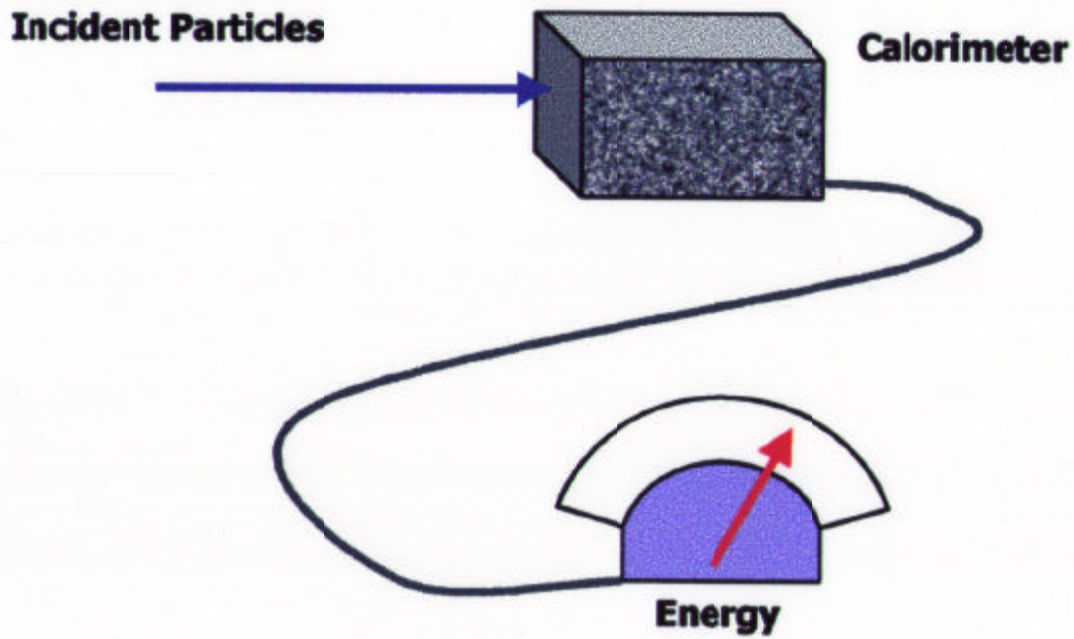
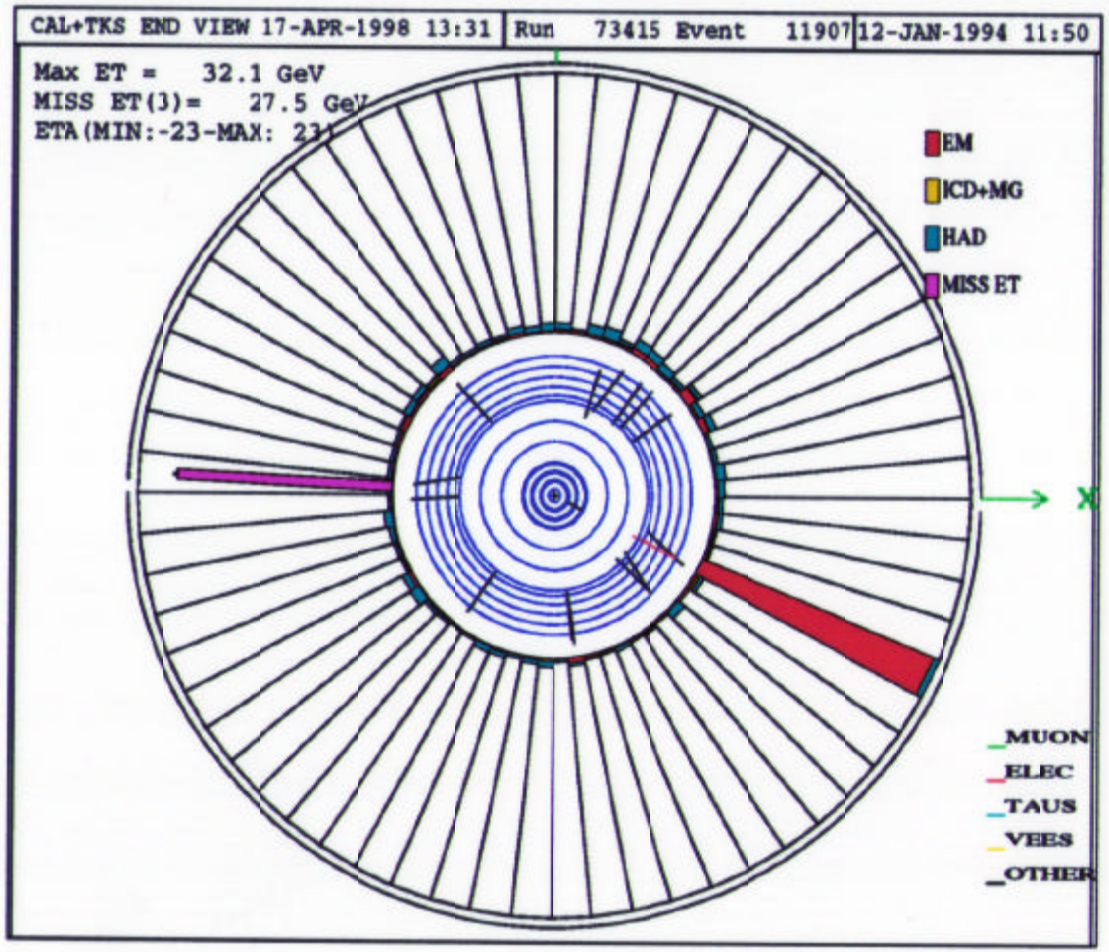
# Calorimeters in High Energy Physics



# Why calorimetry?

- **Electron and photon identification and measurement**
- **Jet identification and measurement**
  - only way to measure neutral particle energy
- **Missing $E_T$**
  - $E_T^{miss} = - \Sigma E_T^{cell}$ $(E_T = E \sin \theta)$
  - detect neutrinos
    - e.g. $W \rightarrow e\nu$

- **Increasingly important at high energy colliders**
  - emphasize jets rather than hadrons as the final state quanta of interest
    - precision jet reconstruction in e.g. top $\rightarrow$ 3 jets, $H \rightarrow bb$
  - size of calorimeter to measure a given E scales like ln E; tracking scales like $\sqrt{E}$
  - no beam energy constraint at hadron colliders




*John Womersley*

# ELECTROMAGNETIC SHOWERS

Cascade of particles produced when high energy $e^{\pm}, \gamma$ is incident on a block of material.

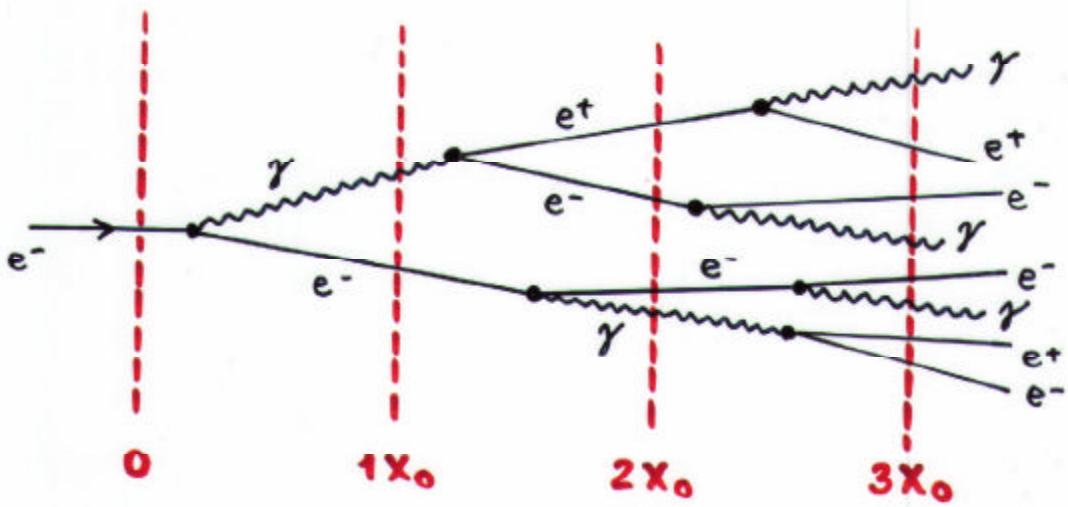
Above 100 MeV : $e^{\pm} \rightarrow e^{\pm}\gamma$ BREMSSTRAHLUNG
$\gamma \rightarrow e^{+}e^{-}$ PAIR PRODUCTION

– dominate energy loss

Shower development scales with # of RADIATION LENGTHS ($X_0$)

$1\ X_0 \doteqdot 180\ A/Z^2\ g/cm^2$

Al : 8.9 cm
$H_2$ : 8.65 m
U : 3.2 mm




Need 25 – 30 $X_0$ for complete containment.

Transverse size ~ scales with MOLIÈRE RADIUS $\approx 7\ A/Z\ g/cm^2$

**Figure 11.2** Shower profiles in lead. The number of electrons should be multiplied by a normalization factor of 0.79. (D. Müller, Phys. Rev. D 5: 2677, 1972.)

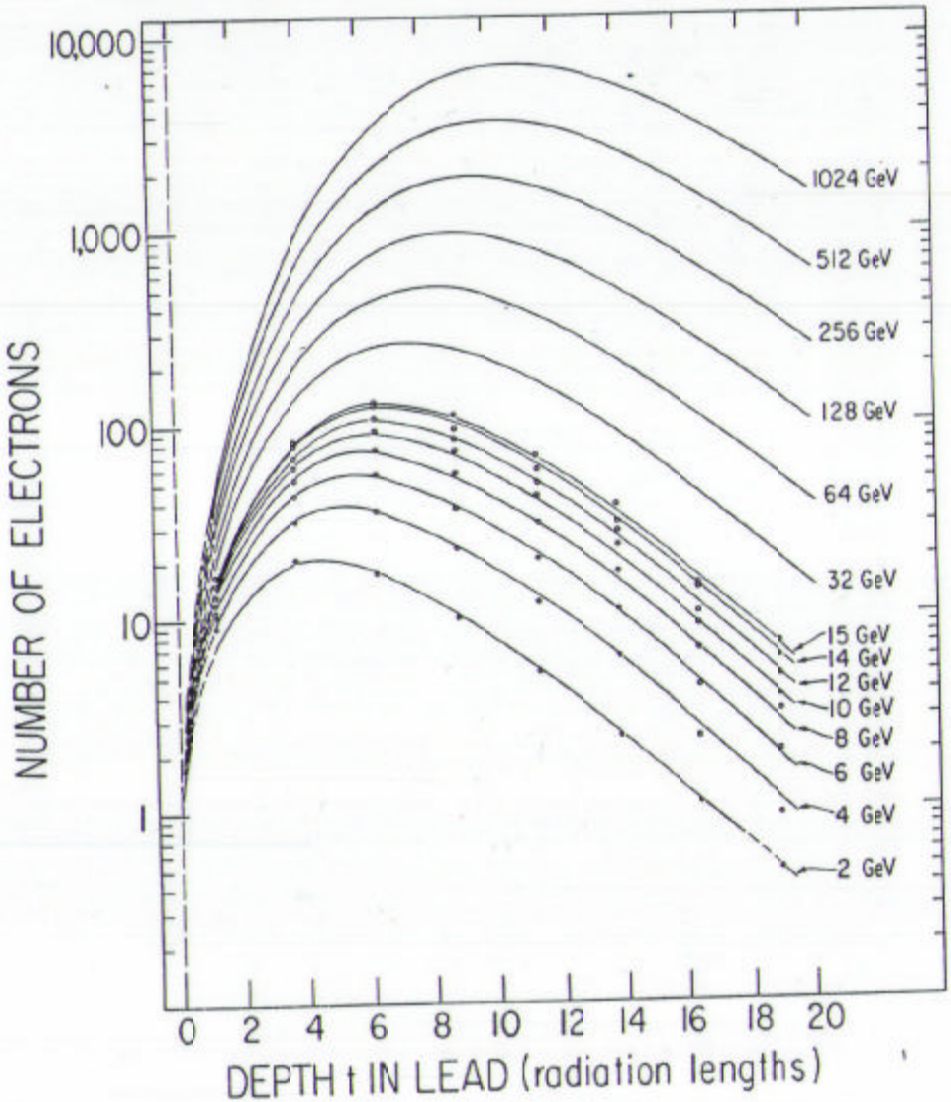
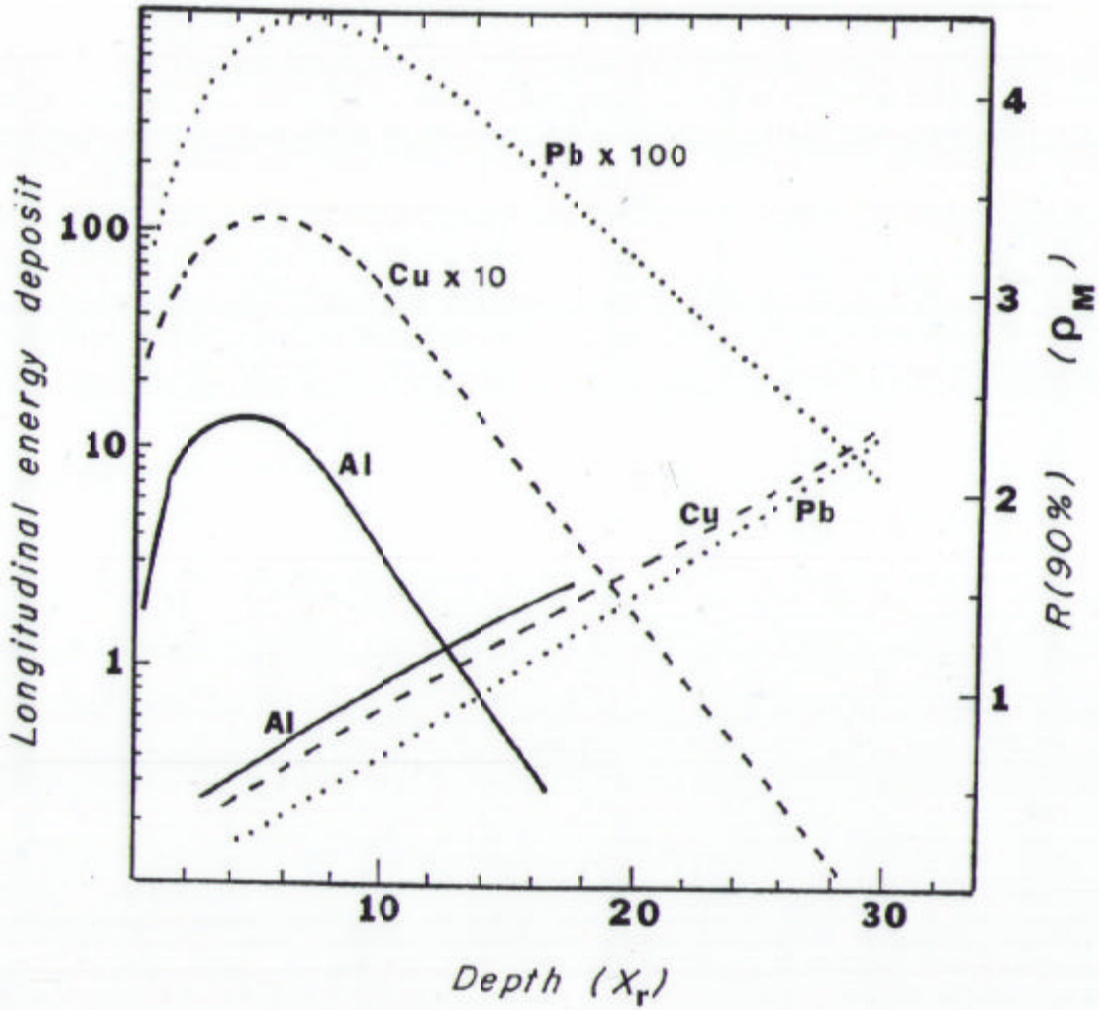


**Figure 11.3** Longitudinal development of electromagnetic showers in different materials. Right scale shows radii for 90% shower containment. (C. Fabjan and T. Ludlam, adapted with permission from the Annual Review of Nuclear and Particle Science, Vol. 32, © 1982 by Annual Reviews, Inc.)



Number of Particles after $t$ $X_0$ is

$$N(t) = 2^t = e^{t \ln 2}$$

Average energy of shower particle at depth $t$ is

$$E(t) = E_0 / 2^t \qquad E_0 = \text{incident energy}$$

Shower propagates until $E(t)$ falls to some value $E_c$ where bremsstrahlung and pair production no longer dominate. At this point:

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

The sum of all the charged track lengths in the calorimeter is then:

$$L = \frac{2}{3} \int_0^{t_{max}} N(t)\, dt \approx \frac{E_0}{E_c}$$

$(\frac{1}{3}\ \gamma\text{'s},\ \frac{1}{3}\ e^+,\ \frac{1}{3}\ e^-)$

So total charged track length $\propto$ incident energy

$\therefore$ $\sum$ ionization in material $\propto$ incident energy

MEASURE ENERGY OF INCIDENT PARTICLE BY CREATING A SHOWER AND MEASURING CHARGED TRACK LENGTH (or a fixed fraction thereof).

# SAMPLING CALORIMETER

For reasons of cost & compactness :

Sample only a fraction of total track length

= "SAMPLING FRACTION"

Alternate Dense absorber e.g. metal

with Sensitive layers e.g. scintillator or ionization det.

