8.701

Introduction to Nuclear and Particle Physics

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10. Instrumentation

1. Particle Interaction with Matter

Particle Detection Principle

In order to detect a particle, it must **interact** with the material of the detector and **transfer energy** in some identifiable manner

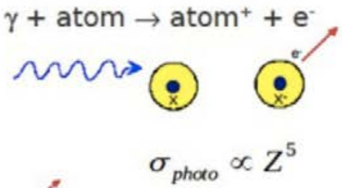
Which particle can we identify?

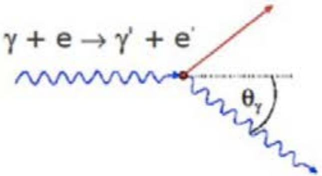
Electrons, muons, pions, kaons, protons, neutrons, heavy ions, and photons.

Photon Interaction

Photo effect

- Used in various photo detectors to create electrons on photo cathodes in vacuum and gas or at semi conductors (surface)
  - Photo multiplier tubes
  - Photo diodes

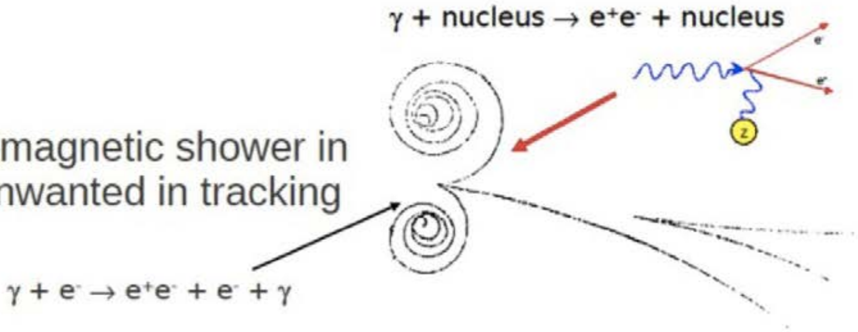




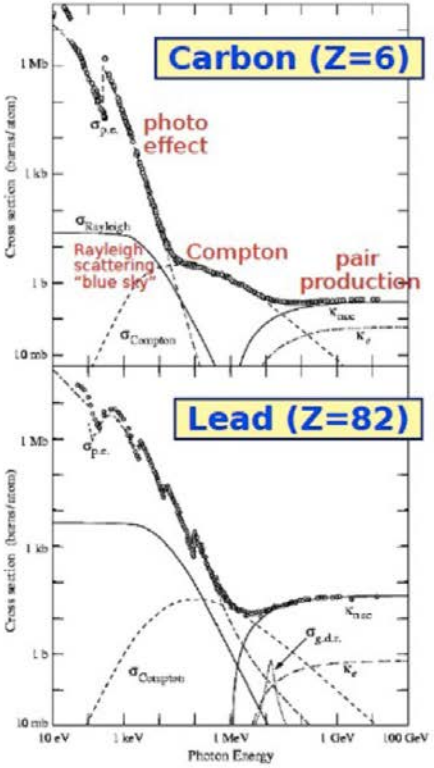
Compton effect

Pair production

- Initiates electromagnetic shower in calorimeters, unwanted in tracking detectors



Photon Interaction



- Photo effect dominating at low energies < some 100 keV
- Compton scattering regime ~some 100 keV to ~10 MeV
  - Exact energy range depends on Z
- Pair production dominating at high energies > 10 MeV

$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_{e} = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [4]. In these interactions, the target nucleus is broken up.

Photon (Electron) Interaction

Main energy loss of high energy photons/electrons in matter

- Pair production (γ) and bremsstrahlung ($e^{\pm}$)

Can characterize any material by its radiation length X_0

- 2 definitions (for electrons and photons)
  - X_0 = length after an electron looses all but 1/e of its energy by brem.
  - X_0 = 7/9 of mean free path length for pair production by the photon.

Very convienient quantity

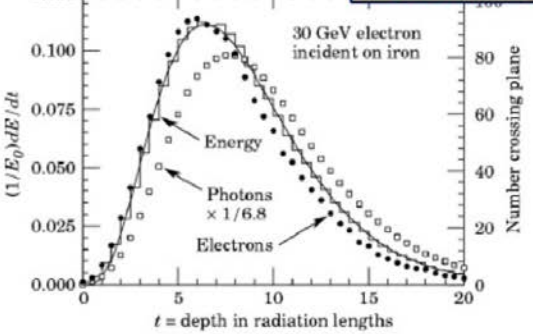
- Rather than using thickness, density, material type ...
  - Often expressed as % of X_0
- Tracking detectors should been transparent
  - ATLAS and CMS trackers: 30%-230% X_0
- Calorimeters should have X0 as high as possible (20-30 X_0)

