Detectors in High-Energy Physics

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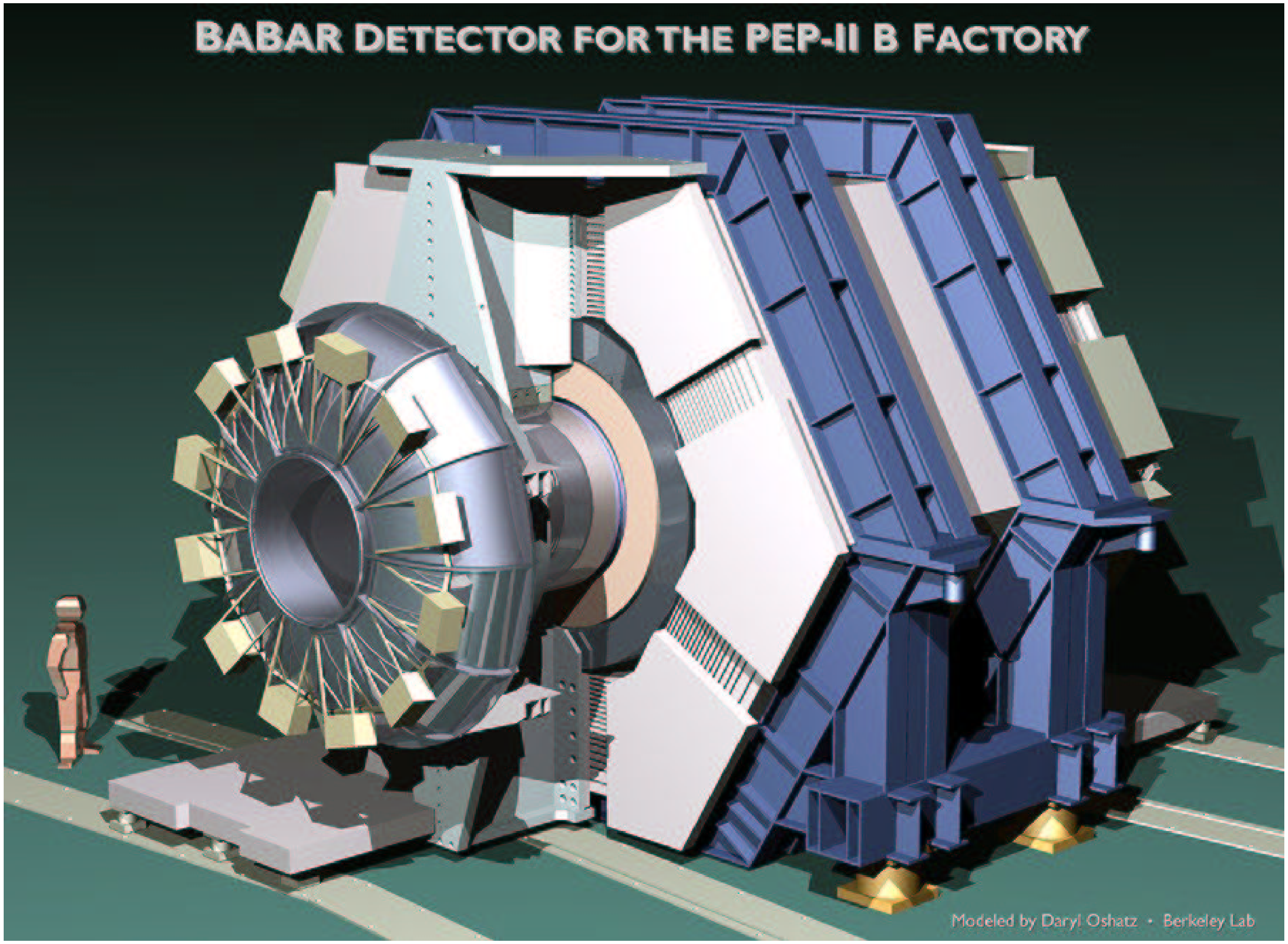
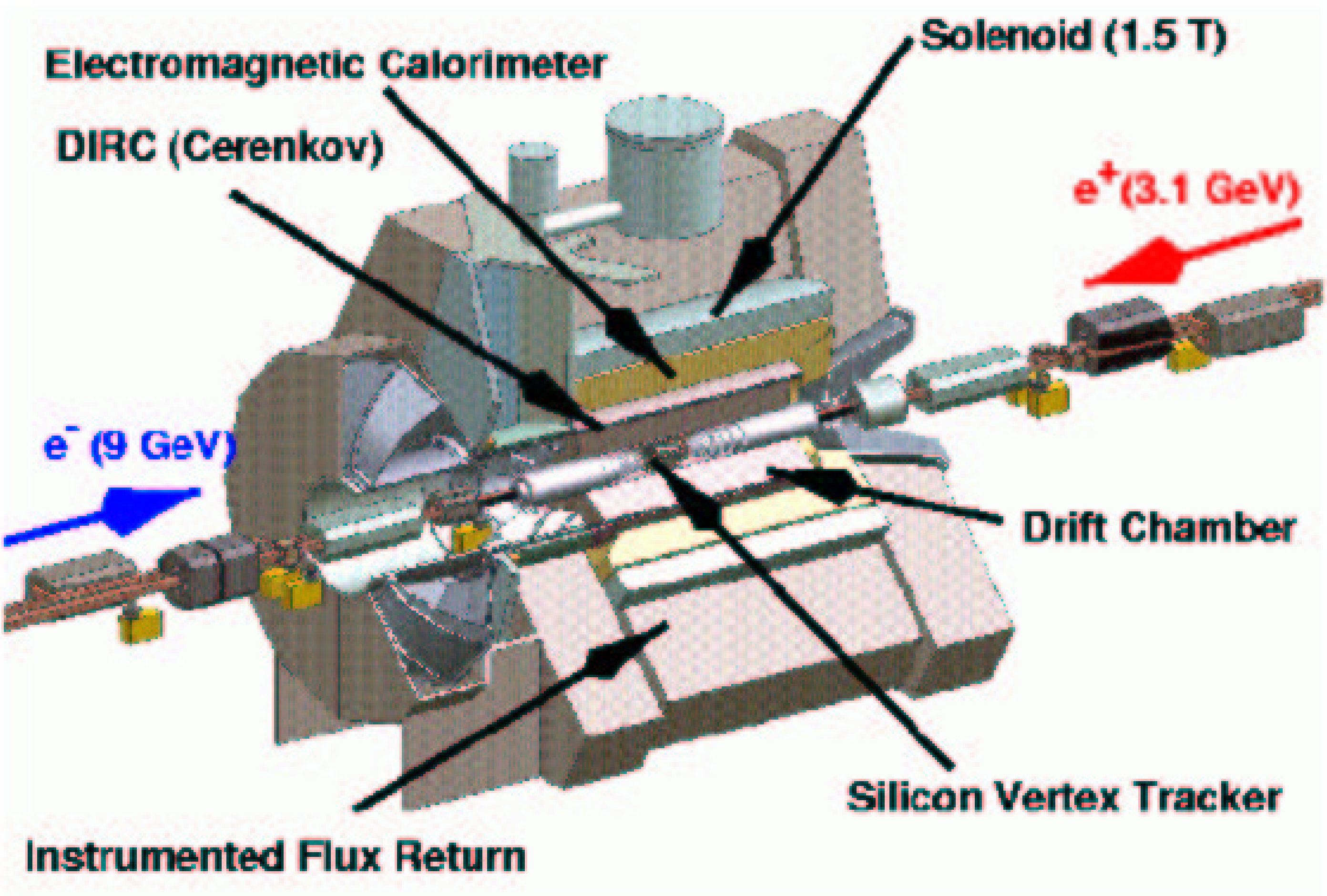
Overview:

- Types of particles produced in high-energy collisions
- Information we want: their momentum, energy, mass, charge, identity
  - get from measurements of position and time (and signal size)
- Ways in which particles interact with matter
  - the basis of our "detective" work!
- Types of detectors – several sorts needed in most experiments
- An interesting collision? – how do we decide? – what do we do?

