Lectures on calorimetry

Christophe Ochando
(LLR/Ecole Polytechnique/CNRS)

Lecture 1

High Granularity
Hybrid Timing
and Energy Calorimetry
a P2IO project by LLR, LAL and IRFU

esipap
European School of Instrumentation in Particle & Astroparticle Physics

esi
European Scientific Institute

IN2P3
Les deux infinis

ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

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Plan of lectures

Lecture 1

Why/what calorimeters ?

Physics of EM & HAD showers

Calorimeter Energy Resolution

Lecture 2

Example of Calorimeter

Calorimeter Objects & Triggering

Exercises

Lecture 3

Future of calorimetry

Lecture 4

Example of calorimeters (suite)

Exercises

Disclaimer

Calorimetry is a vast topic.

This series of lectures only scratch the surface…

No way to cover all technologies, detectors, features.

This is thus a **selective**, **personal** and (surely) **biased** presentation of calorimetry.

Also, it is likely some (unavoidable) redundancy is there wrt the previous lectures.

References

These lectures were built upon numerous (excellent) lectures, books or papers:

➢ Lectures:

- V. Boudry, *“La Calorimétrie”*, Ecole du détecteur à la mesure, mai 2013 (Fréjus)
- D. Cockerill, *“Introduction to Calorimeters”*, Southampton Lecture May 2016
- M. Diemoz, *“Calorimetry”*, EDIT 2011 (CERN)
- D. Fournier, *“Calorimetry”*, EDIT 2011 (CERN)
- E. Garutti, *The art of calorimetry*
- F. Sefkow, *Particle Flow: A Calorimeter Reconstruction Exercise”,* EDIT 2010 (CERN)
- J. Stark, *“Counting Calories at DØ”*, University of DØ 2010, Fermilab
- J. Virdee, “Experimental Techniques, European School of HEP 1998 (St Andrews)
- I. Wingerter-Seez, *“Calorimetry: Concepts and Examples”*, ESIPAP 2016 (Archamps)
- A. Zabi, *“Instrumentation for High Energy Physics”*, TES-HEP 2016 (Yaremche)
- P. Sphicas, “Triggering (at the LHC)”, SLAC Summer Institute 2006 (SLAC)
- A. Hoecker, “Trigger and Data Analysis”, HCPSS 2009 (CERN

➢ Book:

- R. Wigmans,*“Calorimetry, Energy Measurements in Particle Physics”*, Oxford science publications,
- Particle Data Group

➢ Talks, proceedings, articles:

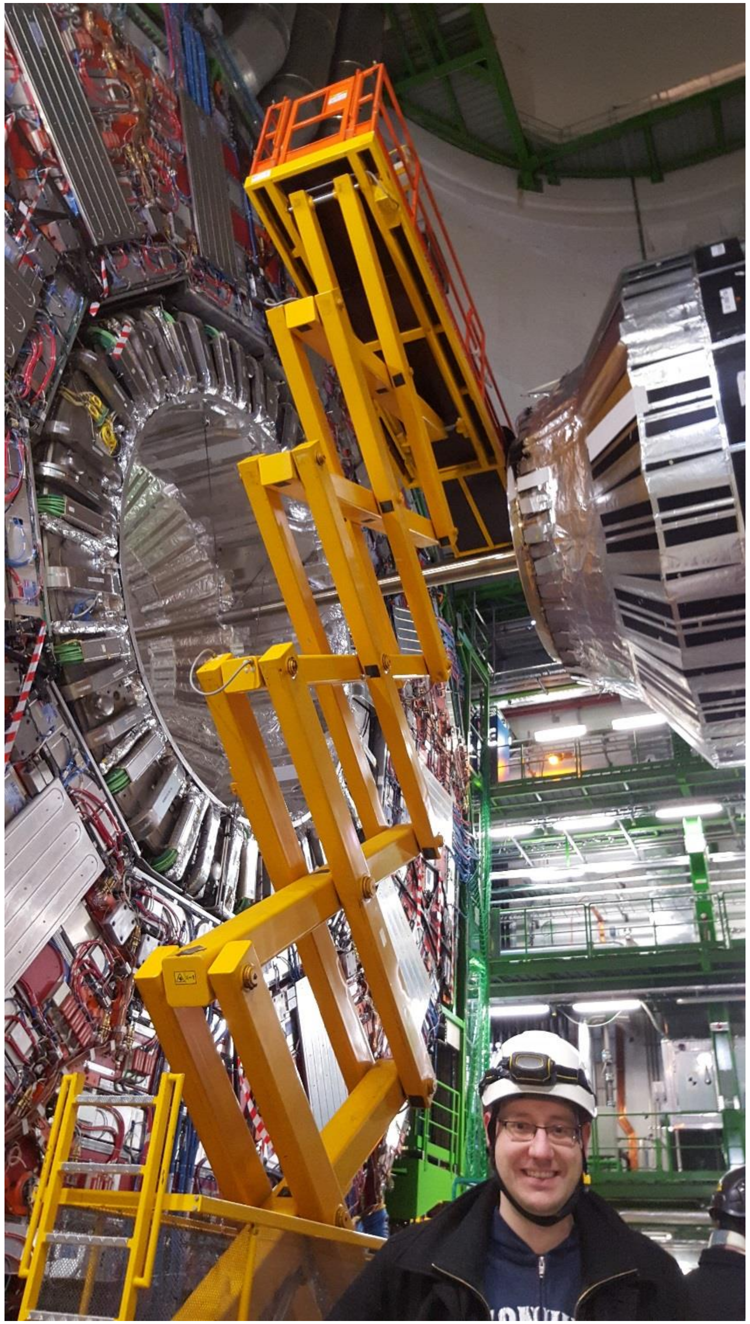
- J-C. Brient, Improving the Jet Reconstruction with the Particle Flow Methodd; An Introduction
- F. Beaudette, *Performance of the Particle Flow Algorithm in CMS*, ICHEP 2010 (Paris)
- F. Beaudette, *The CMS Particle Flow Algorithm*, CHEF 2013 (Paris)
- C. Bernet, Particle Flow and τ, LHC France 2013 (Annecy)
- L. Gray, *Challenges of Single Particle Reconstruction in Hadronic Environment*s, Rencontres du Vietnam: Physics at LHC and Beyond 2014 (Qui-Nhon)
- J.S. Marshall, *Pandora Particle Flow Algorithm*, CHEF 2013 (Paris)
- H. Videau, *Energy Flow or Particle Flow The technique of energy flow for pedestrians.*

A few words about myself

- **Thesis at DØ (at Tevatron ppbar collider)**
  - **Jet Calibration**,
  - **Jet+Missing E_T** Trigger,
  - Search for Higgs boson

- **Post-doc ATLAS (at LHC pp collider)**
  - **Jet** Triggers
  - Z+jets cross section

- **In CMS (LHC) since 2009**.
  - Search and discovery of Higgs boson
    - $H \to ZZ^* \to 4$ lepton channels
  - **Electron Identification**
  - Since 2014, working on the **High Granularity CALorimeter** upgrade project (Endcap CMS calorimeter Phase II Upgrade)

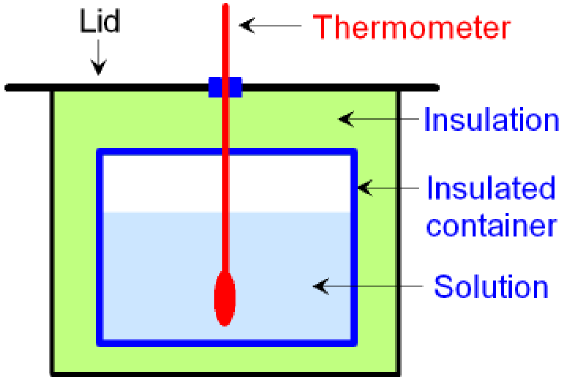


What is a calorimeter ?

Concept comes from thermodynamics.

- *Calor*: latin for “heat”
- **Calorimeter:** thermally isolated box containing a substance to study (e.g., measure its temperature)

  Ex: Calorimeter of Curie-Laborde (1903) to measure heat produced by radium radioactivity (~100 cal / g / h).



- 1 calorie (4,185 J) is the necessary energy to increase the T° of 1g of water at 15°C by 1 degree
- At hadron colliders, we measure GeV particles (0.1 – 1000)

  1 GeV = 10^9 eV ~ 10^9 x 10^{-19} J = $2.4.10^{-9}$ cal !

  <=> 1 GeV particle will heat up 1L water (20°C) by… ~10^{-14} K !

The increase of heat in a material by the passage of particle is negligible !
More sophisticated methods have to be used to detect stable particles…

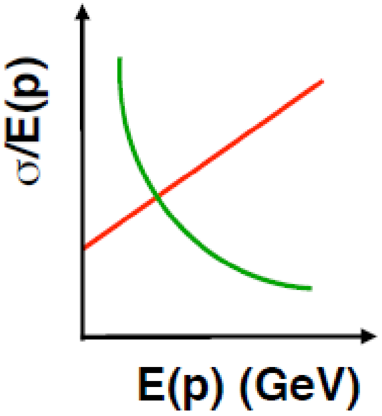
What is a calorimeter… in high energy physics ?

Calorimeters in HEP: detection & measurement of properties of particles
through their absorption in a block of (dense) matter.

- **Up to 1970',** mostly tracking system (with magnetic field) were used:
  - Measure charged particles… (curvature => momentum, charge, dE/dX: information on mass)
  - … and neutrals, through interaction with matter (e.g. $\pi^0 \to \gamma\gamma$ with conversion: $\gamma \to e^+e^-$)
- **But:**
  - Very poor efficiency and/or resolution on π^0
  - Necessity to measure particles of higher and higher mass (W/Z, top quark, Higgs, W/Z', SUSY…)

=> Calorimeter became more and more crucial in HEP

- Measure charged AND neutrals
- Resolution:



$$\frac{\sigma(p)}{p} = ap \oplus b$$

Magnetic analysis

$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

Resolution improves with E
with **Calorimeter**

The measurement in process with calorimeters is **destructive** !

Note: in the absorption, almost all particle's energy is eventually converted to heat, hence the term "calorimeter"

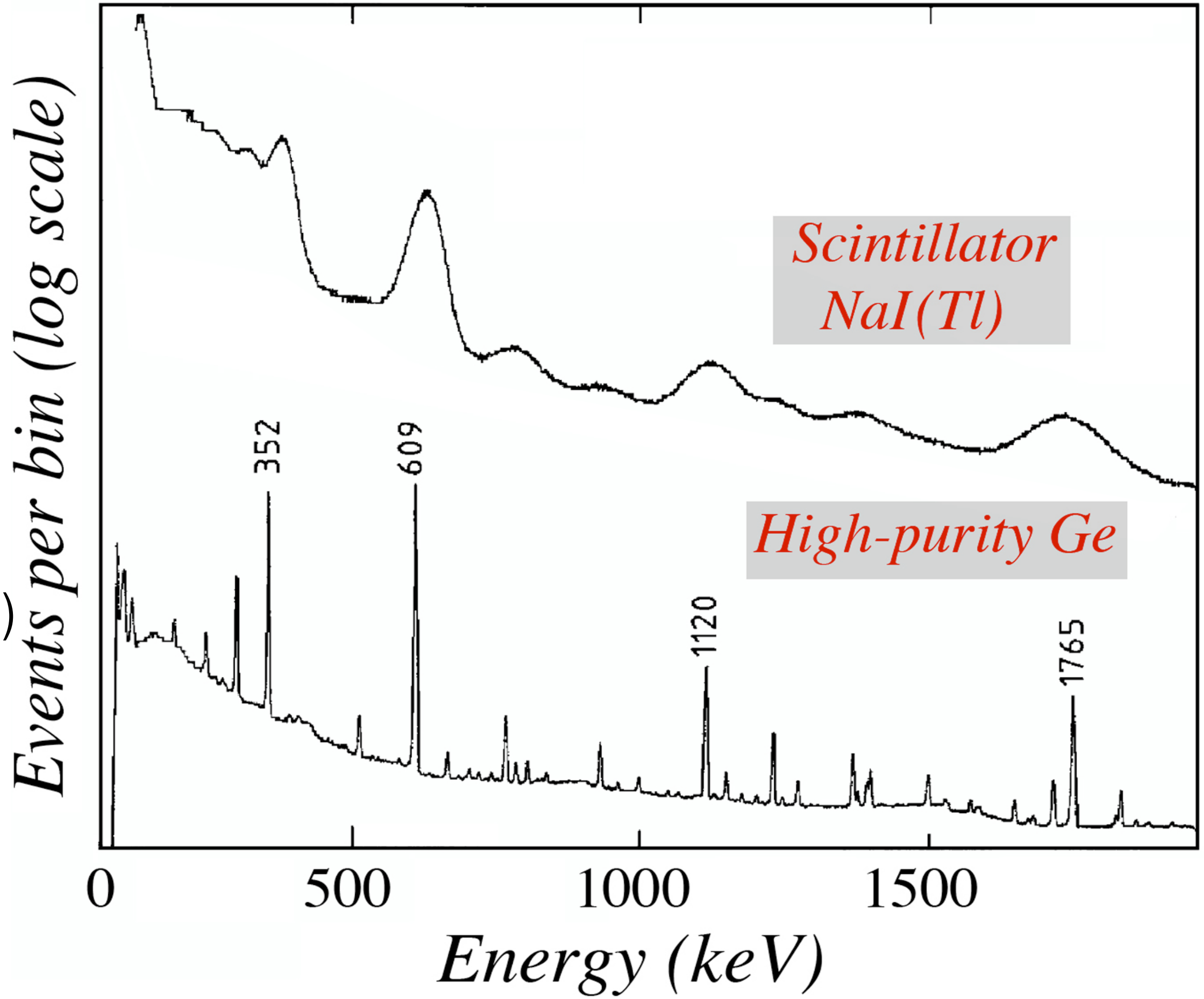
Some (historical) examples… (1)

A wide variety of calorimeters… for a wide physics program !

1940's: calorimeters used for detection of
α, β, γ from nuclear decays
Scintillating crystals
+ PhotoMultiplier Tubes (PMT)

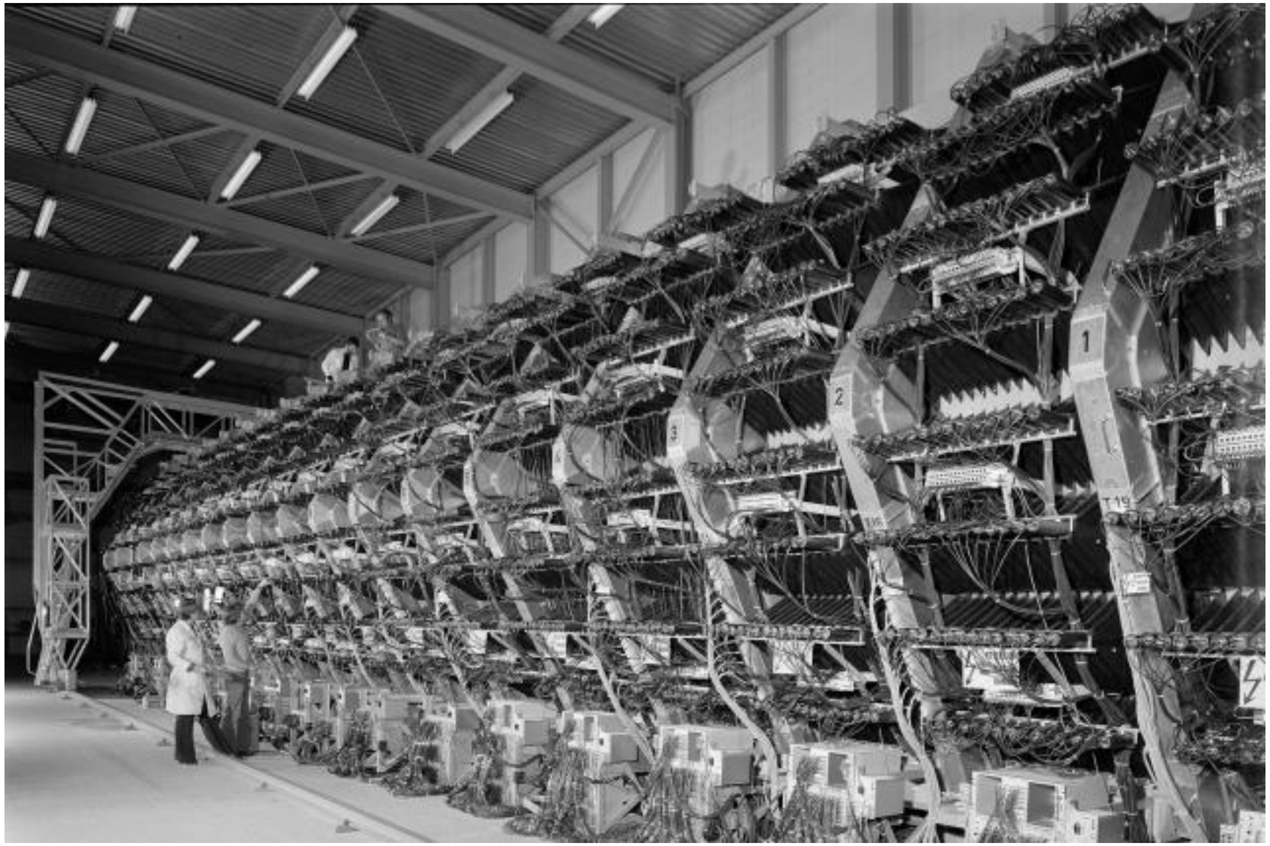
1960's: first **semi-conductor detectors** (Si, Ge)

Impressive improvement in resolution !



Some (historical) examples… (2)

A wide variety of calorimeters… for a wide physics program !



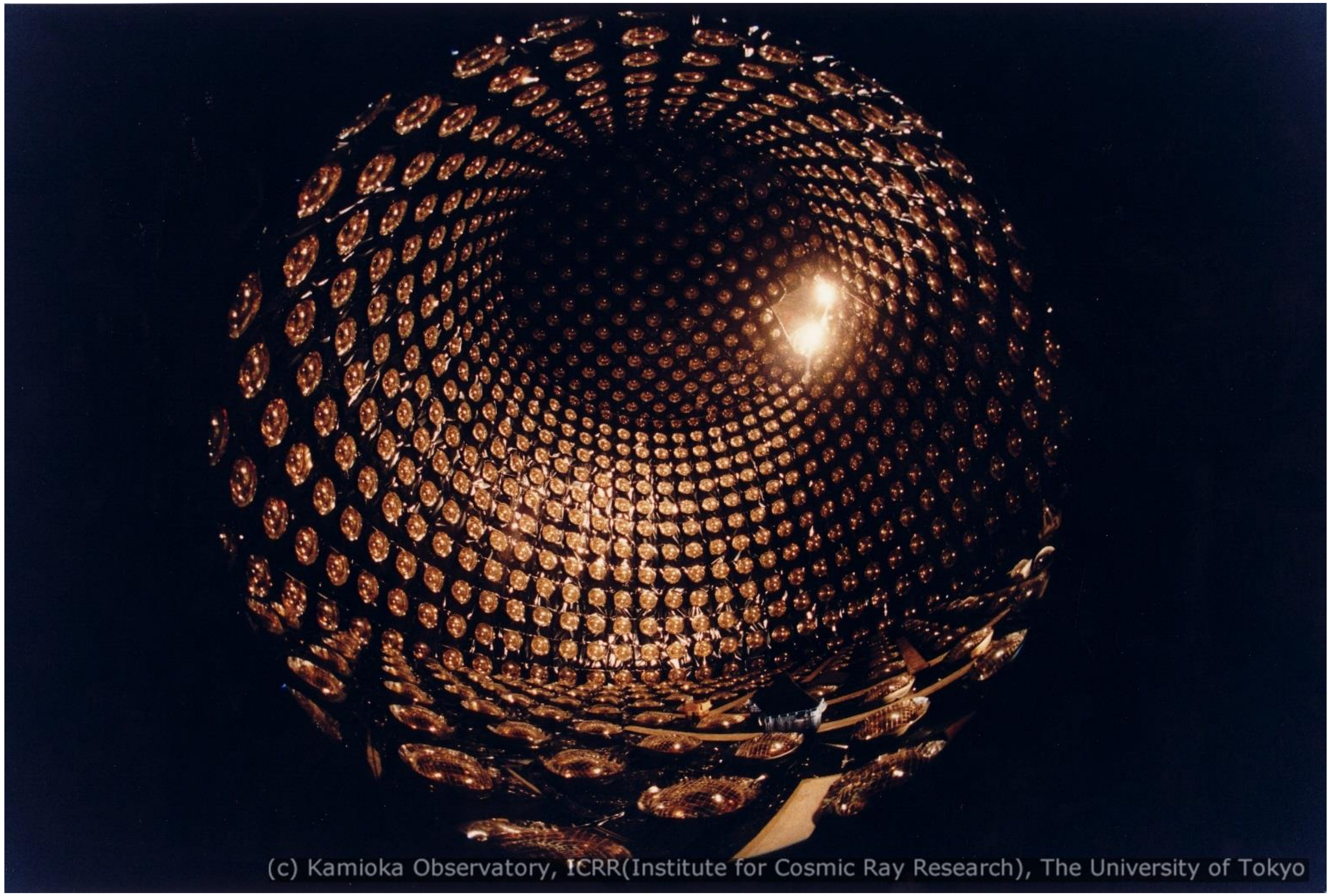
WA1 Experiment (1976 - 1984)

- First neutrino experiment at SPS (CERN)
- Looking at deep inelastic neutrinos interactions.

- Integrated Target (target, calorimeter, tracker):
  - Slabs of (magnetized) Iron, interleaved with scintillators
  - + wire chamber to track muons

Some (historical) examples… (2)

A wide variety of calorimeters… for a wide physics program !



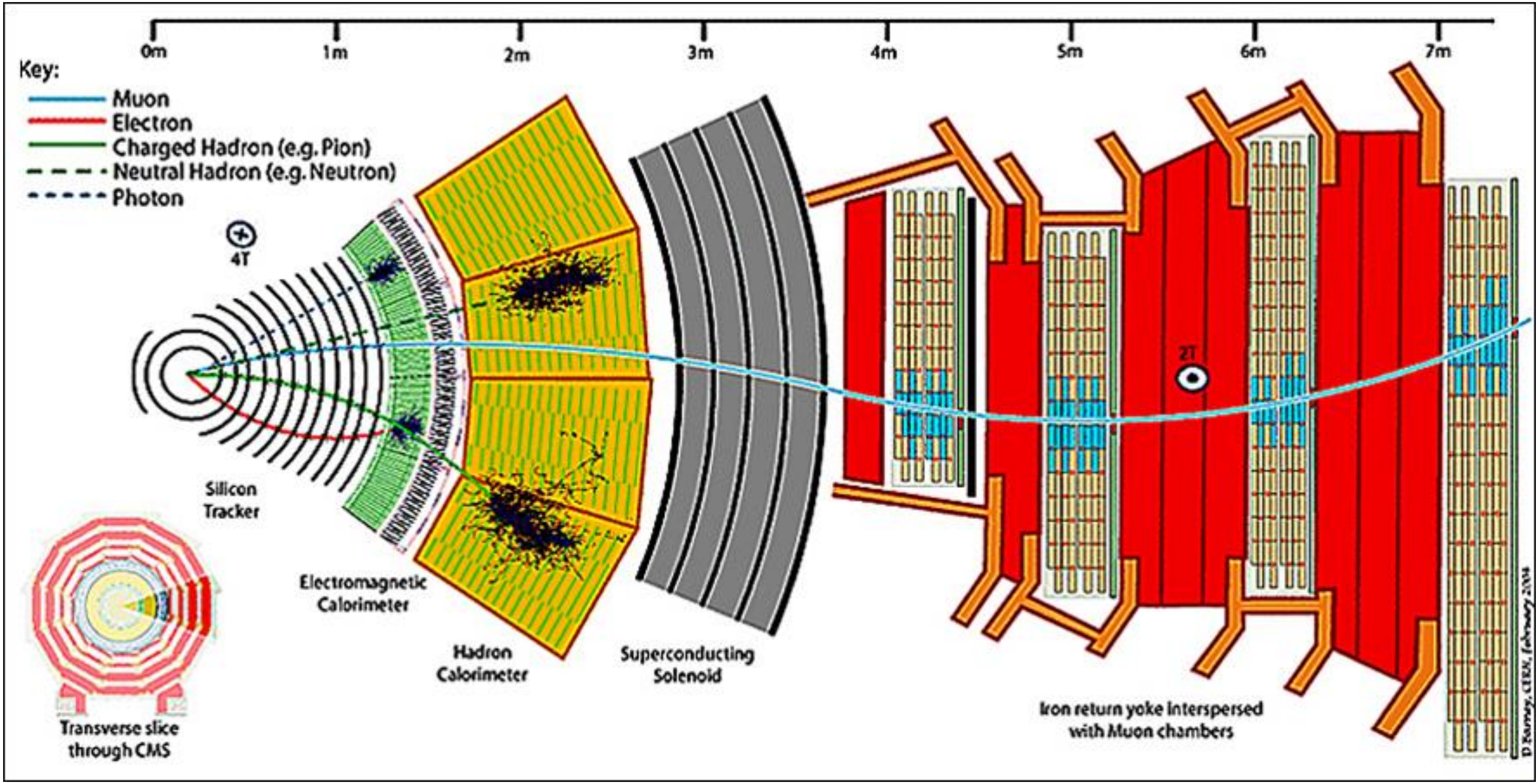
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Kamiokande

- Water tank placed in an underground mine
- >2140 t of water
- Surrounded by 1k of large phototubes
- Detect Cerenkov light emitted by the scattering of neutrinos with electron or nuclei of water

Measurement of solar neutrinos flux deficit (together with “Homestake” experiment) in 1990’s
Nobel Prize in 2002

General Structure of modern HEP colliders detectors



Onion-like structure

- Magnet (or not) to generated B-field for tracking (& muon system)
- Calorimeters (Electromagnetic and Hadronic parts): inside or outside the coil….

Some (historical) examples… (3)

A wide variety of calorimeters… for a wide physics program !

