
Experimentele Technieken
in de Hoge Energie Fysica
en verdere toepassingen
Deel 2: Detektie van deeltjes
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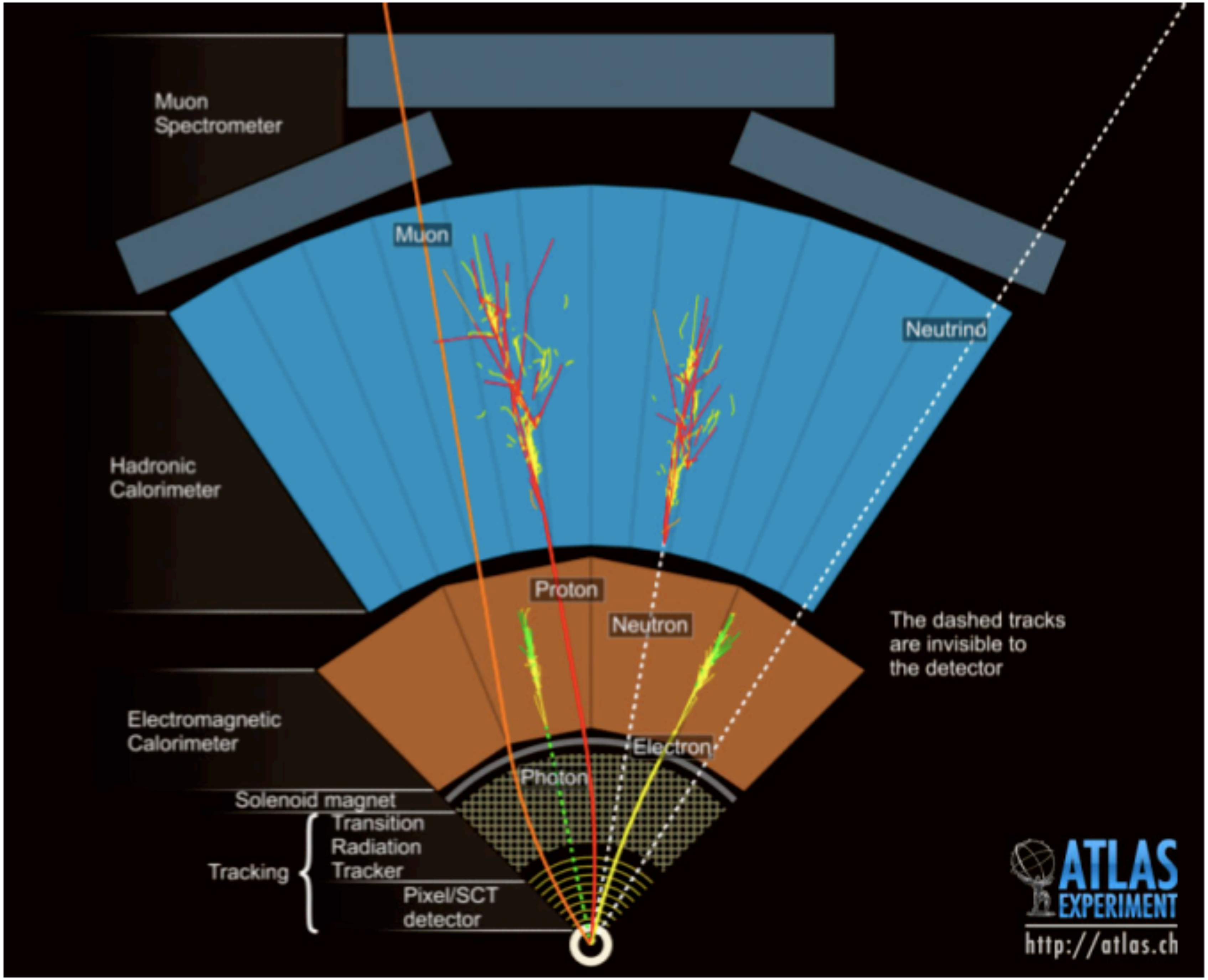
# Inhoud

- Introduction, Kinematics
- Interaction of Charged Particles
  - Ionization, scintillation, Cherenkov and Transition Radiation
  - Bremsstrahlung and nuclear interactions
- Interaction of Neutral Particles
  - photons: photoelectric effect, Compton scattering, pair production
  - neutrons
  - neutrinos
- Electromagnetic Showers
- Hadron Showers

Information from J. Engelfried
G. Herten

# Introduction


Muon
Spectrometer
Muon
Hadronic
Calorimeter
Neutrino
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

# Particles for Detection

| Particle | Mass | Lifetime | Charge | Main interactions |
|---|---|---|---|---|
| Electron | 0.511 MeV | Stable | −1 | Electromagnetic |
| Muon | 105 MeV | $2.2\ 10^{-6}$ s | −1 | Electromagnetic |
| Photon | 0 | Stable | 0 | Electromagnetic |
| Mesons | 140–500MeV | $\approx 10^{-8}$ s | +1, 0, −1 | Strong |
| p, n | 940 MeV | Stable/20min | 1, 0 | Strong |
| Nuclei | 1–240 protons | Many stable | Z (1–92) | Strong |
| Neutrino | < eV | Stable | 0 | Weak |

**Table 1.3: List of the most common directly observable particles.**

# A Few Units

- 1 proton charge = $1.602\ 10^{-19}$ C,
- 1 eV = $1.602\ 10^{-19}$ Joule
- $c$ = 299 792 458 m/s.
- mass of the proton is $1.672\ 10^{-27}$ kg= 938.272 MeV/$c^2$
- mass of the electron = 511 keV/$c^2$
- hbar = $1.054\ 10^{-34}$ *Js*
- hbar$c$= $197.6\ 10^{-15}$ *MeV m*
- Fine structure constant $\alpha$ = 1/137.035
- Classical electron radius $r_e$ = $2.818\ 10^{-15}$ *m* or 2.818 fermi
- 1 barn = $10^{-28}$ $m^2$

http://pdg.lbl.gov/2006/reviews/consrpp.pdf

# Introduction: Particle Detection

- Detection and Identification of Particles and Nuclei important in
  - high-energy physics
  - cosmic ray physics
  - nuclear physics

Basic Idea
**Every effect of particles or radiation can be used as a working principle for a detector**

Main Purpose of particle detectors:
Detection and identification of particles with mass $m$ and charge $z$
In particle physics: Usually $z = 0, \pm 1$, but not in nuclear, heavy ion physics, or cosmic rays

# Examples

- Charged particle (charge $z$) deflected in magnetic field $\rightarrow$ momentum $p$

$$\rho \propto \frac{p}{z} = \frac{\gamma m \beta c}{z}$$

- Time of flight determines particle velocity

$$\beta = \frac{v}{c} \propto \frac{1}{t}$$

- Cherenkov angle determines particle velocity

$$\theta_C = \frac{1}{\beta n}$$

- Calorimeter measurement provides energy measurement

- Charge measurement: Ionization Energy loss

$$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$$

$$\gamma \equiv \frac{c}{\sqrt{c^2 - v^2}} = \frac{1}{\sqrt{1-\beta^2}}$$

- With all the information together one can determine the quadri-vector of the particle.

- Basic detection techniques work mostly for charged particles only.

- Neutral particles usually detected "indirectly" via production of charged particles.

# Literature

## General Detector concepts

- Claus Grupen: Particle Detectors. Cambridge University Press, 2000.
  The best book I know about detectors.
- Konrad Kleinknecht: Detectors for particle radiation. Cambridge University Press, 2nd edition 1998.
  Also a good book.
- Richard C. Fernow: Introduction to experimental Particle Physics. Cambridge University Press, 1986.
- Richard Wigmans: Calorimetry. Oxford Science Publishing, 2000.
  THE book about calorimeters. Written by the expert with all details.
- Lecture notes and Proceedings of ICFA Instrumentation Schools (since 1987 every two years).
- Particle Data Book. short summaries of important things.

+ specialized works (→tasks)

# Introduction: Detectors

Design of Instrumentation and Detectors requires knowledge of

- Basic physics for interaction of charged and neutral particles with matter
- Mechanical Engineering
- Electrical Engineering (high voltage)
- Electronic Engineering
- Interfaces to Trigger, Data Acquisition and Computing (Lecture by Nick Elis)
- Software Engineering (calibration)
- Operation (stability)

- To know any one of them is not sufficient
- You have to apply **all together** to build, operate and **use** an instrument for your **physics measurement**

- **Always keep in mind what you want to measure, and what precision (resolution) you need**

# Charged Particles

# Energy Loss of Charged Particles

A charged particle passing through matter suffers
1. energy loss
2. deflection from incident direction

Main type of reactions:
1. Inelastic collisions with atomic electrons of the material.
2. Elastic scattering from nuclei.

Less important reactions are:
3. Emission of Cherenkov radiation
4. Nuclear reactions
5. Bremsstrahlung

Classification of charged particles with respect to interaction with matter:
1. Low mass: electrons and positrons
2. High mass: muons, pions, protons, light nuclei.

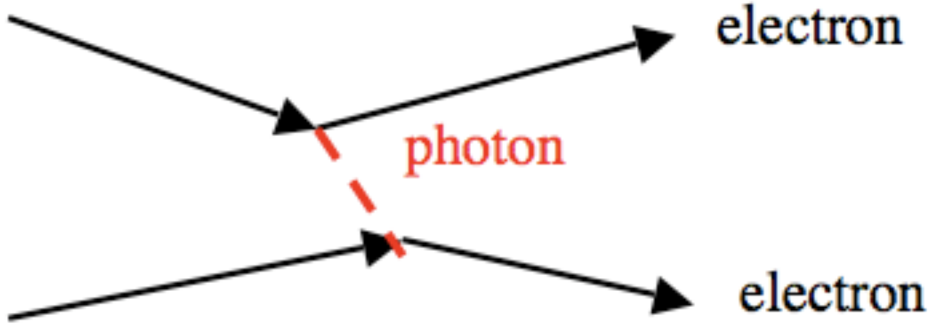
Energy loss:
- mainly due to inelastic collisions with atomic electrons.
- cross section $\sigma \cong 10^{-17} - 10^{-16}$ cm$^2$ !
- small energy loss in each collision, but many collisions in dense material. Thus one can work with average energy loss.
- Example: a proton with $E_{kin}$=10 MeV looses all its energy after 0.25 mm of copper.

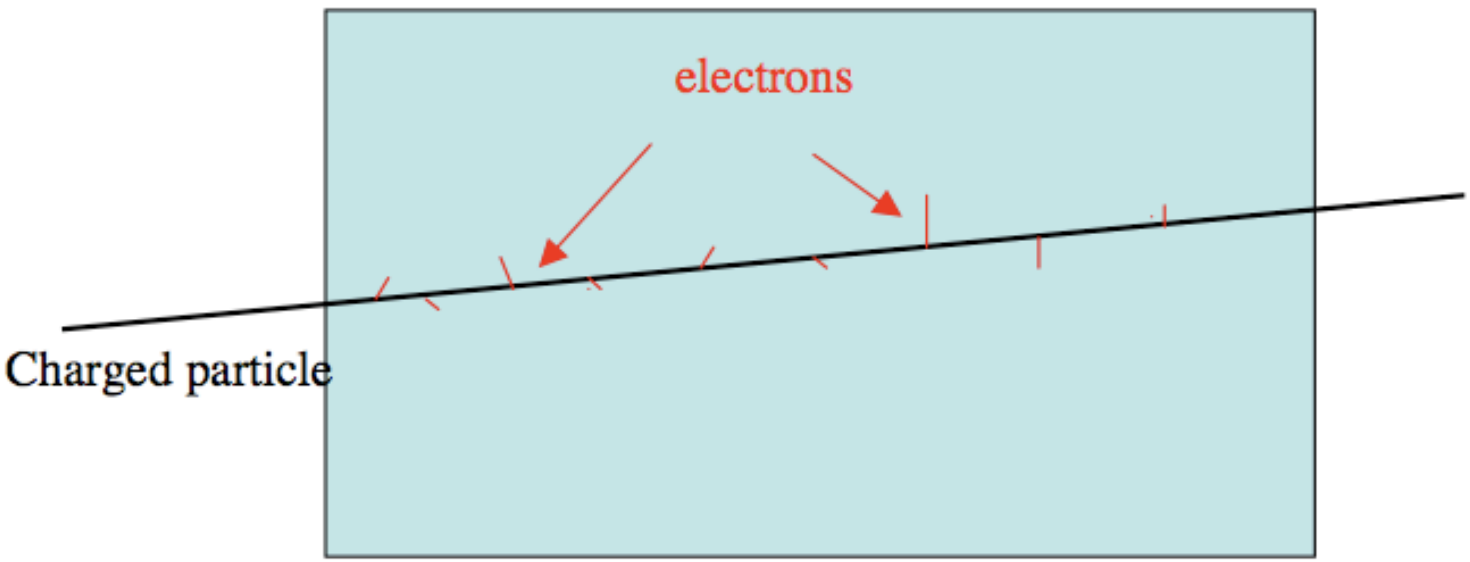
Two groups of inelastic atomic collisions:
- soft collisions: only excitation of atom.
- hard collisions: ionization of atom. In some of the hard collisions the atomic electron get such a large energy that it causes secondary ionisation (δ-electrons).

Elastic collisions from nuclei cause very small energy loss. They are the main cause for deflection.

# Interaction with Matter

Eg electron-electron scattering



# Charged Particles Basic Kinematics

- Conservation of Momentum and Energy: Max. Energy for particle with mass $m$, velocity $v = \beta c$, collision with electron:

$$E_{\text{kin}}^{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma \frac{m_e}{m} + \left(\frac{m_e}{m}\right)^2} = \frac{2m_e p^2}{m^2 + m_e^2 + 2m_e E/c^2}$$

- Limits:
  - Low energy, heavier than electron $(2\gamma \frac{m_e}{m} \ll 1,\, m \gg m_e)$

$$E_{\text{kin}}^{\text{max}} = 2m_e c^2 \beta^2 \gamma^2$$

  - relativistic ($E_{\text{kin}} \approx E$, $pc \approx E$):

$$E^{\text{max}} = \frac{E^2}{E + m^2c^2/2m_e}$$

  - Electron – Electron Collisions ($m = m_e$):

$$E_{\text{kin}}^{\text{max}} = \frac{p^2}{m_e + E/c^2} = \frac{E^2 - m_e^2 c^4}{E + m_e c^2} = E - m_e c^2$$

- Scattering angle (on nucleus $Z$, impact parameter $b$)

$$\Theta = \frac{2z \cdot Z \cdot e^2}{\beta c b} \cdot \frac{1}{p}$$

- Cross Section (Rutherford):

$$\frac{d\sigma}{d\Omega} = \frac{z^2 Z^2 r_e^2}{4} \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \Theta/2}$$

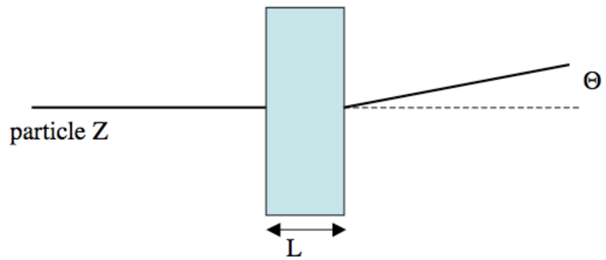
- Multiple Scattering

$$\sqrt{\langle \Theta^2 \rangle} = \Theta_{\text{plane}} = \frac{13.6\,\text{MeV}}{\beta c p} z \cdot \sqrt{\frac{x}{X_0}} \left\{1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right\}$$

$$\Theta_{\text{space}} = \sqrt{2}\, \Theta_{\text{plane}}$$

Approximation by Gaussian:

$$P(\Theta) d\Theta = \frac{1}{\sqrt{2\pi}\Theta_{\text{plane}}} \exp\left\{-\frac{\Theta^2}{2\Theta_{\text{plane}}^2}\right\} d\Theta$$



# Energy Loss for Charged Particles

- Interaction via exchange of Photons (electromagnetic interaction)
- Virtual Photons: Absorbed by atoms in material → Ionization, Excitation
- Real Photons: Radiation is emitted by a charge particle if:
  1. $v > c/n$: Cherenkov radiation
  2. $\vec{v}/c_{\mathrm{ph}} = \vec{v} \cdot n/c$ changes
     (a) $|\vec{v}|$ changes: Bremsstrahlung
     (b) direction of $\vec{v}$ changes: Synchrotron radiation
     (c) $n$ changes: Transition Radiation

# Bethe-Bloch Formula

Bethe-Bloch formula gives the mean rate of energy loss (stopping power) of a heavy charged particle.

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

PDG 2008

with

A : atomic mass of absorber

$\frac{K}{A} = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075 \text{ MeV g}^{-1}\text{cm}^2, \text{ for A} = 1\text{g mol}^{-1}$

z: atomic number of incident particle

I = mean excitation energy

Z: atomic number of absorber

$T_{max}$ : Maximum energy transfer in a single collision $\quad T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$

$\delta(\beta\gamma)$ : density effect correction to ionization loss.

$x = \rho\ s$ , surface density or mass thickness, with unit g/cm$^2$, where s is the length.

dE/dx has the units MeV cm$^2$/g

Project: derive the Bethe-Bloch formula

# History of Energy Loss: dE/dx

1915: Niels Bohr, classical formula, Nobel prize 1922.
1930: Non-relativistic formula found by Hans Bethe
1932: Relativistic formula by Hans Bethe

Bethe's calculation is leading order in pertubation theory, thus only $z^2$ terms are included.

**Additional corrections:**

- $z^3$ corrections calculated by Barkas-Andersen
- $z^4$ correction calculated by Felix Bloch (Nobel prize 1952, for nuclear magnetic resonance). Although the formula is called Bethe-Bloch formula the $z^4$ term is usually not included.
- Shell corrections: atomic electrons are not stationary
- Density corrections: by Enrico Fermi (Nobel prize 1938, for discovery of nuclear reaction induced by slow neutrons).

Hans Bethe
1906-2005

Born in Strasbourg, emigrated to US in 1933. Professor at Cornell U. Nobel prize 1967 for theory of nuclear processes in stars.

