PHY492: Nuclear & Particle Physics

Lecture 25

Particle Detectors

http://pdg.lbl.gov/2006/reviews/contents_sports.html

Minimum ionization in *thin* solids

$$S(T) = -\frac{dT}{dx} \propto nZ = \rho A_0 \frac{Z}{A}$$

Z : atomic number of medium

n : number of atoms/unit volume

$n = \frac{\rho A_0}{A}$; A : atomic number of medium

- Units for energy loss
  - Z/A ~ 0.4 at large A, energy loss proportional to density, S~ρ,
  - Divided by the density -> value nearly independent of material.
- $(dE/dx)_{min}$ for materials in MeV/(g/cm^2)
  - Polystyrene scintillator: 1.95

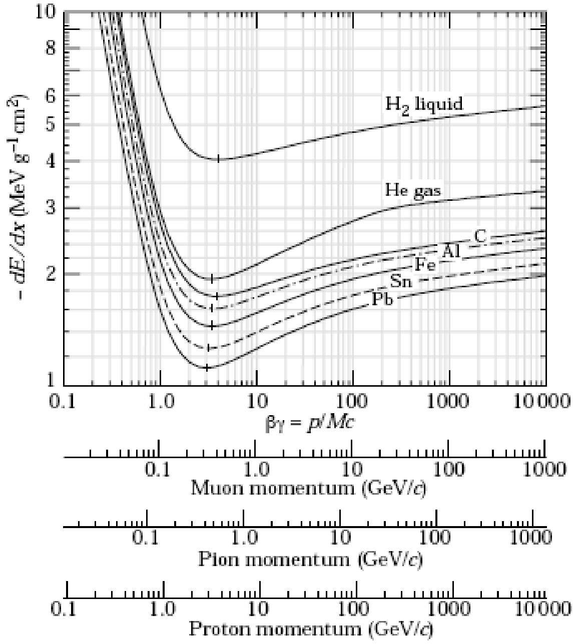
$$\rho_{\text{scintillator}} = 1.03 \text{ g/cm}^3$$

$$-\left.\frac{dT}{dx}\right|_{\text{min}} = 1.95 \left(\frac{\text{MeV}}{\text{g/cm}^2}\right)\rho_{\text{Scintillator}} = 2.0 \text{ MeV/cm}$$

  - Iron (steel) : 1.45

$$\rho_{\text{iron}} = 7.87 \text{ g/cm}^3$$

$$-\left.\frac{dT}{dx}\right|_{\text{min}} = 1.45 \left(\frac{\text{MeV}}{\text{g/cm}^2}\right)\rho_{\text{iron}} = 11.4 \text{ MeV/cm}$$



Relativistic muon loses ~2 MeV/cm in plastic, ~11.4 MeV/cm in Iron

High energy particles in matter

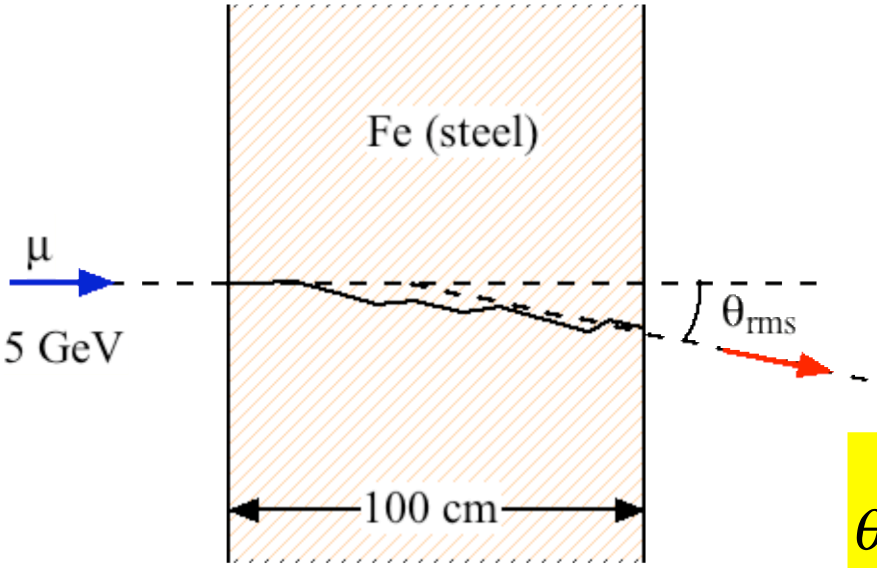
- Particles can be deflected, degraded or absorbed
- Characteristic length is particle, energy, and material dependent