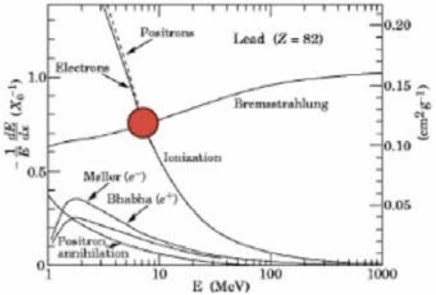
Photon (Electron) Interaction

Starting from the first electron / photon an electromagnetic shower (cascade) develops in thick material

- Shower maximum (peak of energy deposition) is slightly energy dependent
- $t_{max}[X_0] = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$

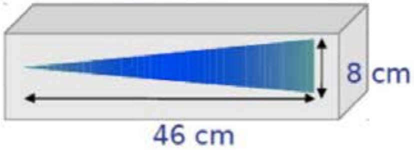
E_c = critical energy where energy loss (Ionization) = energy loss (Bremsstrahlung)





Transversal shower width given by Moliere radius

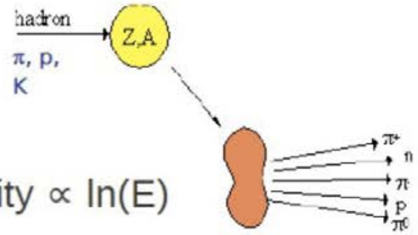
$$R_M = \frac{21\,MeV}{E_c} X_0$$



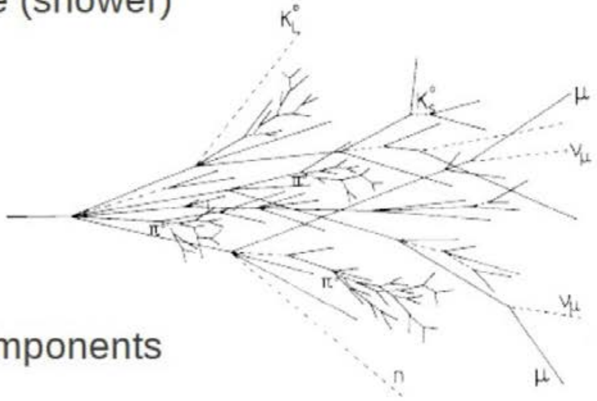
Nuclear Interaction

Similar to radiation length but for strong interaction of hadron with nucleus

- Development of hadronic cascade (shower)



- Multiplicity ∝ ln(E)



Hadronic showers have two main components

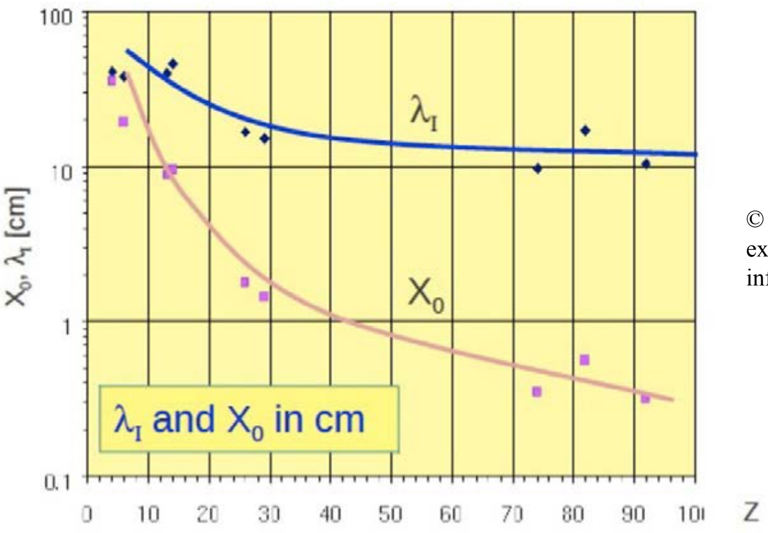
- Hadronic
  - Charged hadrons, breaking up of nuclei, neutrons
- Electromagnetic
  - Decay of neutral pions

