Particle Detectors

Lecture 7 Physics 152

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(thanks again to **Colin Jessop**)

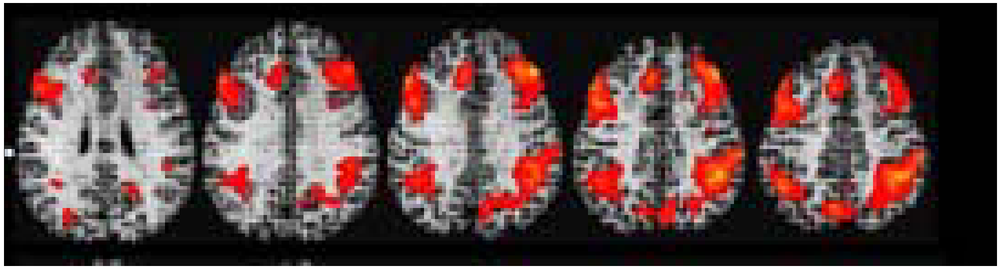
Particle Detectors

Technology developed for particle physics,
but has many other applications. For example:

Medical Imaging: X-rays, PET Scans

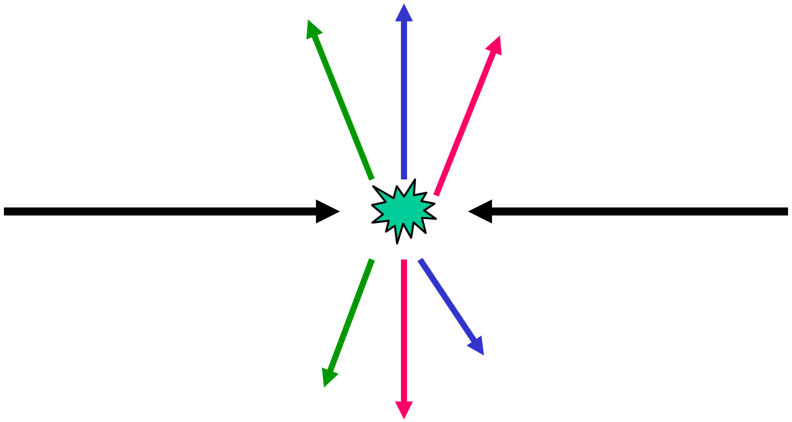
Structure determination in biology and chemistry

Airport Scanners: Explosive detection



A positron emission tomography (PET) scan of brain activity while remembering

Particle Physics Events

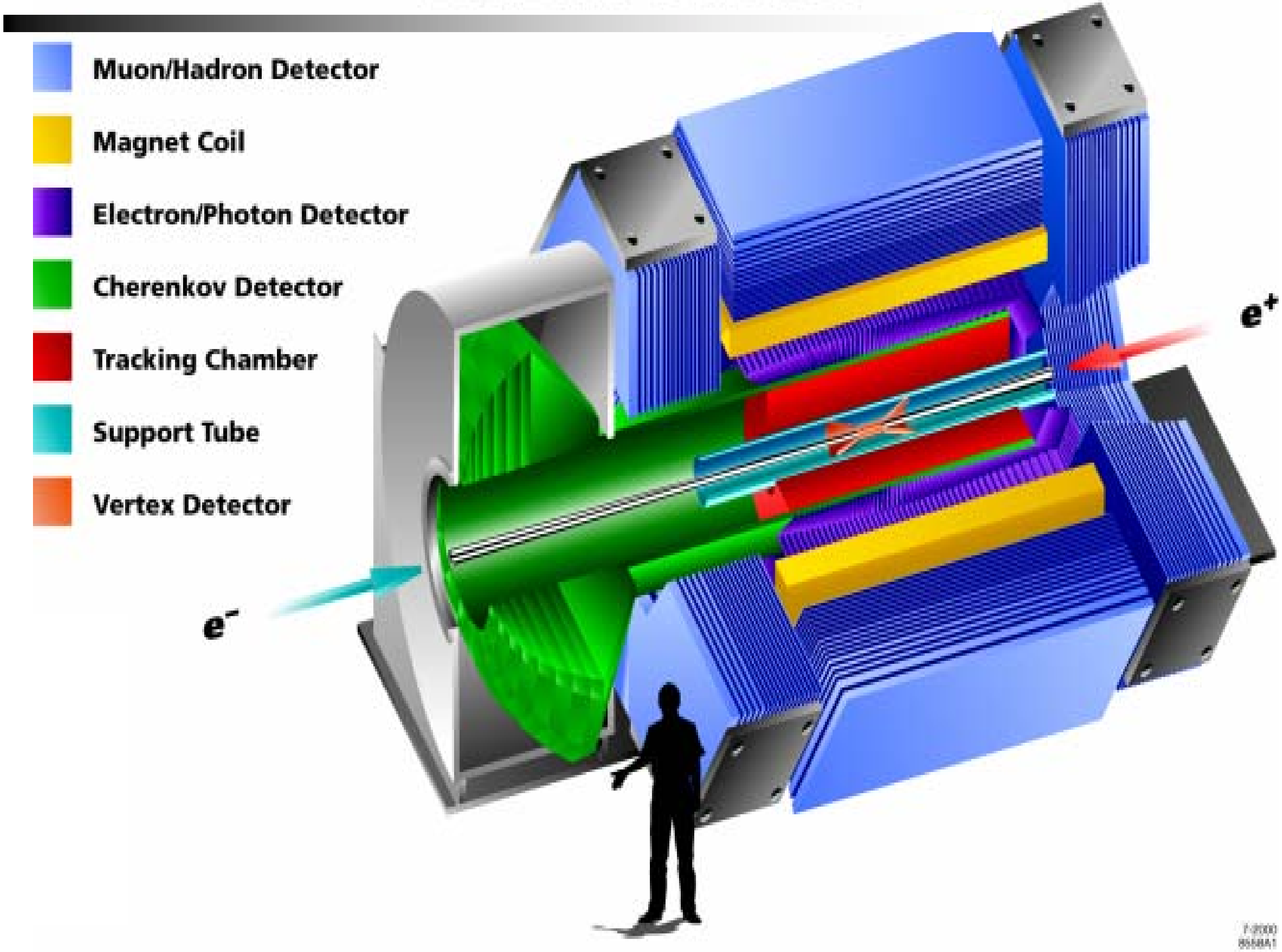


Want to measure 4-vector and identity of all particles produced

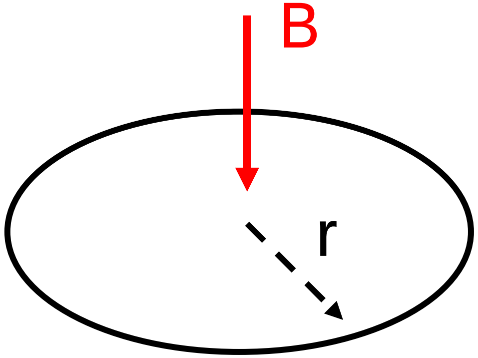
Many different particles are produced but all decay rapidly to

electrons, photons, protons, neutrons, pions, kaons, muons, and neutrinos

BABAR Detector



Momentum of Charged Particle



$$p = qrB$$

Charged particle is bent in a magnetic field.

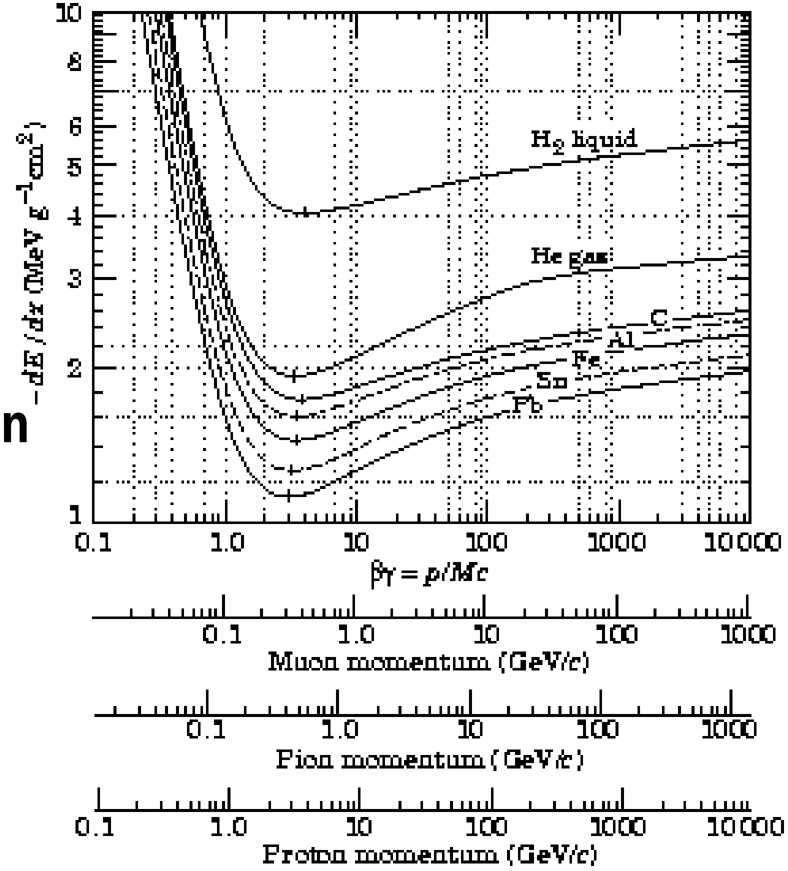
Measuring the trajectory (r) of a charged particle in a known magnetic field gives the momentum - called “Tracking”

Energy Loss of Heavy Charged Particle in Matter

Moderately relativistic charged particles (except electrons) lose energy primarily by ionization as they traverse matter.

Bethe-Bloch equation

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

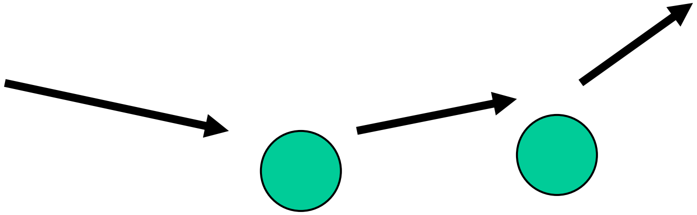


Energy loss per unit distance x is function of velocity and not mass
(i.e. same for all particles)

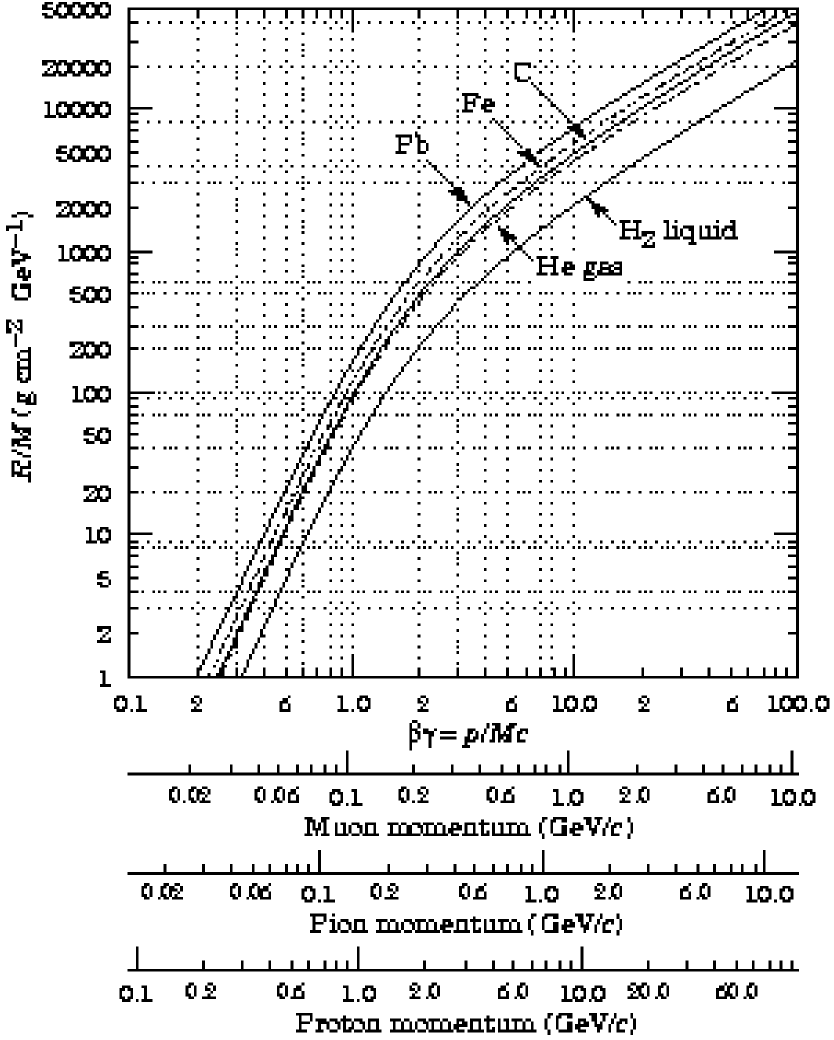
charge z scattering off atom:
atomic no. Z, atomic mass A,
mean ionization potential I.
K and δ are constants

