CALORIMETRY

- Extremely versatile detectors
- Main application is measurement of energy of electrons, photons and hadrons by total absorption (hence "destructive" method)
  - Detector response $\propto E$
  - Size of the calorimeter scales as $\ln E$ and performance improves with energy (tracking volume scales like $\sqrt{E}$)
- A variety of other measurements possible: position, angle; particle ID, triggering
- Works for both charged (e, hadrons) and neutral particles (n, γ)
- Basic mechanisms:
  electromagnetic and strong interactions producing showers of secondary particles with progressively degraded energy
- Basic Types:
  - Electromagnetic and Hadronic Calorimeters
  - Sampling and Homogeneous Calorimeters.

Electromagnetic calorimeters:

used mainly to measure/detect electrons and photons through their electromagnetic interactions (e.g., Bremsstrahlung, Pair Production)

Hadronic calorimeters:

Used to measure mainly hadrons through their strong and electromagnetic interactions.

Sampling Calorimeters:

Consist of alternating layers of an absorber, a dense material to degrade energy (induce showering) and an active medium to detect the signal

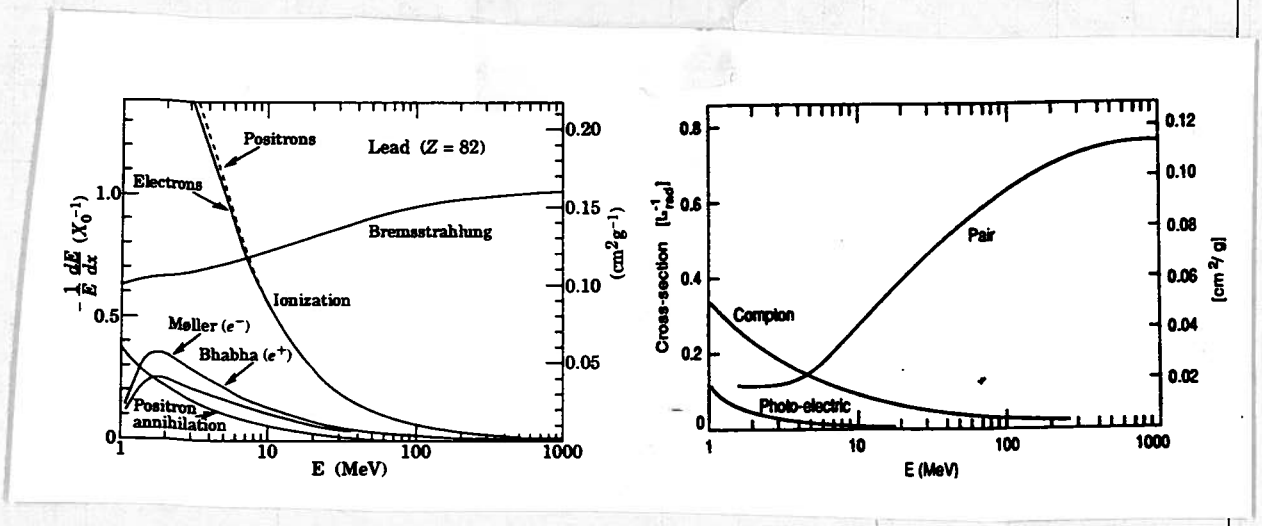
Could be gaseous, liquid or solid medium for detection

Homogeneous Calorimeters:

Built of one type of material which performs both tasks, energy degradation and signal generation

PHYSICS OF ELECTROMAGNETIC SHOWERS

- For $E \gtrsim 10\,\text{MeV}$, the dominant energy loss mechanism for electrons is Bremsstrahlung and for photons, it is Pair production.
- For $E > 1\,\text{GeV}$, both processes become essentially energy independent.



For $E < 10\,\text{MeV}$, electrons lose their energy through ionization, mainly; photons lose energy through Compton Scattering and photoelectric effect.

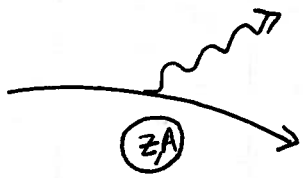
The energy at which Ionization loss $\equiv$ Brem loss

$$\Rightarrow E_c \sim \frac{800\,\text{MeV}}{Z} \quad \text{(Critical Energy)}$$

$$\left.\frac{dE}{dx}(E_c)\right|_{ion} = \left.\frac{dE}{dx}(E_c)\right|_{Brem}$$

Energy Loss of electrons by <u>Bremsstrahlung</u>:

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



$$\simeq \frac{180\,A}{Z^2}\ g/cm^2$$

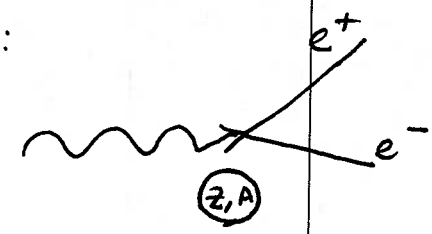
(remember X_0 is defined for electrons, and $X_0 \propto m^2$)

$X_0(H_2) = 8.65\,m$
Al: 8.9 cm
Pb: 5.6 mm
U: 3.2 mm

$$E(x) = E_0\, e^{-x/X_0}$$

i.e., X_0 is the average distance that an electron must travel in a material to reduce its energy to $\frac{1}{e}$ of the original energy.

<u>Pair (e^+e^-) production</u> for photons:



$$\sigma_{pair} \simeq 4\alpha r_e^2 Z^2 \left[\frac{7}{9} \ln \frac{183}{Z^{1/3}}\right]$$

$$\approx \frac{7}{9}\frac{A}{N_A}\cdot\frac{1}{X_0}$$

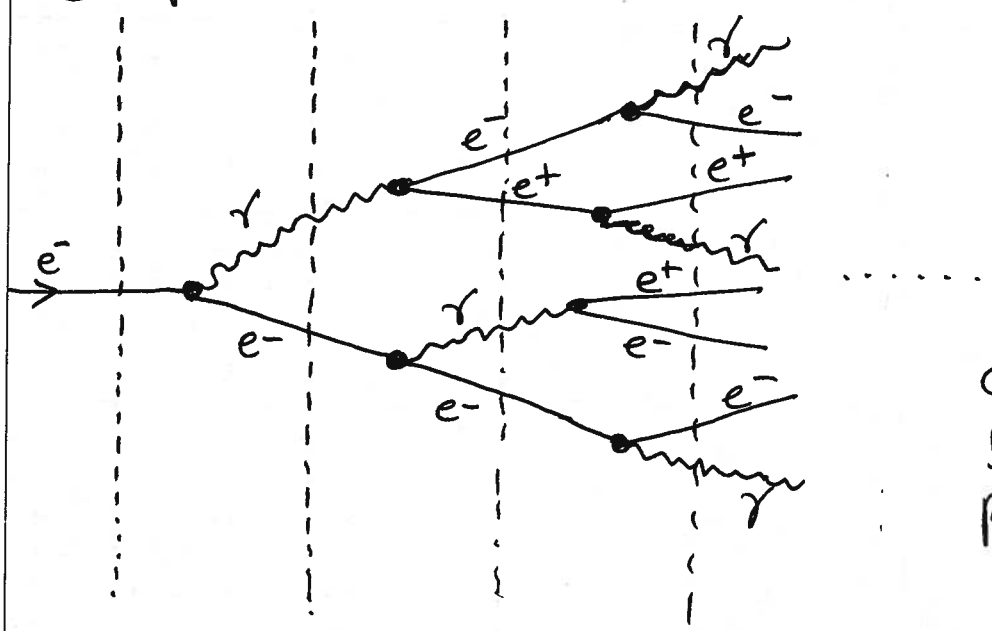
$$\therefore \lambda_{pair} = \frac{9}{7} X_0$$

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

The intensity of photons is reduced by $\frac{1}{e}$ of original intensity after a distance $\frac{9}{7}X_0$

- The physical scale over which the showers develop are similar for incident electrons and photons.

∴ The electromagnetic showers are described in a universal way using simple functions of X_0.
(Simple model due to Heitler (1953))



electromagnetic cascade/shower induced by an electron

Considering only Brem & pair production.

0	$1X_0$	$2X_0$	$3X_0$	Radiation length (t)
E_0	$E_0/2$	$E_0/4$	$E_0/8$	Energy / particle $E(t)$
0	2	4	8	Number of particles $N(t)$

After t radiation lengths,

$$\boxed{N(t) = 2^t = e^{t\ln 2}} \quad ; \quad \boxed{E(t) = E_0/2^t}$$

Cascade continues to develop as long as $E(t) > E_c$

The depth at which the shower energy equals some value E' occurs when $E(t) = E'$

i.e., $E' = E_0 / 2^{t(E')} = \dfrac{E_0}{e^{t(E')\ln 2}}$

$$\frac{E_0}{E'} = e^{t(E')\ln 2}$$

$$\boxed{\therefore\ t(E') = \frac{\ln(E_0/E')}{\ln 2}}$$

Since the production of particles stops at $E(t) = E_c$, the shower has maximum number of particles when $E(t) = E_c$.

So, the "shower-max" depth is,

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

← indicative of the detector thickness needed to absorb a shower

Note: Maximum shower depth increases logarithmically with primary energy

Number of particles at shower-max is,

$$N_{max} = e^{t_{max}\ln 2} = E_0/E_c$$

$\therefore$ The number of particles at shower max $\propto E_0$!

