
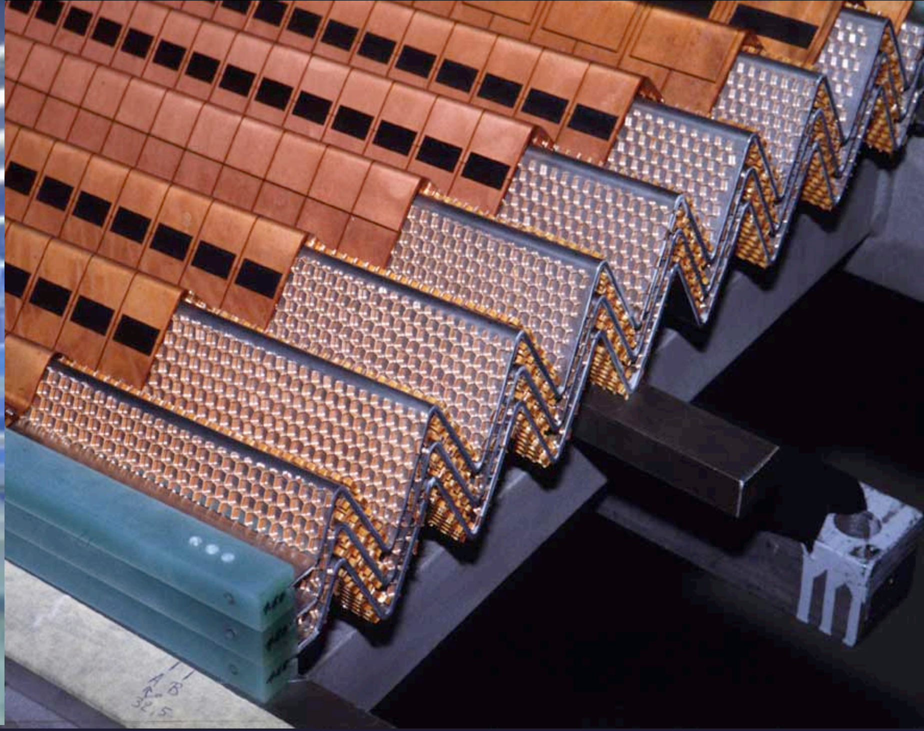

Detectors for Particle Physics

Calorimetry

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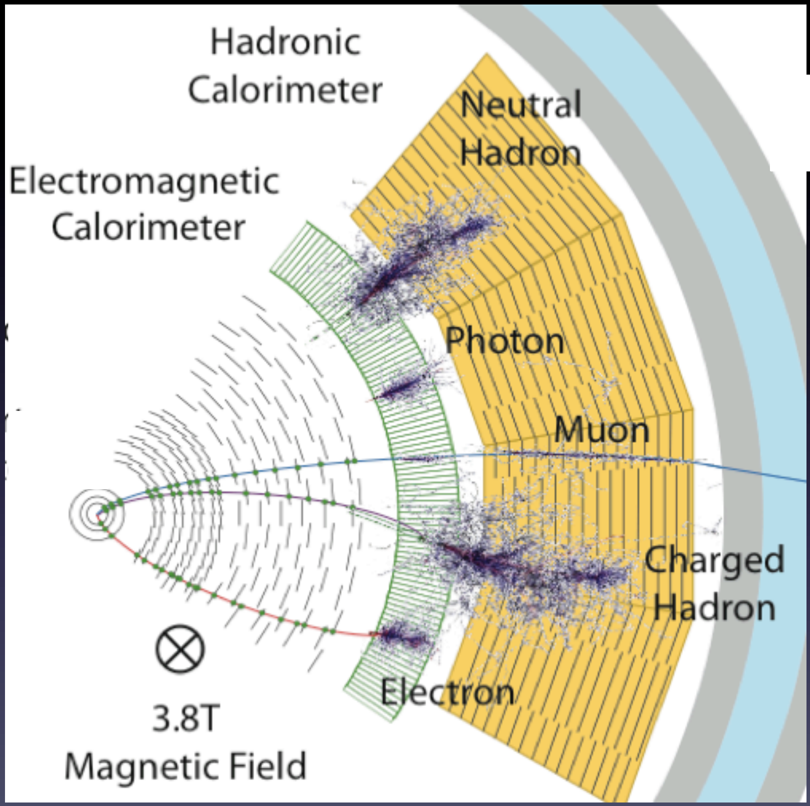
What is a calorimeter ?

- 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 > few MeV) :

Photons: Pair production

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

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

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

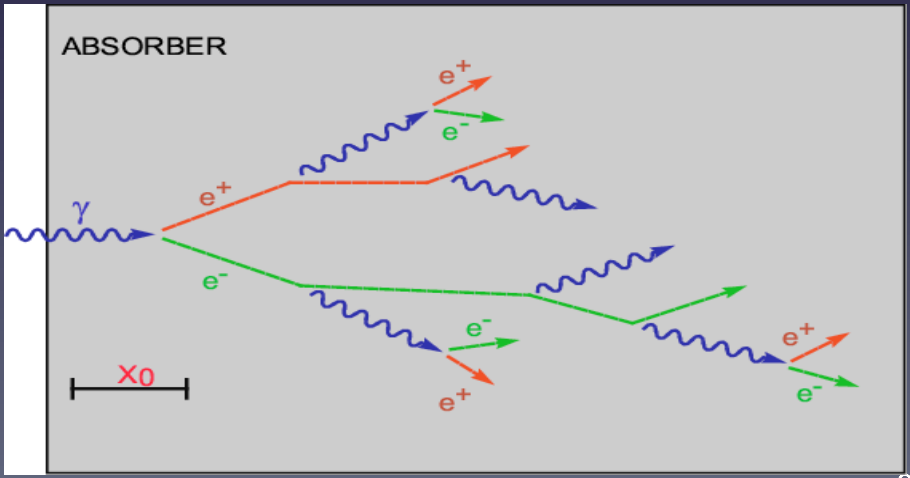
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons: Bremsstrahlung

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

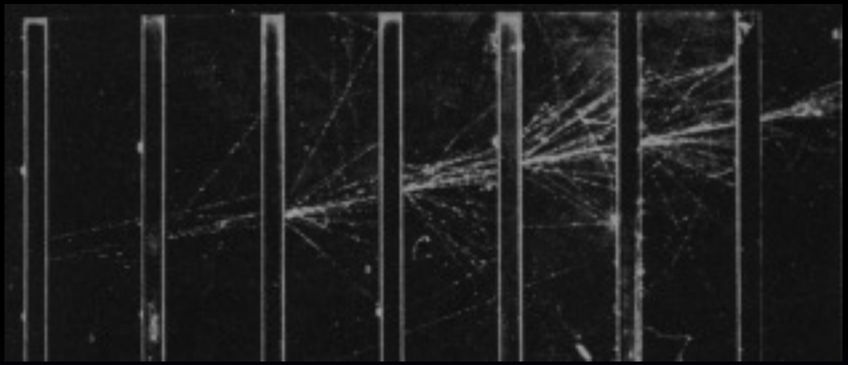
$$E = E_0 e^{-x/X_0}$$

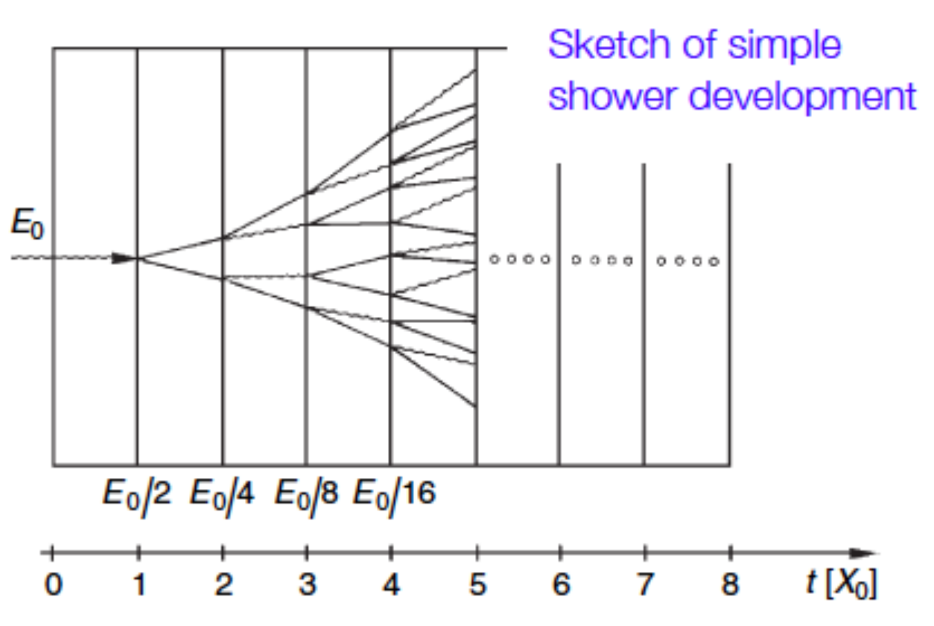
After traversing $x=X_0$ the electron has only 1/e=37% of its initial energy



Analytic shower Model

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

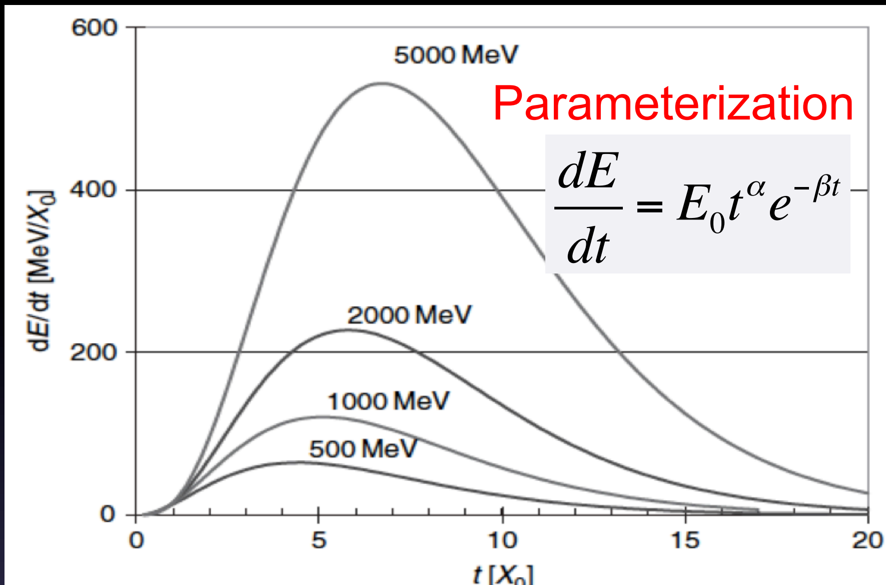


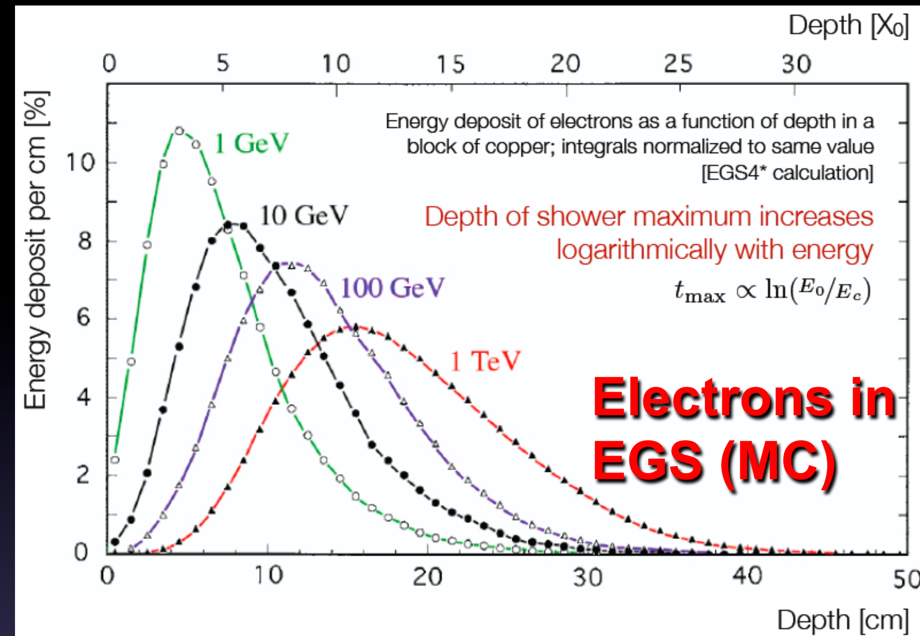


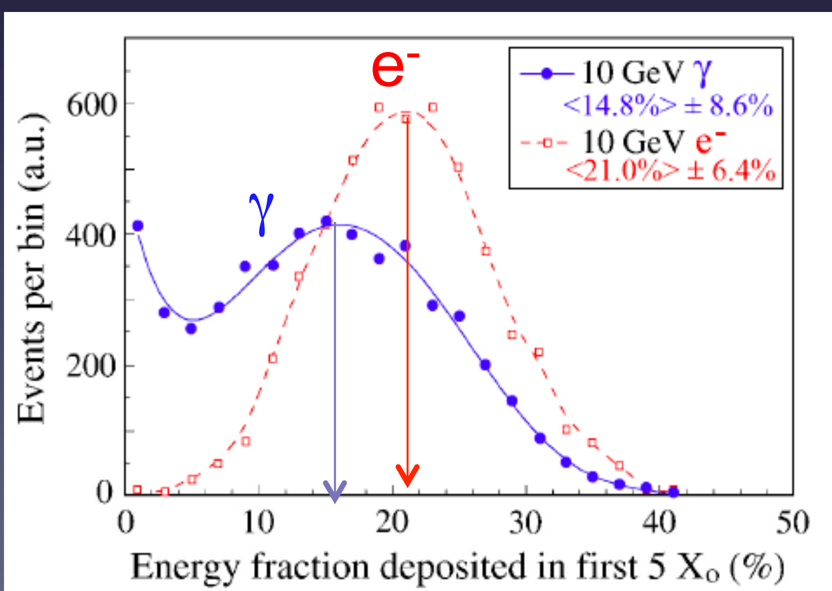
$$t_{\max} = \frac{\ln(E/Ec)}{\ln 2} \propto \ln\left(\frac{E}{E_c}\right)$$

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

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 shower containment

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

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

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

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

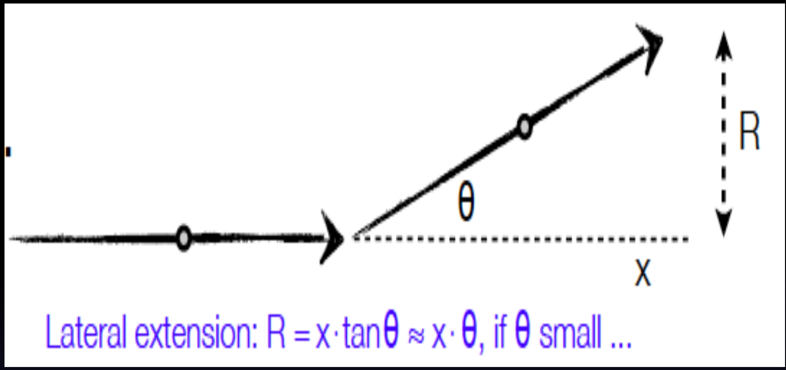
	Scint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

A 100 GeV e^- is contained in 17.5 cm Fe or 5.6 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]

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

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

- **Molière** Radius

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

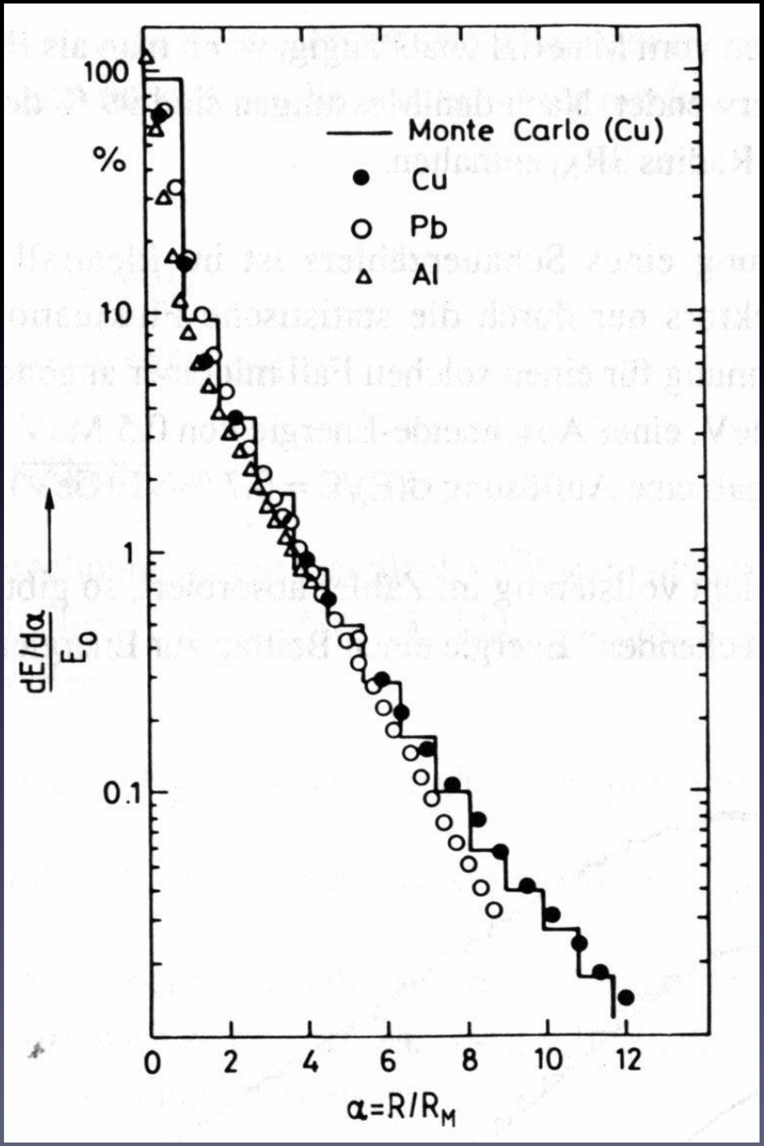
- Assuming the approximate range of electrons to be X_0 yields $\langle \theta \rangle \approx 21.2$ MeV/E_e ➛ lateral extension: $R = \langle \theta \rangle X_0$

Lateral development of EM shower

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

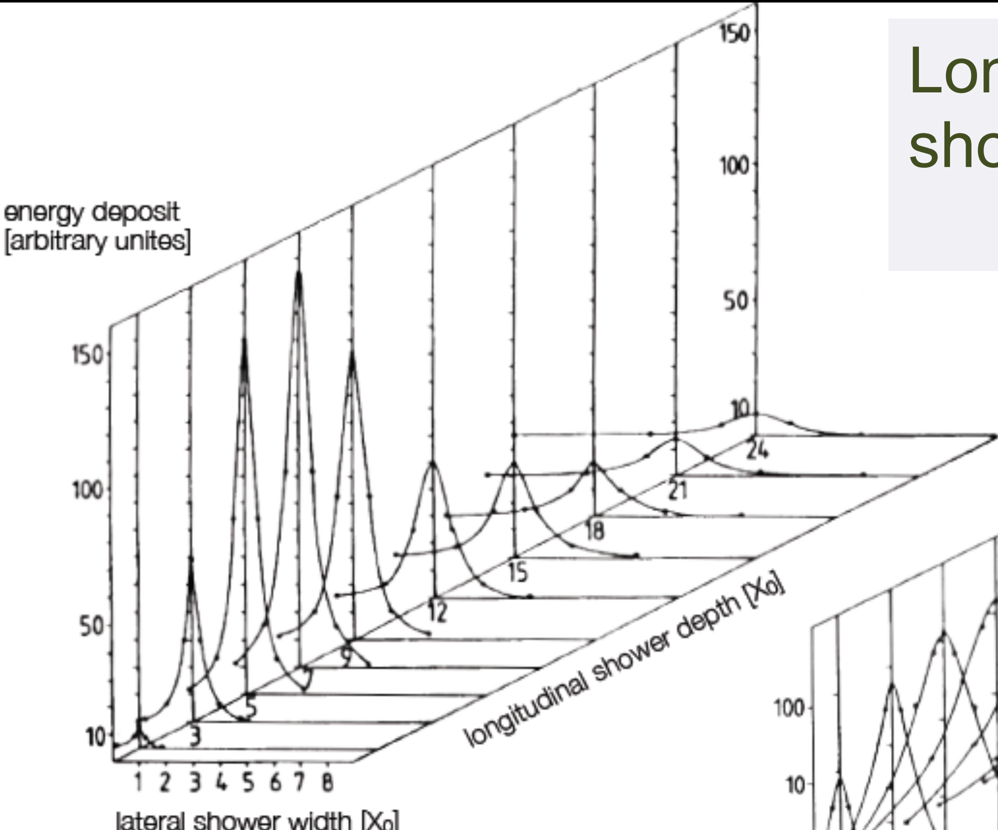
$$\frac{dE}{dr} = \alpha e^{-r/RM} + \beta e^{-r/\lambda_{\min}}$$

