The art of calorimetry part I

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DESY

Shortly about me

- Italian nationality
- 2003 PhD at Amsterdam university (NIKHEF)
  work on HERMES experiment:
  silicon strip detector / heavy nuclei analysis
- First postdoc at DESY in the ILC calorimeter group
  construction / commissioning / analysis of a small HCAL prototype
  construction of a calorimeter for PFLOW validation
- 2006 leader of a HGF Young Investigator group
  topic: "New photo-detectors and their integration in particle physics detectors and beyond"
- currently working on:
  analysis of hadronic showers
  development of a realistic prototype for ILC calorimeter
  new ideas of detectors with Silicon-based photodetectors
  detector for positron emission tomography (PET)

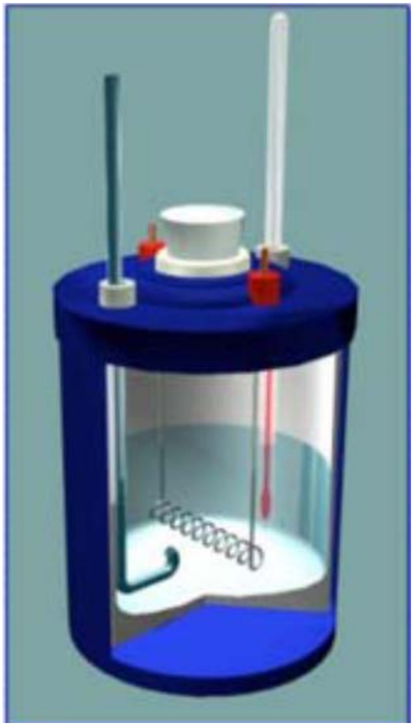
Calorimeter

Thermodynamics:
A calorimeter is a thermally isolated box containing a substance to study

Determine E_{dep} by measuring:

$$\Delta T = \frac{E_{dep}}{c \cdot M_{water}}$$

with $c_{water} = 4\ J\ gr^{-1}\ K^{-1}$



Can one use this calorimeter to detect the Higgs?

Remember: 1.6 10^{-19} Joule = 1 eV

If M_H = 120 GeV

$$\Delta T = \frac{E_{dep}}{c \cdot M_{water}} = \frac{120\text{GeV}}{4\text{J/gr/K} \cdot 1\text{kg}} = \frac{1.2 \cdot 10^{11}\text{eV}}{4\text{J/gr/K} \cdot 10^{3}\text{gr}} \approx \frac{2 \cdot 10^{-8}\text{J}}{4 \cdot 10^{3}\text{J/K}} = 5 \cdot 10^{-12}\text{K}$$

Non detectable T increase ~pK

Possible to change water with crystal c~nJ ➔ ΔT ~ mK but still unrealistic

E_{LHC} = 14 protons x 14 TeV ~ 10^8 Joule

$$\Delta T = \frac{E_{dep}}{c \cdot M_{water}} = \frac{10^{8}\text{J}}{4 \cdot 10^{3}\text{J/K}} = 2.5 \cdot 10^{4}\text{K}$$

our ideal calorimeter would boil quite fast

Thermodynamic calorimeters are good for applications without background
- nuclear weapon laboratories to measure Plutonium amount (^{239}P~2mW/gr)
- astrophysics experiments

Calorimeter

In nuclear and particle physics calorimetry refers to the detection of particles, and measurements of their properties, through total absorption in a block of matter, the calorimeter

Common feature of all calorimeters is that the measurement process is destructive

- Unlike, for example, wire chambers that measure particles by tracking in a magnetic field, the particles are no longer available for inspection once the calorimeter is done with them.
- The only exception concerns muons. The fact that muons can penetrate a substantial amount of matter is an important mean for muon identification.

In the absorption, almost all particle's energy is eventually converted to heat, hence the term calorimeter

Nuclear radiation detectors

late 40's:	invention of PMT (PhotoMultiplier Tubes)
	first calorimeters used in the detection of α,β,γ from nuclear decays
in the 60's:	first semiconductor detectors (Si and Ge)

γ-spectroscopy of Uranium nuclei.

Measurements with scintillator and semiconductor detectors are compared.

Semiconductor technology offers spectacularly improved resolution.

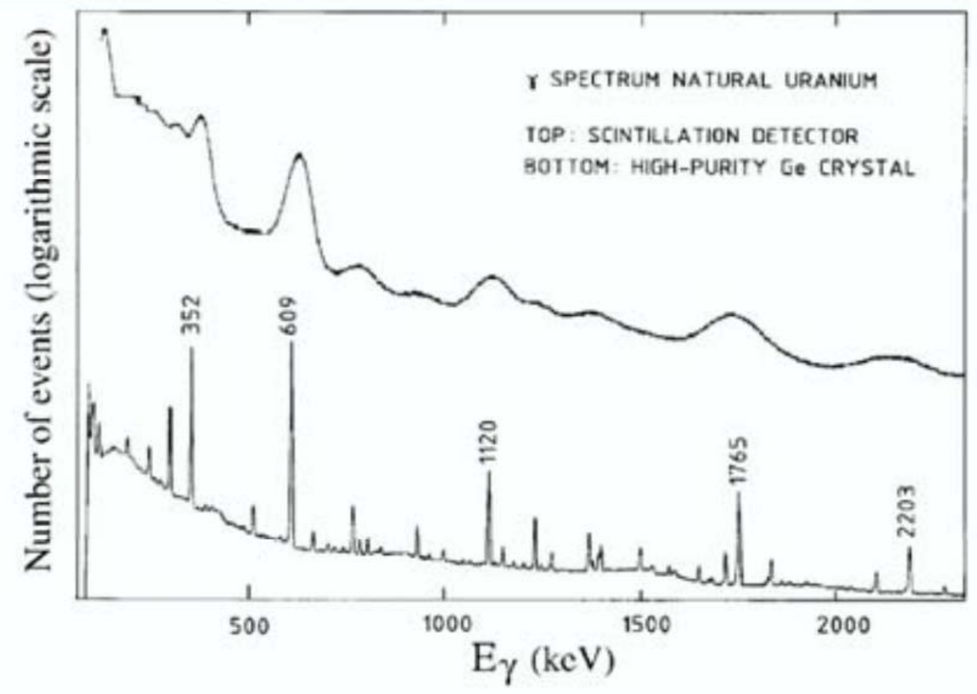


FIG. 1.1. Nuclear γ-ray spectrum of decaying uranium nuclei, measured with a bismuth germaniumoxide scintillation counter (*upper curve*) and with a high-purity germanium crystal (*lower curve*). Courtesy of G. Roubaud, CERN.

Calorimetry in particle physics

Calorimetry is a widespread technique in particle physics:

- instrumented targets
  - neutrino experiments
  - proton decay / cosmics ray detectors
- shower counters
- 4π detectors for collider experiments

Calorimetry makes use of various detection mechanisms:

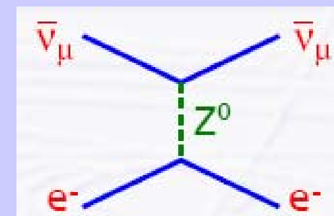
- Scintillation
- Cherenkov radiation
- Ionization
- Cryogenic phenomena

Instrumented targets: bubble chambers

Bubble chambers

- chamber with liquid (e.g. H_2) at boiling point
- charged particles leave trails of ions

Used for the discovery of the "neutral current"
(1973 by Gargamelle Coll.)

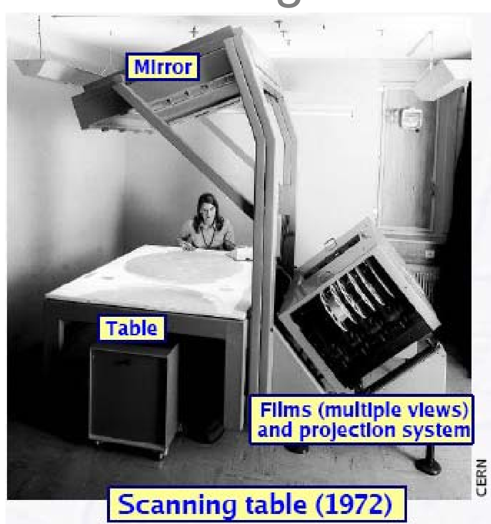


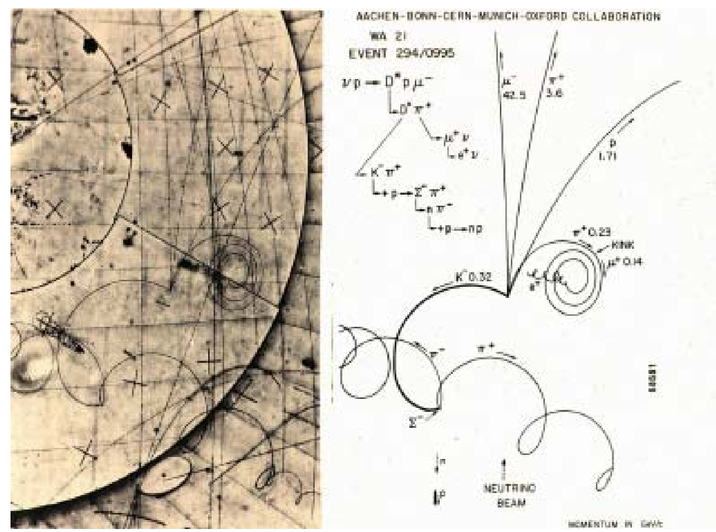
Advantages:

- liquid is both detector & target
- high precision

Disadvantages:

- SLOW!!
- Not possible to trigger





production of D* meson at BEBC (CERN)

Instrumented targets: neutrino experiments

ν interaction probability in a 1 kTon detector ~ 10^{-9}

➔ intense beams and very massive detectors

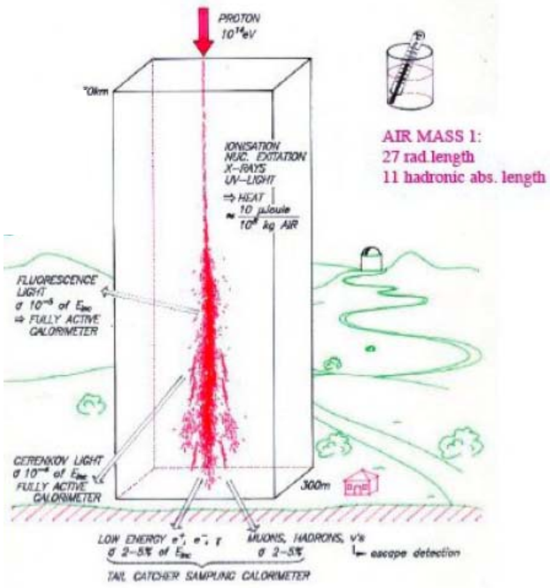
Example: WA1 experiment

Slabs of absorber material (Fe) interleaved with active layers of scintillator.
In the rear: wire chambers to track muons generated in charged currents interactions and/or charmed particles production

Instrumented targets: cosmic rays

- Atmospheric neutrinos from π/K decay in the atmosphere
- Solar neutrinos mainly produced in nuclear fusion of H into He
- High energy cosmic rays up to 1 Joule

➔ Very large instrumented masses are needed



KASCADE cosmic ray experiment near Karlsruhe (D)
Large Tetramethylsilane calorimeter located in the central building, surrounded by numerous smaller plastic-scintillator counters to detect ionizing particles

Instrumented targets: proton decay

In many theories Barion Number conservation breaks down ⇒ proton decay is allowed

-Current experimental limit on the proton lifetime based on the decay $p \rightarrow e+ \pi_0$ is > 10^{32} years

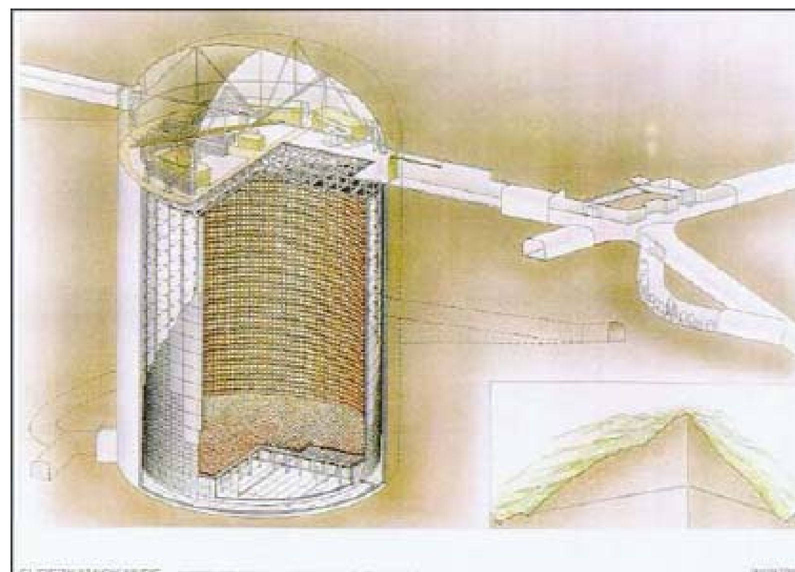
(>21 orders of magnitude longer then the age of the universe!!)

- Need for large instrumented mass (300 m^3 of water = 10^{32} protons)

large PMT

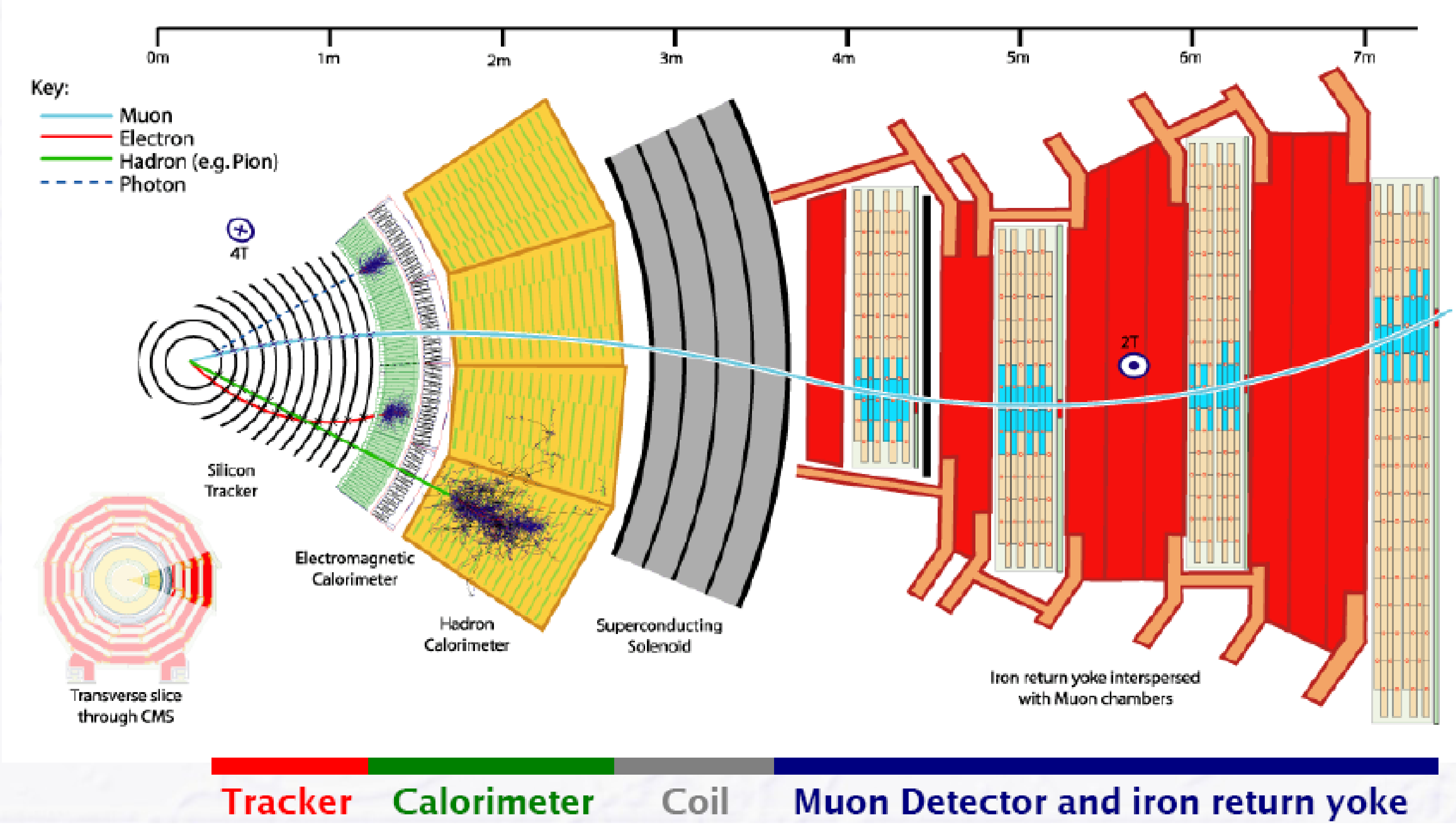
SuperKamiokande

Water Cherenkov calorimeter:
Enormous volume of high purity water viewed by large number of photomultipliers: $p \rightarrow e^+\pi^0$ produces 5 relativistic particles, one e^+ and two e^+e^- pairs from the π^0 decay. The energy carried by these 5 particles must add up to the proton rest mass, 938.3 GeV



Detectors for collider experiments

CMS



Typical onion like structure for most of modern collider detectors

Main difference: - what fraction of detector is inside the coil

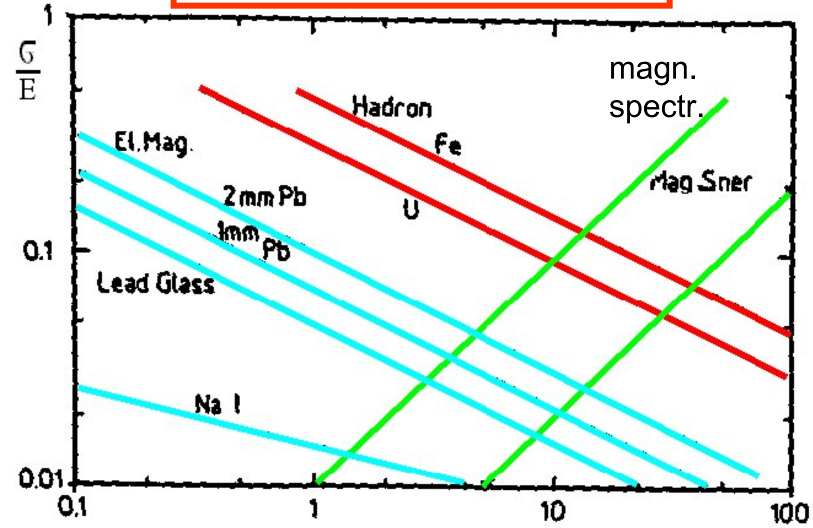
- calorimeter system (most expensive component)

Why calorimetry?

