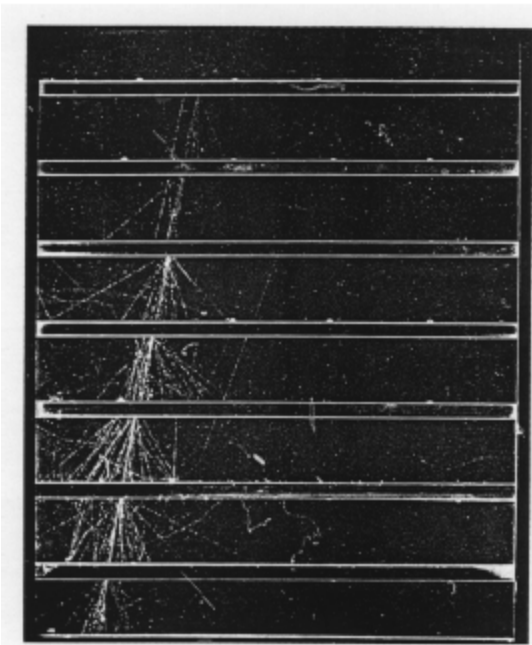


Calorimetry Lecture 1 : Principles of Calorimetry



Electromagnetic shower in spark
chamber

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2010 Hadron Collider Physics
summer school

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*Thanks to Dan Green, Chris Tully,
Ursula Bassler , Beate Heinemann,
Nural Akchurin*

Outline of Lecture 1

- Physics Principles of Calorimetry
 - Energy loss: ionization, cherenkov
 - Scintillation
 - Electromagnetic and hadronic showers
 - Shower profiles and containment
- Calorimeters
 - Sampling vs total absorption
 - Signal detection
 - How to choose a calorimeter

References

- There are many excellent references, here are a few:
 - Calorimetry: Energy Measurements in Particle Physics, Richard Wigmans, 2000.
 - Excellent book, very detailed (but very expensive – ask your advisor to buy it!!)
 - The Physics of Particle Detectors, Dan Green, 2000.
 - Good level of detail, good overall -- covers all detectors
 - Particle Data Booklet
 - Lots of tables and graphs that you will need, but not a lot of explanation.

Disclaimers

- Calorimetry is a huge topic, and I won't cover everything
 - Try to explain the basics and give overview of technology
 - Please forgive any omissions
- Lots of detector pictures, graphics taken from other talks
 - Please forgive repetition of things you may have seen before

Particle Detection

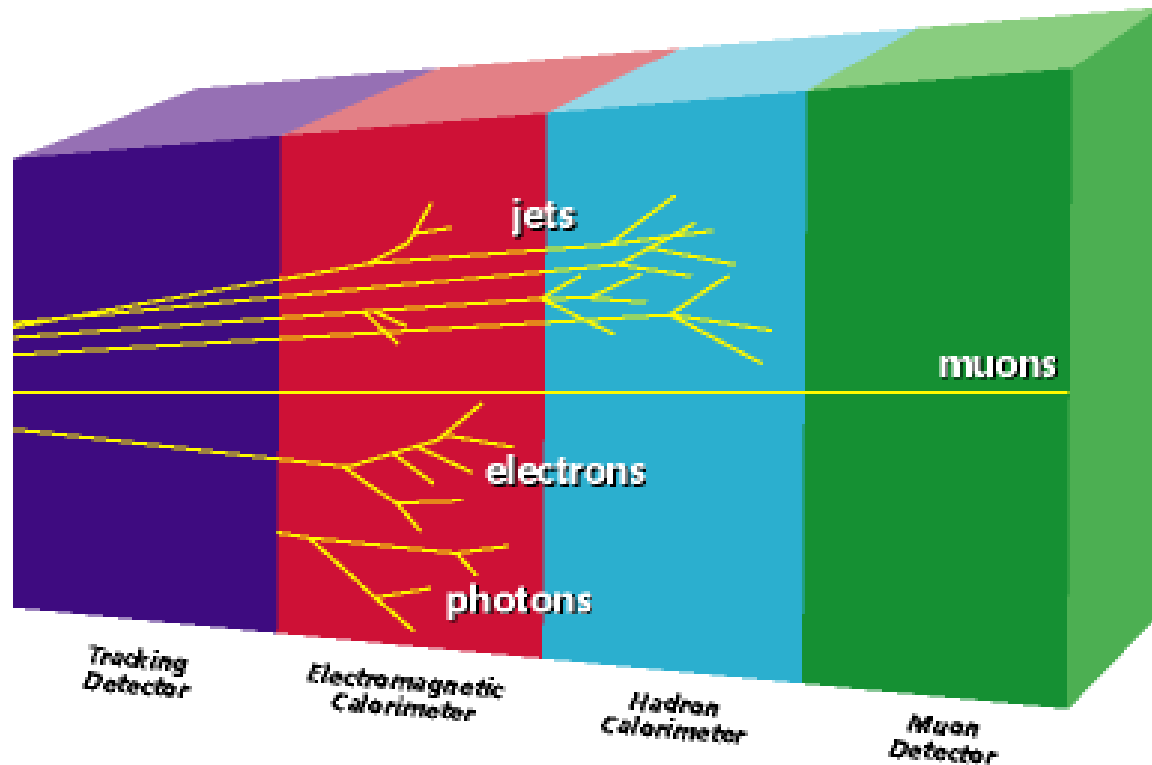
- Depends on interactions of particles with matter
 - Look at physical mechanisms by which we can detect the passage of matter, and try to measure properties
- What particles can we look at?
 - Macroscopic decay length
 - Electrons, photons, neutrons, protons – infinite
 - Muon, kaons, pions – meters
 - K_{short} , Λ – cm -- decay products are detected
 - B , Λ_B -- mm -- decay products
 - Particles must interact
 - Charged particles – electromagnetic interaction
 - Hadrons – strong interaction

What can we measure

- Charged particles – electromagnetic interactions
 - Ionization energy loss (Bethe-Bloch)
 - “tracks”
 - Add a magnetic field → momentum
 - Cherenkov & transition radiation
 - Identify particle species
- Electron/photon
 - Bremsstrahlung, pair production
 - **Electromagnetic showers** ←
- Hadrons ($p^{+/-}$, $K^{+/-}$, K^0_L , p , n)
 - Strong interactions
 - **Hadronic showers** ←

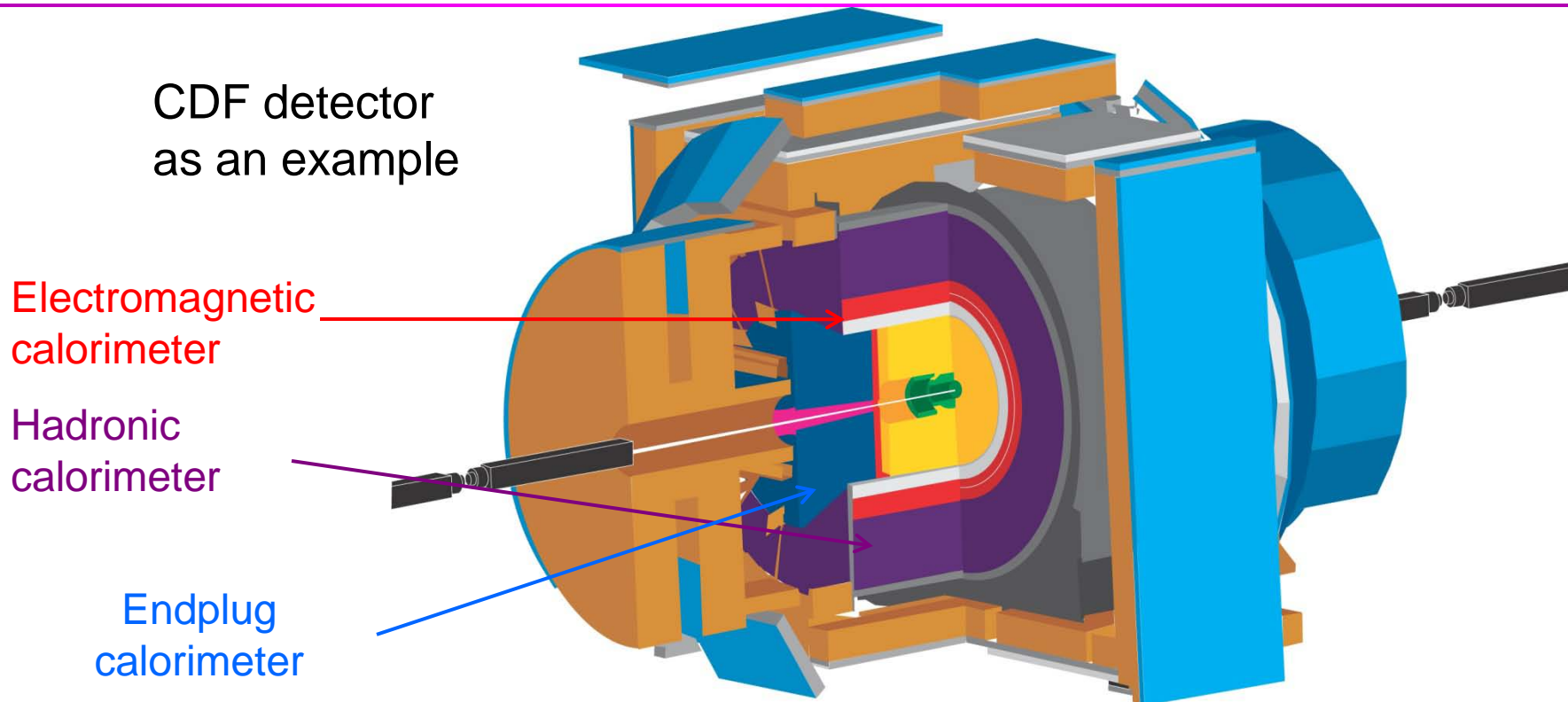
Basis of
calorimetry – but
in practice
detection today
comes back to
electromagnetic
interactions

General HEP detectors



- Put several types of detectors together for the total picture
- Low Z material for trackers, get position but don't stop the particle
- EM and HAD calorimeters – measure energy of showers from radiation and ionization, completely absorb energy of particle
- Reconstruct particle type by characteristics of energy deposit (or lack of)
- Goal – 4π coverage to see what is missing

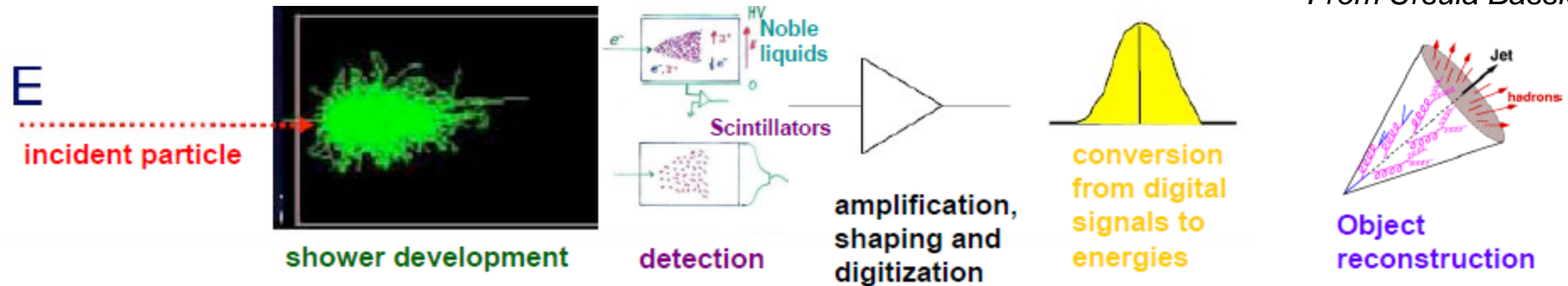
Calorimeters in General



- **Electromagnetic** and **hadronic** section
- Homogeneous (total absorption) or sampling
- Characterized by: energy, position, timing resolution, e/h ratio

Overview of the HEP calorimetry process

From Ursula Bassler



- E_{incident} is absorbed, EM and HAD showers develop, produce signal proportional to E_{incident}
- Signals from: electrons from ionized material or photons from atomic de-excitation
- Electronic readout – signal amplification, digitization
- Granularity – provide position measurement
- If fast enough, use for trigger and timing measurements
- Reconstruct (combined with other detector info) physics objects

Considerations for Detectors

- When designing a calorimeter, take into account physics goals, environmental constraints, cost:
 - What is being measured?
 - What energy resolution is needed?
 - What spatial resolution is needed?
 - What is the event rate (time needed for signal production)?
 - What is your environment (radiation)?
 - What are the size constraints?
 - How much money do you have?
- Compromise...