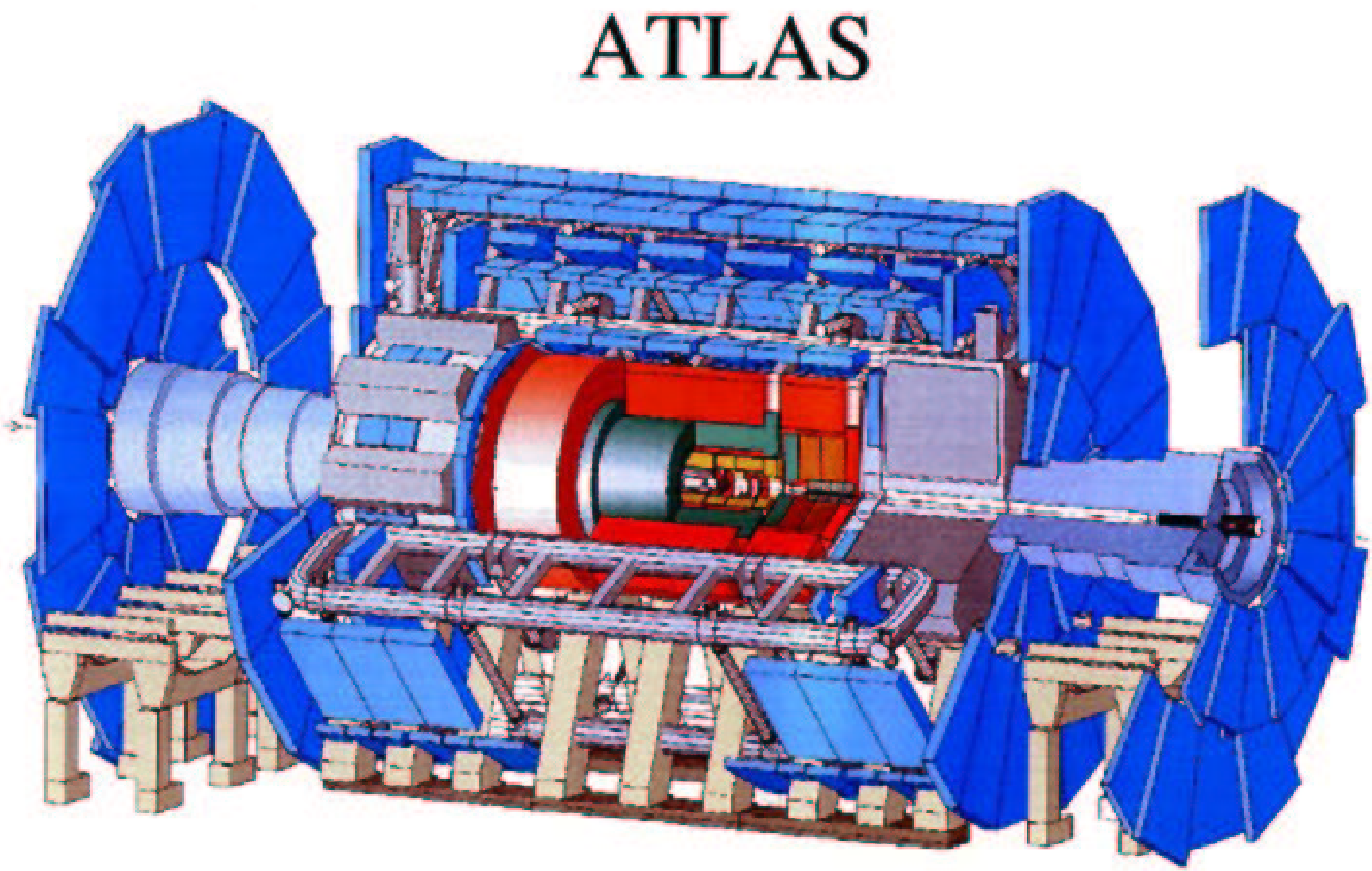
BaBar Experiment at SLAC



BaBar Experiment at SLAC

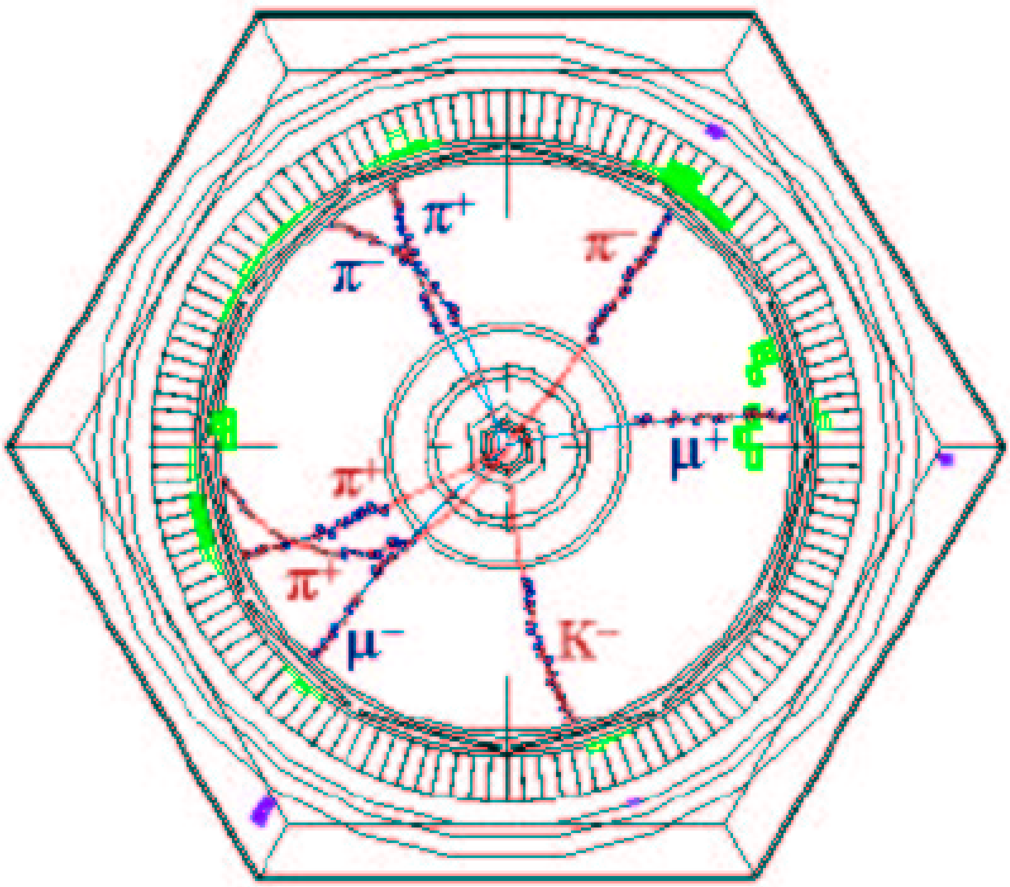


A Future Experiment: ATLAS at CERN



An Event from *BaBar*

- $e^+e^- \to B^0\overline{B^0}$
- $\overline{B^0} \to D^{*+}\pi^-$
  - $D^{*+} \to D^0\pi^+$
  - $D^0 \to K^-\pi^+$
- $B^0 \to \psi(2S)K_s^0$
  - $\psi(2S) \to \mu^+\mu^-$
  - $K_s^0 \to \pi^+\pi^-$



Only long-lived ($> 10^{-10}$sec) particles seen directly

Find short-lived "parents" *via* charge, energy, momentum conservation (and id)

Some Common Particles

Particles we do or don't detect directly, and their mean lifetimes:

Leptons:	electron	$e^{\pm}$	stable	
	muon	$\mu^{\pm}$	2×10^{-6} s	
	tau	$\tau^{\pm}$	3×10^{-13} s	e.g. $\tau^{\pm} \to e^{\pm}\nu\overline{\nu}$
	neutrino	ν	stable	
Hadrons:	pion	$\pi^{\pm}$, π^{0}	3×10^{-8} s, 8×10^{-17} s	$\pi^{0} \to \gamma\gamma$
	kaon	$K^{\pm}$	1×10^{-8} s	
	kaon	K^{0}_{S}, K^{0}_{L}	9×10^{-11} s, 5×10^{-8} s	$K^{0}_{s} \to \pi^{+}\pi^{-}$ or $\pi^{0}\pi^{0}$
	proton	p	stable	
Gauge bosons:	photon	γ	stable	
	gluon	g	$\sim 10^{-24}$ s	
		W, Z	$\sim 10^{-24}$ s	

Interaction of Particles with Matter

Charged particles transfer energy to matter they traverse by:

- ionization of atoms or molecules of the material
  - detect ions in gas in a proportional counter or drift chamber, or
  - electron-hole pairs in solid-state counter, e.g. silicon microstrip detector
- excitation of atoms or molecules, which then emit light
  - scintillation light from some inorganic crystals or organic molecules
  - scintillation counters typically use photomultipliers for light detection

Neutral particles may be detected if they:

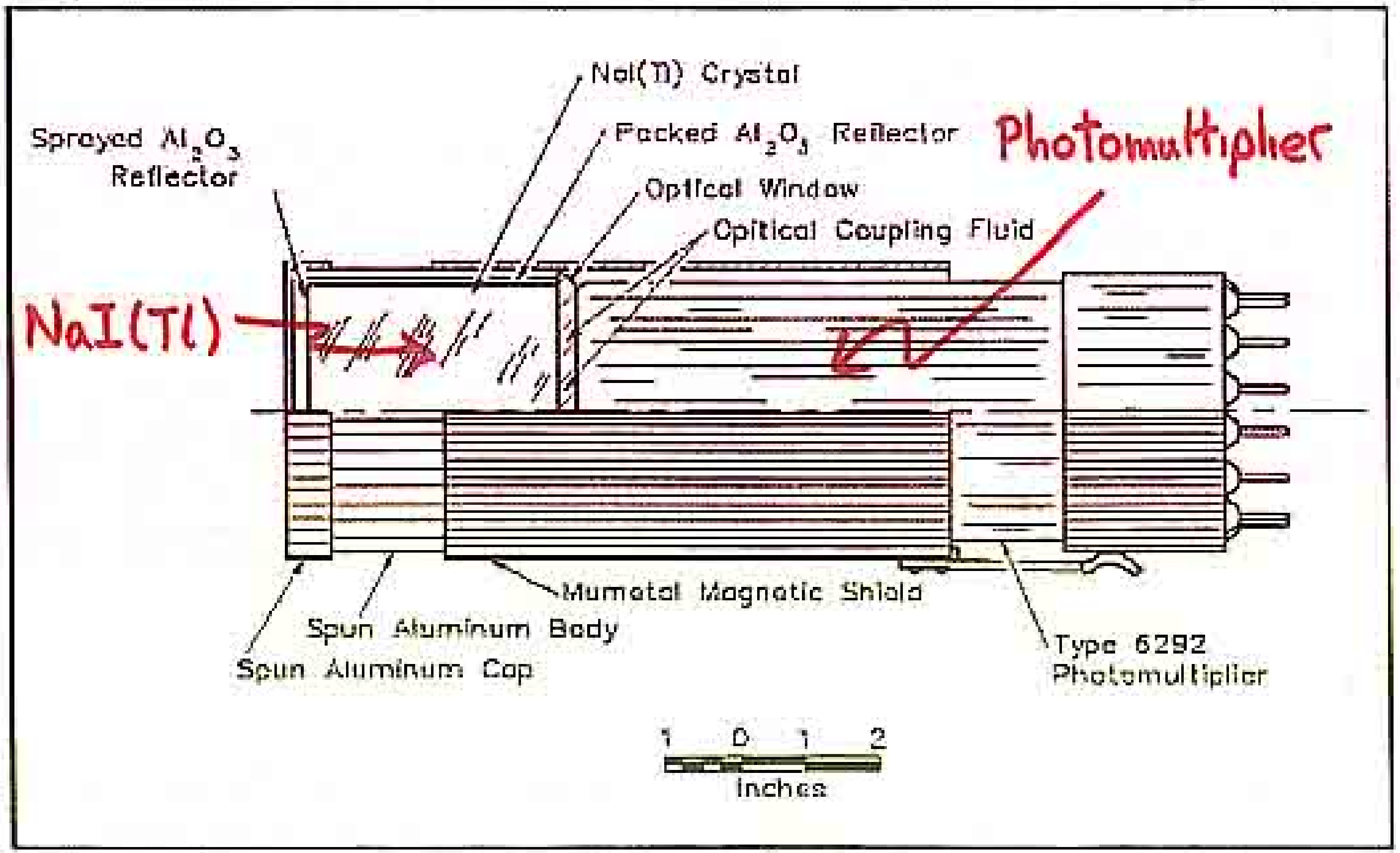
- decay to charged particles, e.g. $K_S^0 \to \pi^+\pi^-$
- interact with matter to produce charged particles, e.g. K_L^0, γ do this
- Neutrinos do neither! But "missing" momentum may indicate a neutrino!

Scintillation Counter

Photomultiplier tube detects light from scintillator, which may be:

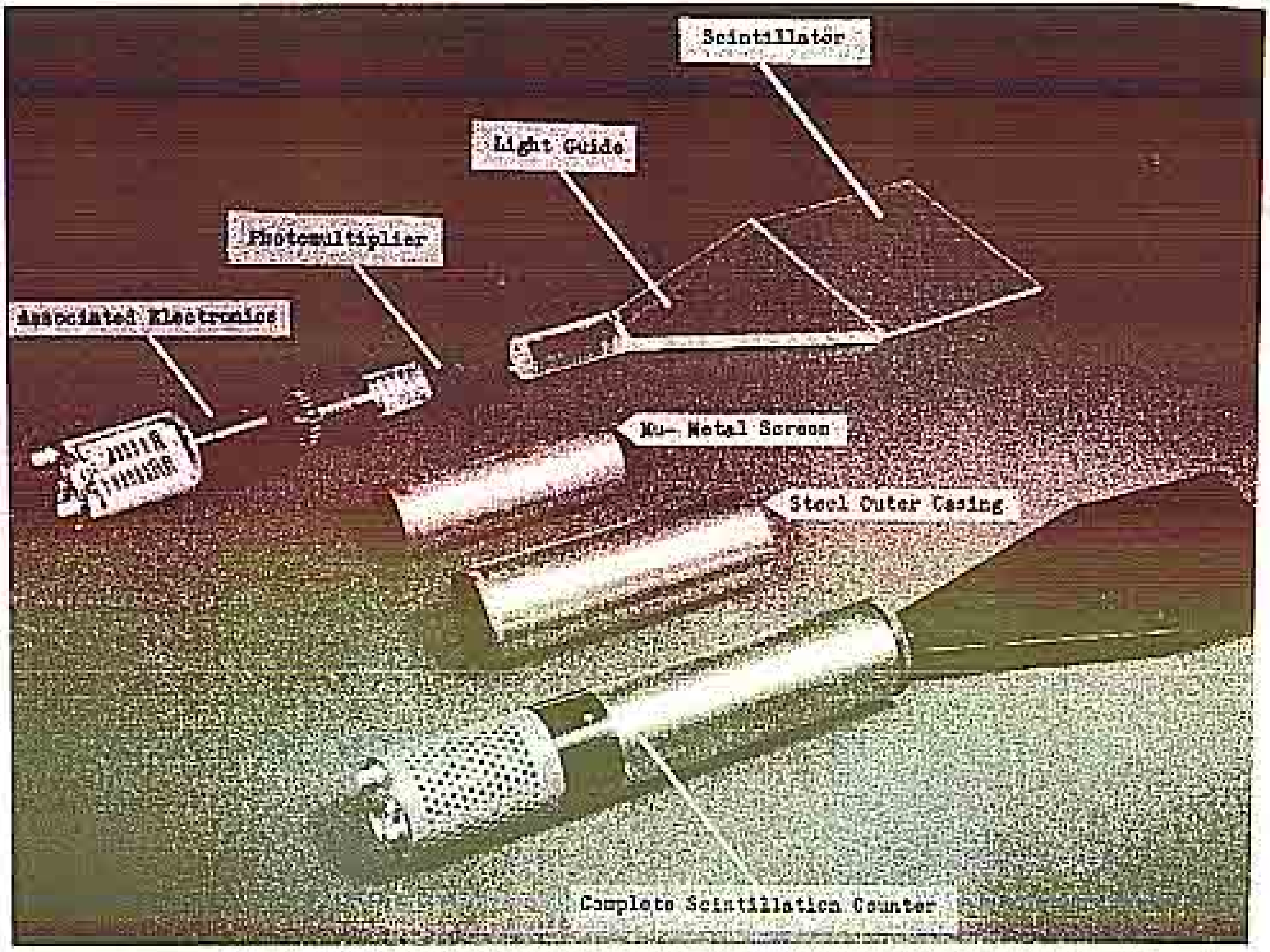
- inorganic crystal such as NaI or CsI, usually doped with thallium (T_l)
  - "activation center" + freed electron $\longrightarrow$ excited state $\longrightarrow$ photon
  - light signal has decay time of about 1 microsecond
  - dense materials – CsI often used in calorimeters
  - used as gamma-ray detectors for same reason
- organic materials with aromatic rings, e.g. anthracene, naphthalene
  - fast charged particle excites molecules $\longrightarrow$ UV light
  - light signal has decay time of about 10 nanoseconds
  - dye molecules (wavelength shifters) absorb UV light, re-emit blue light
- organic molecules added to plastics, e.g. polystyrene
  - light signal has decay time of about 1 – 5 nanoseconds
  - often used in high-energy physics when precise signal time needed
  - also useful as fast neutron detector due to high hydrogen content