Multiple Scattering

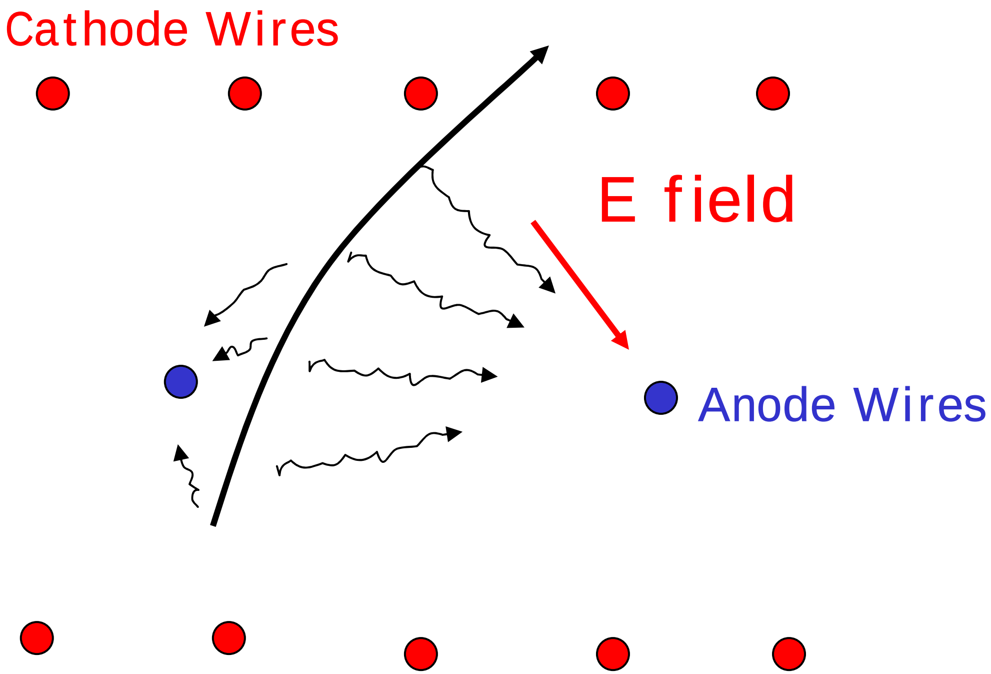
Particle is deflected after many coulomb scatters



To measure trajectory of a particle, measure its ionization trail as it passes through a medium with low mass (to minimize multiple scattering) inside a magnetic field.


Range

Drift Chambers



Ionized Electrons drift to anodes at constant velocity if voltage is high enough

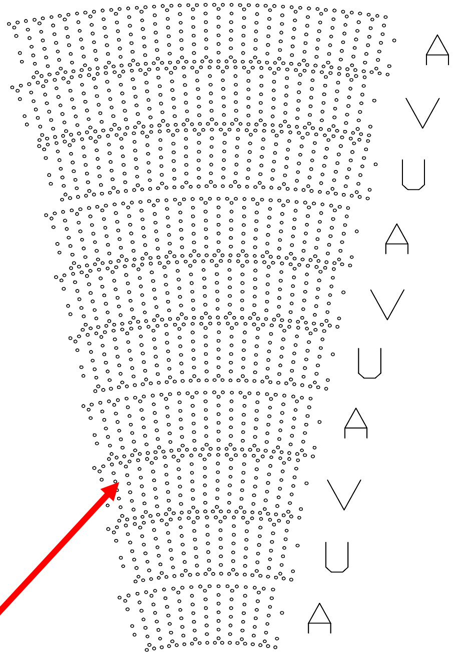
Drift Chambers

Point of ionization is determined from

$$v_{drift} << c$$

~ cm/μs

$$x_{drift} = \frac{v_{drift}}{t_{drift}}$$

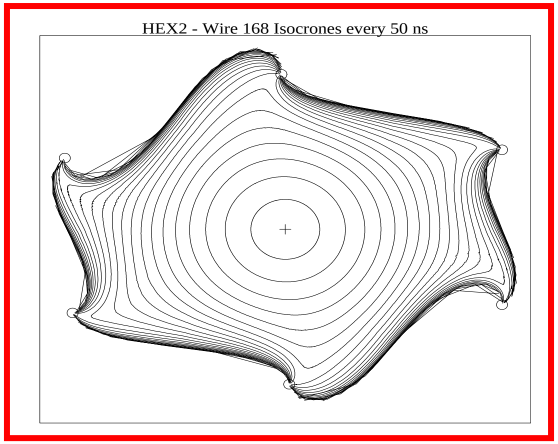


Drift time is difference between anode pulse arrival time, and particle creation time.

Many layers of wires formed into cells

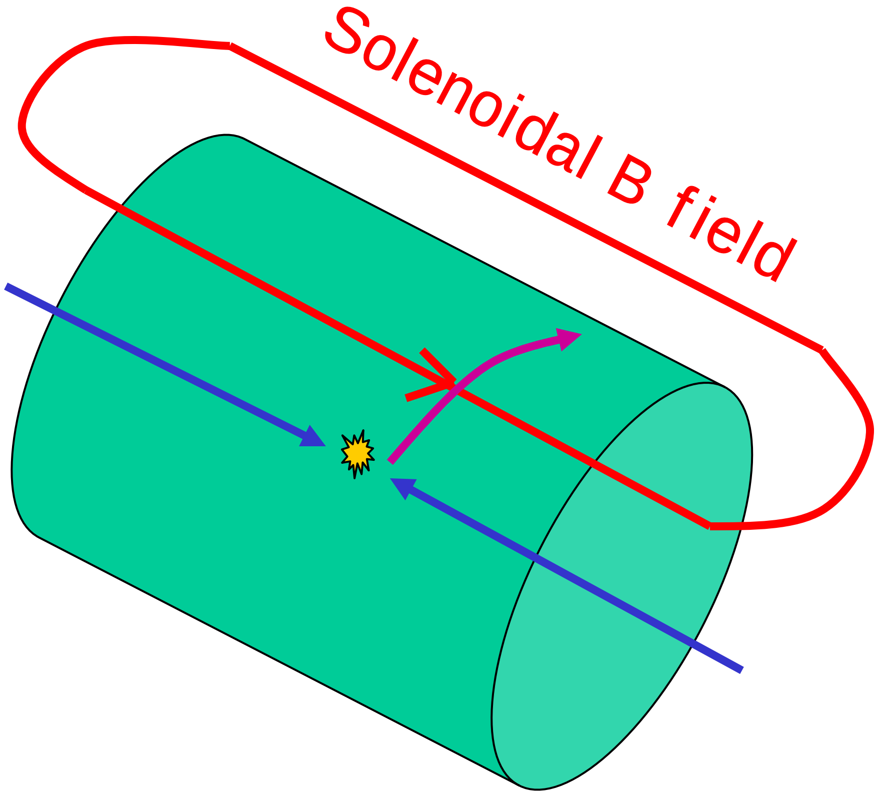
Helium/Isobutane Gas

Isobutane reduces diffusion of electrons as they drift



Drift Cell (isochrones are perp. To field)