UA1 detector

- Modern particle physics detectors at SppS (CERN, $\sqrt{s}$=540 GeV)
- Calorimeters: Lead or Fe + Scintillator

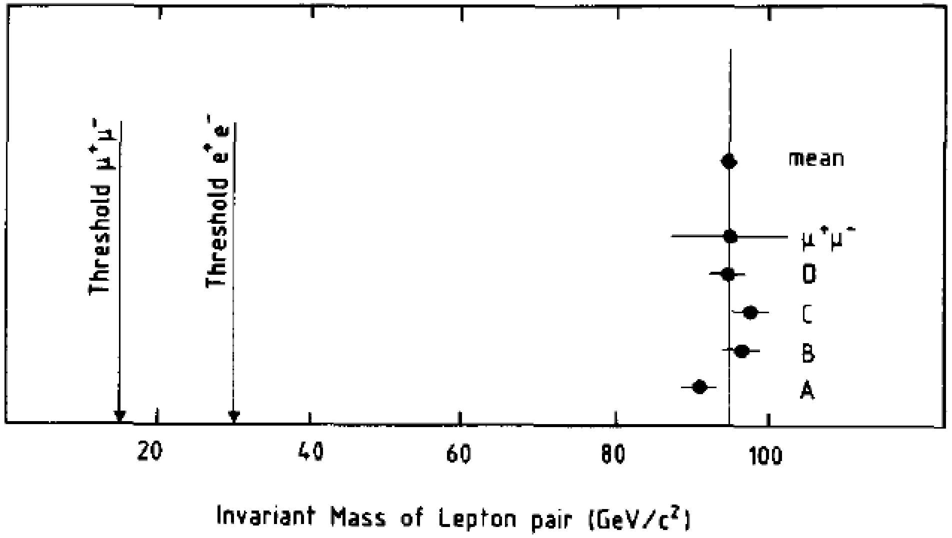
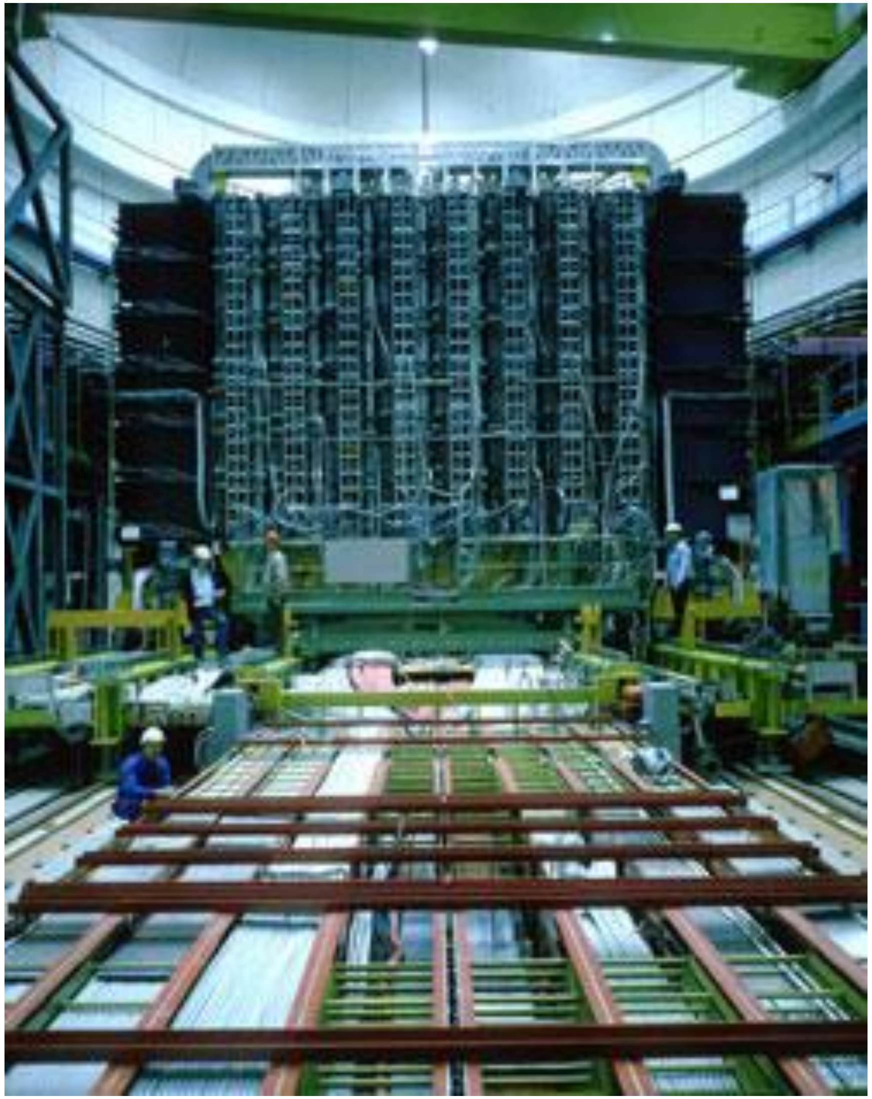


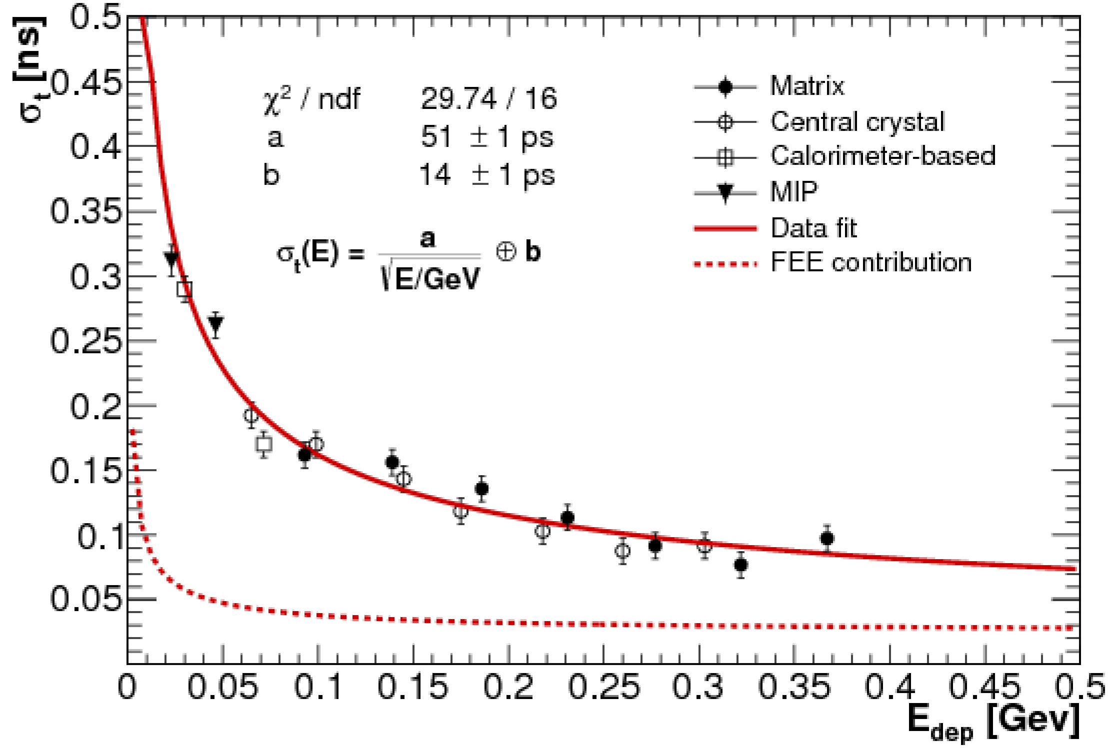
Fig. 8. Invariant masses of lepton pairs.



Discovery of W's and Z bosons (1983)
Nobel Prize in 1984

Calorimeter Features

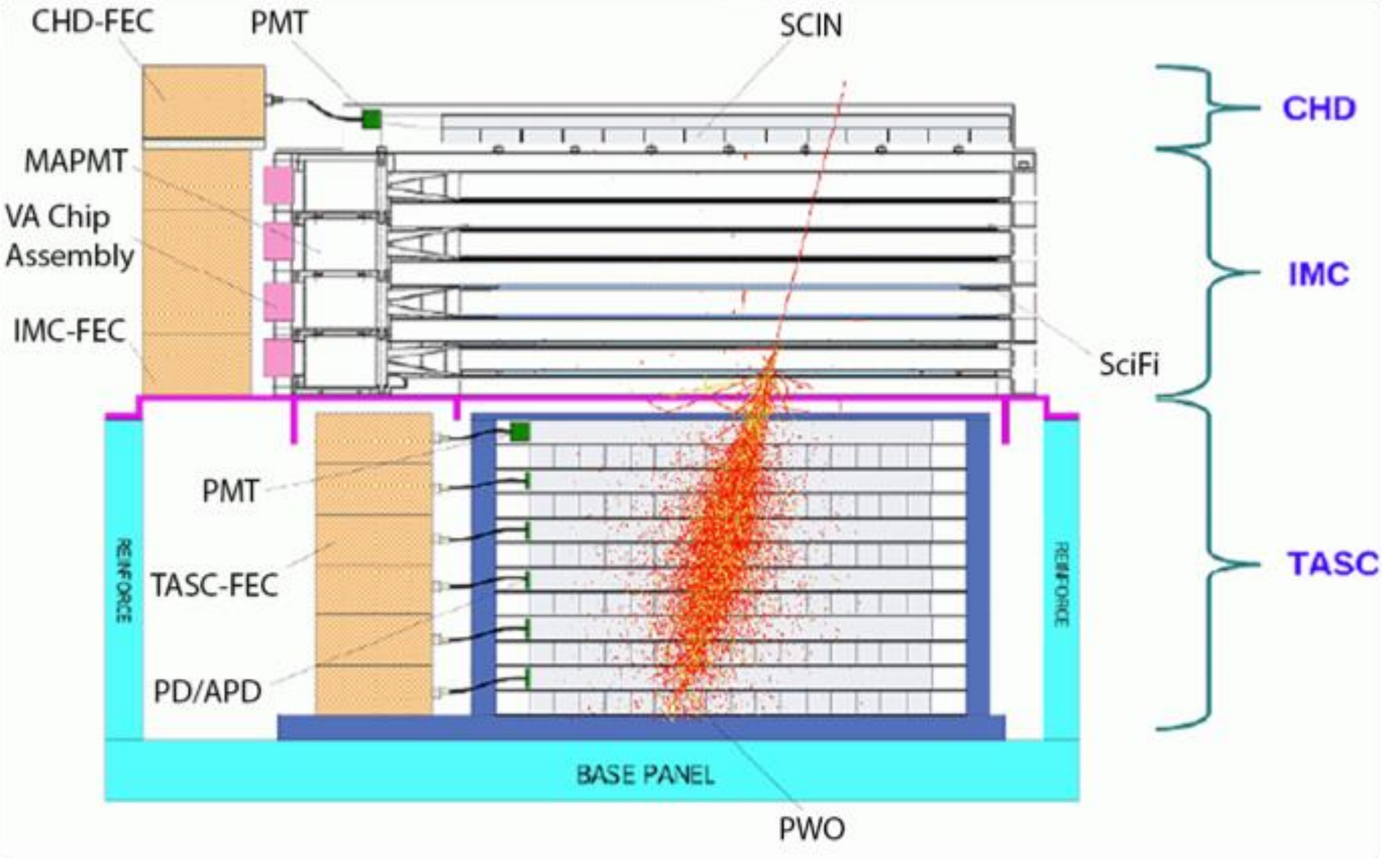
- **Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles**
- **Precision improves with energy**
- Position Measurement
- Particle ID
- Timing
- Triggering



Mu2e LYSO crystal calorimeter

Calorimeter Features

- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- **Position Measurement**
- Particle ID
- Timing
- Triggering

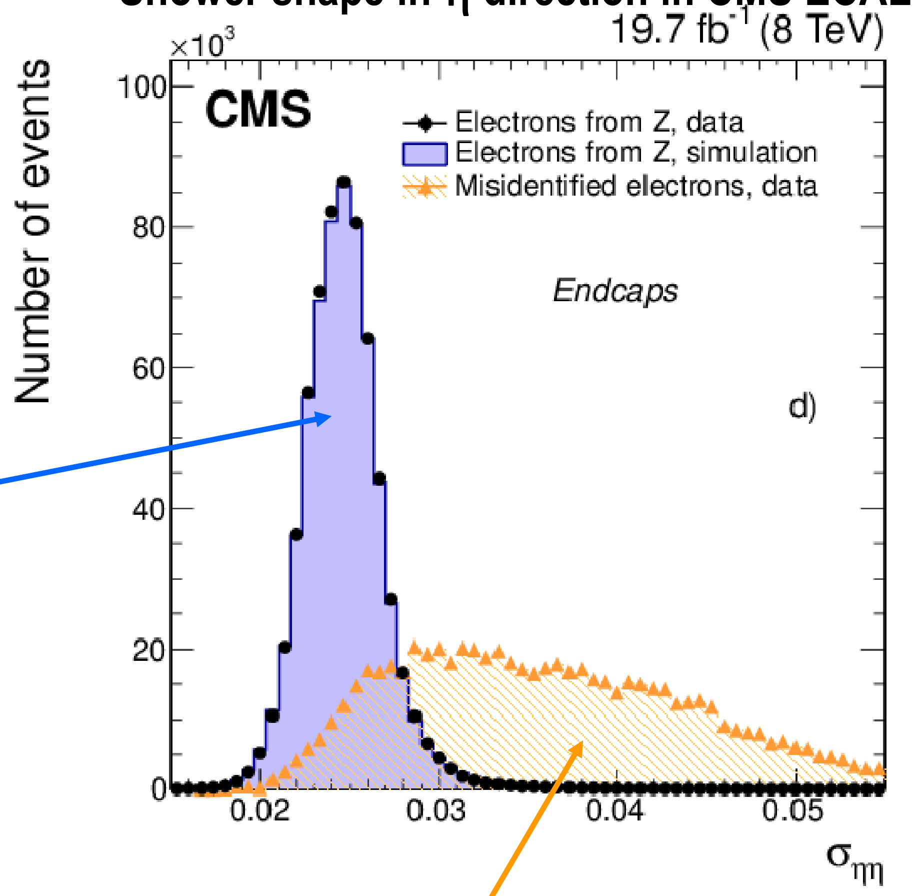


- Segmented calorimeters allows precise position / angle measurement
  - Ex: ATLAS EM: 60 mr / √E

Calorimeter Features

- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- **Particle ID**
- Timing
- Triggering

Shower shape in η direction in CMS ECAL



Electrons

Jets (pions, kaons, …)

- Difference in shower patterns: **Identification is possible**
  - Lateral and longitudinal shower profile
  - Can also **match with tracking**

Calorimeter Features

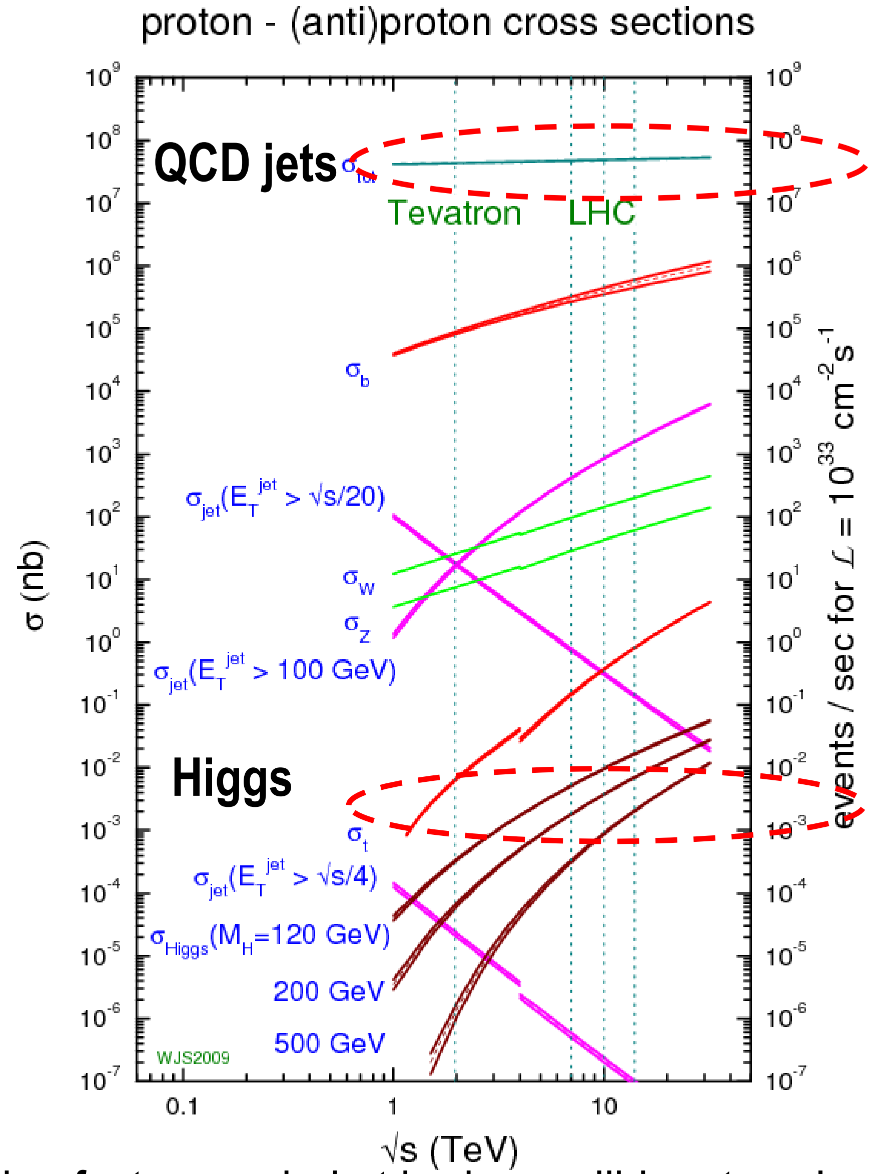
- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- Particle ID
- **Timing**
- Triggering

- Calorimeters can have "fast" signal response with good resolution (50-100 ps achievable)

- Helps mitigating "out of time" Pile-up (PU) at hadron colliders
  - ex: at LHC, collisions every 25ns. Signal from other bunch crossing can pile up…
- May help with **Particle ID** (time structure of showers)
- May allow mitigation of "in time" PU
  - If resolution better than 100ps, can constraint vertex of neutral particles
- **Allows efficient triggering** (see next slide)

Calorimeter Features

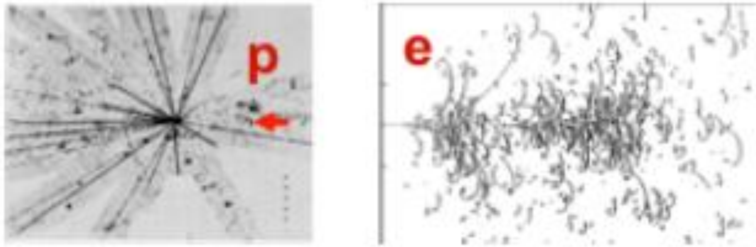
- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- Particle ID
- Timing
- **Triggering**



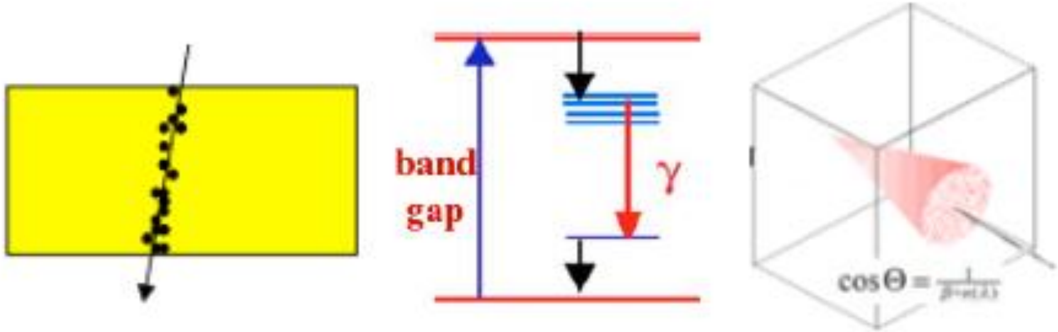
- Enormous rejection factor needed at hadron colliders to select “interesting” events (Higgs, SUSY,…)
- **Calorimeters**, thanks to their fast response and particle ID capabilities play a **leading role in triggering aspects** at hadron colliders !

FOUR STEPS

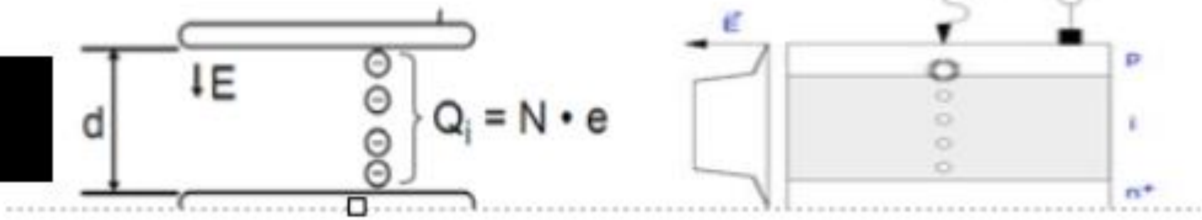
1. Particles interact with matter
   depends on particle and material



2. Energy loss transfer to detectable signal
   depends on the material



3. Signal collection
   depends on signal and type of detection



4. BUILD a SYSTEM
   depends on physics, experimental conditions,….

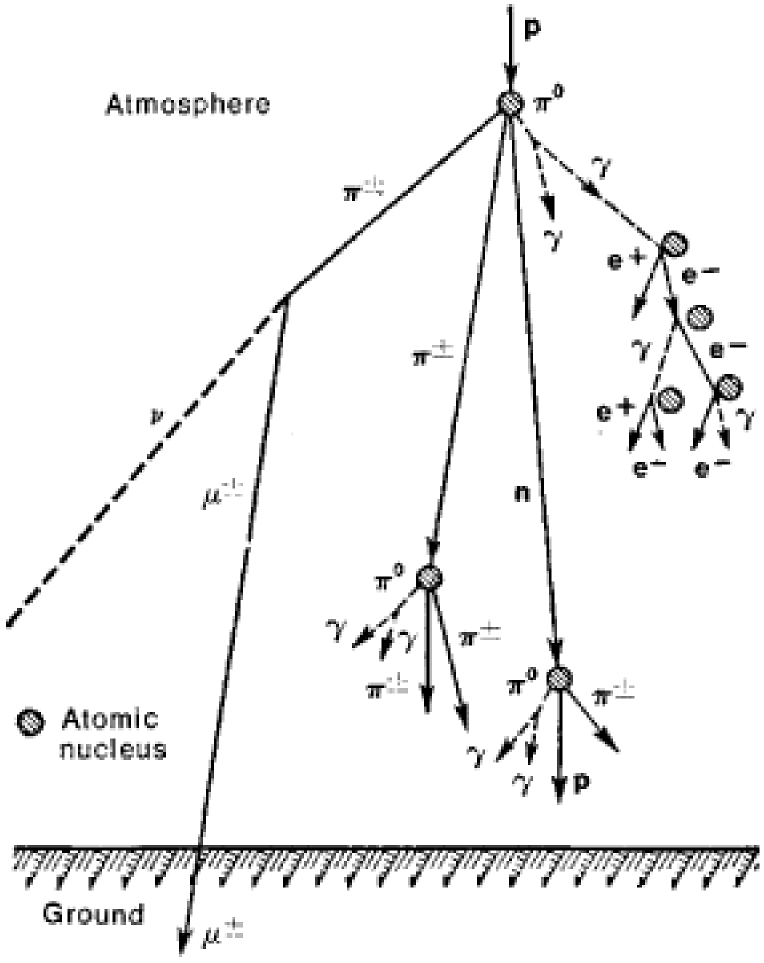
Calorimeter measurement: how ? (1)

1. Particles interact with matter
depends on particle and material

- Particles interact with matter (ie, “absorption” of the initial particle by dense material)
  - Only charged particles ultimately leave signal…
  - Neutrals have to convert ($\gamma \rightarrow e+e-$, …)

- Creates cascade of N secondary particles

$$\boxed{E_{deposited} \propto N \text{ secondary particles}}$$

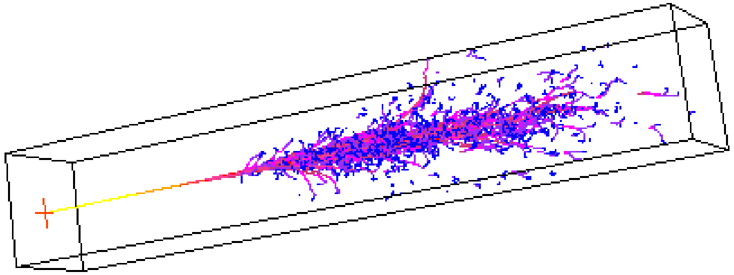


- Need to provide:
  - Dense material to initiate secondary particles: **Absorber**
  - Sensible medium to “measure” secondary particles: **Active medium**

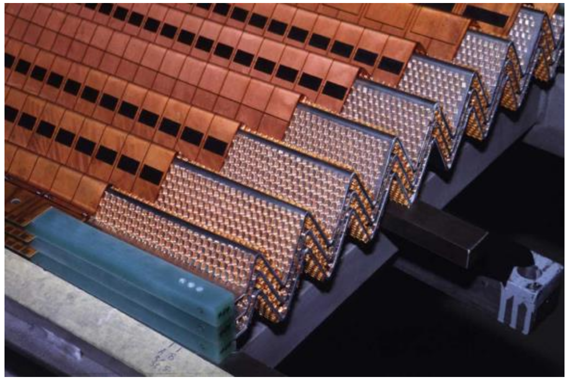
Calorimeter measurement: how ? (2)

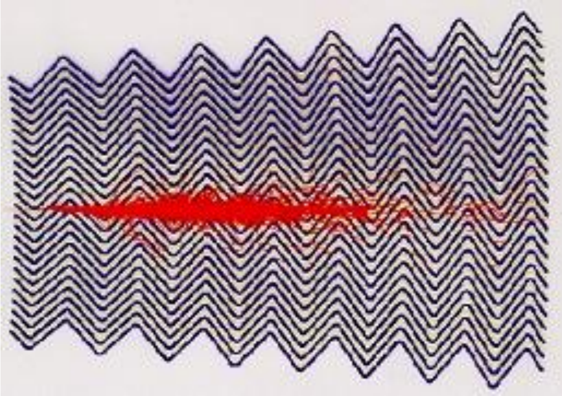
1. Particles interact with matter
depends on particle and material

- Two types of calorimeters:
  - **Homogenous:**
    - Absorber == active medium
    - Material **dense** enough to contain shower, **scintillating** and **transparent** (for light transportation) or non-scintillating **Cerenkov**
      - Ex: CMS (PbWO4 scintillating crystals), L3 (BGO scintillating crystals), Lead Glass (Cerenkov), …



  - **Sampling**
    - Sandwich of **high-Z absorber** (Pb, W, Ur,…) and **low-Z active media** (liquid, gaz, …)
      - Ex: ATLAS (Pb/LAr), DØ (Ur/LAr), …





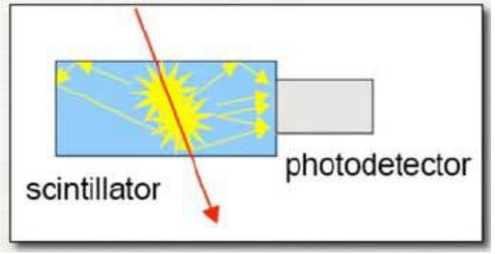
How do we “see” a signal ?

