# Instrumentation of Particle Physics Experiments

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WHEPS – WEIHAI HIGH ENERGY PHYSICS SCHOOL 2015

# Instrumentation

- Instrumentation is a very broad topic, which is everywhere in daily life
  - Oscilloscope, signal generator, digital multimeter …
  - Smartphone – Pocket Geiger for iPhone after Fukushima nuclear disaster
  - Commercial, scientific, military …
  - Wikipedia: **Instrumentation** is defined as the art and science of measurement and control of process variables within a production or manufacturing area
- This lecture will focus on the instrumentation of particle physics experiments
  - Detector & Electronics

# Organization of Lectures

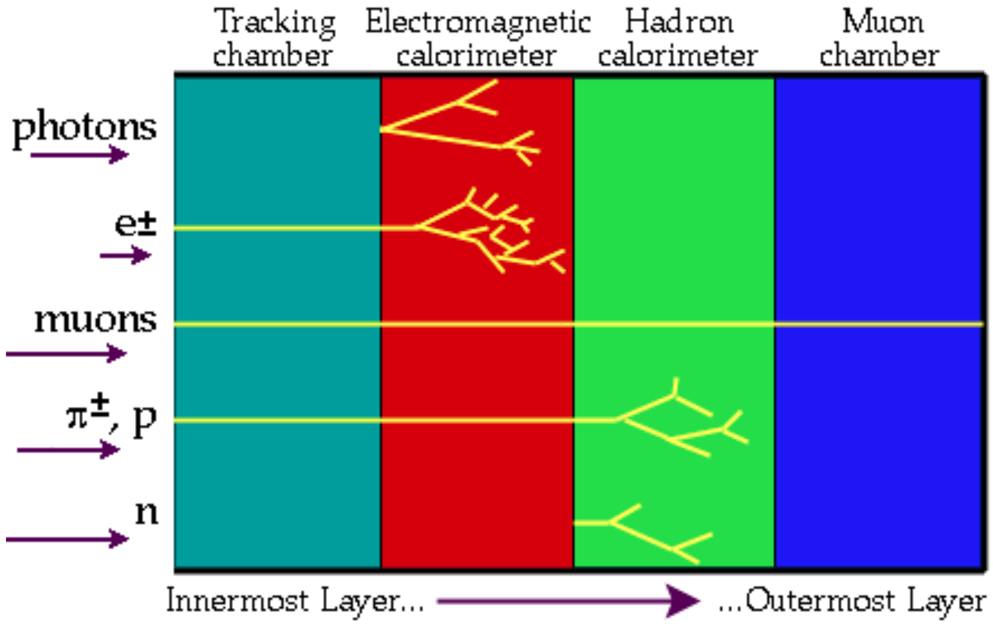
- Lecture 1
  - Calorimetry and Development of Noble Liquid Calorimeter
- Lecture 2
  - Readout Electronics of ATLAS LAr Calorimeters
- Lecture 3
  - ATLAS LAr Readout Electronics Upgrade
- Lecture 4
  - Accelerator Based Neutrino Experiments and Cold Electronics Development

# Lecture 1 – Calorimetry

- Overview of Calorimetry
  - Electromagnetic Calorimeter
  - Hadronic Calorimeter
  - New Calorimeter Development
- Noble Liquid Calorimeter
  - Invention of LAr Calorimeter
  - R806 @ CERN ISR
  - HELIOS @ CERN SPS
  - NA48 @ CERN SPS
  - Accordion – From RD3 to GEM @ SSC and ATLAS @ LHC

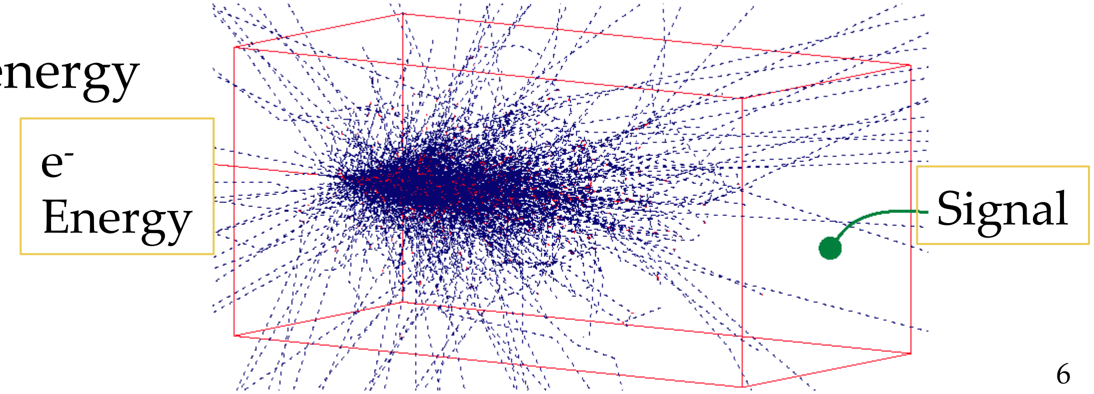
# Calorimetry

- A typical particle physics detector
- Particles characteristics are measured through different type of detectors and identified from specific behaviors due to their interaction with matter
- Calorimeters are used to detect
  - $\gamma$, e
  - Jets (q, g)
  - Missing energy (e.g. $\nu$)



# Calorimetry

- Calorimeter is the detector for energy measurement via total absorption of particles
  - Most calorimeters are position sensitive to measure energy depositions depending on their location
  - Calorimeter is a "destructive" method. Energy and particle get absorbed
- Principle of operation
  - Incoming particle initiates particle shower
  - Energy deposited in form of: heat, ionization, excitation of atoms, Cherenkov light …
  - Signal ~ total deposited energy
  - Signal collection



# Calorimetry

- Energy vs. momentum measurement
  - Calorimeter $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$
  - Gas Detector $\frac{\sigma_p}{p} \sim p$
  - ATLAS:
    $$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}, \quad \frac{\sigma_E}{E} = 1\% @ 100 GeV \qquad \frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t, \quad \frac{\sigma_p}{p} = 5\% @ 100 GeV$$
  - At very high energies one has to switch to calorimeters because their resolution improves while those of a magnetic spectrometer decreases with E
- Shower depth
  - Calorimeter
    - Shower depth nearly energy independent, compact calorimeter is possible
  - Magnetic spectrometer
    - Detector size has to grow quadratically to maintain resolution

# Calorimetry

- Calorimeter features
  - Calorimeters can be built as $4\pi$ detectors, i.e. they can detect particles over almost the full solid angle
    - Compactness: dimension necessary to containment is proportional to $ln$E
  - Calorimeters can provide fast timing signals (1 to 10 ns); can be used for triggering
  - Calorimeters can measure the energy of both, charged and neutral particles, if they interact via electromagnetic or strong forces, e.g. $\gamma$, $\pi^0$, $K^0$, …
  - Segmentation in depth allows separation of hadrons (p, n, $\pi^\pm$), from particles which only interact electromagnetically ($\gamma$, e)
    - Measure of position, direction & particle id on topological basis

# Rules of Thumbs – EM Shower

- Radiation length $X_0 = \frac{180A}{Z^2} \frac{g}{cm^2}$
- Critical energy $E_c = \frac{550 MeV}{Z}$
- Shower maximum $t_{\max} = \ln \frac{E}{E_c} - \begin{cases} 1.0 & \text{e}^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$
- Longitudinal energy containment

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

- Transverse energy containment

$$R(90\%) = R_M$$

$$R(95\%) = 2R_M$$

# EM Calorimeter – Homogeneous

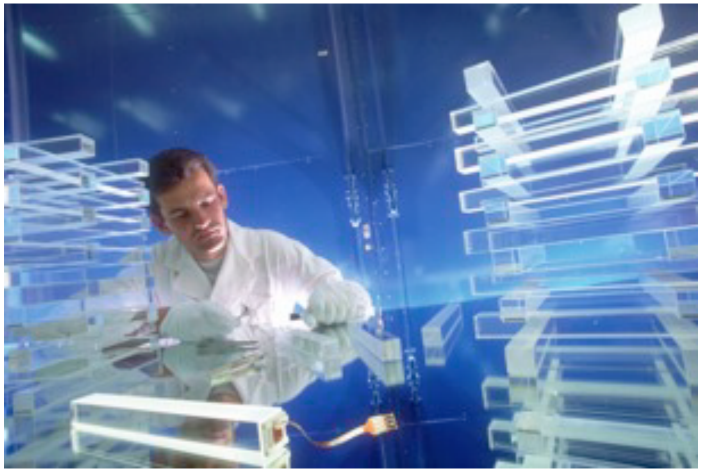
- Homogeneous calorimeters: all the energy is deposited in the active medium.
  - Absorber is active medium as well

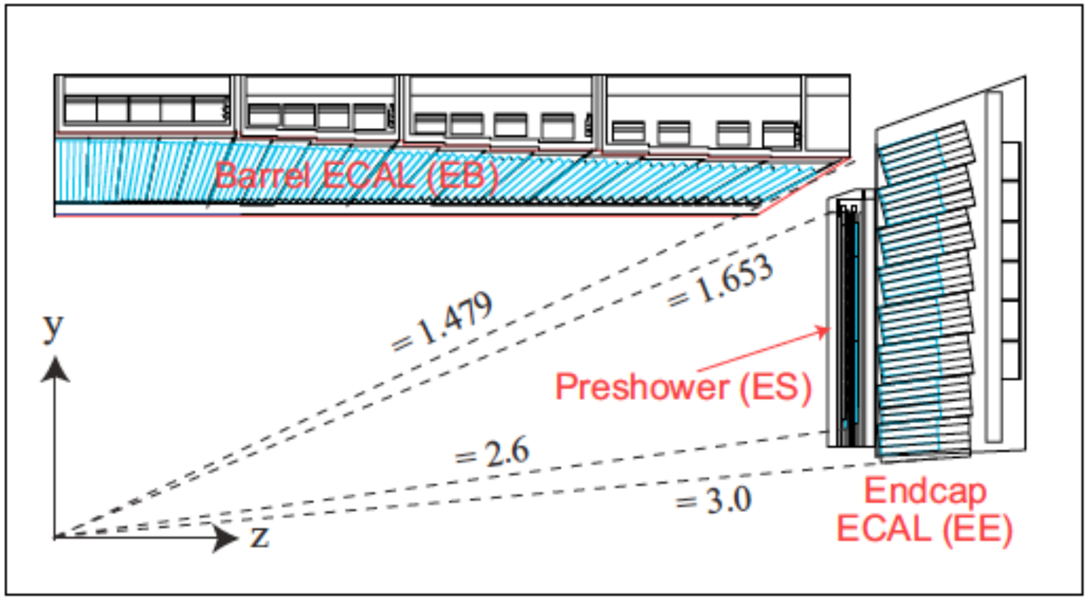
| Signal | Material |
|---|---|
| Scintillation light | BGO, $BaF_2$, $CeF_3$, ... |
| Cherenkov light | Lead Glass |
| Ionization signal | Liquid nobel gases (Ar, Kr, Xe) |

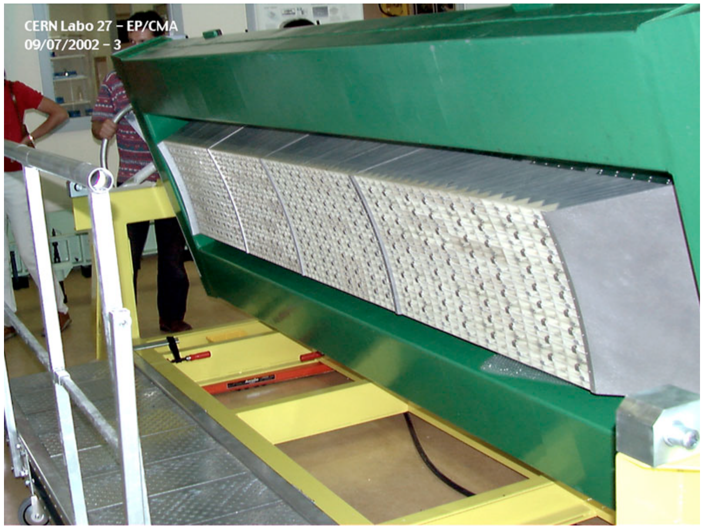
- Pros
  - Excellent energy resolution
- Cons
  - Expensive
  - No information on longitudinal shower shaper

# EM Calorimeter – Homogeneous

- CMS crystal calorimeter
  - Scintillator: $PbWO_4$
  - Photosensor: APDs
  - Number of crystals: ~70,000
  - Light output: 4.5 photons/MeV

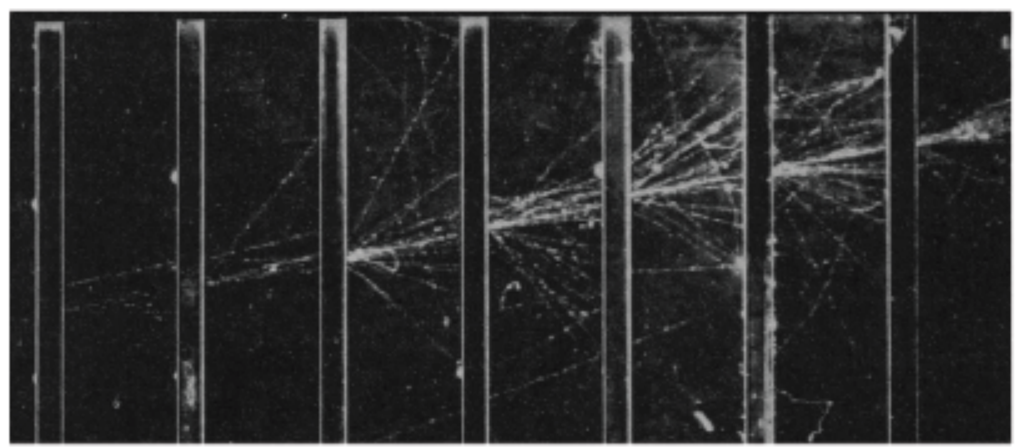




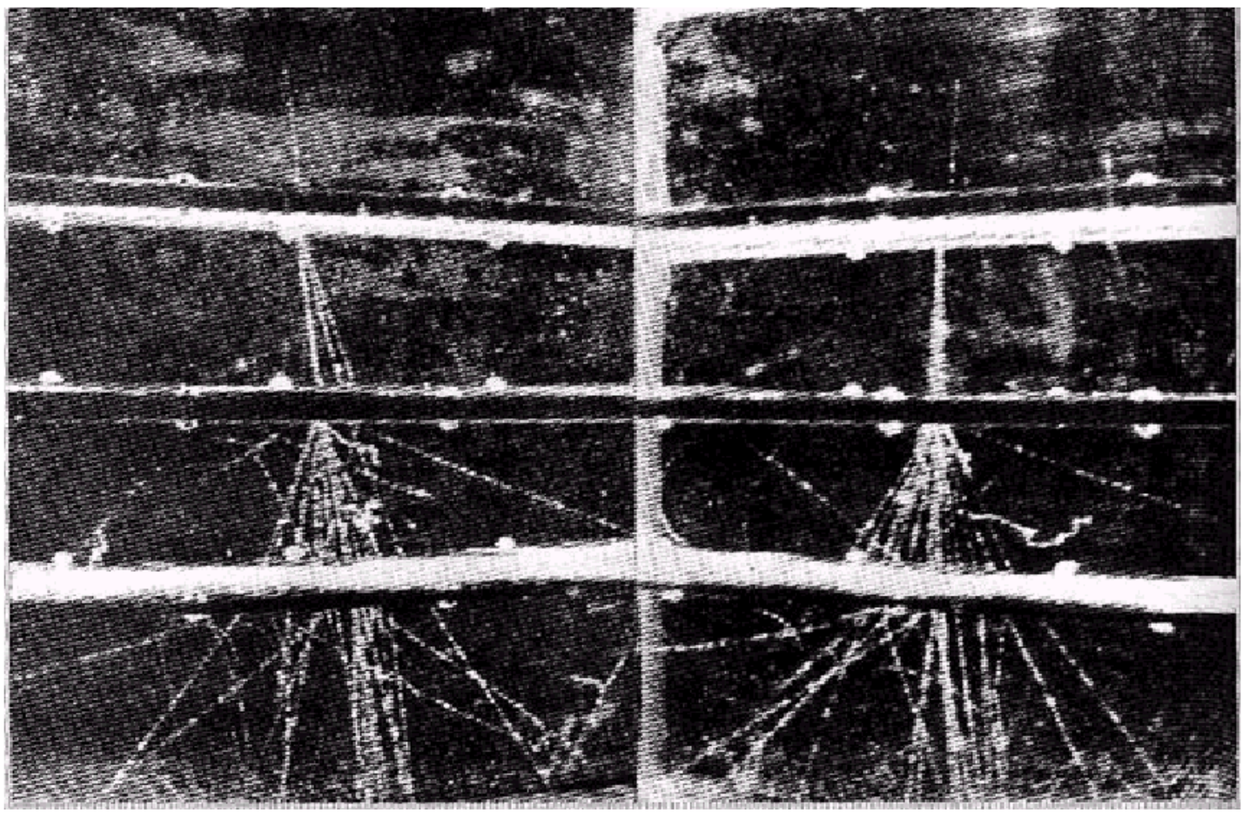
# EM Calorimeter – Sampling

- Sampling calorimeters: shower is sampled by layers of active medium (low Z) alternated with dense absorber (high Z) material
  - Absorber is shower generator, active layers negligible in the shower development
- Absorber materials
  - Iron (Fe), Lead (Pb), Uranium (U)
- Active materials
  - Plastic scintillator
  - Silicon detectors
  - Liquid ionization chamber
  - Gas detector



# EM Calorimeter – Sampling

- Cloud chamber photograph of EM shower developing in lead plates
  - Thickness from top down 1.1, 1.1, $0.13X_0$
  - Exposed to cosmic radiation

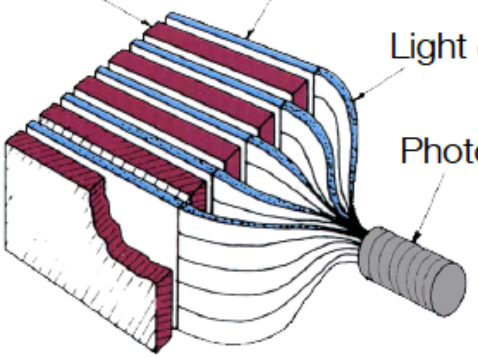


# EM Calorimeter – Sampling

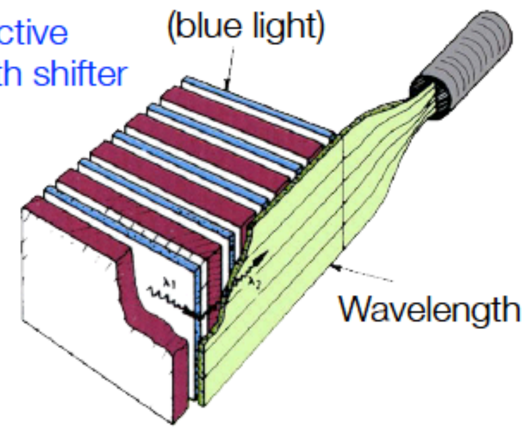
- Pros
  - By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements
  - By freely choosing high-density material for the absorbers one can build very compact calorimeters
  - Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters
  - Detailed shower shaper information is available
- Cons
  - Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only ~$10^{-5}$]
  - Due to this sampling-fluctuations typically result in a reduced energy resolution for sampling calorimeters

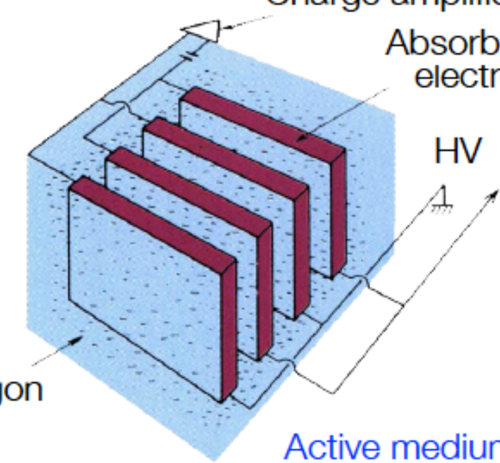
# Sampling Calorimeters – Possible Setup

Scintillators as active layer;
signal readout via photo multipliers



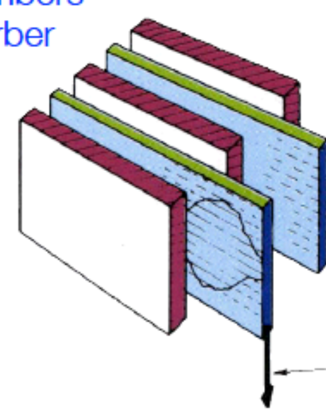

Scintillators as active layer; wave length shifter to convert light



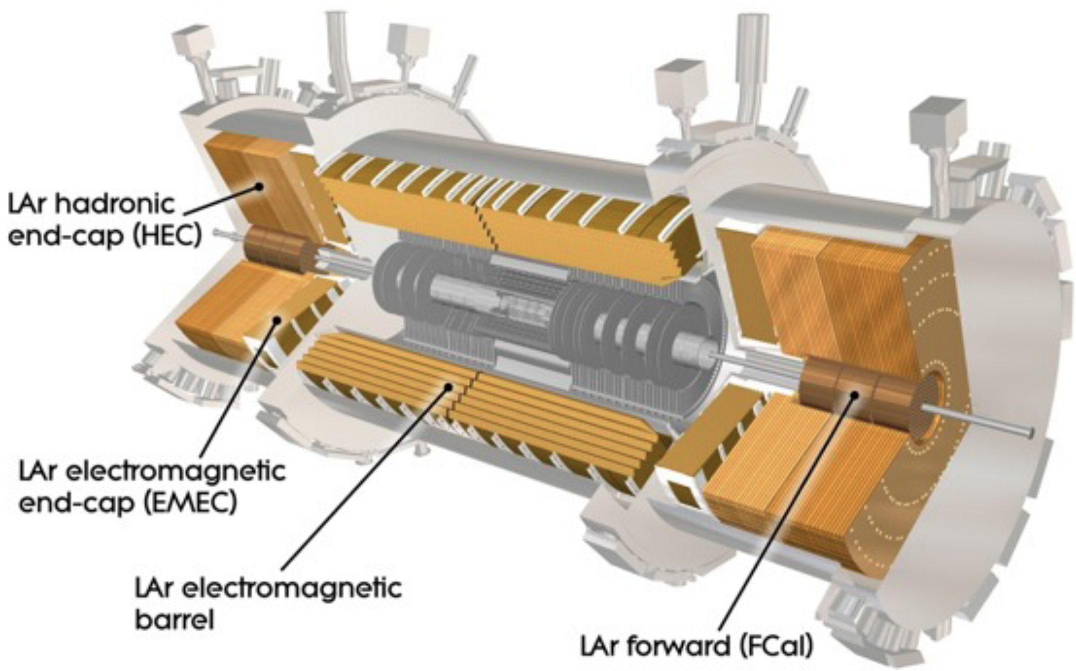

Active medium: LAr; absorber embedded in liquid serve as electrods

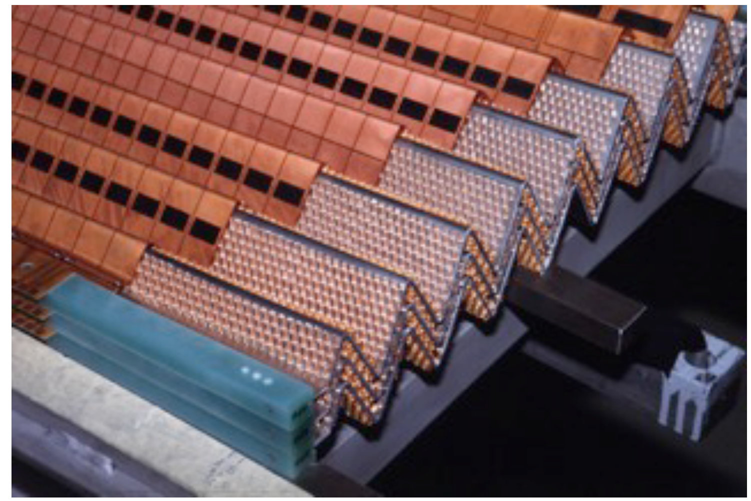
Ionization chambers between absorber plates