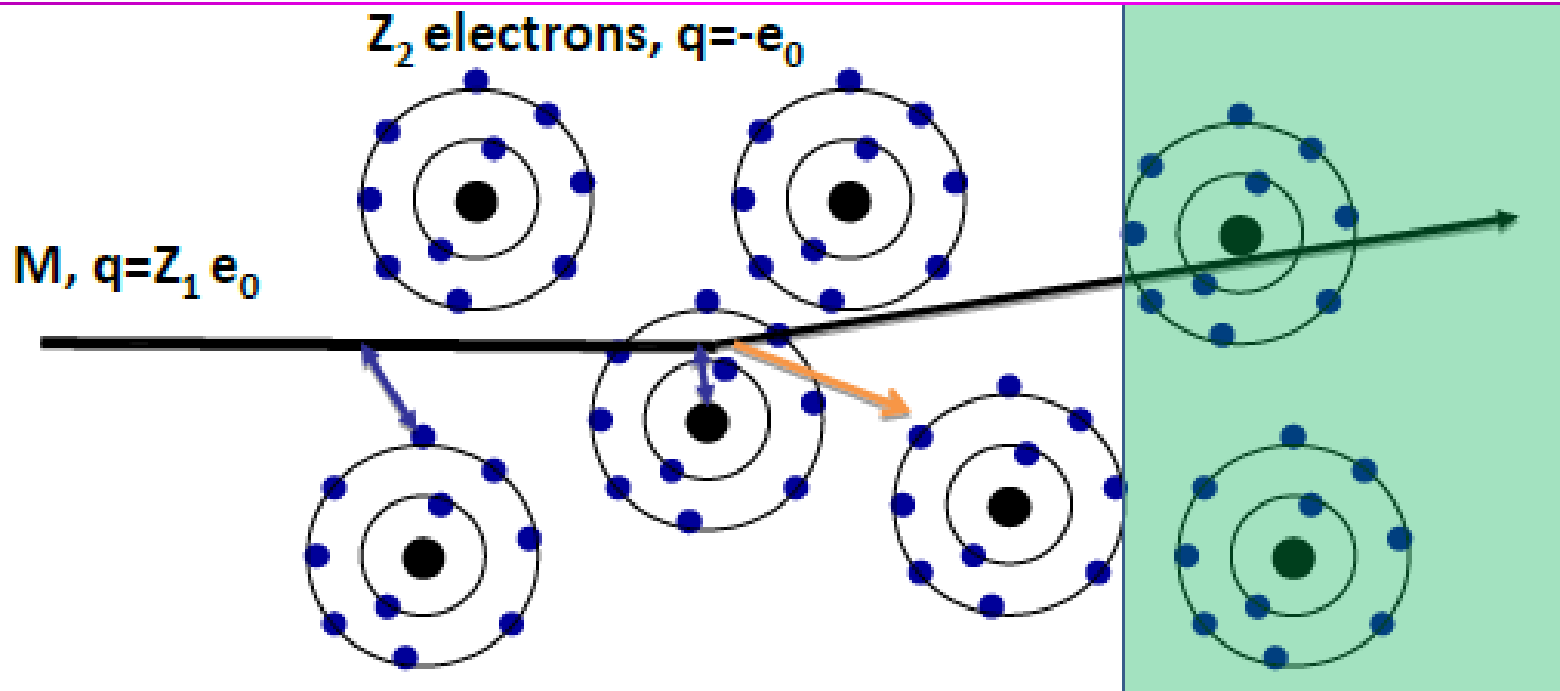
Particle Detection

- Basic idea-- use physical mechanisms by which we can detect the passage of particles, and measure their properties, to reconstruct the event
 - Non destructive – ionization
 - Charged particle passes through matter. Electrons in atoms of the material are basically free electrons, can be accelerated by passage of the high-energy particle. The kinetic energy imparted to these electrons is energy lost to the high-energy particle
 - ⇒ Small energy loss (10 – 100 eV per interaction)
 - ⇒ High energy particle loses small amounts of energy through its path – used for tracking, particle identification
 - Destructive – calorimetry
 - Goal is to measure energy of particle – charged or neutral
 - Material absorbs energy of particle – record or be able to estimate total energy based on sampling

Electromagnetic and Hadronic Calorimetry

- Two types of interactions contribute to discussion of calorimetry:
 - Electron/photon interactions → Electromagnetic (EM) showers
 - Pion, kaon, proton, neutron → hadronic (HAD) showers
- The physical processes lead to different detector choices – collider detectors typically have two distinct calorimeters – EM and HAD
 - Mostly separate detectors, and in today's world of huge collaborations, this is like two different worlds
 - At the level of physics principles, important differences but some similarities, too

Electromagnetic interactions



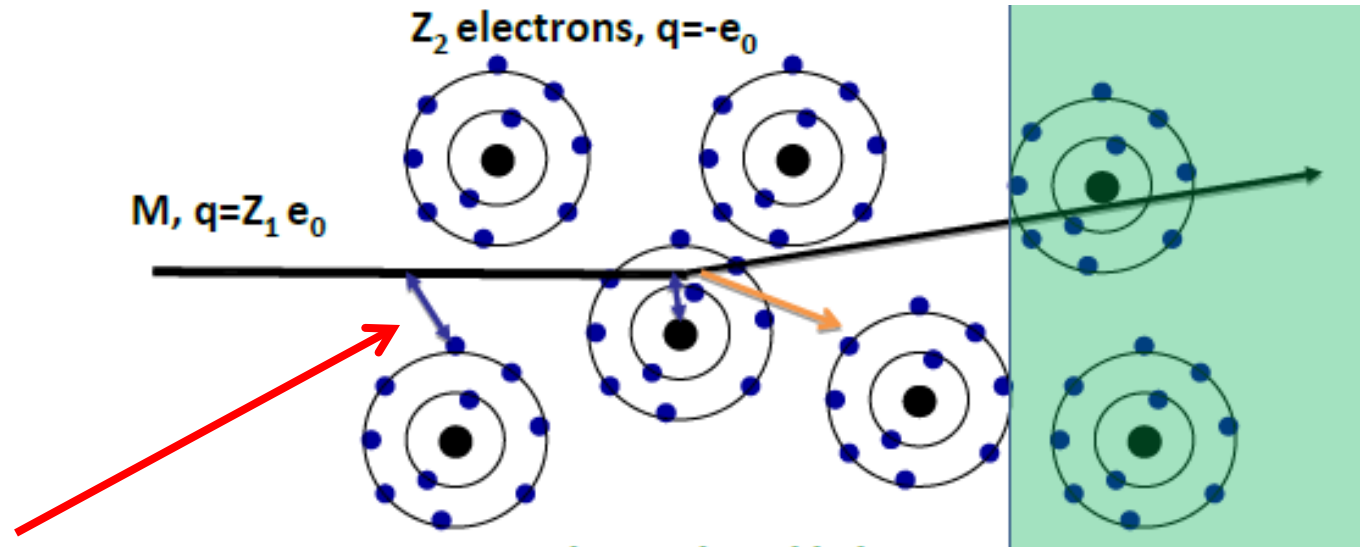
Interaction with atomic electrons – **ionization** and **excitation** – produces measurable signals

Interaction with atomic nucleus – **bremstrahlung** – shower production

If particle velocity is high enough (greater than speed of light in the medium) **cherenkov radiation**

Ionization – described by Bethe-Bloch

- Semi-classical – assume electrons in atoms are basically free particles, accelerated by passage of high-energy particle. Kinetic energy imparted to electrons is energy lost to the HE particle



Quick passage of the charged particle results in Impulse $\Delta p = \int F dt$ to the electron. Integrate over impact parameter to get *average energy loss or stopping power*

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

Bethe-Bloch formula

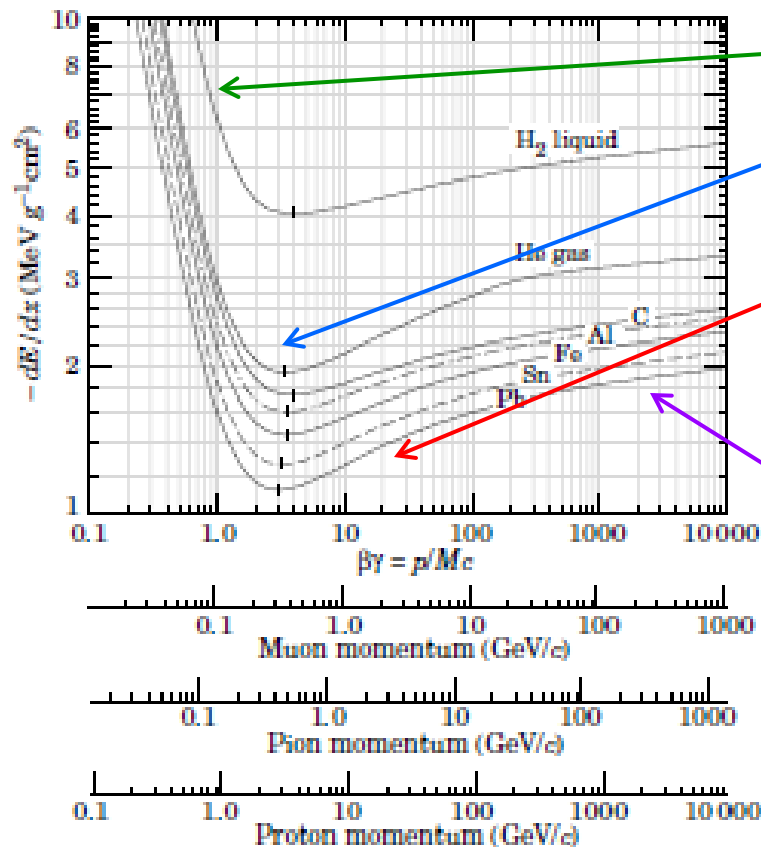
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

Bethe-Bloch curve for particles passing through various materials

Minimum energy loss $\sim I$ (ioniz. Pot.) ~ 10 eV

Maximum energy loss $\sim 10^6$ eV

Most likely energy loss 10 – 100 eV



$1/\beta^2$

Minimum ionizing

Relativistic rise – “flattening of electric field”

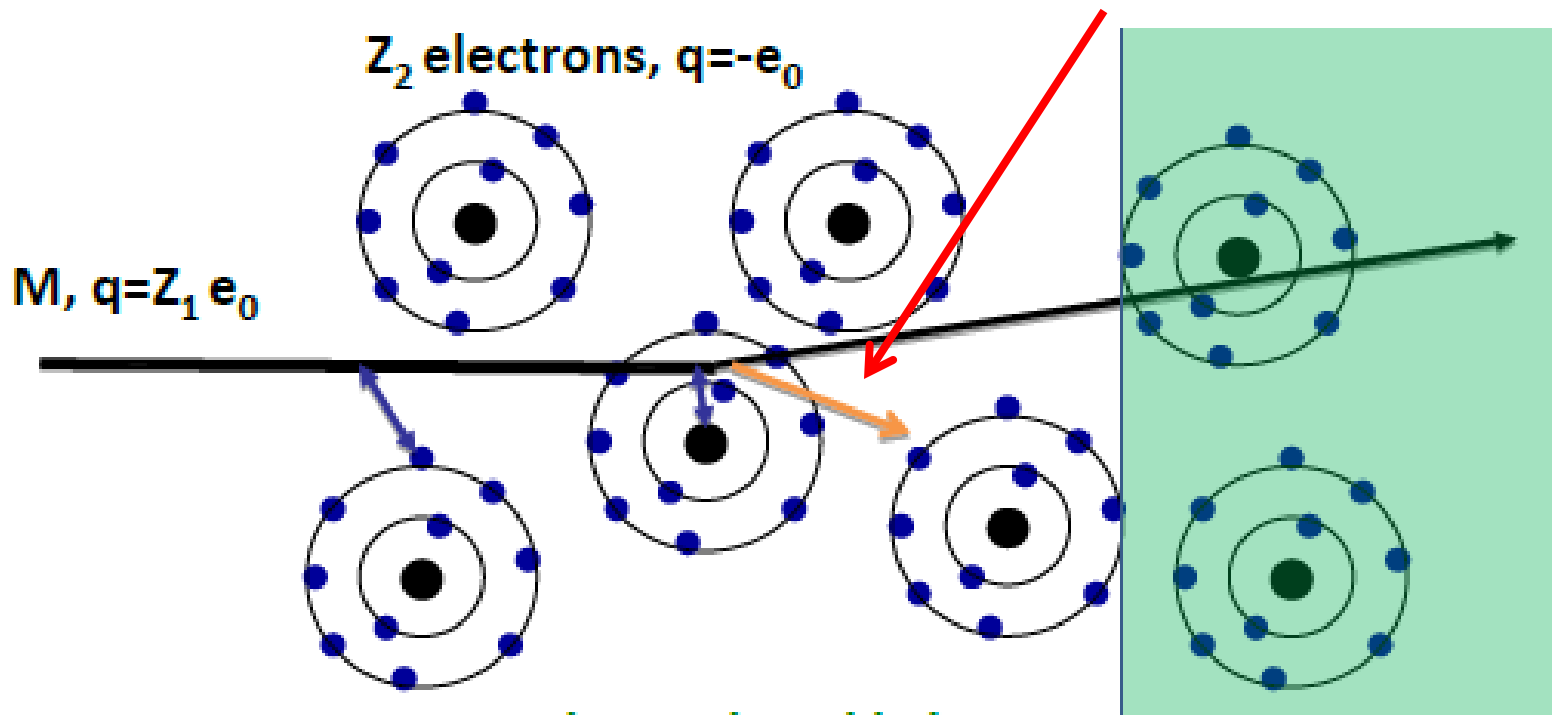
Plateau – density effect -- polarization of the medium halts rise