The number of particles in the shower with $E > E'$ $(E' << E_0)$ would be,

$$N(E>E') = \int_0^{t(E')} N(t)\,dt$$

$$= \int_0^{t(E')} e^{t \ln 2}\,dt \simeq \frac{1}{\ln 2} \cdot \frac{E_0}{E'}$$

$$\therefore \frac{dN}{dE'} \propto \frac{1}{E'^2}$$

The sum of all charged track lengths in the shower,

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

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

$\therefore$ The total charged track length $\propto E_0$

$\Rightarrow$ total ionization in the material $\propto E_0$

$\therefore$ we can measure the energy of the incident particle by measuring ionization produced by the shower particles.

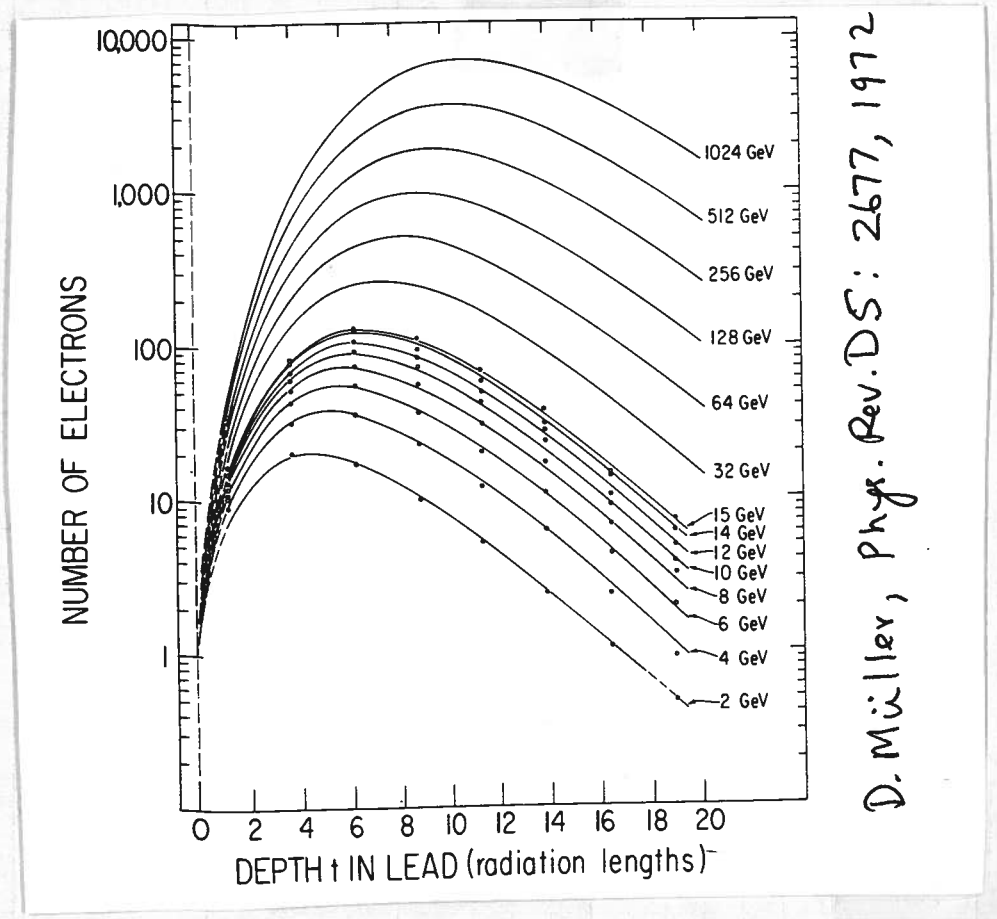
Heitler's assumptions:

1. An electron with $E > E_c$ travels $1 X_0$ and then gives up half its energy to a brem photon
2. A photon with $E > E_c$ travels $1 X_0$ and undergoes pair production with each created particle receiving half of the energy of the photon.
3. Electrons with $E < E_c$ cease to radiate and lose their energy and lose their remaining energy to collisions
4. Photons with $E < E_c$ cease to pair-produce and interact via compton effect and photoelectric effect, etc.
5. Neglect ionization and other mechanisms of energy loss for $E > E_c$.

In the simple model considered, the shower abruptly stops at t_{max}. This discontinuous behaviour is due to the oversimplified assumptions.

More accurate treatments of shower development should take into account the energy dependence of the cross section, the lateral spread of the shower due to multiple scattering, etc.

→ Discontinuity at t_{max} is broadened into a long tail.



D. Müller, Phys. Rev. D5: 2677, 1972

Longitudinal Shower Development:

$$\frac{dE}{dt} \propto t^{\alpha} e^{-t}$$

$$t_{max} = \ln \frac{E_0}{E_c} \cdot \frac{1}{\ln 2}$$

$$t_{95\%} \simeq t_{max} + 0.08Z + 9.6 \quad (95\% \text{ containment depth})$$

E.g.; For 100 GeV e^- in Uranium:

$E_c = 8.7$ MeV, $t_{max} \sim 13\ X_0$ $\quad t_{95\%} \simeq 30 \cdot X_0$

$= \underline{\underline{9.6 \text{ cm}}}$

DØ calorimeters have EM sections with depth $\sim 20 X_0$, backed up by $5-7\ \lambda_a$ (interaction lengths)

Transverse Shower Development:

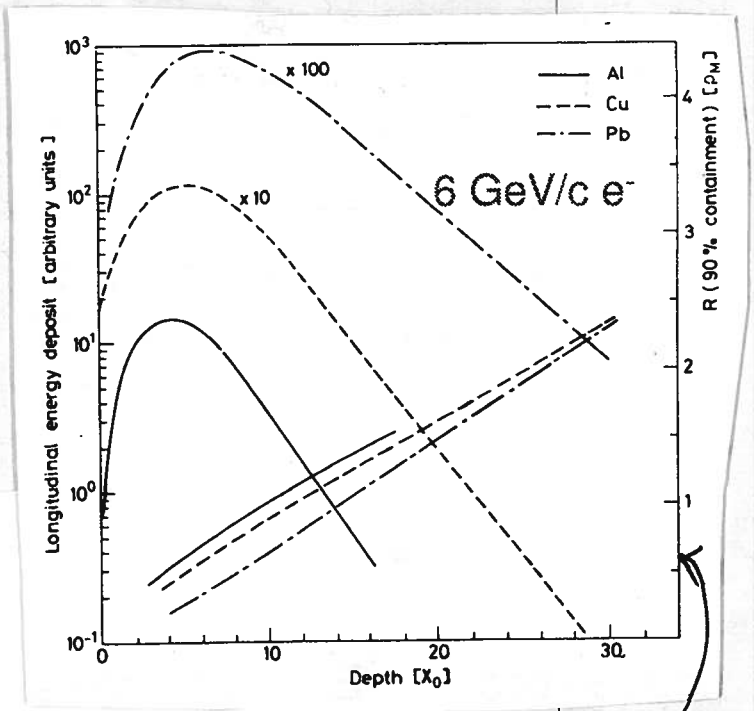
Shower spreads laterally as it penetrates deeper into the material.

95% of the shower cone is located in a cylinder with radius $2R_M$ (R_M = Moliere Radius)

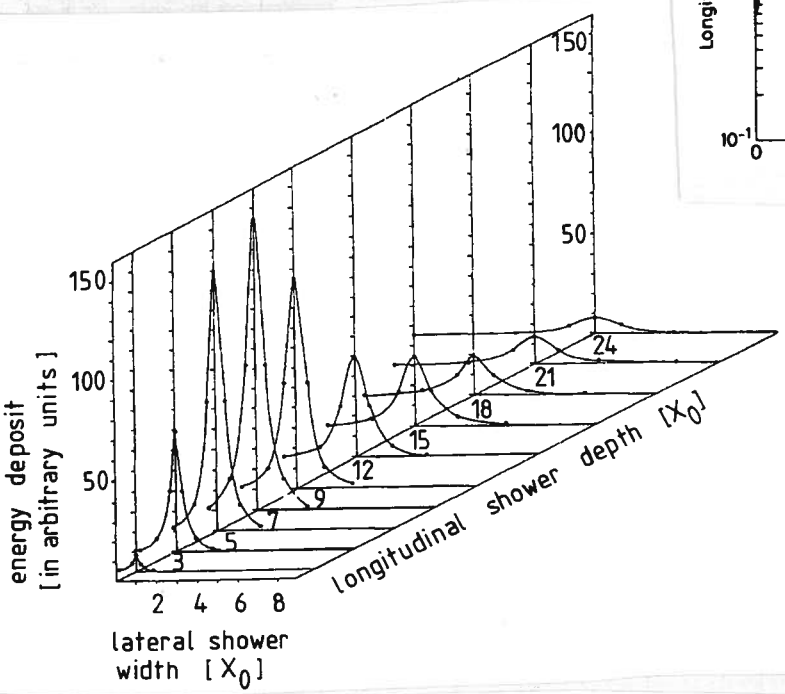
$$R_M = \frac{21 \text{ MeV}}{E_c} \cdot X_0 \quad (g/cm^2)$$

e.g., Uranium: $R_M = 2.4\ X_0 \simeq 0.77$ cm

Longitudinal shower development in different materials →



90% lateral shower containment



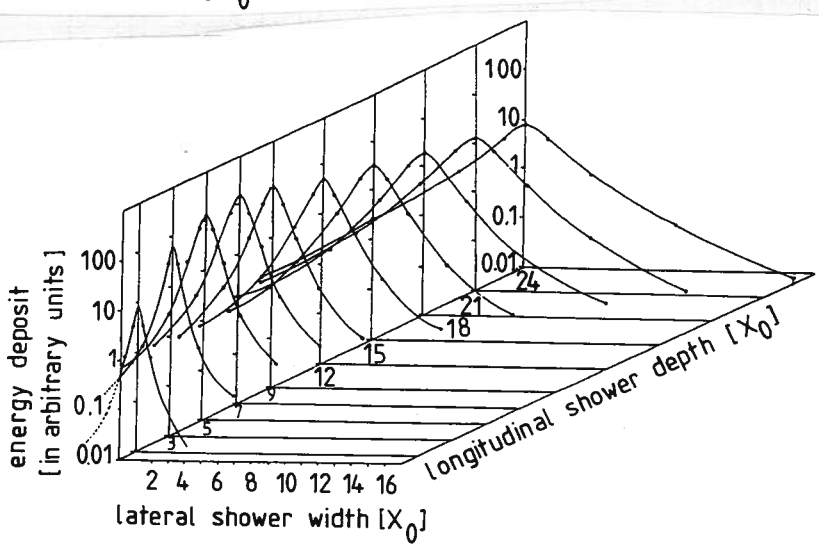


Fig. 7.23. Longitudinal and lateral development of an electron shower (6 GeV) in lead shown with linear and logarithmic scales (based on [504, 505]).