2. Energy loss transfer to detectable signal
depends on the material

In practice, calorimeters used one of the **3 following effects for signal detection**:

Scintillation:

- Charged particles in shower excites atoms in detector, atoms de-excite => emission of light. Light collected by photo-detectors (PMT, APD, SiPM…)
- Rather slow ($10^{-6} – 10^{-12}$ s).
- Ex: crystal, scintillating fibers…

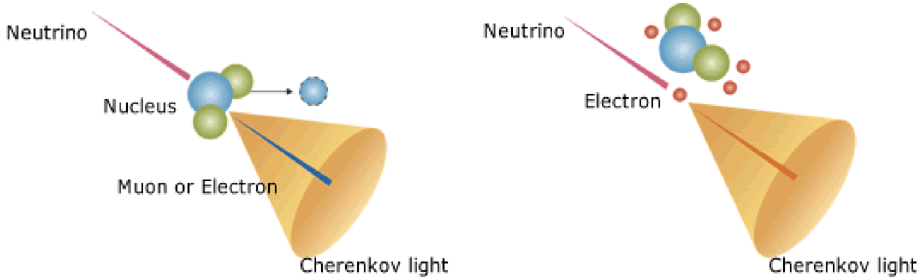


Ionization:

- Charged particles in shower ionize atoms in detector => free charge => “collect” free charge
- Ex: Noble liquid (LAr, Xe, Kr…), gas (wire or drift chambers) , semi-conductor (Si…)

Cerenkov:

- Light emitted when charged particles goes faster than the speed of light in the media.
- Light collected by photo-detectors.
- Very fast
- Ex: quartz fiber



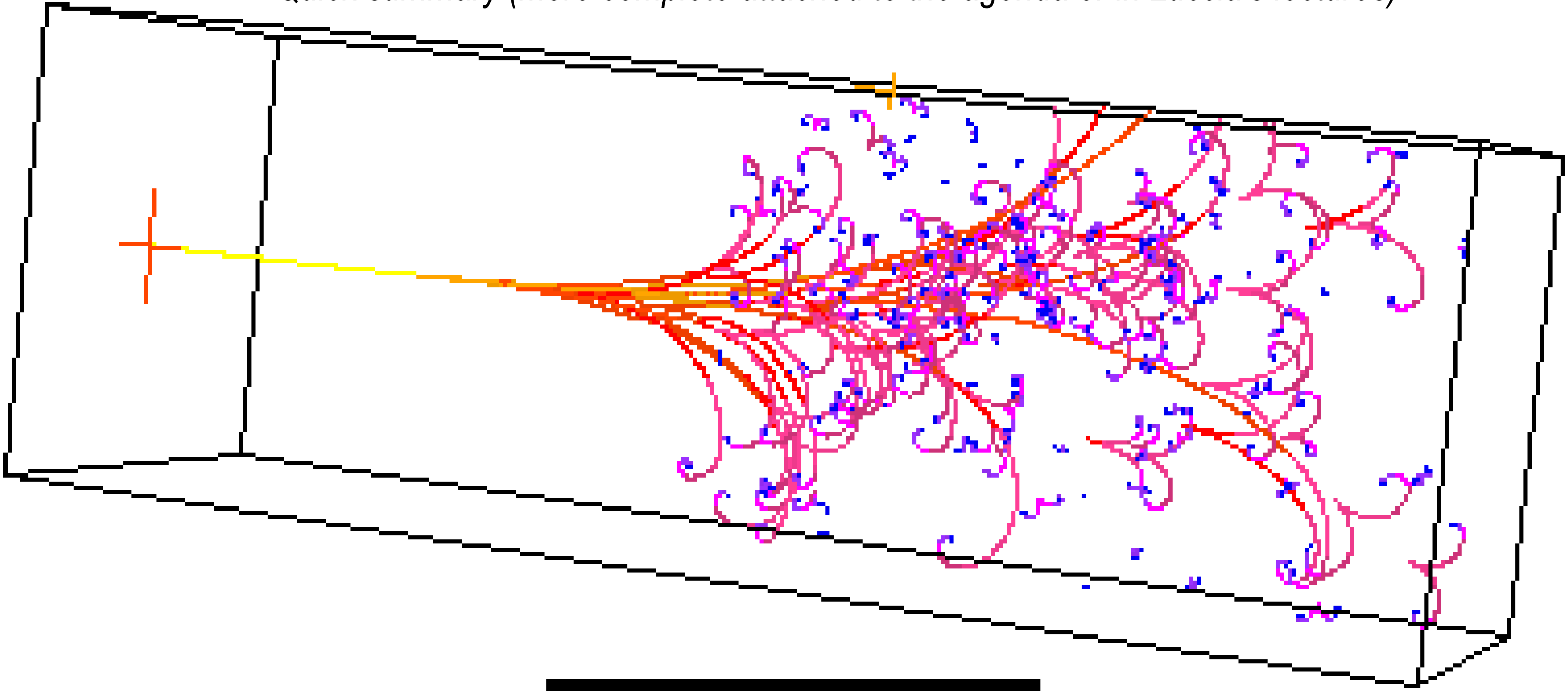
The generated charged particle emits the Cherenkov light.

Note:

- Also,… measure temperature !
- Cryogenic detector for Dark Matter searches, neutrinos, … => bolometers ! (not covered in these lectures)

Physics of Electromagnetic Showers

Quick summary (more complete attached to the agenda or in Luccia's lectures)

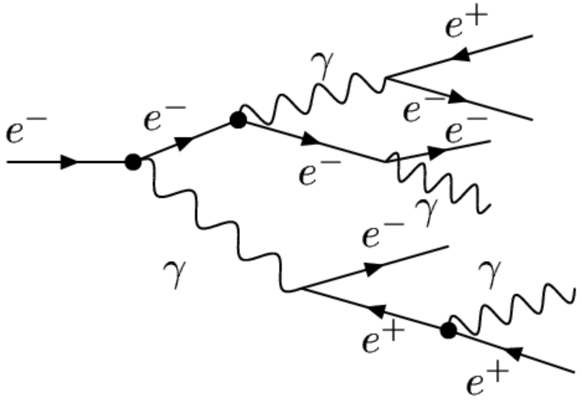


1. Particles interact with matter
   depends on particle and material

Electromagnetic shower: summary

- High-energy electrons or photons interact with dense material from calorimeter:

  cascade of secondary particles



- The number of cascade particles is **proportional to the energy** deposited by the incident particle
- The role of the calorimeter is to **count** these cascade particles
- The relative occurrence of the various processes creating the cascade particles **depends on Z.**
  - Above 1 GeV, *bremsstrahlung radiation* and *pair production* dominates
  - The shower develops like this until secondary particles reaches E_C where loss by *ionization* dominated
  - Below E_C, the number of secondary particles slowly decreases as electrons (photons) are stopped (absorbed)

- **The shower development is governed by the “radiation length” X_0**
- **Needs about 25 X_0 to contain most of the EM showers.**
- **Shower max grows with ln(E)**
- **90% of shower energy contained in a cylinder of radius R_M**

Useful Quantities

Radiation Length:

$$X_0 \approx \frac{180A}{Z^2}$$ (g.cm^{-2})

Radiation Length for composite material:

$$\frac{1}{X_0} = \sum \frac{w_j}{X_j}$$

w_j: fraction of material j
X_j: radiation length of material j
(in g.cm-2)

Moliere Radius:

$$R_M = \frac{21MeV}{E_C} X_0$$

Moliere Radius for composite material:

$$\frac{1}{R_M} = \sum \frac{w_j}{R_{M\,j}}$$

w_j: fraction of material j
R_{Mj}: Moliere Radius of material j
(in g.cm-2)

Energy Resolution:

$$\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

$\oplus$: quadratic sum
S: Stochastic
N: noise
C: constant

EM shower: Energy Resolution

Calorimeter’s resolution is determined by fluctuations.

- Ideally, if all N secondary particles are detected: $E \propto N \Rightarrow \sigma_E/E \propto \sigma(N)/N$

Fluctuation in N follow Poissonian distribution

$\Rightarrow \sigma(N)/N \propto \sqrt{N} / N \propto 1/\sqrt{N}$

- **Intrinsic limit / ultimate resolution: determined by fluctuations of number of shower particles.**

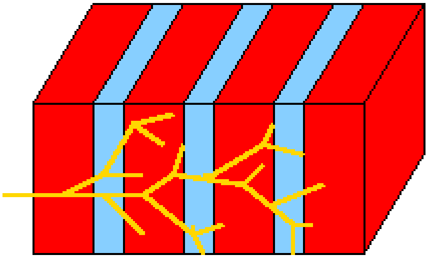
- In reality, only a fraction f_S of secondary particles can be detected (via ionization, Cherenkov, scintillation …)
- $N_{max} = N_{tot} / E_{th}$,
  where E_{th} is the threshold energy of the detector, ie, the minimal energy to produce a detectable signal (100 eV for plastic scintillators, ~3 eV for semi-conductors…)

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}} \frac{1}{\sqrt{f_S}}$$

- Other type of fluctuations may impact resolution, eg:
  - Signal **quantum** fluctuations (photoelectron statistics,….)
  - Shower **leakage**,
  - **Instrumental** effects (electronic noise, light attenuation, structural non-uniformity)
  - **Sampling** fluctuations (in sampling calorimeters)

Sampling Calorimeters

- **Sampling Calorimeters:**
  - Sandwich of **high-Z absorber** (Pb, W, Ur,…) and **low-Z active media** (liquid, gaz, …)
    - Ex: ATLAS (Pb/LAr), DØ (Ur/LAr), …



- **Longitudinal segmentation**
- Energy resolution limited by fluctuations in energy deposited in the active layers (ie, the number n_{ch} of charged particles crossing the active layers)

- n_{ch} increases linearly with incident energy and fineness of the sampling: $n_{ch} \propto E / t$, where t=thickness of each absorber layer

For independent sampling:

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{n_{ch}}} \propto \sqrt{\frac{t}{E}}$$

(stochastic contribution only)

For fixed active layers thickness, the resolution should improves as absorber thickness decreases.

Resolution of sampling calorimeters

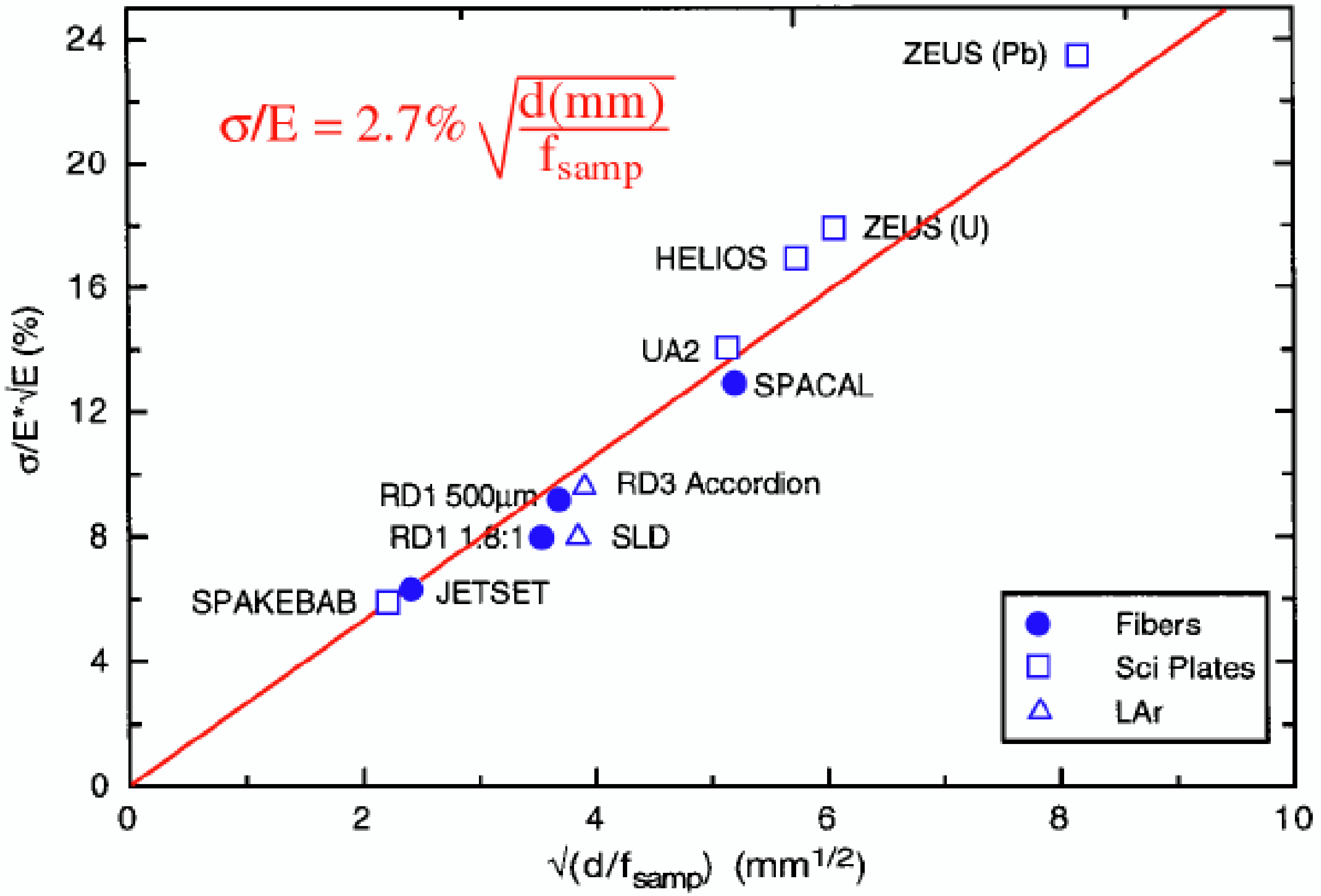


FIG. 4.8. The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{samp})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a scintillator plate or a liquid-argon gap), and f_{samp} is the sampling fraction for mips [Liv 95].

Sampling fluctuations in EM calorimeters determined by sampling **fraction** (f_{samp}) and sampling **frequency**

f_{samp}: energy deposited in active layers over total energy
d: thickness of active layer

Calorimeter: Energy Resolution

- Calorimeter resolution can be parameterized by the following formula:

$$\boxed{\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C}$$

$\oplus$: quadratic sum

Stochastic term (S):

- Accounts for any kind of Poisson-like fluctuations (number of secondary particles generated by processes, quantum, sampling, etc…)

Noise term (N): relevant at **low energy**

- Electronics noise from readout system
- At Hadron colliders: contributions from pile-up (from low energy particles generated by additional interactions): fluctuations of energy entering the measurement area from other source than primary particle.

Constant term (C): dominant at **high energy**

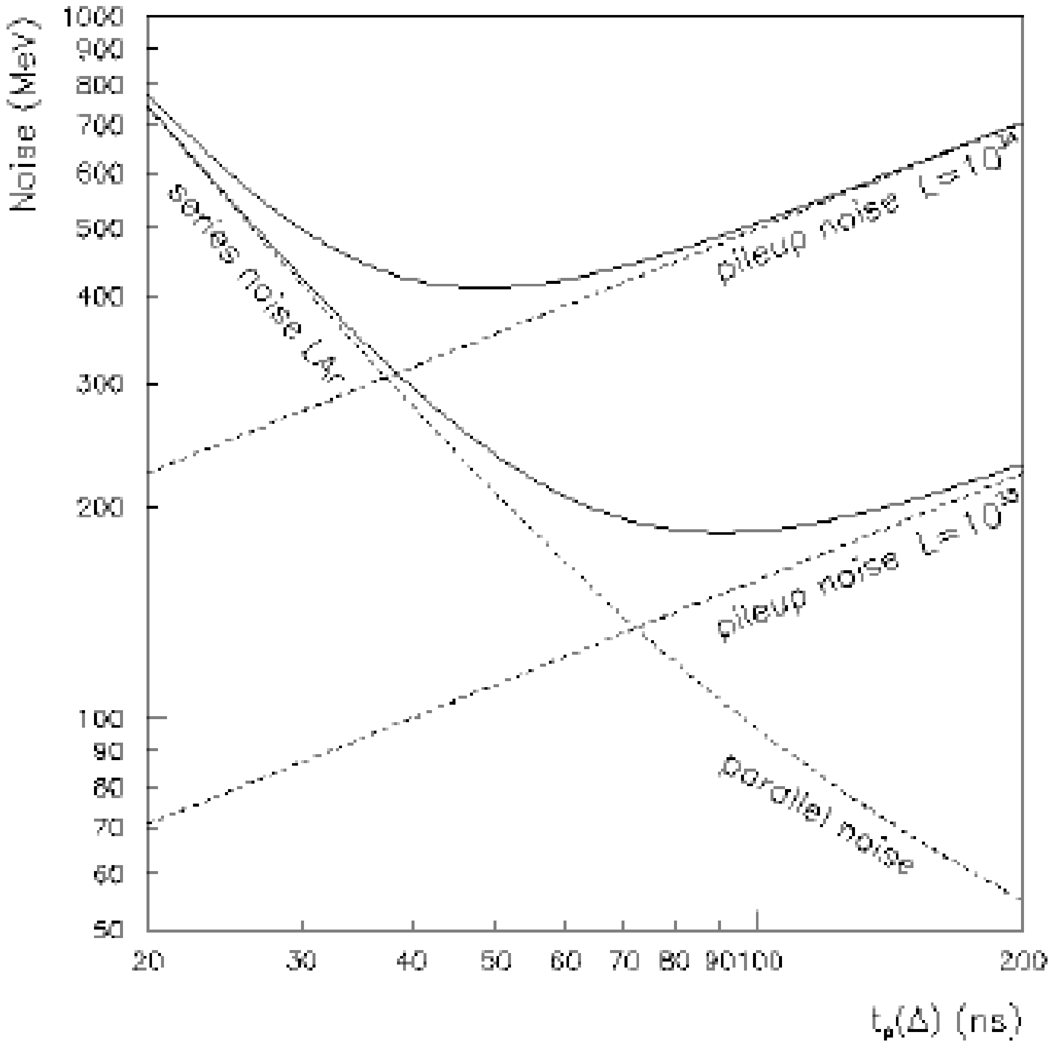
- Imperfections in construction, non-uniformity of signal collection, fluctuations in longitudinal energy containment, loss of energy in dead material, etc…

Noise Term

Electronics noise vs pile-up noise
(example from LAr ATLAS calorimeter)

Electronics integration time was optimized, taking into account both contributions for LHC nominal luminosity ($L=10^{34}$ cm^{-2}s^{-1})

At this luminosity, contribution from noise to an electron is typically ~300-400 MeV



Constant Term

- The constant term describes the level of uniformity of the calorimeter response vs position, time, temperature (and not corrected for)

c = (leakage)⊕(intercalibration)⊕(system instability)⊕(nonuniformity)

To have c ~ 0.5 % all contributions must stay below 0.3 %

- **Leakage:**
  - **Non-Poissonian fluctuations**
  - For a given average containment, **longitudinal fluctuations larger than lateral ones.**
  - Front face: Negligible
  - Rear face:
    - Dangerous
    - Increase as ln(E)
    - Can be removed/attenuated if sufficient X0

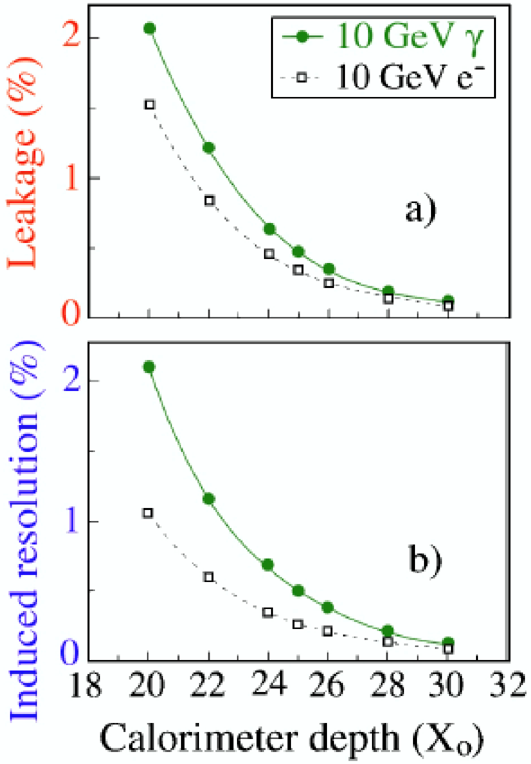
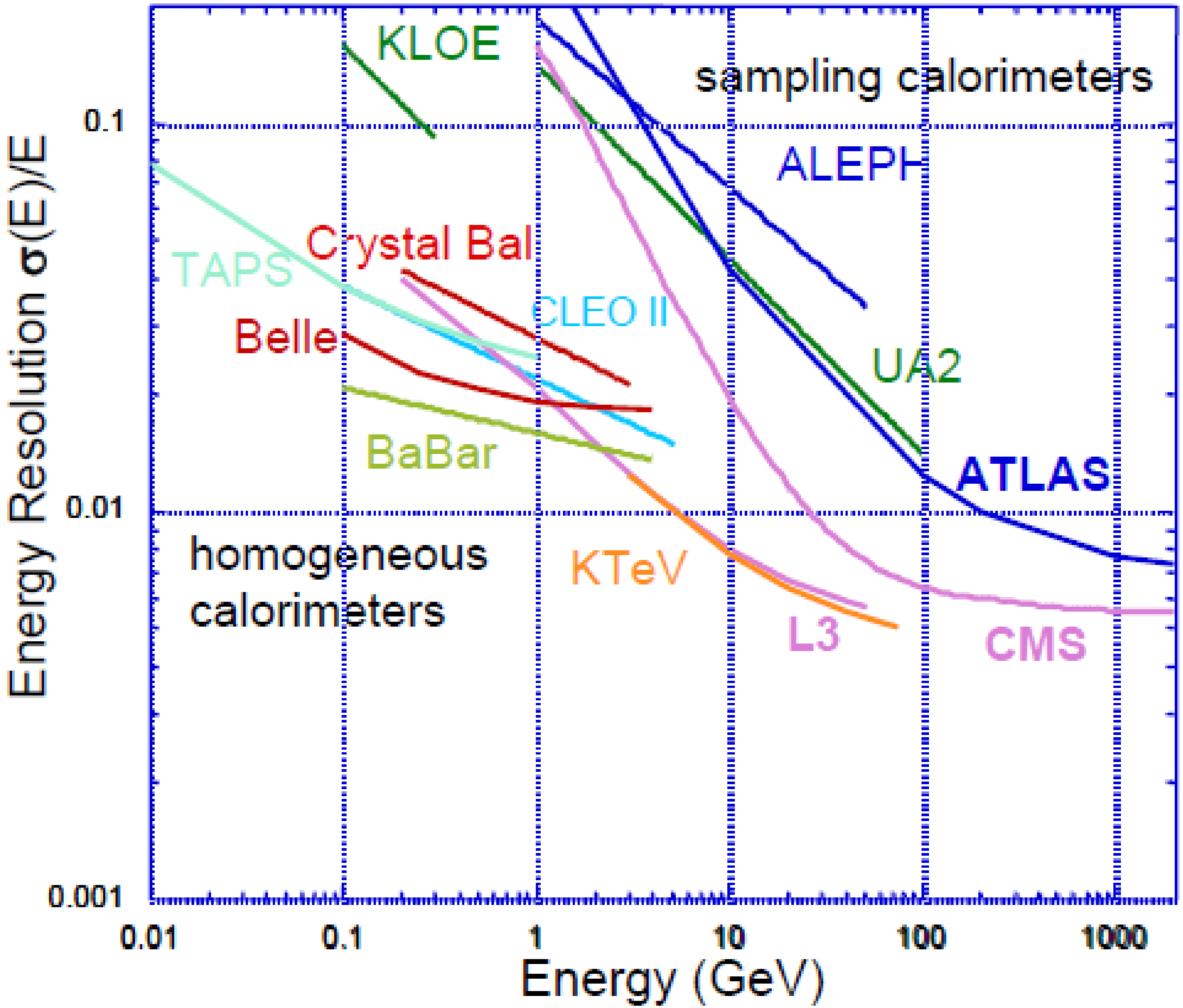


Figure 5: The average fraction of the shower energy carried by particles escaping the calorimeter through the back plane (a) and the relative increase in the energy resolution caused by this effect (b), for showers induced by 10 GeV electrons and 10 GeV γs developing in blocks of tin with different thicknesses, ranging from $20X_0$ to $30X_0$. Results from EGS4 Monte Carlo calculations.

Calorimeters: a comparison



Homogenous vs Sampling EM calorimeter Resolution

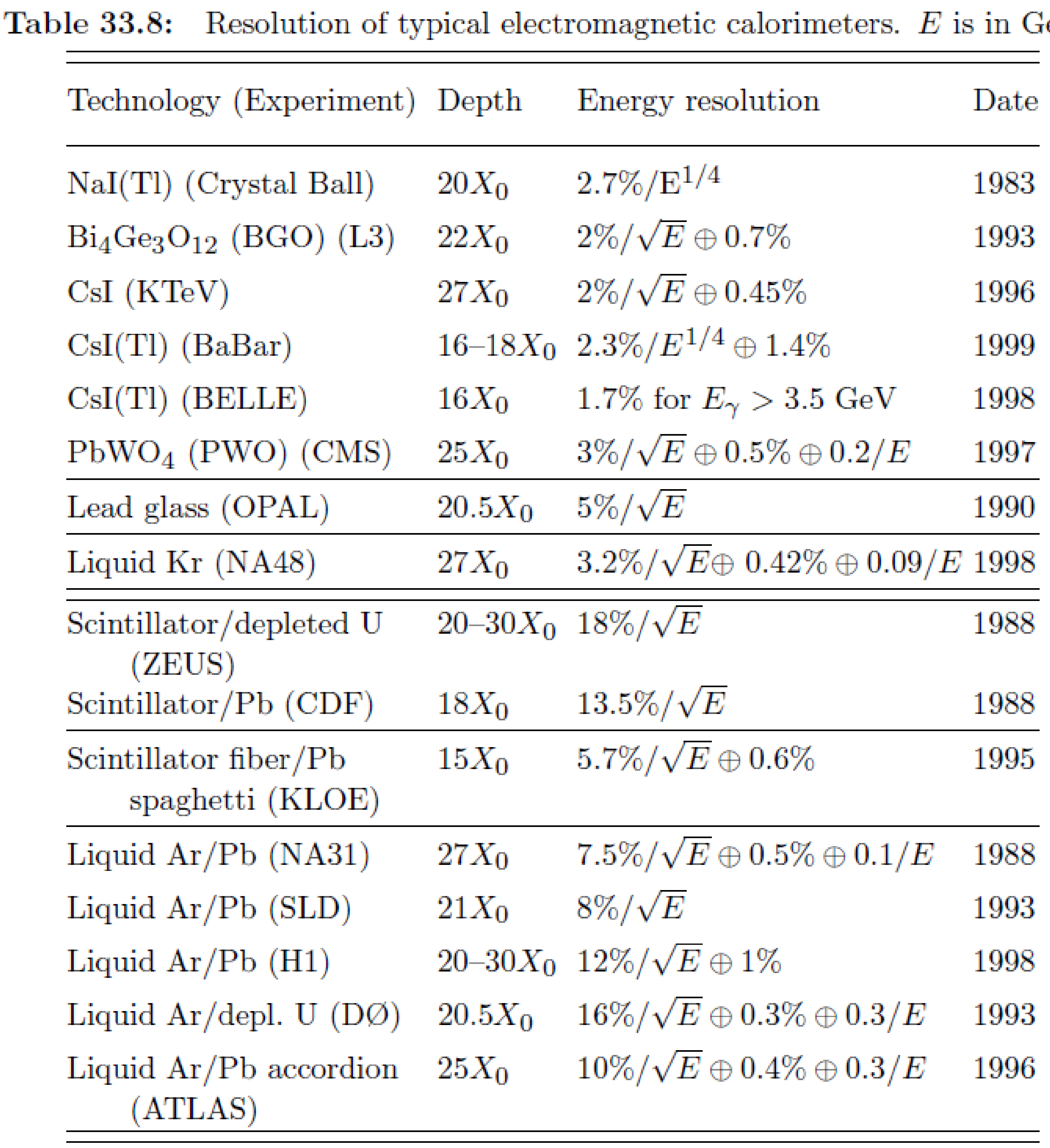


Table 33.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

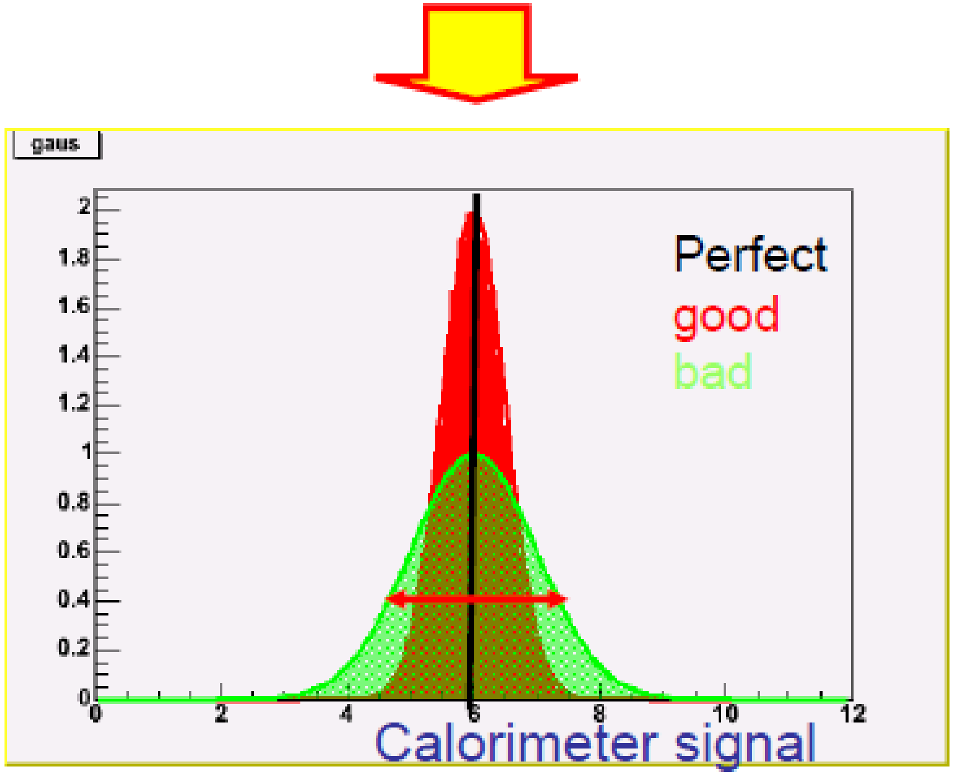
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl)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

Homogenous

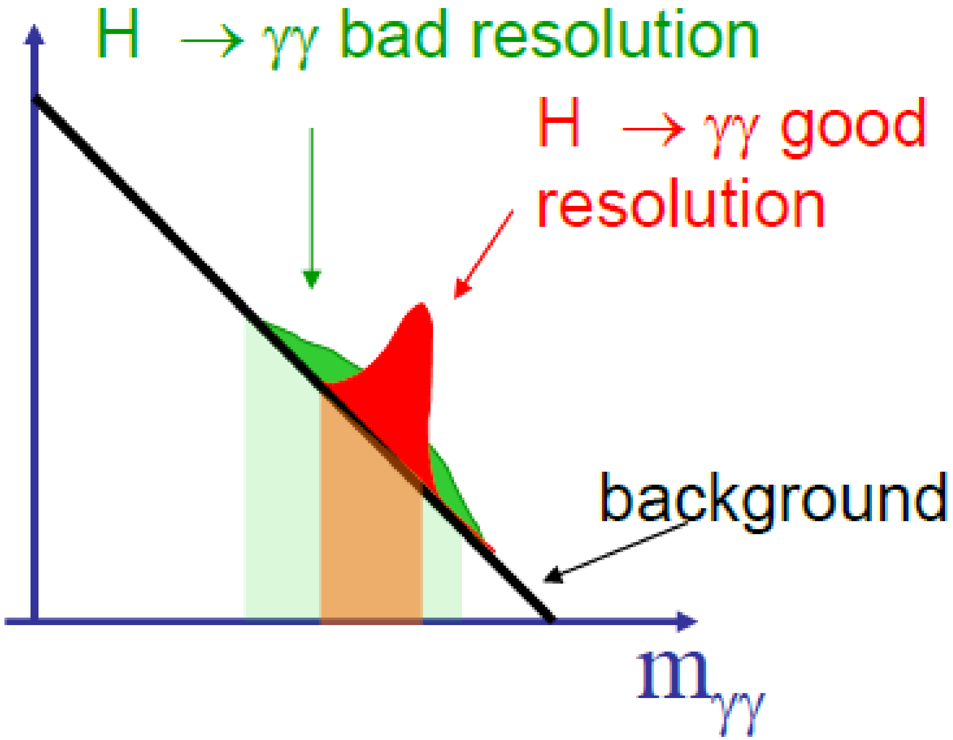
Sampling

Why precision matter so much?

