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

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

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Photon (Electron) Interaction

Main energy loss of high energy photons/electrons in matter

- Pair production ($\gamma$) and bremsstrahlung ($e^\pm$)

Can characterize any material by its radiation length $X_0$

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

Very convenient 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.

\[ t_{\text{max}}[X_0] = \ln \frac{E_0}{E_c} \times \frac{1}{\ln 2} \]

\[ E_c = \text{critical energy where energy loss (ionization) = energy loss (Bremsstrahlung)} \]

Transversal shower width given by Moliere radius

\[ R_M = \frac{21 \text{MeV}}{E_c} \times X_0 \]
Nuclear Interaction

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

- Development of hadronic cascade (shower)

- Multiplicity $\propto \ln(E)$

Hadronic showers have two main components

- Hadronic
  - Charged hadrons, breaking up of nuclei, neutrons

- Electromagnetic
  - Decay of neutral pions

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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

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

Energy loss function (Bethe-Bloch)

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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

\[
\frac{d^2 N}{dx \ d\lambda} \propto \frac{1}{\lambda^2} \quad \frac{d^2 N}{dx \ dE} = \text{const}
\]
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