- Measure *charged + neutral* particles

- Performance of calorimeters
  improves with energy
  $\Delta E/E \propto E^{-1/2}$ + const.
  while in a magnetic spectrometer
  $\Delta p/p \propto p$

At high energy calorimetry is a must



- Obtain information on *energy flow*: total (missing) transverse energy, jets, incoming particle direction (with high segmentation)

- Obtain information *fast* (<100ns feasible)
  → recognize and select interesting events in real time (*trigger*)

Important calorimeter features

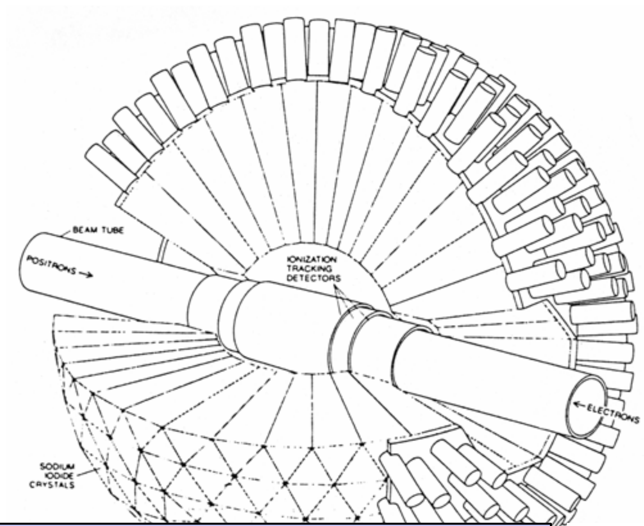
- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

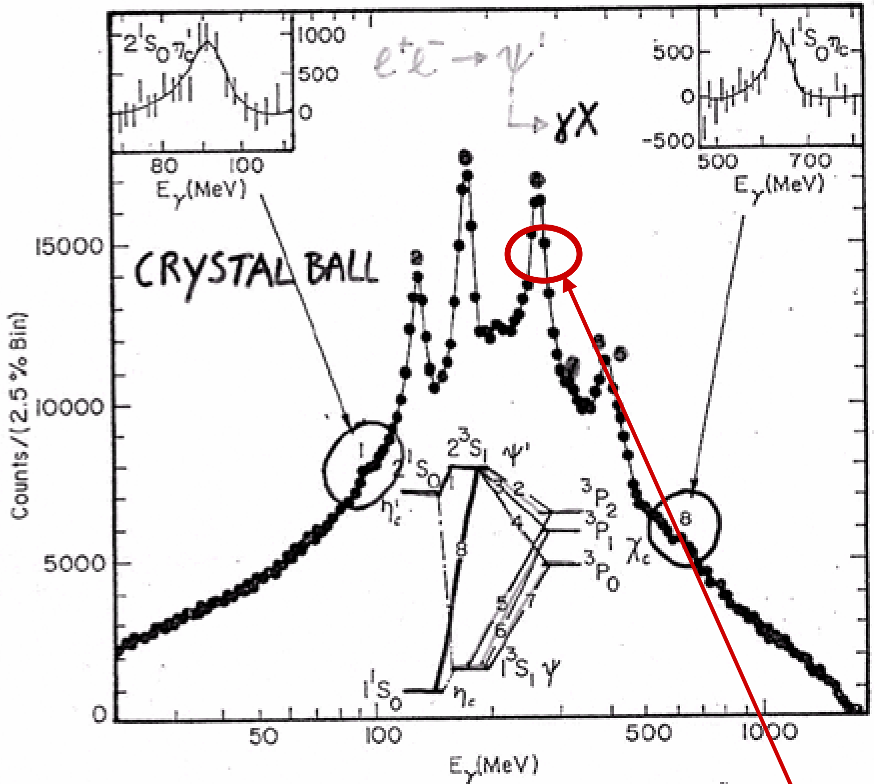
Important calorimeter features

- Energy resolution (EM)

Crystal Ball @ SPEAR - Stanford

The first crystal calorimeter pioneering most of the features of modern barrel calorimeters





1974: J/Ψ discovery

precision in γ energy

energy resolution:
3.5% @ 300 MeV
2.6% @ 1 GeV
solid angle: 93% over 4p

672 + 60 NaI crystals
PM read out
Eγ range 0.1→ 1 GeV

charmonium spectroscopy:
e+e- → Ψ' →γX

Important calorimeter features

- Energy resolution (hadronic)

… energy resolution, hadronic physics

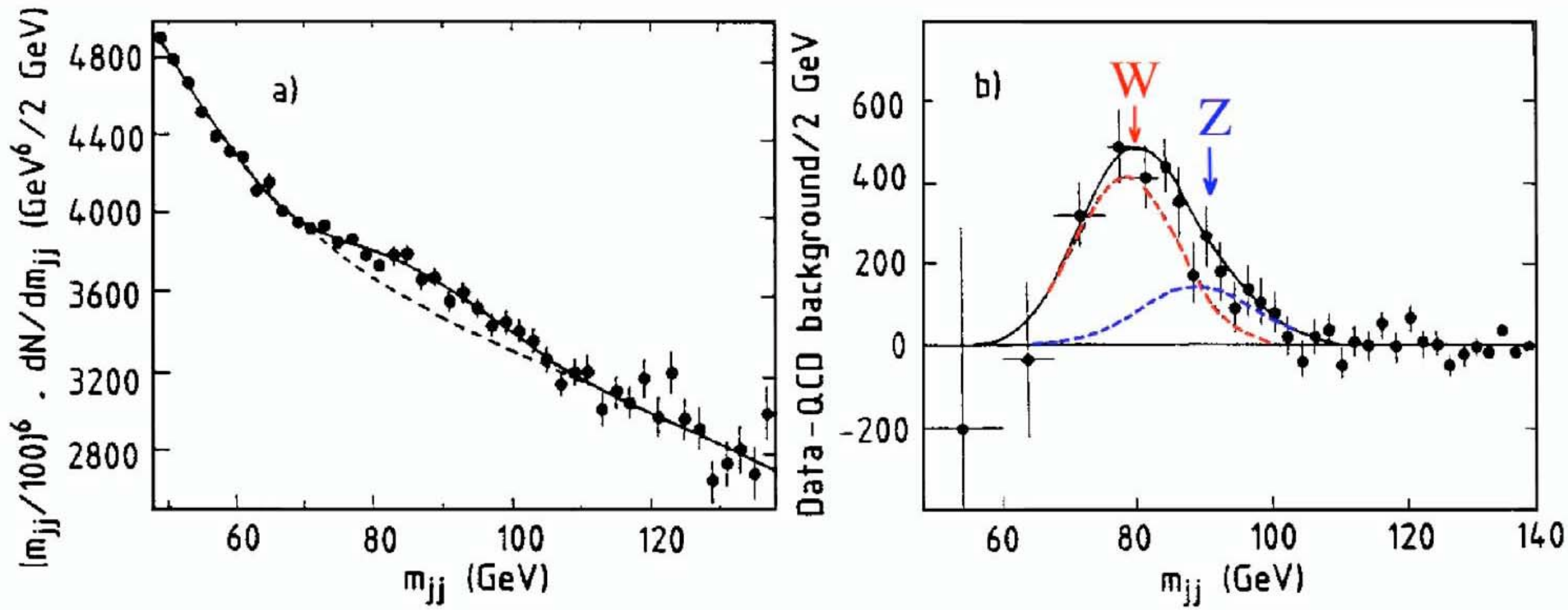
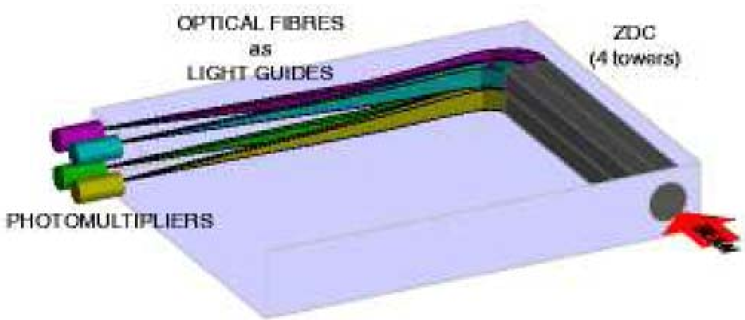
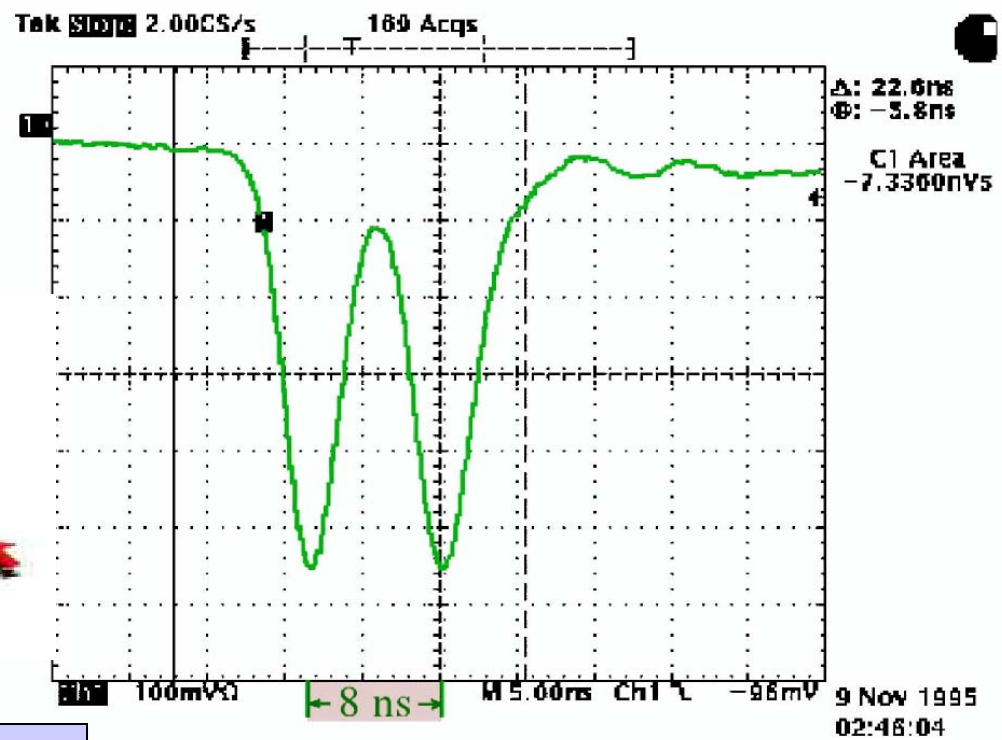


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \to q\bar{q}$ decays. Diagram b) shows the same data after subtracting the QCD background. The data are compatible with peaks at $m_W = 80$ GeV and $m_Z = 90$ GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].

Important calorimeter features

- Energy resolution
- Position resolution (
vectors for physics)
- Signal speed





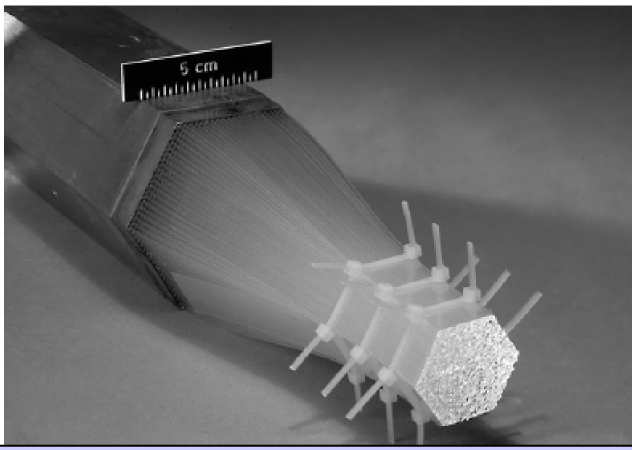
lloscope picture of two events separated by 8 ns in the Zero Degree Quartz eter of the NA50 experiment in the CERN heavy-ion beam [Arn 98].

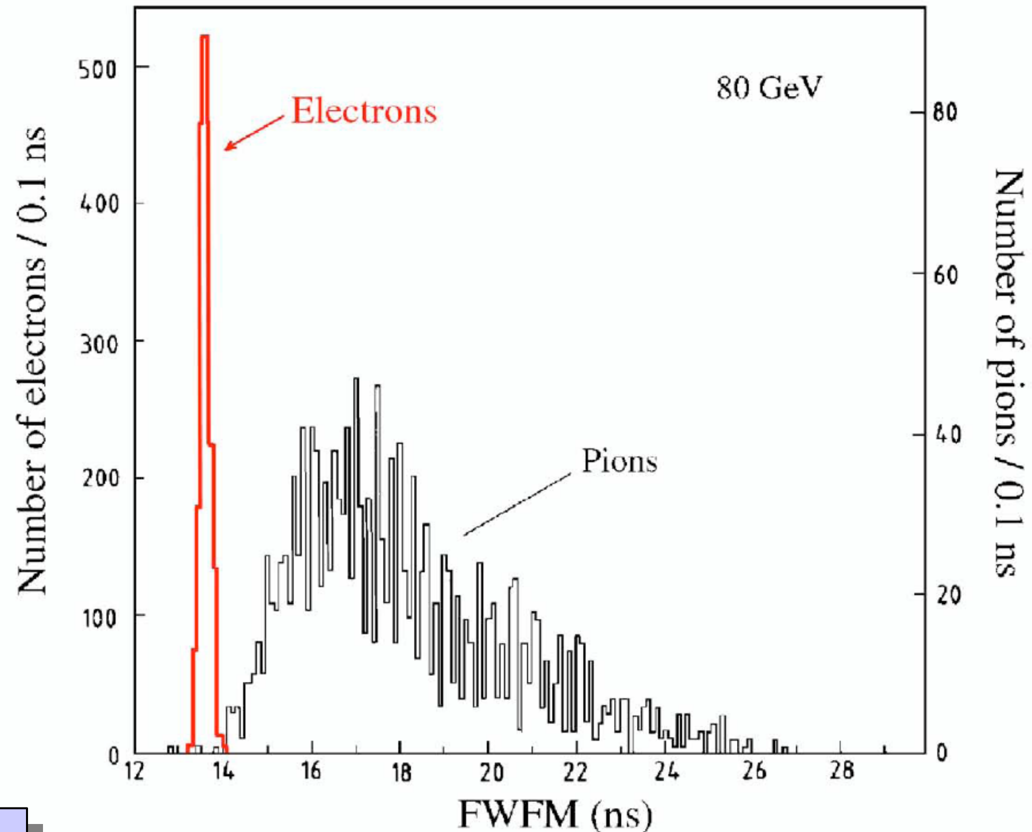
NA50 Zero Degree
4 segmented towers, depth 5.6λ
fibers at 0◦ inclination embedded in grooved absorber plates of tantalum, 30 plates, 1.5 mm thick (Ta: l= 11.5 cm, X0= 0.4cm)

… quartz calorimeters, signal readout

Important calorimeter features

- Energy resolution
- Position resolution (nee vectors for physics)
- Signal speed
- **Particle ID capability**





33. The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV elec- and pion signals in SPACAL [Aco 91a].

SPACAL
Compensating, homogeneous, high resolution calorimeter with no longitudinal segmentation.
Pb-scintillating fibers in ratio 4:1

Particle ID using time structure of signal

… compensation

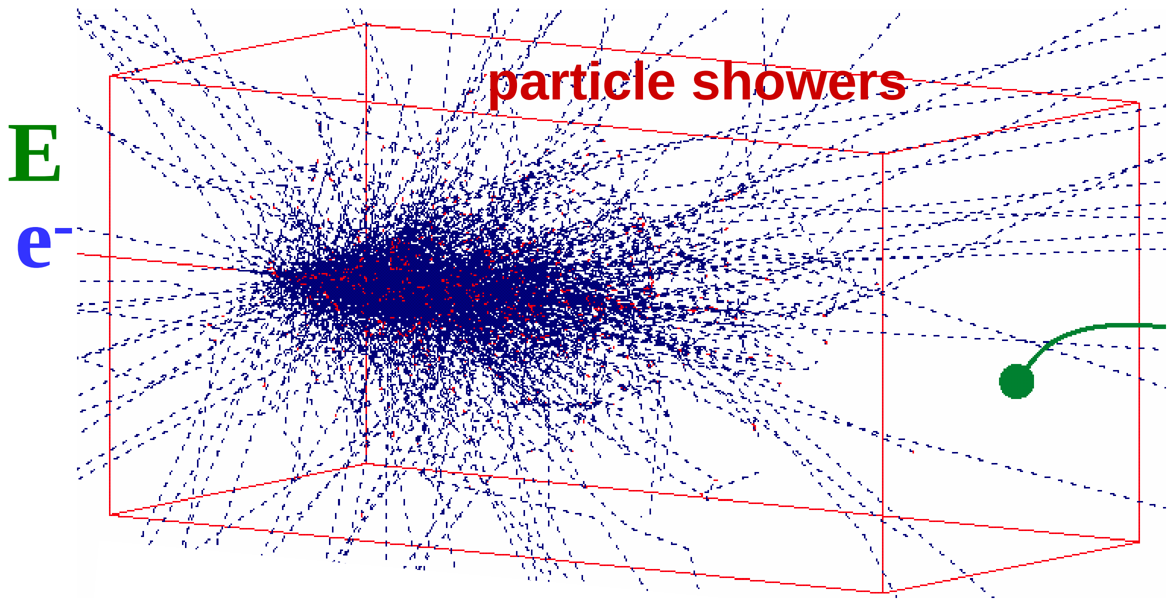
Important calorimeter features

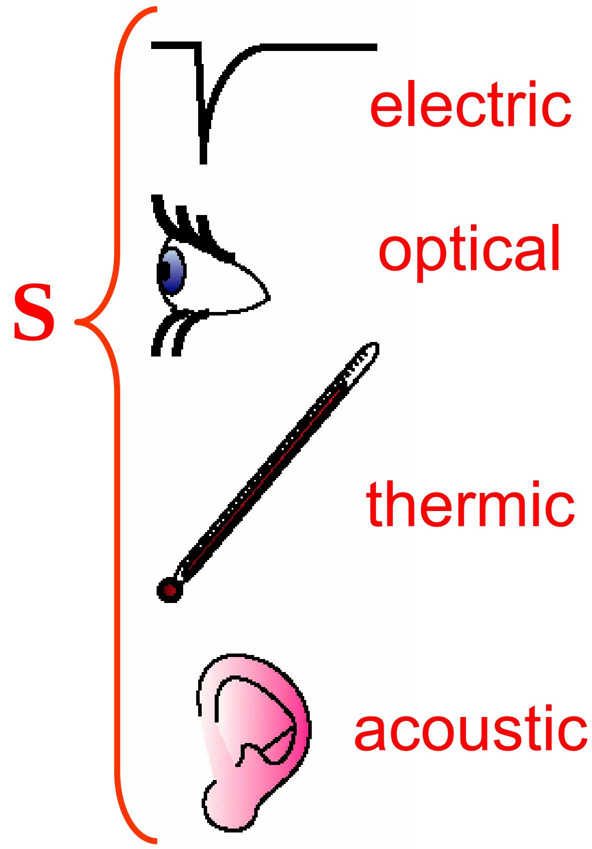
- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

