Particle Detectors

Lecture 4 Physics 152

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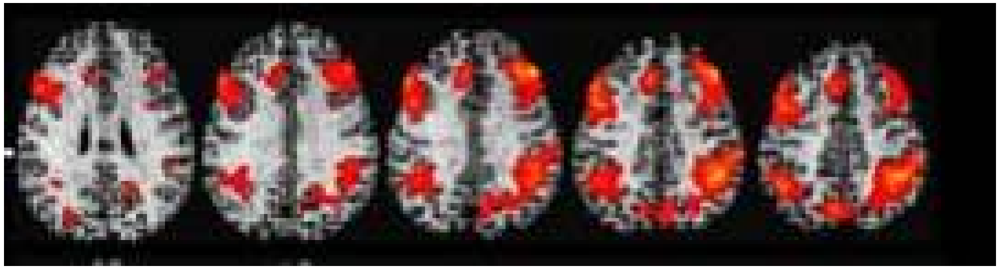
(thanks again to Colin Jessop)

Particle Detectors

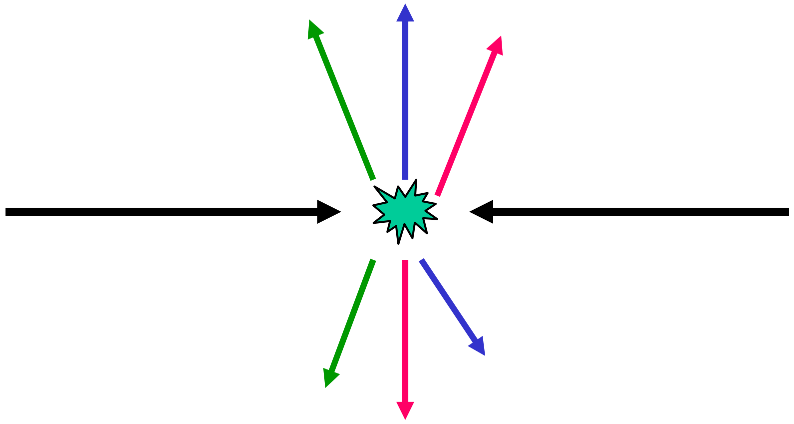
Technology developed for particle physics,
but has many other applications. For example:

- Medical Imaging: X-rays, PET Scans, Proton Radiography and Treatment
- Structure determination via X-ray diffraction in biology and chemistry
- Airport Scanners: Detection of explosives via
- neutron activation → γ rays (nitrogen → 10.6 MeV γ)



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

Particle Physics Events



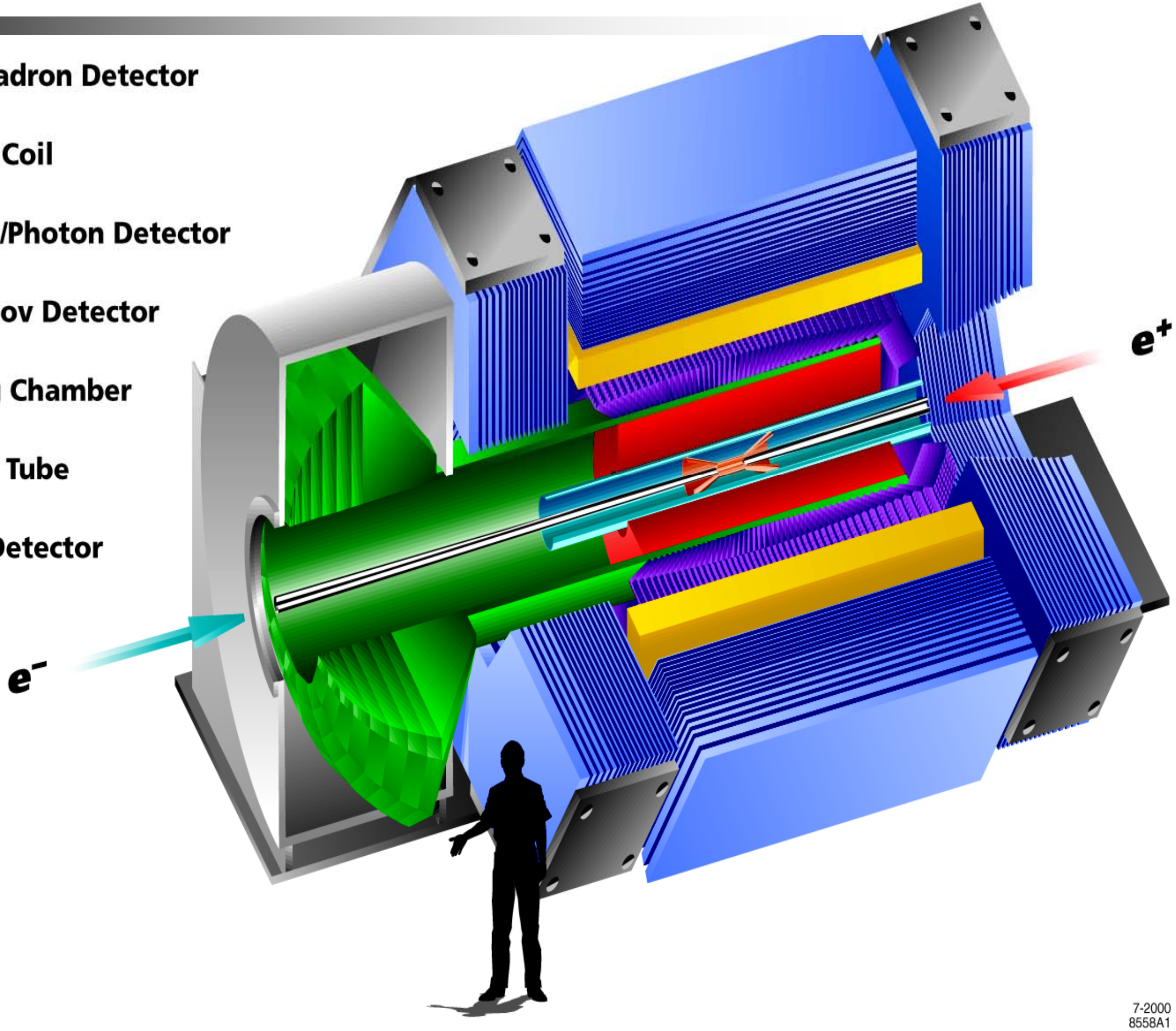
Ideally, want to measure 4-vector and identity of all particles produced

Many different particles are produced but all decay rapidly to

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

Example: The BABAR Detector

- 🟦 **Muon/Hadron Detector**
- 🟨 **Magnet Coil**
- 🟪 **Electron/Photon Detector**
- 🟩 **Cherenkov Detector**
- 🟥 **Tracking Chamber**
- 🟦 **Support Tube**
- 🟧 **Vertex Detector**



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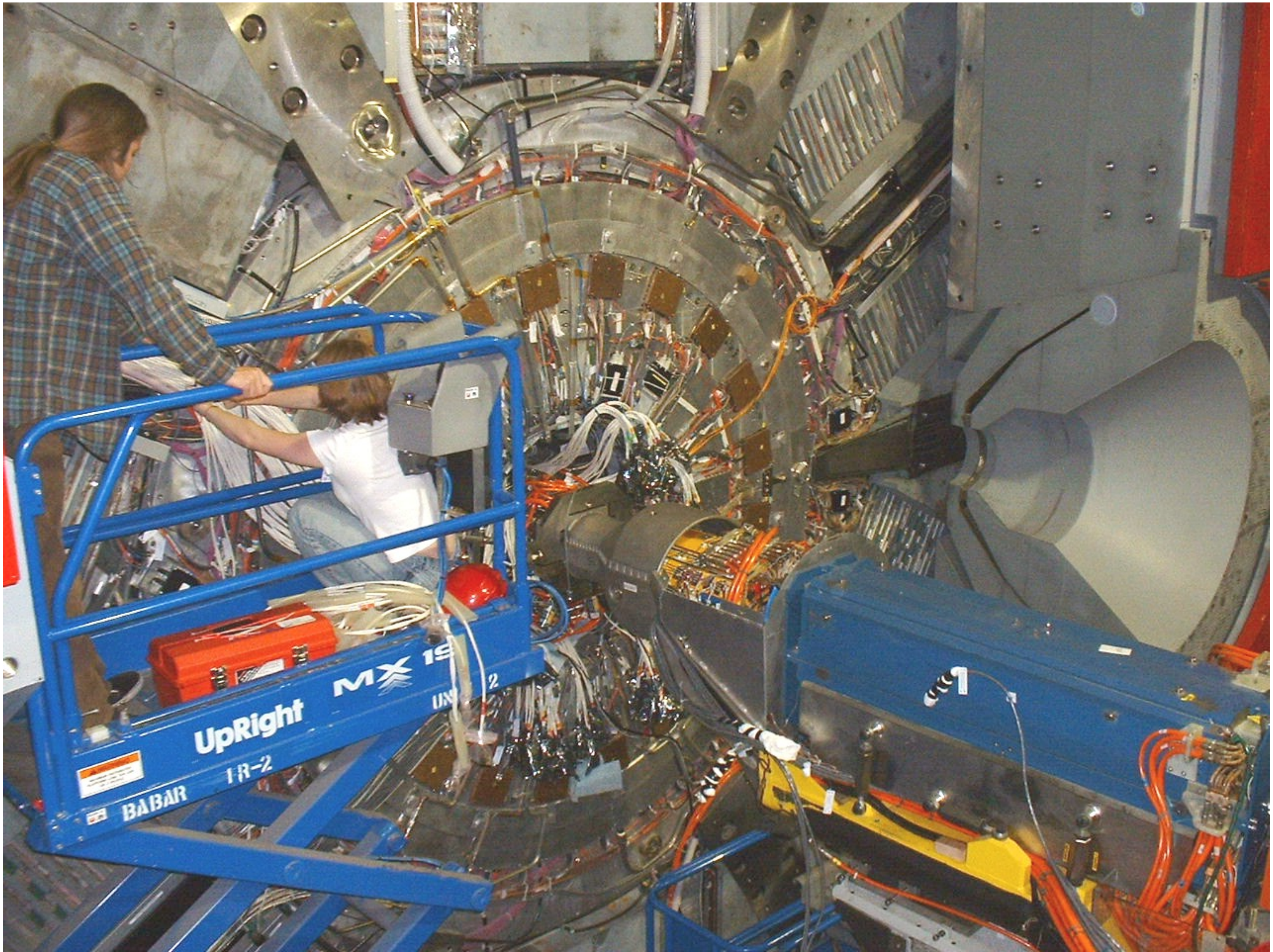
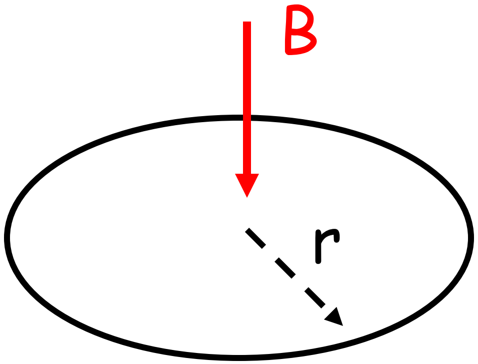
The BaBar Detector



Momentum of Charged Particle



Problem: Show this is true relativistically, from the force law

$$m\frac{dp_\mu}{d\tau} = qp_\nu F_{\mu\nu}$$

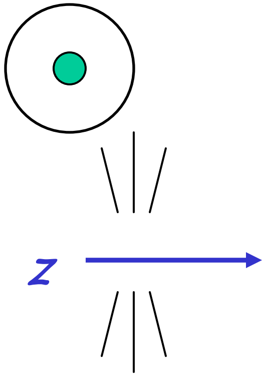
$$p = qrB$$

For unit charge, $p(\mathrm{GeV}) = 0.3r(\mathrm{m})B(\mathrm{T})$

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"

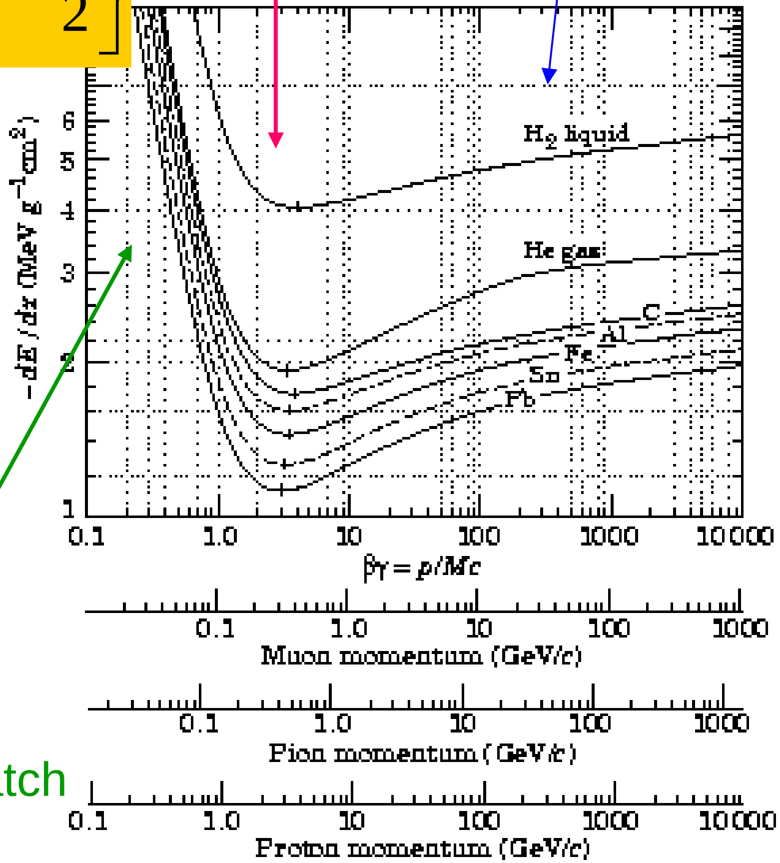
Energy Loss of Charged Particles in Matter