# CALORIMETER ENERGY RESOLUTION

= standard deviation on measurement of $E_0$

Expand variance in a power series in E:

$$\sigma^2(E) \equiv \sigma_0^2 + \sigma_1^2 E + \sigma_2^2 E^2 + \ldots$$

$$\therefore \frac{\sigma(E)}{E} = \sqrt{\frac{\sigma_0^2}{E^2} + \frac{\sigma_1^2}{E} + \sigma_2^2}$$

$\sigma_0$ = NOISE TERM

Independent of E e.g. electronic noise

$\sigma_1$ = SAMPLING TERM (STOCHASTIC TERM)

Contribution to resolution $\propto \sqrt{E}$

e.g. Poisson statistics on # electrons in sensitive material (sampling fluctuations)

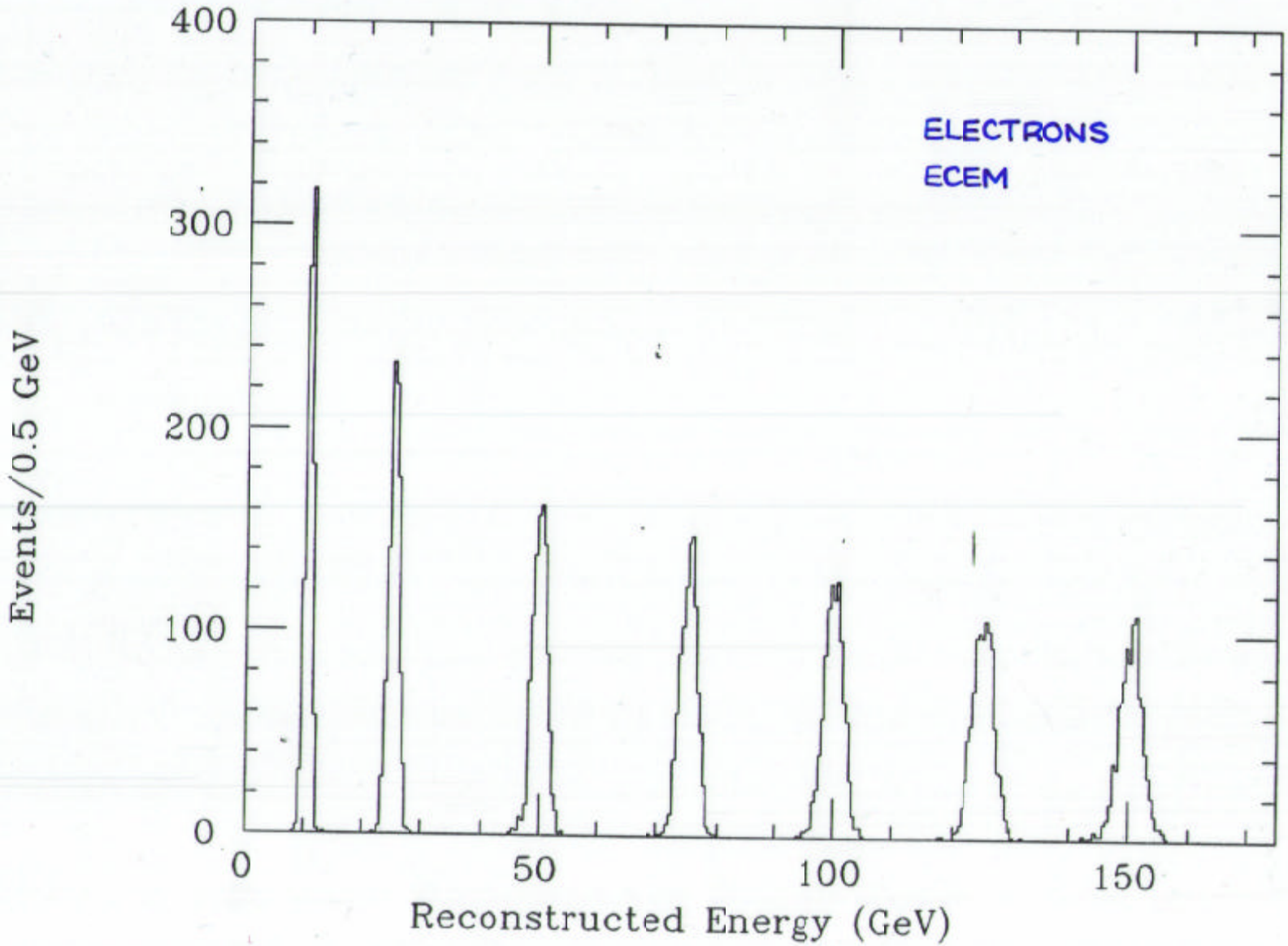
→ Reduce sampling term by increasing sampling fraction.

Often quoted as $\frac{x\%}{\sqrt{E\,(\mathrm{GeV})}}$ e.g. " $\frac{15\%}{\sqrt{E}}$ "

$\sigma_2$ = CONSTANT TERM

Arises from: calibration uncertainties
non-linear response
non-uniform response
leakage out of calorimeter

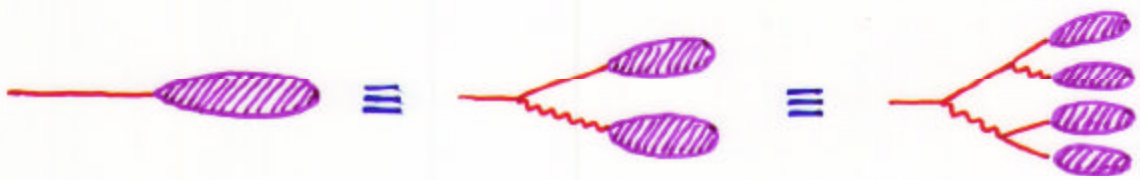
→ Often hard to reduce; dominates at high E.


ELECTRONS
ECEM
Events/0.5 GeV
400
300
200
100
0
0
50
100
150
Reconstructed Energy (GeV)

# WHY $\frac{1}{\sqrt{E}}$ ?

Because an EM shower = $\sum$ many smaller EM showers

(i.e. shower processes indep. of energy)



If a shower of energy $E$ has r.m.s. $\sigma(E)$

Break it into $n$ smaller showers of energy $E_1 = E/n$

$$\text{Then} \quad \sigma^2(E) = \sum_1^n \sigma^2(E_1)$$

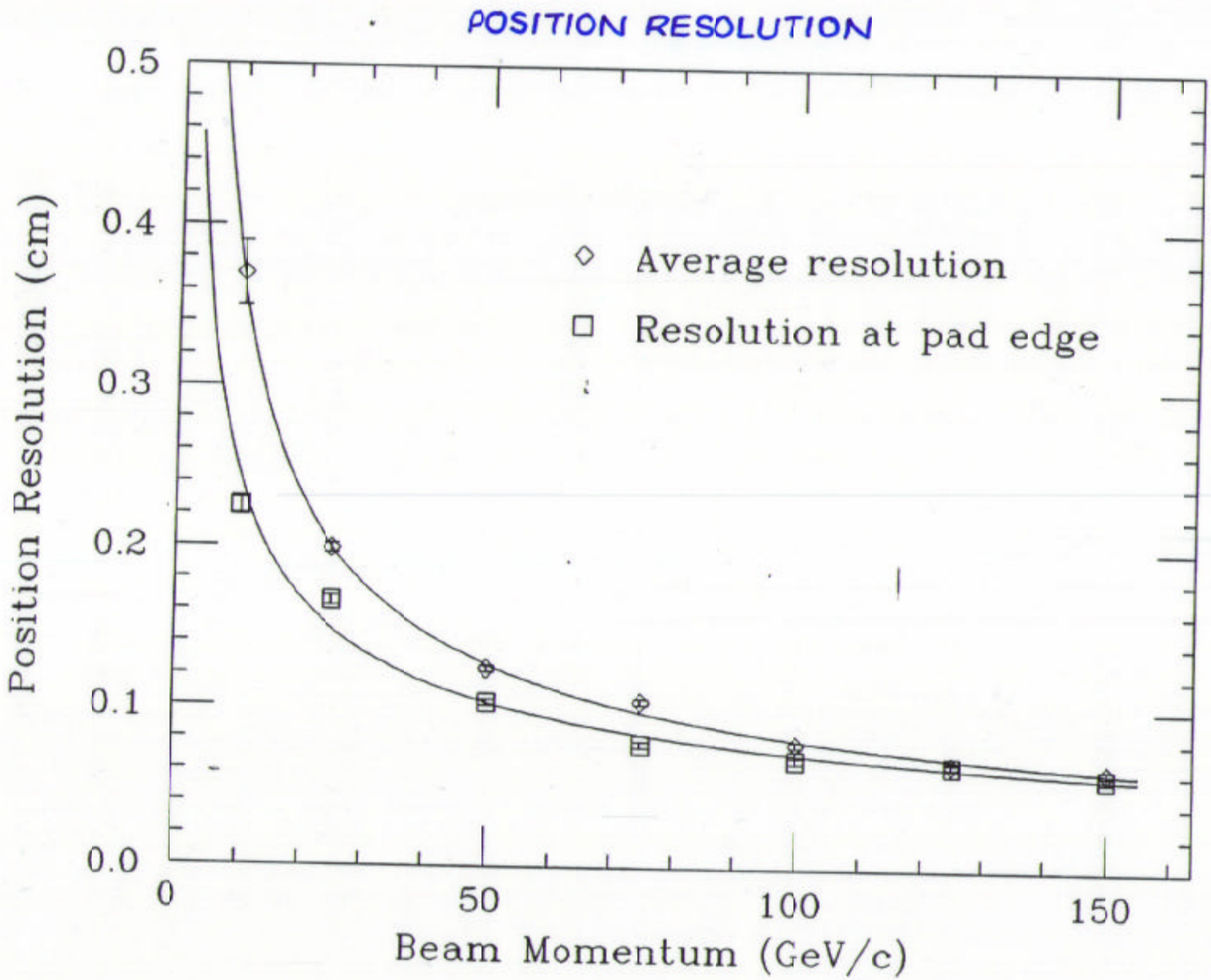
$$= n\sigma^2(E_1)$$

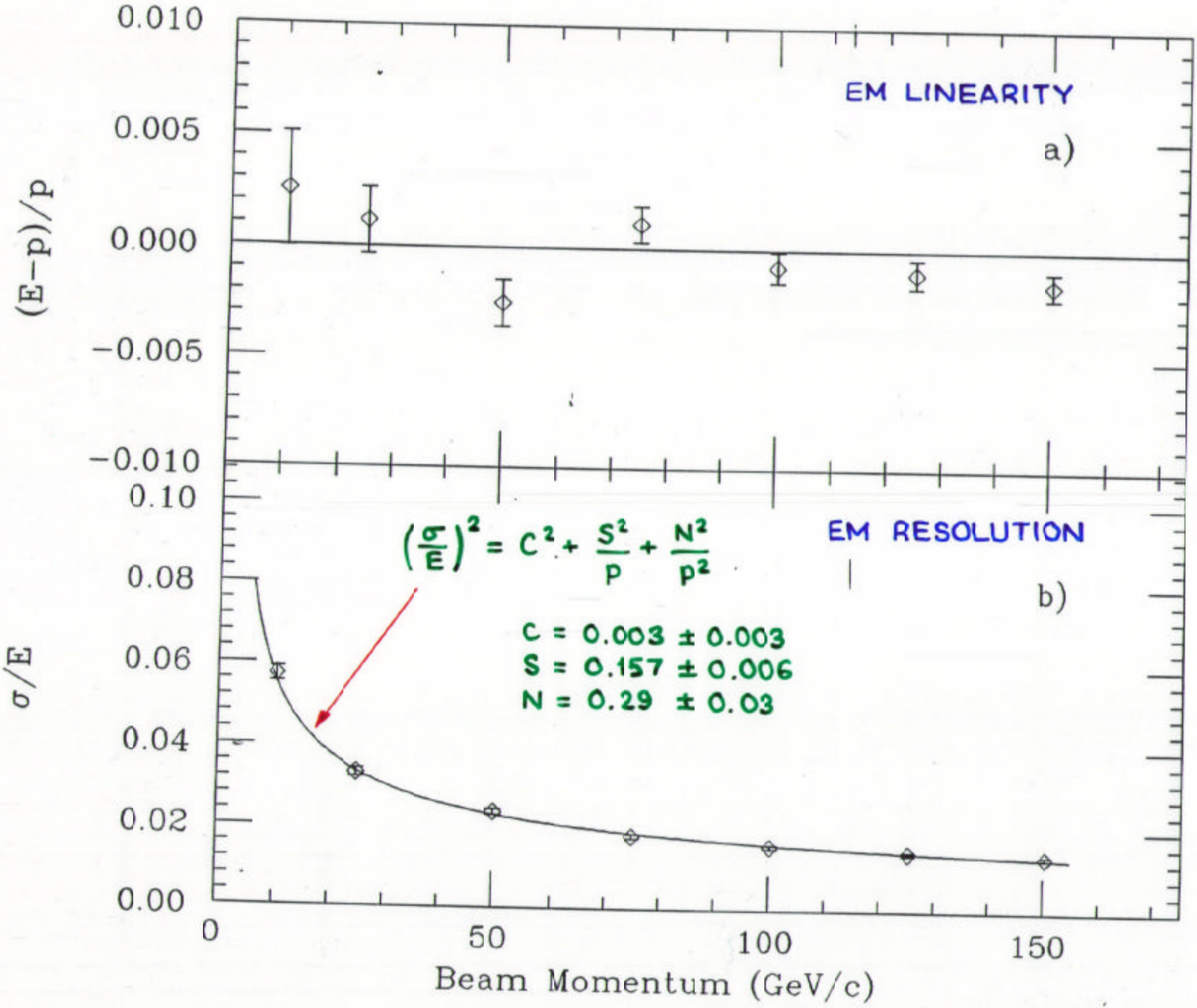
Repeat for $m \neq n$ showers of energy $E_2 = E/m$

$$\Rightarrow \quad \sigma^2(E) = m\sigma^2(E_2) = n\sigma^2(E_1)$$

$$\frac{\sigma(E_1)}{\sigma(E_2)} = \sqrt{\frac{m}{n}} = \sqrt{\frac{E_1}{E_2}}$$

$$\Rightarrow \quad \sigma(E) \propto \sqrt{E} \qquad \text{i.e.} \quad \underline{\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}}$$


POSITION RESOLUTION
Position Resolution (cm)
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
Beam Momentum (GeV/c)
Average resolution
Resolution at pad edge


EM LINEARITY
a)
(E−p)/p
0.010
0.005
0.000
−0.005
−0.010
EM RESOLUTION
b)
$\left(\frac{\sigma}{E}\right)^2 = C^2 + \frac{S^2}{p} + \frac{N^2}{p^2}$
C = 0.003 ± 0.003
S = 0.157 ± 0.006
N = 0.29 ± 0.03
σ/E
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
Beam Momentum (GeV/c)

# HADRONIC SHOWERS

Strongly interacting particles also cascade in material but many more processes involved.

e.g. 10 GeV/c p on Fe/Ar calorimeter (T. Gabriel)

| | | |
|---|---|---|
| Ionization of scattered secondary hadrons | 40% | |
| EM cascade from $\pi^0 \to \gamma\gamma$ | 21% | rises w/ E |
| Nuclear binding energy plus $\nu$ production | 21% | |
| H.E. neutrons (> 10 MeV) | 5% | |
| L.E. neutrons (< 10 MeV) | 4% | |
| Nuclear excitation | 4% | |
| Ionization by nuclear fragments (D, $\alpha$ ...) | 2% | |
| Ionization by primary particle | 2% | |
| Other | 1% | |

Hadron shower development $\approx$ scales with the

NUCLEAR ABSORPTION LENGTH ($\lambda$)

or INTERACTION LENGTH

$$\lambda \approx A / N_A \sigma_{abs}$$

$\lambda =$ 39 cm Al
7.2 m $H_2$
10 cm U

Initial interaction depth $P(t) \approx \exp(-t/\lambda)\, dt$

Shower
- longer
- wider
- more fluctuations
- starts later (on av.)

than EM shower of same energy

Need 8 – 10 $\lambda$ to completely contain a hadron shower

(still get "punchthrough" at $E \gtrsim 150$ GeV)