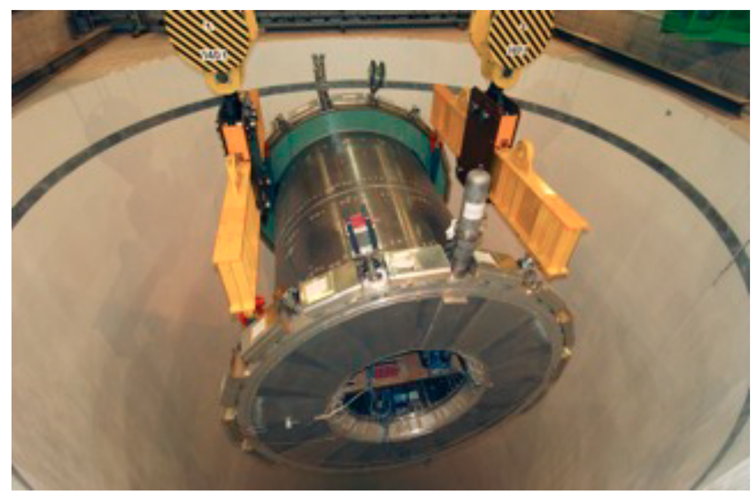


# EM Calorimeter – Sampling

- ATLAS Liquid Argon Calorimeter

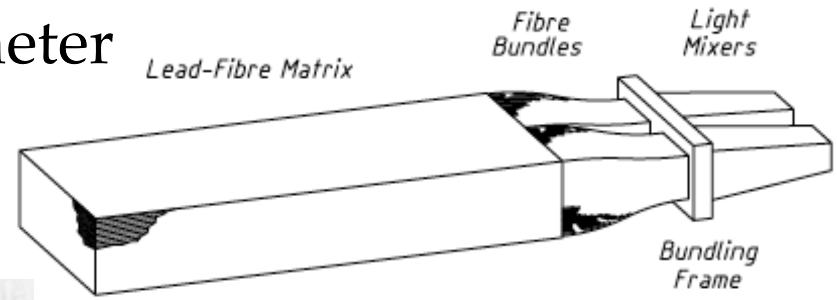


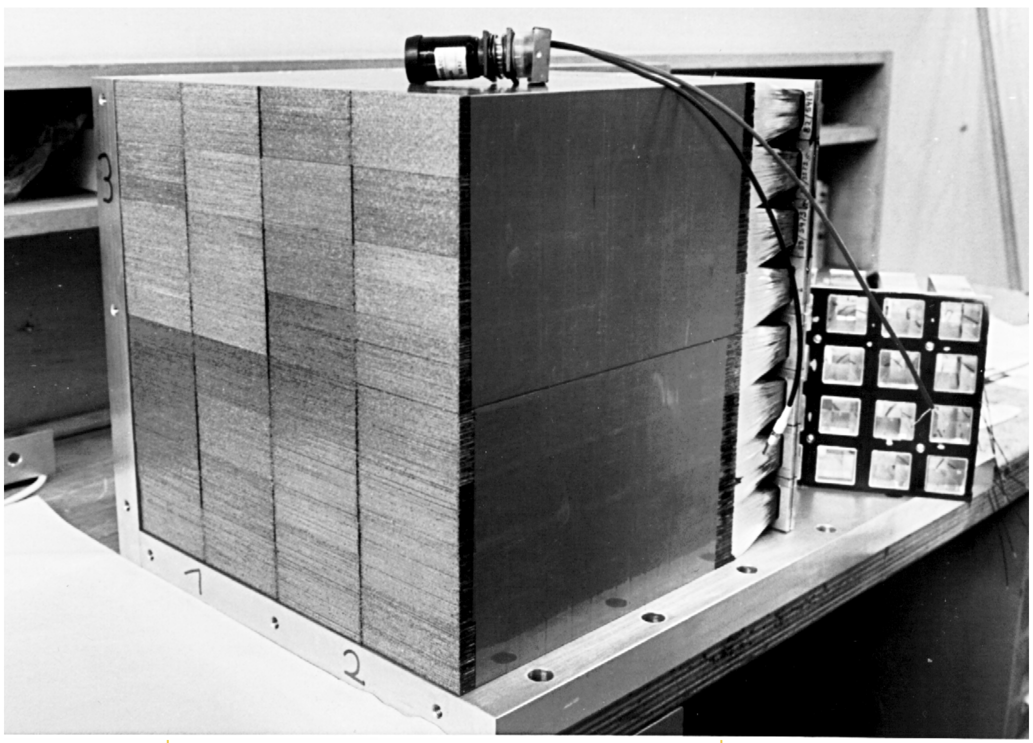





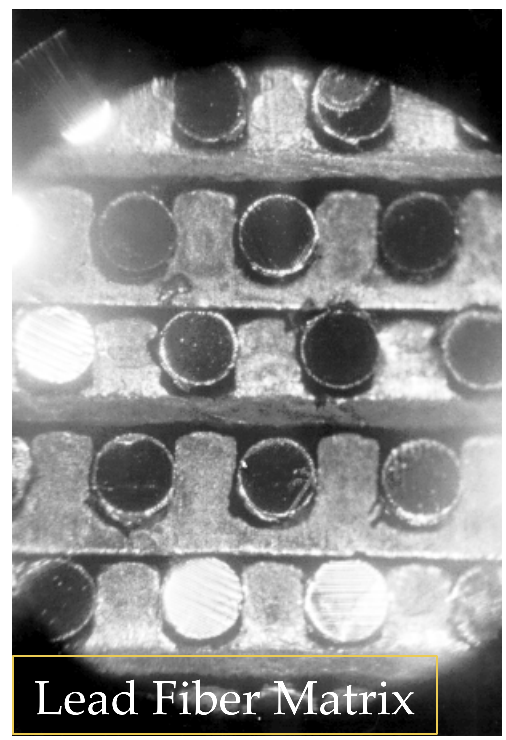
# EM Calorimeter – Sampling

- H1 SpaCal: Spaghetti Calorimeter



4 SpaCal Supermodules



Lead Fiber Matrix

# Homogeneous vs. Sampling Calorimeter

- Resolution of typical EM calorimeter [E is in GeV]

| Technology (Experiment) | Depth | Energy resolution | Date | |
|---|---|---|---|---|
| NaI(Tl) (Crystal Ball) | $20X_0$ | $2.7\%/E^{1/4}$ | 1983 | Homogeneous |
| $Bi_4Ge_3O_{12}$ (BGO) (L3) | $22X_0$ | $2\%/\sqrt{E} \oplus 0.7\%$ | 1993 | Homogeneous |
| CsI (KTeV) | $27X_0$ | $2\%/\sqrt{E} \oplus 0.45\%$ | 1996 | Homogeneous |
| CsI(Tl) (BaBar) | $16–18X_0$ | $2.3\%/E^{1/4} \oplus 1.4\%$ | 1999 | Homogeneous |
| CsI(Tl) (BELLE) | $16X_0$ | $1.7\%$ for $E_\gamma > 3.5$ GeV | 1998 | Homogeneous |
| $PbWO_4$ (PWO) (CMS) | $25X_0$ | $3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$ | 1997 | Homogeneous |
| Lead glass (OPAL) | $20.5X_0$ | $5\%/\sqrt{E}$ | 1990 | Homogeneous |
| Liquid Kr (NA48) | $27X_0$ | $3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$ | 1998 | Homogeneous |
| Scintillator/depleted U (ZEUS) | $20–30X_0$ | $18\%/\sqrt{E}$ | 1988 | Sampling |
| Scintillator/Pb (CDF) | $18X_0$ | $13.5\%/\sqrt{E}$ | 1988 | Sampling |
| Scintillator fiber/Pb spaghetti (KLOE) | $15X_0$ | $5.7\%/\sqrt{E} \oplus 0.6\%$ | 1995 | Sampling |
| Liquid Ar/Pb (NA31) | $27X_0$ | $7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$ | 1988 | Sampling |
| Liquid Ar/Pb (SLD) | $21X_0$ | $8\%/\sqrt{E}$ | 1993 | Sampling |
| Liquid Ar/Pb (H1) | $20–30X_0$ | $12\%/\sqrt{E} \oplus 1\%$ | 1998 | Sampling |
| Liquid Ar/depl. U (DØ) | $20.5X_0$ | $16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$ | 1993 | Sampling |
| Liquid Ar/Pb accordion (ATLAS) | $25X_0$ | $10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$ | 1996 | Sampling |

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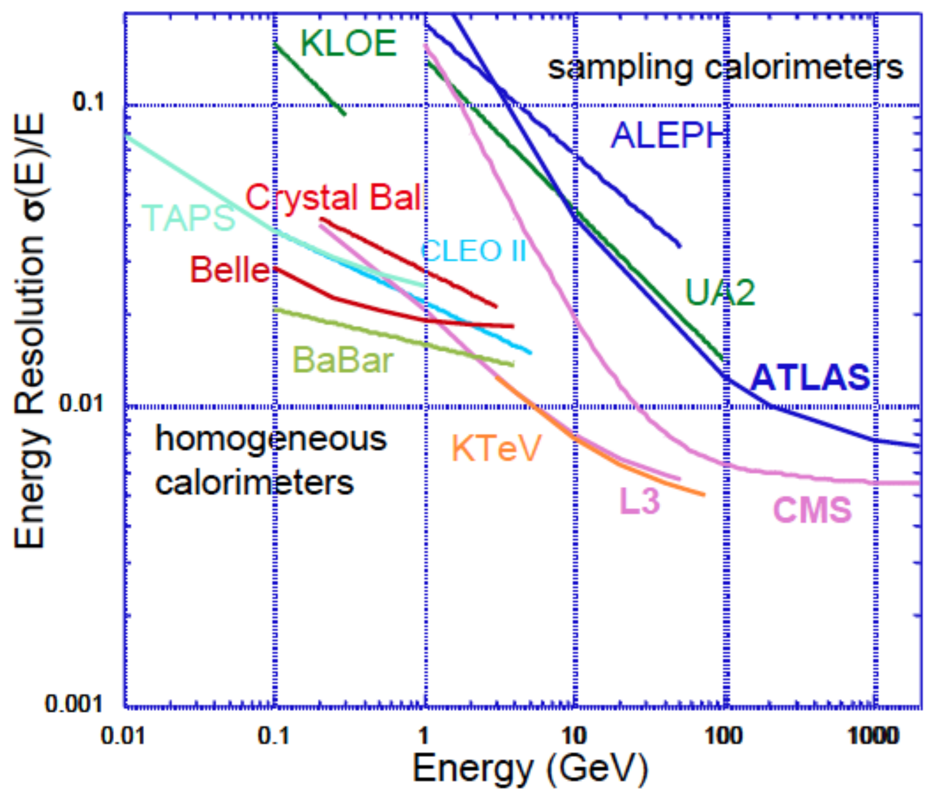


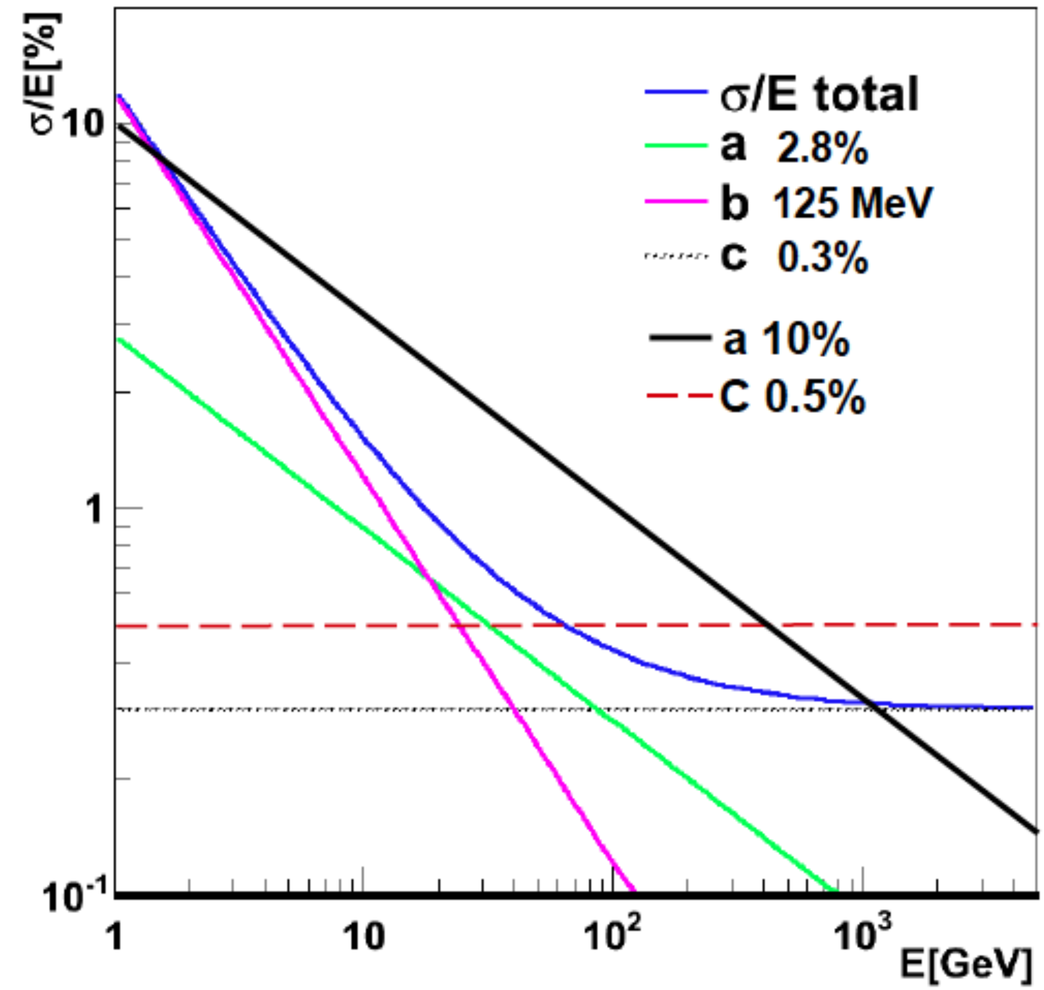
# Energy Resolution

- Energy resolution of a calorimeter can be parameterized as
  - Note the quadratic sum

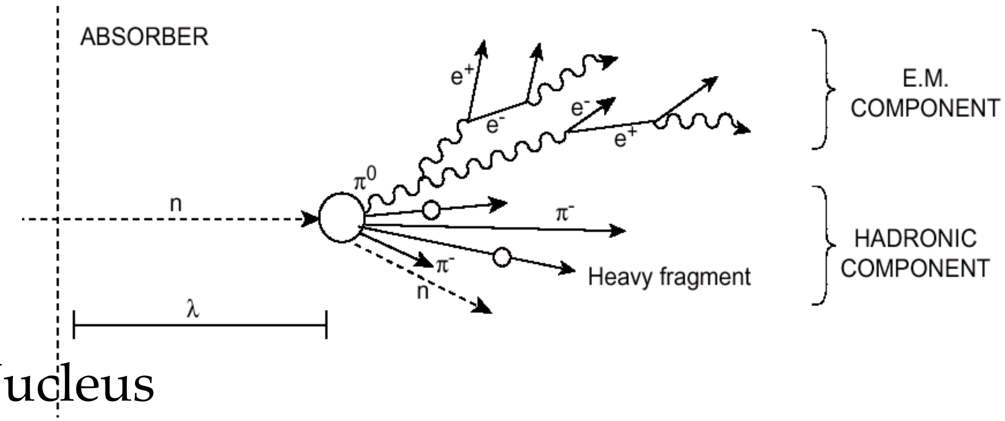
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- a: the stochastic term accounts for any kind of Poisson-like fluctuations
  - Natural merit of homogeneous calorimeters
  - Several contributions add to the "intrinsic one"
- b: the noise term responsible for degradation of low energy resolution
  - Mainly the energy equivalent of the electronic noise
  - Contribution from pileup: the fluctuation of energy entering the measurement area from sources other than the primary particle
- c: the constant term dominates at high energy
  - Its relevance is strictly connected to the small value of a
  - It is mostly dominated by the stability of calibration
  - Contributions from energy leakage, non-uniformity of signal generation and/or collection, loss of energy in dead materials

# When do we have to worry about c



# Hadronic Shower




- Hadronic interaction
  - Elastic: p + Nucleus → p + Nucleus
  - Inelastic: p + Nucleus → $\pi^+ + \pi^- + \pi^0$ + Nucleus*
- Shower development
  - p + Nucleus → Pions + N* + …
  - Secondary particles undergo further elastic collisions until they fall below pion production threshold, $E \sim 2m_\pi = 0.28$ GeV
  - Sequential decays
    - $\pi^0 \rightarrow \gamma\gamma$ yields electromagnetic shower
    - Fission fragments → β-decay, γ-decay
    - Neutron capture → fission
    - Spallation …

# Hadronic Shower

- Hadronic interaction length

$$\lambda_{\text{int}} = \frac{1}{\sigma_{tot} \cdot n} = \frac{A}{\sigma_{pp} A^{2/3} \cdot N_A \rho} \sim A^{1/3} \approx 35 \frac{g}{cm^2} \cdot A^{1/3} \quad N(x) = N_0 \exp\left(-\frac{x}{\lambda_{\text{int}}}\right)$$

- Interaction length characterizes both, longitudinal and transverse profile of hadronic showers

$$\left.\begin{array}{l} X_0 \sim \frac{A}{Z^2} \\ \lambda_{\text{int}} \sim A^{1/3} \end{array}\right\} \rightarrow \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

- Typical longitudinal size [95% containment]: 6 … 9 $\lambda_{\text{int}}$
  - EM: 15-20 $X_0$
- Typical transverse size [95% containment]: 1 $\lambda_{\text{int}}$
  - EM: 2 $R_M$, compact
- Hadronic calorimeter needs more depth than electromagnetic calorimeter

Some numerical values for materials typical used in hadron calorimeters

| | $\lambda_{int}$ [cm] | $X_0$ [cm] |
|---|---|---|
| Szint. | 79.4 | 42.2 |
| LAr | 83.7 | 14.0 |
| Fe | 16.8 | 1.76 |
| Pb | 17.1 | 0.56 |
| U | 10.5 | 0.32 |
| C | 38.1 | 18.8 |

# Hadronic Shower

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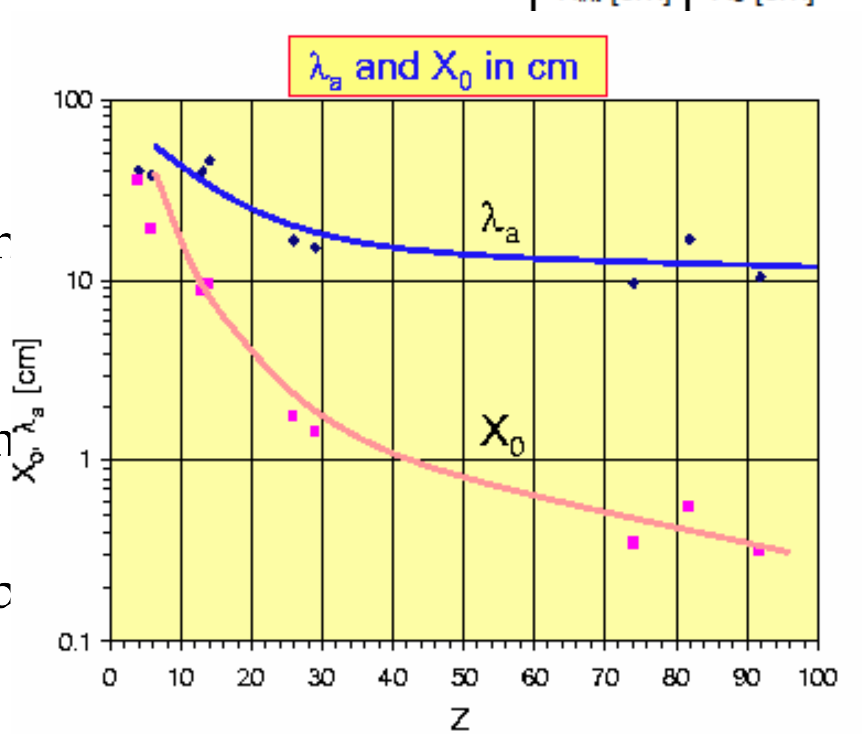
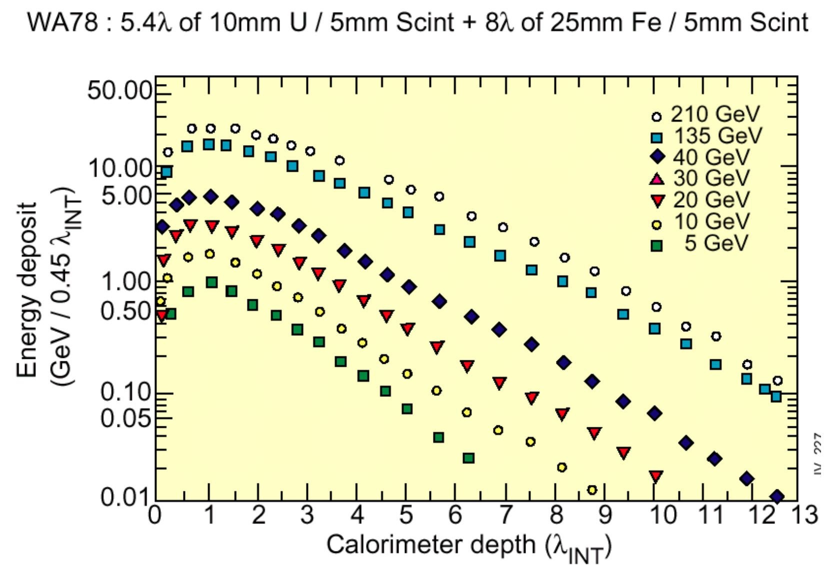
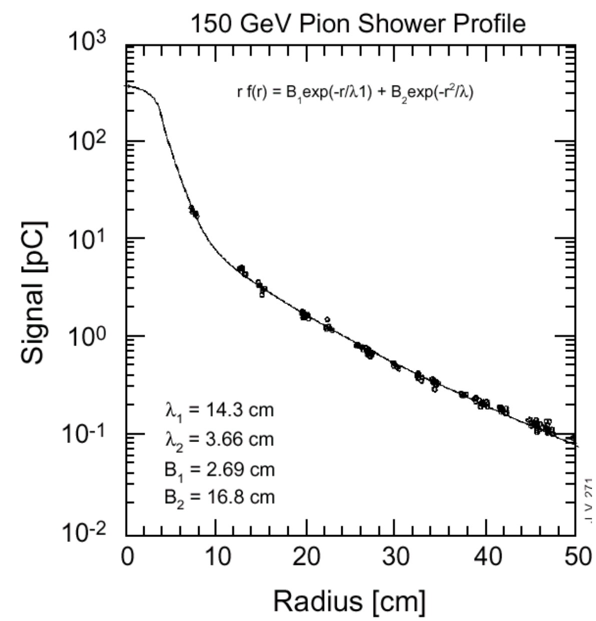


# Hadronic Shower

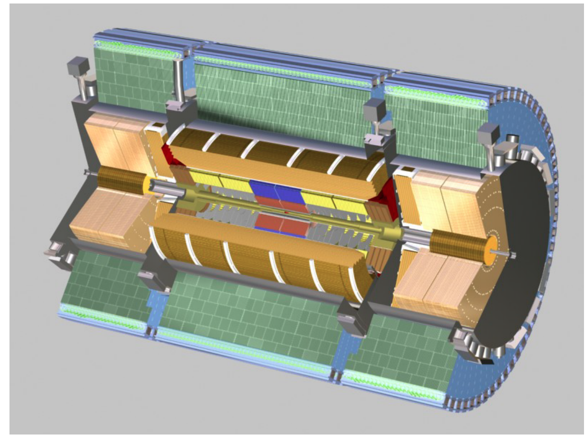
- Longitudinal
  - Sharp peak from $\pi^0$ from the first interaction
  - Gradual extinction with typical scale
  - Need to sample
- Lateral
  - Average $p_t$ secondaries ~ 300 MeV
  - Typical transverse scale $\lambda_{int}$ for 95% E containment
  - Dense core due to $\pi^0$

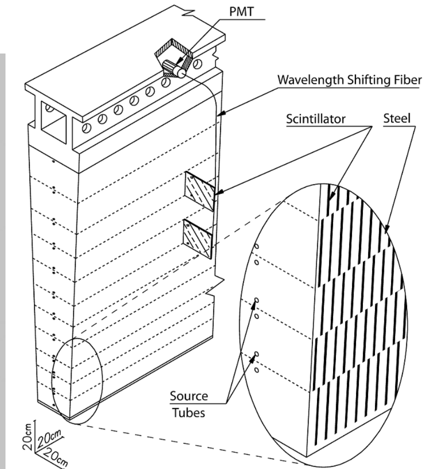


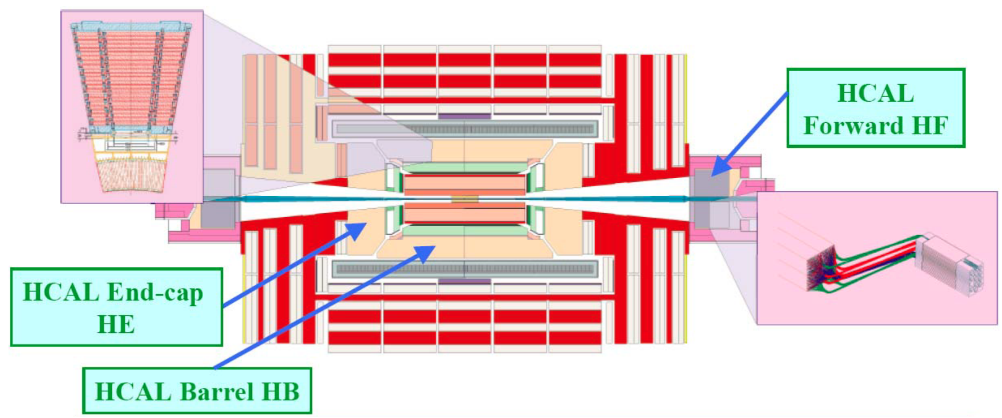



# Hadronic Calorimeter

- Most common realization – Sampling
- ATLAS Tile Calorimeter
  - Iron/plastic scintillator sampling calorimeter
- CMS HCAL
  - Barrel and Endcap are brass/scintillator sampling calorimeter
  - Forward is steel/quartz fibers sampling calorimeter