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

Bethe-Bloch equation

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



m.i.p.

relativistic rise

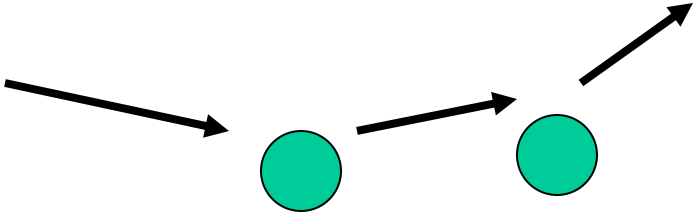
Energy loss per unit distance x is function of velocity and not mass (i.e. same for all particles)

charge z scattering off atom:
atomic no. Z, atomic mass A,
mean ionization potential I.
T_{max} = max K.E. e^- can receive.
K and δ are constants

large loss rate at low β – better match to speeds of atomic electrons

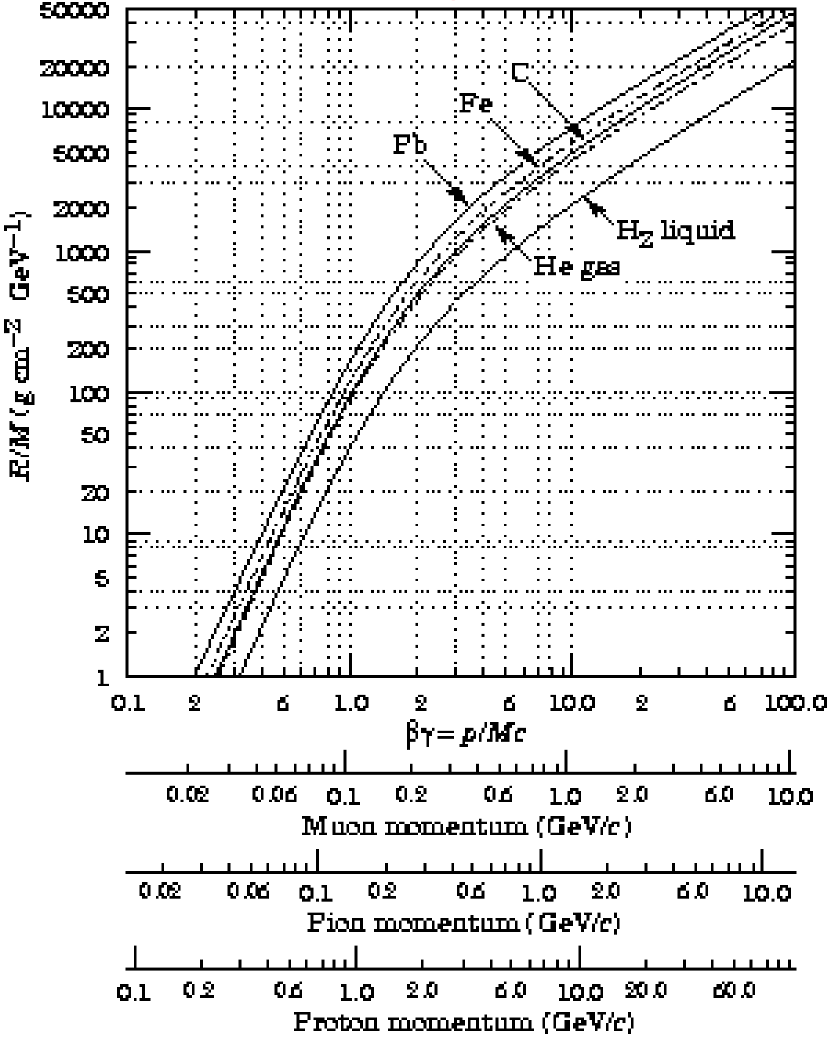
Multiple Scattering

Particle is deflected after many coulomb scatters

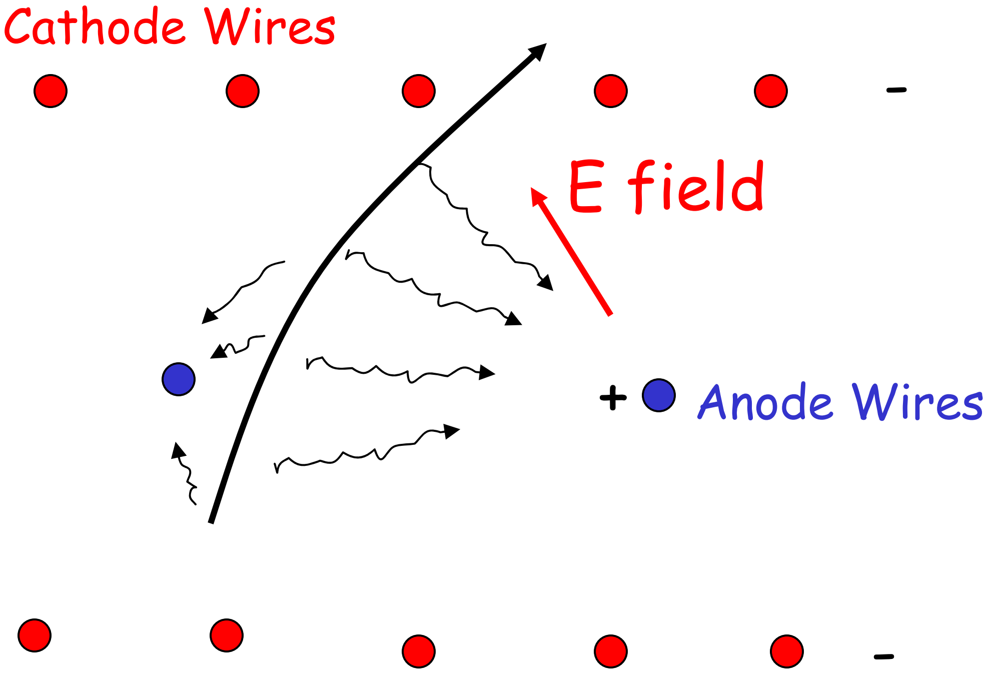


To measure trajectory of a particle, measure its ionization trail as it passes through a medium with low mass (to minimize multiple scattering) inside a magnetic field.

Range



Drift Chambers



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

Drift Chambers

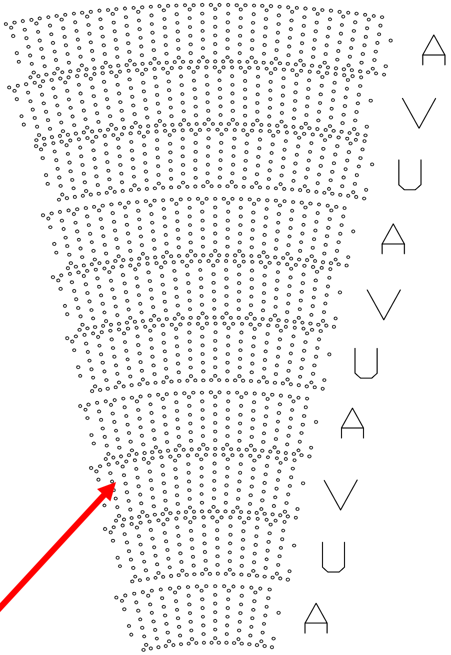
Point of ionization is determined from

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

$v_{drift} << c$ ~ cm/μs

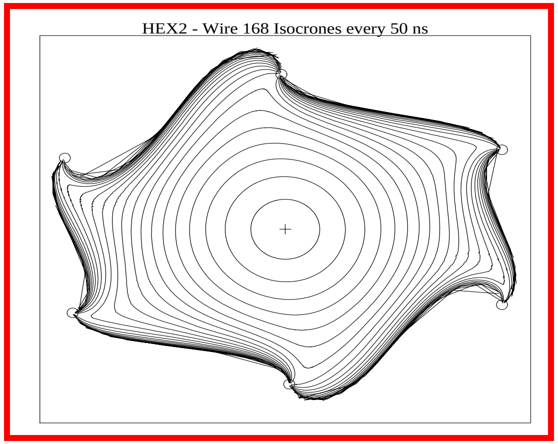
Drift time is difference between anode pulse arrival time, and particle creation time.

Many layers of wires formed into cells



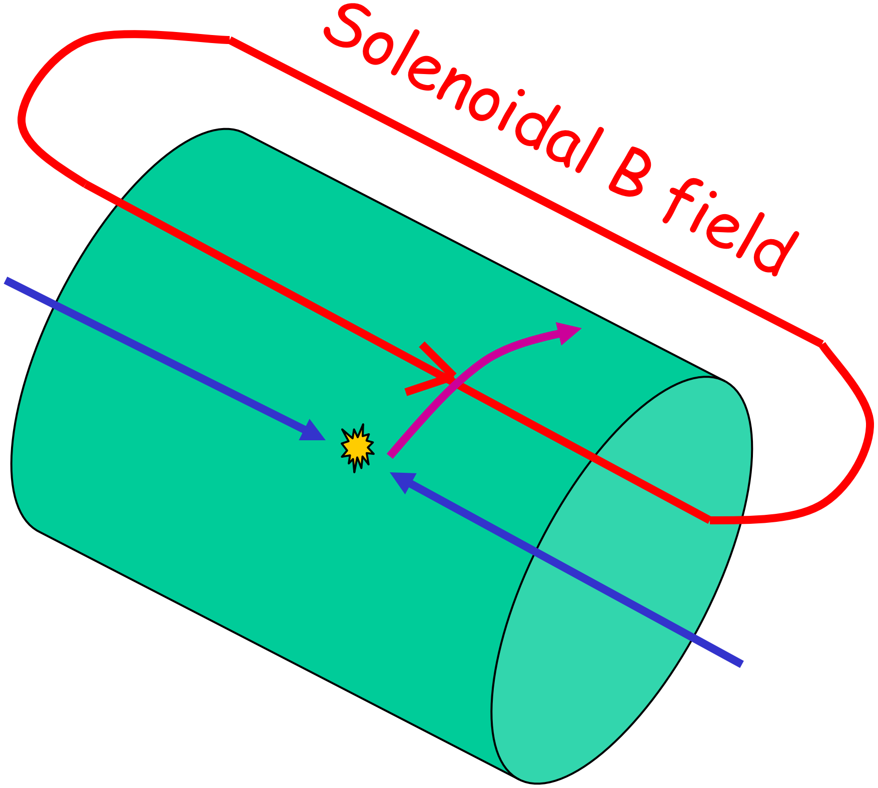
Helium/Isobutane Gas

Isobutane reduces diffusion of electrons as they drift



Drift Cell (isochrones are perp. to field)

Drift Chambers

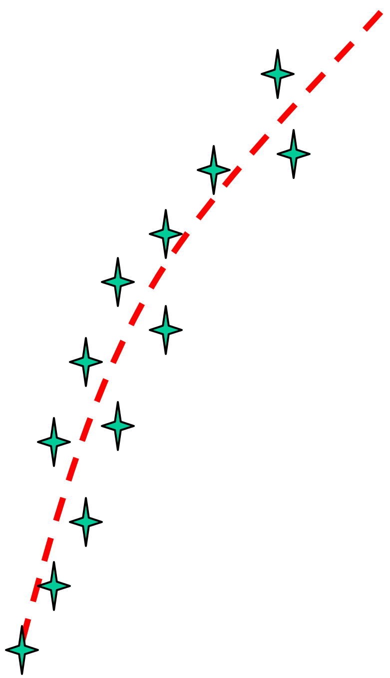


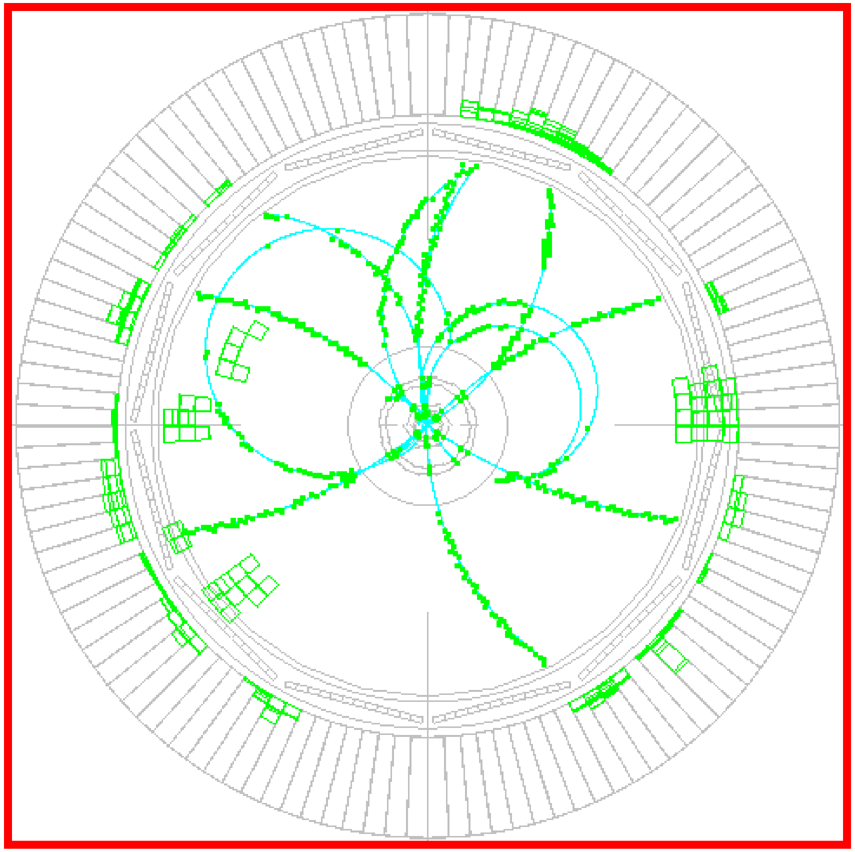

Stanford Liear Accelerator Center/Photo Researchers, Inc.