Response to monochromatic source of energy E



σ(calo) defines the energy resolution for energy E.



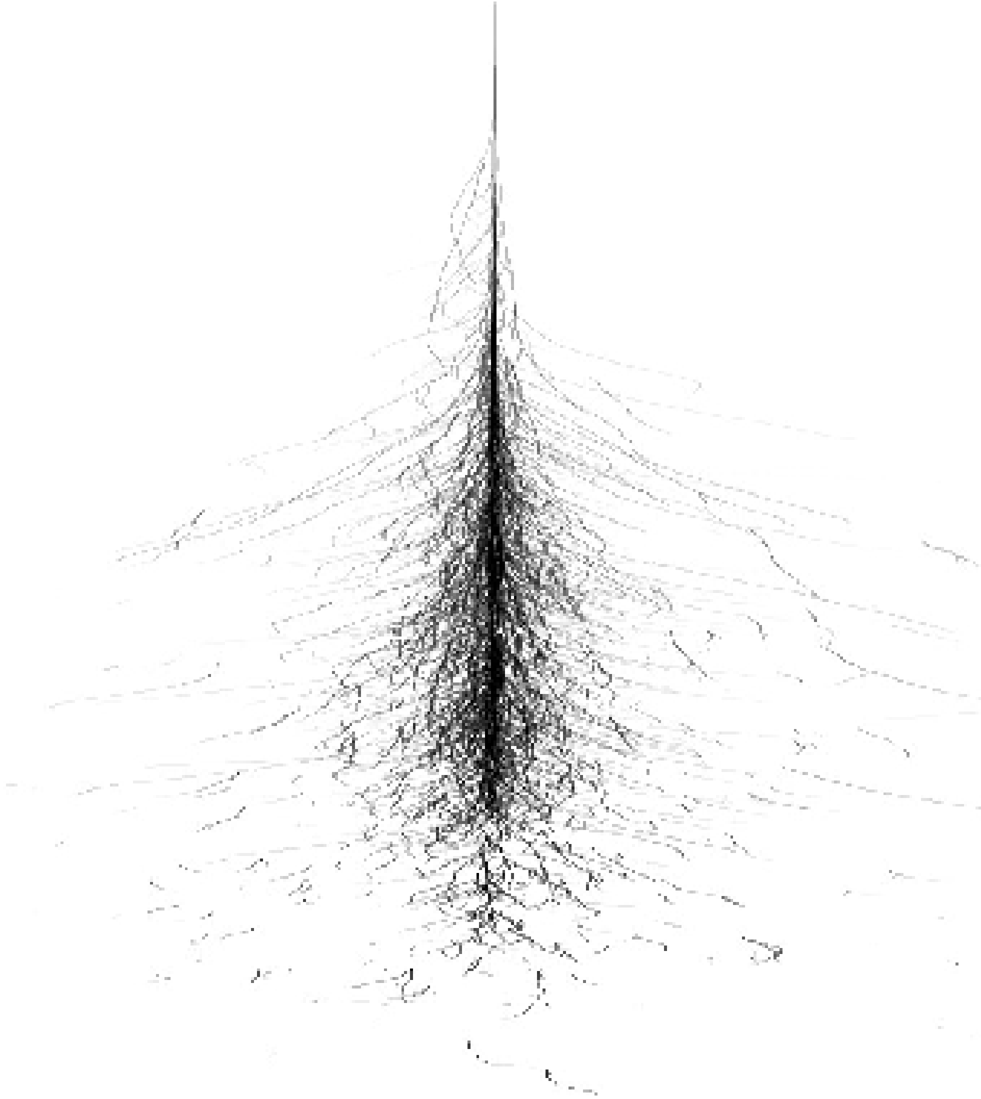
Signal = constant

integrated B $\propto \sigma_{\gamma\gamma} \rightarrow$

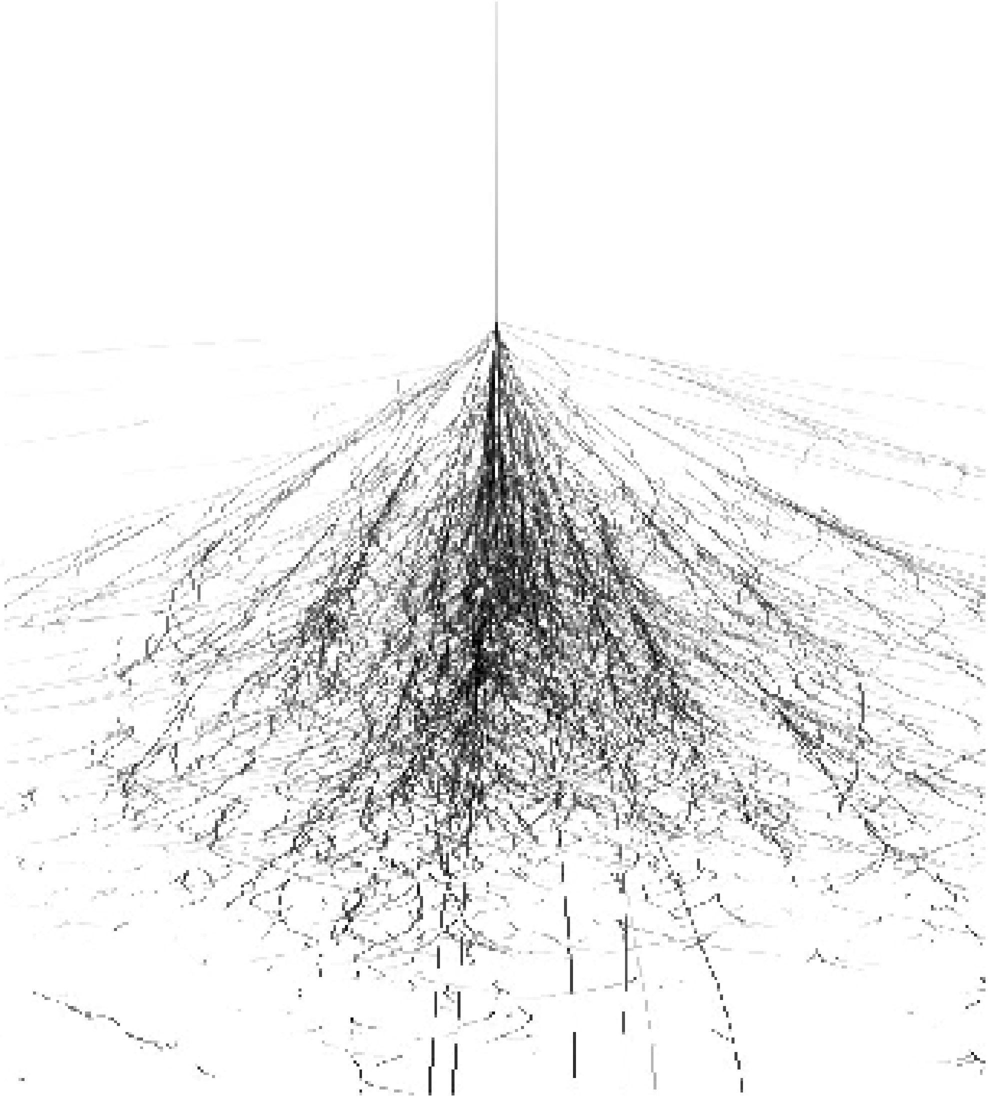
$S/\sqrt{B} \propto 1/\sqrt{\sigma\gamma\gamma}$

… but $\sigma_{\gamma\gamma} = f(\sigma\text{calo})$

Physics of Hadronic Showers



Gamma shower



Hadronic shower

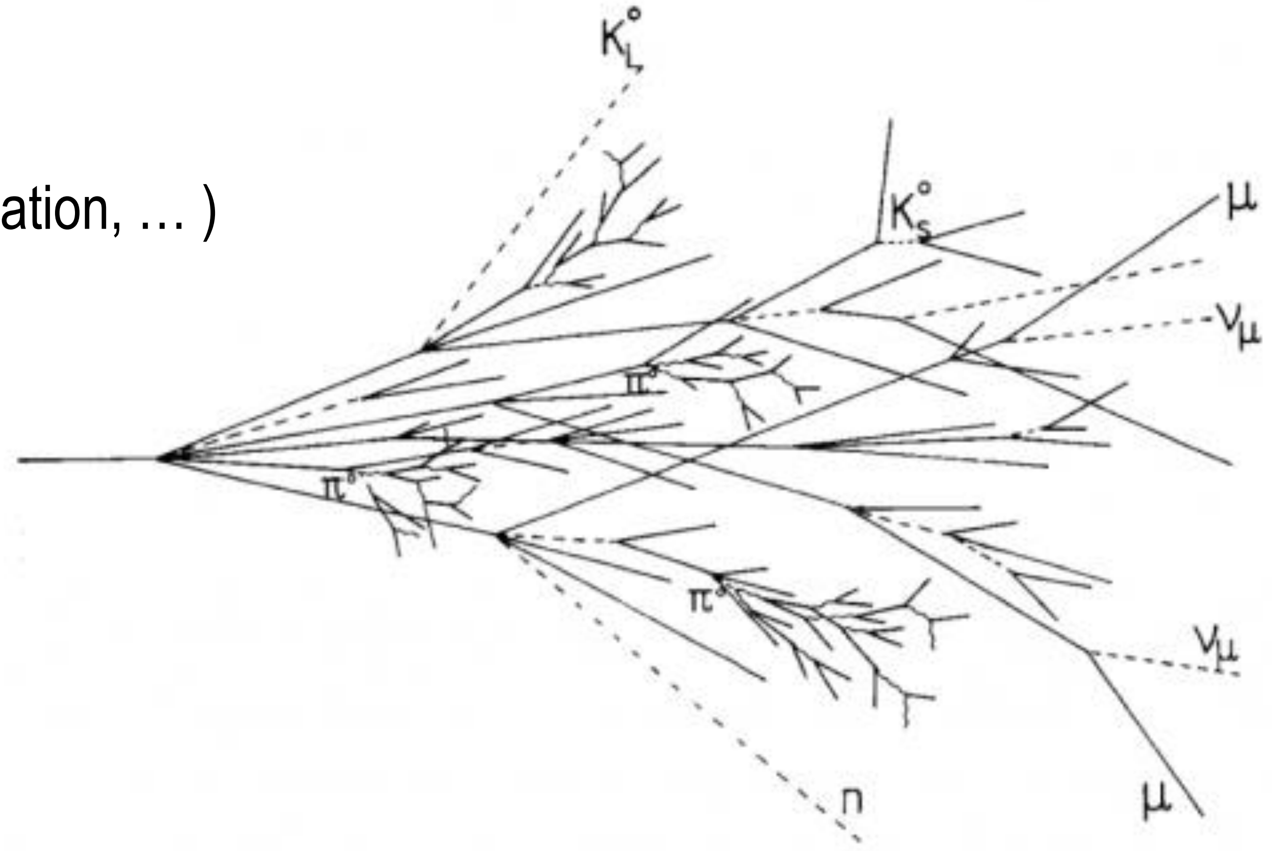
1. Particles interact with matter
   depends on particle and material

Hadronic Showers

An Hadronic (HAD) shower is a cascade of secondary particles initiated by the interaction with matter (ie, energy loss) of an incoming of hadron.

- HAD showers are like EM showers… but **more complicated**, due to **strong interaction** of hadrons with absorber.

- Many processes involved:
  - Ionization,
  - hadron production (fragmentation, …)
  - Charge exchange $\pi^{+/-}n \rightarrow \pi^0 p/\mathrm{pbar}$
  - nuclear de-excitation,
  - nuclear breakup, → spallation neutrons,
  - muon and pion decay,
  - …



Hadronic showers

Hadronic interaction:

Elastic:

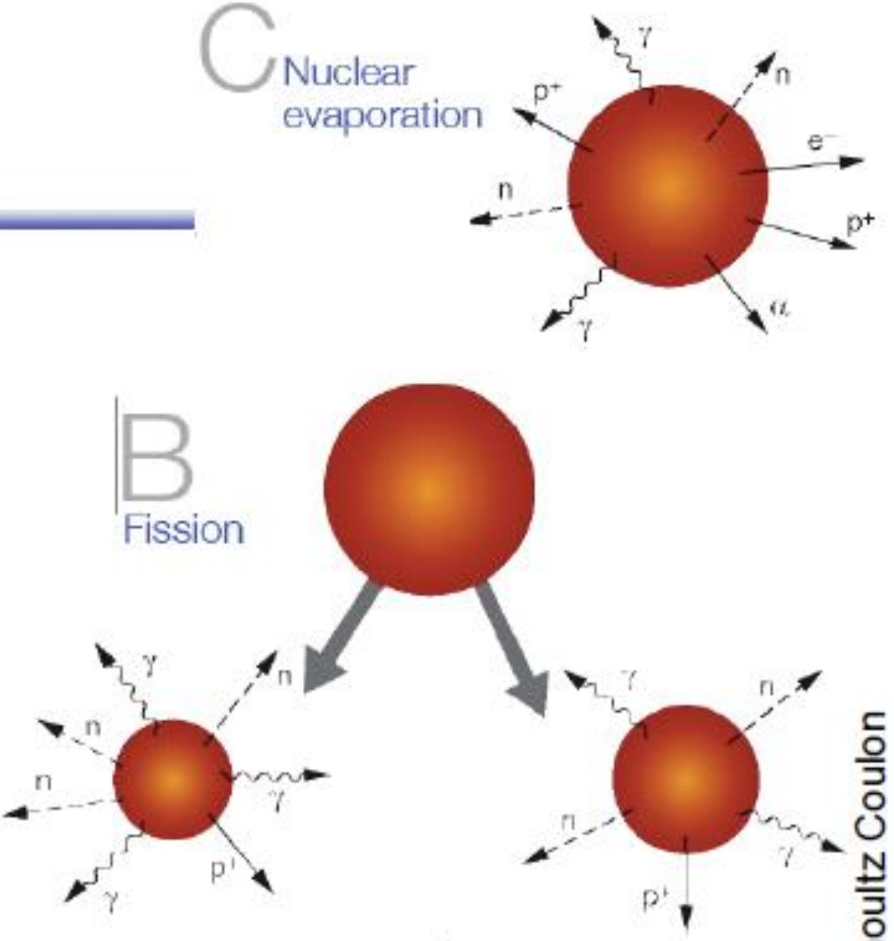
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

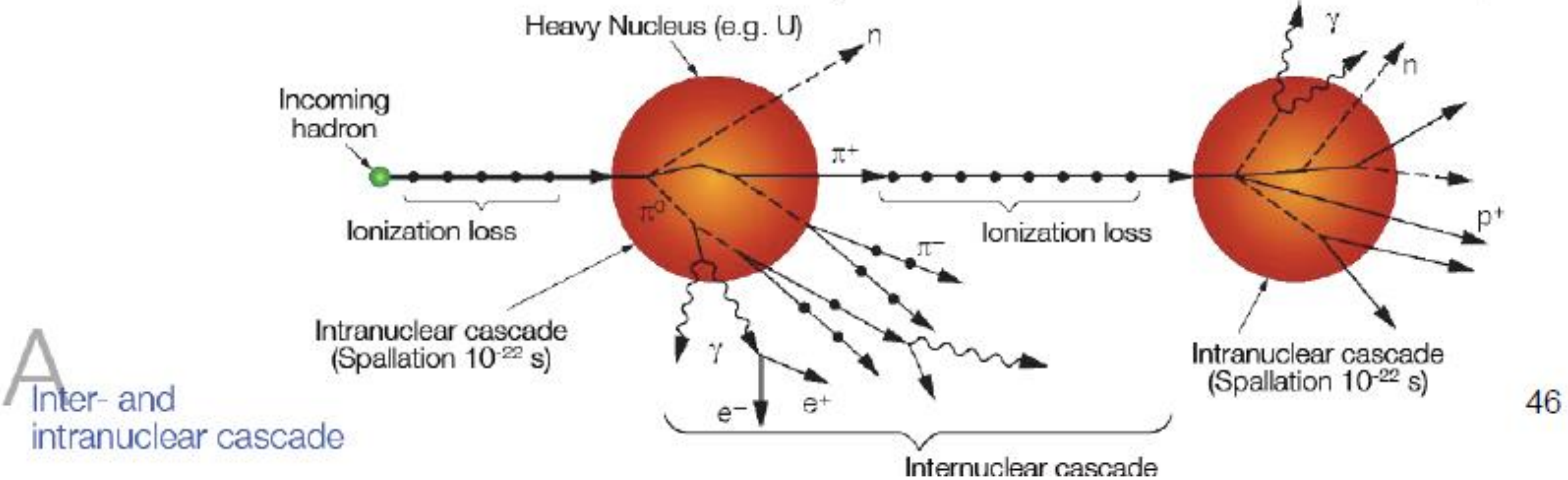
Inelastic:

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

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

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

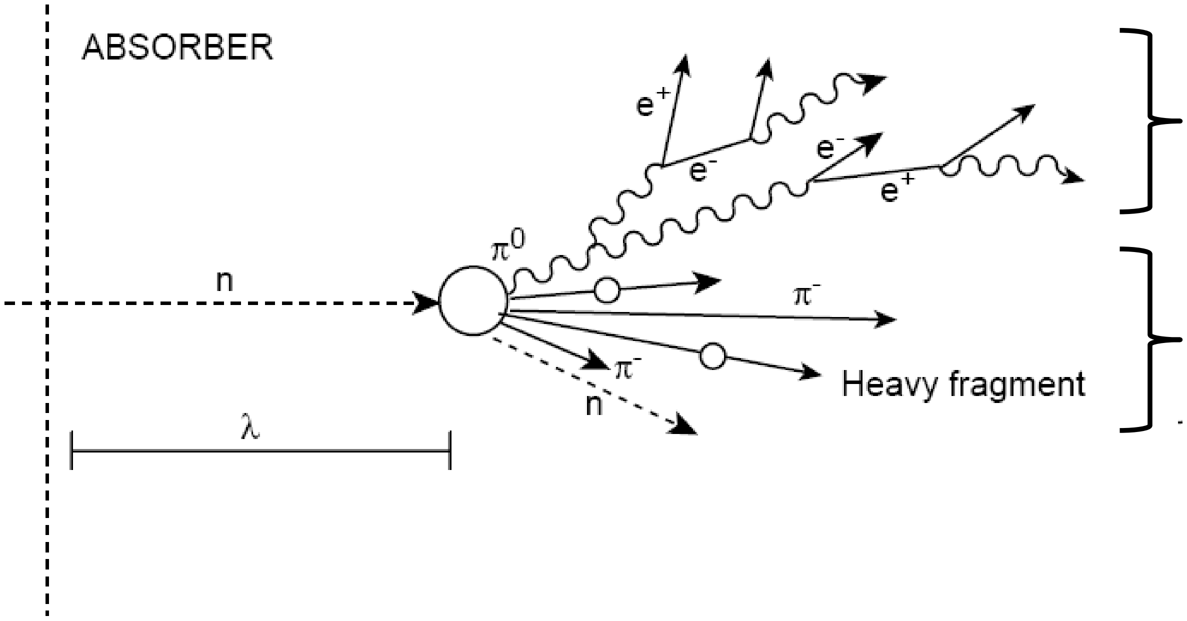




Courtesy of H. C. Schoultz Coulon

Hadronic Showers

HAD showers have thus **two components**:



Electromagnetic component:

- Electrons, photons (from excitation, radiation, decay of hadrons, photo-effect, …)
- Neutral pions (eg, $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$)

Hadronic component:

- Charged hadrons $\pi^\pm$, $K^\pm$, p, …
  - ionization, excitation, nuclei interaction (spallation p/n production, evaporation n, spallation products)
- Neutrons,
  - Elastic collisions, thermalization+capture (=>γ's)
- Break-up of nuclei

➢ Part of the energy is lost in breaking nuclei (nuclear binding energy)

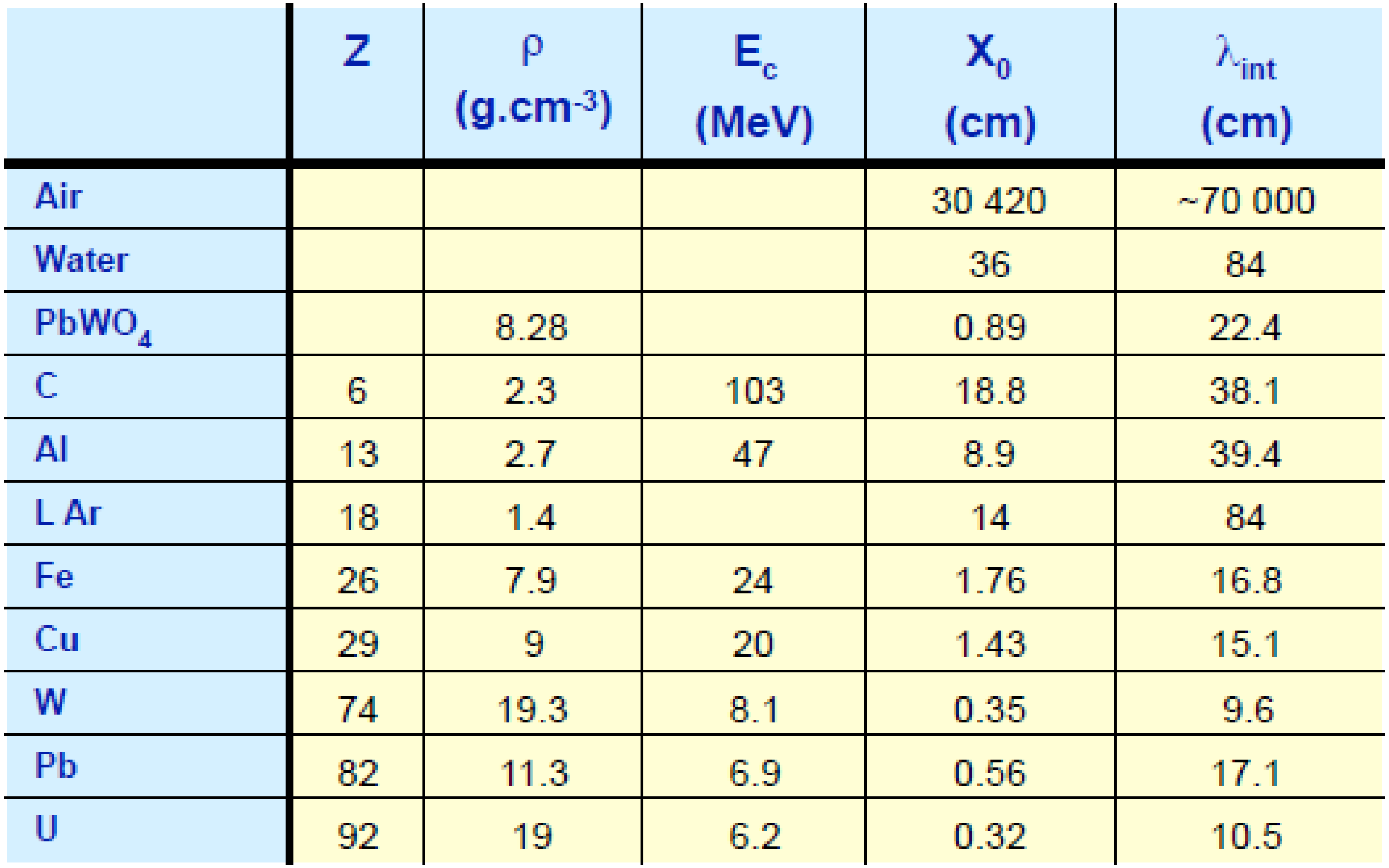
⇒ **Invisible part** of the shower ! **Only part of the shower energy is sampled !**

- Large, **non-Gaussian** fluctuations of each component (EM vs non-EM)
- Large, **non-Gaussian** fluctuations in "invisible" energy losses.