# D0 Calorimeter Upgrade Configuration

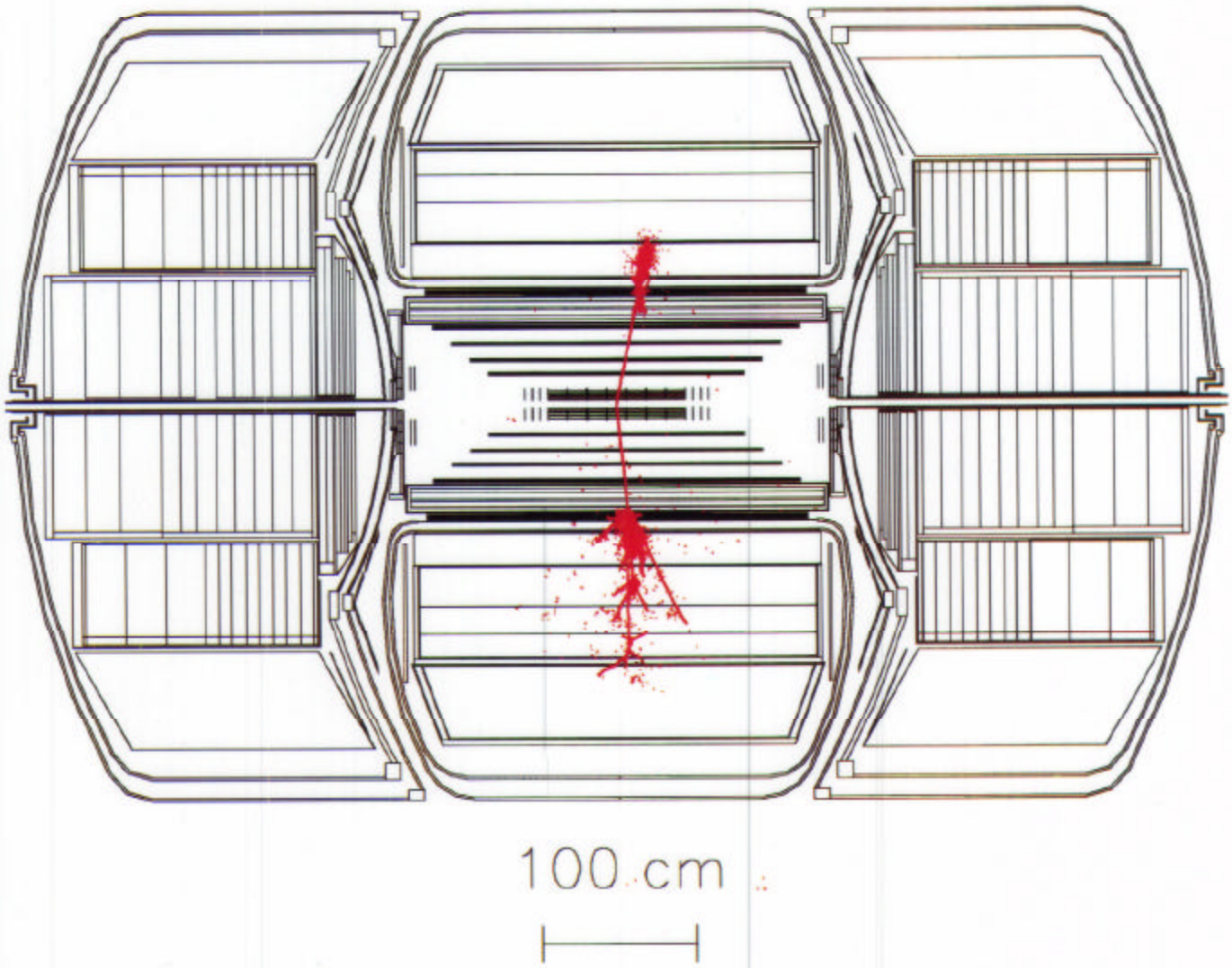
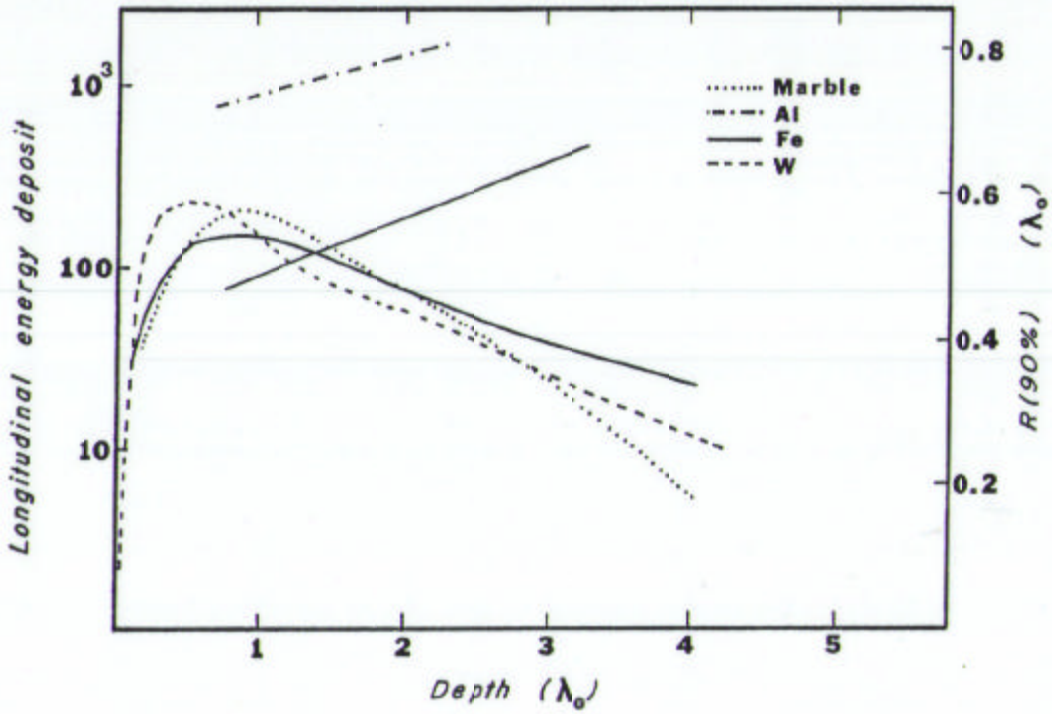


**Figure 11.8** Longitudinal development of hadronic showers in different materials. Right scale shows radii for 90% shower containment. Distances are measured in absorption lengths. (C. Fabjan and T. Ludlam, adapted with permission from the Annual Review of Nuclear and Particle Science, Vol. 32, © 1982 by Annual Reviews, Inc.)



# COMPENSATION ( $e/\pi$, $e/h$ and all that ... )

Since hadron shower energy goes into processes like

- nuclear excitation
- neutrino production
- neutrons

it is not all sampled by calorimeter.

$\therefore$ Hadron response at a given energy < EM response.

Usually quote $\dfrac{e}{\pi} = \dfrac{\text{EM response}}{\pi \text{ response}}$

$e/\pi > 1$ (normally)

If calorimeter measures EM energy with efficiency $\varepsilon_{EM}$ and measures other energy deposition with efficiency $\varepsilon_H$

Then $e$ response $= \varepsilon_{EM} \cdot E_0$

$\pi$ response $= f_{EM}\,\varepsilon_{EM}\,E_0 + (1 - f_{EM})\,\varepsilon_H E_0$

where $f_{EM}$ = fraction of EM energy within $\pi$ shower

$\approx 0.1 \ln (E/\text{GeV})$ 10 – 100 GeV

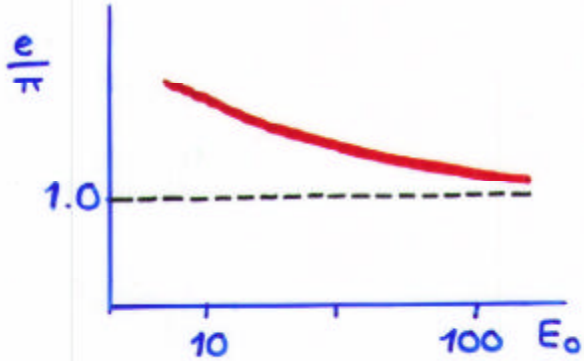
$f_{EM} \uparrow$ as $E \uparrow$; $f_{EM} \sim 0.5$ @ 150 GeV.

So $$\frac{e}{\pi} = \frac{\varepsilon_{EM}}{\varepsilon_H - f_{EM}(\varepsilon_H - \varepsilon_E)} = \frac{e/h}{1 - f_{EM}(1 - e/h)}$$

where $$\text{"}\frac{e}{h}\text{"} = \frac{\varepsilon_{EM}}{\varepsilon_H}$$

Find ... "$\frac{e}{h}$" is fixed by calorimeter geometry, A, Z etc.

Since $f_{EM}$ is function (E), so is $e/\pi$ :




If $e/h \neq 1$, calorimeter is NONLINEAR for hadrons.
hadronic resolution has larger constant term.

→ Want <u>COMPENSATION</u> ⇔ $e/h = 1$
→ $e/\pi = 1$ for all E.

Obtained by suppressing EM signal :

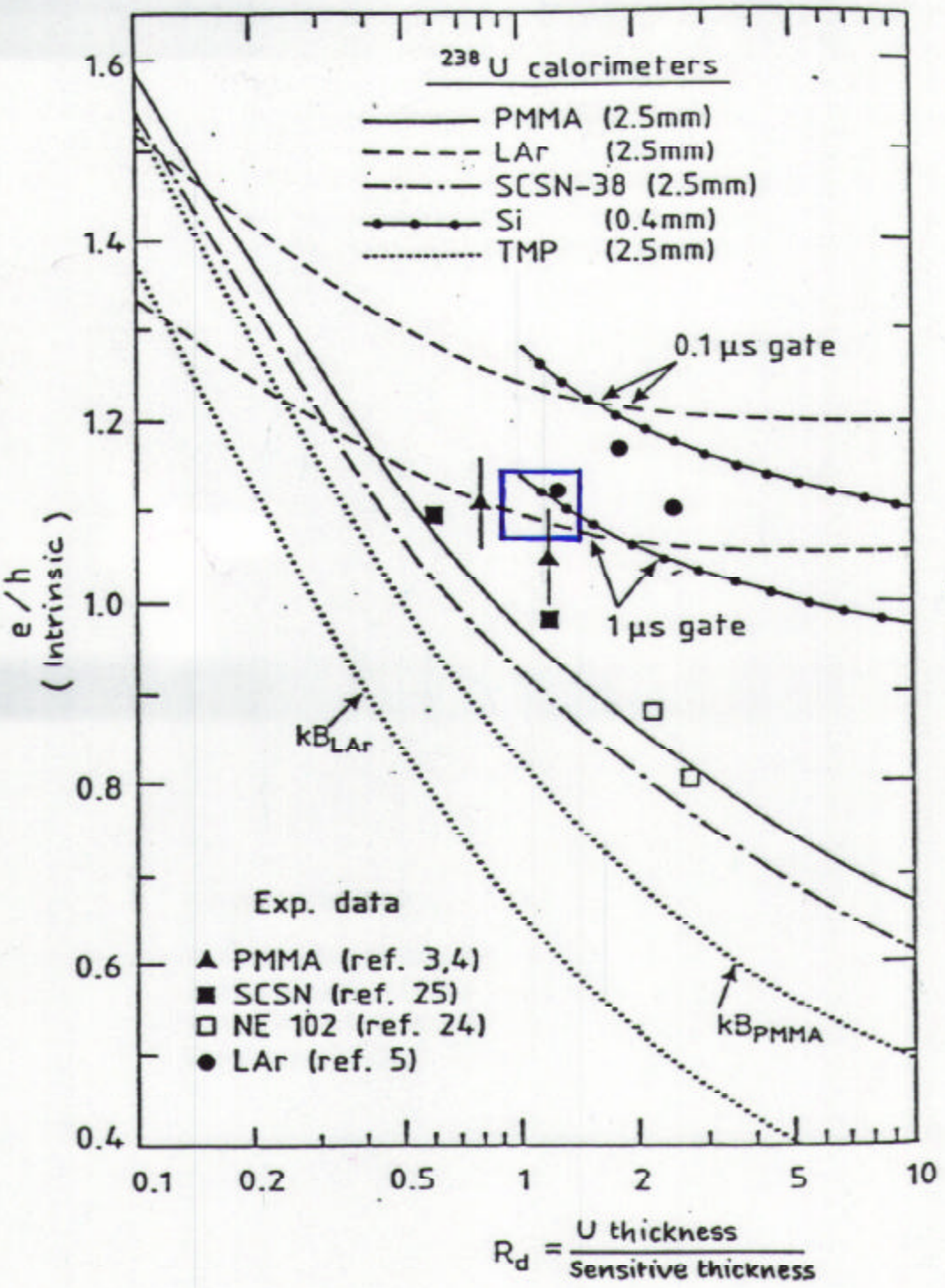
- high Z absorber U (Pb)
- thinner sampling layers

Relatively recent understanding,

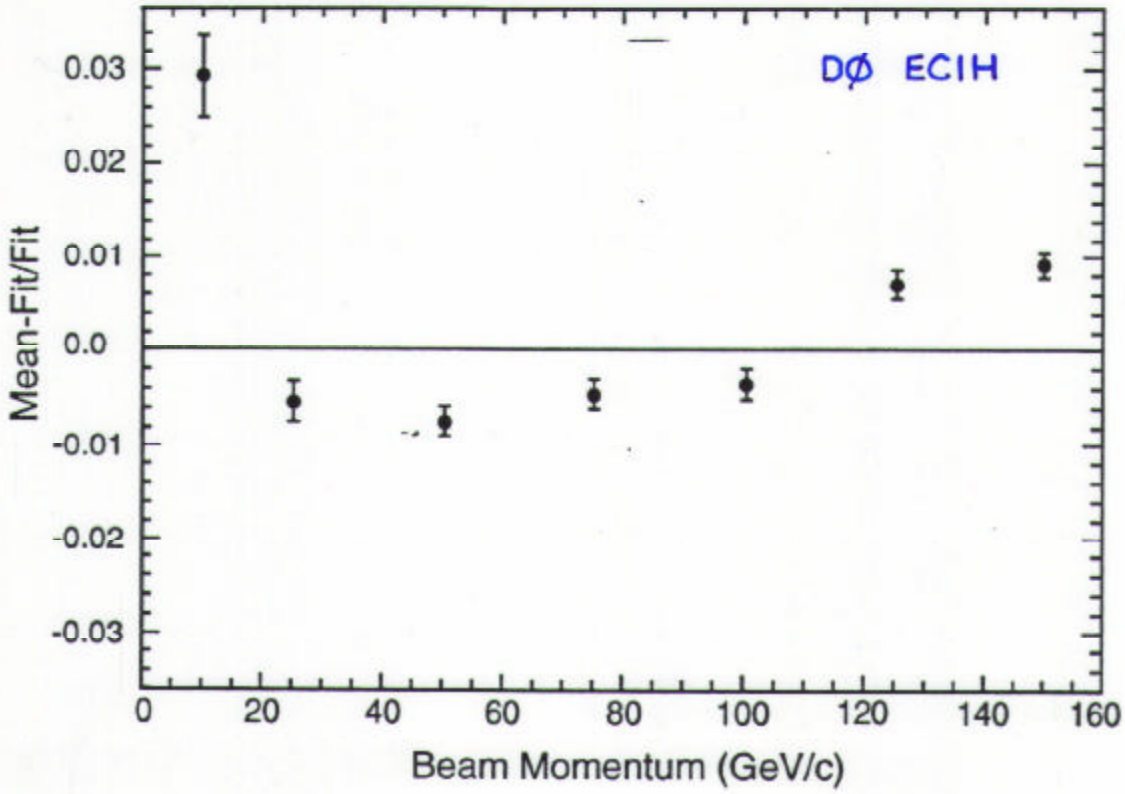
| | | | | |
|---|---|---|---|---|
| e.g. | CDF | iron / scint | $e/h \approx 1.6$ | early 80's |
| | DØ | U / Ar | $e/h \approx 1.1$ | late 80's |
| | ZEUS | U / scint | $e/h \approx 1.0$ | late 80's |

( see R. Wigmans NIM A265 pp 273-290 )

# WIGMANS' e/h PREDICTION



## HADRONIC LINEARITY

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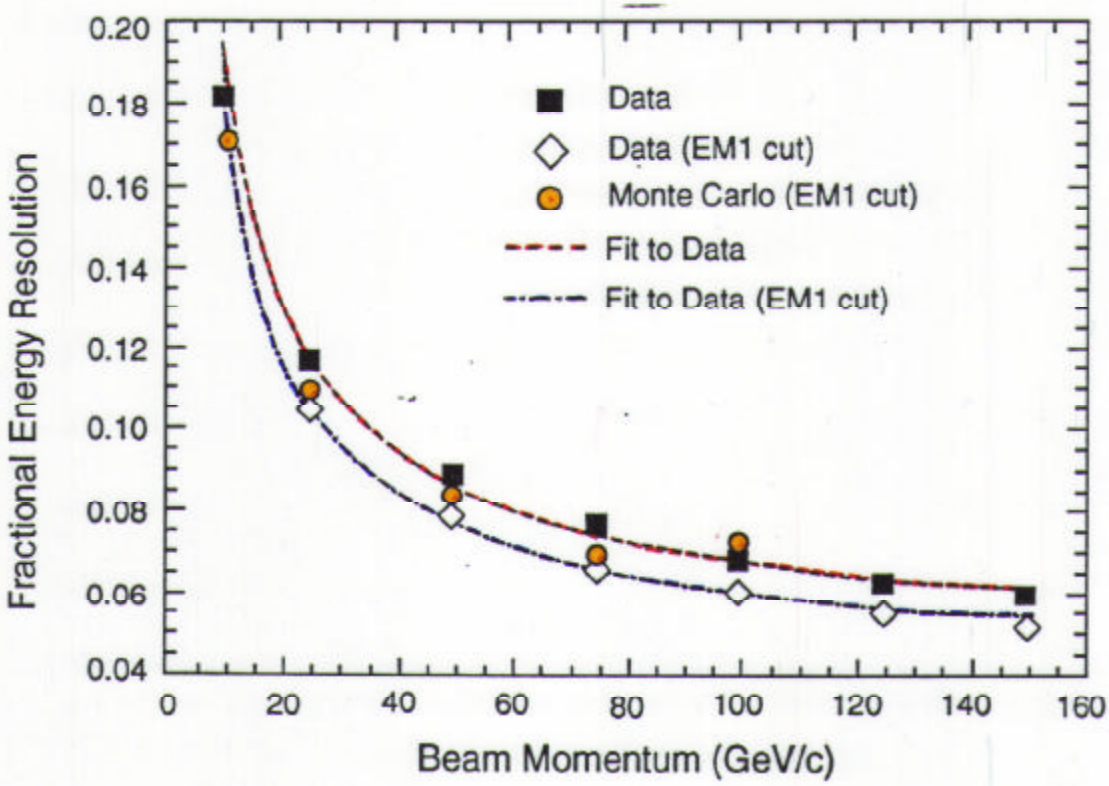
## HADRONIC RESOLUTION




