

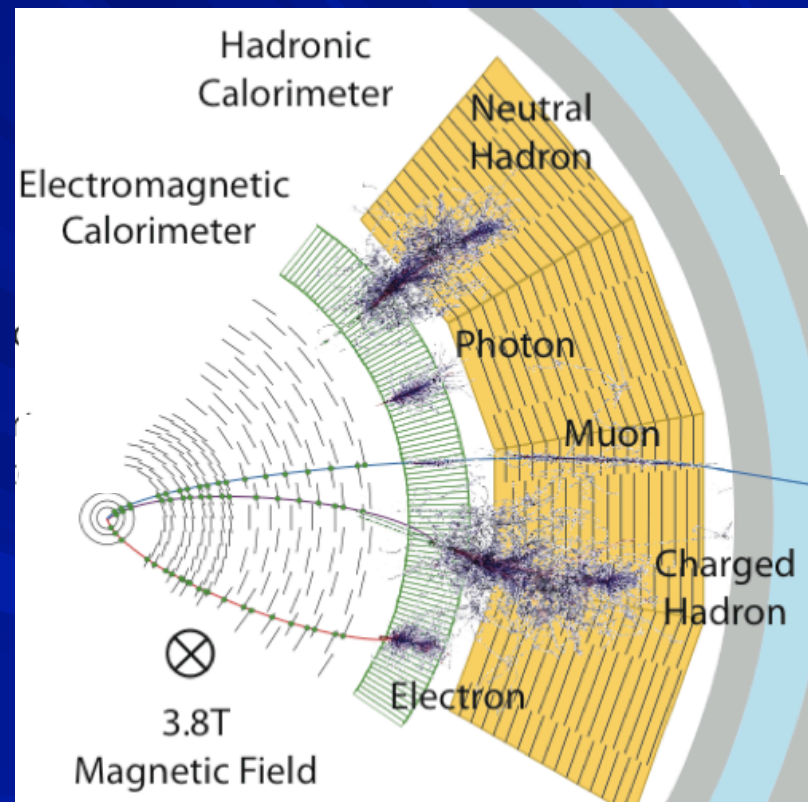
Detectors for Particle Physics

Calorimetry

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What is a calorimeter ?

- In nuclear and particle physics calorimetry refers to the detection of particles through total absorption in a block of matter
 - The measurement process is destructive for almost all particle
 - The exception are muons (and neutrinos) → identify muons easily since they penetrate a substantial amount of matter
- In the absorption, almost all particle's energy is eventually converted to heat → calorimeter
- Calorimeters are essential to measure neutral particles



Electromagnetic shower

■ Dominant processes at high energies ($E > \text{few MeV}$) :

■ Photons: Pair production

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

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

μ = attenuation coefficient

X_0 = radiation length in [cm] or [g/cm²]

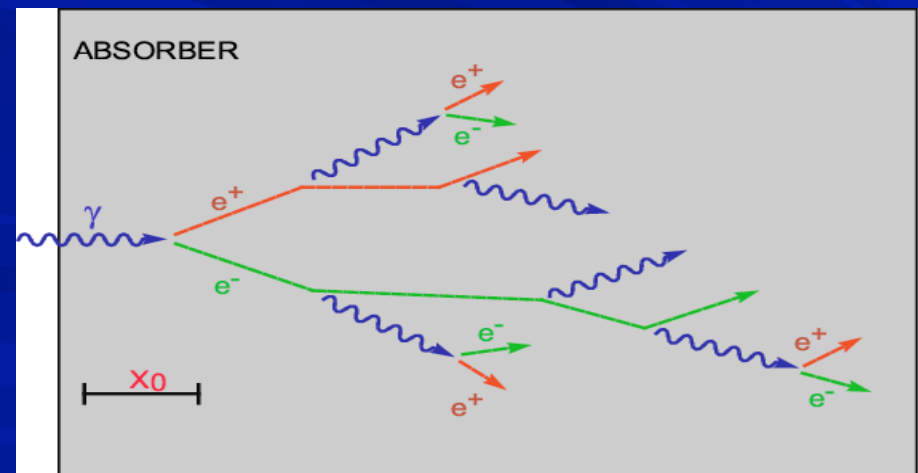
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

■ Electrons: Bremsstrahlung

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

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

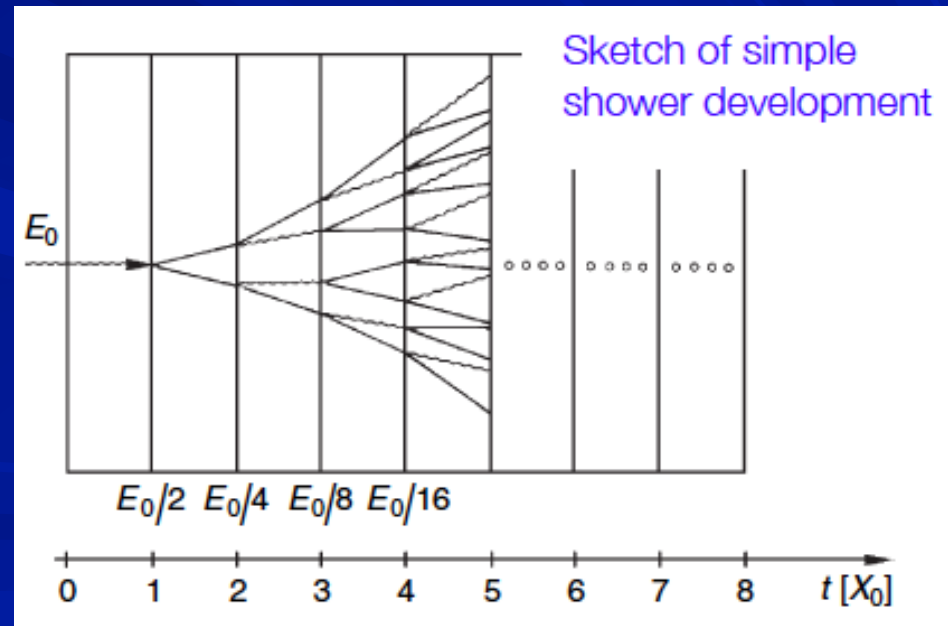
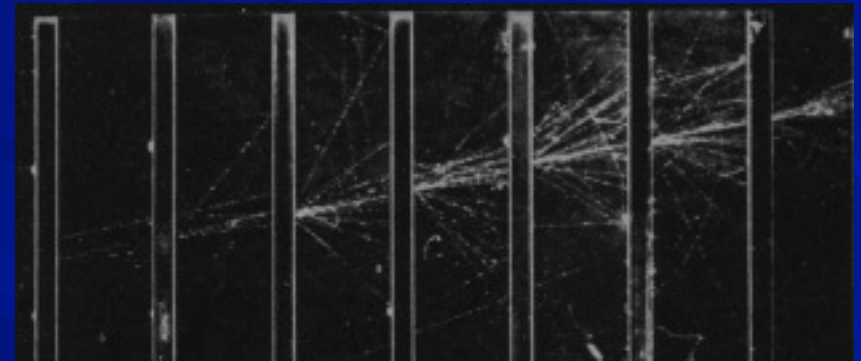
After traversing $x=X_0$ the electron has only $1/e=37\%$ of its initial energy



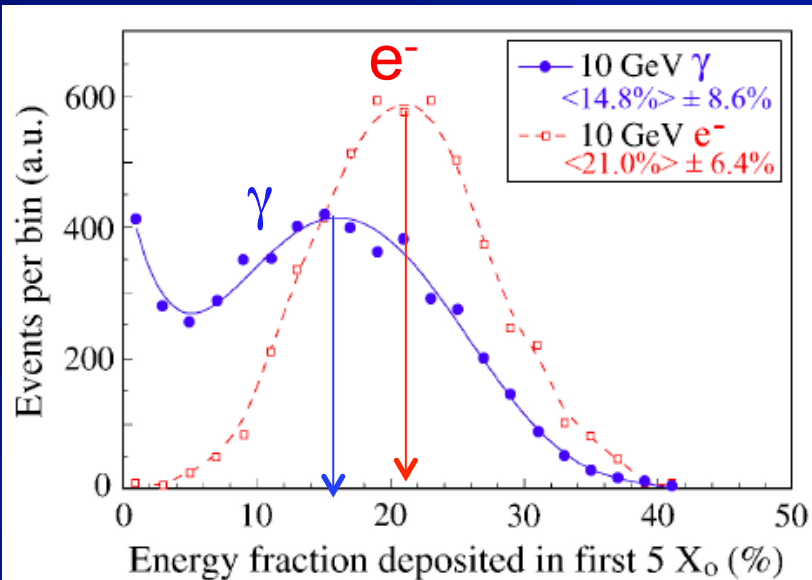
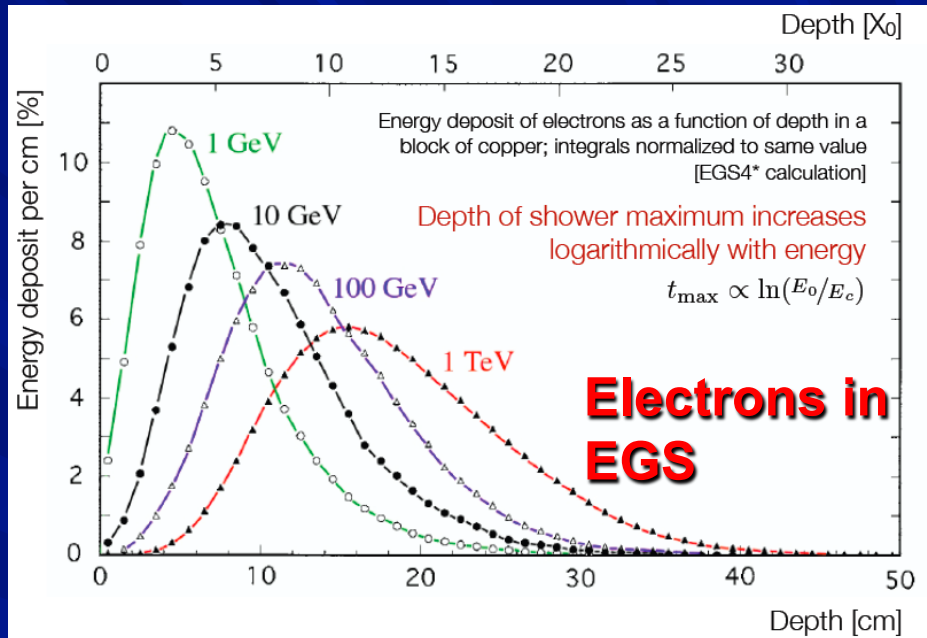
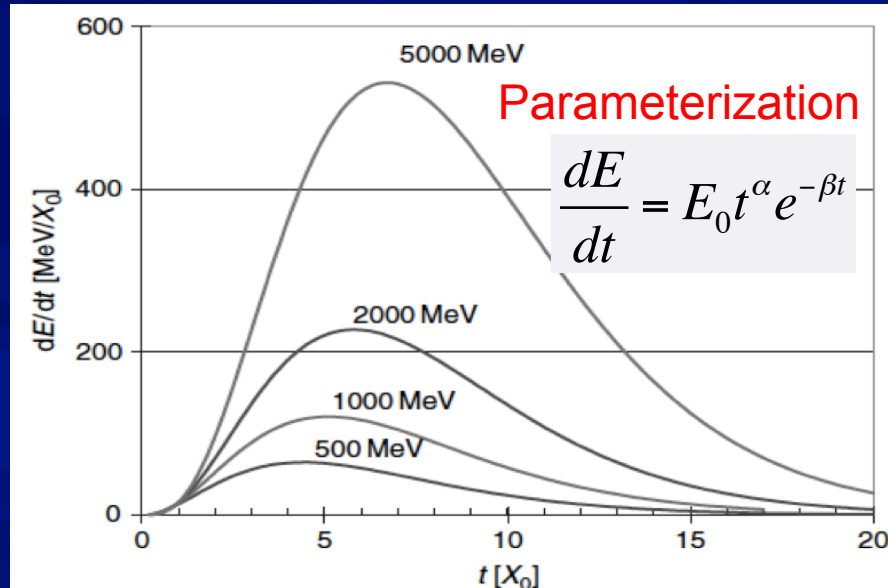
Analytic shower Model

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

$$t_{\max} \propto \ln \left(\frac{E}{E_c} \right)$$



Longitudinal shower distribution



- Differences between electrons and photons generated showers
- Some photons penetrating (almost) the entire slab without interacting (peak at 0)

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

$C_{e\gamma} = -0.5$ for photons
 $C_{e\gamma} = -1$ for electrons

Longitudinal containment

- Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle, i.e. calorimeters can be compact
- $L(95\%) = t_{\max} + 0.08 Z + 9.6 [X_0]$

$$\text{Number of particle in shower} = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$

$$\text{Location of shower max} = t_{\max} \approx \ln\left(\frac{E_0}{E_c}\right)$$

$$\text{Longitudinal shower distribution} = L \approx \ln\left(\frac{E_0}{E_c}\right)$$

Transverse shower distribution

Example

$$E_c \approx 10 \text{ MeV} \quad E_0 = 1 \text{ GeV} \quad \Rightarrow t_{\max} = \ln 100 \approx 4.6 \quad N_{\max} = 100$$

$$E_0 = 100 \text{ GeV} \quad \Rightarrow t_{\max} = \ln 10,000 \approx 9.2 \quad N_{\max} = 10,000$$

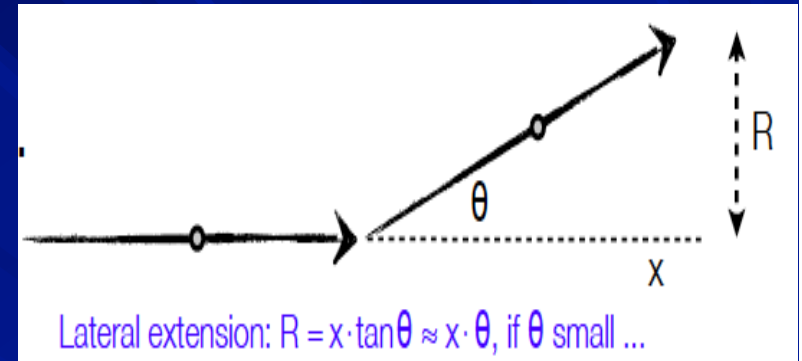
	Scint.	LAr	Fe	Pb	W
$X_0(\text{cm})$	34	14	1.76	0.56	0.35

A 100 GeV electron is contained in 16 cm Fe or 5 cm Pb

Lateral development of EM shower

- Opening angle:
 - bremsstrahlung and pair production

$$\langle \theta^2 \rangle \approx \left(\frac{m_e c^2}{E_e} \right)^2 = \frac{1}{\gamma^2}$$



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

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

- Main contribution from low energy electrons as $\langle \theta \rangle \sim 1/E_e$, i.e. for electrons with $E = E_c$

■ Molière Radius

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

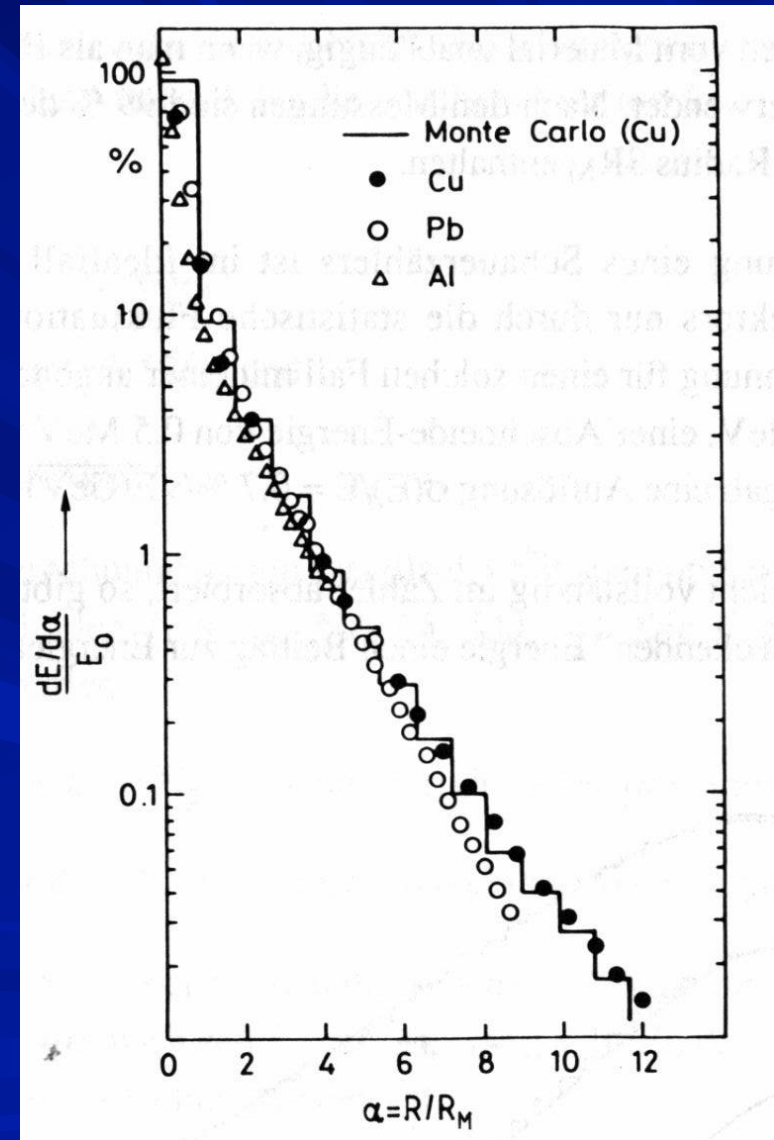
- Assuming the approximate range of electrons to be X_0 yields $\langle \theta \rangle \approx 21 \text{ MeV} / E_e \rightarrow$ lateral extension: $R = \langle \theta \rangle X_0$