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Energy Resolution :

$$N_{Total} \propto \frac{E_0}{E_c}$$

Total charged particle track length

$$T \propto \frac{E_0}{E_c} \quad ; \quad \text{Measured ionization} \propto T \propto E_0$$

$$T_{det} = F(\xi)\, T \qquad \xi \propto \frac{E_{cut}}{E_c}$$

$\uparrow$ detectable track length above energy E_{cut}

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_{det})}{T_{det}} \propto \frac{1}{\sqrt{T_{det}}} \propto \frac{1}{\sqrt{E_0}}$$

More generally, if we expand the variance into a power series in E

$$\sigma^2(E) = \sigma_0^2 + \sigma_1^2 E + \sigma_2^2 E^2 + \cdots$$

$$\left(\frac{\sigma(E)}{E}\right)^2 = \frac{\sigma_0^2}{E^2} + \frac{\sigma_1^2}{E} + \sigma_2^2 + \cdots$$

or $$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

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

Constant term
All contributions that do not depend on energy

Stochastic term
intrinsic fluctuations in the shower development

Noise term
electronic noise
radioactivity
pile-up

<u>Stochastic Term:</u> (Sampling Term)

In homogeneous calorimeters, intrinsic fluctuations are very small.

- energy deposited in the active volume of the detector by a monochromatic beam of particles does not fluctuate event by event
- the resolution better by "Fano Factor"
- a few %

In Sampling calorimeters, there are variations in the number of charged particles that cross the active layers.

$$N_{ch} \sim \frac{E_0}{t} \; ; \quad t = \text{thickness of absorber layers in } X_0.$$

$$\therefore \frac{\sigma(E)}{E} \sim \frac{1}{\sqrt{N_{ch}}} \sim \sqrt{\frac{t}{E_0(\text{GeV})}}$$

$\Rightarrow$ smaller resolution with smaller t or more sampling.

86/13

PHYSICS OF HADRONIC SHOWERS

- Hadrons produce a cascade of secondary particles: charged and neutral pions, neutrons, protons, etc.

$$\langle N \rangle \propto \ln E \; ; \langle p_T \rangle \sim 0.35 \text{ GeV/c} .$$

- More complex than electromagnetic showers because of the nature of strong interactions and because they are made up of both hadronic and electromagnetic components.

$$- \pi^0\text{'s} \rightarrow 2\gamma \longrightarrow \text{electromagnetic cascade}$$

- For $E > 1$ GeV, the cross-sections depend only weakly on the energy and on the type of the incident particle

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \simeq 35 \text{ mb}$$

- In analogy to X_0, we can define a hadronic absorption length,

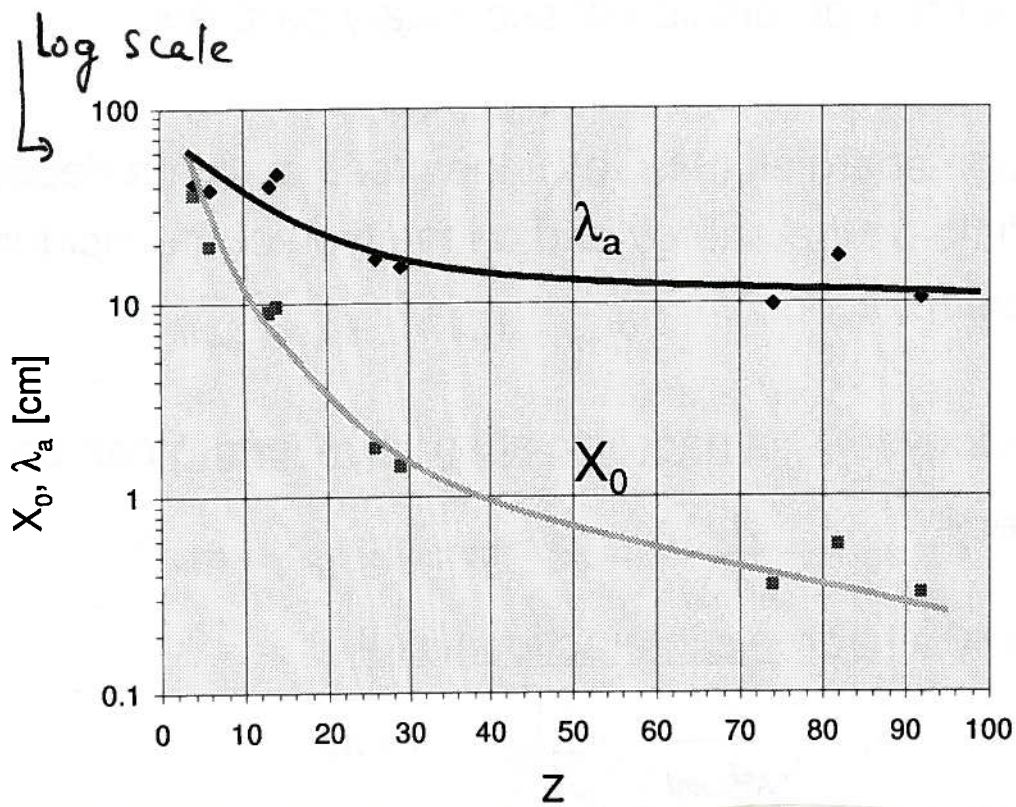
$$\lambda_a = \frac{A}{N_A \rho \cdot \sigma_{inel}}$$

and a hadronic interaction length

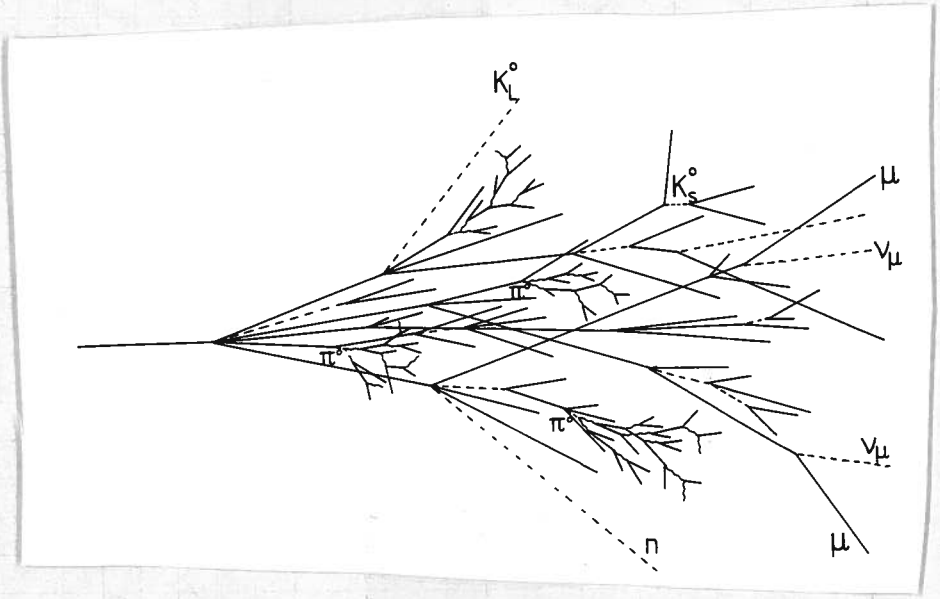
$$\lambda_I = \frac{A}{N_A \rho \cdot \sigma_{total}} \; ; \quad \lambda_I < \lambda_a$$

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	X_0(cm)	λ_a [g/cm^2]	λ_a(cm)
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63		50.8	
Helium (gas)	2	4.00	0.1786 (g/l)	94		65.1	
Beryllium	4	9.01	1.848	65.19		75.2	
Carbon	6	12.01	2.265	43		86.3	
Nitrogen (gas)	7	14.01	1.25 (g/l)	38		87.8	
Oxygen (gas)	8	16.00	1.428 (g/l)	34		91.0	
Aluminium	13	26.98	2.7	24	8.9	106.4	39
Silicon	14	28.09	2.33	22		106.0	
Iron	26	55.85	7.87	13.9	1.8	131.9	17
Copper	29	63.55	8.96	12.9		134.9	
Tungsten	74	183.85	19.3	6.8		185.0	
Lead	82	207.19	11.35	6.4		194.0	
Uranium	92	238.03	18.95	6.0	0.31	199.0	10

For Z > 6: $\lambda_a > X_0$ $\qquad \lambda_a \sim 35 \cdot A^{1/3}\ g/cm^2$



- Lots of secondary particles produced in each interaction. Transverse energy of secondaries considerable so, shower spreads out more transversely than e.m. shower.