$$\left(\frac{\sigma}{E}\right)^2 = C^2 + \frac{S^2}{P} + \frac{N^2}{P^2}$$

------ $C = 0.044 \pm 0.001$ ; $S = 0.501 \pm 0.008$

-·-·-·- $C = 0.039 \pm 0.001$ ; $S = 0.446 \pm 0.009$

with cut on EM layer 1

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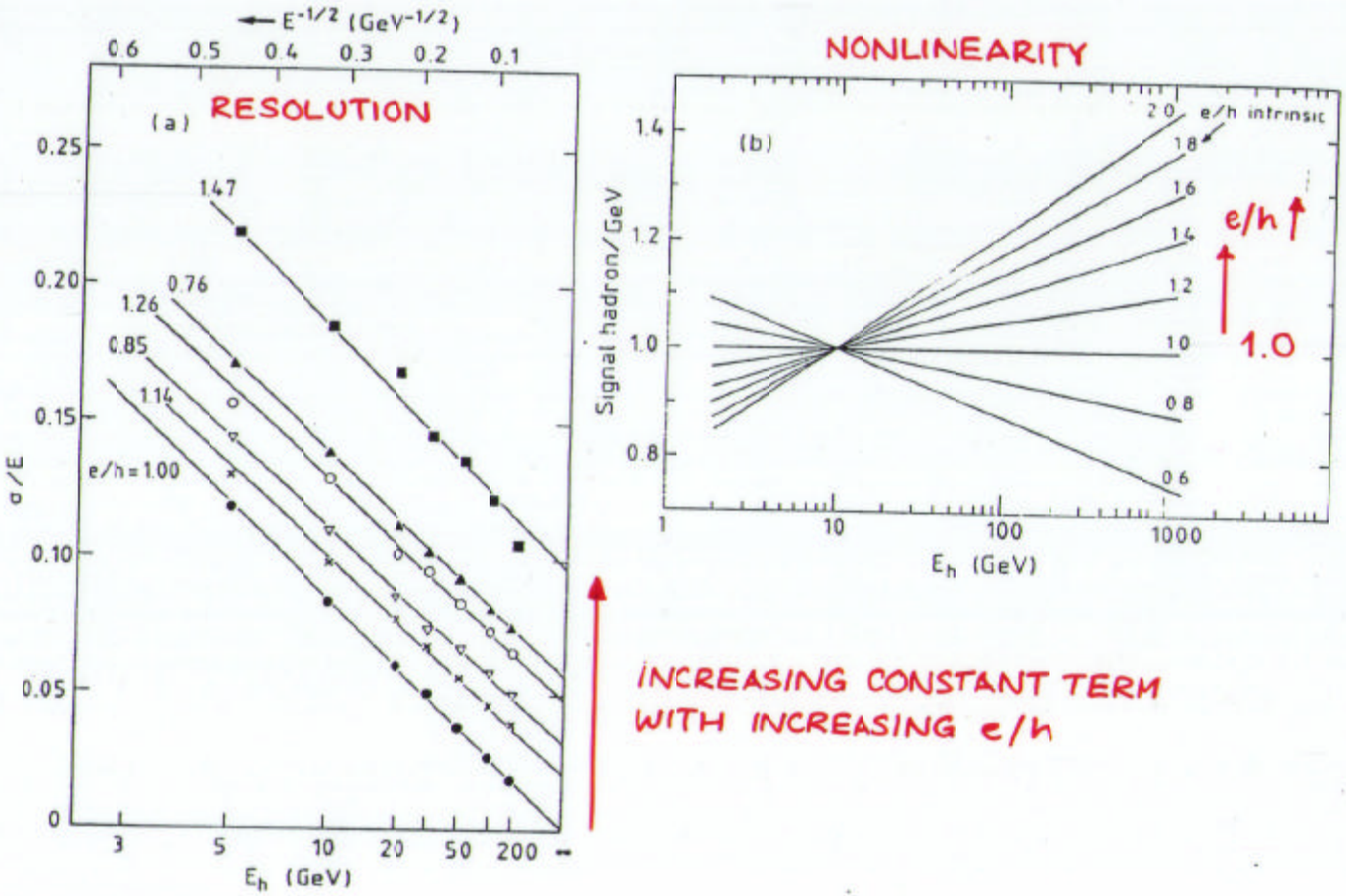
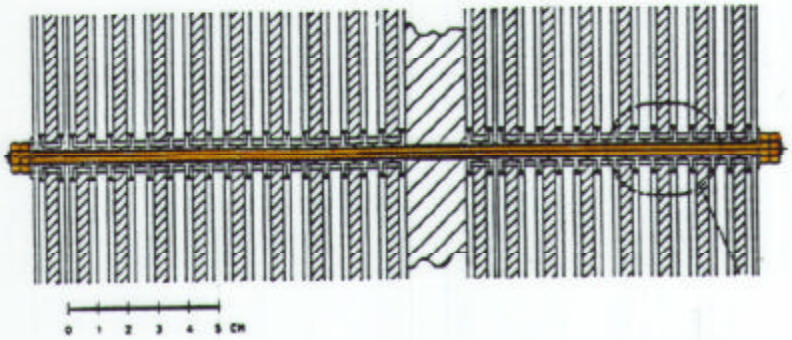
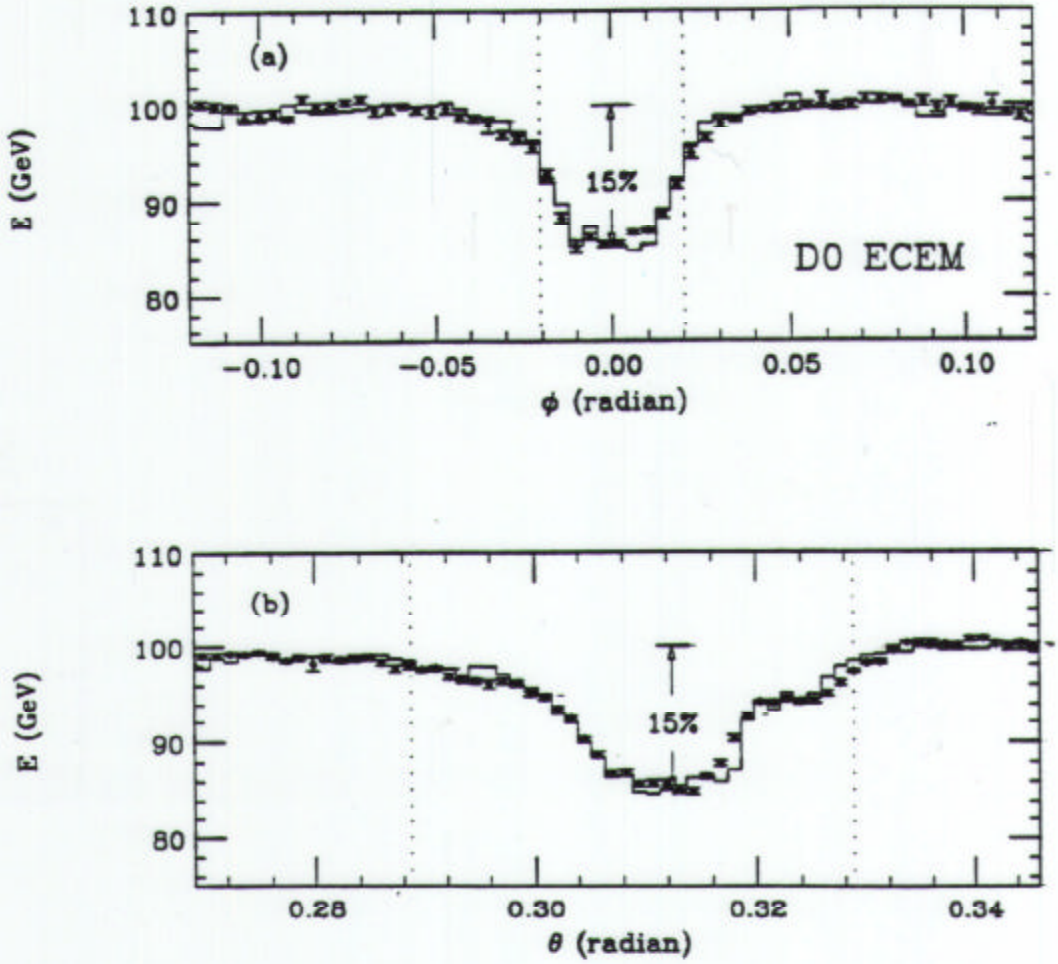



Fig. 3. Monte Carlo simulation of the effects of $e/h \neq 1$ on the energy resolution and signal linearity of hadron calorimeters.

R. WIGMANS NIM

# Tie Rods in EM Calorimeter




Mean pulse height as a function of azimuth (a), and of polar angle (b) for 100 GeV electrons in the vicinity of the $\eta$=2.05 tie-rod. The dotted lines indicate the boundary of the 20 mm diameter zone where the resistive coat has been removed from the signal disks. The points are the data and the histograms are from the Monte Carlo simulation.

# SIMULATION

Essential to understand performance & design

## GEANT

CERN program tracks particles & interacts them in detector.

- Geometry must be created by user from a repertoire of standard shapes (BOX, TUBE... PGON, HYPE) and materials (can define your own e.g. polymers).

- Provide input particles

- GEANT calls other programs for hadronic interactions
  GHEISHA
  HADRIN
  or FLUKA

## EGS

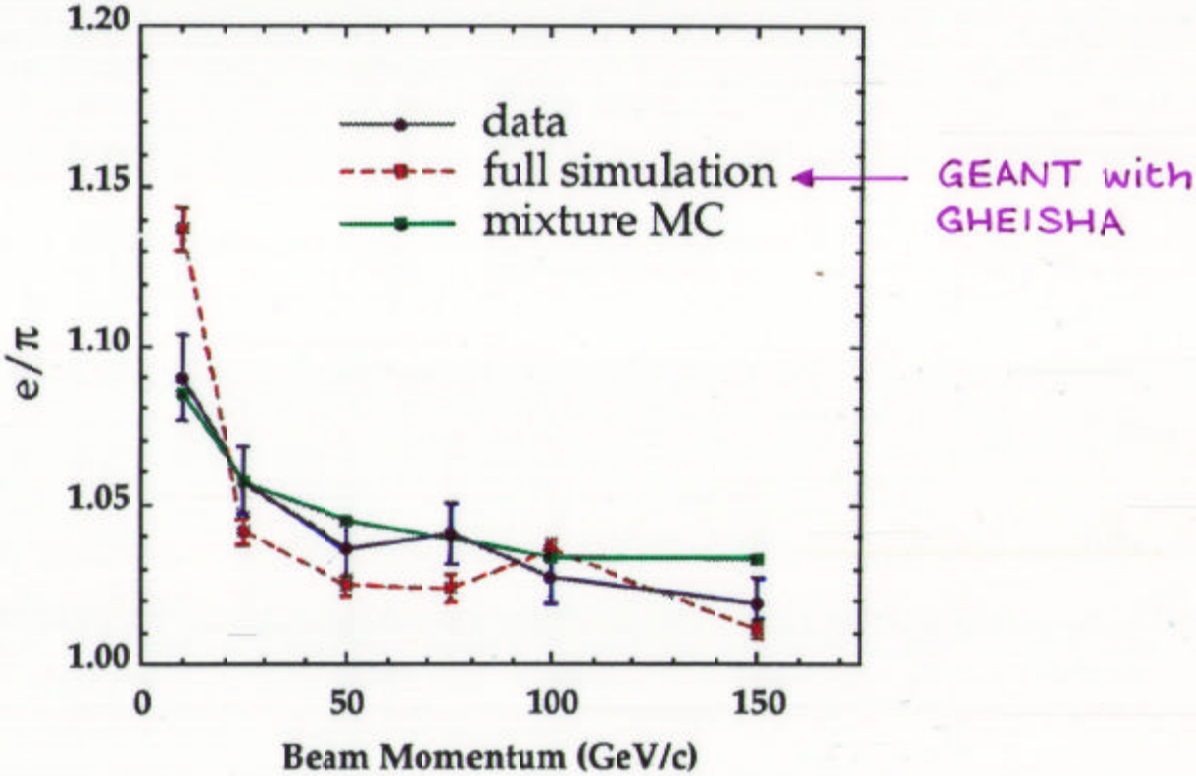
Detailed simulation of EM showers (W. Nelson et al)

## CALOR 89

Detailed simulation of hadron showers (T. Gabriel et al.)

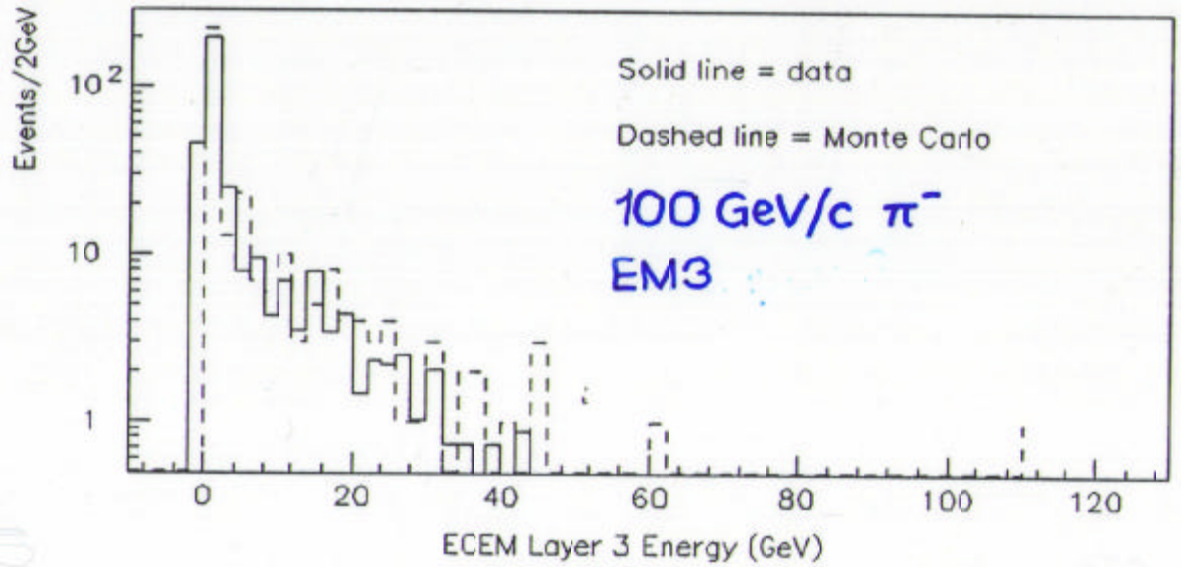
- useful to predict $e/\pi$, resolution
- too slow for whole event simulations.
- shielding calculations

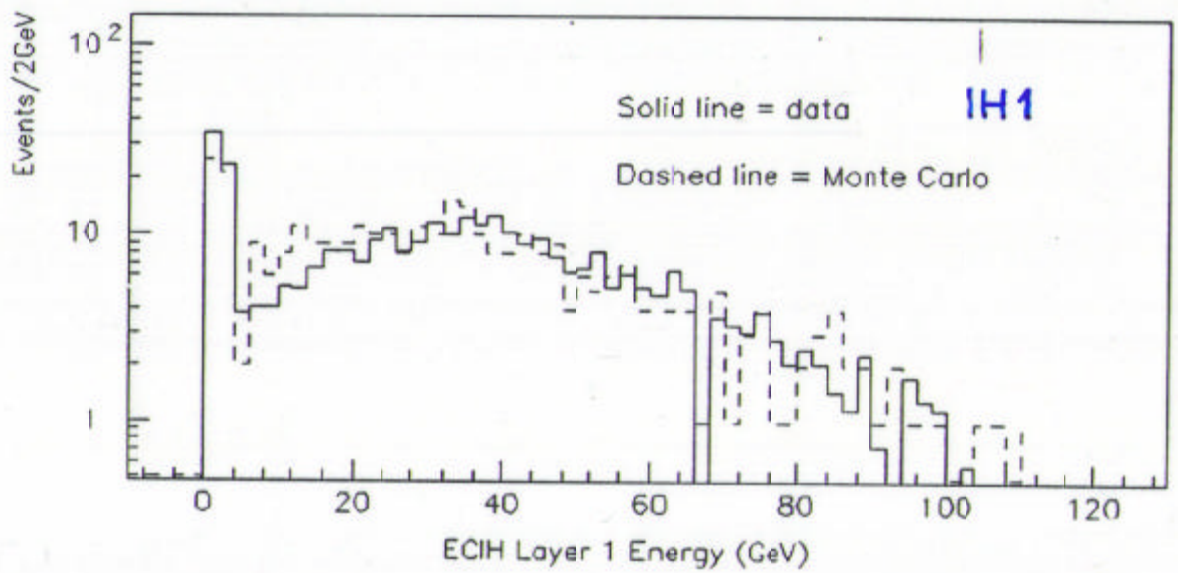
# e/π response ratio



Mixture MC

# Spectra of Energies in Calorimeter Layers



# PARAMETRIZATION OF LONGITUDINAL SHAPE

e.g. R.K. Bock, et al ; NIM 186 (1981) 533

$$\delta E = \underbrace{\frac{E_0}{\Gamma(a)} \underline{w} (bs)^{a-1} e^{-bs} b\,ds}_{\text{EM PART}} + \underbrace{\frac{E_0}{\Gamma(c)} \underline{(1-w)} (td)^{c-1} e^{-td}\, \delta t}_{\text{HADRONIC PART}}$$

where $s$ = distance from start of shower in $X_0$
$t$ = " " " " " " $\lambda$

and $a, b, c, d$ and $w$ are fitted parameters.