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

Drift Chambers

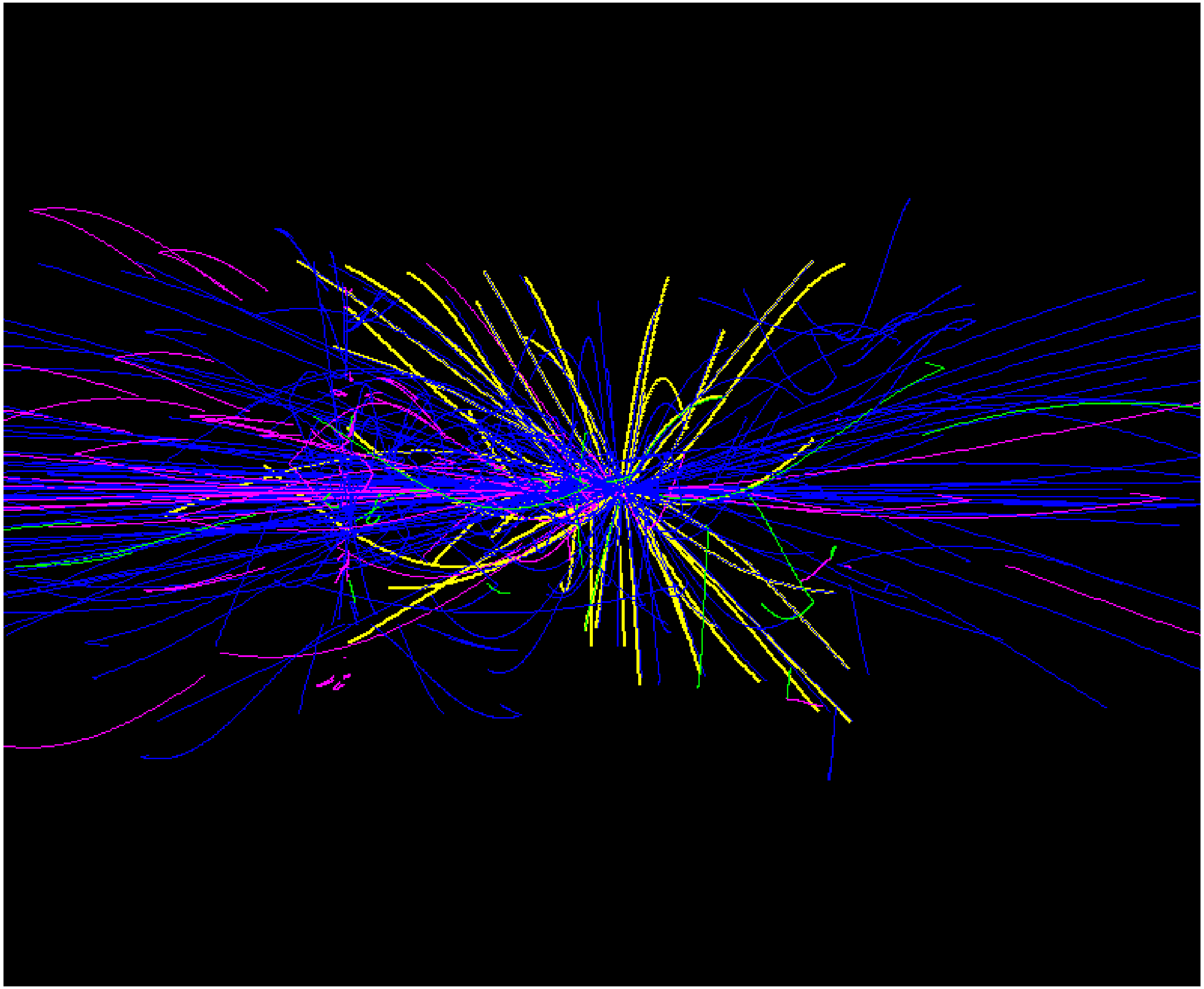
Pattern Recognition to find a “road” of hits





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

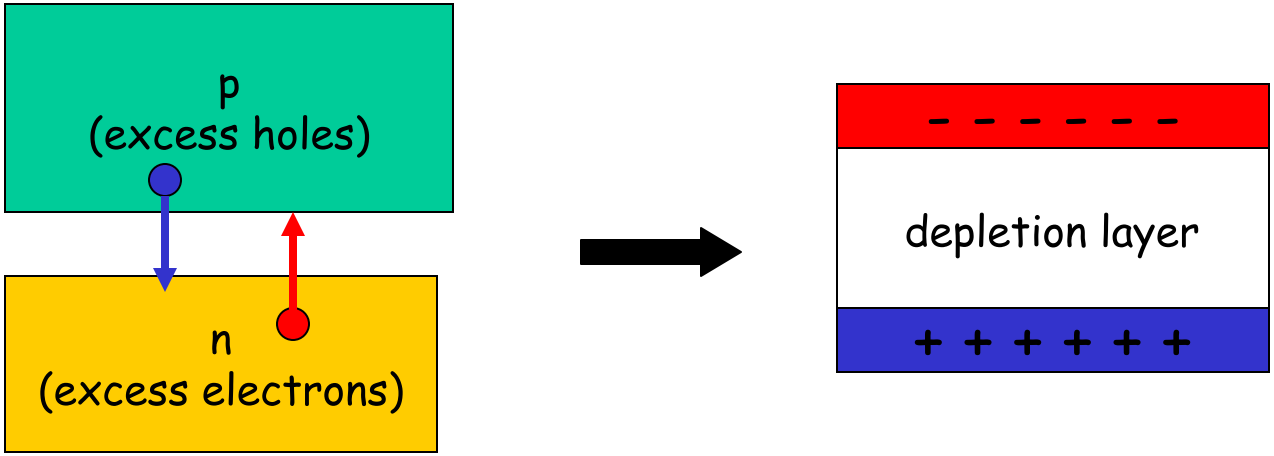


Solid State Tracking Devices

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).

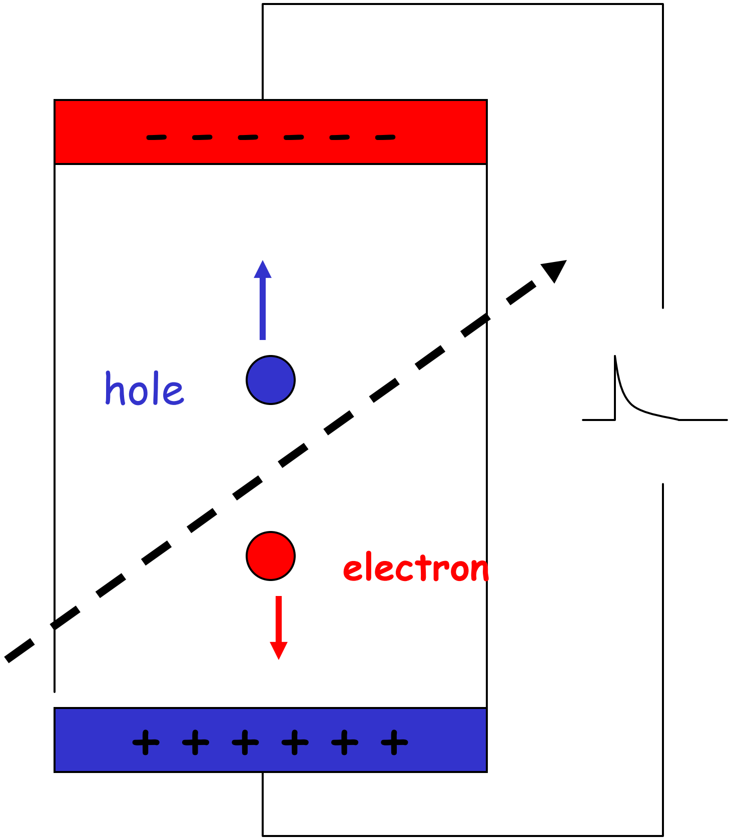


Solid State Tracking Devices

Ionizing particle creates electron/hole pair

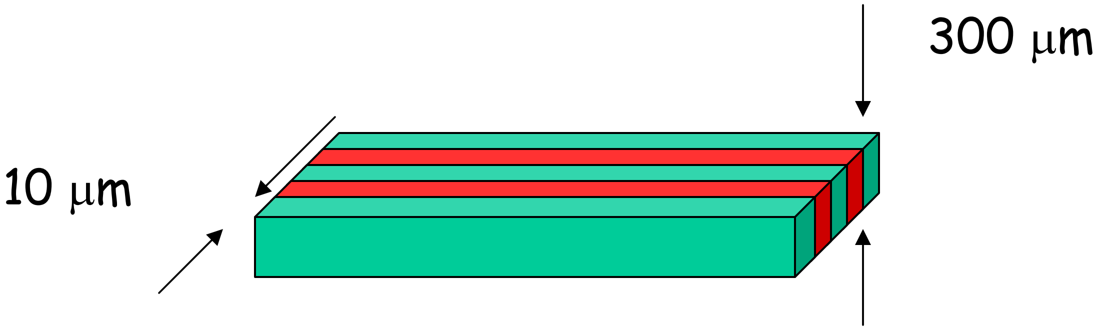
Electron/hole drift to the -ve (p) /+ve (n) surfaces, where they are majority carriers and can escape to electrodes.

If connect to electrical circuit get a pulse of charge



Solid State Tracking Devices

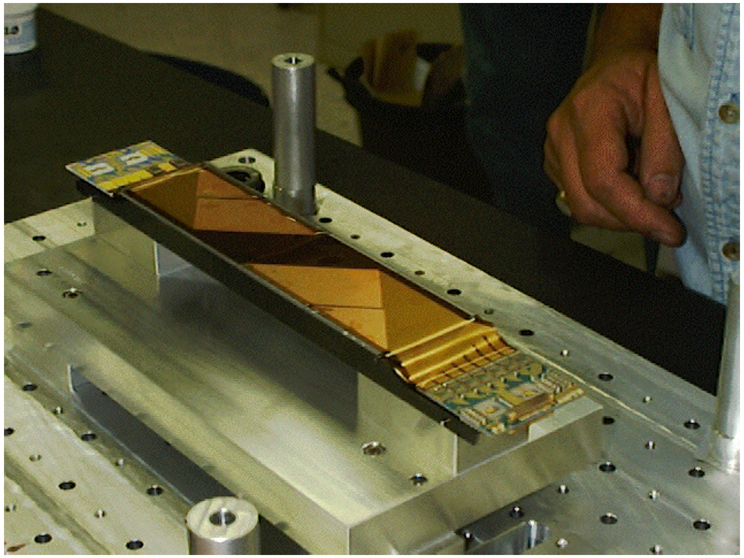
Detectors constructed of strips of width 10 μm to give O(10 μm) precision



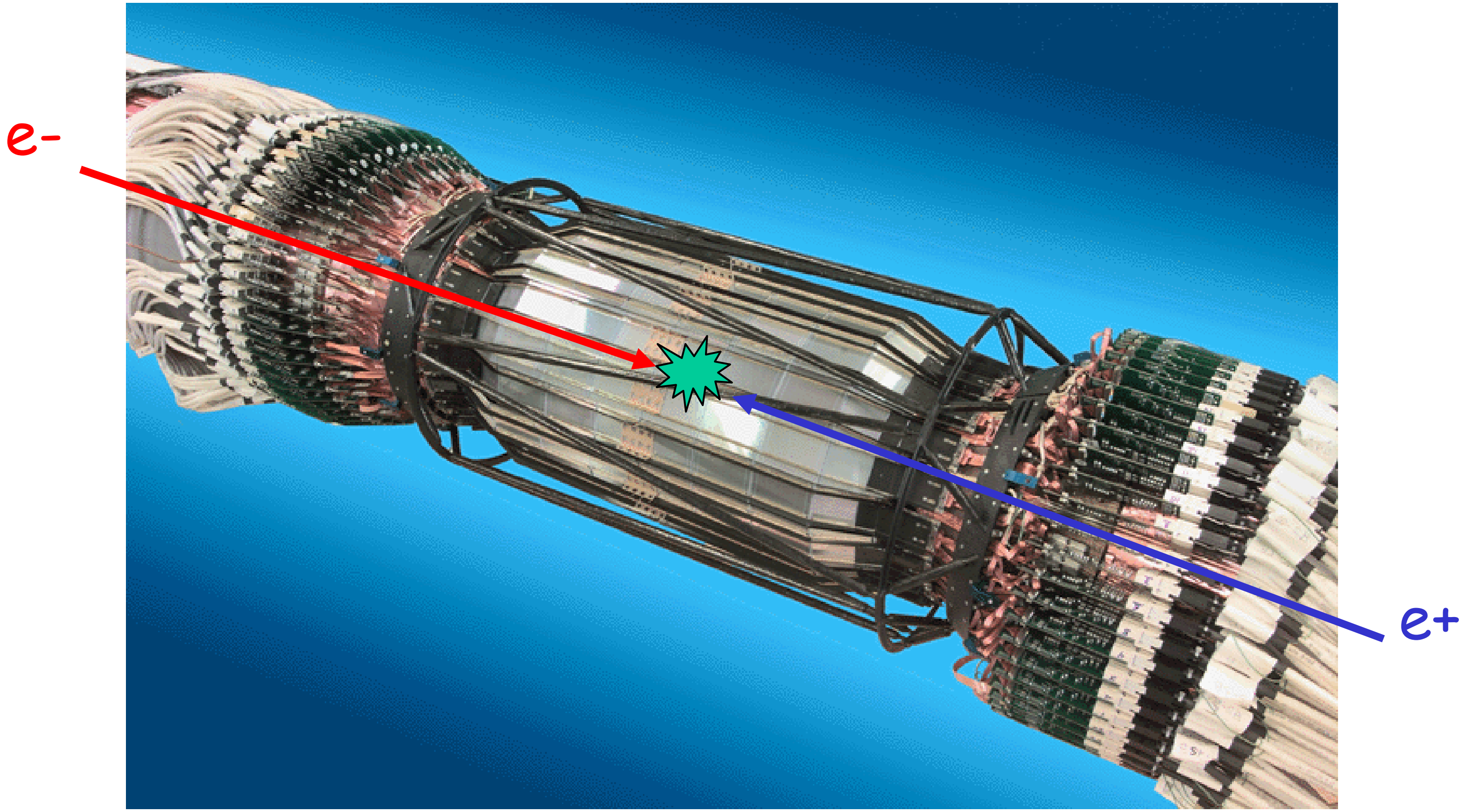
Construct detector of layers of thin strips.