Lateral development of EM shower

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

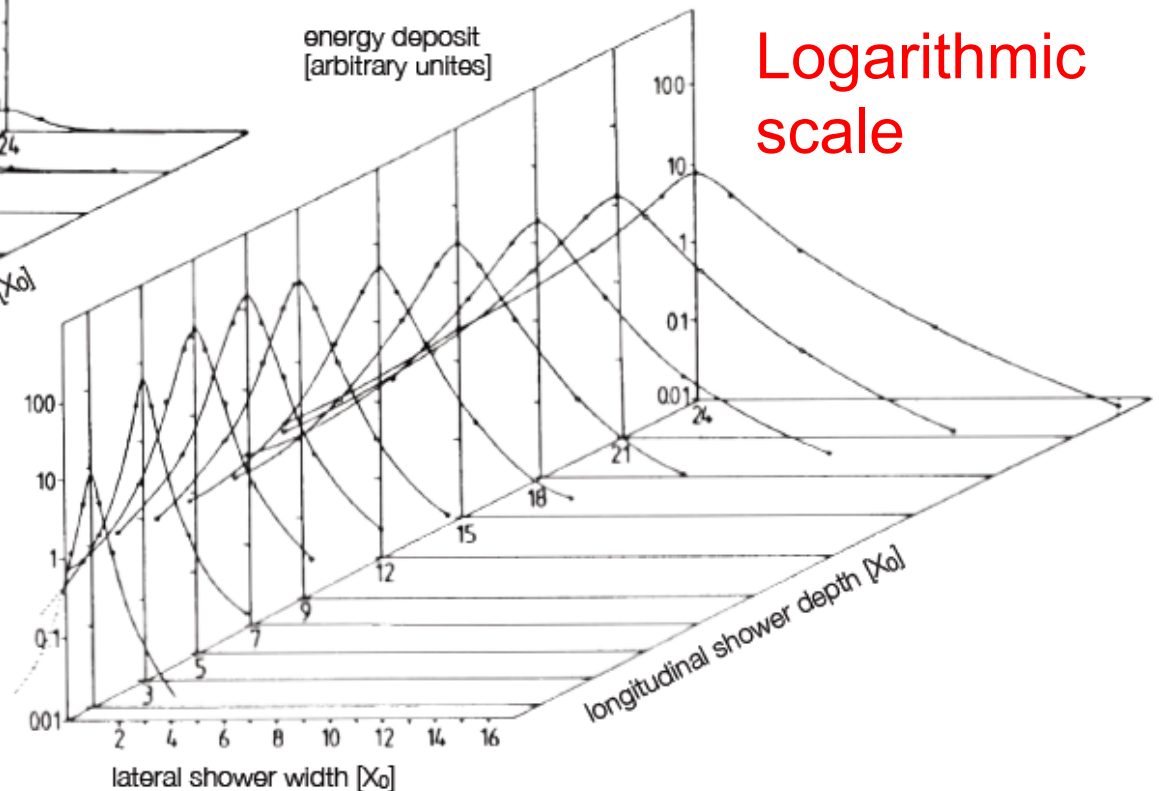
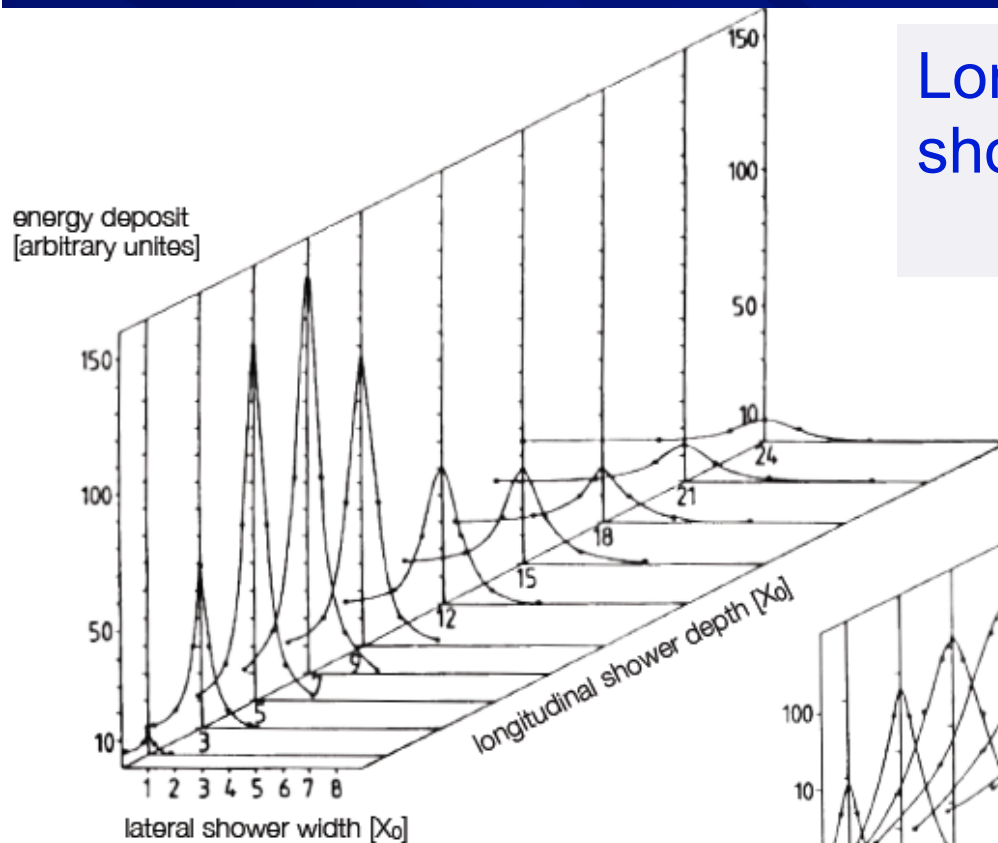
$$\frac{dE}{dr} = \alpha e^{-r/R_M} + \beta e^{-r/\lambda_{\min}}$$

- The shower gets wider at larger depth
- An infinite cylinder of radius $1 R_M$ contains 90% of the shower



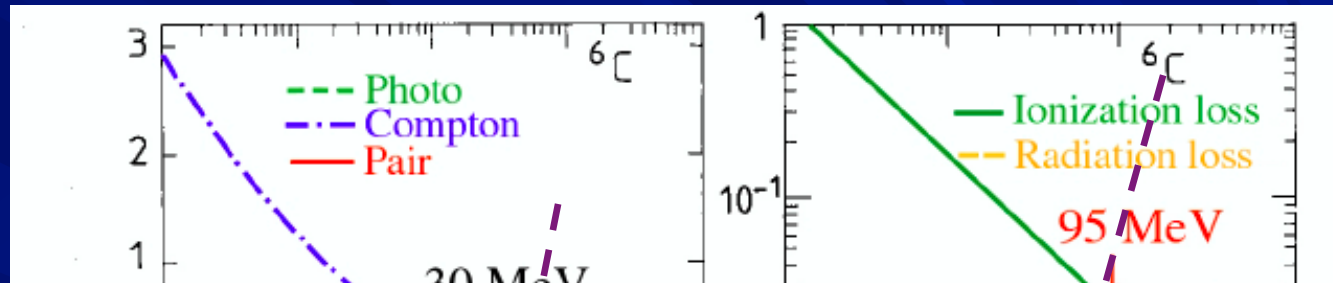
3D EM Shower development

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

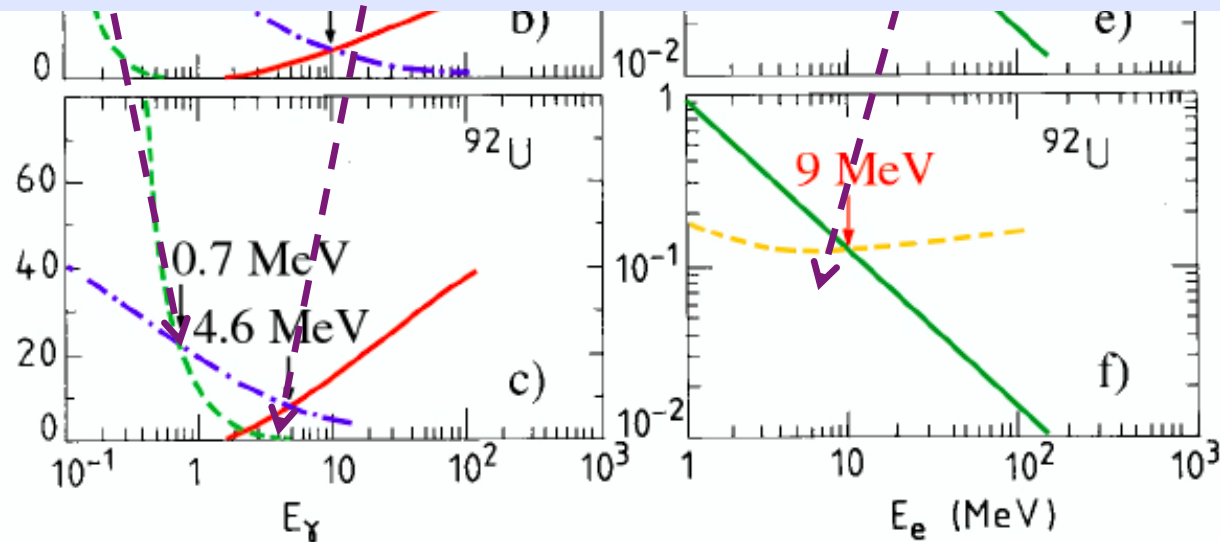


Material dependence

Z



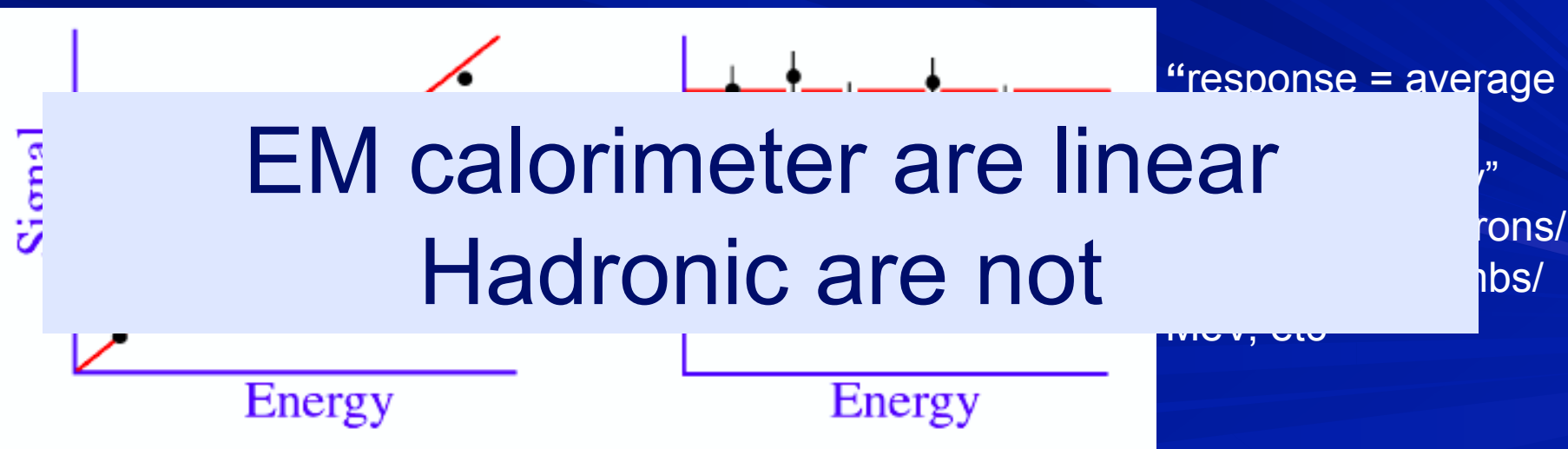
Even though calorimeters are intended to measure GeV, TeV energy deposits, their performance is determined by what happens at the MeV - keV - eV level



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Energy Measurement

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



Sources of Non Linearity

- Instrumental effects
 - Saturation of gas detectors, scintillators, photo-detectors, Electronics
- Response varies with something that varies with energy
- Examples:
 - Deposited energy “counts” differently, depending on depth
 - And depth increases with energy
- Leakage (increases with energy)

Signal linearity for electromagnetic showers

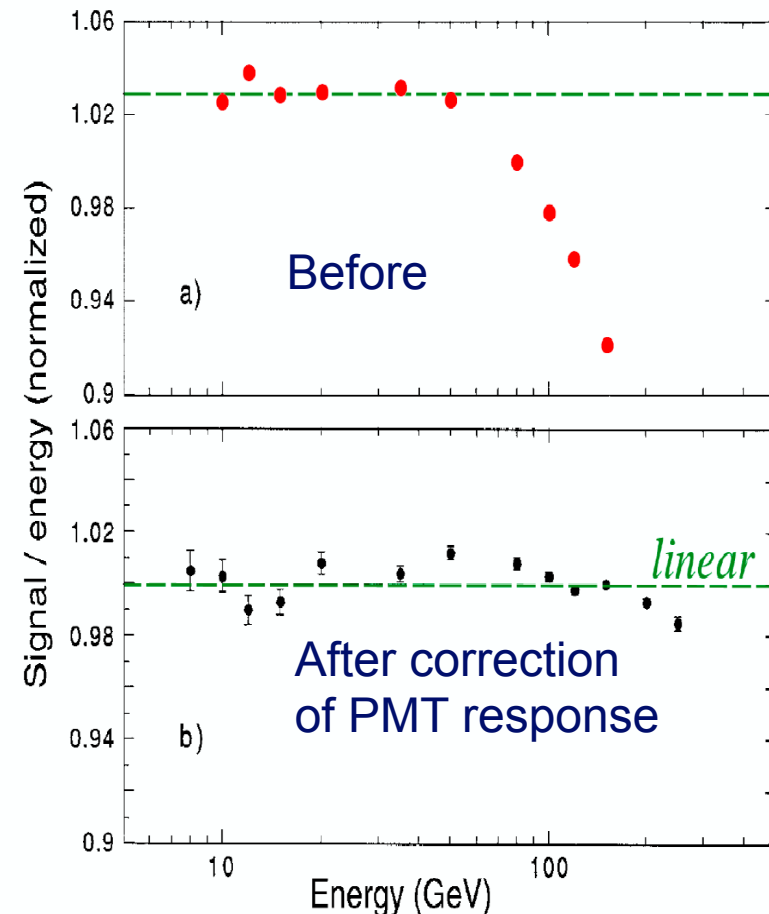


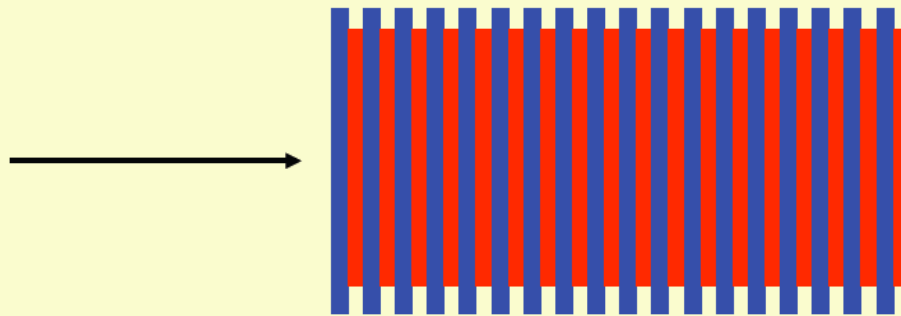
FIG. 3.1. The em calorimeter response as a function of energy, measured with the QFCAL calorimeter, before (a) and after (b) precautions were taken against PMT saturation effects. Data from [Akc 97].

Typical Calorimeter configurations

There are two general classes of calorimeter:

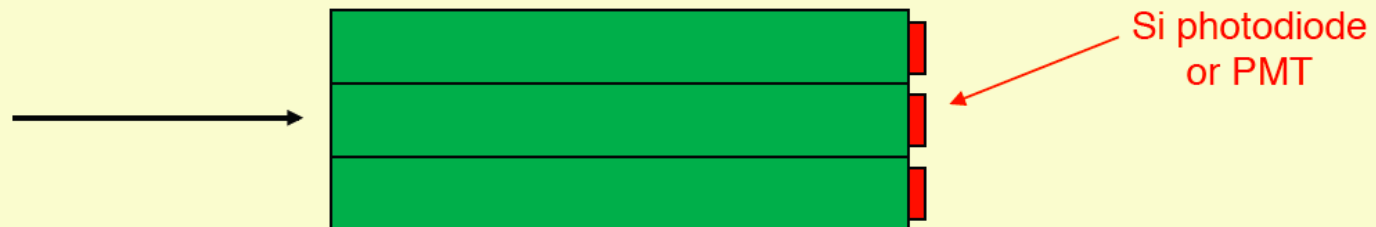
Sampling calorimeters:

Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon



Homogeneous calorimeters:

A single medium serves as both absorber and detector, eg: liquified Xe or Kr, dense crystal scintillators (BGO, PbWO_4 ), lead loaded glass.