$a = c = 0.62 + 0.32 \ln E$
$b = 0.22$
$d = 0.91 - 0.02 \ln E$
$w = 0.46$

Note: $\underline{w \equiv f_{EM}}$

$$\left[ \Gamma(a) \equiv \int_0^\infty t^{a-1} e^{-t} dt \right]$$

— useful for fast simulation where details of shower are not critical

Nuclear Instruments and Methods 186 (1981) 533–539
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# PARAMETRIZATION OF THE LONGITUDINAL DEVELOPMENT OF HADRONIC SHOWERS IN SAMPLING CALORIMETERS

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Received 24 November 1980

A parametrization of the longitudinal development of hadronic showers in calorimeters is presented; this is being used for simulation of showers in the experiment UA1. These calorimeters cover almost $4\pi$ solid angle, and consist of stacked electromagnetic (lead) and hadronic (iron) sandwiches. We have used published data of fine granularity together with new test data obtained for our calorimeter prototypes in order to extract the longitudinal shower shape in lead and iron. A satisfactory parametrization for the average longitudinal development of the showers is obtained. An example for fluctuating about this mean is also given for [illegible]ely integrated read-out.

## 1. Introduction

Calorimetric methods have become increasingly [illegible] essential for [illegible] hadronic energy and, [illegible] hadron shower [illegible] pur-

We restrict ourselves to two da[illegible] granularity, made available to us in all desira[illegible] detail, and to test data from our own UA1 setup. These data are described below.

### 2.1. WA1 hardonic test runs [10,11]

For calibrating the magnetised iron calorimeter used in the CERN neutrino experiment WA1, a test setup was used consisting of 45 plates of iron of average thickness 5 cm, each plate being followed by 6 mm of plastic scintillator (NE110) viewed indivi-

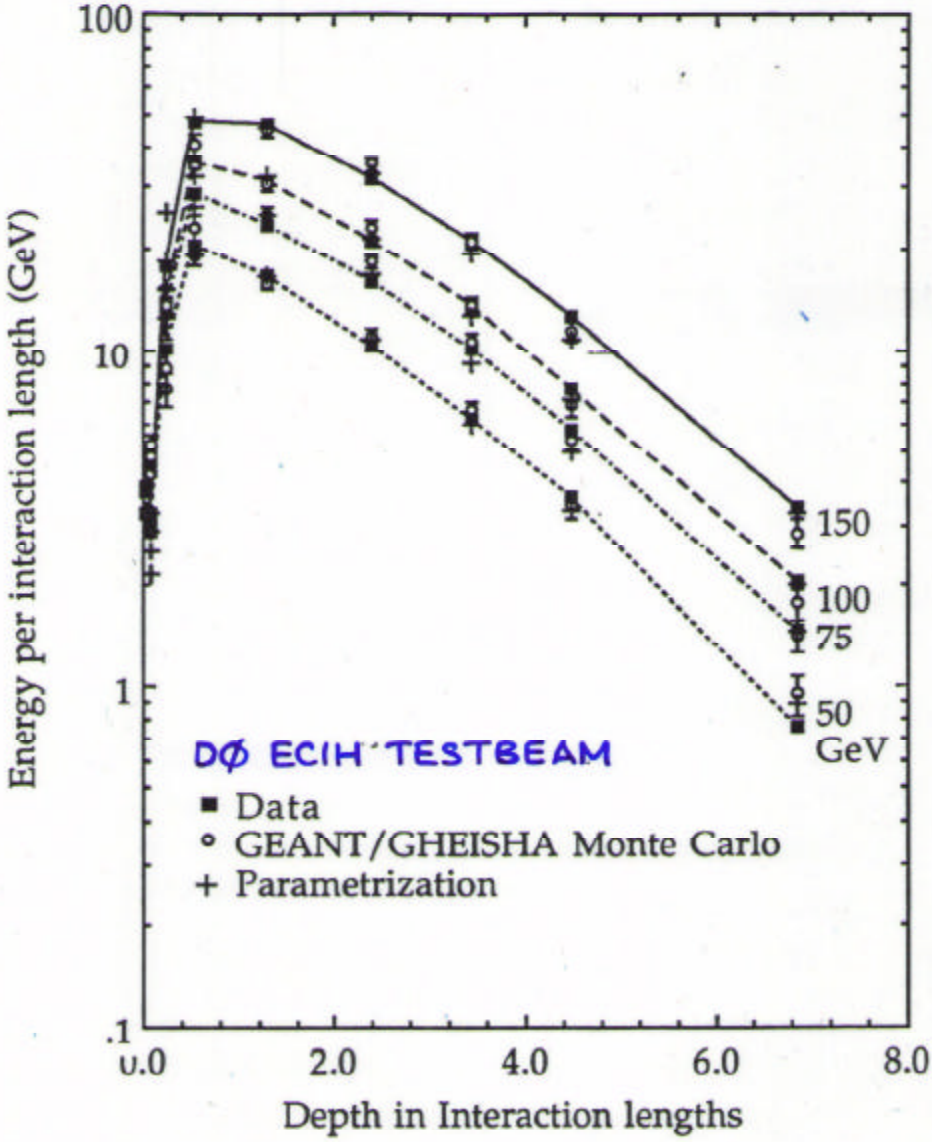
Attempts to describe showers globally by empirical parametrization have been successful for electromagnetic showers [5]. The resulting formula for the shape of the longitudinal e.m. shower development is:

$$dE = k\, s^{a-1}\, e^{-bs}\, ds\,,$$

[illegible]re $s$ is the depth of the calorimeter expressed in [illegible] length units, and $a$, $b$ are energy-dependent [illegible]ess constants describing the shower shape [illegible] factor $k$ can be chosen to suit the unit [illegible] hower depositions are read out and [illegible] the scintillator/absorber ratio. It is [illegible] postulate

CER[illegible]
fore co[illegible]
but also
The
sible sol[illegible]
hadronic [illegible]larly satisfactory parametri-
[illegible]r development in the litera-
[illegible]re used various test data

THE PARAMETRIZATION DOES A PRETTY GOOD JOB :



# TECHNOLOGIES

## ABSORBER CAN BE:

| | | |
|---|---|---|
| LEAD | Cheap | High Z for $e/\pi \approx 1$ |
| URANIUM | Highest density | |
| STEEL | Cheap, can weld assembly | |
| COPPER | Denser | |
| IRON | For magnetic field routing | |
| TUNGSTEN | $$$! | |
| ⋮ | | |

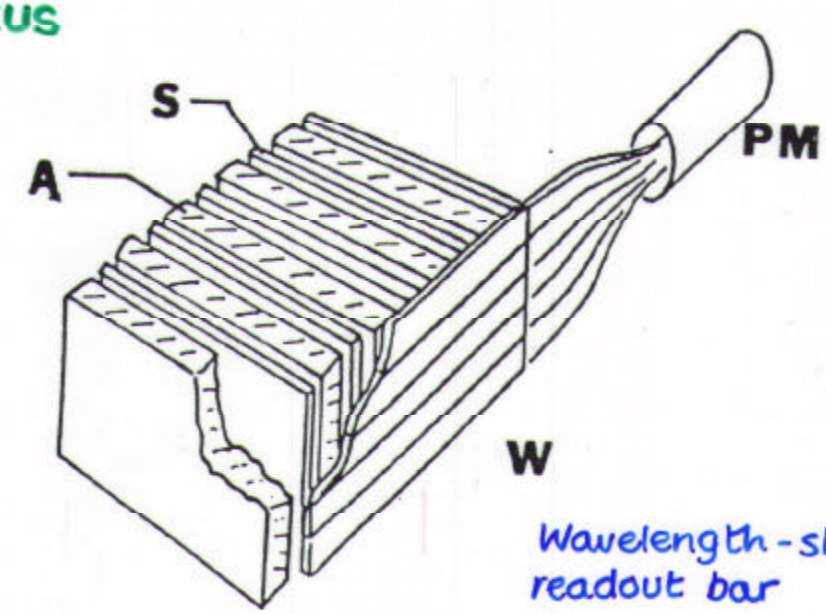
## SENSITIVE LAYERS CAN BE:

| | |
|---|---|
| SCINTILLATOR | emits light when traversed by ionizing particle |
| WIRE CHAMBERS | avalanche in gas → charge on wire |
| LIQUID ARGON | electrons liberated — drift under HV |
| ( "WARM LIQUIDS" | TMS, TMP... ) |
| SILICON | usually too expensive, but fine sampling (specialized applications ) |

89-754-12

# 'CLASSIC' SCINTILLATOR CALORIMETER

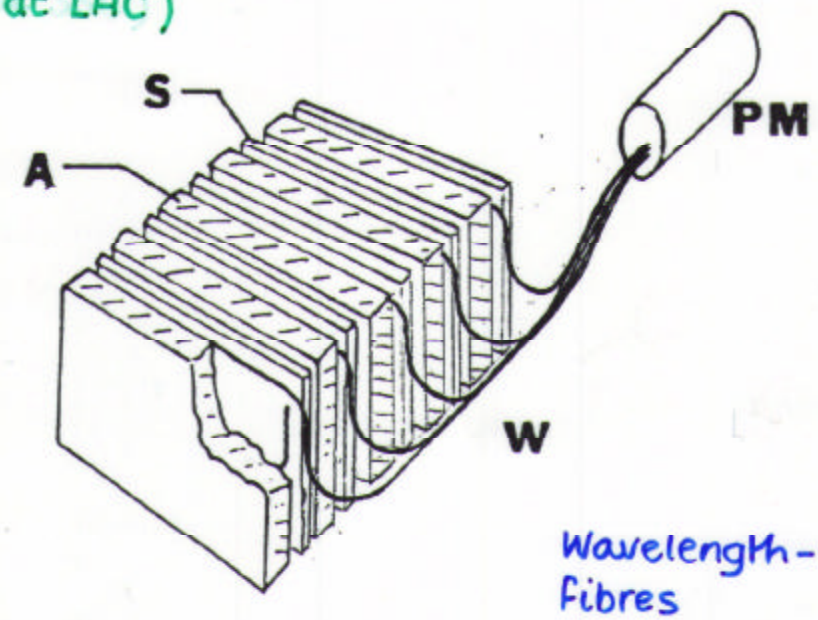
e.g. CDF, ZEUS




Wavelength-shifter readout bar

# TILE-FIBRE CALORIMETER

e.g. CMS (at LHC)




Wavelength-shifting fibres

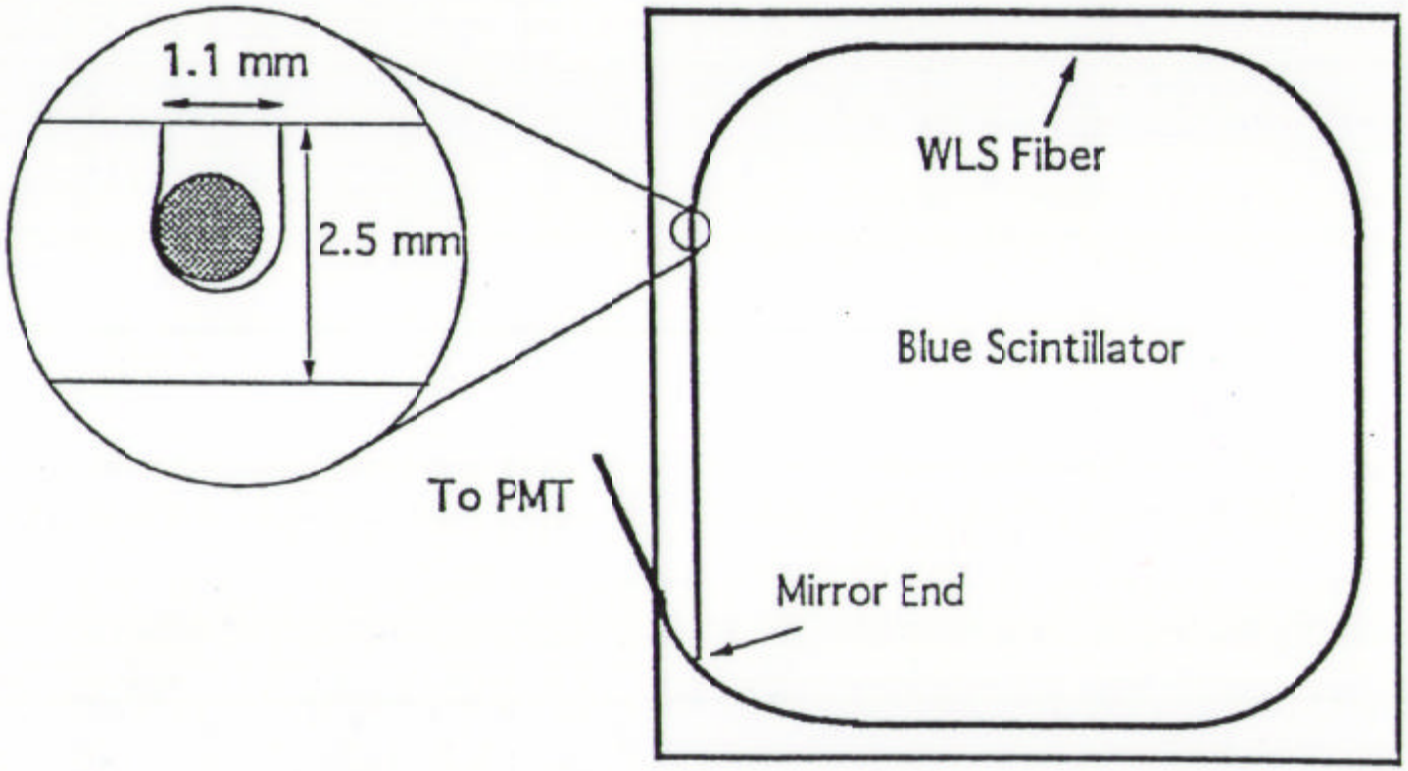
— more compact.

Advantages

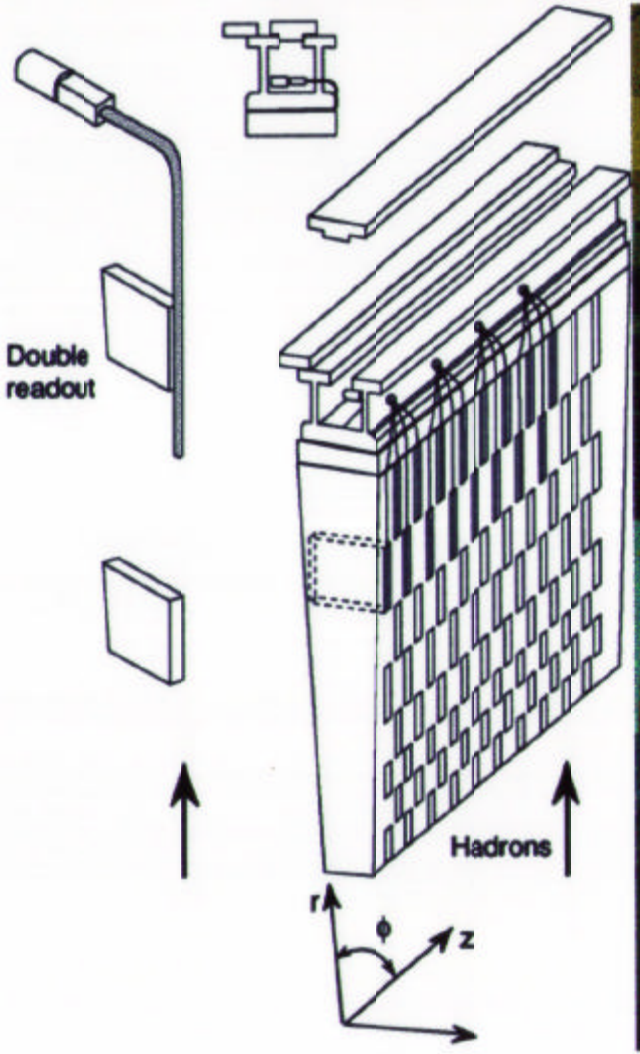
— Robust, Cheap, Fast

Disadvantages

— Radiation Damage to plastic; calibration complex; cracks.


1.1 mm
2.5 mm
WLS Fiber
Blue Scintillator
To PMT
Mirror End

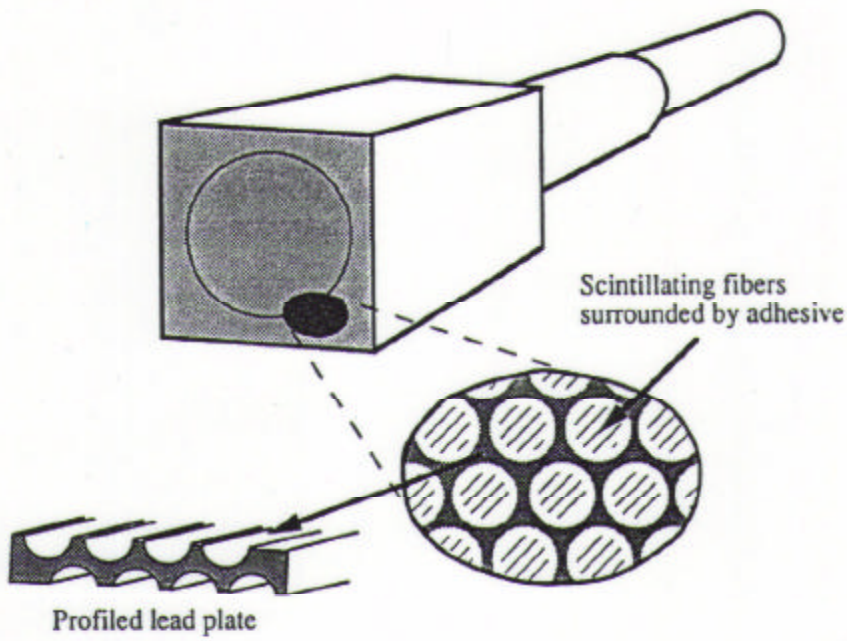
# ATLAS tile calorimeter



*John Womersley*

# CMS HCAL

# "SPAGHETTI" CALORIMETER




Advantages:

- No cracks between towers
- Good resolution and $e/\pi \approx 1$

Disadvantages

- Non-Gaussian response from particles travelling up fibres
- Hard to segment longitudinally (e.g. into EM & had.)