- *Gaussian response function* (avoid bias for steeply falling distributions)
- *Signal linearity*, or at least
  well known relationship between signal & energy
  (*reliable calibration*)

➔ *Most hadron calorimeters fall short in this respect*

Calorimeters: a simple concept

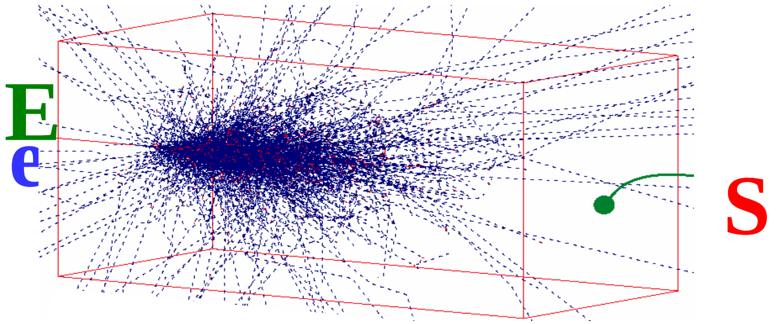




Convert energy **E** of incident particles to detector response **S**:

$$S \propto E$$

Homogeneous vs non-homogeneous



Ideal calorimeter:
Contain all energy of one particle+
Convert all energy into measurable signal
➔Homogeneous (i.e. crystal)

In practice:
Homogeneous calorimeter only possible for electrons (shorter showers)
Sometimes too expensive also for electrons
Lateral segmentation possible but no depth information

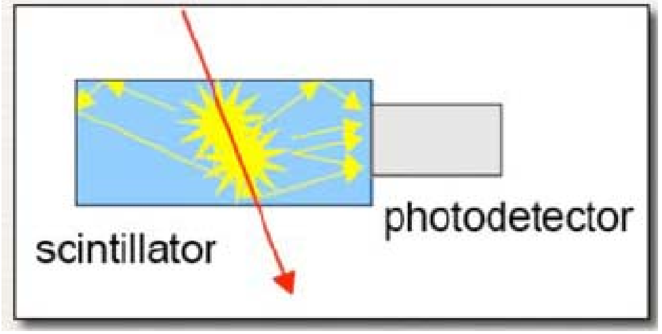
Alternative solution ➔ Sampling calorimeter
Contain all energy of one particle+
Sample its energy during shower development ($E_{visible} \propto E_{total}$)

Many different designs
- calorimeter imbiss: sandwich, shashlik, spaghetti
- liquid versions: LAr
- …

How to "look" at the signal

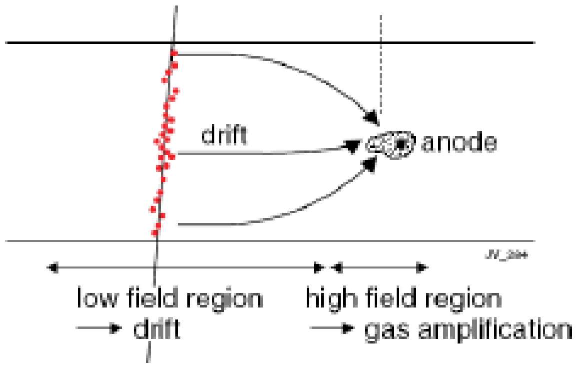
1) Convert particle energy to light:
scintillator (org. / in-org.)

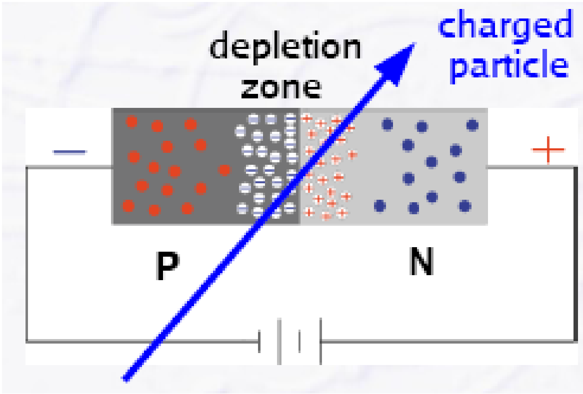
& measure light:
PMT / APD / HPD / SiPM …



2) Measure ionization E:
gas
noble liquids
semiconductors

& measure charge signal





3) Measure temperature:
specialized detectors for: DM, solar νs, magnetic monopoles, double β–decay
very precise measurements of small energy deposits
phenomena that play a role in the 1 Kelvin to few milli-Kelvin range

Choosing a calorimeter

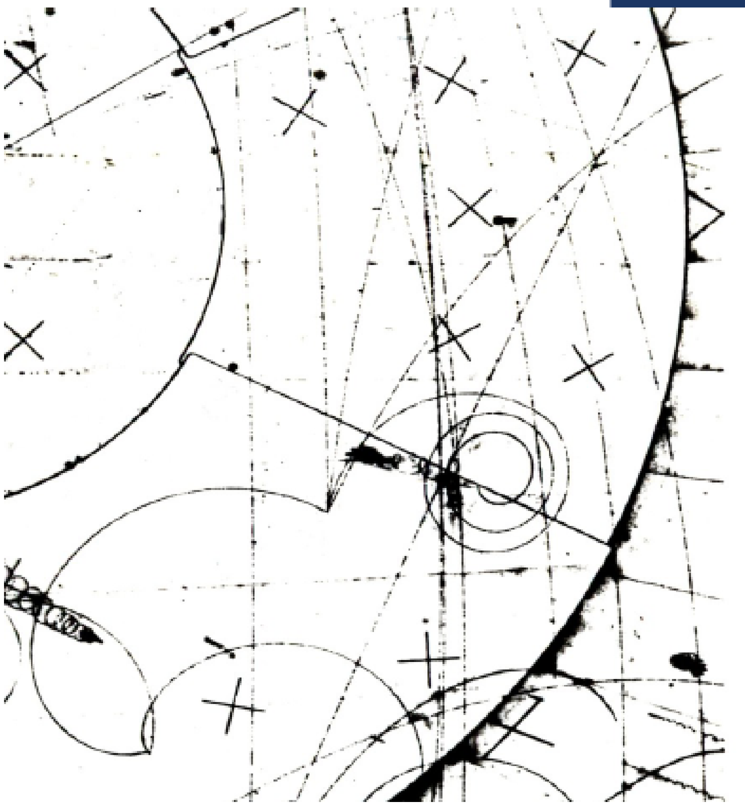
Many factors:

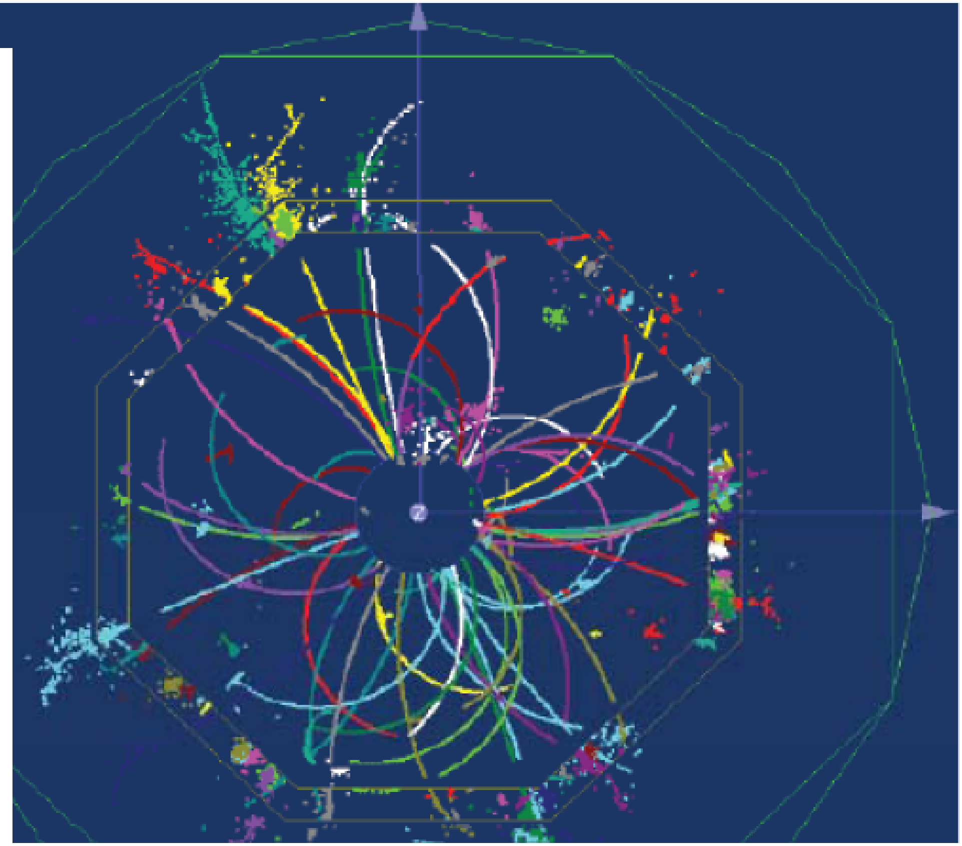
- Choices: active, passive materials, longitudinal and lateral segmentation etc.
- Physics, radiation levels, environmental conditions, budget

CAVEAT: Test beam results sometimes misleading

- Signals large integration time or signal integration over large volume could be not possible in real experimental conditions
- Miscellaneous materials (cables, support structures, electronics etc.) present in the real experiment can spoil resolution
- Jet resolution not measurable in a test beam

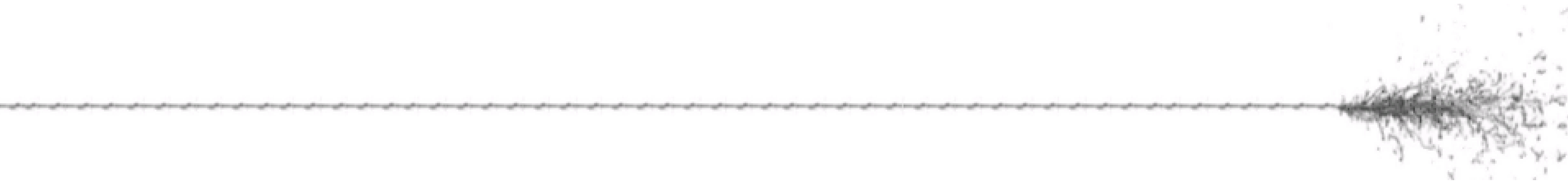
From bubble chambers to…



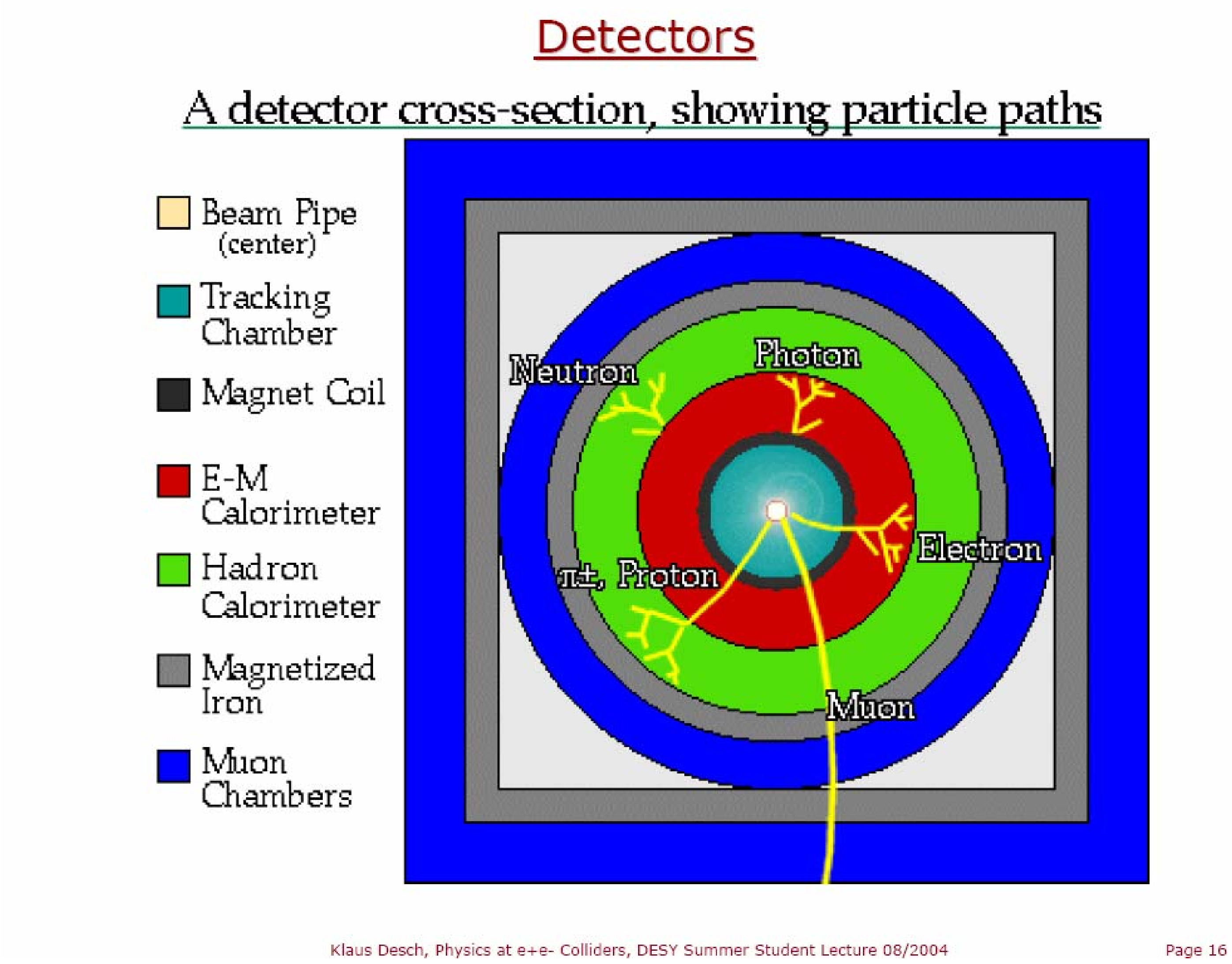


High granularity and segmentation allows “tracking capability” in the calorimeter … pro%cons ?