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

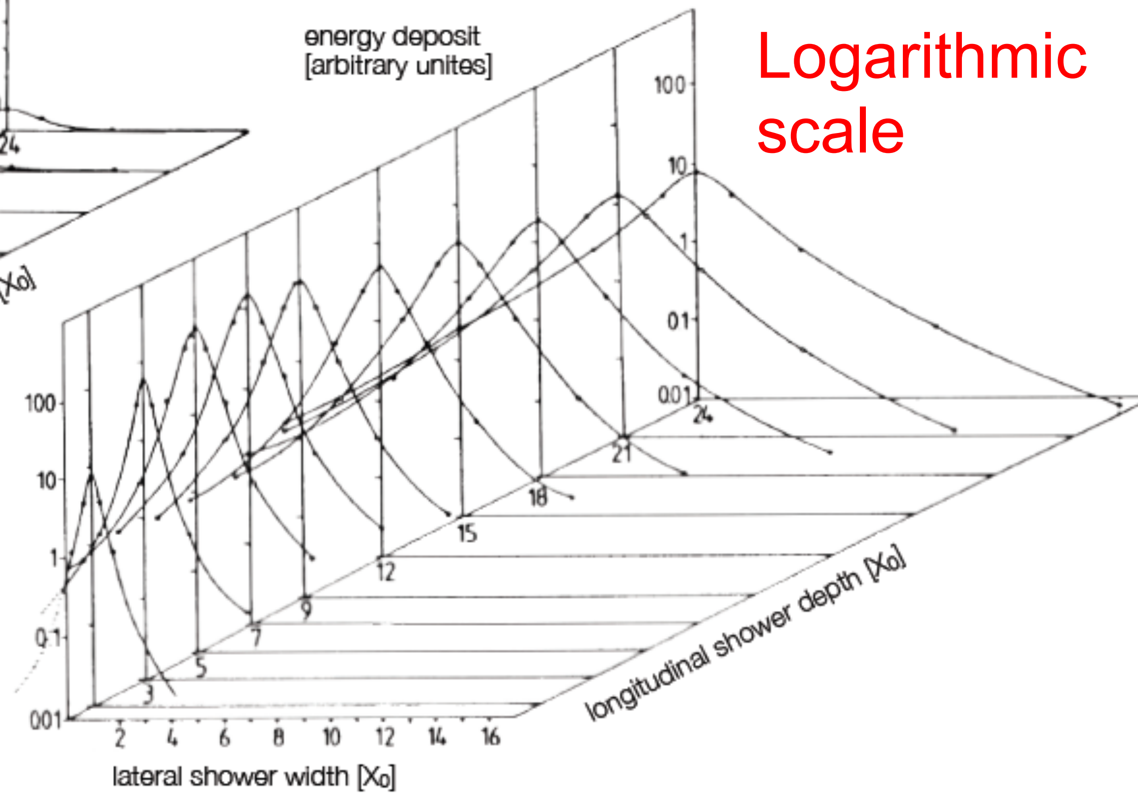


3D EM Shower development

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

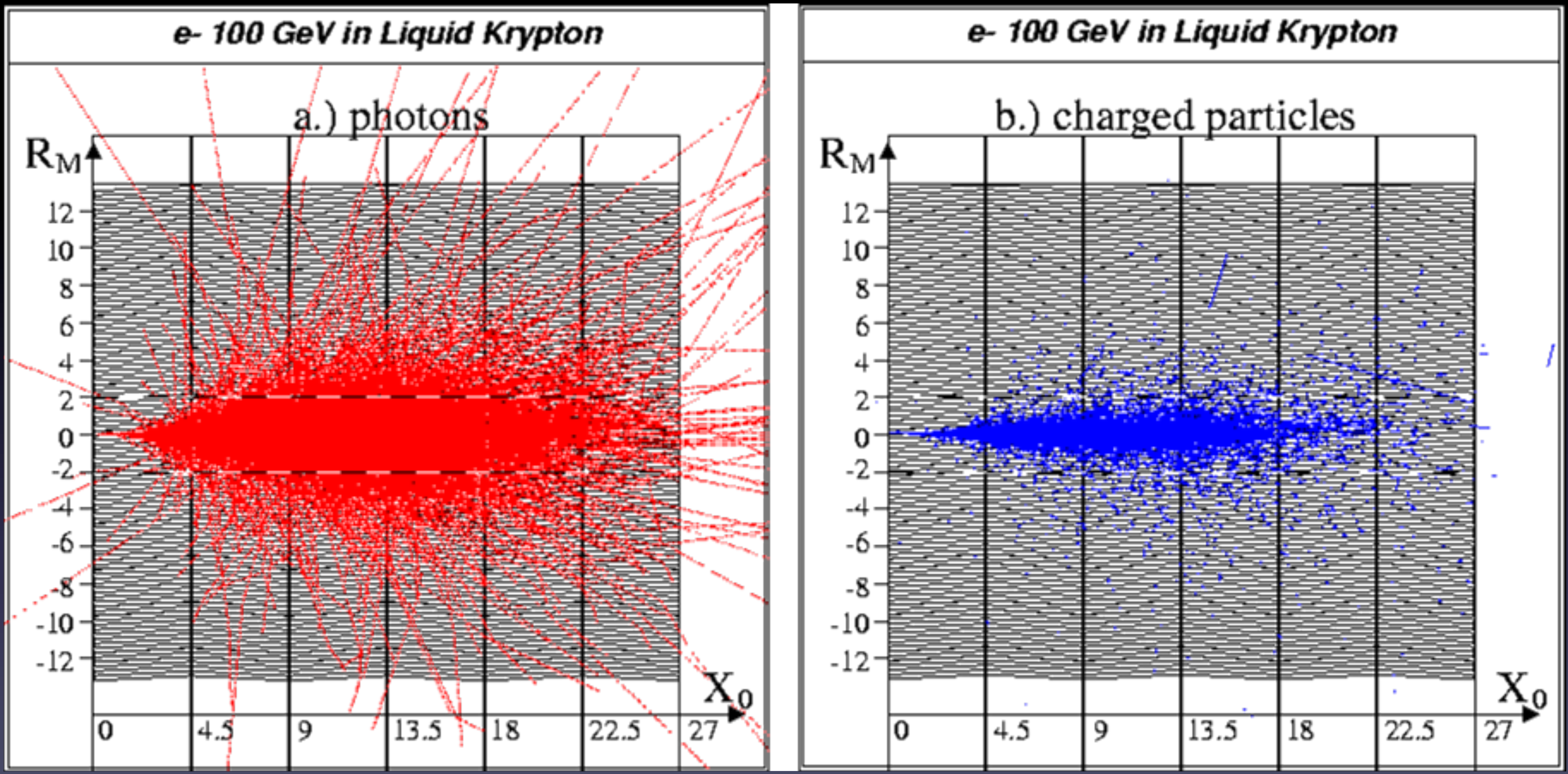


Linear scale



Logarithmic scale

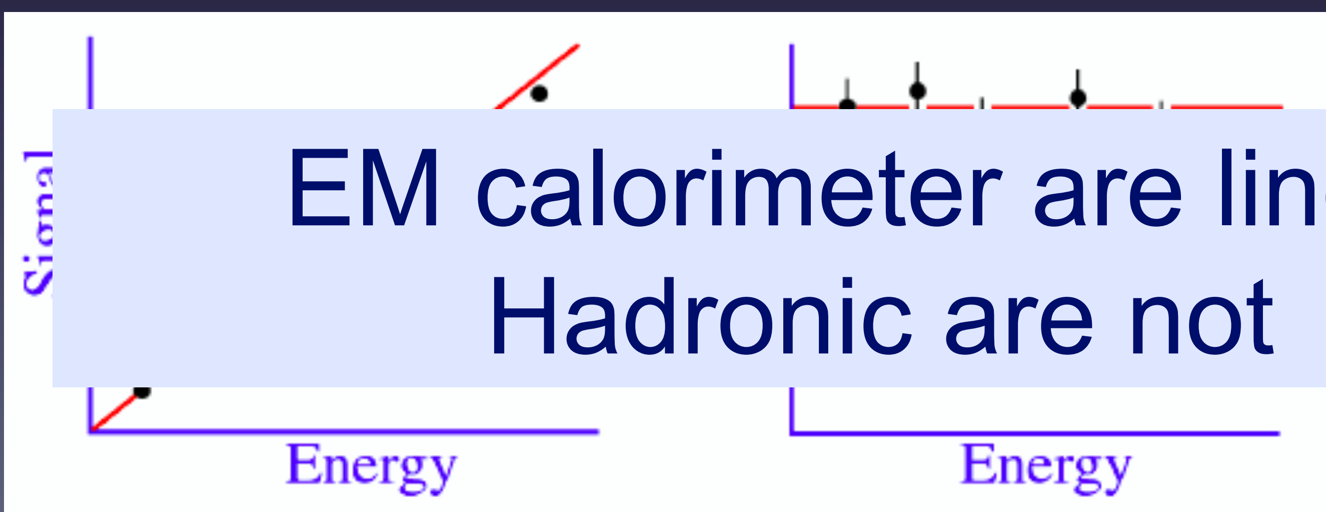
EM shower development in liquid krypton (Z=36, A=84)



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

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?



“response = average

y”

rons/

bs/

EM calorimeter are linear
Hadronic are not

Sources of Non Linearity

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

Signal linearity for electromagnetic showers

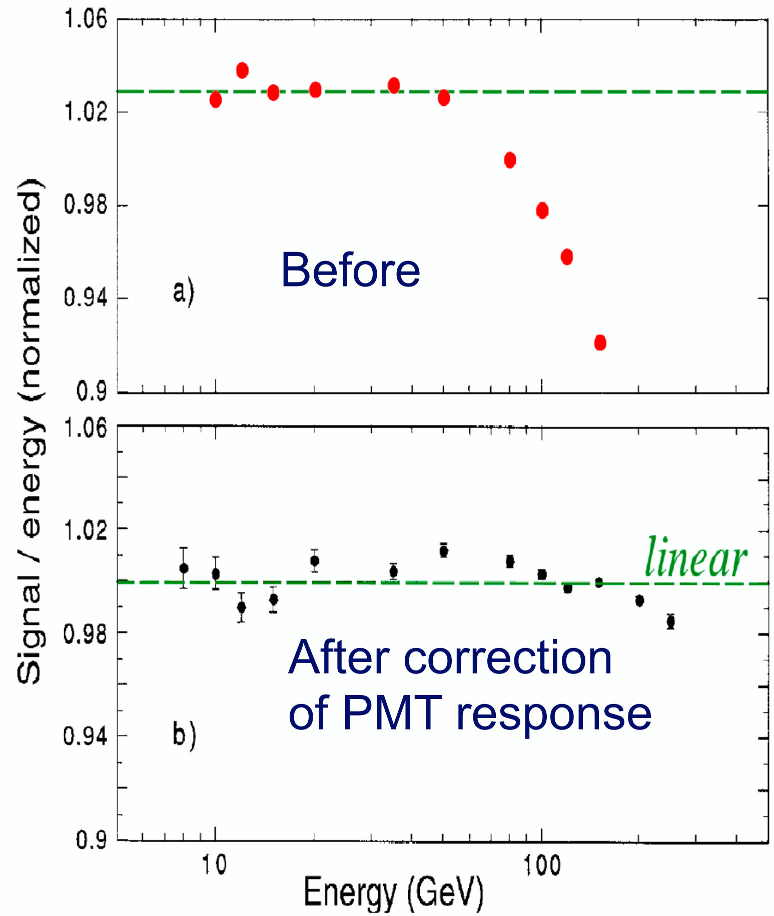


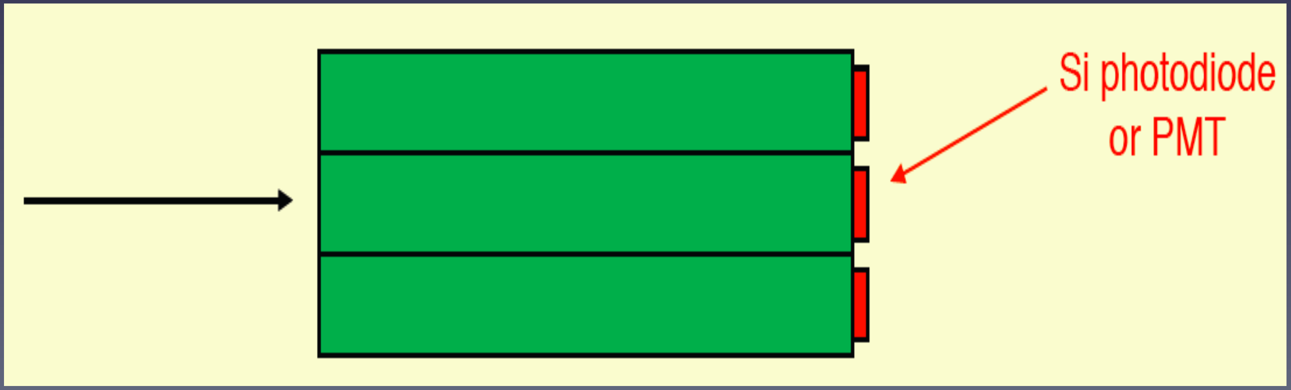
FIG. 3.1. The em calorimeter response as a function of energy, measured with the QFCAL calorimeter, before (a) and after (b) precautions were taken against PMT saturation effects. Data from [Akc 97].

EM Calorimeter configurations

- Total absorption
  - Electrons and photons stop in calorimeter
  - Scintillation proportional to energy of electron
  - Usually non-organic scintillator (BGO, $PbWO_{4,...}$) or liquid Xe
  - Advantage: Excellent energy resolution
    - see all charged particles in the shower (but for shower leakage) → best statistical precision
    - Uniform response → good linearity
  - Disadvantages:
    - cost and limited segmentation

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

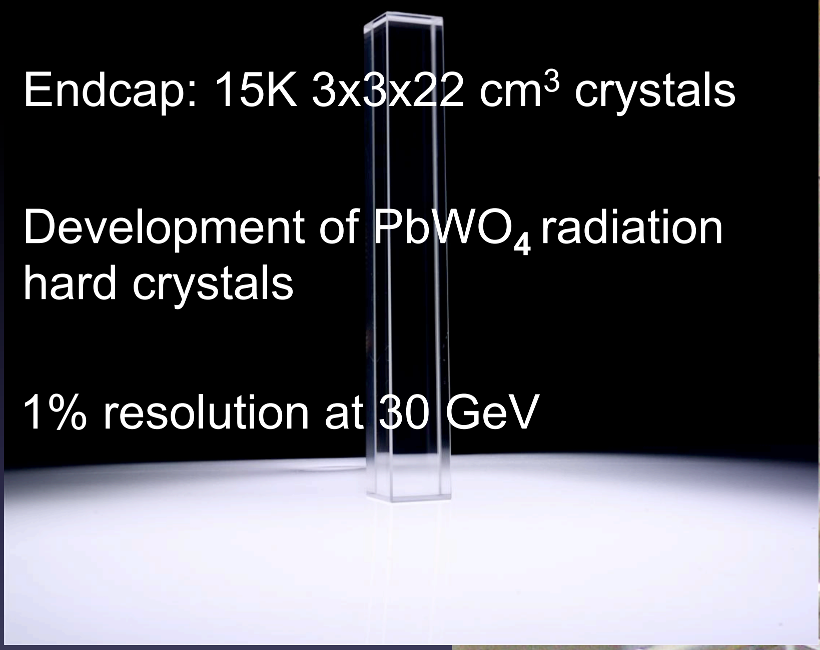
$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}$$



- Examples:
  - B factories: small photon energies
  - CMS ECAL which was optimized for $H \rightarrow \gamma\gamma$

Homogenous calorimeters

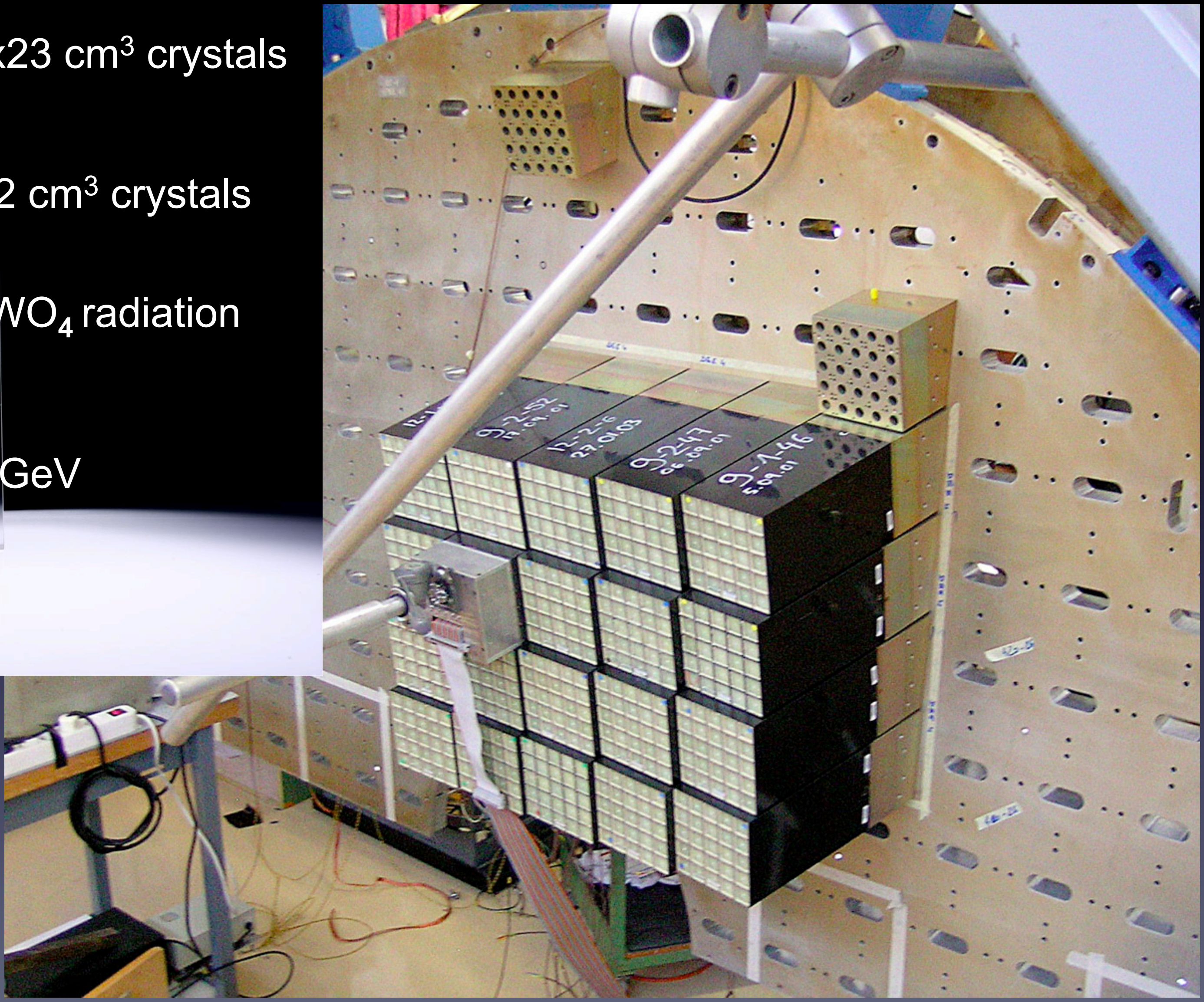
Barrel: 62K 2.2x2.2x23 cm^3 crystals



Endcap: 15K 3x3x22 cm^3 crystals

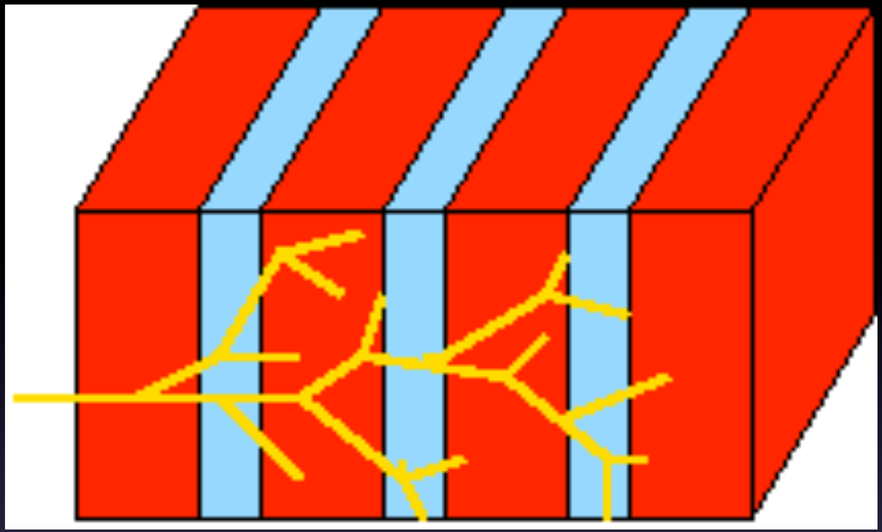
Development of $PbWO_4$ radiation hard crystals

1% resolution at 30 GeV



EM Calorimeter configurations

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

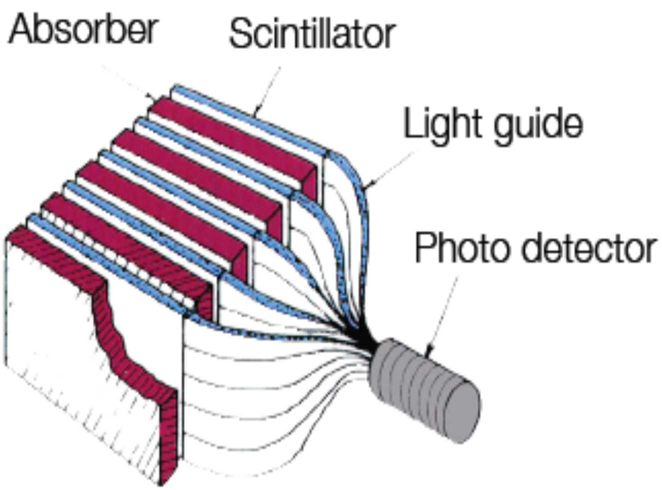


- Sampling fraction

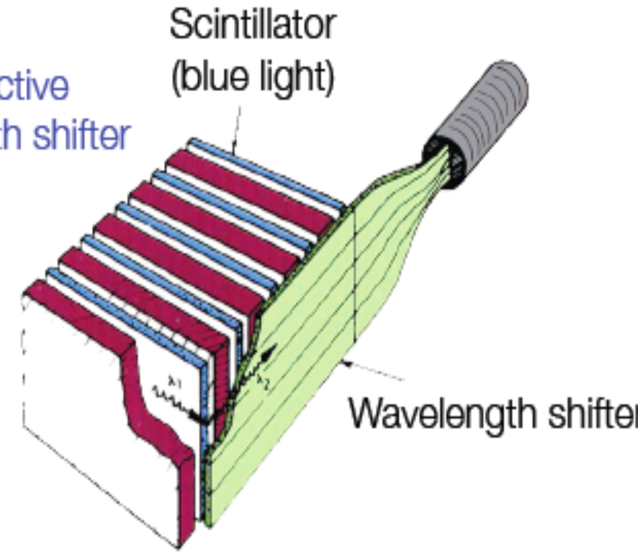
$$f_{sampling} = \frac{E_{visible}}{E_{deposited}}$$