Atomic excitation

- Along with ionization, electromagnetic interactions of the charged particle with the Coulomb fields of the atoms/molecules of the material result in excitation.
- Excited states are unstable, return to ground state emitting a photon
- Timescale – excitation energy, number of available return paths
- When photons are in visible domain → scintillation
 - 10^{-12} to 10^{-6} s
- Material that produces light -- scintillators → signal readout by Photodetectors
 - Basis of detection for many calorimeters

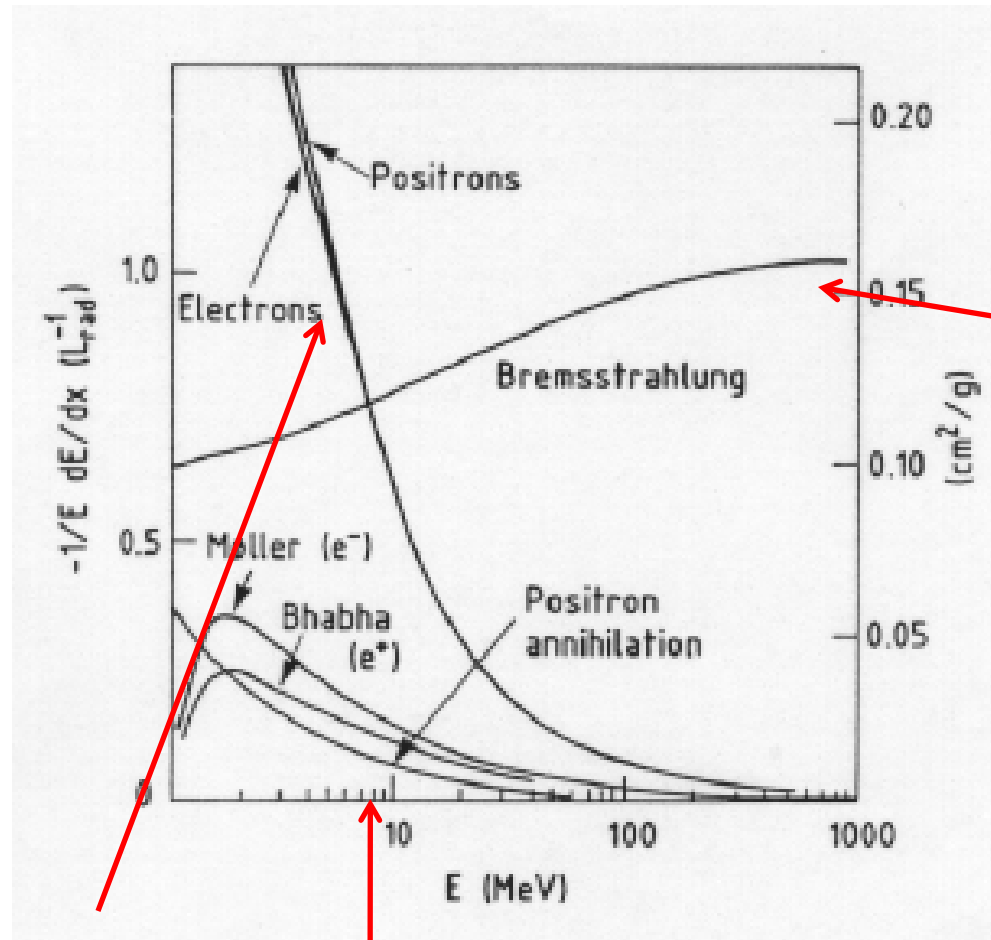
Electromagnetic Interactions -- Bremsstrahlung

- When charged particles pass through matter which is dense enough that they start to interact with the atomic nuclei:
 - Collisions leading to particle scattering
 - Large energy transfer, resulting in bremsstrahlung radiation
 - Emitted photon can be very energetic → start a shower



Electron Energy Loss

- Dominant energy-loss process depends on electron energy



Ionization and
excitation at low E

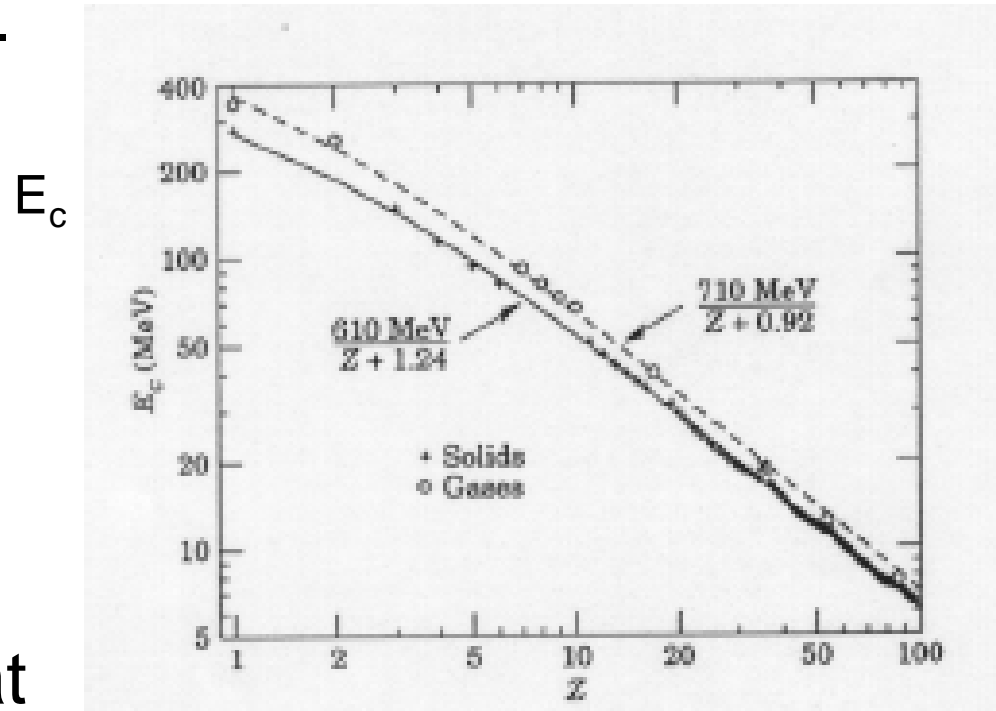
Critical energy
~ 600 MeV/(Z of material)

Bremsstrahlung
dominates at
high energy –
can lose large
energy in 1 brems

E_c = Critical energy
-- crossover where
probability of
bremsstrahlung =
ionization probability

E_C – Critical Energy

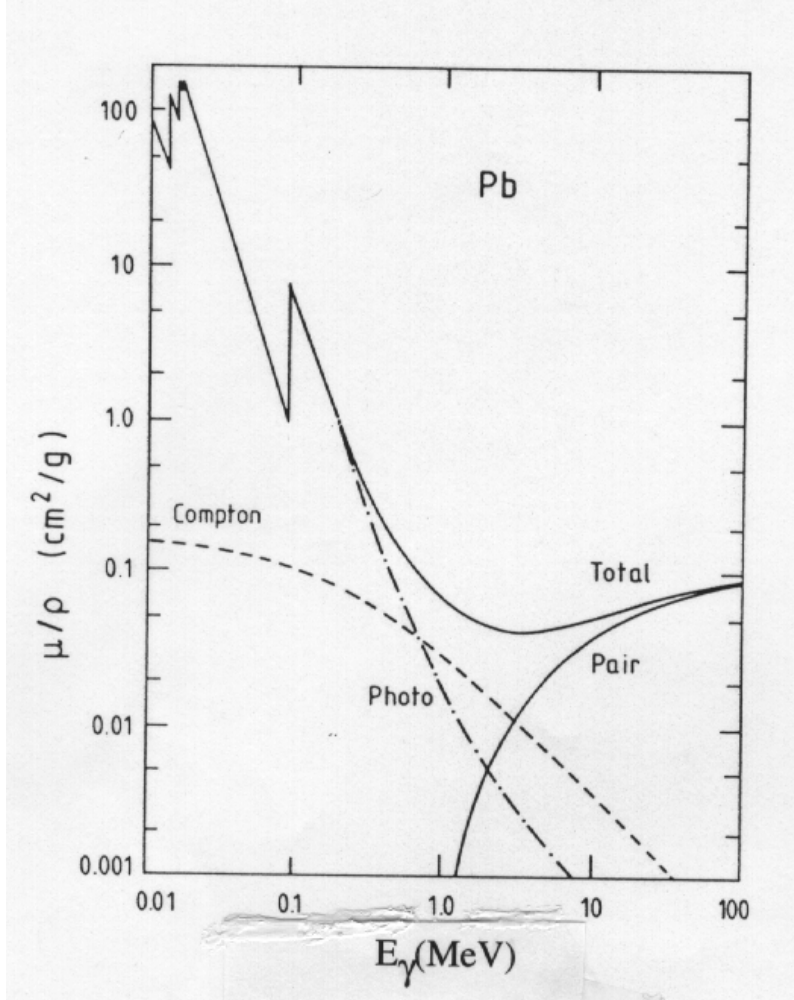
- E_C = Critical energy -- crossover where probability of bremsstrahlung = ionization probability
- EM shower stops multiplying at E_C – ionization/excitation at lower energies
- $\sim 1/Z$ behavior of E_C
 - Pb=7.4 MeV,
Fe=22MeV



Z of material

Photon Interaction with Matter

- Photon from bremsstrahlung (along with electron/positron from pair production) form the electromagnetic shower



Photon interactions

- photoelectric effect dominates for Energy 10 – 100 keV ($\sigma \sim 1/E^3$)
- Compton scattering at low energy ($\sigma \sim 1/E$)
- Pair production above energy threshold, dominates at high energy

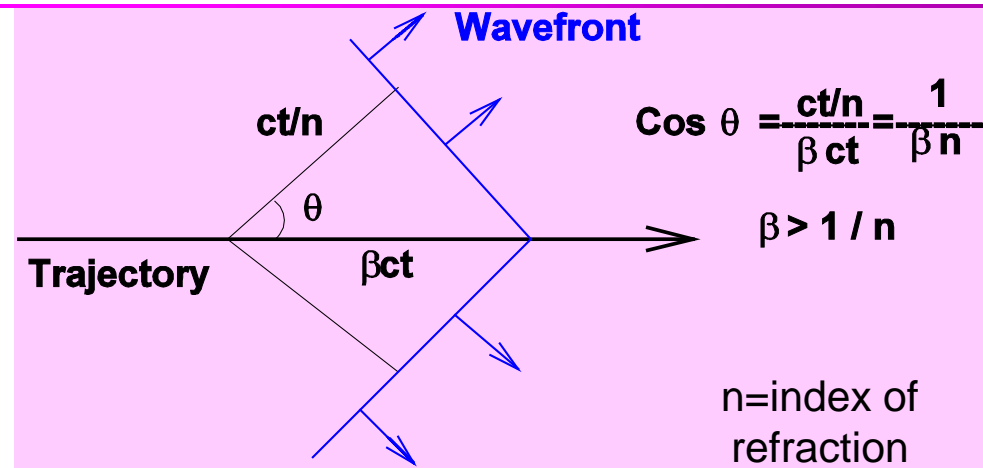
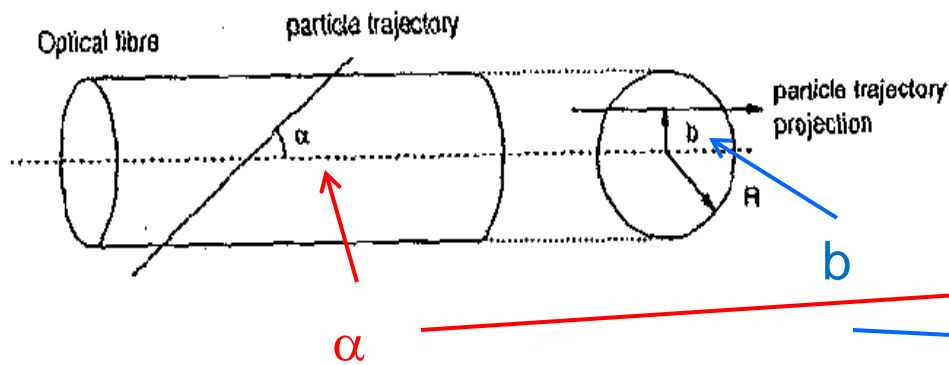
Cherenkov Light Generation

- When high energy charged particles traverse dielectric media, a coherent wavefront is emitted by the excited atoms at a fixed angle θ : called Cherenkov light.
- Sensitive to relativistic charged particles