# Bethe-Bloch

$p_b = \frac{2 r_e m_e c}{b\beta} z$ Momentum transfer per target electron $b$: impact parameter

Energy transfer (classical approximation)

$$\epsilon = \frac{p_b^2}{2m_e} = \frac{2 r_e^2 m_e c^2}{b^2 \beta^2} z^2$$

Interaction rate per (g/cm$^2$), atomic cross section $\sigma$

$\Phi[\mathrm{g}^{-1}\mathrm{cm}^2] = \frac{N_A}{A} \sigma[\mathrm{cm}^2/\mathrm{atom}]$ $N_A$ Avogadro's number, $A$ atomic mass

$$\Phi(\epsilon)\, d\epsilon = \frac{N_A}{A} 2\pi b\, db\, Z$$

$2\pi b\, db$ area of annulus $Z$ Number of electrons per atom

# Bethe-Bloch

$$\epsilon = \epsilon(b) \Rightarrow b^2 = \frac{2r_e^2 m_e c^2}{\beta^2} z^2 \frac{1}{\epsilon}$$

$$\Phi(\epsilon)\, d\epsilon = \frac{N_A}{A} \pi \frac{2r_e^2 m_e c^2}{\beta^2} z^2 Z \frac{d\epsilon}{\epsilon^2}$$

energy loss

$$-dE = \int_0^\infty \Phi(\epsilon)\, \epsilon\, dx = \int_0^\infty \frac{N_A}{A} 2\pi\, bdb\, Z\, \epsilon\, dx$$

$$-\frac{dE}{dx} = \frac{2\pi N_A}{A} Z \int_0^\infty \epsilon\, b\, db = 2\pi \frac{Z\, N_A}{A} \frac{2r_e^2 m_e c^2}{\beta^2} z^2 \int_0^\infty \frac{db}{b}$$

Problem: Integral is divergent at $b \to 0$ and $b \to \infty$

# Bethe-Bloch

$b \to 0?$ assume $b_{\min} = \frac{h}{2p} = \frac{h}{2\gamma m_e \beta c}$

half the de Broglie wavelength

$b \to \infty?$ if revolution time $\tau_R$ of electron in target atom is smaller than interaction time $\tau_i$ target looks neutral

$$\tau_i = \frac{b_{\max}}{v}\sqrt{1-\beta^2} \quad \text{Lorentz contraction}$$

$$\tau_R = \frac{1}{v_Z \cdot Z} = \frac{h}{I}$$

mean excitation energy $I \approx 10\,\text{eV} \cdot Z$

$\tau_i = \tau_R \qquad \Rightarrow b_{\max} = \frac{\gamma h \beta c}{I}$

$$-\frac{dE}{dx} = 2\pi\ \frac{Z\,N_A}{A}\frac{2r_e^2 m_e c^2}{\beta^2} z^2 [\ln \frac{2\gamma^2\beta^2 m_e c^2}{I} - \eta]$$

$\eta$: screening effect

# Bethe-Bloch

Exact treatment: Bethe-Bloch formula (summary in PDG)

$$-\frac{dE}{dx} = 2\pi \frac{Z\,N_A}{A}\frac{2\,r_e^2\,m_e\,c^2}{\beta^2} z^2 [\frac{1}{2}\ln\frac{2\,m_e\,c^2\gamma^2\beta^2}{I^2}\beta^2 - \frac{\delta}{2}]$$

density correction

$$\frac{\delta}{2} = \ln\frac{\hbar\omega_p}{I} + \ln\beta\gamma - \frac{1}{2}$$

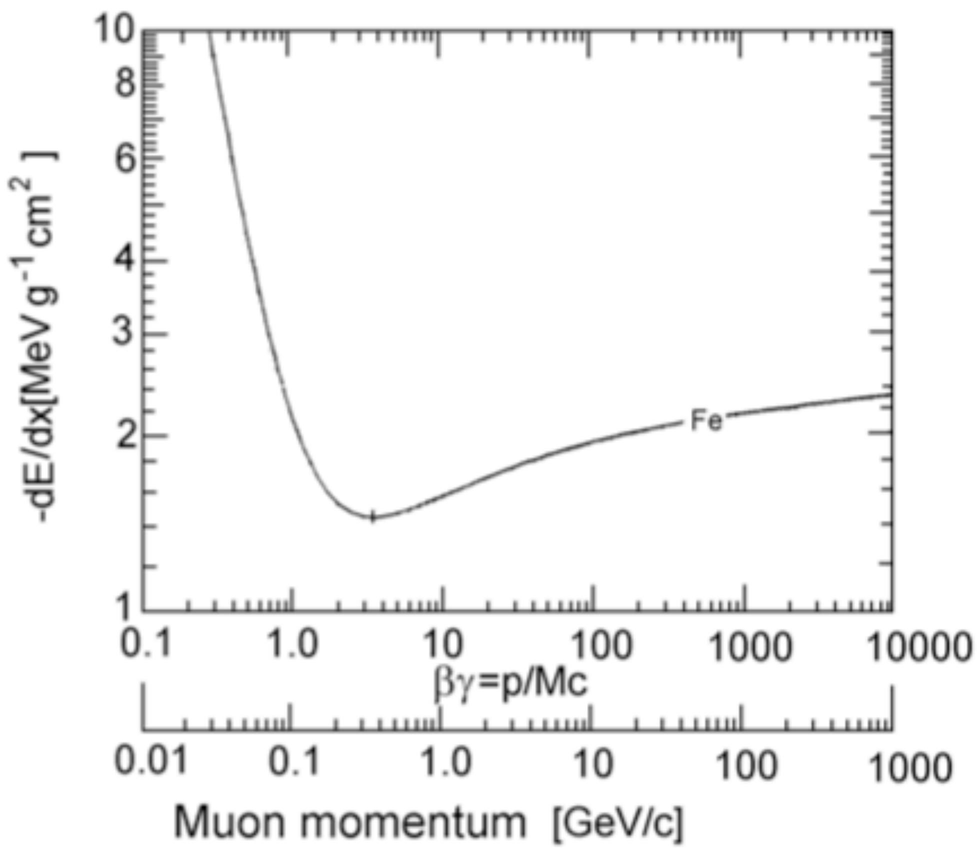
$$\hbar\omega_p = \sqrt{4\pi N_e r_e^2}\,\frac{m_e\,c^2}{\alpha} \quad \text{plasma energy}$$

$N_e$ electron density of absorbing material

$\alpha$ fine structure constant

# Bethe Bloch

Example:
Energy loss of muons in iron




- Minimum at $3 \leq \beta\gamma \leq 4$
- Minimum ionizing particles:
  - helium: $-dE/dx = 1.94\,\mathrm{MeV/(g/cm^2)}$
  - uranium: $-dE/dx = 1.08\,\mathrm{MeV/(g/cm^2)}$
  - hydrogen: exceptionally large $(Z/A = 1)$
- $\ln\gamma$ term: relativistic (logarithmic) rise
- Fermi-Plateau due to density effect
- in gases: Plateau $\approx 60\,\%$ higher as min. ion.

# Examples of Mean Energy Loss

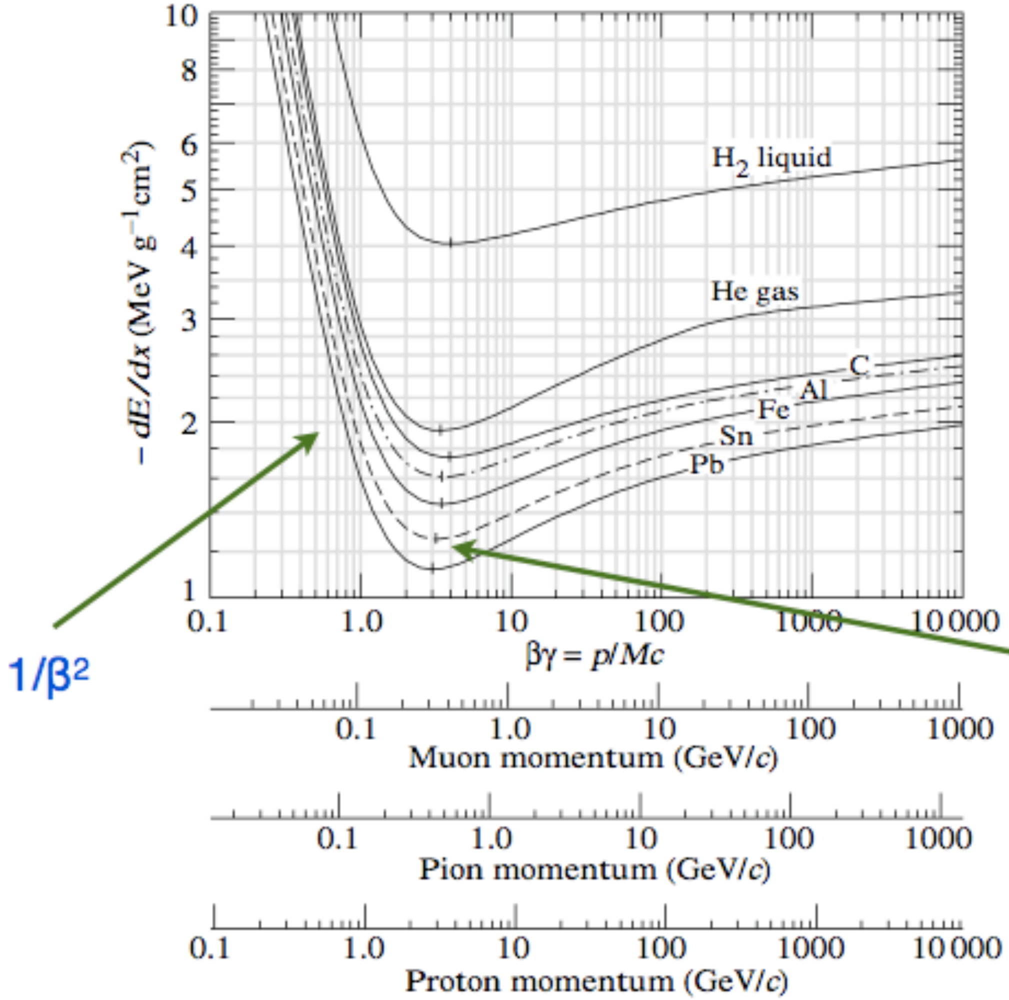



**Figure 27.3:** Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-$Z$ absorbers. See Fig. 27.21.

PDG 2008

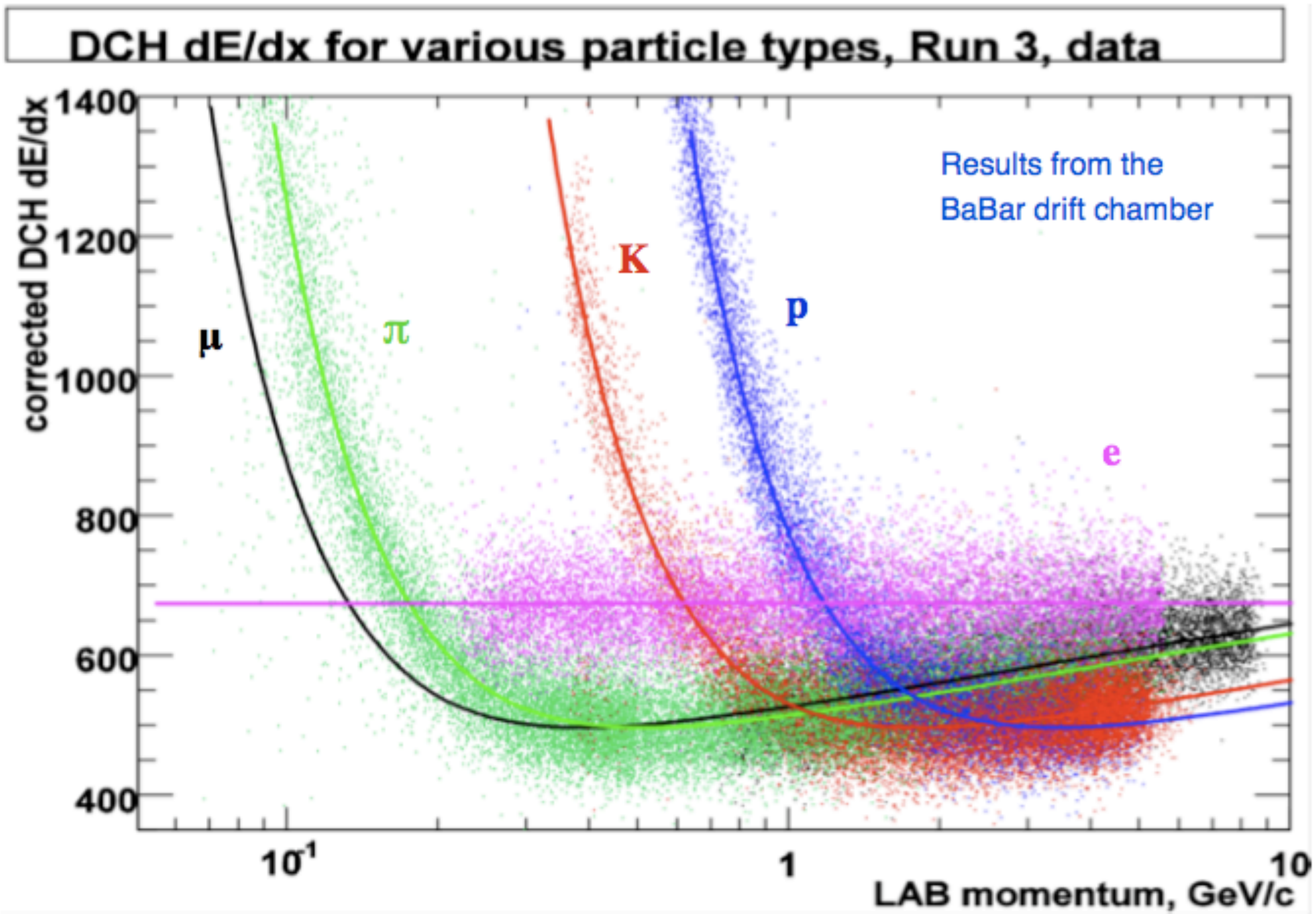
Bethe-Bloch formula:

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}]$$

Except in hydrogen particles of the same velocity have similar energy loss in different materials.

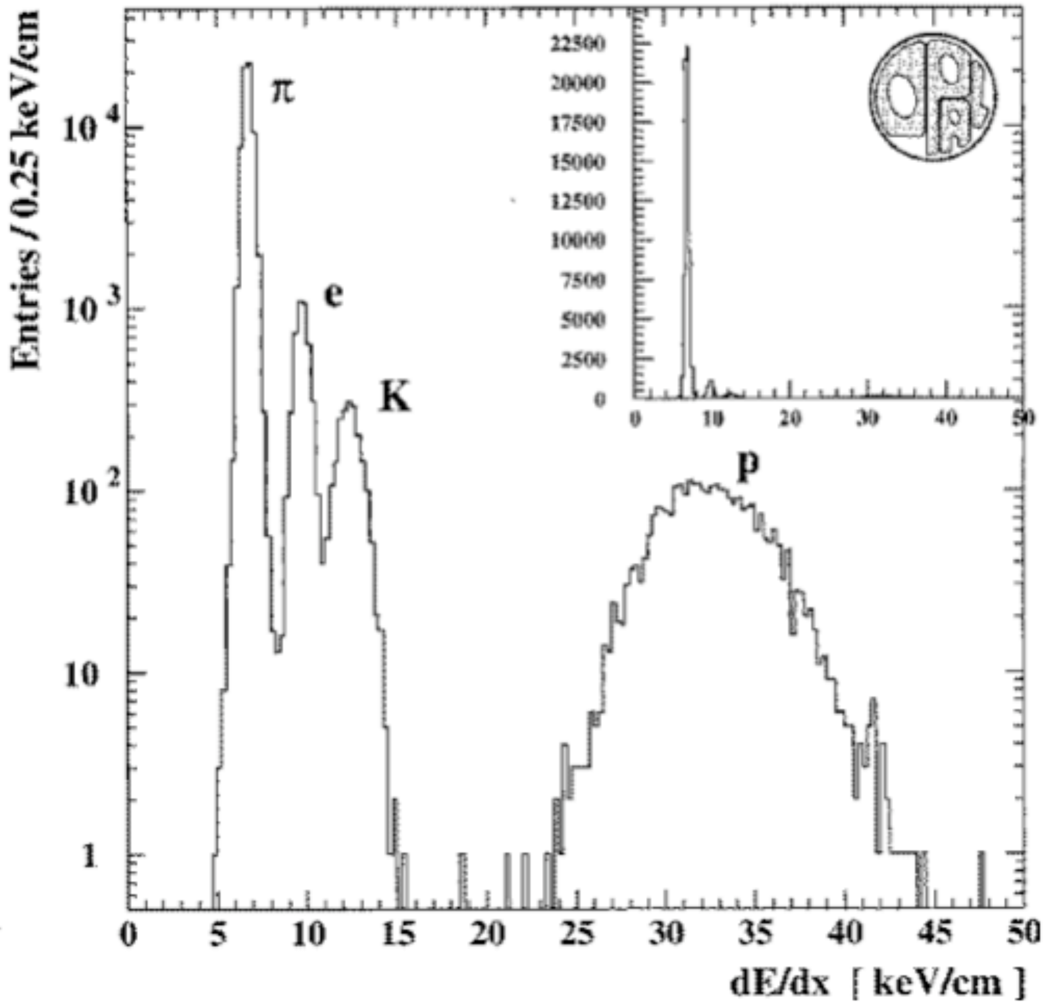
The minimum in ionization occurs at $\beta\gamma$=3.5 to 3.0, as Z goes from 7 to 100

# Particle Identification from dE/dx



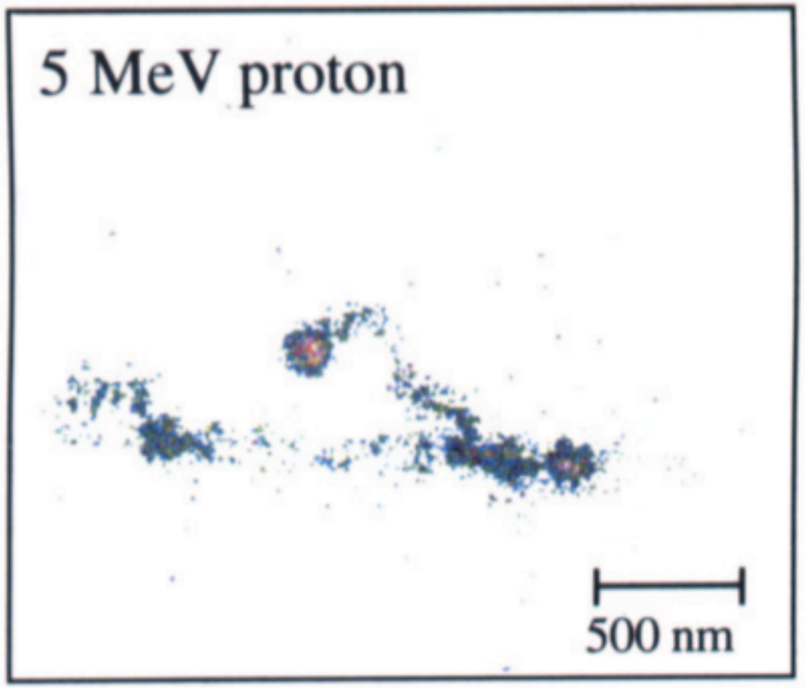

A simultaneous measurement of dE/dx and momentum can provide particle identification.

