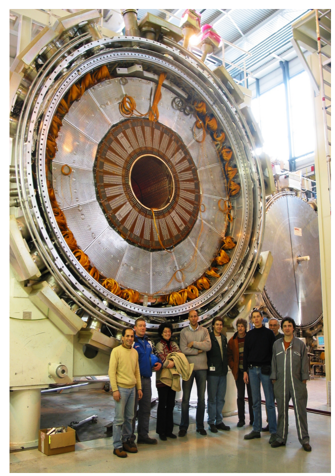
Ready for installation



Summing board



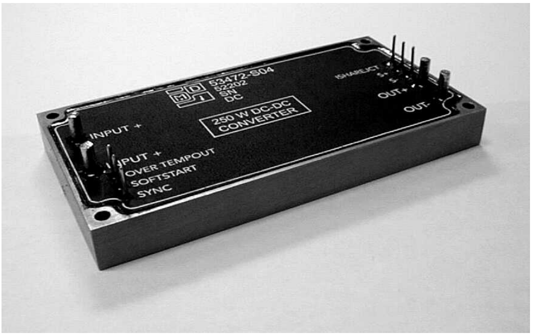
Installation



Electronics installation complete

Endcap assembly complete

Crates and Power supplies



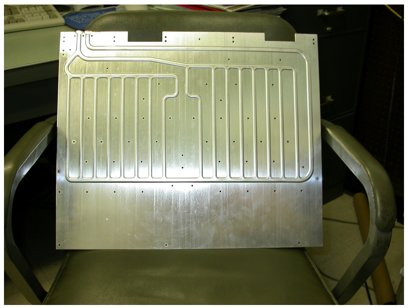
DC-DC converter module

Power supply unit

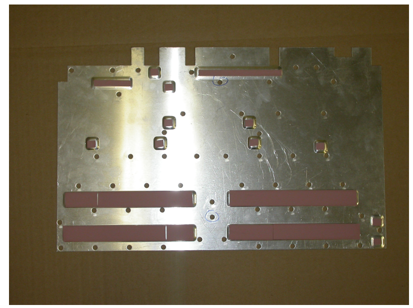
Power supply installed
on the barrel

Front End
crate

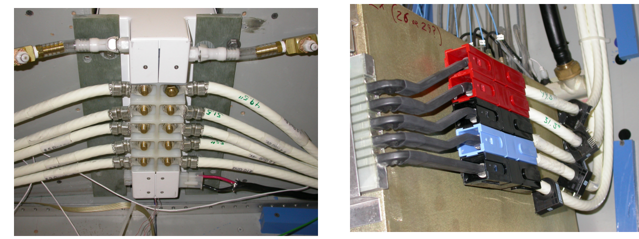
Cooling and services



Cooling plate



Heat transfer plate

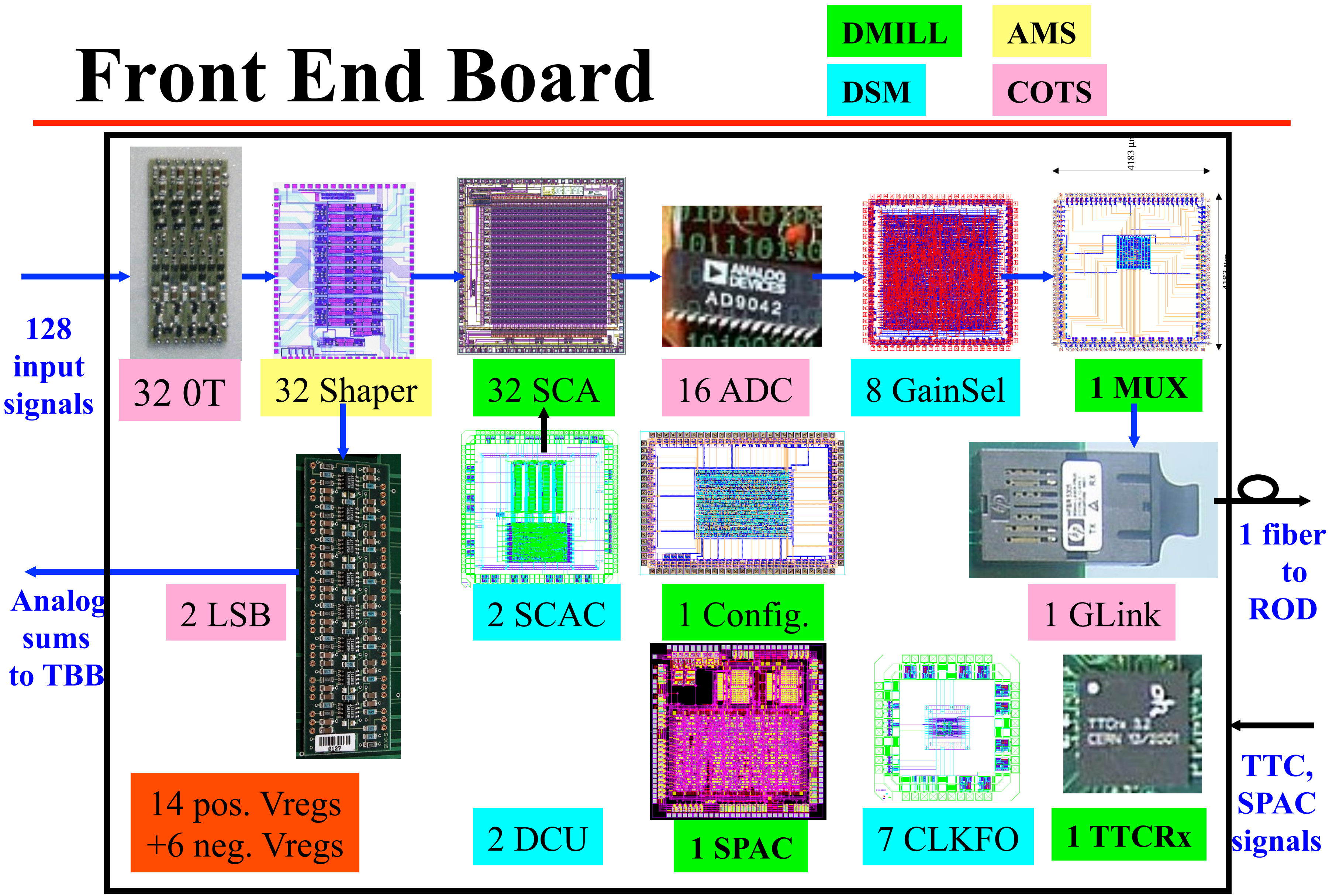