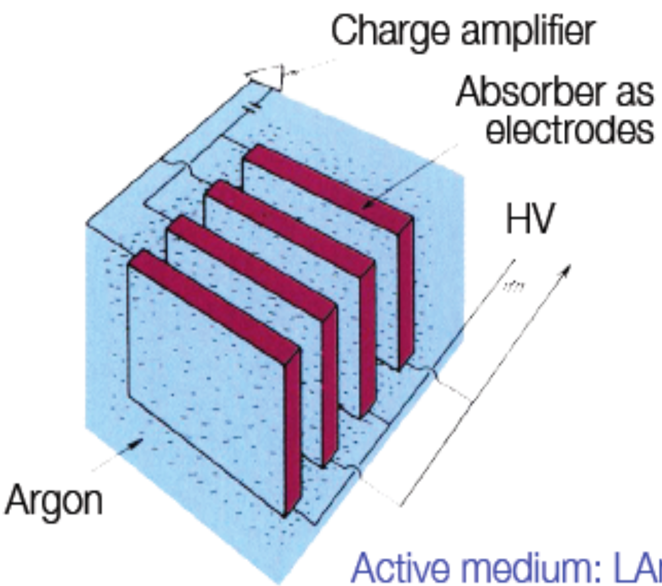
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



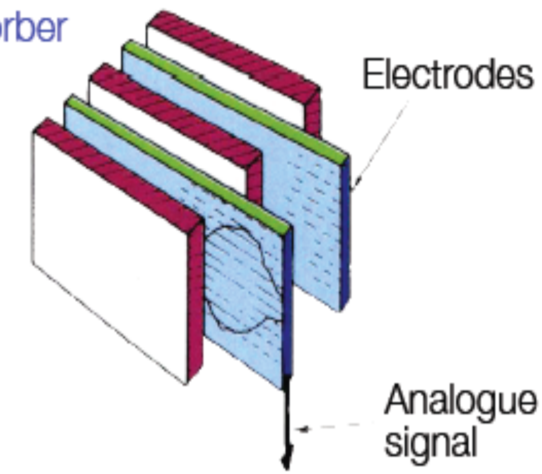
Scintillators as active layer; wave length shifter to convert light





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

Ionization chambers between absorber plates



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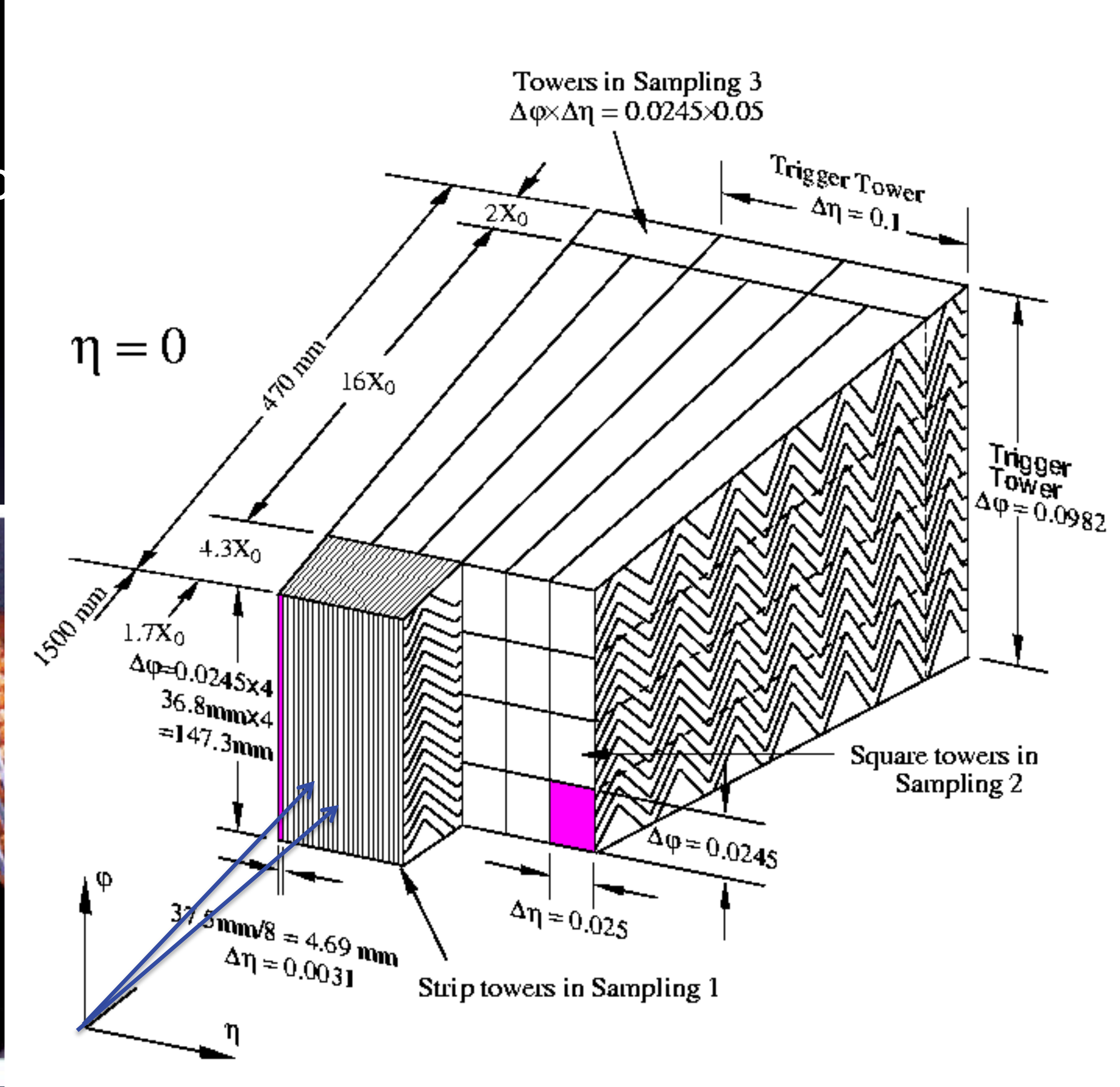
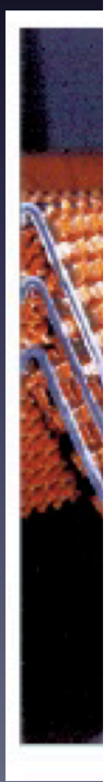




HV

r gap

r

eel.

Energy resolution

- Ideally, if all shower particles counted: $E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$
- In practice

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

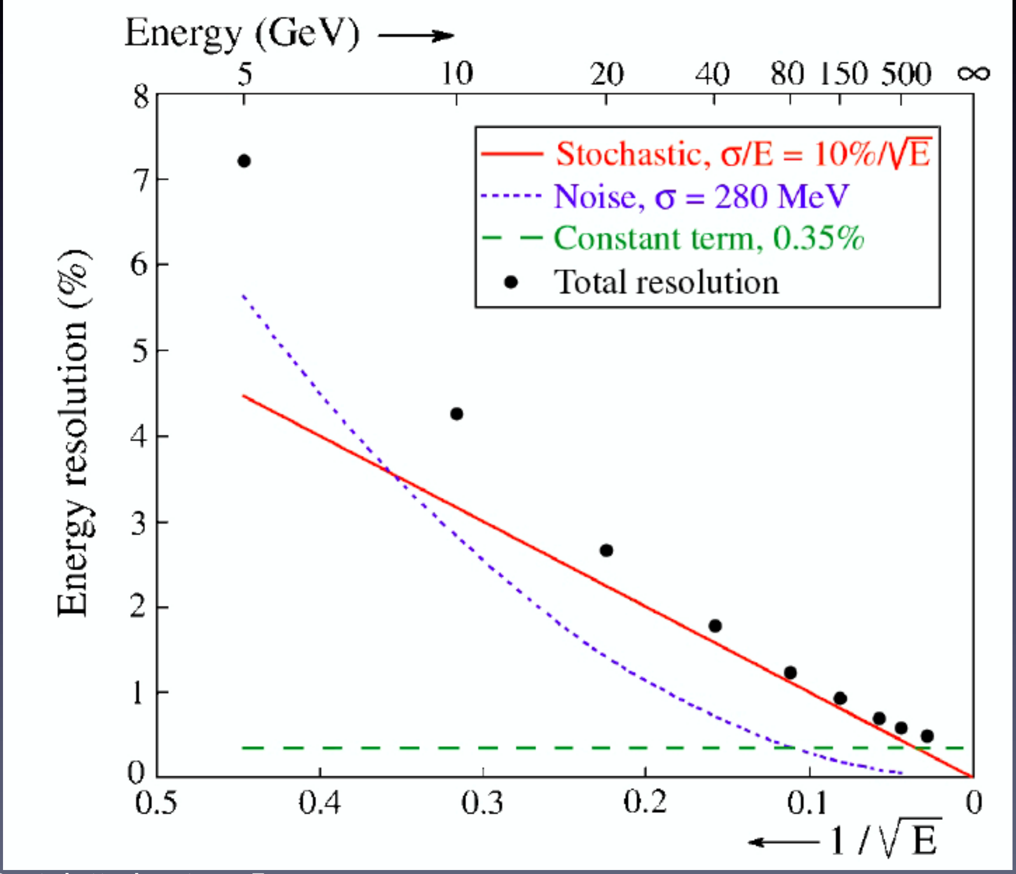
- a: stochastic term
  - intrinsic statistical shower fluctuations
  - sampling fluctuations
  - signal quantum fluctuations (e.g. photo-electron statistics)
- b: constant term
  - inhomogeneities (hardware or calibration)
  - imperfections in calorimeter construction (dimensional variations, etc.)
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

Effects on energy resolution

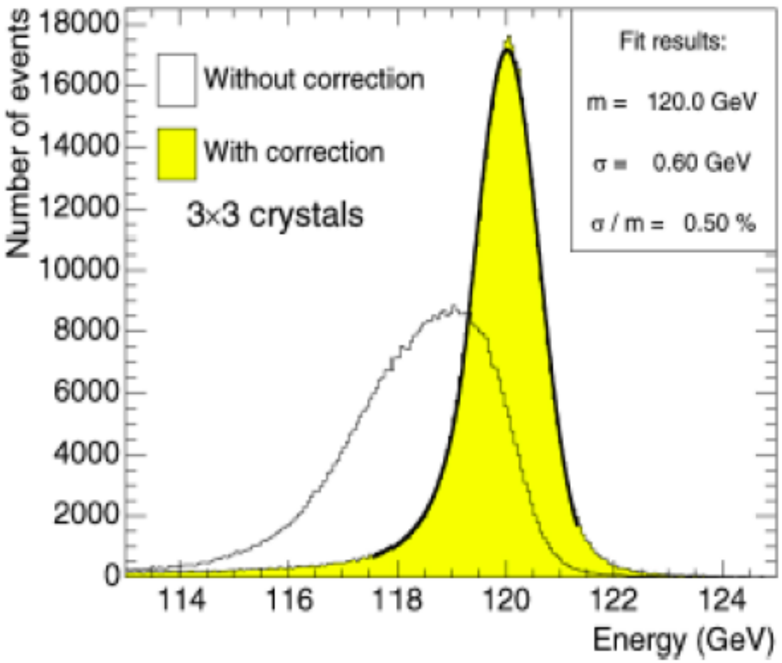
- Different effects have different energy dependence
  - Sampling fluctuations $\sigma/E \sim E^{-1/2}$
  - shower leakage $\sigma/E \sim E^{-1/4}$
  - electronic noise $\sigma/E \sim E^{-1}$
  - structural non-uniformities: $\sigma/E = \text{constant}$
- $\sigma^2_{tot} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 + \sigma^2_4 + \ldots$

ATLAS EM calorimeter

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



CMS ECAL resolution

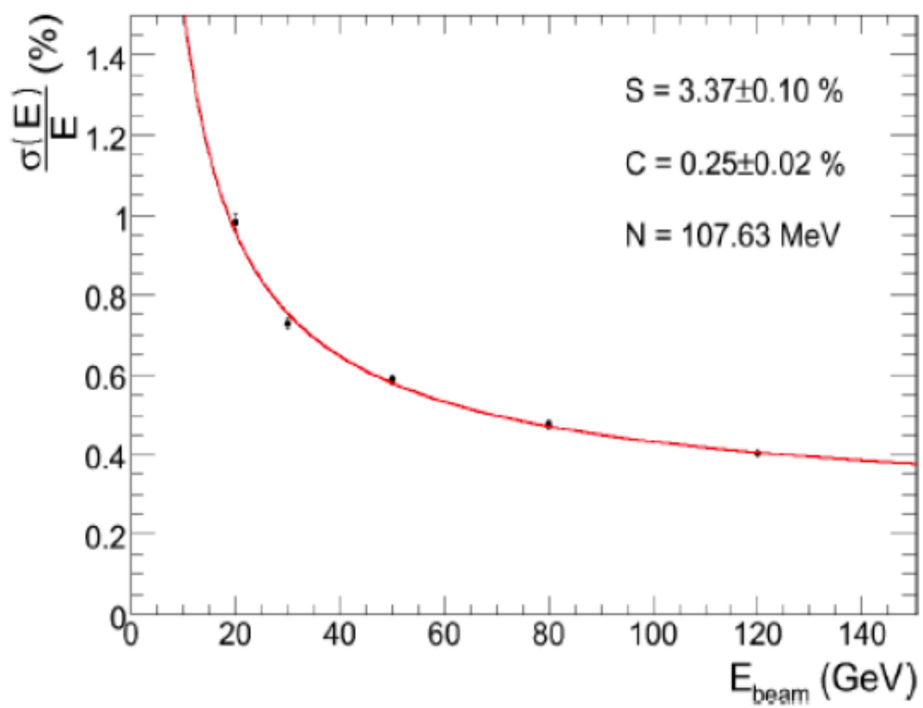


Correction for radial loss

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

Stoch. Noise Const.

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{120MeV}{E} \oplus 0.3\%$$



Homogeneous vs Sampling

E in GeV

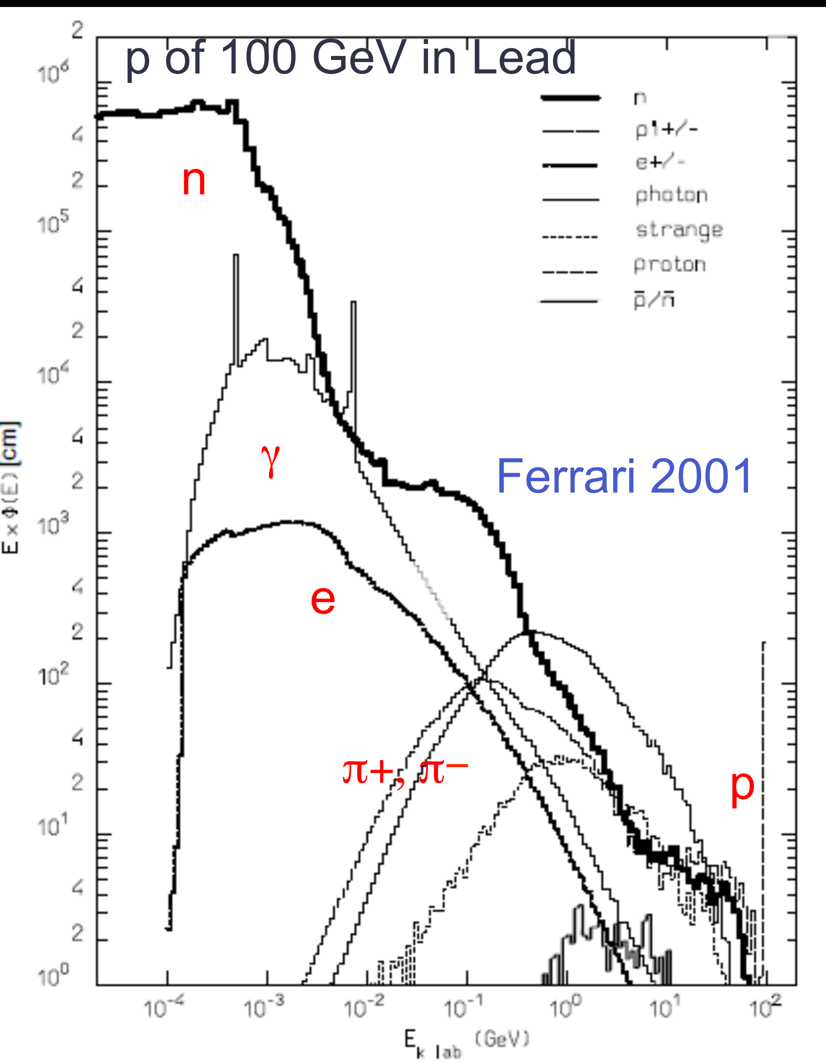
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	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:



entary to track measurement

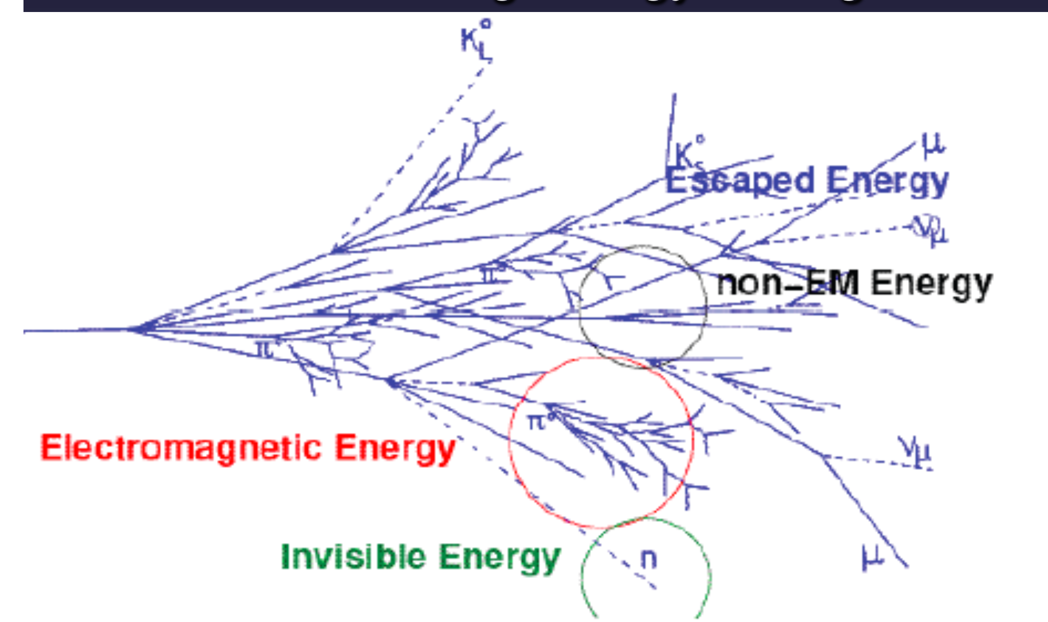
ay to measure their energy

ondary particles are produced

reactions → hadronic cascades

ng particles (**π,η**) initiate EM shower

ed as nuclear binding energy or target recoil



Hadronic shower

Hadronic interaction:

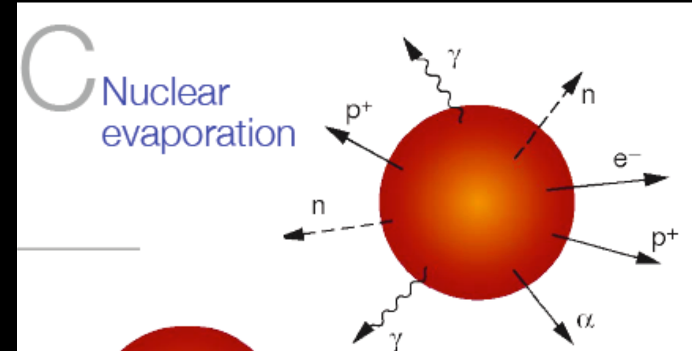
Elastic:

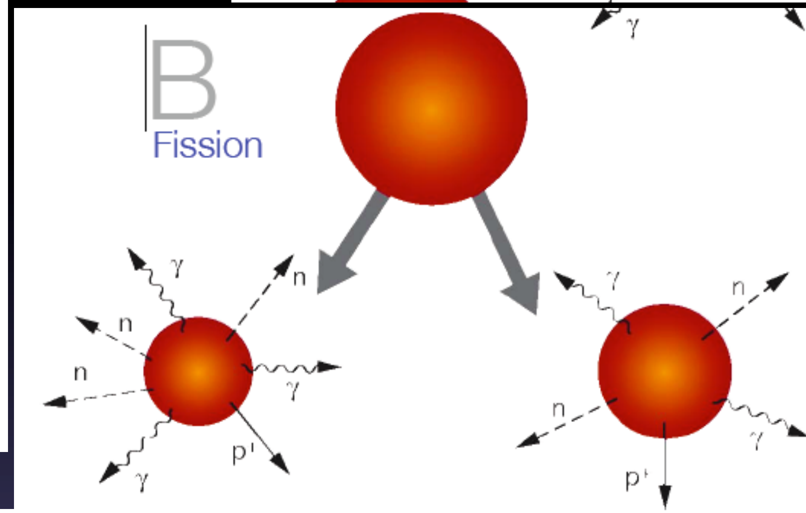
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

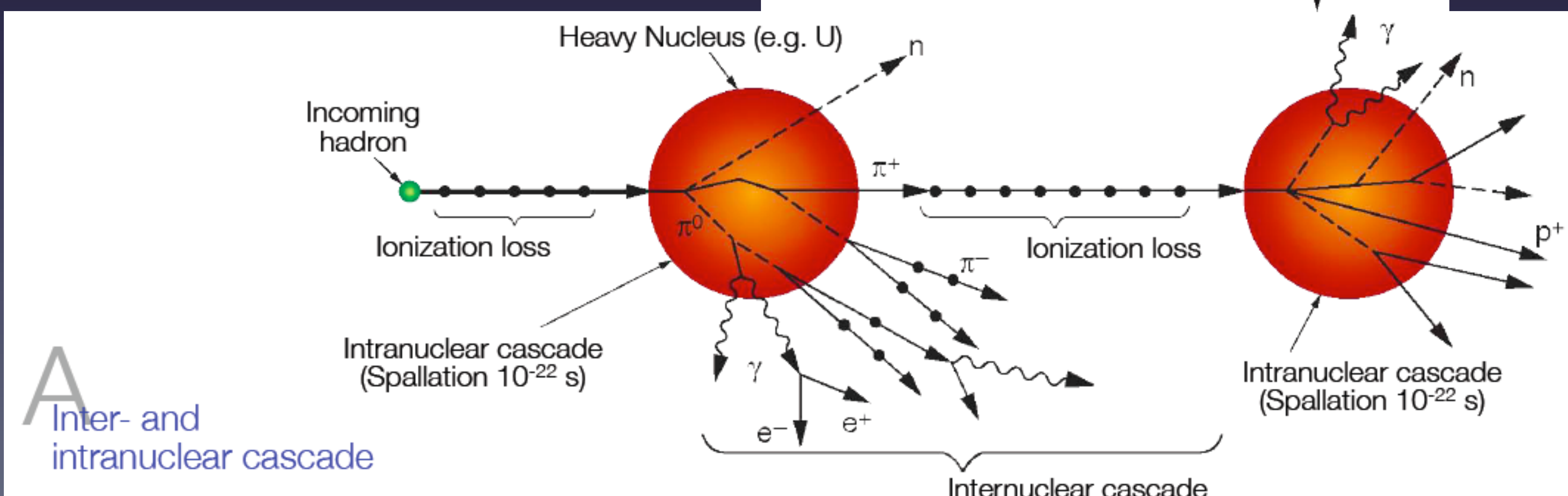
Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \quad\quad\quad\quad \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \quad\quad\quad\quad \rightarrow \text{Nuclear fission} \end{array}\right]$$







Courtesy of H. C. Schoultz Coulon

Hadronic shower

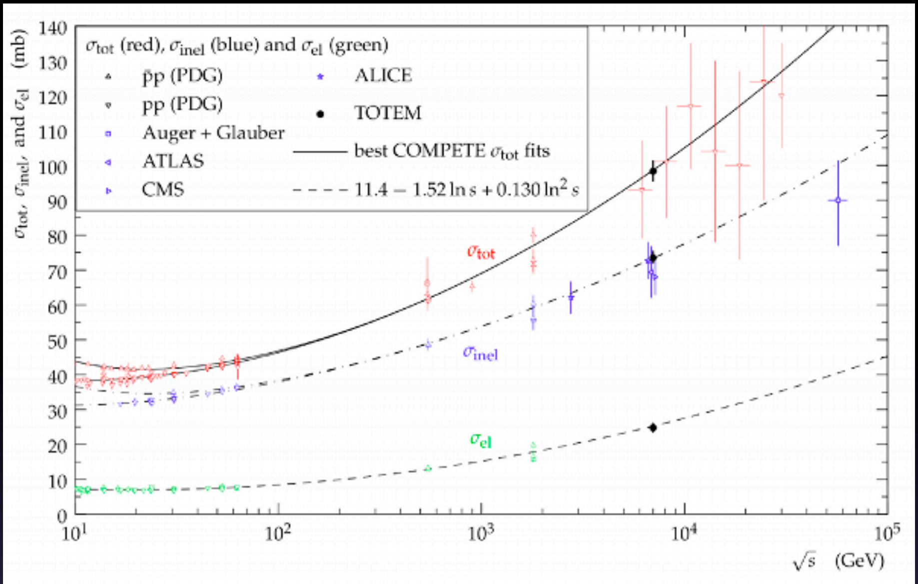
- Hadronic interaction Cross section

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

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

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

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



- Hadronic interaction length

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

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

- 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 gm/cm^2 units scales as $A^{1/3}$.