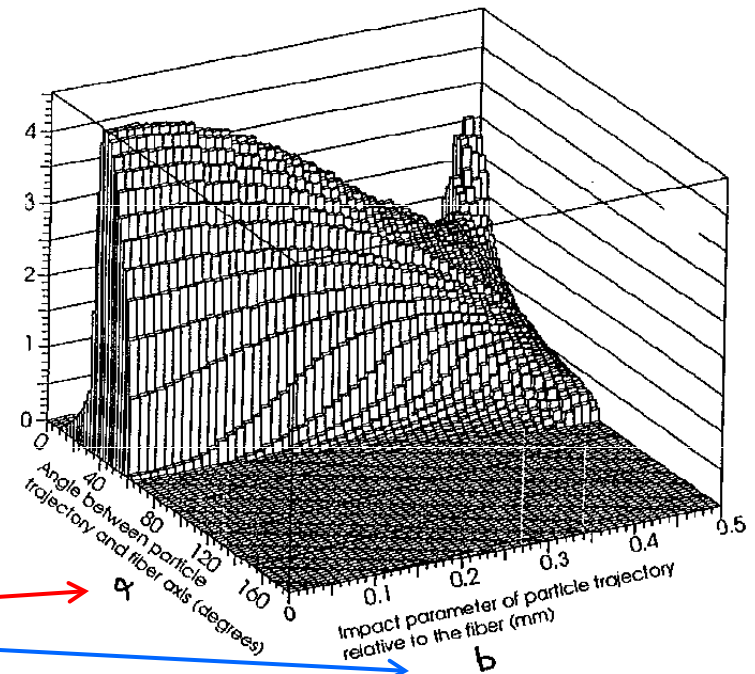
$$\beta_{min} = 1/n$$

$$E_{min} \sim 200 \text{ KeV}$$

- Example detector – quartz fibers :
 - Amount of collected light depends on the angle between the particle path and the fiber axis

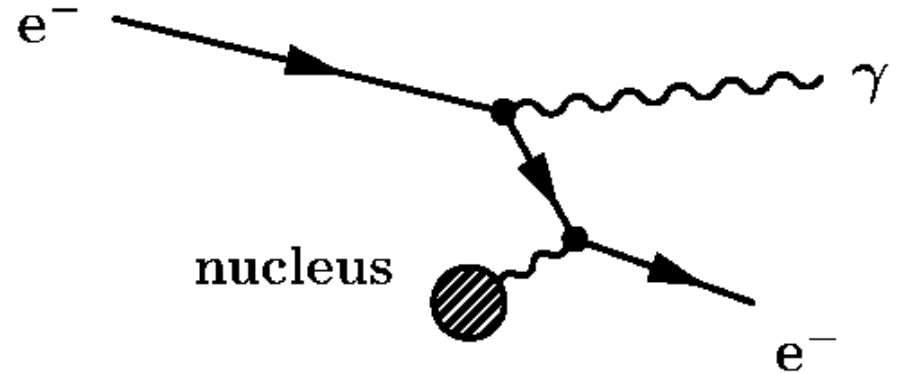
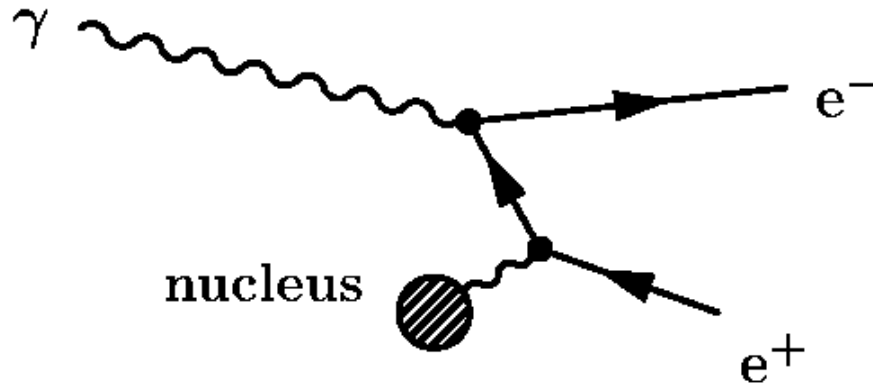


Light out



EM shower formation

Pair Production



Bremsstrahlung

- Pair production and bremsstrahlung are the two processes which perpetuate the EM shower
- Interaction with nuclear E field decelerates electron
- Interaction with the nucleus is necessary to satisfy E/p conservation

How often do we get interactions?

- Radiation length X_0
 - Characteristic distance (in g/cm²) traversed for bremsstrahlung or pair production
 - Mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung
 - 7/9 of the mean free path for pair production of a high-energy photon
 - Sets the scale for the EM shower
 - Input for calorimeter design parameters

- Can be written as:

$$X_0 = \frac{716.4 \text{ g cm}^{-2} \text{ A}}{Z(Z+1) \ln(287/\sqrt{Z})}$$

or can estimate as $X_0 = 180 \frac{\text{A}}{Z^2}$

Radiation length of various materials

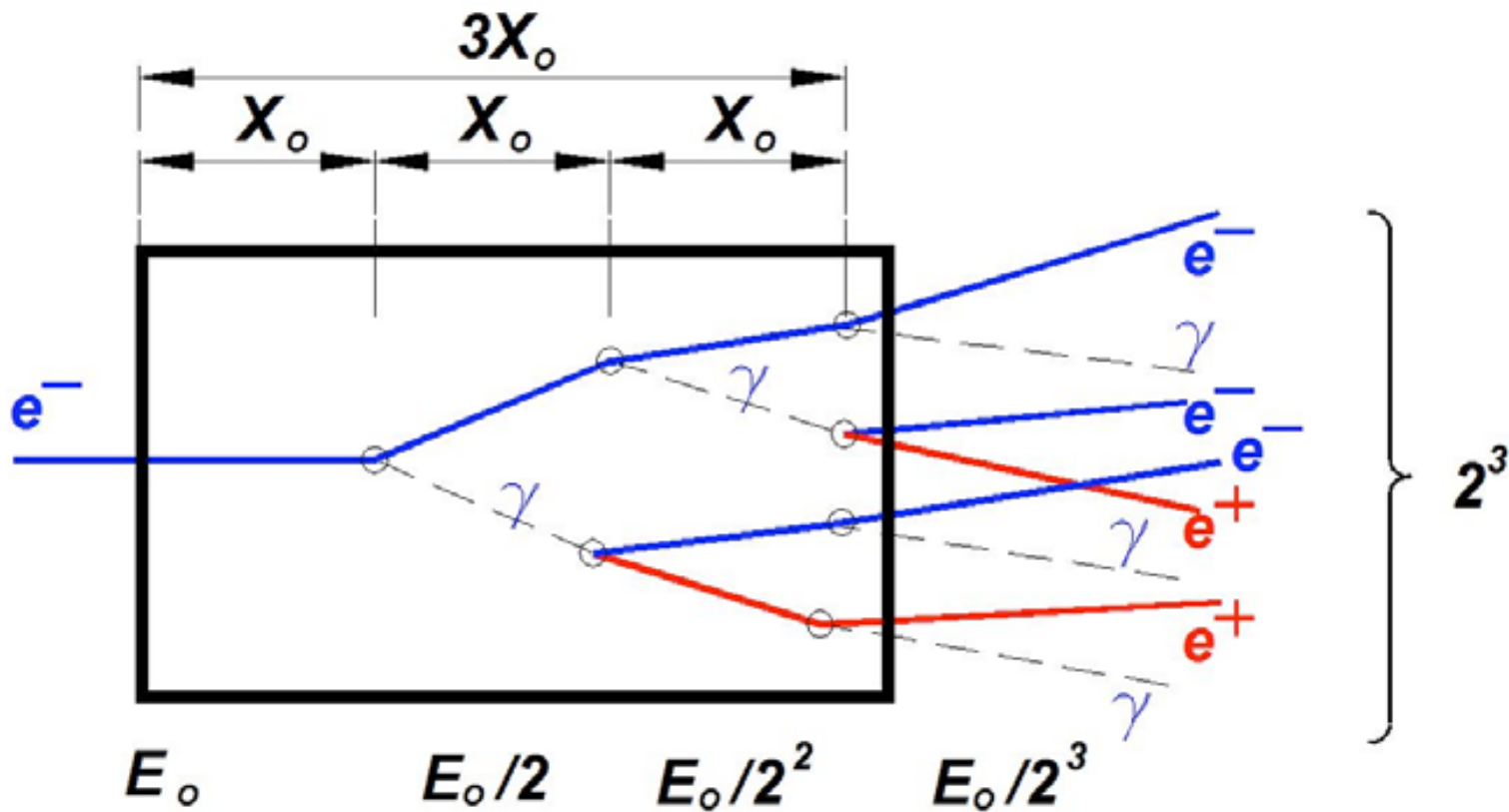
- Compare estimated ($X_0 = 180 A/Z^2$) with actual

Material	A	Z	$X_0(\text{est})$ g/cm ²	$X_0(\text{actual})$ g/cm ²
Lead	207	82	5.5	6.4
Uranium	238	92	5.1	6.0
Silicon	28	14	25.7	21.8

-- why we use thin layers of silicon for tracking detectors (we want the particles to go through) and thick layers of lead or uranium for calorimeters (we want the particles to stop)!

Electromagnetic Shower Development

- Example: incoming electron, interacts within $1 X_0$
- Brem photon interacts: $X_0^\gamma = (9/7) X_0$



Simplified model of EM shower formation

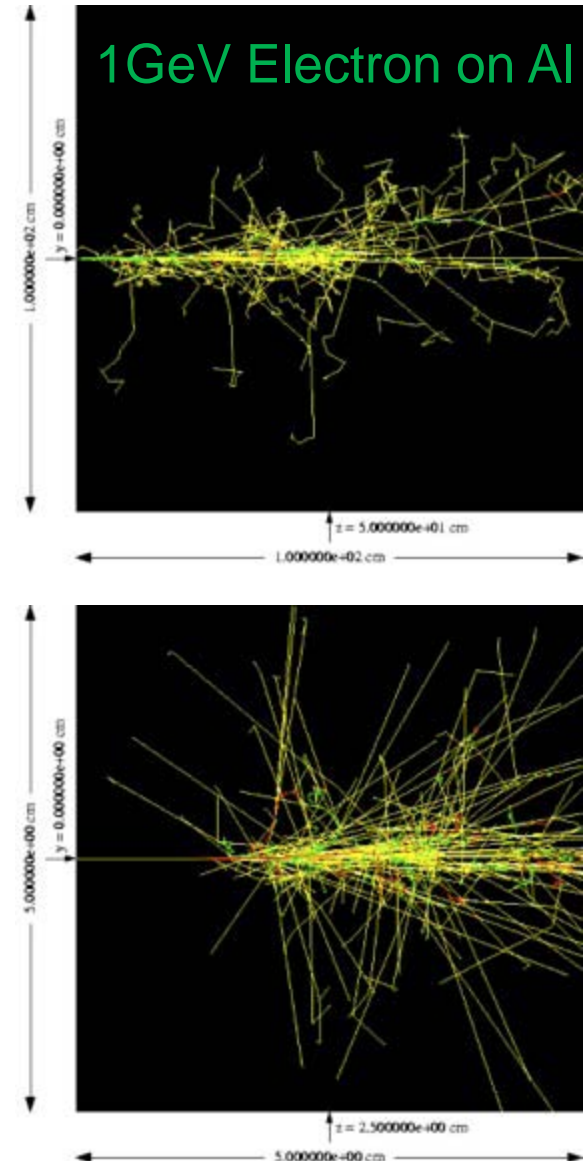
Simplified EM Shower Model

- For example, take electron (γ similar) with $E_0 \gg E_c$
 - After 1 X_0 , we have : 1 e^- , 1 γ , both have $E = E_0/2$
 - After 2 X_0 , we have : 2 e^- , 1 e^+ , 1 γ , all have $E = E_0/4$
 - Exponential growth until $E \sim E_c$ (then shower stops, ionization dominates)
 - some calculations based on this model:
 1. # of particles after t radiation lengths : $N(t) = 2^t$
 2. Average energy of a particle at depth t : $E(t) = E_0/2^t$
 3. Depth at which $E(t) = E'$ (solve eqn 2 for t) :
 $t(E') = \ln(E_0/E')/\ln 2$
 4. Shower -- max # of particles when $E(t) = E_c$ (“shower max”)
 - $t_{\max} = \ln(E_0/E_c)/\ln 2$ depth of shower max
 - $N_{\max} = E_0/E_c$ → # particles proportional to E_0
- Measure E_0 by detecting ionization along the e^-/e^+ tracks

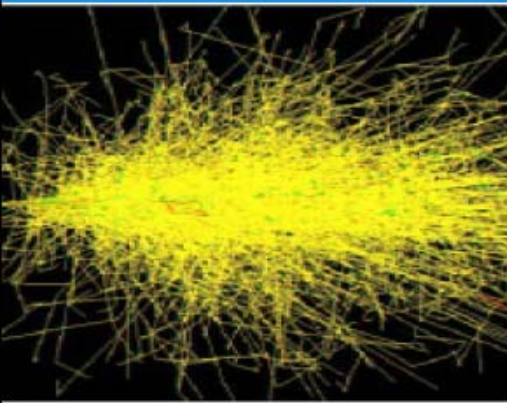
Simple Model of EM shower

- Gives estimate for considering EM calorimeter parameters.
- Missing features:
 - Energy dependence of cross sections
 - Lateral spread → multiple scattering
 - Statistical fluctuations
- More detailed simulations needed