Examples: Proposed for GEM

# RADIATION DOSES AT LHC

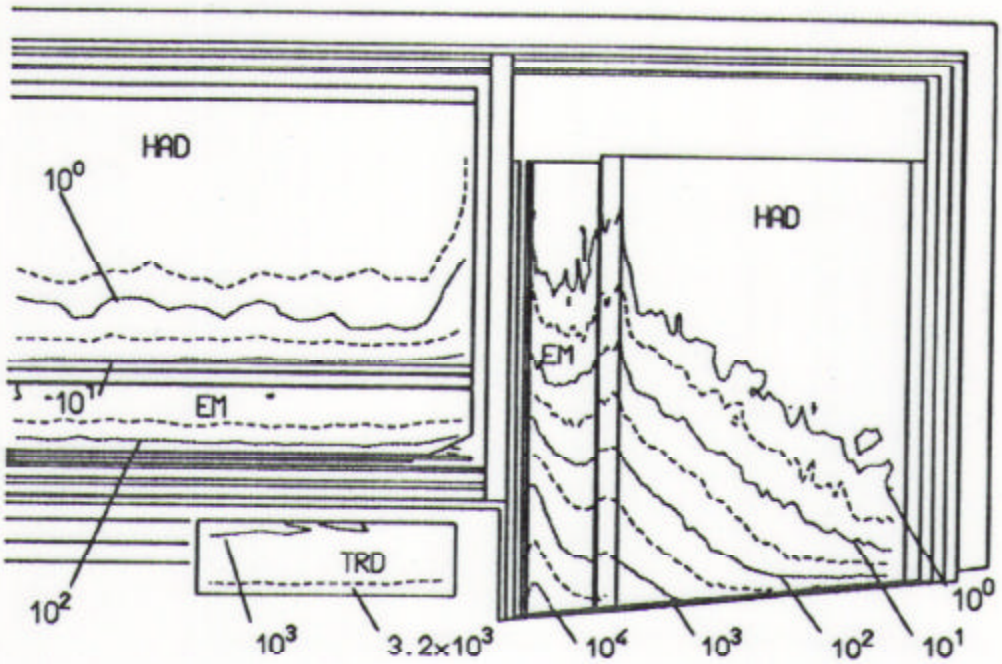



Figure 7.1: *Lines of constant radiation doses in Gy/year for a yearly integrated luminosity of* $10^5$ $pb^{-1}$

— ATLAS LOI

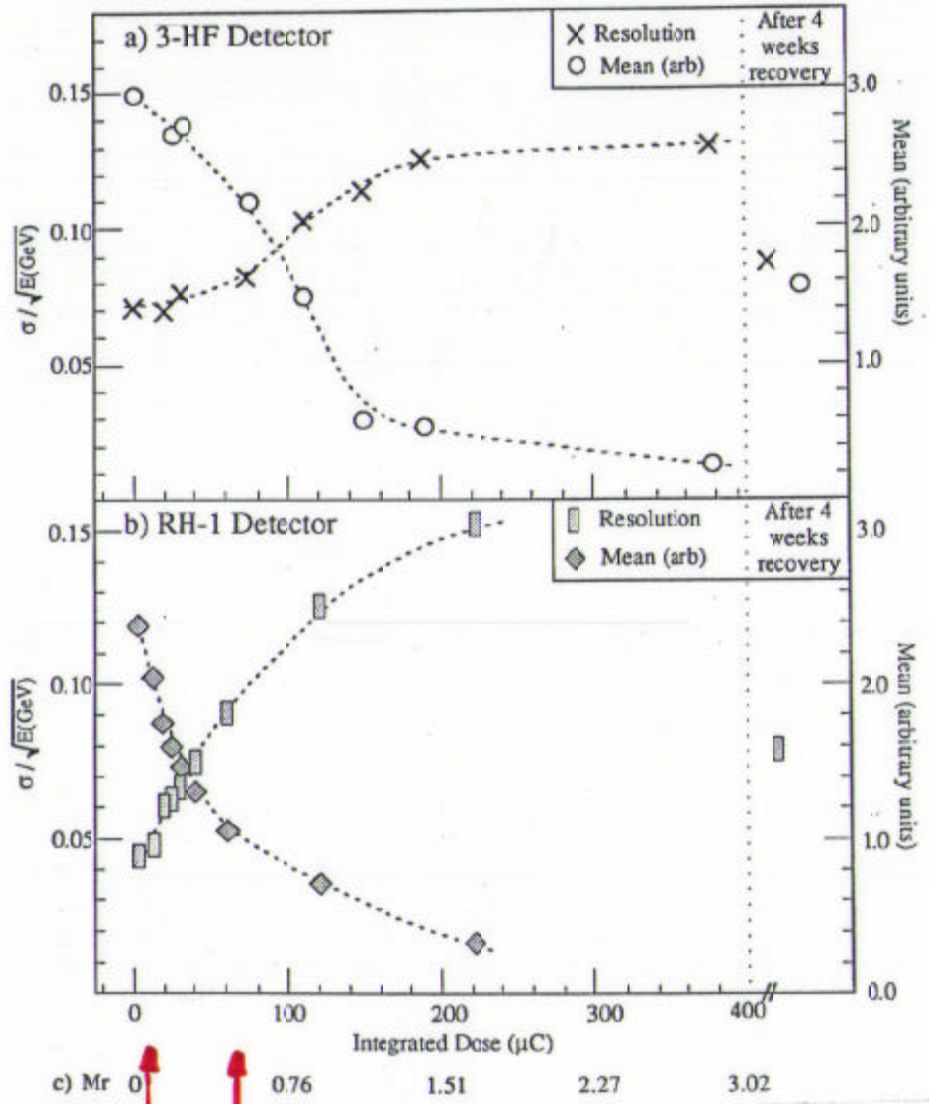
$10^4$ Gy = 1 Mrad

For comparison,

DOE limit is 5 rem / year for humans

450 rem → 50% probability of survival after 30 days

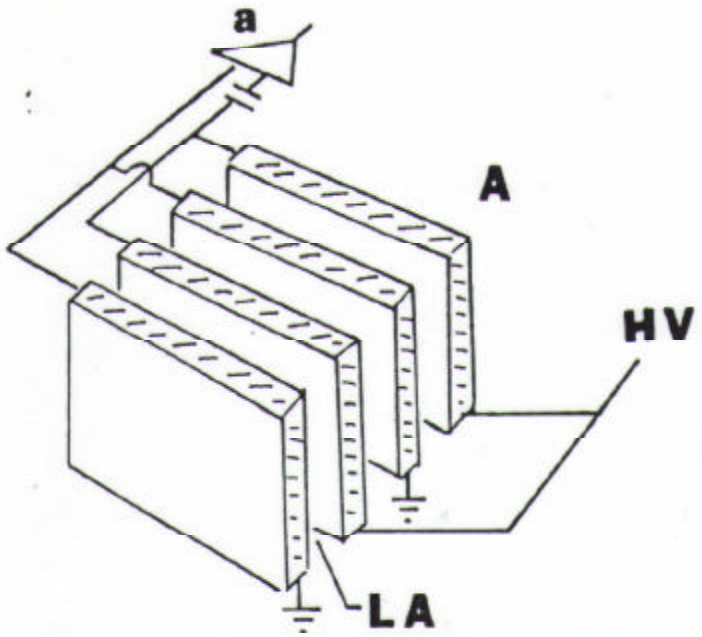
# RADIATION DAMAGE IN CALORIMETER




SDC Barrel
1 year

SDC 6°
1 year

# LIQUID ARGON




Advantages:

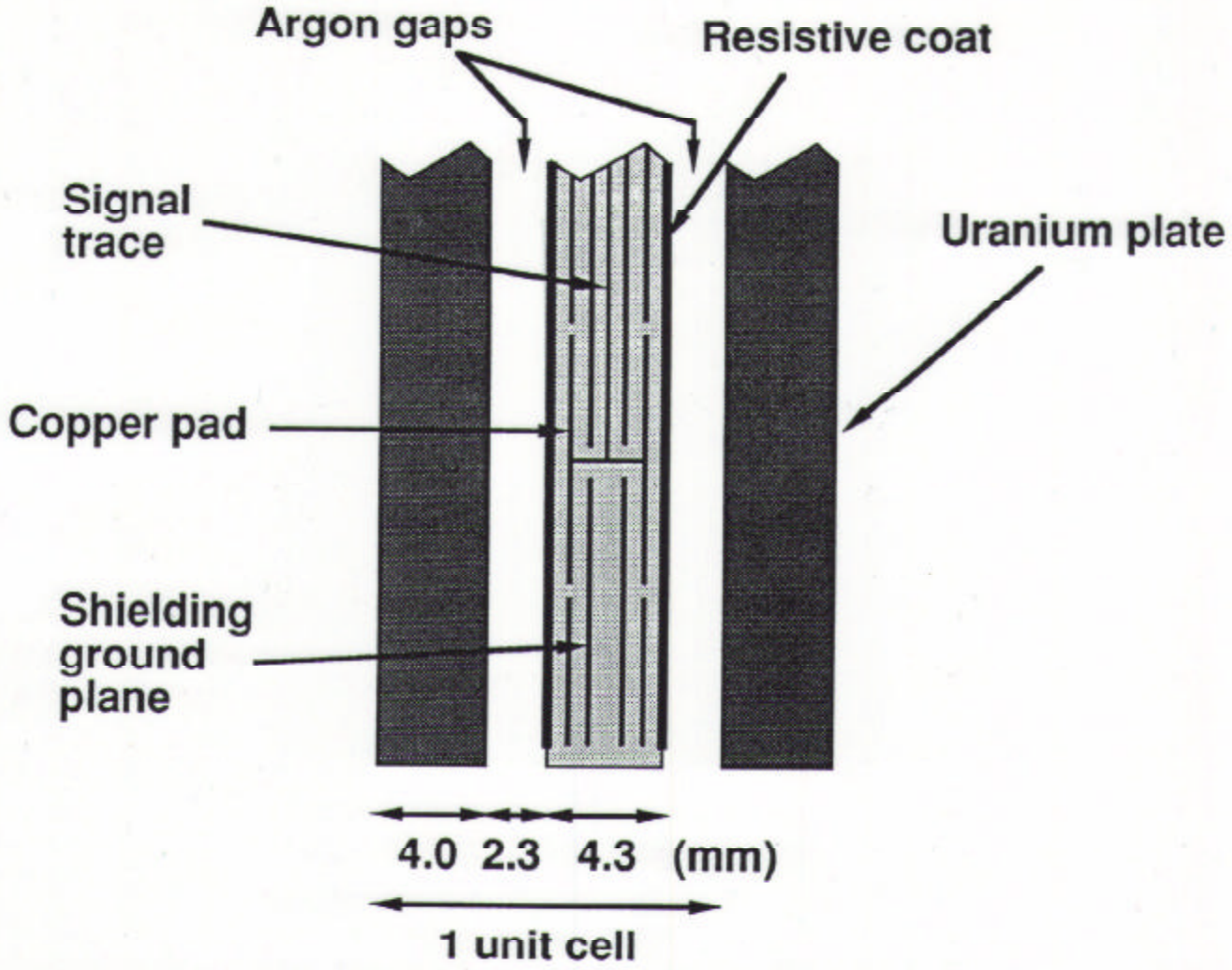
- no amplification in argon, so stable, easy to calibrate, linear
- rad hard
- arbitrary segmentation

Disadvantages:

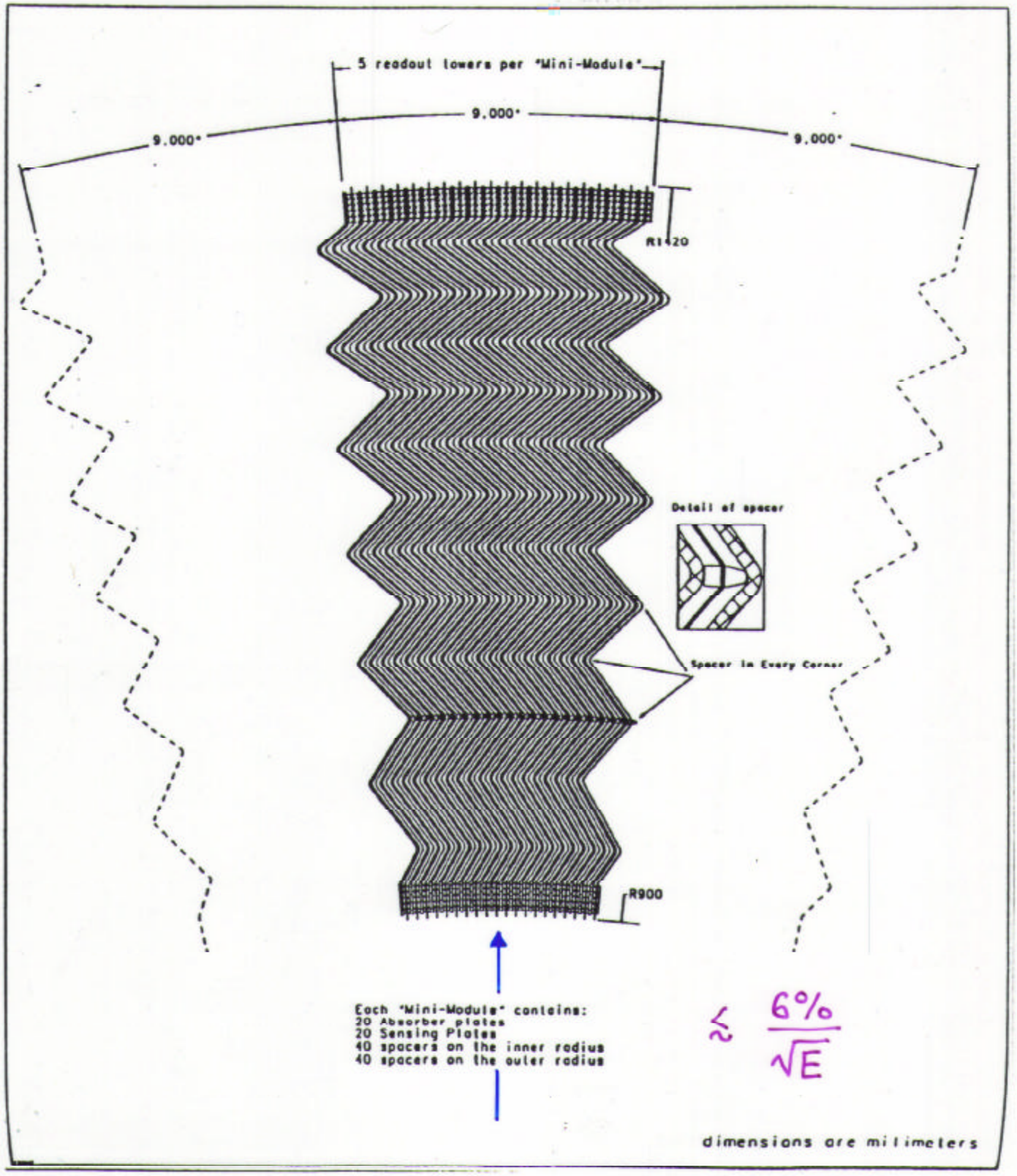
- operates at 80K: cryostat vessel required

(Slow signal: but can differentiate to fast pulse)

Examples: DØ at Tevatron
H1 at HERA
SLD at SLC

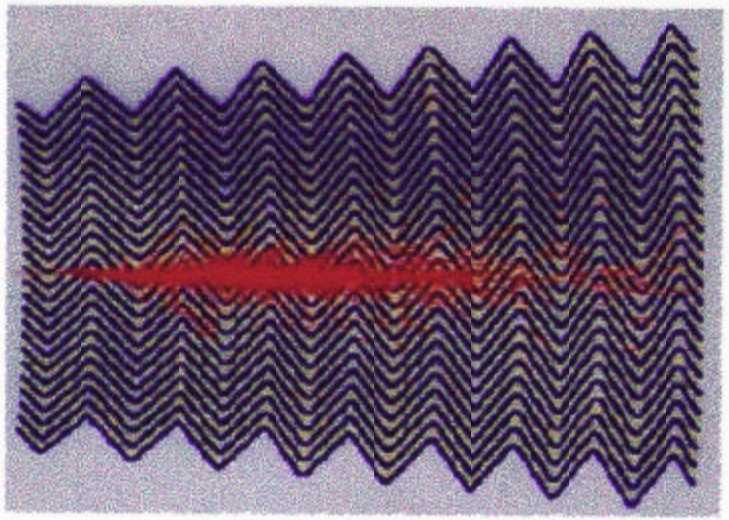

Argon gaps
Resistive coat
Signal trace
Uranium plate
Copper pad
Shielding ground plane
4.0 2.3 4.3 (mm)
1 unit cell

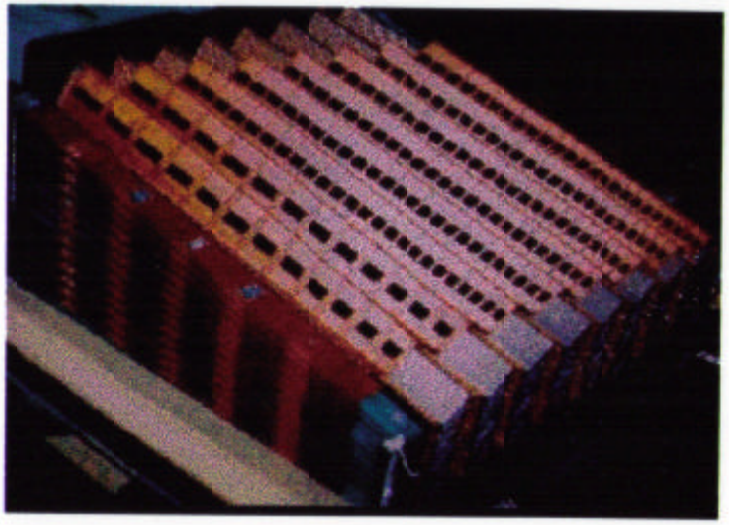
# GEM LEAD-LIQUID KRYPTON ACCORDION (BNL)



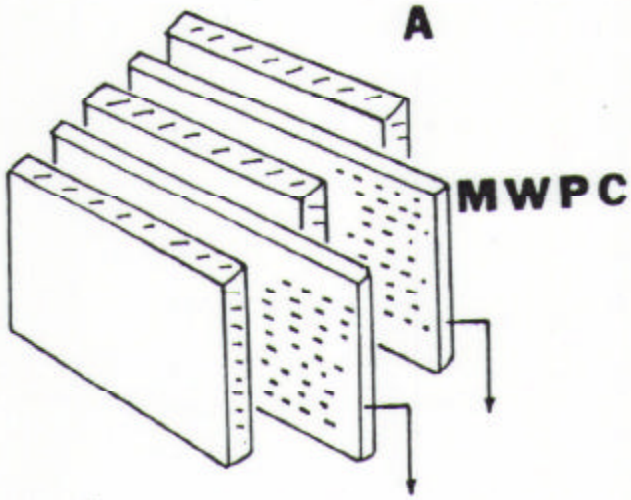

$$\lesssim \frac{6\%}{\sqrt{E}}$$

# ATLAS accordion EM calorimeter





# GAS CALORIMETER




Advantages :

- Easy to segment ( pads on cathode planes )
- Cheap

Disadvantages:

- TEXAS TOWERS
  very low sampling fraction ⇒ high gain ⇒ can get huge signals from highly-ionizing particles (slow protons... )

Examples : CDF forward calorimeters
ALEPH, OPAL, L3,
SLD WIC

Can partially alleviate problems with high pressure gas tubes.