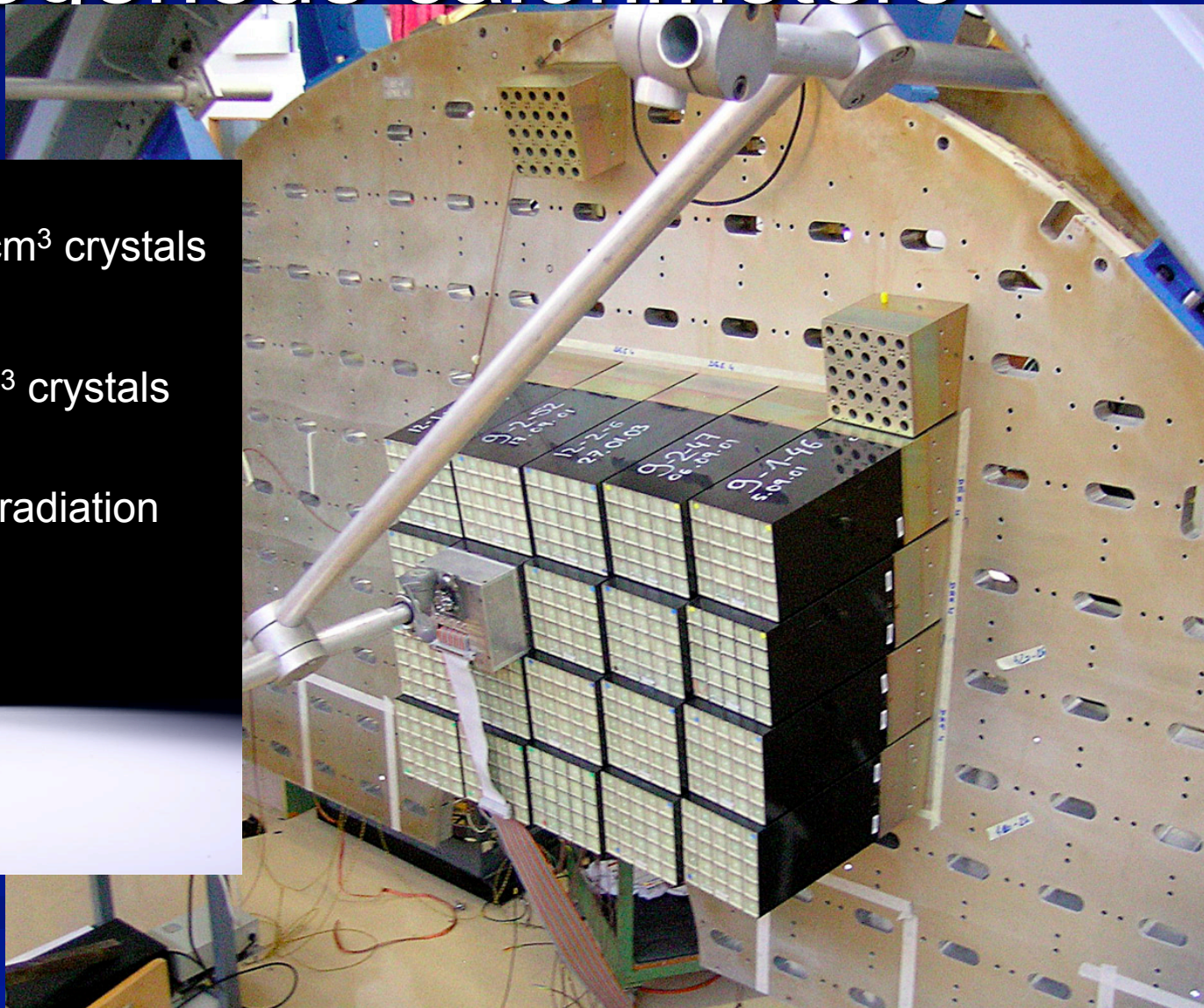
Homogenous calorimeters

■ A block of material

Barrel: 62K $2.2 \times 2.2 \times 23 \text{ cm}^3$ crystals

Endcap: 15K $3 \times 3 \times 22 \text{ cm}^3$ crystals

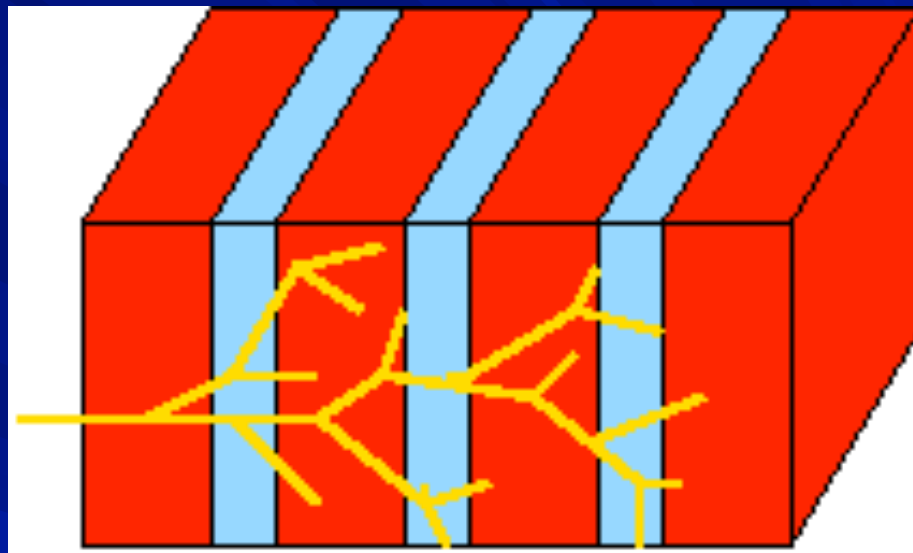
Development of PbWO_4 radiation hard crystals



Sampling Calorimeters

- Use High density absorber Interleaved with active readout devices
 - sandwich structures
 - embedded fibres,
- Sampling fraction

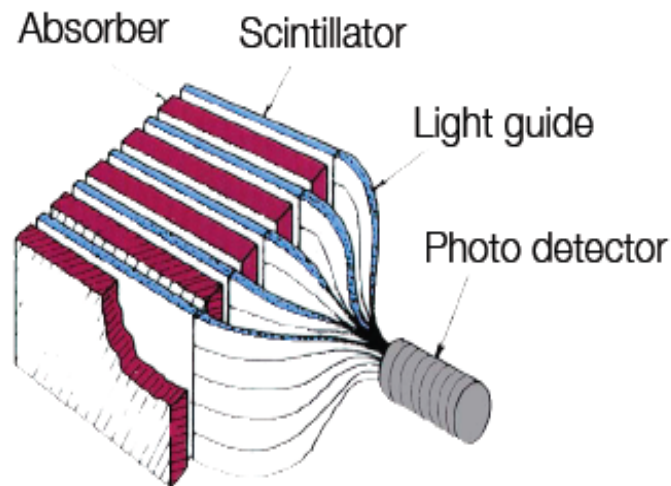
$$f_{\text{sampling}} = \frac{E_{\text{visible}}}{E_{\text{deposited}}}$$



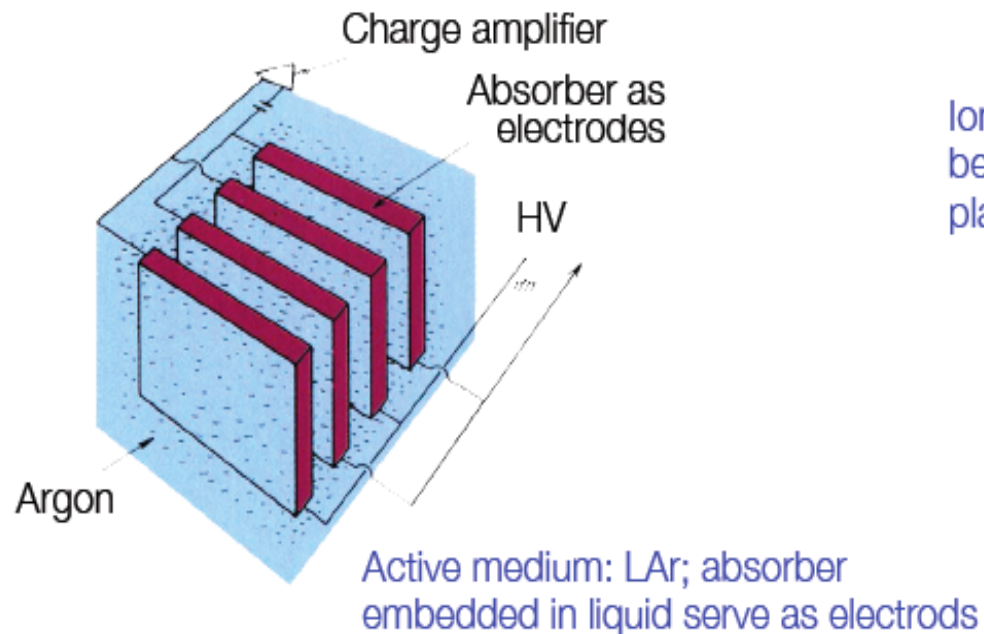
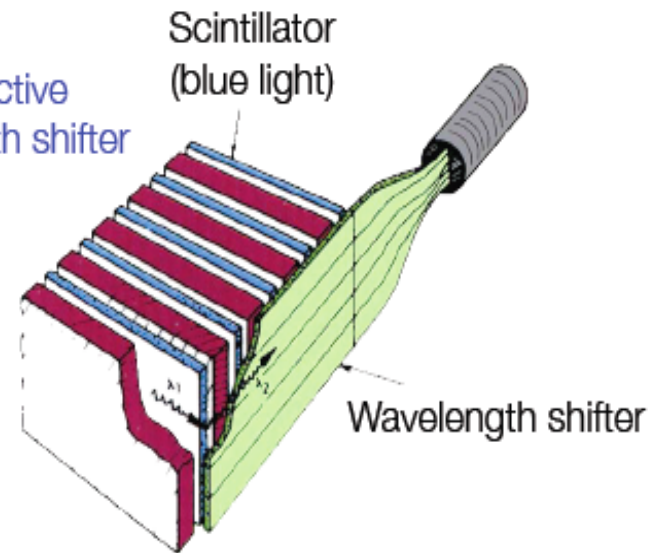
- Advantages
 - Cost, transverse and longitudinal segmentation
- Disadvantages:
 - Only part of shower seen, less precise
- Examples
 - ATLAS ECAL
 - Most HCALs

Possible setups

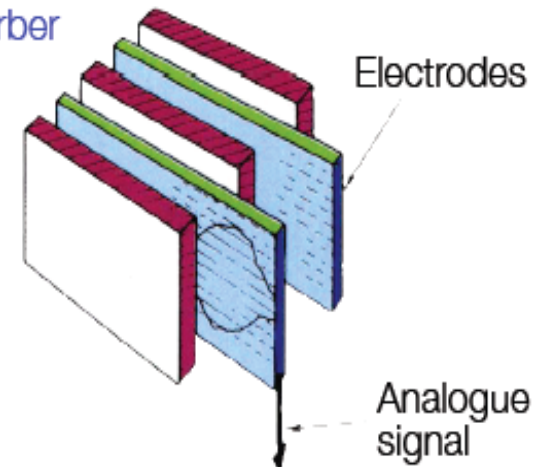
Scintillators as active layer;
signal readout via photo multipliers



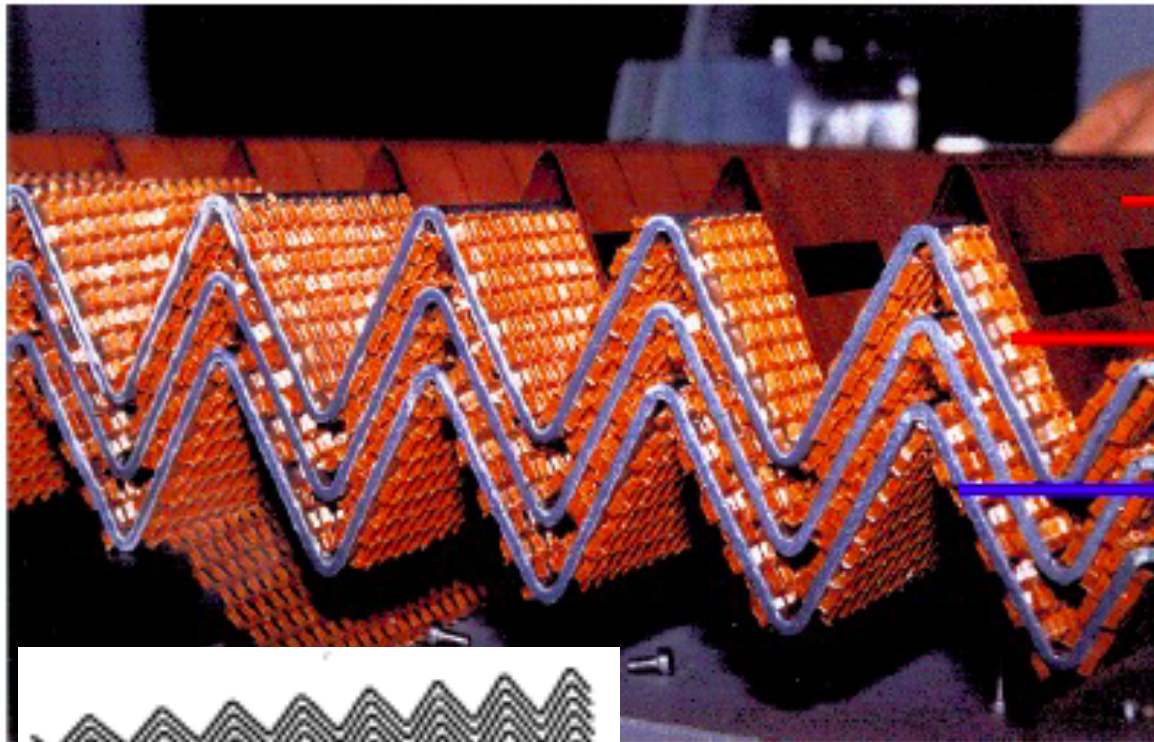
Scintillators as active
layer; wave length shifter
to convert light



Ionization chambers
between absorber
plates



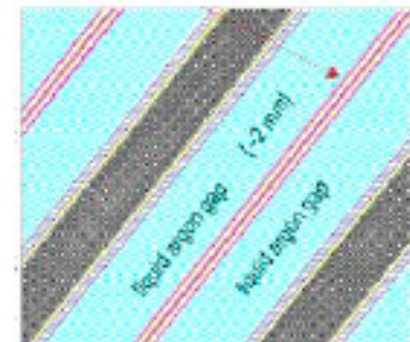
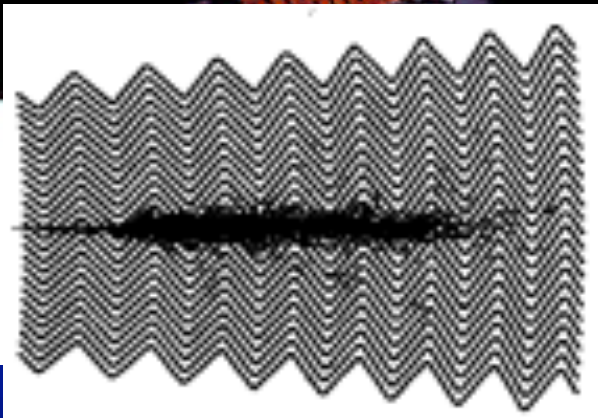
ATLAS Lar ECAL



Cu electrodes at +HV

Spacers define LAr gap
 2×2 mm

2 mm Pb absorber
clad in stainless steel.



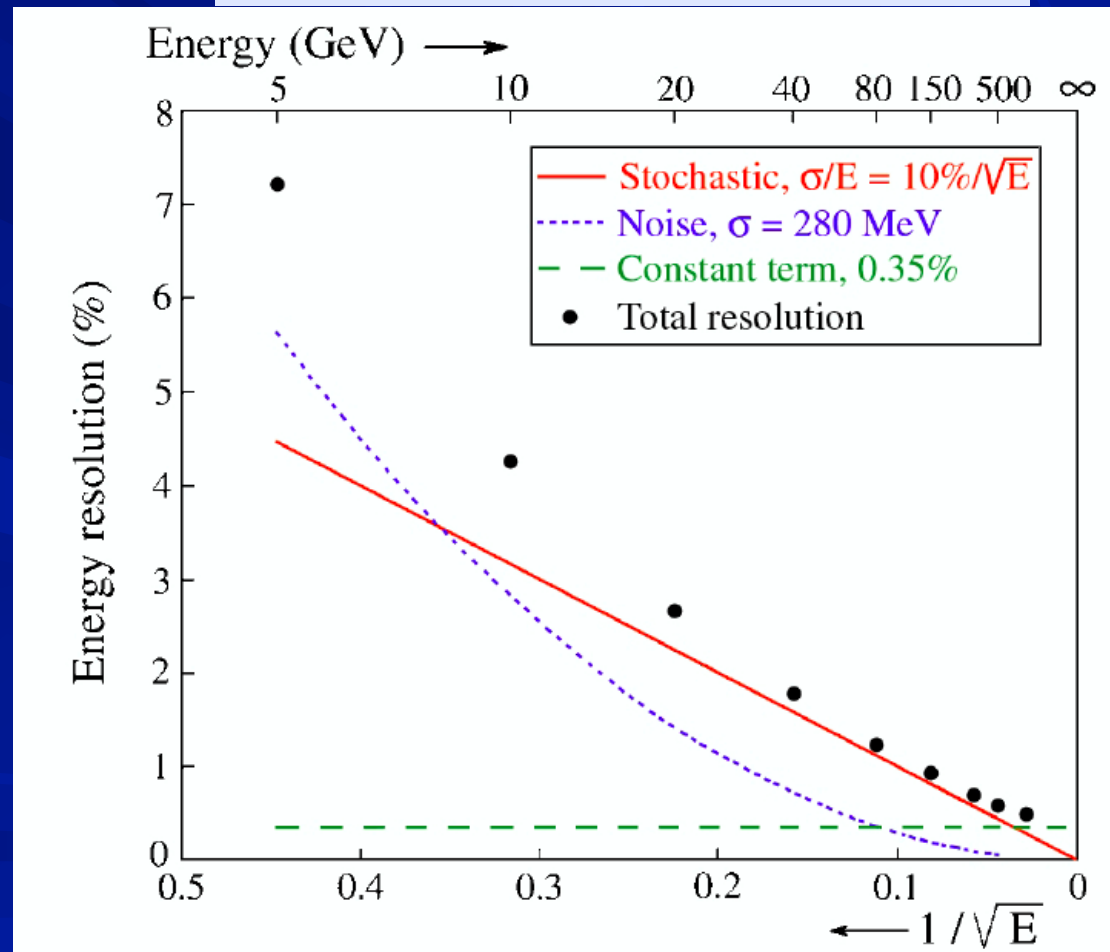
Effects on energy resolution

■ Different effects have different energy dependence

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

■ $\sigma_{\text{tot}}^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \dots$

ATLAS EM calorimeter



Energy resolution

- Ideally, if all shower particles counted:

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

- In practice

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

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

- a: stochastic term

- intrinsic statistical shower fluctuations
- sampling fluctuations
- signal quantum fluctuations (e.g. photo-electron statistics)

- b: constant term

- inhomogeneities (hardware or calibration)
- imperfections in calorimeter construction (dimensional variations, etc.)
- non-linearity of readout electronics
- fluctuations in longitudinal energy containment (leakage can also be $\sim E^{-1/4}$)
- fluctuations in energy lost in dead material before or within the calorimeter

- c: noise term

- readout electronic noise
- Radio-activity, pile-up fluctuations

Resolution in Homogenous calorimeters

- Homogeneous calorimeters: signal = sum of all E deposited by charged particles with $E > E_{\text{threshold}}$
- If W is the mean energy required to produce a 'signal quantum' (eg an electron-ion pair in a noble liquid or a 'visible' photon in a crystal) the mean number of 'quanta' produced is $\langle n \rangle = E / W$
- The intrinsic energy resolution is given by the fluctuations on n.