A Scintillation Counter: NaI(Tl) Crystal and Photomultiplier



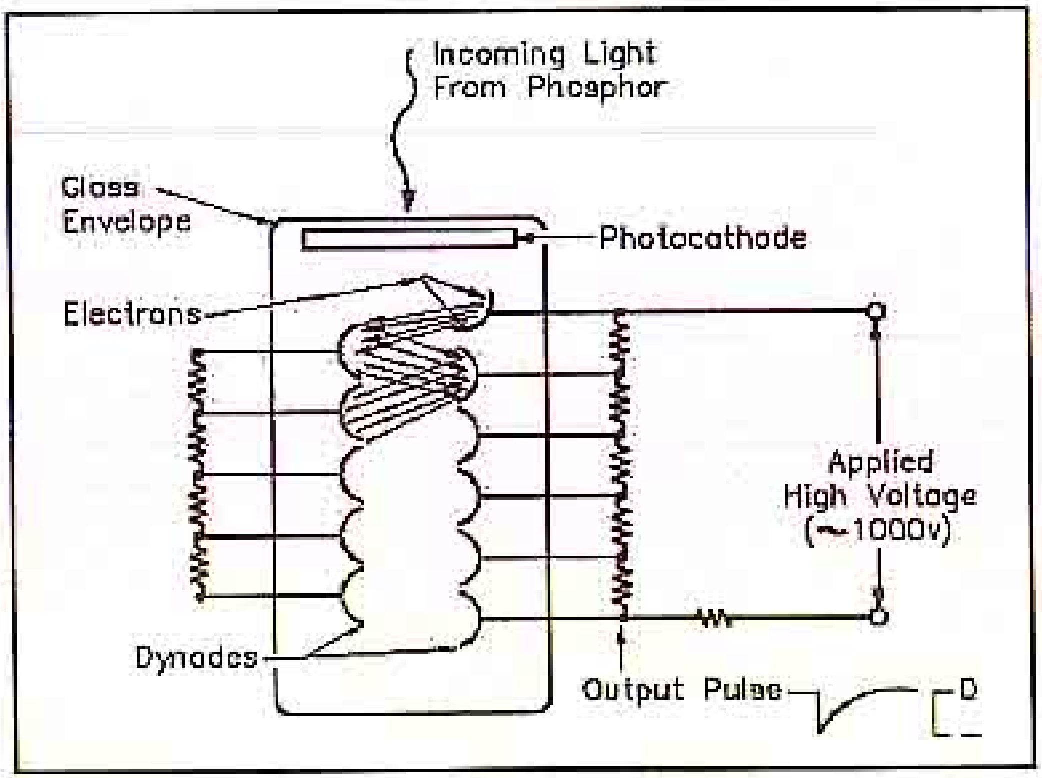
e.g. to detect gamma-rays in a nuclear physics experiment

Plastic Scintillator, Light-Guide, and Photomultiplier



- light reaches photomultiplier by series of "internal reflections"
- light-guide allows use of large area of scintillator

Photomultiplier Tube



- incoming photon kicks electron out of photocathode
- electron accelerated through voltage to dynode → more electrons
- repeat process for e.g. 12 dynodes: amplification at each stage

More Interactions of Particles with Matter

Recall: charged particles moving fast through matter lose energy by ionizing or exciting atoms or molecules

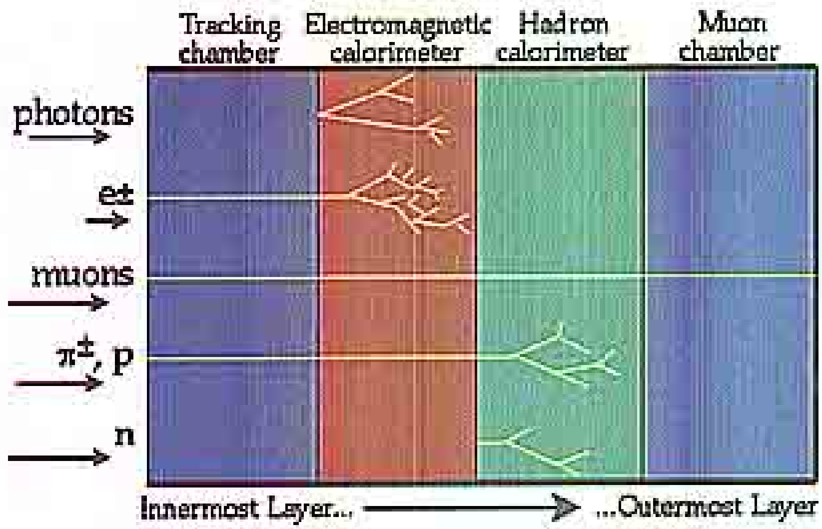
- this is what muons do
- but some particles do other things as well!

Hadrons such as pions (π^+, π^-) and protons (p) have strong interaction with atomic nuclei, and lose some energy in nuclear reactions producing more particles → "hadronic shower"

Electrons are so light they are easily buffetted around by the electromagnetic fields of atomic nuclei, and radiate photons which interact to produce electron-positron pairs → "electromagnetic shower"

The reason that detectors are divided into many components is that each component tests for a special set of particle properties. These components are stacked so that all particles will go through the different layers sequentially. A particle will not be evident until it either interacts with the detector in a measurable fashion, or decays into detectable particles.

The interaction of various particles with the different components of a detector:



Neutrinos are not shown on this chart because they rarely interact with matter, and can only be detected by missing matter and energy. Just so you know, the pion (π) is a charged meson.

A few important things to note:

- Charged particles, like electrons and protons, are detected both in the tracking chamber and the electromagnetic calorimeter.
- Neutral particles, like neutrons and photons, are not detectable in the tracking chamber; they are only evident when they interact with the detector. Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadron calorimeter.
- Each particle type has its own "signature" in the detector. For example, if a physicist detects a particle **only** in the electromagnetic calorimeter, then he is fairly certain that he observed a photon.

Charged Particles: Measuring Momentum and Charge

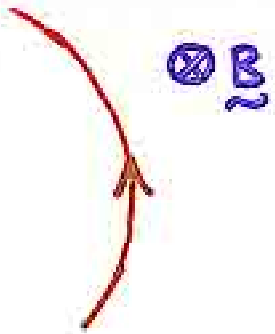
Measure curvature of particle's path in magnetic field

- more curved ⇒ lower momentum
- straighter path ⇒ higher momentum

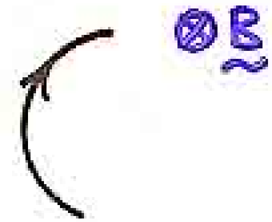
} radius of curvature ∝ momentum

- positively charged particles bend to one side
- negatively charged particles bend to other side

high momentum
positive charge

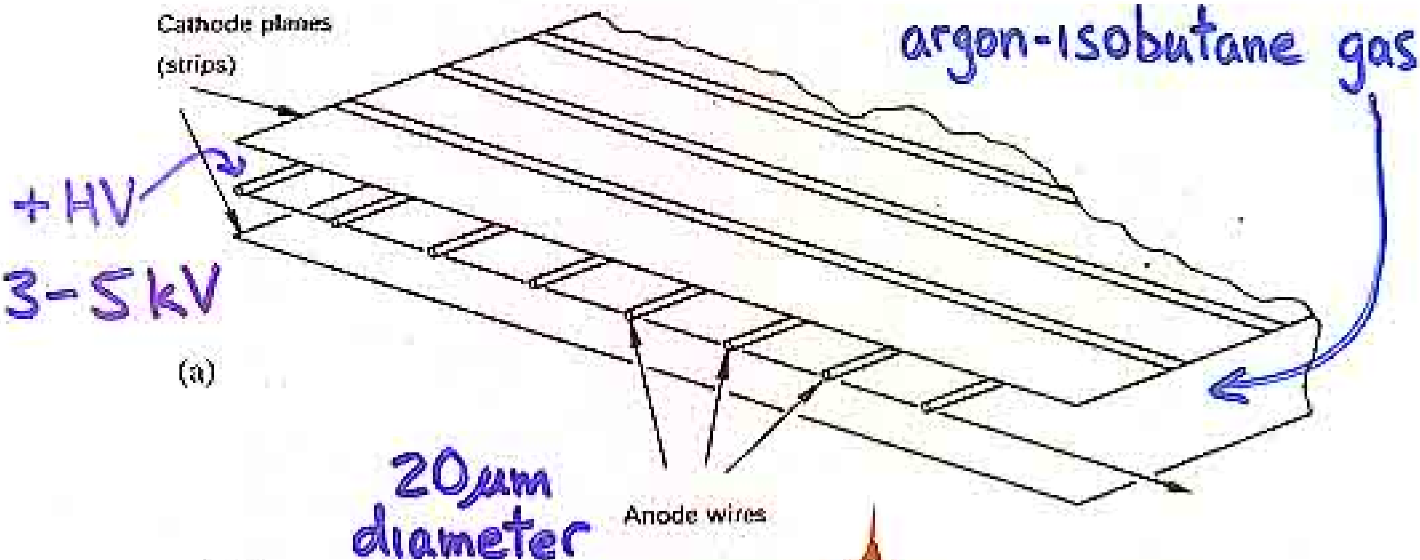


low momentum
negative charge



- want curvature as constant as possible ⇒ { want very little scattering / want very little energy loss }
- detect trail of ionization in gas (e.g. drift chamber) or in well-spaced <u>thin</u> sheets of silicon (e.g. silicon microstrip detector)
- these "tracking" detectors should have minimal material

Multi-Wire Proportional Chamber



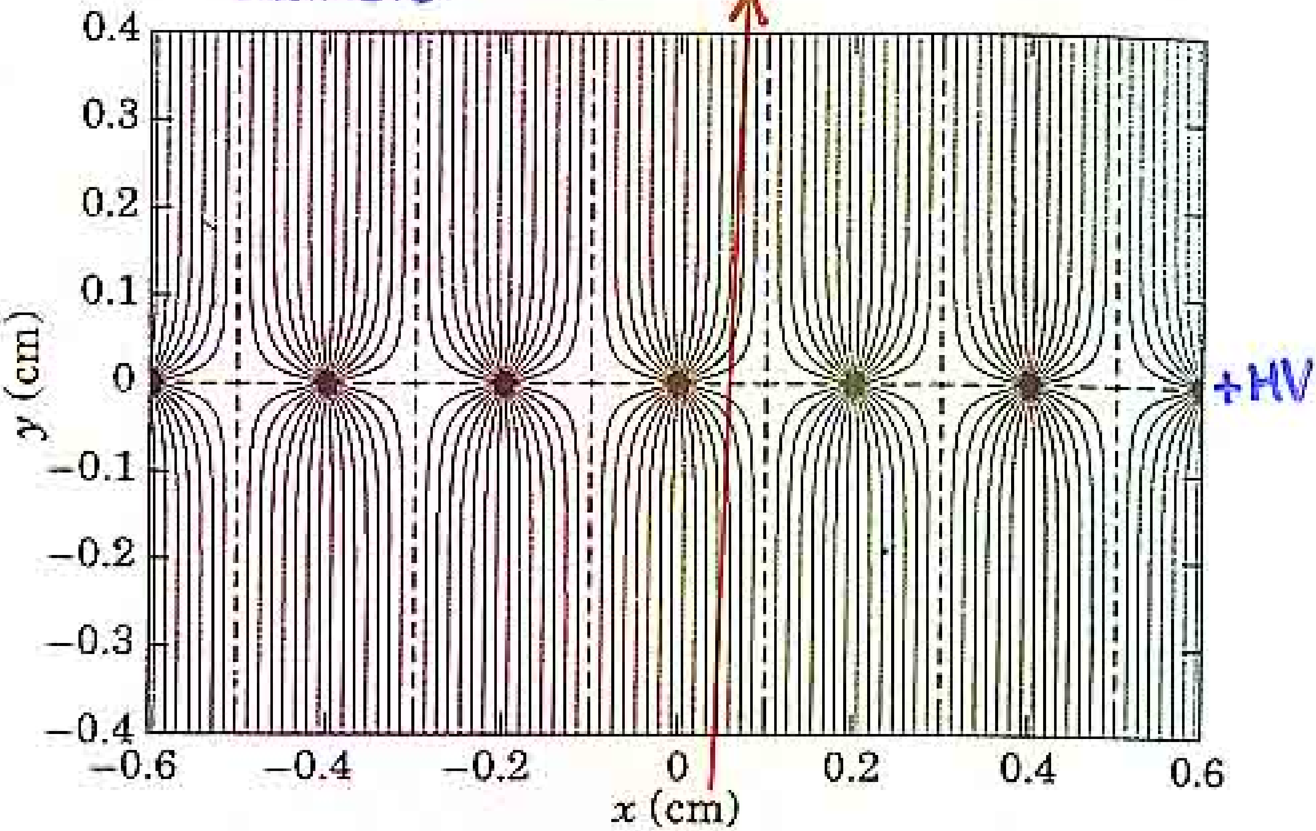
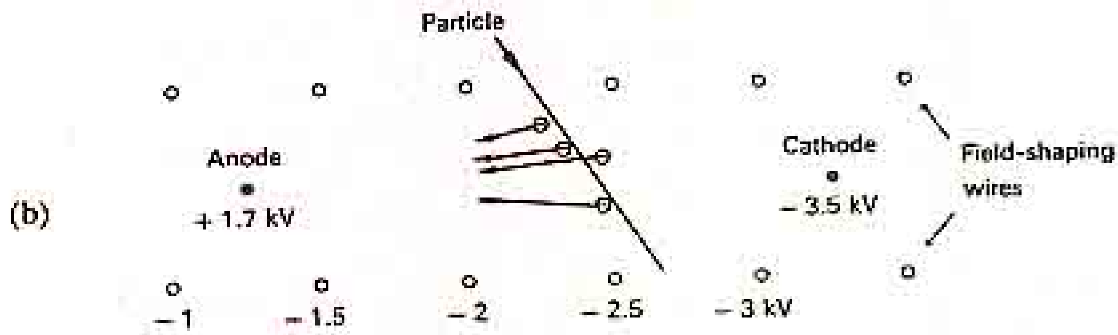