Long lived particles ($\tau > 10^{-10}$ s)

- Muons (mass $m_\mu \sim 200\ m_e$)
  - lose energy mostly by ionization -> energy determines range
  - rare energy loss by photon radiation in the EM field of nucleus
  - very rare EM interaction on nuclear charges, nuclear disintegration
  - deflection by multiple scatterings on atomic electrons
- Electrons and photons at high energy (T > 1 GeV)
  - Electron radiates photons: X_0 is the "radiation length"
  - Photon converts to e^+e^- pair: $9X_0/7$ is the "pair creation length"
  - Electrons and Photons interact with the charge of the nucleus
- Hadrons (proton, neutron, charged pi-meson, K-meson, ...)
  - nuclear interactions; absorption length, X_{abs} proportional to density ρ
  - additional hadrons often created

Muon multiple scattering

- 5 GeV muon ($m=105.6$ MeV/c^2) through 1 m of steel looses about 1.1 GeV by ionization. Some atomic electrons are kicked hard.
- Muon will be deflected (either direction) with a probability distribution that peaks at $\theta = 0$ but spread by θ_{rms}.



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

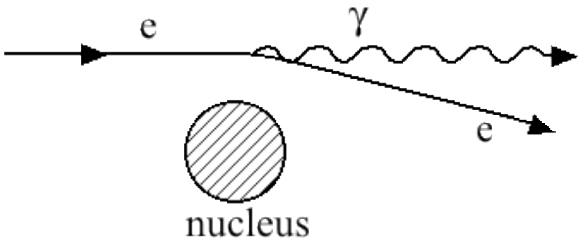
$$\text{Iron } X_0 = 1.76\,\text{cm}$$

$$\theta_{rms} = \frac{20}{5000}\sqrt{\frac{100}{1.76}} = 30\text{ mr} = 2^{\circ}$$

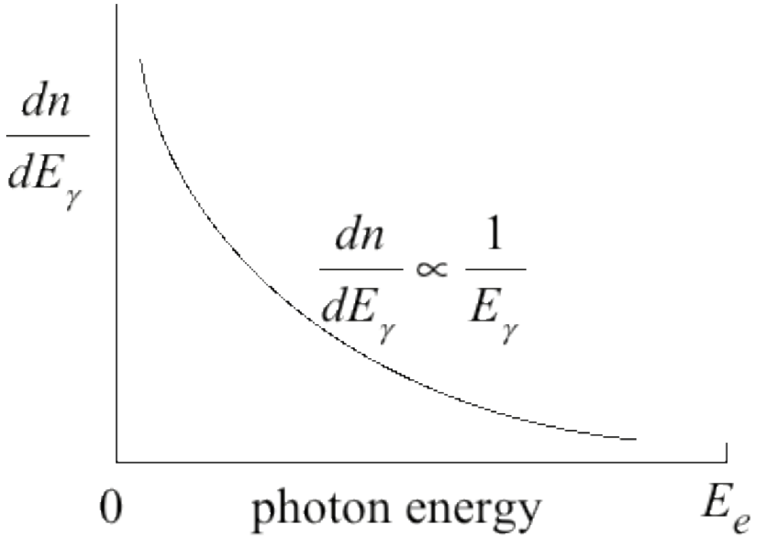
Bremsstrahlung

- High energy electrons loose energy primarily by radiating photons
- The characteristic length, X_0 is material dependent
- Kinetic energy (on average) will drop exponentially.

$$\left.\frac{dT}{dx}\right|_{\text{Brem}} = -\frac{T}{X_0} \longrightarrow T = T_0 e^{-T/X_0}$$



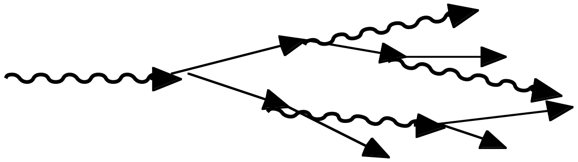
- Photon energies are discrete with a $1/E_\gamma$ distribution
- Many low energy photons (even IR) and a few high energy photons



Photons in matter

- E < 1 MeV, photoelectric absorption and Compton scattering dominate the interactions of photons
- E = 1 - 10 MeV, Compton scattering dominates but pair production is rising
- E > 10 MeV, pair production dominates the interactions

Cascading interactions



1. 1 GeV photon enters a block of lead (X_0 = 0.56 cm)
2. After 5 mm the photon produces a e+e- pair (0.4 and 0.6 GeV)
3. After 3 mm the e+ “brems” a 100 MeV photon. After 6 mm the e- “brems” a 300 MeV photon (e+ and e- are both 300 MeV).
4. After a few more mm each, the 100 MeV and 300 MeV photons pair produce, the 300 MeV e+ and e- both brems
5. Repeats until photons and electrons drop below 1 MeV.