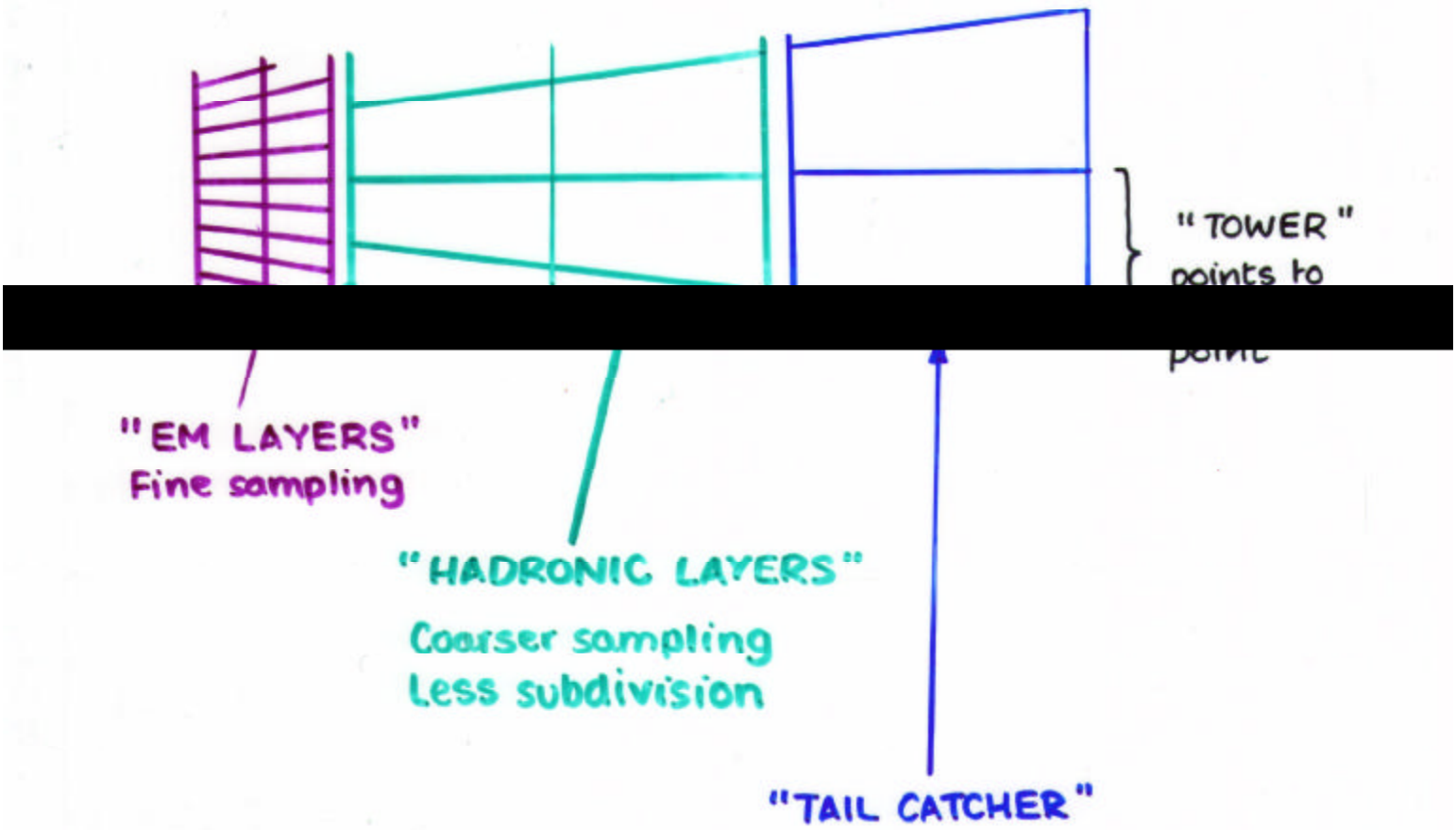
$\gamma$:

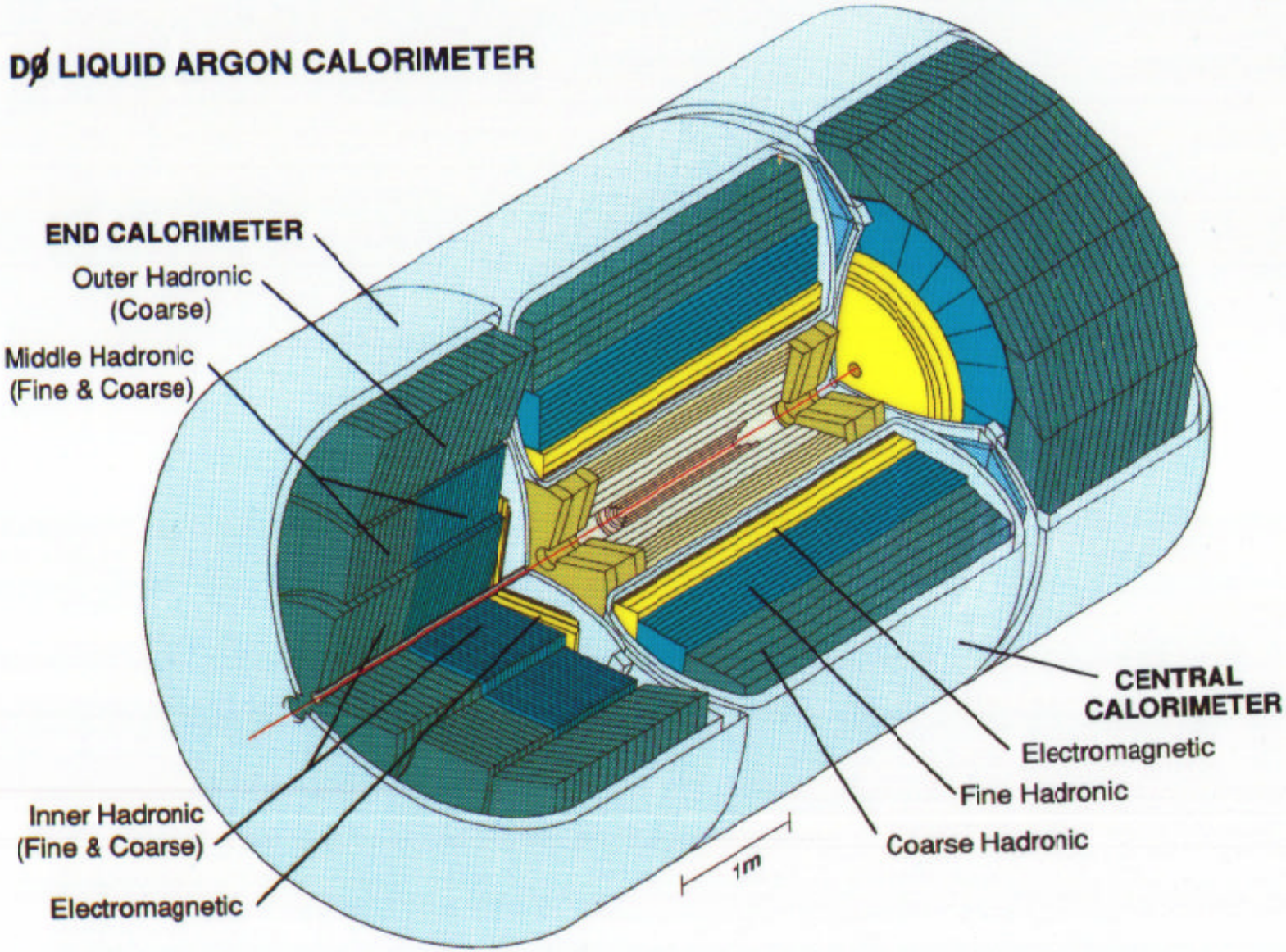
e:

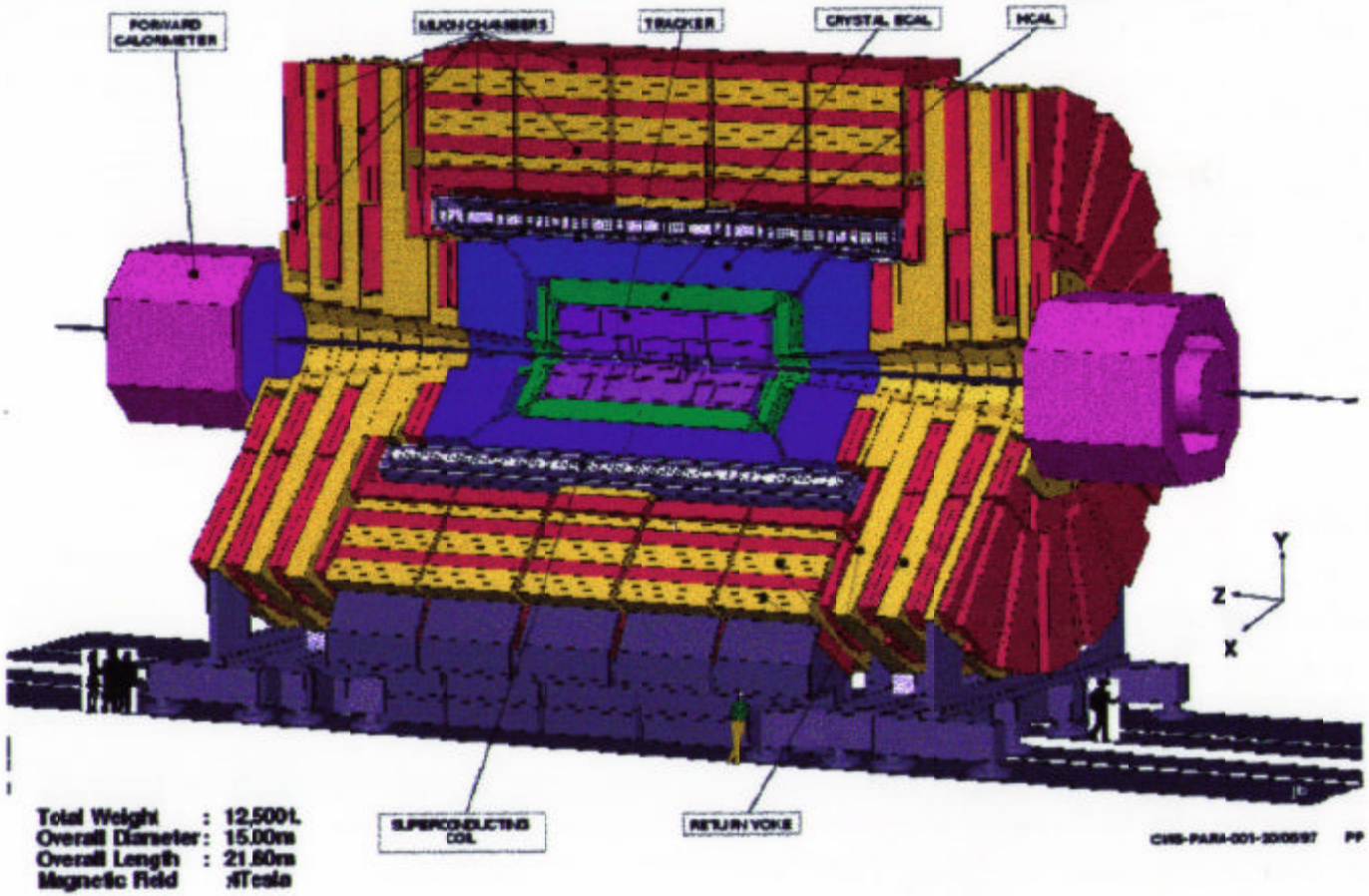
hadron

$\mu$:

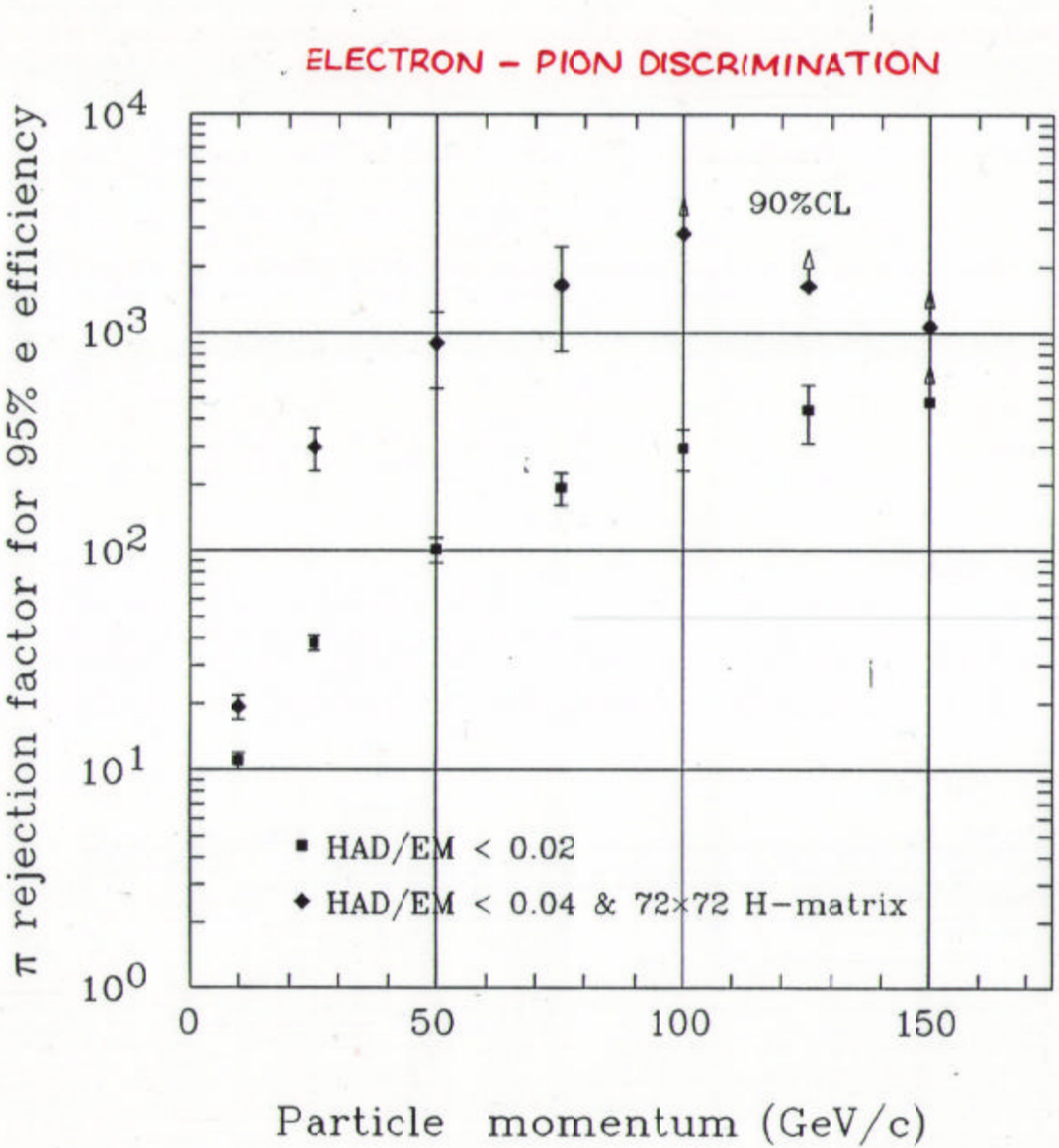
# TYPICAL DETECTOR ARRANGEMENT




DØ LIQUID ARGON CALORIMETER
END CALORIMETER
Outer Hadronic
(Coarse)
Middle Hadronic
(Fine & Coarse)
Inner Hadronic
(Fine & Coarse)
Electromagnetic
CENTRAL
CALORIMETER
Electromagnetic
Fine Hadronic
Coarse Hadronic
1m




*John Womersley*


ELECTRON – PION DISCRIMINATION
π rejection factor for 95% e efficiency
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
90%CL
HAD/EM < 0.02
HAD/EM < 0.04 & 72×72 H−matrix
0
50
100
150
Particle momentum (GeV/c)

# CALIBRATION

1. ESTABLISH ENERGY SCALE
2. STABILITY OVER TIME

TEST BEAM $e, \pi, \mu$ of known energy (1)

RADIOACTIVE SOURCE in argon;
LIGHT PULSER LED or laser into PM tubes (2)

ELECTRONICS PULSER known Q into amplifiers (2)

PHYSICS PROCESSES: (1)

$\pi^0 \to \gamma\gamma$
$\eta^0 \to \gamma\gamma$

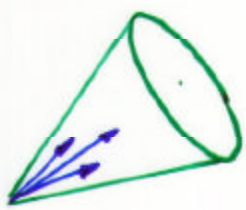
$J/\psi \to e^+e^-$
$\Upsilon \to e^+e^-$
$Z \to e^+e^-$

# CALORIMETER MEASUREMENT OF JETS

quark / gluon $\xrightarrow{\text{fragments}}$ jet of particles $\xrightarrow{\text{showers}}$ calorimeter energy

Found experimentally that

$$\sum_{\substack{\text{Calorimeter}\\ \text{Towers}}} R \lesssim 0.7 \quad \approx \quad \text{measure } E, \underline{p} \text{ of quark or gluon}$$



Cone radius $R = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$

[ Other ways of summing energy also possible — e.g. successive combination of pairs of cells ]

Need calorimeter because $\sim \frac{1}{3}$ of jet particles are neutral ($\pi^0$, $K^0$ ... ) $\rightarrow$ no way to see them in a tracking chamber.