Figure 24.3: Electric field lines in a (MWPC) with an anode pitch of 2 mm as calculated with GARFIELD program [49].

- ionization: electrons → nearest anode wire
- intense electric field near wire → more ionization and therefore bigger signal
- positive ions → cathode planes or strips

Drift Chamber

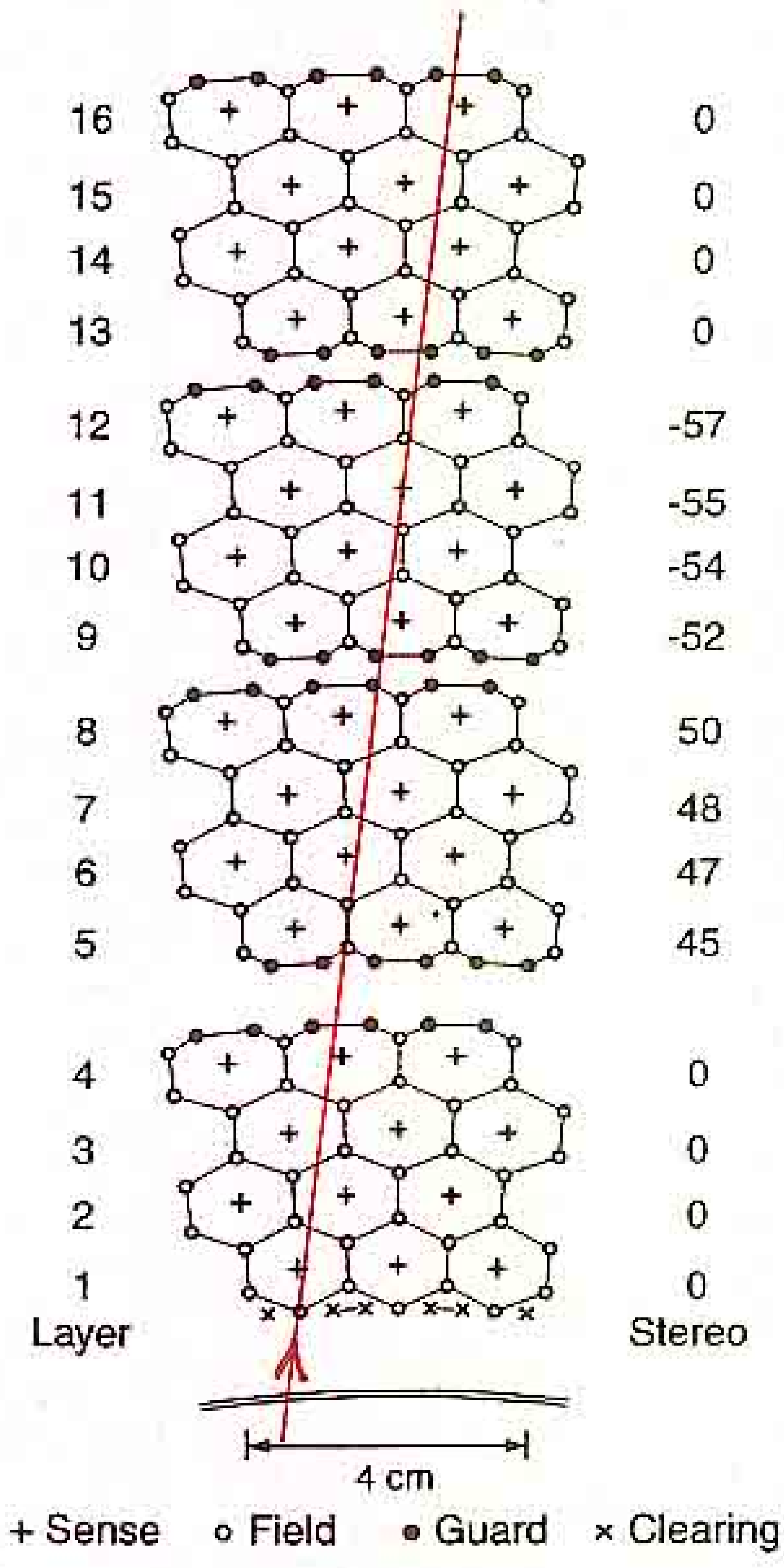
- shape electric field so electrons drift to anode wires at almost constant speed
- drift time → distance of track from wire



Advantages over multiwire proportional chamber:

- better position measurement precision
- can space anode wires further apart
  - cheaper – fewer electronics channels
  - better suited for bigger chambers

Inner Part of BABAR Drift Chamber



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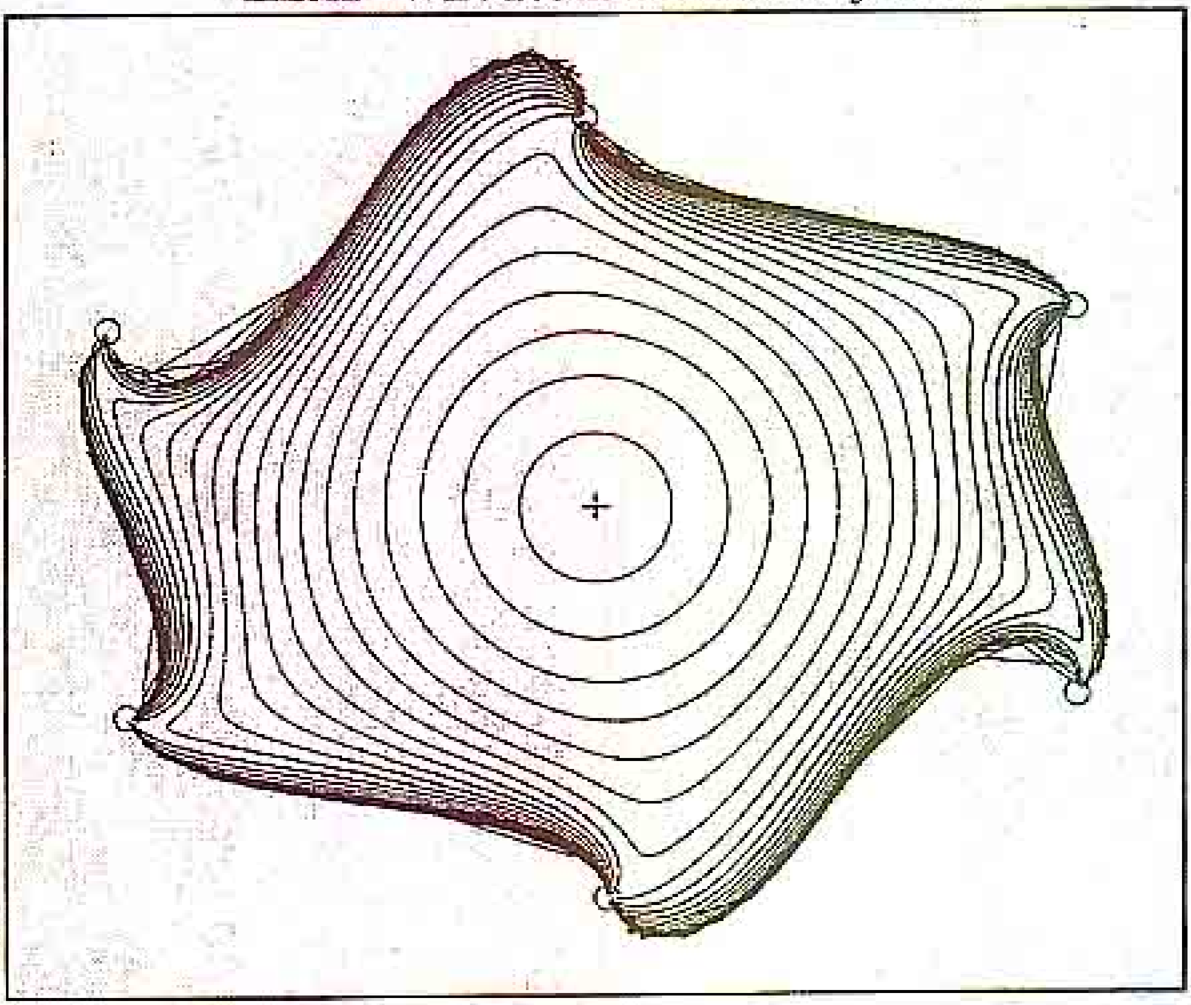
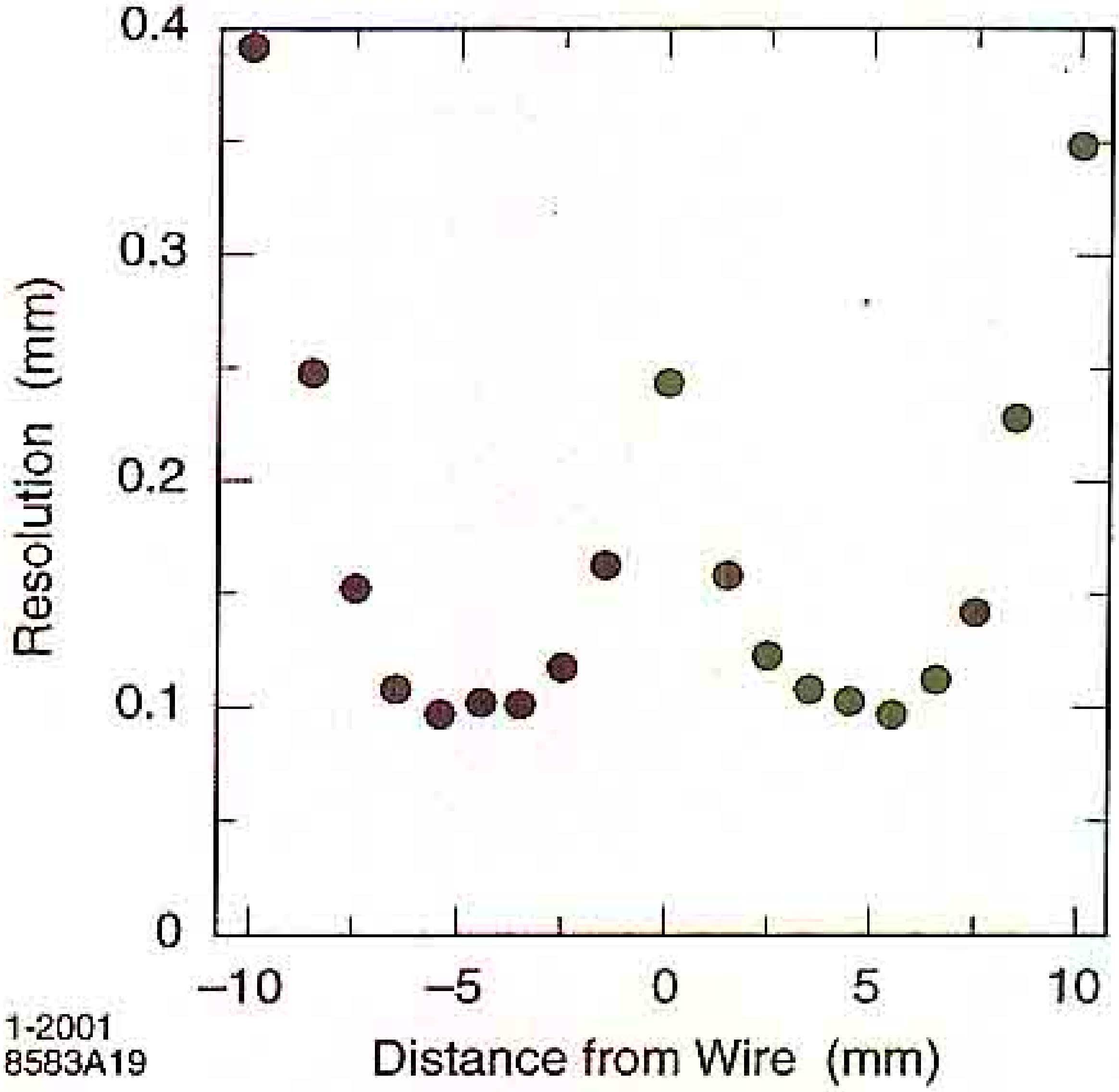
BABAR Drift Chamber "Cell"