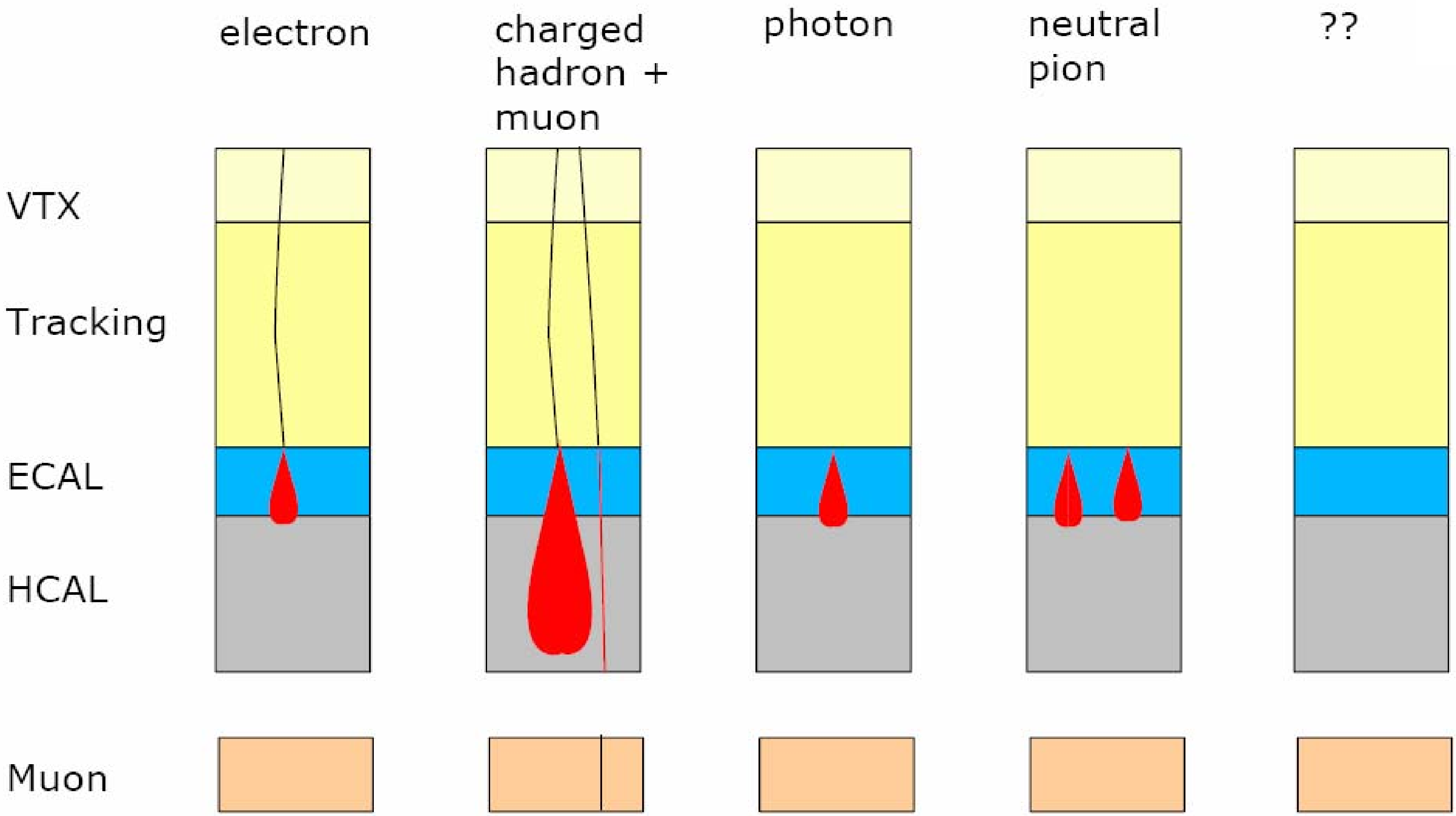
… particle flow, dual readout



Detection of particles in HEP detectors



Detectors



Klaus Desch, Physics at e+e- Colliders, DESY Summer Student Lecture 08/2004 Page 17

Particle detection

The detector sees only "stable" particles:

- Electrons, muons, photons, pions, kaons, protons and neutrons

In order to detect a particle, it has to interact - and deposit energy

Ultimately, the signals are obtained from the interactions of charged particles

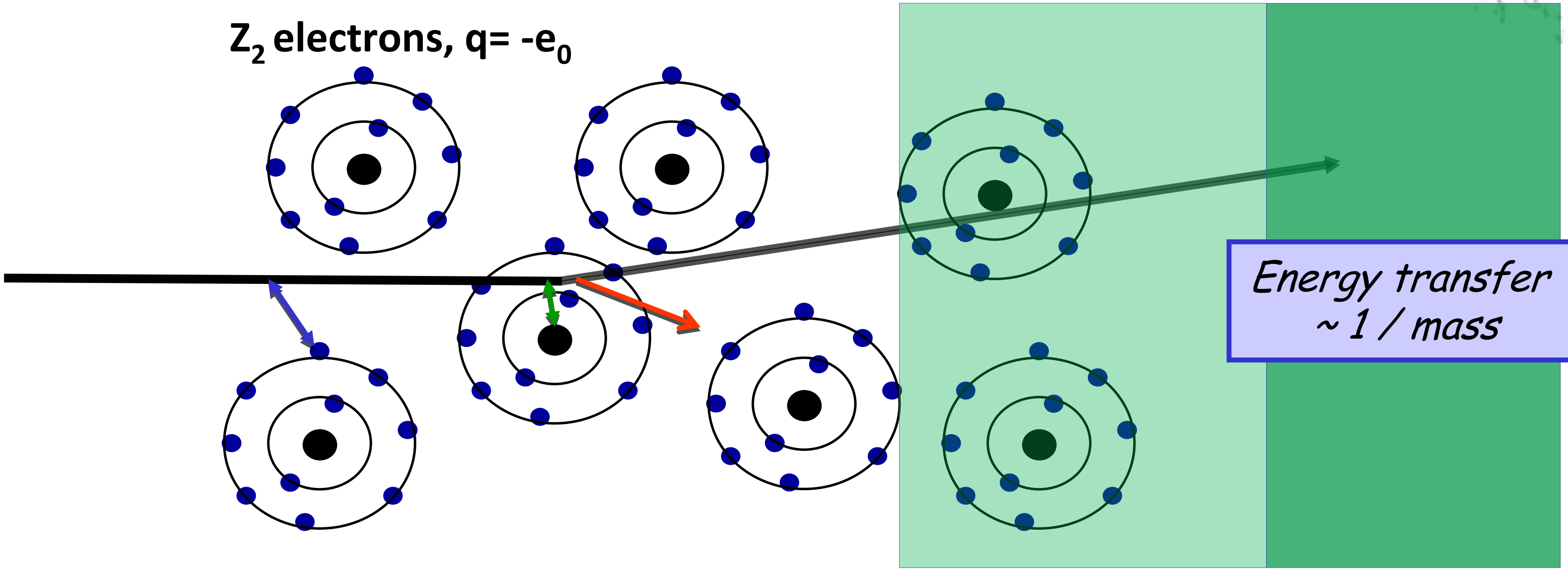
Neutral particles (gammas, neutrons) have to transfer their energy to charged particles to be measured

➔ calorimeters

Interaction of particles with matter

I. Electromagnetic interactions

EM interaction of particles with matter



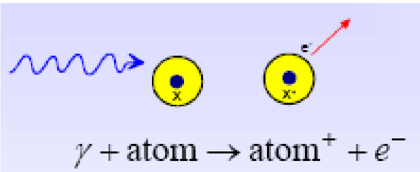
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

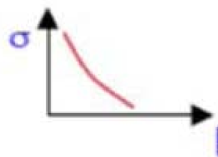
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

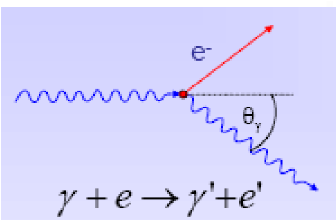
Electromagnetic interactions

Gammas

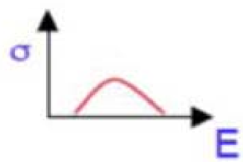


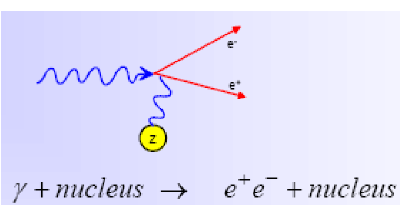
- Photoelectric effect



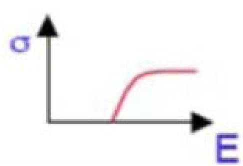


- Compton effect





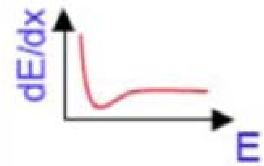
- Pair production



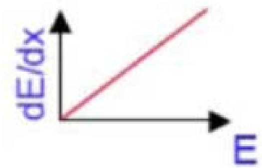
Electrons

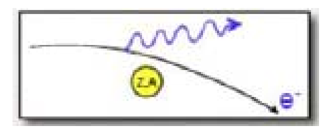
- Ionisation

!! Bethe-Block formula is valid only for $m \gg m_e$



- Bremsstrahlung



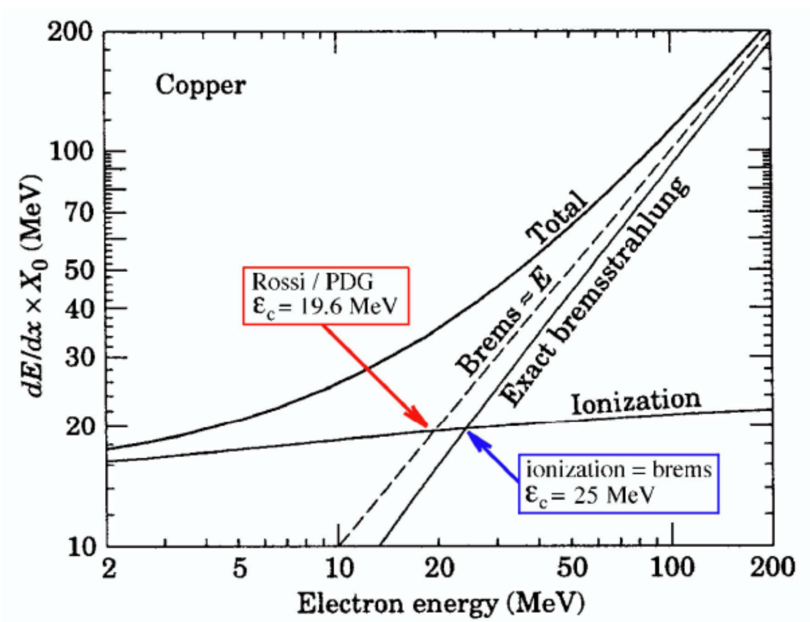


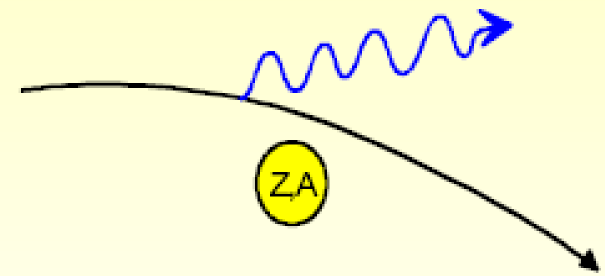
Bremsstrahlung

Interaction of electrons with the Coulomb field of atomic nuclei

dE/dx ~ E: becomes dominant at high energy
i.e. for $E > \varepsilon_C$ = critical energy:

- ε_C: dE/dx (ion) = dE/dx (brems)
- electrons in copper: ε_C = 20 MeV





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

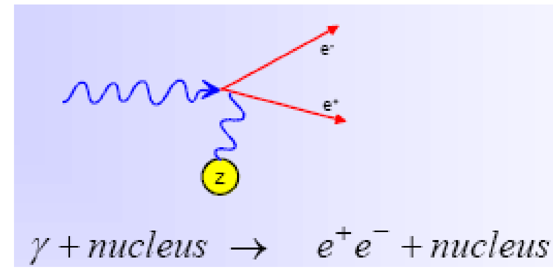
$$-\frac{dE}{dx} = \frac{E}{X_0} \Rightarrow E(x) = E \cdot e^{-x/X_0}$$

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

Pair production

Only possible in the field of a nucleus (or an electron) if:

$E_\gamma > 2m_ec^2$



Cross-section (High energy approximation)

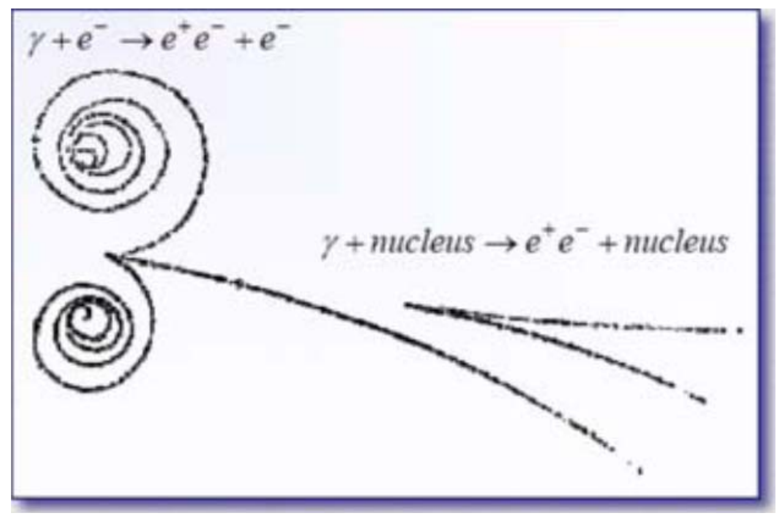
$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} \right)$$

independent of energy !

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

$$\approx \frac{A}{N_A} \frac{1}{\lambda_{pair}}$$

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



The physics of EM showers

Multiplication of secondary particles = shower development up to shower maximum

For E>1 GeV: $\sigma_{bremsstrahlung}$ and $\sigma_{pair\text{-}production}$ are ~ E independent
Both can be expressed in terms of a scaling variable:

the radiation length = X_0

The absorption length λ in terms of radiation length is expressed by:

$\lambda_e = X_0/\ln(E/E_c)$ for electrons (E_c = min. detectable E)

$\lambda_\gamma = \frac{9}{7} X_0$ for photons

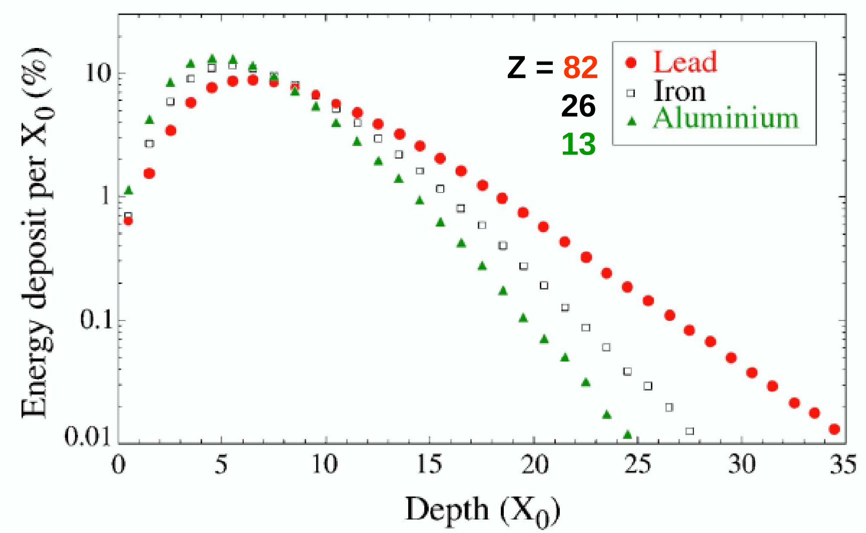
Longitudinal shower development scales with X_0 up to shower max

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

The physics of EM showers

Shower decay:

after the shower maximum the shower decays slowly through ionization and Compton scattering ➔ NOT proportional to X_0



Scale energy $E_s = m_e c^2 \sqrt{4\pi/\alpha}$

Multiple Compton scattering of e^- responsible for lateral shower development

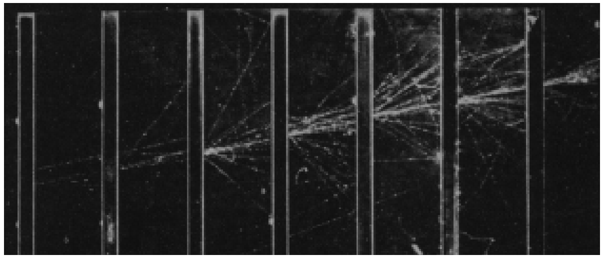
Scaling variable in lateral direction:

Moliere unit = R_M

$$R_M = \frac{E_s}{\varepsilon} X_0 \approx \frac{21\,\mathrm{MeV}}{\varepsilon} X_0$$

IMPORTANT: in order to describe the average shower development the minimum detectable energy E_c should be specified in addition to X_0, R_M

Shower development



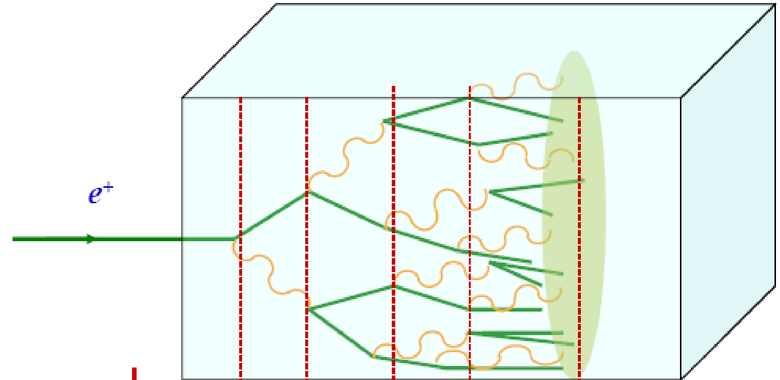
Lead absorbers in cloud chamber

Simplified model:

only Bremsstrahlung and pair prod.

e^- loses [1 - 1/e] = 63% of energy in 1 Xo

the *mean free path* of a γ is 9/7 Xo



x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
<E>	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

2^n particles after n X_0

each with energy $E/2^n$

Stops if E < critical energy ε_C

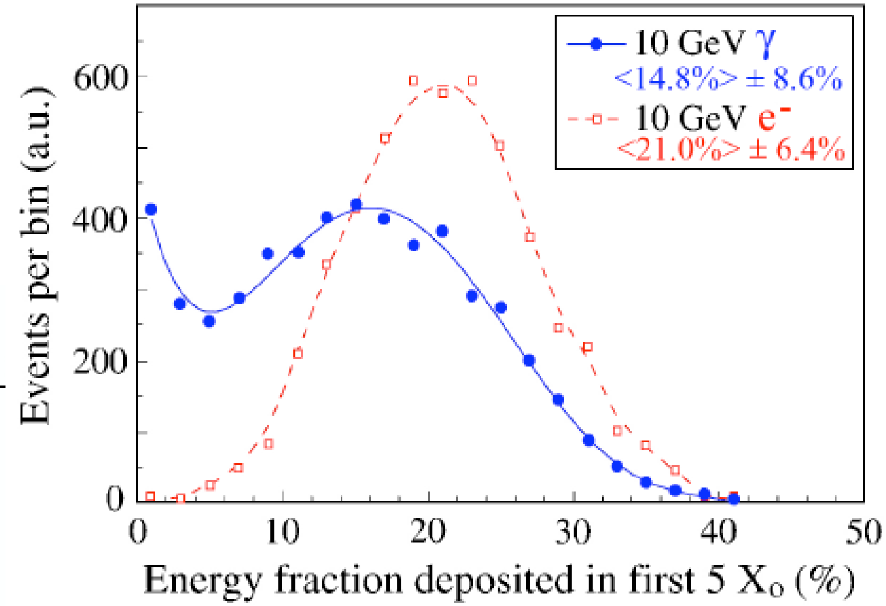
Maximum at $n_{max} = \ln E/\varepsilon_C / \ln 2$

