PHYS 3446 – Lecture #15

Thursday, April 9, 2012

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Energy Deposition in Media

Detecting Particles

- An ideal detector would
  - Detect particles without affecting them
- Real detectors
  - Use electromagnetic interactions of particles with matter
    - Ionization of matter by energetic, charged particles
    - Ionized electrons can then be accelerated within an electric field to produce a detectable electric current
  - Particles like neutrinos, which do not interact through EM force and have low cross sections, require special detection methods

Charged Particle Detection

- What do you think is the primary interaction when a charged particle is traversing through a medium?
  - Interactions with the atomic electrons in the medium
- If the energy of the charged particle is sufficiently high
  - It deposits its energy (or loses its energy in matter) by ionizing the atoms along its path   electrons
  - Or by exciting atoms or molecules to higher states   photons
  - What are the differences between the above two methods?
    - In the former case you get electrons, for the latter photons
    - At high energy both result in EM showers
- If the charged particle is massive, its interactions with atomic electrons will not affect the particle's trajectory
- Sometimes, the particle undergoes nuclear collisions

Ionization Process

- Ionization properties can be described by the stopping power variable, S(T)
  - Definition: amount of kinetic energy lost by any incident object per unit length of the path traversed in the medium
  - Referred to as ionization energy loss or energy loss

$$S(T) = -\frac{dT}{dx} = n_{ion}\bar{I}$$

Why negative sign?

The particle's energy decreases.

- T: Kinetic energy of the incident particle
- n_{ion}: Number of electron-ion pair formed per unit path length
- $\bar{I}$: The average energy needed to ionize an atom in the medium; for large atomic numbers ~10Z eV.

Ionization Process

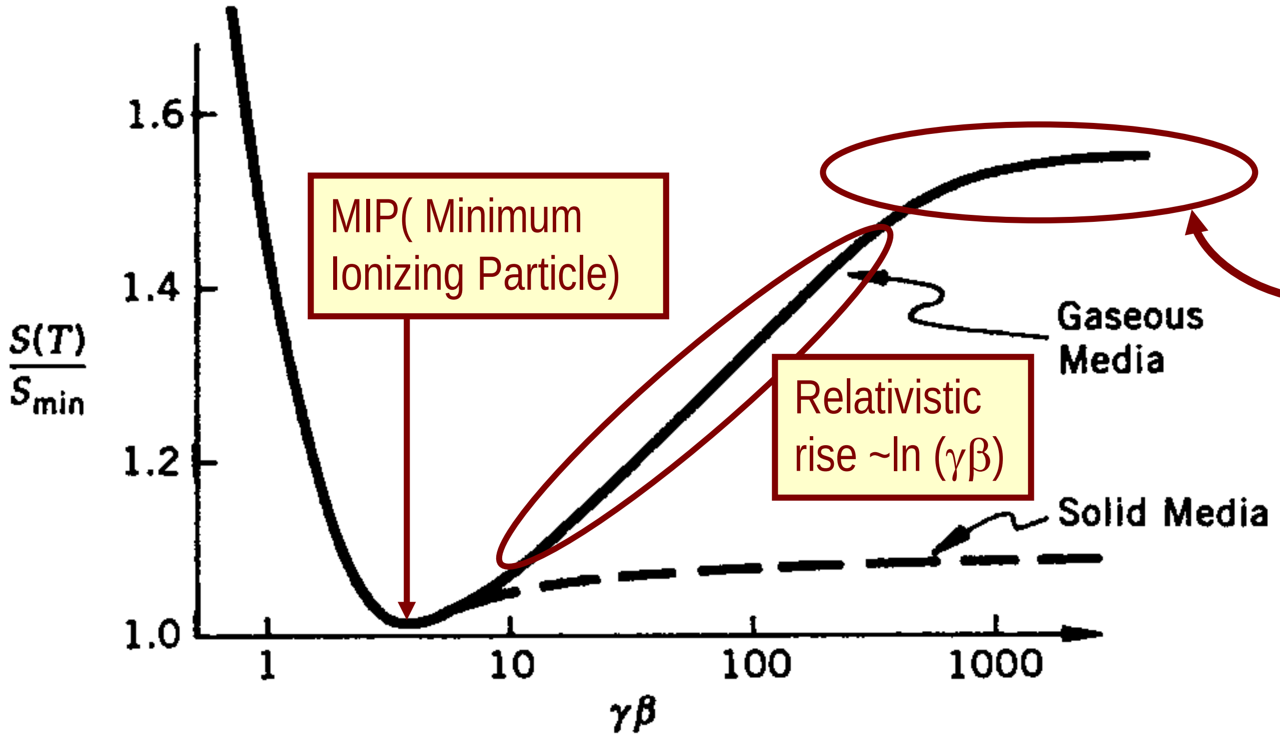
- What do you think the stopping power of a given medium depends on?
  - Energy of the incident particle
  - Electric charge of the incident particle
- Since ionization is an EM process, “easily” calculable
  - Bethe-Bloch formula for relativistic particle