Measuring a particle's momentum, energy, and mass

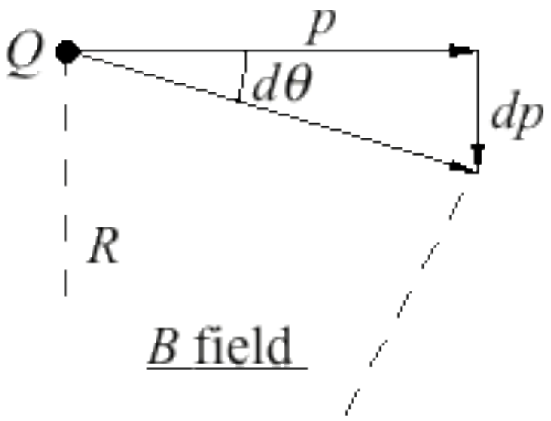
MWPC = Multi-Wire Proportional Chamber

GEM = Gas Electron Multiplier

- Charged particle tracking
  - Gas: MWPC, Drift Chamber, GEM
  - Solid state: Silicon, diamond
- Scintillators
  - scintillation and conversion -> electronic signals
  - Organic: Plastic, liquid hydrocarbon, fibers
  - Inorganic: Crystals, liquid noble gas
- Calorimeters
  - total absorption
  - sampling
- Particle identification (ID)
  - time of flight
  - ionization
  - Cerenkov light
  - transition radiation

Momentum measurements

- Charge Q bending in a magnetic field



Relativistic Derivation

$$p = \gamma m v$$

$$dp = p\,d\theta = p\frac{v\,dt}{R}$$

$$\frac{dp}{dt} = p\frac{v}{R} = QvB$$

$$\underline{p = QBR}$$

Units transformation

$$1\ \mathrm{eV} = 1.6\times 10^{-19}\ \mathrm{J}$$

$$q = Q\big/\left(1.6\times 10^{-19}\,\mathrm{C}\right)$$

$$p = QBR\left(1\ \frac{\mathrm{kg\cdot m\cdot s^{-1}}}{\mathrm{C\cdot T\cdot m}}\right)\left[\left(\frac{c}{c}\right)\left(\frac{e}{e}\right)\right]$$

$$= qBR\left(\frac{3\times 10^{8}\ \mathrm{eV}/c}{\mathrm{T\cdot m}}\right)$$

$$= 0.3qBR\left(\frac{\mathrm{GeV}/c}{\mathrm{T\cdot m}}\right)$$

- Transform to more useful units

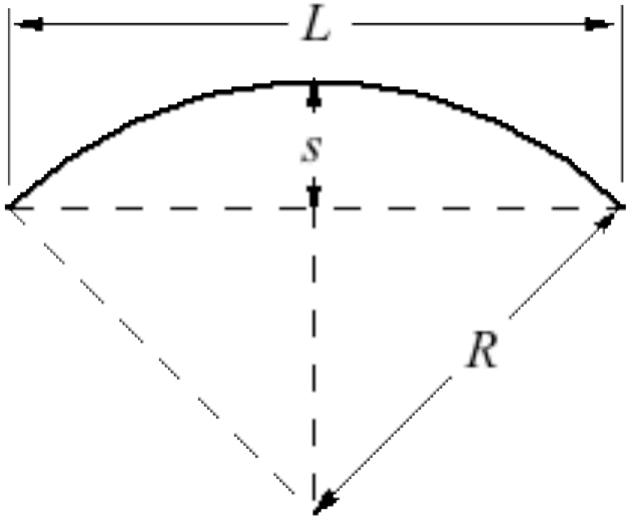
$$p \approx 0.3qBR$$

p in GeV/c, q in # of e's

B in Tesla, R in meters

Using the sagitta to find R

- Bending of elementary charge in a magnetic field
  - large radius -> weak bending -> large momentum
  - typically see only a small portion of the circle
  - measurement of momentum is equivalent to a measurement of the sagitta.