Hadronic vs EM showers

Hadronic vs. electromagnetic interaction length:

$$X_0 \sim \frac{A}{Z^2}$$

$$\lambda_{int} \sim A^{1/3}$$

$$\rightarrow \frac{\lambda_{int}}{X_0} \sim A^{4/3}$$

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

[λ_{int}/X_0 > 30 possible; see below]

Typical
Longitudinal size: 6 ... 9 λ_{int} [EM: 15-20 X_0]
[95% containment]

Typical
Transverse size: one λ_{int} [EM: 2 R_M; compact]
[95% containment]

Hadronic calorimeter need more depth than electromagnetic calorimeter ...

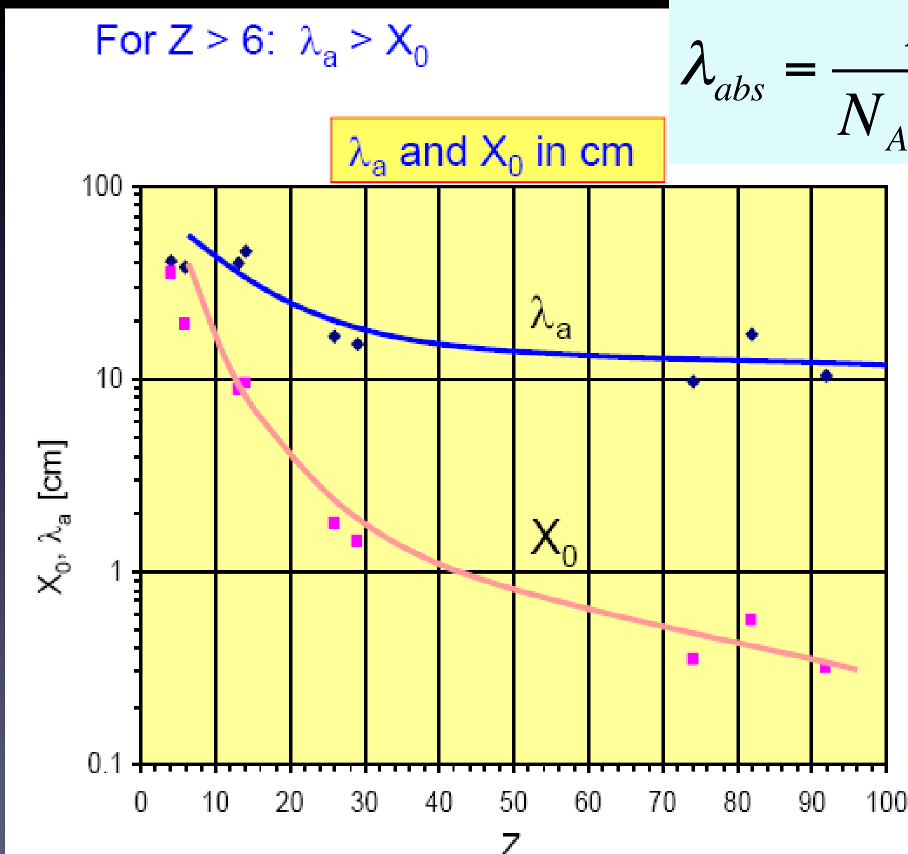
Some numerical values for materials typical used in hadron calorimeters

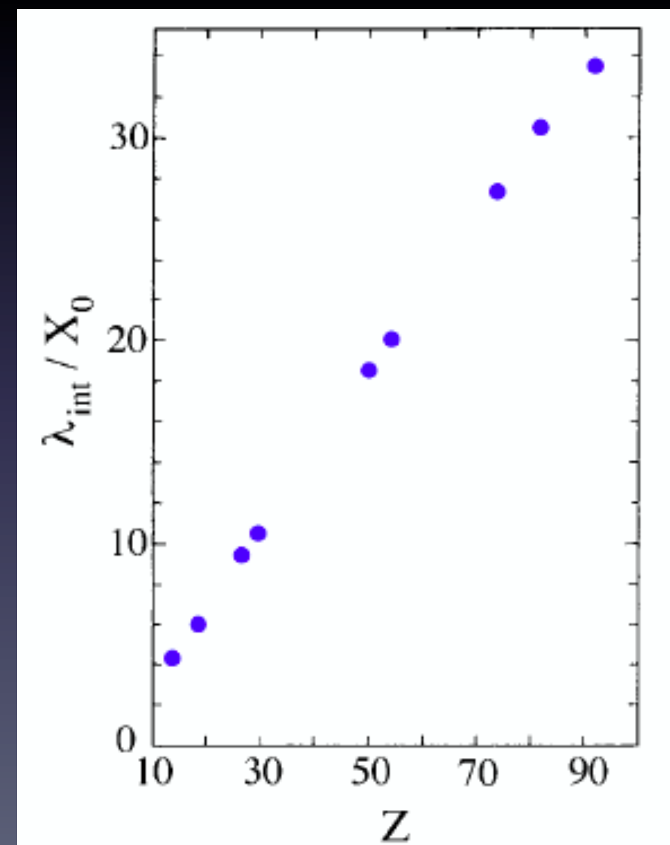
	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

Material dependence

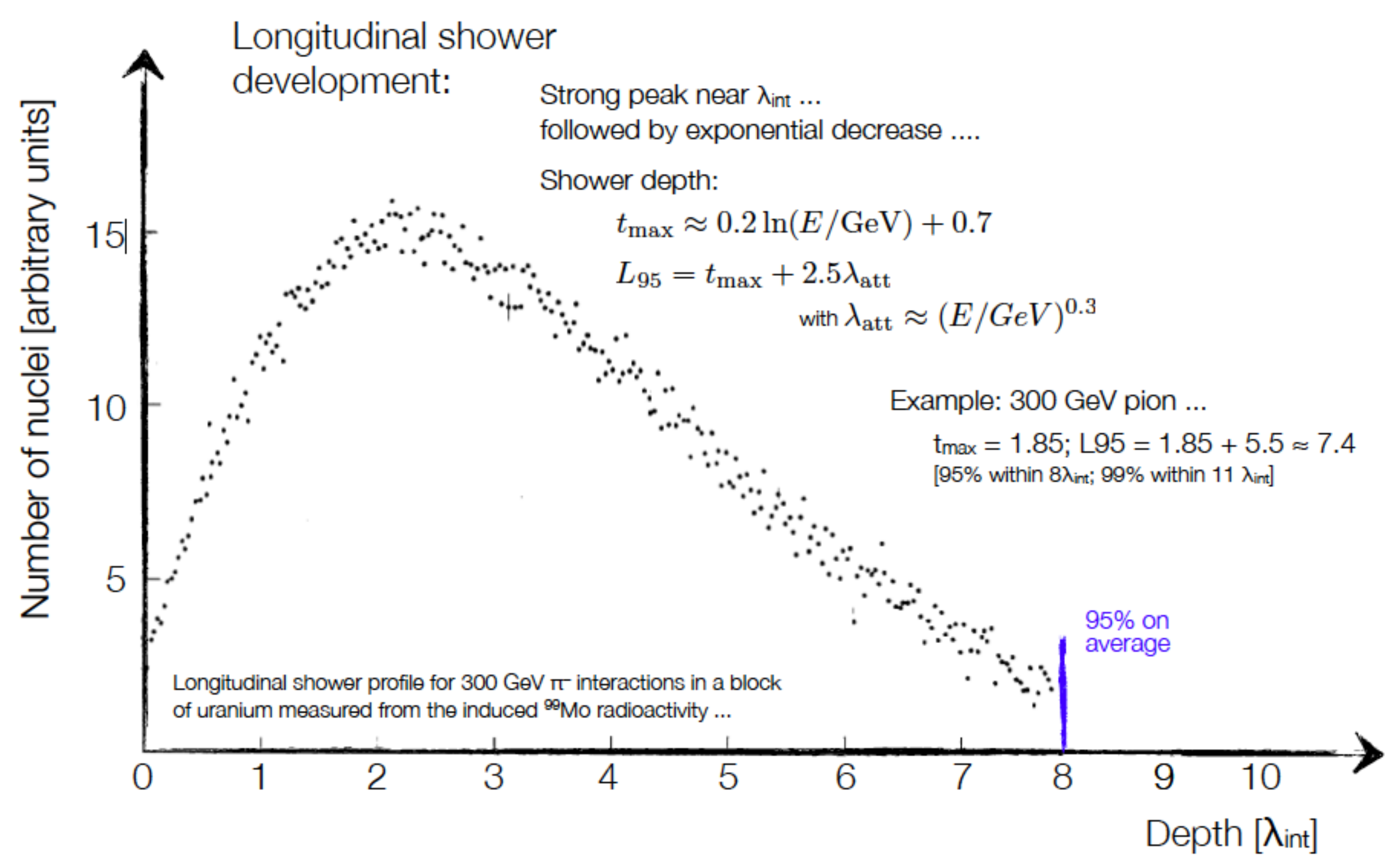
- λ_{int}: mean free path between nuclear collisions: $\boldsymbol{\lambda}_{int}$ (g cm^{-2}) $\propto A^{1/3}$
- λ_{abs}: Hadronic absorption length for inelastic processes
- Hadron showers are much longer than EM ones. Length depends on Z

$$\lambda_{abs} = \frac{A}{N_A \sigma_{inel}}$$

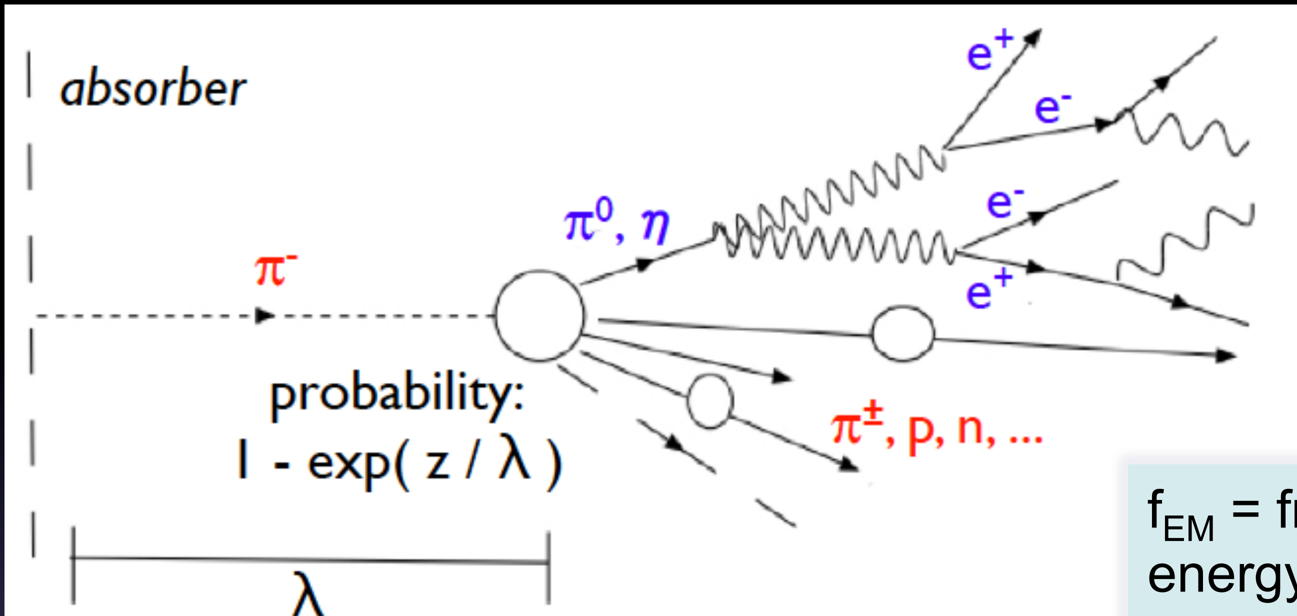




Hadronic shower: Longitudinal development



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 ($\pi^{\pm}$, p)
  - invisible energy (binding, recoil)

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

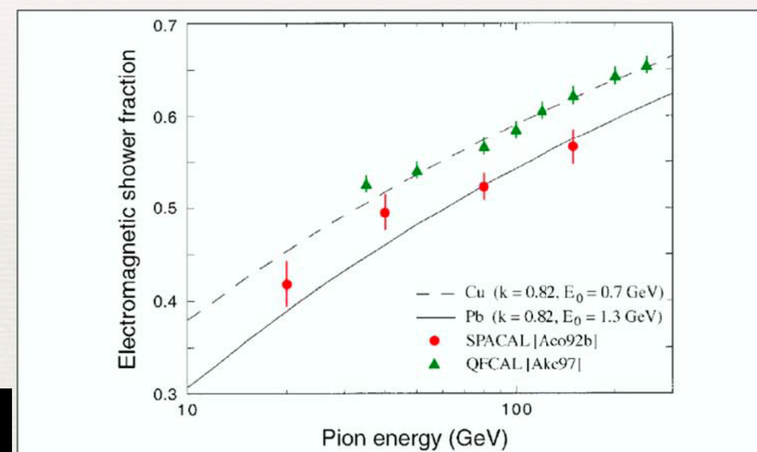


FIG. 2.22. Comparison between the experimental results on the em fraction of pion-induced showers in the (copper-based) QFCAL and (lead-based) SPACAL detectors. Data from [Akc 97] and [Aco 92b].

Energy resolution and compensation

- Compensation for loss of invisible energy: e/h=1
- Non compensating detectors show deviations from scaling in $1/\sqrt{E}$ and non-linearity in signal response
- How can compensation be achieved?
  - Reduce e and increase h component
  - High-Z material such as U absorbs larger fraction of energy of electromagnetic part of shower ➔ decreases e
  - Tuning n response. Interaction of n with hydrogen (large cross section) through elastic n-p scattering ➔ efficient sampling of n through the detection of recoiling proton ➔ increases h
  - Tune the ratio of absorber to active material which sets e/h
  - Other techniques: Software compensation

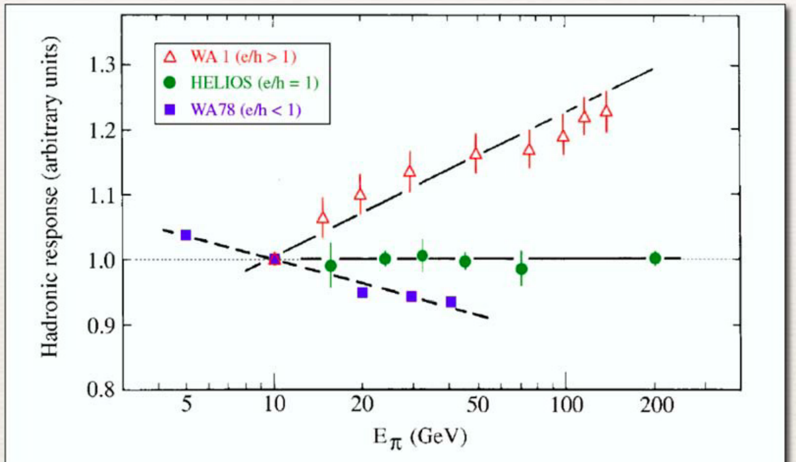
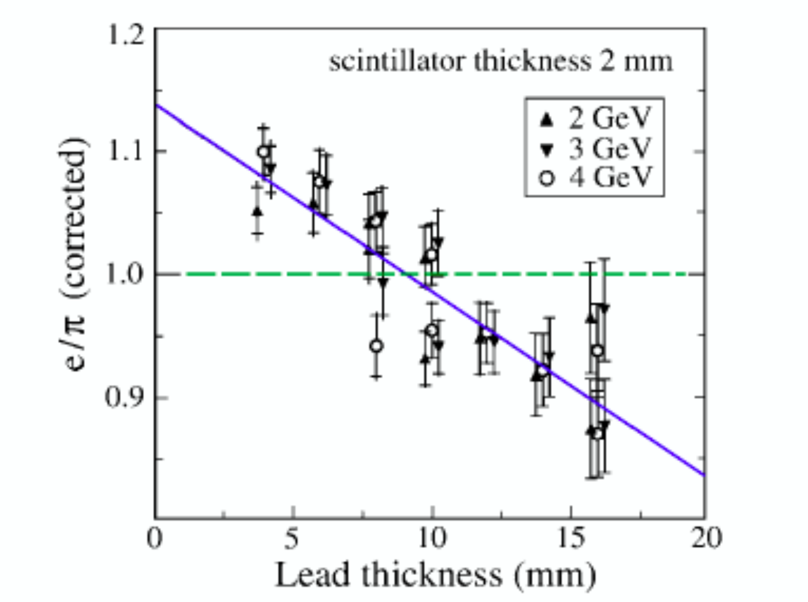


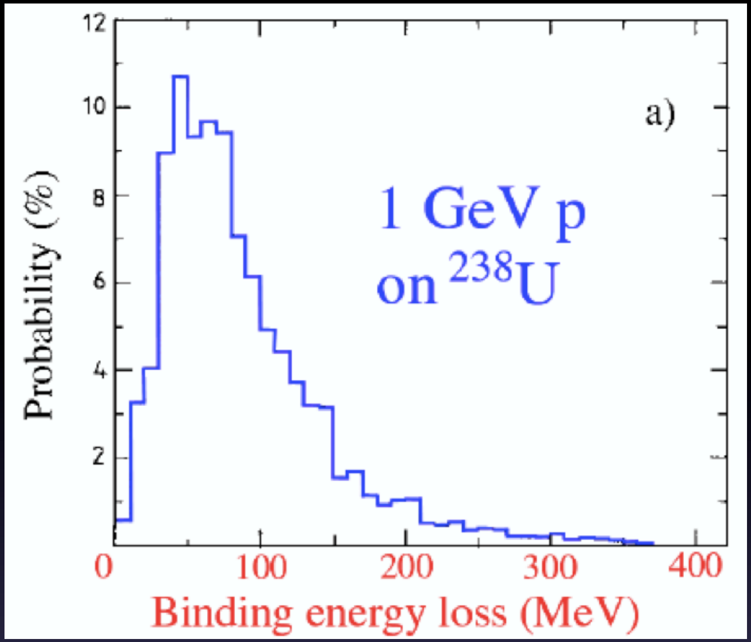
FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10 GeV.