Radiation Length

Gases, e.g. Argon ~100m

Light materials, e.g. Aluminum, Silican ~10cm

Heavier metals, e.g. Iron, Copper, Lead ~0.5 - 1.5cm



Charged Particle Interaction

Multiple elastic scattering with atoms

- Mostly unwanted, changes initial direction, affects momentum resolution

Ionization

- Basic mechanism in tracking detectors

Photon radiation

- Bremsstrahlung
- Cerenkov radiation
- Transition radiation

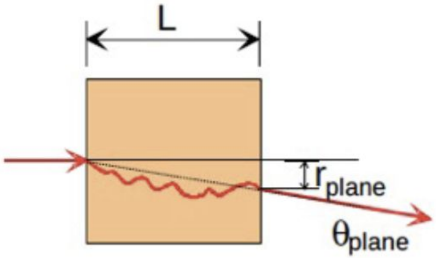
Excitation

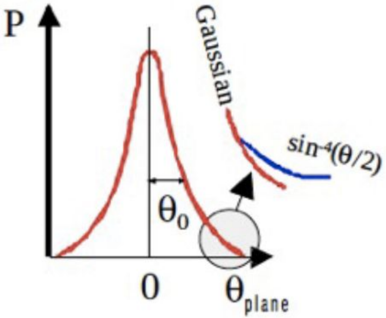
- Creation of scintillation light in calorimeters

Multiple Scattering

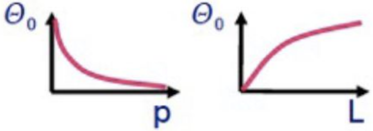
- After passing a layer of thickness L particle leaves with some displacement r and some deflection angle

- Dominates momentum measurement for low momenta (later)



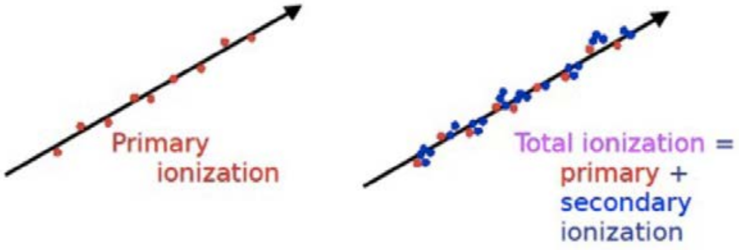


$$\Theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$



Ionization

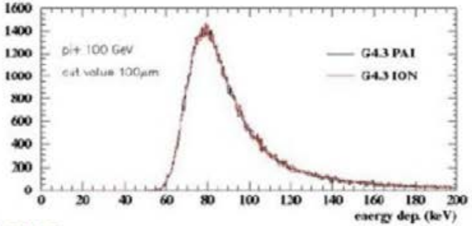
- Primary number of ionizations per unit length is Poisson-distributed
  - Typically ~30 primary interactions / cm in gas @ 1 bar
- Primary electrons sometimes get large energies
  - Can lead to secondary ionization
  - Can even create visible secondary track (“delta-electron”)
  - Large fluctuations of energy loss by ionization

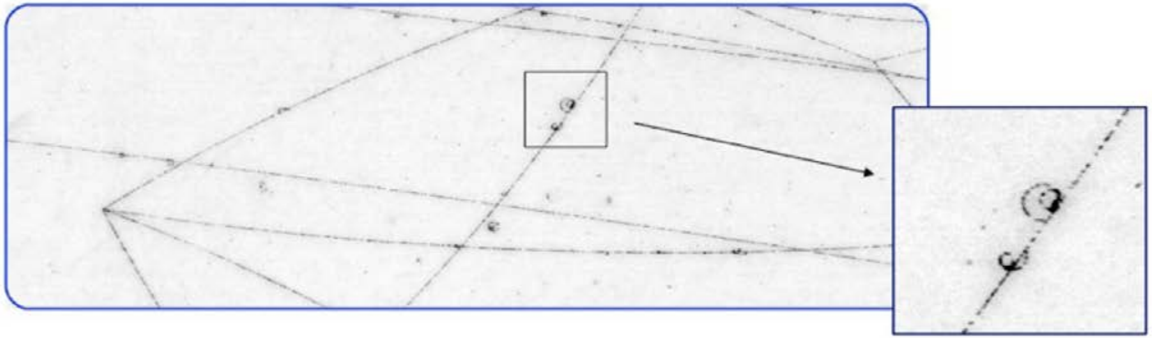


  - Typically: total ionization = 3 x primary ionization

Ionization

- Energy loss distribution
  - Cluster size fluctuations cause large variations of energy loss from particle to particle
    - Landau distribution
      - Large broad peak
        - Single or few el. cluster
      - Looooong tail
        - Multiple el. cluster, δ – electrons