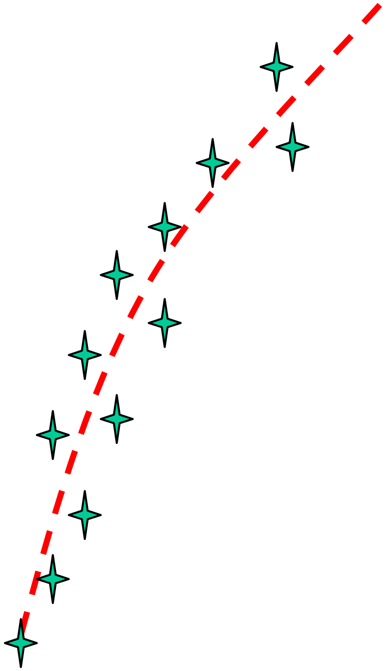
Drift Chambers

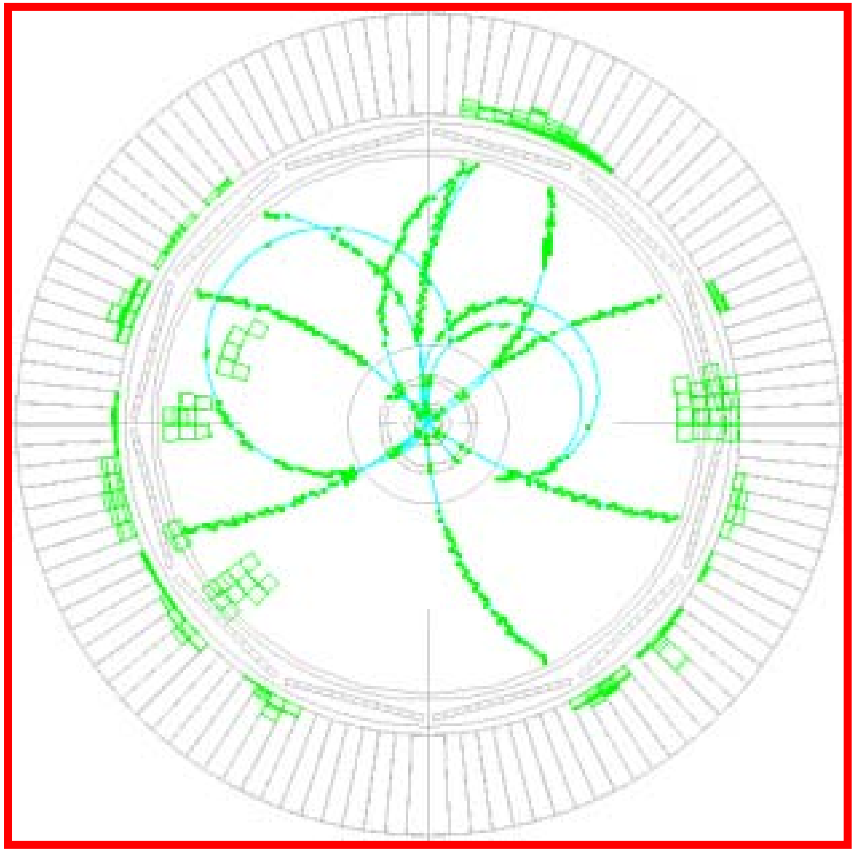


40,000 wires in BaBar drift Chamber with B field parallel to beam axis

Drift Chambers

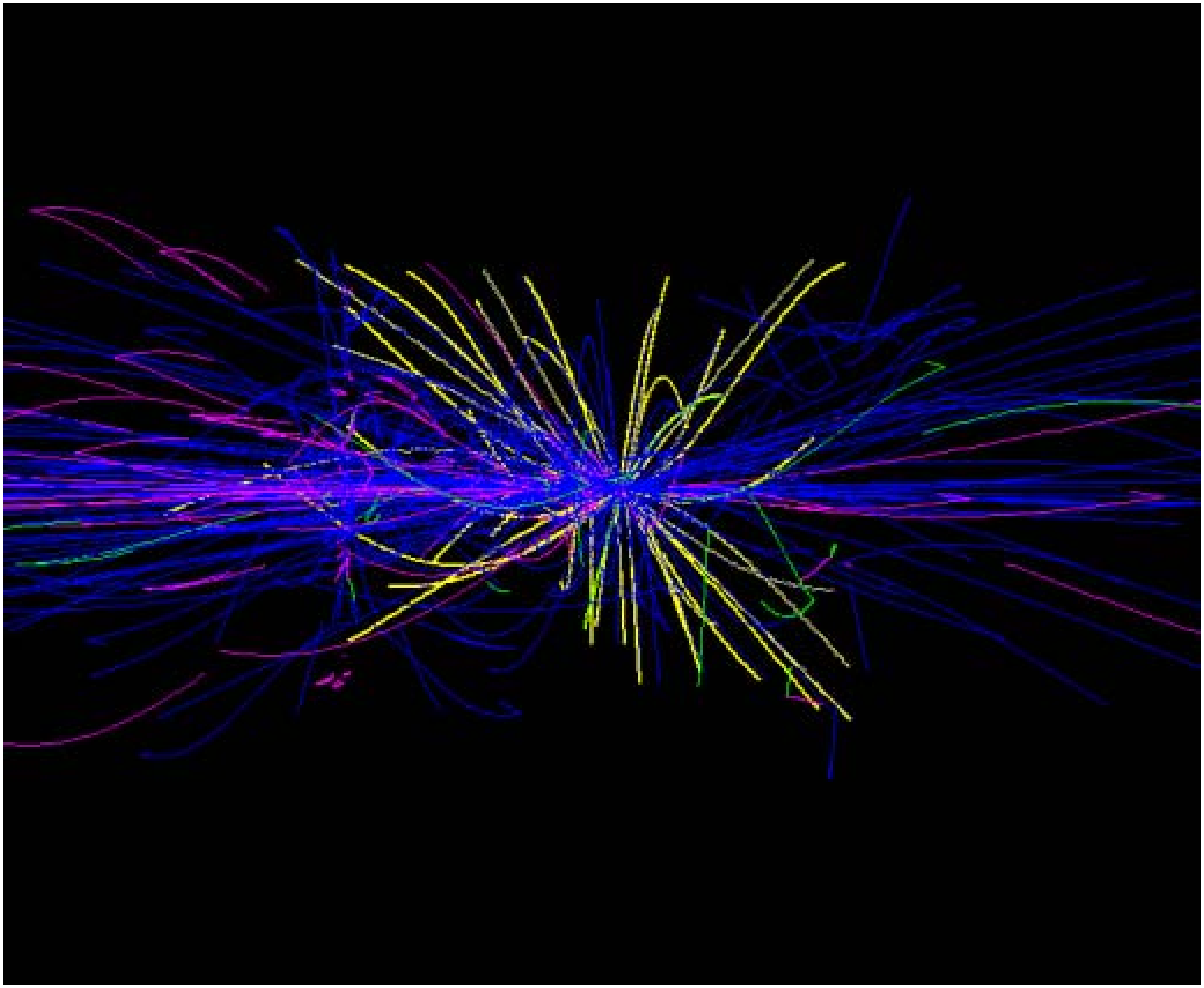
Pattern Recognition to find a “road” of hits





χ^2 fit to helix with correction for dE/dx to measure momentum.
Precision of 80 microns achievable

Tracks in 3d from a proton-antiproton collision

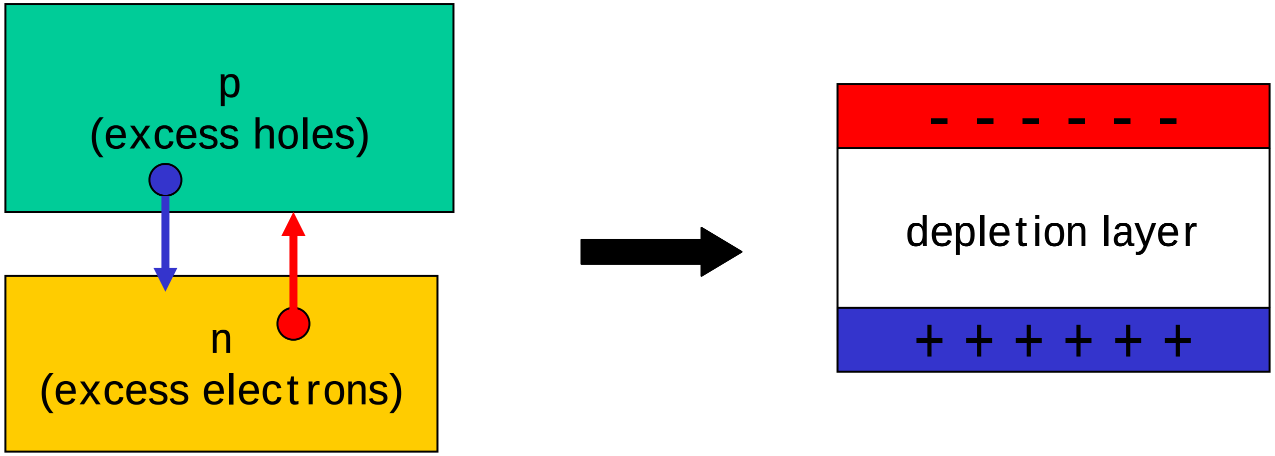


Solid State Tracking Devices

Silicon Devices have been developed in the last decade.
Increase spatial precision from O(100 μm) to 0(10 μm)

Ionization detection in silicon (3.6 eV per electron hole pair) rather than gas (30 eV ionization potential)

p doped (excess holes) in contact with n doped (excess electrons) forms a diode. Apply a reverse-bias voltage, $V_n > V_p$.
Very little current flow (few electrons in p doped region).

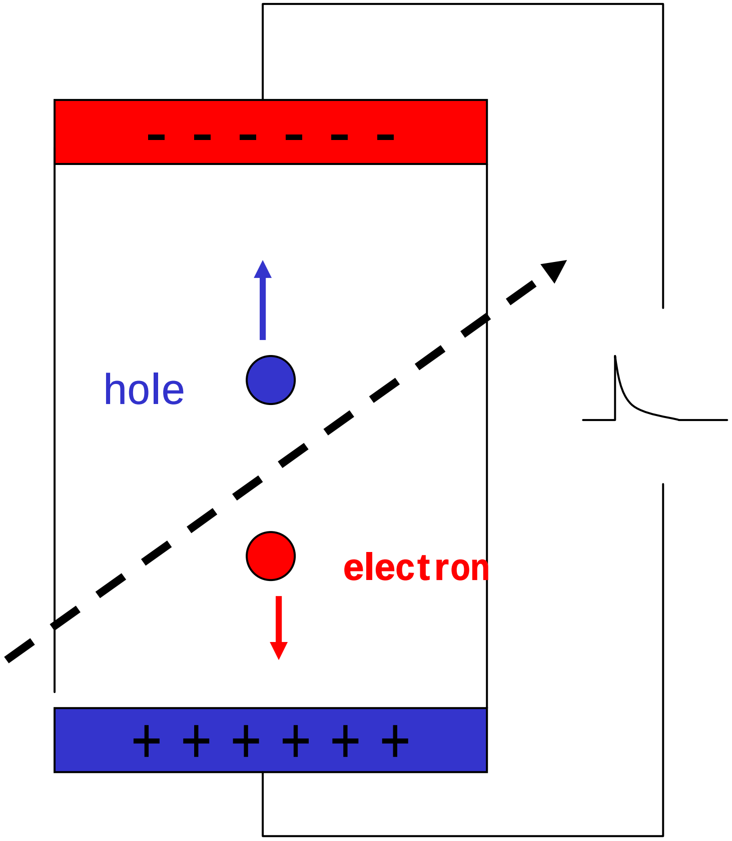


Solid State Tracking Devices

Ionizing particle creates electron/hole pair

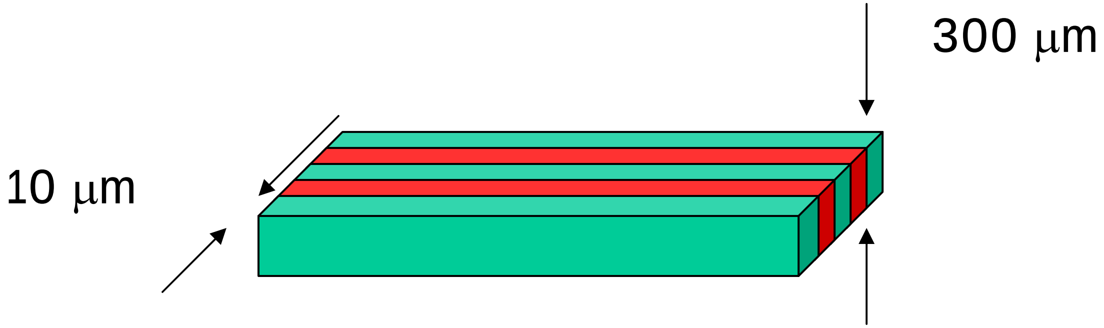
Electron/hole drift to the -ve (p) /+ve (n) surfaces, where they are majority carriers and can escape to electrodes.

If connect to electrical circuit get a pulse of charge



Solid State Tracking Devices

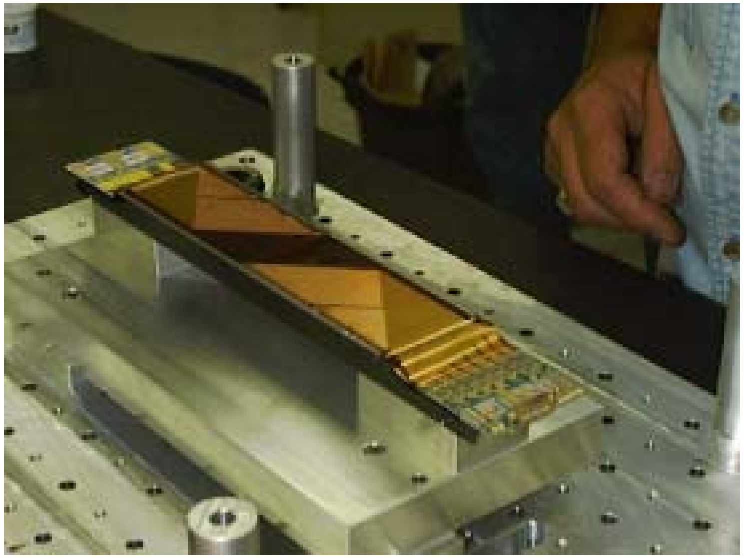
Detectors constructed of strips of width 10 μm to give O(10 μm) precision



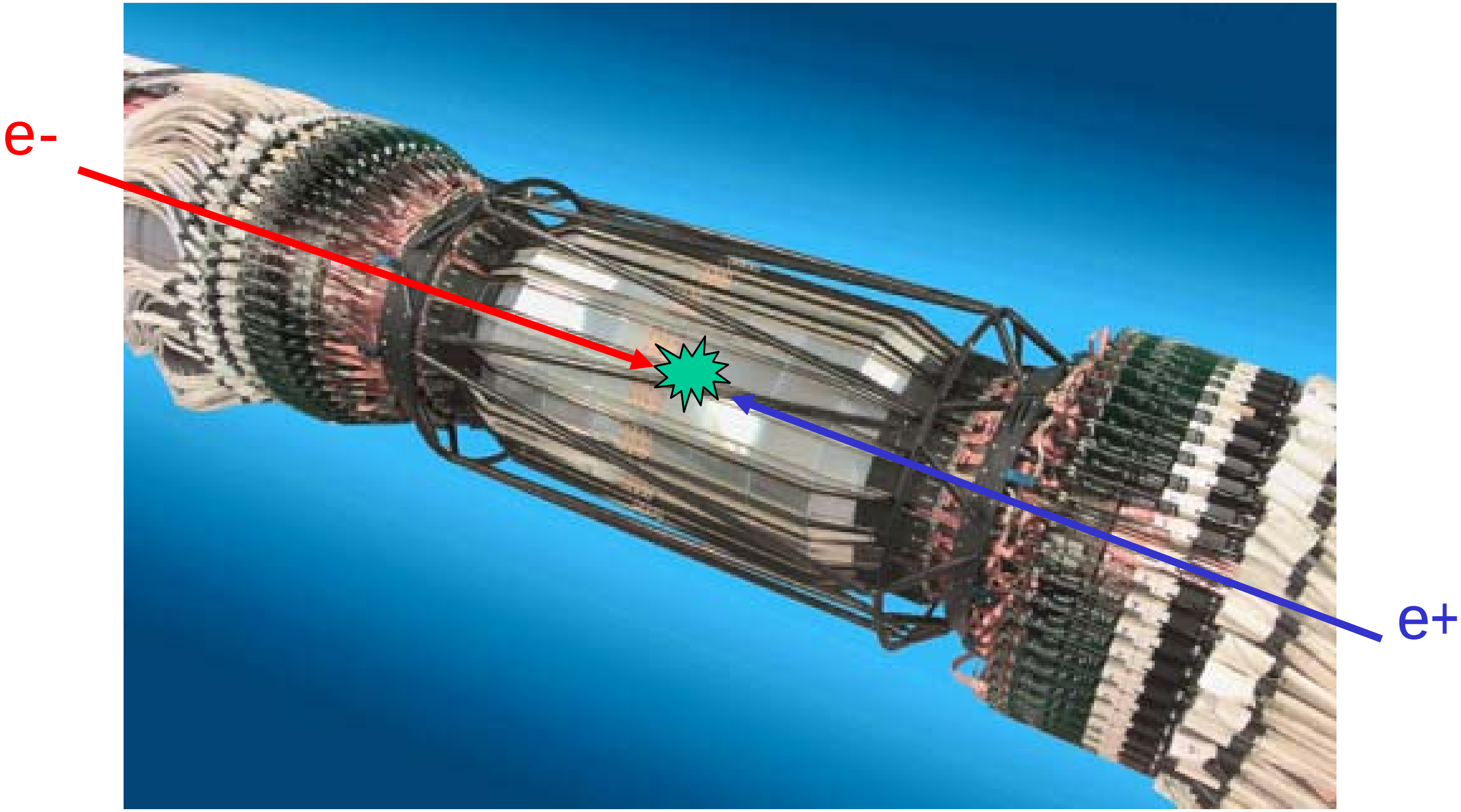
Construct detector of layers of thin strips.