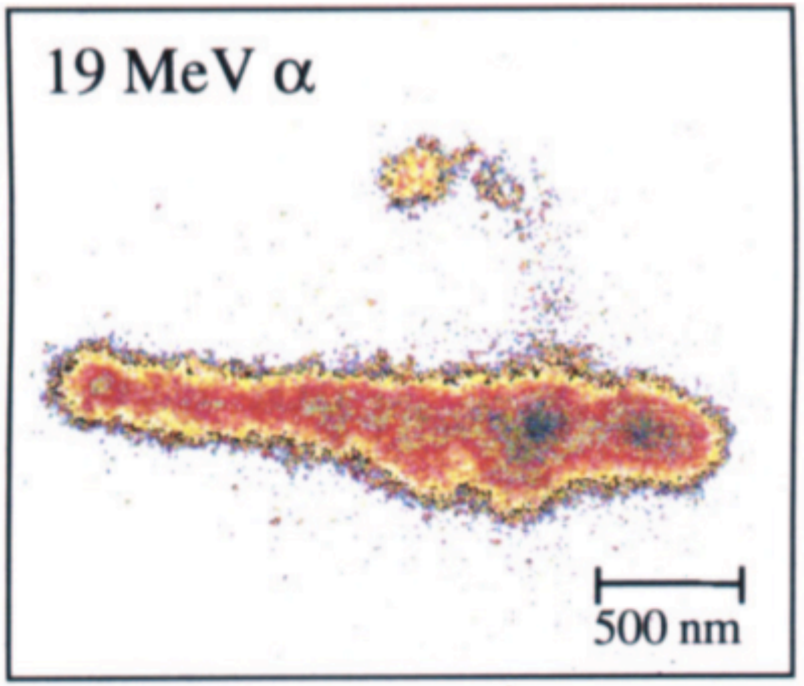
# Particle Identification with dE/dx




Momentum interval 0.45 GeV/$c$ − 0.48 GeV/$c$

# Energy Loss in an optical micro-dosimeter



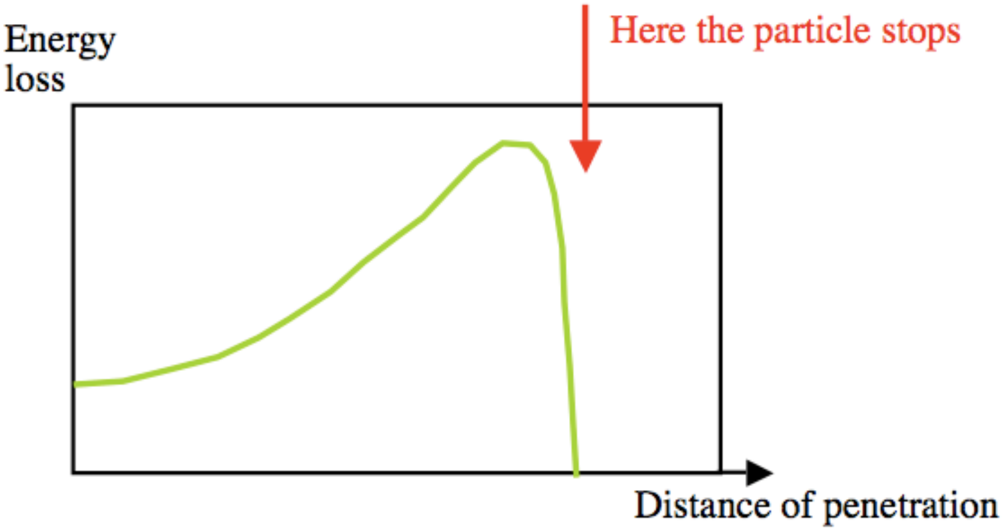

$$\frac{dE}{dx}|_\alpha \gg \frac{dE}{dx}|_p$$

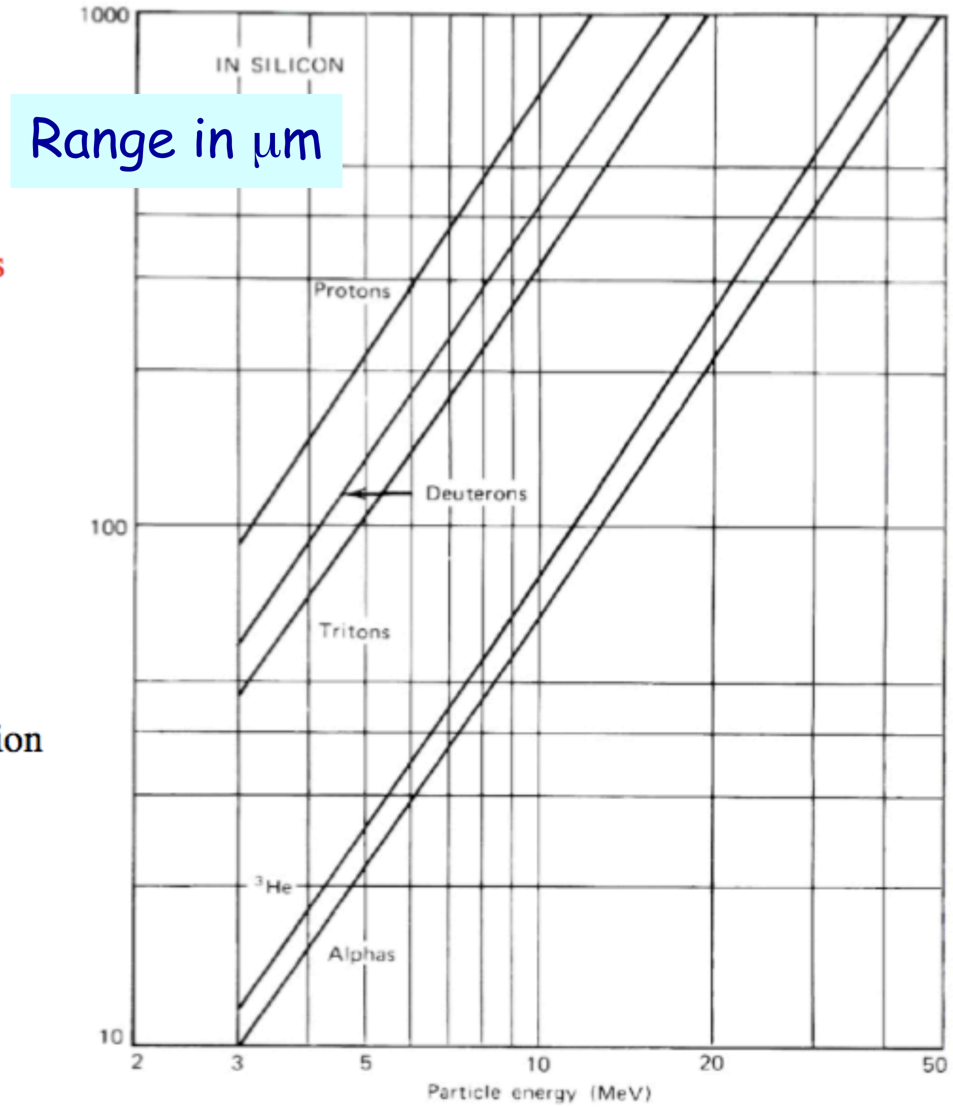
$$\frac{dE}{dx} \propto z^2$$

note increase of ionization at end of track, also the $\delta$-rays

# Stopping Power

Particle looses all the energy and stops



# Distance a 10 MeV particle can cross

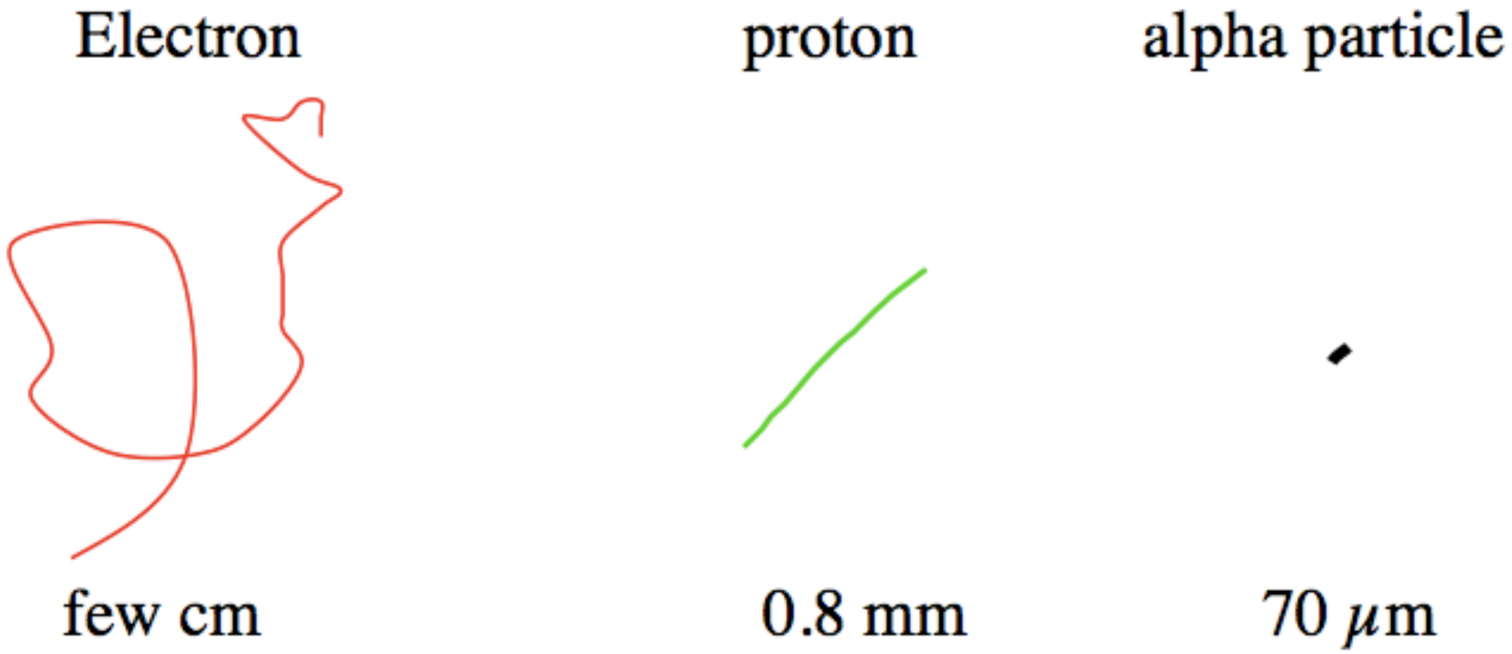
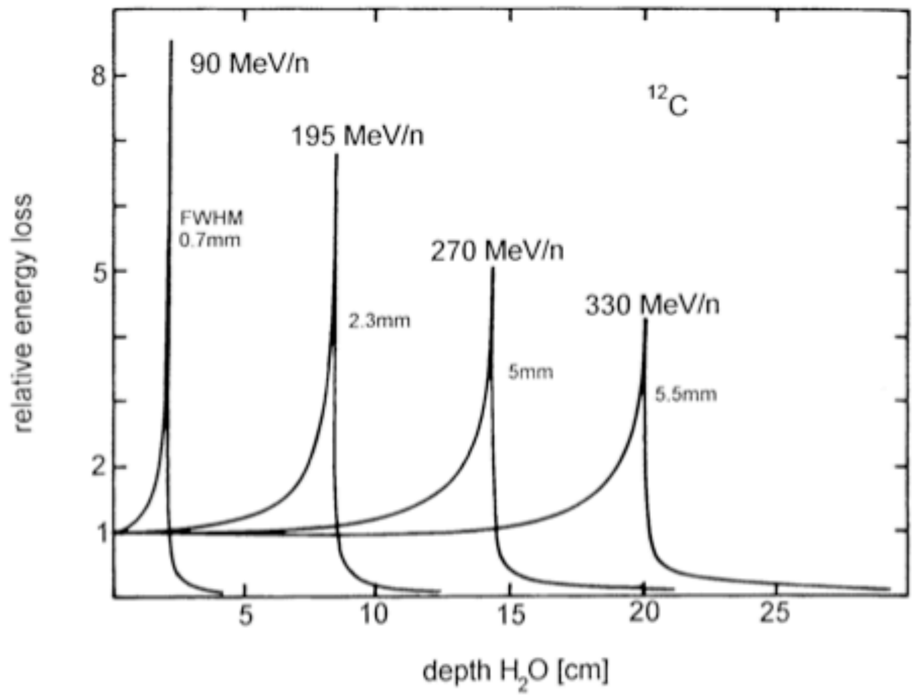
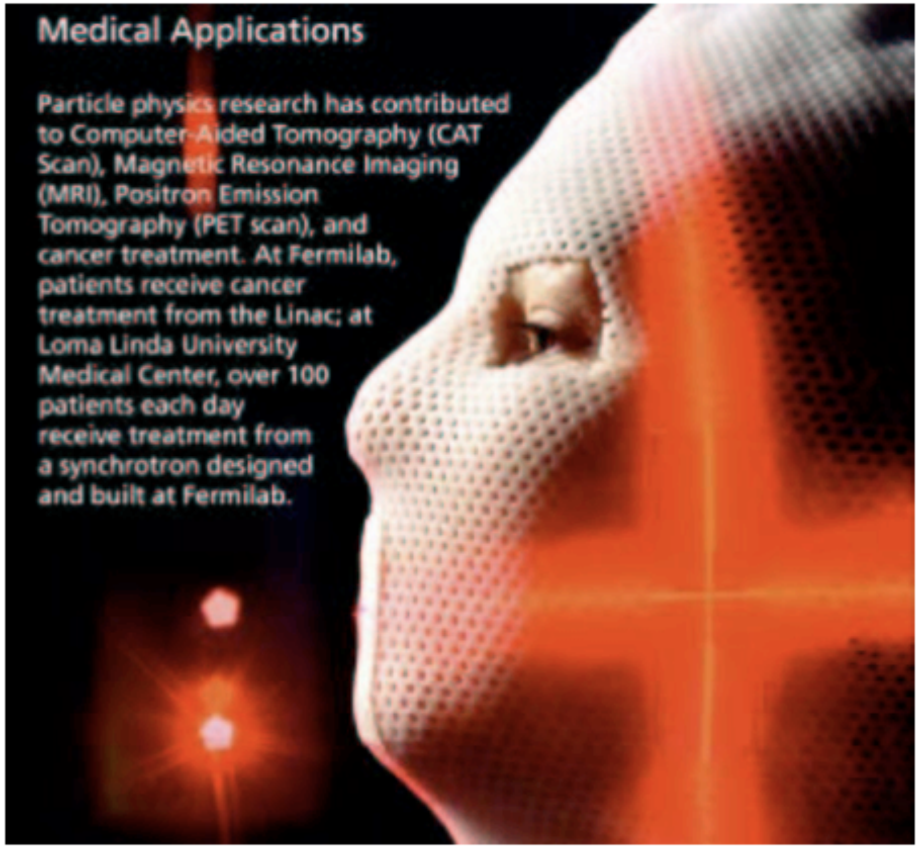



***Figure 2.2.2:*** *A typical trajectory for an electron, a proton and an alpha particle of 10 MeV in silicon. The electron trajectory is drawn on a scale 10 times smaller than the trajectory of the proton and the alpha particle.*

# Application: Bragg Peak




$^{12}$C ions in water. Treatment of deep-seated tumors.




Proton Cancer Therapy

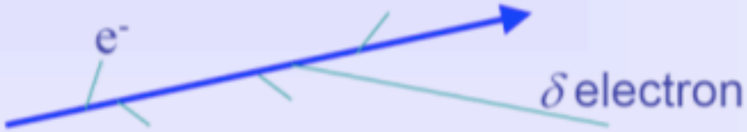
# Fluctuations and Energy Loss

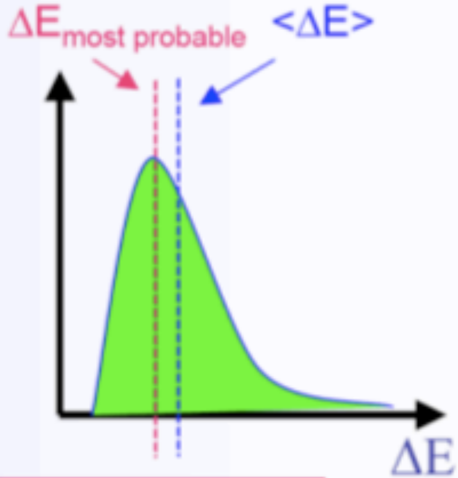
Real detector (limited granularity) can not measure $\langle dE/dx \rangle$ !

It measures the energy $\Delta E$ deposited in a layer of finite thickness $\delta x$.

**For thin layers or low density materials:**

→ Few collisions, some with high energy transfer.



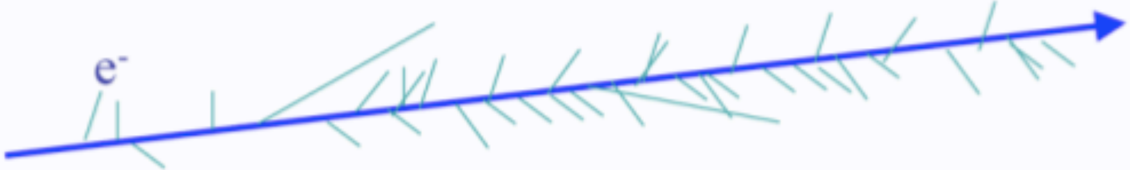



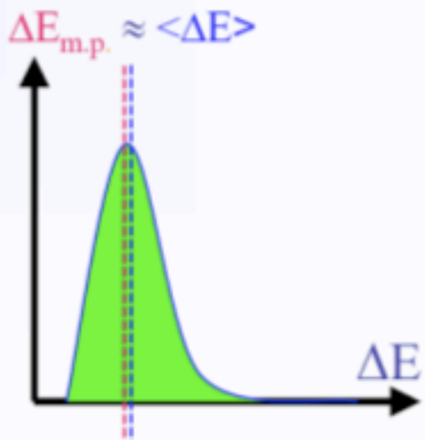

→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

Example: Si sensor: 300 μm thick. $\Delta E_{m.p} \sim 82$ keV $\langle \Delta E \rangle \sim 115$ keV

**For thick layers and high density materials:**

→ Many collisions.
→ Central Limit Theorem → Gaussian shaped distributions.




from L. Ropelewski

# Landau Distribution

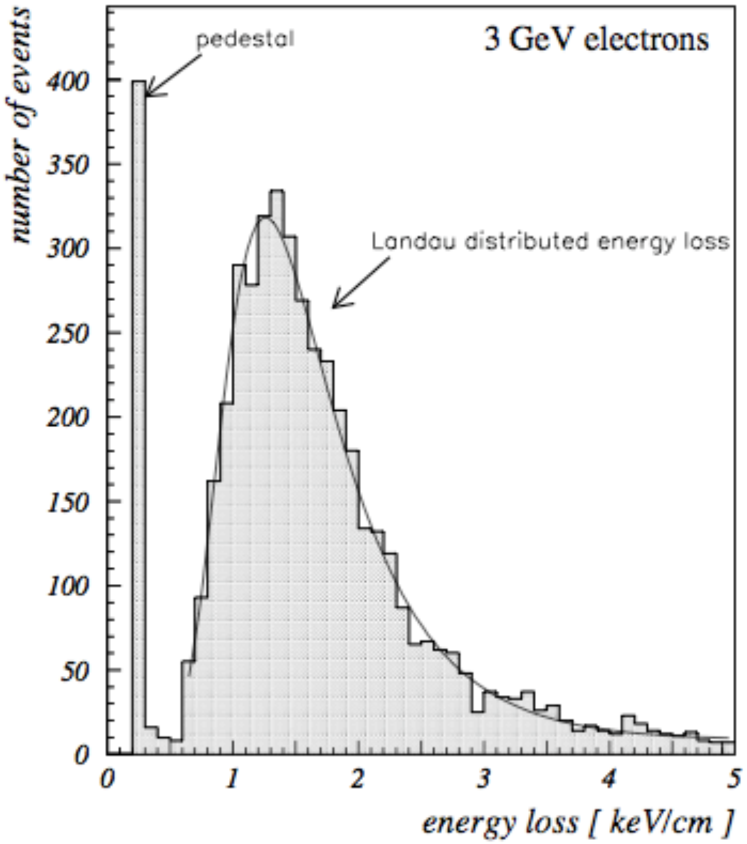
- Bethe-Bloch describes mean energy loss
- Energy loss is distributes asymmetrically
- approximated by

$$\Omega(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$

$$\lambda = \frac{\left(\frac{dE}{dx}\right) - \left(\frac{dE}{dx}\right)^{\mathrm{m.p.}}}{0.123\,\mathrm{keV}}$$

$\left(\frac{dE}{dx}\right)^{\mathrm{m.p.}}$ most probable energy loss

- important in gases, thin absorbers
- Argon, $\beta\gamma = 4$: $\left(\frac{dE}{dx}\right)^{\mathrm{m.p.}} = 1.2\,\mathrm{keV/cm}$; $\langle\frac{dE}{dx}\rangle = 2.69\,\mathrm{keV/cm}$
- For Particle Identification:
  - Measure often (typ. 160) to get distribution
  - Use "Truncated Mean"




Electrons in Ar:$CH_4$ (80:20)

# Scintillation

| | |
|---|---|
| inorganic crystals | effect of the lattice<br>electron-hole pair creation, excitons<br>de-excitation at activator centers<br>NaI(TI); CsI(TI); $BaF_2$; BGO; ... |
| organic liquids or plastic | three components<br>primary scintillator: antracene $C_{14}H_{10}$;<br>naphthalene $C_{10}H_8$; ...<br>wavelength shifter: POPOP*; BBO#; ...<br>base material: mineral oil; PMMA+; ... |
| gases | energy loss by excitation<br>recombination<br>Xe, Kr, Ar, $N_2$ ... |

* $C_{24}H_{16}N_2O_2$: 1.4-Bis-[2-(5-phenyloxazolyl)]-benzene
\# $C_{27}H_{19}NO$: 2.5-di-(4-biphenyl)-oxazole
\+ $C_5H_8O_2$: polymethylmetacralate

# Organic Plastic Scintillator

Non-Linear light yield to Energy Loss:

$$N = N_0 \frac{dE/dx}{1 + k_B \cdot (dE/dx)}$$

$k_B \approx 0.01\,\mathrm{g/MeV\,cm^2}$ Birk's density Parameter
Recently better approximation, by A. Menchaca et al.