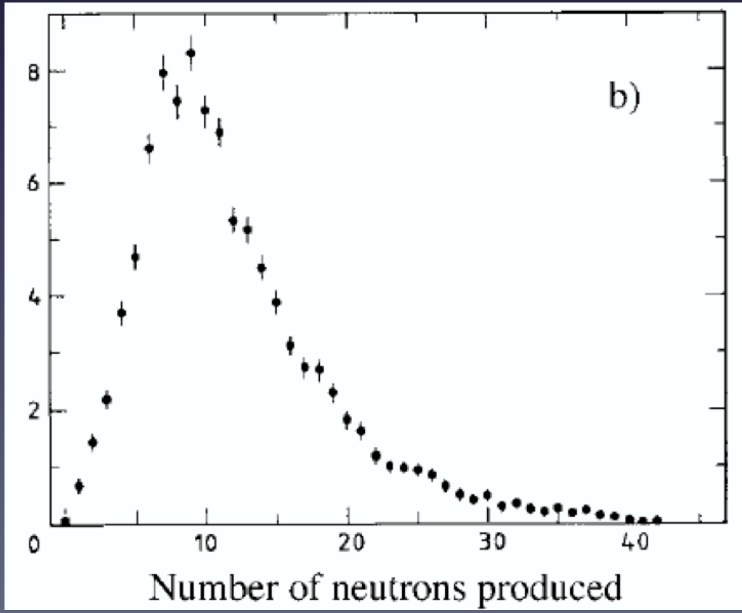
Pb/Scintillator



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 ~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 only minor contribution to hadronic resolution in non-compensating calorimeter





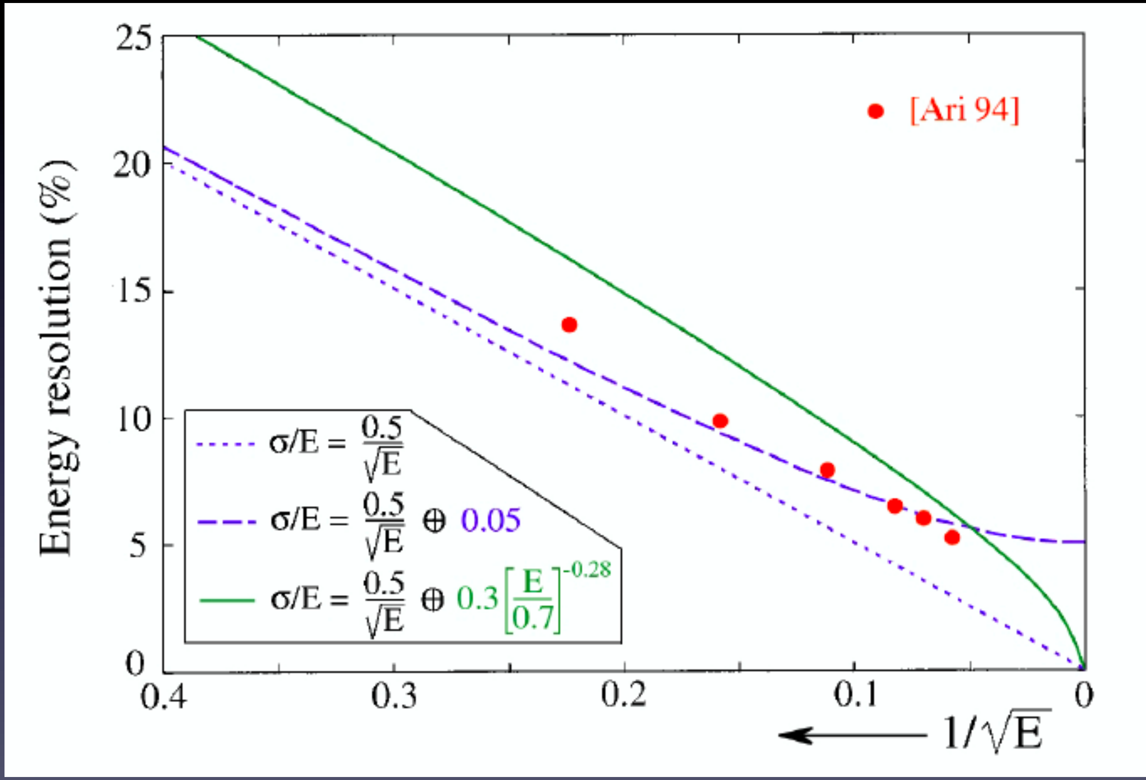
Energy resolution of hadron showers

- Hadronic energy resolution of non-compensating calorimeters does not scale with 1/√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) ...

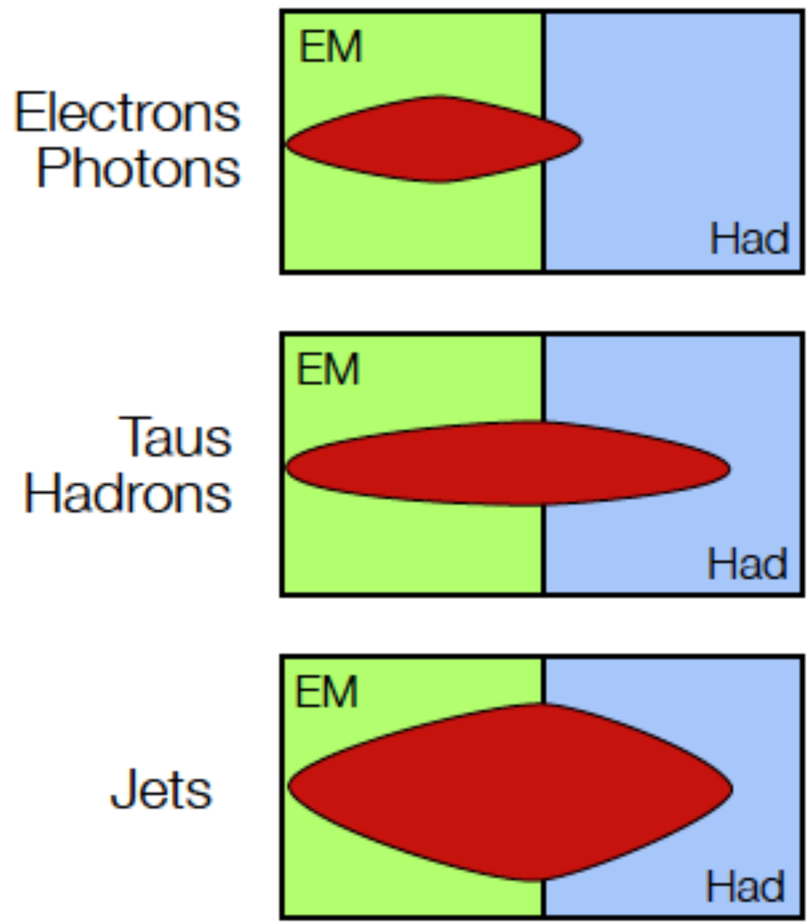
Different setups chosen for
optimal energy resolution ...

But:

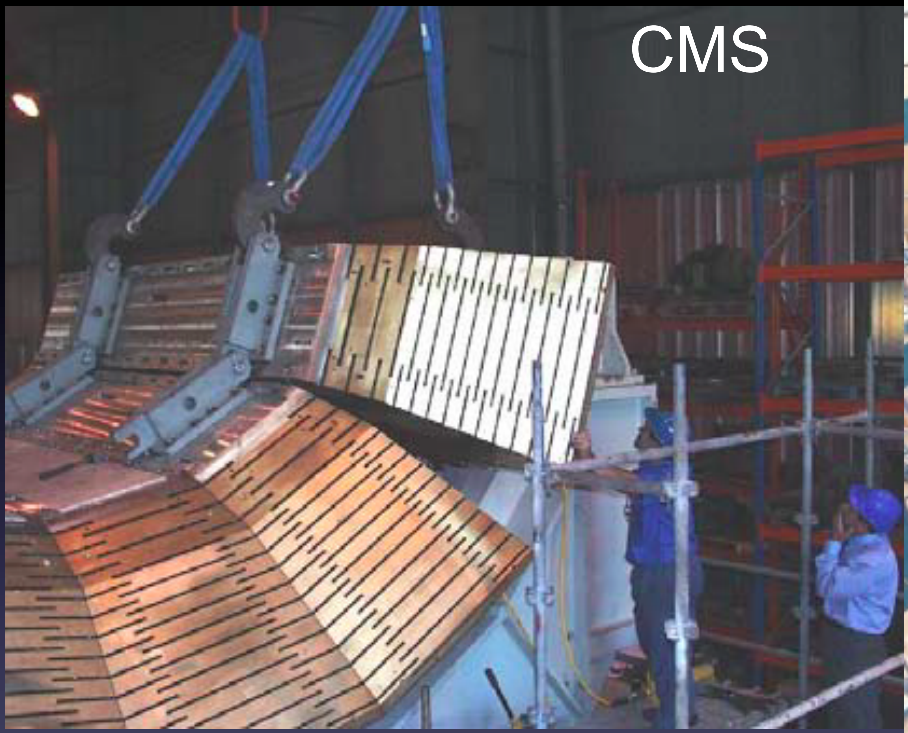
Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



LHC CALORIMETERS



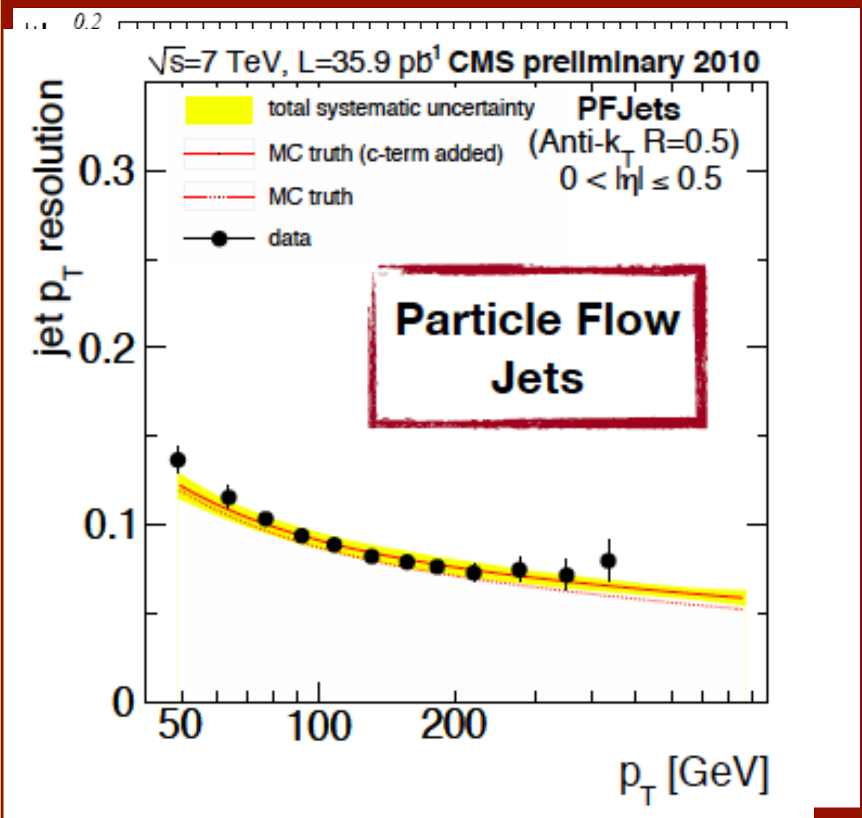
5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

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

Hadronic calorimeters resolution

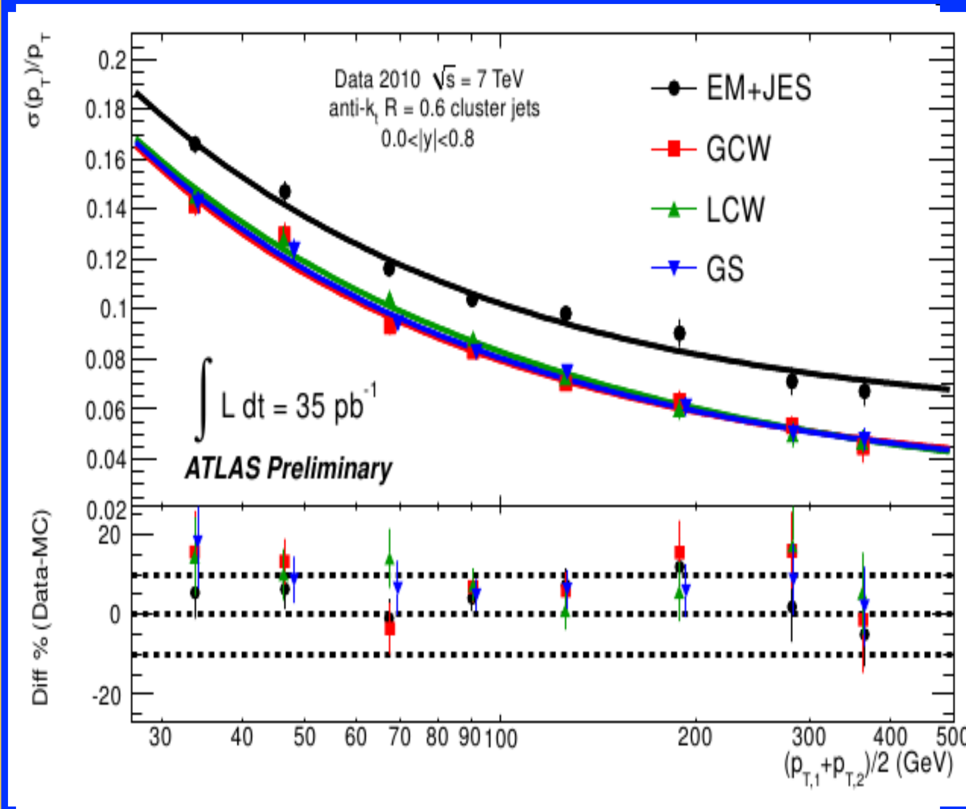
CMS

- HCAL only
  $\sigma/E = (93.8\,)\%/\sqrt{E} \oplus (7.4\,)\%$
- ECAL+HCAL
  $\sigma/E = (82.6)\%/\sqrt{E} \oplus (4.5)\%$



ATLAS

- Standalone tile calorimeter
  $\sigma/E = (52.9)\%/\sqrt{E} \oplus (5.7)\%$
- Improved resolution using full calorimetric system (ECAL+HCAL)
  $\sigma/E = (42)\%/\sqrt{E} \oplus (2)\%$

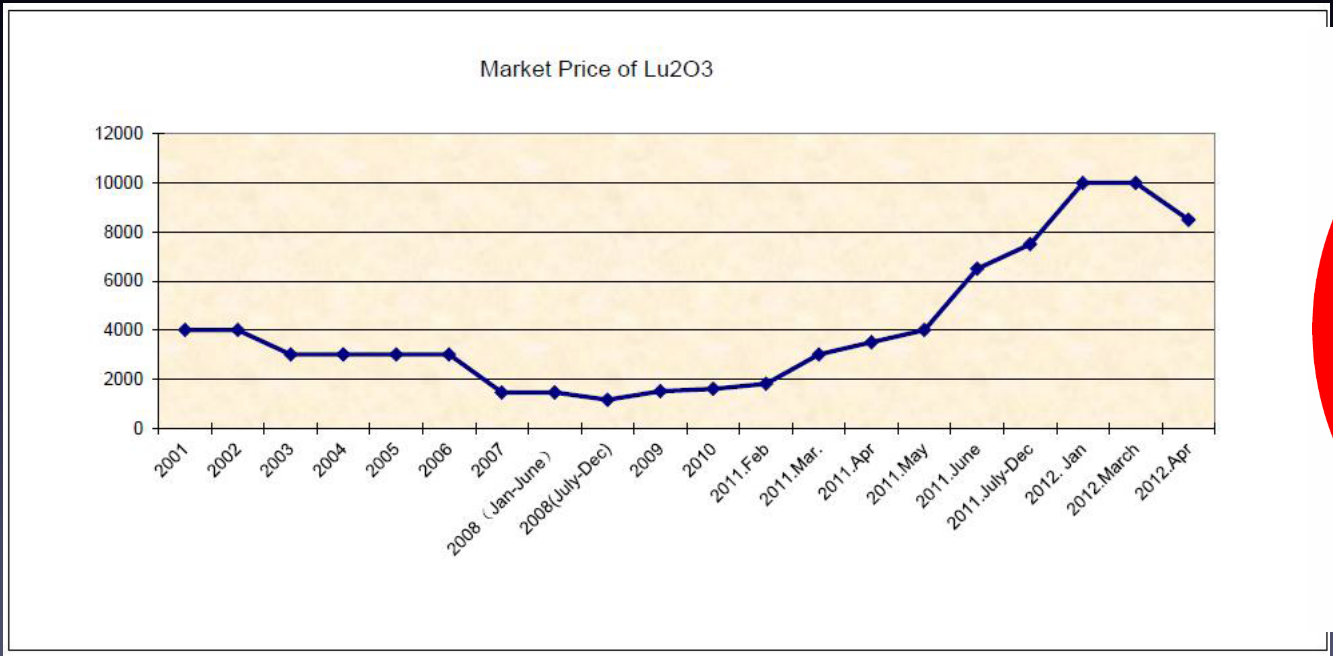


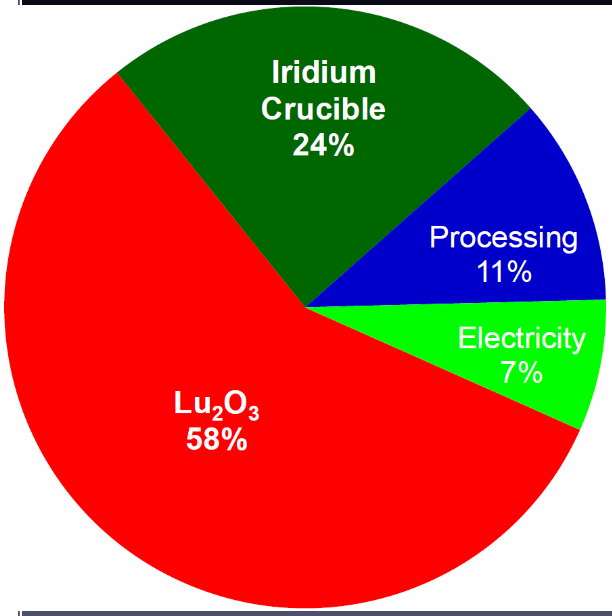
Future calorimeters

- 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
- Also looking for more radiation hard crystals

Crystals for HL-LHC

- LSO/LYSO is a heavy (7.4 g/cm3) crystal with bright (200 times light of PWO) and fast (40 ns) scintillation light. It has been widely used in the medical industry.
- Very rad-had

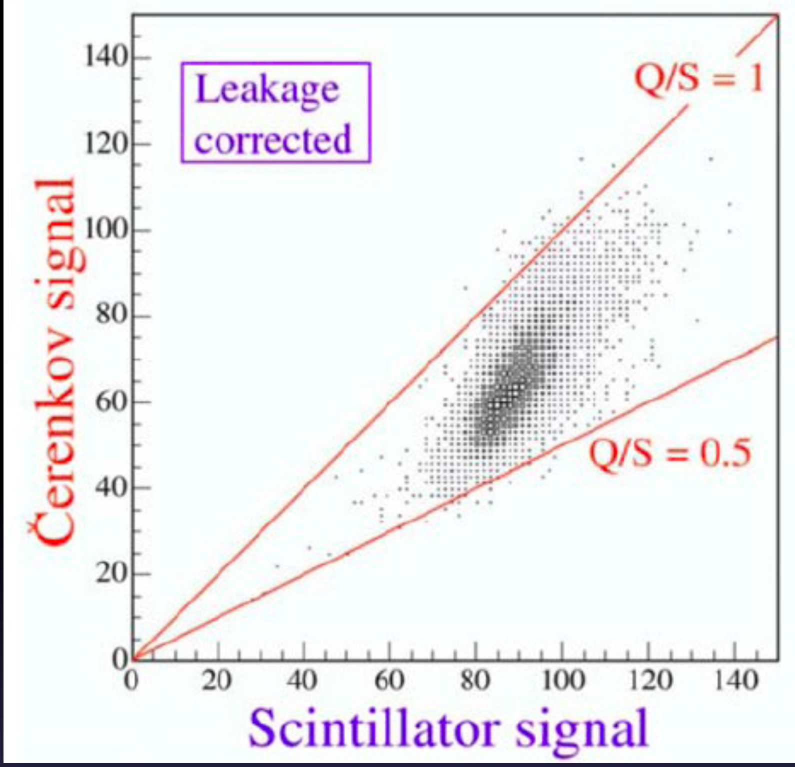


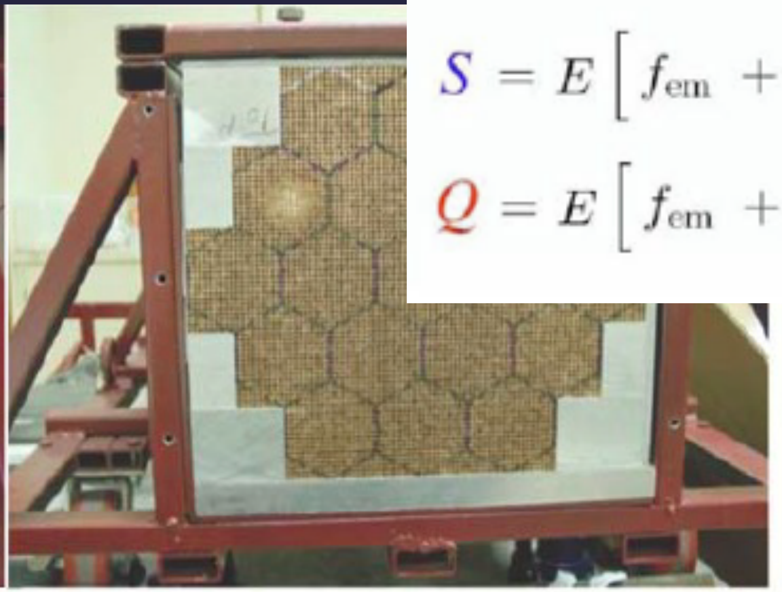


Assuming Lu2O3 at $400/kg and 33% yield the cost is about $18/cc.
Quotations received at $22-25/cc.