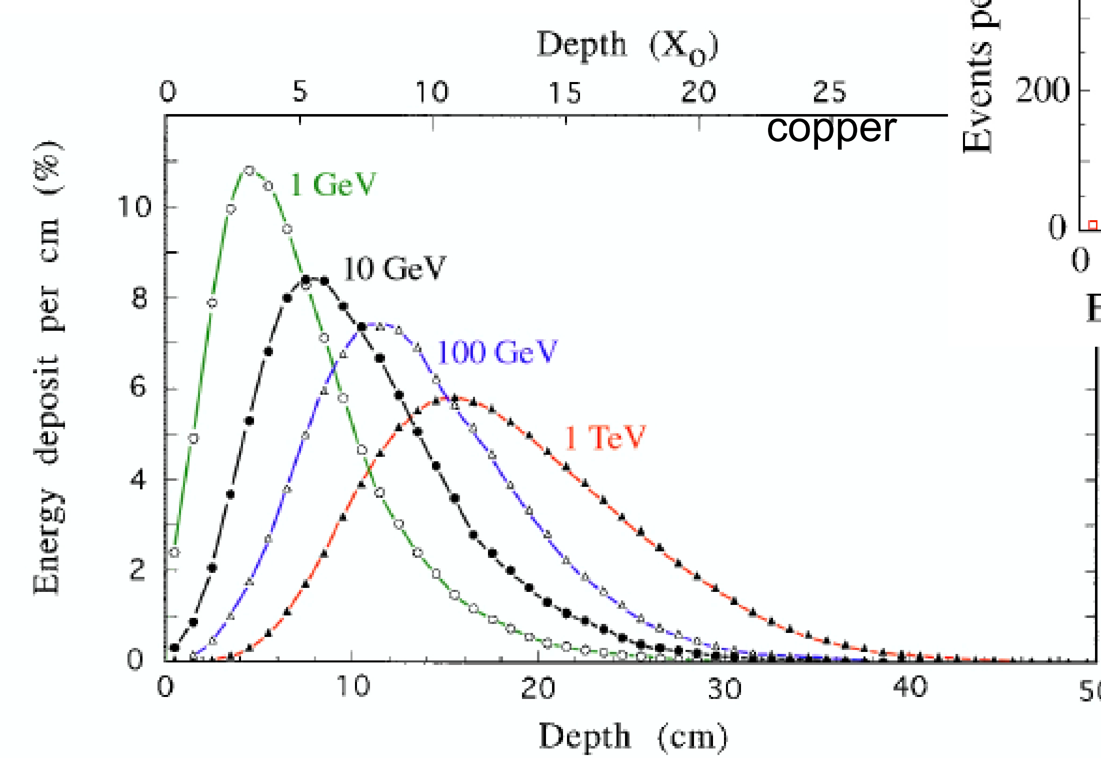
Number of particles $N = E/\varepsilon_C$

After shower max is reached:
only ionization, Compton, photo-electric

Longitudinal shower development

important *differences between* showers induced by *e*, γ:
e. g. Leakage fluctuations,
effects of material upstream, …





Shower maximum $\propto$ ln(E)

Useful "Rule of thumb" formulas

$$X_o = \frac{180\ A}{Z^2} \quad \frac{g}{cm^2}$$

$$\varepsilon_c = \frac{550\ MeV}{Z}$$

$$R_M = 7\ \frac{A}{Z}\ g/cm^2$$

$$t_{MAX} = ln\ \frac{E}{\varepsilon_c} - \begin{cases} 1 & e^-\ \text{induced shower} \\ 0.5 & \gamma\ \text{induced shower} \end{cases}$$

$$L\ (95\ \%)/X_o = t_{MAX} + 0.08\ Z + 9.6$$

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

Can you calculate how many cm of Pb or Fe are needed to stop (95%) a 10 GeV e^-?
and for a 10 GeV μ?

From theory to reality

The real calorimeter can be quite different from the back of the envelope one

The right way to add materials:

$$\frac{1}{X_{g0}} = \sum_i \frac{f_i}{X_{g0i}}$$

$$\frac{1}{R_M} = \frac{1}{E_M} \sum_i \left(f_i \frac{\epsilon_{c,i}}{X_{0i}} \right)$$

useful ref. table

material	Z	A	ρ	dE/dx	λ_0	X_0	R_M	ϵ
			[g/cm^3]	[MeV/cm]	[cm]	[cm]	[cm]	[MeV]
Al	13	27.0	2.70	4.37	37.2	8.9	4.68	39.3
Liq. Ar	18	40.0	1.40	2.11	80.9	14.0		29.8
Fe	26	55.9	7.87	11.6	17.1	1.76	1.77	20.5
Cu	29	63.5	8.96	12.9	14.8	1.43	1.60	18.7
W	74	183.9	19.3	22.6	10.3	0.35	0.92	7.9
Pb	82	207.2	11.35	12.8	18.5	0.56	1.60	7.2
U	92	238.0	18.95	20.7	12.0	0.32	1.00	6.6
NaI			3.67	4.84	41.3	2.59		12.4
Plastic scintillator			1.032	2.03	68.5	42.9		87.1

material	ρ	λ_0	λ_{0g}	X_0	X_{0g}	R_M
	g/cm^3	cm	g/cm^2	cm	g/cm^2	cm
Fe	7.87	16.8	131.9	1.76	13.85	1.77
Ni	8.9	15.28	136.0	1.42	12.64	1.44
Cr	7.19	18.17	130.6	2.26	16.25	1.98
steel	7.83	16.86	132.0	1.8	14.09	1.78
scint.	1.032	68.5	70.7	42.4	43.76	10.32
FR4	1.85	53.6	99.2	17.4	32.19	7.85
air	0.00129	66312	85.5	28516	36.79	8004
AHCAL layer	5.95	22.84	135.9	2.62	15.59	2.47

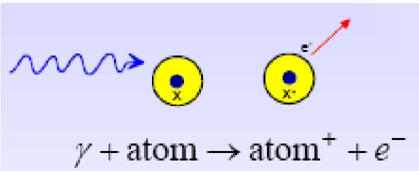
ideal

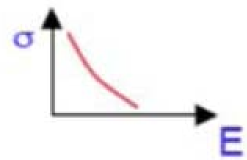
real

Electromagnetic interactions

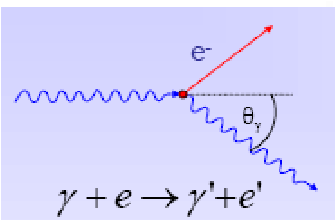
Gammas

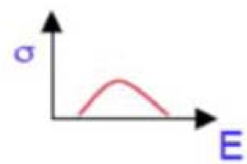
- Photoelectric effect



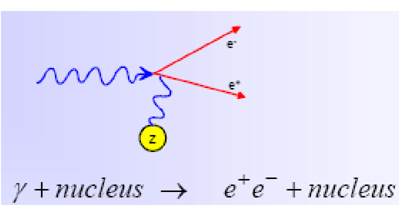


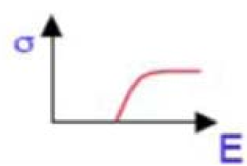
- Compton effect





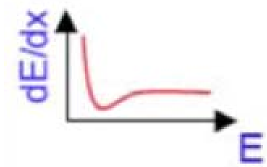
- Pair production



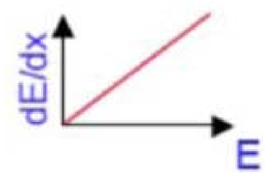


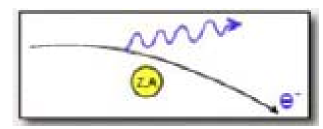
Electrons

- Ionisation



- Bremsstrahlung



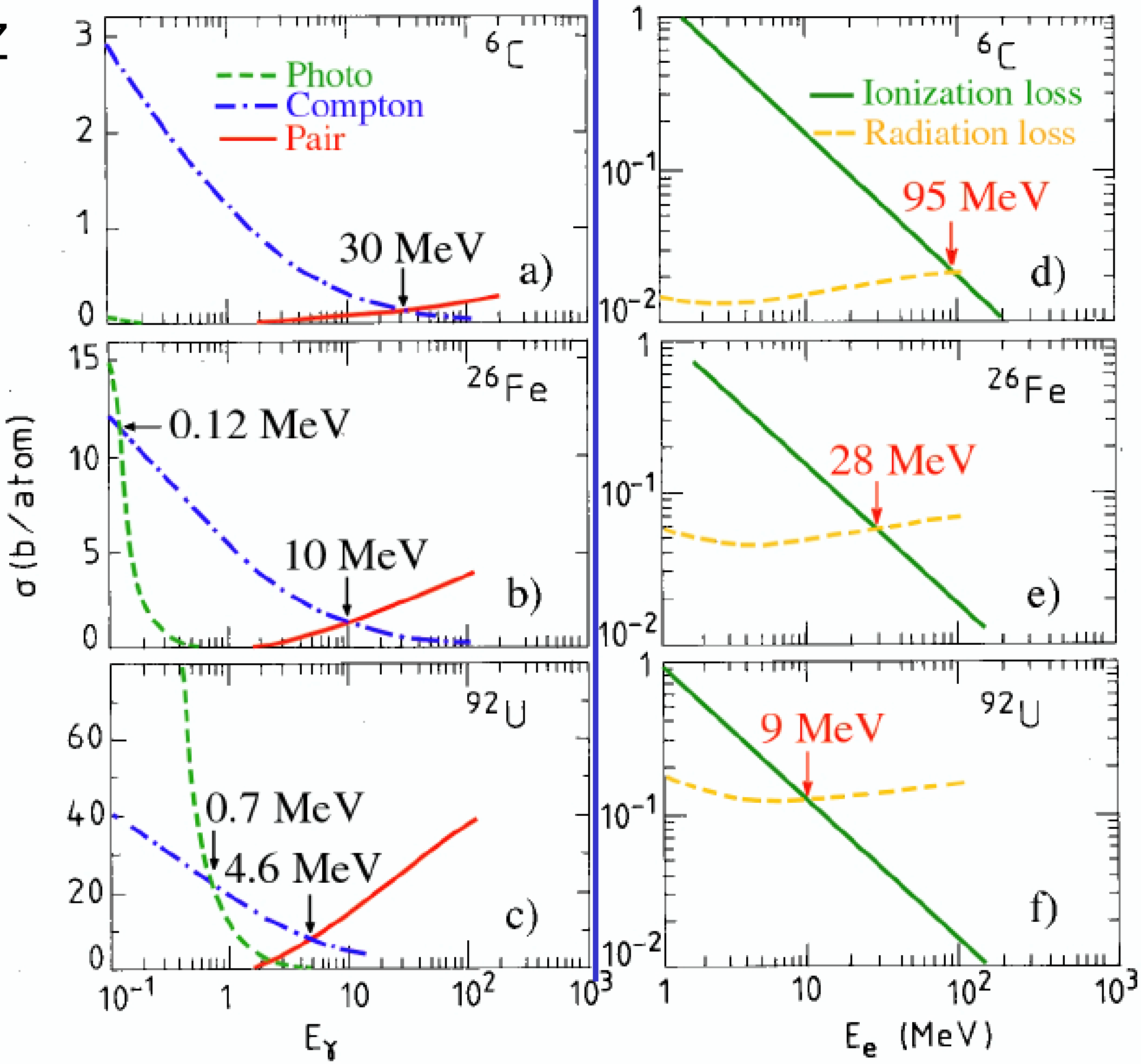


Material dependence

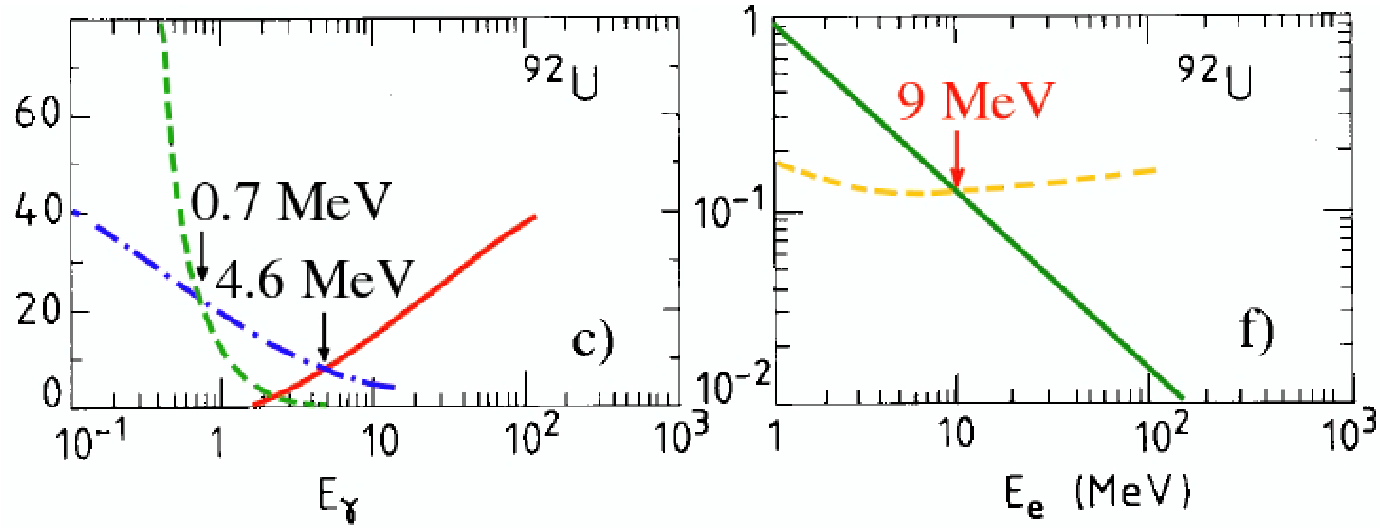
Increasing Z

Gammas

Electrons

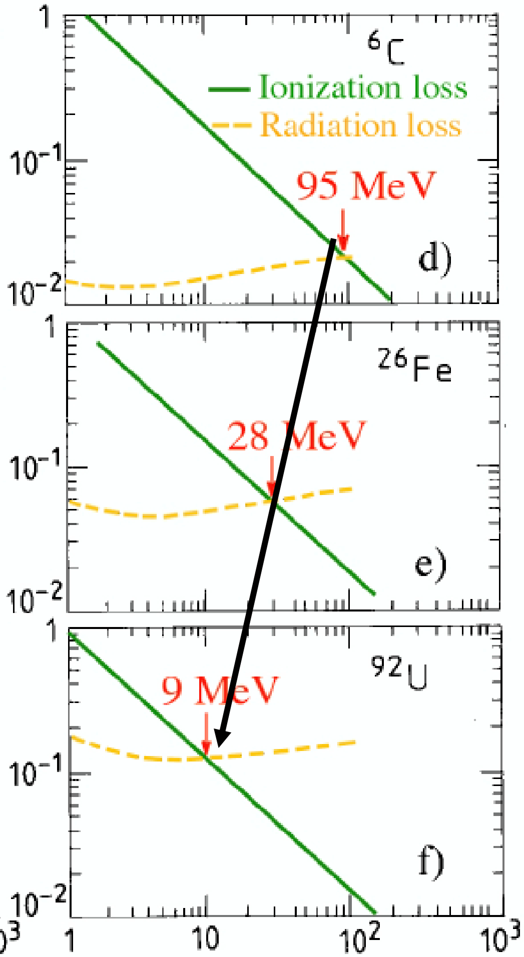


Interpretation / comments



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

Electrons



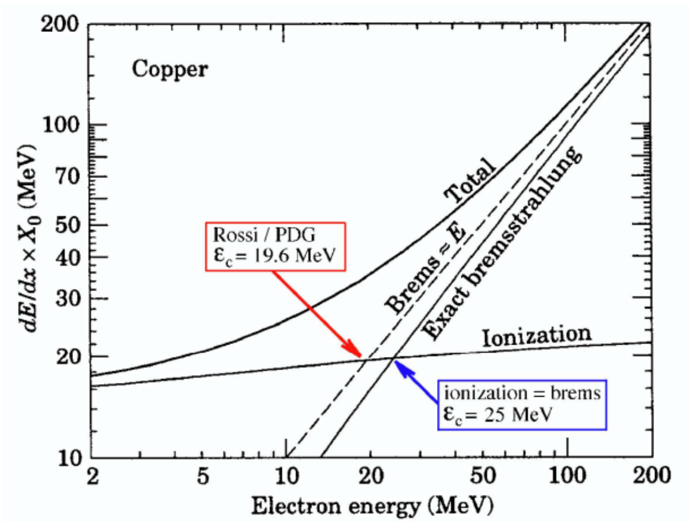
Increasing Z

Electrons lose energy by: *ionization* *radiation*

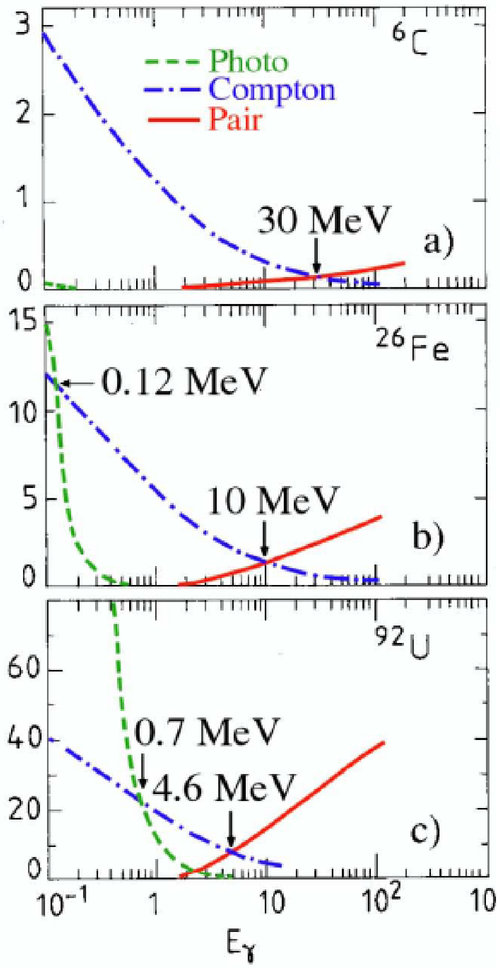
Critical energy ϵ_c: $\frac{dE}{dx}(\text{ion}) = \frac{dE}{dx}(\text{rad})$

$\epsilon_c \propto 1/Z$ PDG: $\epsilon_c = 610\ \text{MeV}/(Z + 1.24)$

In high Z materials particle multiplication at lower energies



Photons



Increasing Z

- *Photons* interact by:

1) *Photoelectric* effect $\sigma \propto Z^5,\ E^{-3}$
2) *Compton* scattering $\sigma \propto Z,\ E^{-1}$
3) *Conversion* into e^+e^- σ increases with E, Z, asymptotic at ~ 1 GeV

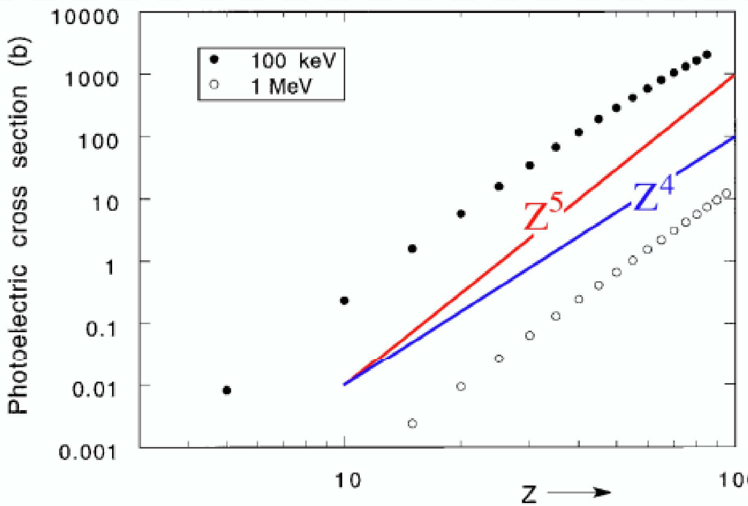


FIG. 2.3. Cross section for the photoelectric effect as a function of the Z value of the absorber. Data for 100 keV and 1 MeV γs.