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

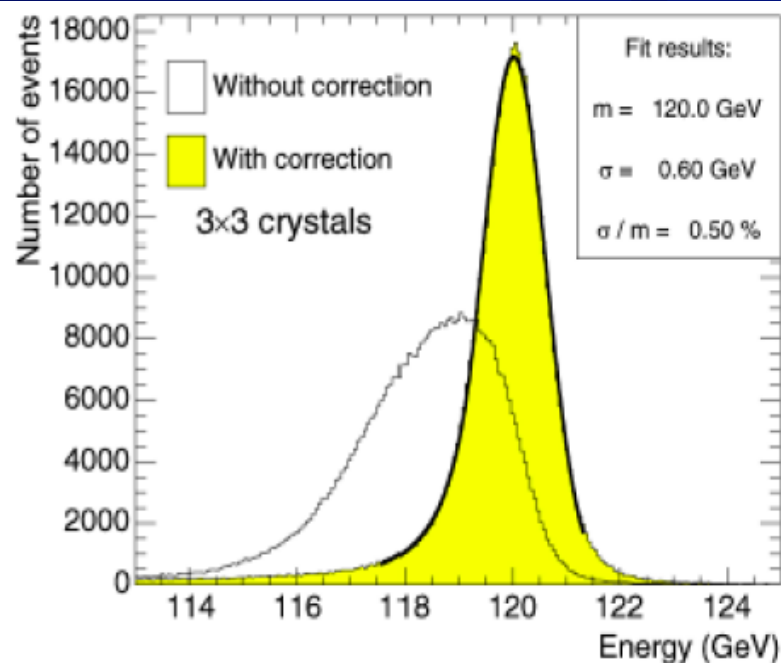
i.e. in a semiconductor crystals $W \approx 3$ eV (to produce e-hole pair)
1 MeV $\gamma = 350000$ electrons $\rightarrow 1/\sqrt{n} = 0.17\%$ stochastic term

- Fluctuations on n are reduced by correlation in the production of consecutive e-hole pairs: the Fano factor F

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

The Fano factor depends on the material

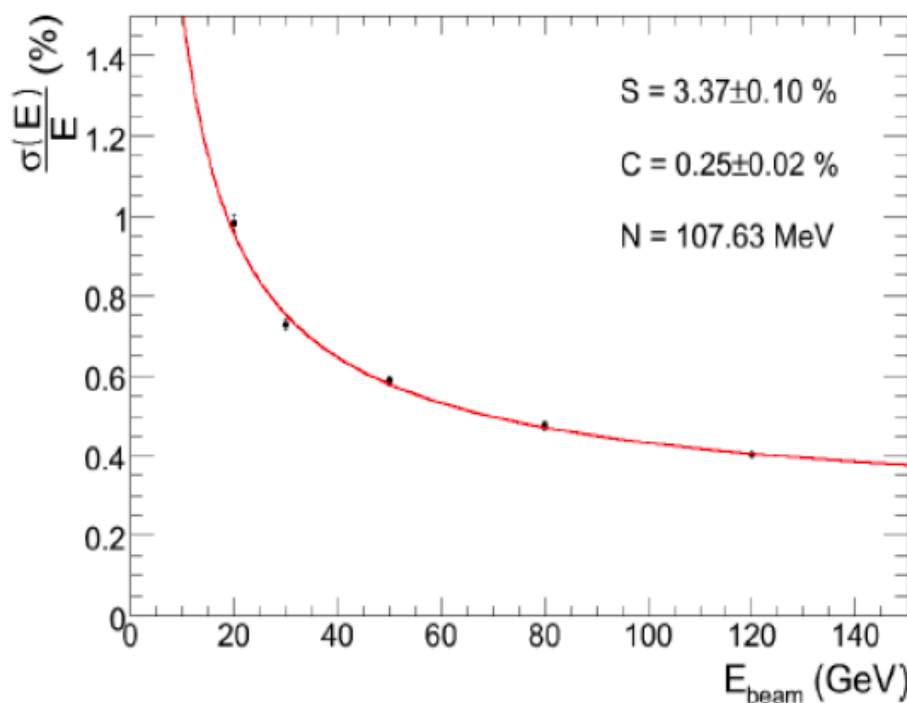
CMS ECAL resolution



Correction for radial loss

The sampling term is 3 times smaller than ATLAS; other terms are similar

$$\left(\frac{\sigma}{E}\right)^2 = \underbrace{\left(\frac{3.37\%}{\sqrt{E}}\right)^2}_{\text{stoch.}} + \underbrace{\left(\frac{0.107}{E}\right)^2}_{\text{noise}} + \underbrace{(0.25\%)^2}_{\text{const.}}$$



Resolution in Sampling calorimeters

- Main contribution: sampling fluctuations, from variations in the number of charged particles crossing the active layers.
- Increases linearly with incident energy and with the finess of the sampling.
- Thus:

$n_{ch} \propto E / t$ where t is the thickness of each absorber layer)

- For statistically independent sampling the sampling contribution to the stochastic term is:

$$\frac{\sigma_{samp}}{E} = \frac{1}{\sqrt{n_{ch}}} \propto \sqrt{\frac{t}{E}}$$

- Thus the resolution improves as t is decreased.
- For EM calorimeters the 100 samplings required to approach the resolution of homogeneous devices is not feasible

- Typically

$$\frac{\sigma_{samp}}{E} = \frac{10\%}{\sqrt{E}}$$

Homogeneous vs Sampling

E in GeV

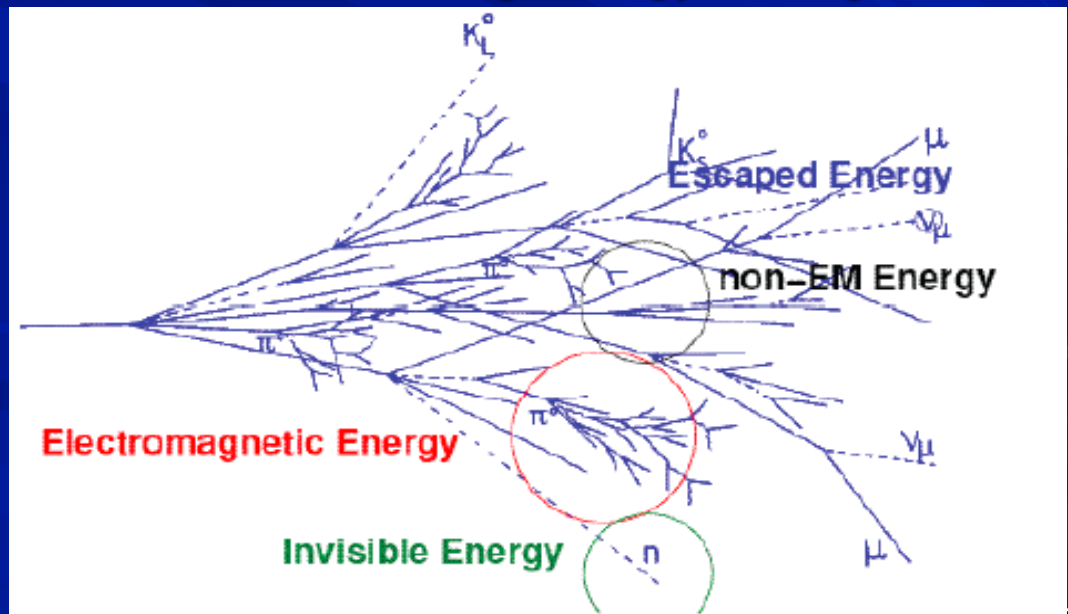
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
Bi ₄ Ge ₃ O ₁₂ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16-18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)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

Homogeneous

Sampling

Hadron Showers

- Hadrons interact with detector material also through the strong interaction
- Hadron calorimeter measurement:
 - Charged hadrons: complementary to track measurement
 - Neutral hadrons: the only way to measure their energy
- In nuclear collisions many secondary particles are produced
 - Secondary, tertiary nuclear reactions → hadronic cascades
 - Electromagnetically decaying particles (π, η) initiate EM shower
 - Energy can also be absorbed as nuclear binding energy or target recoil (Invisible energy)
- Similar to EM showers, but more complex → need simulation tools (MC)
- Characterized by the hadronic interaction length



Hadronic shower

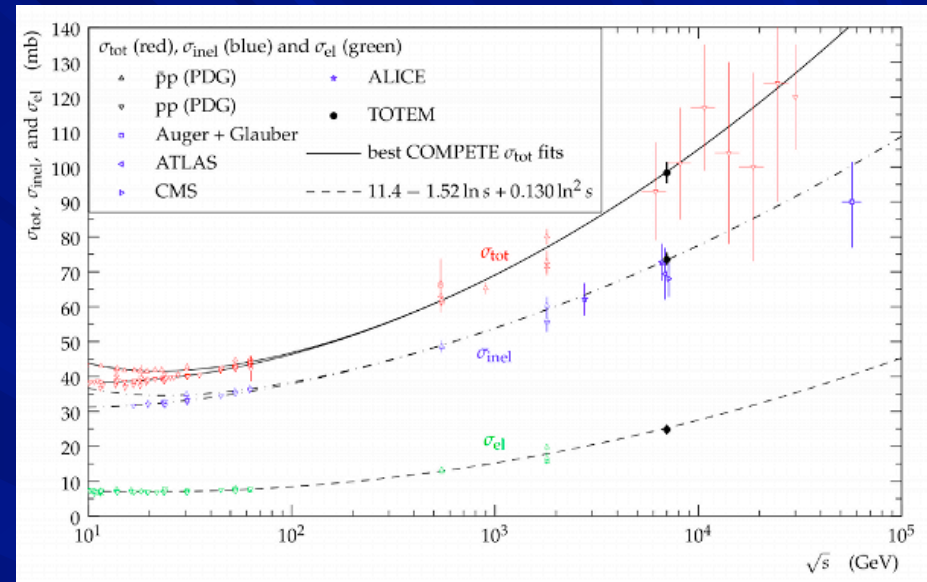
■ Hadronic interaction Cross section

$$\sigma_{Tot} = \sigma_{el} + \sigma_{inel}$$

$$\sigma_{el} \approx 10mb \quad \sigma_{inel} \approx A^{2/3}$$

$$\sigma_{Tot} = \sigma_{tot}(pp)A^{2/3}$$

where: $\sigma_{tot}(pp)$ increases with \sqrt{s}



■ Hadronic interaction length

$$\lambda_{int} = \frac{1}{\sigma_{tot} \cdot n} = \frac{A\rho}{\sigma_{pp}A^{2/3}N_A} \approx (35g/cm^2)A^{1/3}$$

$$N(x) = N(0)e^{-x/\lambda_{int}}$$

■ λ_{int} characterizes both longitudinal and transverse shower profile

Rule of thumb argument: the geometric cross section goes as the square of the size of the nucleus, a_N^2 , and since the nuclear radius scales as $a_N \sim A^{1/3}$, the nuclear mean free path in g/cm^2 units scales as $A^{1/3}$.

Hadronic vs EM showers

Hadronic vs. electromagnetic interaction length:

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

$$\lambda_{\text{int}} \gg X_0$$

[$\lambda_{\text{int}}/X_0 > 30$ possible; see below]

Typical
Longitudinal size: $6 \dots 9 \lambda_{\text{int}}$
[95% containment]

[EM: $15-20 X_0$]

Typical
Transverse size: one λ_{int}
[95% containment]

[EM: $2 R_M$; compact]

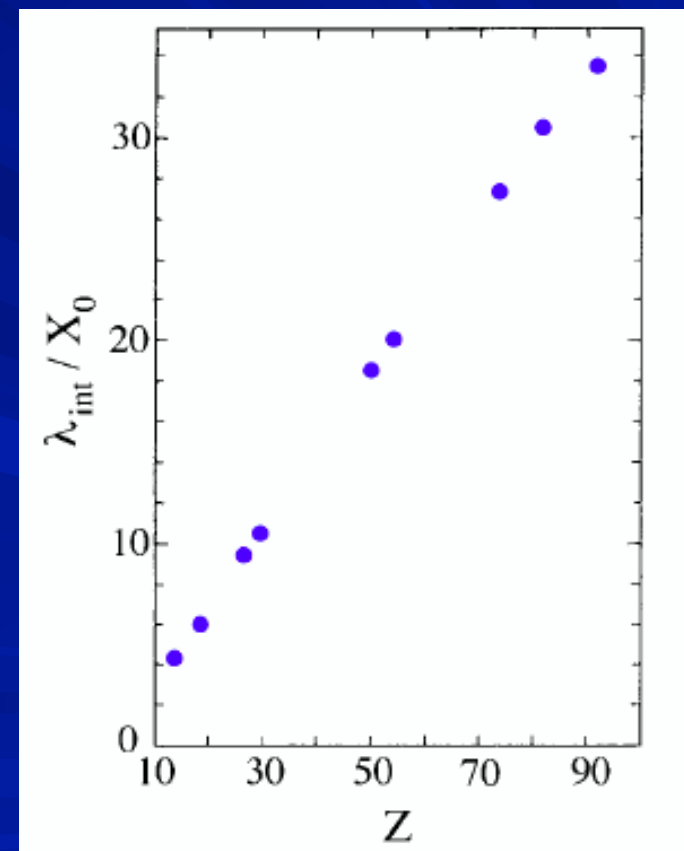
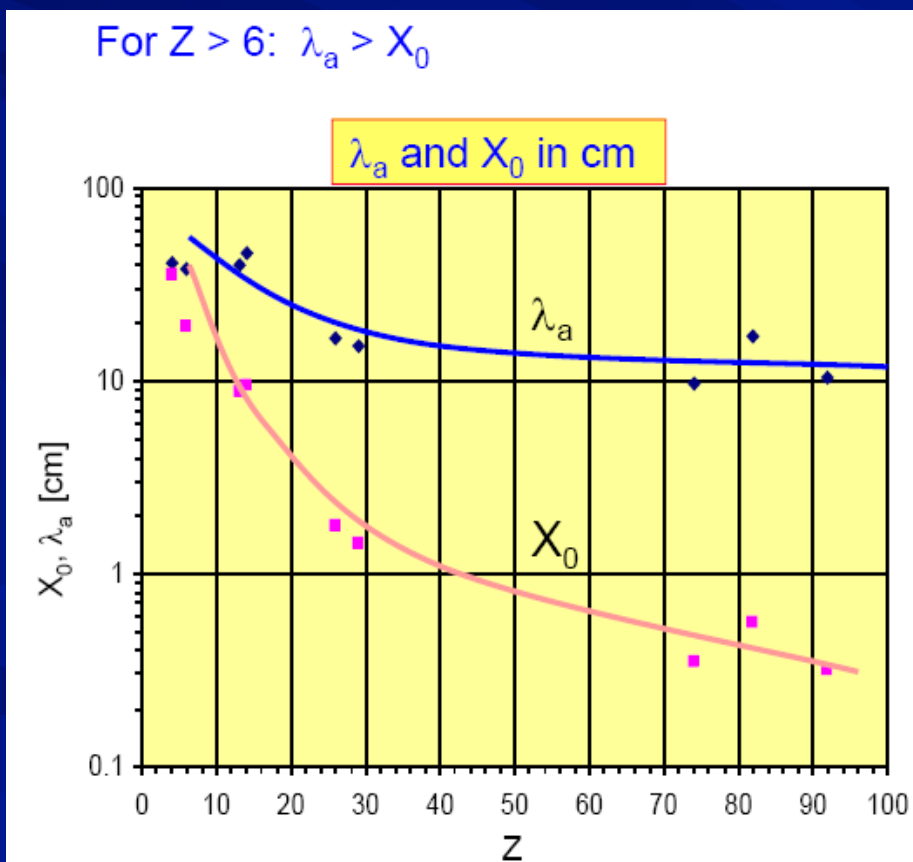
Hadronic calorimeter need more depth
than electromagnetic calorimeter ...

Some numerical values for materials
typical used in hadron calorimeters

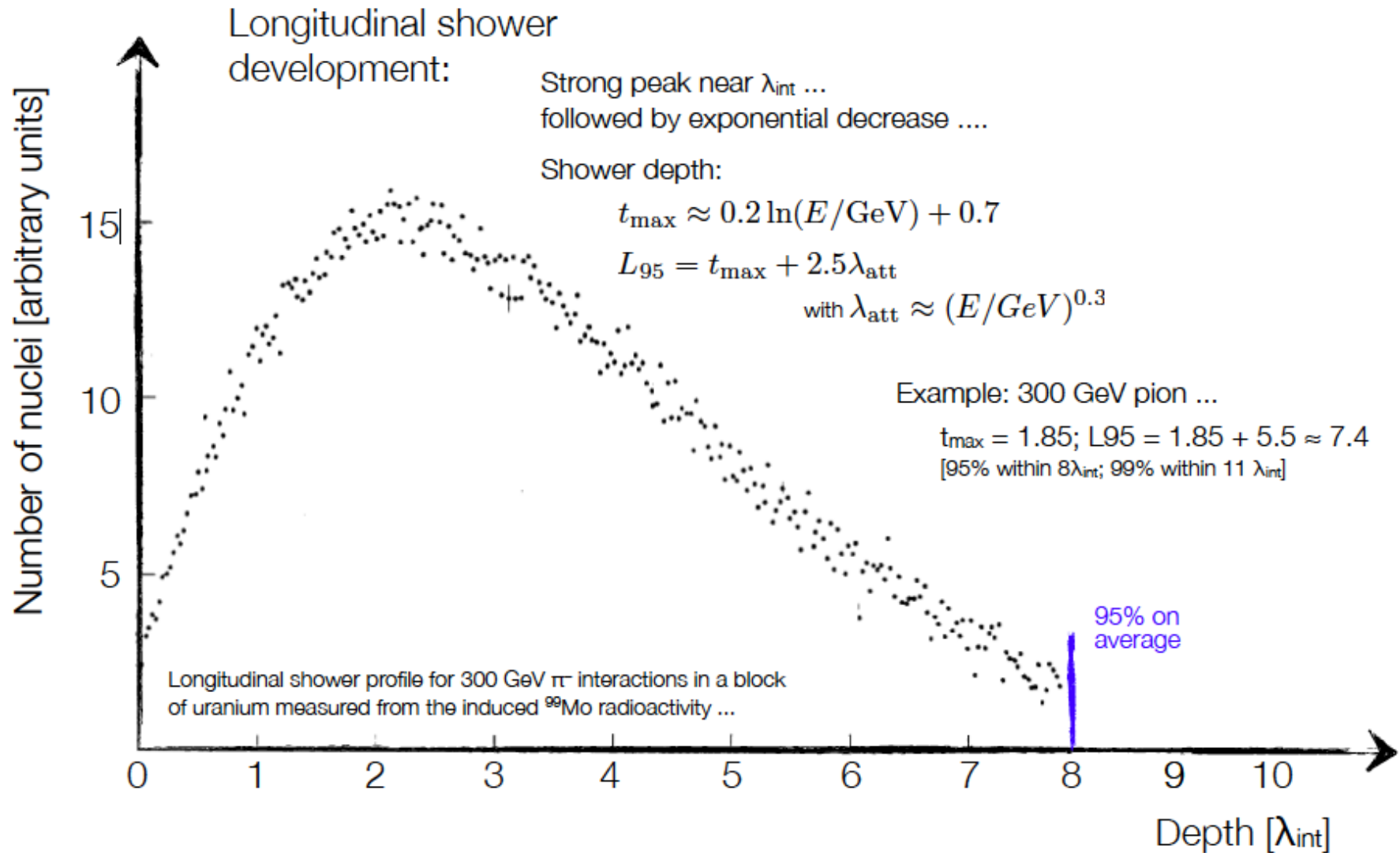
	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