Low voltage cables and connectors

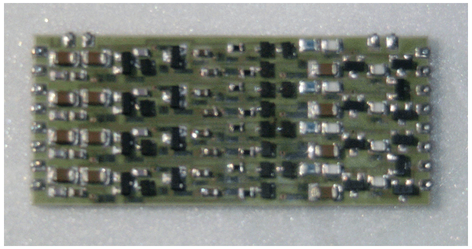
Cooling pipes, cable trays and local cables

Cable trays for the calorimeters services

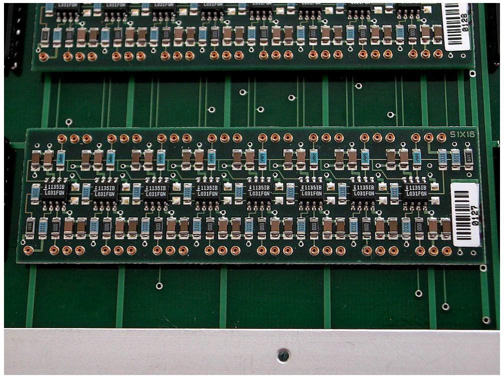
Front End Board



Readout electronics

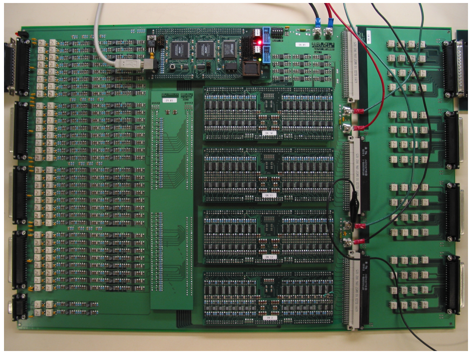


Preamplifiers

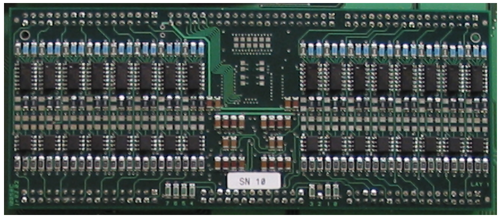


Layer sums board

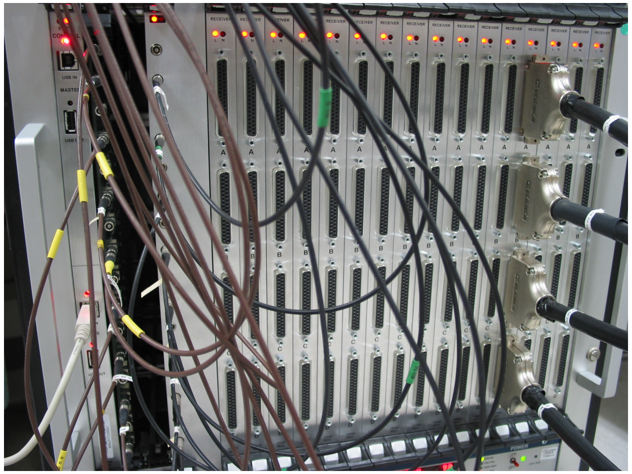
Level 1 Receiver

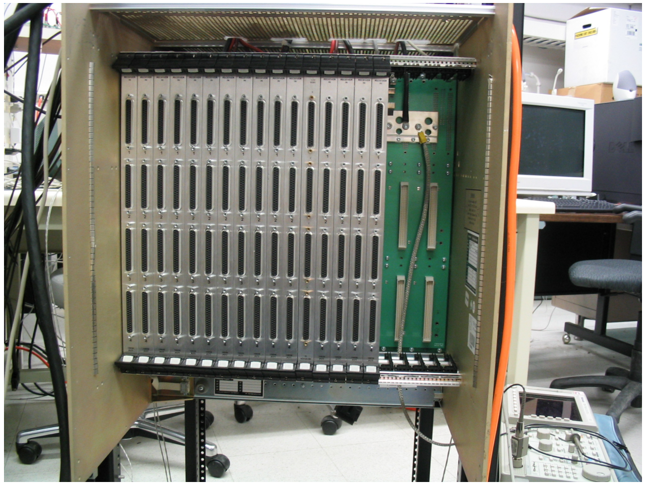


LV1 Receiver board



Variable Gain Amplifier





Front

Back