EM shower in matter

Differences between high-Z/low-Z materials:

- Energy at which *radiation* becomes dominant
- Energy at which *photoelectric effect* becomes dominant
- Energy at which e + e - *pair production* becomes dominant

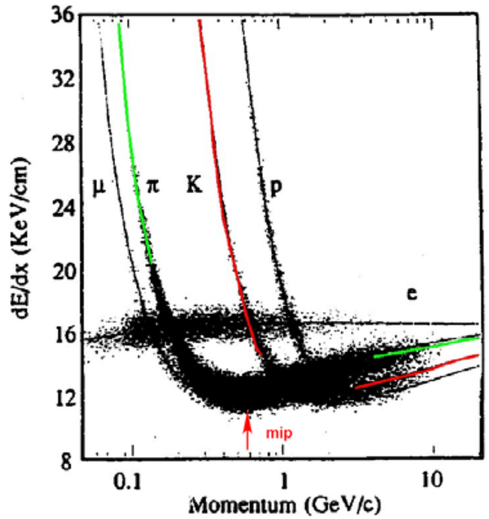
Is it better a Pb or a Fe calorimeter? (or differently phrased)

Can you calculate how many cm of Pb or Fe are needed to stop (95%) a 10 GeV e^- ?
And for a 10 GeV μ?

➔ let's discuss about the muon

What about the muons?

Heavy particles: $M \gg m_e$
➔ Bethe-Bloch



Minimum Ionizing Particle:
dE/dx = minimum

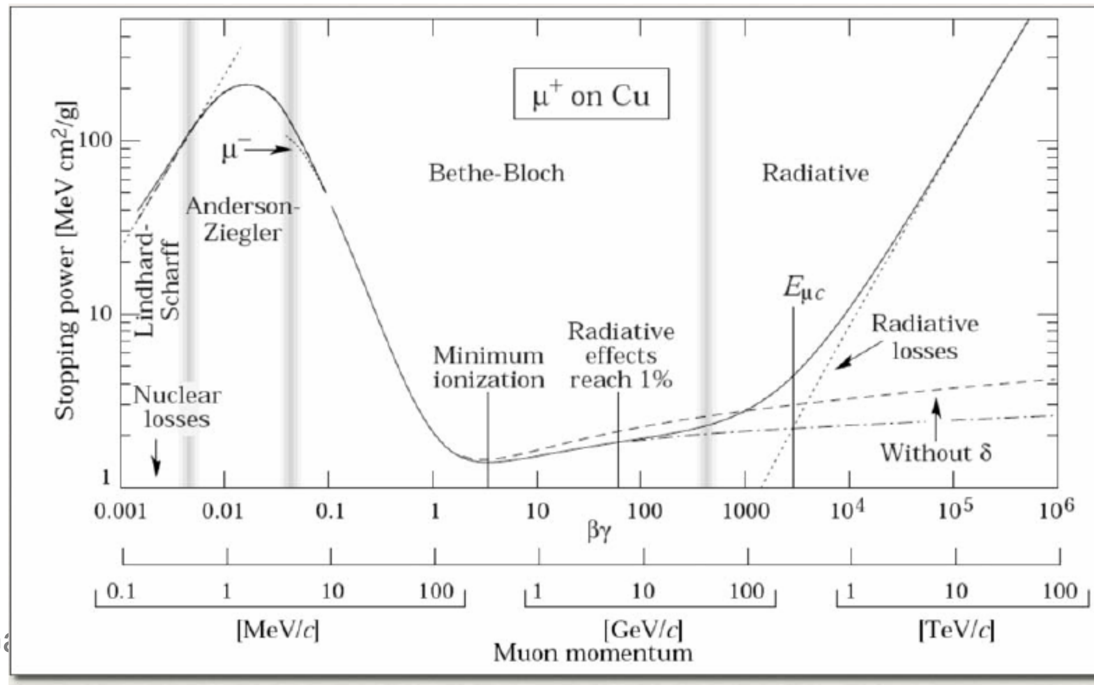
$$E_c^{\mu} = E_c^{e}\left(\frac{m_{\mu}}{m_e}\right)^2 \approx 4 \cdot 10^4 E_c^{e}$$

$E_c(e^-)$ in Cu = 20 MeV

$E_c(\mu)$ in Cu = 1 TeV

Z_{Cu}=29

Muon energy losses mainly via ionization ➔ "no shower"



dE/dx: some typical values

Typically dE/dx = 1-2 MeV /g cm^2 x ρ [g/cm^3]

- Iron ρ=7.87 g/cm^3: dE/dx = 11 MeV / cm = 1.1 GeV / m
- Silicon 300 μm : dE/dx = 115 keV (MPV = 82keV) (~ 4 MeV / cm)
- Gas: dE/dx = few keV / cm

Ionization energy: ~ Z x 10 eV

- 300 μm Silicon: 30’000 e/h pairs (~10^6 e/h pairs /cm)
  - Small band gap, 3.6 eV/pair
  - Still a small charge: depletion
- Gas: few 10 electron ion pairs/cm
  - Need gas amplification

To be compared to typical pre-amplifier electronic noise equivalent: 1000 e

dE/dx fluctuations

Distance between interactions: exponential distribution

- $P(d) \sim \exp(-d / \lambda)$ with $\lambda = A / N_A \sigma \rho$

Number of collisions in given thickness: Poisson distribution

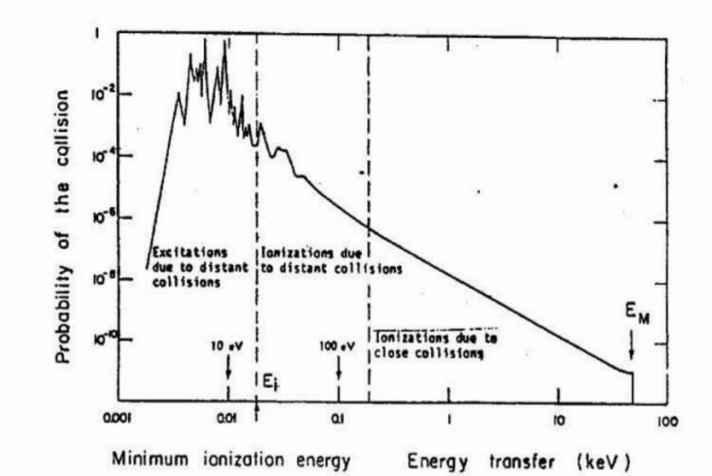
- Can fluctuate to zero ➔ inefficiencies

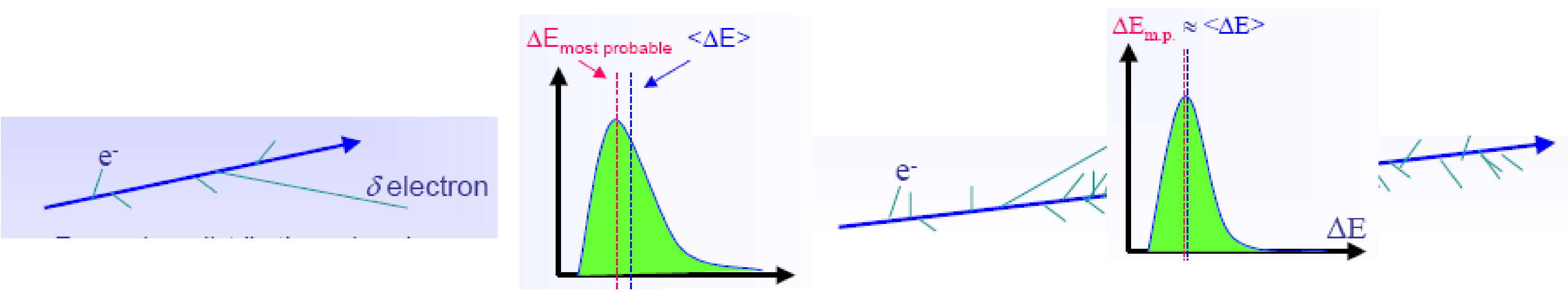
Energy loss distribution in each collision ➔

- Large values possible (δ electrons)

P(dE/dx) is a **Landau distribution**

- Asymmetric (tail to high dE/dx)
- Mean ≠ most probable value
- Approaches Gaussian for thick layers





Muons are not MIP

The effects of radiation are clearly visible in calorimeters, especially for high-energy muons in high-Z absorber material

like Pb (Z=82)

$E_c(e^-) = 6$ MeV

$E_c(\mu) = 250$ GeV

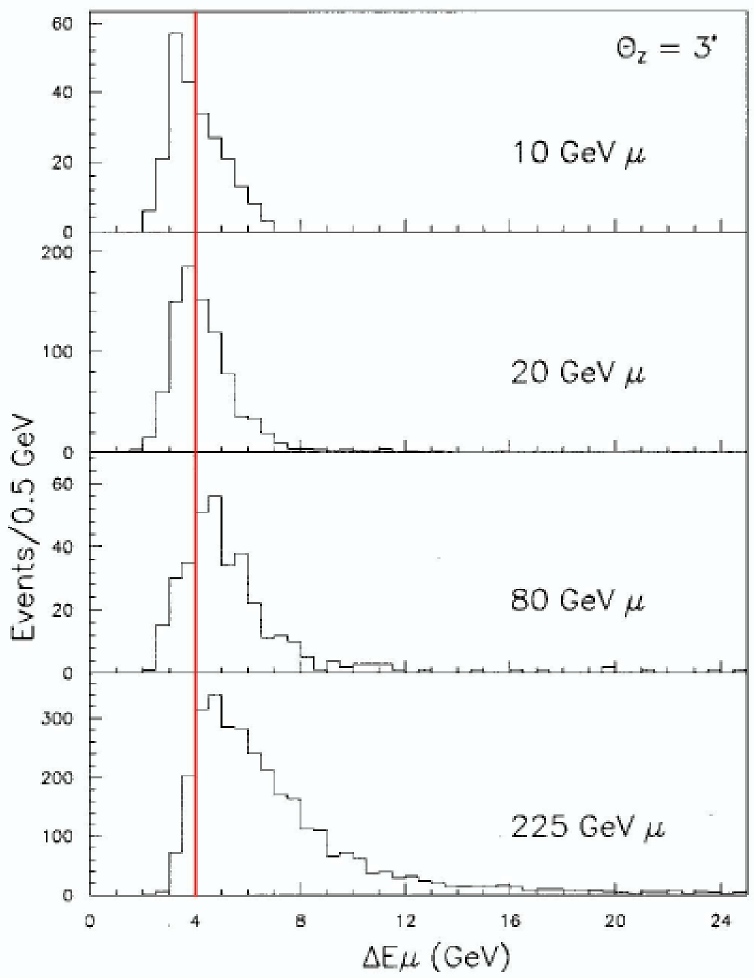


FIG. 2.19. Signal distributions for muons of 10, 20, 80 and 225 GeV traversing the $9.5\lambda_{int}$ deep SPACAL detector at $\theta_z = 3°$. From [Aco 92c].

Interaction of particles with matter

II. Hadronic interactions

Hadron showers

Extra complication: ***The strong interaction*** with detector (absorber) material

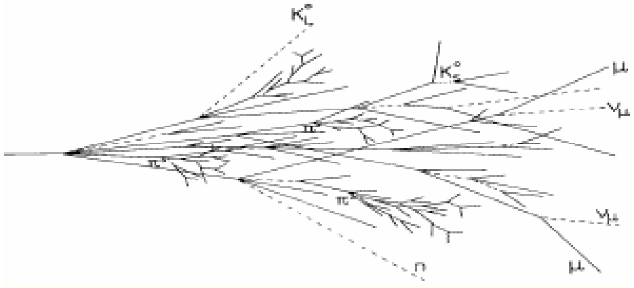
- Charged hadrons: complementary to track measurement
- Neutral hadrons: the only way to measure their energy

In nuclear collisions numbers of secondary particles are produced

- Partially undergo secondary, tertiary *nuclear reactions* ➔ formation of hadronic cascade
- Electromagnetically decaying particles (π, η) initiate EM showers
- Part of the energy is absorbed as nuclear binding energy or target recoil (*Invisible energy)*

Similar to EM showers, but much more complex

Different scale: hadronic interaction length



Hadronic interactions

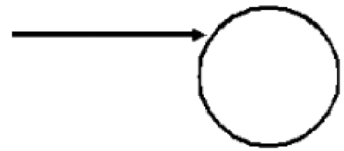
1st stage: the hard collision

before first interaction:

• pions travel 25-50% longer than protons (~2/3 smaller in size)

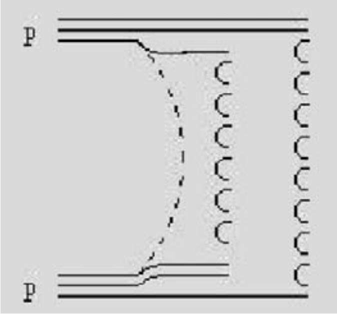
• a pion loses ~100-300 MeV by ionization (Z dependent)

Particle nucleus collision according to cross-sections



- particle multiplication
  (one example: string model)

average energy needed to produce a pion 0.7 (1.3) GeV in Cu (Pb)



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

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

Hadronic interactions

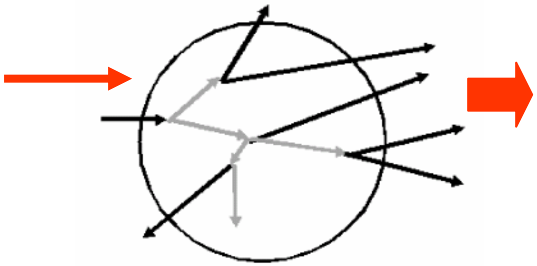
2nd stage: spallation

- Intra-nuclear cascade

  Fast hadron traversing the nucleus frees protons and neutrons in number proportional to their numerical presence in the nucleus.