Some of the electronics is incorporated in the silicon

Very light support structure (low multiple scattering)



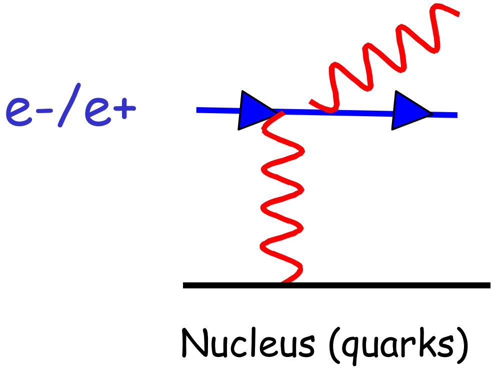
Solid State Tracking



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

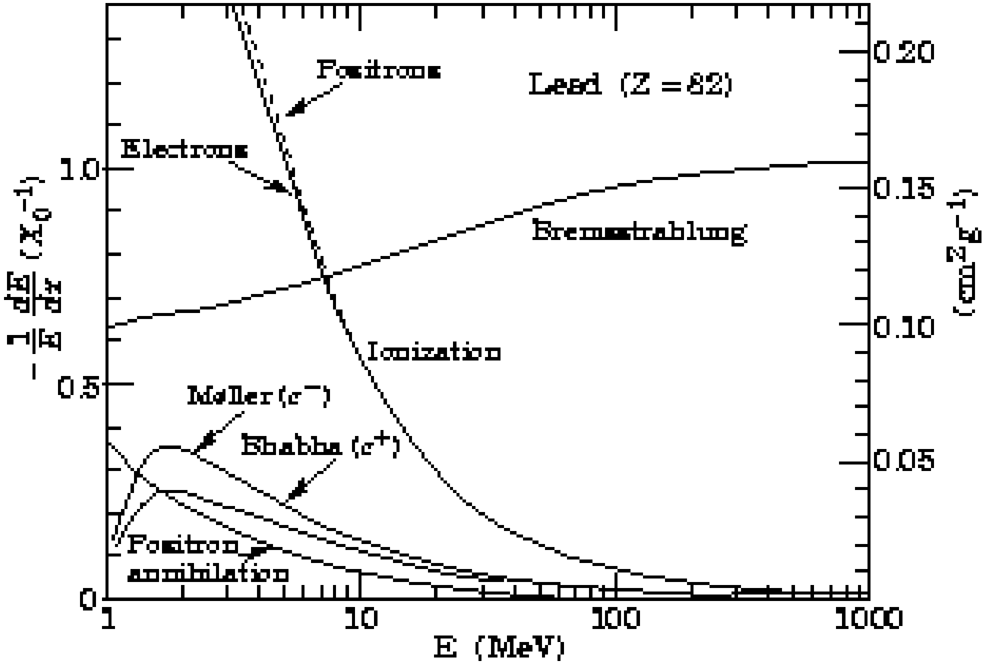
Measuring Particle Energy

Electron/Positron Energy Loss



e-/e+

Nucleus (quarks)



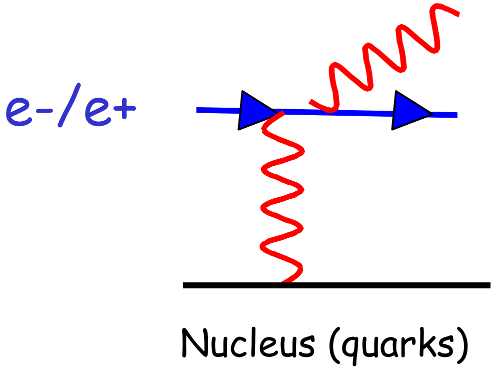
Bremsstrahlung
(radiation of photon)

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

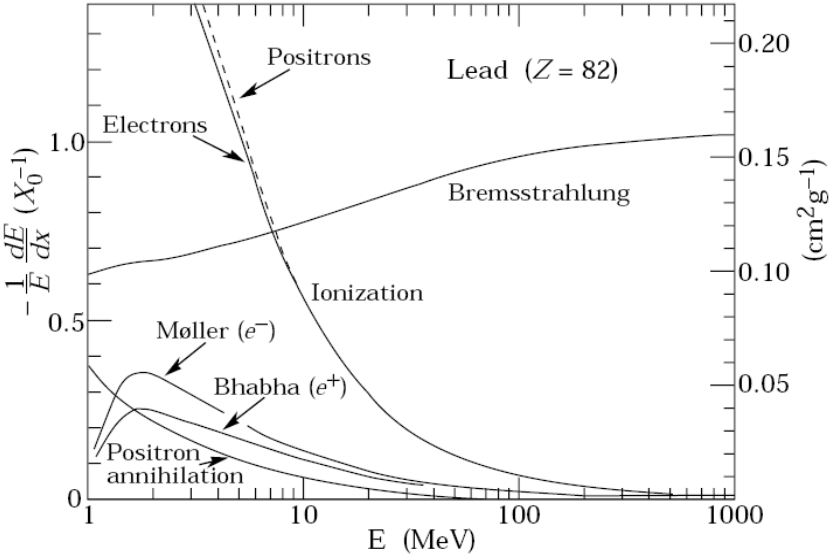
Radiation Length

Electron/Positron Energy Loss

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



Bremsstrahlung
(radiation of photon)



radiation length

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

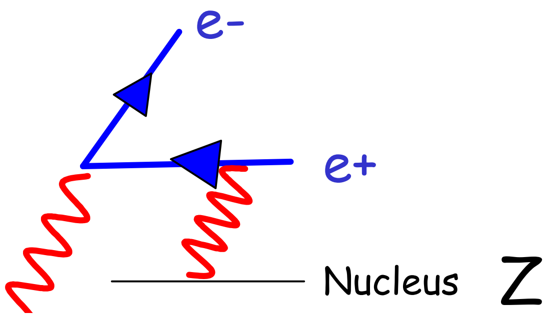
divide by ρ to get in *cm*

Radiation probability depends on radiation length X_0

Photon Energy Loss

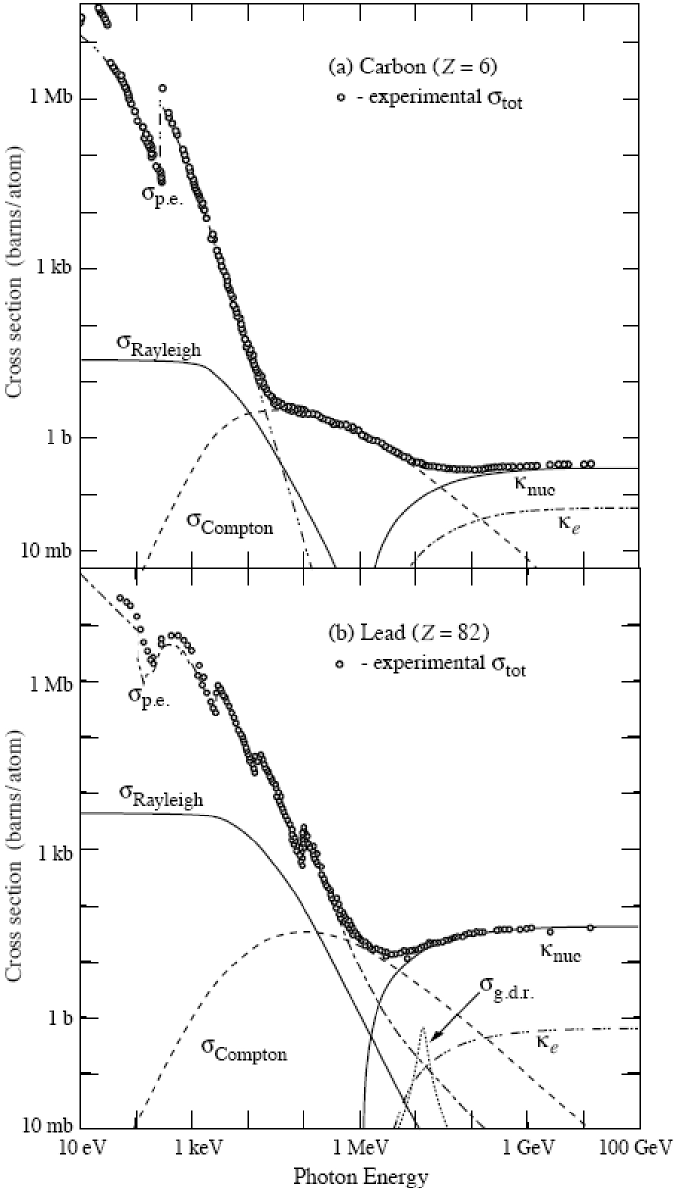
Photon energy loss primarily
- pair production at E > 20 MeV
- Compton scattering ($\gamma + e \rightarrow \gamma + e$) below 20 MeV.

Crossover depends on Z.

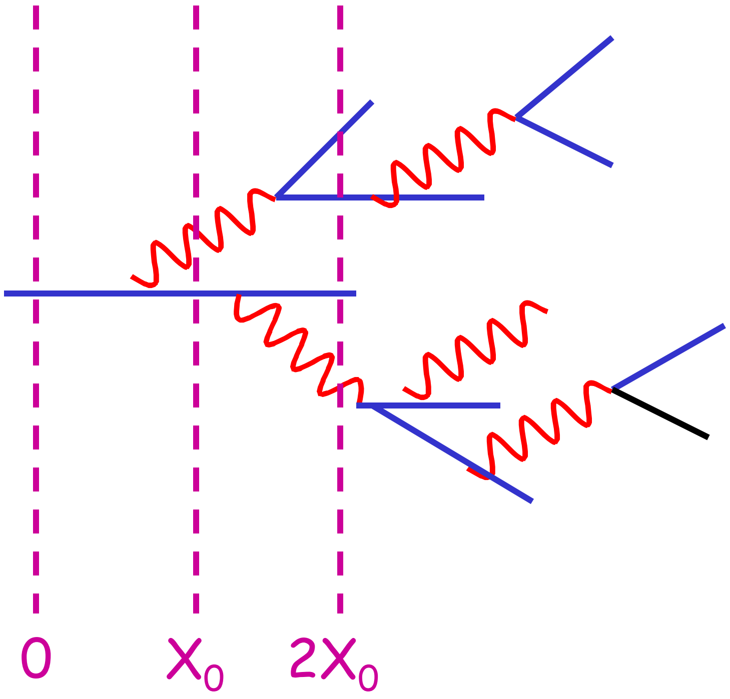


$\underline{\gamma + N \rightarrow e^+ + e^- + N}$

Pair Production, also known as
photon conversion
or Bethe-Heitler process



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

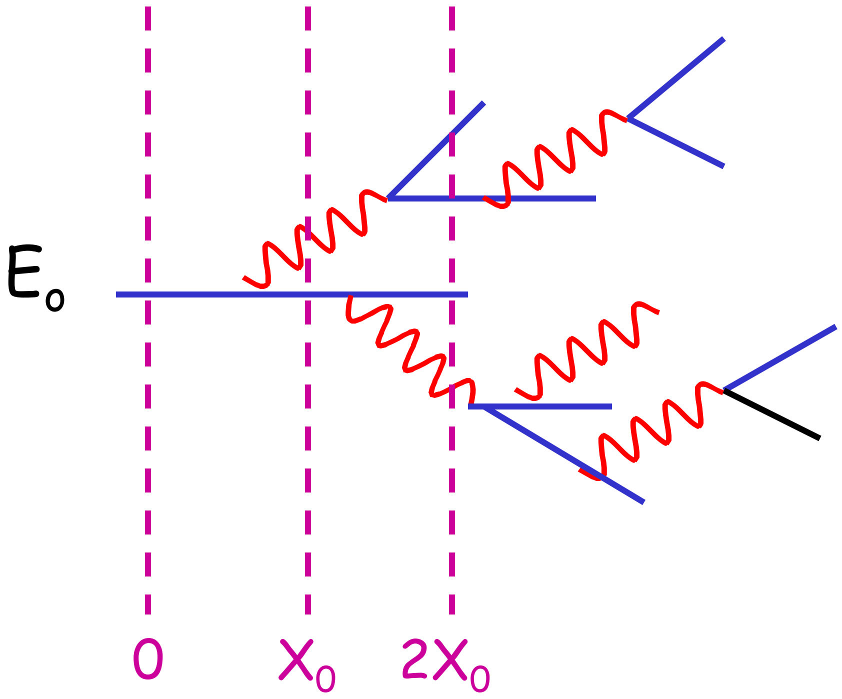
3. Electrons with $E < E_c$ stop

$E_c = 1 - 20$ MeV

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)