DREAM

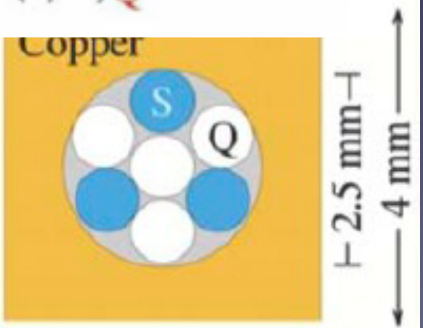
- Measure f_{EM} cell-by-cell by comparing Cherenkov and dE/dx signals
- Densely packed SPAgetti CALorimeter with interleaved Quartz (Cherenkov) and Scintillating Fibers
- Production of Cerenkov light only by em particles (f_{EM})
- **Aim at: $\sigma_E/E \sim 15\%/\sqrt{E}$**





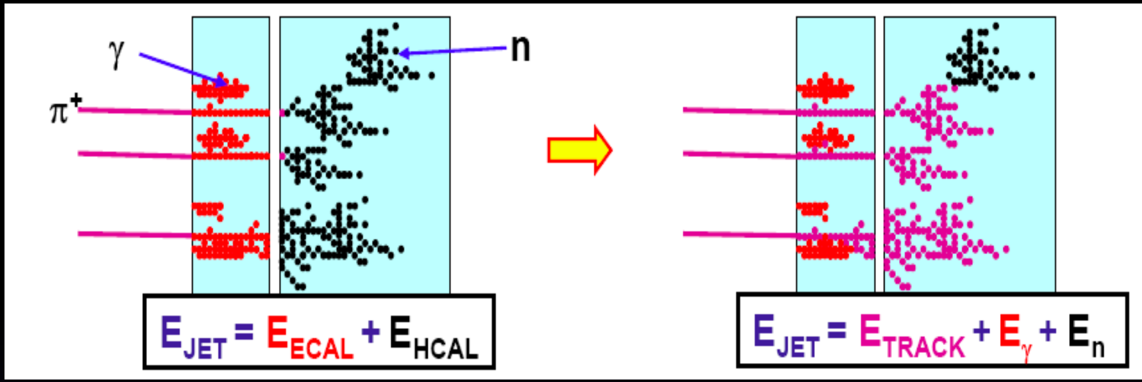
$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

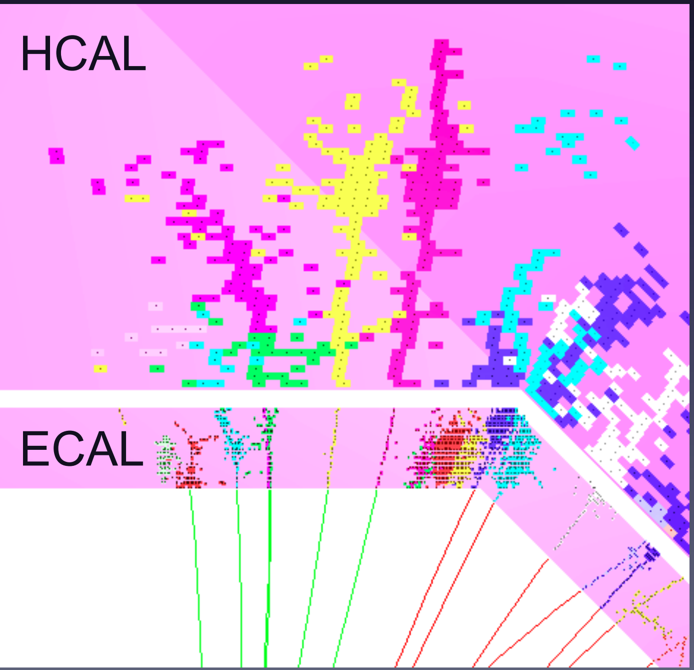
$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$



PF calorimetry (CALICE)

- Design detectors for Pflow
  - ECAL and HCAL: inside solenoids
  - Low mass tracker
  - High granularity for imaging calorimetry
  - It also require sophisticated software

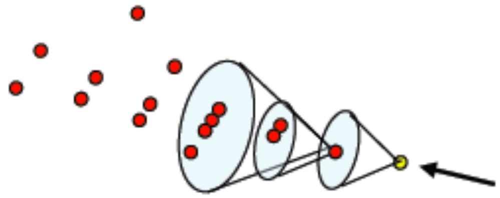




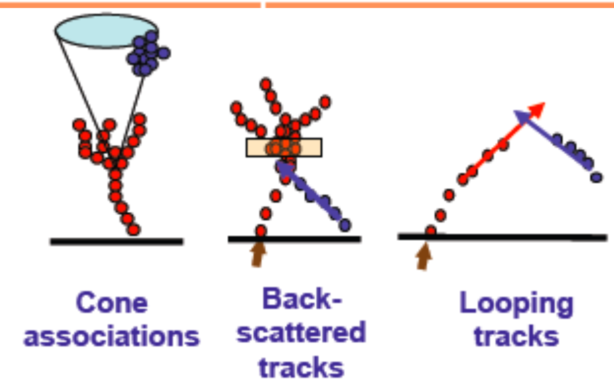
- Two proto-collaborations for ILC (ILD and SLD)
  - ECAL: Highly segmented S_iW or Scintillator-W sampling calorimeters
    - Transverse segmentation: ~5 x 5 mm^2
    - ~30 longitudinal sampling layers
  - HCAL: Highly segmented sampling calorimeters Steel or W absorber+ active material (RPC, GEM)
    - Transverse segmentation: 1x1 cm^2 – 3x3 cm^2
    - ~50 Longitudinal sampling layers !
  - Aiming at $\sigma_E / E < 3.5\%$

Particle flow

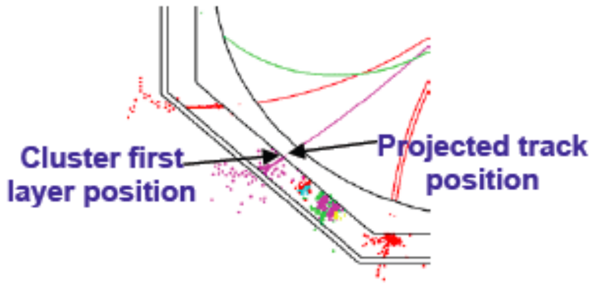
Mark Thomson



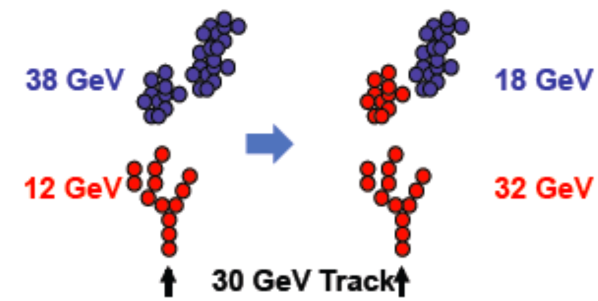
ConeClustering Algorithm



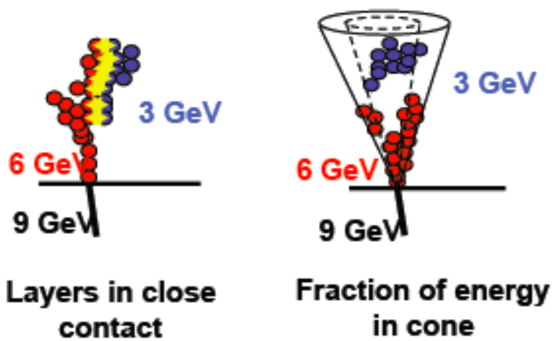
Topological Association Algorithms



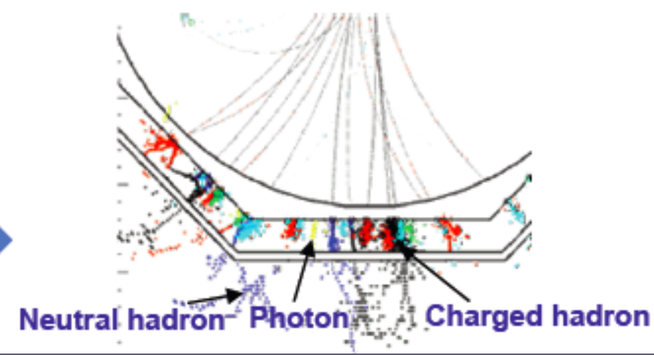
Track-Cluster Association Algorithms



Reclustering Algorithms



Fragment Removal Algorithms

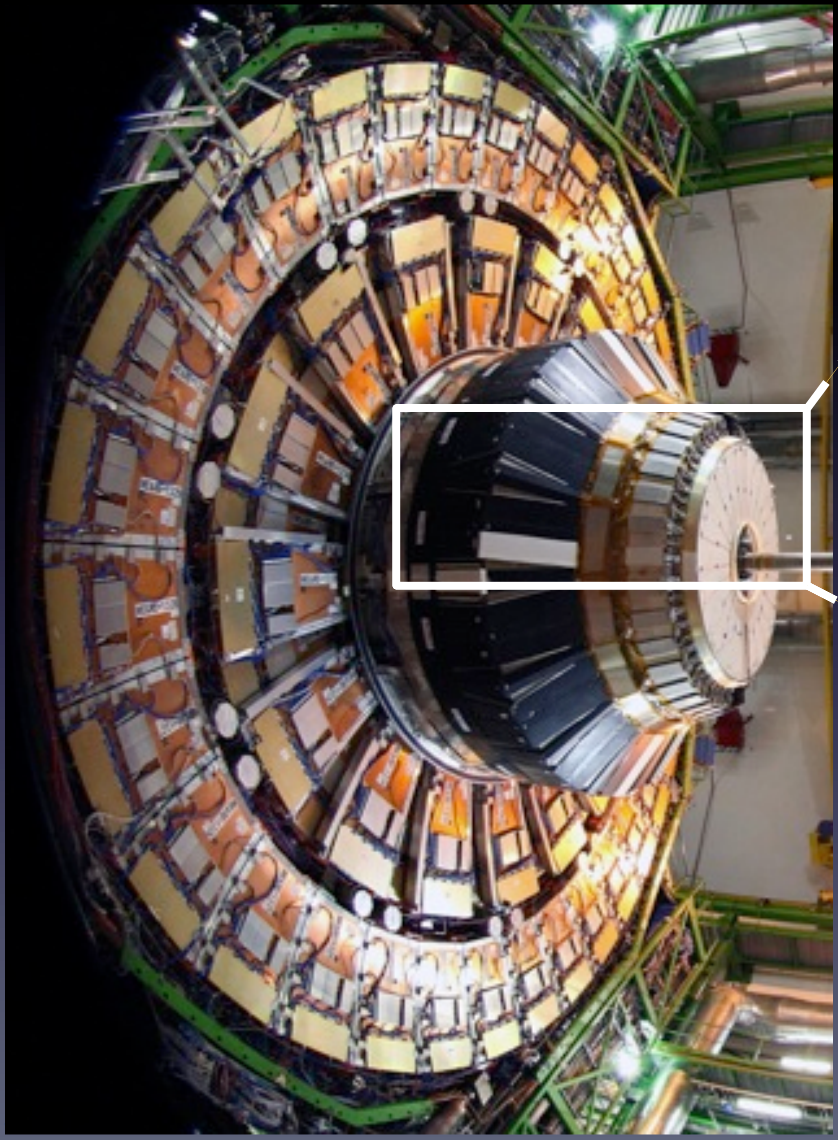


PFO Construction Algorithms

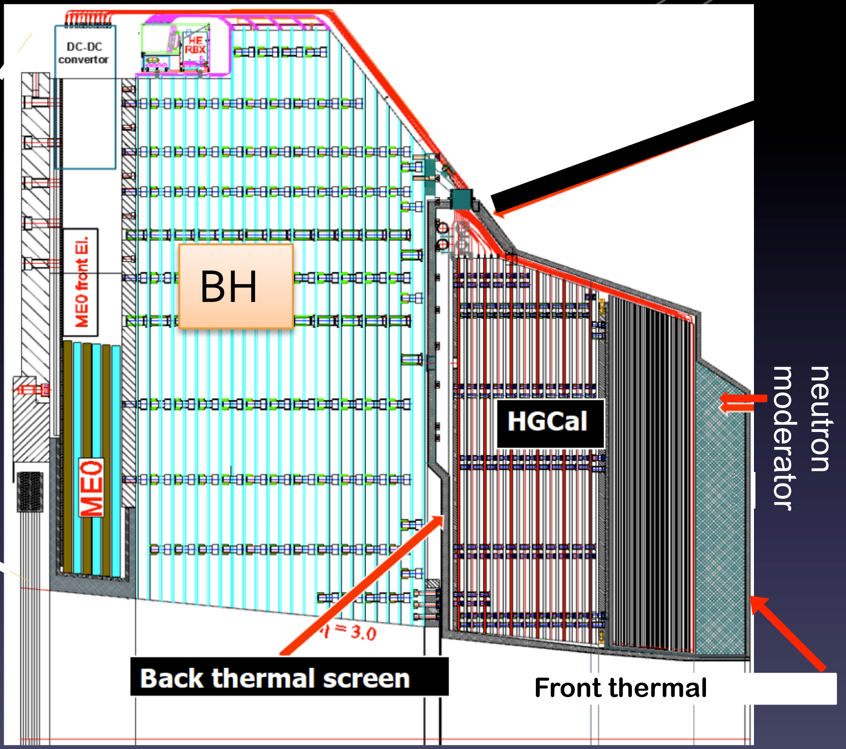
Proposed CMS Si-based Endcap Calorimeter

- The CMS endcap calorimeters will be replaced for the high luminosity LHC running that aims to record an integrated luminosity of 3000 fb^{-1}.
- A dense and compact approach is proposed for both electromagnetic and hadronic calorimetry that uses a high lateral and longitudinal granularity.
- Recent advances in Si sensors in terms of cost per unit area and radiation tolerance, and advances in electronics and data transmission bring up the possibility of their use in such high granularity calorimetry.
- High granularity calorimeters are proposed for future ILC/CLIC detectors, for which they have been shown to provide very high resolving power for single particles in dense jet environments, with energies of several hundred GeV's.
- The challenges faced for high-luminosity LHC operation are mainly in the area of engineering (mechanical and thermal), data transmission and Level-1 trigger formation

Integrated sampling Silicon ECAL+HCAL and Backing Calorimeters

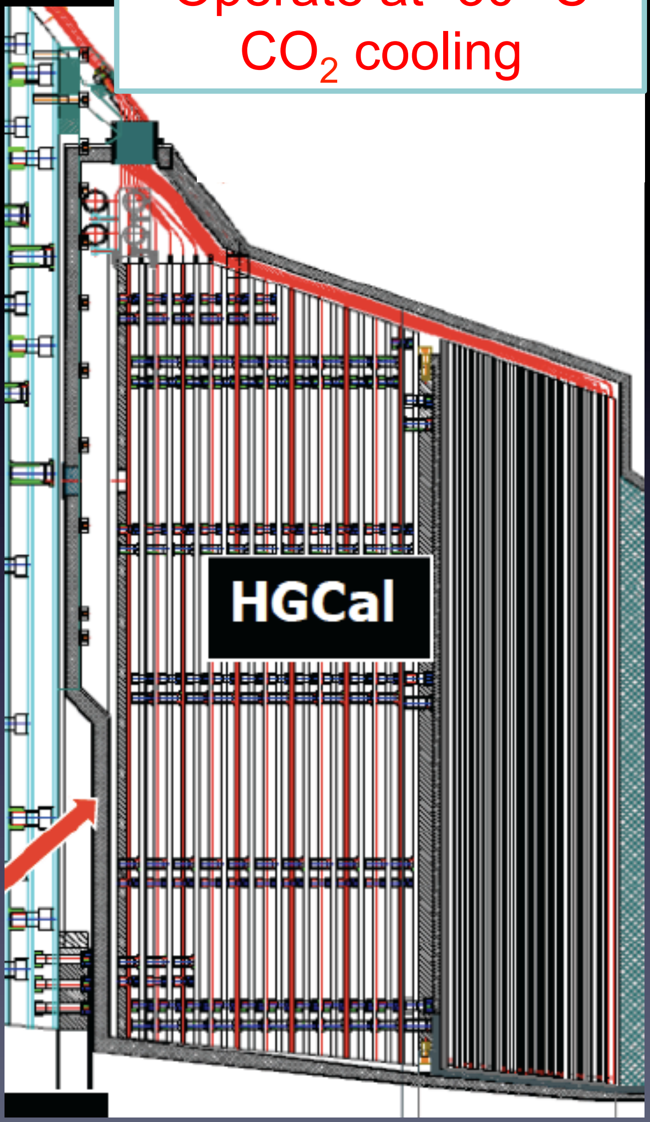


HGCAL



EE	Cu-W / Si	26 X_0 (1.5 λ)
FH	Brass / Si	3.5 λ
BH	Brass / scint. tiles	5 λ

Endcap Calorimeter for HL-LHC: HGCal



Operate at -30 °C
CO_2 cooling

Si/W-ECAL Section (Σ_{depth}>25X_0, 1.5λ)
10 × 0.65X_0
10 × 0.88X_0
8 × 1.26X_0

Si/Brass Front HCAL (FH) Section (Σ_{depth}> 3.5λ)
12 × 0.3λ

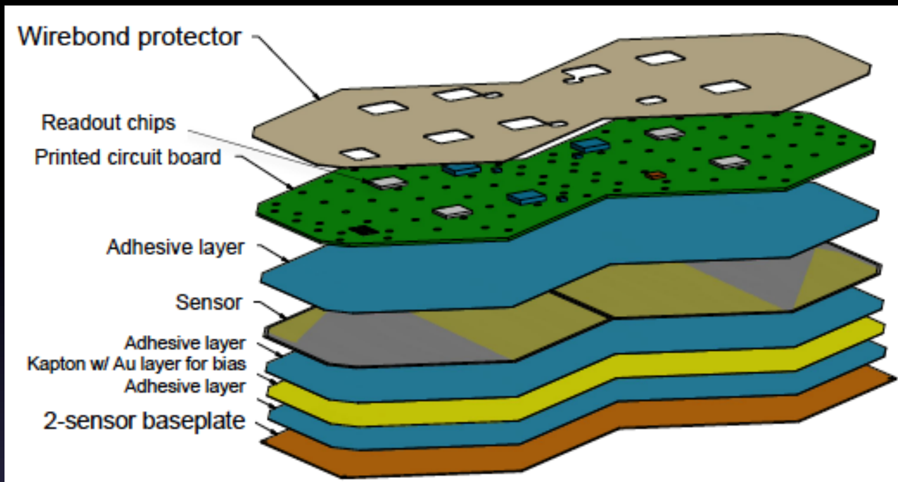
Scint/Brass Backing HCAL(BH)Section(Σ_{depth}> 5λ
12 × 0.45λ

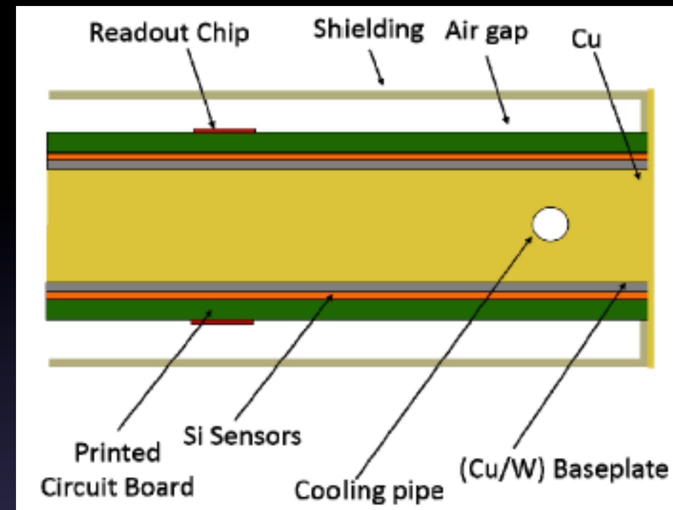
Total Depth >10λ

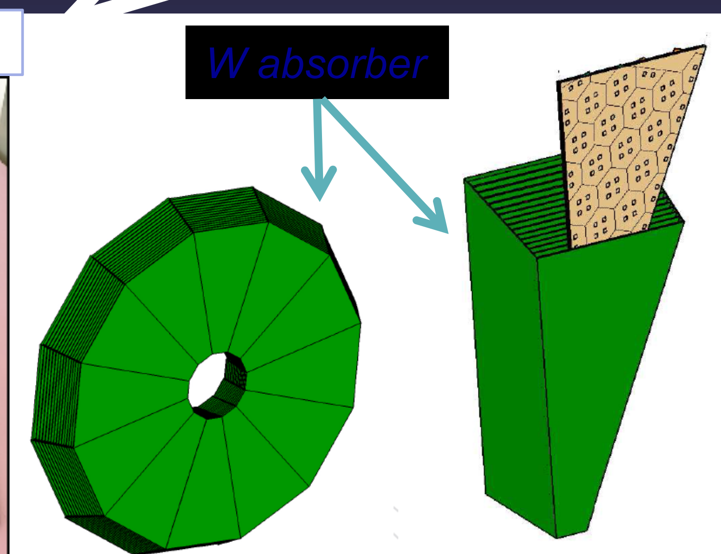
Table 3.2: Parameters of the EE and FH.

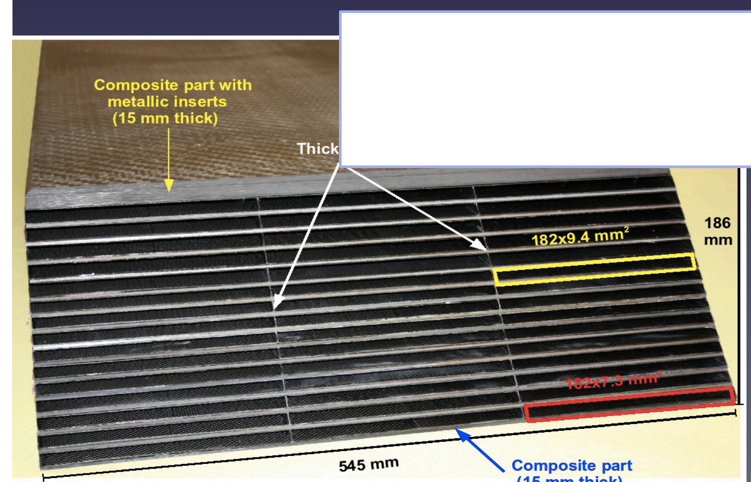
	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

Endcap Calorimeter for HL-LHC: HGCal

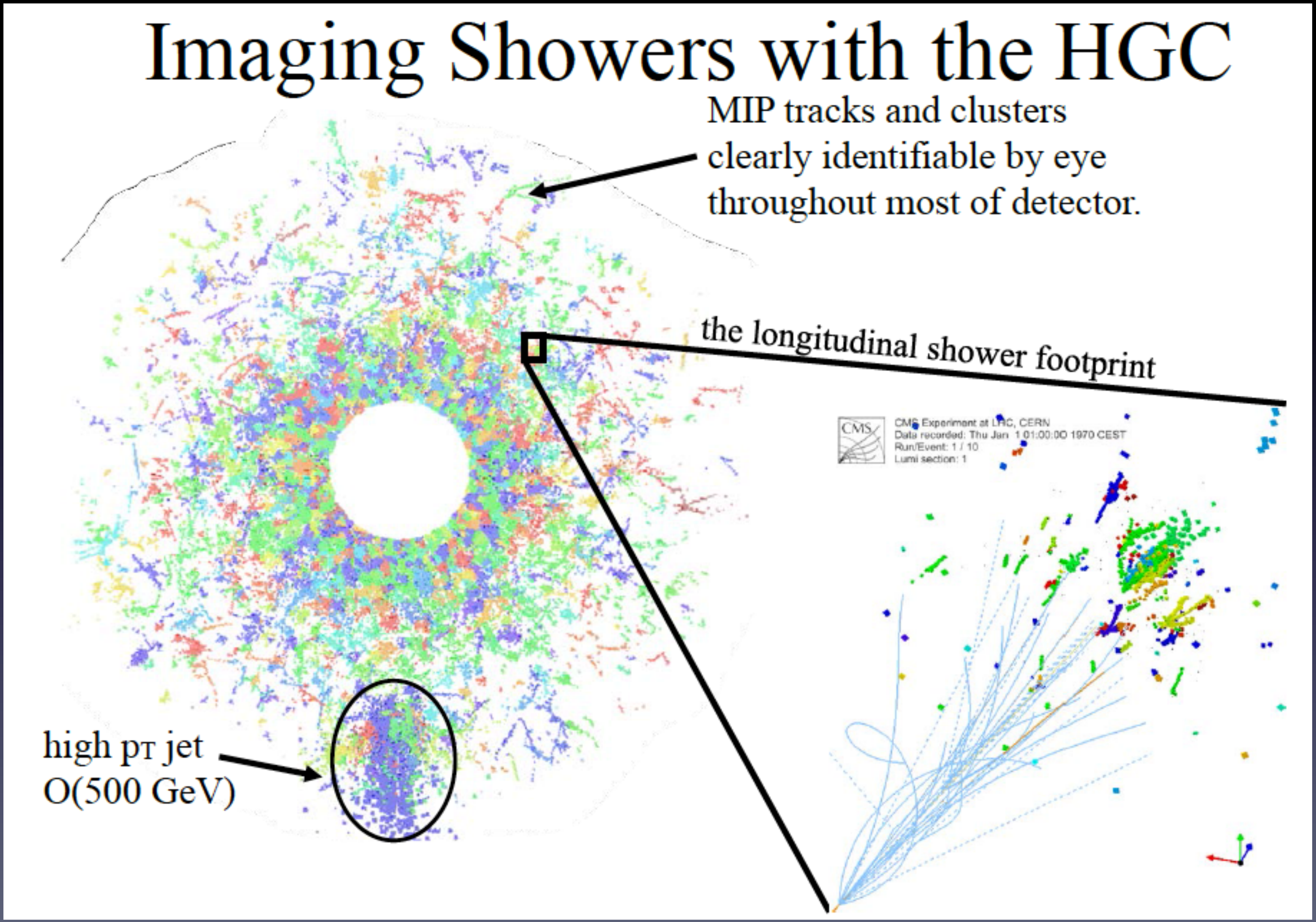








Extends tracking into calorimeter!