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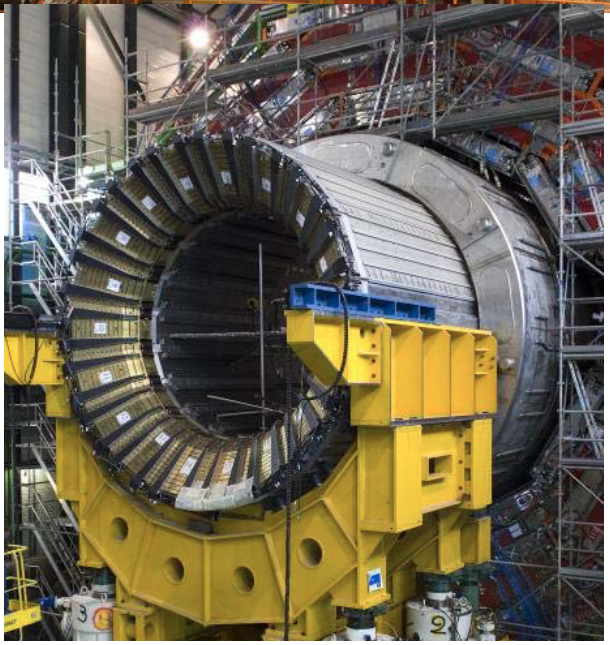
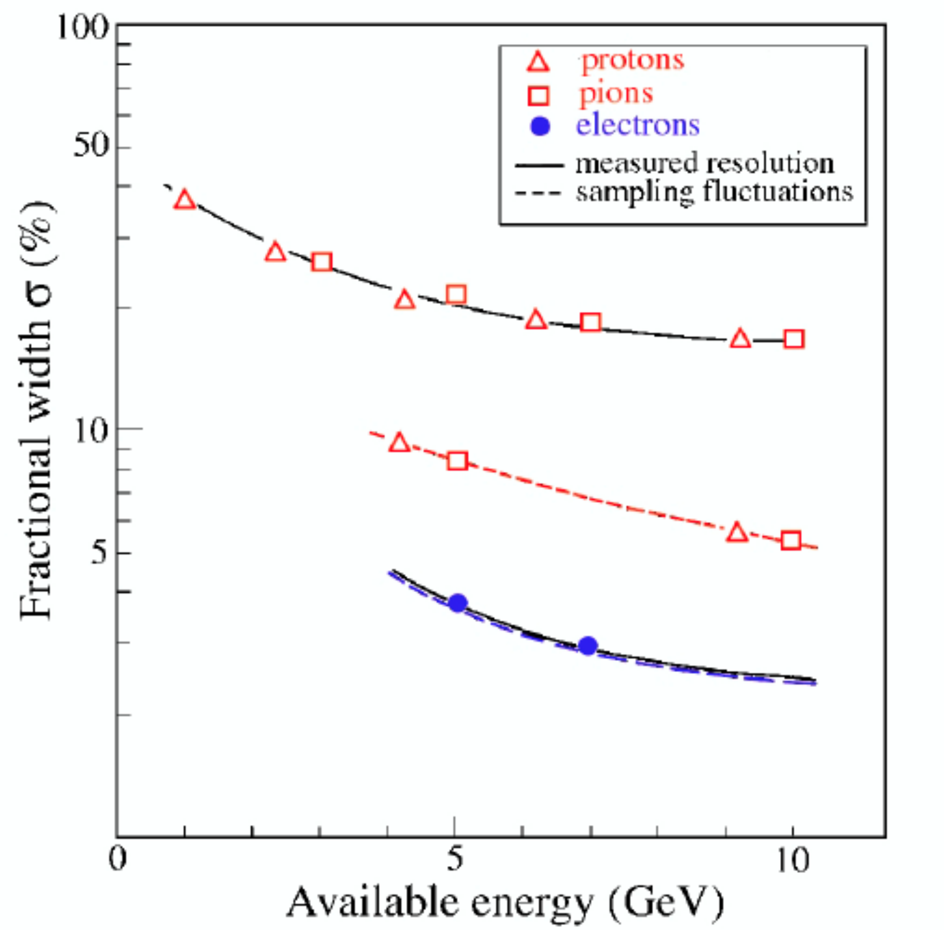


# Energy Resolution

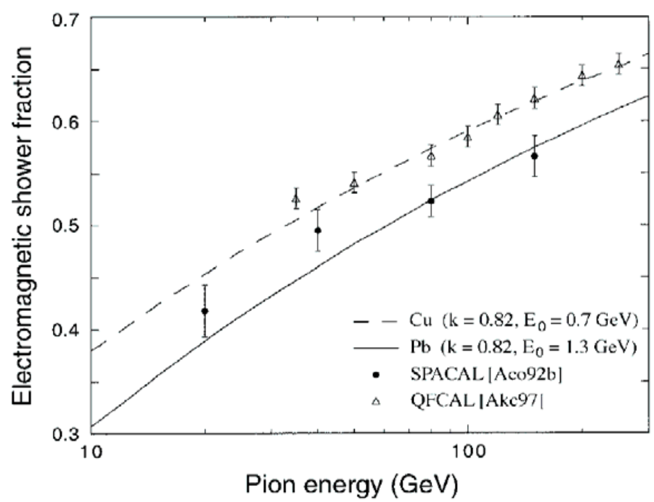
$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

- A – typical 0.5 – 1.0 [record: 0.35]
  - Leakage fluctuations, sampling fluctuation, fluctuation of EM fraction, nuclear excitations, fission, binding energy fluctuations, heavily ionizing particles
- B – typical few%
  - Sampling fraction variations, electronic noise
- C – typical 0.03 – 0.05
  - Inhomogeneous shower leakage

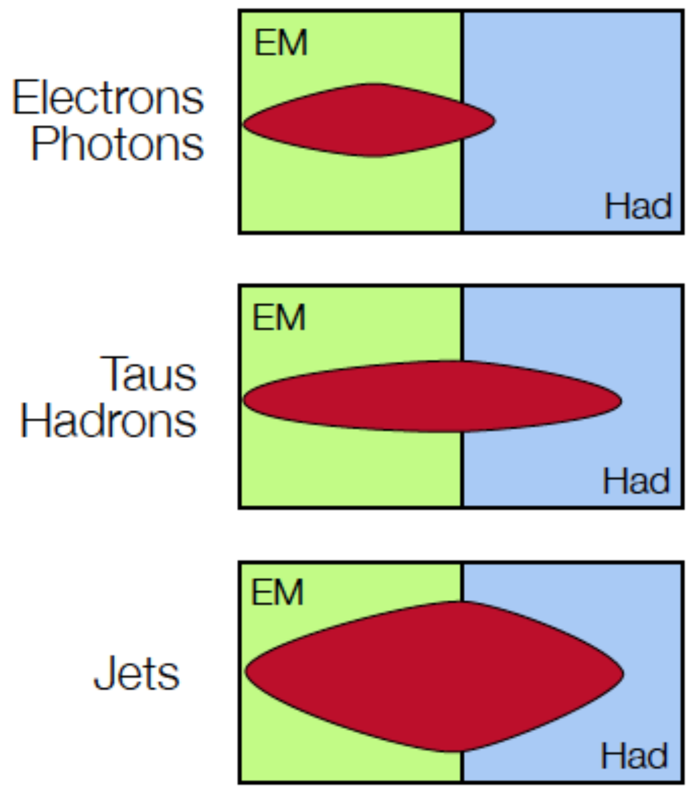


# Hadronic Calorimeter

- Typical calorimeter has two components
  - Electromagnetic (EM)
  - Hadronic (Had)
- Hadronic energy measured in both parts of calorimeter
  - Needs careful consideration of different response
  - A priori e and h in a calorimeter give a different response, e.g. e/h > 1
  - The fluctuations in the fraction of energy deposited by e and h limits resolution
  - Moreover in average this fraction is energy dependent

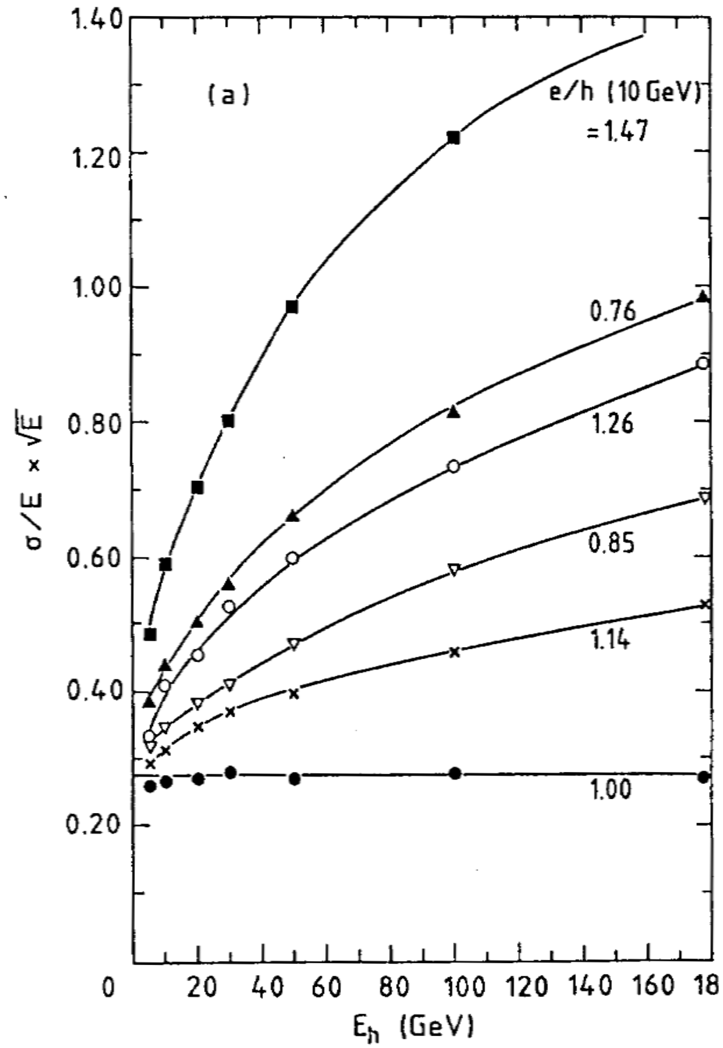



Schematic of a typical HEP calorimeter



# Hadronic Calorimeter

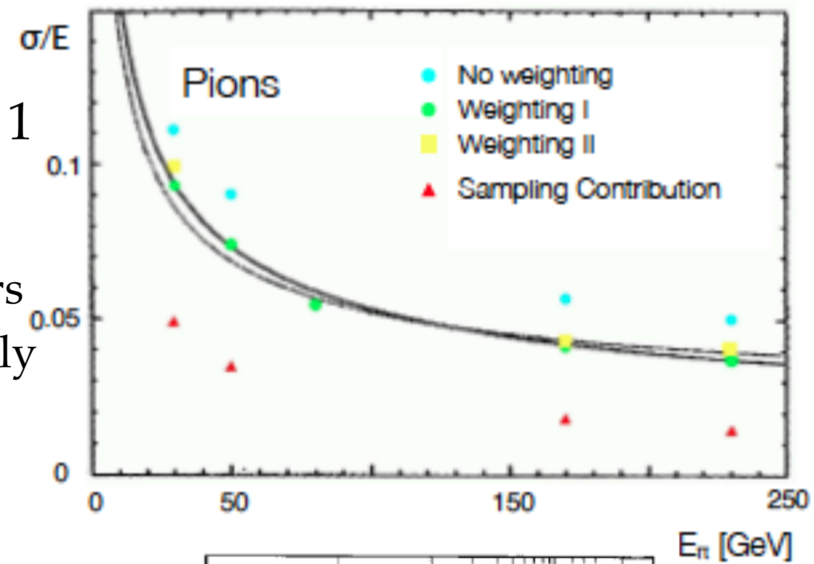
- e/h ratio
  - Response of calorimeters very different to EM and Had energy deposits
  - Usually higher weight for EM component, e.g. e/h > 1
- e/h ≠ 1 leads to
  - Non-uniform energy response due to fluctuations in $f_{em}$
  - Non-linear behavior
  - Worsening of resolution
  - Deviation from 1/√E resolution dependence

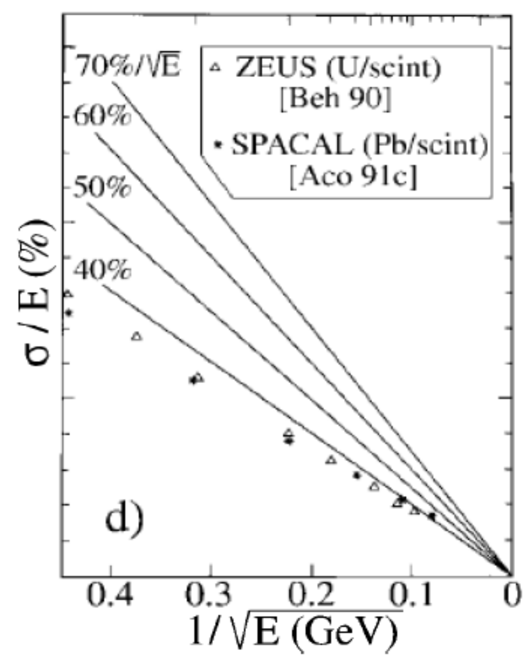


# Hadronic Calorimeter

- Compensation is important to get e/h = 1
- Software compensation
  - Segmentation of calorimeter into cells/layers
  - Identification of cells/layers with particularly large energy
  - Give small weight to layers with larger energy density
- Hardware compensation
  - Choose suitable hardware parameters to either increase h/mip or decrease e/mip
  - Suppress EM component with high Z absorber
  - Enhance h production through fission and spallation
  - Enhance response to n using active materials hydrogen rich

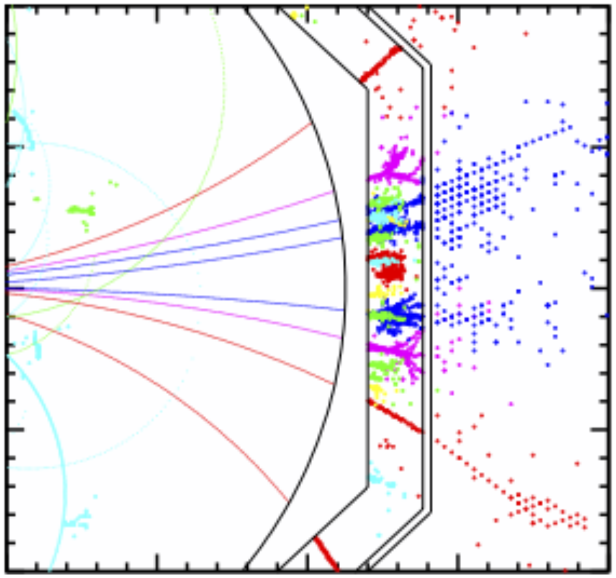
Energy resolution of LAr calorimeter with and without weighting ...



# New Calorimeter Development

- PFA – Particle Flow Approach
  - Imaging calorimeter for Linear Collider
  - Highly granular calorimeter can identify the energy deposit of every visible particle ($10^7$ to $10^{12}$ readout channels)
  - The energy of charged hadrons will be measured by the tracking detectors
  - The energy of photons will be measured by the electromagnetic calorimeter
  - The hadronic calorimeter is then used only to measure the energy of neutral hadrons
  - The reduced dependence on the hadronic calorimeter will lead to an unprecedented jet energy resolution (~25%)



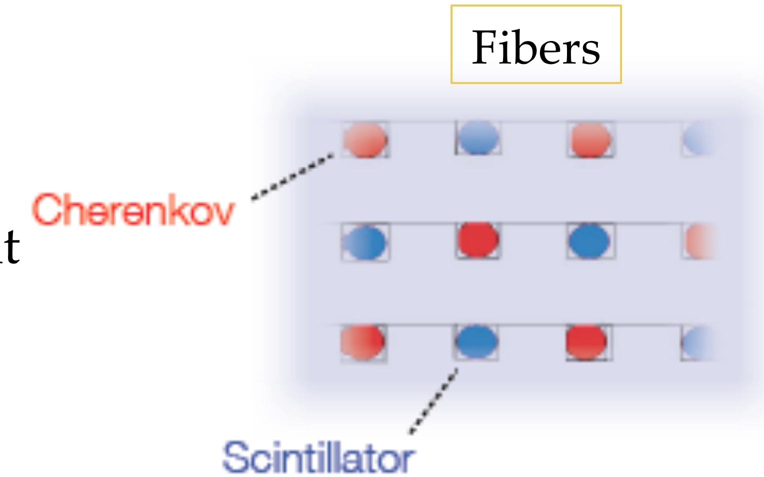
| Component | Detector | Fraction | Part. resolution | Jet Energy Res. |
|---|---|---|---|---|
| Charged ($X^{\pm}$) | Tracker | 60% | $10^{-4}\,E_X$ | negligible |
| Photons ($\gamma$) | ECAL | 30% | $0.1/\sqrt{E_\gamma}$ | $.06/\sqrt{E_{jet}}$ |
| Neutral Hadrons (h) | E/HCAL | 10% | $0.5/\sqrt{E_{had}}$ | $.16/\sqrt{E_{jet}}$ |

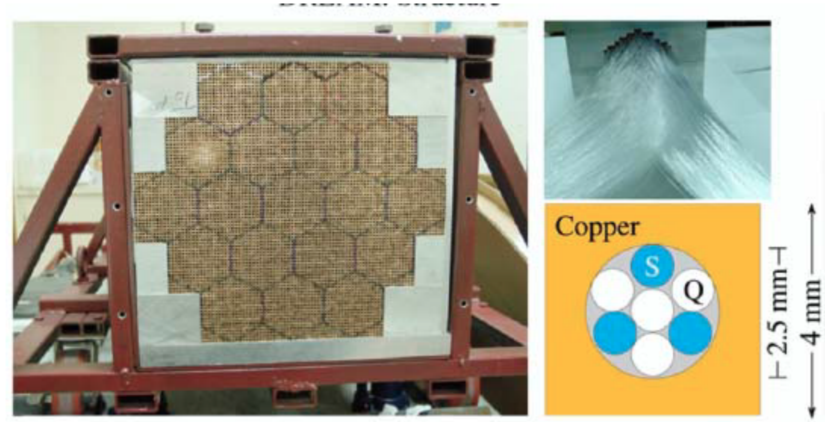
# New Calorimeter Development

- Dual Readout Calorimetry
  - Cherenkov assisted Hadron Calorimetry
  - EM: clear fibers for Cherenkov light to sample EM part of the shower [$E_{Cherenkov}$]
  - Charged: scintillation fibers to sample all components [$E_{Ionization}$]

$$\frac{E_{em}}{E_{tot}} = \frac{E_{Cherenkov}}{E_{Ionization}}$$

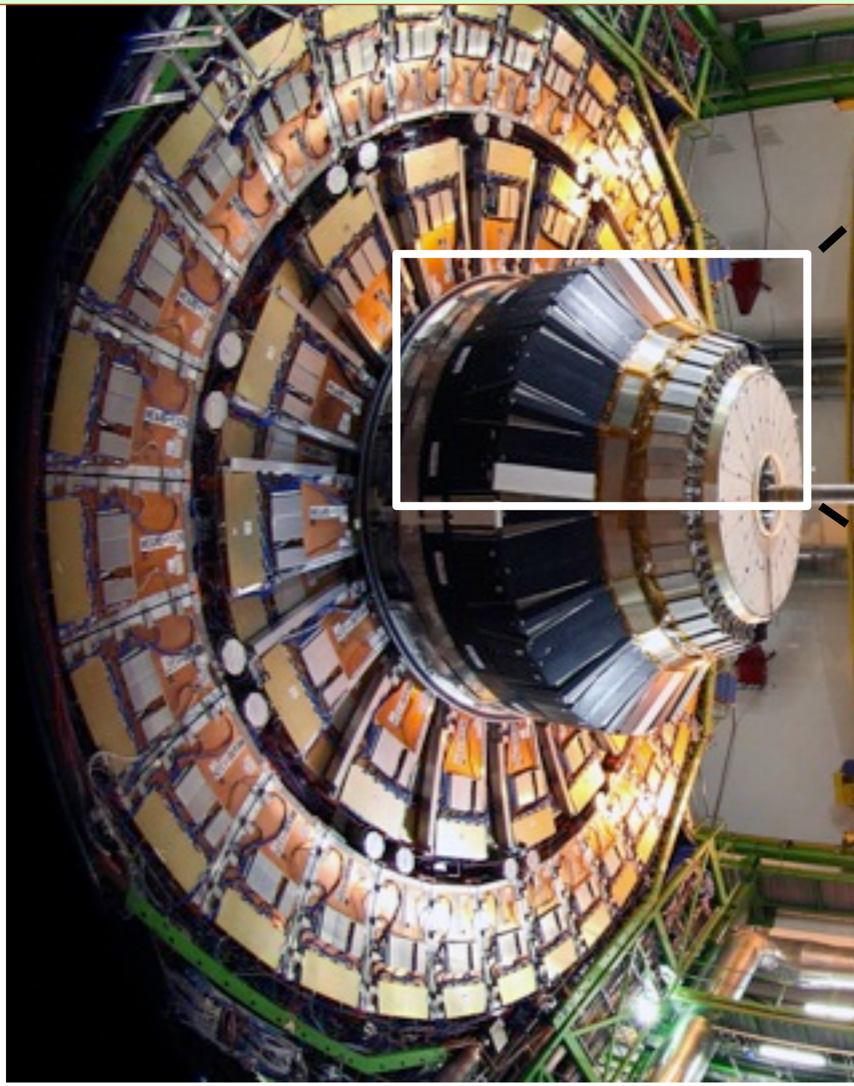
  - RD52 – DREAM (Dual-READout Method)
    - Measure $f_{em}$ event by event to improve hadronic energy resolution

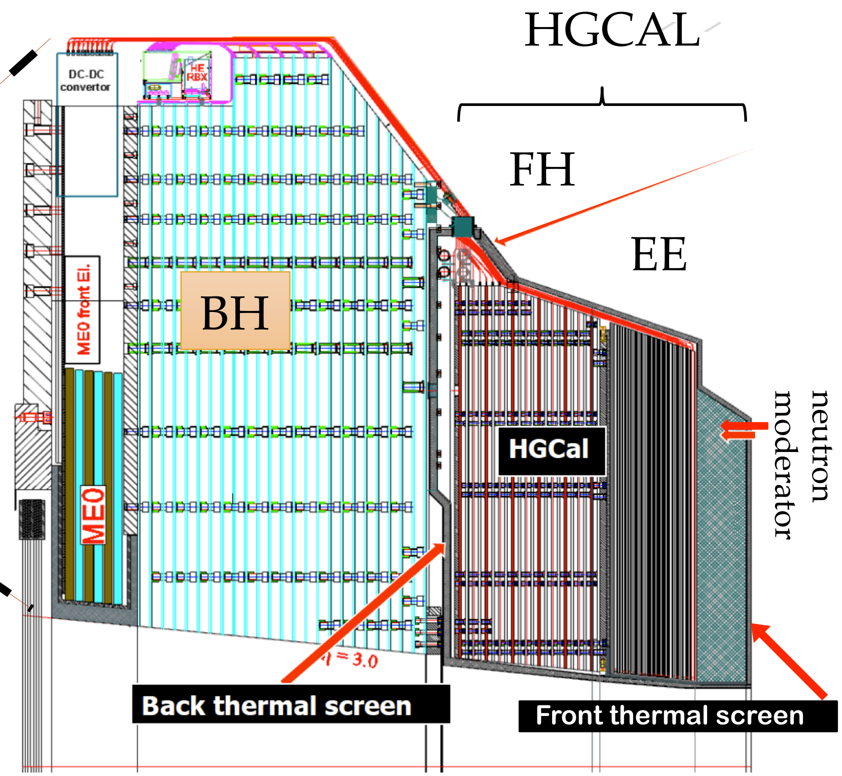


# Endcap Calorimeter for HL-LHC: High Granularity Cal

**Integrated sampling Silicon ECAL+HCAL and Backing Calorimeters**





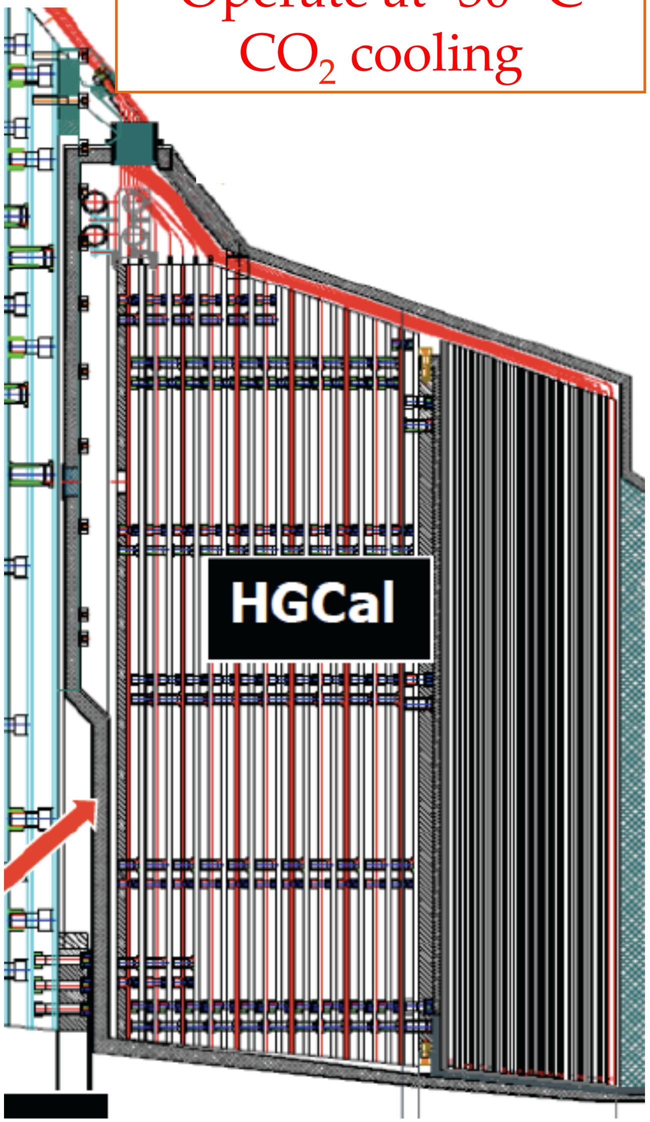

**EE** Cu-W / Si 26 $X_0$ (1.5 $\lambda$)

**FH** Brass / Si 3.5 $\lambda$

**BH** Brass / scint. tiles 5 $\lambda$

# Endcap Calorimeter for HL-LHC: HGCal

Operate at -30 °C
$CO_2$ cooling




Si/W-ECAL Section ($\Sigma_{depth}$>25$X_0$, 1.5λ)

- $10 \times 0.65X_0$
- $10 \times 0.88X_0$
- $8 \times 1.26X_0$

Si/Brass Front HCAL (FH) Section ($\Sigma_{depth}$> 3.5λ)

- $12 \times 0.3\lambda$

Scint/Brass Backing HCAL(BH) Section($\Sigma_{depth}$> 5λ)