Material dependence

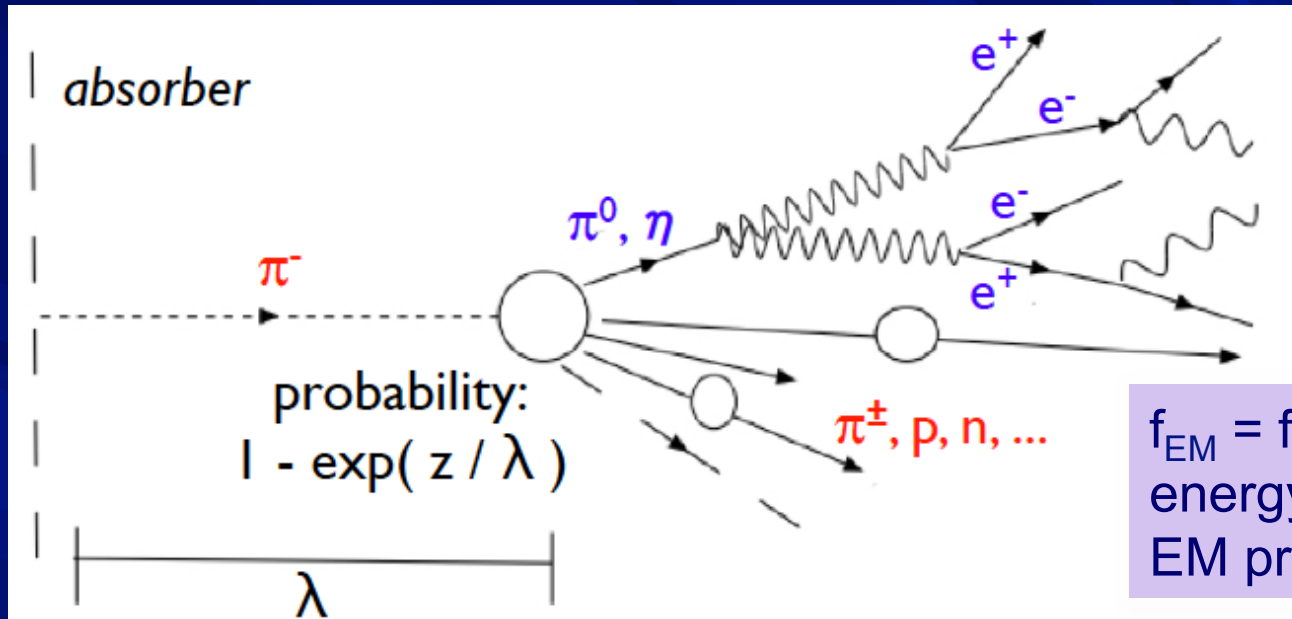
- λ_{int} : mean free path between nuclear collisions
- $\lambda_{\text{int}} \text{ (g cm}^{-2}\text{)} \propto A^{1/3}$
- Hadron showers are much longer than EM ones. Length depends on Z



Hadronic shower: Longitudinal development



Hadronic Shower



π^0 can deposit energy via EM processes

f_{EM} = fraction of hadron energy deposited via EM processes

- Electromagnetic
 - ionization, excitation (e^\pm)
 - photo effect, scattering (γ)
- Hadronic
 - ionization (π^\pm, p)
 - invisible energy (binding, recoil)

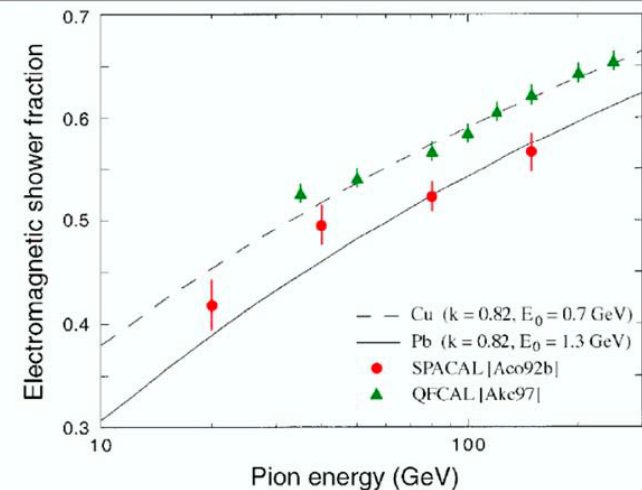


FIG. 2.22. Comparison between the experimental results on the em fraction of pion-induced showers in the (copper-based) QFCAL and (lead-based) SPACAL detectors. Data from [Ake 97] and [Aco 92b].

EM fraction in hadronic calorimeters

Charge conversion of $\pi^{+/-}$ produces electromagnetic component of hadronic shower (π^0)

- e = response to the EM shower component
- h = response to the non-EM component

$$\pi = f_{\text{em}} e + (1 - f_{\text{em}}) h$$

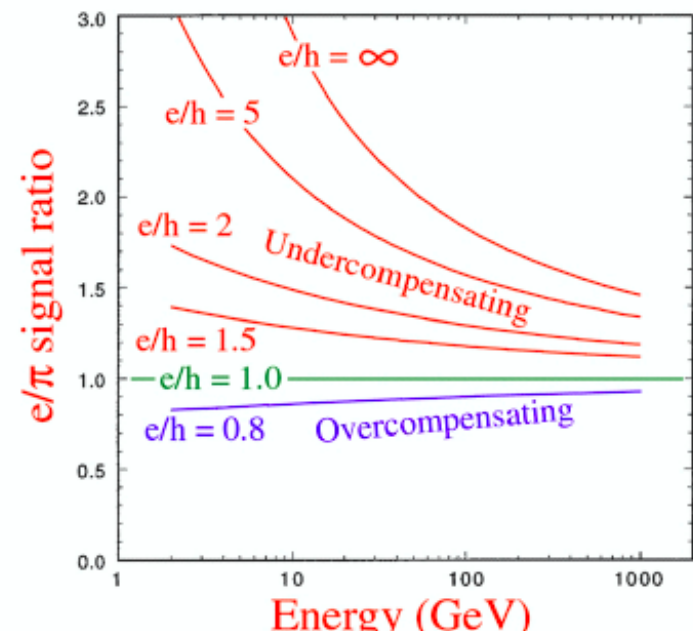
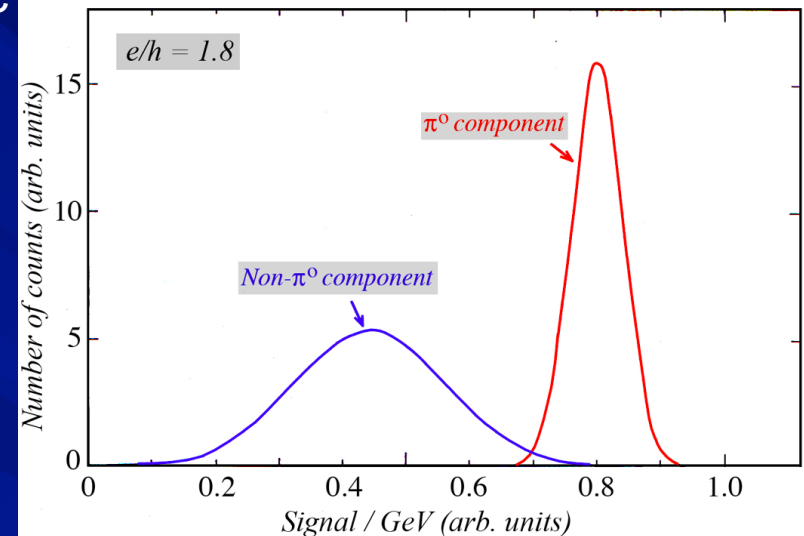
Comparing pion and electron showers:

$$\frac{e}{\pi} = \frac{e}{f_{\text{em}} e + (1 - f_{\text{em}}) h} = \frac{e}{h} \cdot \frac{1}{1 + f_{\text{em}} (e/h - 1)}$$

Calorimeters can be:

- Overcompensating $e/h < 1$
- Undercompensating $e/h > 1$
- Compensating $e/h = 1$

The origin of the non-compensation problems



Compensation

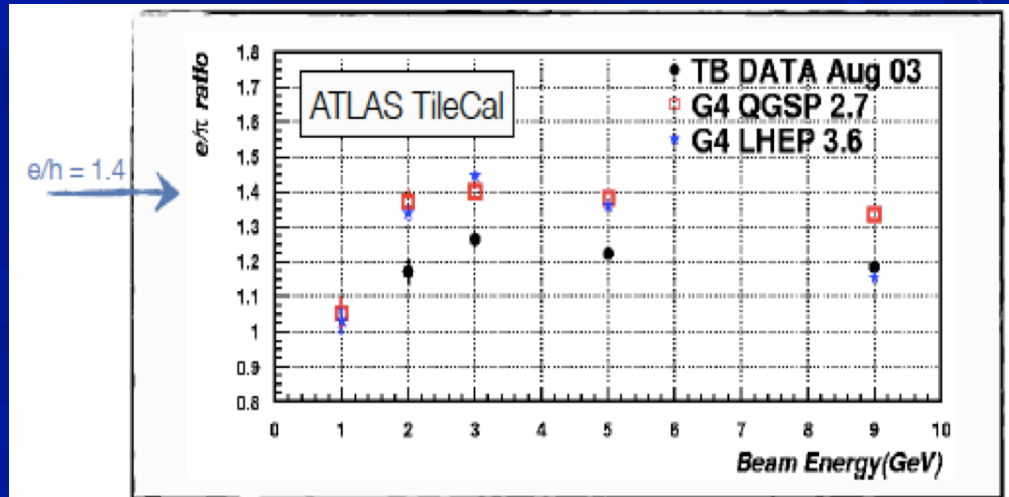
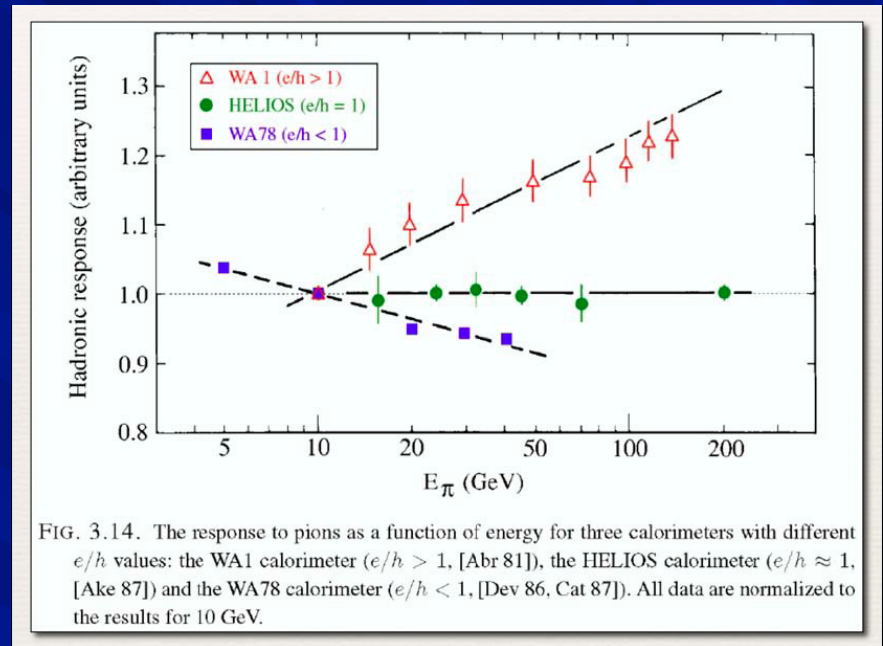
- Non-linearity determined by e/h value of the calorimeter
- Measurement of non-linearity is one of the methods to determine e/h
- Assuming linearity for EM showers, $e(E_1)=e(E_2)$:

$$\frac{\pi(E_1)}{\pi(E_2)} = \frac{f_{\text{em}}(E_1) + [1 - f_{\text{em}}(E_1)] \cdot e/h}{f_{\text{em}}(E_2) + [1 - f_{\text{em}}(E_2)] \cdot e/h}$$

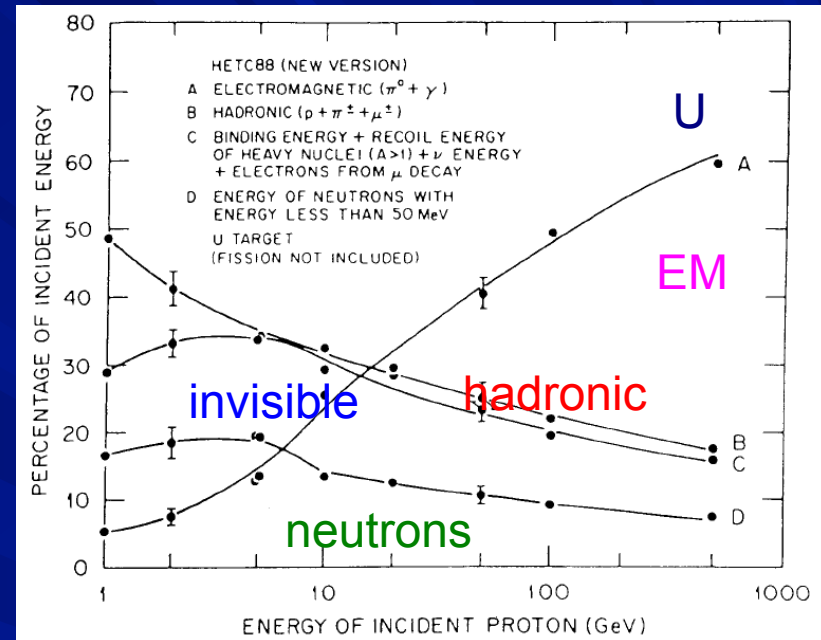
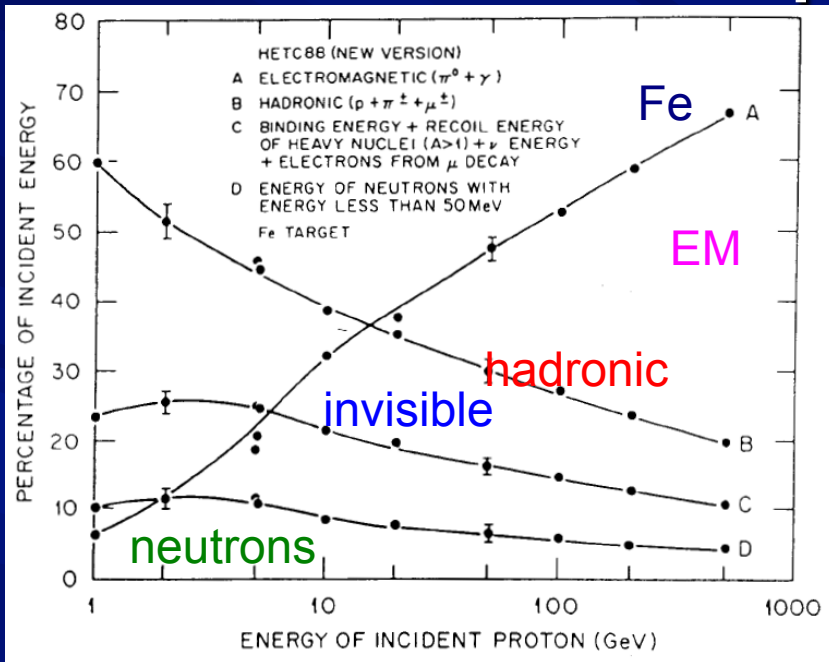
For $e/h=1 \rightarrow$

$$\frac{\pi(E_1)}{\pi(E_2)} = 1$$

- Response of calorimeters is usually higher for electromagnetic (e) than hadronic (h) energy deposits $\rightarrow e/h > 1$



Compensation



$$E_p = f_{em} e + (1 - f_{em}) h$$

$$h = f_{rel} \cdot rel + f_p \cdot p + f_n \cdot n + f_{inv} \cdot inv$$

Energy deposition mechanisms

- f_{rel} = Ionization by charged pions
- f_p = spallation protons
- f_n = neutrons evaporation
- f_{inv} = invisible energy by recoil nuclei

■ Compensation:

- Tuning the neutron response using hydrogenous active material (L3 Uranium/gas calorimeter)
- Compensation adjusting the sampling frequency