HEX2 - Wire 168 Isocrones every 50 ns



- contours of constant drift time with 50ns spacing
- amplification in high-field region near wire, as in MWPC

BABAR Drift Chamber



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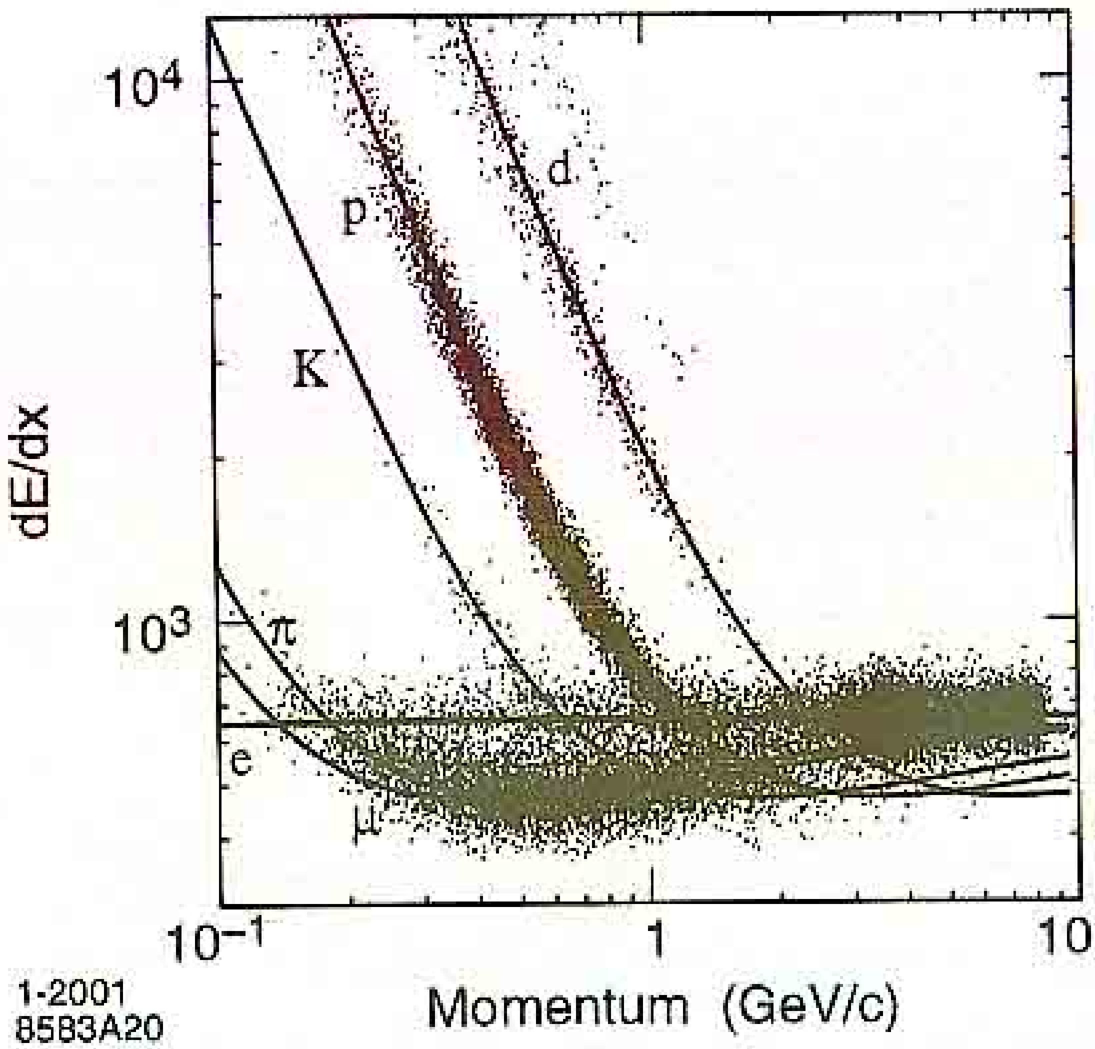
Particle identification via {energy loss / signal size} in drift chamber



- for fixed low momentum, heavier slower particles ionize more
  → bigger "dE/dx" and bigger signal

Physics Background (5)

- **The (Famous) Bethe-Bloch Eq$^{\underline{n}}$**
  - ***Describes energy loss for heavy charged, moderately relativistic particles***

Max. E_k that can be imparted to a single electron

Density effect correction

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

Mean rate of energy loss

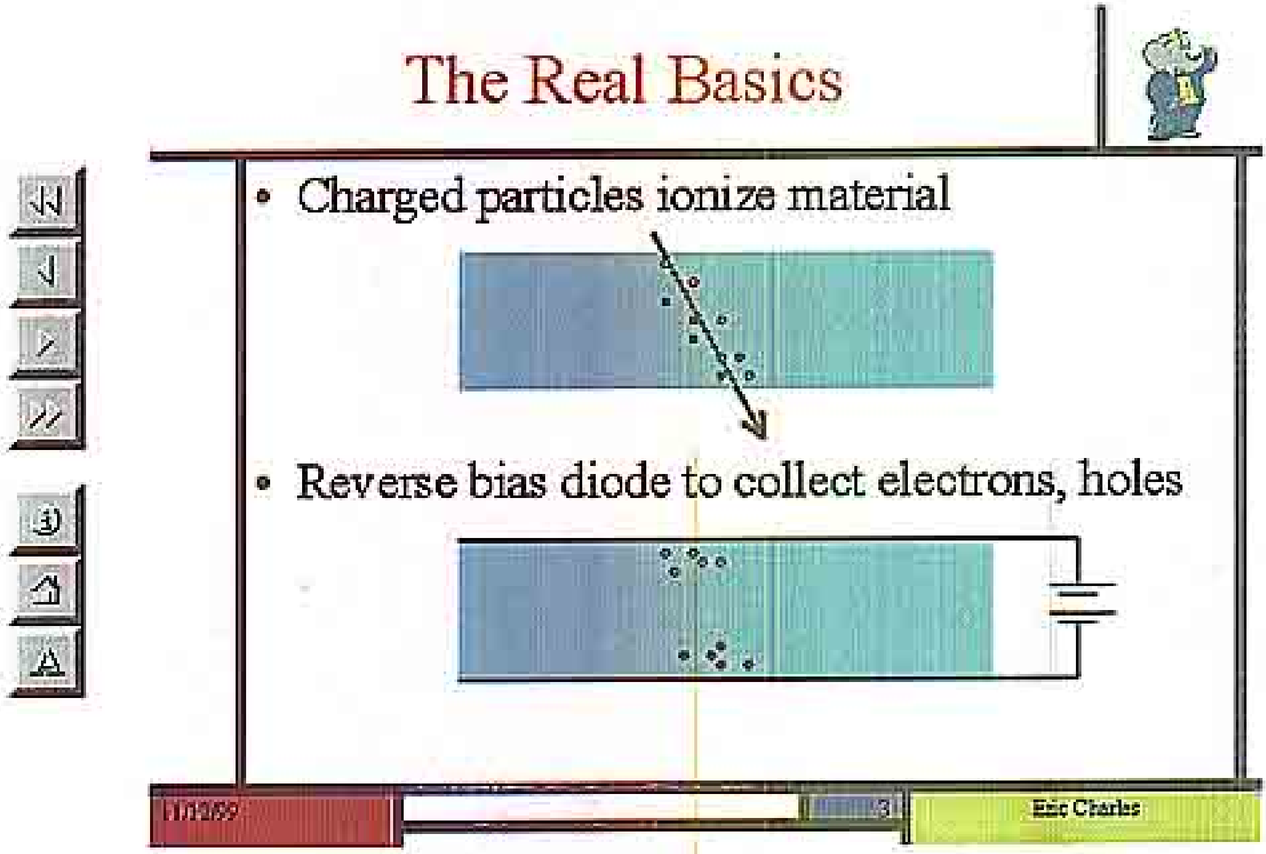
Mean excitation energy

$I \approx 10Z$ eV

- **Basically a function of β.**

$\beta = v/c$

Silicon Microstrip Detector



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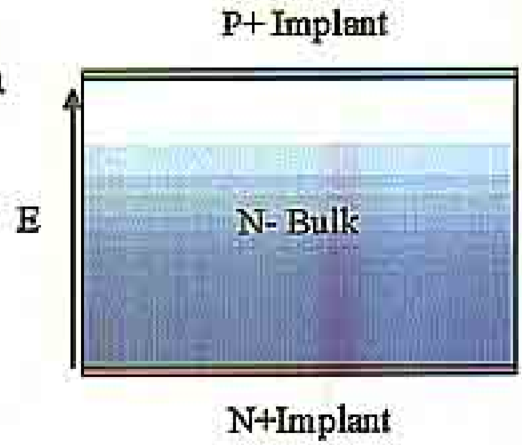
- Si wafers about 250μm (¼ mm) thick
- electron-hole pair creation needs 3.6eV
  - * ionization in gas needs 20-40eV
- closely spaced strips on surface give very precise position measurement
- use as detector closest to beam-pipe to get best measurement of decay vertex of particles such as B, τ

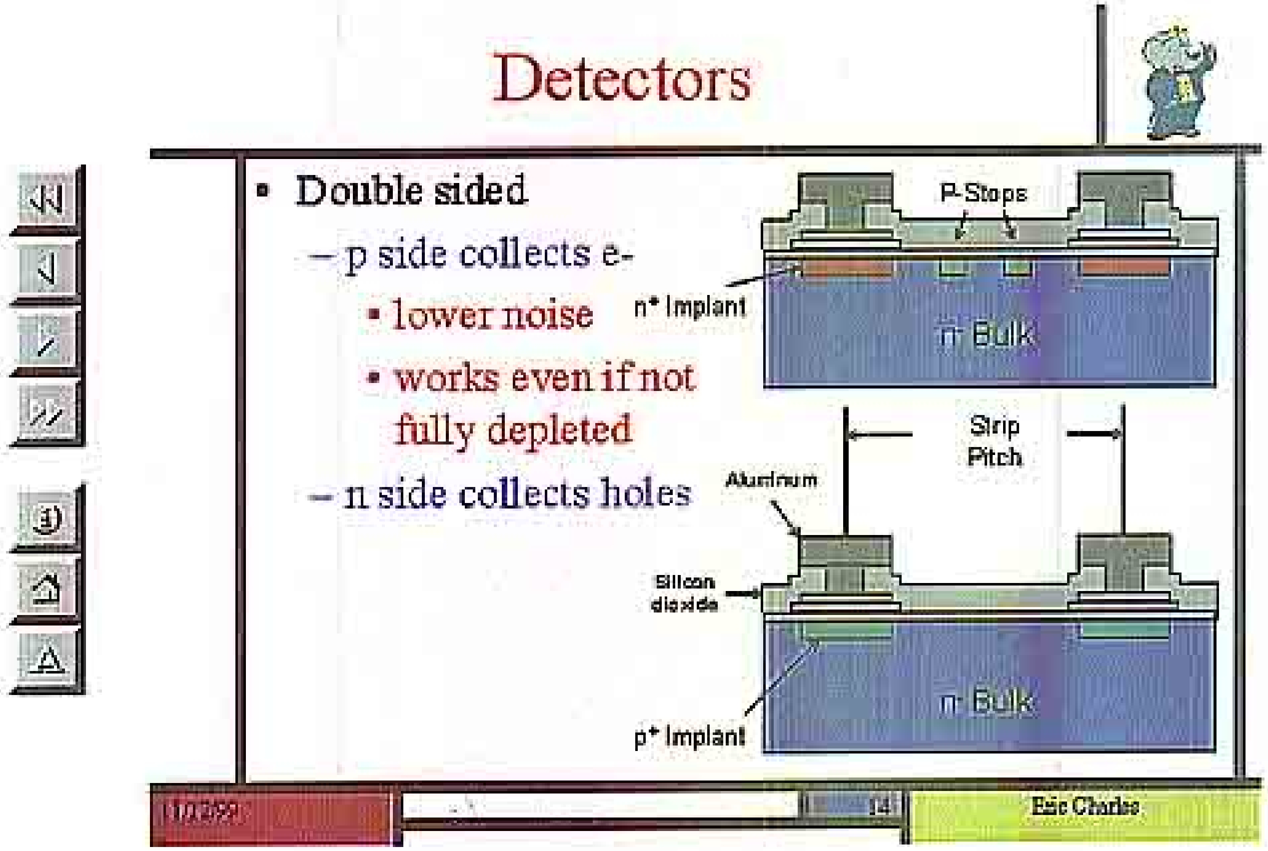
Silicon Microstrip Detector

Doping And Depletion

- Depletion on N- Bulk starts at P side.
- Drift is only possible in depleted region.
  - Must be fully depleted
    - $V_{dep} \sim 20\text{-}30V$