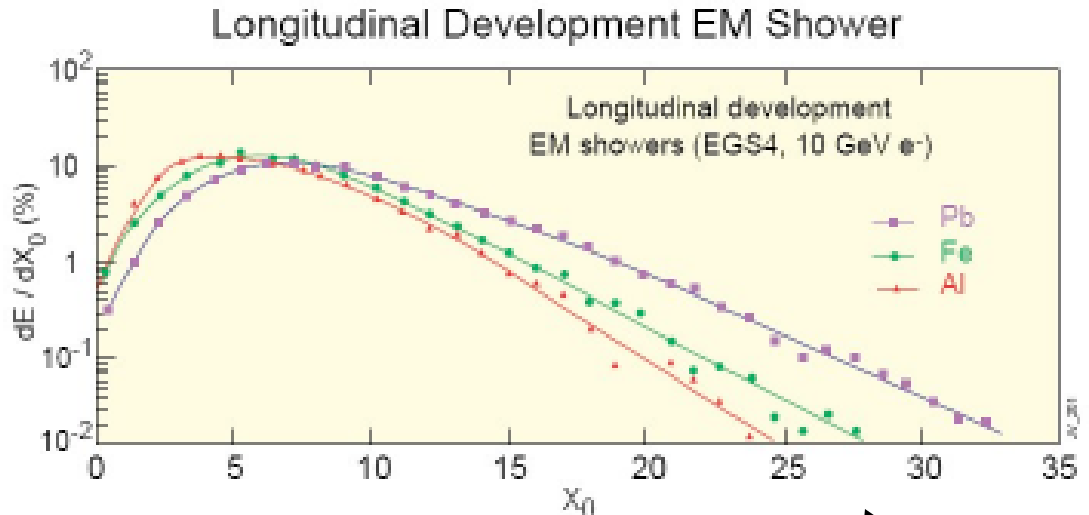
1GeV photon
on Pb



Longitudinal shower profiles



Simulation of 1 GeV electron in copper



- Simulation of electrons shows behavior of shower:

- Multiplication of e/γ up to shower max depth

- Then exponential fall off

- Shower max at $\sim 6 X_0$

- Differences with Z

- Deeper shower max

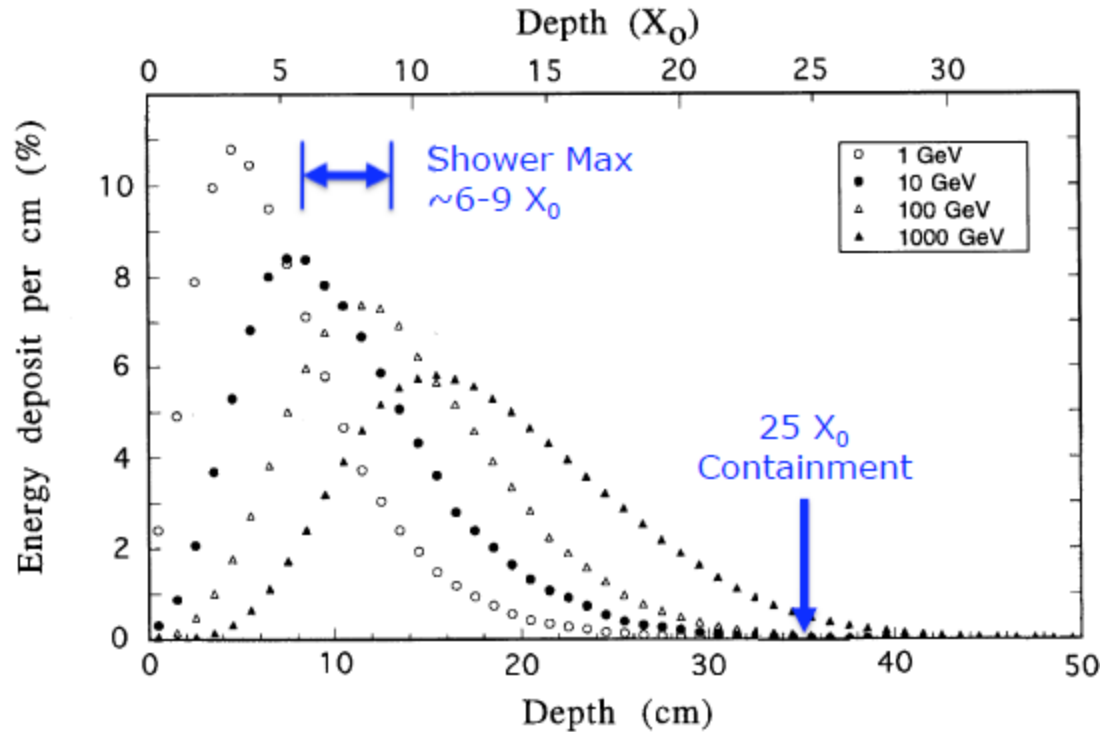
- Slower fall

- **Critical energy goes as $1/Z$**

Shows depth needed for containment of shower

Longitudinal Shower Profile

- Simulation of energies of incoming electron from 1 GeV to 1000 GeV
- Look at energy deposit per cm (%) versus depth



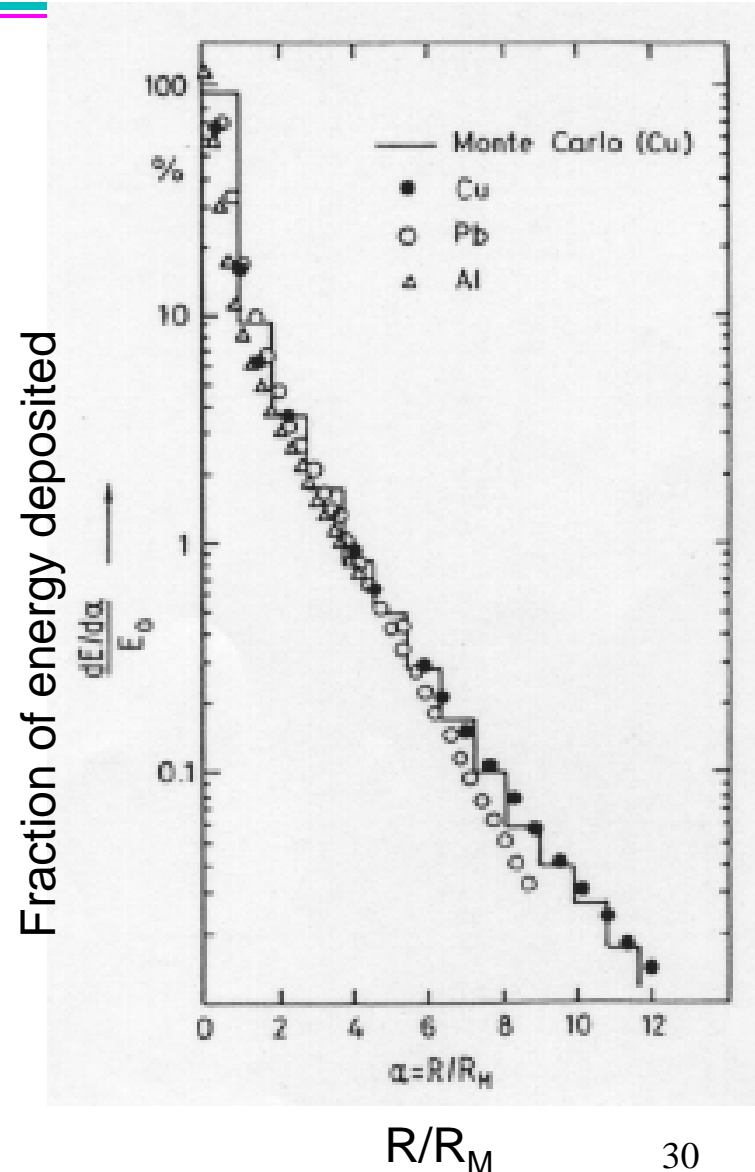
(Courtesy of R. Wigmans)

- Energy dependence of calorimeter depth needed for containment of shower

Lateral Shower Profile -- Moliere Radius

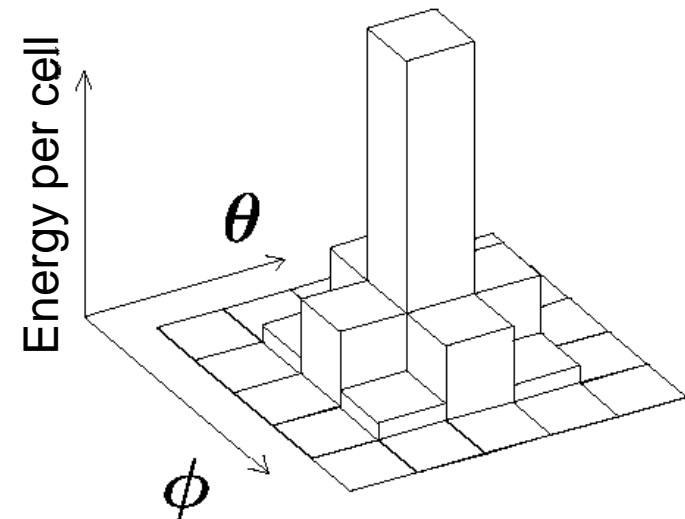
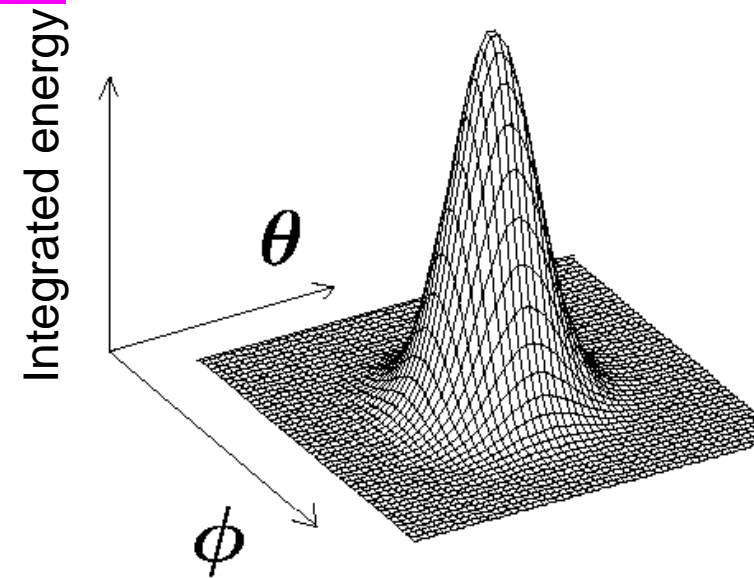
- Characteristic transverse size of the EM shower
→ Moliere radius (R_M)
 - average lateral deflection of electron with E_c after 1 X_0
 - $R_M = (21 \text{ MeV}/E_c)X_0$
 - 99% of shower in 3 R_M

Fraction of energy deposited as a function of distance (in units of R_M)



Lateral Shower Profiles

- R_M important parameter for shower separation
 - Calorimeter cell granularity should be $< R_M$ for precise position measurement



Energy Resolution

- In our simple model, detectable signal (which gives us E) is proportional to N (# of e/γ – large number)

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

In reality, we aren't able to detect all of the energy:

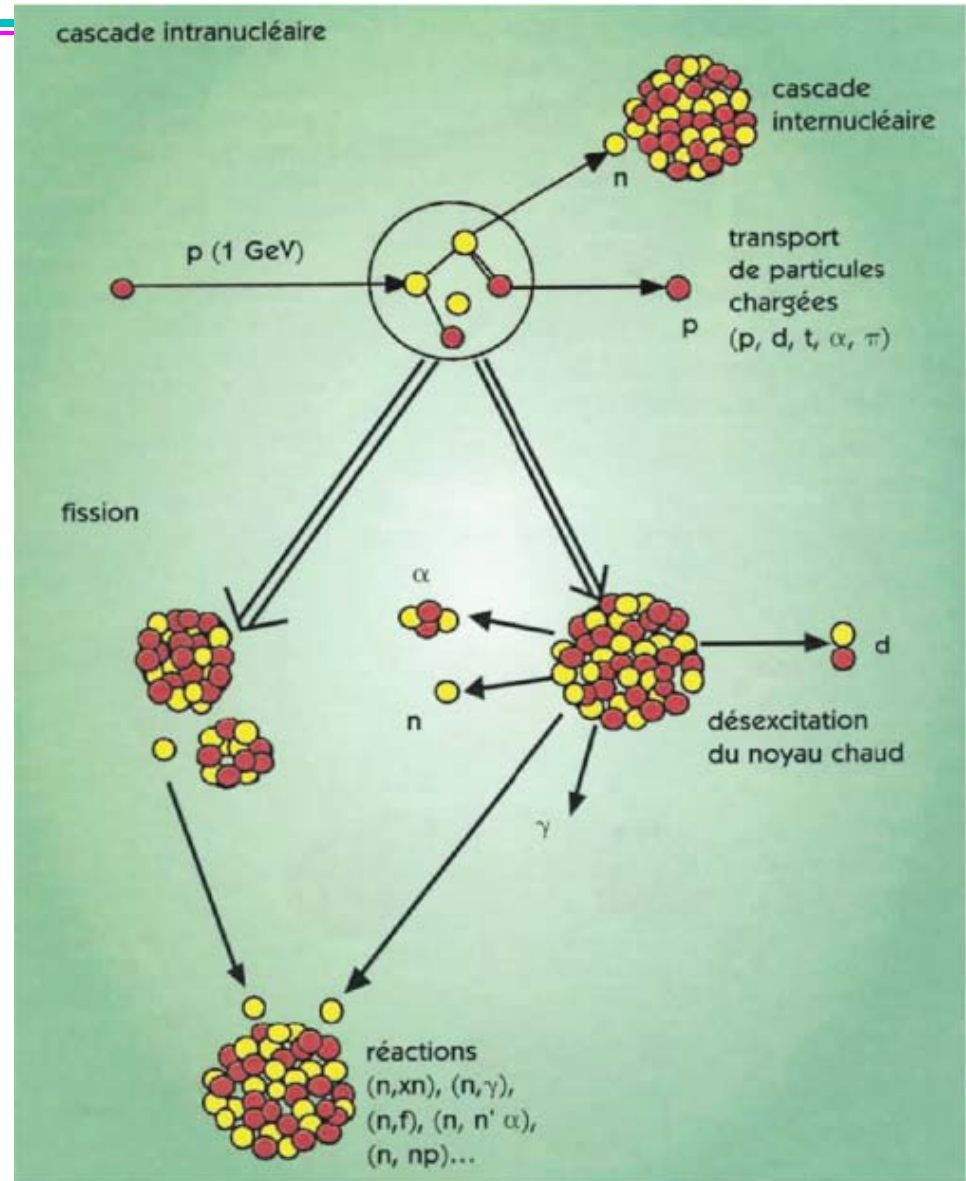
- upstream non-instrumented material
- leakage from back of calorimeter or into adjacent towers
- reconstruction effects