Typically 100 eV energy loss for one photon
wavelength shifting necessary to avoid self-absorption

# Cherenkov Radiation

A charged particle with a velocity $v$ larger than the velocity of light in a medium emits light (Pavel A. Cherenkov, Ilja M. Frank, Igor Y. Tamm, Nobel Price 1958)

Threshold: $$\beta_{\text{thres}} = \frac{v_{\text{thres}}}{c} \geq \frac{1}{n} \qquad \gamma_{\text{thres}} = \frac{n}{\sqrt{n^2-1}}$$

Angle of emission: $$\cos\theta_c = \frac{1}{\beta\, n} = \frac{1}{\frac{v}{c}\, n}$$

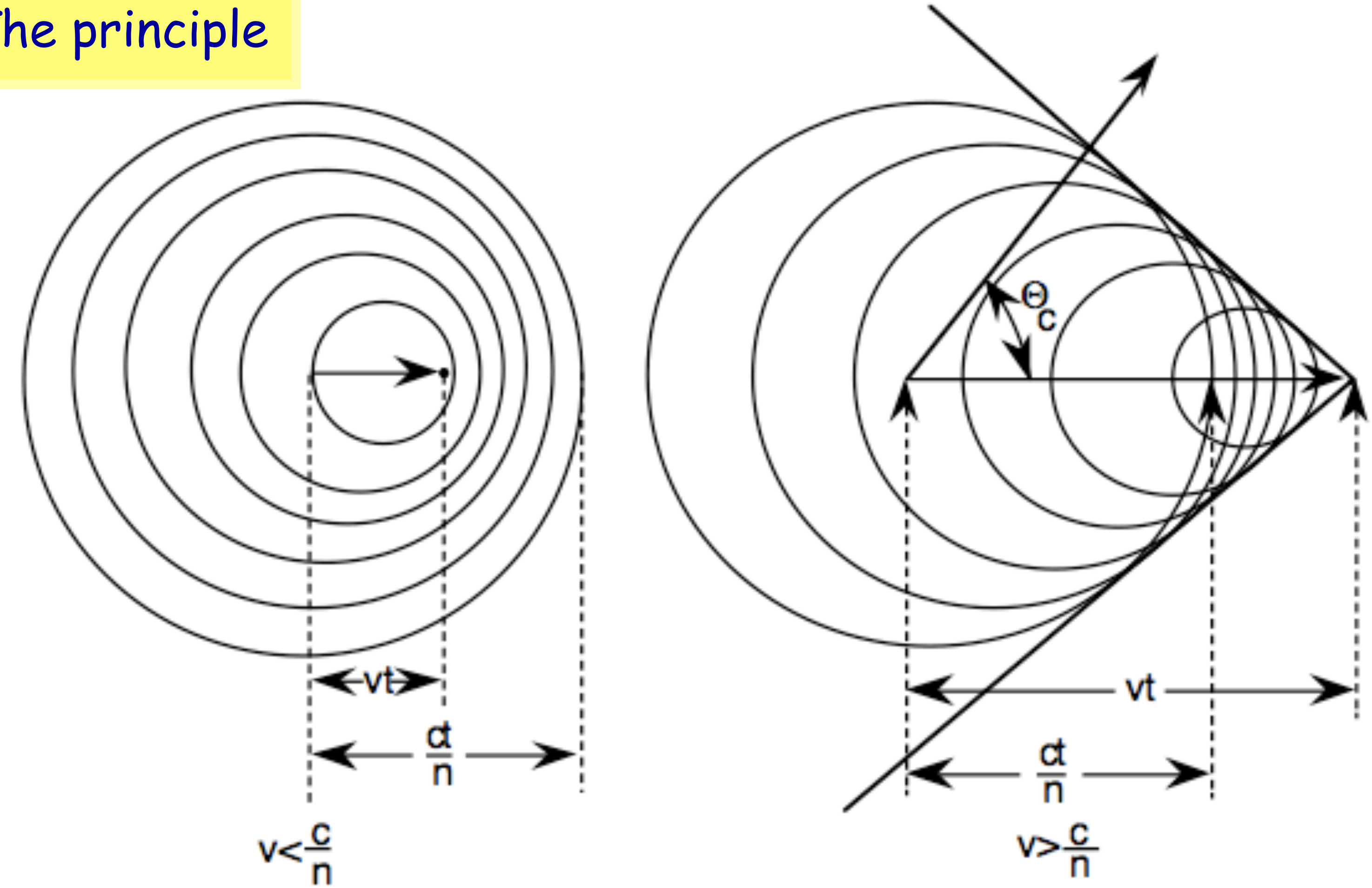
$$\theta_c^{\text{max}} = \arccos\frac{1}{n} \quad \text{Water: } \theta_c^{\text{max}} = 42^\circ \quad \text{Neon (1atm): } \theta_c^{\text{max}} = 11\,\text{mrad}$$

Number of photons: $$\frac{d^2N}{dE dl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$

$$\frac{d^2N}{d\lambda dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

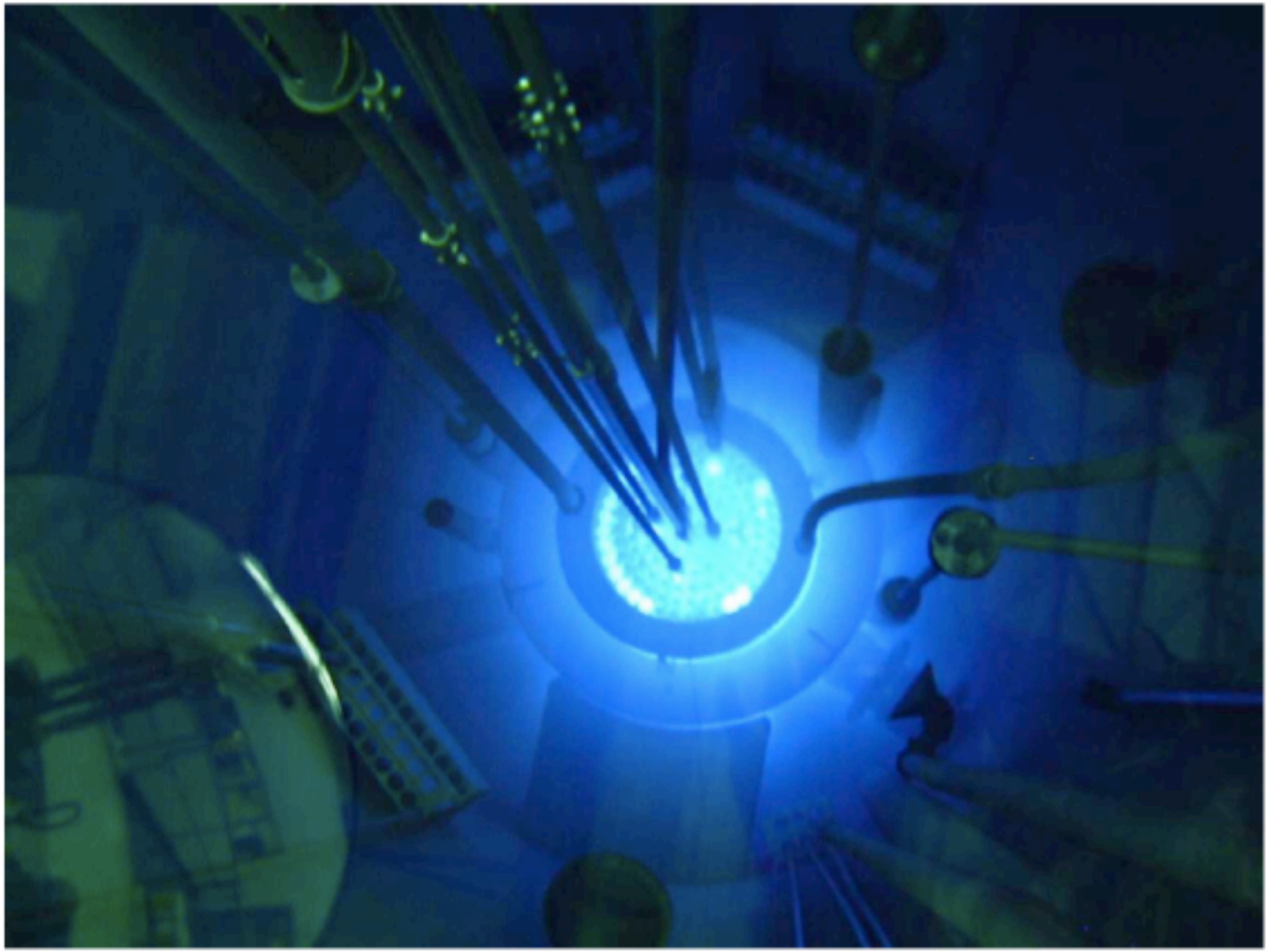
# Cherenkov Radiation

The principle

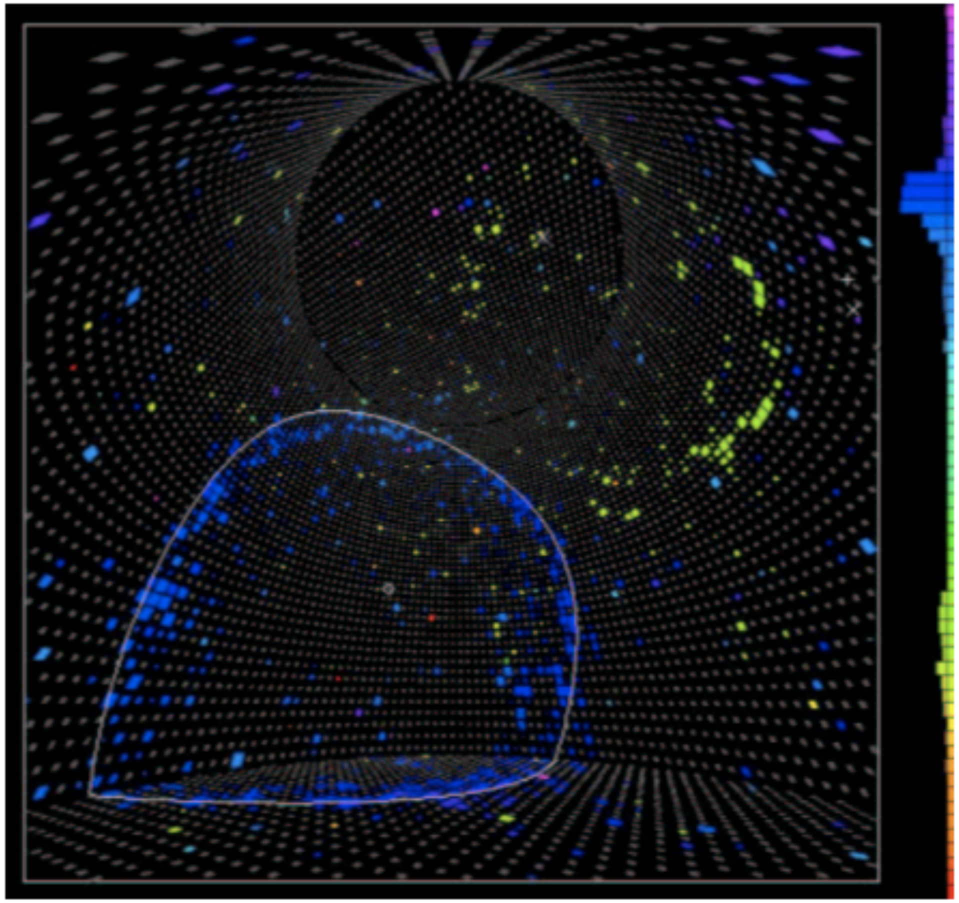



Project: calculate the Cherenkov radiation characteristics

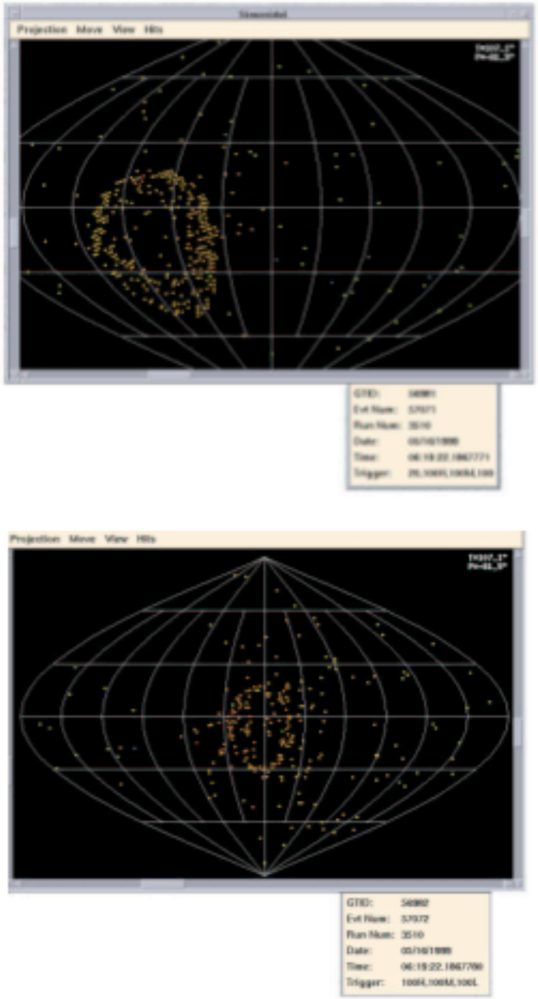
# Cherenkov Radiation in a Nuclear Reactor



# Water Cherenkov

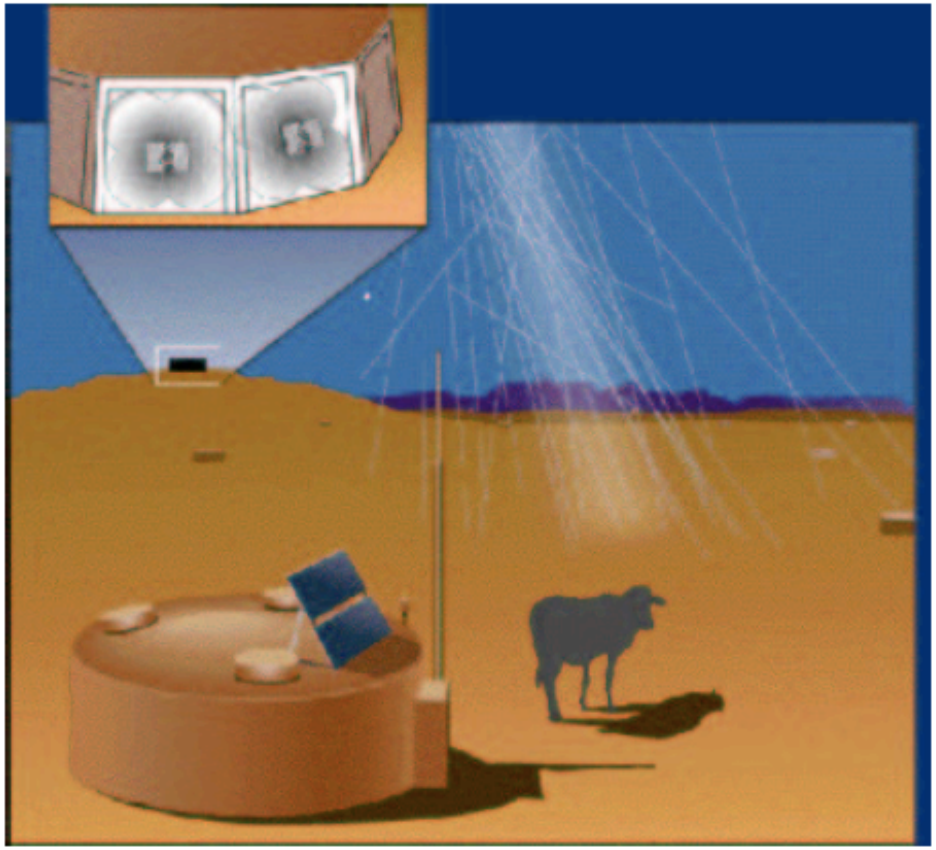


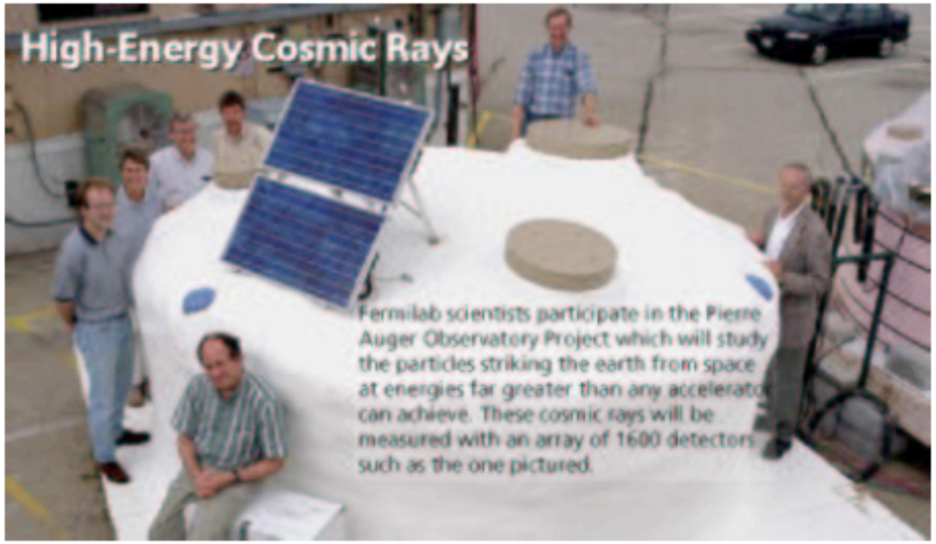
neutrino induced muon in SuperKamiokande