$$S(T) = \frac{4\pi (ze)^2 e^2 nZ}{m\beta^2 c^2}\left[\ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right) - \beta^2\right]$$

  - z: Incident particle atomic number
  - Z: medium atomic number
  - n: number of atoms in unit volume (=$\rho A_0/A$)
  - m: electron mass

Properties of Ionization Process

- Stopping power decreases with increasing particle velocity independent of incident particle mass
  - Minimum occurs when $\gamma\beta$~3
    - Particle is minimum ionizing when v~0.96c
    - For massive particles the minimum occurs at higher momenta
  - This is followed by a ln($\gamma\beta$) relativistic rise (see Beth-Bloch formula)
  - Energy loss plateaus at high $\gamma\beta$ due to long



Projects

1 UA1 Higgs (non) discovery/Carlo Rubbia Nick Stadler, John Havens, Paul T.

2 Top Discovery CDF/Dzero John Crouch, Matthew Gartman

3 J/Ψ (Charm quark) Michael Davenport, Charles Knight, Richard Humphries

4 Top Quark at LHC: Kathleen Brackney, David Soward, Kevin Strehl

5 Charged Higgs1 search/discovery: Ashley Herbst, Anthony Rich

6 Charged Higgs2: Kelly Claunch, Robert Mathews, Charles Jay

7 Higgs Discovery (ATLAS/CMS): Raul Dominguez, Peter Hamel, Kennedy

8 B quark Discovery: Garrett Leavitt, Bernard Nuar, Rajendra Paudel

1) Intro/Theory-what are you looking for and what is it's signature and background: how do you know if you find it
2) Detector-how is detector optimized for the task at hand, trigger/data collection
3) Analysis-operate on the data to accomplish the goals/Conclusion
4) Grading will include iintermediate milestones

Ionization Process

- At very high energies
  - Relativistic rise becomes an energy independent constant rate
  - Cannot be used to distinguish particle-types purely using ionization
  - Except for gaseous media, the stopping power at high energies can be approximated by the value at $\gamma\beta\sim3$ (MIP)
  - Ionization loss is very small when the velocity is very small
  - Detailed atomic structure becomes important

Ranges of Ionization Process

- Once the stopping power is known, we can compute the expected range of any particle in the medium
  - The distance the incident particle can travel in the medium before its kinetic energy runs out

$$R = \int_0^R dx = \int_T^0 \frac{dx}{dT} dT = \int_0^T \frac{dT}{S(T)}$$

- At low E, two particles with same KE but different mass can have very different ranges
  - This is why α and β radiation have quite different stopping requirements

Units of Energy Loss and Range

- What would be the sensible unit for energy loss?
  - MeV/cm
  - Equivalent thickness of g/cm^2: $MeV/(g/cm^2)$
- Range is expressed in
  - cm or g/cm^2 (units related through density)
- Minimum value of S(T) for z=1 at $\gamma\beta=3$ is

- Using B-B formula we can approximate

$$S(T)_{\min} \approx 3.5\frac{Z}{A}\ \mathrm{MeV}/\left(\mathrm{g/cm}^2\right)$$

review

Ex. 1+2

Multiple Scattering

- Phenomenological calculations can describe average behavior, but large fluctuations are observed on an event-by-event bases
  - This is due to the statistical nature of scattering process
- Statistical effect of angular deviation experienced in Rutherford scattering off atomic electrons in the medium
  - Consecutive collisions add up in a random fashion and provide net deflection of any incident particles from its original path
  - Called "Multiple Coulomb Scattering" ➔ Increases as a function of path length

$$\theta_{rms} \approx \frac{20MeV}{\beta pc} z \sqrt{\frac{L}{X_0}}$$

- z:particle charge L: material thickness, X_0: radiation length of the medium (distance electron travels before T'=T/e)