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

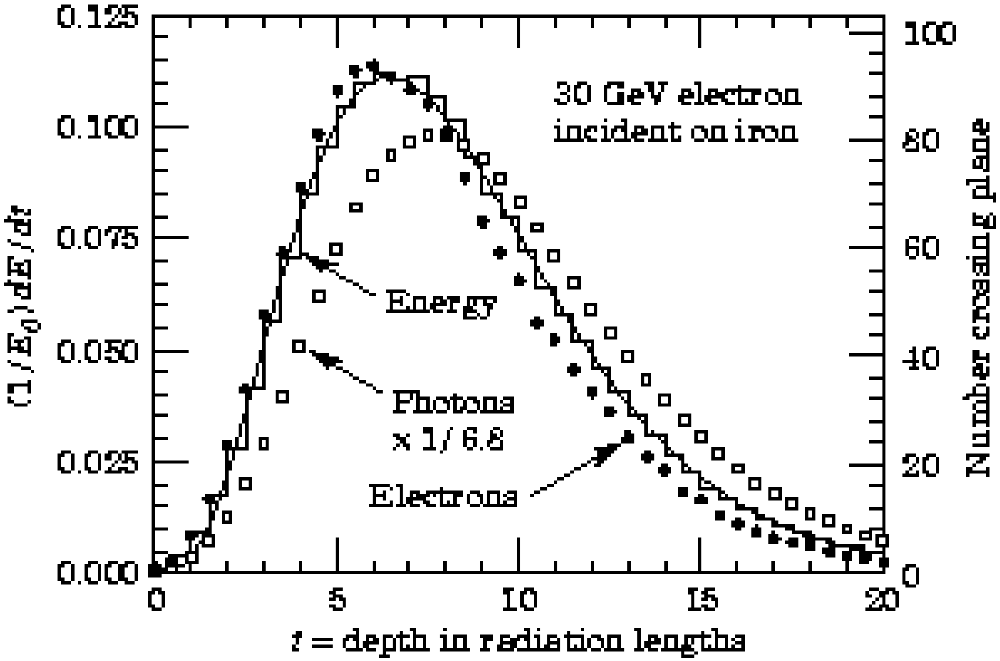
The total track length of particles

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

Problem set: Use Monte Carlo program (EGS) at

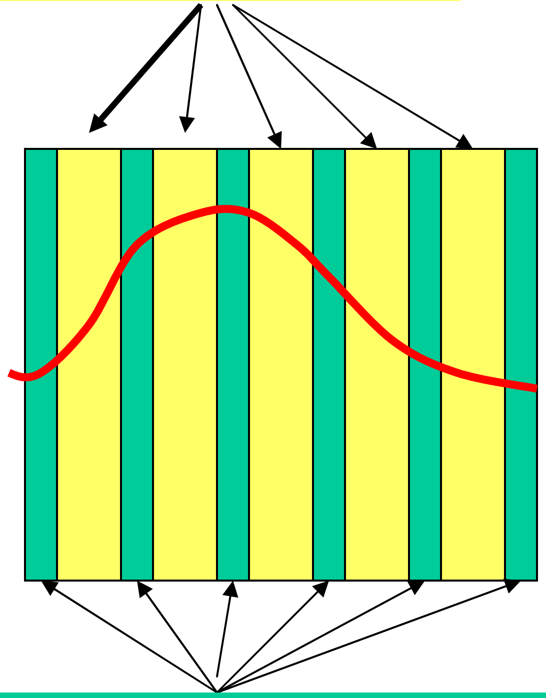
http://www2.slac.stanford.edu/vvc/egs/basicsimtool.html

Shower Development



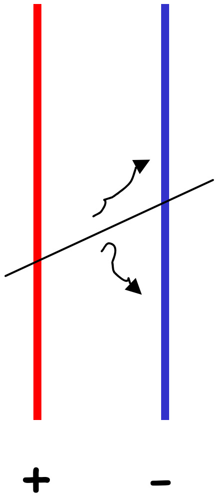
The Sampling Calorimeter

Lead- causes shower



Active Detector to measure total track length L

E.g. Ionization Chamber

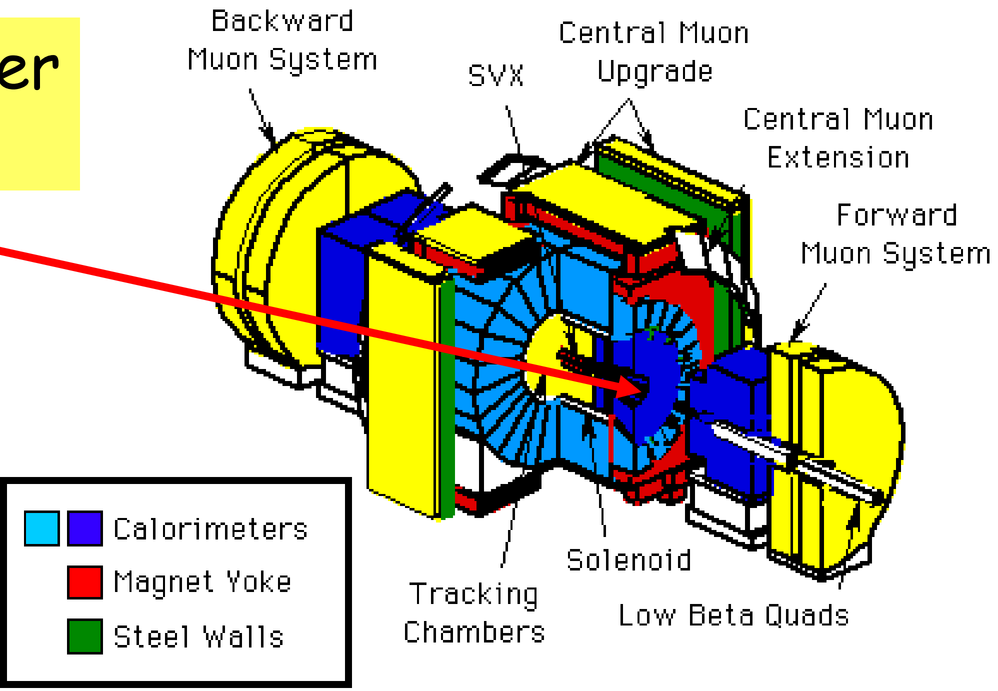


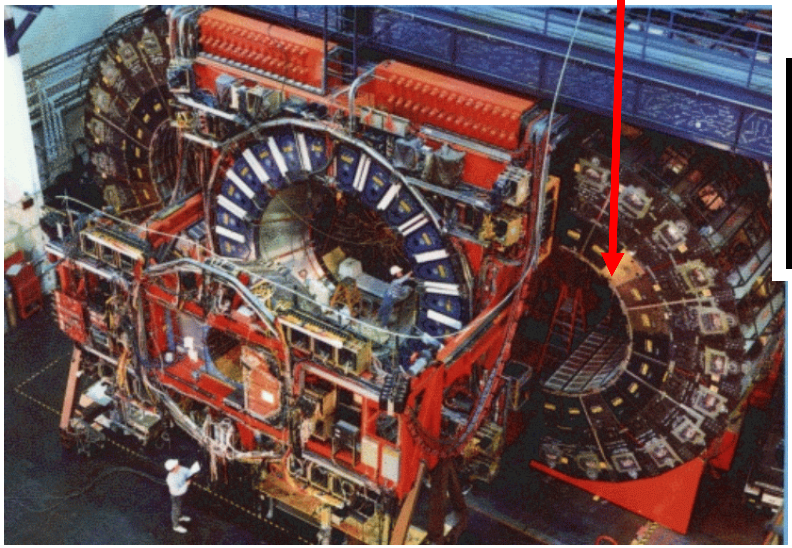
$$Q_{ionization} \propto L$$

Example of Sampling Calorimeter

Sampling Calorimeter
(Lead/Scintillator)

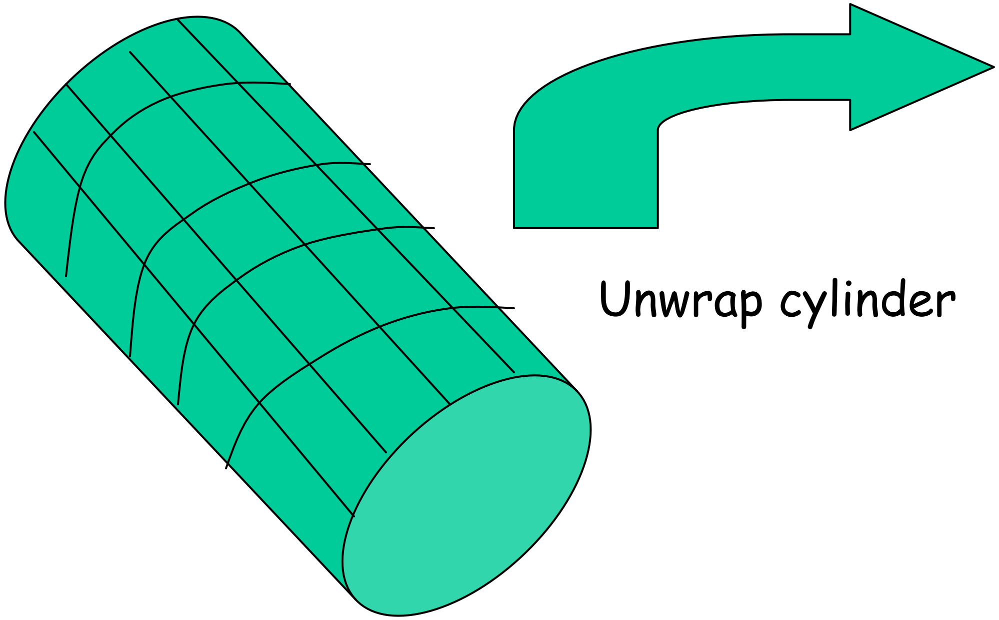
CDF Detector





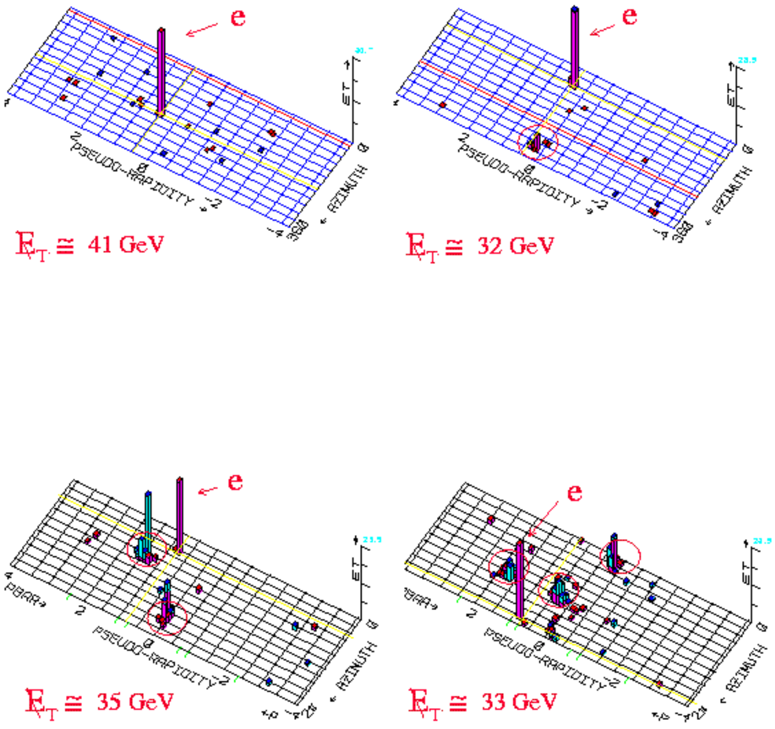
Sampling Calorimeters

Calorimeters segmented into towers



Unwrap cylinder

CDF:
W + 0,1,2,3 jet(s) Events



$E_T \cong$ 41 GeV

$E_T \cong$ 32 GeV

$E_T \cong$ 35 GeV

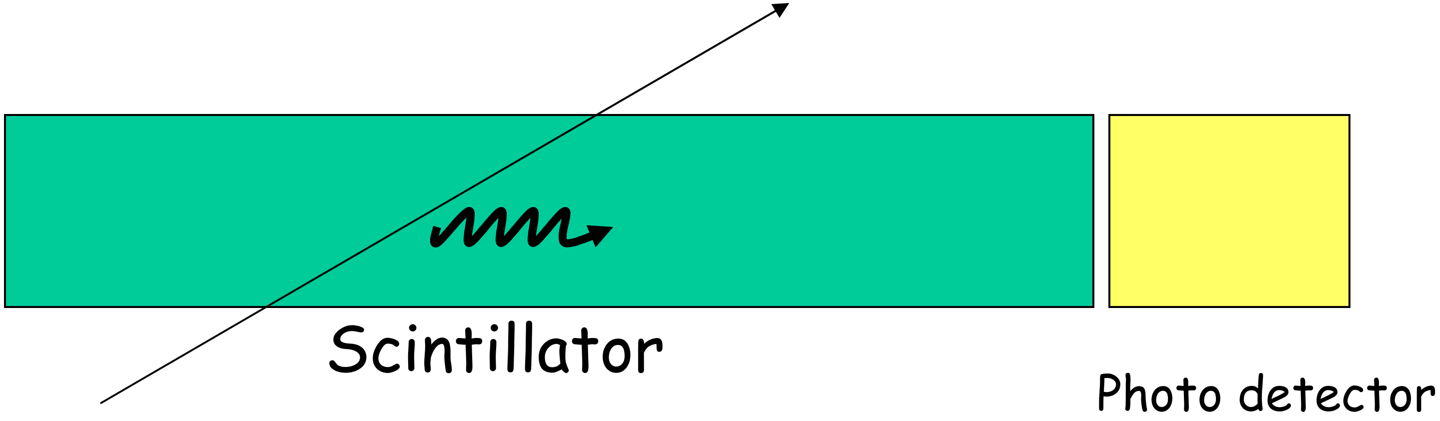
$E_T \cong$ 33 GeV

$$\eta = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = -\ln(\tanh\frac{\theta}{2})$$