Silicon Microstrip Detector



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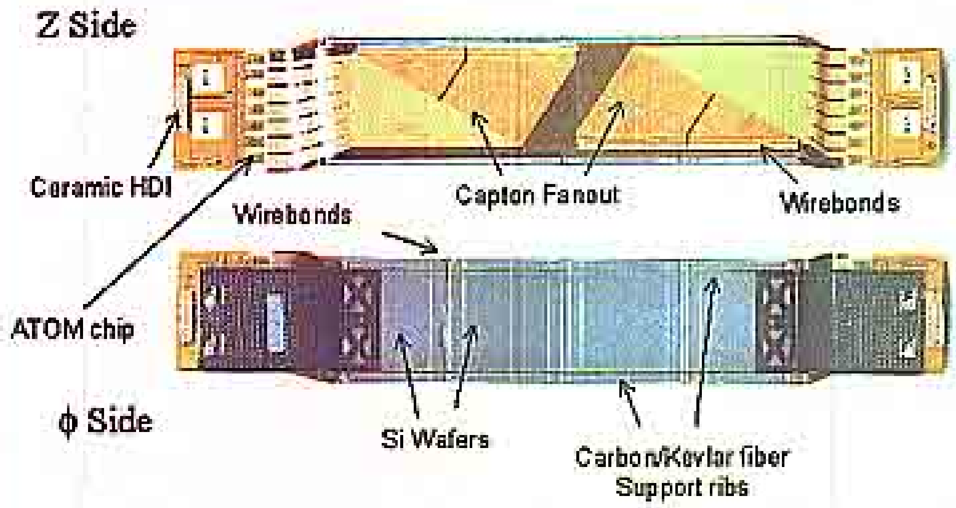
- strips typically ≈ 20 μm apart
- position resolution ≈ 10 μm

Silicon Microstrip Detector

Modules



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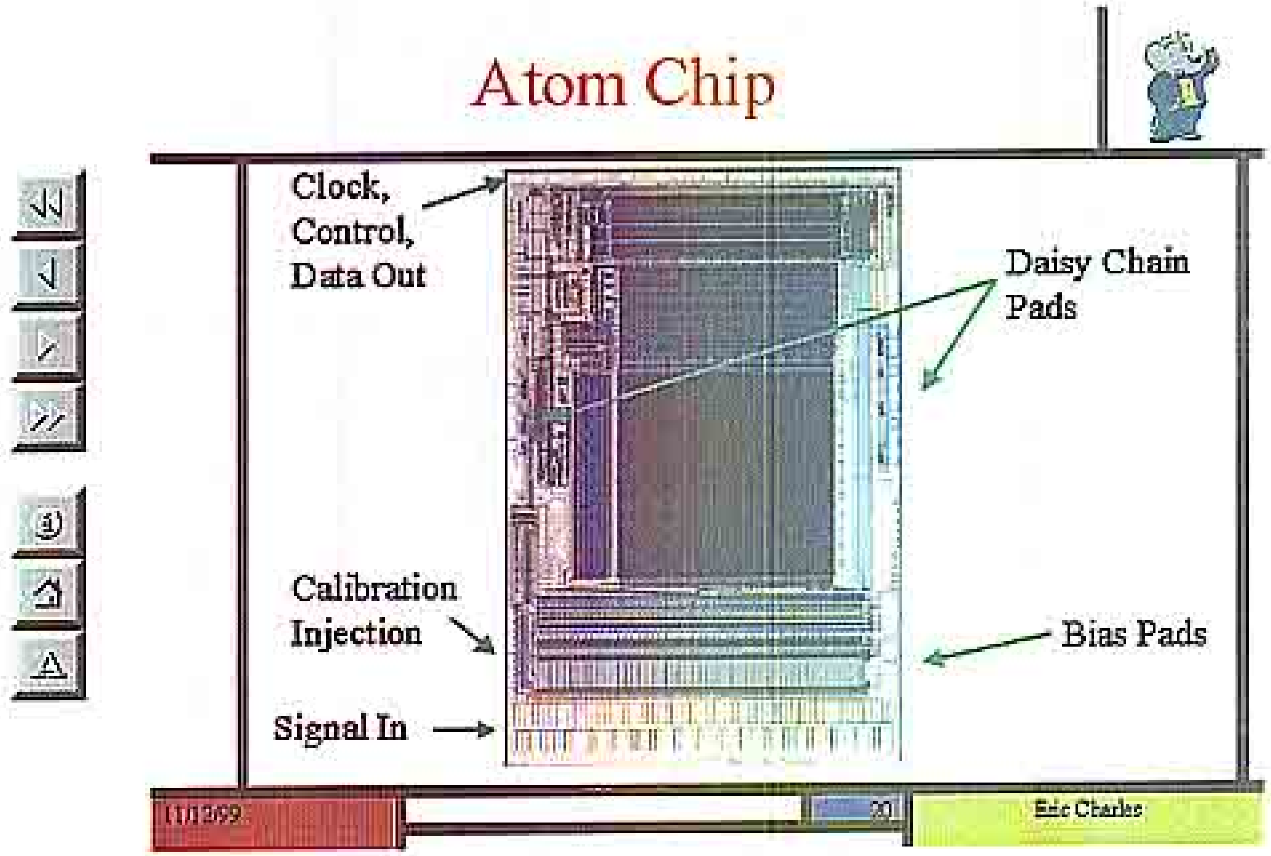
Silicon Microstrip Detector



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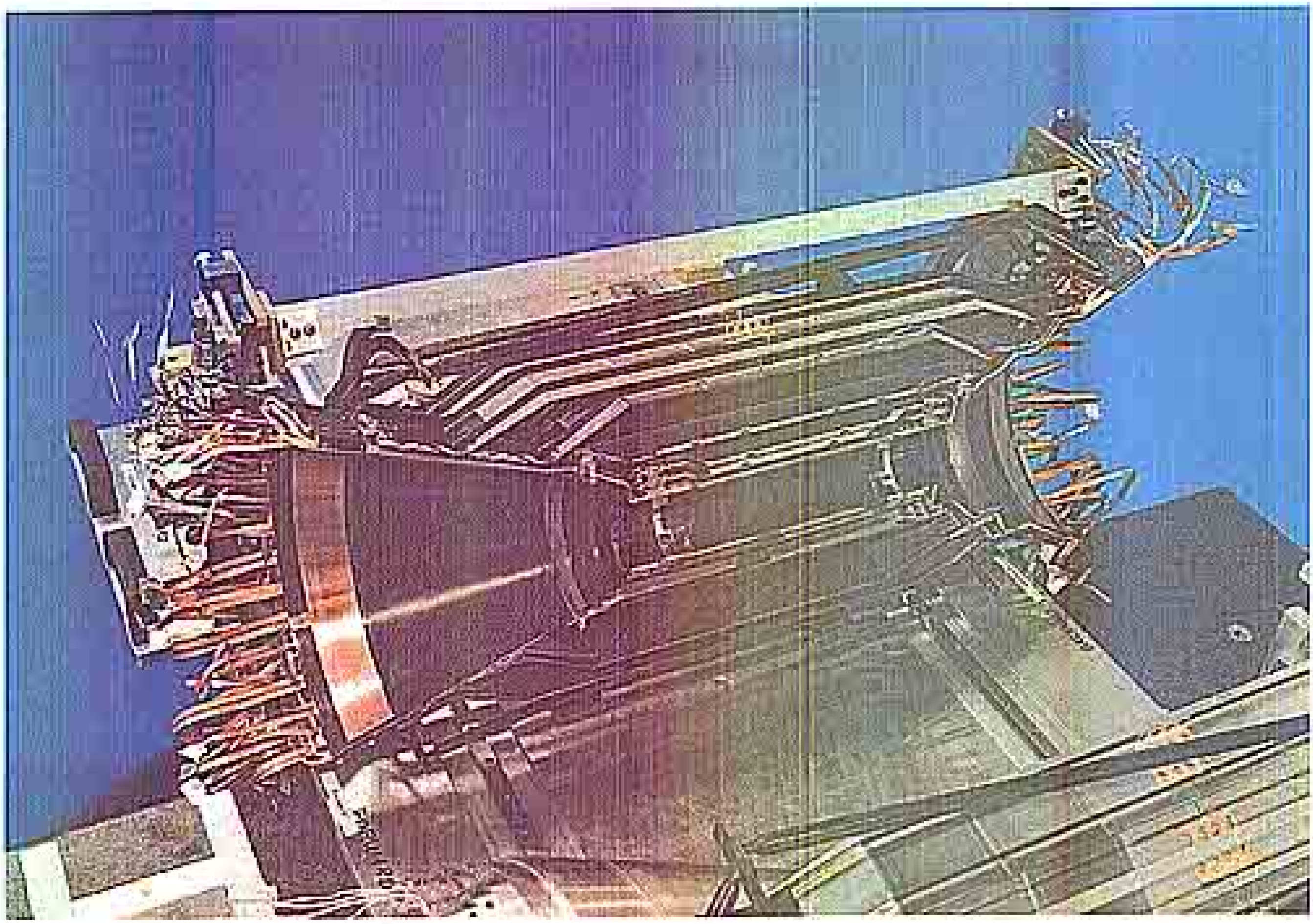
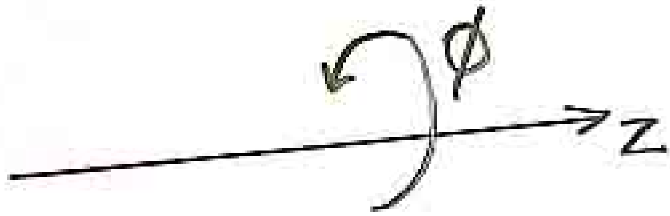
Silicon Microstrip Detector