Some of the electronics is incorporated in the silicon

Very light support structure (low multiple scattering)



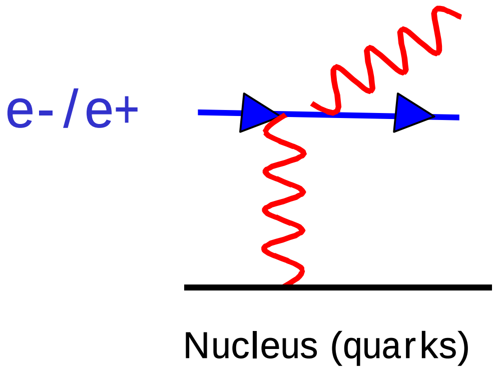
Solid State Tracking



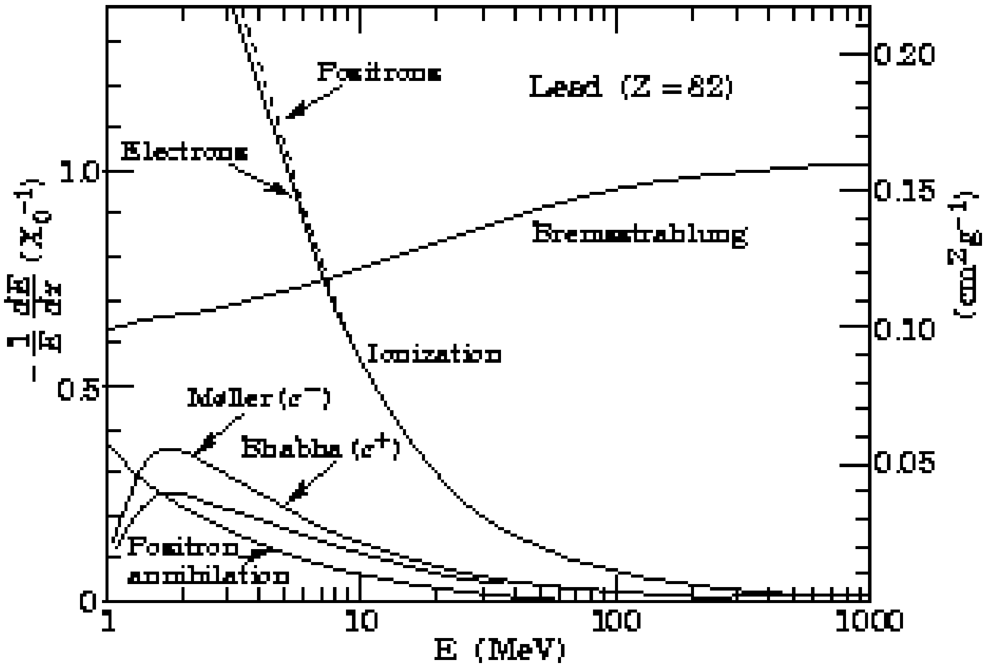
The BaBar Silicon Detector
5 layers, r = 3.2 to 14.4 cm

Measuring Particle Energy

Electron/Positron Energy Loss



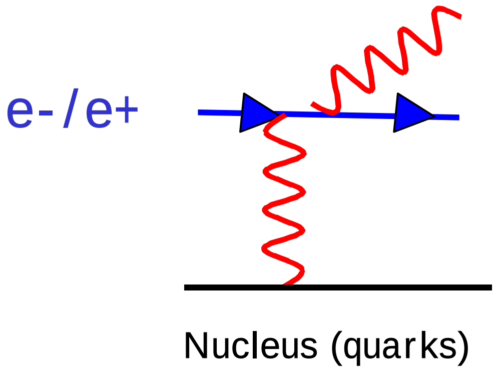
Bremsstrahlung (radiation of photon)



Electron energy loss primarily by Bremsstrahlung at E > 20 MeV and ionization below 20 MeV

Radiation Length

Electron/Positron Energy Loss



$$\frac{dE}{dx}_{Brem} = -\frac{E}{X_0}$$

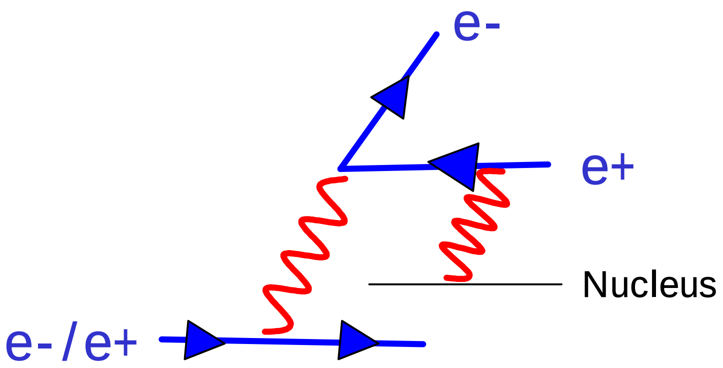
$$X_0 = \frac{180A}{Z^2} g\ cm^{-2}$$

Bremsstrahlung
(radiation of photon)

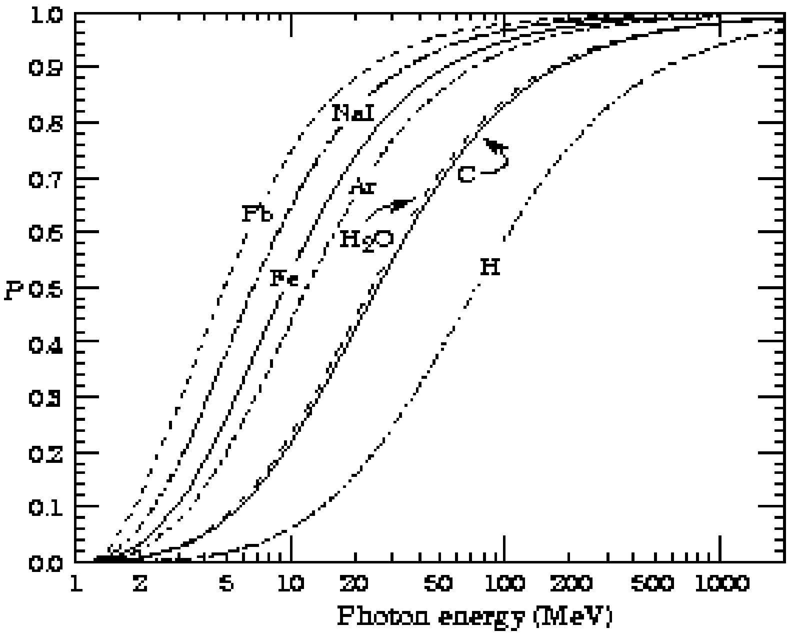
Radiation probability depends on radiation length X_0

Measuring Particle Energy

Photon Energy Loss

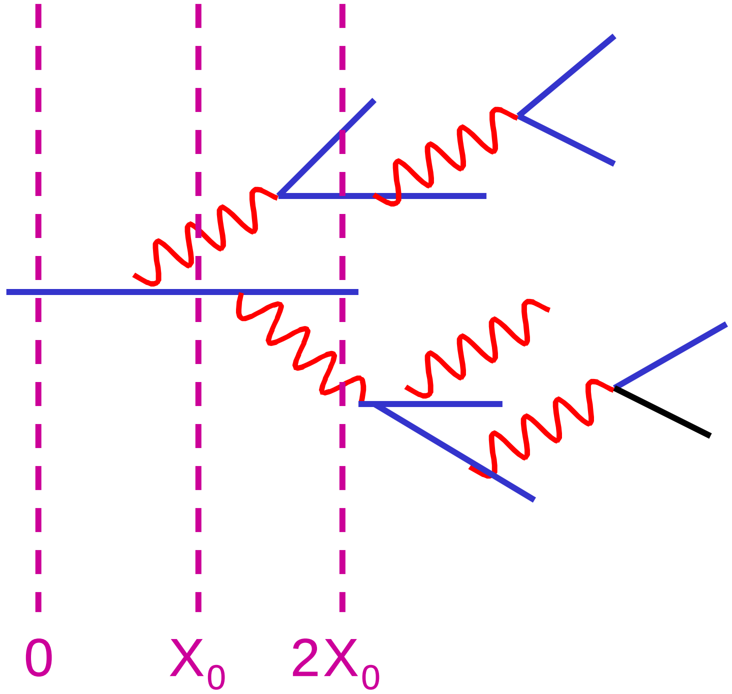


Pair Production



Photon energy loss primarily pair production at E > 20 MeV and Compton scattering (γe -> γe) below 20 MeV

Electromagnetic Showers



Assume

1. Each electron $E > E_c$ travels 1 X_0 and gives up 50% E to photon

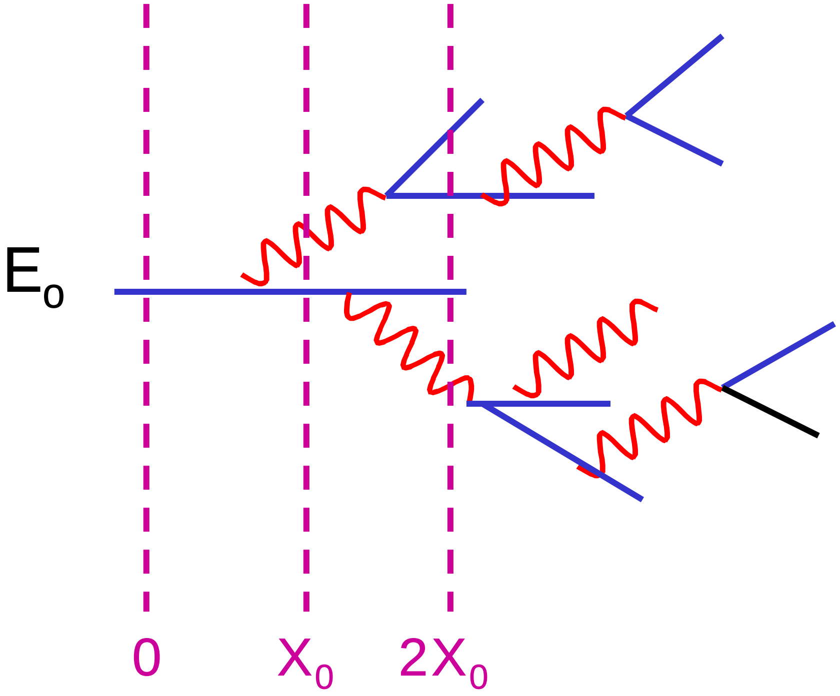
2. Each photon travels 1 X_0 and pair produces with 50% E to each

3. Electrons with $E < E_c$ stop

Electrons/positrons or photons will form a cascade by the combination of Bremsstrahlung and pair production

Electromagnetic Showers

Number of particle after
t radiation lengths= N(t)