Interaction Length

- The hadronic shower is governed by the interaction length λ_{int}
  - λ_{int}: Mean free path between inelastic interaction

$$\lambda_{\text{int}} \approx 35A^{1/3}(g.cm^{-2})$$



	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19	6.2	0.32	10.5

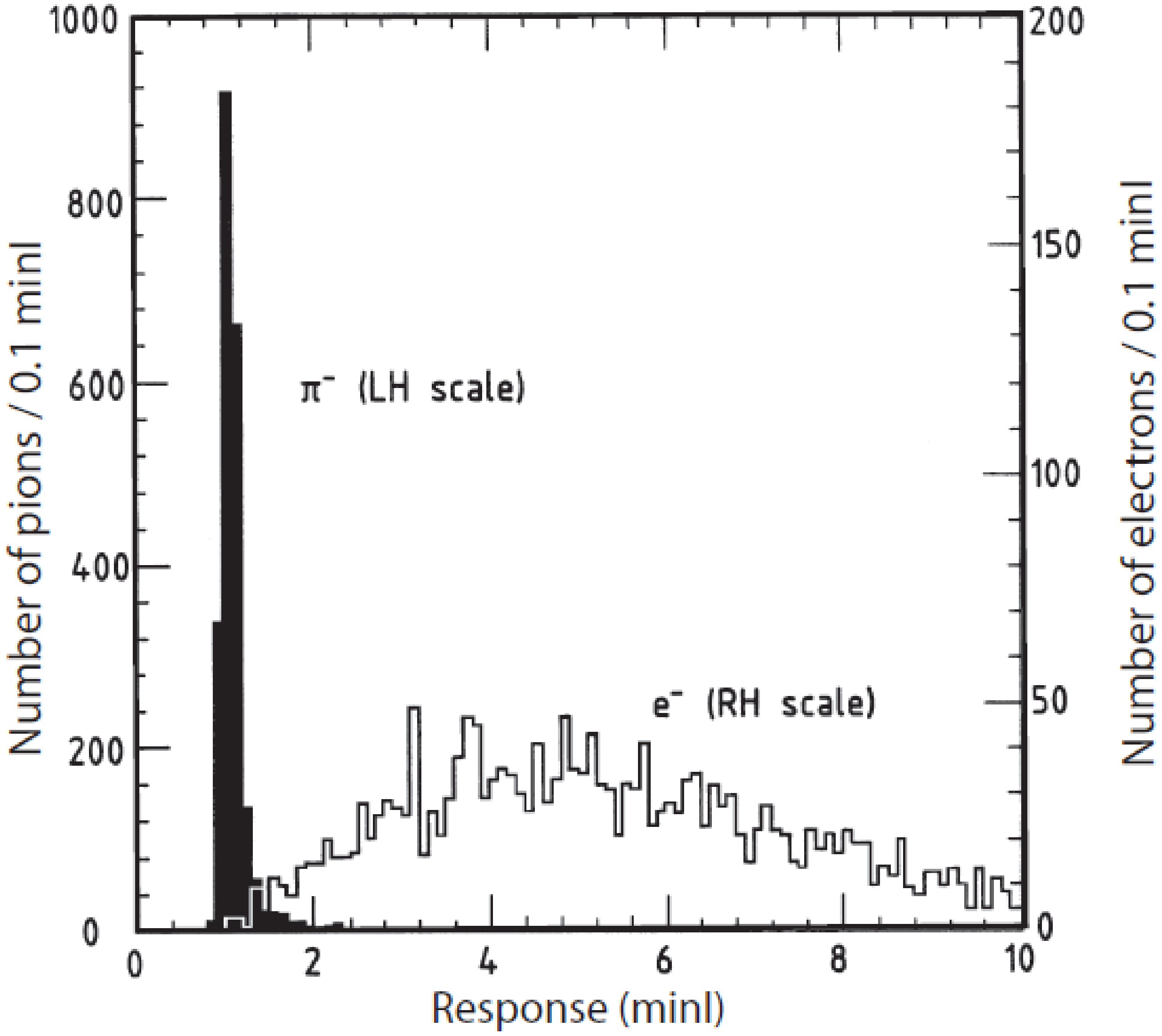
Hadronic shower are longer than EM shower…

Particle ID

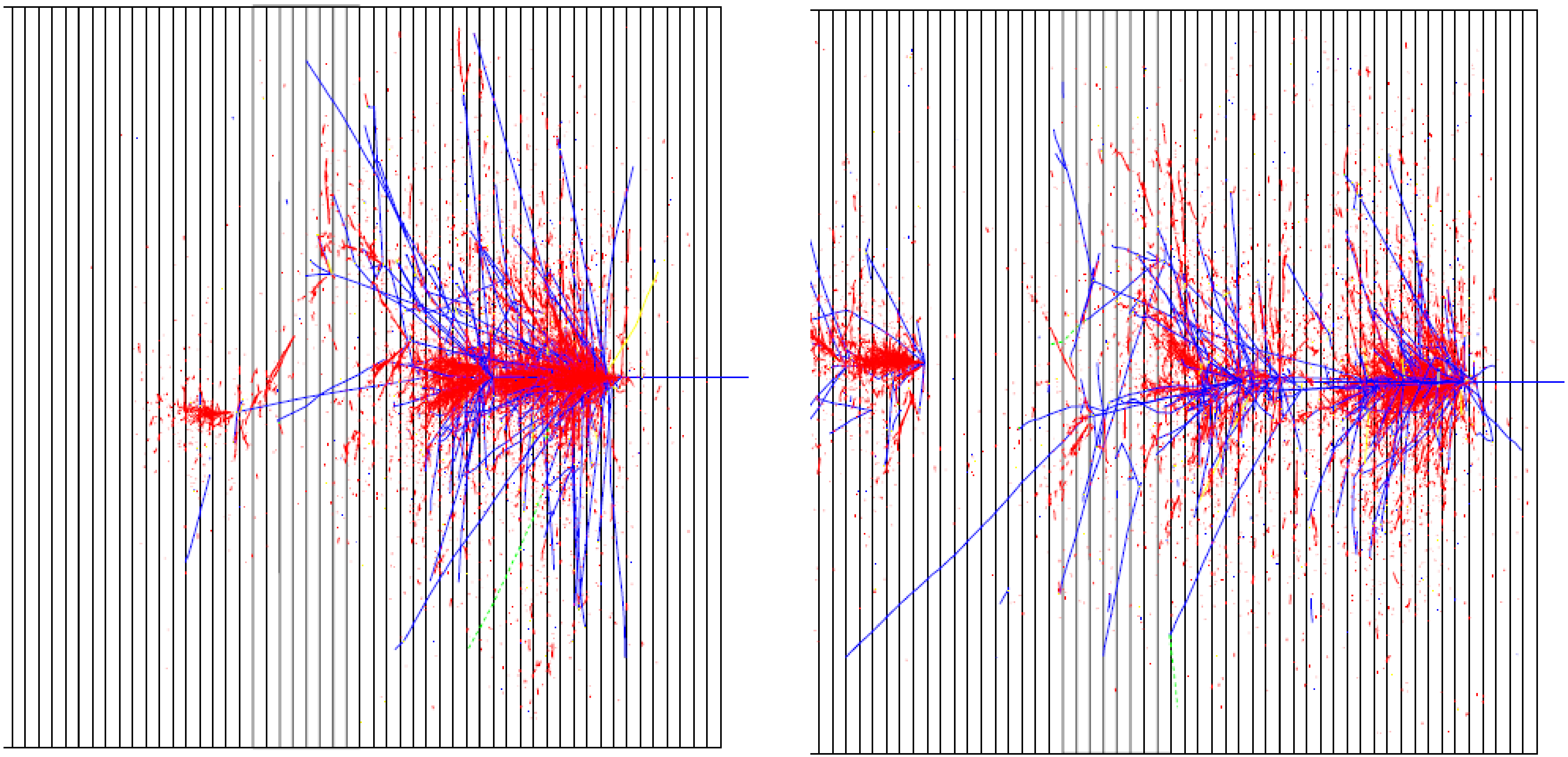
The ratio $R=\lambda_{int} / X_0$ is important for Particle Identification

In high-Z material, R~30 => **excellent e/π separation !**

1 cm Pb + scintillator plates makes an excellent “Pre-Shower”



Hadron shower in Cu



red - e.m. component
blue - charged hadrons

HAD showers: intrinsic fluctuations

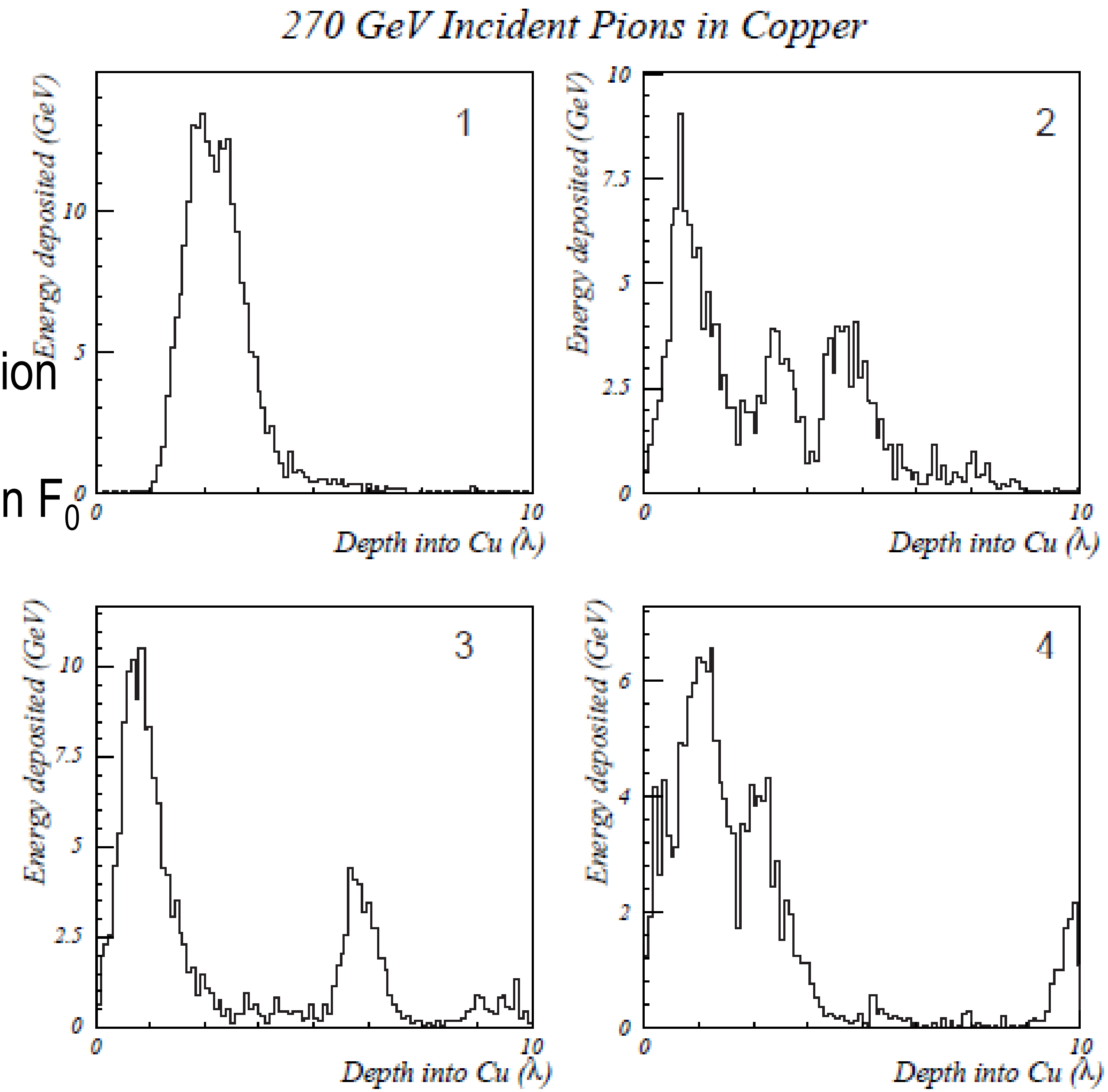
No “characteristic” profile…

Size of the EM component (F_0) is essentially determined by the 1st interaction

Considerable event-to-event fluctuation in F_0

On average 1/3 of mesons produced in the first interaction with be π^0’s

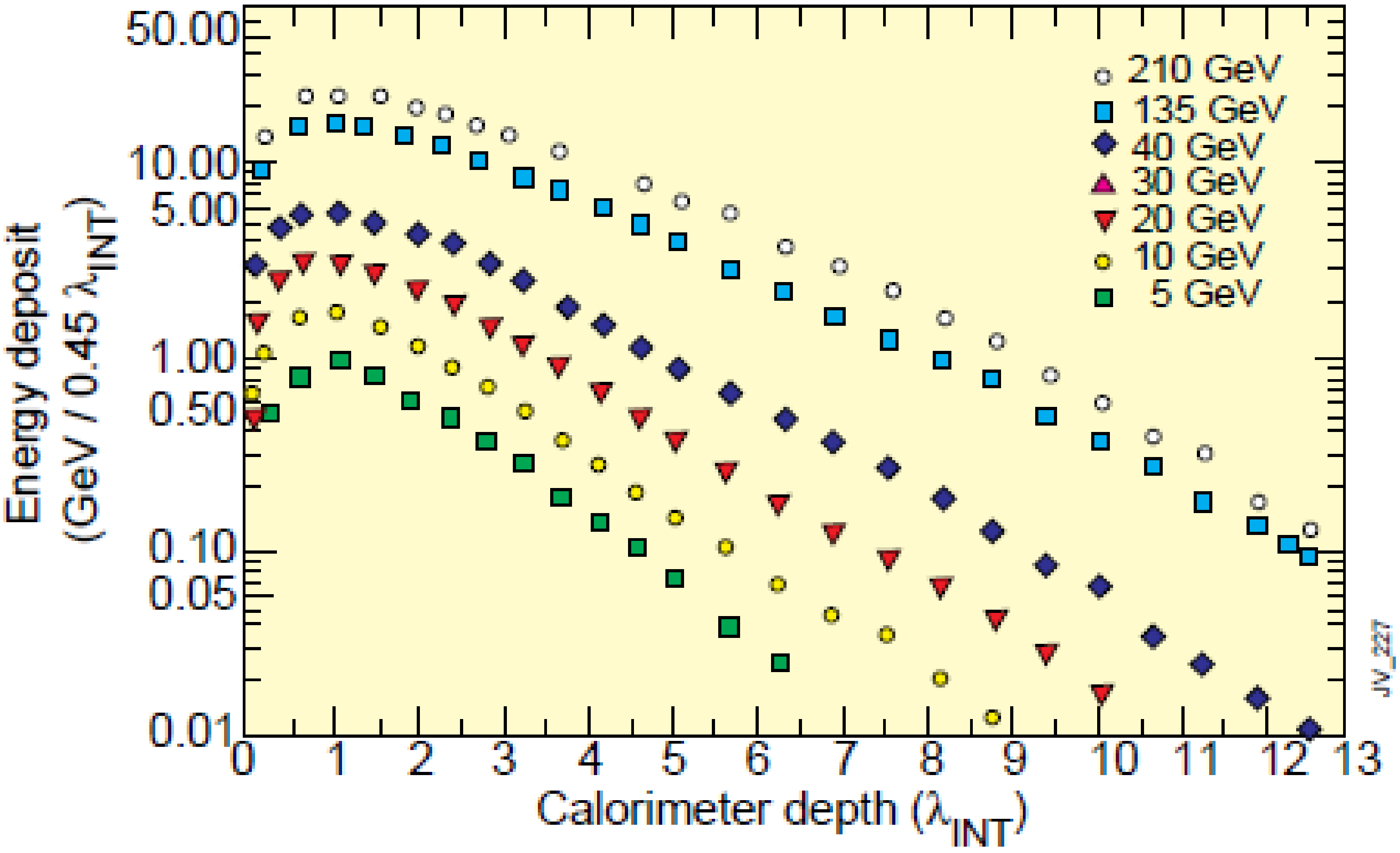
The 2nd generation $\pi^{\pm}$’s also produced π^0’s if sufficiently energetic.


270 GeV Incident Pions in Copper

HAD showers: Longitudinal Profile

- As for EM showers, **depth to contain an HAD shower increase with ln(E)**

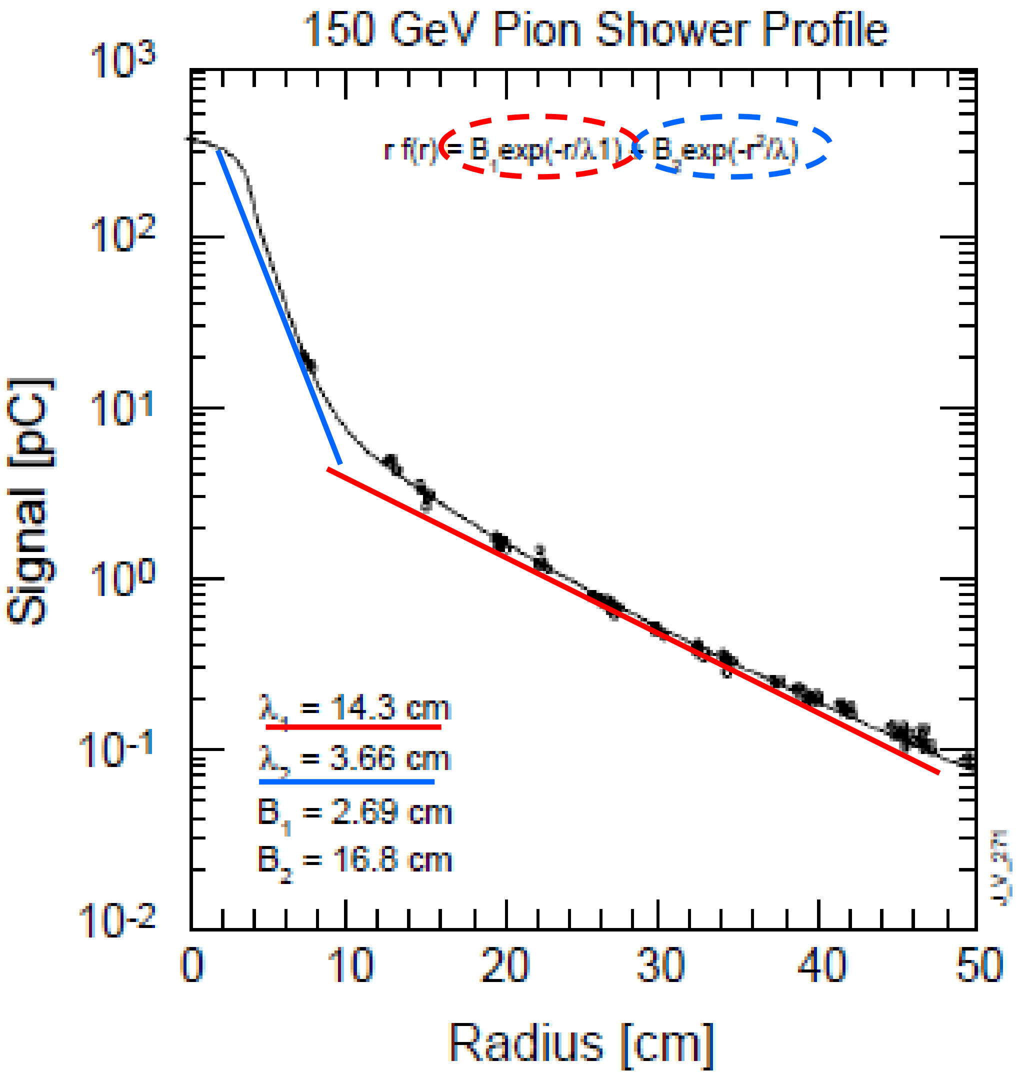
WA78 experiment: 5.4 λ (10mm U/5mm Scint), 8 λ (25 mm Fe / 5mm Scint.)



- sharp peak near the 1st interaction point (from π^0's produced in the 1st interaction)
- Then more gradual falloff (characterized by λ_{int})

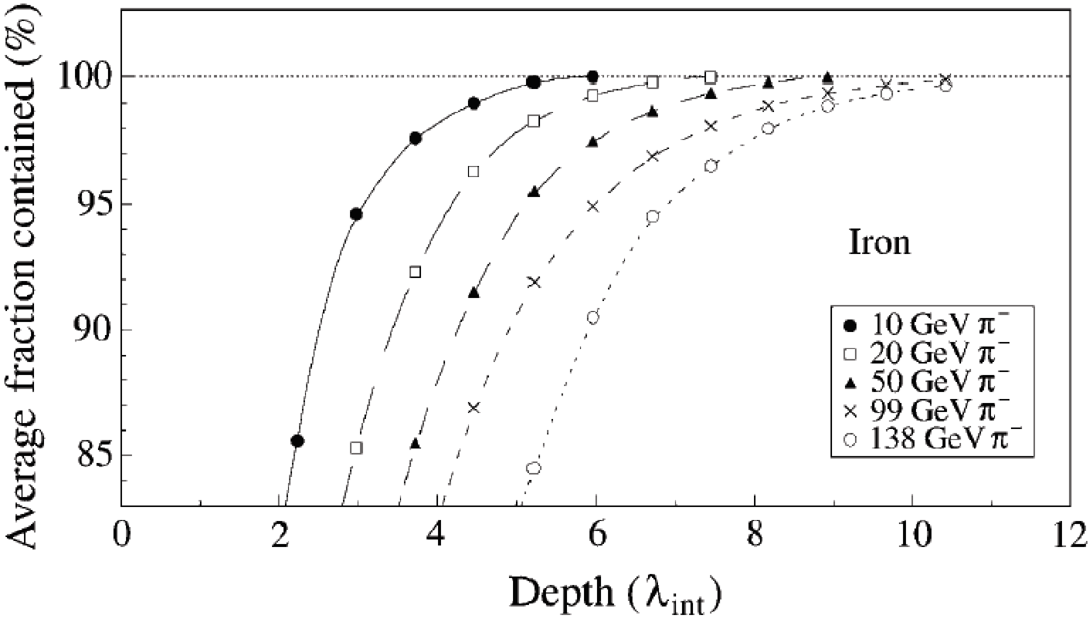
HAD showers: Lateral Profile

- Lateral shower profile has two components:
    - **Electromagnetic core** (from $\pi^0 \rightarrow \gamma\gamma$)
    - **Non-EM halo** (mainly non-relativistic shower particles)

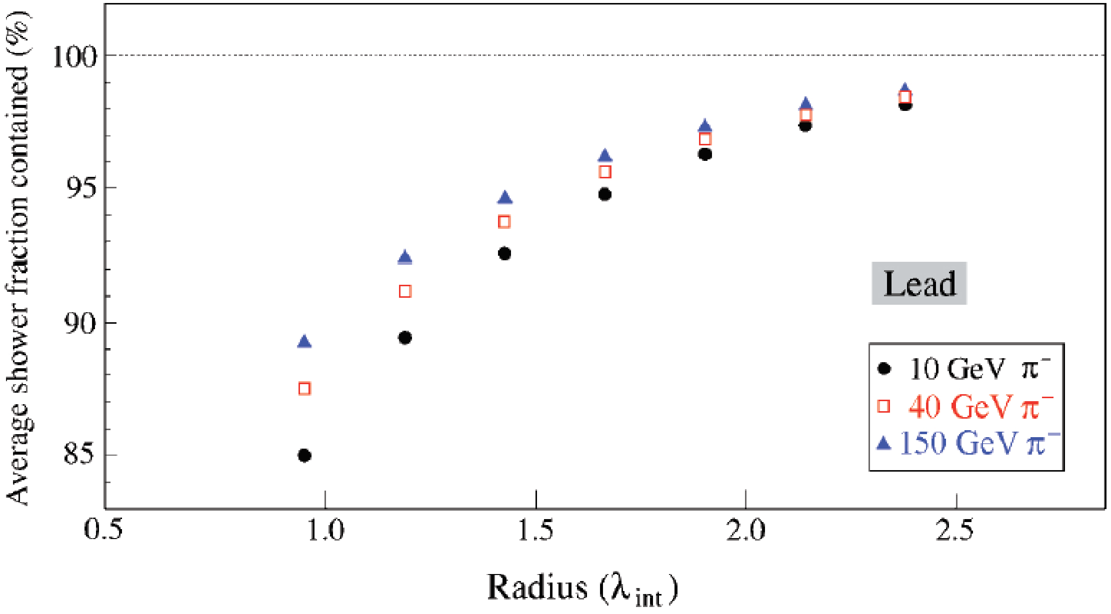


HAD showers: containment

Longitudinal



Lateral



Need about **~10 λ_{int}** to contain most of the hadronic showers

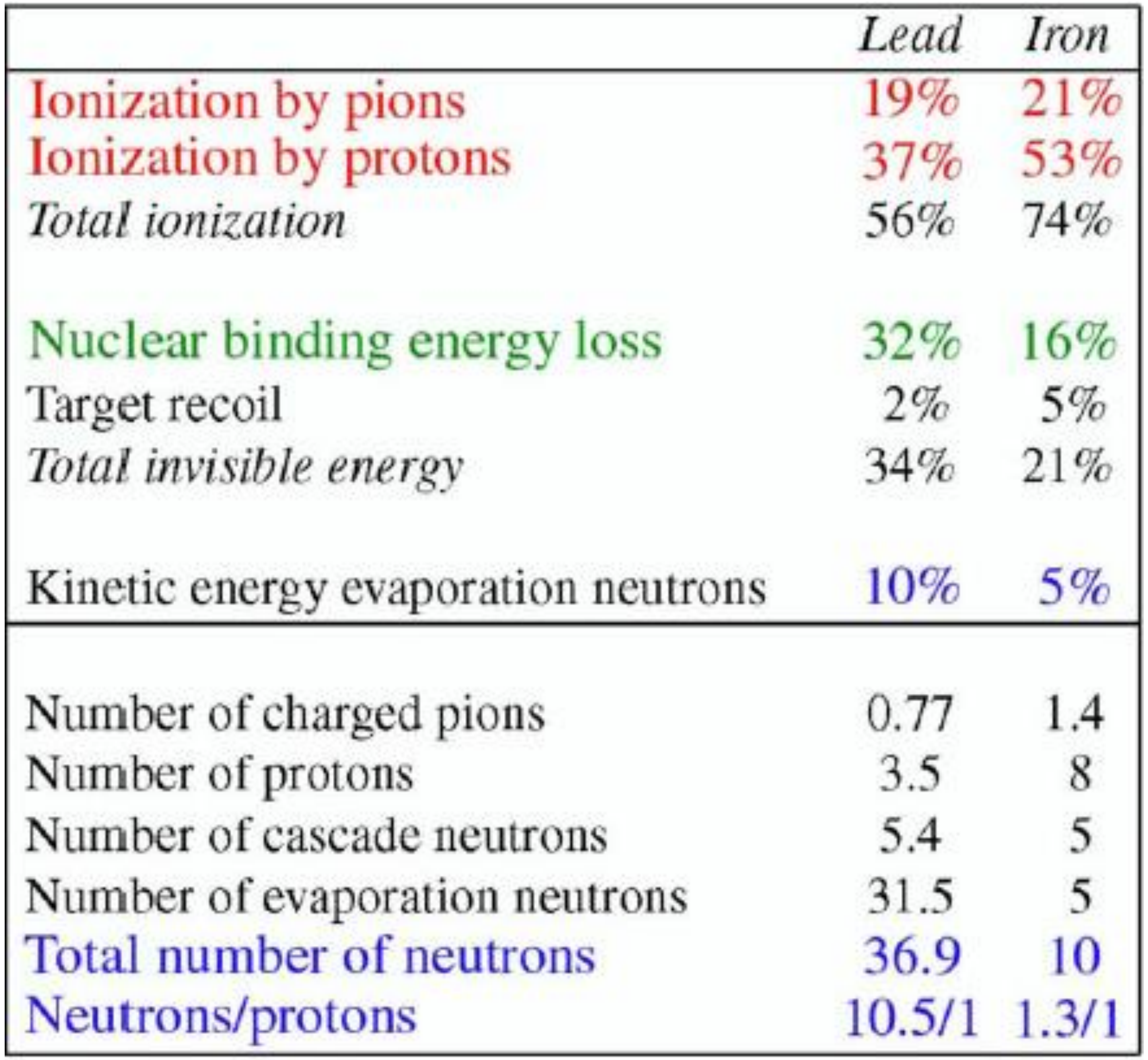
Lateral containment increases with energy ! (*)

Transverse radius for 95% containement ~ 1.5 λ_{int}

(*) f_{EM} increase with E, and γ from π^0 emitted along the π^0 axis.