- λ, the mean free path between interactions large ~10 cm in U, 17 cm in Fe.

Max of hadronic shower

$$t_{max}(\lambda) \sim 0.2 \ln E_0 (\text{GeV}) + 0.7$$
$$\sim 1-2\lambda$$

- $10-11\lambda$ needed to contain showers upto ~1 TeV
- So, hadronic calorimeters must be much thicker than electromagnetic calorimeters.
- ~95% of shower laterally is contained in a cylinder of radius ~1λ.
  $\Rightarrow$ Granularity need not be as fine as e.m. cell size ~ several cm.

A variety of processes involved in energy-loss.

⟨Fractional energy⟩ deposited by 10 GeV p in Fe/LAr
(Gabriel & Schmidt ORNL TM-5105, 1975)

Process	% of total	
Secondary proton ionization	31.6	
Electromagnetic cascade	21.0	rises with E
Nuclear B.E. + γ production	20.6	invisible
Secondary $\pi^{\pm}$ ionization	8.2	
Neutrons $E > 10$ MeV	4.9	
Neutrons $E < 10$ MeV	3.9	
Residual nuclear excitation energy	3.7	
$Z > 1$ particles ionization	2.3	
Ionization by primary protons	1.4	

Unlike e.m. showers which convert nearly all energy into ionization, hadronic showers produce a variable fraction of invisible energy.

- nuclear break-up absorbs binding energy
- neutrinos, low energy neutrons
- muons deposit very little energy

$\Rightarrow$ much less signal than e.m. showers
"Compensation" needed

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- Fluctuations between electromagnetic and hadronic components in a hadronic shower are large

  - Varying π^0 content → varying e.m. component
  - fluctuations in the nature of secondaries

  ⇒ worse energy resolution

- Even ~10λ calorimeter may not contain a high energy hadronic shower (≳ 150 GeV) completely (containment issues)

  — "punch through" beyond the calorimeter or "leakage"

  → energy loss → degradation in energy resolution (some correction can be applied)

  → background for other detectors beyond (mainly muon detectors)

- Hadronic showers are

  longer
  wider
  fluctuate more
  start later

  than EM showers of same energy

COMPENSATION

In general,

Calorimeter response to hadrons < response to EM particles at the same energy

$\therefore \frac{e}{\pi} > 1$

Also, calorimeter response to the EM component in hadronic showers is larger than to the hadronic component.

$\varepsilon_e / \varepsilon_h > 1$ (or $e/h > 1$)

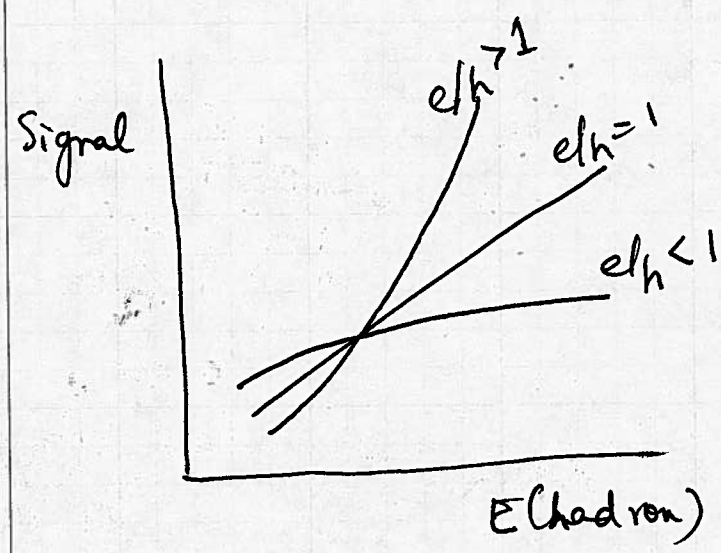
Response $R_h = f_{EM} \cdot \varepsilon_{EM} \cdot E_0 + (1 - f_{EM})\, \varepsilon_h E_0$

$R_e = \varepsilon_{EM} \cdot E_0$

$$\therefore \frac{e}{\pi} = \frac{R_e}{R_h} = \frac{\varepsilon_{EM}}{\varepsilon_h - f_{EM}(\varepsilon_h - \varepsilon_e)} = \frac{e/h}{1 - f_{EM}(1 - e/h)}$$

f_{EM} = fraction of EM energy within the hadronic shower

$\simeq 0.1 \ln(E(\text{GeV}))$



Energy Resolution:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b \cdot \left| \frac{e}{h} - 1 \right|$$

Some examples:

CDF Pb/Scint $e/h \sim 1.6$

DØ U/LAr $e/h \sim 1.1$

ZEUS U/Scint $e/h \sim 1.0$

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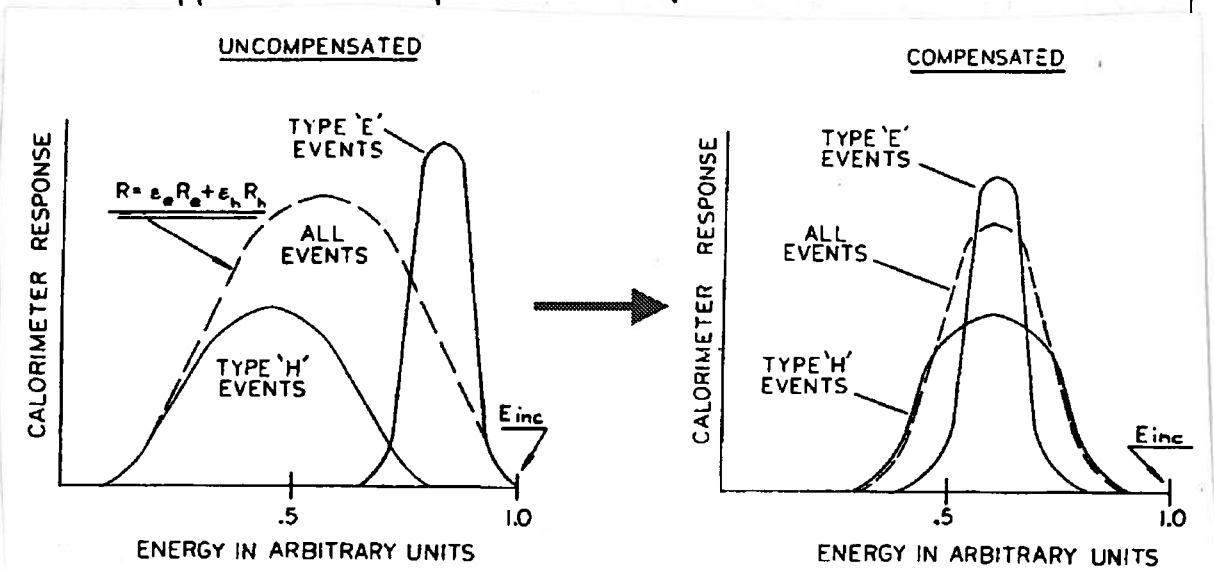
Need compensation $e/h \simeq 1$; $e/\pi \simeq 1$ for all E

Methods to
Achieve compensation:

- increase ε_h
  - Use Uranium absorber → amplify neutron and soft-γ component of fission
    (extra energy released in ^{238}U fission compensates for the nuclear binding energy losses.)
  - use hydrogeneous active material → high in detection efficiency
- decrease ε_e:
  - Use thin sheets of passive low-Z material shielding the active medium
    For $E < 1$ MeV, photoelectric effect is the important energy loss mechanism $\sigma_{photo} \propto Z^5$.
    ∴ Suppress low energy γ-detection.
- offline compensation possible but cumbersome.



(Cushman, Instrumentation In High Energy Physics, World Scientific, 1992))

Other Issues:

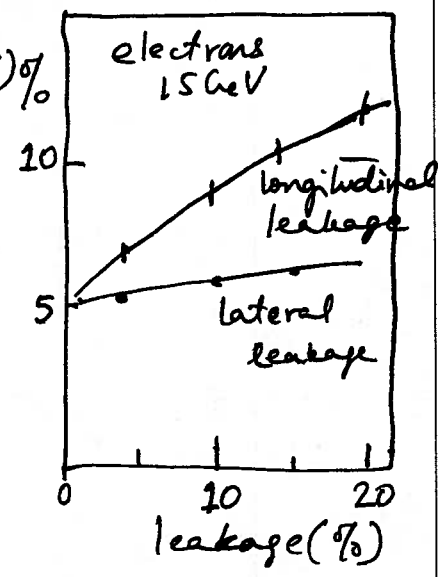
Longitudinal Leakage:

Finite size of the calorimeter
$\Rightarrow$ longitudinal & lateral leakage

Energy resolution gets degraded

$$\frac{\sigma(E)}{E} = \frac{\sigma(E)}{E}\Big|_{0\%} \left(1 + f(E) + 50 \cdot f^2(E)\right)$$

where,
$f(E)$ = lost energy fraction
(depends on energy)



Can install low-resolution tail-catcher behind the hadronic calorimeter.

Up-stream Energy Loss:

- Showers start in "dead" material in front of calorimeter (other detectors, solenoid, support structures)

– Use Pre-shower detector in front of Calorimeter
→ recover some energy
→ improved background rejection due to better spatial resolution

Homogeneous Calorimeters

- Excellent energy resolution (1-5%) since most of the energy is deposited in the active medium
- More difficult to segment laterally and longitudinally
- Mainly used as EM Calorimeters in HEP.