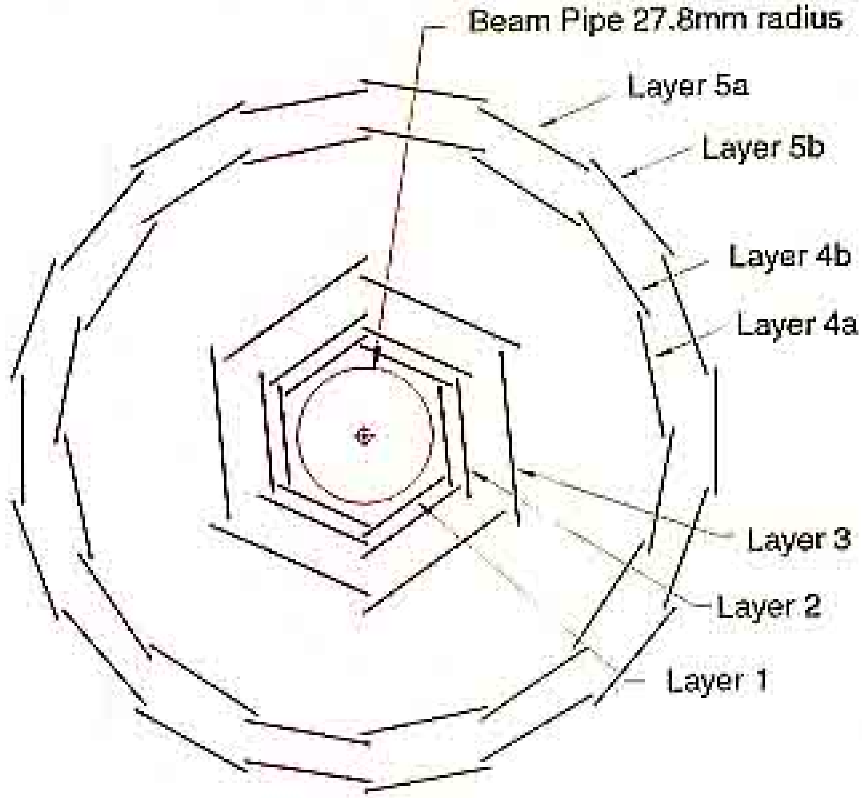


BABAR

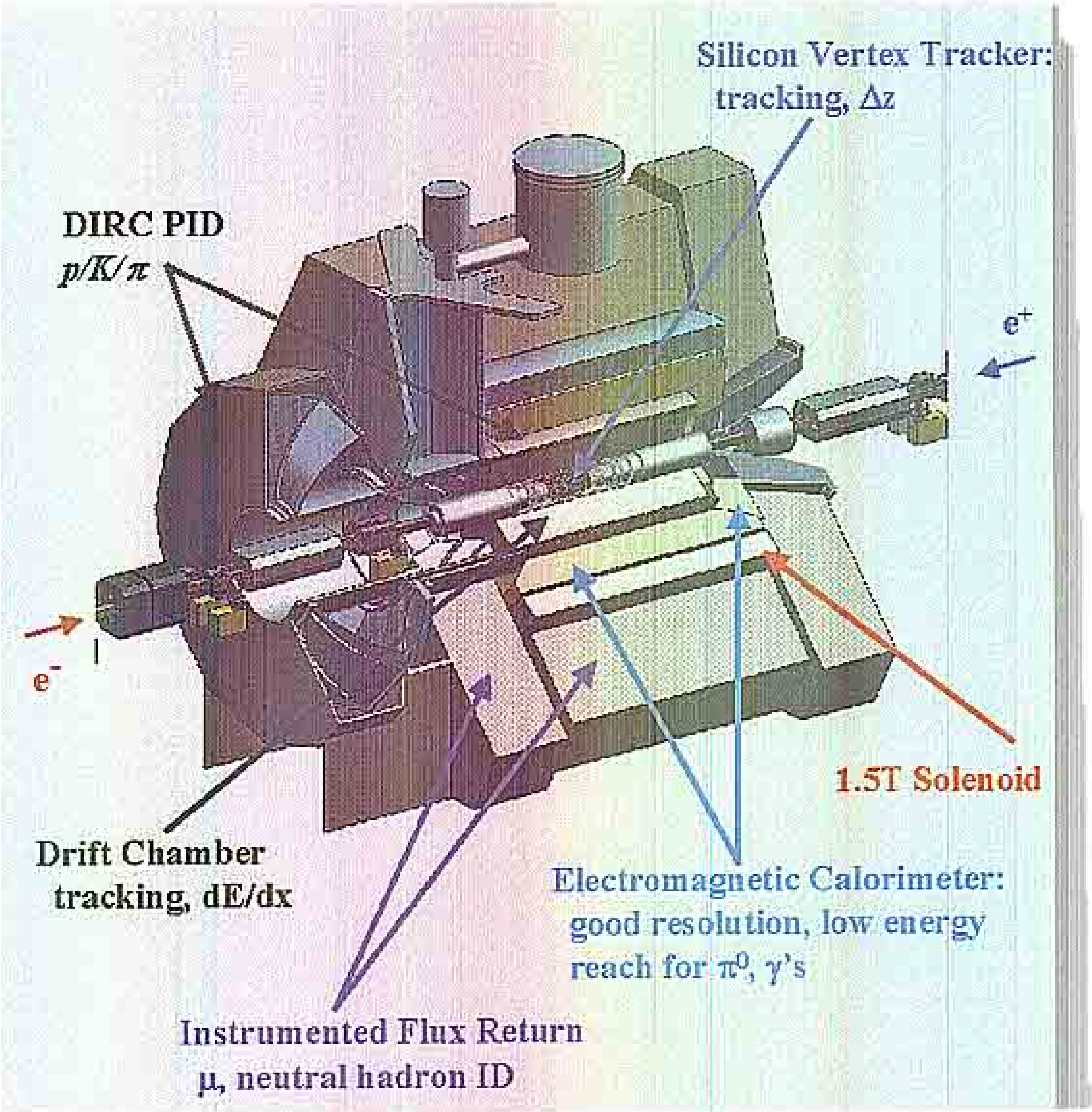
- 5 layers each measuring z and ϕ



BABAR Silicon Microstrip Detector



The Dirc for BaBar



Cherenkov Radiation: Definition

Consider:

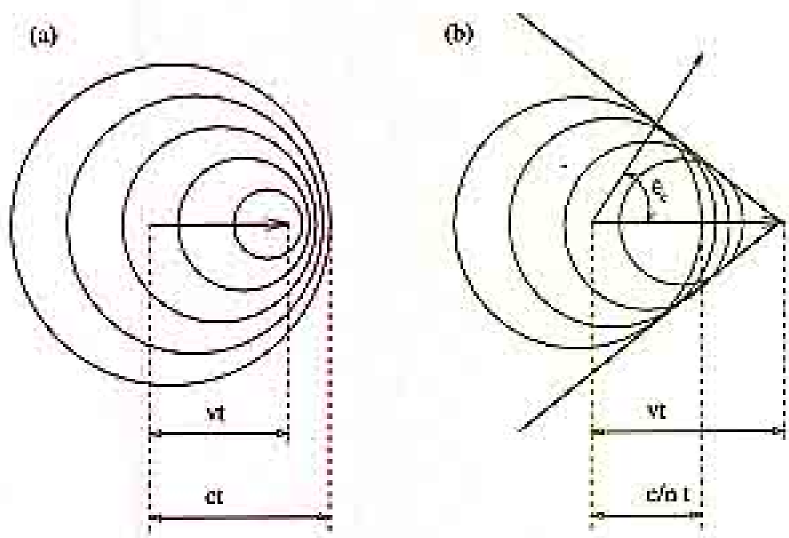
- a *charged* particle of speed $v = \beta c$...
- ...moving in a medium of index n. ← refractive index

- Threshold Condition: $\beta = \frac{1}{n}$:

  If $\beta < \frac{1}{n}$ (case (a)), no or synch. emission.

  If $\beta > \frac{1}{n}$ (case (b)), coherent emission of light:

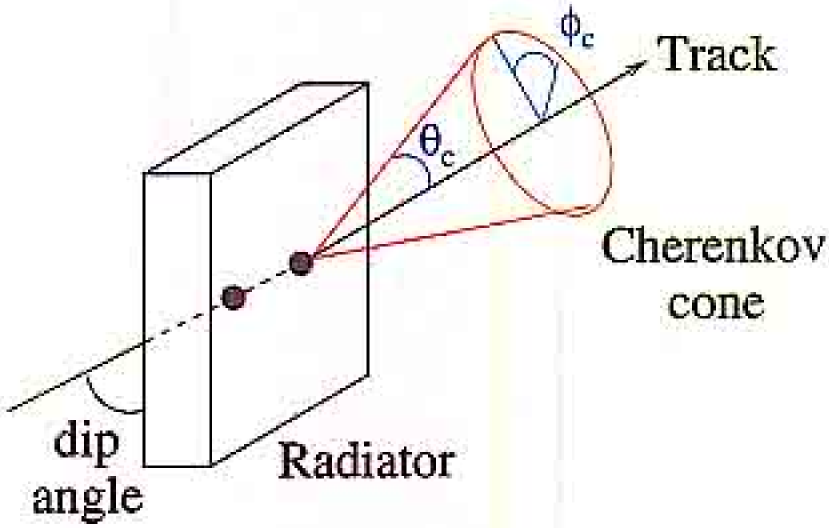
The Cherenkov effect



⇒ Think of the supersonic "*bang*" of a plane at Mach 1...

- cone angle → speed if $\beta = v/c > 1/n$
- combine with momentum to get mass (e.g π or K)

Cherenkov Radiation: Properties



1. Threshold condition:

$$\boxed{\beta > \frac{1}{n}}$$

2. Angular distribution: (ϕ_c uniform)

$$\boxed{\cos(\theta_c) = \frac{1}{\beta \cdot n(\lambda)}}$$

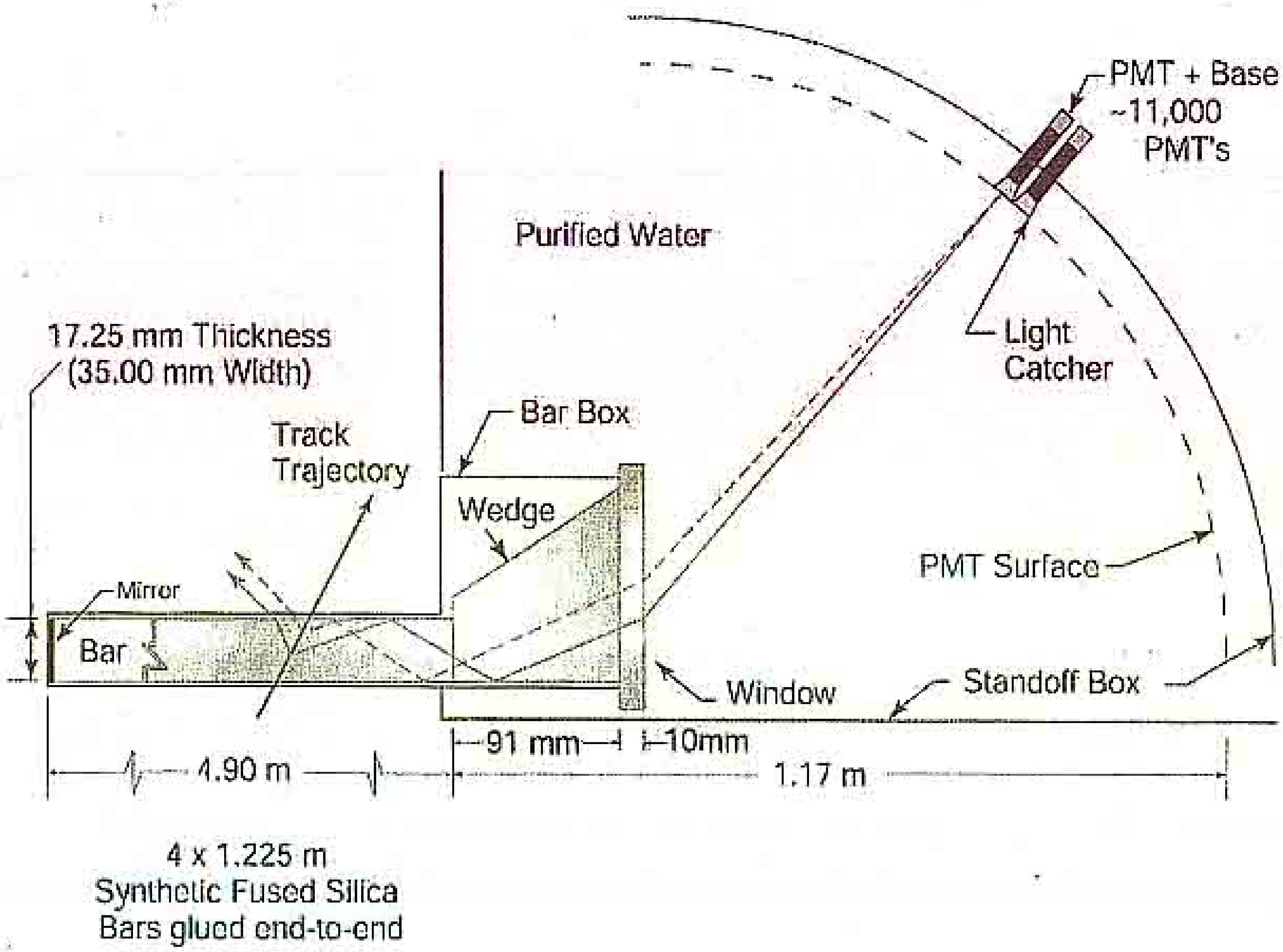
3. Franck-Tamm relation:

$$\boxed{\frac{\mathrm{d}^2 N_{ph}}{\mathrm{d}x\ \mathrm{d}\lambda} = \frac{2\pi\alpha Z^2}{\lambda^2}\sin^2(\theta_c)}$$

- Spectrum is *not* monochromatic!
  $\Rightarrow$ smearing of θ_c: chromatism.