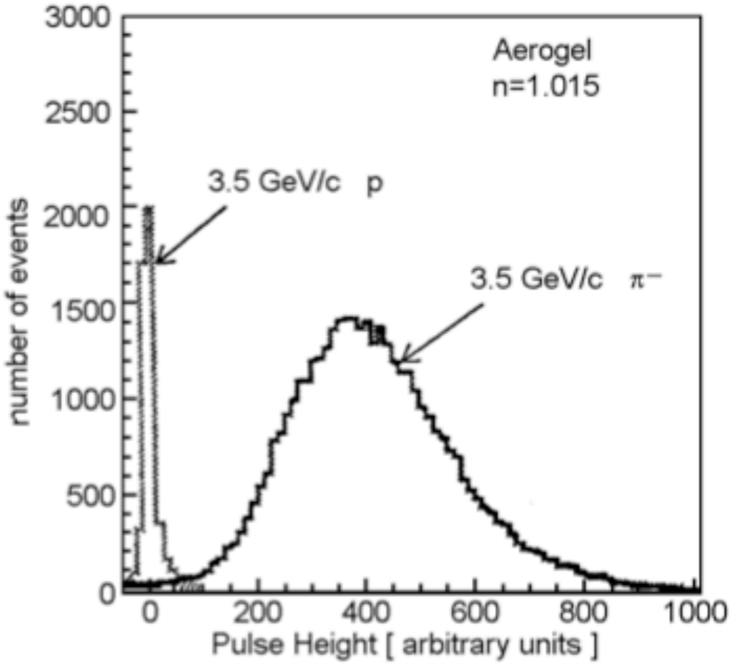

neutrino induced muon (top) and electron (bottom) in SNO

# Water Cherenkov (Auger Experiment)





# Threshold Cherenkov Detector



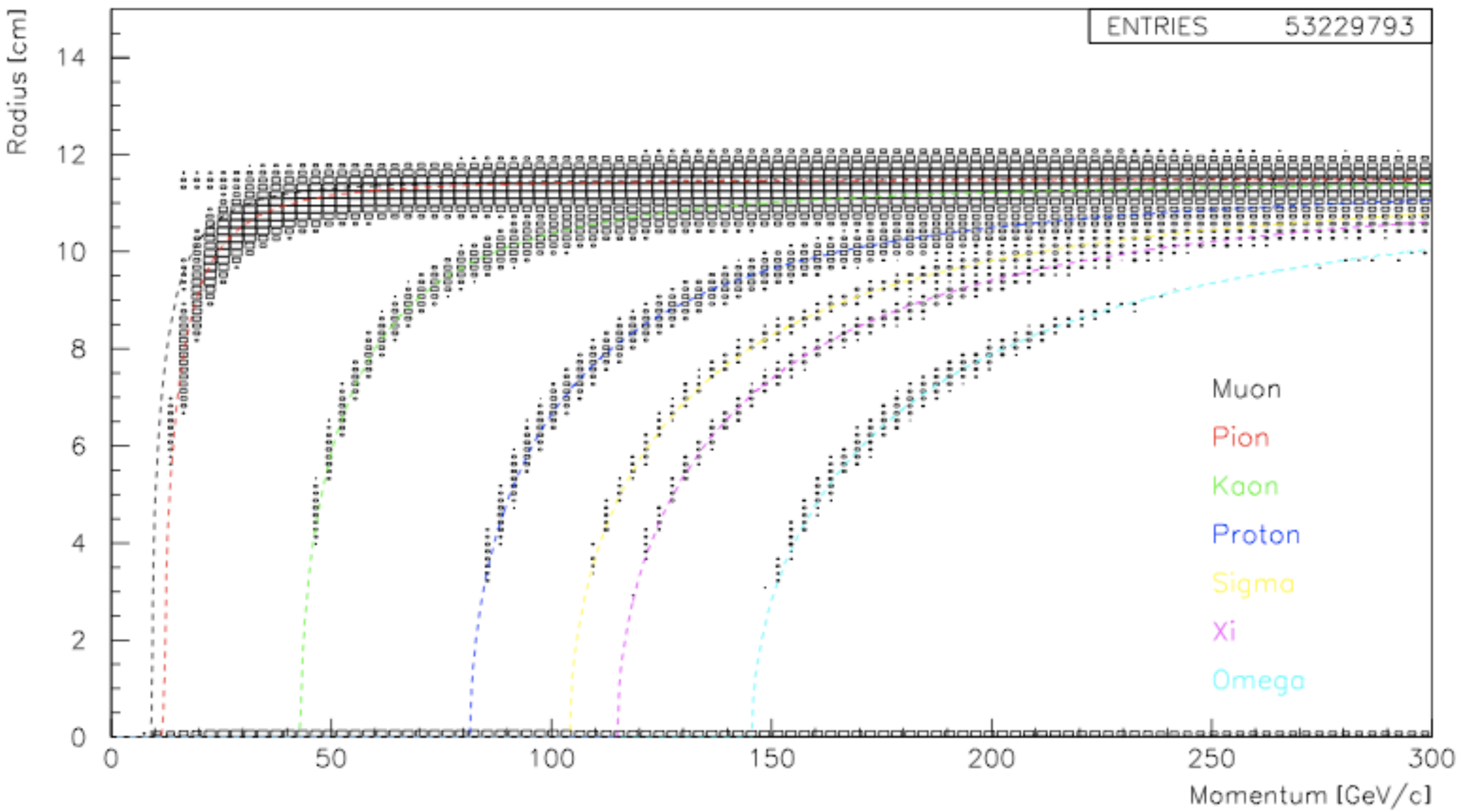

$$\text{Aerogel:} \quad n = 1.015 \Rightarrow \gamma_{\text{thres}} = 5.84$$

$$3.5\,\text{GeV/c} \Rightarrow \gamma_\pi = 24.2, \quad \gamma_p = 2.86$$

To identify more than 2 particles and/or to cover wider momentum range: Several counters at different thresholds

# Ring Imaging Cherenkov Detector (RICH)

Measure Cherenkov angle, not only threshold




SELEX RICH, 53 Million single negative track events

# Transition Radiation Detectors

Transition Radiation: Reformation of particle field while traveling from medium with $\epsilon = \epsilon_1$ to medium with $\epsilon = \epsilon_2$.

Energy of radiation emitted at a single interface

$$S = \frac{\alpha \hbar z^2}{3} \frac{(\omega_1 - \omega_2)^2}{\omega_1 + \omega_2} \gamma$$

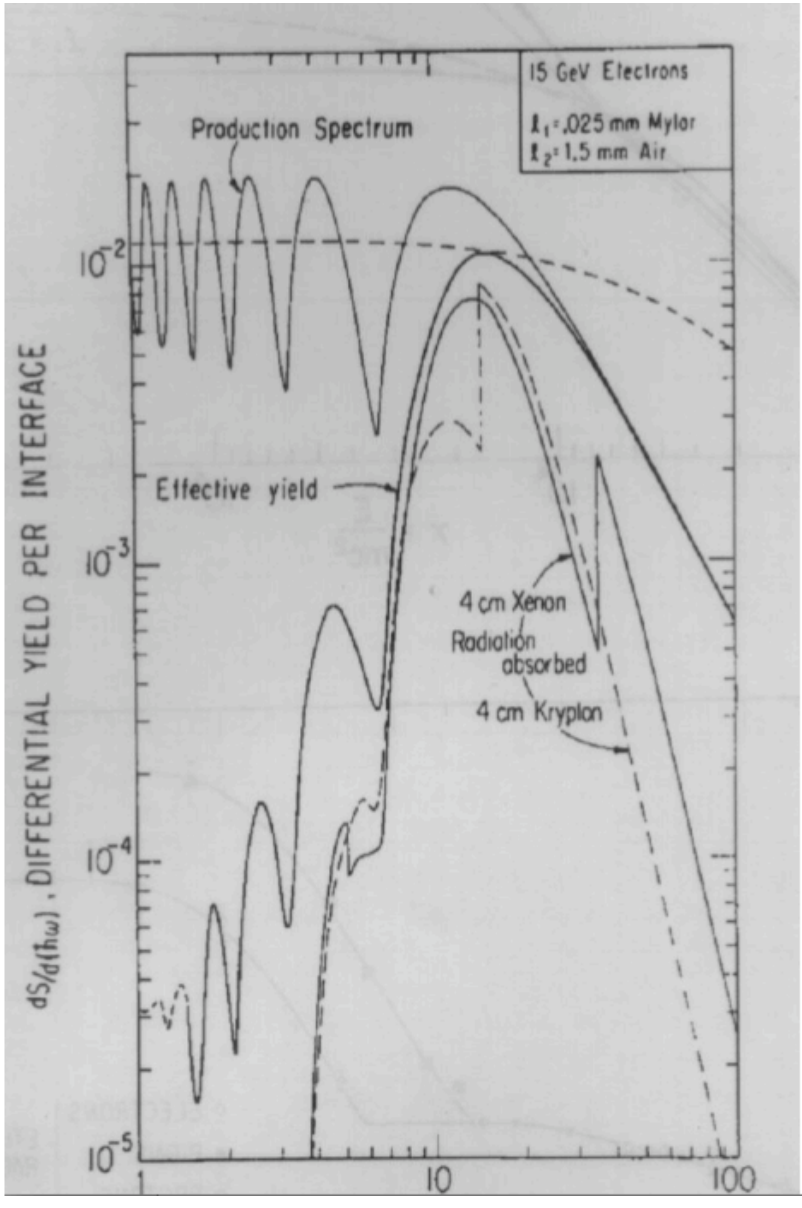
$\alpha = 1/137$, $\omega_1$, $\omega_2$ plasma frequencies, $\gamma = E/mc^2$.
Typical values: Air $\omega_1 = 0.7\,\text{eV}$, polypropylene $\omega_2 = 20\,\text{eV}$

Spectral and angular dependence of Transition Radiation:

$$\frac{d^2}{d\vartheta d\omega} = \frac{2e^2}{\pi c} \left( \frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_1^2/\omega^2} - \frac{\vartheta}{\gamma^{-2} + \vartheta^2 + \omega_2^2/\omega^2} \right)^2$$

$\Longrightarrow$ Most of radiation in cone with half angle $1/\gamma$: forward in particle direction.

# Transition Radiation Detector




- Large photon energies $\omega > \gamma\omega_2 \approx 20 - 30$ KeV: large drop of intensity $\propto \gamma^4/\omega^4$
- Medium energies $\gamma\omega_1 < \omega < \gamma\omega_2$: Logarithmic decrease with $\omega$
- Small energies $\omega < \gamma\omega_1 \approx 1$ KeV: intensity almost constant

Probability to emit a KeV photon: $\approx 10^{-2} \Longrightarrow$ Need a lot of interfaces: stack of radiator foils.
Consequences:

- Need minimum foil thickness so particle field reaches new equilibrium
- Transition $\omega_1 \rightarrow \omega_2$ and $\omega_2 \rightarrow \omega_1$ equal $\Longrightarrow$ Interference effects (min and max in fig)
- Equally spaced foils: Interference between amplitude of different foils
- Finite thickness of foils: re-absorption of radiation ($\propto Z^5$): Low $Z$ materials.

Typical values used in TRDs:
Thickness: 30 $\mu$m, distance: 300 $\mu$m,
materials: mylar, $CH_2$, carbon fibers, lithium.

# Detection of Transition Radiation

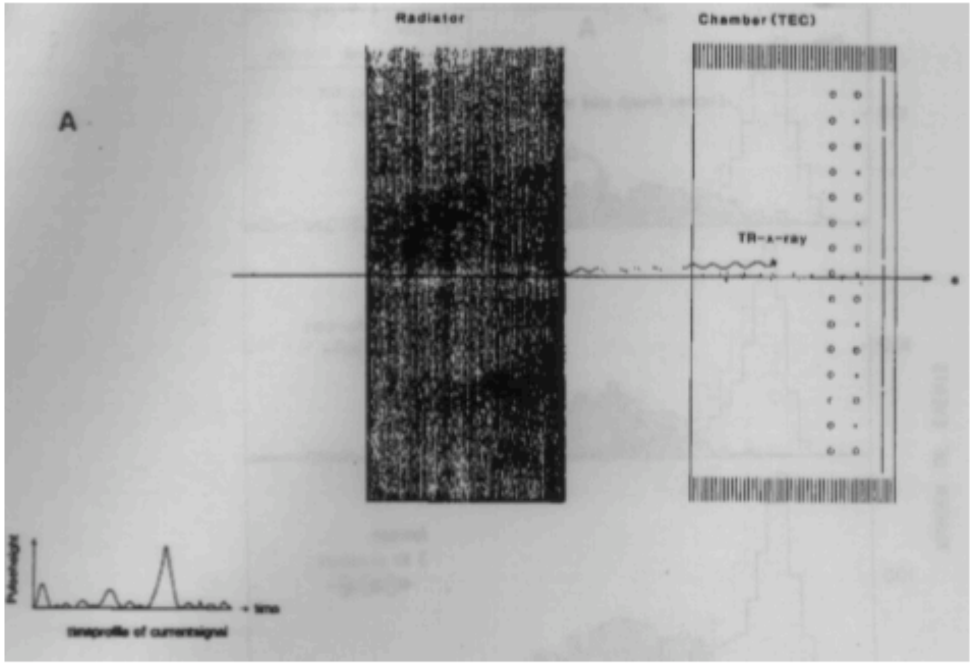
X-rays emitted under small angle to particle track

$\Longrightarrow$ X-ray detector sees X-rays and particle $dE/dx$ together.

Typical $dE/dx$ in gas detectors: some KeV/cm and Landau distributed

$\Longrightarrow$ Signals from $dE/dx$ and X-ray similar

Detector: Use "thin" MWPC, with Xenon or Krypton, several (10) radiator / chamber units to beat Landau



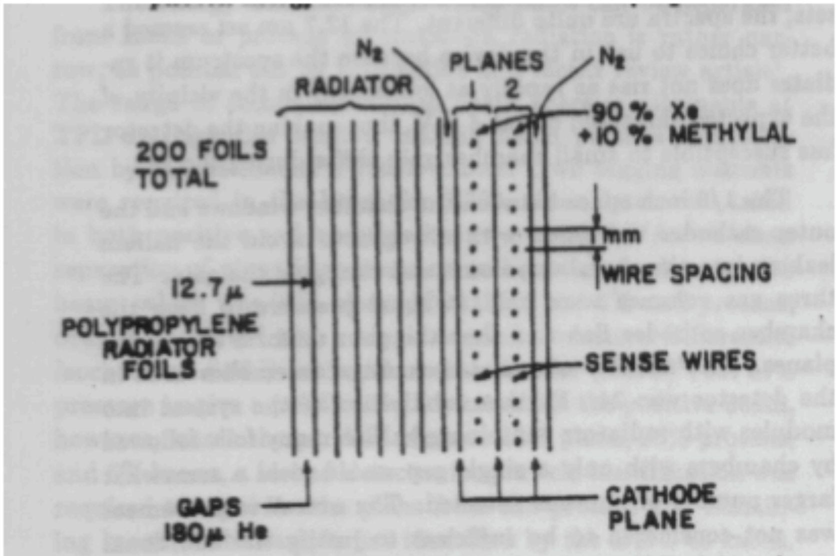
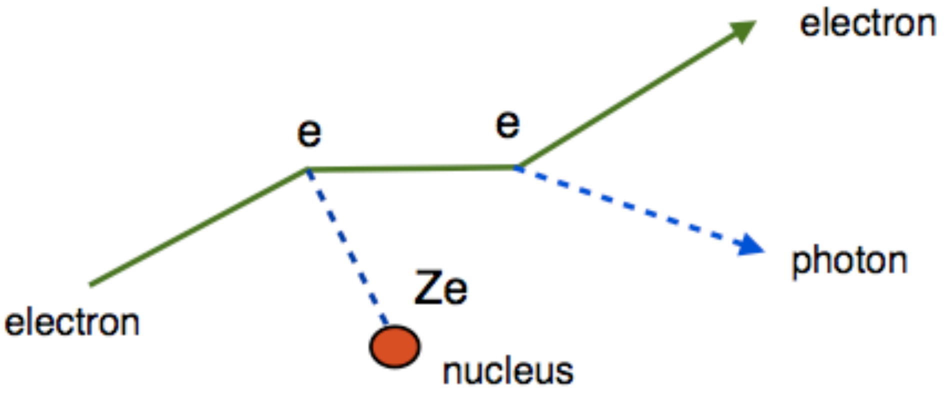




*Fig 4.* Schematic of a radiator-chamber module showing the final design parameters discussed in the text.

Two identification methods: Charge integration, Cluster counting

# Bremsstrahlung

High energy electrons loose their energy predominantly through radiation (bremsstrahlung).




Cross section:

$$\sigma \sim (Z\,e^3)^2 \sim Z^2\ \alpha^3$$

The electron is decelerated (accelerated) in the field of the nucleus. Accelerated charges radiate photons. Thus the bremsstrahlung is strong for light charged particles (electrons), because its acceleration is large for a given force. For heavier particles like muons bremsstrahlung effects are only important at energies of a few hundred GeV.

The presence of a nucleus is required to restore energy-momentum conservation. Thus the cross section is proportional to $Z^2$ and $\alpha^3$ ($\alpha$ = fine structure constant).

The characteristic length which a electron travels in material until a bremsstrahlung happens is the radiation length $X_0$.

# Radiation Length

The radiation length is the characteristic length scale to describe electromagnetic showers in material. It is usually measured in g/cm$^2$.

The radiation length is:
- the mean distance over which a high energy electron looses all but 1/e of its energy.
- 7/9 of the mean free path for pair production by a high energy photon.