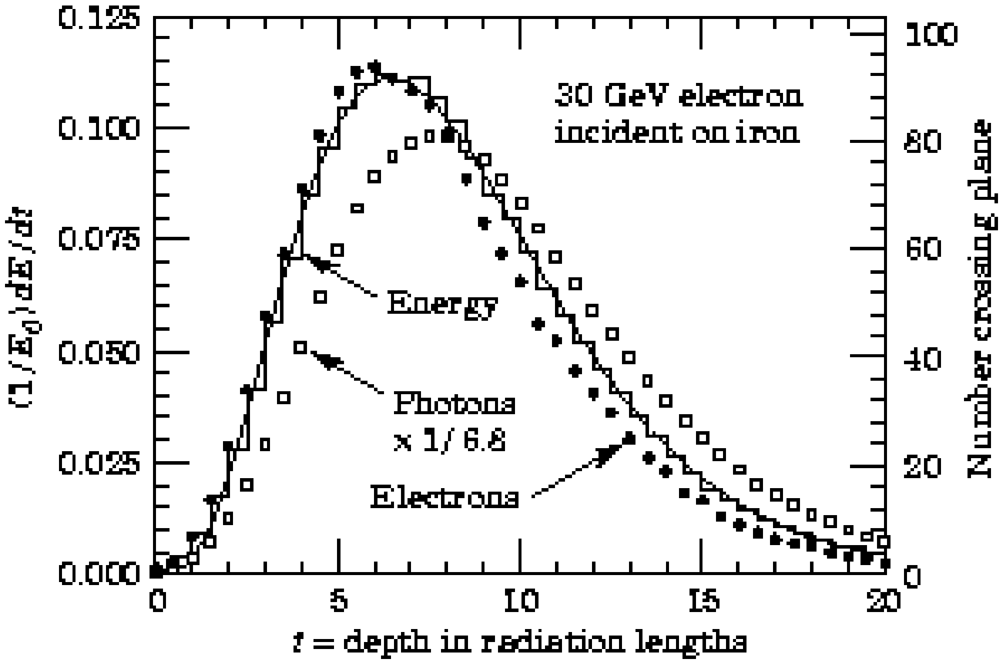


$$N(t) = 2^t = e^{t\ln 2}$$

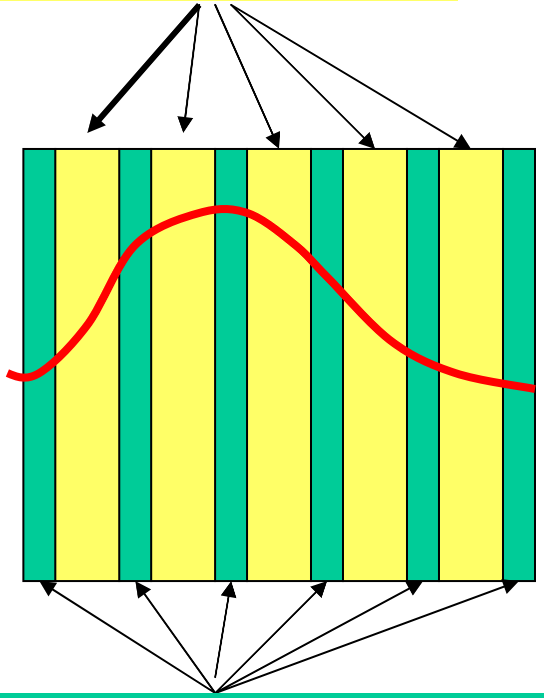
The total track length of particles

$$L = \frac{E_0}{E_c}$$

Shower Development



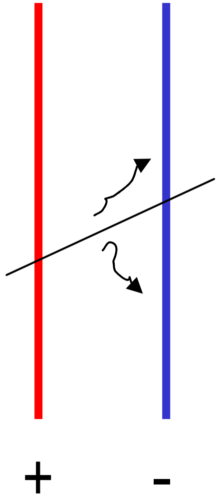
The Sampling Calorimeter



Lead- causes shower

Active Detector to
measure total track length L

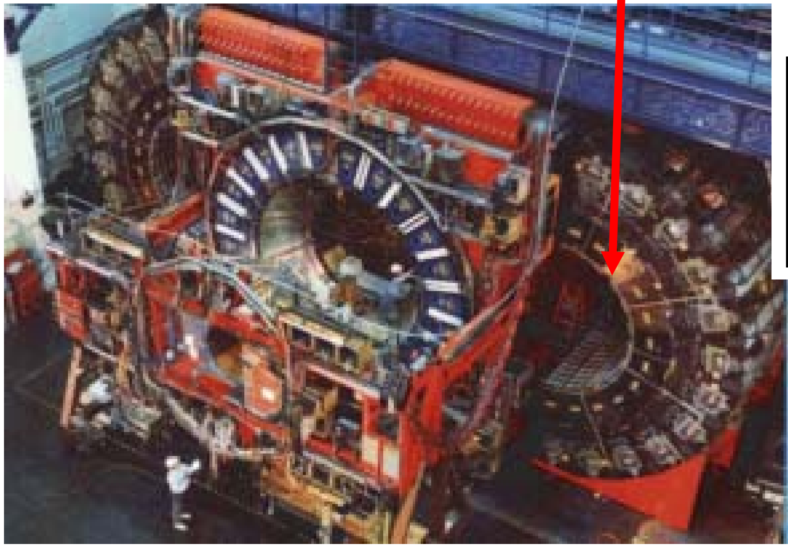
E.g. Ionization Chamber

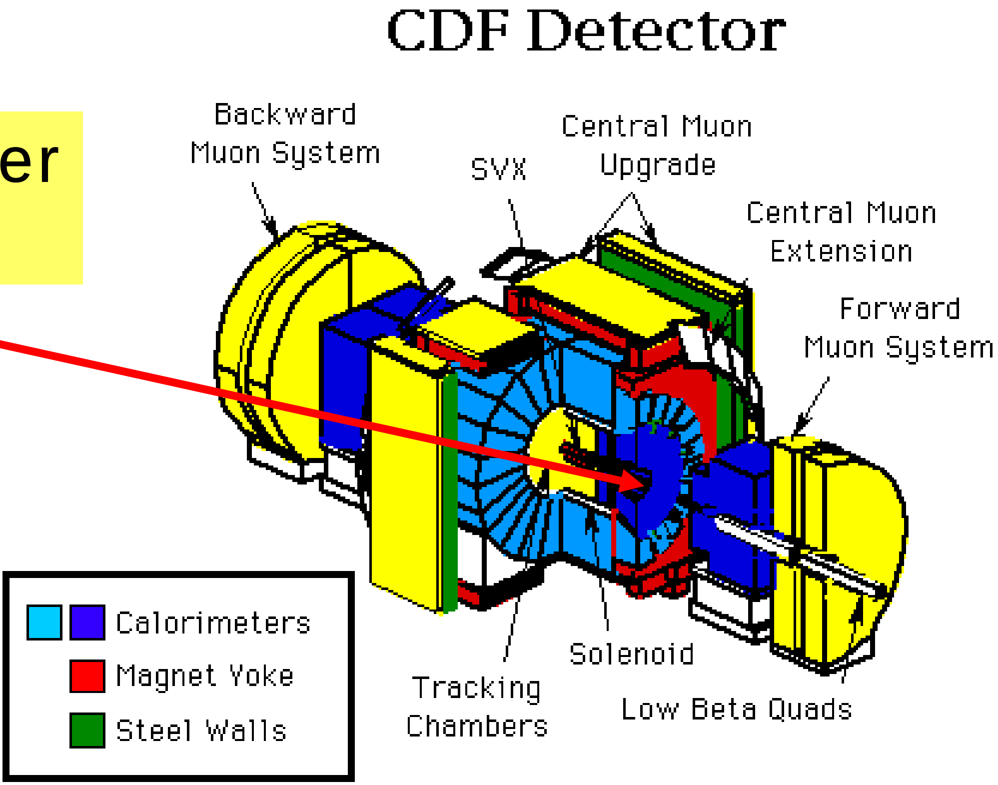


$$Q_{ionization} \propto L$$

Example of Sampling Calorimeter

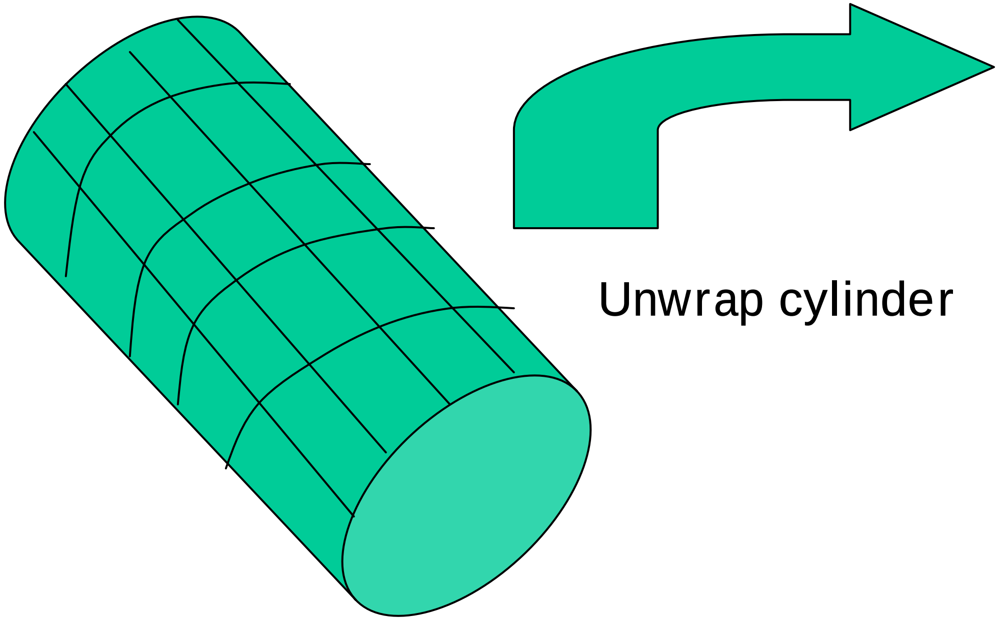
Sampling Calorimeter
(Lead/Scintillator)