easy to show

$$R \approx \frac{L^2}{8s}, \quad s << R$$

s = sagitta

$$p = 0.3qBR$$

$$\frac{\delta p}{p^2} = \left(\frac{8}{0.3qBL^2} \right) \delta s$$

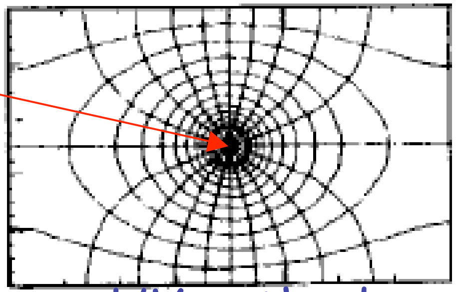
δs is fixed by detectors

make δs as small as possible

- Momentum errors minimized by big *B*, or even better by big *L*

Basics of wire chamber tracking

- Wire chamber features
  - Isolated gas volume ("chamber")
  - Anode wire, Au plated W, dia. <50μ
  - Cathodes at high voltage
- Gas properties (big subject)
  - Noble gas (Ar) no negative ions
  - UV quencher (hydrocarbon)
  - Cost
    - Cheap (flow & exhaust)
    - Expensive (recirculate & clean)
- Electronics
  - 1 circuit for each wire
  - fast, low noise
  - multi-channel ICs



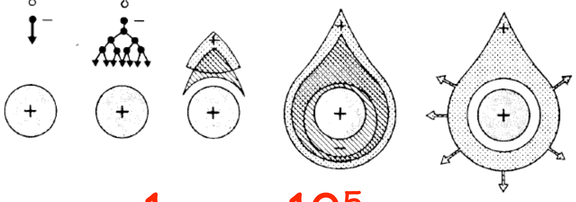
-HV cathode

Anode wire

GND potential

-HV cathode

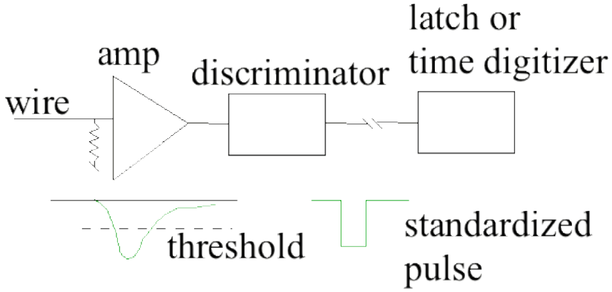
avalanche ~ 100μ from wire



(F. Sauli, CERN 77-09)

1 e^- -> 10^5 e

one electronics "channel"



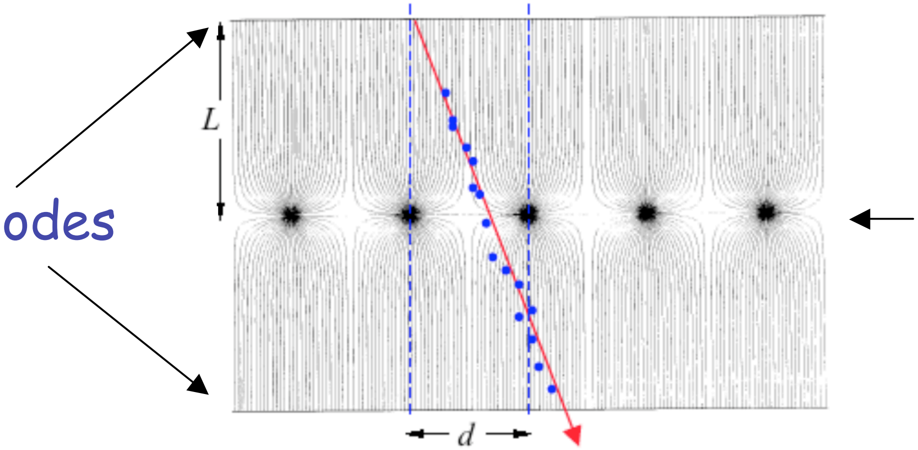
Multiwire proportional chambers (MWPC)

- MWPC capable of very high rates
- Mechanically difficult (wires break)

typical dimensions

d = 2mm, L = 10mm

anode wire dia. < 50μ

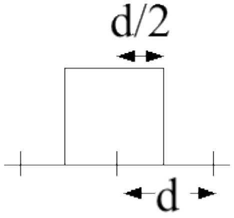


cathodes

large chambers with
>1500 anode (+) wires

- Resolution: know only hit wire

Flat probability
distribution



$$\langle x\rangle = 0;\ \text{where } x = x' - x'_{\text{wire}}$$

$$\langle x^2\rangle = \frac{\int_0^{d/2} x^2\,dx}{\int_0^{d/2} dx} = \frac{2}{d}\,\frac{x^3}{3}\Big|_0^{d/2} = \frac{d^2}{12}$$