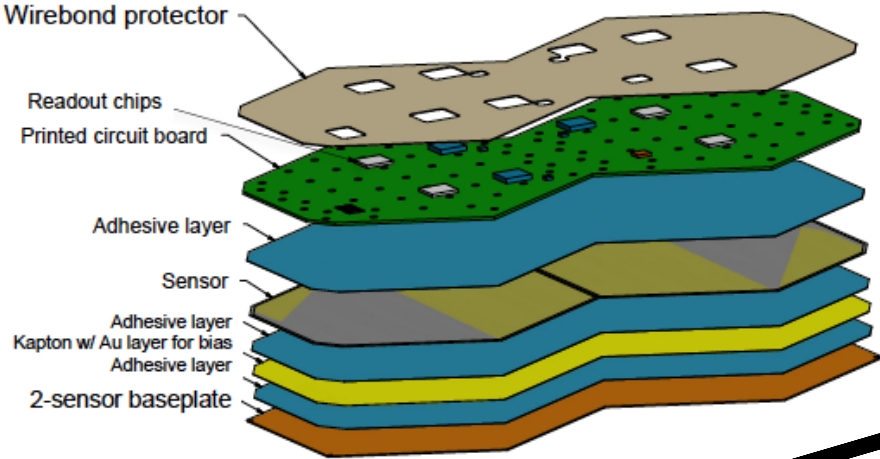
- $12 \times 0.45\lambda$

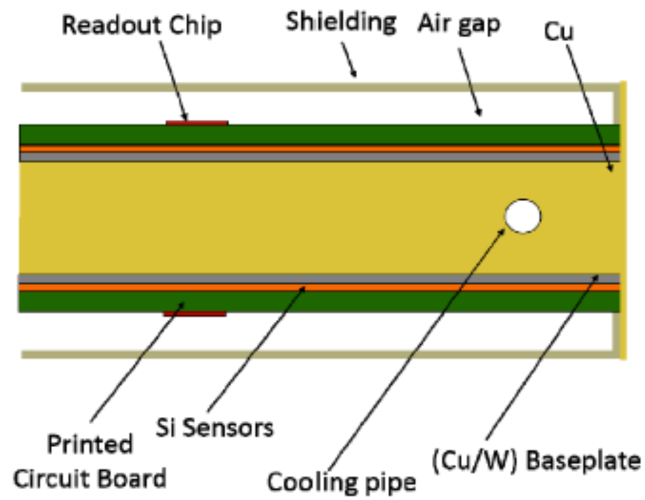
Total Depth >10λ

Table 3.2: Parameters of the EE and FH.

| | EE | FH | Total |
|---|---|---|---|
| Area of silicon ($m^2$) | 380 | 209 | 589 |
| Channels | 4.3M | 1.8M | 6.1M |
| Detector modules | 13.9k | 7.6k | 21.5k |
| Weight (one endcap) (tonnes) | 16.2 | 36.5 | 52.7 |
| Number of Si planes | 28 | 12 | 40 |

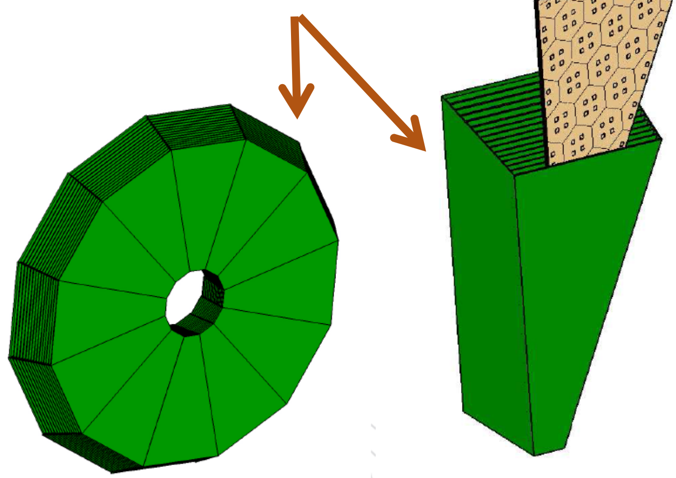
# Endcap Calorimeter for HL-LHC: HGCal



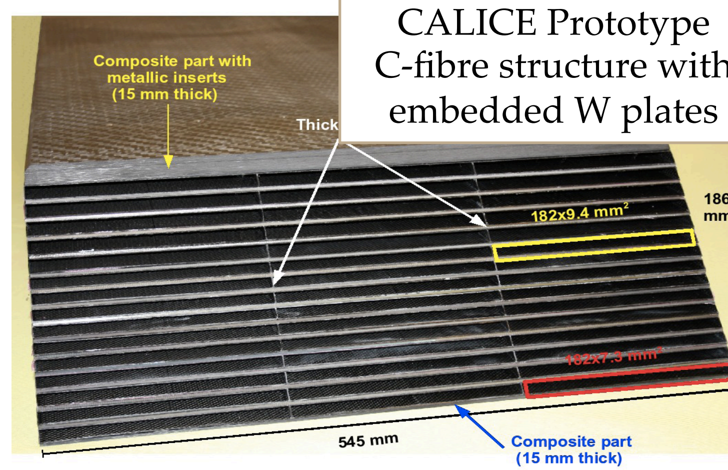




Cassette thermal tests

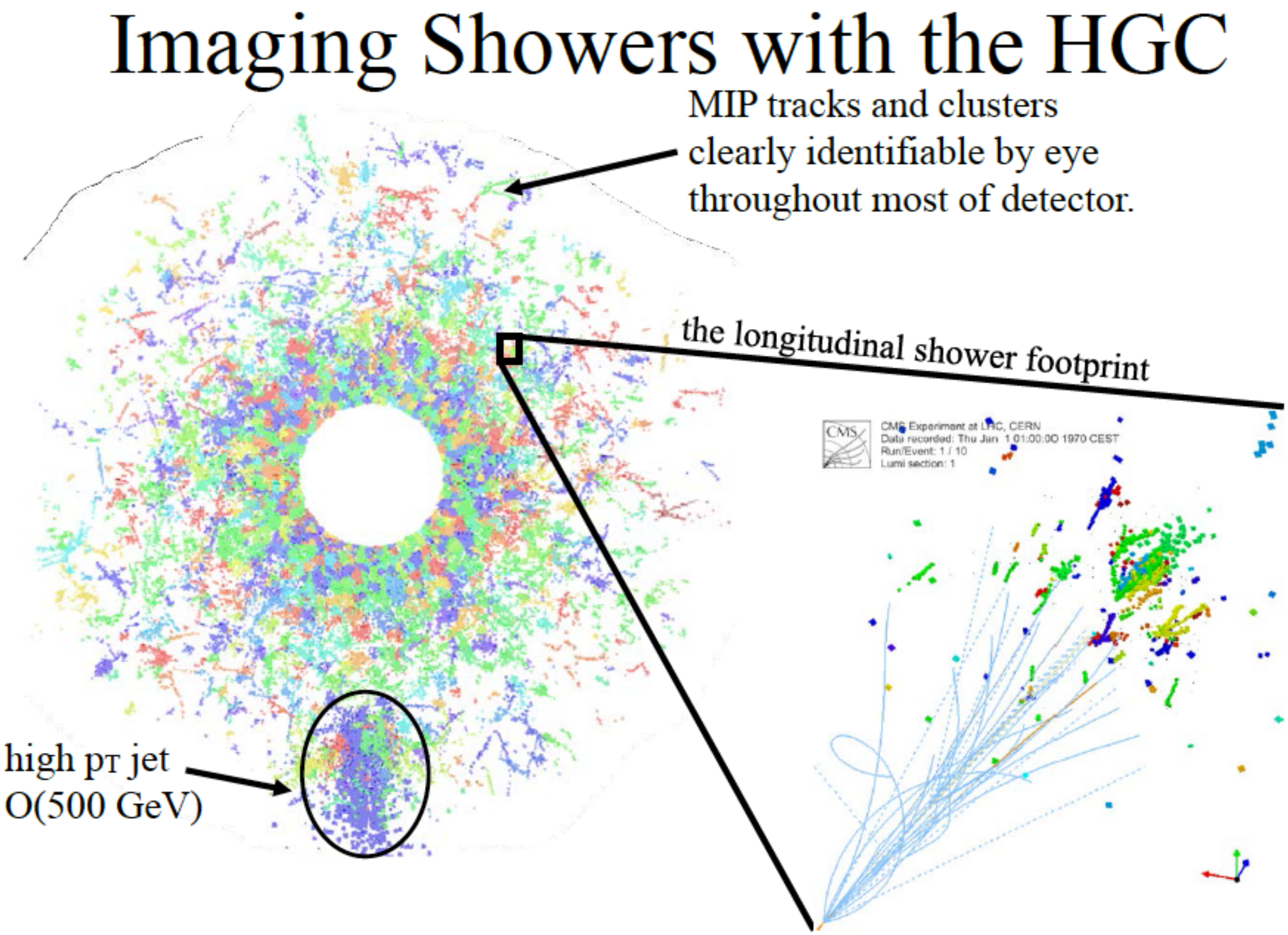
*W absorber*



CALICE Prototype C-fibre structure with embedded W plates

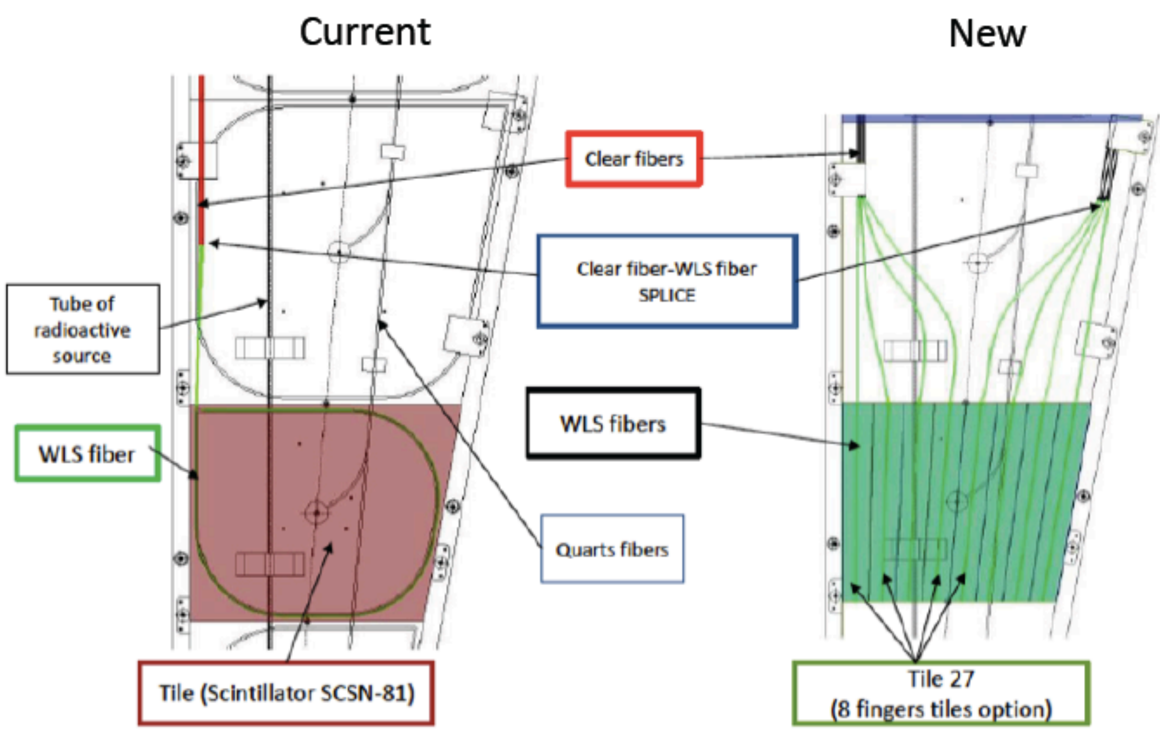


# Net effect: extends tracking into calorimeter!



# Endcap Calorimeter: Backing Hadronic

- Improvement of current HE tiles for ≃ 5 Mrad tolerance
  - Doubly-doped plastic scintillator x 2 light after irradiation
  - Finger tile design - shorter light path




Synergy with Barrel HCAL upgrade – same scintilltor, different geometry depending on location (i.e. expected radiation doses)

- And also increased granularity ≃ x 2 in Φ & x 1.3 in η

# The Invention of Liquid Argon Calorimeter

- By Bill Willis and Veljko Radeka in 1974

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

## LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

W. J. WILLIS†

*Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.*

and

V. RADEKA

*Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.*

Received 14 May 1974

A new detector for the measurement of energy by total absorption, based on the use of multiple-plate ion chambers, is described. The use of liquid argon as the working medium and optimized readout results in an electronic noise contribution to the resolution of less than 0.1 GeV, in a large detector. The use of thin plates, 0.1 radiation length, ensures that sampling fluctuations are small The technique allows absolute calibration and very good gain stability. Tests on a detector large enough to absorb a high-energy electromagnetic shower are described, where the energy resolution is limited by the residual sampling fluctuations.

### 1. Principles and limitations of calorimetric detectors

If a high-energy particle enters a sufficiently large block of matter, all of its energy will be transformed into ionization and eventually into heat, with certain important exceptions. Thus, detectors relying on total

for incident electrons or photons. Thus, the first effect above can be appreciable for incident hadrons of low energy ($\lesssim 2$ GeV), but is always rather small for electrons. Effect (ii) comes mainly from positive pions which come to rest, which then convert about 135 MeV

# The Invention of LAr Calorimeter

- By Bill Willis and Veljko Radeka in 1974

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

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

Received 14 May 1974

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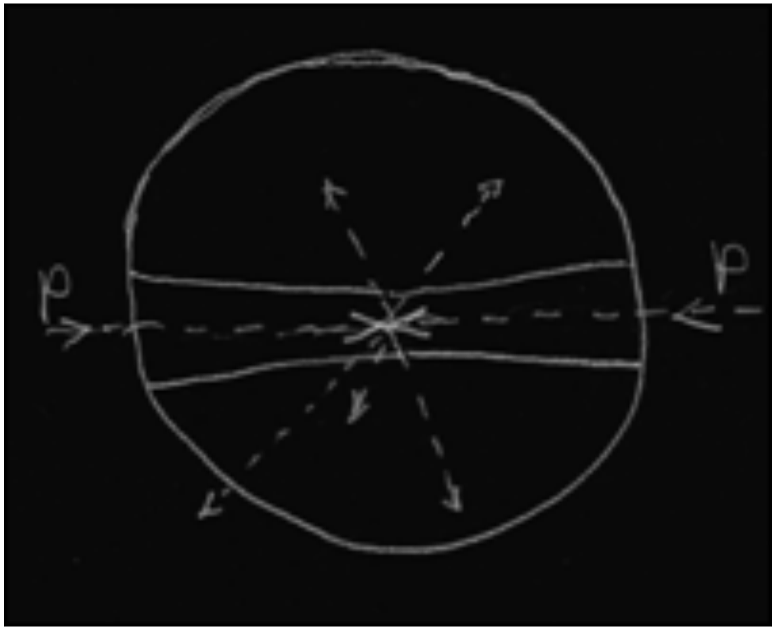
# How LAr Calorimeter was Invented

- Bill Willis, a professor at Yale University, was in sabbatical at BNL 1972-1973
- Bill met Veljko Radeka, a scientist/ electronics engineer at Instrumentation Division of BNL, in October 1972
- Impactometer
  - A circle representing a sphere with two openings at the poles, through which beams of particles from opposite directions would collide in the center of the sphere
  - Measure the energy of *almost all* the debris that comes from such collisions
  - The idea was motivated by the high luminosity challenge of the future colliders. It was to be demonstrated at the CERN ISR



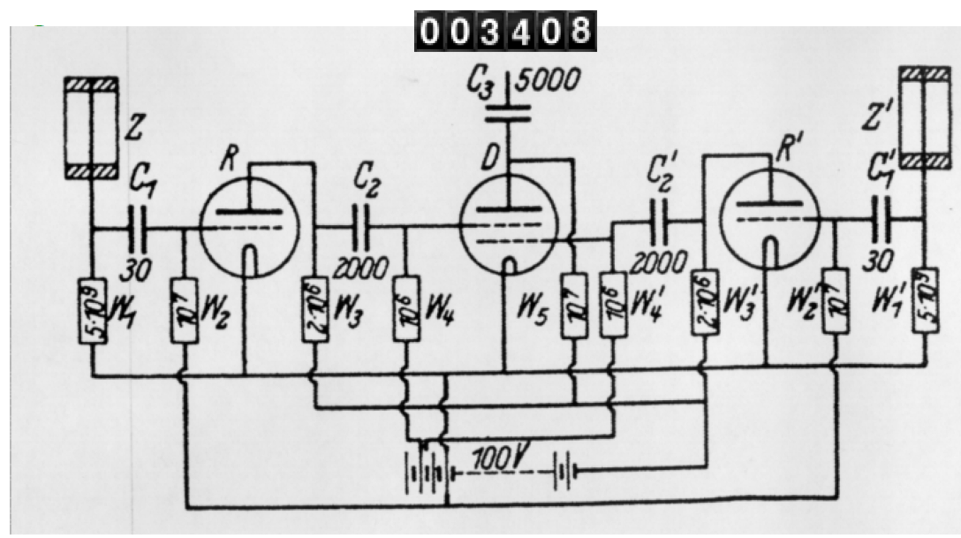
# How to realize an "Impactometer"

- Bill Willis *"After working with a calorimeter made with steel and scintillator plates, I knew one could make a calorimeter covering all solid angle, but what about very good energy resolution and fine spatial resolution? I built a 1m long, LA(r) device and measured light, but it did not seem attractive. Detecting charge would be better, if charge gain isn't needed.* "
- What: "Just a simple ionization chamber?"
- Detecting charge from ionization with high precision was not a strong trait of "counter detectors", aka "electronic detectors" in particle physics at that time …

# Electronic detectors in particle physics then…

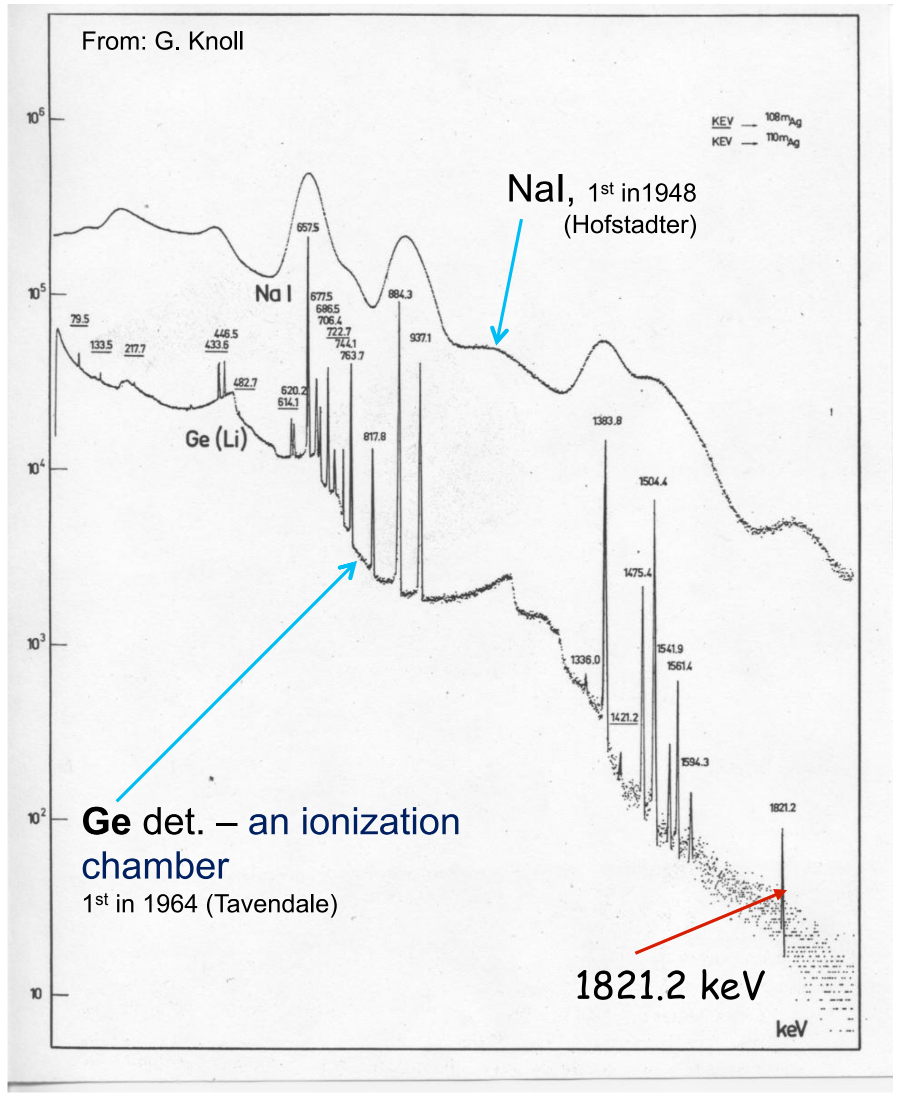
- Example: Coincidence and timing circuits to measure angular distributions and correlations
- **1960-ies**: *nanosecond ("millimicrosecond")* resolution was achieved using *tunnel diodes* and new transistors
- Scintillators and photomultipliers had replaced Geiger-Miller tubes
- Spark chambers were producing Nobel prizes
- Radeka looked elsewhere how to read LAr ionization chambers…

**'Zur Vereinfachung von Koinzidenzzählungen'**
**('On the simplification of coincidence counting')**
**W. Bothe, November 1929**

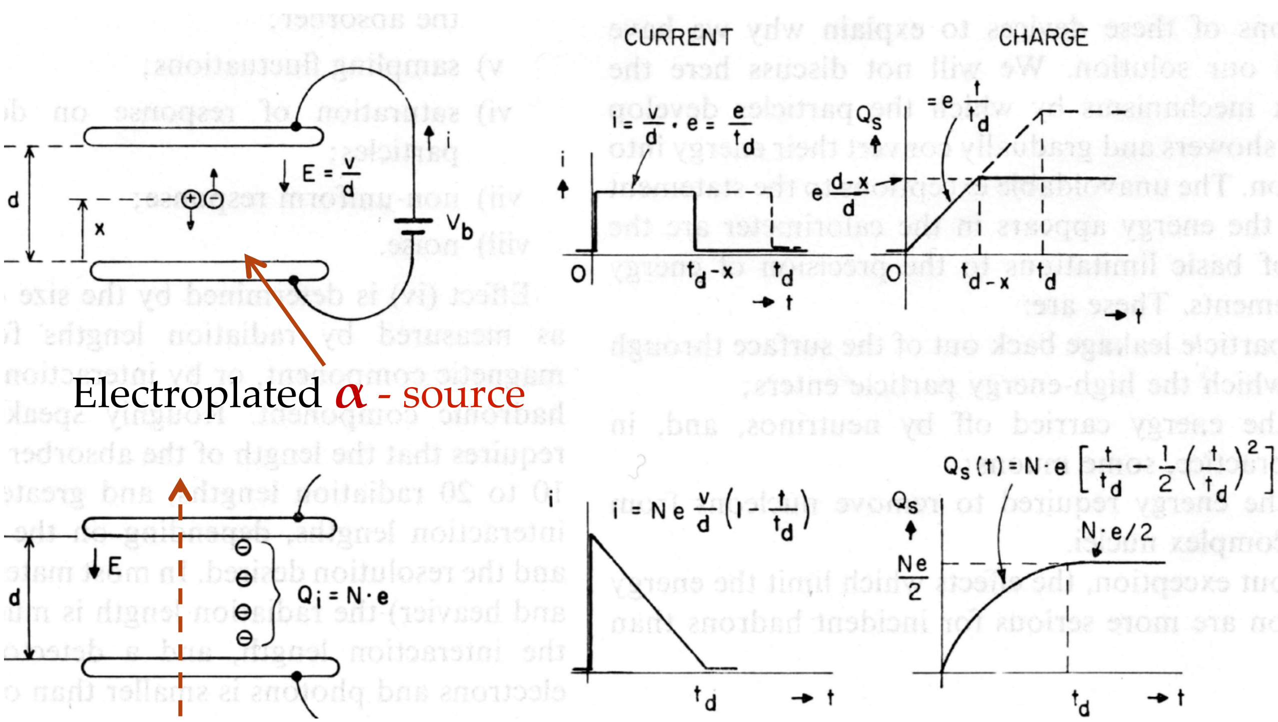


# Detectors in nuclear physics

- Germanium vs. Sodium Iodide for gamma-ray spectrometry
- High precision ionization charge measurements, high precision calibration and low noise electronics were developed for germanium detectors in ~1965-1970
  - For gamma ray energy resolution of ~0.1% in the ~0.1 to 10 MeV range
  - This provided the basis for later use of such techniques in particle physics