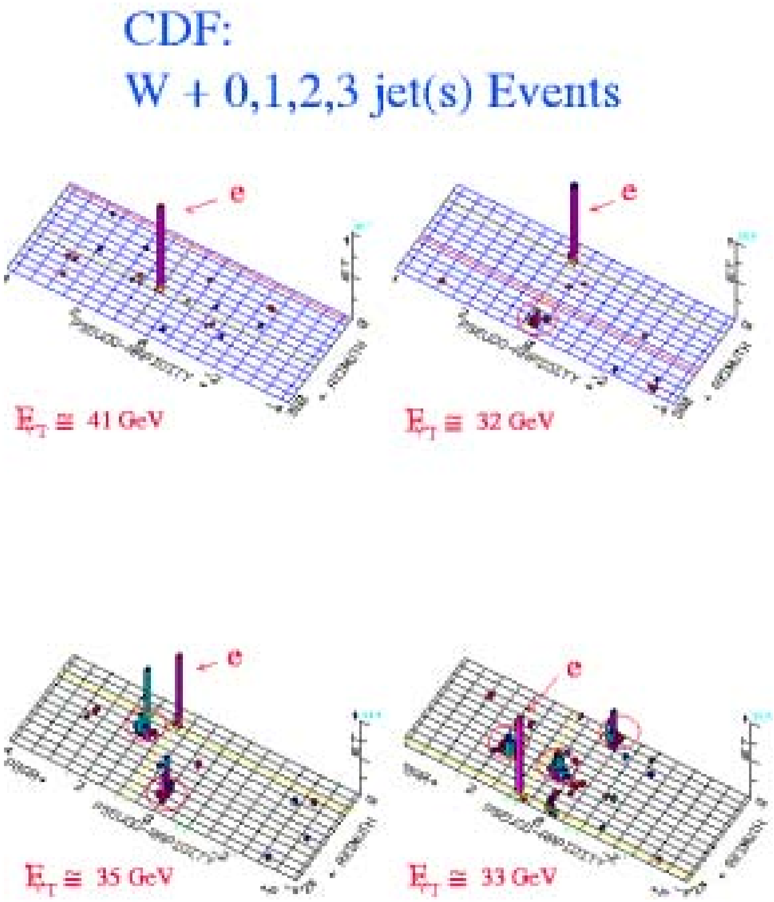

CDF Detector

Sampling Calorimeters

Calorimeters segmented into towers

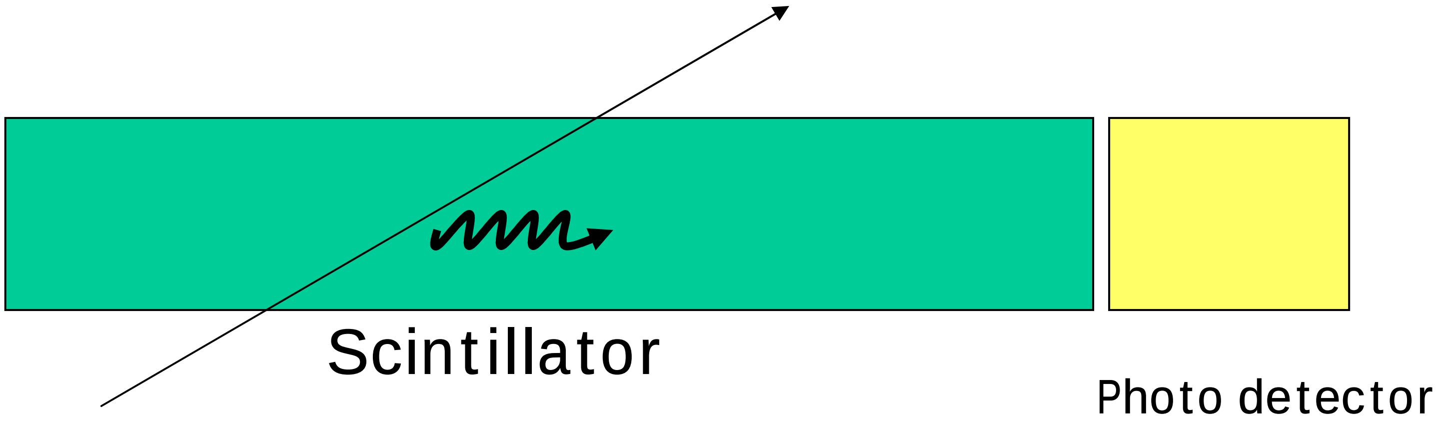


Unwrap cylinder



Scintillation

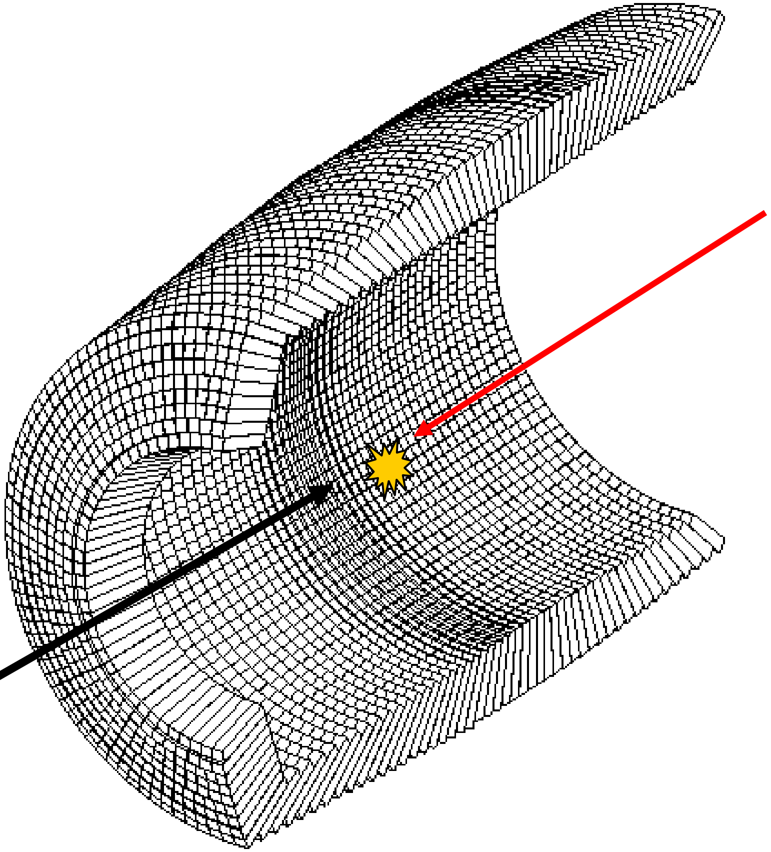
Particle causes excitation which results in light pulse

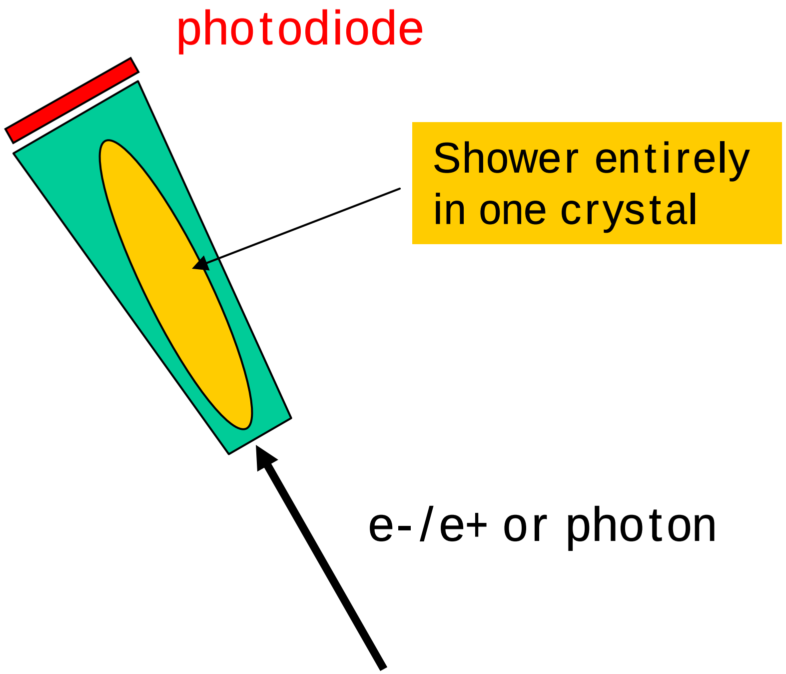


Number of photons proportional to track length

Crystal Calorimeters

Dense scintillating crystals like CsI(Tl) can be used without showering medium - all the energy of particle is measured





photodiode

Shower entirely in one crystal

e-/e+ or photon

The BaBar Calorimeter has 6580 crystals in a cylinder

Construction of the BaBar Calorimeter

Identifying Particles

Can distinguish photons and electrons

photon = electromagnetic shower without track
electron = electromagnetic shower with track

but

Protons, charged kaons, charged pions, muons
do not make a shower but do make a track.
How to distinguish ?

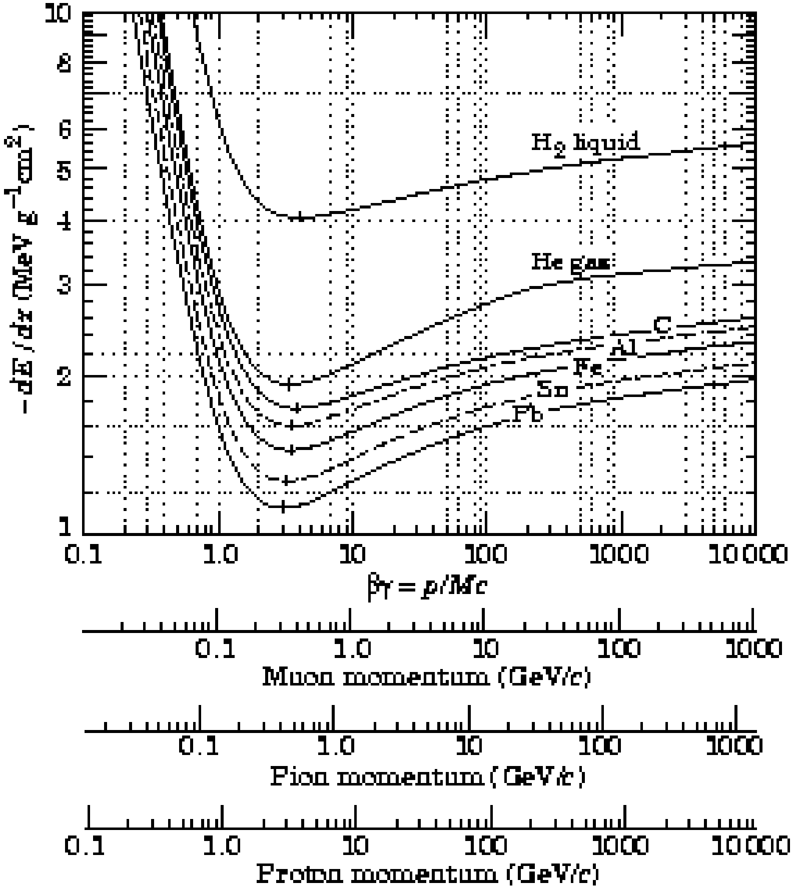
Since $p = mv$ if we know the momentum then we need to measure the mass or velocity

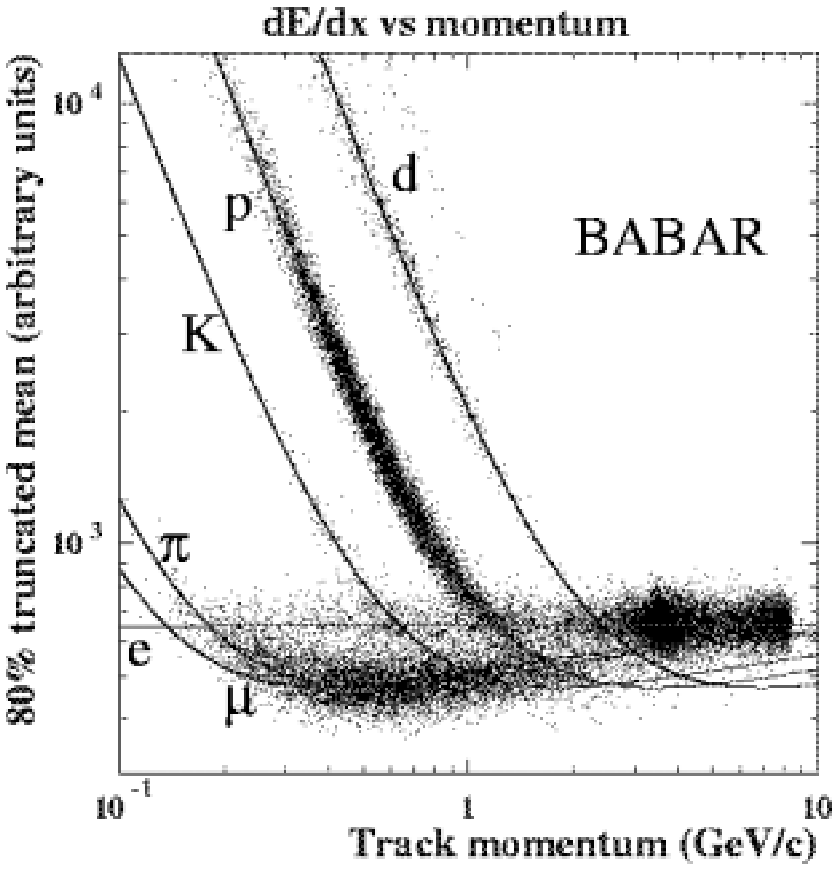
1. dE/dx - less than 1 GeV, where dependence on β is steep

2. Cerenkov Detectors > 1 GeV

dE/dx using Drift Chamber

Recall dE/dx depends on velocity only

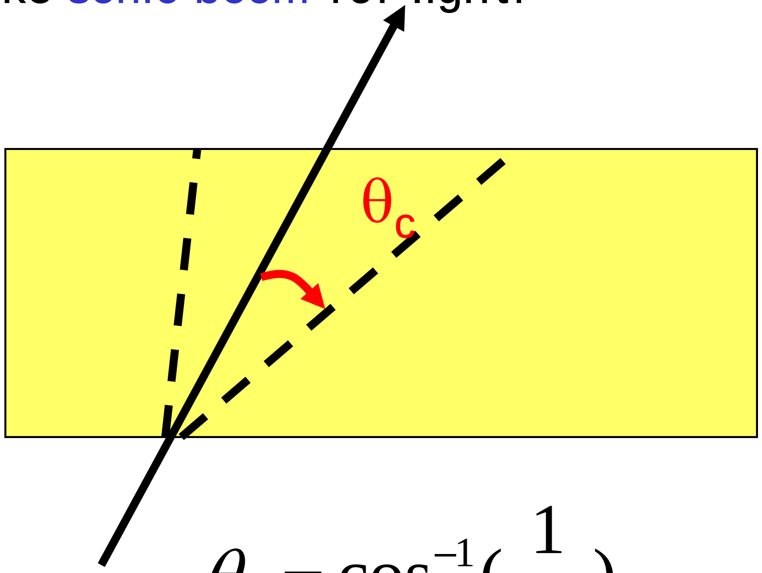




Measure dE/dx (velocity) and momentum to infer mass

The Cerenkov Effect

Light in medium with refractive index
n moves at velocity c/n.
If particle velocity > c/n
then Cerenkov light is emitted.
Like sonic boom for light.