Examples: intrinsic resolution for crystal or homogeneous noble liquids 1-3%

Sampling calorimeters 8-12%

Hadronic Calorimetry

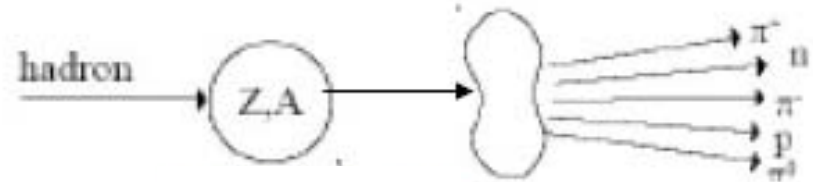
- Hadronic calorimetry is more difficult than electromagnetic
 - More complicated processes
 - More susceptible to fluctuations
 - Inherently poorer resolution
 - But essential in HEP to get the full picture of the interaction!



From Chris Tully

Hadronic showers

- Inelastic collision of π, K, p, n with atomic nuclei



- r_N (range of nuclear force, radius of nuclei) $\sim 10^{-15}\text{m}$

$$\rightarrow \sigma_N \sim \pi \times 10^{-30} \text{ m}^2 \sim 30\text{mb}$$

- Probability of collision

$$= \frac{N_{\text{nucleons}} \cdot \sigma_N}{\text{Area}_{\text{target}}} = \rho_{\text{Nucleons}} \sigma_N dx$$

- If we know the beam intensity I ,

$$\frac{dI}{I} = - \text{prob of collision}$$

$$= - \rho_{\text{Nucleons}} \sigma_N dx$$

$$I = I_0 e^{-\rho_{\text{Nucleons}} \sigma_N x} = I_0 e^{-x/\lambda}$$

- λ interaction length

- scale of hadronic shower

$$\lambda = \frac{1}{\rho_N \sigma_N}$$

- Crude calculation of λ :

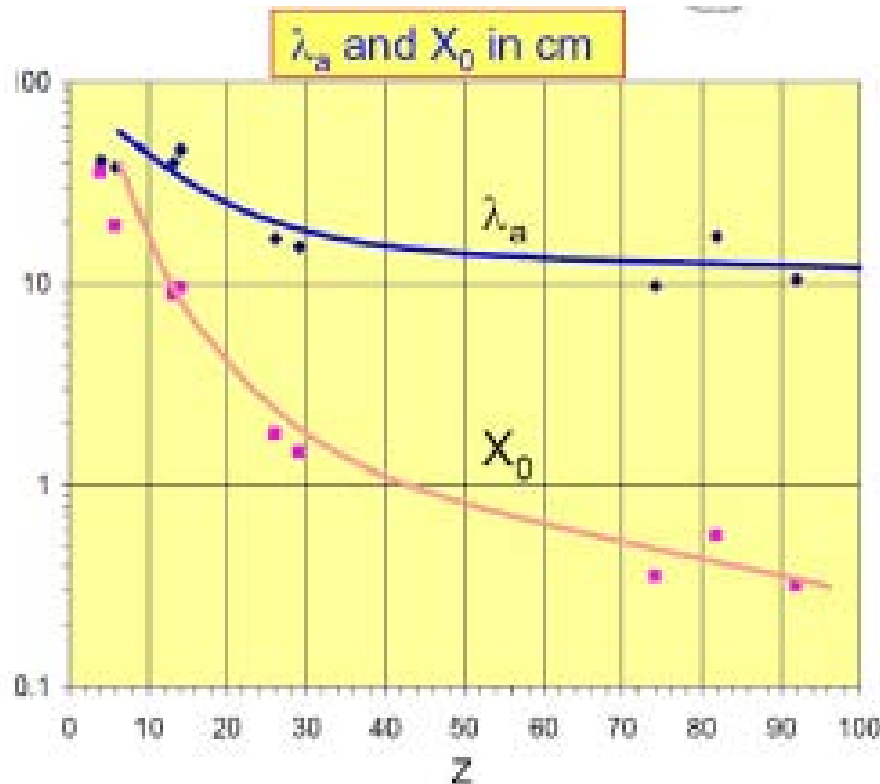
$$\rightarrow \rho_N = N_A / \text{cm}^3 = 6 \times 10^{23} / \text{cm}^3$$

$$\rightarrow \lambda = 53\text{cm}$$

- Also estimate $\lambda \sim 35 A^{1/3}$

Interaction length

- In EM showers, Radiation length X_0 was the scale
- In HAD showers \rightarrow Interaction Length λ
 - \rightarrow Also called absorption length, λ_a , λ_{int}



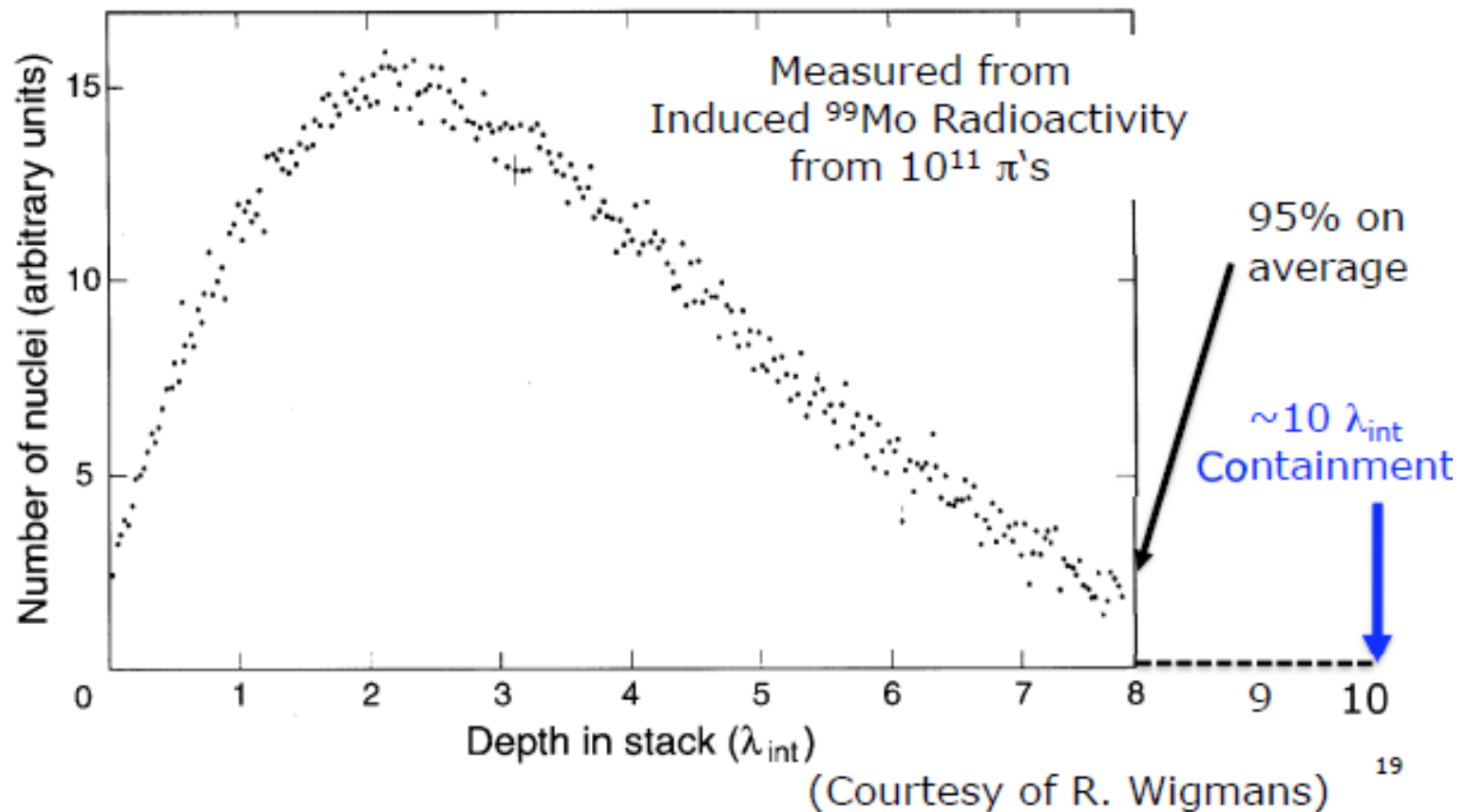
	X_0 (cm)	λ_{int} (cm)
Pb	0.56	17.0
PbWO ₄	0.89	18.0
Fe	1.76	16.8
Cu	1.43	15.1

Hadronic showers

- Many components
 - Fast secondaries (Number of particles $\sim \ln(E)$)
 - Ionization energy loss (mip) -- $\sim 10\%$ of shower energy
 - Nuclear interactions $\pi^0 \rightarrow \gamma\gamma$ — EM component
 - Lots of neutrons – slow showering means LHC detectors can't wait
 - “clumpy” and spread out
- EM and HAD interactions
 - Per nucleon, σ_{brem} proportional to Z^2 , σ_{had} prop. to $A^{2/3} \sim Z^{2/3}$
 - Bremsstrahlung goes higher faster with high Z material
 - Separate EM from HAD showers by using high Z material (eg lead)
 - Useful for particle ID (e/π)

Hadronic Shower Profile and Containment

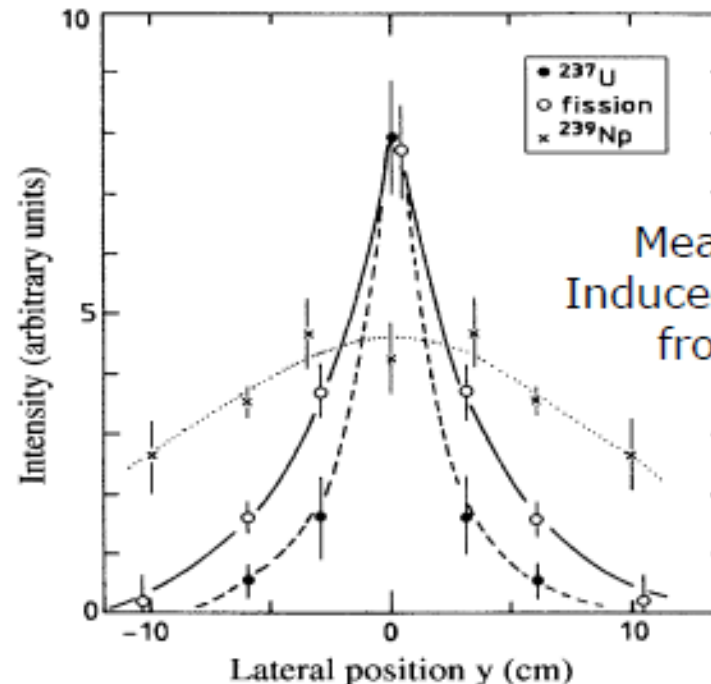
- 300 GeV pion in Uranium



- Shape similar to 1 GeV electron in X_0 shower max 2-3 λ

Hadronic Shower Profile and Containment

- Transverse profile depends on the shower particle species and the depth
 - Narrow EM core in first few λ
 - Broad linear drop-off after several λ
- Features:
 - More γ from π^0 in core
 - Energetic neutrons and charged pions form a wider core
 - Thermal neutrons form a broad tail