The radiation length is give by:

$I = I_0 \exp[-x/X_0]$

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 \left[ L_{\rm rad} - f(Z) \right] + Z\, L'_{\rm rad} \right\}$$

For $A = 1$ g mol$^{-1}$, $4\alpha r_e^2 N_A/A = (716.408\ \mathrm{g\ cm^{-2}})^{-1}$.

$$f(Z) = a^2 \left[ (1+a^2)^{-1} + 0.20206 - 0.0369\, a^2 + 0.0083\, a^4 - 0.002\, a^6 \right]$$

where $a = \alpha Z$

| Element | $Z$ | $L_{\rm rad}$ | $L'_{\rm rad}$ |
|---|---|---|---|
| H | 1 | 5.31 | 6.144 |
| He | 2 | 4.79 | 5.621 |
| Li | 3 | 4.74 | 5.805 |
| Be | 4 | 4.71 | 5.924 |
| Others | $> 4$ | $\ln(184.15\, Z^{-1/3})$ | $\ln(1194\, Z^{-2/3})$ |

# Bremsstrahlung

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{PDG: } X_0 = \frac{716.4\,A}{Z(Z+1)\,\ln(287/\sqrt{Z})}\,[\mathrm{g/cm^2}]$$

$$\frac{dE}{dx} \propto E \Rightarrow \qquad \text{Critical Energy } \frac{dE}{dx}|_{\mathrm{ion}} = \frac{dE}{dx}|_{\mathrm{brems}}$$

$$E^e_{\mathrm{crit}} = \begin{cases} \frac{610\,\mathrm{MeV}}{Z+1.24} & \text{for solids and liquids} \\ \frac{710\,\mathrm{MeV}}{Z+0.92} & \text{for gases} \end{cases}$$

# Bremsstrahlung

| Material | $X_0$ [g/cm$^2$] | $X_0$ [cm] | $E^e_{\text{crit}}$ [MeV] |
|---|---|---|---|
| air | 37 | 30000 | 84 |
| iron | 13.9 | 1.76 | 22 |
| lead | 6.4 | 0.56 | 7.3 |

$$-\frac{dE}{dx} \propto \frac{1}{m^2} \Rightarrow \text{Electron Bremsstrahlung dominates}$$

$$\text{But: Muons in iron:} \quad E^\mu_{\text{crit}} = E^e_{\text{crit}} \left(\frac{m_\mu}{m_e}\right)^2 = 960\,\text{GeV}$$

$\Rightarrow$ Muon Calorimetry at TeV Energies

Bremsstrahlung important for electromagnetic cascades (Calorimetry)

# Direct Electron Pair Production

in Coulomb field of Nucleus via virtual photons

$$-\frac{dE}{dx}|_{\text{pair}} \propto E \quad \text{for large E}$$

$$-\frac{dE}{dx} = a(E) + b(E)E$$

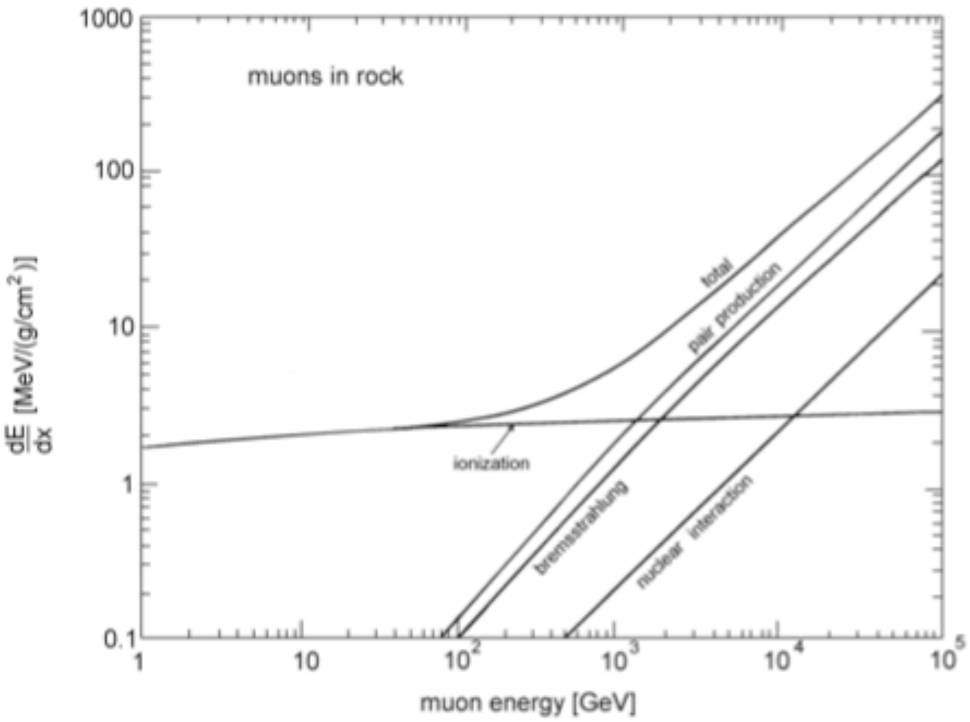
$a(E)$ – Ionization energy loss

$b(E) = b_{\text{brems}}(E) + b_{\text{pair}}(E) + b_{\text{nucl.int.}}(E)$

Range of muons

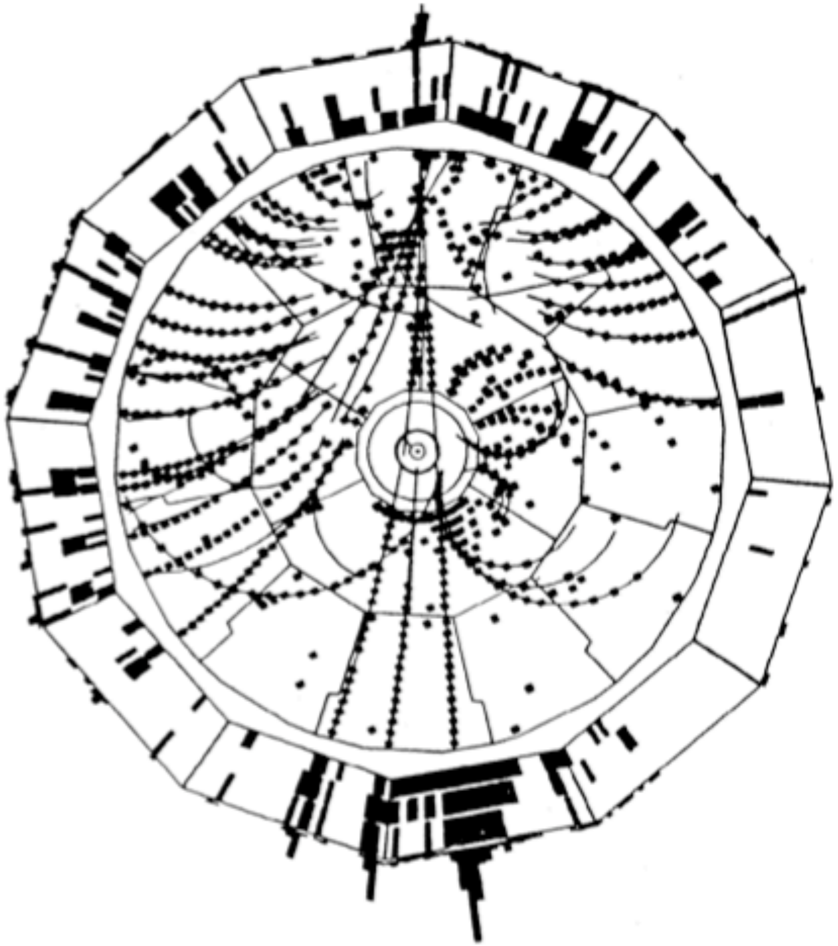
$$R = \int_E^0 \frac{dE}{-dE/dx} = \frac{1}{b}\ln(1 + \frac{b}{a}E)$$

$$R = \begin{cases} 140\,\text{m} \quad \text{rock for } E = 100\,\text{GeV} \\ 800\,\text{m} \quad \text{rock for } E = 1\,\text{TeV} \\ 2300\,\text{m} \quad \text{rock for } E = 10\,\text{TeV} \end{cases}$$




Energy loss of muons in Rock
($Z = 11,\ A = 22;\ \rho = 3\,\text{g/cm}^2$)

# High Energy Muon Bremsstrahlung



Bremsstrahlung off muons starts to be important for momenta of a few hundred GeV.

Cosmic muon bremsstrahlung event in the ALEPH detector at LEP.

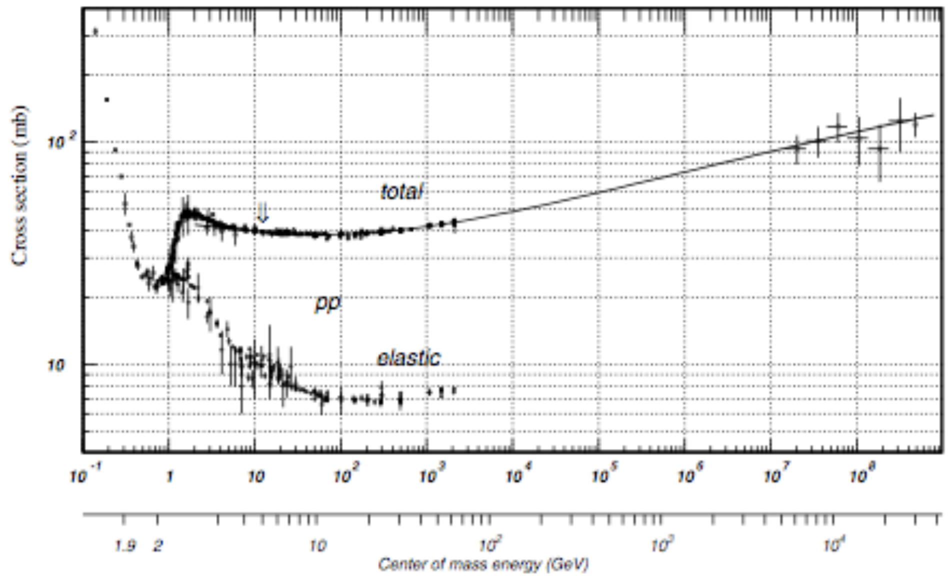
# Nuclear Interactions

Important for the detection of neutral particles

$\sigma_{\text{tot}} \approx 50\,\text{mbarn} \qquad \sigma_{\text{inel}} \propto A^{\alpha}, \alpha = 0.71$

Nuclear Interaction length $\lambda_I = \dfrac{A}{N_A\,\rho\,\sigma_{\text{tot}}}$

Nuclear Absorption length $\lambda_a = \dfrac{A}{N_A\,\rho\,\sigma_{\text{inel}}}$




for most material $\lambda_I, \lambda_a > X_0$

| | Al | Fe | Pb | air |
|---|---|---|---|---|
| $\lambda_I$ [cm] | 26.2 | 10.6 | 10.4 | 48000 |
| $\lambda_I$ [g/cm] | 70.6 | 82.8 | 116.2 | 62.0 |

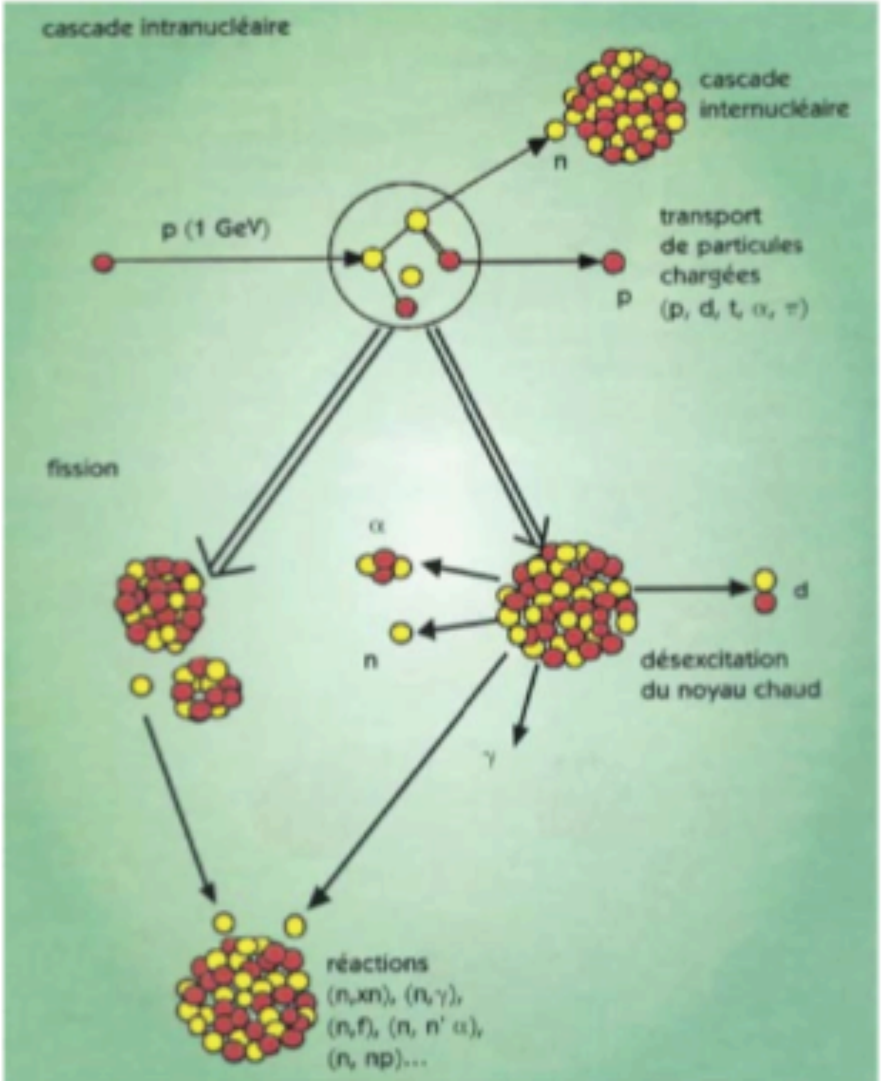
Multiplicity grows logarithmically with $E$,
Average $p_T = 350\,\text{MeV}/c$

# Interaction Lenght

- Completely different!

  Hadron calorimetry is not for the weak at heart

- Most notably, neutrons are abundantly produced



# Material Characteristics

| Material | Z | Density [g/cm$^3$] | $X_0$ [cm] | $\lambda_{int}$ [cm] | $dE/dx_{mip}$ [MeV/cm] |
|---|---|---|---|---|---|
| Fe | 26 | 7.9 | 1.8 | 17 | 11 |
| Cu | 29 | 9.0 | 1.4 | 15 | 13 |
| Pb | 82 | 11 | 0.6 | 17 | 13 |
| **W** | **74** | **19** | **0.4** | **9.6** | **22** |
| **$^{238}$U** | **92** | **19** | **0.3** | **11** | **21** |
| **Plastic Scint.** | **-** | **1.0** | **42** | **80** | **2.0** |
| **LAr** | **18** | **1.4** | **14** | **84** | **2.1** |
| **Quartz** | **-** | **2.3** | **12** | **43** | **3.9** |
| Si | 14 | 2.3 | 9.4 | 46 | 3.9 |
| Al | 13 | 2.7 | 8.9 | 39 | 4.4 |

# Interaction of Neutral Particles

# Introduction: Interactions of Photons

Photons are attenuated in matter.

$$I = I_0\, e^{-\mu x}$$

$\mu$ Mass Attenuation Coefficient

$$\mu = \frac{N_A}{A} \sum_{i=1}^{3} \sigma_i$$

$$\sigma_i = \begin{cases} i = 1\text{: Photoelectric Effect} \\ i = 2\text{: Compton Scattering} \\ i = 3\text{: Pair Production} \end{cases}$$

# Photoelectric Effect

$$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^- \qquad \text{predominantly in K-shell}$$

Complicated energy and Z dependence

$$\sigma^K_{\text{photo}} = \left(\frac{32}{\epsilon^7}\right)^{1/2} \alpha^4 \, Z^5 \, \sigma_{\text{Thomson}} \quad [\text{cm}^2/\text{atom}]$$

$$\epsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma_{\text{Thomson}} = \frac{8}{3}\pi \, r_e^2 = 665 \, \text{mbarn}$$

For high energies:

$$\sigma^K_{\text{photo}} = 4\pi \, r_e^2 \, Z^5 \, \alpha^4 \, \frac{1}{\epsilon}$$

# Compton Scattering

$$\gamma + e \rightarrow \gamma' + e'$$

at high energies: $\sigma_C \propto \frac{\ln \epsilon}{\epsilon} \cdot Z$

$$\frac{E'_\gamma}{E_\gamma} = \frac{1}{1 + \epsilon(1 - \cos\theta_\gamma)}$$

$$E_{\text{kin}}^{\text{max}}(\theta_\gamma = \pi) = \frac{2\epsilon^2}{1 + 2\epsilon} m_e c^2 \quad \text{for } \epsilon \gg 1 \;\; E_{\text{kin}}^{\text{max}}(\theta_\gamma = \pi) \rightarrow E_\gamma$$

# Pair Production

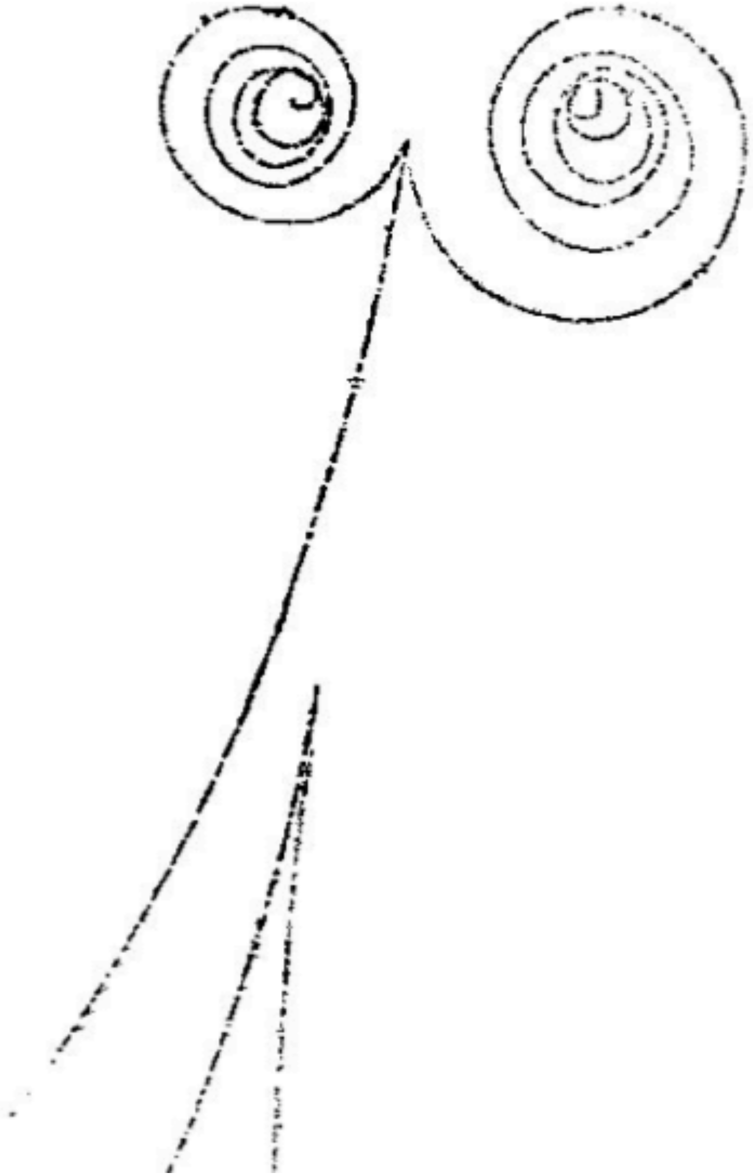
$$\gamma + \text{nucleus} \rightarrow \text{nucleus}' + e^+ + e^-$$

threshold energy:

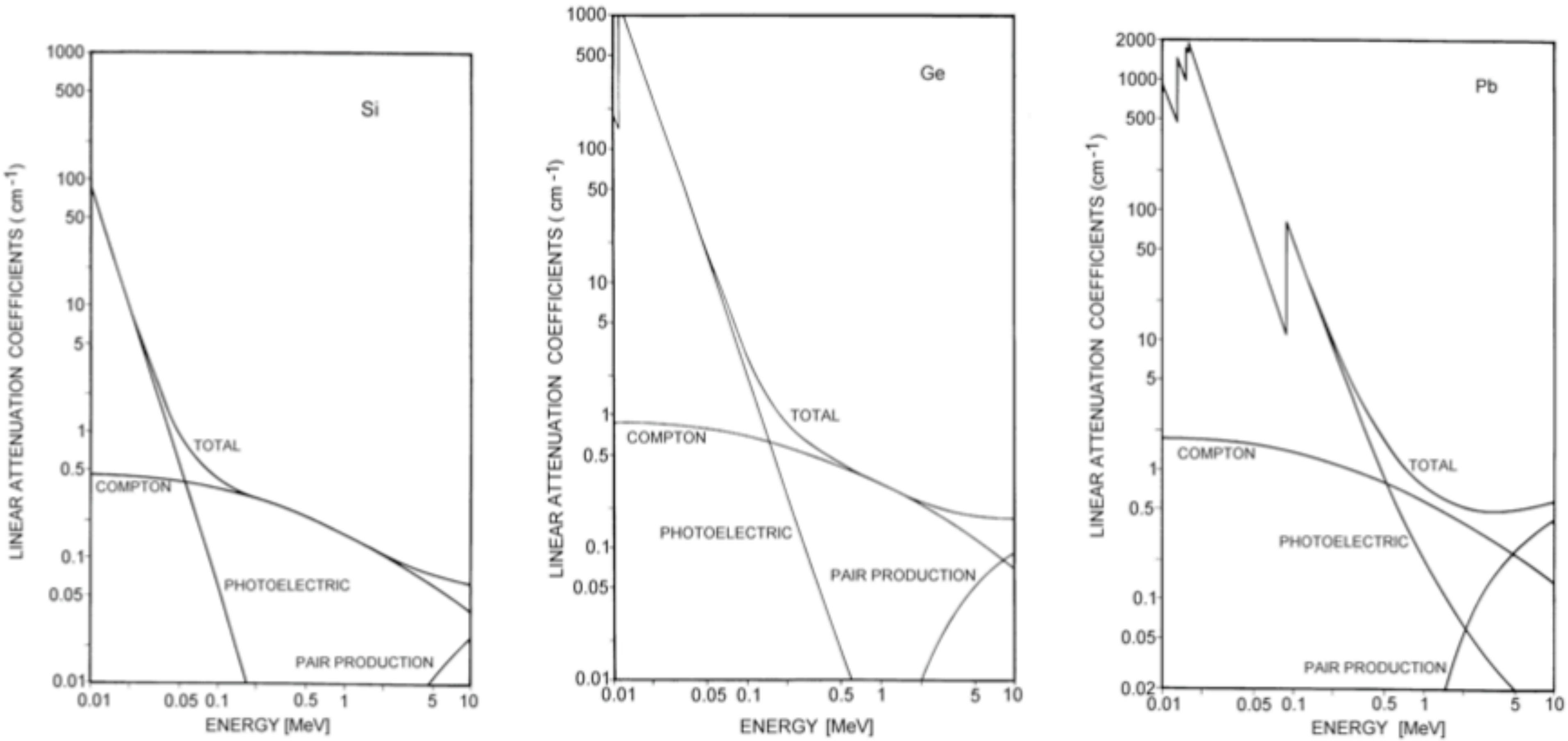
$$E_\gamma \geq 2\, m_e c^2 + \frac{2\, m_e c^2}{m_{\text{target}}} = \begin{cases} \approx 2\, m_e c^2 & \text{on a nucleus} \\ 4\, m_e c^2 & \text{on an electron} \end{cases}$$

Cross section for $E_\gamma \gg 20\,\text{MeV}$

$$\sigma_{\text{pair}} = 4\, \alpha\, r_e^2\, Z^2 \left( \frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \quad [\text{cm}^2/\text{atom}]$$
$$\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

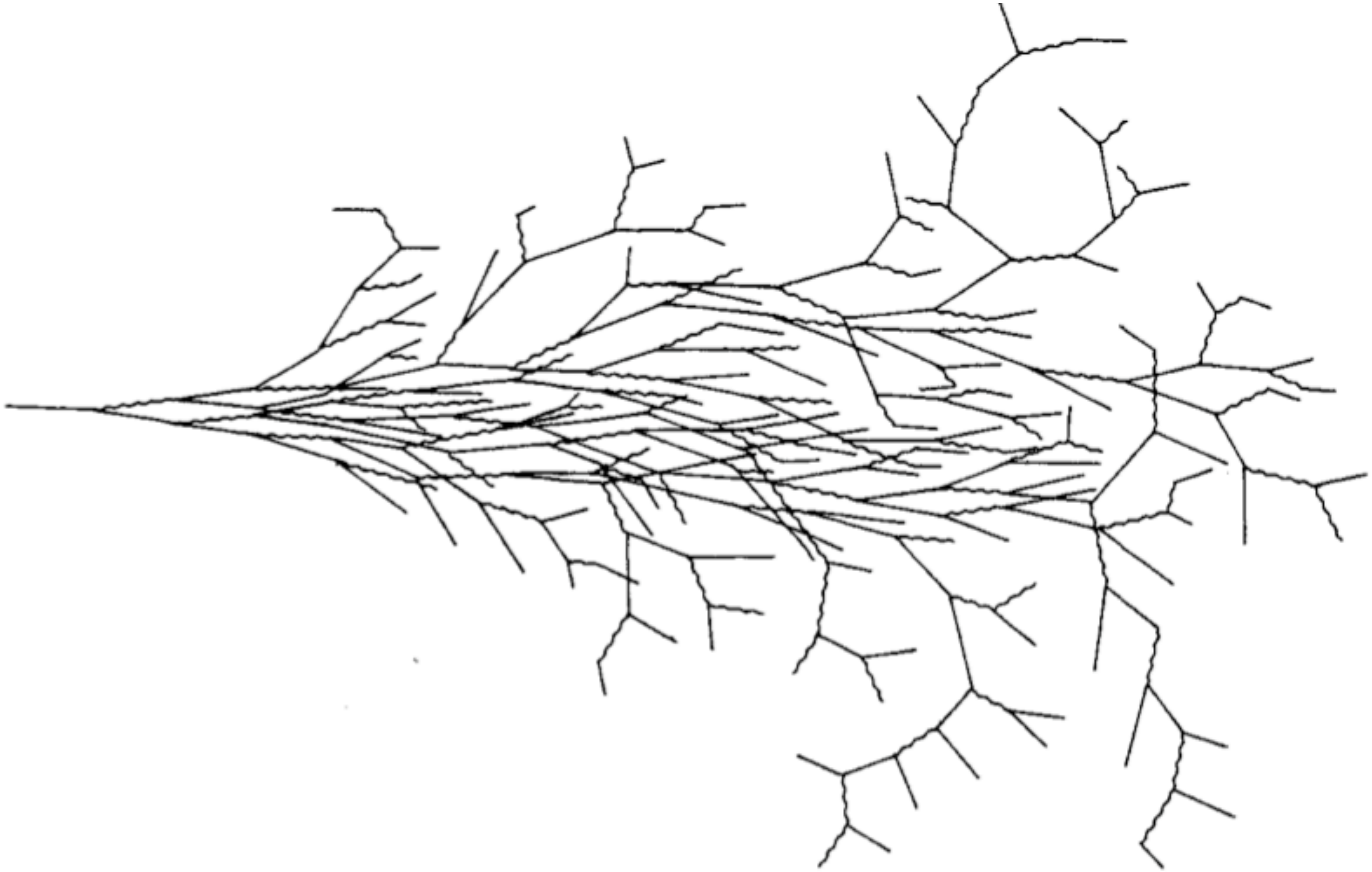


# Mass Attenuation Coefficients



# An Electromagnetic Shower

Photon → Pair Production     Electron / positron → Bremsstrahlung (Photon)

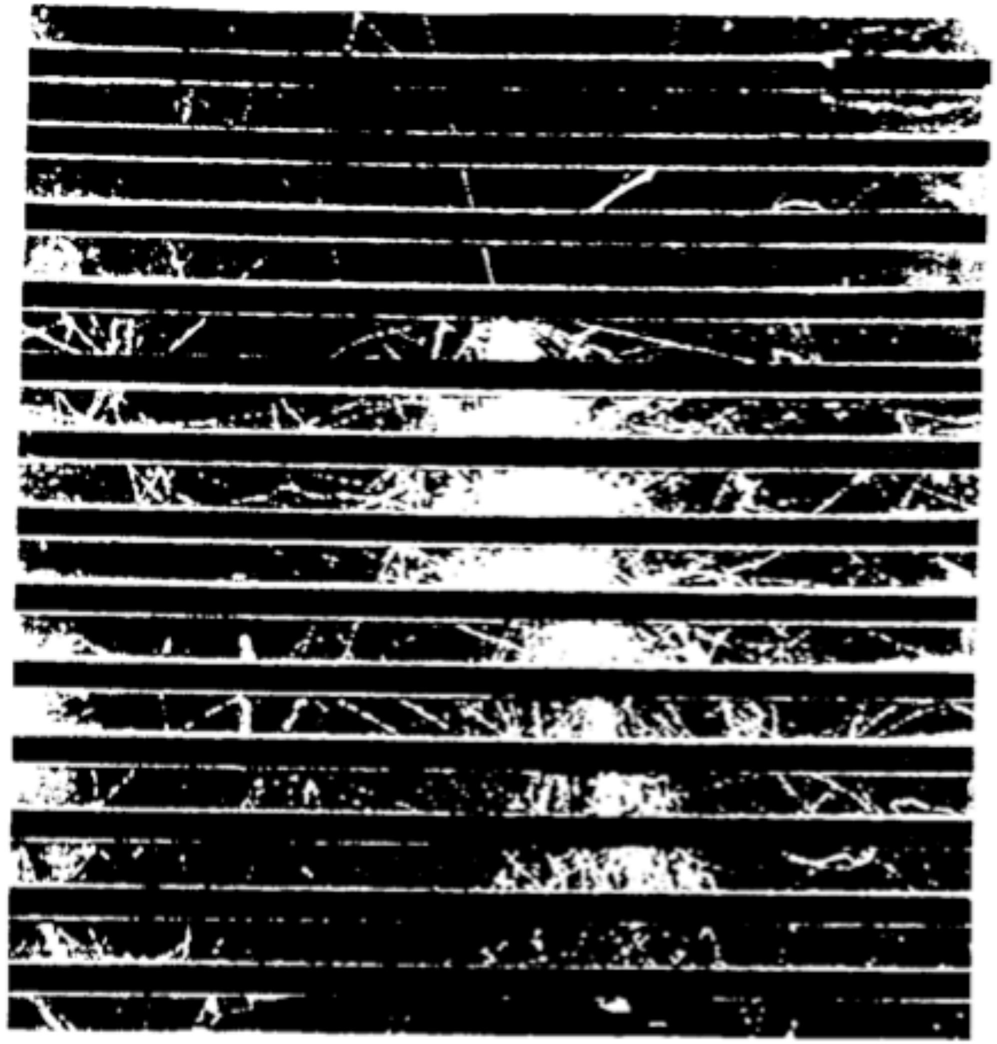


# Electromagnetic Showers

$$\mu^- + \text{nucleus} \rightarrow \mu^- + \text{nucleus}' + \gamma$$

$$\gamma \rightarrow \text{electromagnetic shower}$$

Multiplate Cloud Chamber

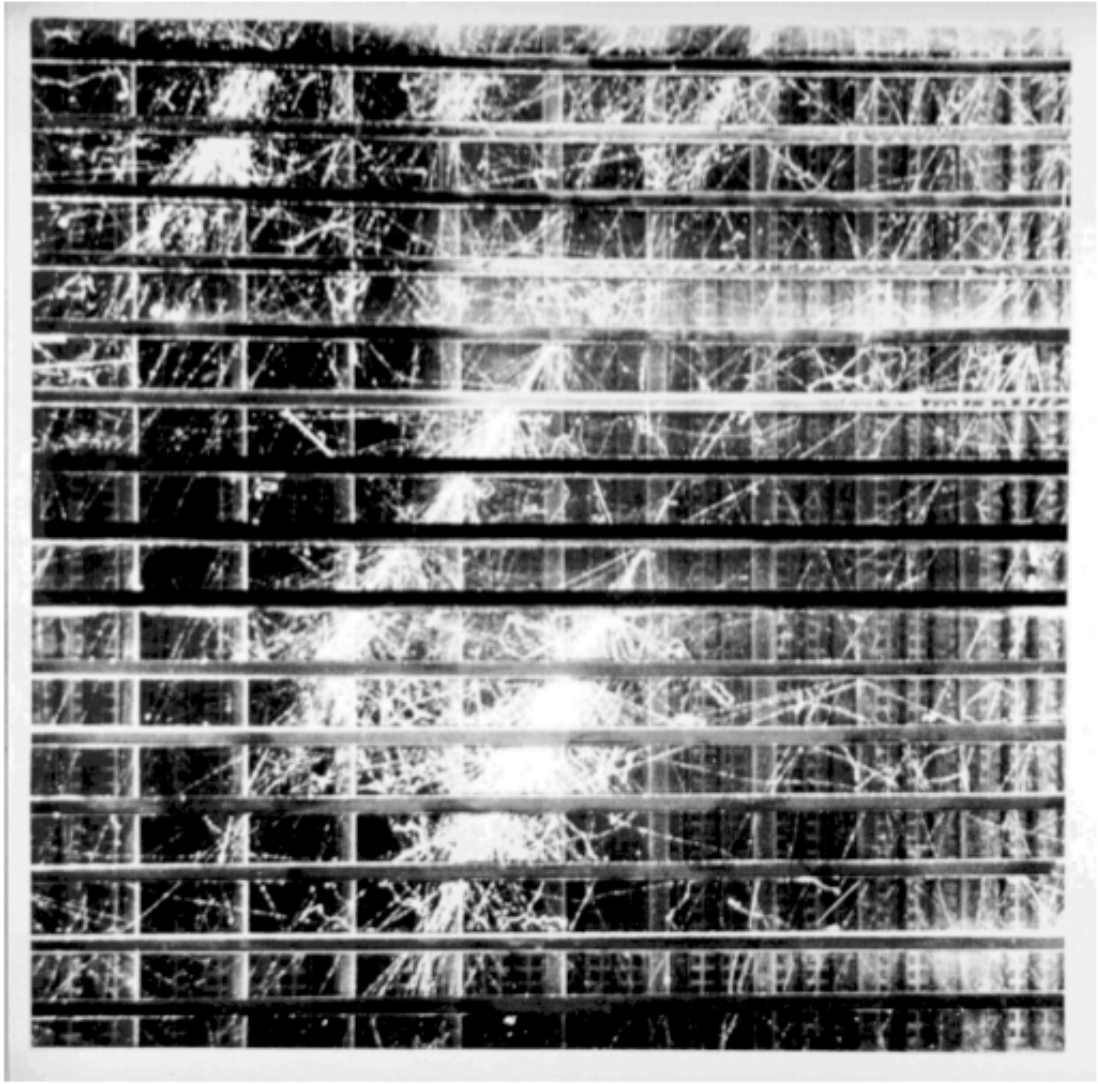


# Electromagnetic Showers

Air shower experiment

Multiplate Cloud Chamber below 3 m of concrete

Electromagnetic showers initiated by muon Bremsstrahlung



# Hadronic Showers

Longitudinal development: governed by nuclear interaction length $\lambda_I$
Lateral development: transverse momentum $p_T$ of particles
since $\lambda_I > X_0$ and $\langle p_T \rangle \gg \langle p_T \rangle^{\text{mult. scatt.}}$
$\Rightarrow$ hadron showers are wider and longer than electromagnetic showers

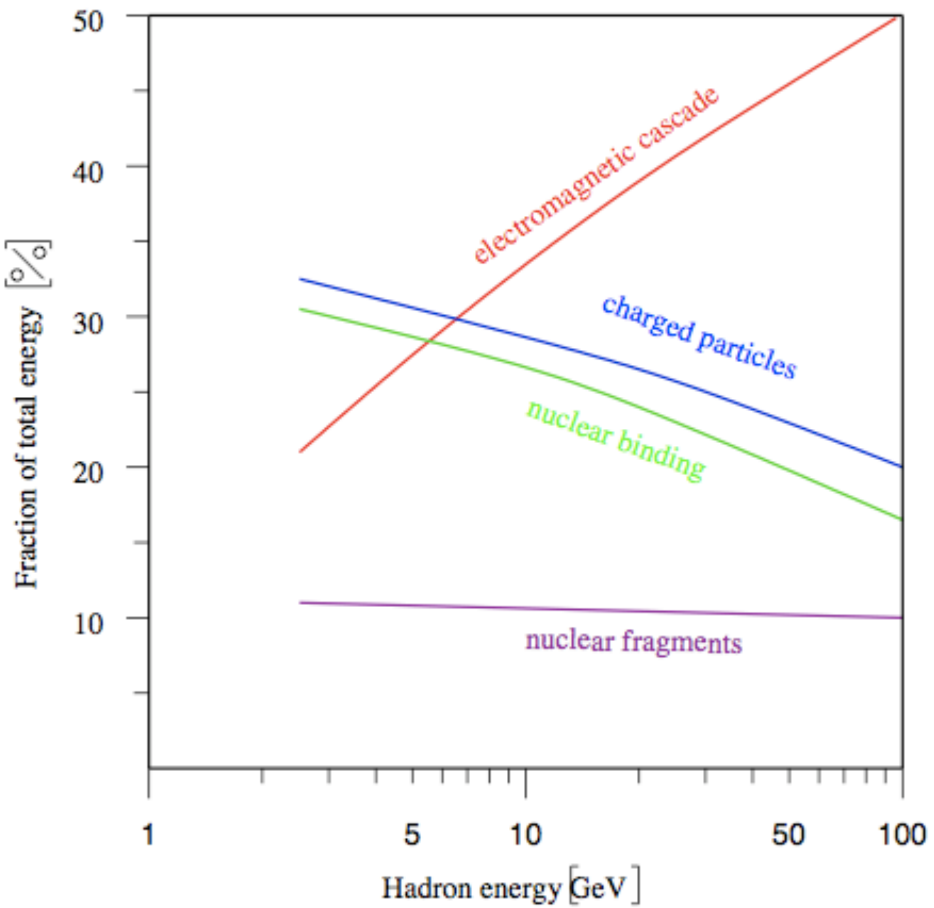
$$\text{Hadron Energy} \Rightarrow \begin{cases} \text{charged particles } (\mu\text{'s are lost}) \\ \text{electromagnetic showers via } \pi^0 \, (e, \gamma; \text{ contained}) \\ \text{nuclear binding energy (can be partially recovered)} \\ \text{nuclear fragments (partially lost)} \end{cases}$$