$\phi =$ azimuthal angle

Scintillation

Particle causes excitation which results in light pulse

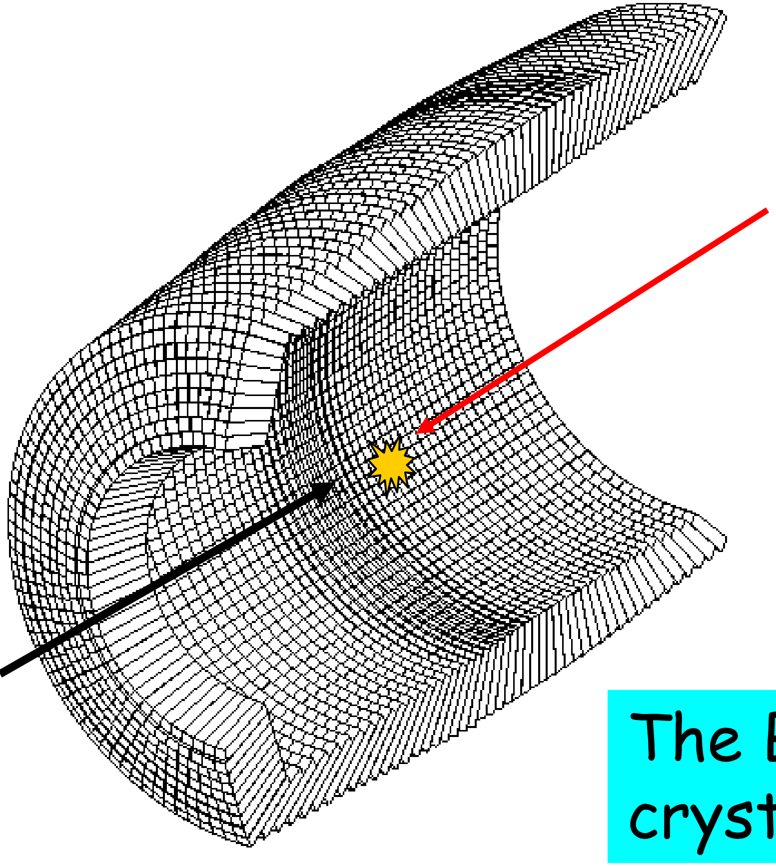


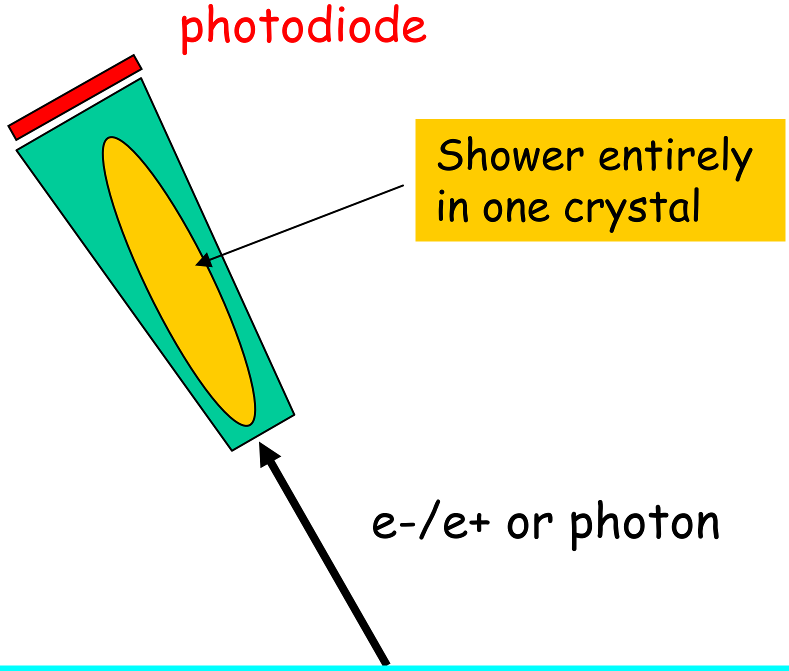
Number of photons proportional to track length

Fast response → can use for time-of-flight (TOF) systems to measure velocity (particle ID)

Crystal Calorimeters

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





The BaBar Calorimeter has 6580 CsI crystals in a cylinder

[CMS ECAL: 75,000 $PbWO_4$ crystals. X_0 = 0.89cm]

Construction of the BaBar Calorimeter

Identifying Particles

Can distinguish photons and electrons

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

but

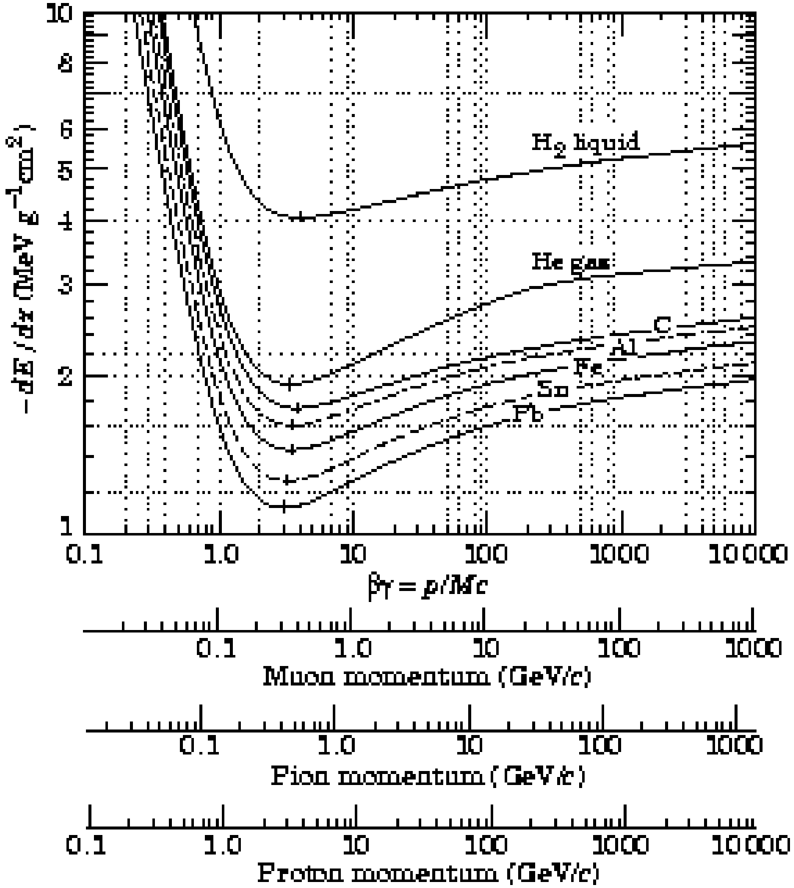
Protons, charged kaons, charged pions, muons do not make a shower but do make a track.
How to distinguish ?

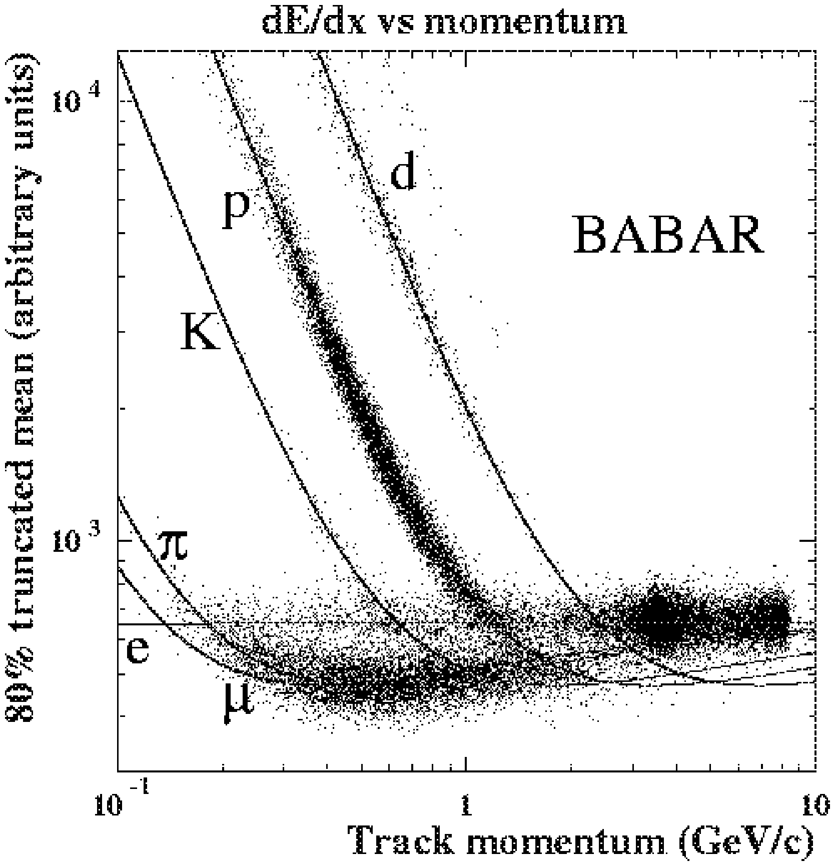
Since $p = m\beta\gamma$ if we know the momentum then we need to measure either the mass or velocity

1. dE/dx - less than 1 GeV, where dependence on β is steep
2. Cerenkov Detectors > 1 GeV
3. Time of Flight (few GeV?)

dE/dx using Drift Chamber

Recall dE/dx depends on velocity only

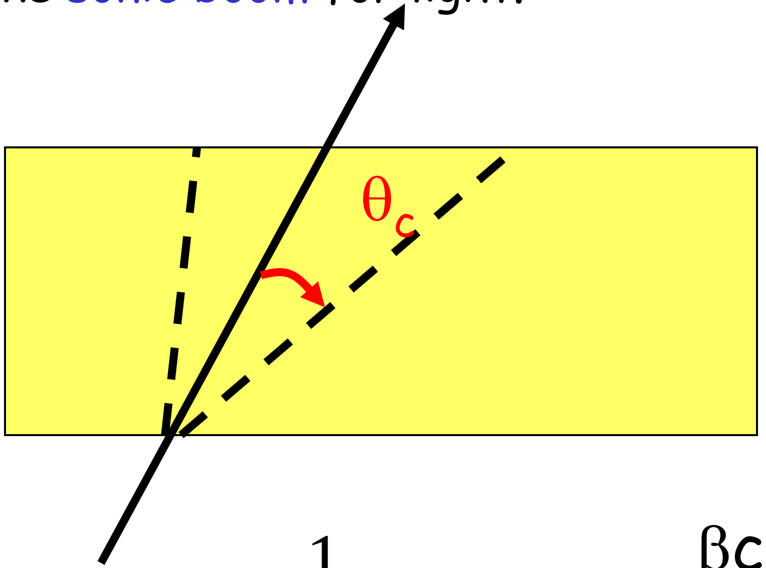




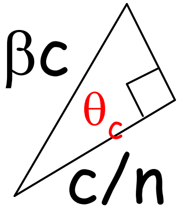
Measure dE/dx (velocity) and momentum to infer mass

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.



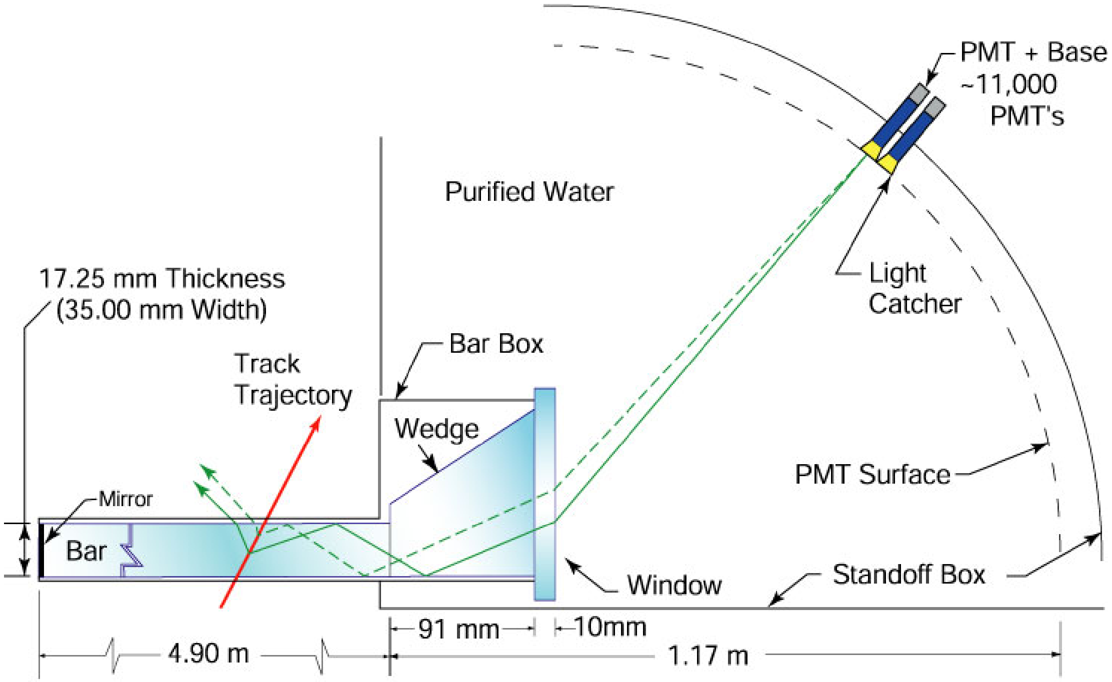
$$\theta_c = \cos^{-1}(\frac{1}{\beta n})$$