Non-EM fraction breakdown

- In Lead, non-EM component energy breakdown:
  - ~56% ionizing particle
    - 2/3 are protons (from spallation). <E>~50-100 MeV
  - **~10% neutrons,**
    - very soft (3 MeV typically),
    - on average 37 n
      per deposited GeV !
  - **~34% invisible**



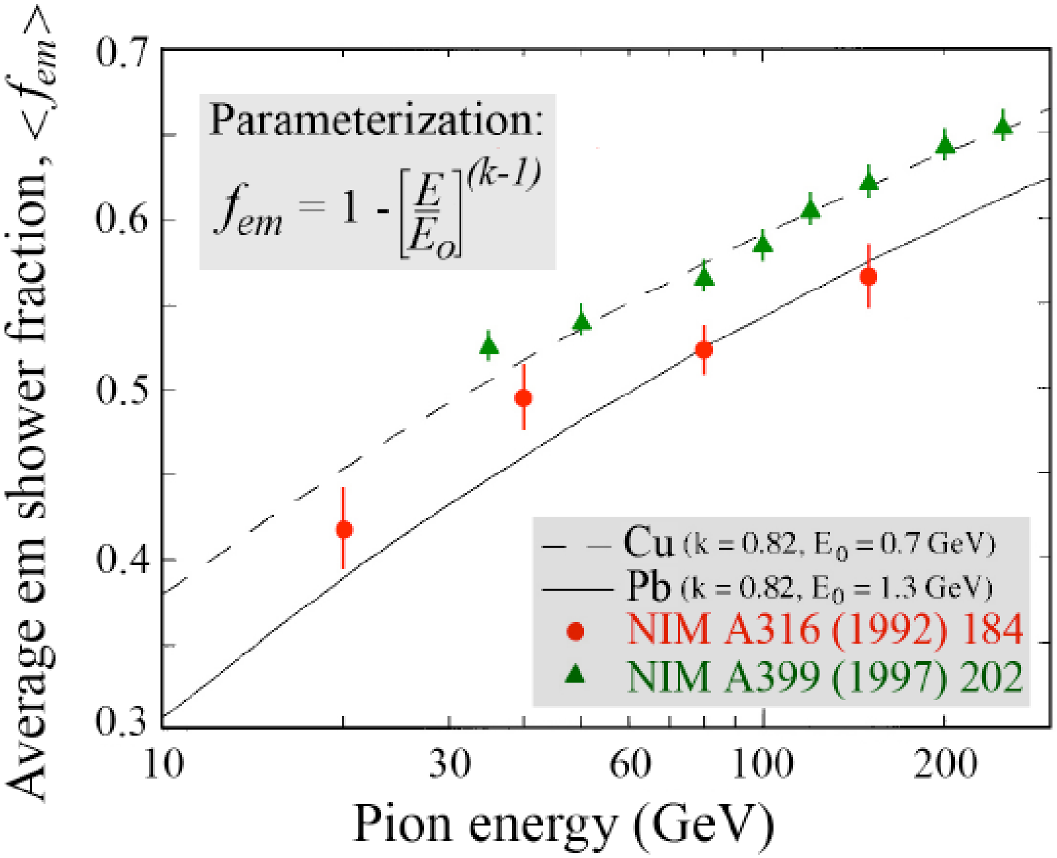
	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

EM fraction (1)

- **EM fraction ($f_{EM}=E_{EM} / E_{tot}$)** due to $\pi^0/\eta \to \gamma\gamma$.
  - In first interaction, ~1/3 of produced particles are π^0.
  - Remaining hadrons may undergo neutral pions too.

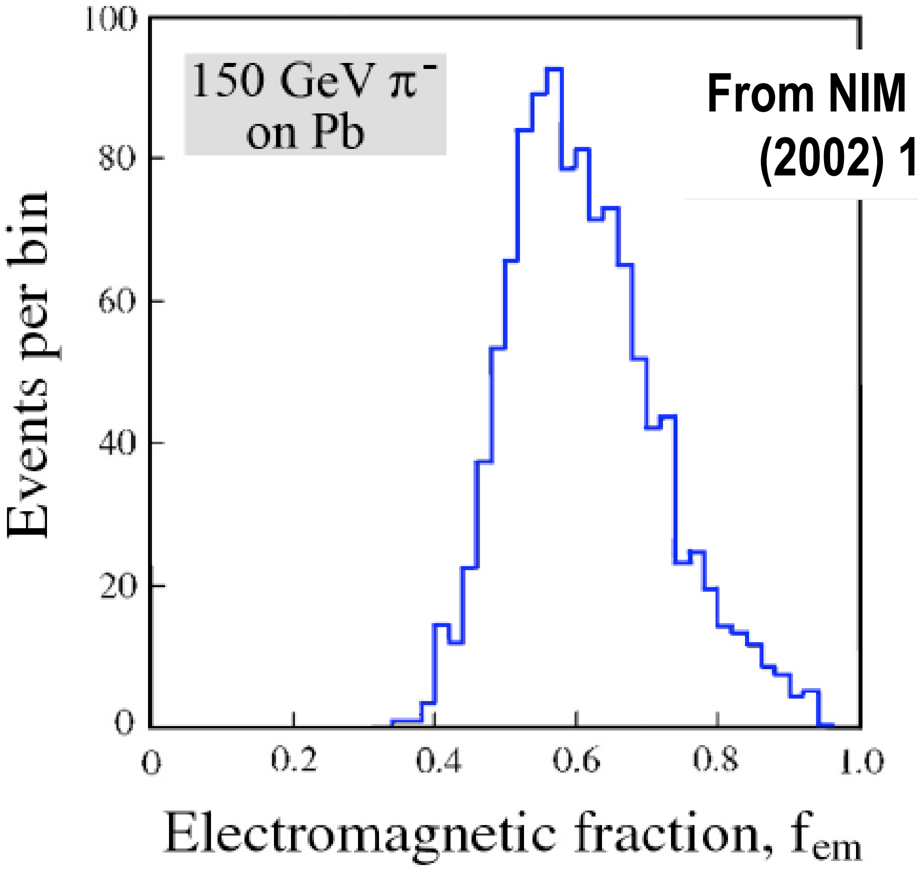
- **Considerable variations from shower to shower**

- On average, f_{EM} increase with shower energy (typically ~30% at 10 GeV, ~50% at 100 GeV)

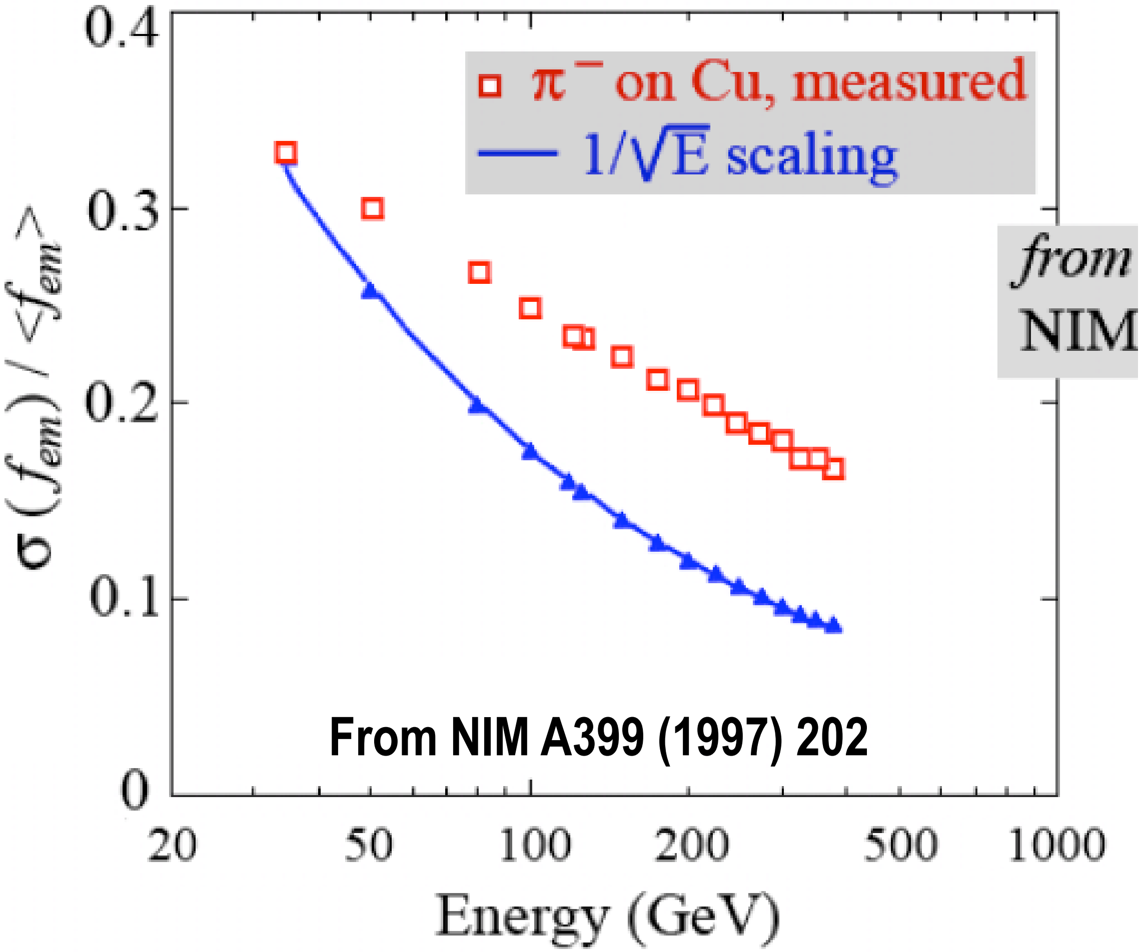


$<f_{EM}>$ is large, energy dependent and material dependent

EM fraction (2)



From NIM A316 (2002) 184



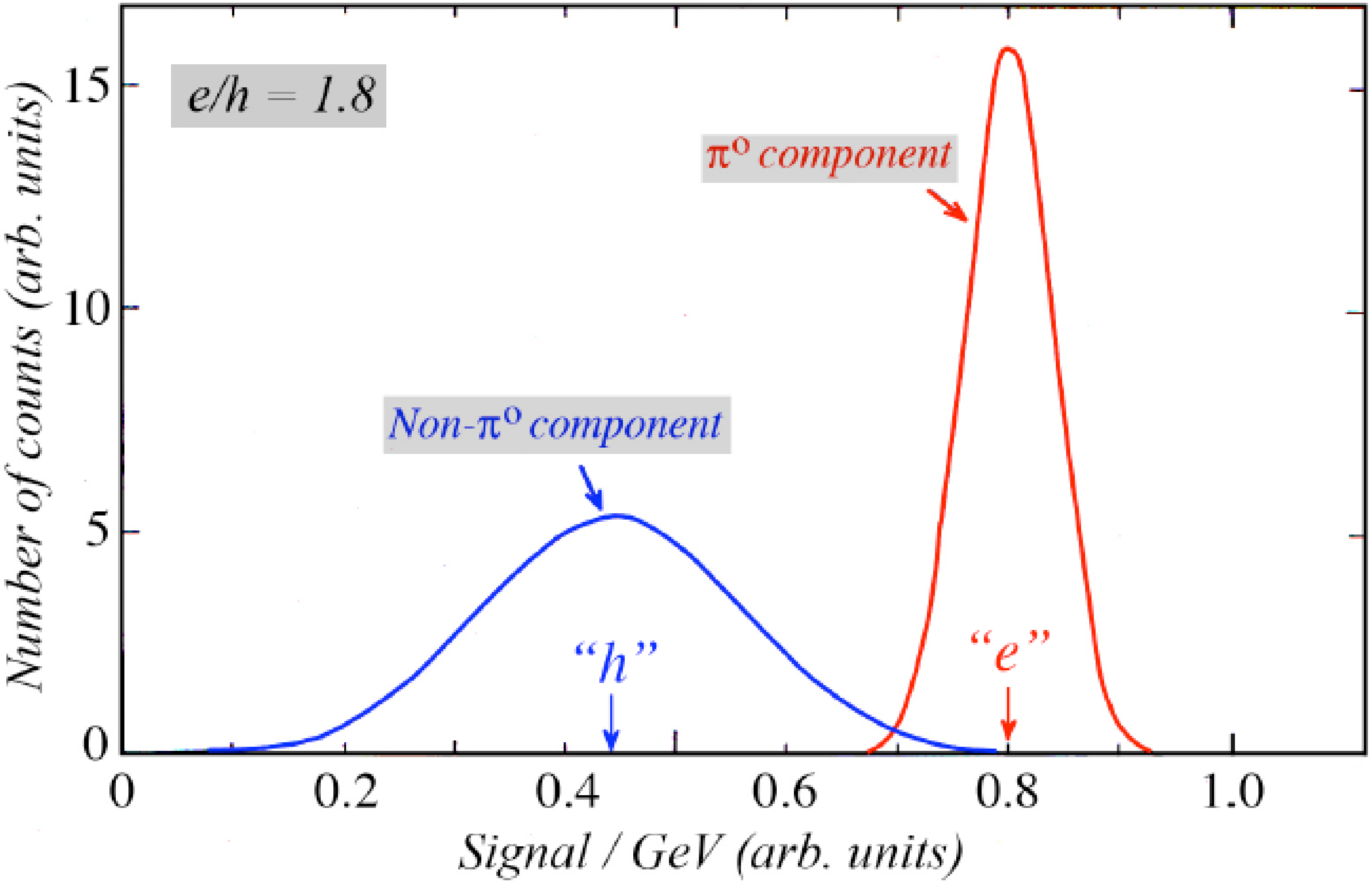
From NIM A399 (1997) 202

- **Fluctuations in f_{EM} are non-Poissonian**
- Deviations from E-1/2 scaling

HAD shower response (1)

- The response to the **HAD part (h)** of a hadron-induced shower is usually smaller than that of the **EM part (e)** (due to invisible energy: energy used to release nucleons from nuclei, neutrinos, …)
  ⇒ **"non-compensation"** (see next)

- Moreover, as $<f_{EM}>$ varies with energy, **hadron calorimeters are non-linear.**



HAD shower response (2)

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

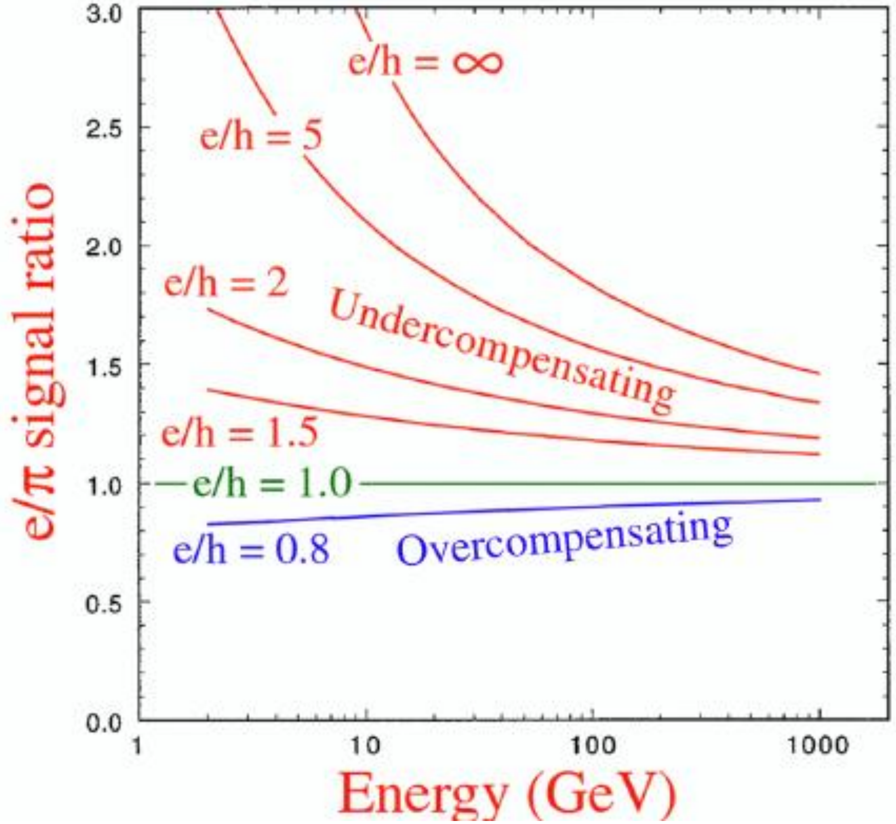
$$\frac{e}{\pi} = \frac{e}{f_{EM}\, e + (1 - f_{EM})\, h}$$

π: response to pions-induced showers
e: response to em shower component
h: response to non-em shower component

$$\boxed{\frac{e}{\pi} = \frac{(e/h)}{1 - f_{EM}\,(1 - e/h)}}$$

- **e/h**: energy independent way to characterize hadron calorimeters
  - Cannot be measured directly (inferred by e/π at several energies)

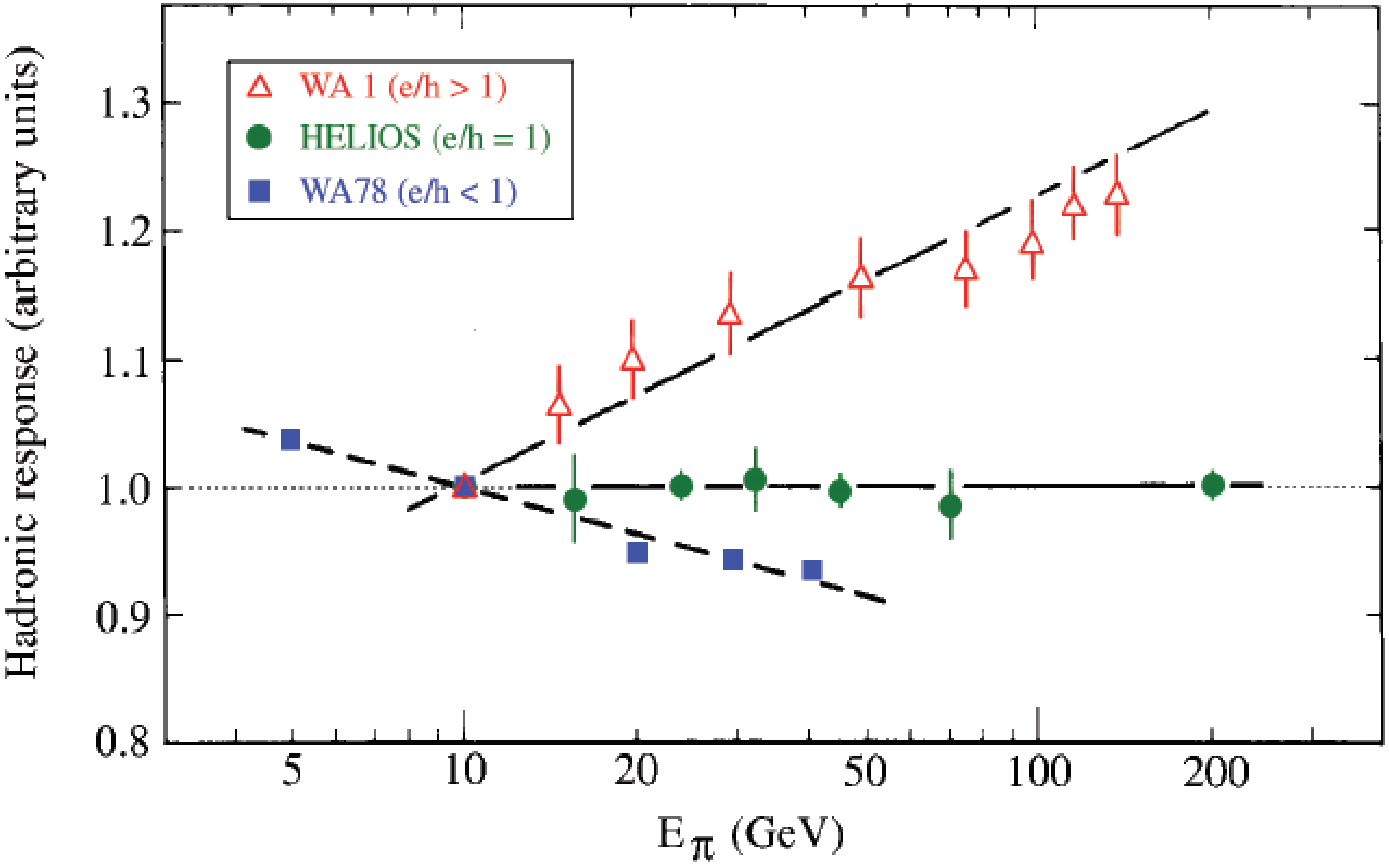
Calorimeters can be:
- under-compensating (e/h>1)
- over-compensating (e/h<1)
- **Compensating (e/h = 1)**



Consequences of (non-)compensation

(some) Consequences of non-compensation:

- Non-linearity of the hadronic calorimeter response
- Degradation of the energy resolution
  - Event-by-event, fluctuations in em and non-EM fraction creates event-by-event signal fluctuations



How to achieve compensation ?

- Long-story… it took a lot of R&D to understand the underlying mechanisms of hadron calorimetry and identify several ways to achieve compensation:

- **Build a sampling calorimeter**
  - Compensation can never be achieved with homogenous calorimeter !

- **Boost the non-EM response**
  - Amplify neutron and soft photons component by:
    - Fission: usage of ^{238}U plates (depleted).
    - hydrogenous detector: optimize sampling fraction, integrate signal over a large enough window, …

- **Suppress EM response**
  - Usage of high-Z absorber (Pb, Ur,…) and low-Z active.
    - Photo-electric effect dominates ($\sigma_{photo\text{-}e} \propto Z^5$)
    - Suppress low energy photon detection (γ < 1 MeV captured in absorber)
  - Further suppression: shield active layers with thin sheets of passive low Z material.
    - e.g. Ur wrapped with Stainless Steel sheets in ZEUS.

- **Offline compensation:**
  - Recognize, event-by-event, cells rich in EM and non-EM deposits, and weight their energy accordingly
    - Need fine segmentation

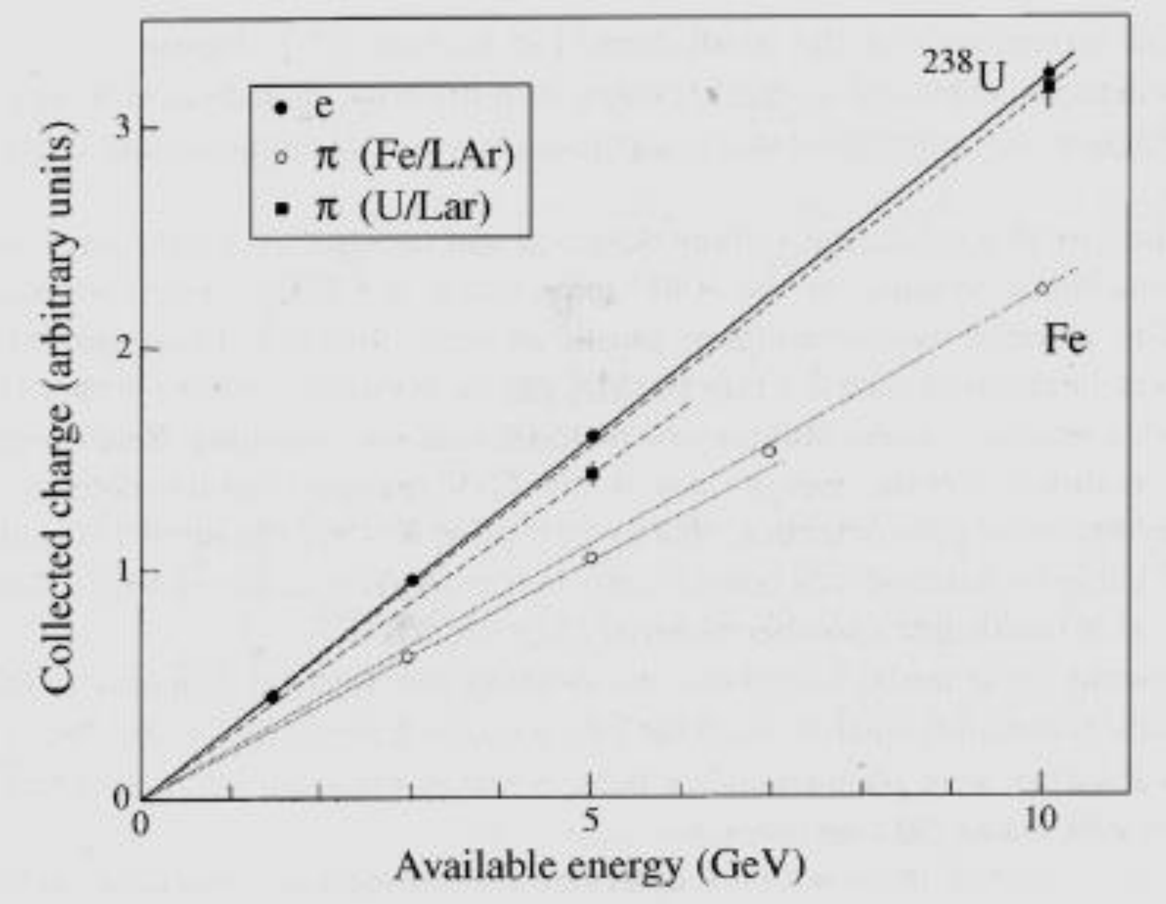
First "compensating" calorimeter

- First Uranium calorimeter by Fabjan & Willis

250 ^{238}U plates (1.7mm thick)
+ LAr (20mm gap between plates)