Gaussian
equivalent:

$$\sigma = \sqrt{\langle x^2\rangle} = \frac{d}{2\sqrt{3}}$$

$$\approx 600\mu,\ d = 2\,\text{mm}$$

Drift chambers

- Graded potential, ~uniform drift field
- Drift followed by avalanche at wire

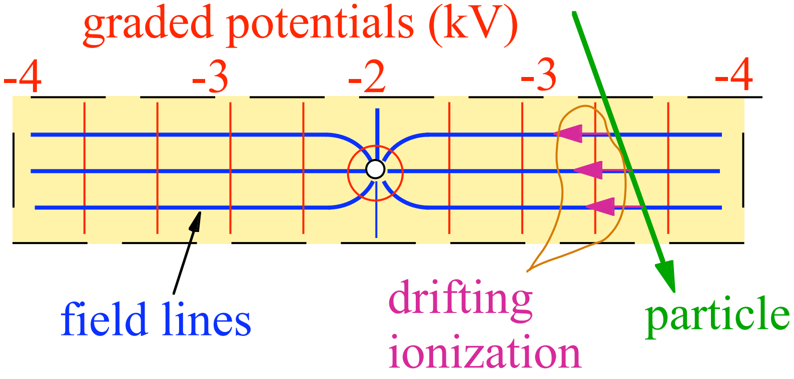
Particle crosses at time t
Ionization arrives at t + Δt

$$x = \pm v(t)\,\Delta t$$

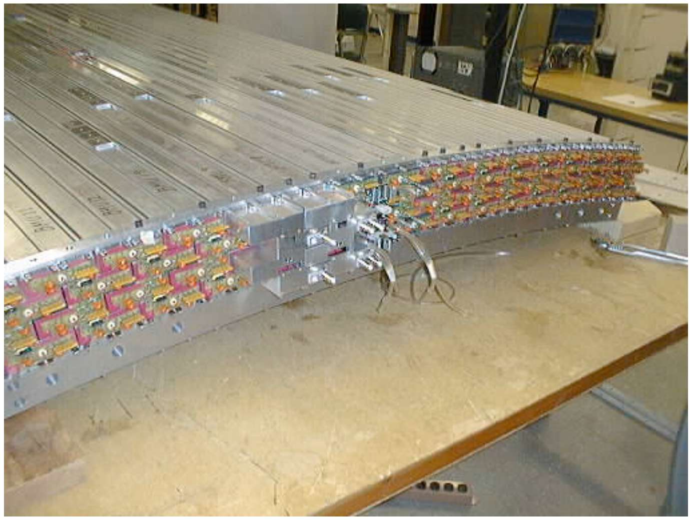
+/- left right ambiguity

- Position resolution ($\sigma = 50\text{-}200\mu$)
  - $v(t)$ distortions, e.g., near wire
  - ionization fluctuations
  - dispersion while drifting
  - electronic noise

drift cell

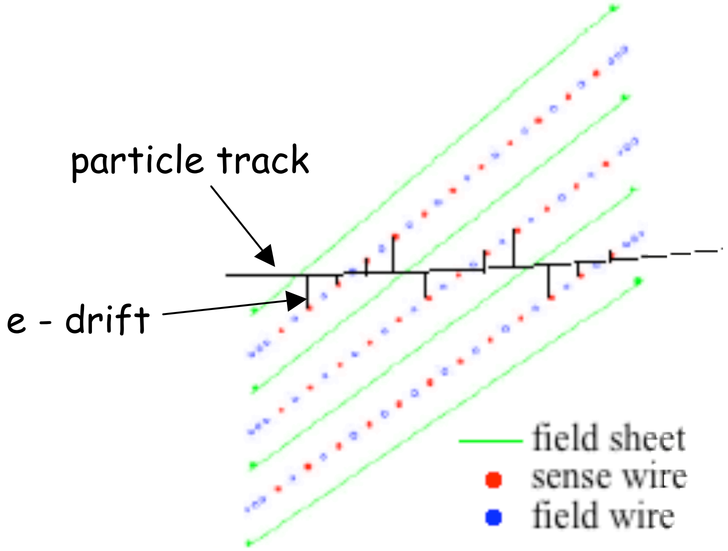


CDF muon chambers



Drift chambers for colliders

- CDF "jet chamber" technique
  - up to 30,000 wires, many samples
  - l/r resolved easily
  - ionization (pulse width)
  - magnetic field complications



- Other technologies (at LHC)
  - Micro-strip Gas Chambers
  - Gas Electron Multiplier (GEM)

CDF Central Outer Tracker (COT) during wire/field sheet installation

- Second coordinate techniques
  - stereo wire planes
  - timing or charge division
  - induced charge on cathode strips