Energy Loss Through Bremsstrahlung

- Energy loss of incident electrons
  - Bethe-Bloch formula works well (up to above 1 MeV for electrons)
  - But due to the small mass, electron's energy loss gets complicated
    - Relativistic corrections have large effect even down to a few keV level
    - Electron projectiles can transfer large fractions of energies to the atomic electrons they collide with
      - Produce δ-rays (ejected electrons) ➔ Which have the same properties as the incident electrons
  - Electrons are accelerated as a result of interaction with electric field by nucleus. What does this do?
  - Causes electrons to radiate or emit photons
    - Bremsstrahlung ➔ Braking radiation (as electron decelerates) an important mechanism of relativistic electron energy loss

Total Electron Energy Loss

- The electron energy loss can be written

$$\left(-\frac{dT}{dx}\right)_{tot} = \left(-\frac{dT}{dx}\right)_{ion} + \left(-\frac{dT}{dx}\right)_{brem}$$

- Relative magnitude between Bremsstrahlung and ionization is

$$\left(-\frac{dT}{dx}\right)_{brem} \Big/ \left(-\frac{dT}{dx}\right)_{ion} \approx \frac{TZ}{1200 m_e c^2}$$

  - Z: Atomic number of the medium, m_e: rest mass of the electron, T: Kinetic energy of the electron in MeV

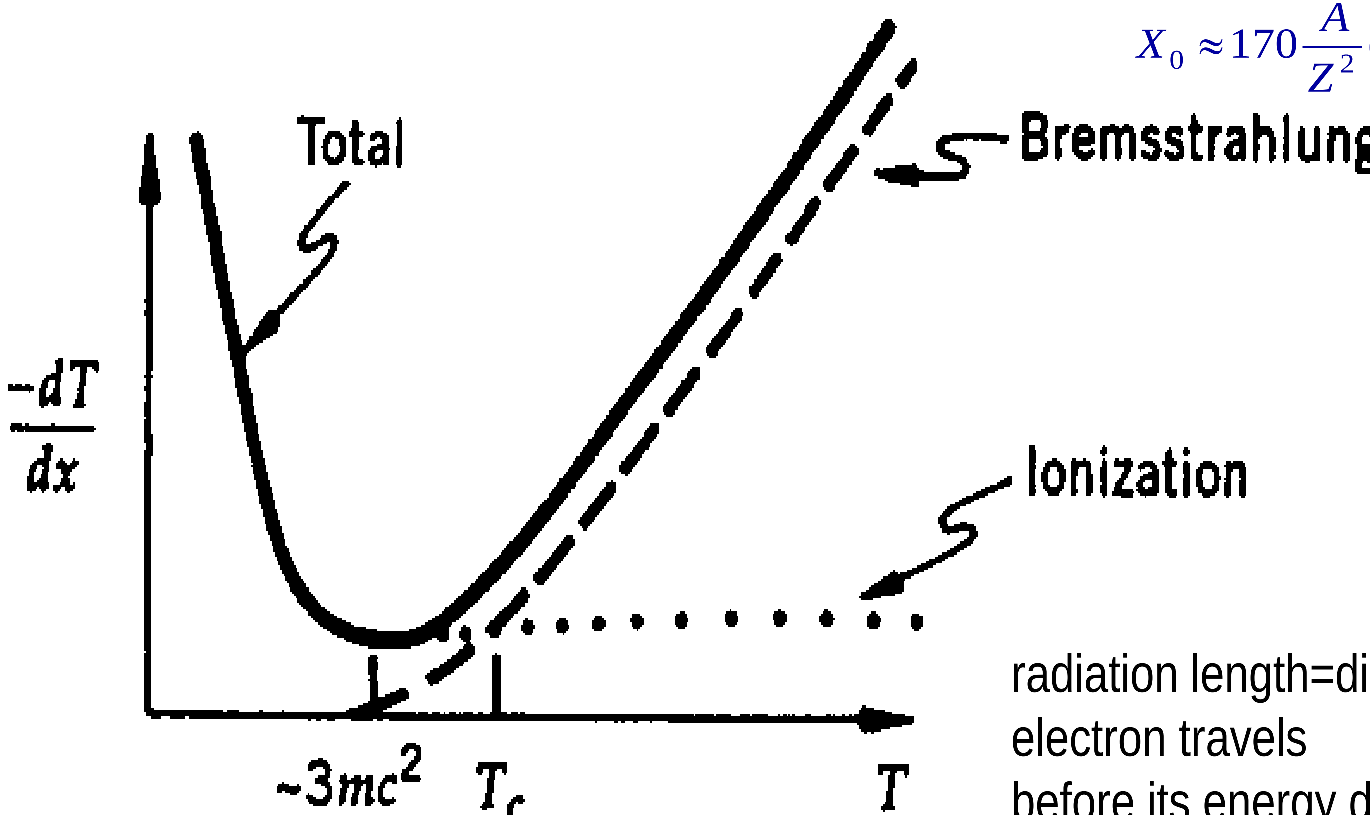
- At high energies, ionization loss is constant
  - Radiation dominates the energy loss
  - The energy loss is directly proportional to incident energy
  - $T=T_0\, e^{-x/X_0}$ (electrons radiate most of energy within a few radiation lengths)