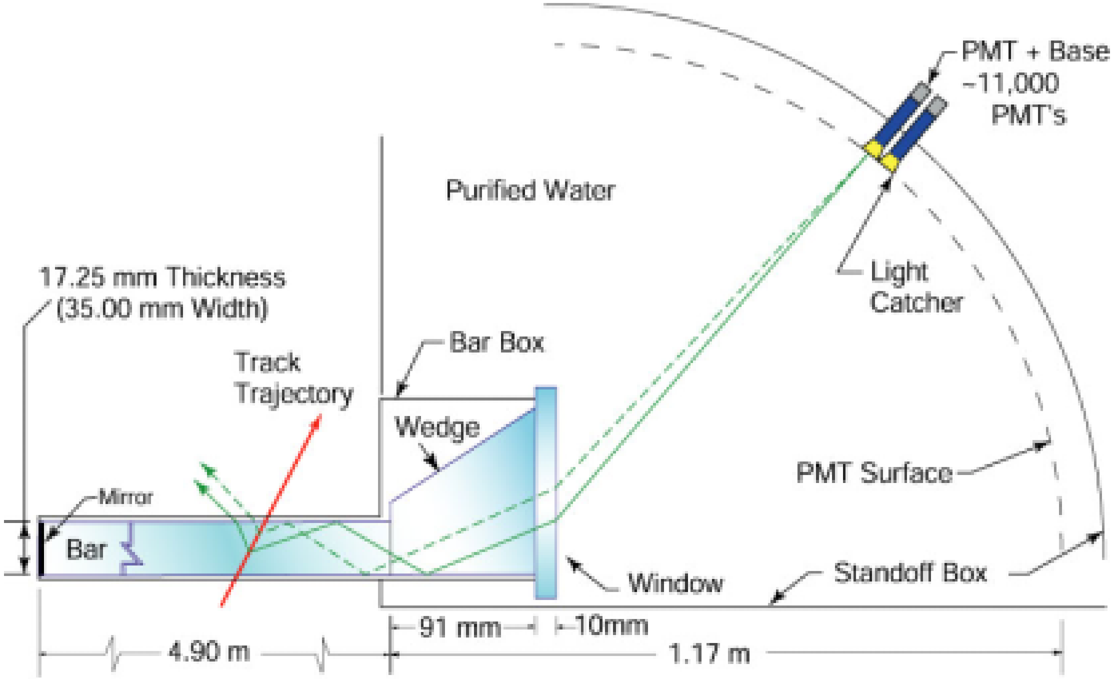


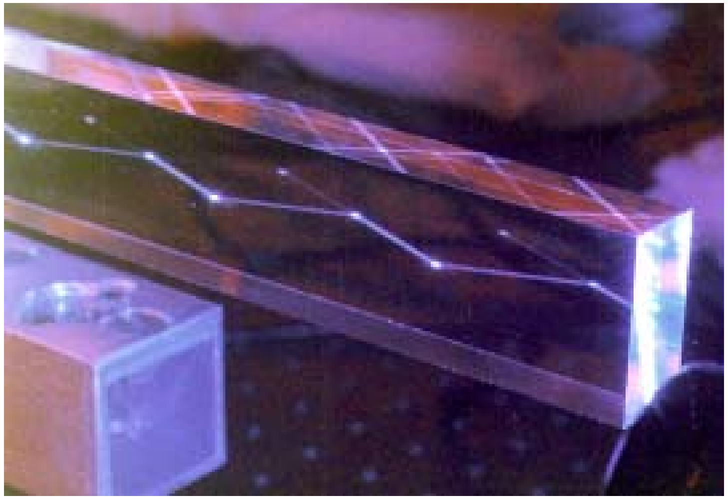
$$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