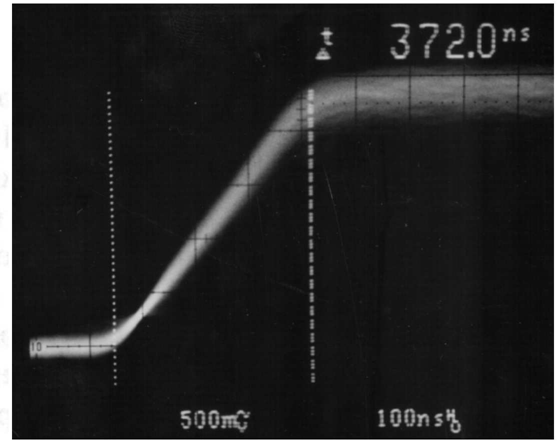


# Dec 1972 – Jan 1973: Charge Collection and Drift Velocity Studies in LAr

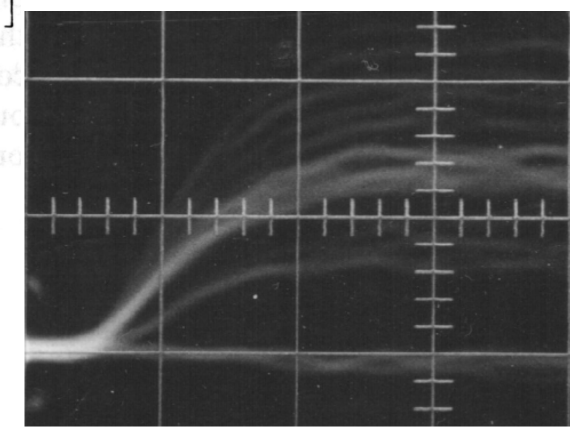



Electroplated $\alpha$ - source

β-source

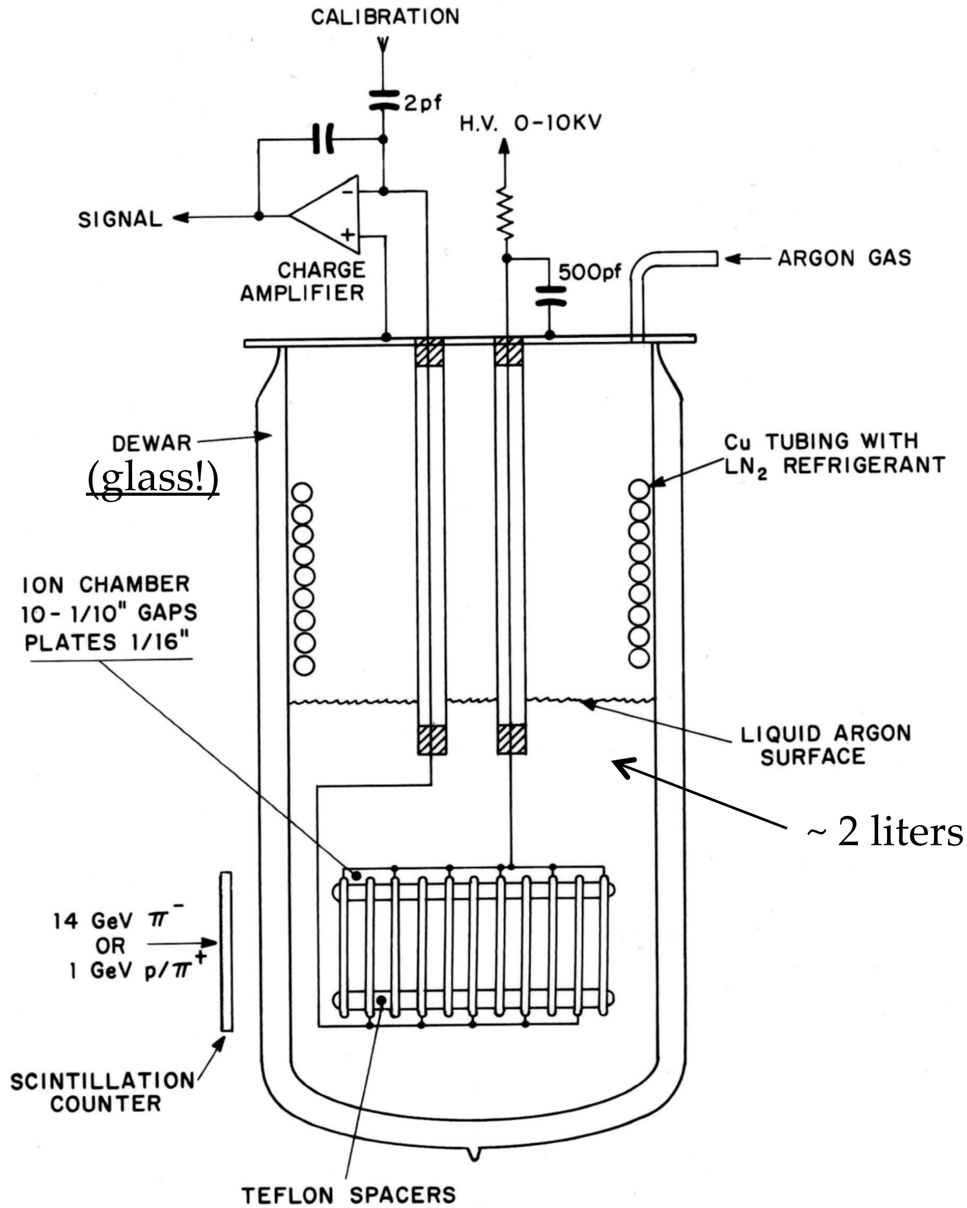



2 mm electrode spacing



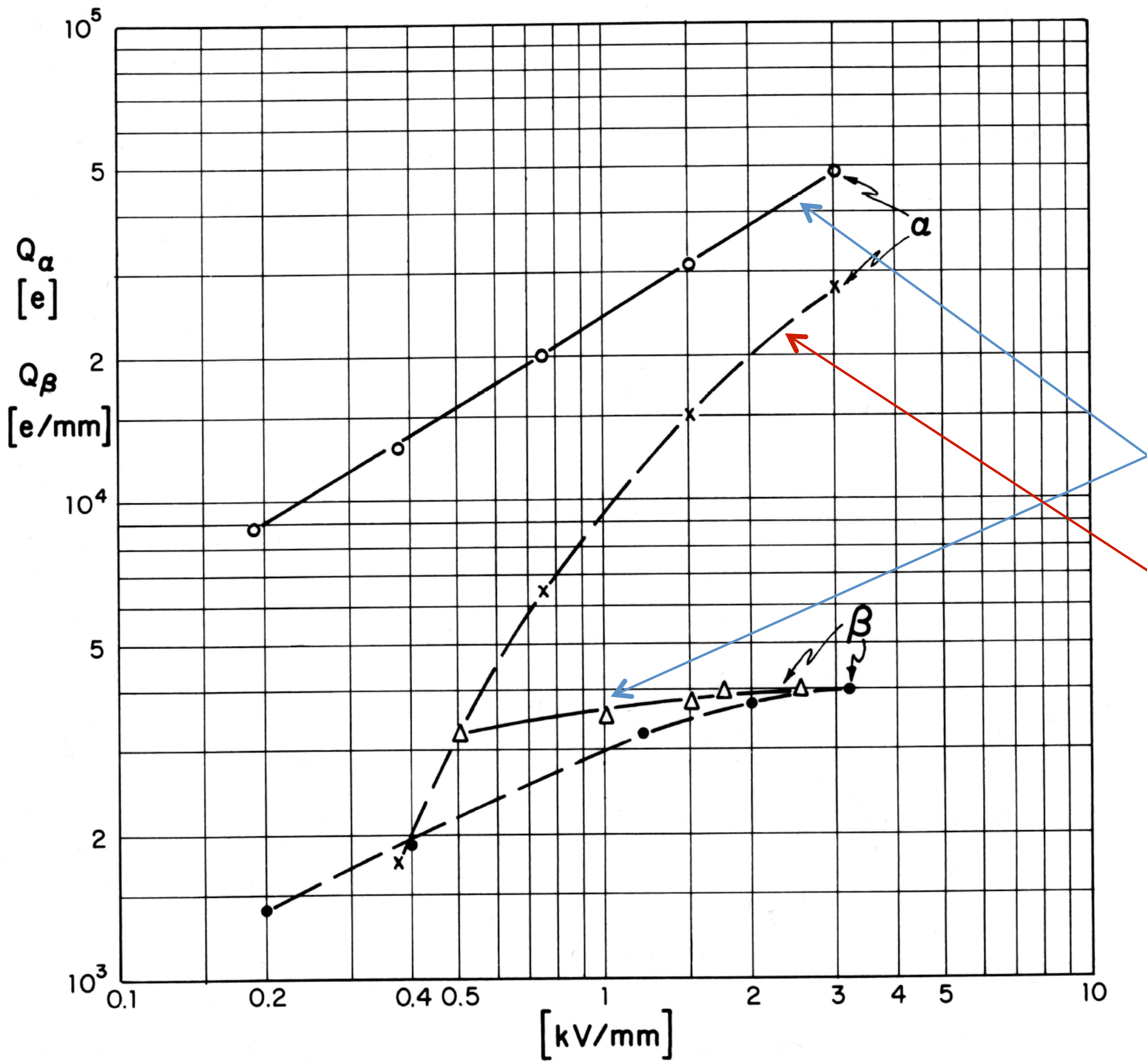
Only electrons induce a signal in the time of interest <1 μs; mobility $\mu_{electron} \gg \mu_{ion}$

# Dec 1972 – Jan 1973: Small test cells to study charge collection




Charge calibration ~0.1%

# Measured charge vs electric field for 5.5 MeV $\alpha$ and MIPs

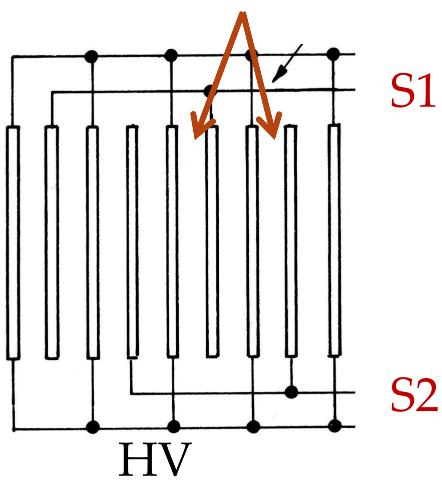


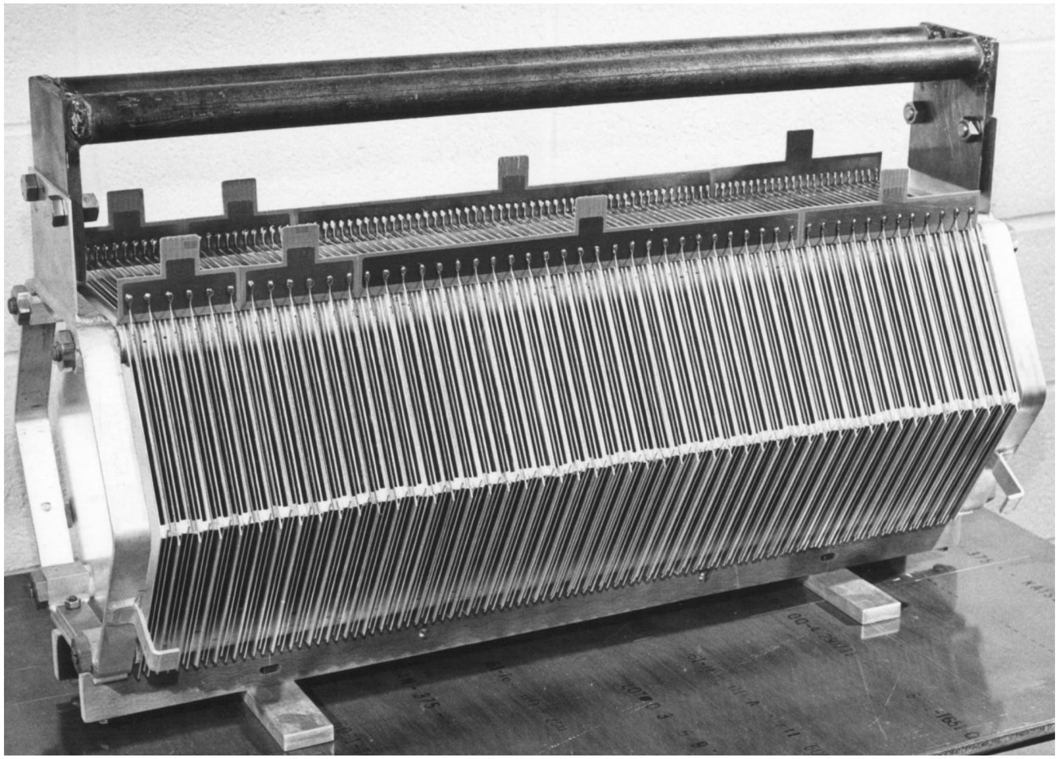

High purity LAr

Welding grade Ar with oxygen at ≈50 ppm

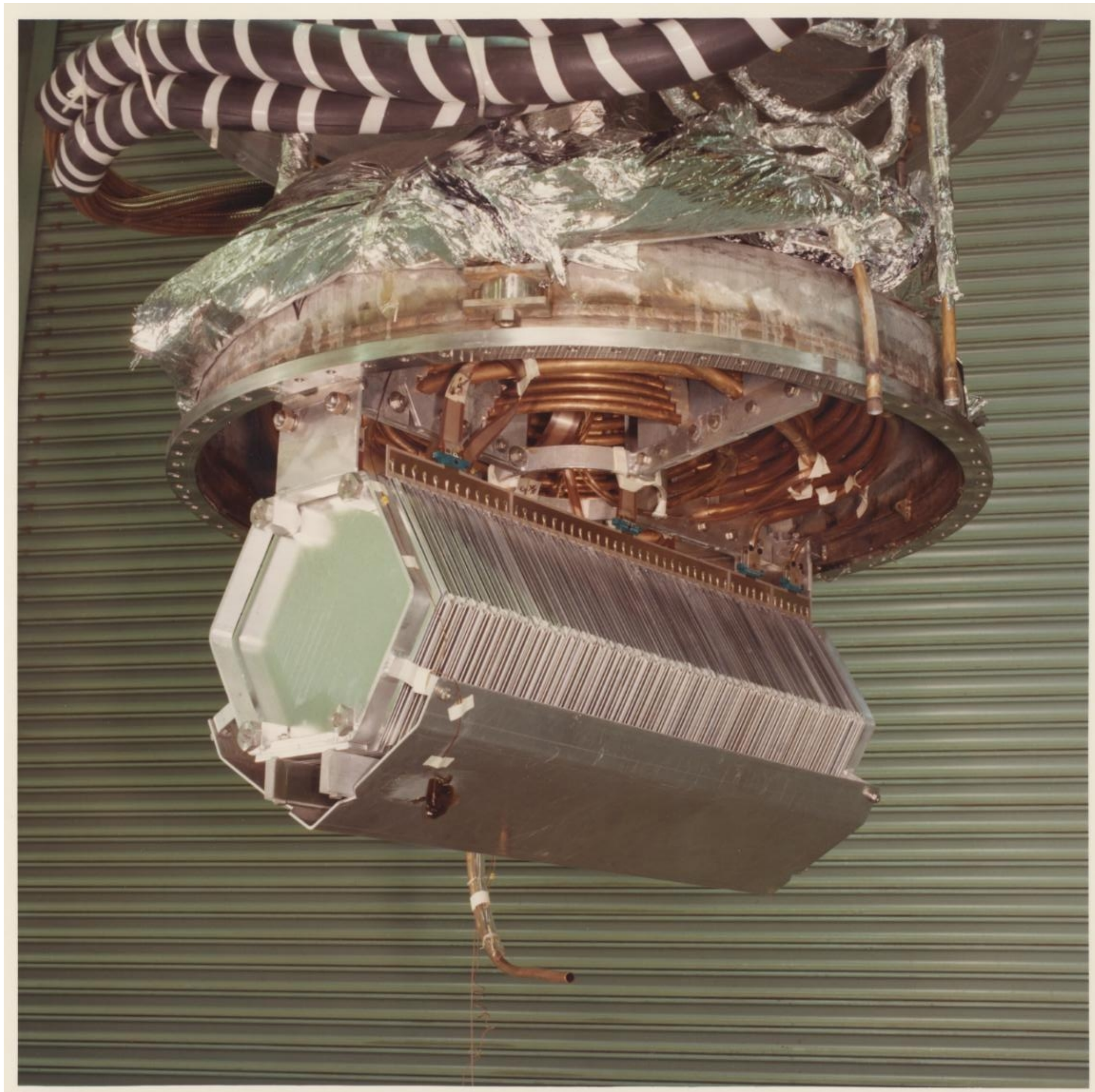
# Jan-Apr 1973: Design and build the first LAr sampling electromagnetic calorimeter

- 20 radiation lengths long, 200 steel 1.6 mm plates with 2 mm LAr gaps; $\Delta E/\Delta x \approx (11.6 + 2.1)$ MeV/cm, or 0.1 $X_0$
- Charge from ion chamber with ~100 nF electrode capacitance brought out on low impedance strip transmission lines
- Interleaved readout from alternate gaps for studies of sampling fluctuations



# April 1973: Ready for cooling and beam tests at AGS



# May-June 1973: The 1st LAr EM Cal. – Spectra and Difference Signals

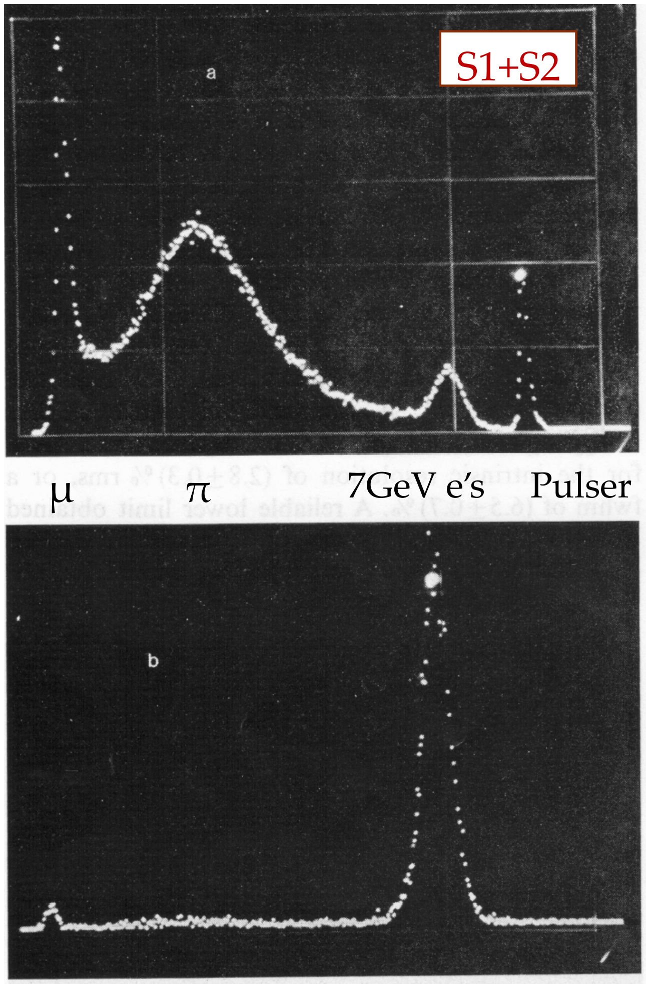



Fig. 12. Charge spectrum with large test chamber for 7 GeV/$c$ negative beam. (a) peaks from left to right: muons, $\pi$'s, electrons, calibration pulser; (b) electrons enhanced with a Cherenkov detector.

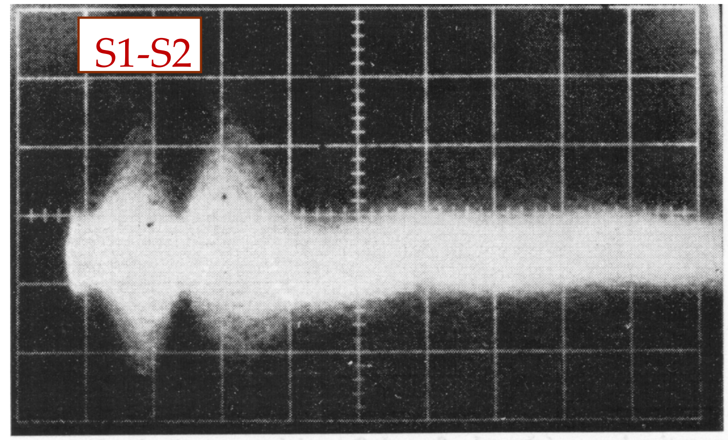



Fig. 15. Difference signals from two interleaved chambers for 7 GeV electrons (see text).

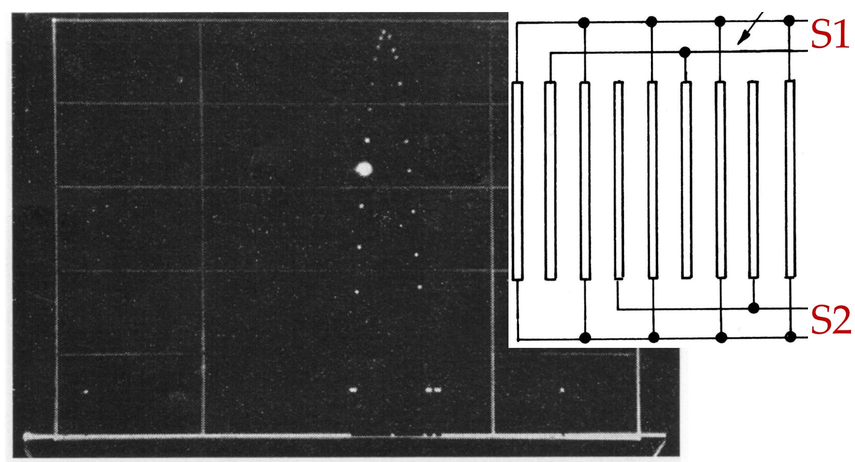



Fig. 16. Distribution of difference signals from two interleaved chambers with 7 GeV electrons. The three-decade logarithmic display shows a Gaussian distribution.

# R806

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

M.H. BLEWETT

ISR * 16/11/73

ISRC/73/33

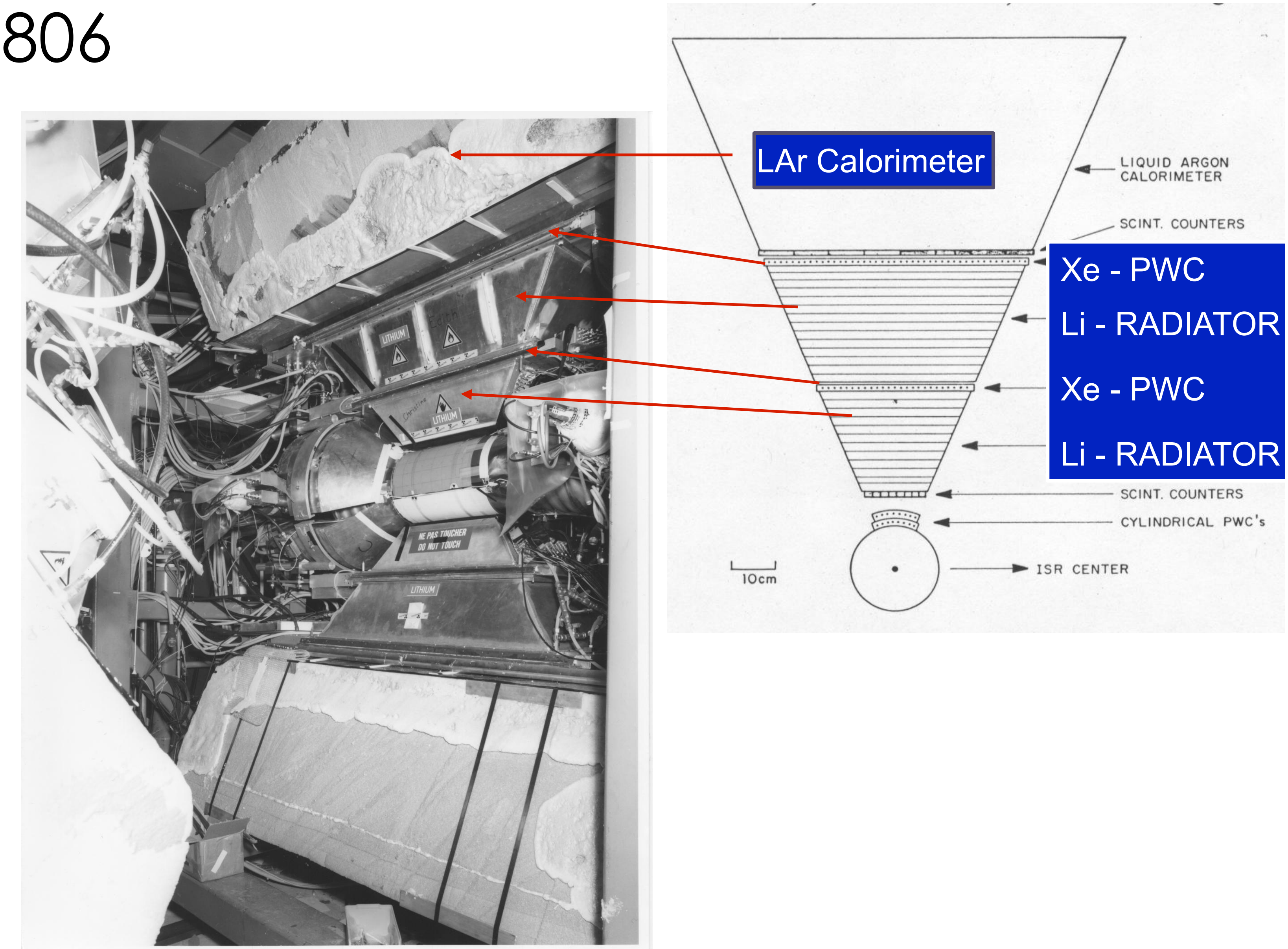
STUDY OF LARGE TRANSVERSE MOMENTUM PHENOMENA

Brookhaven, CERN, Saclay, Syracuse, Yale Collaboration

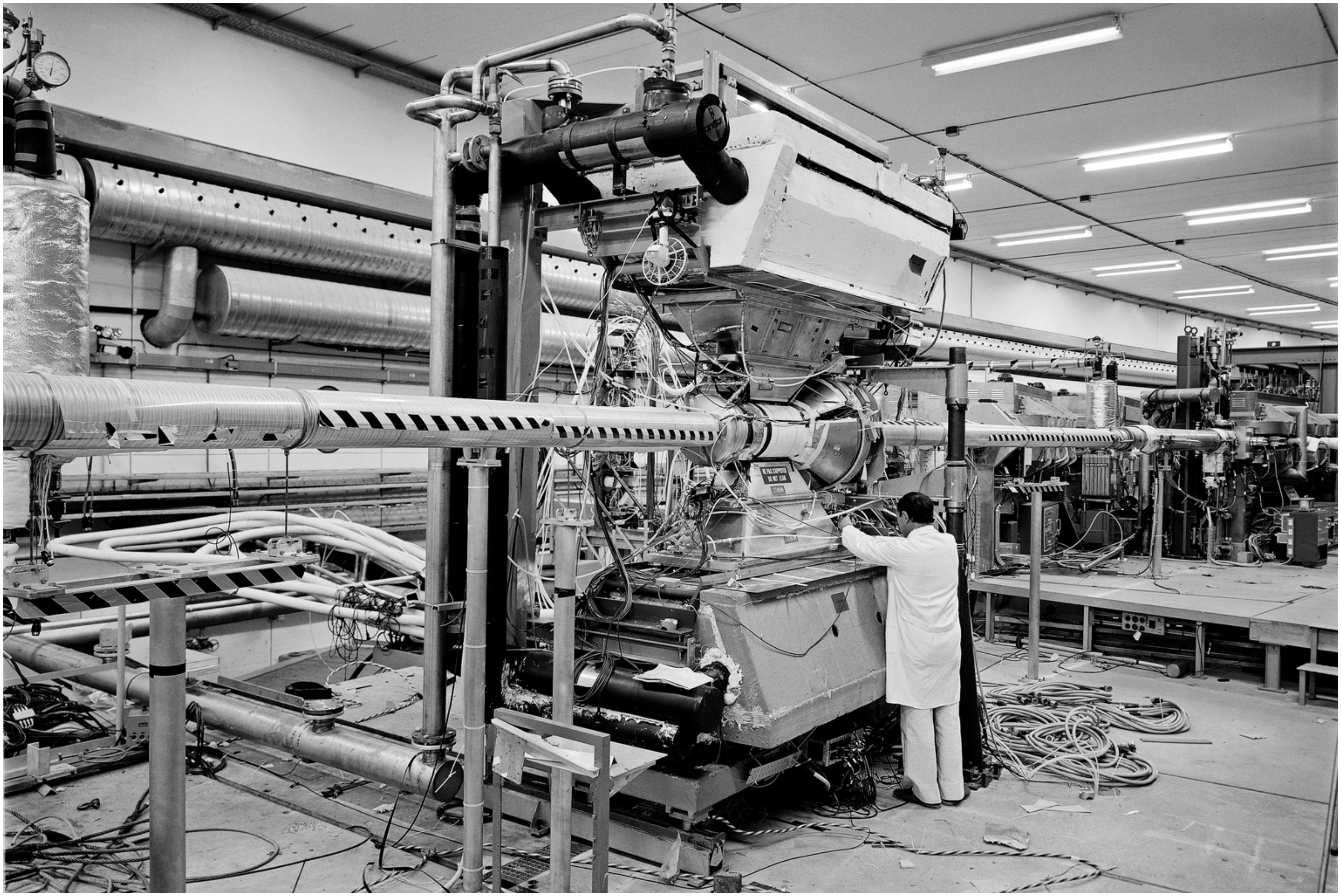
INTRODUCTION

Three of the most exciting questions in high-energy physics are: (i) the existence of massive particles[1] (ii) the production of massive virtual photons[2] and (iii) the properties of "jets" at high transverse momentum[3] These questions are all related from an experimental point of view, as well as theoretically. For instance, we have in mind the detec-