# JET ENERGY CORRECTIONS

- Jets contain many low energy particles (few GeV)
  - → response of calorimeter is very non-linear because $e/\pi \gg 1$ at low E
  - → Potentially large corrections to jet energy
    - DØ 15 – 30%
    - CDF ~ 50%

    — Direct $\gamma$ events

- Normally correct back to $\sum$ all particles in $R <$ Cone
  - → Corrections for shower energy which is lost outside cone ("out of cone corrections")

    — Monte Carlo

## HOMOGENEOUS MEDIA

Better EM resolution $\Rightarrow$ Higher sampling fraction

If one wants the best possible resolution, go to a non-sampling (fully-live) calorimeter

Need high density or size becomes unreasonable (so plastic scintillator is not an option)

LEAD GLASS eg CLEO

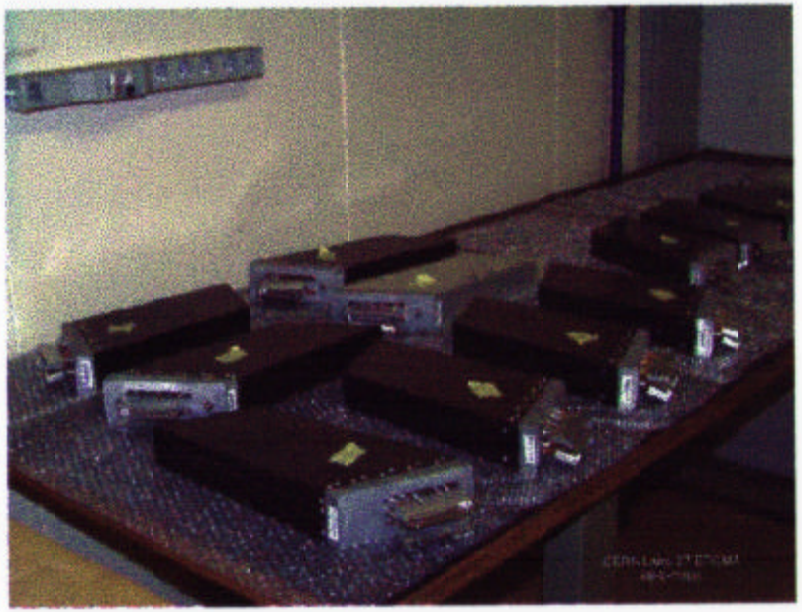
LIQUID SCINTILLATOR e.g. LSND

CRYSTALS : CsI e.g. CLEO II, kTeV
BGO e.g. L3
$PbWO_4$ e.g. CMS
$BaF_2$

Can get $\sigma_E \sim \frac{1-3\,\%}{\sqrt{E}}$

Issues: radiation damage
uniformity
$e/h \gg 1$

# CMS ECAL ($PbWO_4$)



# CALORIMETRY AT LHC

- Precision EM calorimeters ($\eta \lesssim 2.5$)

  $H \to \gamma\gamma$ large QCD $\gamma\gamma$ background
  reduce $\sigma(m_{\gamma\gamma}) \to$ increase $S/B$

  ATLAS: Accordion LAr
  CMS: $PbWO_4$ crystals

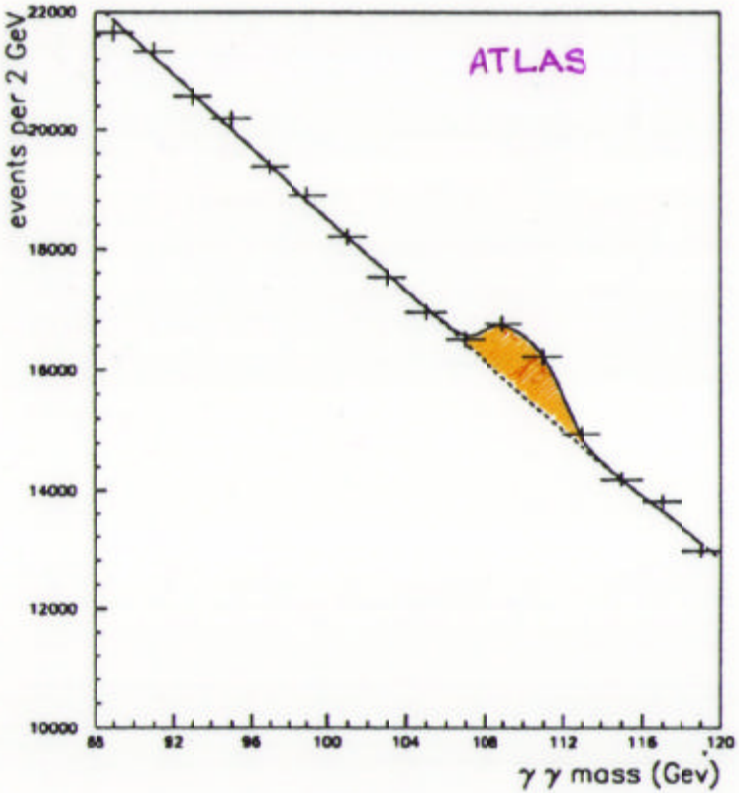
- Jet Spectroscopy

  e.g $m_t$ from $m$ (3 jets)

- Forward Calorimeters

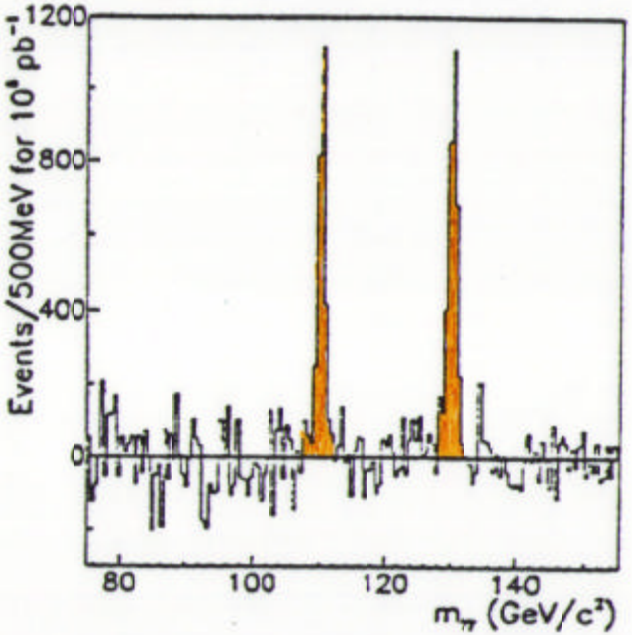
  Need to cover $\eta \leq 5$ for $\not{E}_T$ signatures
  $\to$ go forward (or beampipe subtends $\eta \geq 4$)
  radiation!
  (detectors become dangerously achivated)

# $H \to \gamma\gamma$




$m_{\gamma\gamma}$

CMS (Bkg. subtracted)

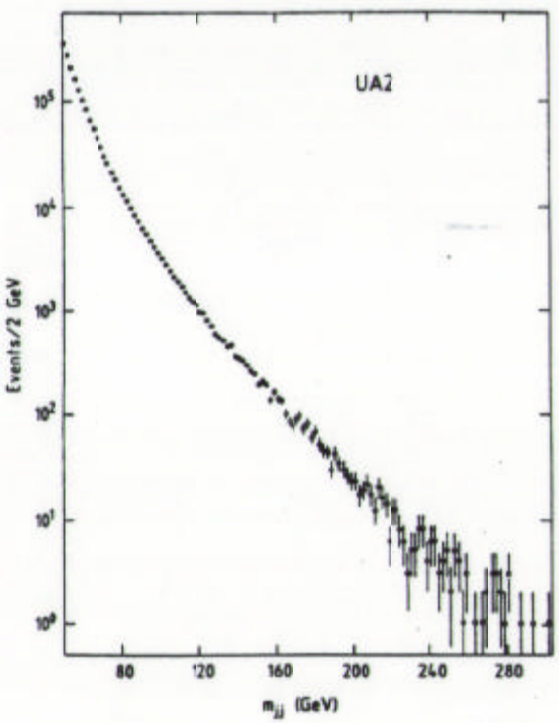



$m_{\gamma\gamma}$

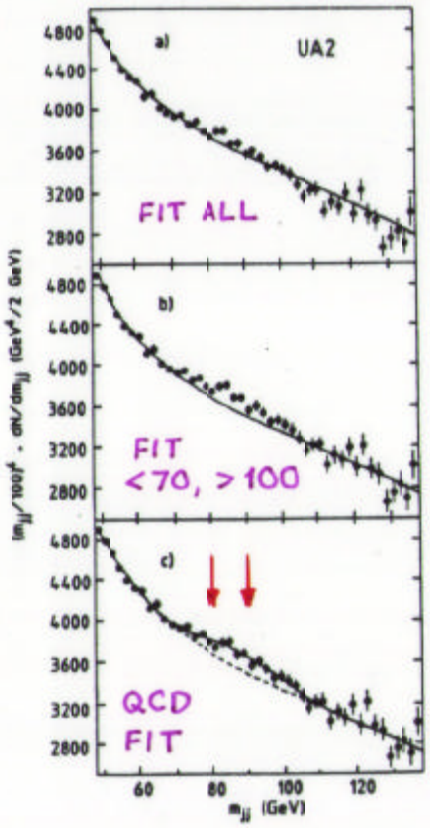
# W/Z → j j in UA2

Z. Phys. C 49 (1991) 17

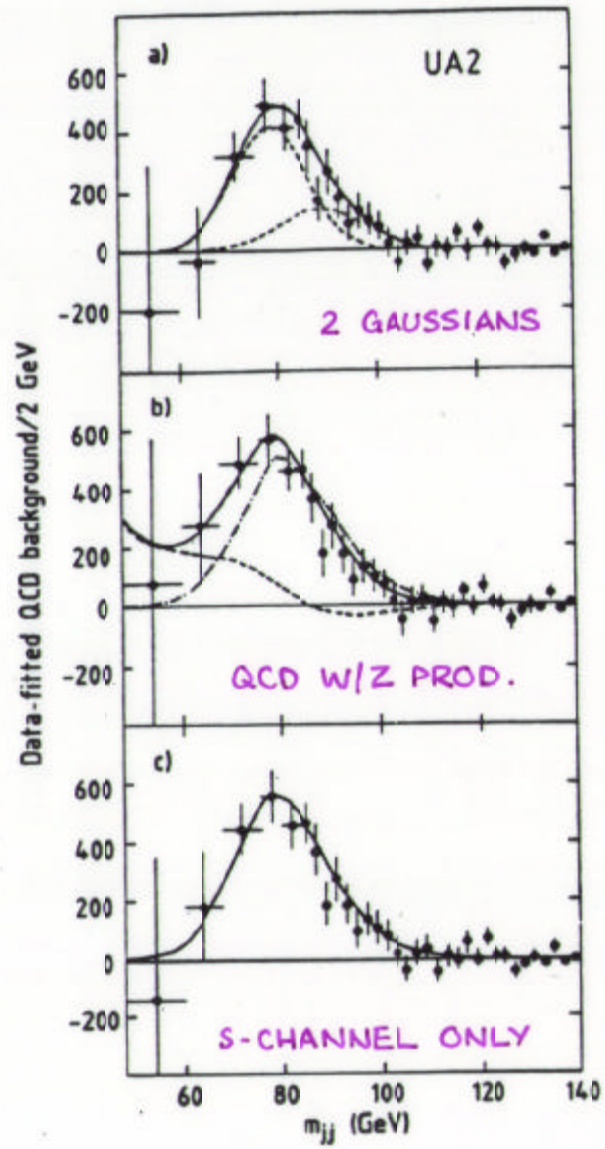
$m_{jj}$ spectrum




$* (m/100)^6$




bkg. subtracted



# ČERENKOV TECHNIQUES

All technology described so far samples ionization

Can look for Čerenkov light instead

↓

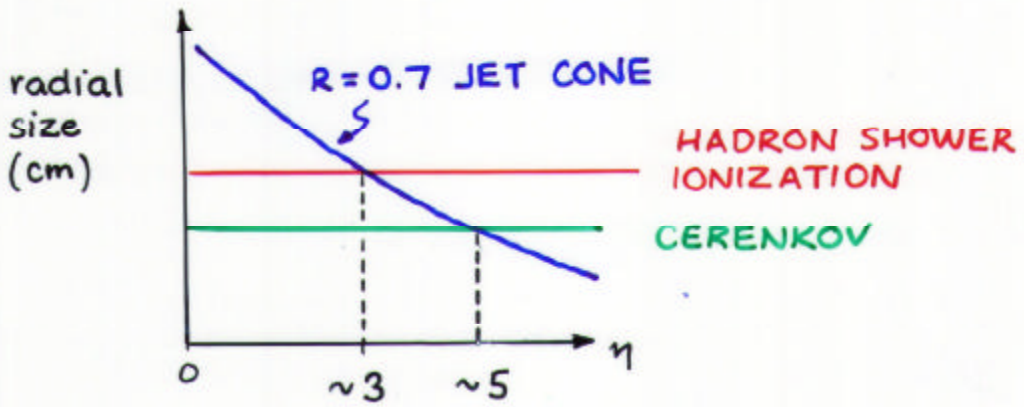
Lower signal

Restricted to core of shower

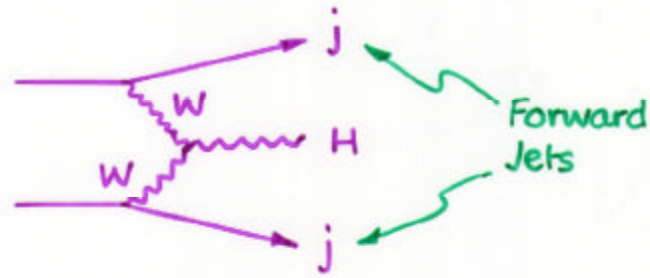
↓

An advantage if you want to make the showers "smaller"

e.g. Jet Tagging at very high $\eta$



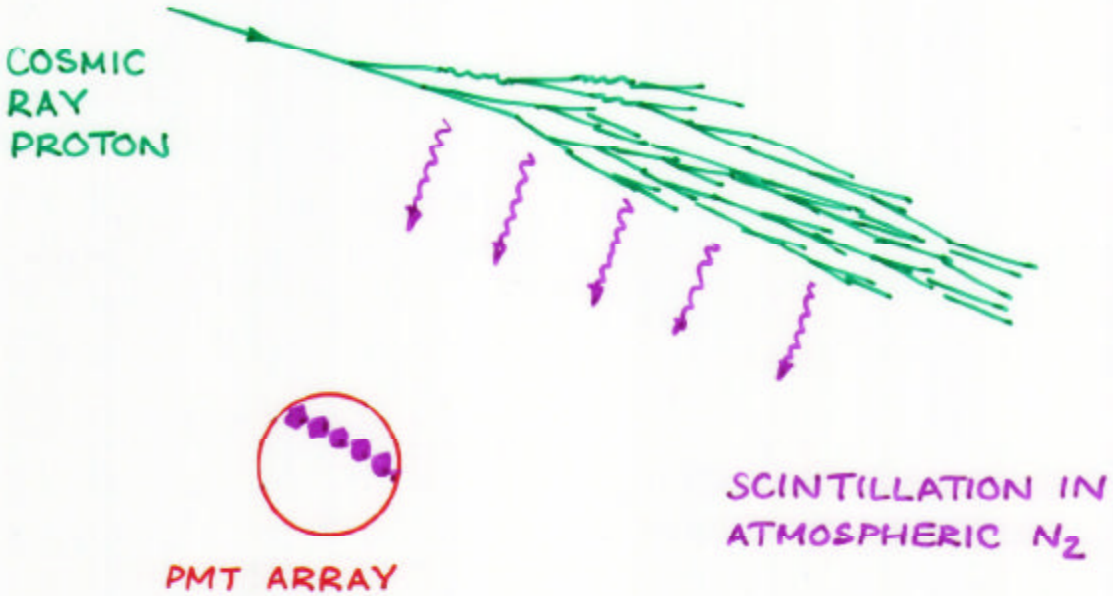

pp → Higgs via




Quartz fibers in "spaghetti" calorimeter

proposed for CMS very forward calorimeter

THE WORLD'S BIGGEST CALORIMETER

FLY'S EYE COSMIC RAY DETECTOR (UTAH)

Use Earth's atmosphere as absorber