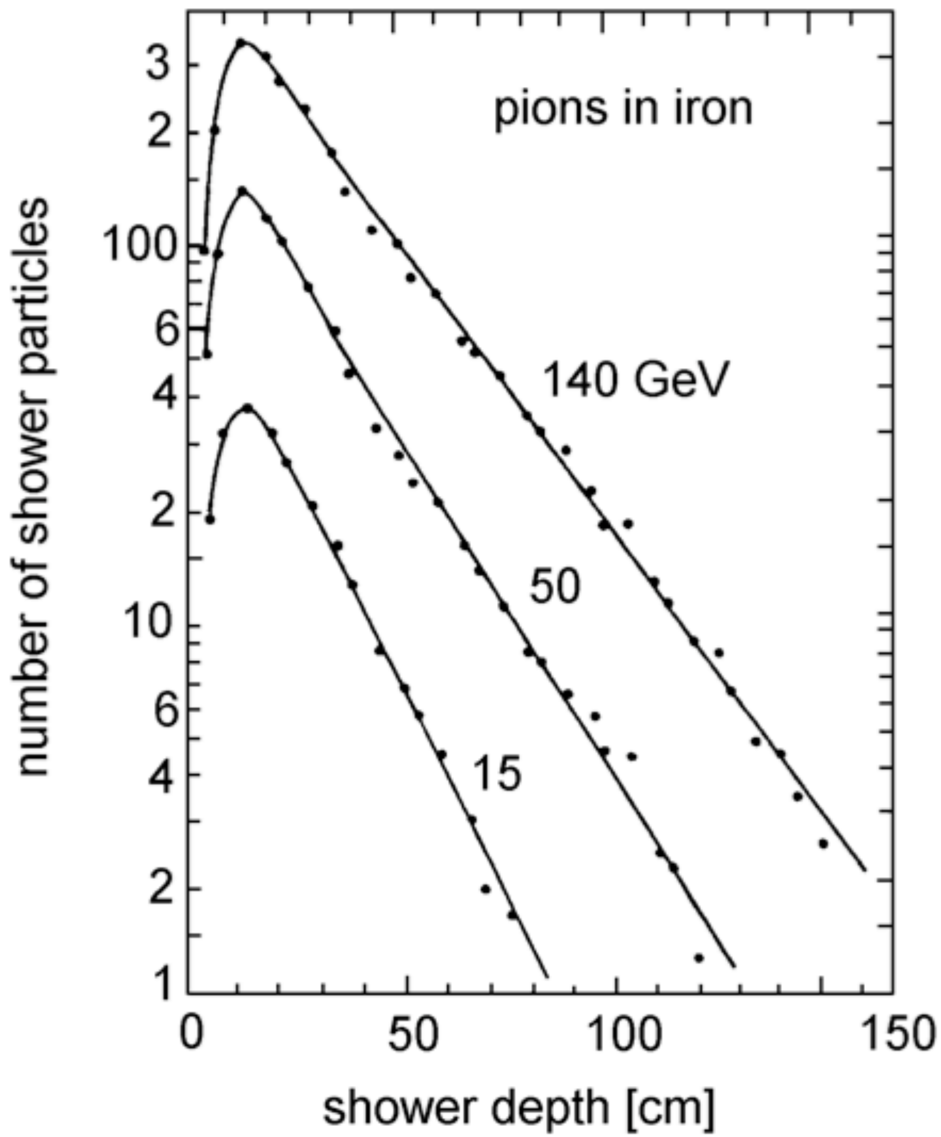
$\Rightarrow$ Visible energy systematically lower

$\Rightarrow$ Due to fluctuations in energy losses Energy resolution is worse than for electromagnetic calorimeters

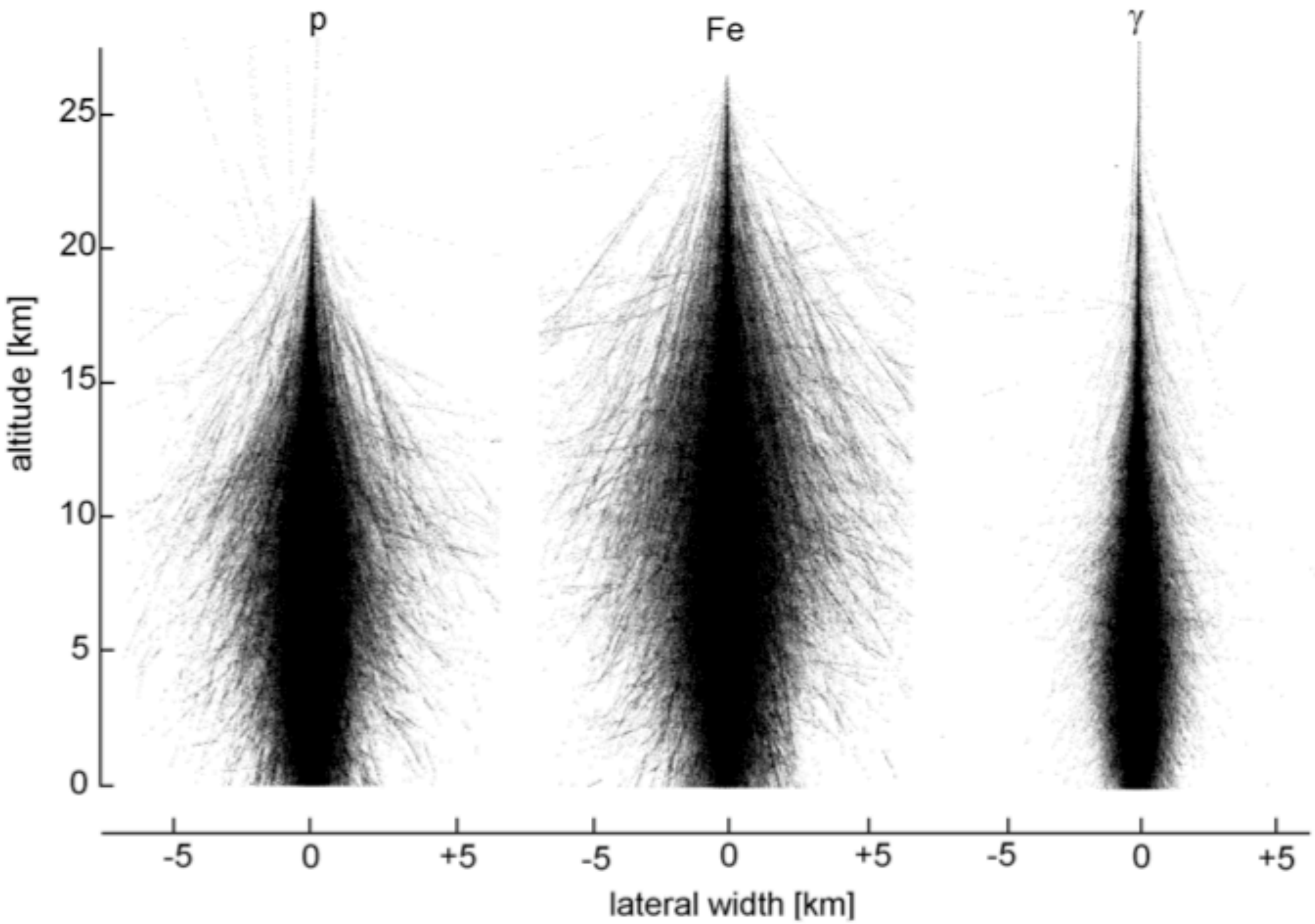
Problem of compensation: different response to electrons and hadrons. Need to balance to $e/\pi = 1$

# Hadronic Showers



# Extensive Air Showers




Extensive Air Showers, $10^{14}$ eV

# Interaction of Neutrons

indirect technique: neutrons interact and produce charged particles

- Low Energies ($< 20\,\mathrm{MeV}$):

  $n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H} \quad \Rightarrow$ LiI(Tl) scintillators

  $n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li} \quad \Rightarrow$ $BF_3$ gas counters

  $n + {}^{3}\mathrm{He} \rightarrow p + {}^{3}\mathrm{H} \quad \Rightarrow$ ${}^{3}$He-filled proportional counters

  $n + p \rightarrow n + p \quad \Rightarrow$ proportional chambers with for example $CH_4$

- High Energies ($E > 1\,\mathrm{GeV}$)

  $n + {}^{235}\mathrm{U} \rightarrow$ fission products $\Rightarrow$ coated proportional counters

  $n + \mathrm{nucleus} \rightarrow$ hadron cascade $\Rightarrow$ calorimeters

# Interaction of Neutrinos

$$\begin{aligned} \nu_e + n &\rightarrow p + e^- & \qquad \bar{\nu_e} + p &\rightarrow n + e^+ \\ \nu_\mu + n &\rightarrow p + \mu^- & \qquad \bar{\nu_\mu} + p &\rightarrow n + \mu^+ \\ \nu_\tau + n &\rightarrow p + \tau^- & \qquad \bar{\nu_\tau} + p &\rightarrow n + \tau^+ \end{aligned}$$

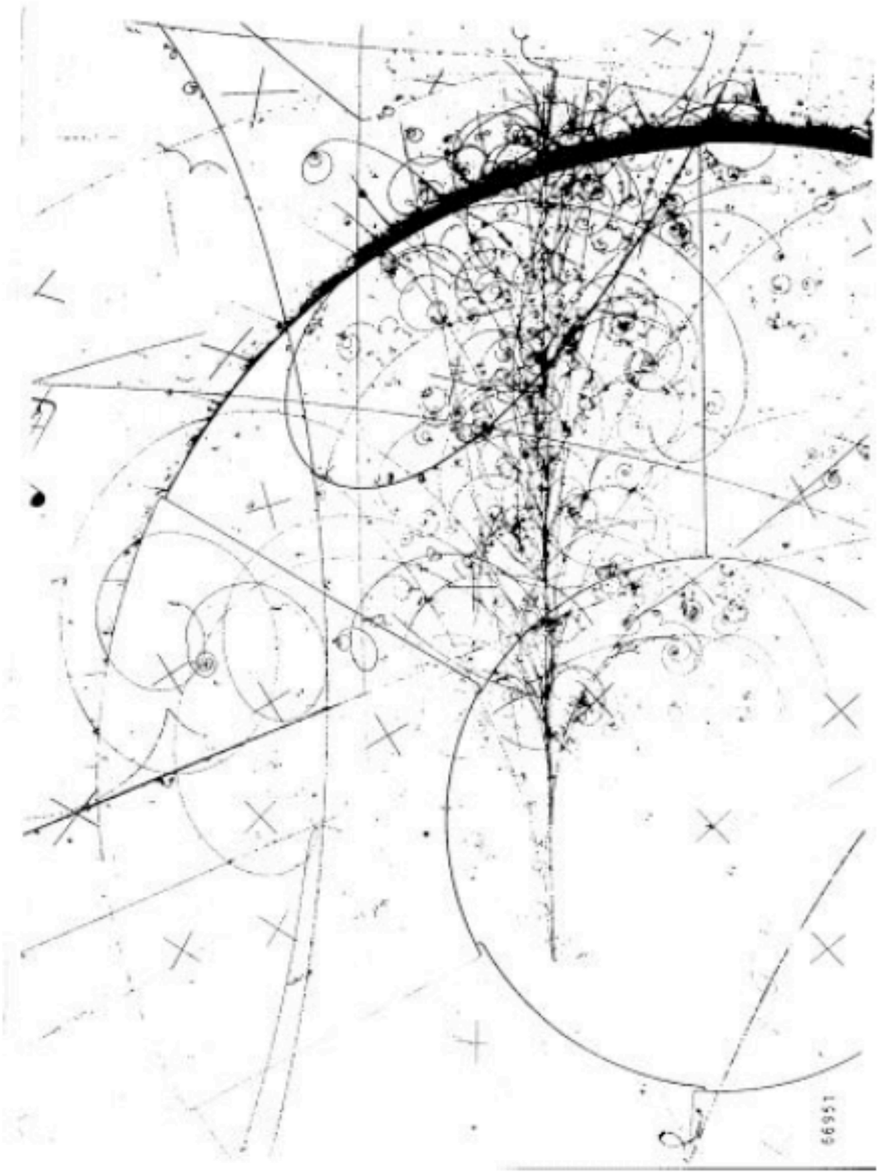
Small cross section: (MeV range): $\sigma(\nu_e N) = \frac{4}{\pi} \cdot 10^{-10} \left( \frac{\hbar p}{(m_p c)^2} \right)^2 = 1.6 \cdot 10^{-44}\,\mathrm{cm}^2$ for 0.5 MeV

for high Energies (GeV range):

$$\begin{aligned} \sigma(\nu_\mu N) &= 0.67 \cdot 10^{-38}\, E_\nu\, \mathrm{cm}^2/(\mathrm{nucleon\ GeV}) \\ \sigma(\bar{\nu_\mu} N) &= 0.34 \cdot 10^{-38}\, E_\nu\, \mathrm{cm}^2/(\mathrm{nucleon\ GeV}) \end{aligned}$$

- Indirect Measurement by missing momentum and missing energy technique

# Interaction of Neutrinos




$\nu_e + \text{nucleon} \rightarrow e^- + \text{hadron}$

Electromagnetic shower

# Radiation Length

- For a material with N atoms/cm$^3$ there will be n collisions for a path length L

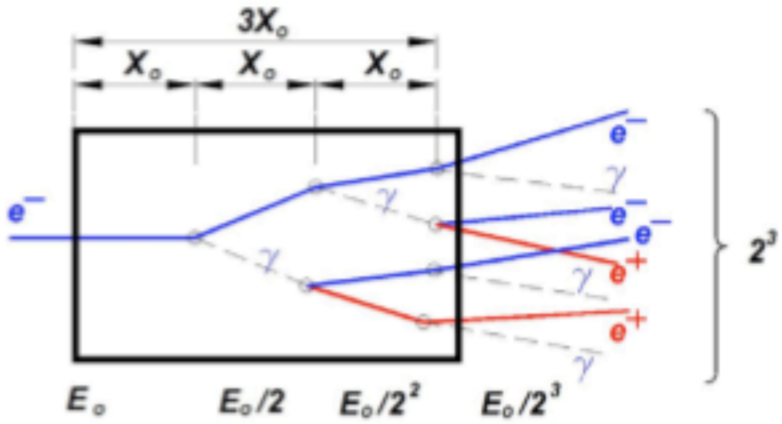
$$n = N\sigma_{radiative} L$$

- Setting n=1 and writing L=$X_0$, a radiation length is given by

(Inverse) Radiation Length

$$\frac{1}{X_0} = N\sigma_{radiative} \approx 4N\alpha\left(\frac{\alpha}{m_e}\right)^2 Z^2 \log\left(\frac{183}{Z^{1/3}}\right)$$

Electron Impinging on a Target




For photons

$$X_0^{\gamma} = \frac{9}{7} X_0$$

FNAL-CERN Summer School 2009
Calorimetry Lecture 1

# End of Lecture 2

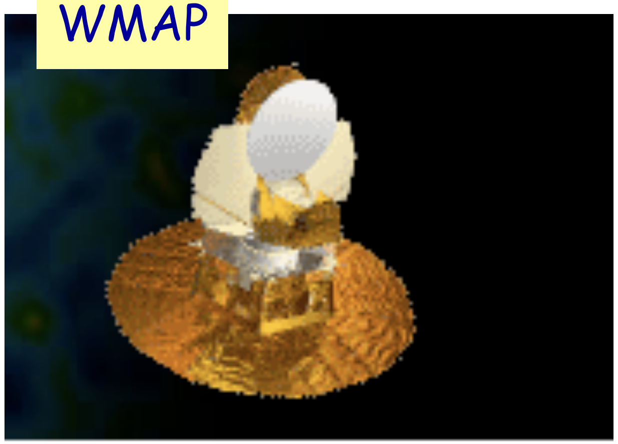
# Projects

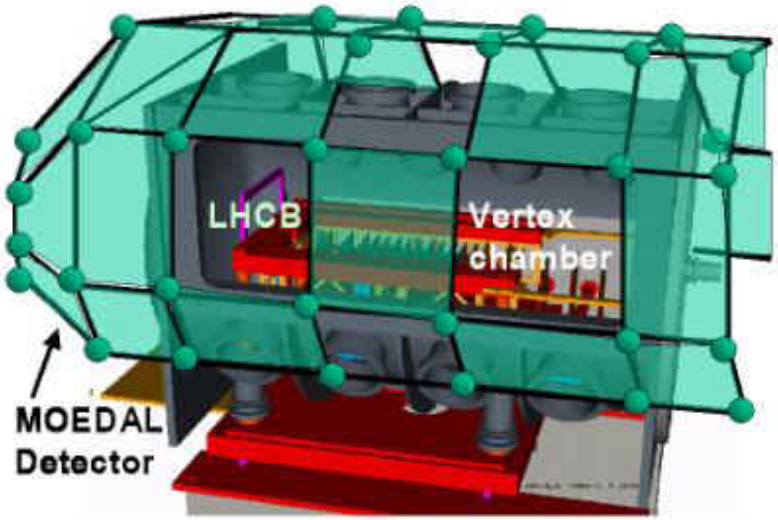
- Simple Projects (*)
  - Derive the Bethe Bloch Formula (Grupen)
  - Cherenkov light radiation (Grupen)
- Other key experiments (**)
  - The Auger cosmic ray experiment. Ultra High Cosmic Rays
  - The WMAP experiment (satellite, dark matter/dark energy)
  - The Planck experiment (satellite, dark mater dark energy)
  - Ligo: gravitational waves / laser interferometry
  - The MOEDAL experiment at CERN (monopole search)
- Detection techniques (**)
  - General: EM shower calorimeters (Grupen)
  - Had shower calorimeters (Grupen)
  - Compensating calormeters (Wigmans lectures)
  - Dual readout calorimeters (Wigmans lectures)
  - Silicon detectors (Kleinknecht)
  - MSGC gas detectors
- Difficult projects (***)
  - CMS papers with real data (calibration, alignment, efficiency of the CMS detector

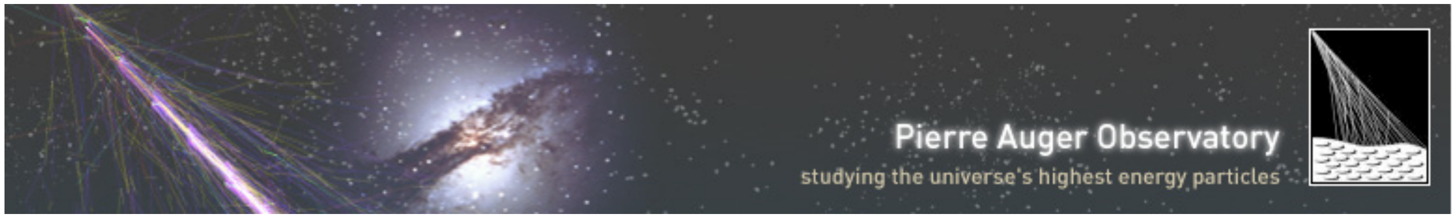
# Other Experiments

LIGO
Gravitational waves

WMAP



# Timeline & Projects

- Report (5-10 pages) + Presentation of ~ 15 minutes
- When?
- ⇒ Agenda
  - 2 oct : ADR Particles through matter
  - 9 oct : ADR Detectors and CMS
  - 16 oct : JD (Brussels)
  - 23 oct : -- no lectures
  - 30 oct : ADR Other LHC experiments/ other applications (medicine/other areas)
  - 6 nov : JD
  - 13 nov : JD
  - 20 nov : ADR?
  - 27 nov : JD
  - 4 Dec: ADR Projects <---
  - 11 Dec: JD?
  - 18 Dec: ---

# Drift and Diffusion in Gases

- Electrons and Ions lose Energy by multiple collisions: $\rightarrow$ Thermalization

- Ionization diffuses (Gaussian) Width $\propto \sqrt(t)$

- With electric field:
  Drift with constant velocity $v_{\text{drift}}$
  In argon-isobutane: Typical $v_{\text{drift}}^{\text{electron}} \approx 5\,\text{cm}/\mu\text{sec}$
  Longitudinal and transverse diffusion different
  $(\sigma = \sigma(E_e))$

- $v_{\text{drift}} \propto 1/m$: Ions $> 10^3$ times slower!

- With additional magnetic field:
  drift under angle (Lorentz force)