# R806


LAr Calorimeter
LIQUID ARGON CALORIMETER
SCINT. COUNTERS
Xe - PWC
Li - RADIATOR
Xe - PWC
Li - RADIATOR
SCINT. COUNTERS
CYLINDRICAL PWC's
10cm
ISR CENTER
LITHIUM
NE PAS TOUCHER
DO NOT TOUCH

# R806: work in progress – early days



# Understanding the physics limitation of Hadron Calorimetry

- Distinguish instrumental effects, such as sampling fluctuations from intrinsic effects
- It's not the sampling which limits performance
- What matters is the response difference to electron and hadrons
- Uranium is the answer

# Willis' notes on Uranium compensation

ENERGY RELEASE IN
$^{238}U$ FISSION

| | $E_f$ MeV | |
|---|---|---|
| FRAGMENTS | 167 | |
| NEUTRONS | 5.5 | "VISIBLE" 13 MeV |
| INITIAL $\gamma$'s | 7.5 | |
| $\gamma$'s / $\beta$ | 8.4 | |
| $\beta$ | 8.9 | |
| $\bar{\nu}$ | 11.9 | |
| TOTAL | 206. | |

FROM ORNL-3940 LIVINGSTON ET AL

1 n FOR 16 MeV, $^{238}U$
35 MeV Pb

neutron mult. factor 1.87

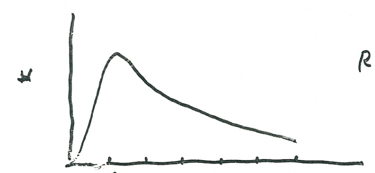
5, COMPARE:

Pb: $n \to \gamma \to 5$ MeV

U: $n \to .71 \times 13 = 9.23$ MeV
$+ 3.3 \times 5 = 16.5$
$25.73$ MeV

DIFFERENCE IN $\gamma$ = 20.7 MeV

6. BUT SPECTRUM IS SOFTER THAN SHOWER SPECTRUM:




REL. TRANSMISSION $\simeq$ 0.6 (2mm) PLATES

7. DETECTED EXCESS $\gamma$ IN $U^{238}$/PRIMARY NEUT. = $0.6 \times 20.7 = 12.4$ MeV IN $\gamma$

8. OR, PER GeV INCIDENT / GeV K
$\Rightarrow 29 \times 12.4 = 360$ MEV

9. ADD TO ~ 700 MeV "HADRONIC VIS." (FE)
$\simeq$ 1.06 GeV HURRAH!

PHYSICS LIMITATIONS ON CALORIMETRY

(Summary of a Contribution presented to the FNAL Workshop on Calorimeters, May 9/10, 1975)

C.W. Fabjan and W.J. Willis

CERN, Geneva, Switzerland

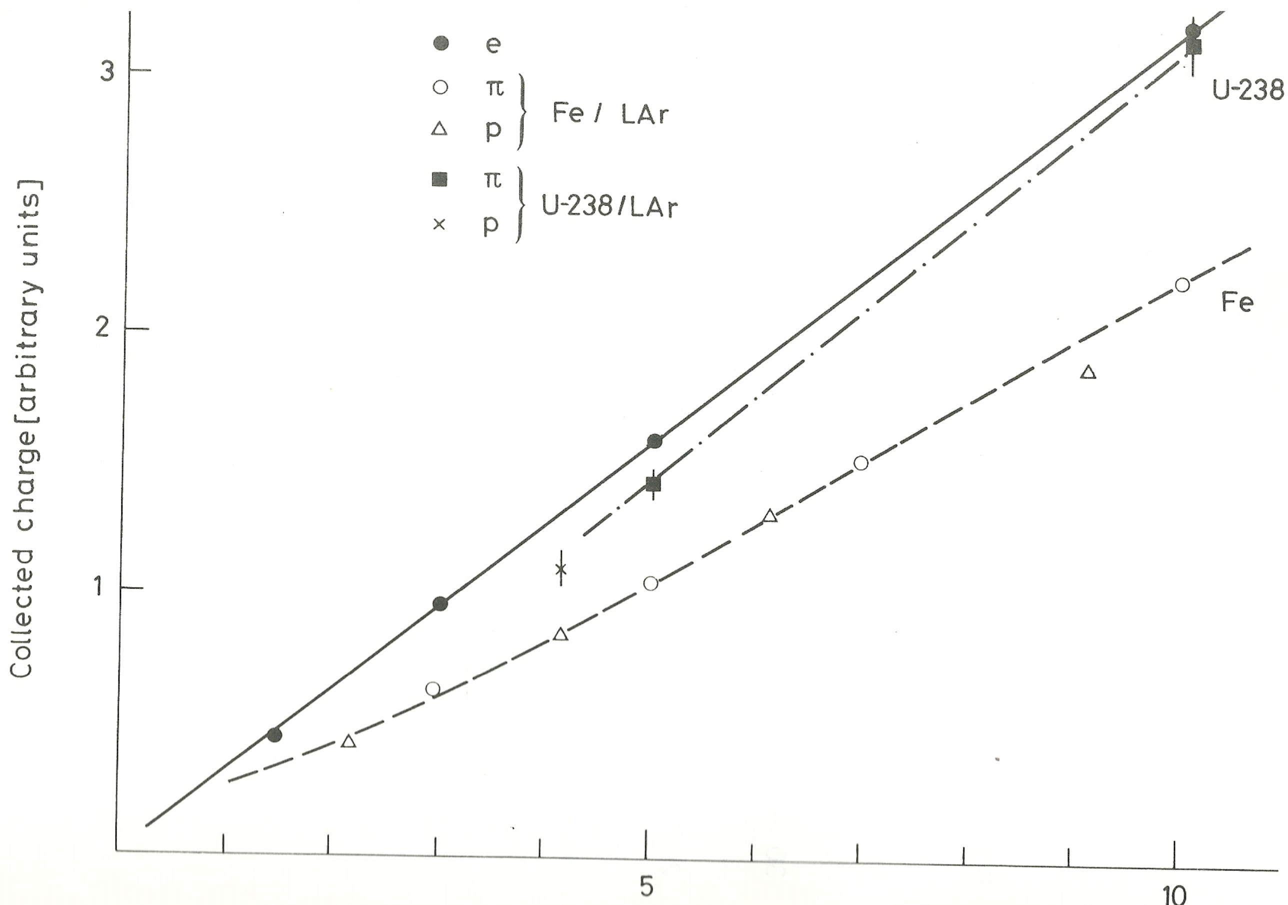
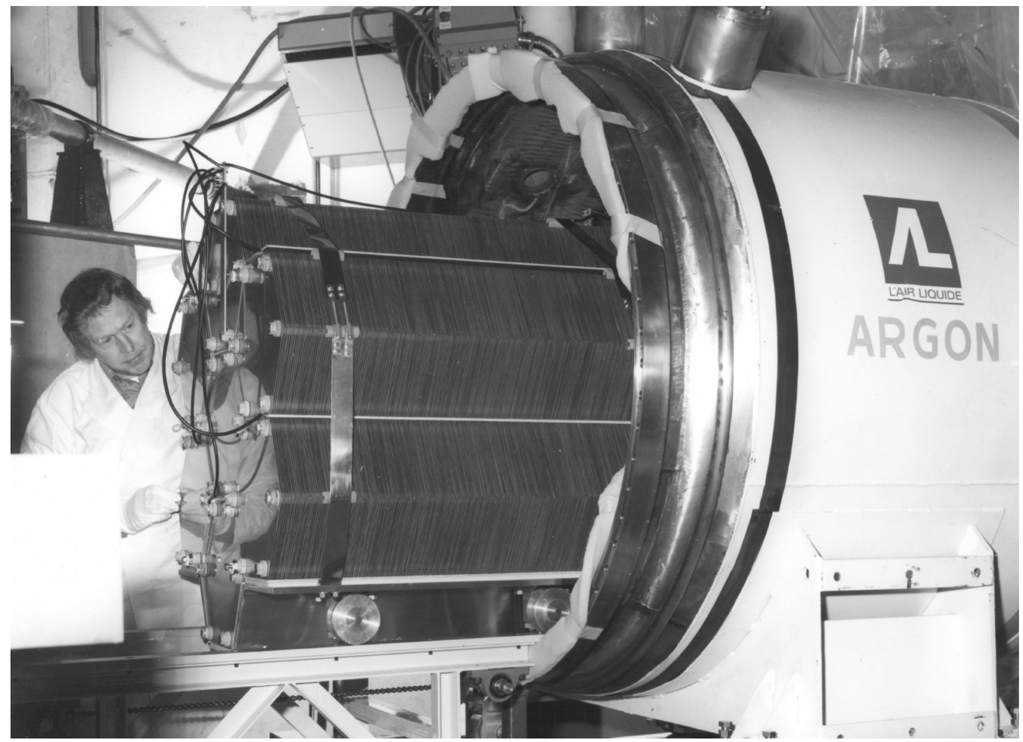



Fig. 4

# 1974-1976 LAr "Impactometer"

- Depleted Uranium as absorber in the center hexagon, surrounded by six hexagons with steel plates
- Studies of hadron showers
- Opening of the e/h response compensation issue
  - The contribution of fission to the hadron signal was not as high as expected
  - There was more to the compensation mechanism
- Uranium was later used in HELIOS, ZEUS and D0 calorimeters



# NA34 – HELIOS

- 1983 – The new horizon was to convert the SPS into an Ion accelerator to study nuclear matter under extreme conditions

CERN/SPSC 83-8
SPSC/I 144
20 January 1983

LETTER OF INTENT TO THE SPSC

SPS EXPERIMENTS WITH PRECISE FULL ANGLE ENERGY MEASUREMENTS

C.W. Fabjan - D. Lissauer - W.J. Willis

1. Introduction
2. Origin of Leptons, Neutrinos and Neutrino-like Objects
3. Deeply Inelastic Reactions of Hadrons with Nuclei
4. Interaction of Nuclear Beams with Heavy Nuclei
5. The New Spectrometer and its Performance.

# NA34 – HELIOS

- HELIOS – High Energy Lepton and Ion Spectrometer
- Also an experiment in sociology: particle physicists meeting the nuclear physicists
- BNL-CERN-Heidelberg-Lund-McGill-Montreal-Lebedev-Novosibirsk-Pittsburgh-Saclay-Syracuse-Tel Aviv
- 1983-1988: at the CERN SPS, HELIOS single-lepton detector with a uranium-LAr em+hadron calorimeter in p-p reactions and 4π showers in *heavy ion* experiment
  - Radeka introduced cryogenic electronics!

CERN-SPSC/84-43
SPSC/P203
21 May 1984

PROPOSAL

STUDY OF HIGH ENERGY DENSITIES OVER EXTENDED NUCLEAR VOLUMES VIA NUCLEUS-NUCLEUS COLLISIONS AT THE SPS

NA34 Collaboration

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Brookhaven National Laboratory

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S. Katsanevas, U. Mjornmark, J. Schukraft, W.J. Willis
CERN

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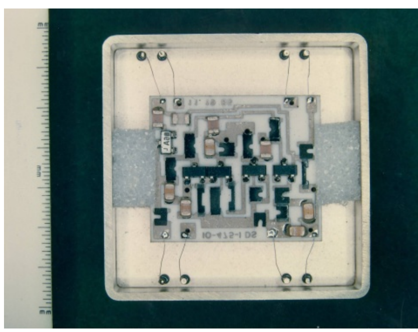
ABSTRACT

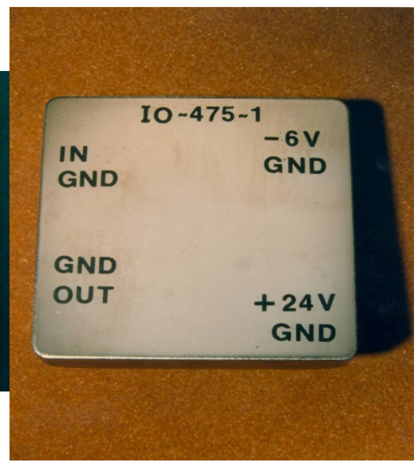
We propose to examine in detail the characteristics of ultra-relativistic nucleus-nucleus interactions using $^{16}O$ beams of 200 GeV/A from the SPS. The experiment combines 4π calorimeter coverage with measurements of inclusive particle spectra, two-particle correlations, low- and high-mass lepton pairs and photons. A multi-wire active target allows maximum interaction rates with a minimum of secondary interactions.

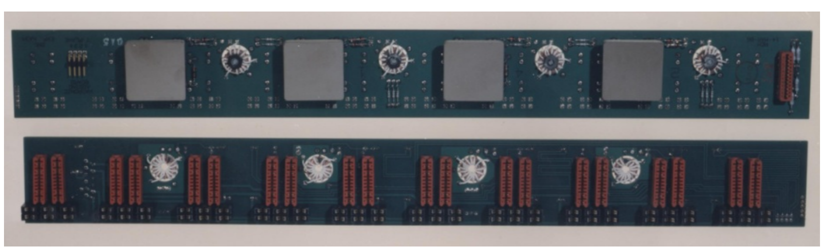
*) Spokesman

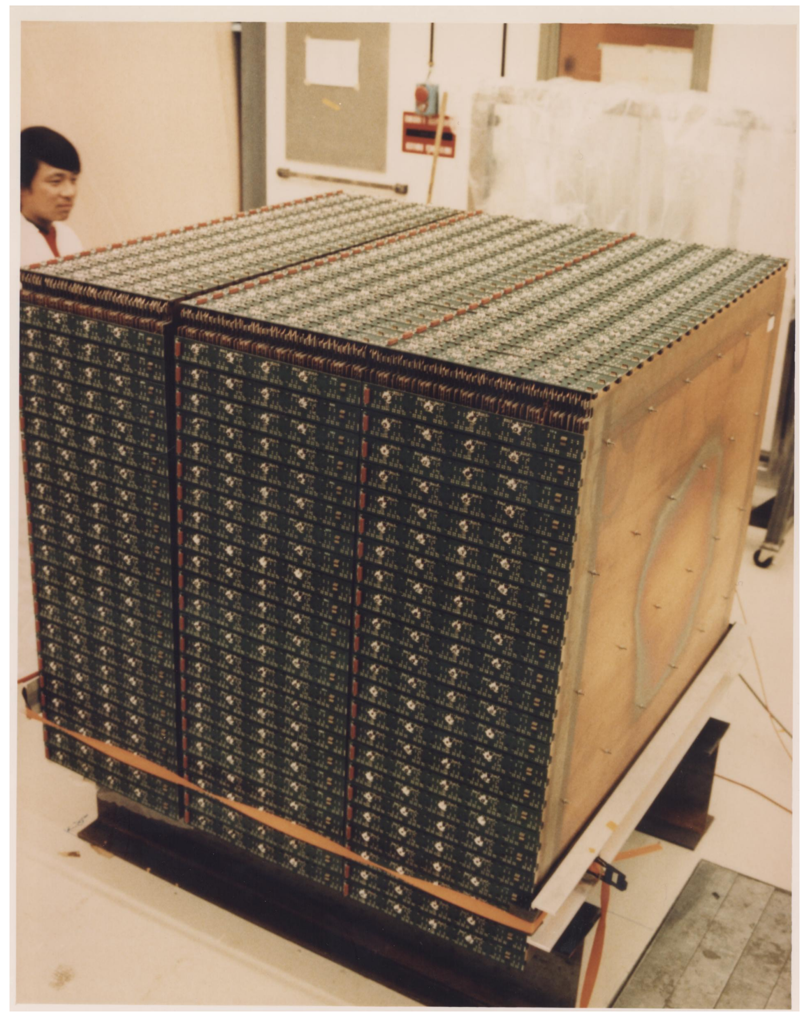
# HELIOS Uranium-LAr: Hadronic Module

- 576  x and y strips with <u>*interleaved readout*</u> and preamplifiers operated in LAr





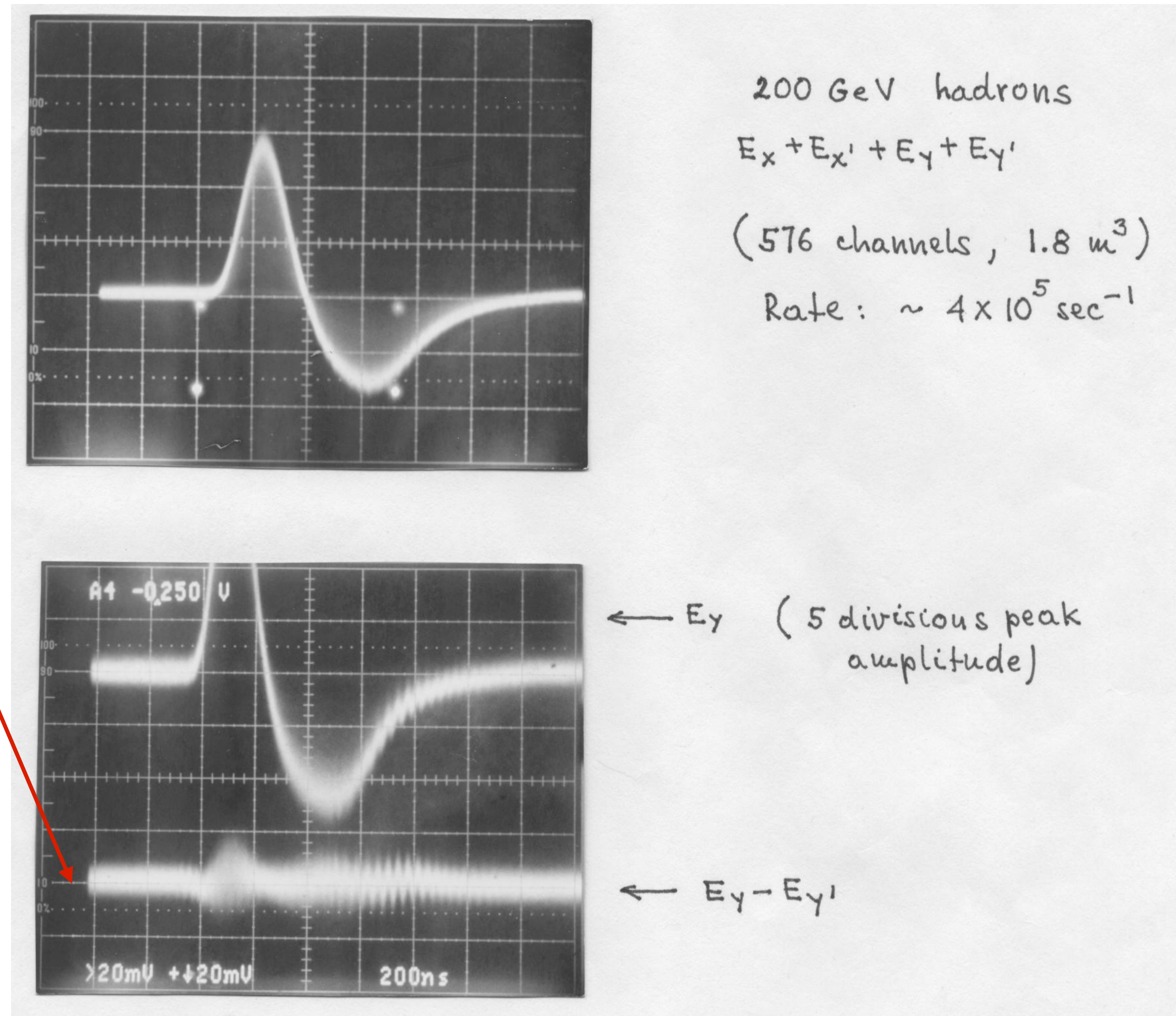





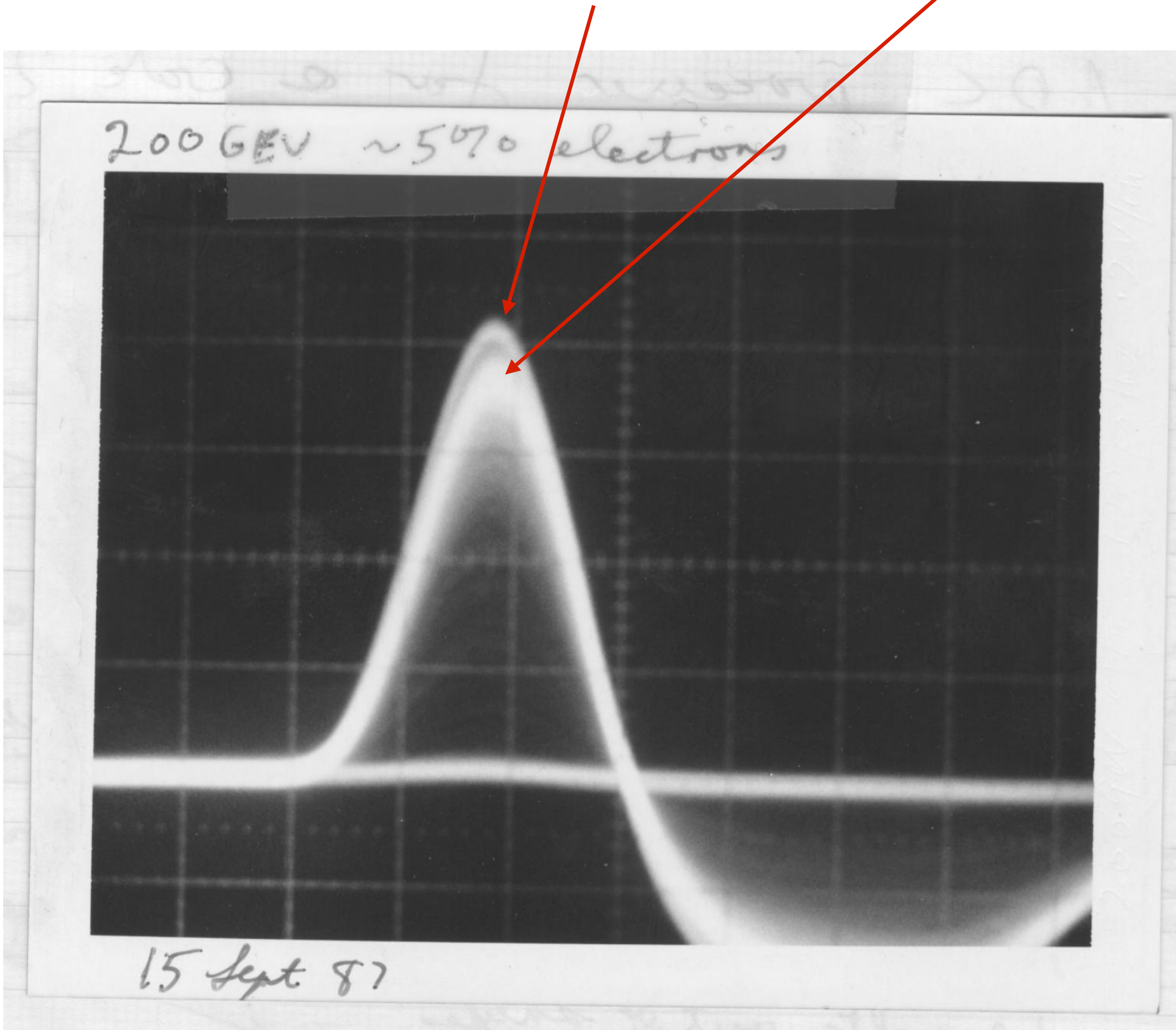
# HELIOS Uranium-LAr EM+Hadron Calorimeter ready for cooling