Total Electron Energy Loss

- Above the critical energy (T_c) the brem process dominates

$$\left(\frac{dT}{dx}\right)_{brem} = \left(\frac{dT}{dx}\right)_{ion} = -\frac{T_c}{X_0}$$

$$X_0 \approx 170\frac{A}{Z^2}(g/cm^2)$$



radiation length=distance electron travels before its energy drops to T/e

Photon Energy Loss

- Photons are electrically neutral
  - They do not feel Coulomb force
  - They cannot directly ionize atoms
- Photons are EM force carriers
  - Can interact with matter resulting in ionization
  - What are the possible processes?
    - Photo-electric effect
    - Compton scattering
    - Pair production (dominates above 10 MeV)

Light Attenuation

- Reduction of intensity in a medium
- Can be described by an effective absorption coefficient μ
  - μ reflects the total cross section for interaction
  - μ depends on energy or frequency of the incident light
- The intensity of light at any given point through the medium, x, is given as $I(x) = I_0 e^{-\mu x}$
- Half-thickness, the thickness of material such that a photon's intensity is reduced by half: $x_{1/2} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$
- μ^{-1} is the mean free path for absorption

Pair Production

- What is the minimum energy needed to produce an electron-positron pair?
  - Twice the rest mass energy of the electron

$$h\nu \approx 2m_e c^2 = 2\times 0.511MeV = 1.02MeV$$

- The pair production cross section is proportional to Z^2
  - Z: atomic number of the medium
  - Rises rapidly and dominates all energy-loss mechanisms for photon energies above 10MeV or so.
  - It saturates and can be characterized by a constant mean free path for conversion
    - A constant absorption coefficient → Electron radiation length of medium