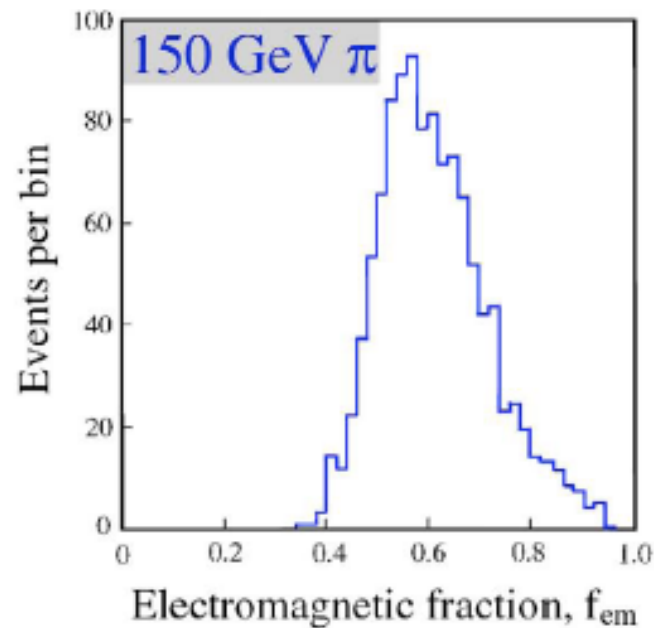
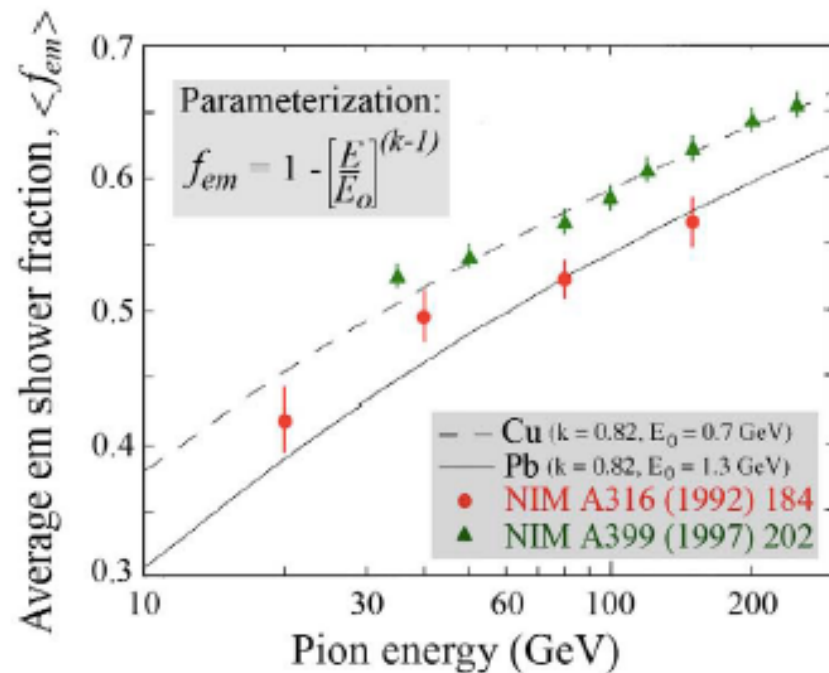


Measured from
Induced Radioactivity
from 10^{11} π 's

(Courtesy of
R. Wigmans)

EM fraction of charged pion showers

- A large fraction of the hadron shower energy shows up as EM energy – $\pi^0 \rightarrow \gamma\gamma$, π^+ ionization/excitation
- Subject to large fluctuations



Hadronic Showers -- Fluctuations

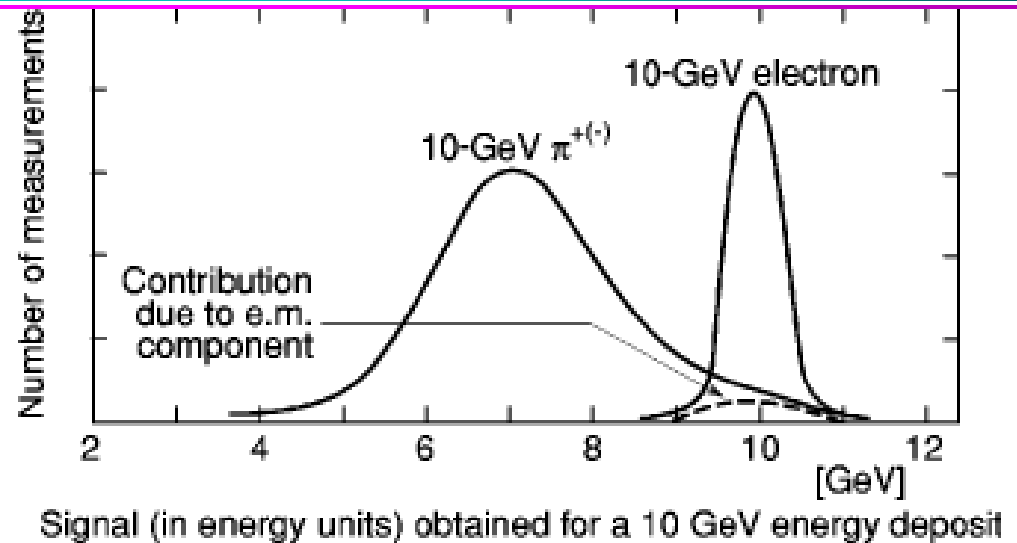
- Much of the HAD energy is EM (from γ 's)
- $\pi^{+/-}$ lose energy by ionization, for many λ
- “binding energy” effects
 - Another effect in HAD compared to EM
 - The medium itself is excited by amounts which are substantial on the scale of the incident energy
 - ⇒ In EM interactions, the nucleus only balances energy/momentum, so energy exchange is $\sim m_e$, small compared to nuclear binding energy ($\sim 8\text{MeV/nucleon}$)
 - ⇒ In HAD showers, substantial (and varying with E and particle type) energy goes into nuclear effects
 - Binding energy appears in calorimeter – nucleus can de-excite, emitting n, p, γ , etc – but often too slow to detect
 - Fluctuations lead to poorer resolution in HAD showers

Compensation and e/h

- Different efficiency for detecting EM vs HAD energy deposits
 - Ratio of efficiencies $== e/h$
 - $h ==$ hadronic energy in the shower, not the energy from the shower of the hadron (which has both EM and HAD)
- Compensation – try to design a calorimeter that has equal efficiency for both types of energy deposit
 - $e/h = 1$
 - But this requires detecting the neutrons, which takes too much time in modern (LHC) situations, due to bunch crossing rate
 - We will see examples of compensation in Lecture 2

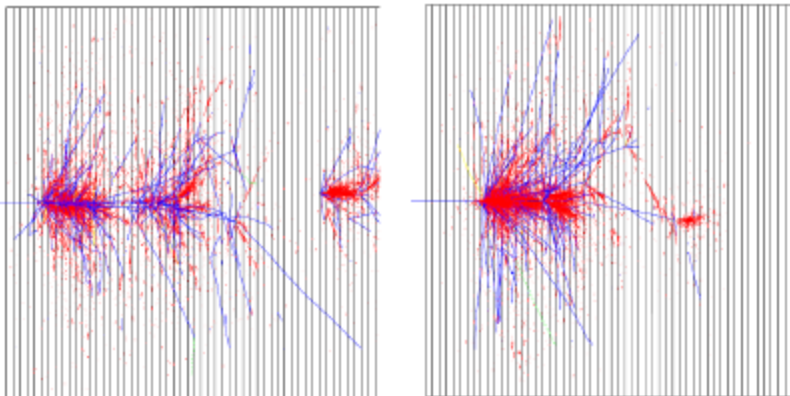
Resolution for Hadron Calorimeters

- EM and HAD components have large fluctuations
- $e/h > 1$ (imperfect compensation)
- EM component not linear with energy



Typical resolutions:

$$\frac{\sigma(E)}{E} \approx \frac{50-100\%}{\sqrt{E}} \oplus 3-5\% (E \text{ en GeV})$$

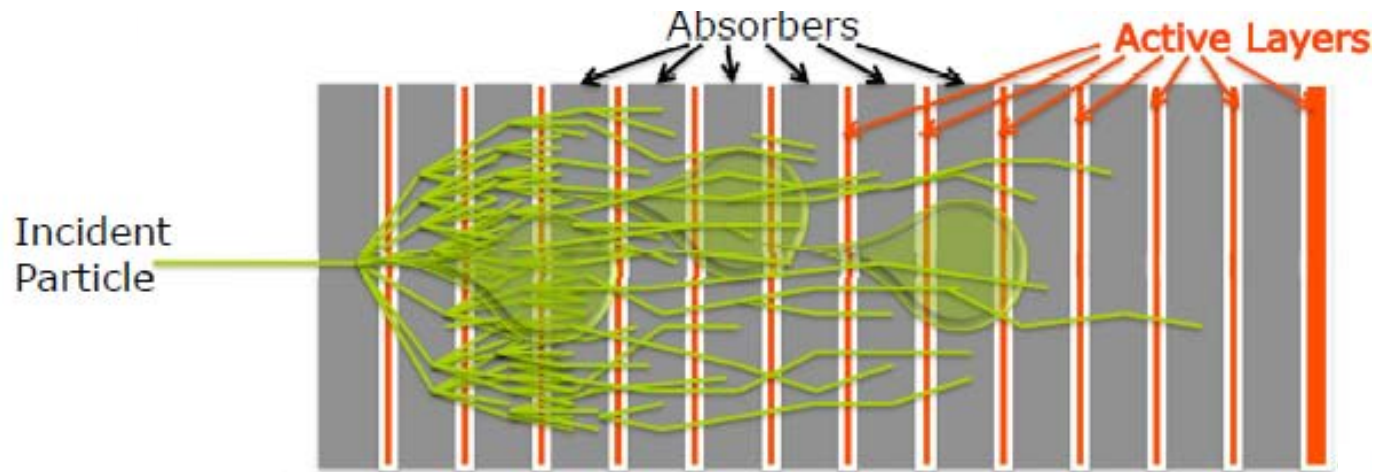


red: em component

blue: hadronic component

Detection of EM and HAD showers

- Two basic types of calorimeters:
 - ➔ Total absorption calorimeter – usually homogeneous material, entire volume is sensitive to the energy deposited
 - ➔ Sampling calorimeter – layers of material (sandwich), interleave absorber (dead material to cause shower) and active material to detect (sample) shower as it progresses



Total absorption calorimeters

- Resolution will depend on counting statistics – particles released by the active material and recorded

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

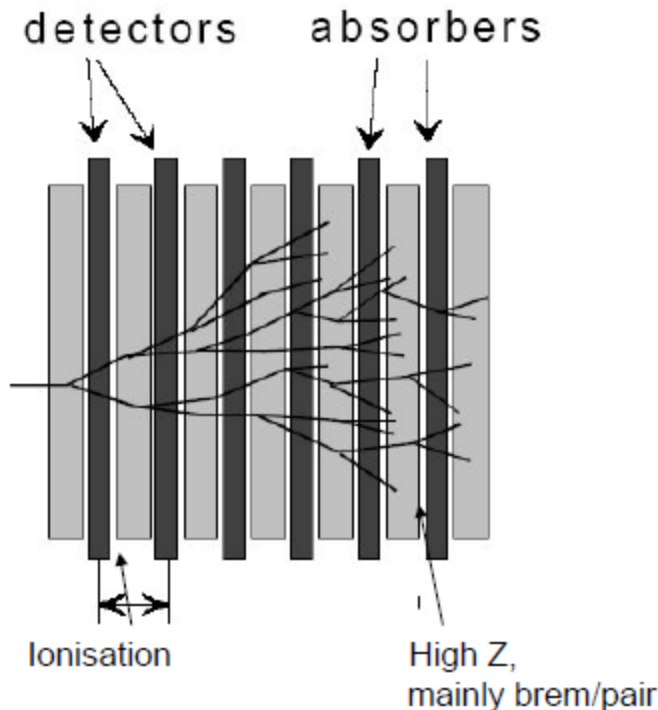
- Examples :
 - ➔ Solid-state detector (Si, Ge(Li)), liberate electron-hole pair with ~3.8 eV on average (bandgap is 1.1 eV) – most of the deposited energy goes into electron-hole pair creation
 - ➔ Scintillator – visible light with energies 2-3 eV can be emitted for a given amount of energy deposition in the crystal
 - ➔ Cherenkov radiator (lead-glass or quartz) will emit in the UV (~3-6 eV) for relativistic charged particles

Total Absorption Calorimeters

- Some disadvantages:
 - Possible to contain an EM shower, but not a HAD shower in a homogeneous calorimeter
 - Can suffer from stability
 - Can't be longitudinally segmented
 - Can be expensive

Sampling calorimeters

- shower created by the absorber layer
 - High-Z (Pb, Ur, W, Fe) material to start EM showers quickly
 - Enough material to contain shower
- Shower detected (sampled) by active layer
 - Scintillator, noble liquid, gas, solid state detector