- Compensation almost achieved

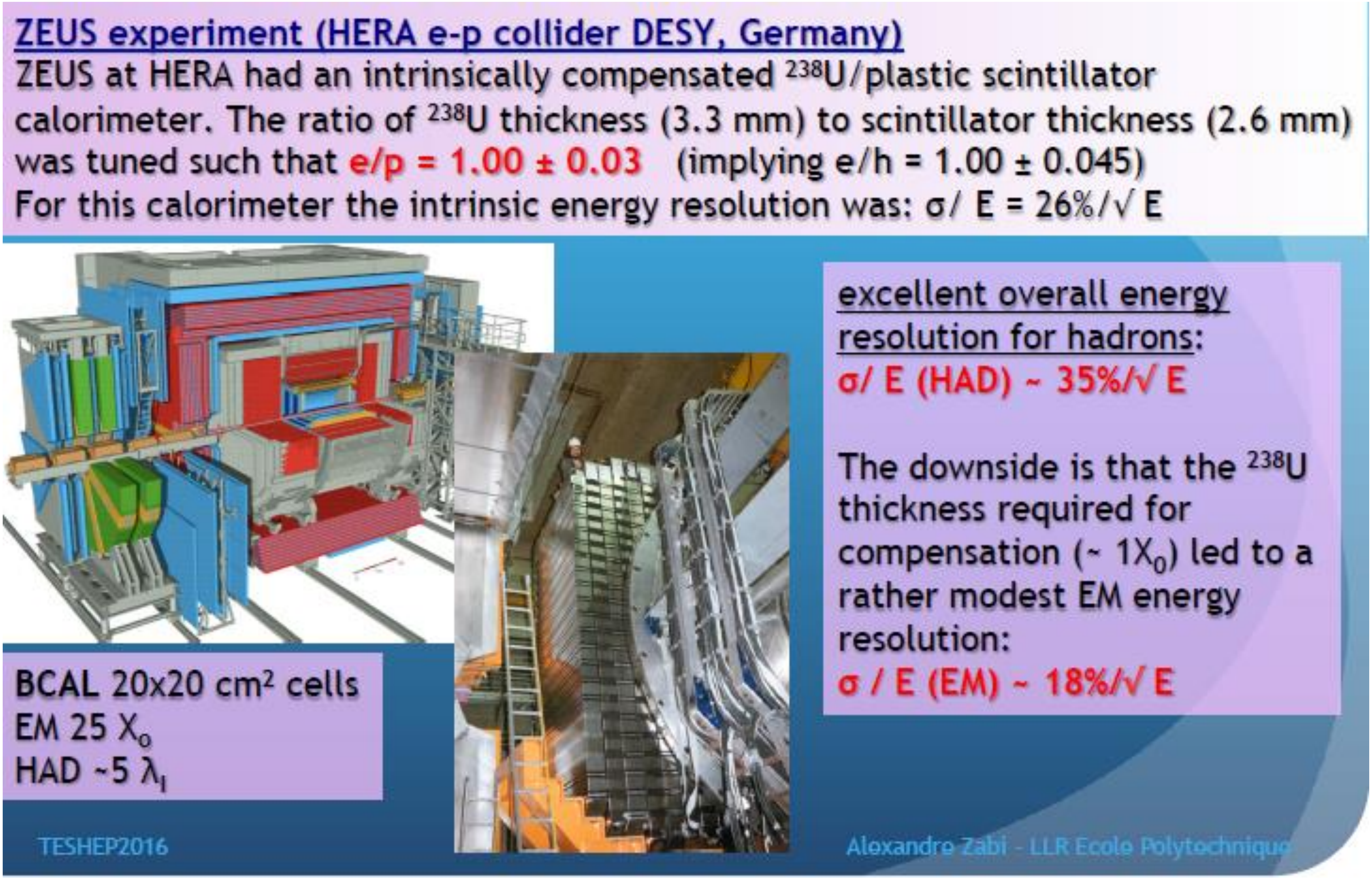
=> e/h ~1.1 – 1.2



- **Mechanism: nuclear fission**
  - Extra energy from fission fragment: carries a lot of energy (nuclear γ's and soft evaporation neutrons).
  - Should "compensate" for losses in nuclear binding energy

- For a long time, thought to be the solution to compensation…

Compensated calorimeter: example



ZEUS experiment (HERA e-p collider DESY, Germany)

ZEUS at HERA had an intrinsically compensated ^{238}U/plastic scintillator calorimeter. The ratio of ^{238}U thickness (3.3 mm) to scintillator thickness (2.6 mm) was tuned such that $e/p = 1.00 \pm 0.03$ (implying $e/h = 1.00 \pm 0.045$)

For this calorimeter the intrinsic energy resolution was: $\sigma/E = 26\%/\sqrt{E}$

excellent overall energy resolution for hadrons:

$\sigma/E\ (HAD) \sim 35\%/\sqrt{E}$

The downside is that the ^{238}U thickness required for compensation ($\sim 1X_0$) led to a rather modest EM energy resolution:

$\sigma/E\ (EM) \sim 18\%/\sqrt{E}$

BCAL $20\text{x}20\ cm^2$ cells

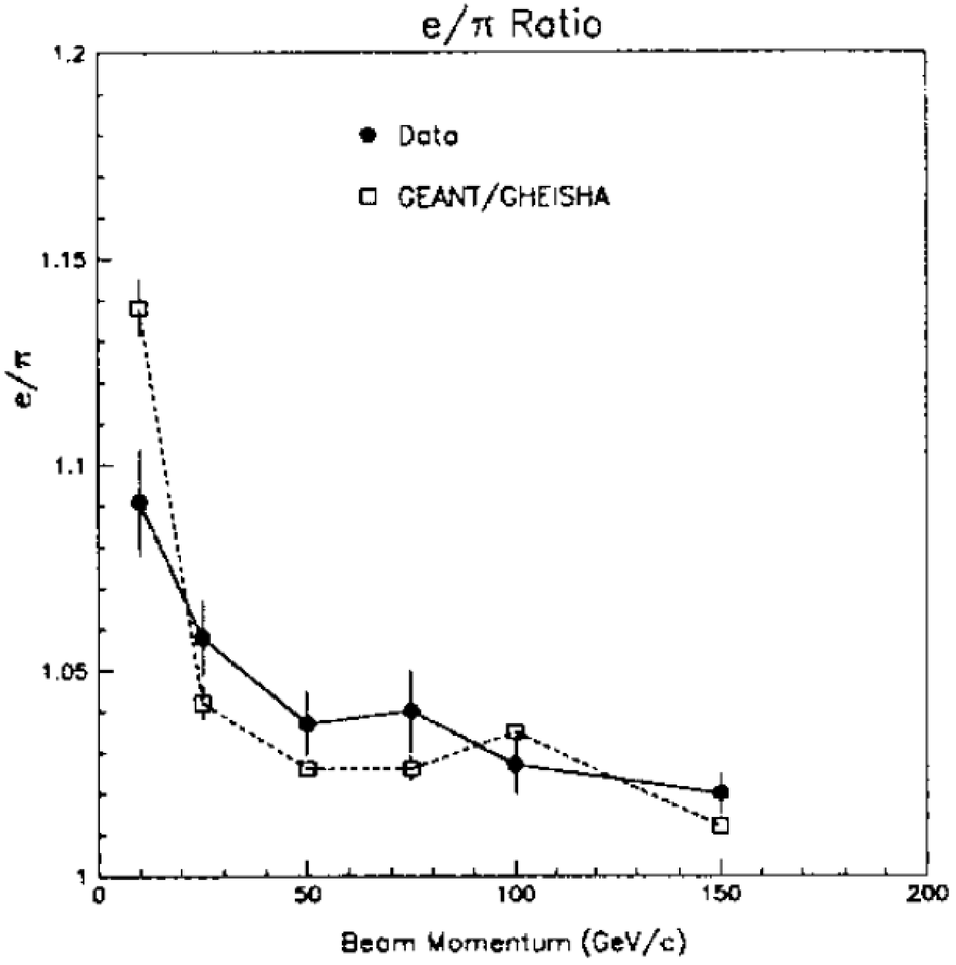
EM 25 X_0

HAD $\sim 5\ \lambda_I$

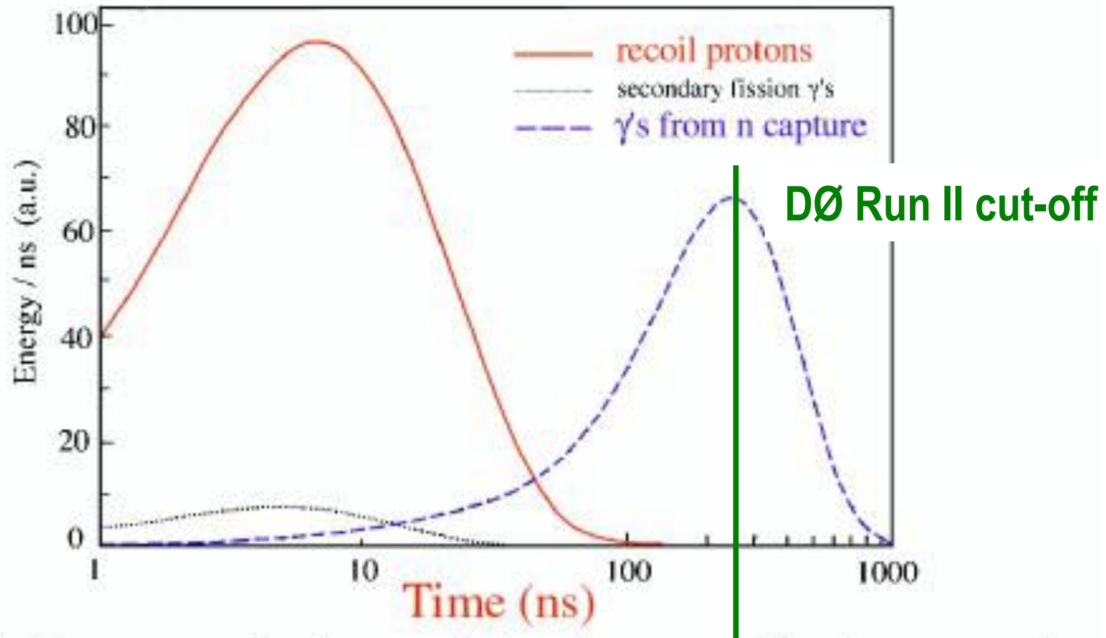
Compensation: examples

DØ Ur/LAr calorimeter

Almost compensated during Run I (1992-1996)



- During Tevatron Run II (2001-2011):
  - bunch crossing 3200->396 ns
  - => Smaller ~0.45ms (vs~2ms) charge integration window



DØ Run II cut-off

FIG. 3.22. Time structure of various contributions from neutron-induced processes to the hadronic signals of the ZEUS uranium/plastic-scintillator calorimeter [Bru 88].

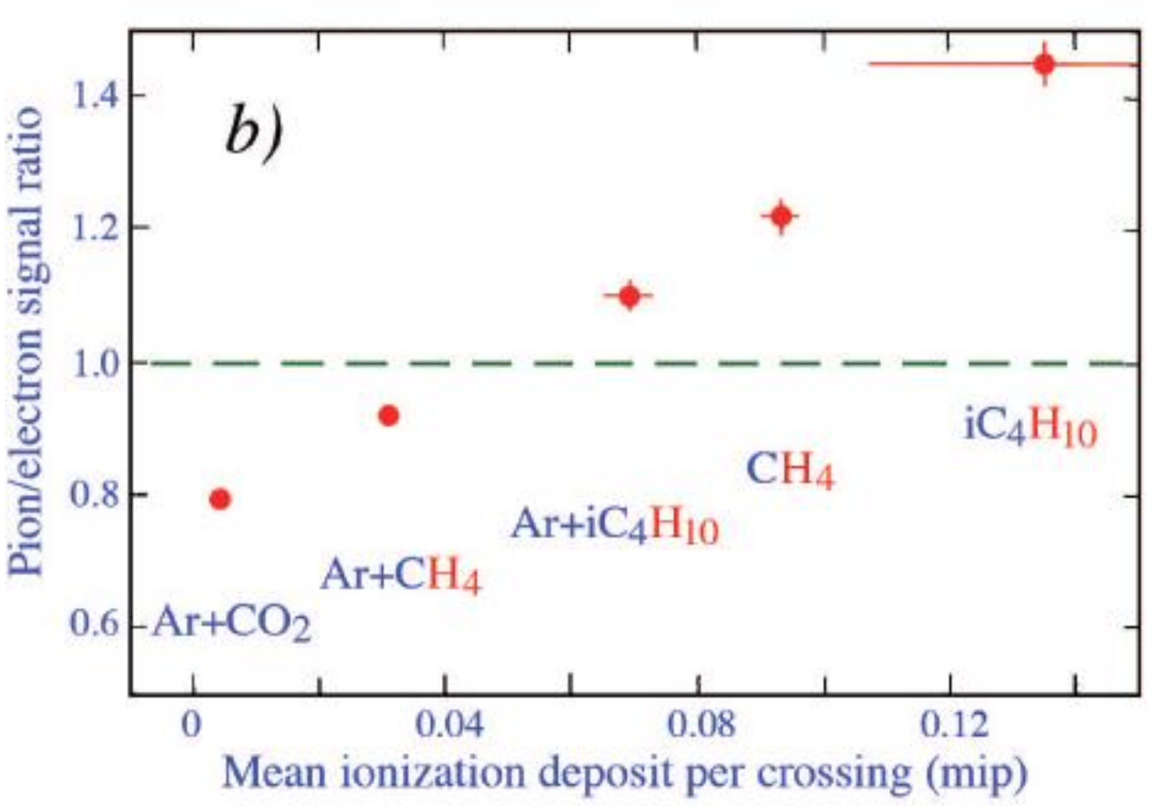
Decays of excited uranium nuclei happen long after shower development and corresponding charge not captured with short integration time (*).

=> **Compensation deteriorated and thus resolution for Run II**.

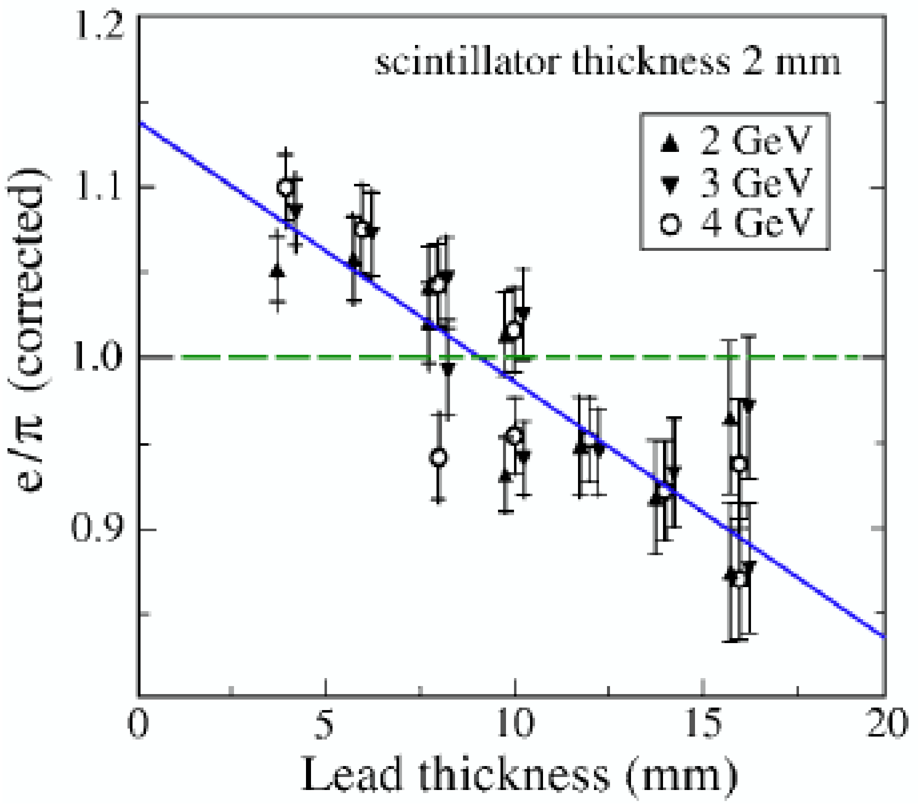
(*) Recoil protons are fast… neutron capture is slow (only works for thermal neutrons and thermalisation takes time…

Compensation: examples

Hydrogen in active material (gas mixture)



Lead / Scintillator



Elastic n-p scattering:
Efficient sampling of neutrons through the detection of recoiling protons!

(material with lots of “free” proton (H): elastic scattering of n on p => large signal from recoiling protons)

Sampling fraction can be tuned to achieve compensation

e/h not determined by absorber but by active medium (and in particular its H-content)

Pros & Cons of Compensating Calorimeters

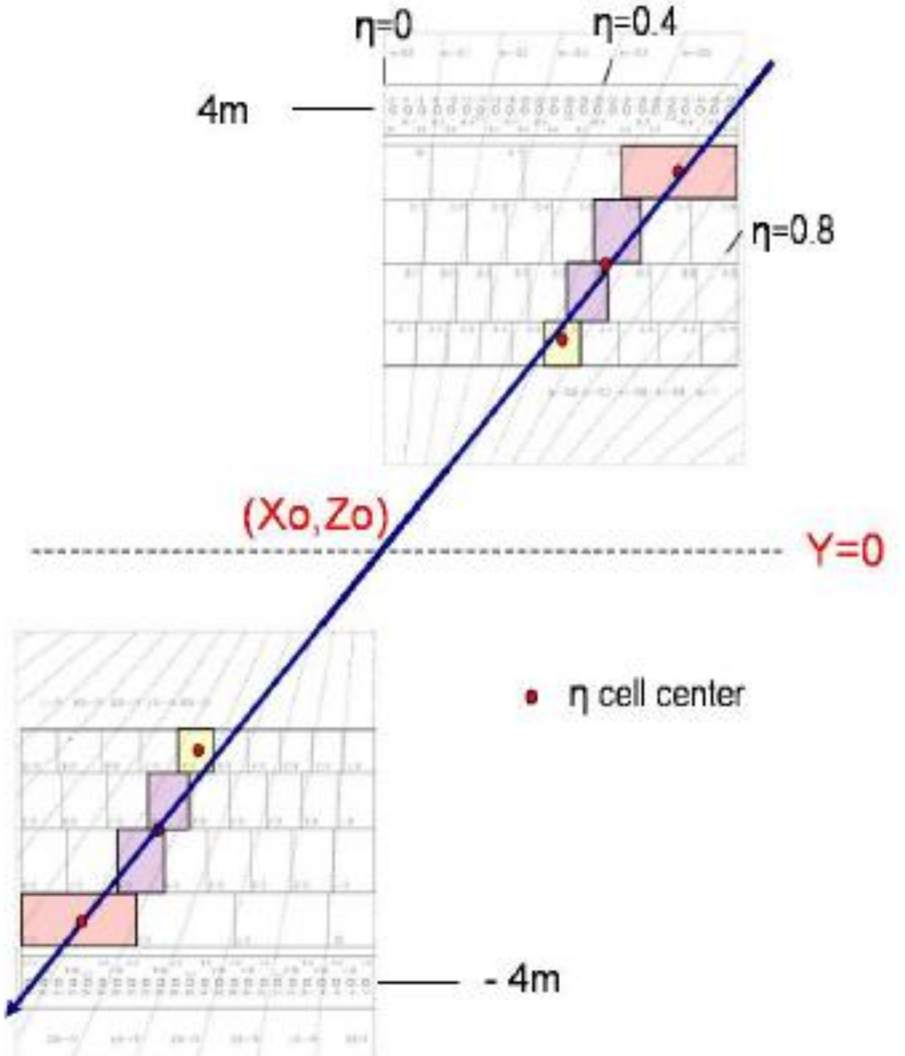
Pros

- Same *energy scale* for electrons, hadrons and jets. No ifs, ands or buts.
- *Calibrate* with electrons and you are done.
- Excellent hadronic *energy resolution* (SPACAL: 30%/$\sqrt{E}$).
- *Linearity,* Gaussian *response function* and all that good stuff.
- Compensation fully understood.
  We know how to build these things, even though GEANT doesn't

Cons

- Small sampling fraction (2.4% in Pb/plastic)
  ⟶ *em energy resolution limited* (SPACAL: 13%/$\sqrt{E}$, ZEUS: 18%/$\sqrt{E}$)
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ Long *integration time* (~50 ns)

What about muons ?



Muons vs electrons

Muons are charged leptons, like electrons… but much heavier !

$m_{e \sim 0.511}$ MeV/c^2

$m_\mu \sim 105{,}66$ MeV/c^2

$\boxed{m_e/m_\mu \sim 200}$

$(m_e/m_\mu)^2 \sim 4000$

- Loss of energy via brem ?
  Remember:

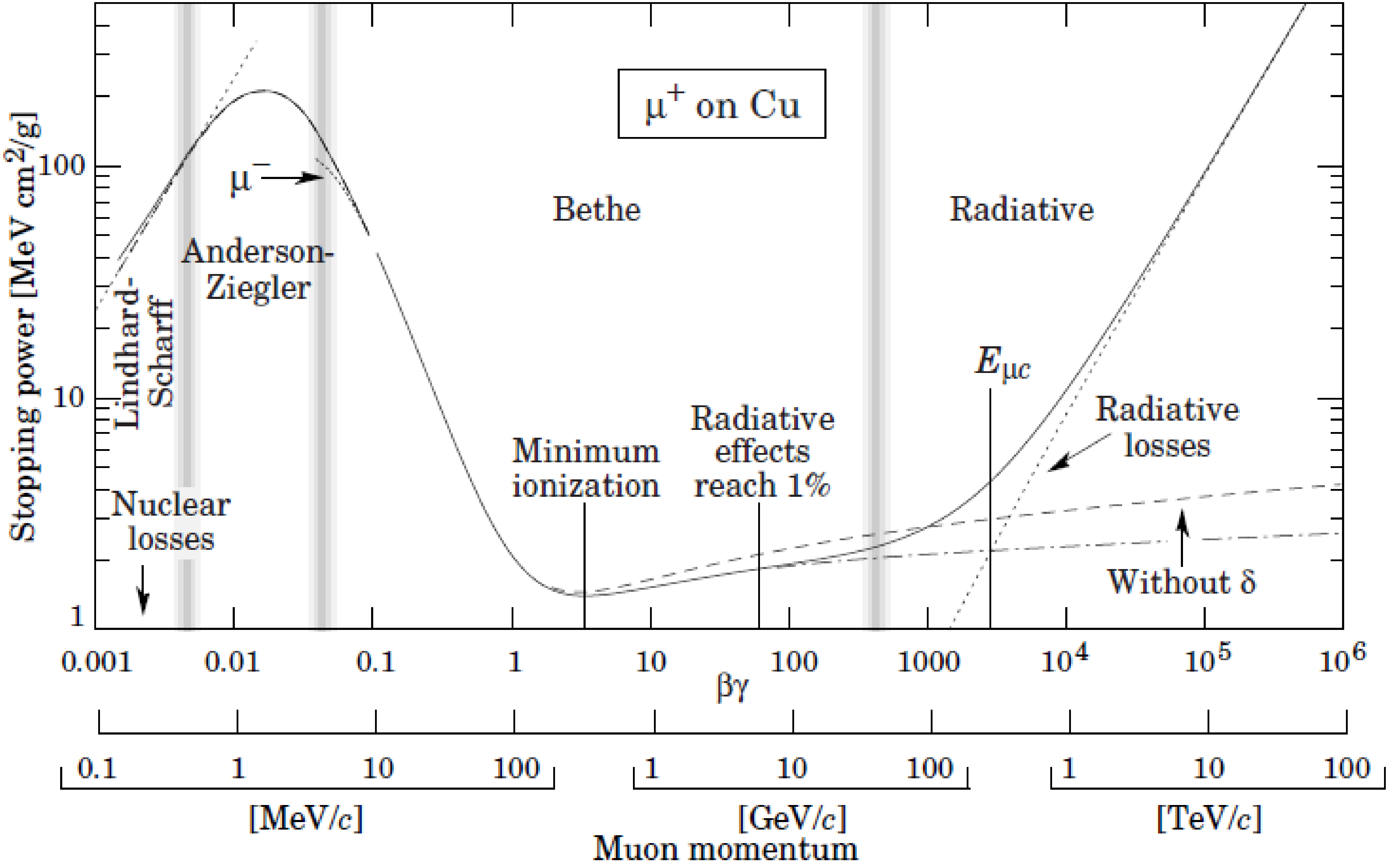
$$\left(-\frac{dE}{dx}\right)_{rad} \propto \frac{E}{m^2}$$

Much less important than for electrons…

$\boxed{\text{Main mechanism for muons is ionization => no “shower” !}}$

E_C (e-) in Cu: 20 MeV
E_C (μ) in Cu: 1 TeV…

Muon energy loss in Cu



Muons in calorimeter

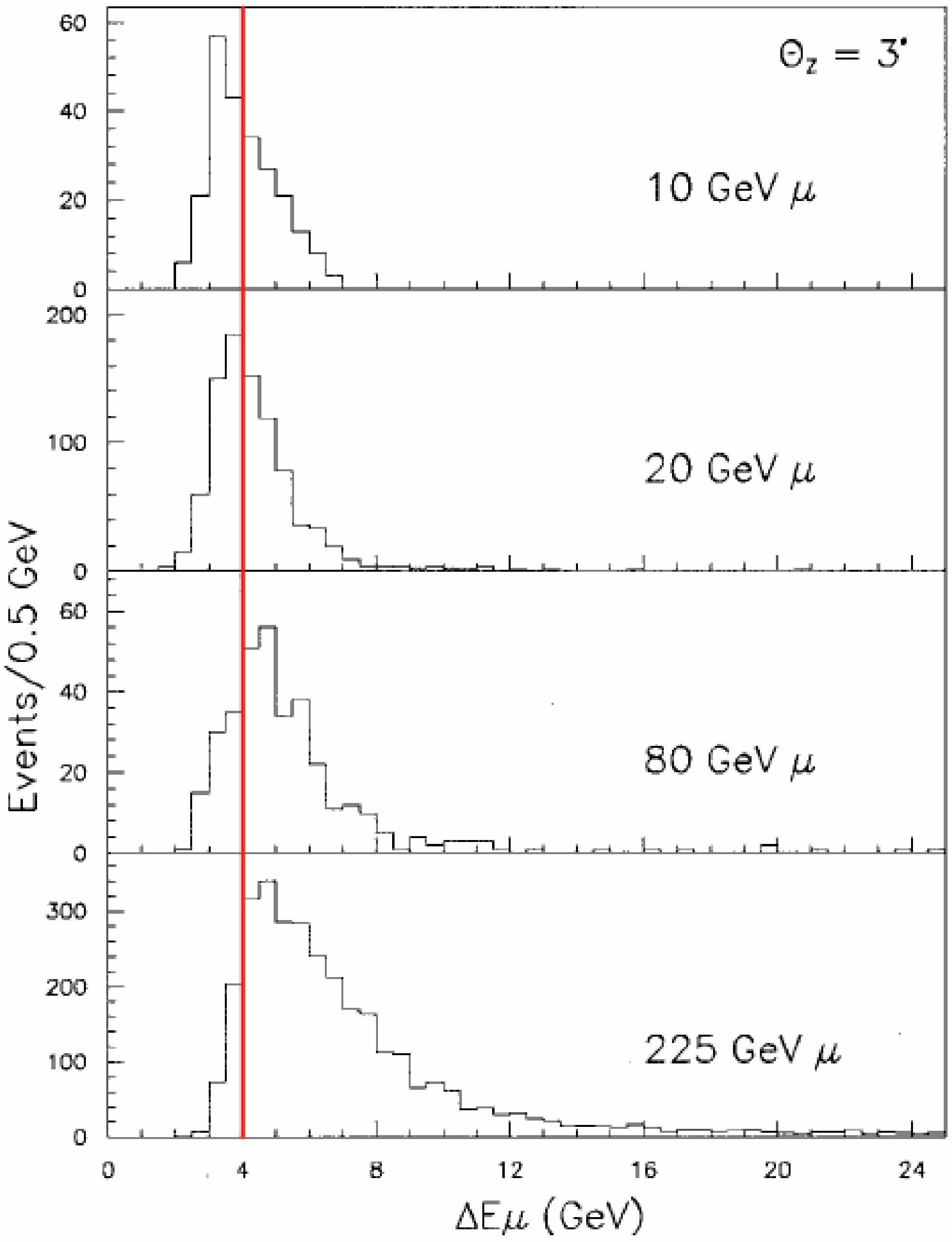


FIG. 2.19. Signal distributions for muons of 10, 20, 80 and 225 GeV traversing the $9.5\lambda_{\text{int}}$ deep SPACAL detector at $\theta_z = 3^\circ$. From [Aco 92c].