# HELIOS Uranium-LAr: Sum response to 200 GeV protons (576 signal channels)

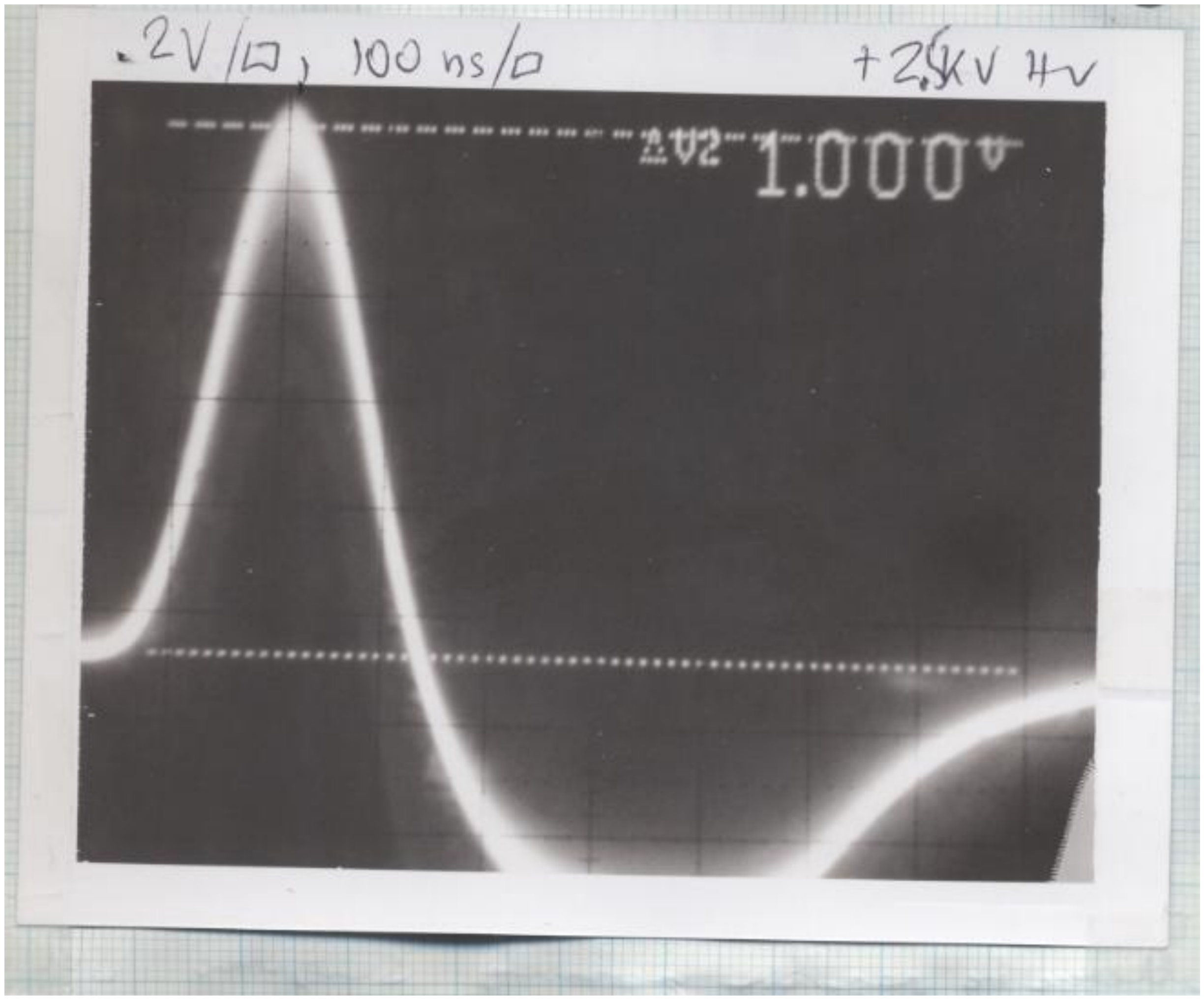
- Difference signal from alternate LAr gaps → ***sampling fluctuations***
- Energy resolution (single particles): ***~21%/√E***



# HELIOS Uranium-LAr: Electrons and Pions (e/ $\pi \approx 1.15$)

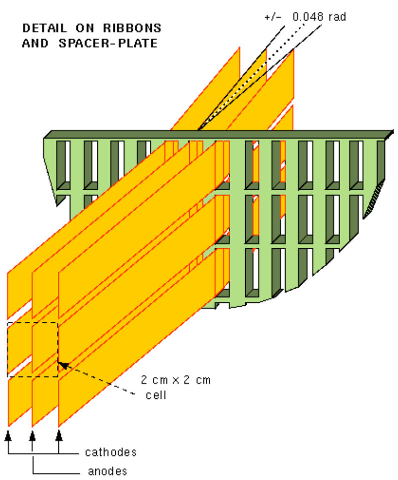


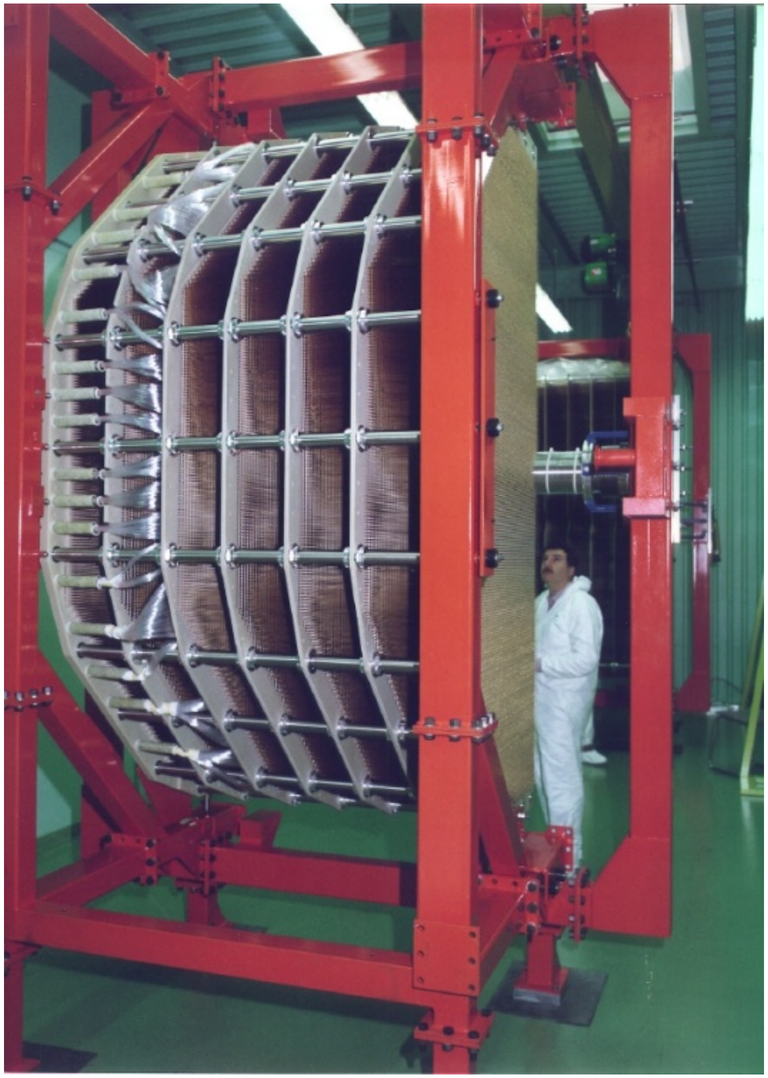
# HELIOS Uranium-LAr: Sulphur ions 200 GeV/nucleon 6.4 TeV total



# NA48

- NA48 is an experiment launched in the early 1990s to study direct CP violation in the neutral kaon decay system at the North Area of the SPS at CERN
  - Homogeneous calorimeter
  - NA62 is the successor and still running
- Liquid Krypton calorimeter with silicon JFET preamplifiers operated in LKr, total 13,212 channels
  - Continuation of cryogenic electronics



# Accordion

- 1990 – RD3 proposal
- R&D proposal – Liquid Argon Calorimetry with LHC-performance specifications
- LAr technology for collider
- Pros
  - Reasonable cost
  - Good energy resolution
  - Good stability
  - Accurate inter-calibration
  - Intrinsically radiation resistant
- Cons
  - Relatively slow: 400 ns for 2 mm gap
  - Long connections to electronics → large C → large noise
  - Large dead space due to readout electronics



CERN/DRDC/90-31
DRDC/P5
13th August, 1990

R&D PROPOSAL

**LIQUID ARGON CALORIMETRY WITH LHC-PERFORMANCE SPECIFICATIONS**

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F. Nessi-Tedaldi, M. Pepe, G. Polesello, G.R. Stevenson, W.J. Willis
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C. Battistoni*, C. Birattari, D. Camin, D. Cavalli, G. Costa, A. Ferrari,
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G. Guilhem, A. Hrisoho, L. Iconomidou-Fayard, B. Merkel, J.M. Noppe,
G. Parrour, P. Pétroff, J.P. Repellin, A. Schaffer, N. Seguin
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Manne Siegbahn Institute, Stockholm, Sweden

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1) Spokesperson
2) Contactperson
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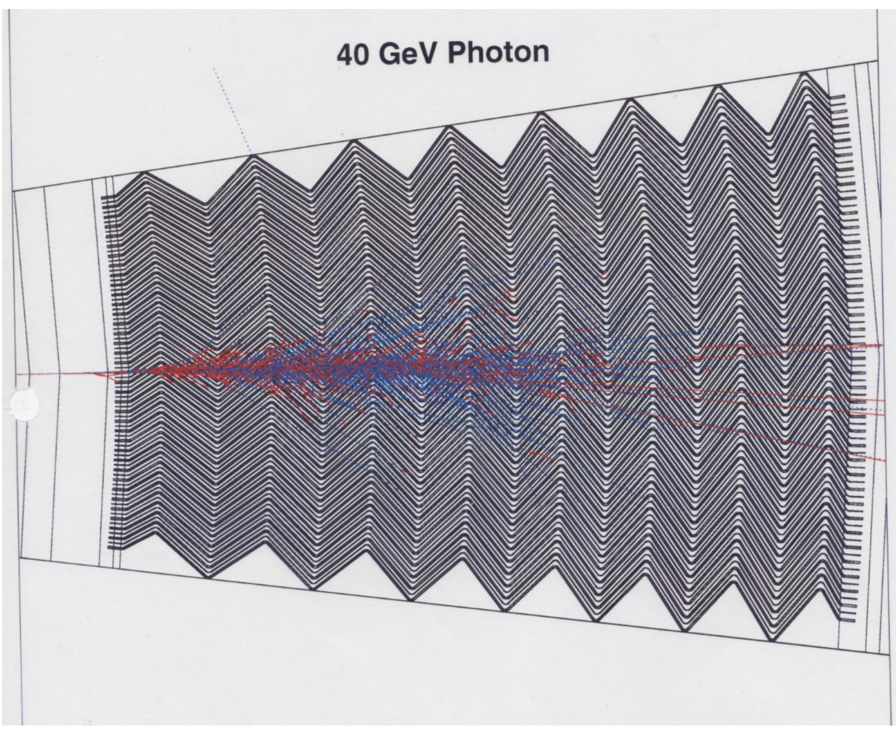
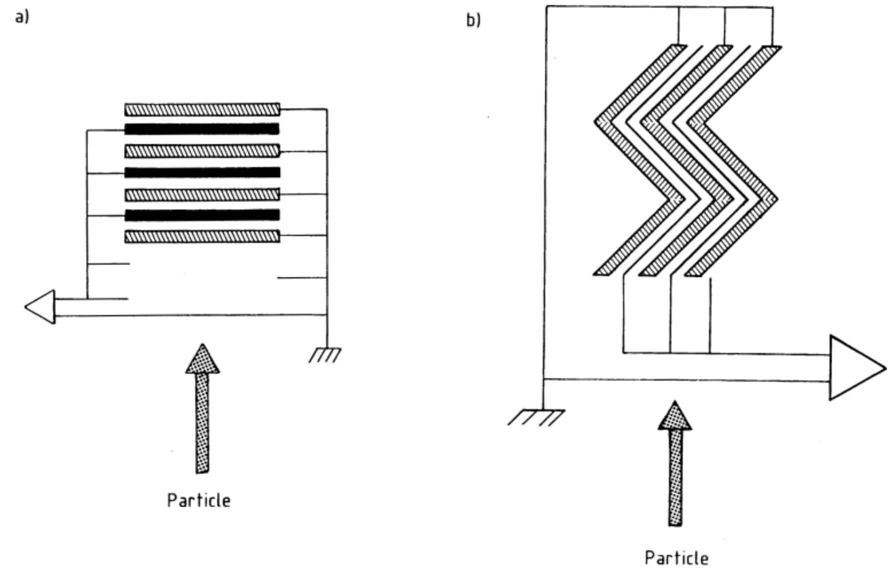
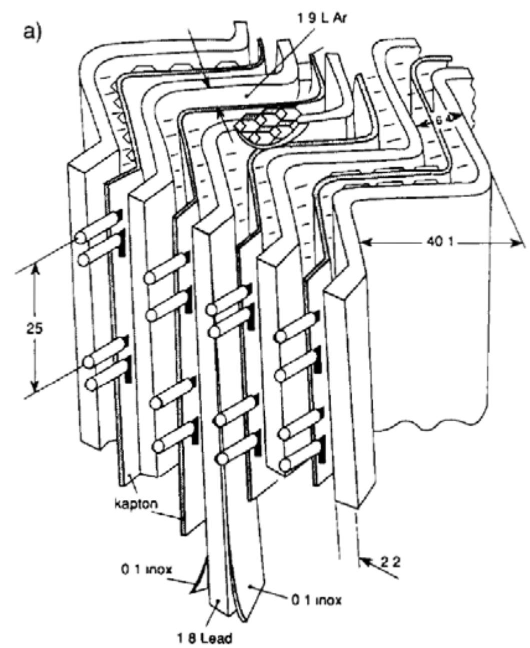
2144004

# Accordion

- 1990/RD3 – Daniel Fournier introduced accordion geometry
- From RD3 to GEM/SSC and ATLAS/LHC: LKr and LAr accordion EM Calorimetry



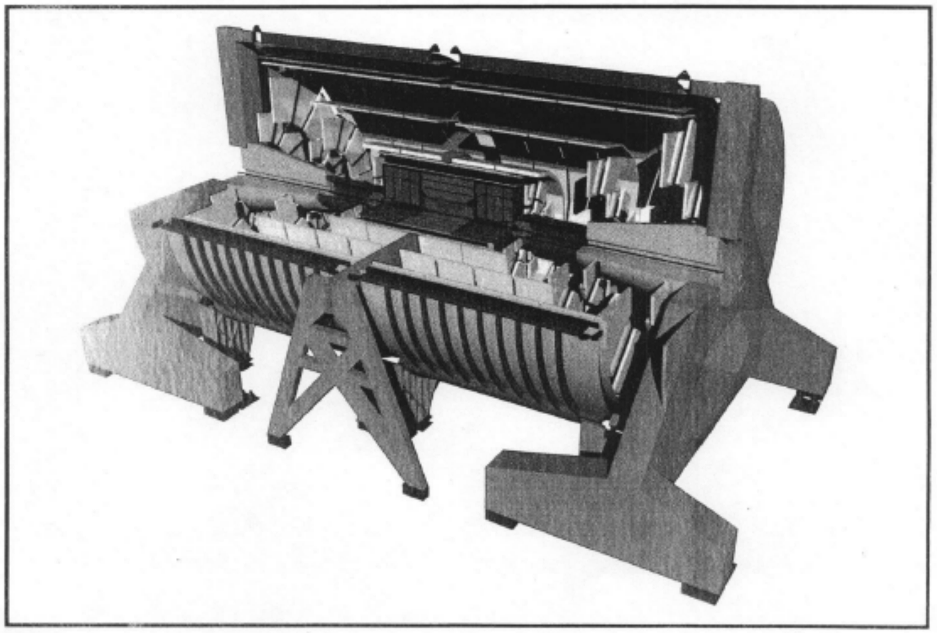
# GEM – Gammas, Electrons and Muons

# GEM

GEM-TN-93-262
SSCL-SR-1219

gem γeμ

## Technical Design Report



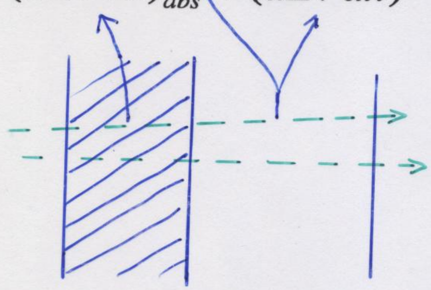
**April 30, 1993**

# Consider Liquid Krypton for GEM detector

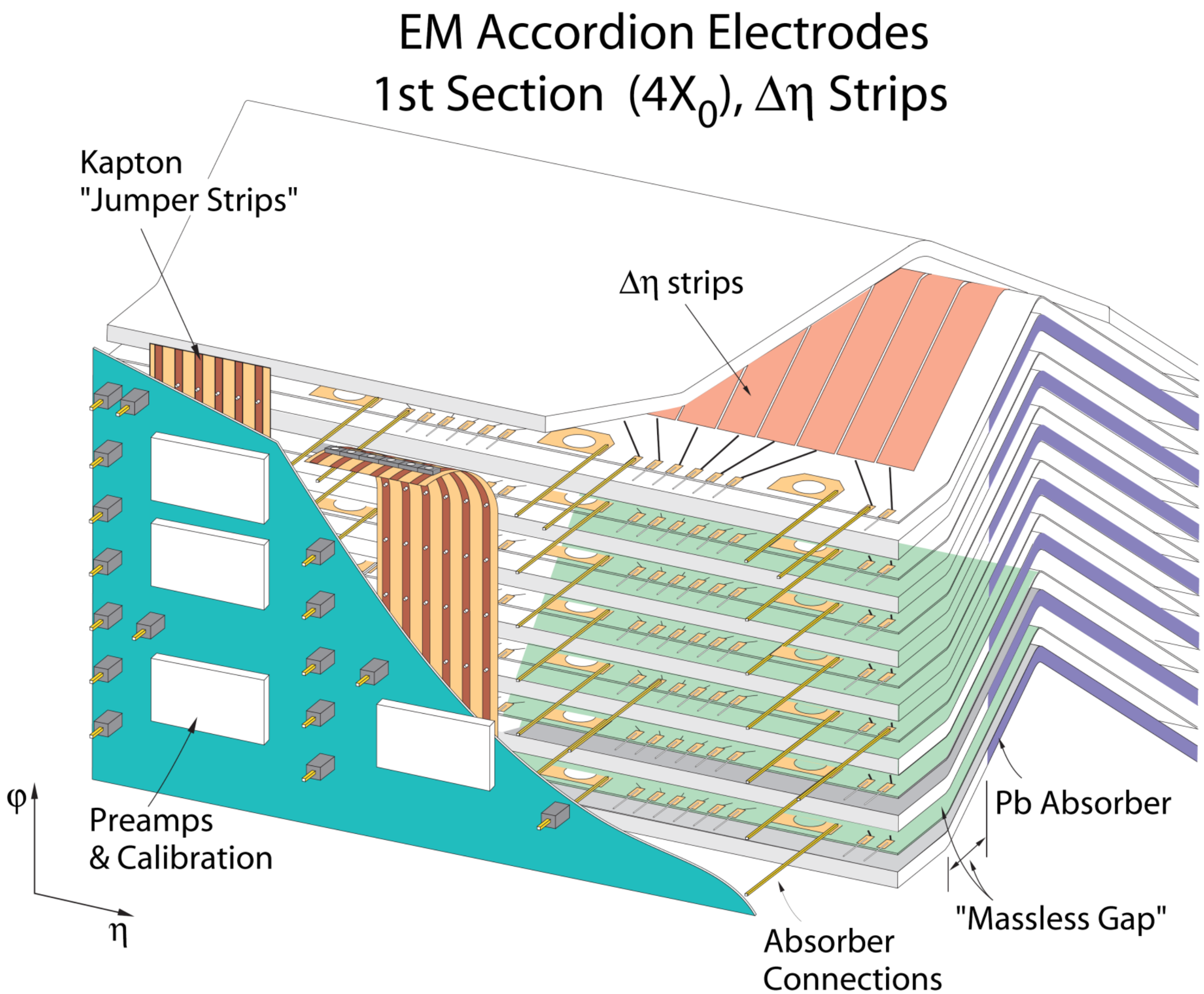
| | LAr | LKr | LXe |
|---|---|---|---|
| $X_o$ [cm] | 14.0 | 4.72 | 2.77 |
| $R_M$ [cm] | 10.1 | 4.8 | 4.1 |
| $W_i$ [eV / pair] at 10 kV/cm | 25.1 | 19.1 | |
| $dE/dx$ [MeV / cm] | 2.11 | 3.45 | |
| $v_d$ [cm / μs] -"- | 4.4 | 3.83 | |
| ℓ for $25X_0$ [m] | 3.5 | 1.2 | |

**Peak induced current in a sampling calorimeter:**

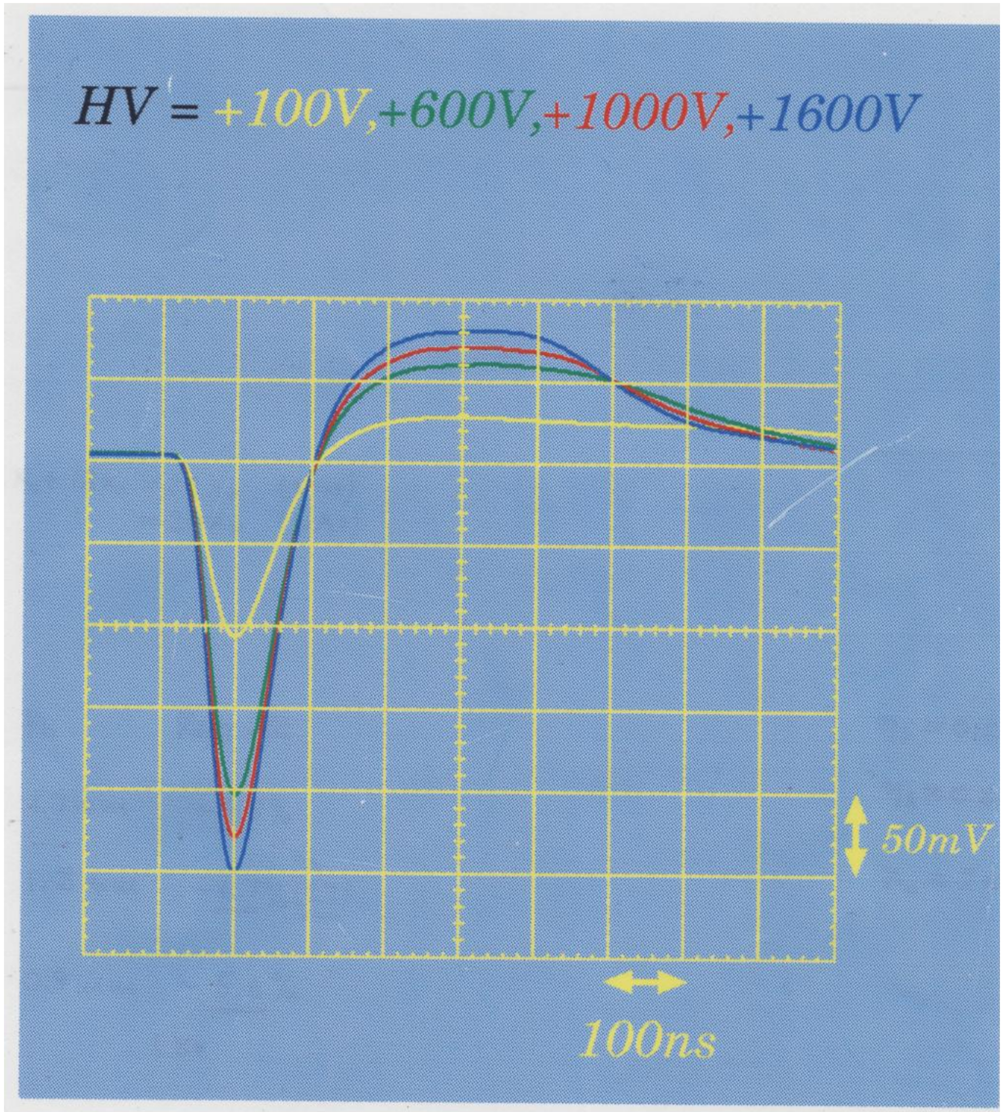
$$I_m / E \propto \frac{(dE/dx)}{(dE/dx)_{abs} + (dE/dx)} \cdot \frac{v_d}{W_i} \cdot (\text{"}e/\mu\text{"})$$

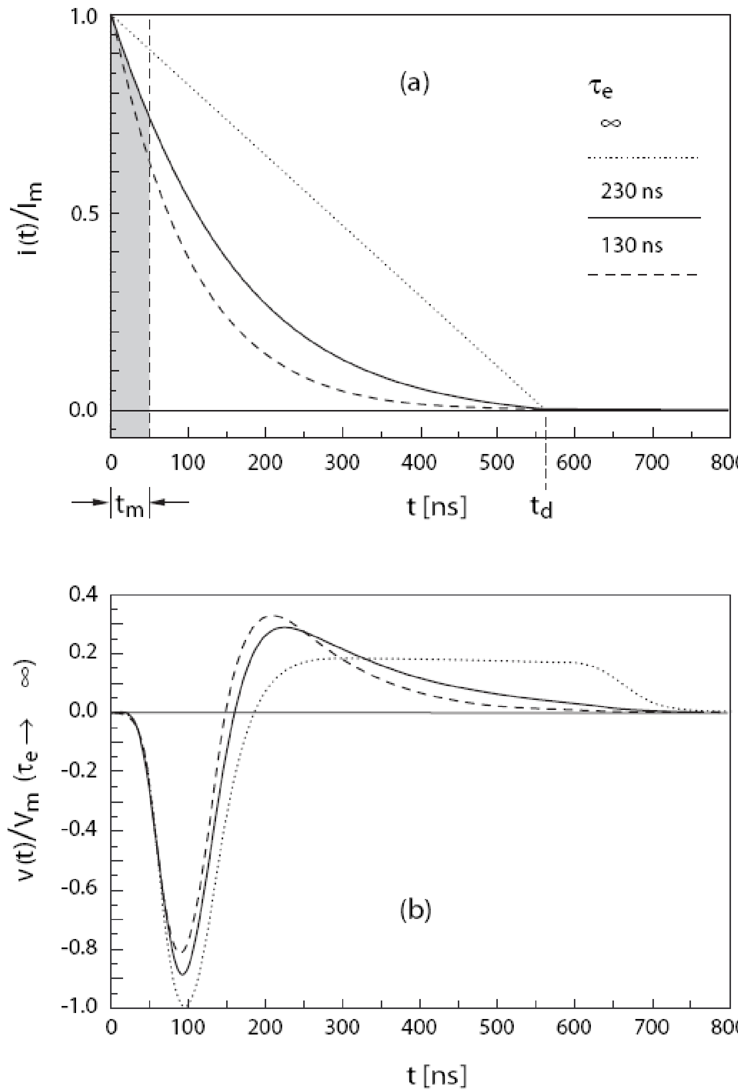


# Tests of a new design with LKr and LAr at AGS in 1992 and at CERN SPS in 1994



# LKr Accordion EM tests: Waveforms (shower sums)



# LAr and LKr Accordion EM: Results

- **Energy Resolution:**

| | | Pb absorber [mm] | $\frac{\sigma_E}{E}\sqrt{E}$ [%] |
|---|---|---|---|
| CERN RD3 | LAr | 1.8 | 9.6 |
| BNL 1992 | LAr | 1.3 | 7.7 |
| " | LKr | 1.3 | 6.7 |
| " | LAr | 2 x 0.8 | 6.3 |
| CERN 1994 (by BNL et al.) | LKr | 1mm | $\frac{5.6\%}{\sqrt{E}} \oplus 0.2$ |