Compensation by tuning neutron response

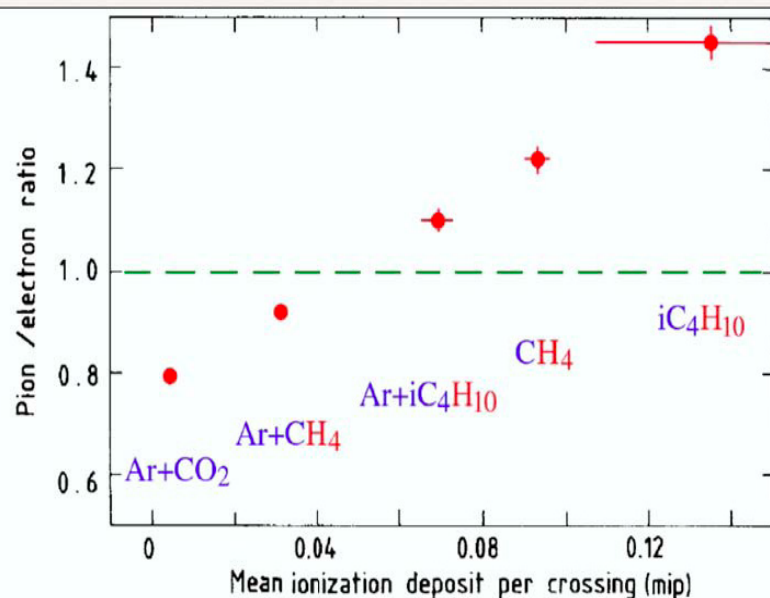
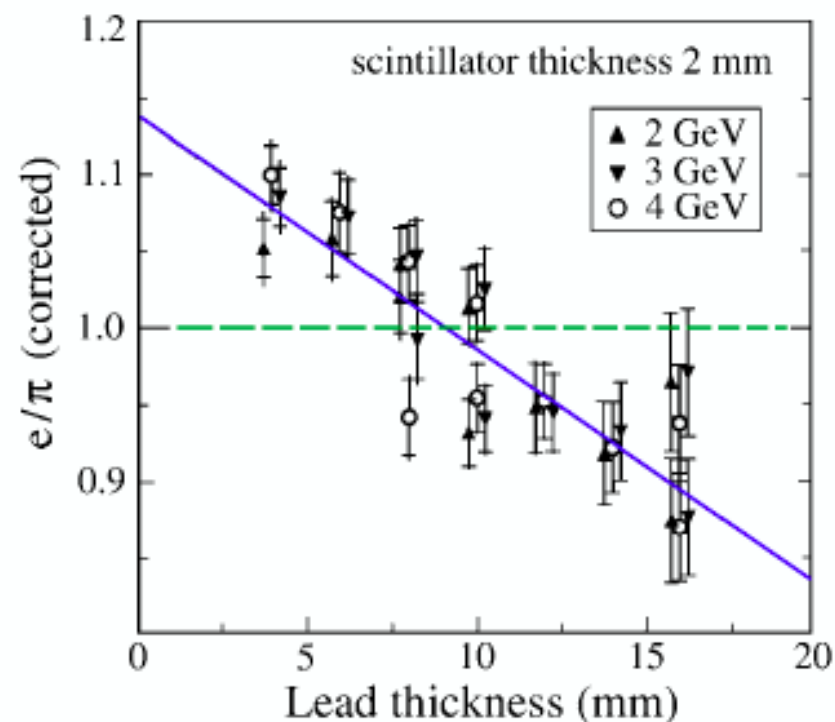
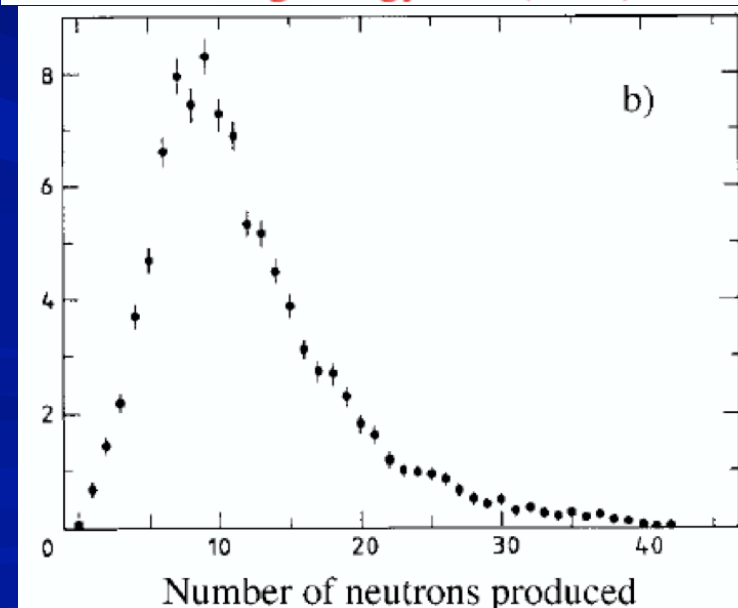
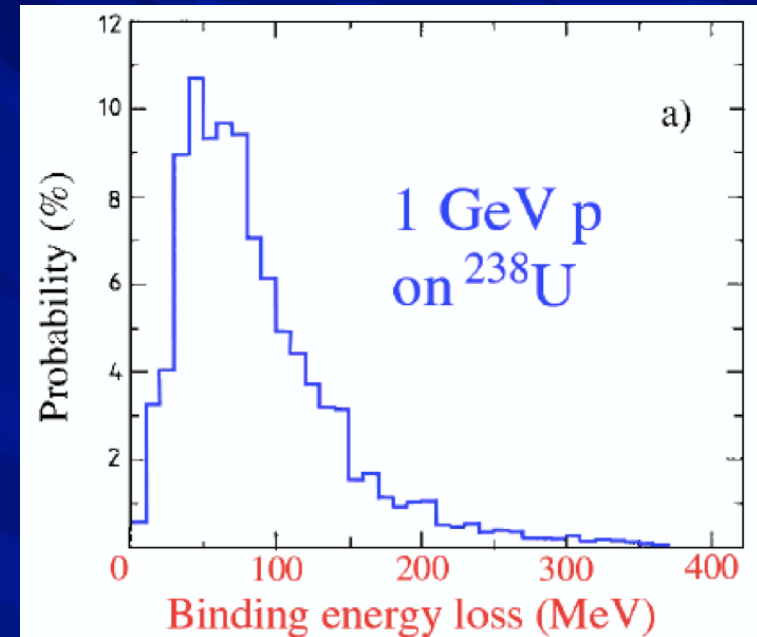


FIG. 3.32. The pion/electron signal ratio, averaged over the energy range 1.5 GeV, measured for different gas mixtures with the uranium/gas calorimeter of the L3 Collaboration. The horizontal scale gives the (calculated) average energy deposit in a chamber gap by slow neutrons [Gal 86].



Energy resolution of hadronic showers

- Fluctuations in visible energy (ultimate limit of hadronic energy resolution)
 - fluctuations of nuclear binding energy loss in high-Z materials $\sim 15\%$
- Fluctuations in the EM shower fraction, f_{em}
 - Dominating effect in most hadron calorimeters ($e/h > 1$)
 - Fluctuations are asymmetric in pion showers Differences between p , π induced showers
 - No leading π^0 in proton showers
- Sampling fluctuations sampling fluctuations only minor contribution to hadronic resolution in non-compensating calorimeter



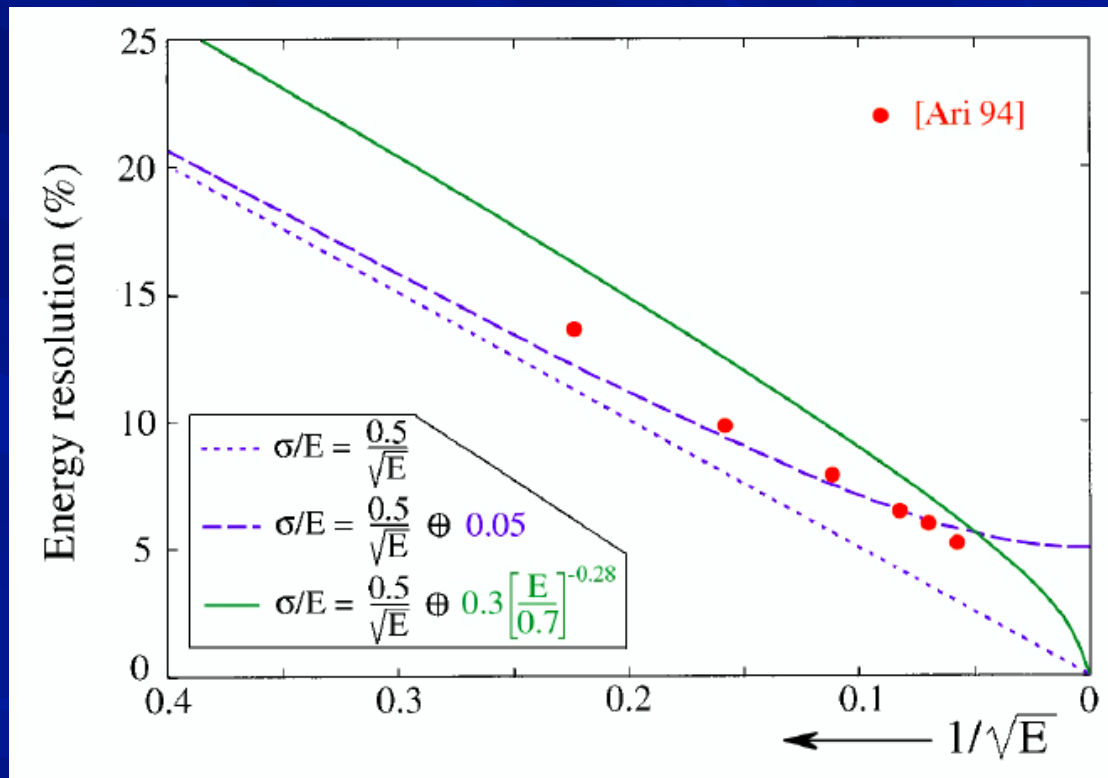
Energy resolution of hadron showers

- Hadronic energy resolution of non-compensating calorimeters does not scale with $1/\sqrt{E}$ but as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \left(\frac{E}{E_0} \right)$$

- But in practice we use

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



A realistic calorimetric system

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

Different setups chosen for
optimal energy resolution ...

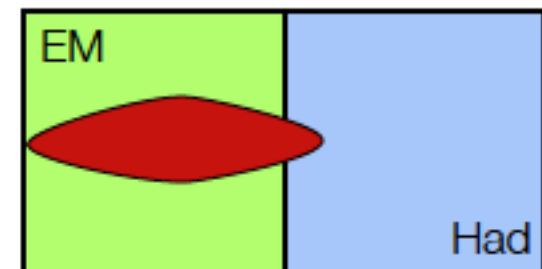
But:

Hadronic energy measured in
both parts of calorimeter ...

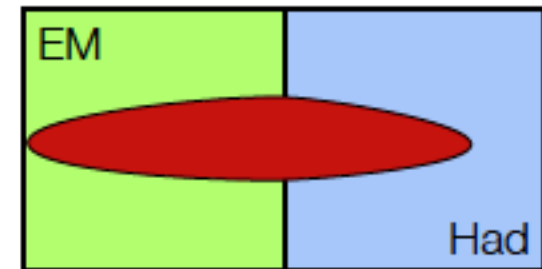
Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter

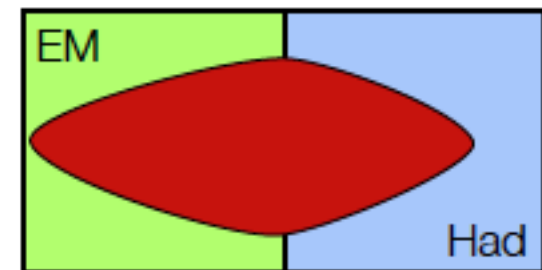
Electrons
Photons



Taus
Hadrons



Jets



LHC CALORIMETERS



CMS

5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout



ATLAS

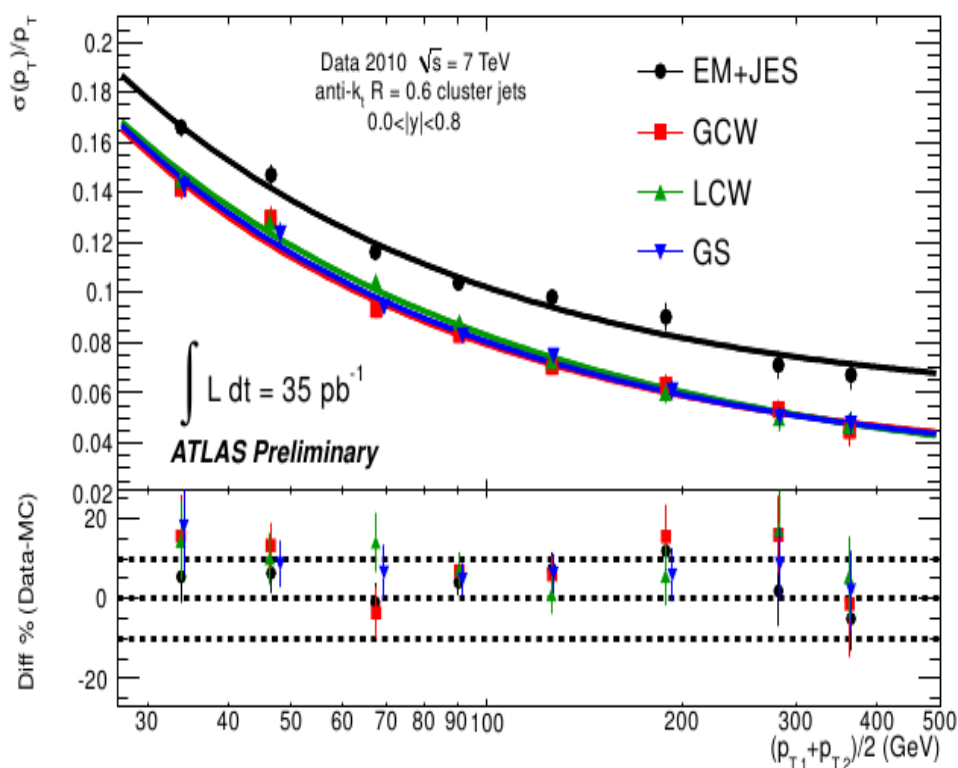
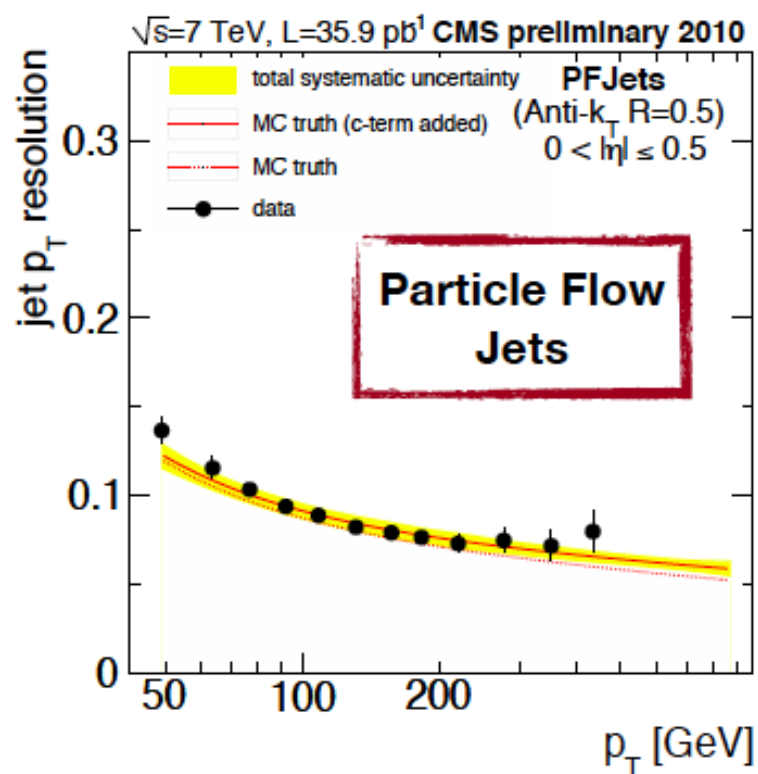
14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

Hadronic calorimeters resolution

- HCAL only
 $\sigma/E = (93.8 \pm 0.9)\%/\sqrt{E} \oplus (4.4 \pm 0.1)\%$
- ECAL+HCAL
 $\sigma/E = (82.6 \pm 0.6)\%/\sqrt{E} \oplus (4.5 \pm 0.1)\%$

- Improved resolution using full calorimetric system (ECAL+HCAL)

ATLAS LAr + Tile for pions: $\frac{\sigma(E)}{E} = \frac{42\%}{\sqrt{E}} \oplus 2\%$

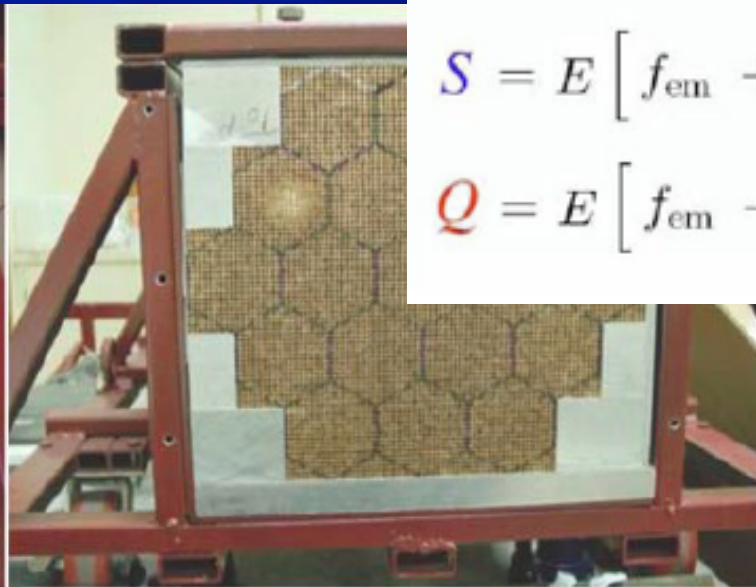
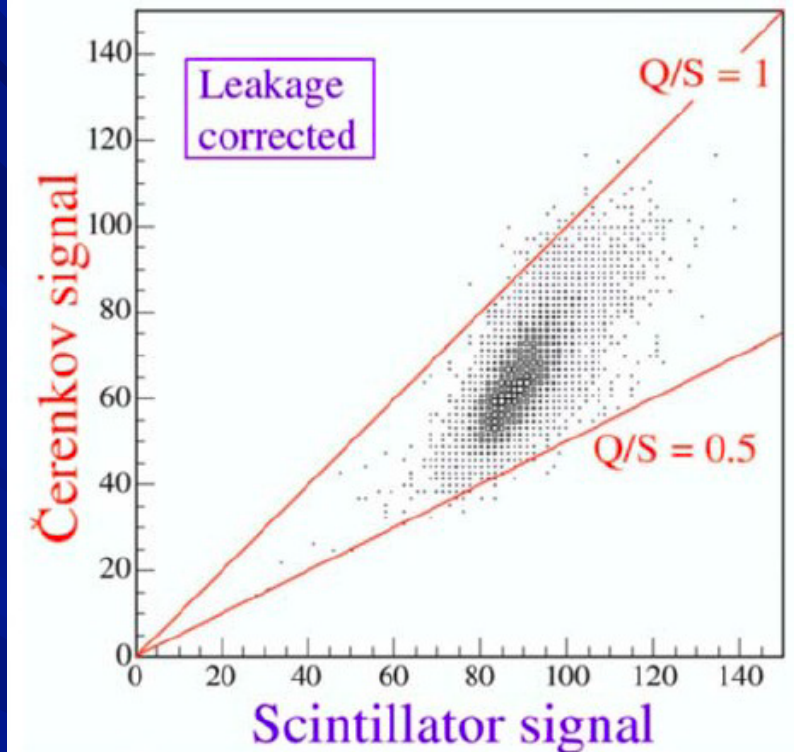


Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 30-50 years:
- Two approaches:
 - minimize the influence of the calorimeter and measure jets using the combination of all detectors → Particle Flow
 - measure the shower hadronic shower components in each event & weight directly access the source of fluctuations → Dual (Triple) Readout

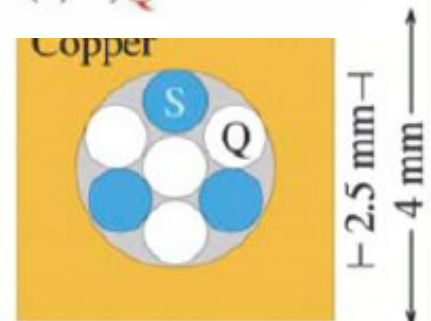
DREAM

- Measure f_{EM} cell-by-cell by comparing Cherenkov and dE/dx signals
- Densely packed SPAGetti CALorimeter with interleaved Quartz (Cherenkov) and Scintillating Fibers
- Production of Cherenkov light only by em particles (f_{EM})
- Aim at: $\sigma_E/E \sim 15\%/\sqrt{E}$



$$S = E \left[f_{em} + \frac{1}{(e/h)_S} (1 - f_{em}) \right]$$

$$Q = E \left[f_{em} + \frac{1}{(e/h)_Q} (1 - f_{em}) \right]$$



Particle flow

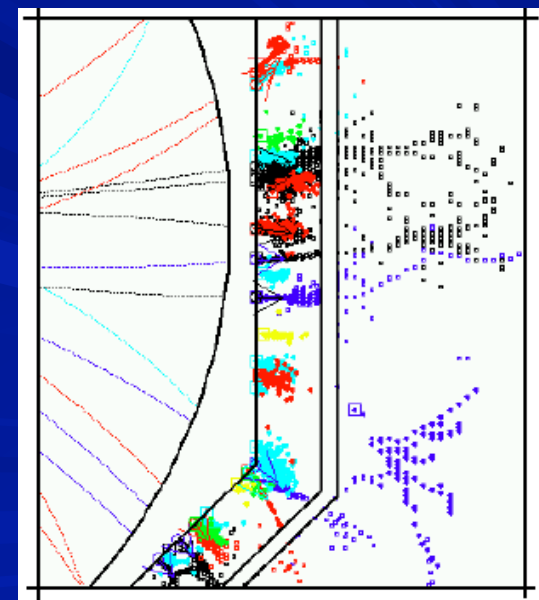
Component	Detector	Fraction	Part. resolution	Jet Energy Res.
Charged (X^\pm)	Tracker	60%	$10^{-4} E_x$	negligible
Photons (γ)	ECAL	30%	$0.1/\sqrt{E_\gamma}$	$.06/\sqrt{E_{jet}}$
Neutral Hadrons (h)	E/HCAL	10%	$0.5/\sqrt{E_{had}}$	$.16/\sqrt{E_{jet}}$

$$E_{JET} = E_{ECAL} + E_{HCAL}$$

$$E_{JET} = E_{TRACK} + E_\gamma + E_n$$

■ Granularity more important than resolution

- ECAL Tungsten – silicon
- ECAL Tungsten - scintillator strips
- ECAL Tungsten – MAPS (Monolithic Active Pixel Sensors, CMOS technology) (DECAL)
- HCAL scintillator Tiles
- HCAL digital RPC or GEM (DHCAL)
- ➔ HCAL semidigital gas (RPC or MICROMEAS) device (SDGHCAL)
- TCMT : Scintillator/SiPM muon tagger



■ BACKUP

Summary

Radiation length:

$$X_0 = \frac{180A}{Z^2} \frac{\text{g}}{\text{cm}^2}$$

Critical energy:

[Attention: Definition of Rossi used]

$$E_c = \frac{550 \text{ MeV}}{Z}$$

Shower maximum:

$$t_{\max} = \ln \frac{E}{E_c} - \begin{cases} 1.0 & e^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

Longitudinal
energy containment:

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

Transverse
Energy containment:

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

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

Problem:

Calculate how much Pb, Fe or Cu is needed to stop a 10 GeV electron.

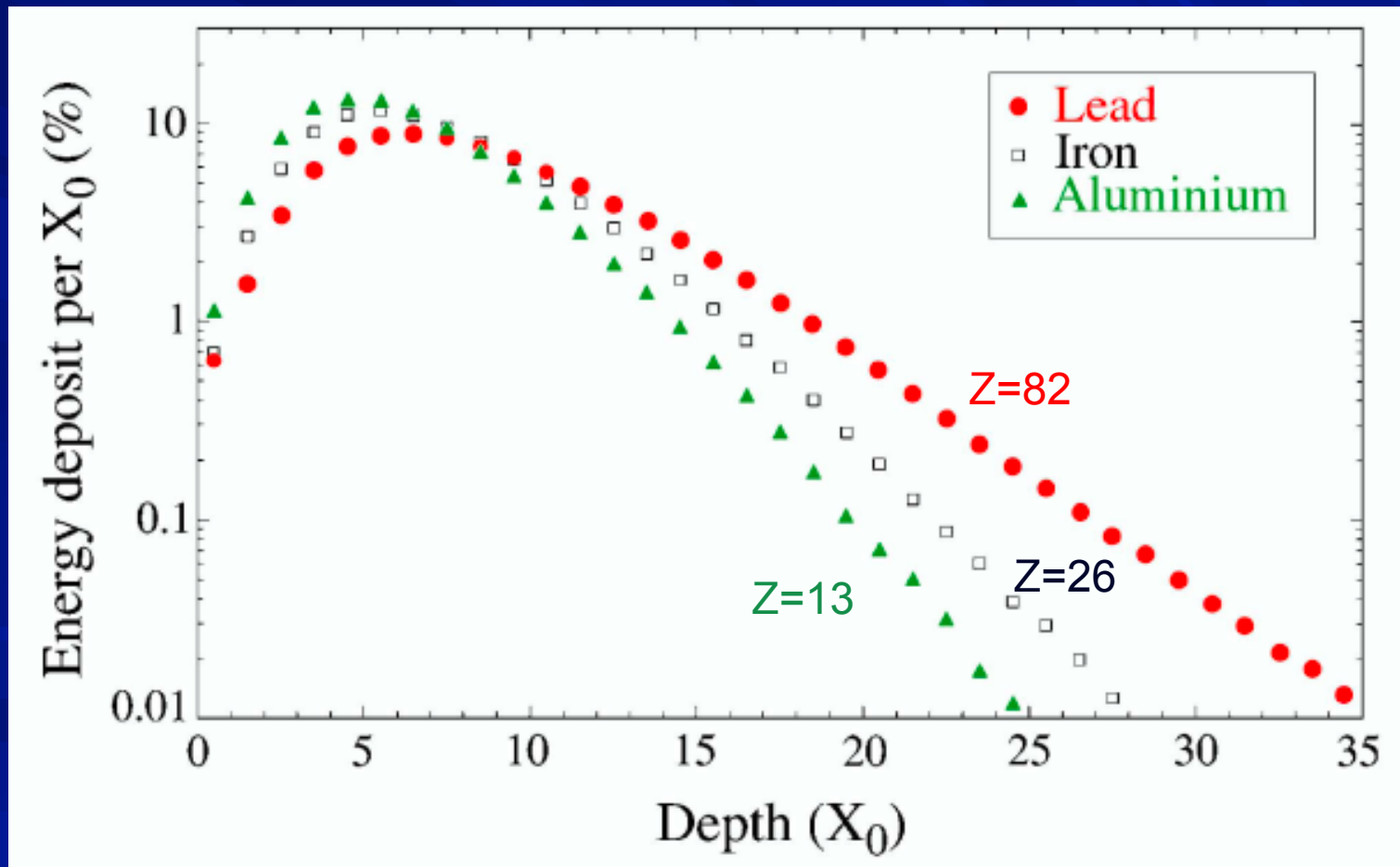
Pb : $Z=82$, $A=207$, $\rho=11.34 \text{ g/cm}^3$

Fe : $Z=26$, $A=56$, $\rho=7.87 \text{ g/cm}^3$

Cu : $Z=29$, $A=63$, $\rho=8.92 \text{ g/cm}^3$

Longitudinal development of EM shower

- Shower decay: after the shower maximum the shower decays slowly through ionization and Compton scattering → proportional to X_0

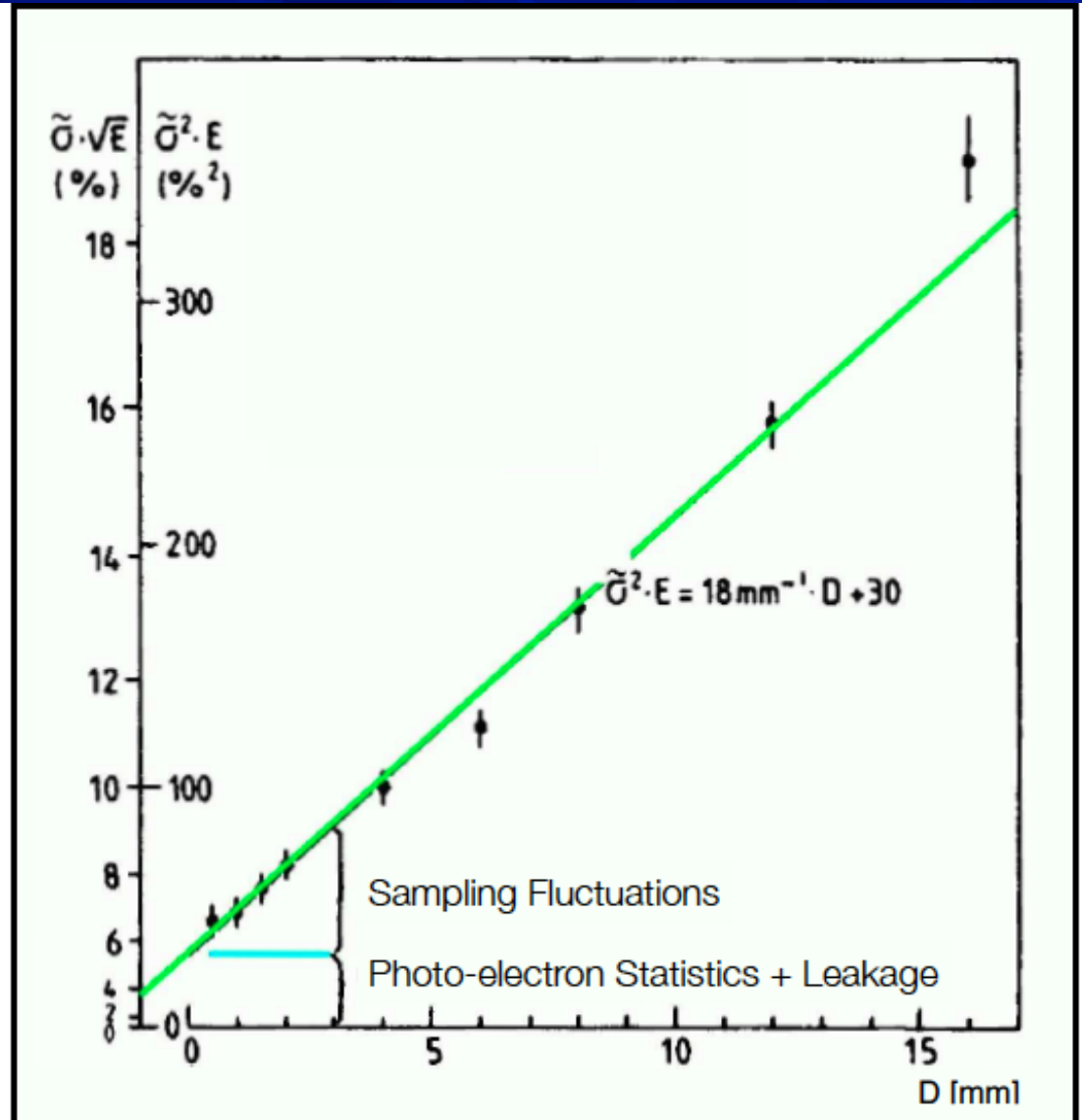


Dependence on sampling

Measure energy resolution of a sampling calorimeter for different absorber thicknesses

Sampling contribution:

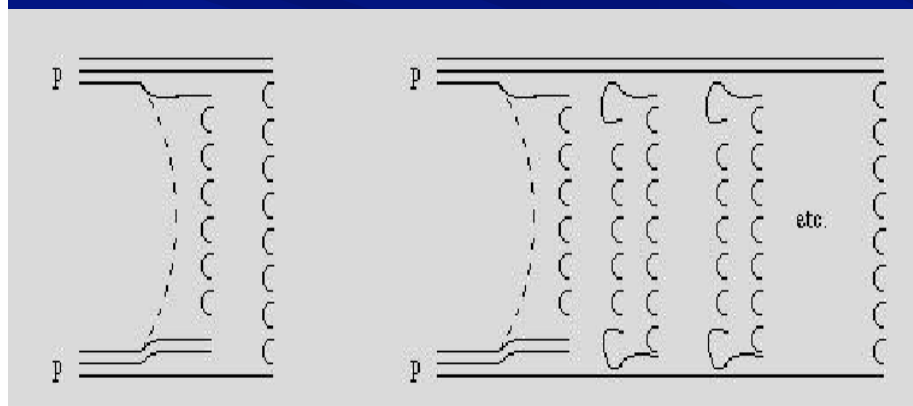
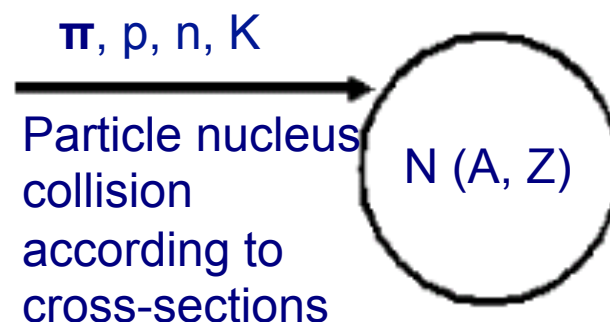
$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c [\text{MeV}] \cdot t_{\text{abs}}}{F \cdot E [\text{GeV}]}}$$



Hadronic interactions

1st stage: the hard collision

- pions travel 25-50% longer than protons ($\sim 2/3$ smaller in size)
- a pion loses ~ 100 -300 MeV by ionization (Z dependent)



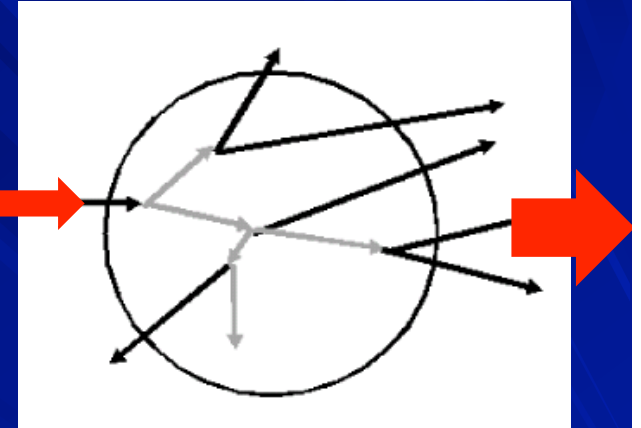
Nucleon is split in quark di-quark
Strings are formed String hadronisation
(adding $q\bar{q}$ pair)
fragmentation of damaged nucleus

- Particle multiplication (string model)
 - average energy needed to produce a pion 0.7 (1.3) GeV in Cu (Pb)
 - Multiplicity scales with E and particle type
 - $\sim 1/3 \pi^0 \rightarrow \gamma\gamma$ produced in charge exchange processes: $\pi^+p \rightarrow \pi^0n$ and $\pi^-n \rightarrow \pi^0p$
 - Leading particle effect: depends on incident hadron type e.g fewer π^0 from protons, baryon number conservation

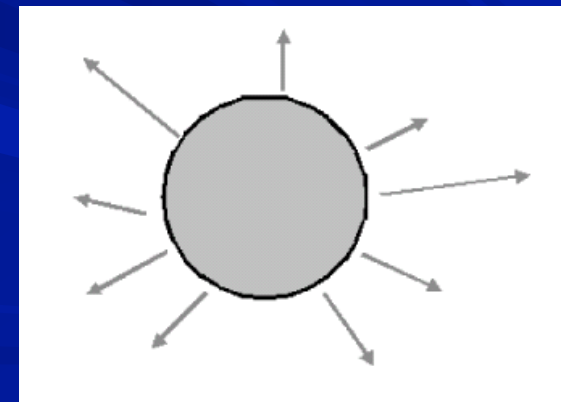
Hadronic interactions

2nd stage: spallation

- A fast hadron traversing the nucleus frees protons and neutrons in number proportional to their numerical presence in the nucleus.
- The nucleons involved in the cascade transfer energy to the nucleus which is left in an excited state
- Nuclear de-excitation
 - Evaporation of soft (~ 10 MeV) nucleons and α
 - fission for some materials
- The number of nucleons released depends on the binding E (7.9 MeV in Pb, 8.8 MeV in Fe)
- Mainly neutrons released by evaporation \rightarrow protons are trapped by the Coulomb barrier (12 MeV in Pb, only 5 MeV in Fe)