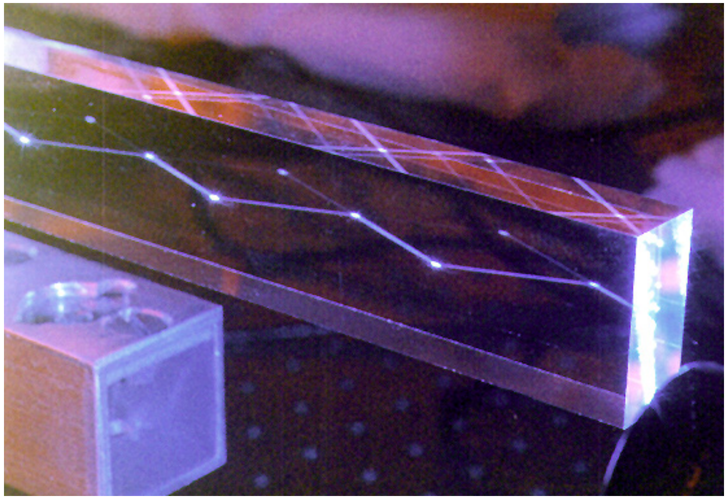


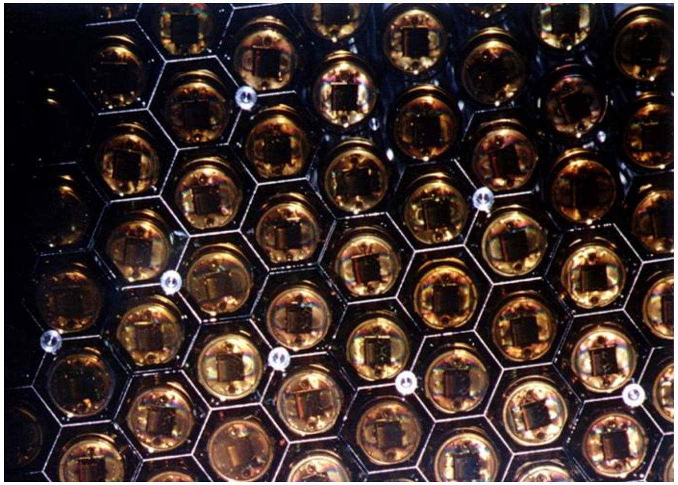
Cone angle measures velocity

electrons in nuclear reactor pool emit Cerenkov light

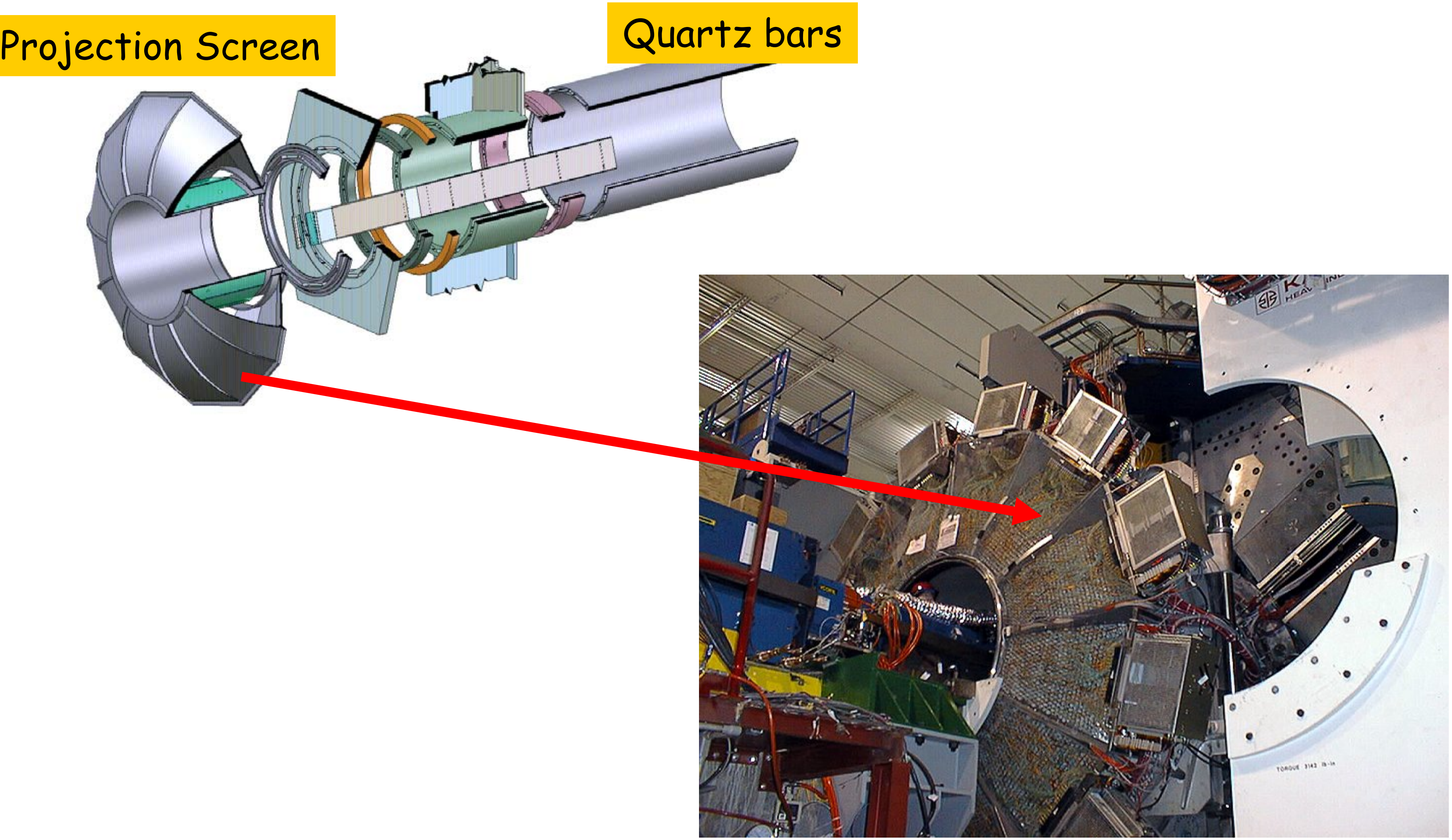
The BaBar Cerenkov Detector







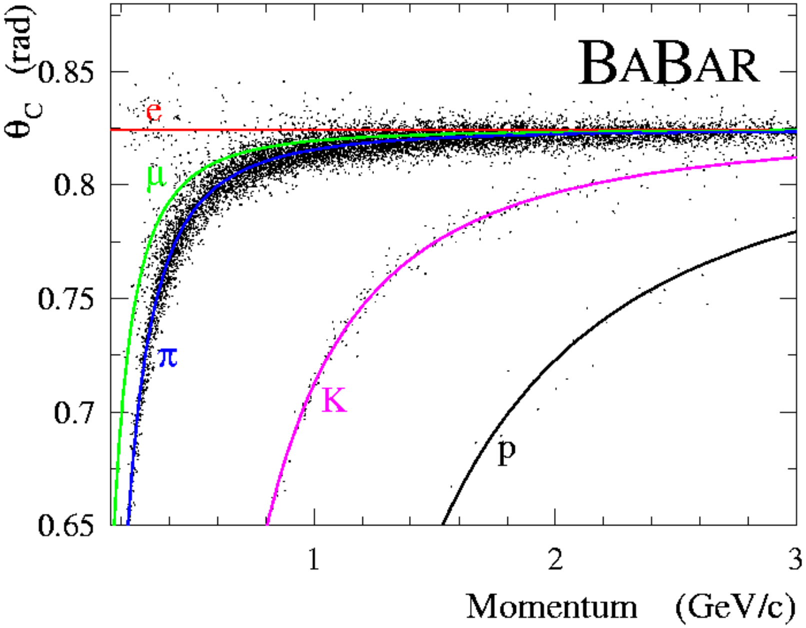
BaBar Cerenkov Detector Construction

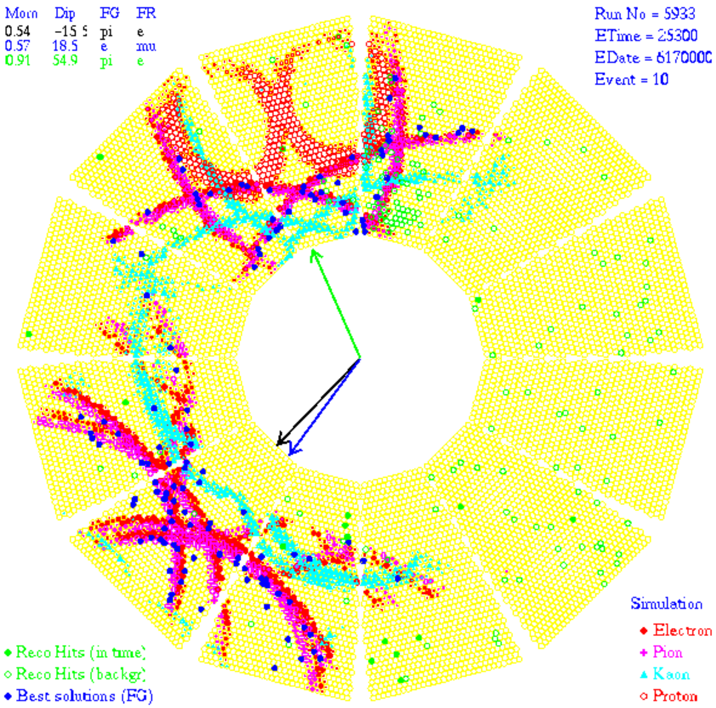


Projection Screen

Quartz bars

Event Showing Cerenkov Rings in BaBar



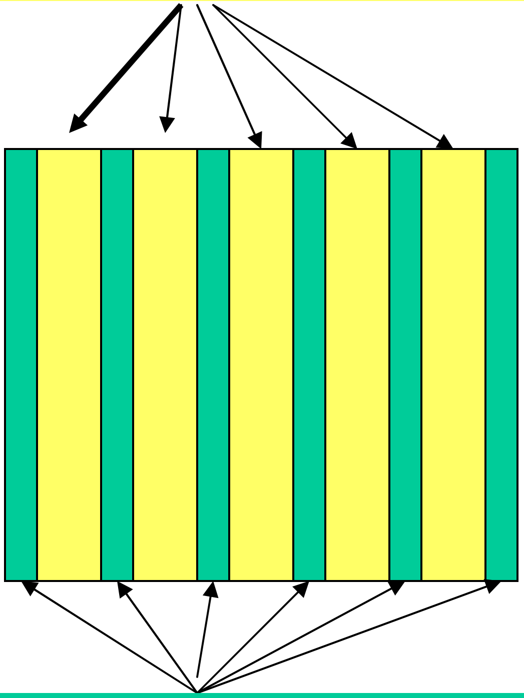


Mom	Dip	FG	FR
0.54	−15 5	pi	e
0.57	18.5	e	mu
0.91	54.9	pi	e

Run No = 5933
ETime = 25300
EDate = 6170000
Event = 10

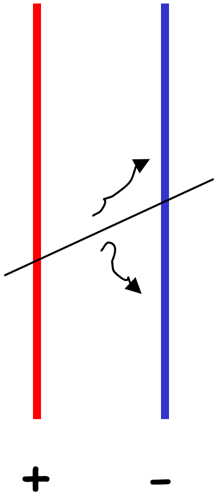
Muon Identification

Iron shields other particles



Active Detector to
measure total track length L

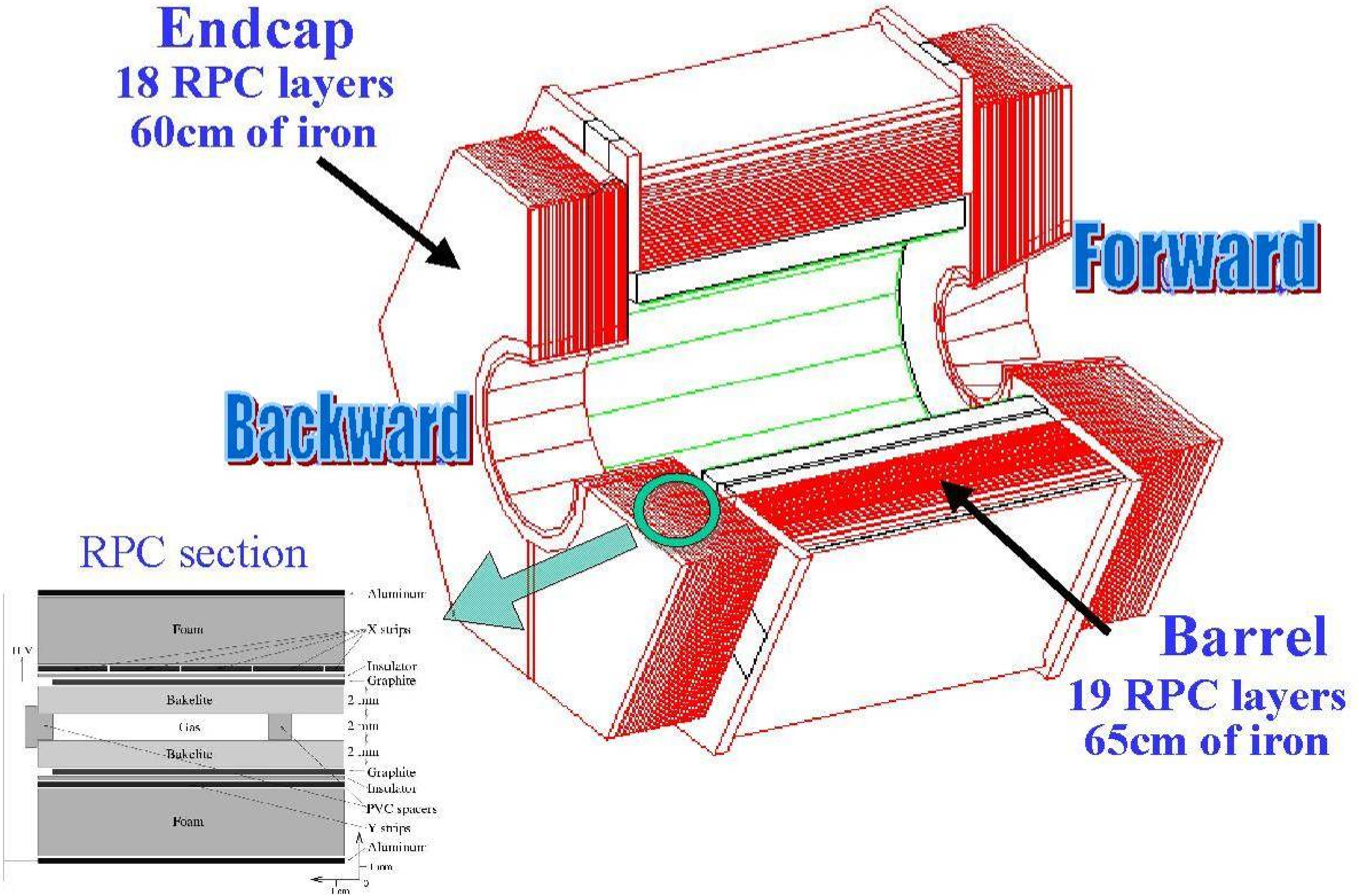
E.g Ionization Chamber



$$Q_{ionization} \propto L$$

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

The BaBar Muon Detector



Endcap
18 RPC layers
60cm of iron