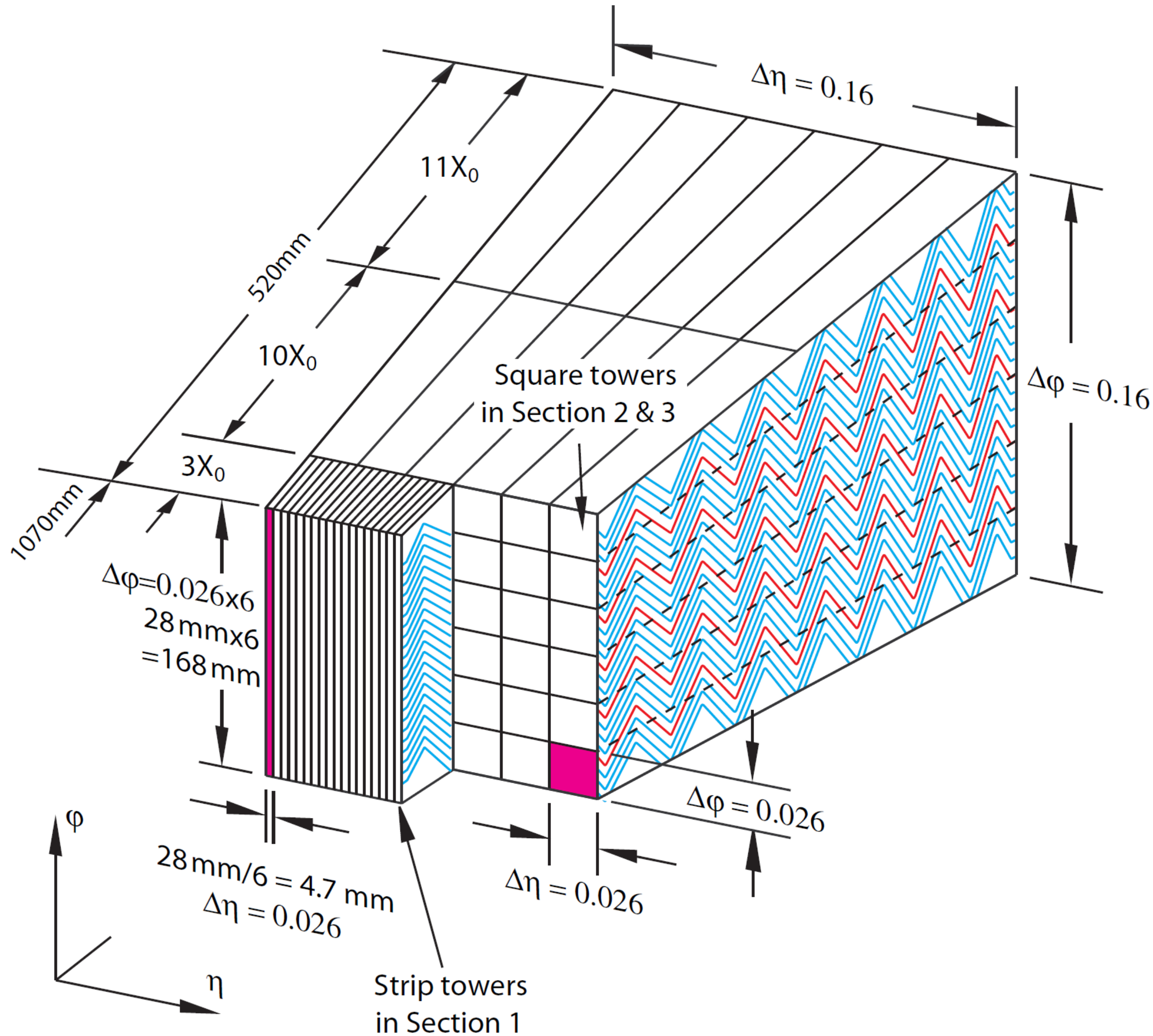
- **Timing Resolution:** (single tower) $\frac{1.16\ ns}{E} \oplus 73\ ps$

- **Pointing Resolution:** $\frac{32.2}{\sqrt{E}}\ mrad$

- **Peak Current LKr / LAr:** (for equal length cal.) $\approx 2$

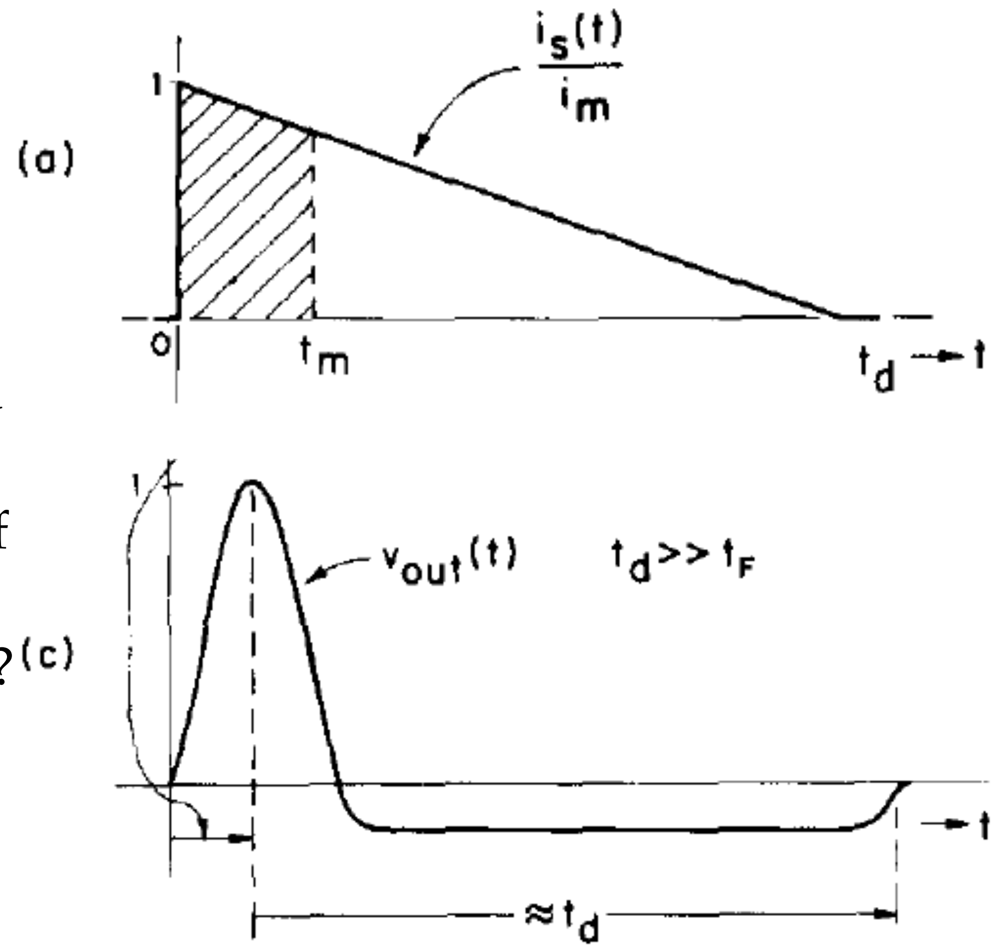
# EM electrode design with fine granularity intended for GEM and later adapted for ATLAS

- Used in ATLAS with a different longitudinal subdivision



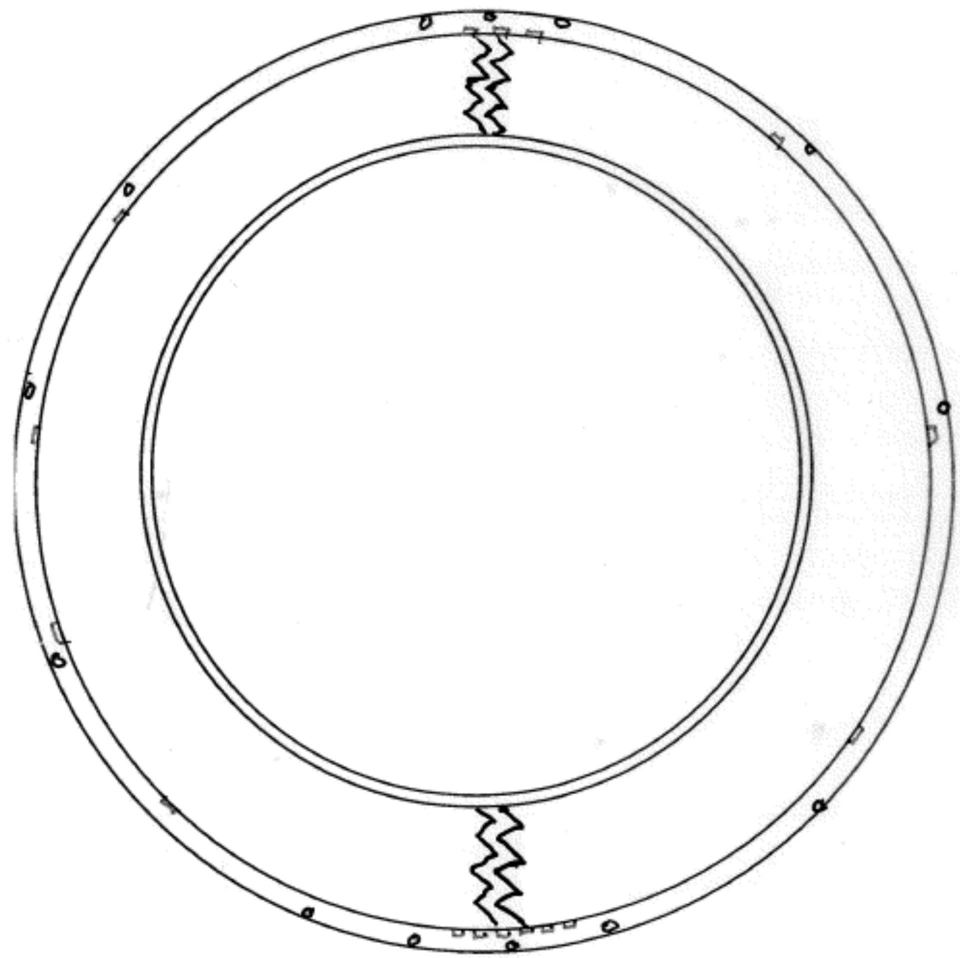
# ATLAS LAr Calorimeter

- Two remaining problems
- Problem #1: LAr maybe too slow for LHC?
  - 400 ns (2 mm gap) ←→ collision rate = 25 ns @ LHC
  - Induced current rises quickly → take only the front part using bipolar shaping time of $\tau < 50$ ns
  - How to handle negative tails? → pileup may compensate. This is an advantage to restore baseline in high rate operation with high pileup



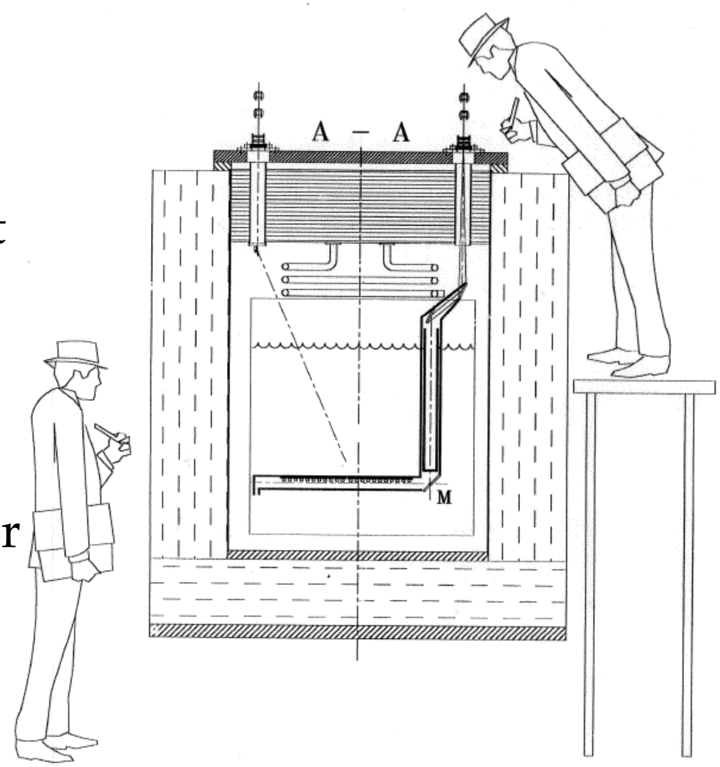
# ATLAS LAr Calorimeter

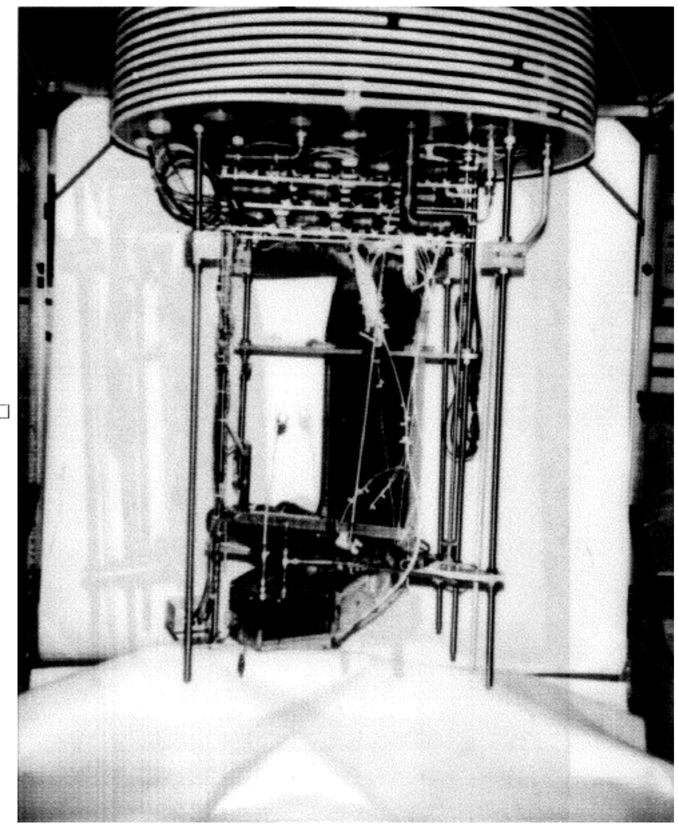
- Problem #2: Preamplifiers be in the calorimeter?
  - With preamplifiers directly mounted, no additional cables are needed and the most favorable configuration for high speed, low noise and small cross-talk is reached
  - The ATLAS barrel calorimeter will have a problem which is not permitting convective cooling of the preamps



# Cooling Tests at BNL

- Cooling tubes located at the top of the preamps were unable to stop the boiling
- Signal variation with respect to temperature is at least 2% per degree
- The temperature variations over different regions of the calorimeter would lead to large corresponding variations in the signal outputs



# ATLAS LAr Calorimeter

- Problem #2: Preamplifiers be in the calorimeter?
  - It was found that cables do not contribute to noise for fast shaping with accurately matched line-termination
  - ATLAS decided to place all preamps outside the cryostats for EM calorimeter, because of maintenance, pile-up effects …

Nuclear Instruments and Methods in Physics Research A330 (1993) 228-242
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Transmission line connections between detector and front end electronics in liquid argon calorimetry *

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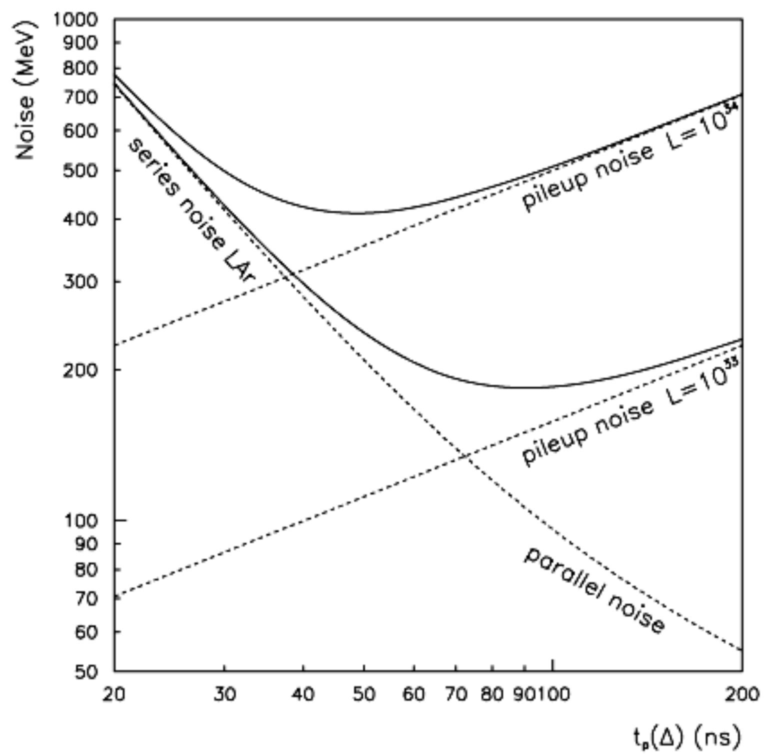
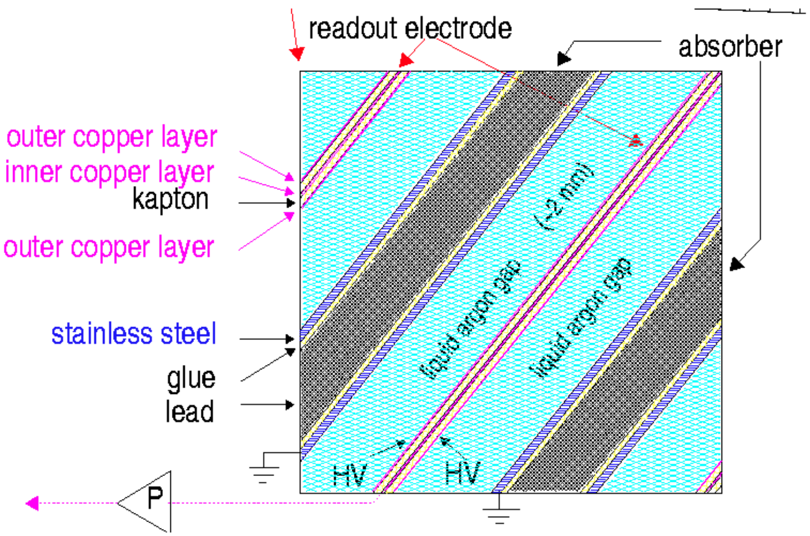
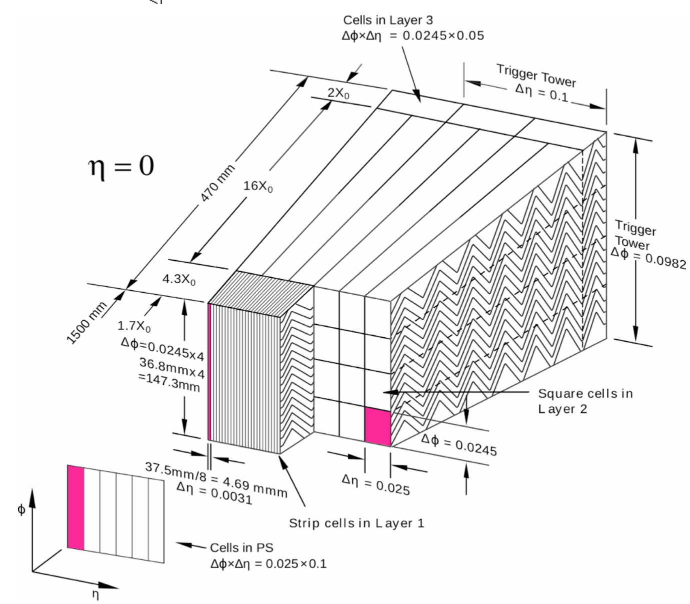
Received 9 August 1992 and in revised form 8 January 1993



# Design of ATLAS LAr EM Calorimeter

- Acceptance: |η|<2.4 (full), 2.4~3.2 (coarse)
- Fine segmentations
  - Depth: 1+3 layers
  - Transverse: 0.025x0.1 (presampler)
  - 0.003125x0.1 (front)
  - 0.025x0.025 (middle)
  - 0.025 x 0.05 (back)
- Thickness
  - 26 $X_0$ for barrel
  - 28 $X_0$ for endcap



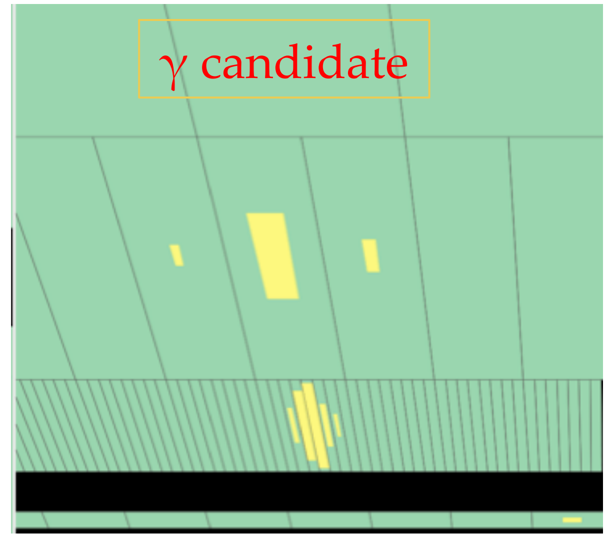



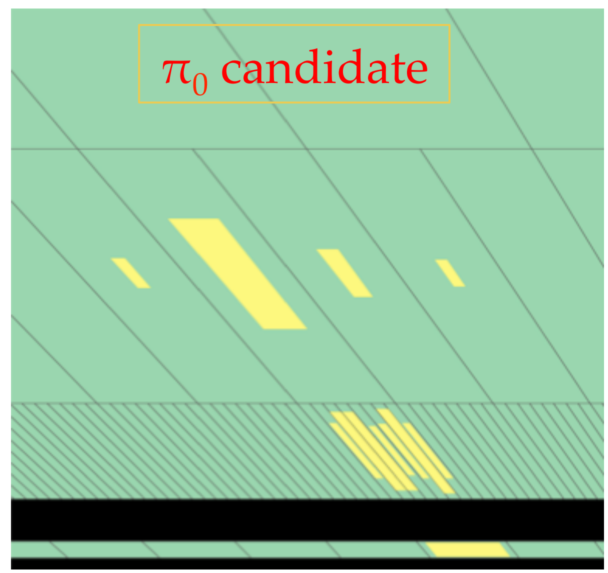
# Design of ATLAS LAr EM Calorimeter

- Dynamic range
  - 35 MeV ~ 3 TeV → readout electronics 16-bit accuracy
- Total readout channels: 182,468
- Energy resolution (E in [GeV])

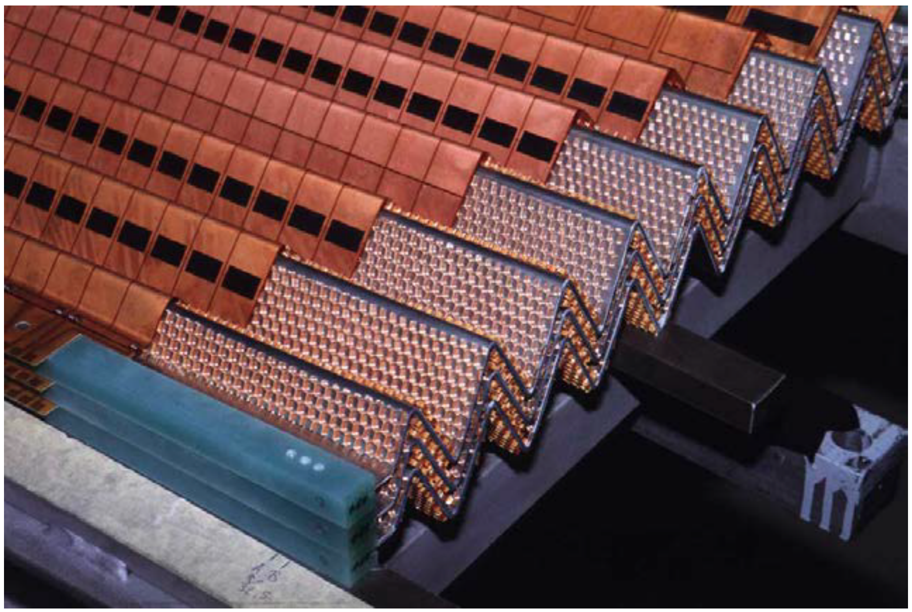
$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.4}{E} \oplus 0.7\%$$

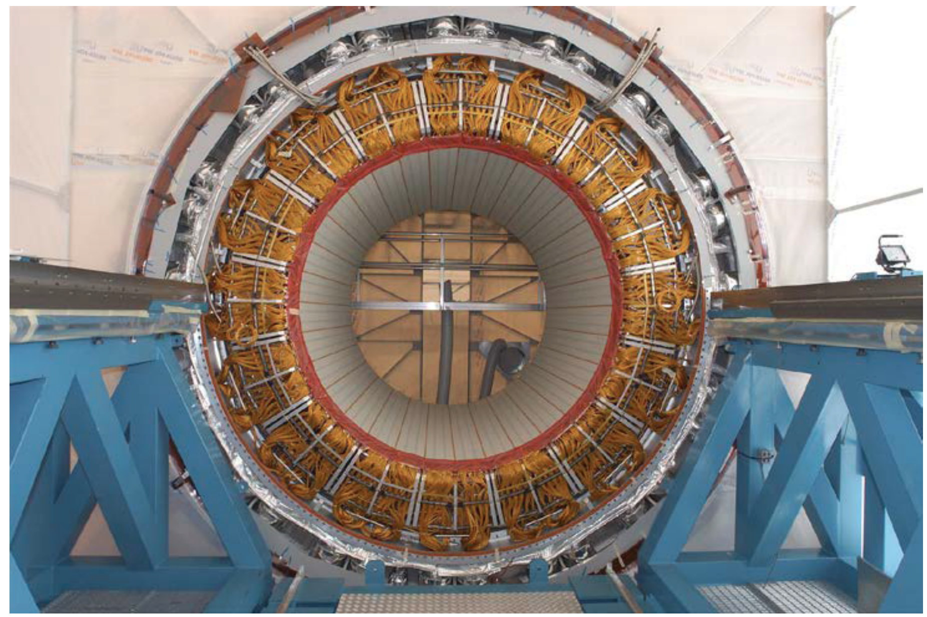
- Angle resolution: 40 mrad/√E



# ATLAS LAr Calorimeter – From Construction





# ATLAS LAr Calorimeter – To Higgs Discovery