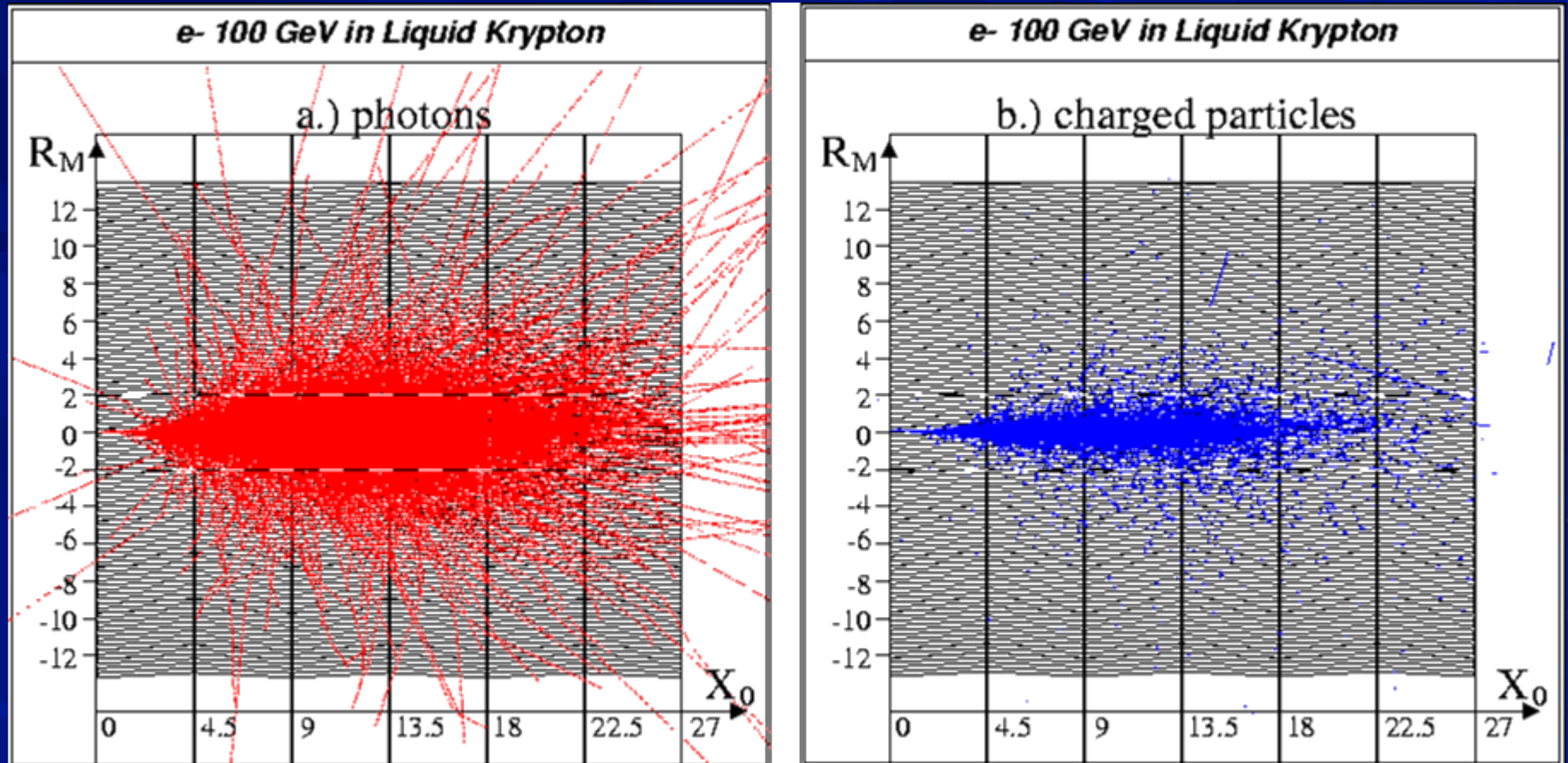


Dominating momentum component along incoming particle direction



isotropic process

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

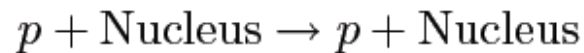


GEANT simulation of a 100 GeV electron shower in the NA48 liquid Krypton calorimeter (D.Schinzel)

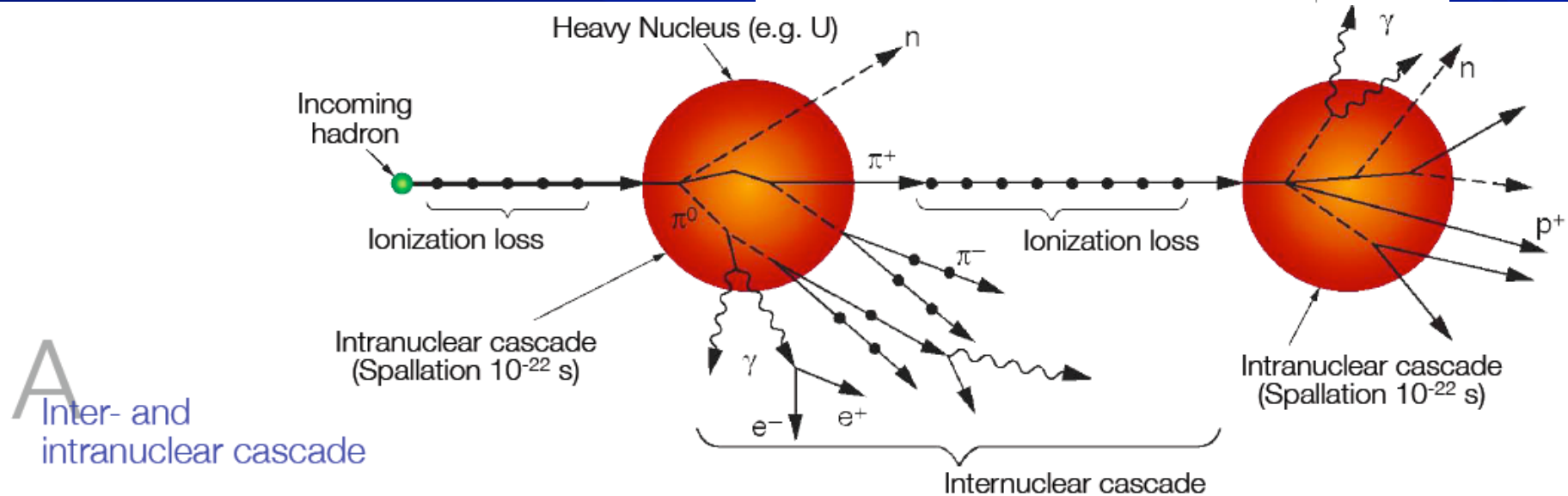
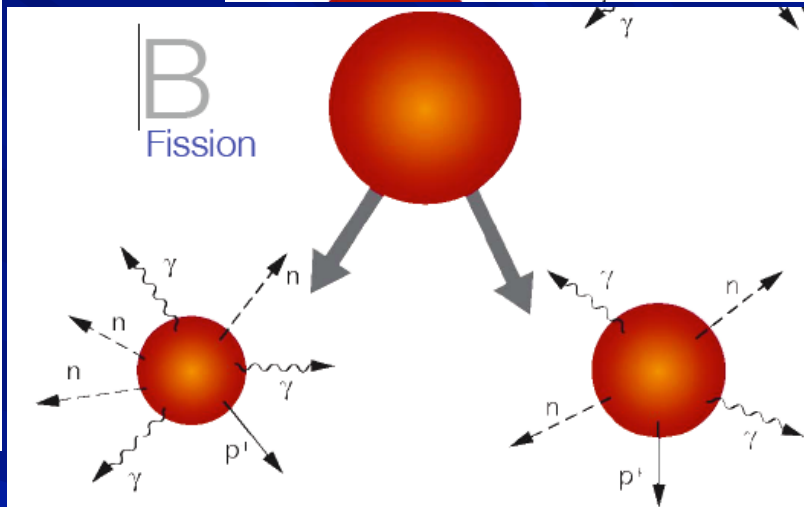
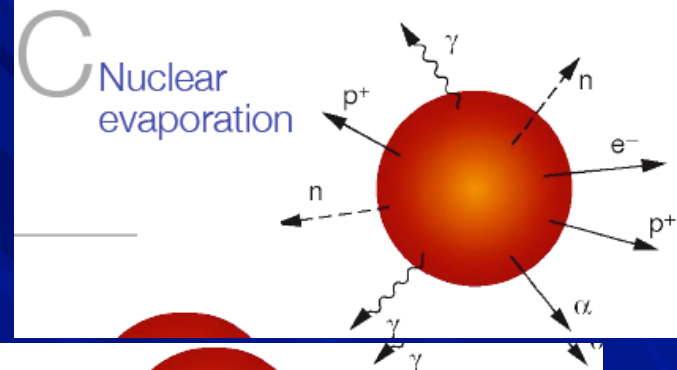
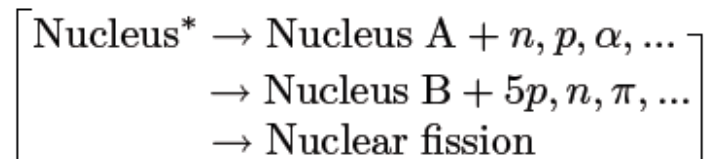
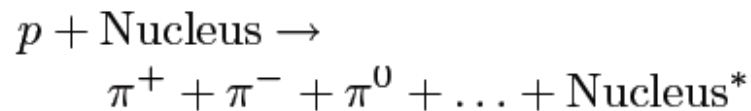
Hadronic shower

Hadronic interaction:

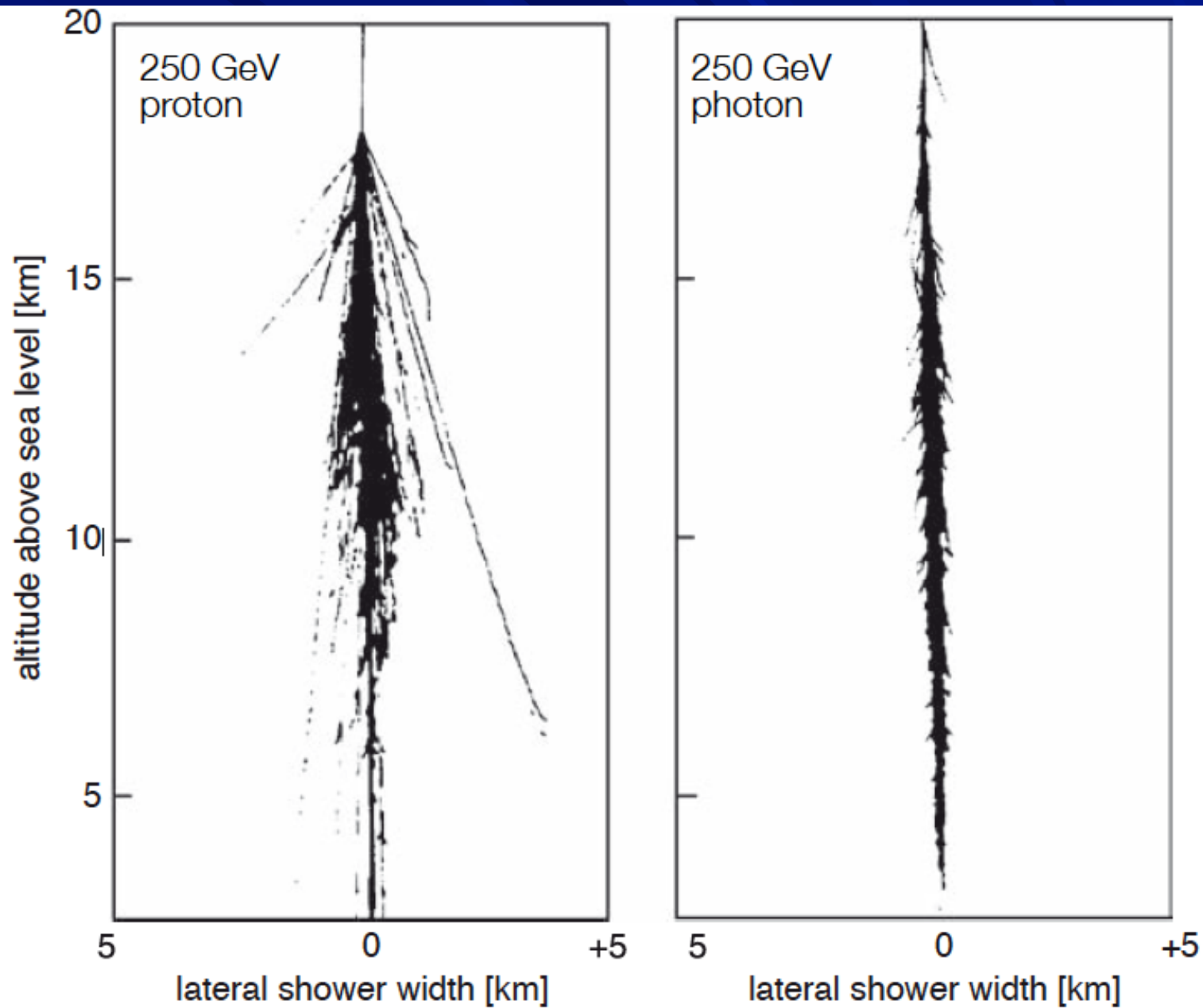
Elastic:



Inelastic:



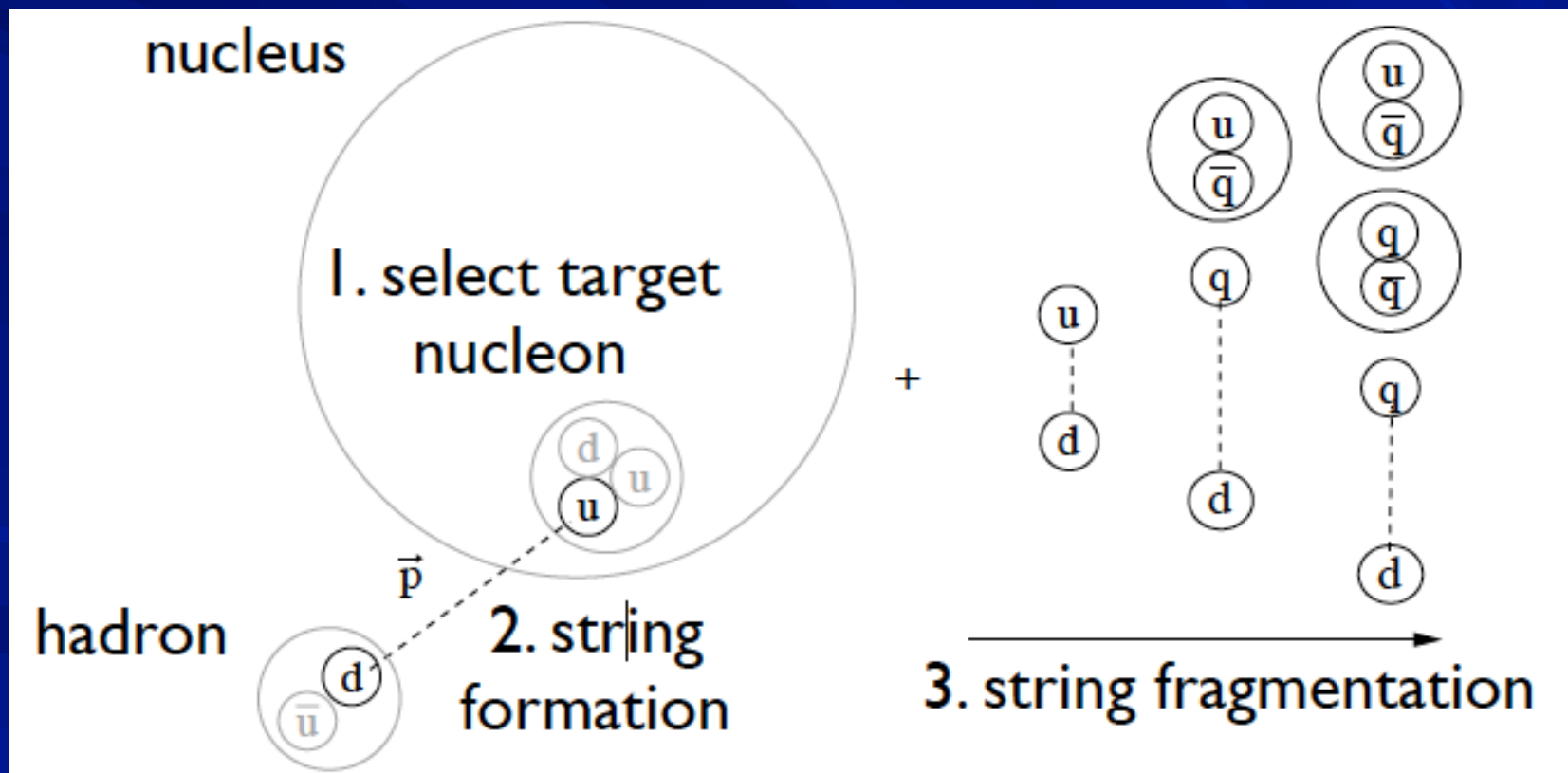
Hadronic shower



EM shower

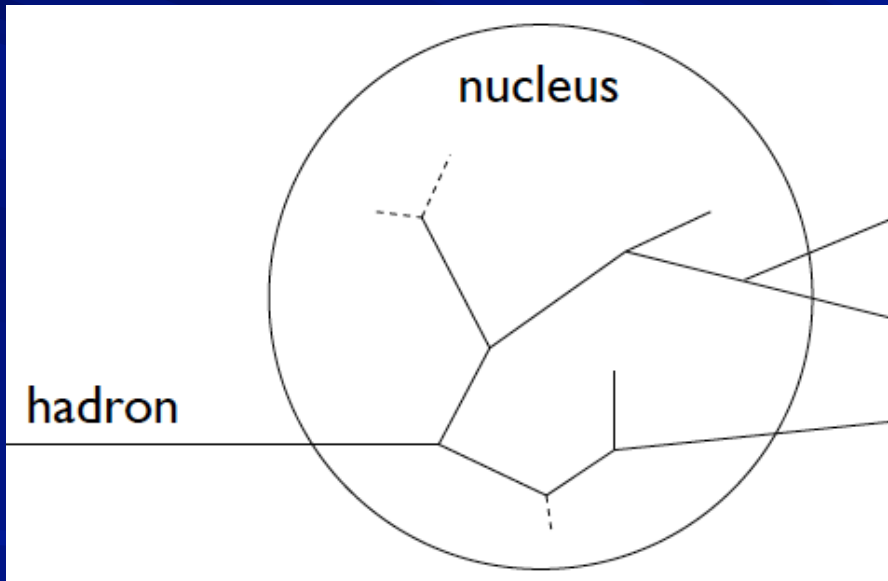
Simulation

- Interaction of hadrons with $E > 10$ GeV described by string models
 - projectile interacts with single nucleon (p,n)
 - a string is formed between quarks from interacting nucleons
 - the string fragmentation generates hadrons



Simulation

- Interaction of hadrons with $10 \text{ MeV} < E < 10 \text{ GeV}$ via intra-nuclear cascades
- For $E < 10 \text{ MeV}$ only relevant are fission, photon emission, evaporation, ...



Approximations

- $\lambda_{\text{deBroglie}} \leq d \text{ nucleon}$
- nucleus = Fermi gas (all nucleons included)
- Pauli exclusion: allow only secondaries above Fermi energy