$$X_{pair} = \left(\mu_{pair}\right)^{-1} \approx \frac{9}{7}X_0$$

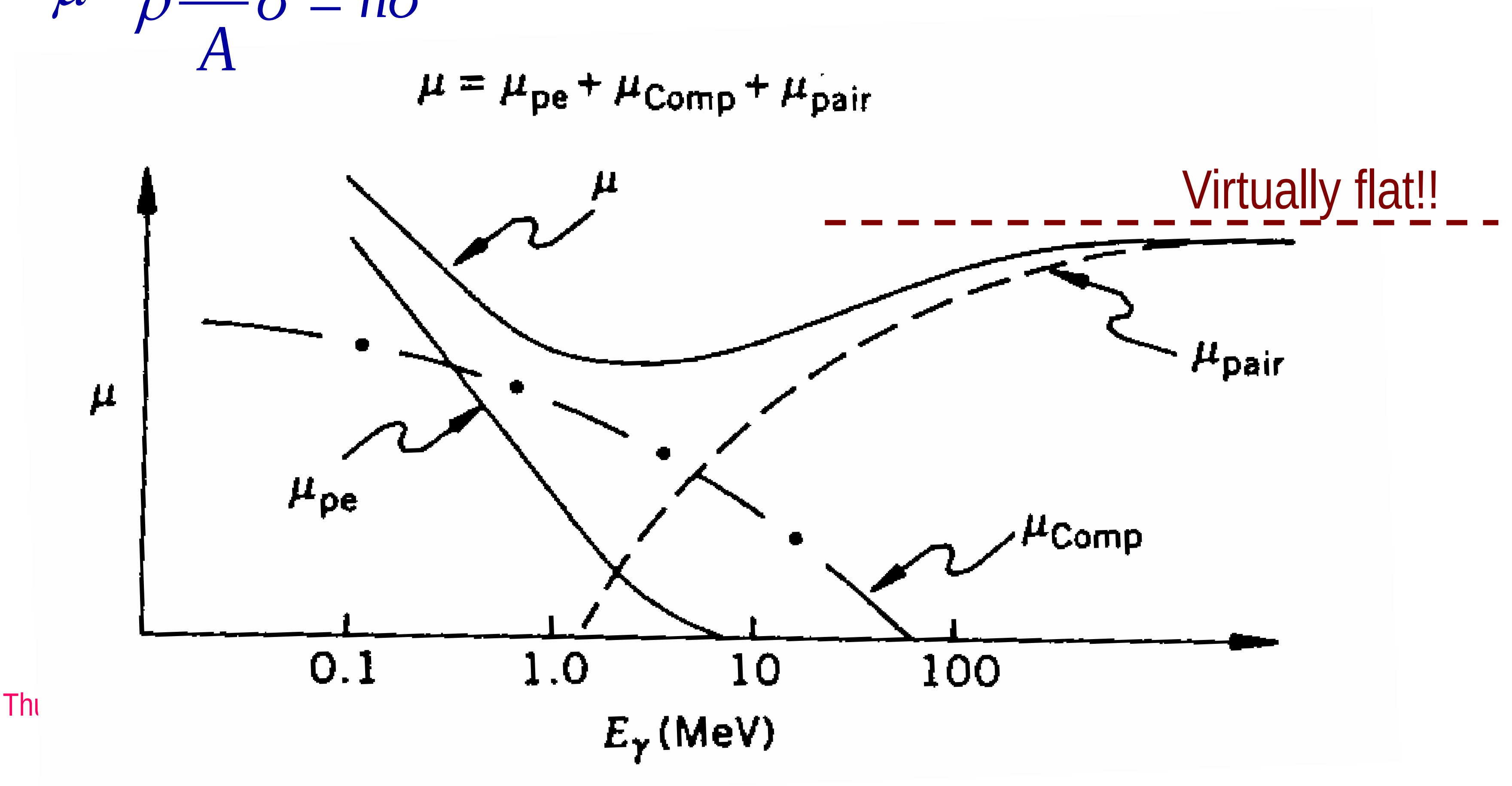
Photon Energy Loss Processes

- Total absorption coefficient of photons in a medium can be written as

$$\mu = \mu_{pe} + \mu_{Comp} + \mu_{pair}$$

- The absorption coefficient can be related to the cross section as

$$\mu = \rho \frac{A_0}{A} \sigma = n\sigma$$



Interaction of Neutrons

- What are the characteristics of neutrons?
  - Constituent of nuclei
  - Have the same nucleon number as protons
  - Have the same spin as protons
  - Electrically neutral ➔ Do not interact through Coulomb force
  - Interact through strong nuclear force
- When low energy neutrons interact inelastically
  - Nucleus get excited and decay to ground levels through emission of photons or other particles
  - Such photons or other particles can be detected

Interaction of Neutrons

- In an elastic scattering of neutrons, energy loss is smaller if the media's nucleus is heavy
  - Hydrogen-rich paraffin is used to slow down neutrons

- Neutrons produced in reactors and accelerator experiments are a potential background concern
  - Since normally there are no hydrogen nuclei available for kinetic energy absorption
    - can be reduced with the use of appropriate moderators

Interaction of Hadrons at High Energies

- Hadrons
  - All particles interact through the strong nuclear force
  - Examples: neutrons, protons, pions, kaons, etc.
  - Protons are easy to obtain and can be used with to produce other particles
- At low (<2 GeV) energies the cross section for producing different particles differs dramatically
  - The collision cross sections can have a significant energy dependence
  - Nuclear effect is significant
- Above 5 GeV, the total cross section of hadron-hadron interaction changes slowly as a function of energy
  - Typical size of the cross section is 20 – 40 mb at 70 – 100 GeV
  - And increases logarithmically as a function of energy