  Some of these n and p can escape the nucleus

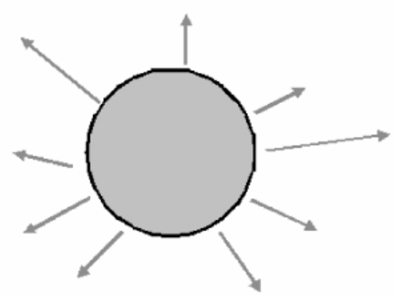
For $^{208}_{82}$Pb ~1.5 more cascade n than p



dominating momentum component along incoming particle direction

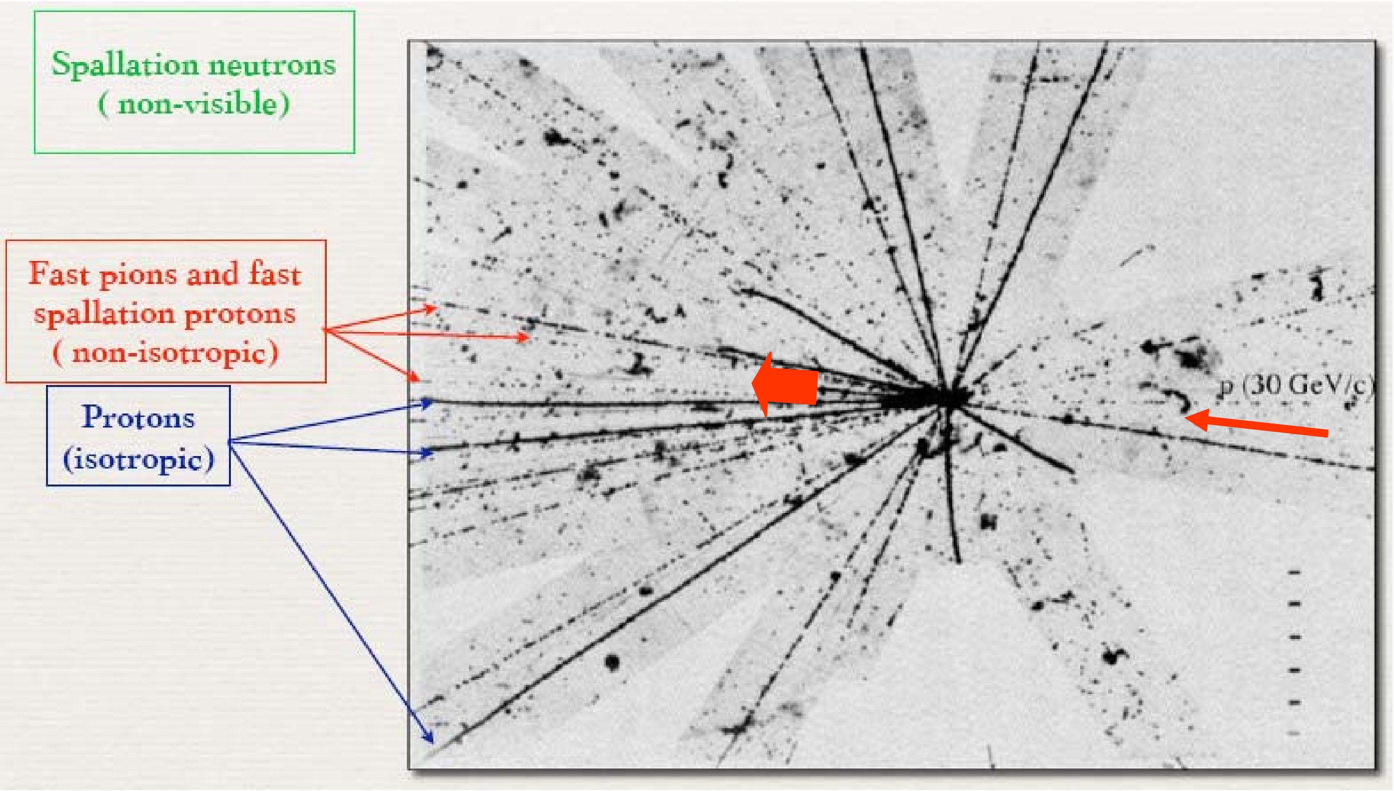
- The nucleons involved in the cascade transfer energy to the nucleus which gets in an excited state
- Nuclear de-excitation
  - Evaporation of soft (~10 MeV) nucleons and α
  - + fission for some materials

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)



isotropic process

“nuclear star”



Nuclear interaction induced by a proton of 30GeV in a photographic emulsion:
~20 ionizing particles produced isotropicaly, probably all protons, + forward less dense ionization tracks, mostly pions and protons from cascade process

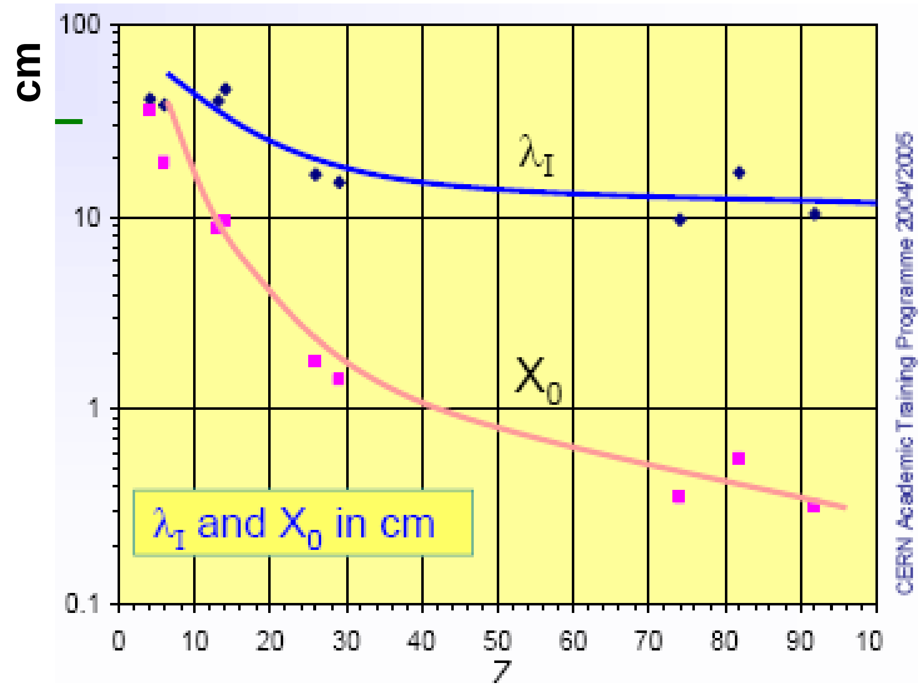
Hadronic interaction length

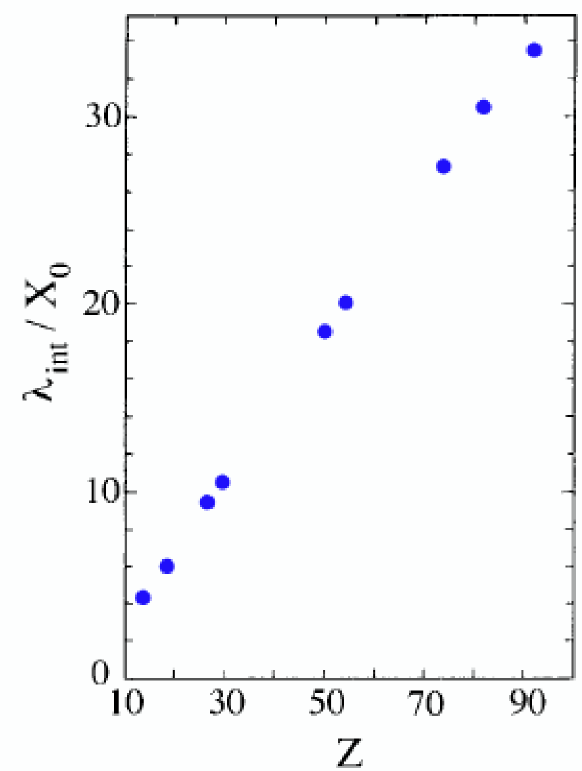
λ_{int}: mean free path between nuclear collisions

$$\lambda_{int}\ (g\ cm^{-2}) \propto A^{1/3}$$

typical values: Fe 16.8 cm, Cu 15.1 cm, Pb 17.0 cm, U 10.0 cm

Hadron showers are much larger than EM ones – how much, depends on Z



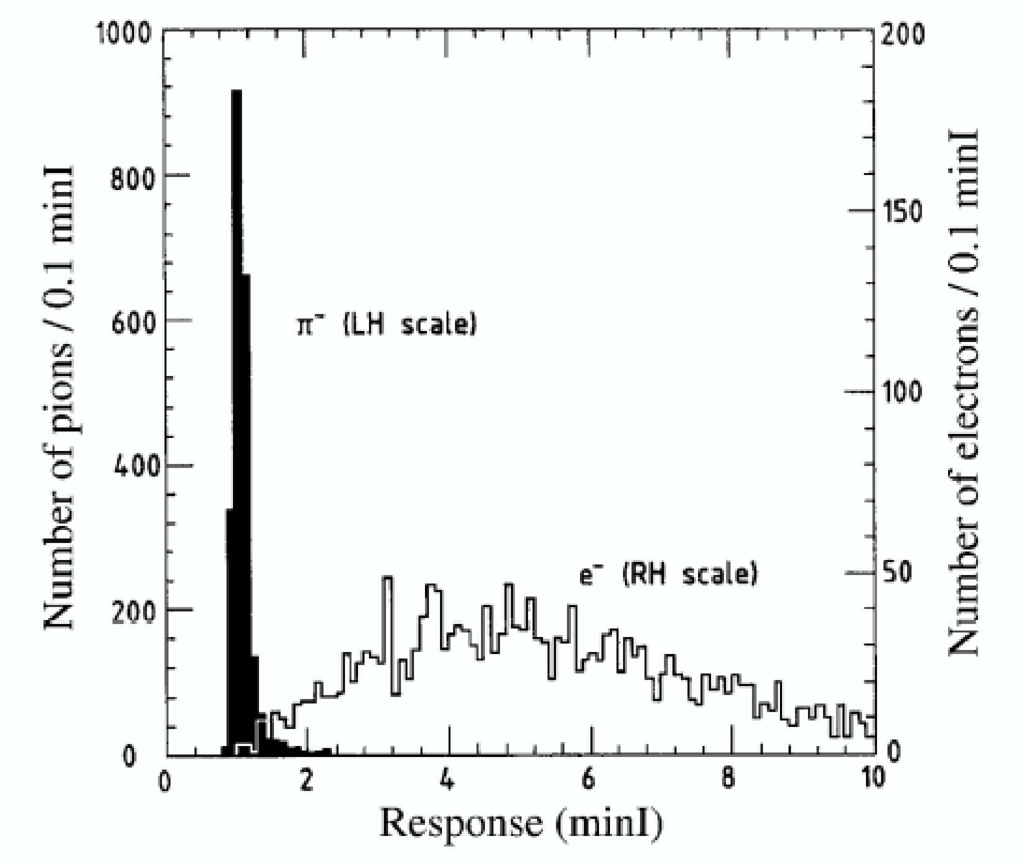


Particle ID

The λ_{int}/X_0 ratio is important for ***particle*** ID

In high-Z materials: λ_{int}/X_0 ~30 → excellent *e* / π separator

1 cm Pb + scintillator plate makes a spectacular ***preshower detector***



Electromagnetic fraction

In first collision, ~ 1/3 of produced particles are π^0

π^0 ➔ $\gamma\gamma$ produce EM shower, no further hadronic interaction

Remaining hadrons undergo further interactions ➔ more π^0

π^0 production irreversible; "one way street"

- EM fraction increases with energy

Empirically: $\langle f_{em} \rangle = 1 - (E/E_0)^{k-1}$

- E_0= average energy needed to produce a π^0
- (k-1) related to the average multiplicity ➔ k~0.8
- < fem > slightly Z dependent

Large fluctuations

- E.g. charge exchange $\pi^+ p$ ➔ $\pi^0 n$ (prob. 1%) gives f_{em} = 100%

Energy dependence

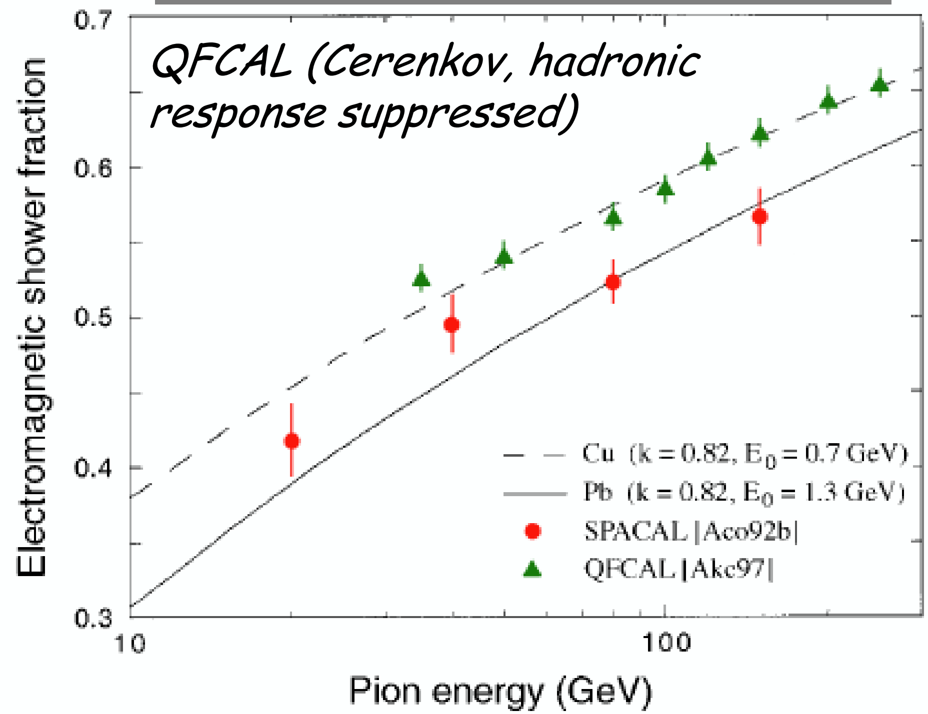
SPACAL: Pb- scintillating fibers
QFCAL: Cu – quartz fibers

Numerical example for copper

- 10 GeV: $f_{em} = 0.38$
  - 9 charged h, 3 π^0
- 100 GeV: $f_{em} = 0.59$
  - 58 charged h, 19 π^0

Energy deposition by ionization of charged hadrons significant

- 200-300 MeV between two interactions



Material dependent

for ultra-high energies, cosmic rays, asymptotically reaches 1

Non-em fraction breakdown

Energy breakdown for the non-em component of hadronic showers in Lead:

- Ionizing particles ~ 56% (2/3 from spallation protons)
- Neutrons ~10% (37 neutrons/GeV)
- Invisible ~34%

Comparison Lead / Iron ➔

The listed numbers of particles are per GeV of non-em energy

Spallation protons carry typically 100 MeV

Evaporation neutrons ~ 3 MeV

	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

Interaction of neutrons

Cascade neutrons:

- Nuclear reactions X(n, yn)X' with (y-1) new evaporation neutrons

Evaporation neutrons:

- Elastic scattering
  - Dominant at 1-few eV
  - Average energy transfer: 1% for Pb, 3% for Fe, 50% for H
  - Important for hydrogenous active material (e.g. scintillator)
- Neutron capture
  - At lowest energies
  - Followed by γ or sometimes α emission
  - Sizeable energy, but late w.r.t. main shower component
- Decay
- Less important: inelastic scattering

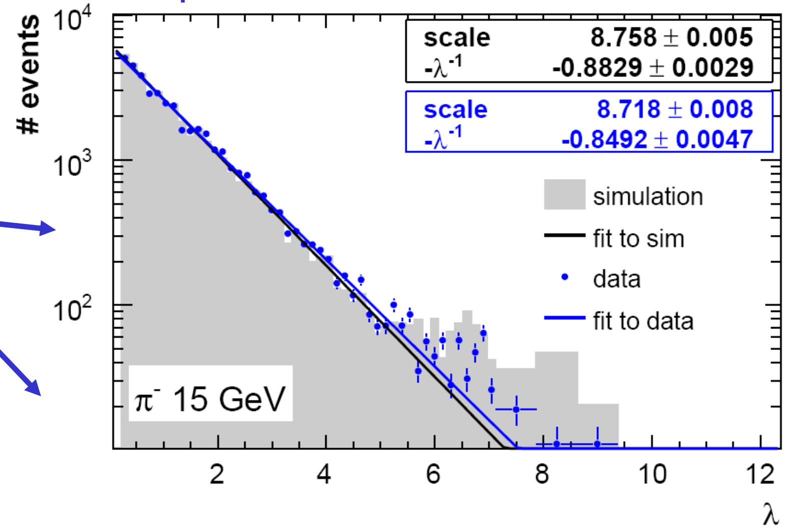
Range: tens of cm, sometimes meters: "neutron gas"

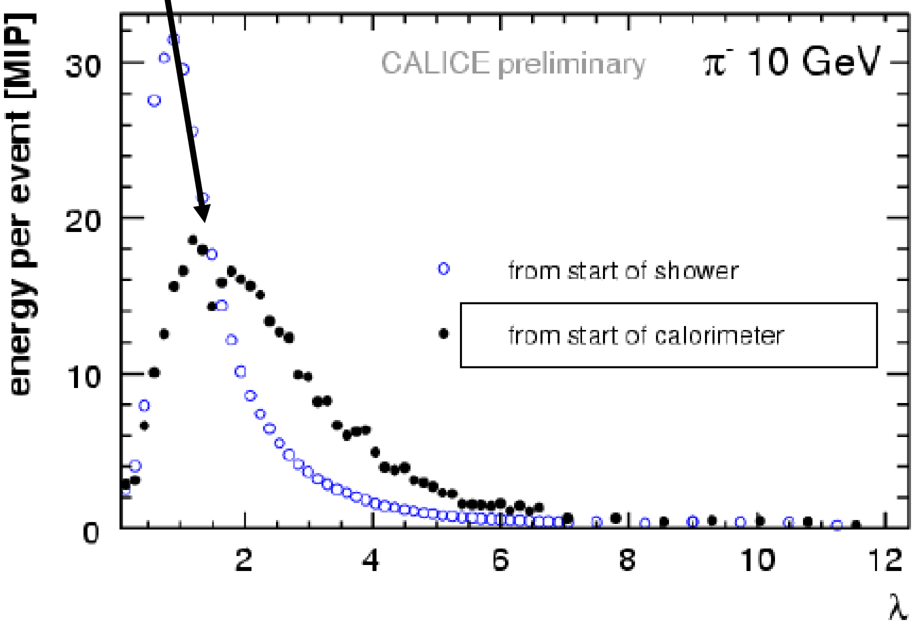
Longitudinal profile

The average longitudinal profile is normally measured from the front of the calorimeter,

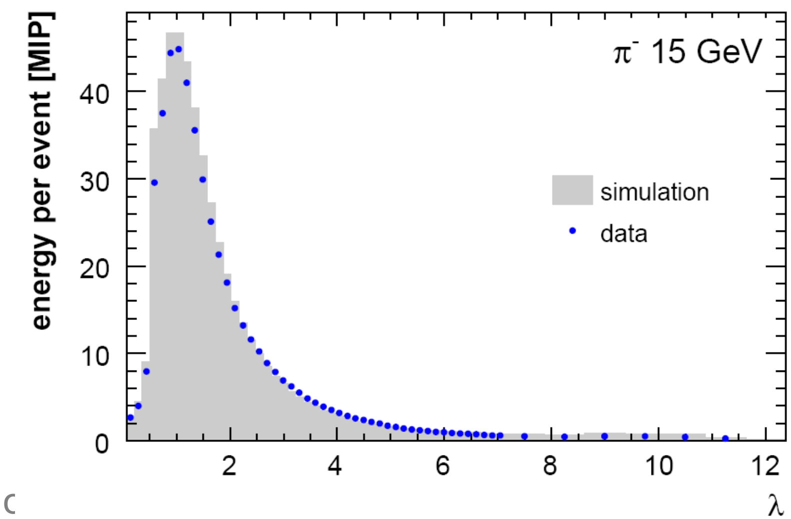
BUT it is a convolution of two components