Sampling calorimeters

- Sampling fraction = (energy deposited in active)/(energy deposited in passive material)
- Advantages
 - Not possible to contain a hadronic shower in a total absorption detector (need 10λ) in a finite thickness (few meters) and for a finite cost
 - With sampling, can use a passive high-Z material for stopping particles
 - Get the best of both worlds, best absorber and best detection
 - Easy to segment – spatial resolution, particle ID
 - Compact and inexpensive to construct
- Disadvantage – worse resolution $\frac{\sigma(E_M)}{E_M} = a \sqrt{\frac{d}{f_{\text{samp}}}} \frac{1}{\sqrt{E}} \approx \frac{5-20\%}{\sqrt{E}}$

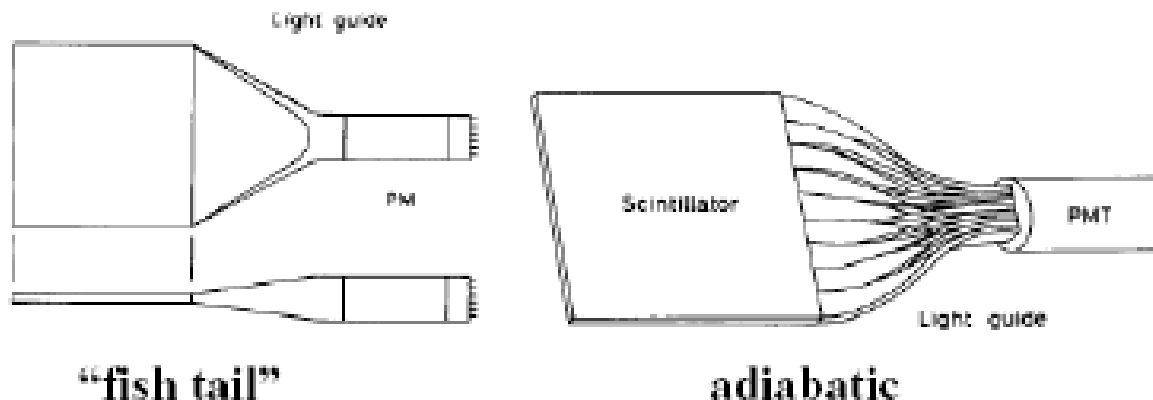
Active Layers

- Detection of ionization/excitation
 - Gas (example L3's Uranium/gas hadron cal)
 - Amplification of signal using proportional tubes
 - But slow (too slow for today's experiments)
 - Noble liquid (eg LAr, LKr)
 - Planar geometry
 - High density of liquid means no amplification needed
 - Radiation hard...but not very fast
 - Scintillators (fibers, tile)
 - Bring light out for photodetector readout
 - Flexible, fast
 - Common choice
 - Cherenkov radiating fibers
 - Also fast

More examples
in Lecture 2

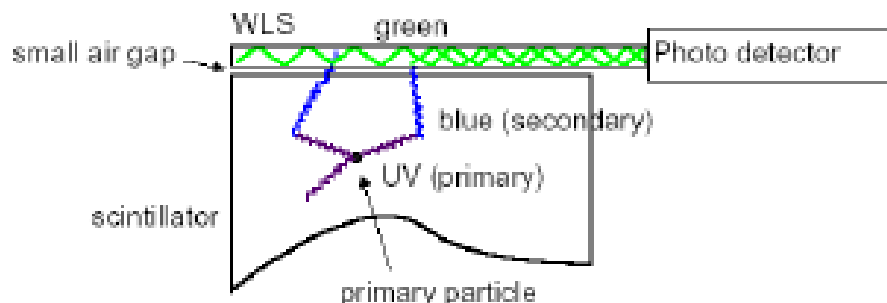
How do we see the signal?

- Must transform energy deposited into signals
 - Light from scintillator in active element
 - Bring out to photodetector – convert light to analog signal
 - Example : photomultiplier tubes (PMT) – avalanche multiplication of photoelectrons
 - Can detect single photon
 - Waveguides maximize collection



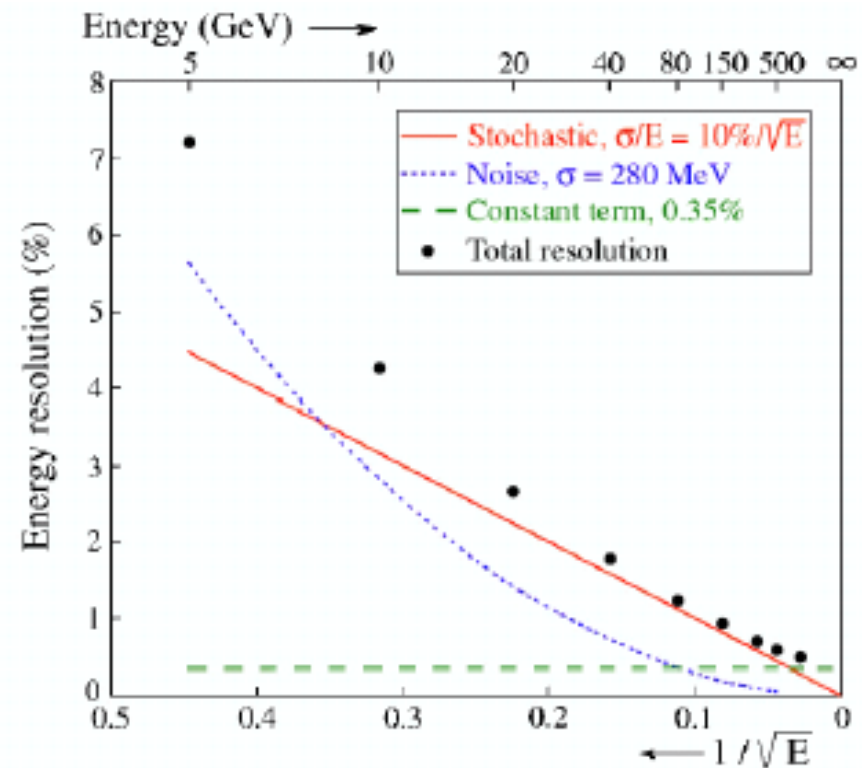
Wavelength shifting

- In some cases it is difficult to collect the light uniformly over the volume of the scintillator
- ie, large area of scintillator → light pipe must have same area (flux per solid angle may not increase) → photodetector must have same area
 - Use a wavelength shifter
 - Absorbs and re-emits light into a material which gives total internal reflection
 - Effectively “cools” photons, so can reduce area

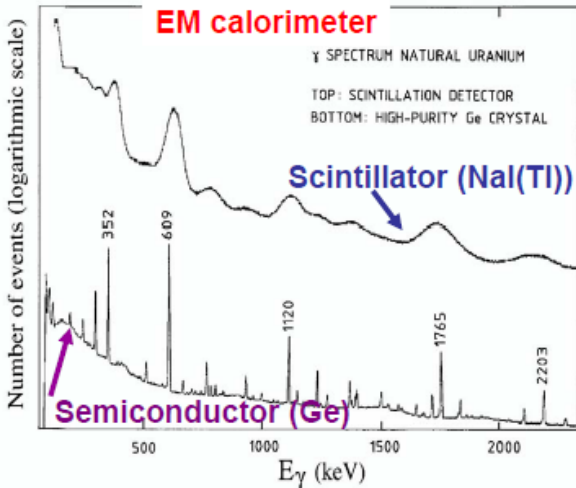


Energy resolution

- Usually written as
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$
- a: intrinsic resolution or stochastic term
 - Determined by technology choice
- b: noise contribution -- material, electronics, pileup
 - Determined by electronics design
- c: constant term -- uniformity, time stability, temperature effects
 - Determined by all aspects



Some examples



From Ursula Bassler

- Resolution also depends on what type of particles you are measuring

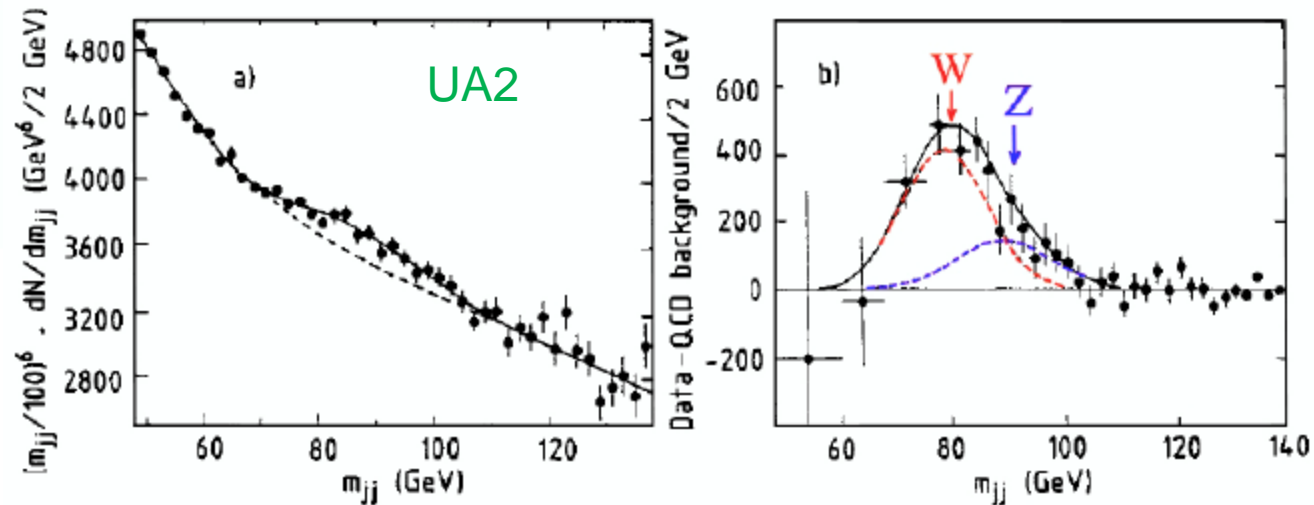
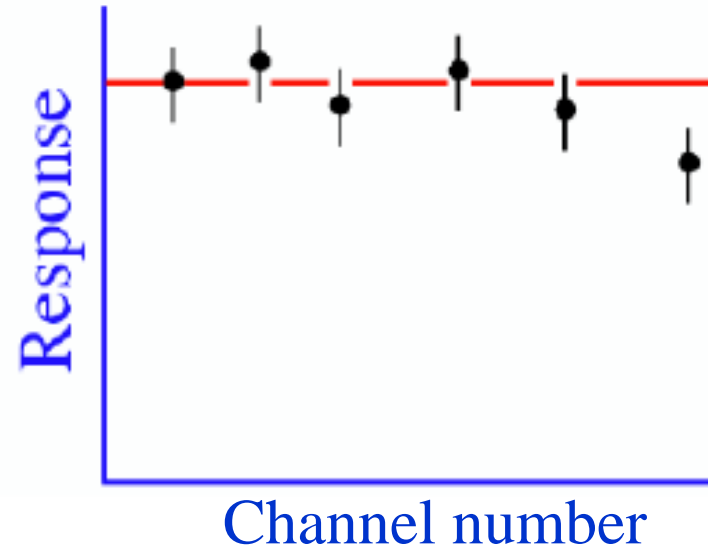
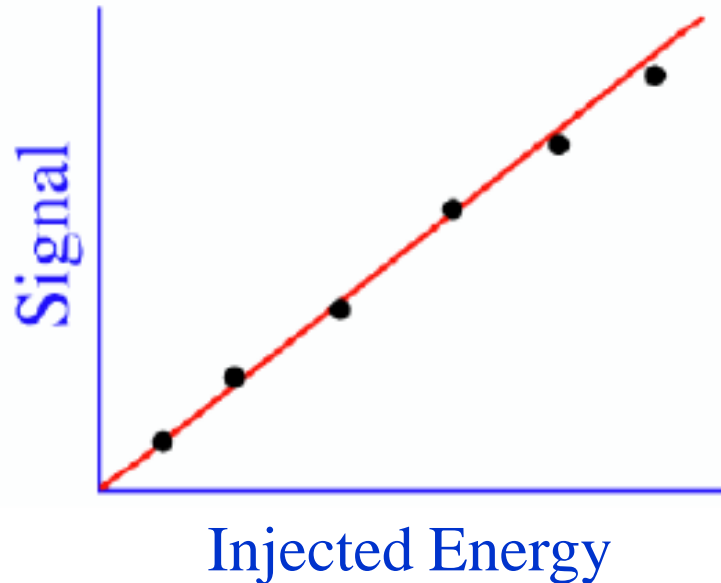


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ 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].

Calibration and Linearity



- Signal (charge) is in pC, digitized to ADC counts – want linear response
- channel-to-channel differences : leakage, upstream material, electronics
- Calibrations:
 - ➔ Relative calibration normalizes the response between all channels
 - ➔ Absolute calibration translates it to energy units (from ADC counts)
- How-to : testbeam, electronics calibration, in-situ, simulation
- More on this in Lecture 3

Summary

- Overview of basics of Calorimetry
 - Electromagnetic and Hadronic showers
 - Physics processes
 - Detection chain
 - Some of the impact of technology choices
- Lecture 2 will talk more about technology choices and impact, with examples of HEP calorimeters