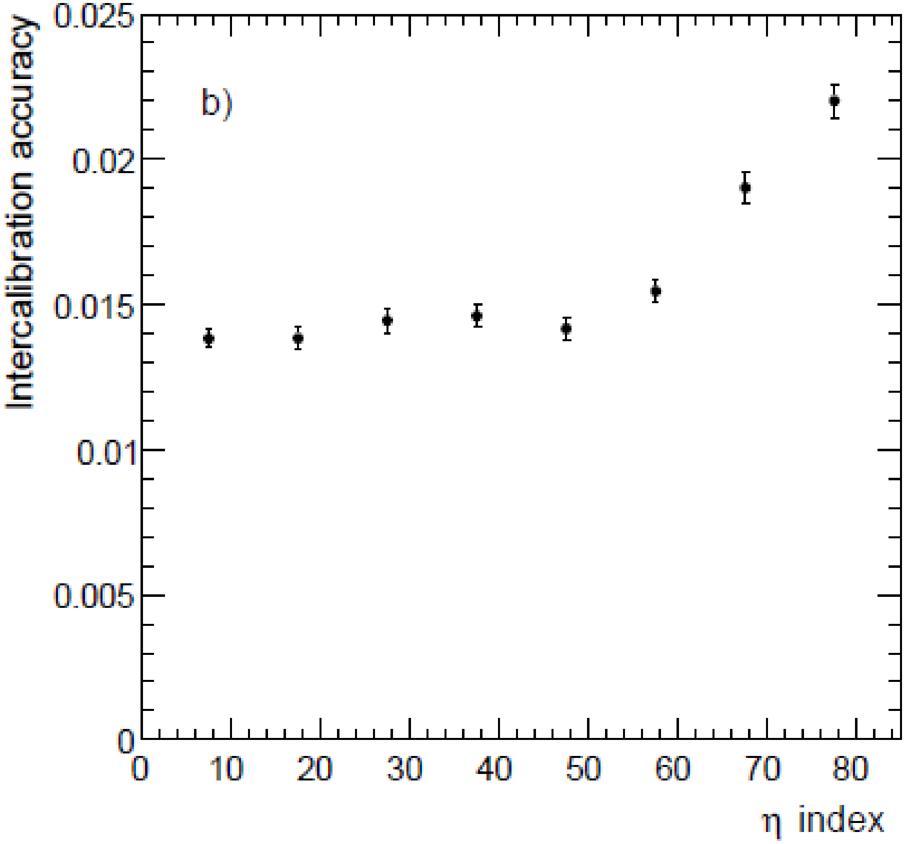
- Muons are NOT “mip” (Minimum Ionizing Particles) !
- Effect of radiation can be seen, especially at high energy and in high-Z material.
  - In Pb (Z=82), E_C (μ) =250 GeV (vs 6 MeV for e-)
- Muon energy deposit in matter NOT proportional to their energy

Muons for calorimeter

- Energy deposits from muons in calorimeter:
  - Very little (except for catastrophic loss from radiation)
  - Well known
  - Local

⇒ Muons heavily used to assess:
  - Calorimeter response uniformity (low energy), dead cells,…
  - Analyze the calorimeter geometry,

- **Cosmic muons are essential part of commissioning of calorimeters !**

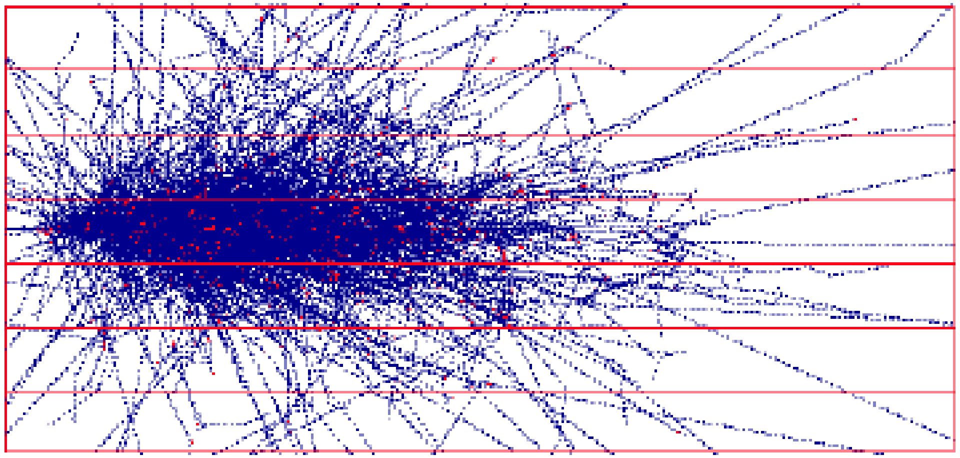


Ex: CMS ECAL

The intercalibration precision ranges from 1.4% in the central region to 2.2% at the high η end of the ECAL barrel **BEFORE real collisions !**

BACK UP
SLIDES

Homogenous Calorimeter



All the energy is deposited in the active medium

- Excellent energy resolution
- No longitudinal segmentation

All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

Scintillating crystals

$E_{th} \approx \beta.E_{gap} \sim$ eV

$\rightarrow 10^2 \div 10^4$ γ/MeV

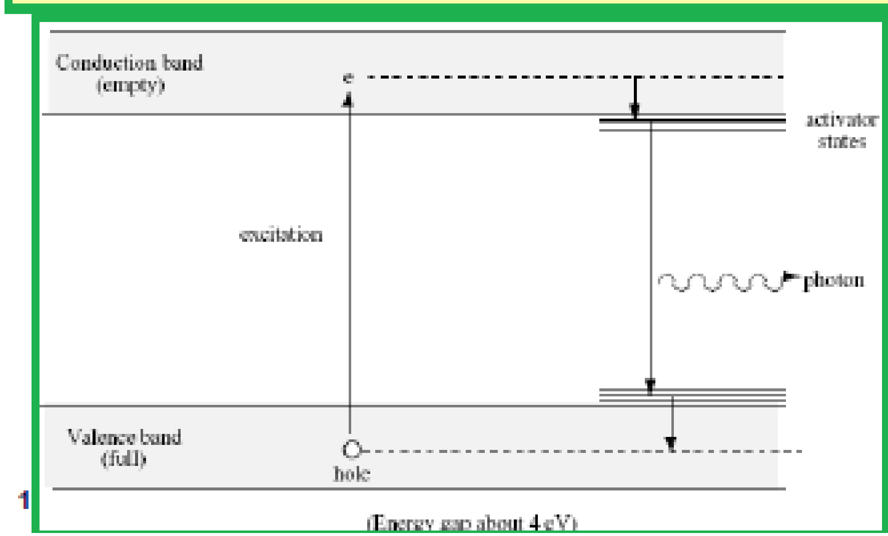
$\sigma/E \sim (1 \div 3)\%/\sqrt{E}$ (GeV)

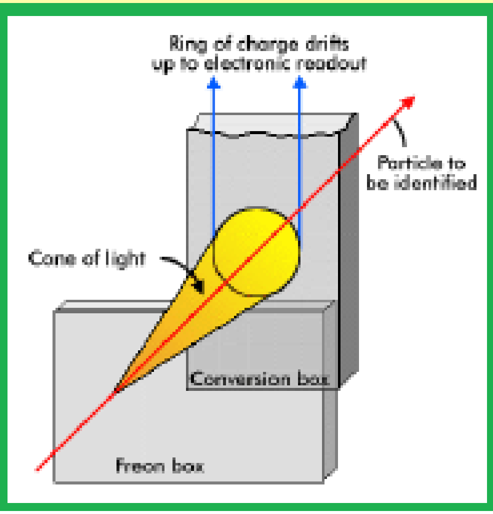
Cerenkov radiators

$\beta > 1/n \rightarrow E_{th} \approx 0.7$ MeV

$\rightarrow 10 \div 30$ γ/MeV

$\sigma/E \sim (5 \div 10)\%/\sqrt{E}$ (GeV)





Example

Take a Lead Glass crystal

E_c = 15 MeV

produces Cerenkov light

Cerenkov radiation is produced par $e^\pm$ with $\beta > 1/n$, i.e $E > 0.7$MeV

Take a 1 GeV electron

At maximum 1000 MeV/0.7 MeV $e^\pm$ will produce light

Fluctuation $1/\sqrt{1400} = 3\%$

In addition, one has to take into account the photon detection efficiency which is typically 1000 photo-electrons/GeV: $1/\sqrt{1000} \sim 3\%$

Final resolution $\sigma/E \sim 5\%/\sqrt{E}$

Glossary

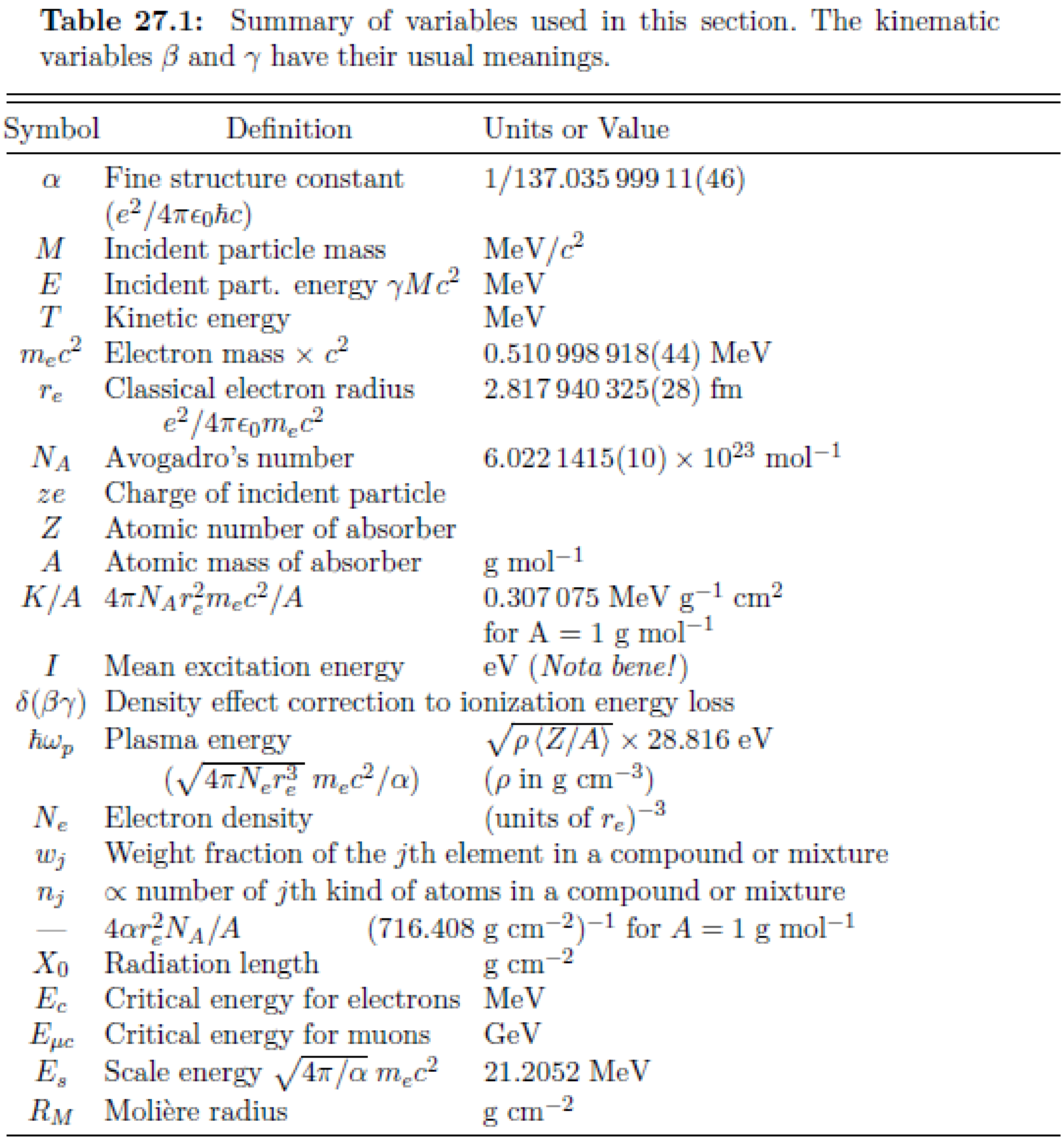


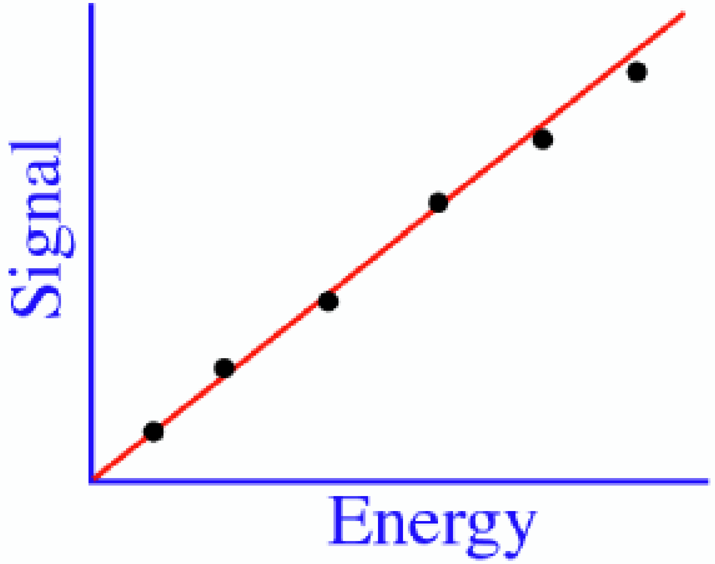
Table 27.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

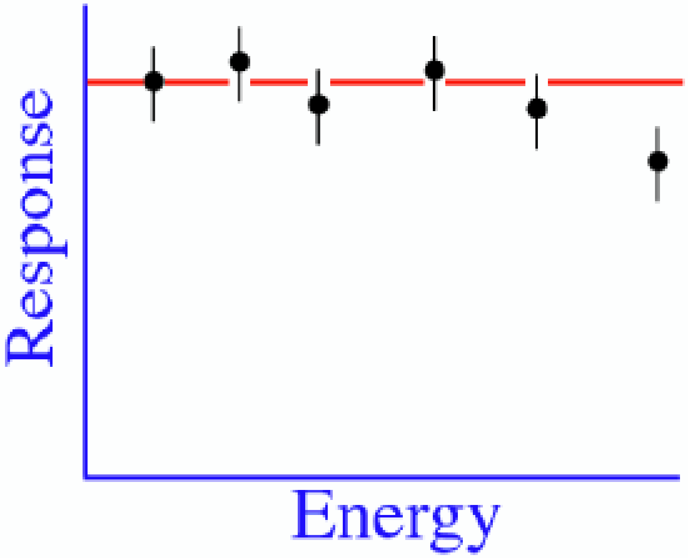
Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	$1/137.035\,999\,11(46)$
M	Incident particle mass	MeV/c^2
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times$ c^2	$0.510\,998\,918(44)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	$2.817\,940\,325(28)$ fm
N_A	Avogadro's number	$6.022\,1415(10) \times 10^{23}$ mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_ec^2/A$	$0.307\,075$ MeV g^{-1} cm^2 for A = 1 g mol^{-1}
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha)$	$\sqrt{\rho\,\langle Z/A\rangle} \times 28.816$ eV (ρ in g cm^{-3})
N_e	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	$(716.408$ g cm$^{-2})^{-1}$ for $A = 1$ g mol^{-1}
X_0	Radiation length	g cm^{-2}
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\ m_ec^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

LINEARITY

Response: mean signal per unit of deposited energy
e.g. # of photons electrons/GeV, pC/MeV, µA/GeV

➔A linear calorimeter has a constant response





Electromagnetic calorimeters are in general linear.
All energies are deposited via ionisation/excitation of the absorber.

RADIATION LENGTH

Approximation

$$X_0 \approx \frac{180A}{Z^2} \quad g.cm^{-2}$$

Energy loss by radiation

$$< E(x) > = E_0 \, e^{-\frac{x}{X_0}}$$

γ Absorption (e^+ e^- pair creation)

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

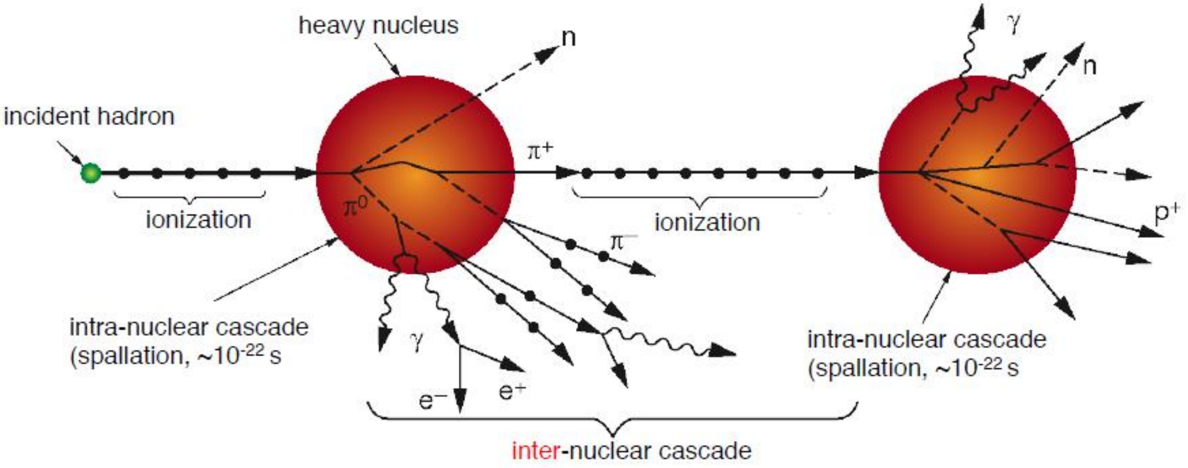
For compound material

$$1/X_0 = \Sigma \, w_j / X_j$$

6.3.1 Hadronic Showers

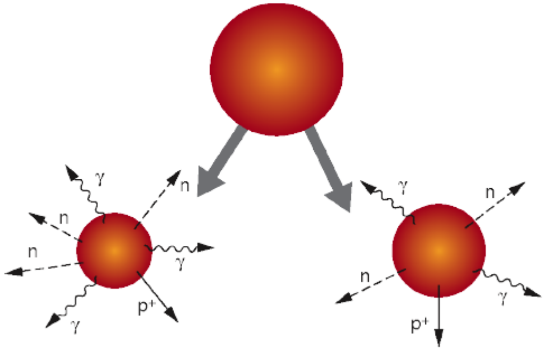
Hadronic interactions

- **Intra-nuclear cascade:** Components of the nucleus receive enough energy to interact with each other and to produce pions or other hadrons.
- **Inter-nuclear cascade:** Particles escaping the nucleus hit another nucleus.

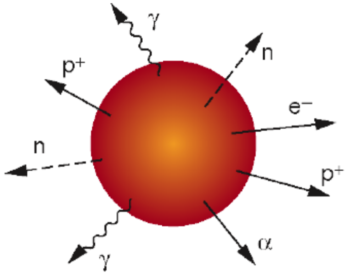


- Spallation is the transformation of a nucleus caused by an incident, high energetic, hadronically interacting particle. During spallation a large number of elementary particles, α-particles, and possibly larger debris of the nucleus are emitted.
- Spallation is the most probable process when a hadron hits a nucleus.
- Following spallation the target nucleus is in an excited state and releases further particles or undergoes fission.
- The secondary particles from the spallation process have mostly enough energy to itself interact with a nucleus.

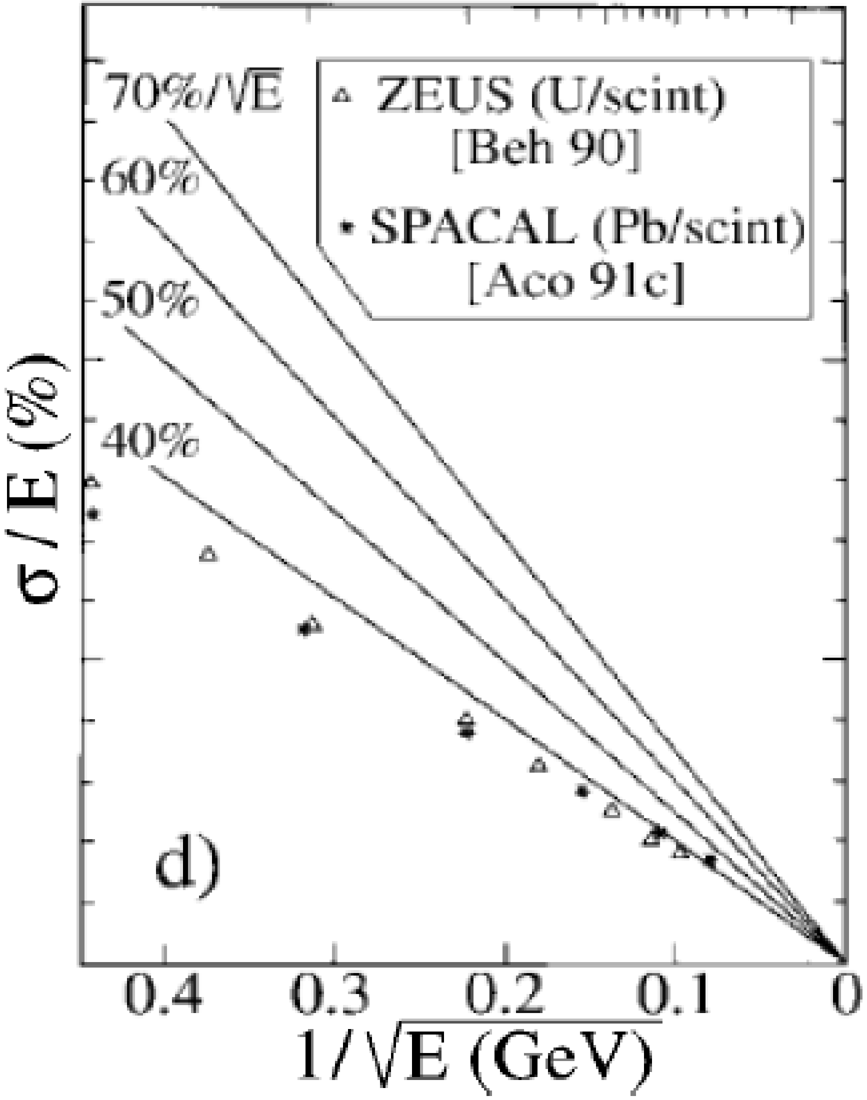
- In heavy elements, e.g. ^{238}U, fission may occur following spallation or due to the capturing of slow neutrons.
  The nucleus decays in two (possibly 3) approximately equal debris. Additionally photons and neutrons are emitted and if enough excitation energy remains further hadrons are emitted.

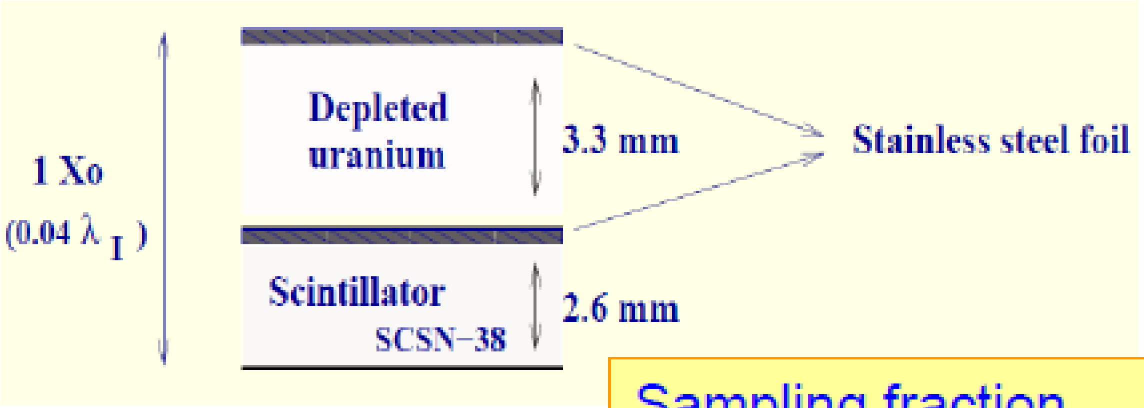


- **Nuclear evaporation:** excited nuclei emit particles until the remaining excitation energy is below the binding energy of the components in the nucleus.
  Highly excited nuclei loose most of their excitation energy in typically ~10^{-18} s.



ZEUS calorimeter





Sampling fraction tuned to have $e/\pi = 1$

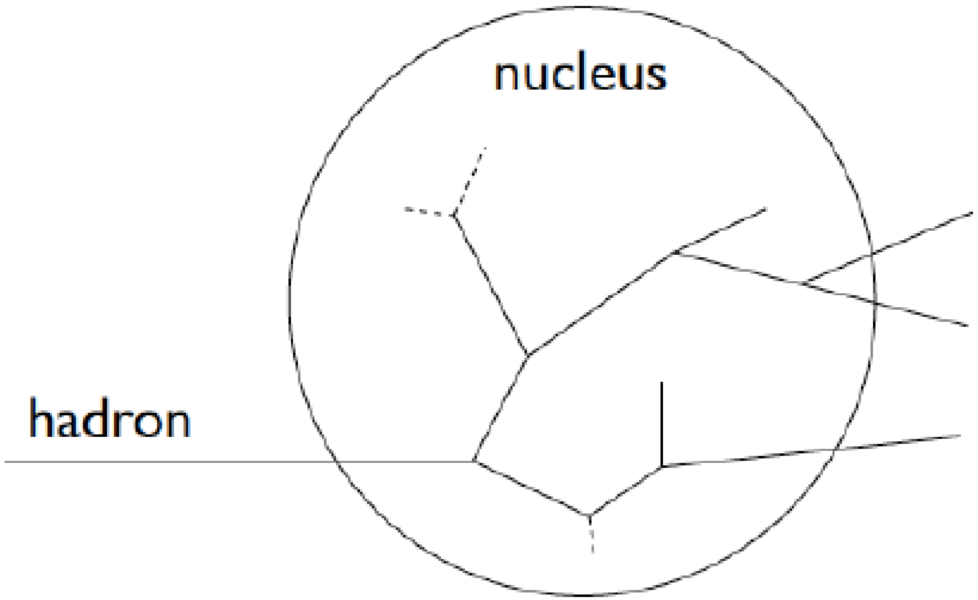
Excellent hadron resolution:

σ/E (hadrons) = $0.35/\sqrt{E}$(GeV

σ/E (electrons) = $0.18/\sqrt{E}$(GeV)

“naïve” model (simulation programs)

Interaction of hadrons with 10 MeV < E < 10 GeV via intra-nuclear cascades



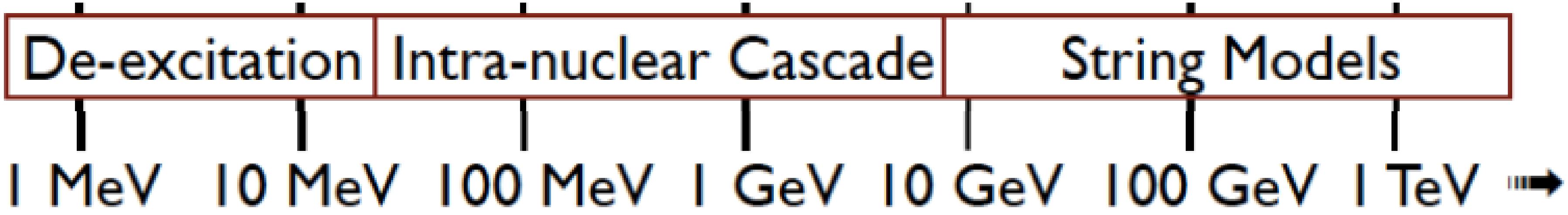
- $\lambda_{deBroglie} \leq$ d nucleon
- nucleus = Fermi gas

(all nucleons included)

- Pauli exclusion:

allow only secondaries above Fermi energy

For E < 10 MeV only relevant are fission, photon emission, evaporation, …


De-excitation | Intra-nuclear Cascade | String Models

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV ➡