References

- Particle flow- M. Thompson
- Calorimetry for Particle Physics- C. Fabjan and F. Gianotti- CERN-EP/ 2003-075

- BACKUP

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

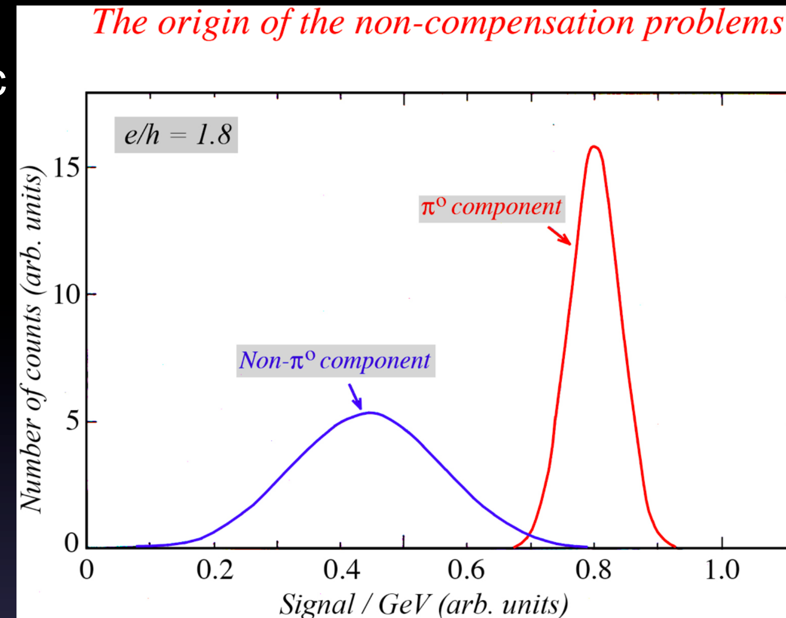
$$\pi = f_{em}\,e + (1 - f_{em})\,h$$

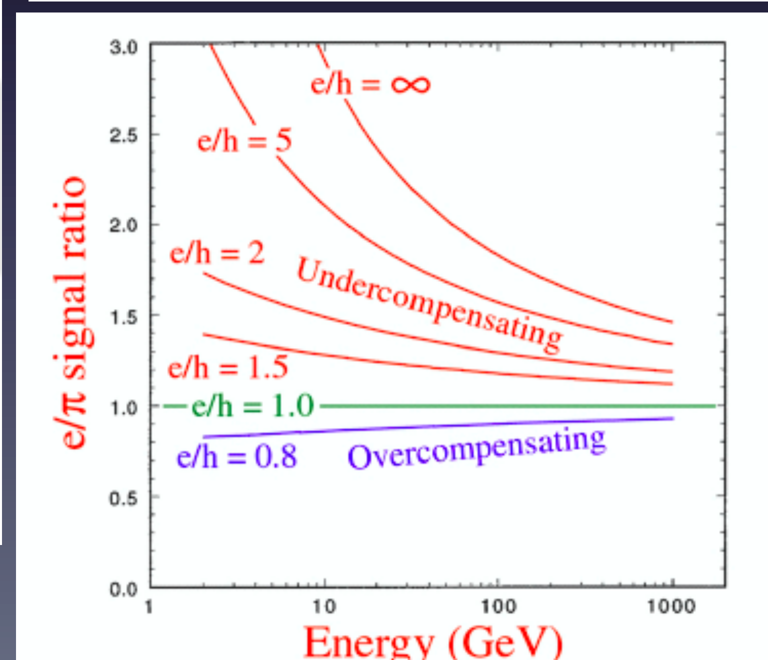
Comparing pion and electron showers:

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

Calorimeters can be:

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





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(E1)=e(E2):

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

For e/h=1 ➔ $$\frac{\pi(E_1)}{\pi(E_2)} = 1$$

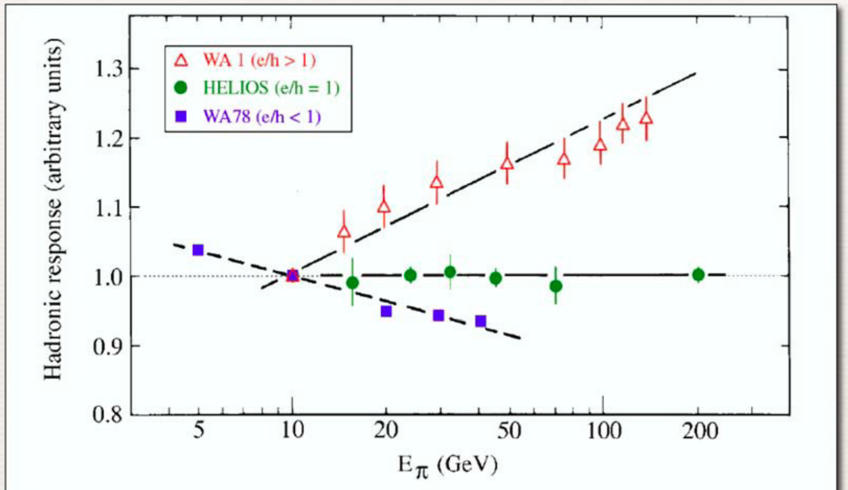
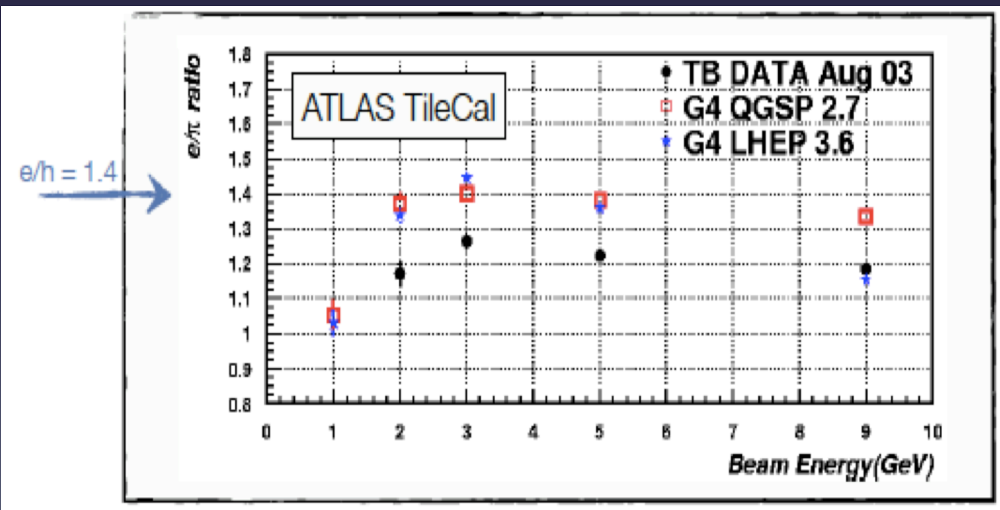
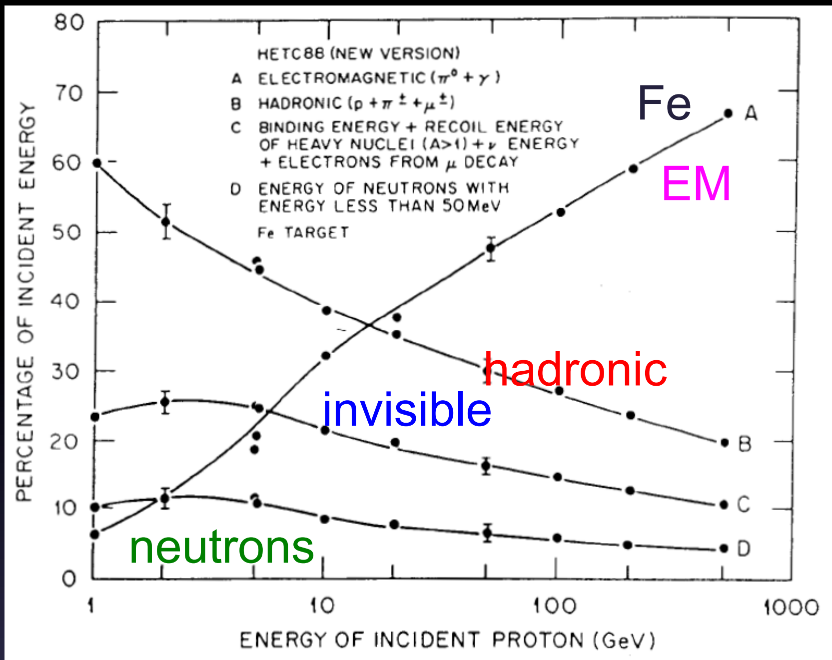


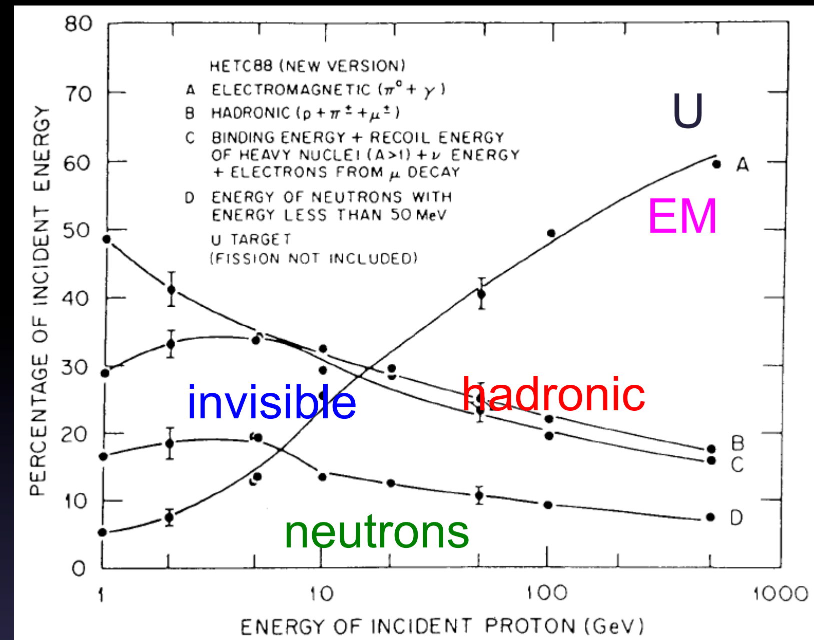
FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10 GeV.



- Response of calorimeters is usually higher for electromagnetic (e) than hadronic (h) energy deposits→ 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

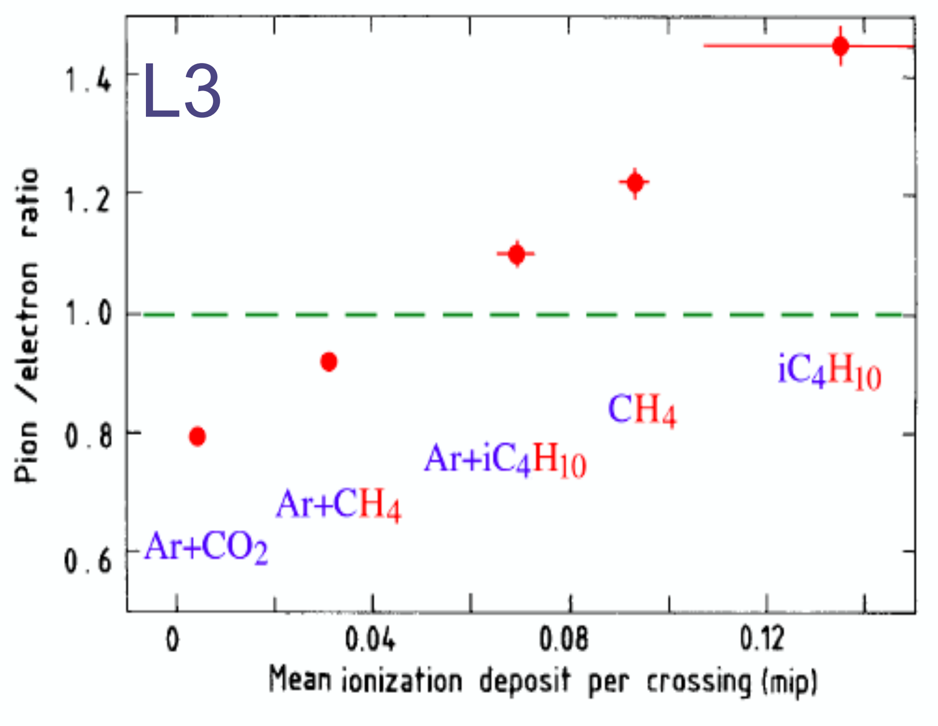
- f_{rel}= Ionization by charged pions (relativistic shower component)
- f_p=spallation protons
- f_n=neutrons evaporation
- f_{inv}=invisible energy by recoil nuclei

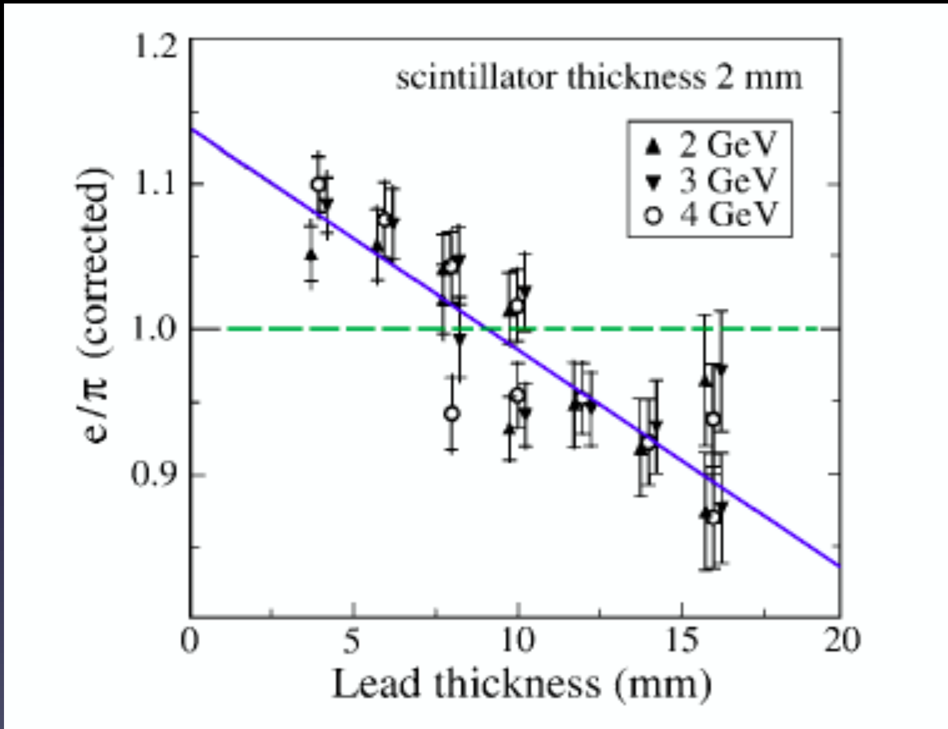
- Compensation:
  - Tuning the neutron response using hydrogenous active material (L3 Uranium/gas calorimeter)
  - Compensation adjusting the sampling frequency

Compensation by tuning neutron response

Hydrogen in active material (gas mixture)

Pb/Scintillator



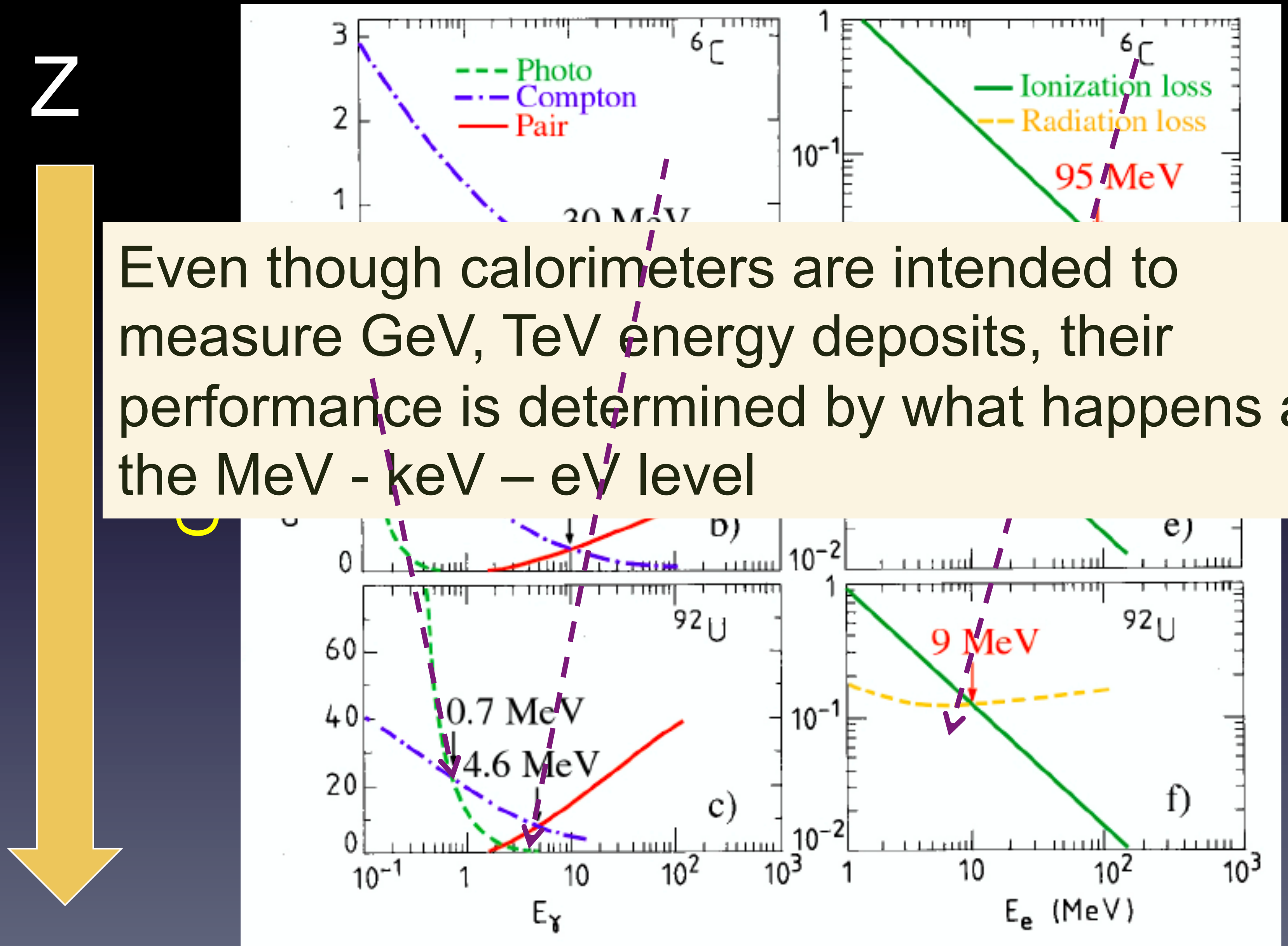


Elastic n-p scattering:
efficient sampling of neutrons through the detection of recoiling proton

Sampling fraction can be tuned to achieve compensation

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

Summary

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

Pb : Z=82 , A=207, ρ=11.34 g/cm^3
Fe : Z=26 , A=56, ρ=7.87 g/cm^3
Cu : Z=29 , A=63, ρ=8.92 g/cm^3

Radiation length:

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

Critical energy:
[Attention: Definition of Rossi used]

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

Shower maximum:

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

Longitudinal
energy containment:

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

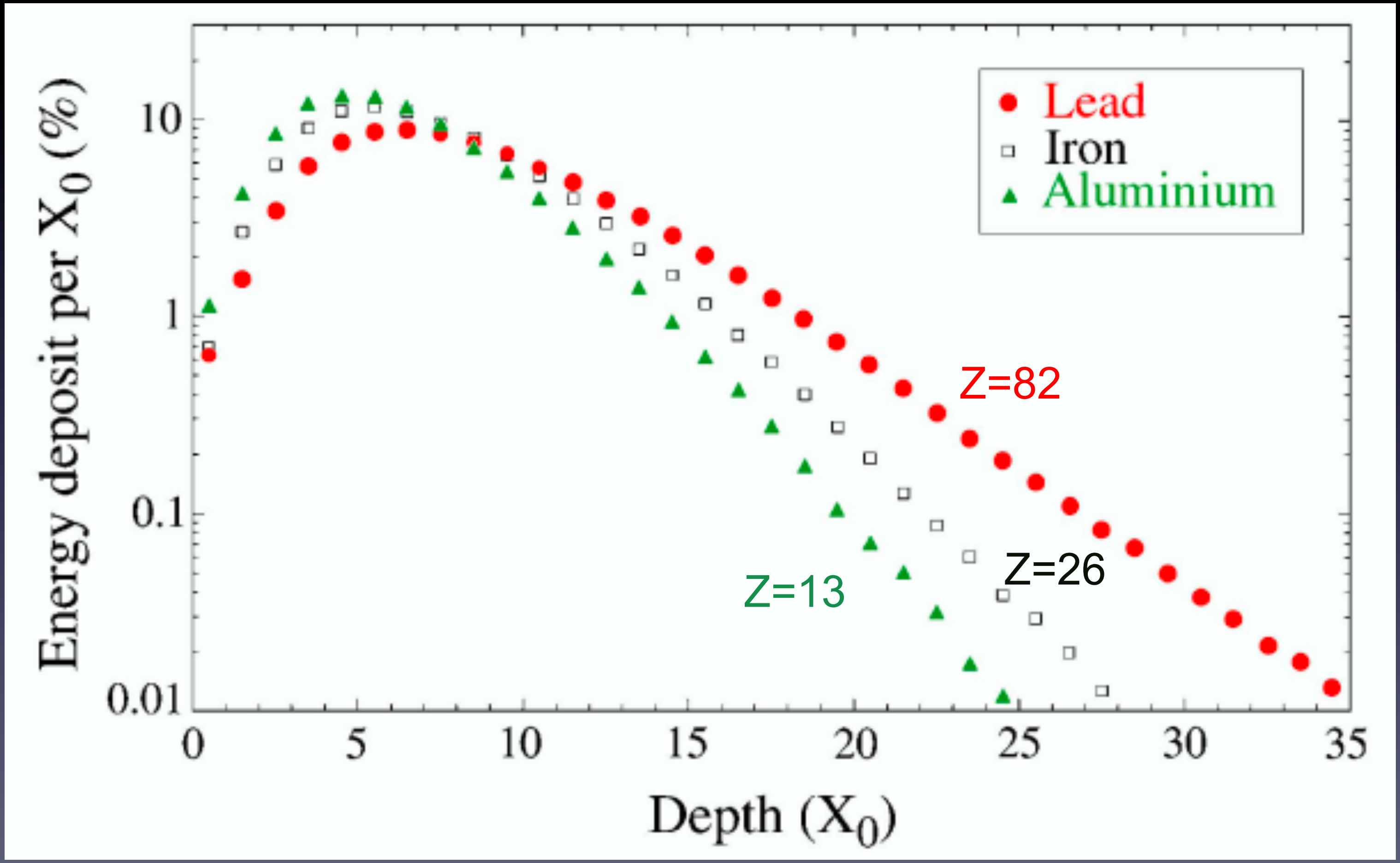
Transverse
Energy containment:

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

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

Longitudinal development of EM shower

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



Resolution in Homogenous calorimeters

- Homogeneous calorimeters: signal = sum of all E deposited by charged particles with $E > E_{threshold}$
- 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 ≈ 3 eV (to produce e-hole pair)

1 MeV **γ** = 350000 electrons➔ $1/\sqrt{n} = 0.17\%$ 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

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 (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**

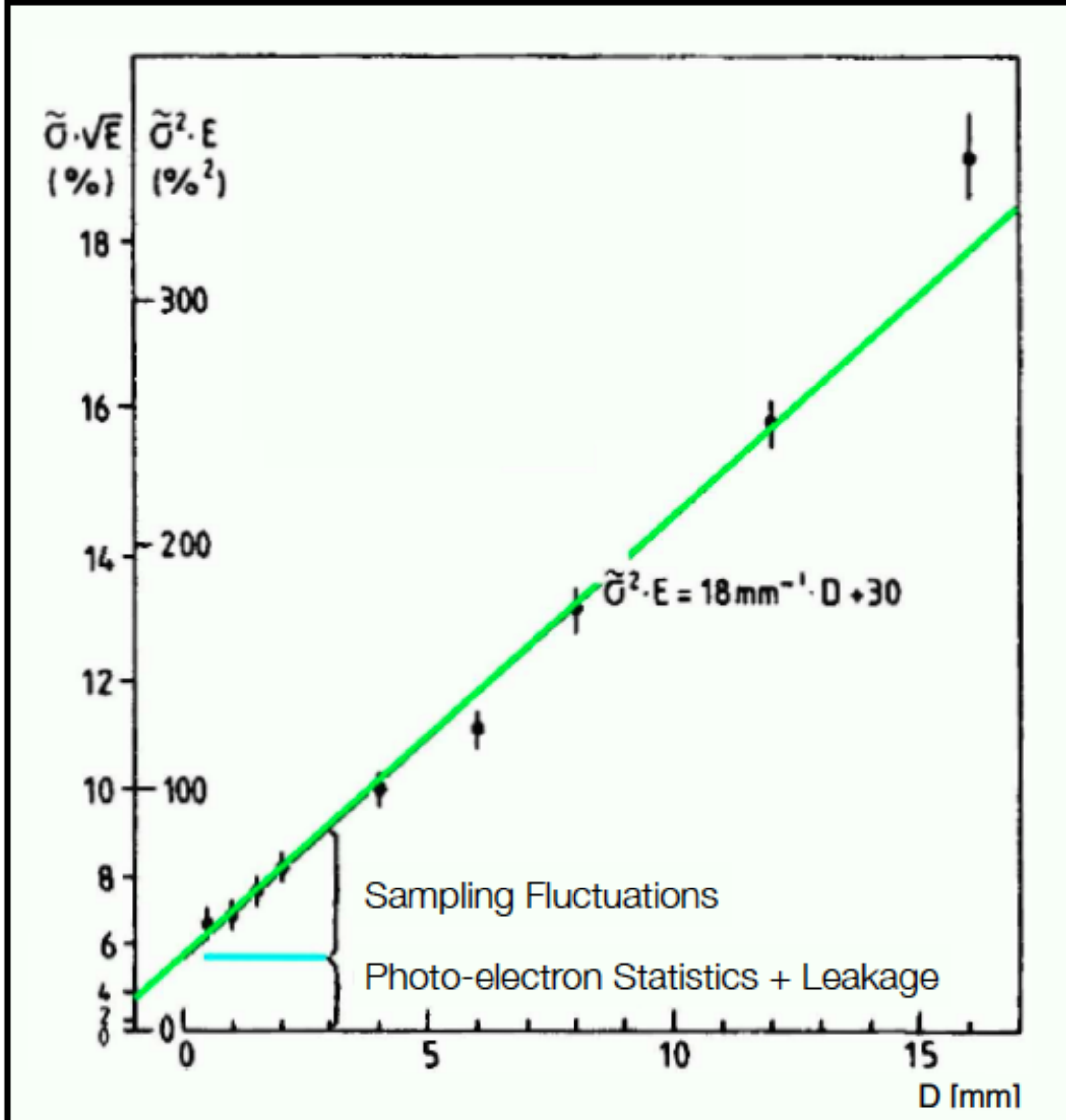
$$\frac{\sigma_{samp}}{E} = \frac{10\%}{\sqrt{E}}$$

Dependence on sampling

Measure energy resolution of a sampling calorimeter for different absorber thicknesses

Sampling contribution:

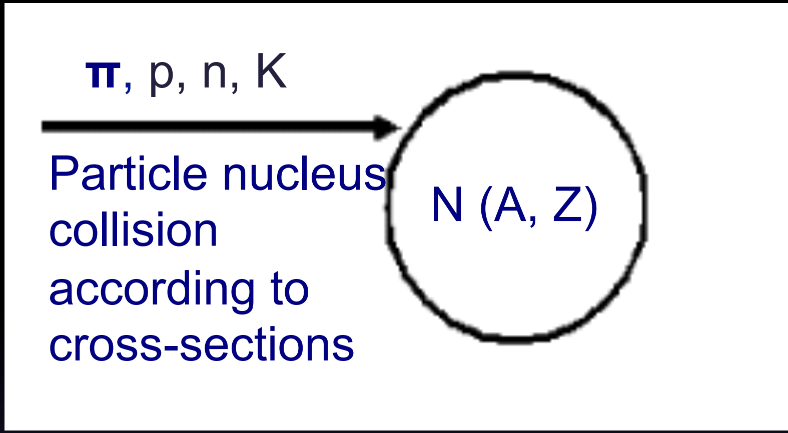
$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c\ [\mathrm{MeV}] \cdot t_{\mathrm{abs}}}{F \cdot E\ [\mathrm{GeV}]}}$$

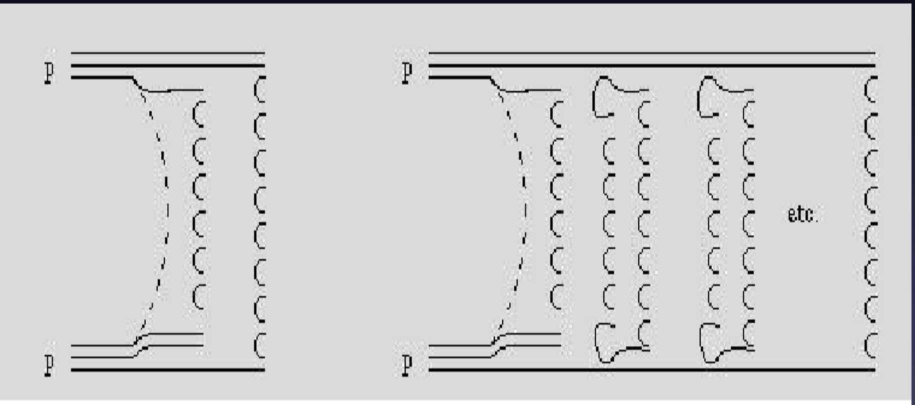


Hadronic interactions

1st stage: the hard collision

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





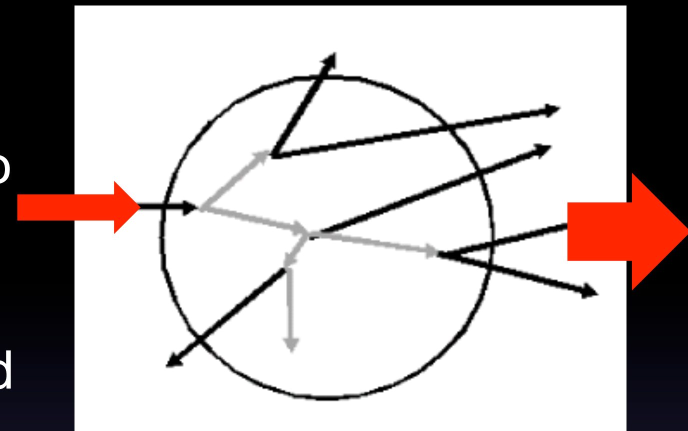
Nucleon is split in quark di-quark
Strings are formed String hadronisation (adding qqbar pair)
fragmentation of damaged nucleus

- 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
  - ~ 1/3 $\pi^0 \rightarrow \gamma\gamma$ produced in charge exchange processes: $\pi^+ p \rightarrow \pi^0 n$ and $\pi^- n \rightarrow \pi^0 p$
  - Leading particle effect: depends on incident hadron type e.g fewer π^0 from protons, barion number conservation

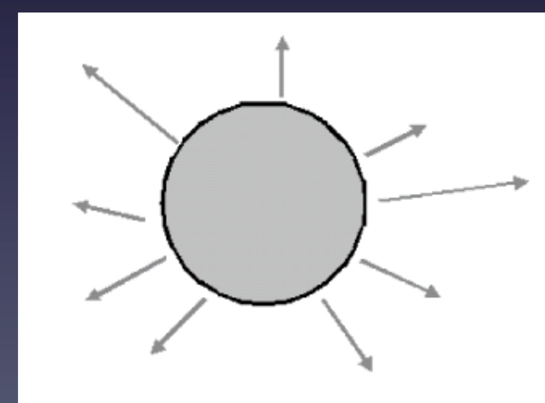
Hadronic interactions

2nd stage: spallation

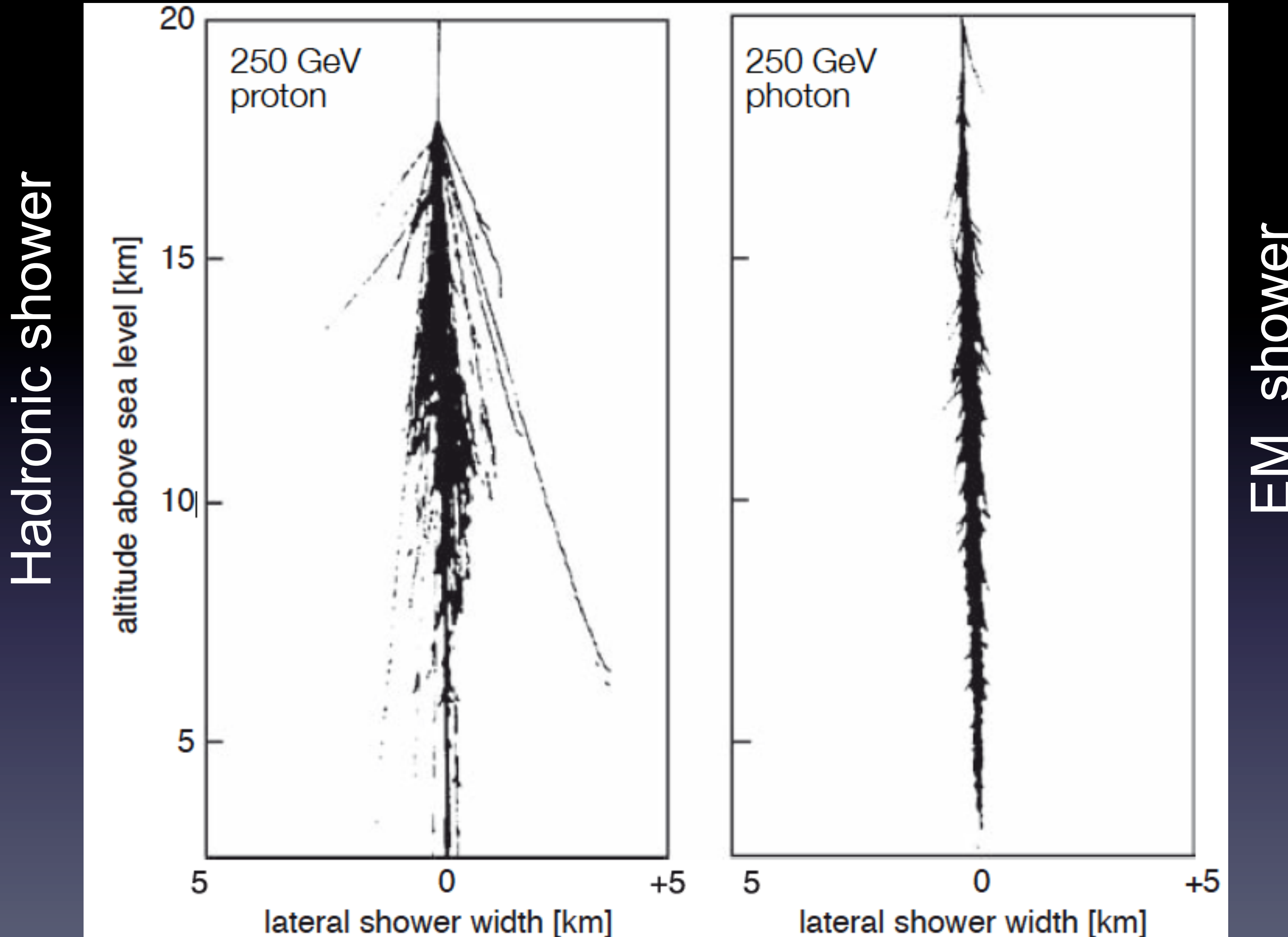
- A fast hadron traversing the nucleus frees protons and neutrons in number proportional to their numerical presence in the nucleus.
- The nucleons involved in the cascade transfer energy to the nucleus which is left in an excited state
- Nuclear de-excitation
  - Evaporation of soft (~10 MeV) nucleons 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➔ protons are trapped by the Coulomb barrier (12 MeV in Pb, only 5 MeV in Fe)



Dominating momentum component along incoming particle direction

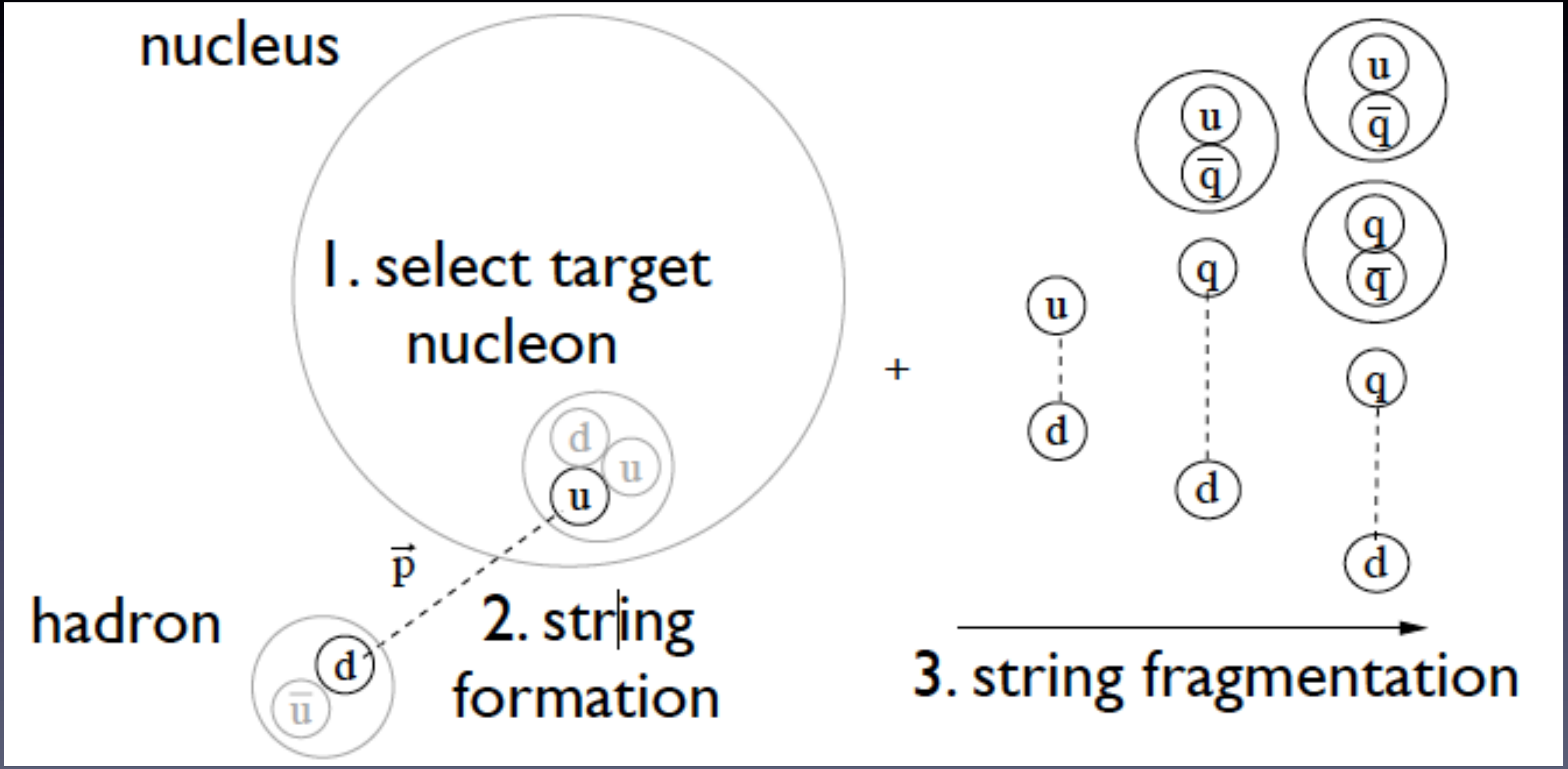


isotropic process


Hadronic shower
250 GeV
proton
altitude above sea level [km]
20
15
10
5
5
0
+5
lateral shower width [km]
250 GeV
photon
5
0
+5
lateral shower width [km]
EM shower

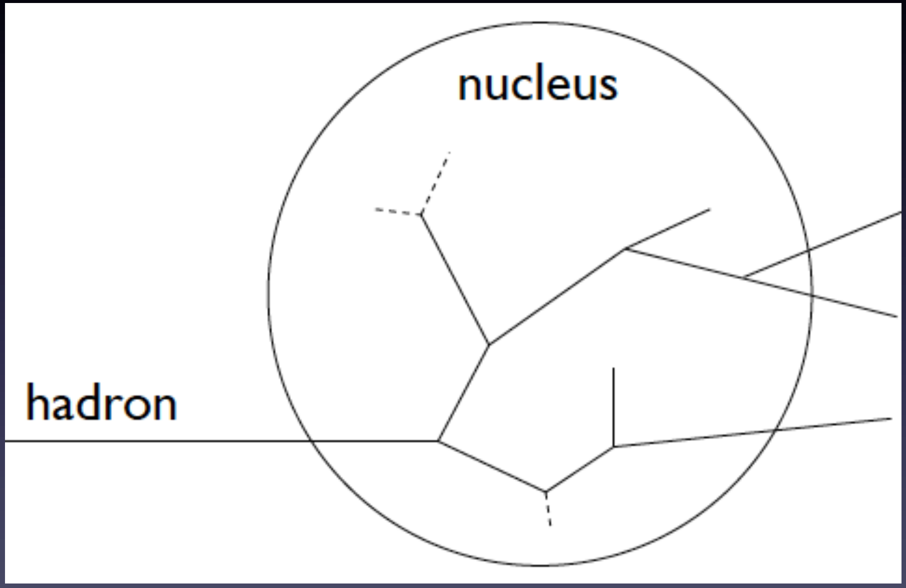
Simulation

- 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 MeV < E < 10 GeV via intra-nuclear cascades
- For E < 10 MeV only relevant are fission, photon emission, evaporation, ...



Approximations

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