– Scintillator calorimeters

ionization → light

BGO (Bismuth Germanate or $Bi_4Ge_3O_{12}$) used by L3

CsI (CsI (Tl) used by Babar
E735 @ CØ used NaI (Tl))

$PbWO_4$ (Lead Tungstate; to be used by ATLAS)

– Cerenkov Calorimeters

Material with high refractive index where relativistic $e^{\pm}$ tracks in the shower produce Cerenkov photons.

E.g., PbO (Lead-Glass)

– Noble Liquid Calorimeters (Ar, Kr, ..)

Noble gas at cryogenic temperatures
ionization collected (LKr in NA48)

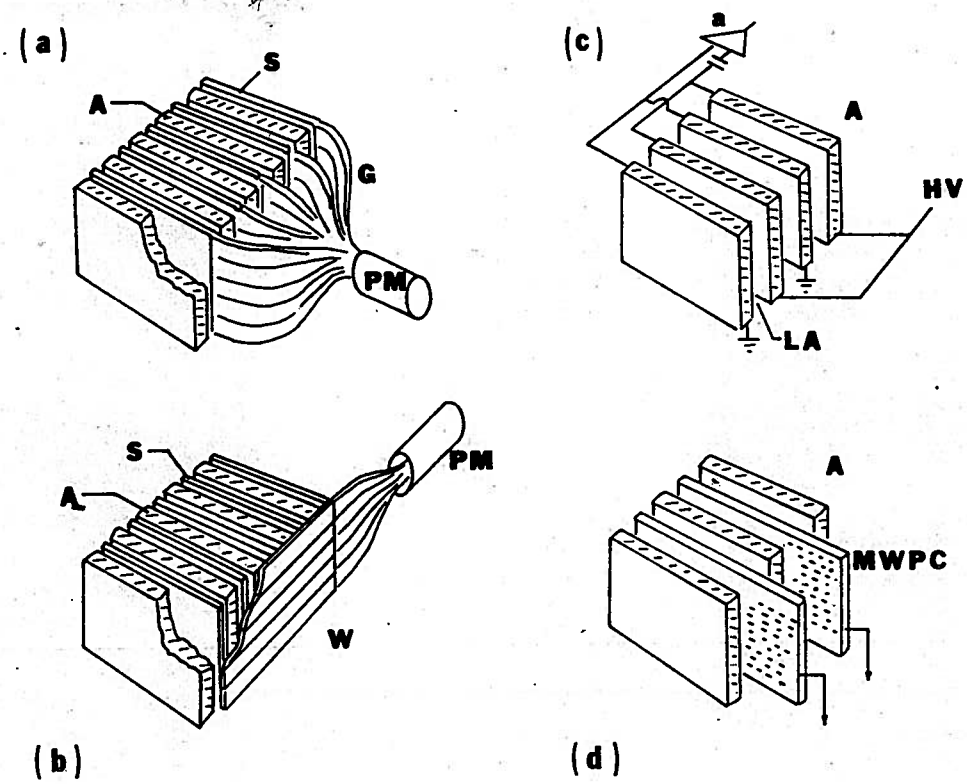
– SemiConductor Calorimeters (Si, Ge)

best energy resolution, but too compact for HEP.

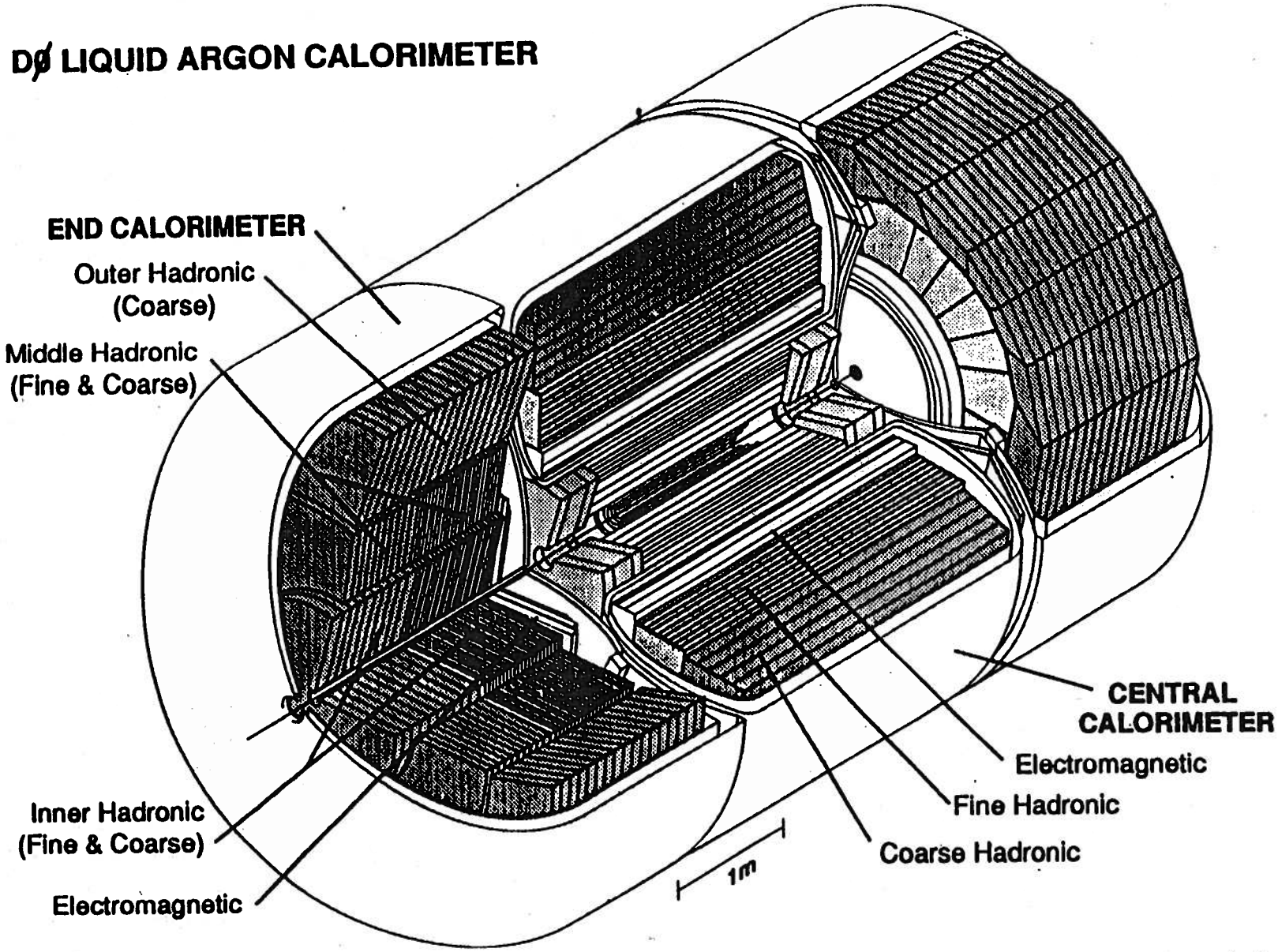
SAMPLING CALORIMETERS

- Absorber + detector (gaseous, liquid, solid) alternate
- MWPC, Streamer tubes
- Warm liquids (TMP: Tetramethylpentane)
- Cryogenic noble liquids: LAr, LXe, LKr
- Scintillators, Scintillation fibers, Silicon detectors

Figure 11.4 Typical readout techniques for calorimeters: (a) lead–scintillator sandwich, (b) lead–scintillator sandwich with wavelength shifter bars, (c) liquid argon ionization chamber, and (d) lead–MWPC sandwich. (C. Fabjan and T. Ludlam, adapted with permission from the Annual Review of Nuclear and Particle Science, Vol. 32, © 1982 by Annual Reviews, Inc.)



DØ LIQUID ARGON CALORIMETER



CC EM: 3 mm depleted U

EC EM: 4 mm "

FH: 6 mm U-Nb (2%)

CCCH: 46.5 mm Cu; ECCH: 46.5 mm

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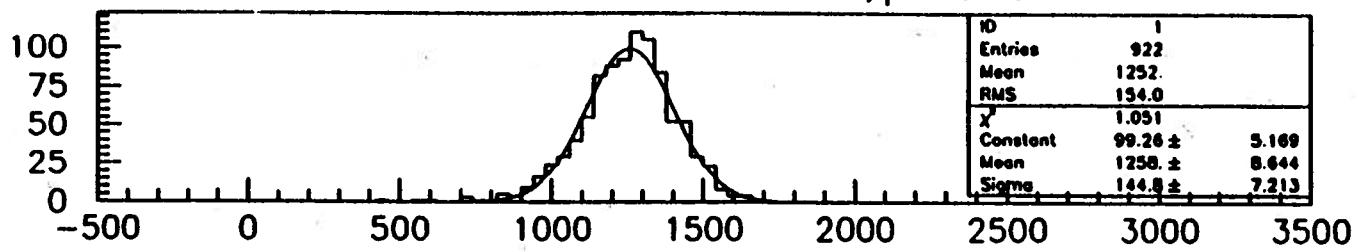
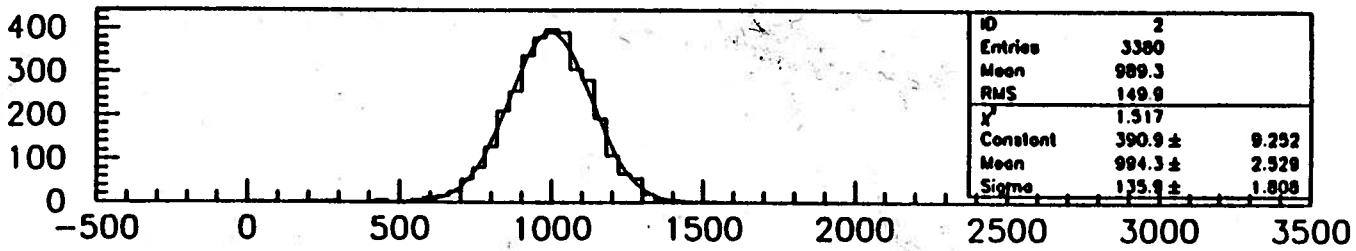
P. Bhat (DØ) DPF 1992