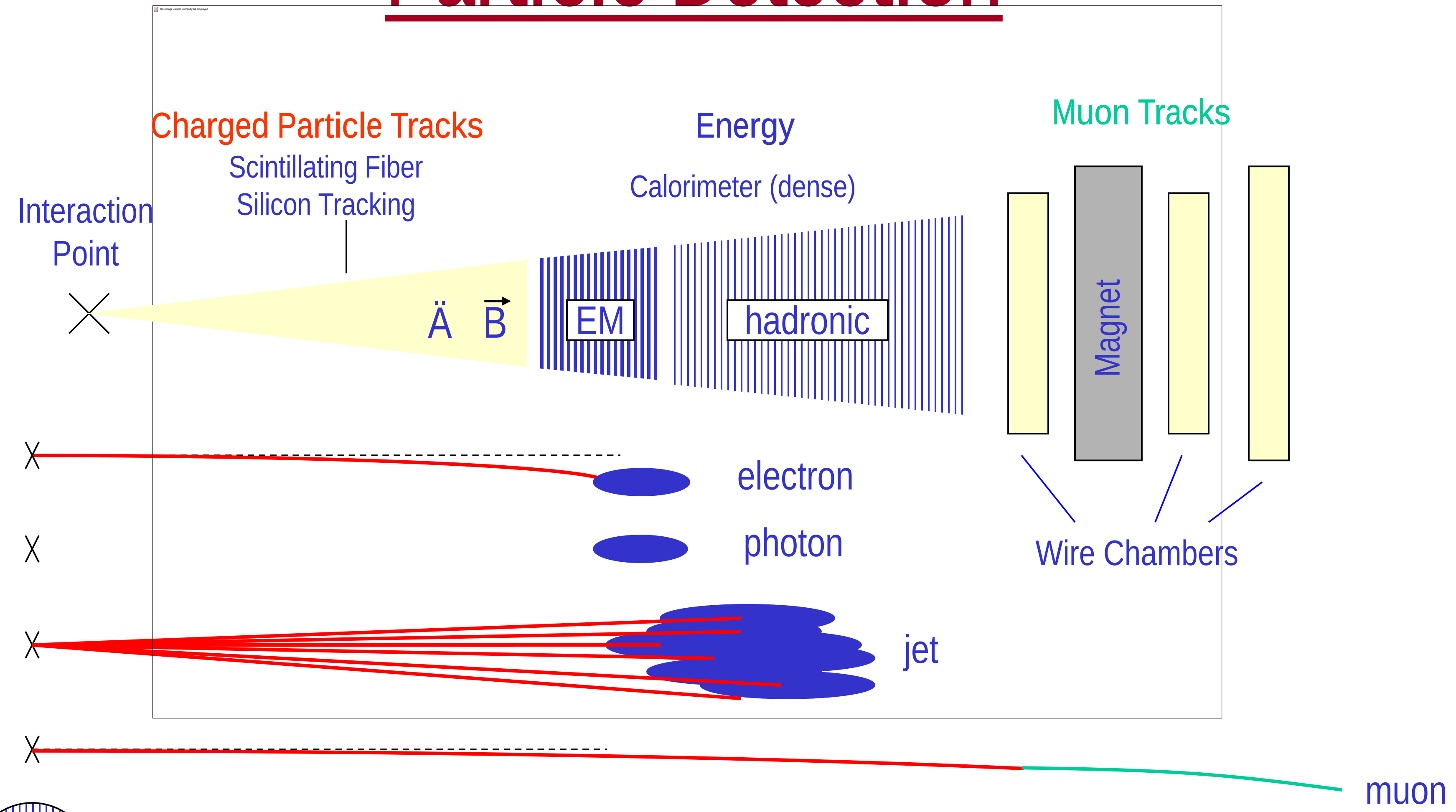
Interaction of Hadrons at High Energies

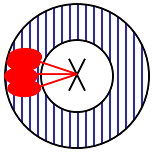
- Hadronic collisions involve very small momentum transfers, small production angles and interaction distance of order 1fm
- Typical momentum transfer in hadronic collisions are of the order $q^2 \sim 0.1\ (GeV/c)^2$
- Mean number of particles produced in hadronic collisions grows logarithmically as a function of incident energy
  - ~3 at 5 GeV
  - ~12 at 500 GeV
- High energy hadrons interact with matter, they break apart nuclei, produce mesons and other hadrons
  - These secondary particles also interact through the strong force

Particle Detectors

- Subatomic particles cannot be seen by the naked eye but can be detected through their interactions within matter
- What do you think we need to know first to construct a detector?
  - What kind of particles do we want to detect?
    - Charged particles and neutral particles
  - What do we want to measure?
    - Momenta
    - Trajectories
    - Energies
    - Origin of interaction (interaction vertex)
  - To what precision do we want to measure these quantities?
- Depending on the answers to the above questions we use different detection techniques

Particle Detection





neutrino -- or any non-interacting particle missing transverse momentum

We know x,y starting momenta is zero, but along the z axis it is not, so many of our measurements are in the xy plane, or transverse