Depth of first interaction



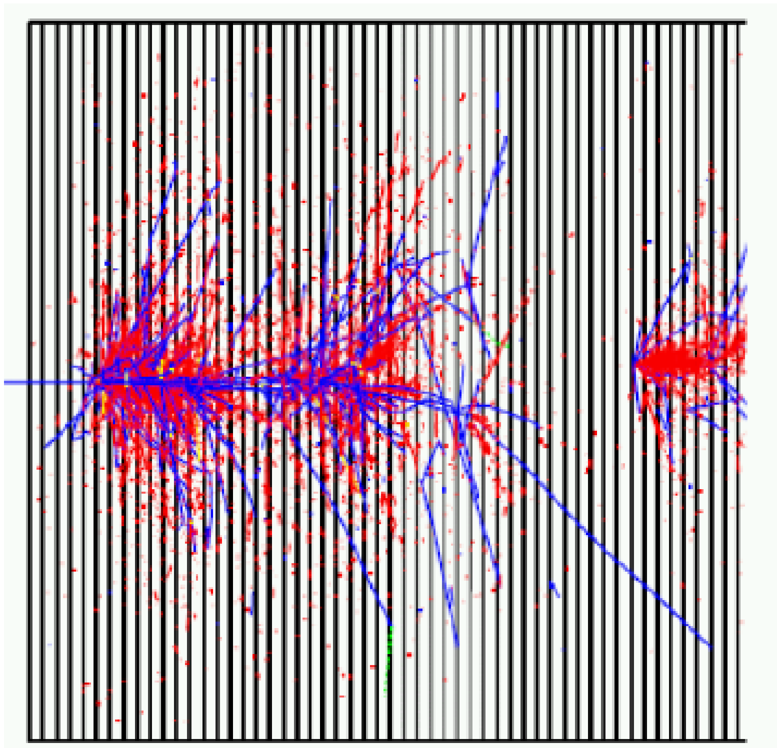


Longitudinal shower development



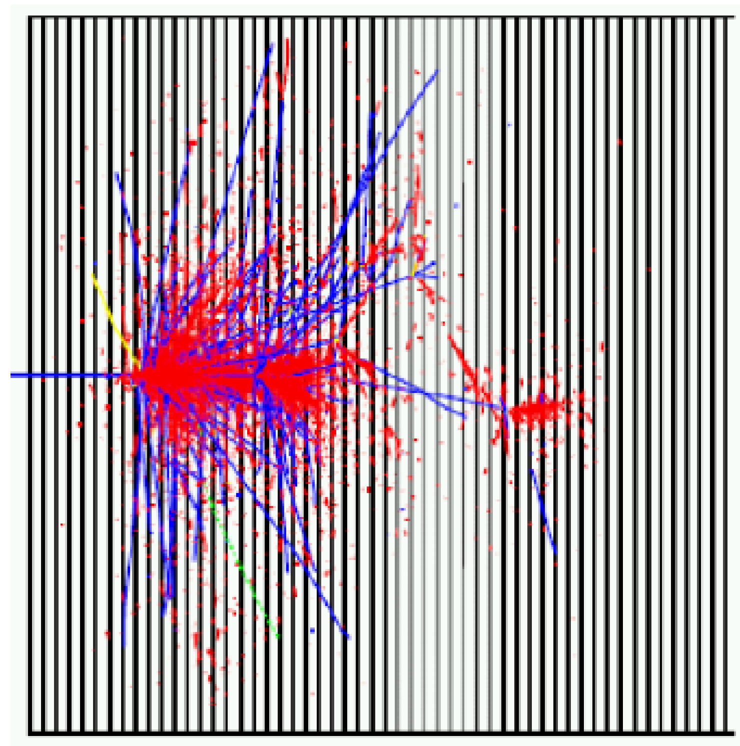
Fluctuations

event 1



blue = hadronic component

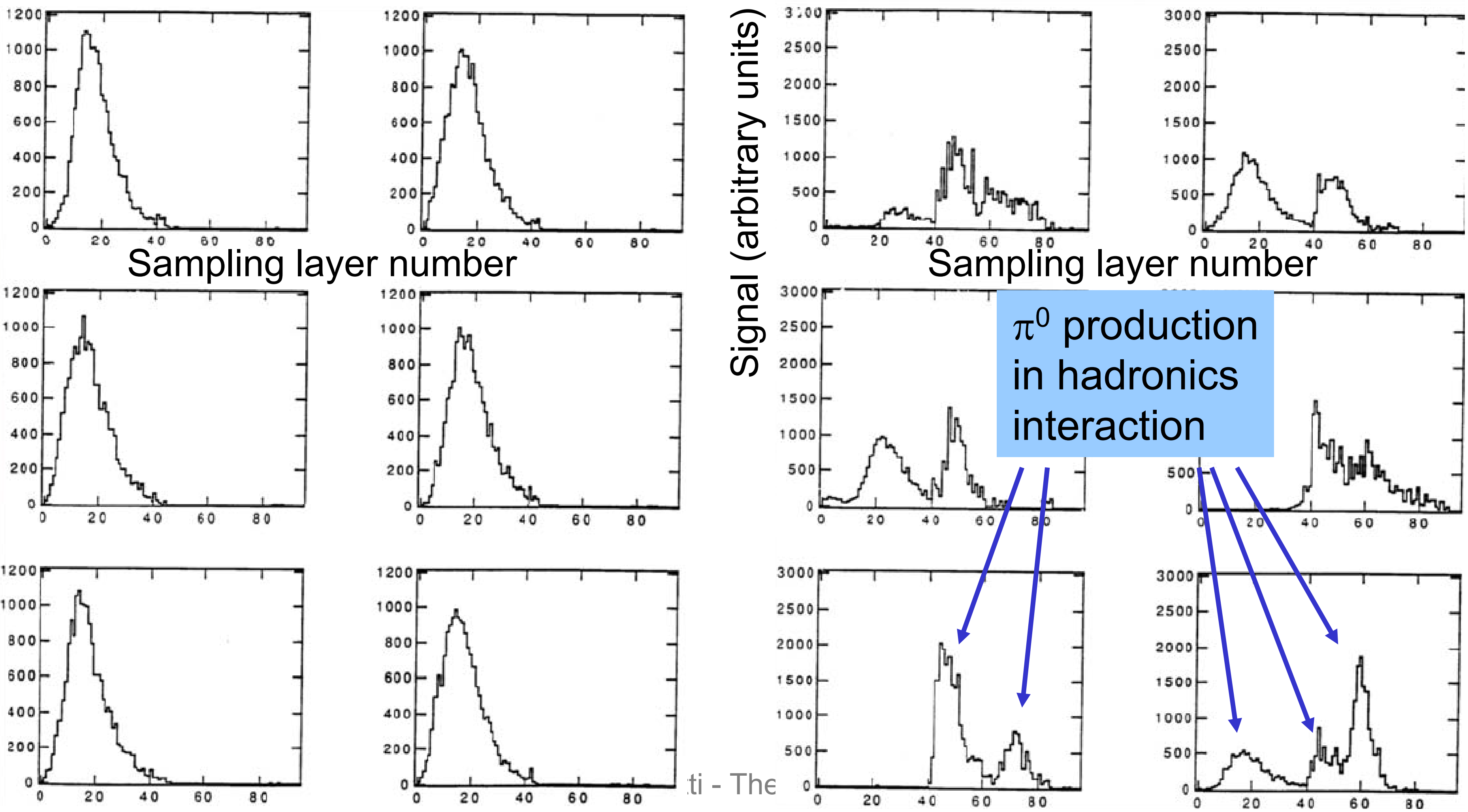
event 2



red = electromagnetic component

Fluctuations

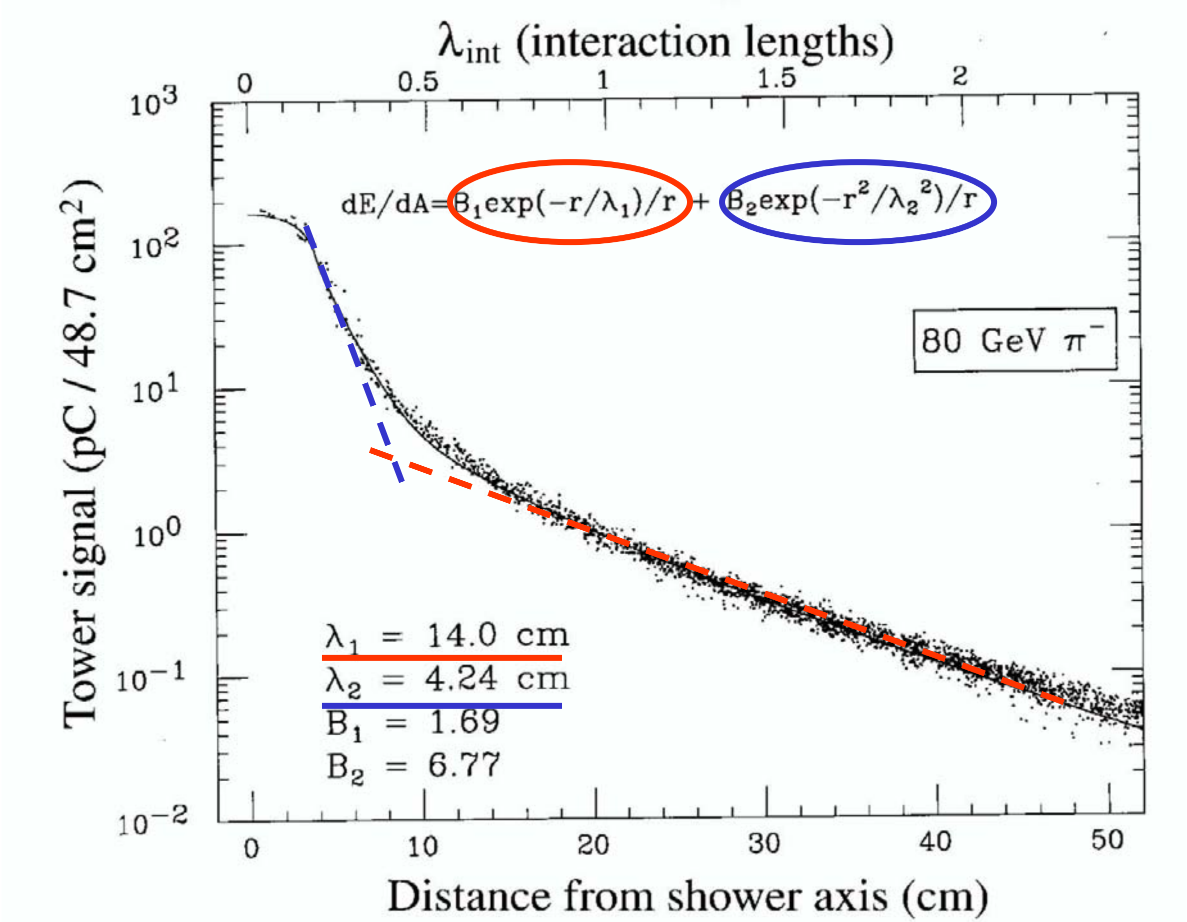
Single events as measured with the “hanging file” calorimeter (lead/iron/scint) for 270 GeV electrons and 270 GeV pions



Lateral shower profile

Lateral shower profile has two components:

- *Electromagnetic core* (π^0)
- *Non-em halo* (mainly non-relativistic shower particles)



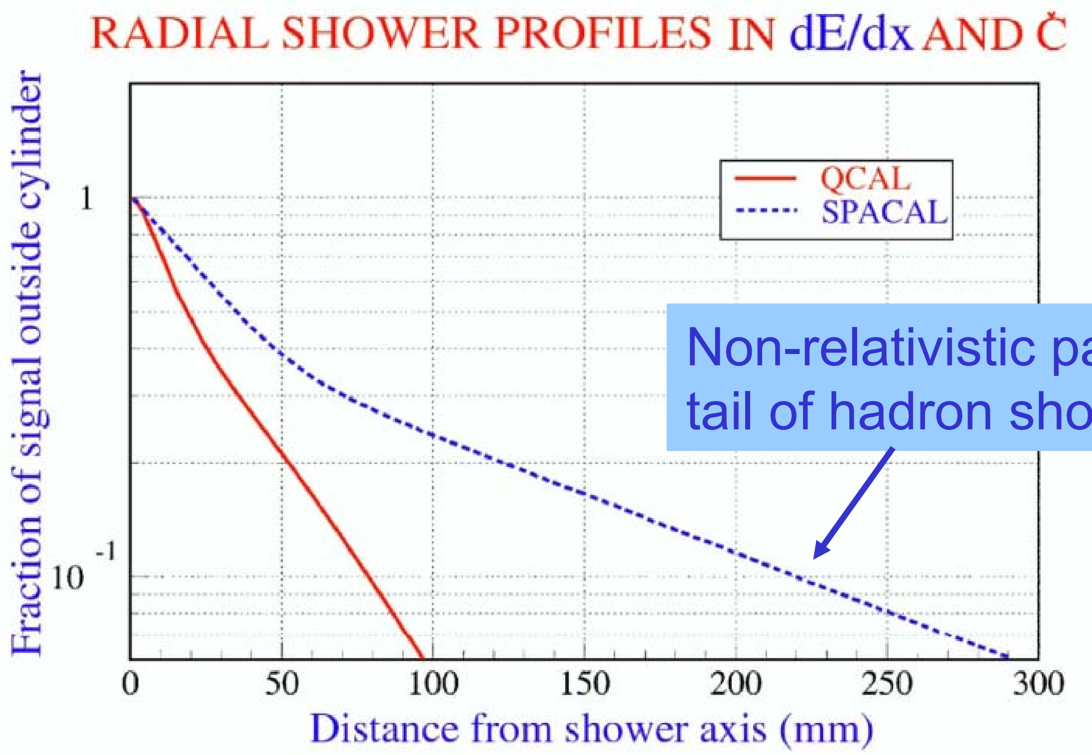
Lateral shower profile II

Spectacular consequences for *Cerenkov calorimetry*

Cerenkov light is emitted by particles with $\beta > 1/n$

e.g. quartz (n = 1.45): Threshold 0.2 MeV for *e*, 400 MeV for p

➔ Cerenkov detector not sensitive to hadronic part of shower

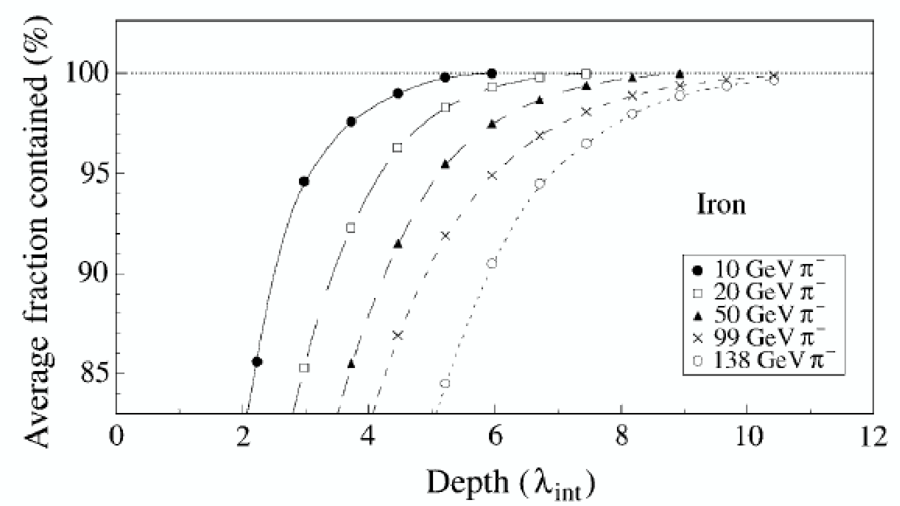


Non-relativistic particles dominate tail of hadron shower

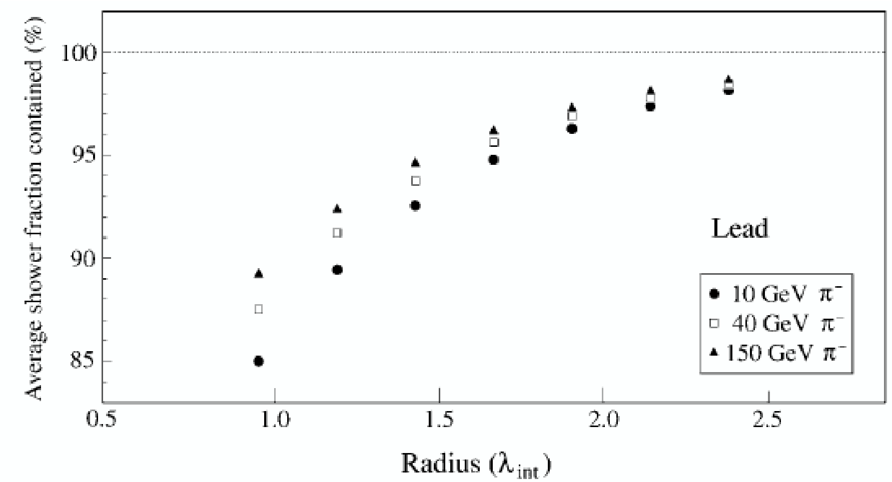
Shower containment

Depth to contain showers increases with log E

Lateral leakage ***decreases*** as the energy goes up!



Leakage in principle no problem, can correct in average



But: leakage fluctuations are

Rule of thumb: $\sigma \sim 4\ f_{leak}$

much smaller for transverse

Lessons for calorimetry

In absorption process, most of the energy is deposited by ***very soft shower particles***

Electromagnetic showers:

- 3/4 of the energy deposited by *e*-, 1/2 by Compton photoelectrons

These are *isotropic,* have forgotten direction of incoming particle

- The typical shower particle is a 1 MeV electron, range < 1 mm

➔ important consequences for *sampling calorimetry*

Hadron showers:

- Typical shower particles are a 50 - 100 MeV proton and a 3 MeV evaporation neutron
- Range of 100 MeV proton is 1 - 2 cm

Neutrons travel typically several cm

What they do depends crucially on details of the absorber

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