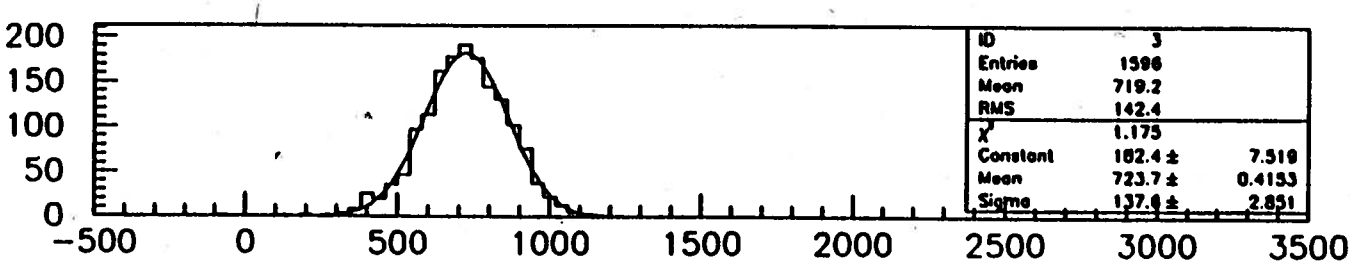
Test Beam Electrons eta=0.05, phi=31.6



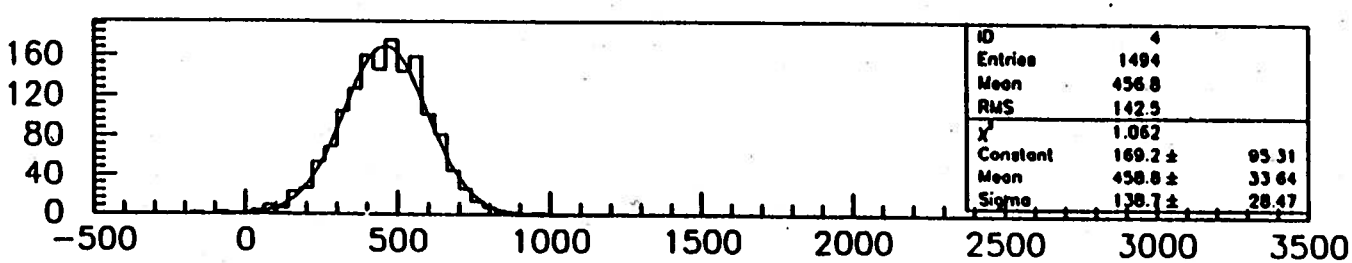
EMzTOT+FH1, 5 GeV



EMzTOT+FH1, 4 GeV



EMzTOT+FH1, 3 GeV



EMzTOT+FH1 2 GeV

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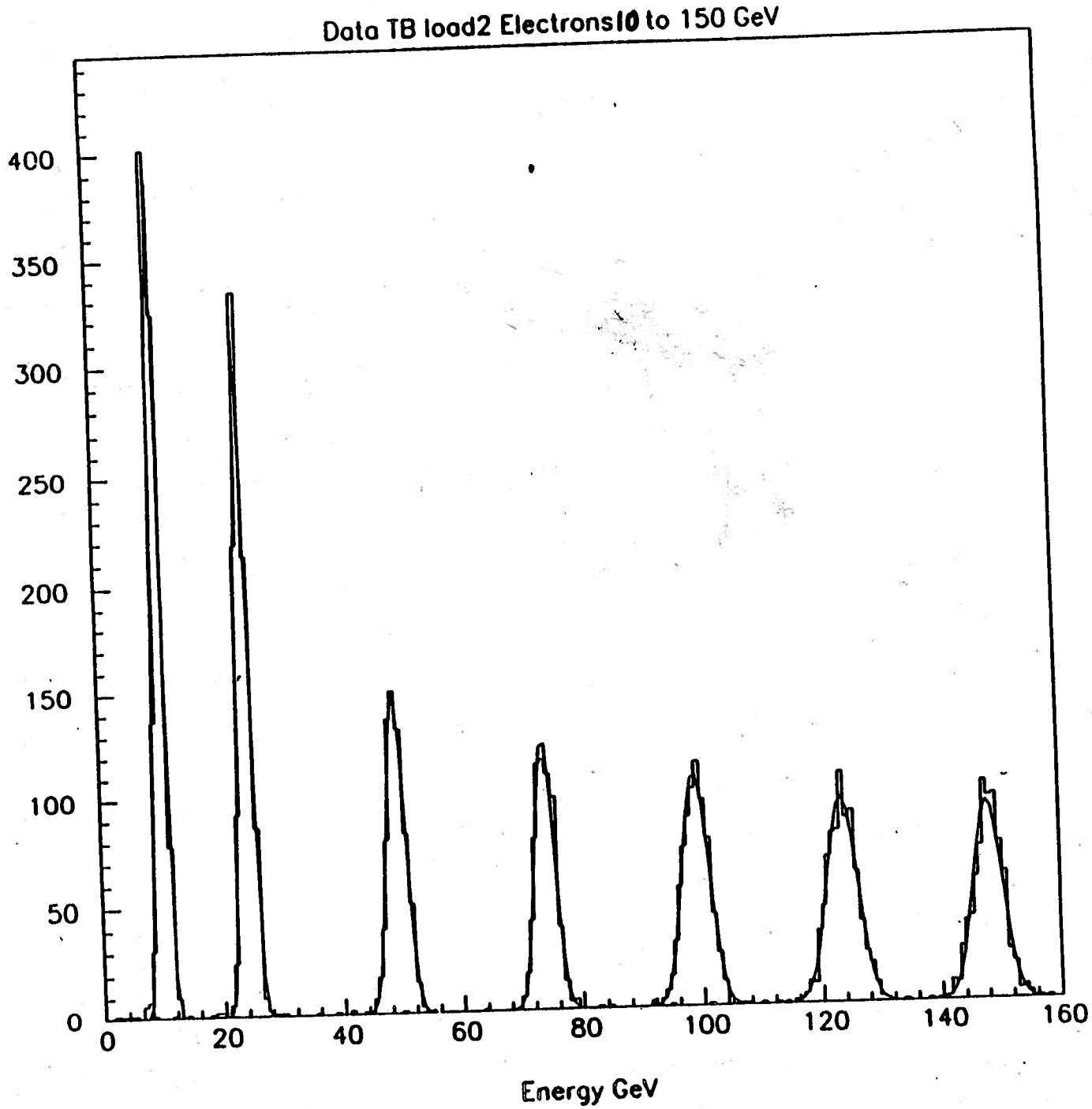
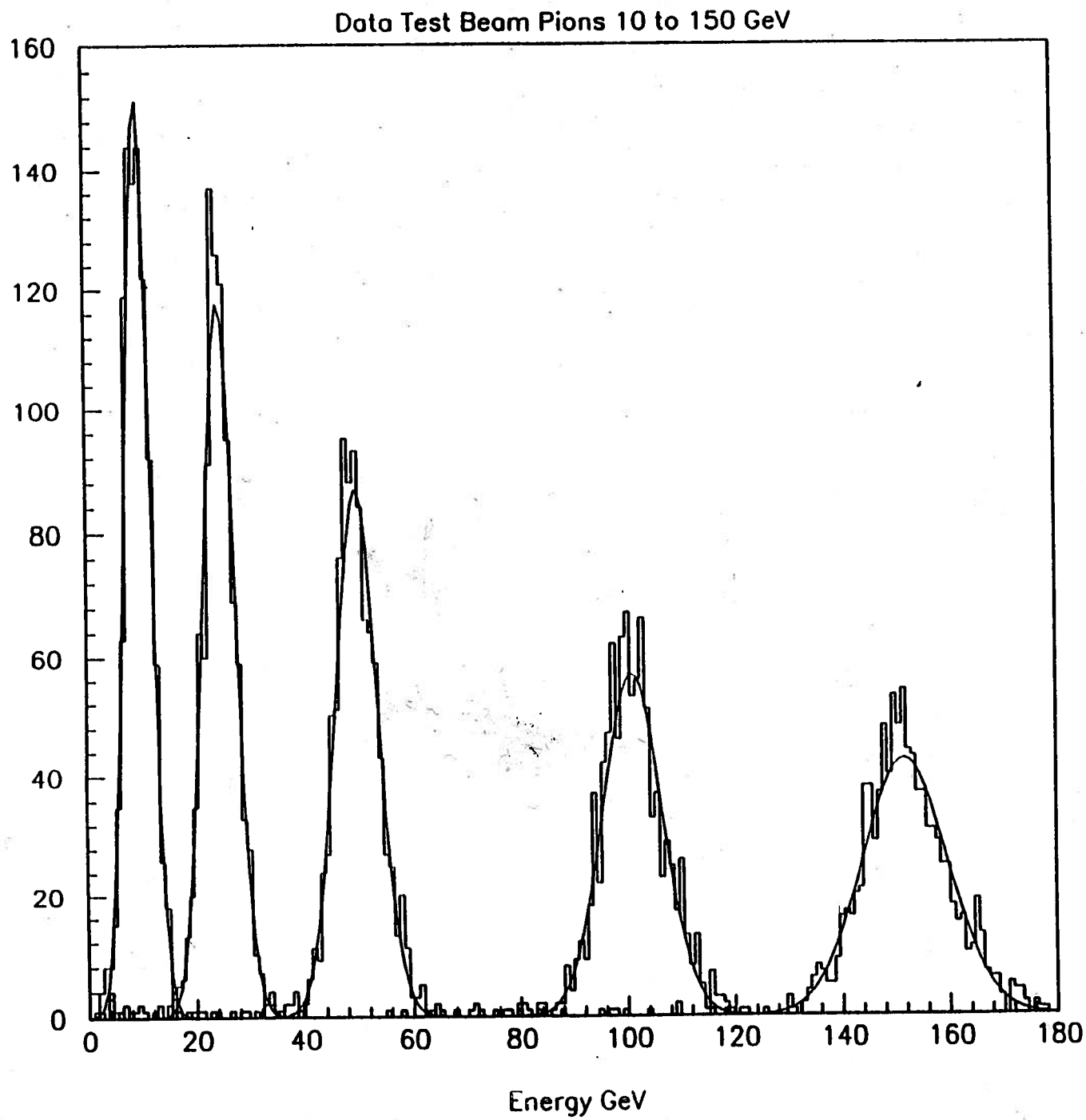
P. Bhat (DØ) DPF 1992