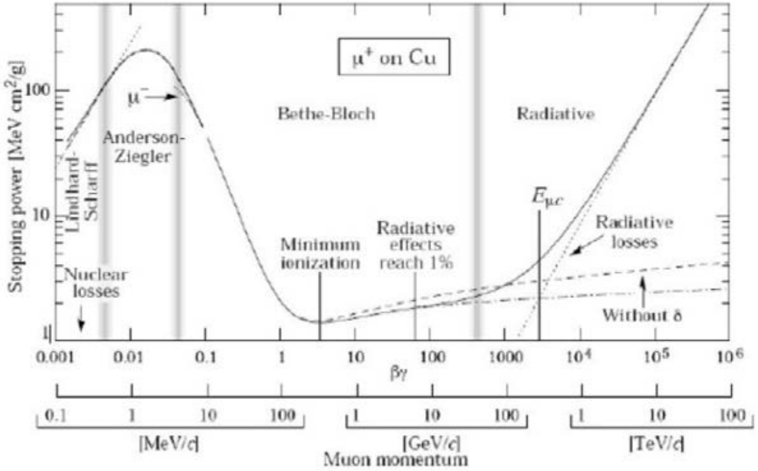




Charge Particle Interaction

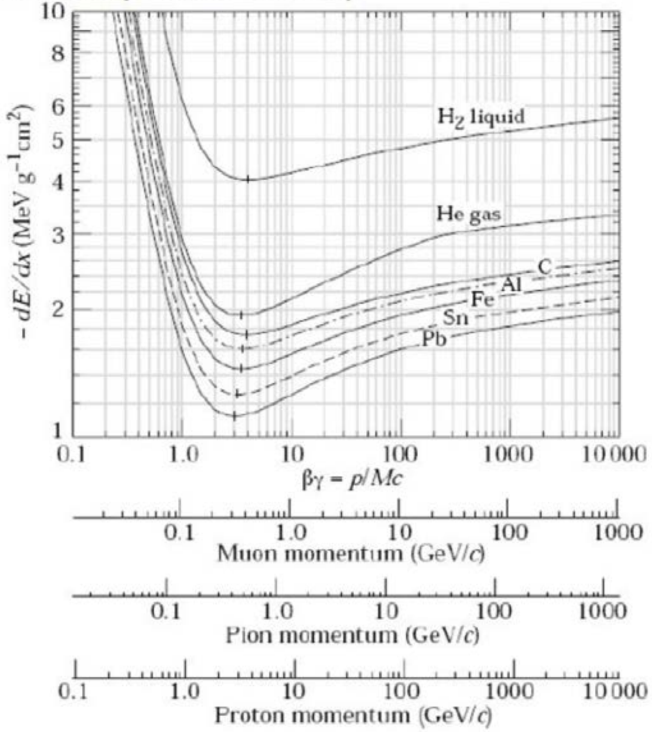
- Energy loss function (Bethe-Bloch)
  - Good description for pion from 6 MeV to 6 GeV

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



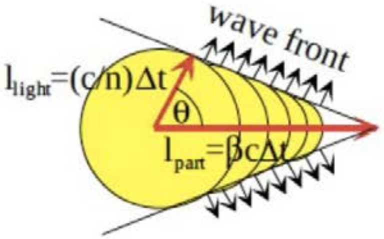
Charge Particle Interaction

Energy loss function (Bethe-Bloch)

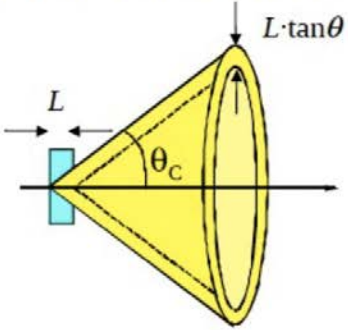


Cherenkov Radiation

- Emitted when a charged particle passes through a dielectric medium with speed greater than the speed of light in that medium
- Classical picture: wave front or cone under Cerenkov angle



$$\cos \Theta_C = \frac{1}{n\beta}$$

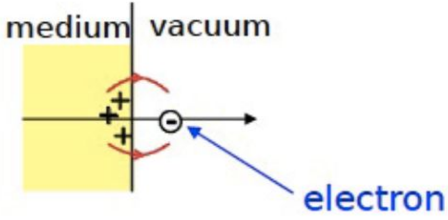


- Number of emitted photons per unit length and unit wave length

$$\frac{d^2 N}{dx\, d\lambda} \propto \frac{1}{\lambda^2} \qquad \frac{d^2 N}{dx\, dE} = const$$

Transition Radiation

- Predicted by Ginzburg and Franck in 1946
  - Emission of photons when a charged particle traverses through the boundary of two media
  - Very simple picture
    - Charged particle is polarizing medium
    - Polarized medium is left behind when particle leaves media and enters vacuum
    - Formation of an electrical dipole with radiation



- Radiated energy per boundary
  - Only very high energetic particles can radiate significant energy.
  - In our present energy range only electrons can radiate transition radiation (particle ID!)
  - Need many boundaries to get enough photons