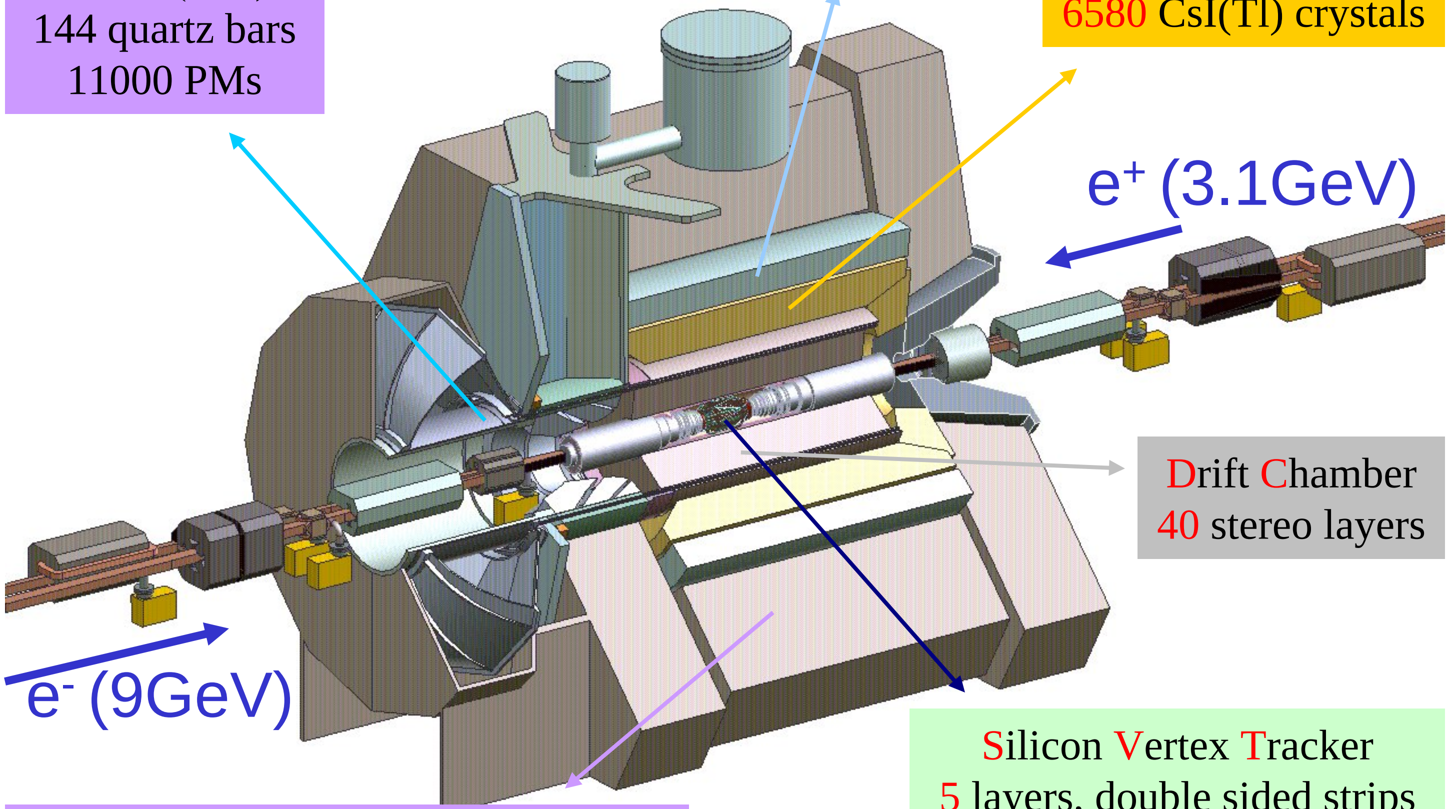
Forward

Backward

Barrel
19 RPC layers
65cm of iron

RPC section

The Complete BaBar Detector



DIRC (PID)
144 quartz bars
11000 PMs

1.5T solenoid

EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

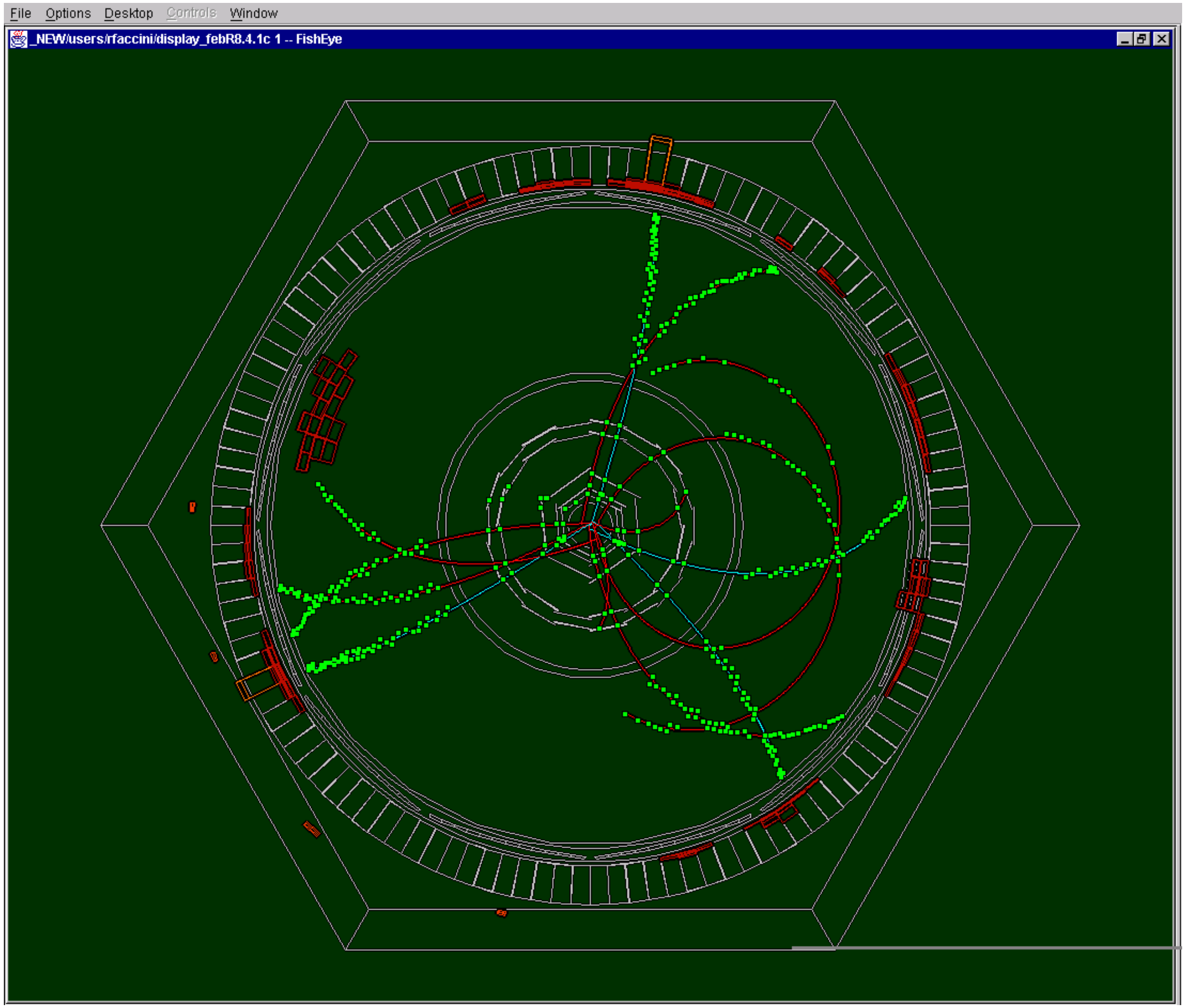
Drift Chamber
40 stereo layers

e^- (9GeV)

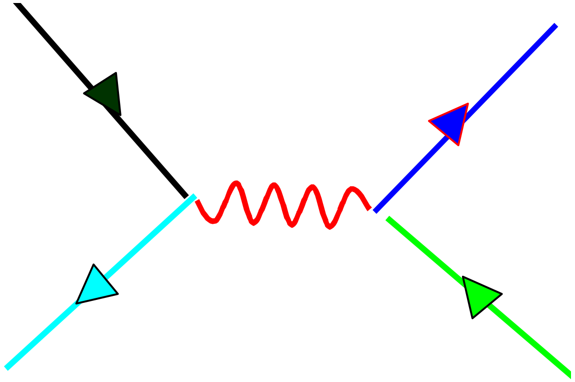
Silicon Vertex Tracker
5 layers, double sided strips

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

A matter-antimatter Event



e+e- -> μ+μ-   at PEP II

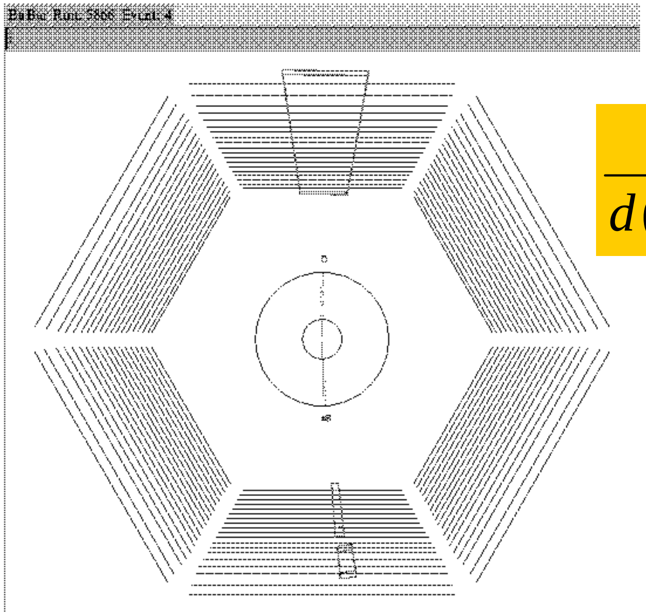


$$\frac{d\sigma}{d(\cos\vartheta)_{cm}} = \frac{\pi\alpha^2}{2s}(1+\cos^2\vartheta)$$

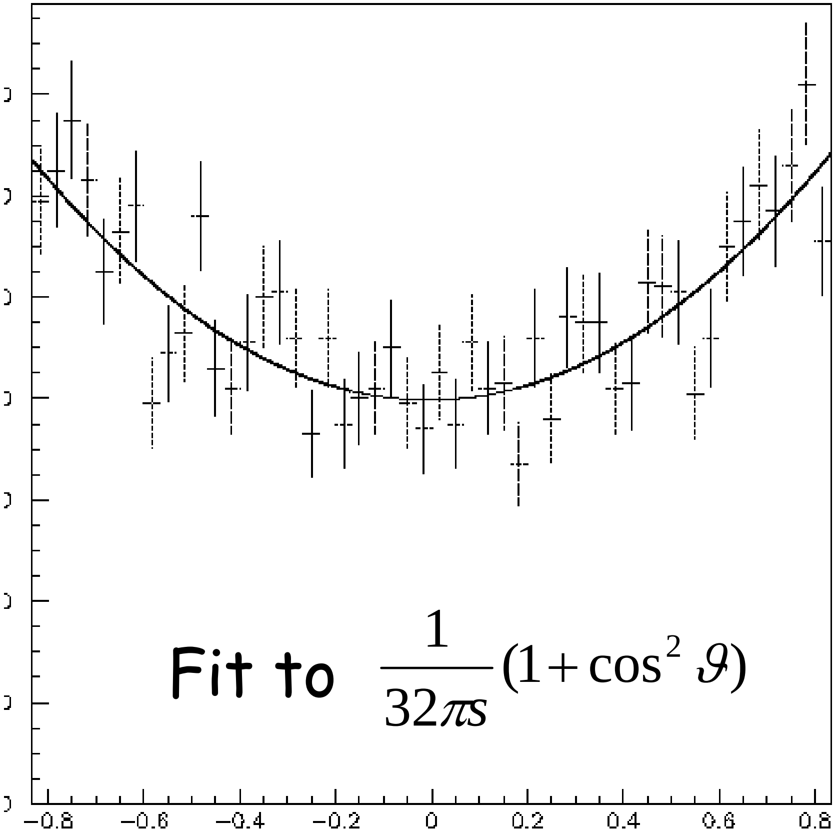
$$\sigma = \frac{4\pi\alpha^2}{3s}$$

At $s = (10.58\ \mathrm{GeV})^2$ (PEP II)
σ(e+e- -> μ+μ-)= 0.78 nb

Muon Pair Production Data from BaBar



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



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

$$\cos\vartheta_{cm}$$