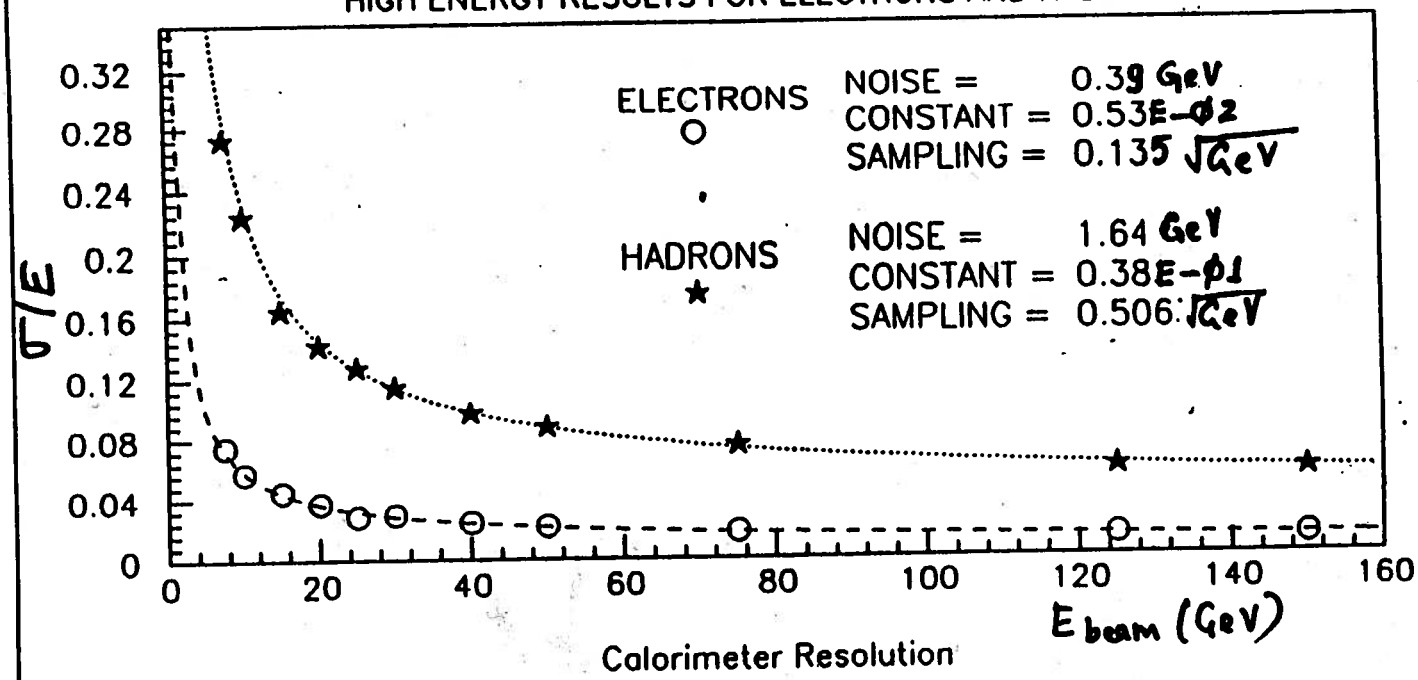
P. Bhat (DØ) DPF 1992



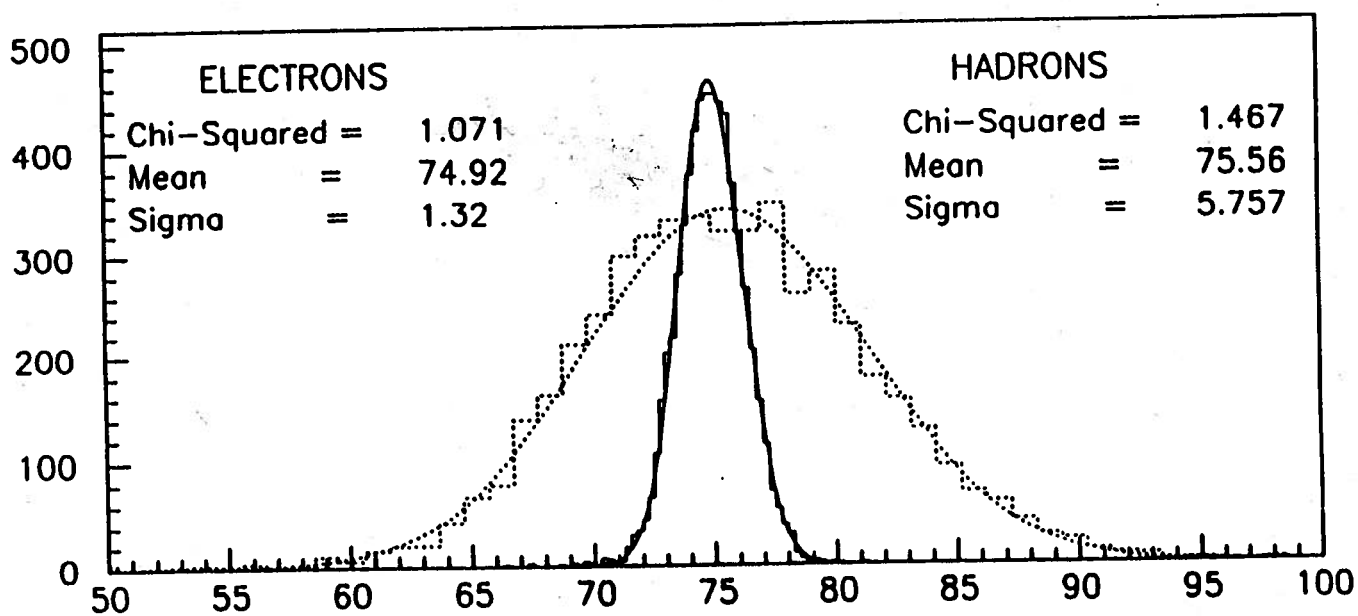
P. Bhat (DØ) DPF 1992

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

HIGH ENERGY RESULTS FOR ELECTRONS AND HADRONS



Calorimeter Resolution

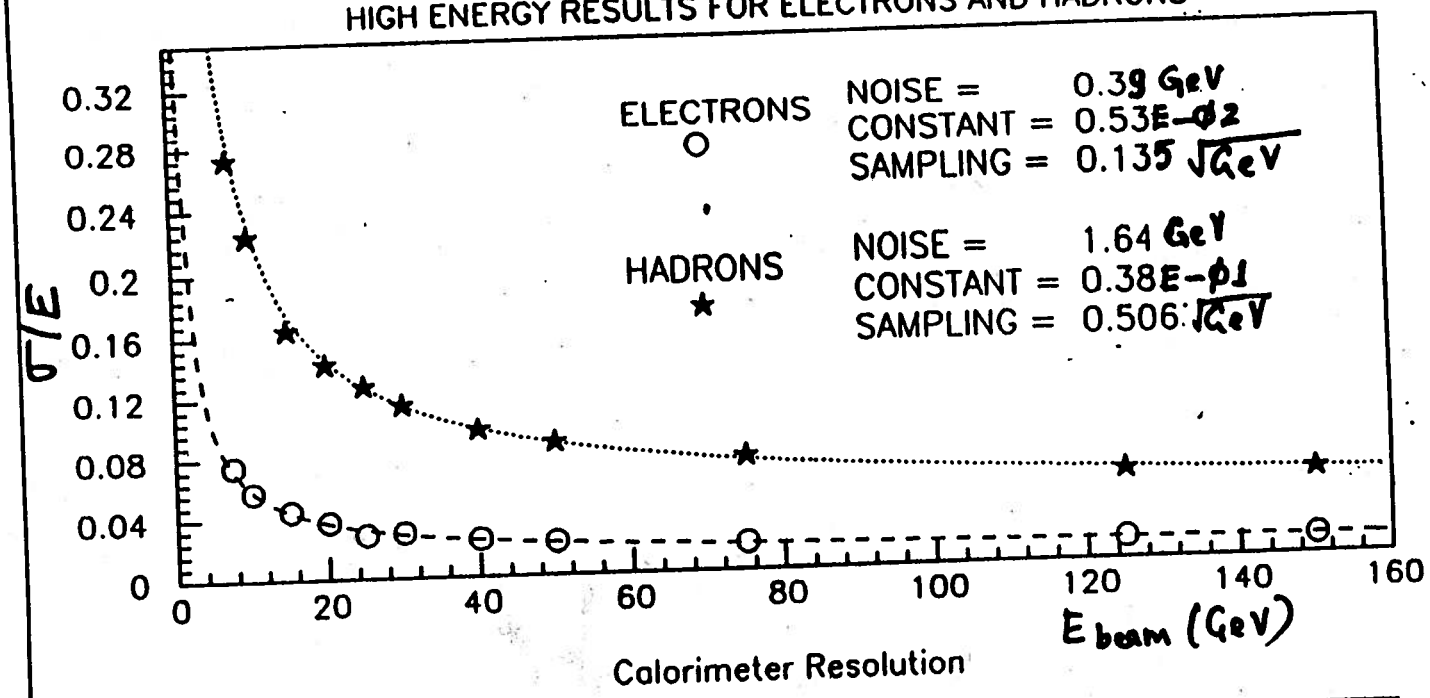


75 GeV Energy Peaks

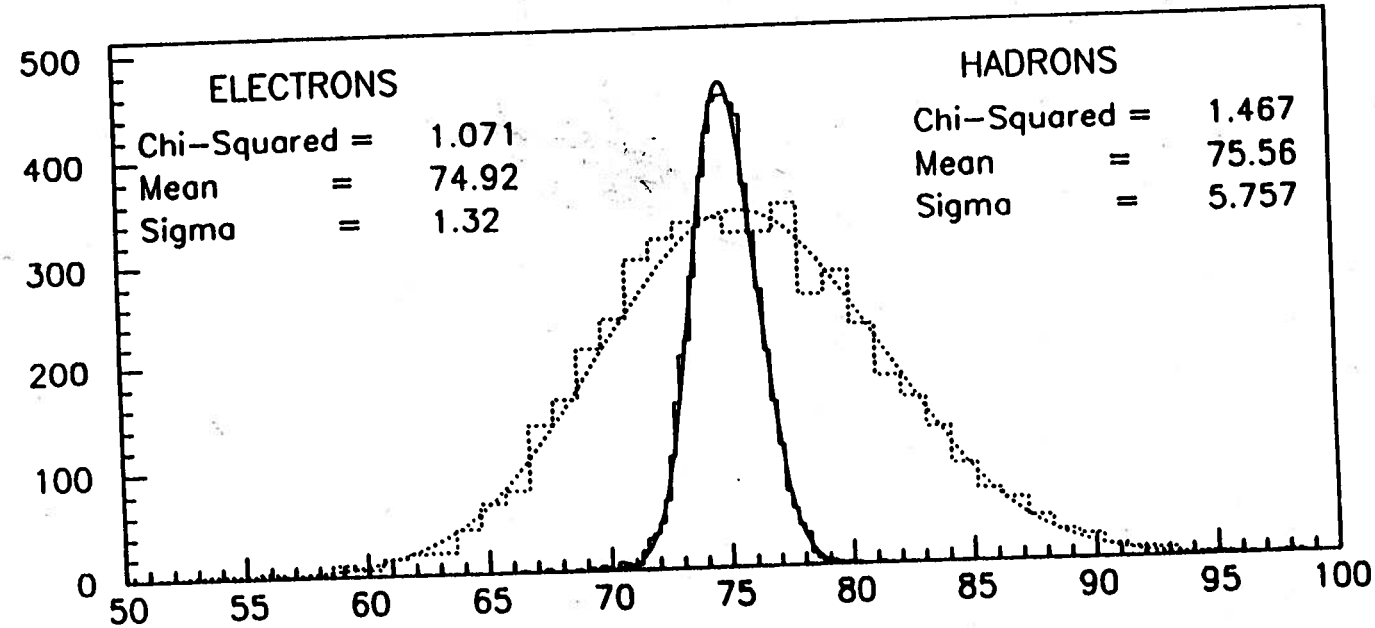
P. Bhat (DØ) DPF 1992

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

HIGH ENERGY RESULTS FOR ELECTRONS AND HADRONS



Calorimeter Resolution



75 GeV Energy Peaks

P. Bhat (DØ) DPF 1992

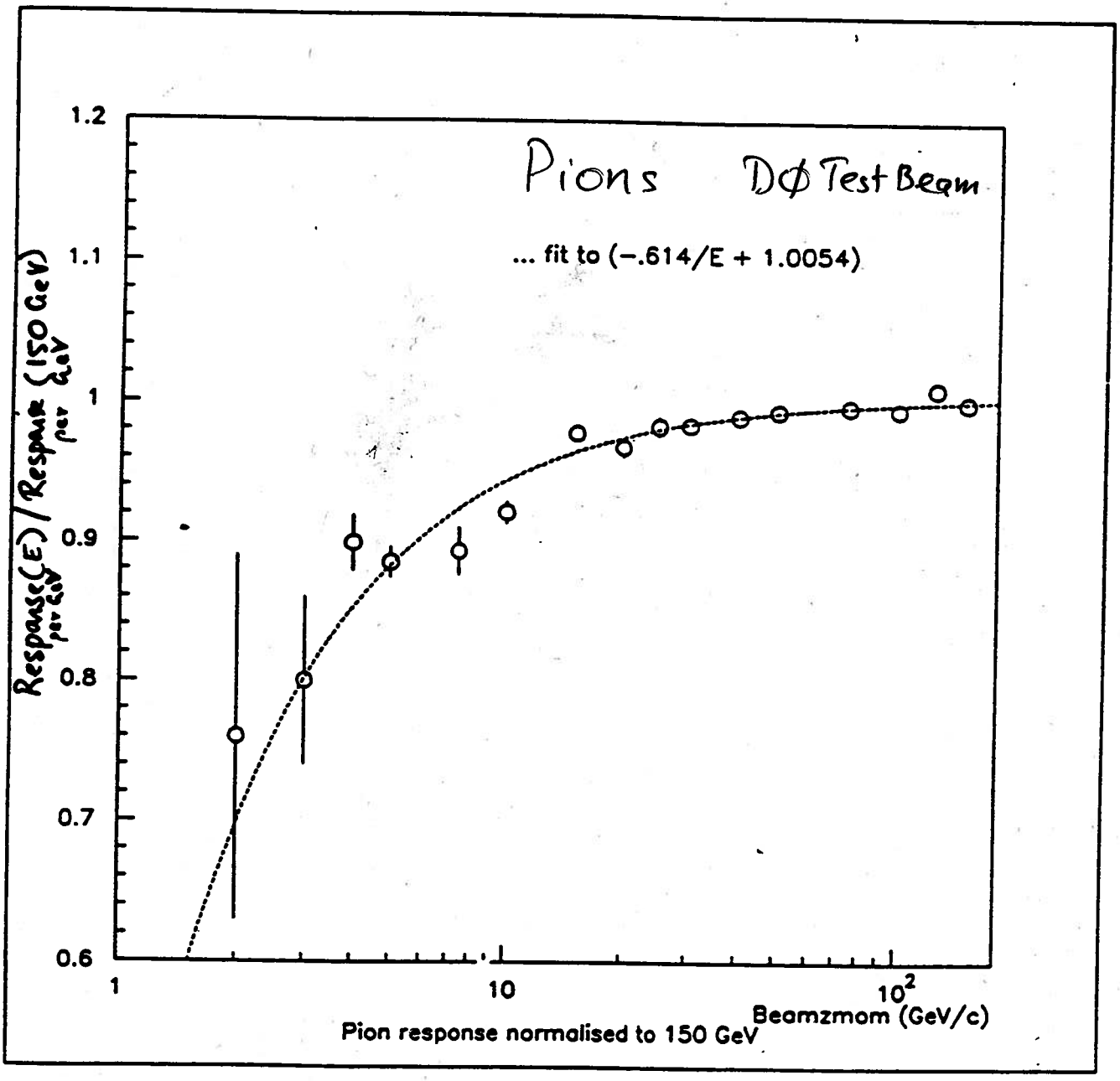


Table 2.1. *Energy resolution for electro gnetic and hadronic calorimeters*

Experiment	Type	Resolution $\Delta E/E$	Reference
	Electromagnetic		
Crystal Ball	NaI (TI)	$0.026/\sqrt[4]{E}$	Bloom and Peck 1983
OPAL	Lead glass	$0.05/\sqrt{E}$	Akrawy *et al.* 1990
Crystal Barrel	CsI (TI)	$0.025/\sqrt[4]{E}$	Landua 1996b
ZEUS	sampling: U + plastic scint.	$0.18/\sqrt{E}$	Behrens *et al.* 1990
D0	sampling: U + liquid Ar	$0.15/\sqrt{E}$	Abachi *et al.* 1994
ATLAS	sampling: Pb + liquid Ar	$0.10/\sqrt{E}$	Gingrich *et al.* 1995
	Hadronic		
CHARM	sampling: Marble + scint.	$0.53/\sqrt{E}$	Diddens *et al.* 1980
ZEUS	sampling: U + plastic scint.	$0.35/\sqrt{E}$	Behrens *et al.* 1990
D0	sampling: U/Fe + liquid Ar	$0.50/\sqrt{E}$	Abachi *et al.* 1994

Note: All energies are to be taken in GeV; the constant terms, to be added quadratically, typically are a fraction of a percent for electromagnetic, and 0.02–0.03 for hadronic calorimeters.