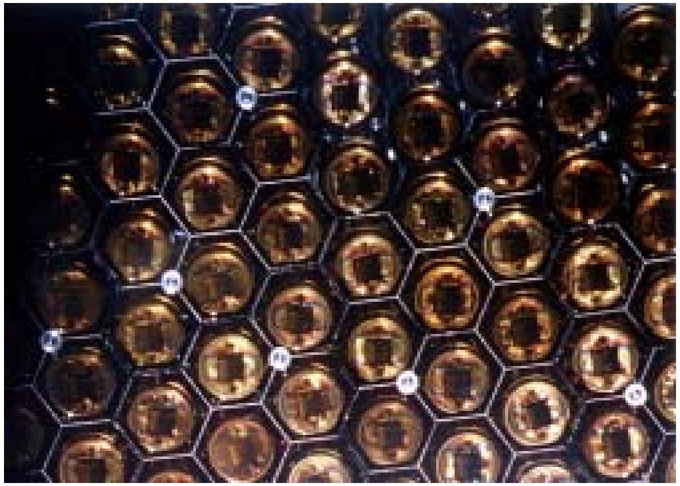
Cone angle measures velocity

electrons in nuclear reactor
pool emit Cerenkov light

The BaBar Cerenkov Detector



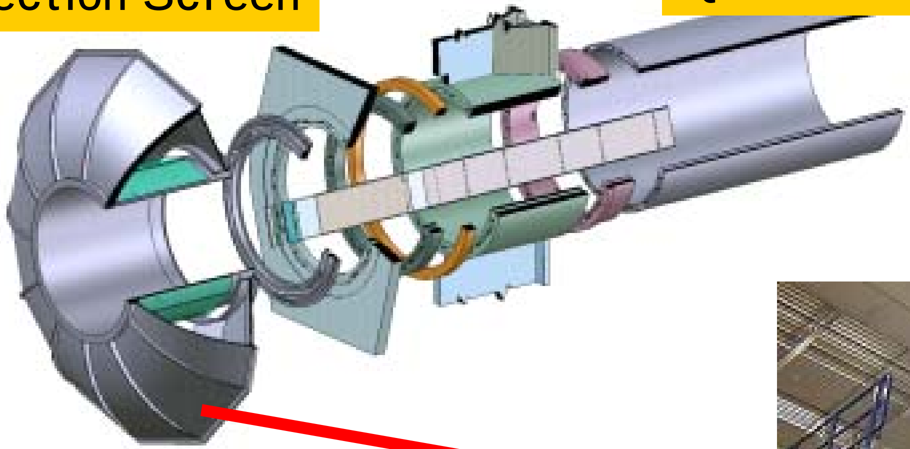


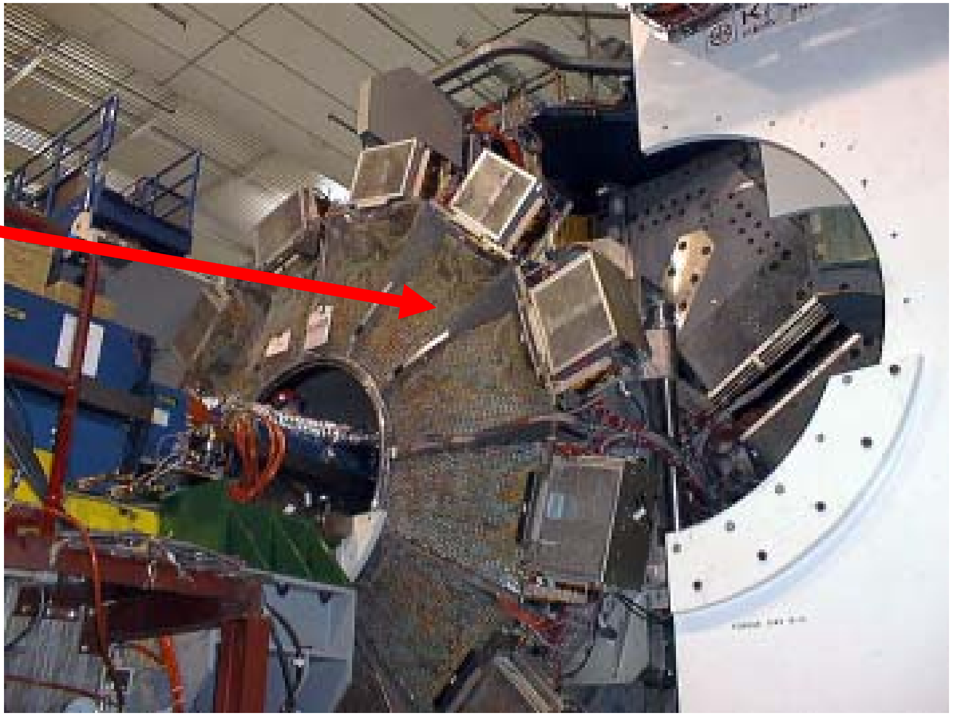


BaBar Cerenkov Detector Construction

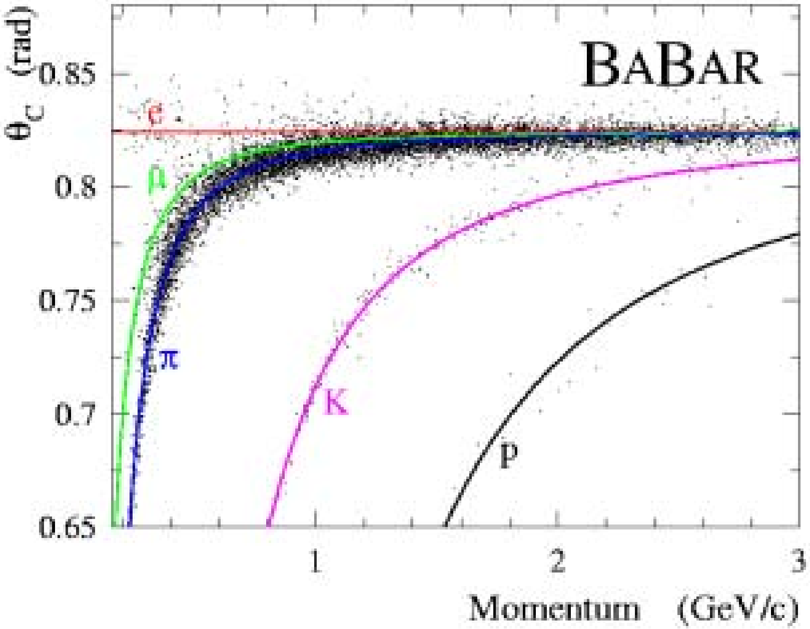
Projection Screen

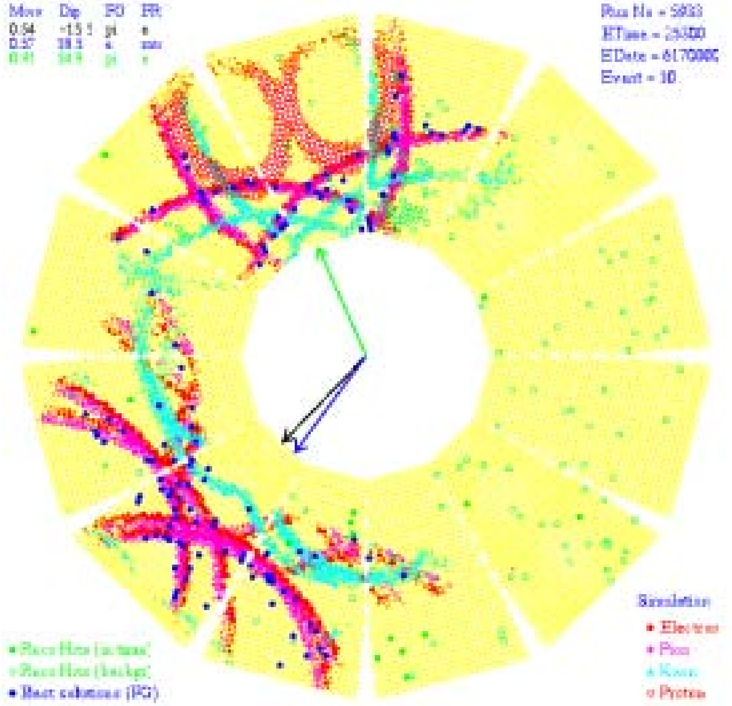
Quartz bars





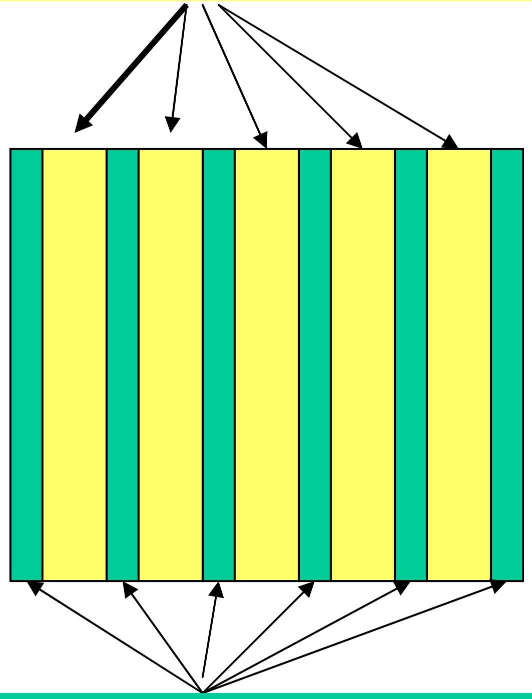
Event Showing Cerenkov Rings in BaBar





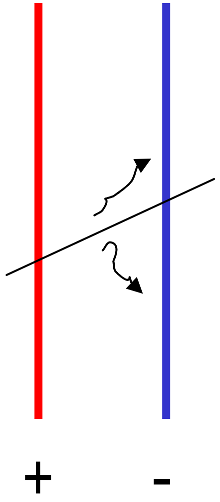
Muon Identification

Iron shields other particles



Active Detector to measure total track length L

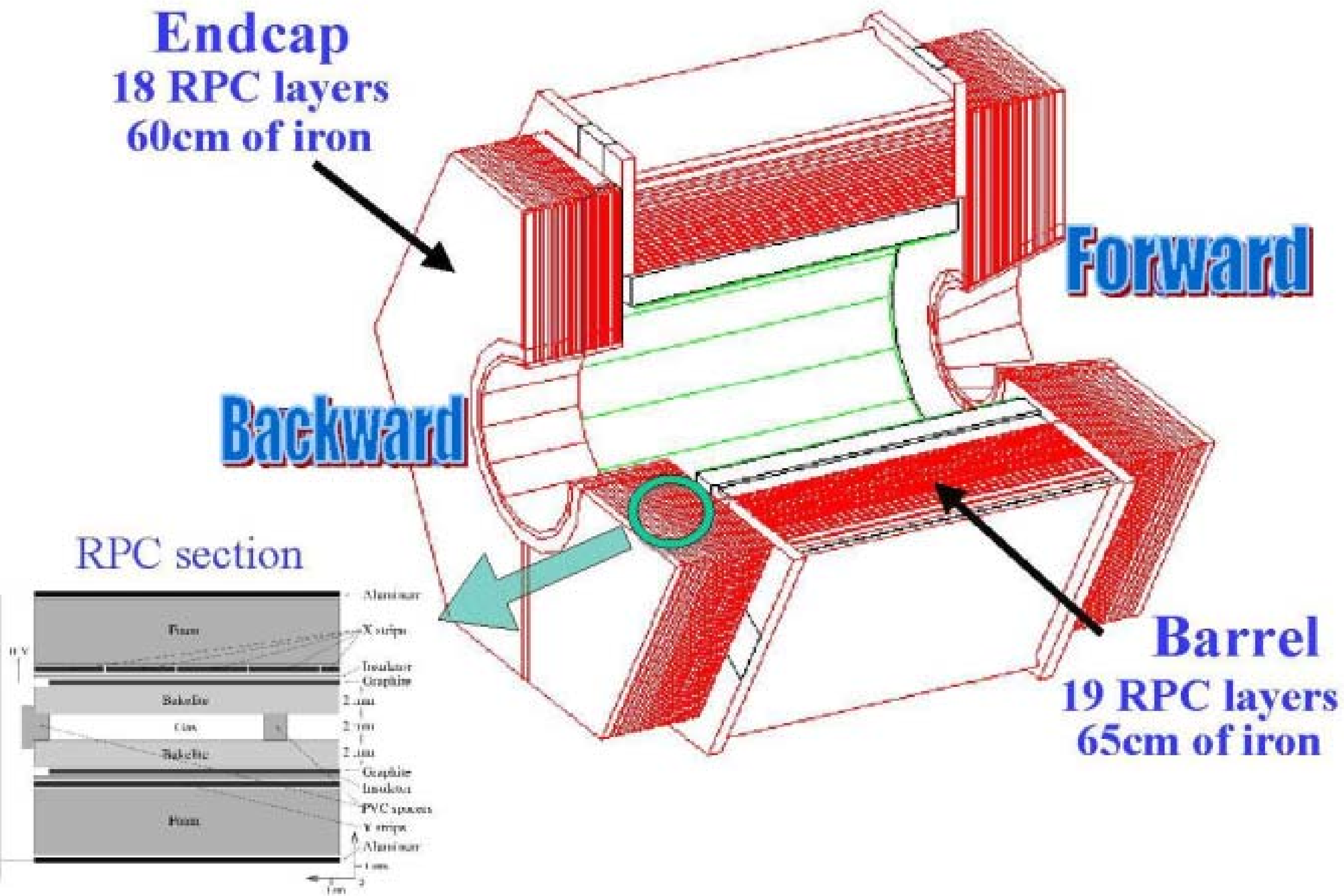
E.g Ionization Chamber



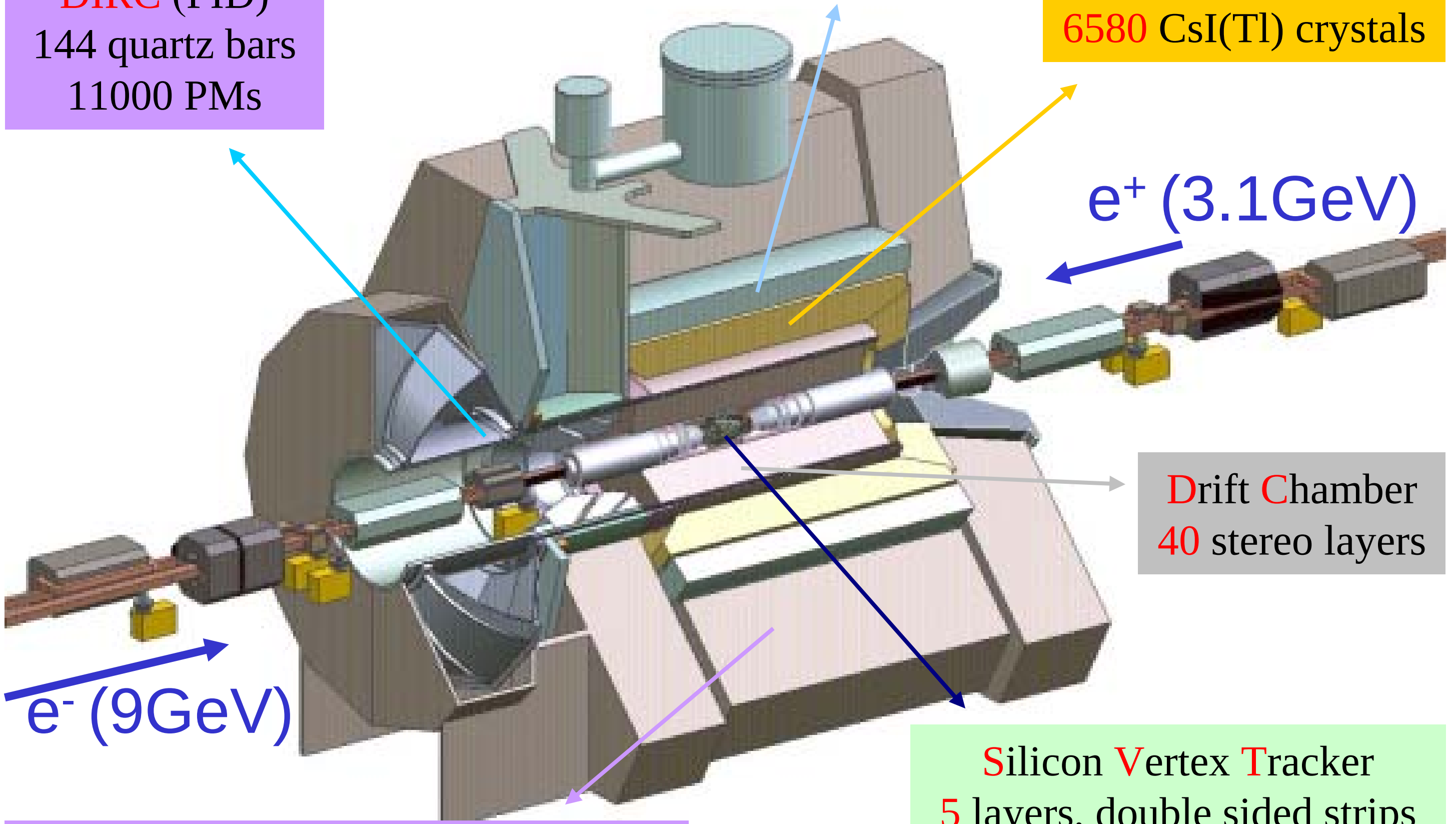
$$Q_{ionization} \propto L$$

Pions range out in iron due to strong interactions - only muons left

The BaBar Muon Detector



The Complete BaBar Detector



DIRC (PID)
144 quartz bars
11000 PMs

1.5T solenoid

EMC
6580 CsI(Tl) crystals

e$^+$ (3.1GeV)

Drift Chamber
40 stereo layers

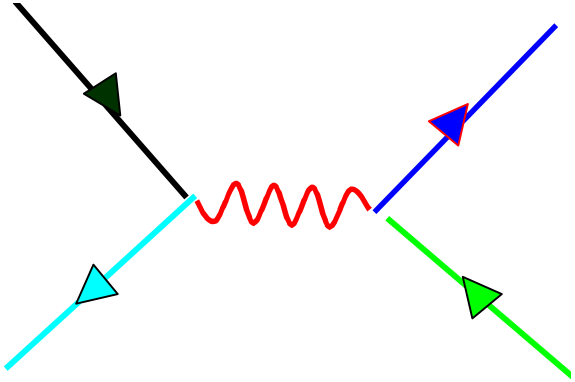
e$^-$ (9GeV)

Silicon Vertex Tracker
5 layers, double sided strips

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

A matter-antimatter Event

e+e- -> μ+μ- at PEP II

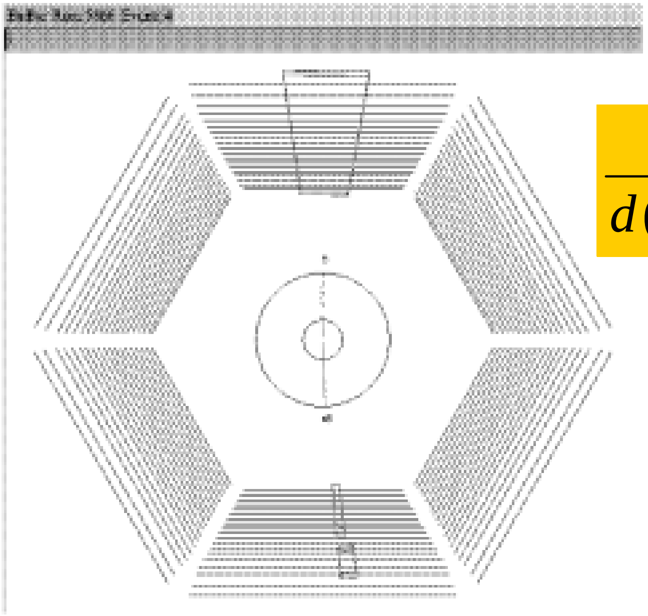


$$\frac{d\sigma}{d(\cos\vartheta)_{cm}} = \frac{\pi\alpha^2}{2s}(1+\cos^2\vartheta)$$

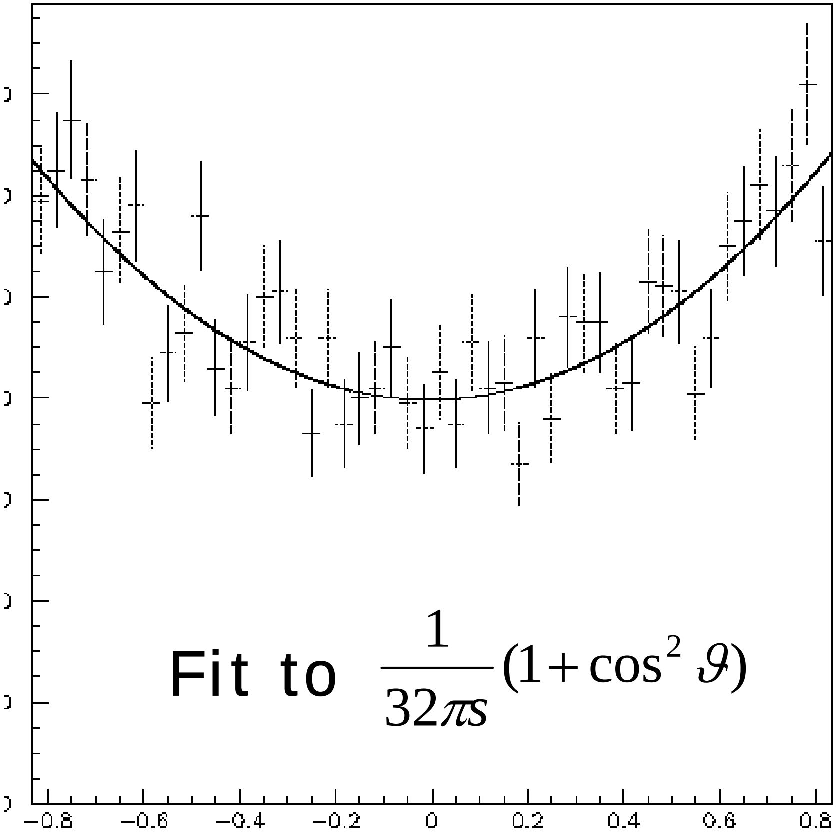
$$\sigma = \frac{4\pi\alpha^2}{3s}$$

At s = (10.58 GeV)^2 (PEP II)
σ(e+e- -> μ+μ-)= 0.78 nb

Muon Pair Production Data from BaBar



$$\frac{dE}{d(\cos\vartheta)_{cm}}$$



Fit to $\dfrac{1}{32\pi s}(1+\cos^2\vartheta)$

$\cos\vartheta_{cm}$