- Number of generated photons $\propto \lambda^{-2}$
  $\Rightarrow$ photons generated preferentially in the U.V and visible.

DIRC (BABAR)


PMT + Base
~11,000
PMT's
Purified Water
Light
Catcher
17.25 mm Thickness
(35.00 mm Width)
Bar Box
Track
Trajectory
Wedge
PMT Surface
Mirror
Bar
Window
Standoff Box
91 mm
10mm
4.90 m
1.17 m
4 x 1.225 m
Synthetic Fused Silica
Bars glued end-to-end

DIRC

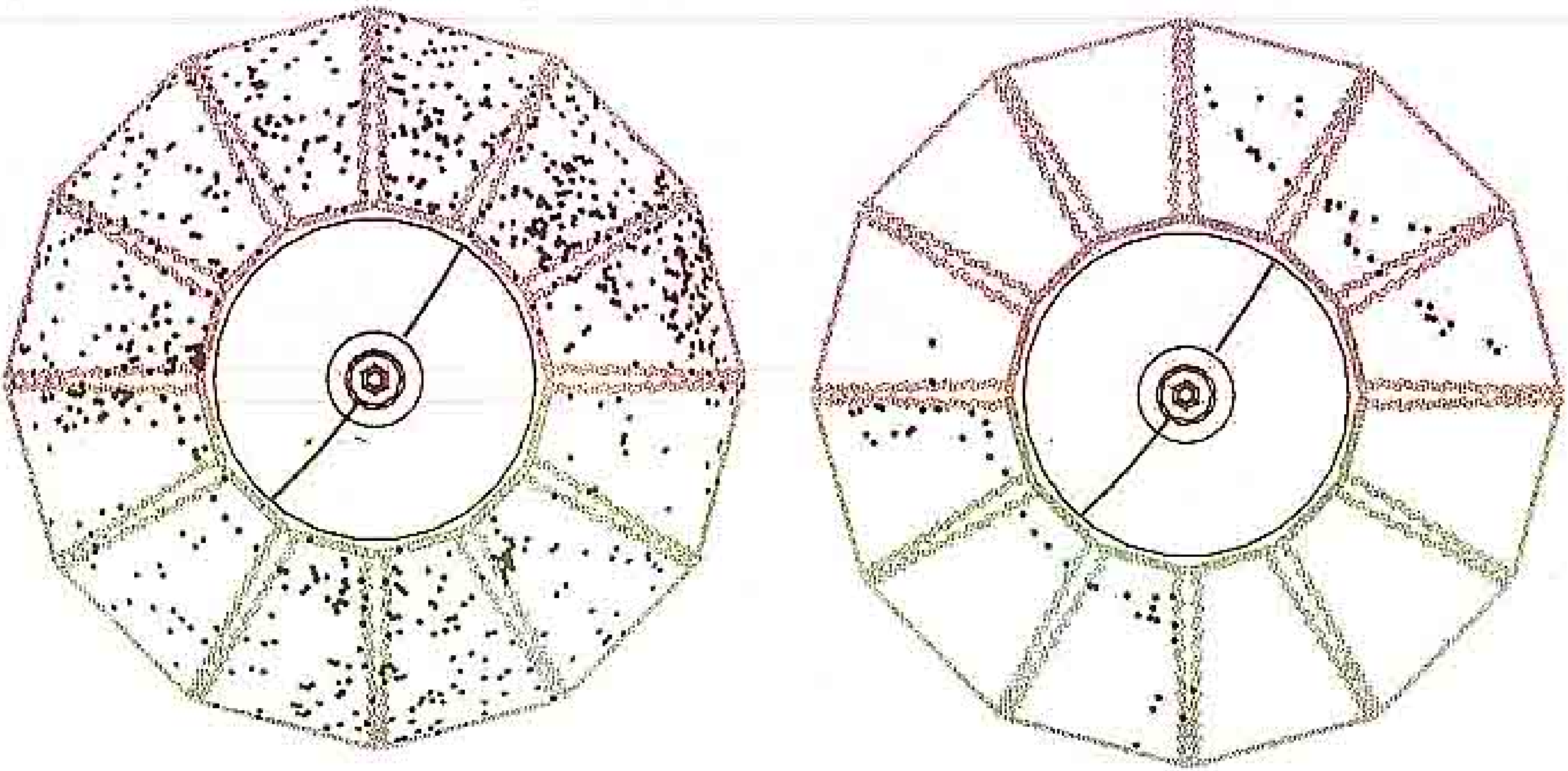


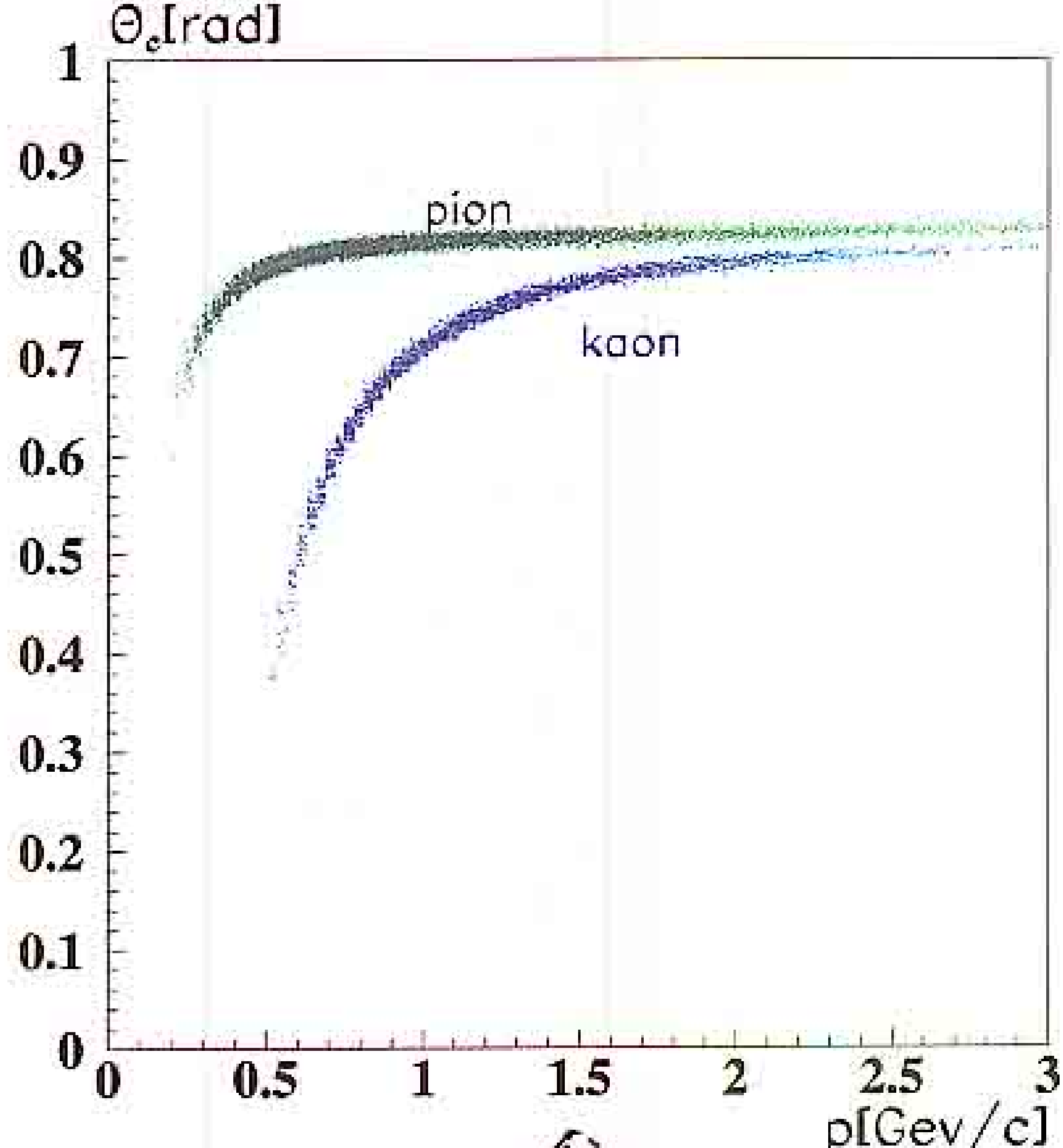
Fig. 54. Display of an $e^+e^- \to \mu^+\mu^-$ event reconstructed in BABAR with two different time cuts. On the left, all DIRC PMTs with signals within the ± 300 ns trigger window are shown. On the right, only those PMTs with signals within 8 ns of the expected Cherenkov photon arrival time are displayed.

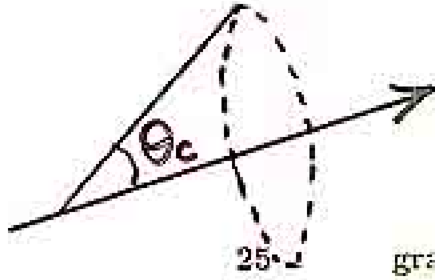
An Example: $K^* \to K^- \pi^+$

4. Dirc Selection:

$$\frac{|\theta_c^{meas} - \theta_c^{exp}(\pi)|}{\sigma_{\theta_c}} < 3 \text{ AND } \frac{|\theta_c^{meas} - \theta_c^{exp}(K)|}{\sigma_{\theta_c}} > 6 \quad \Rightarrow \pi$$

$$\frac{|\theta_c^{meas} - \theta_c^{exp}(\pi)|}{\sigma_{\theta_c}} > 6 \text{ AND } \frac{|\theta_c^{meas} - \theta_c^{exp}(K)|}{\sigma_{\theta_c}} < 3 \quad \Rightarrow \text{K}$$





Calorimeter

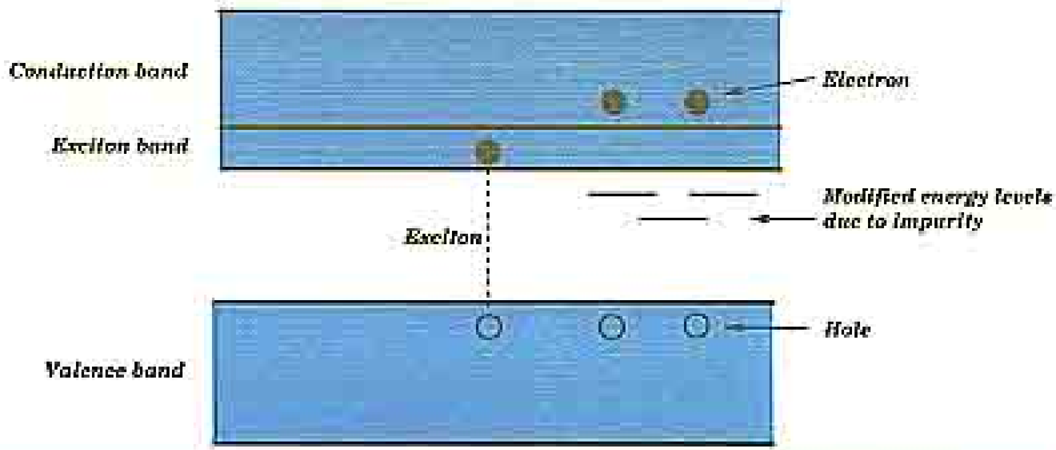
Introduction

- A device which measures the total energy deposited by a primary particle is called a calorimeter. (also measures position)
- The primary particles energy is degraded by interactions with the calorimeter material.
- A scintillating crystal calorimeter converts this energy into scintillation light.
- The scintillation light is converted to an electrical signal.
- Electrical signal proportional to primary energy. (of electrons, photons)
- Other experiments using crystal calorimeters- Crystal Ball-NaI(Tl),KTev-CsI, L3-BGO, CLEO, BELLE, BaBar-CsI(Tl) ,CMS -$PbWO_4$.

CsI(Tl) Scintillation and Radiation Damage Mechanisms

Scintillation Mechanism

- CsI(Tl) is an inorganic scintillator.
- Scintillation mechanism depends on energy states - determined by the structure of the crystal lattice.
- Well defined valence and conduction bands.
- Impurities, called activators (Thalium) added to modify energy levels - increase the probablility and λ of scintillation light.



Particle Interactions With Matter

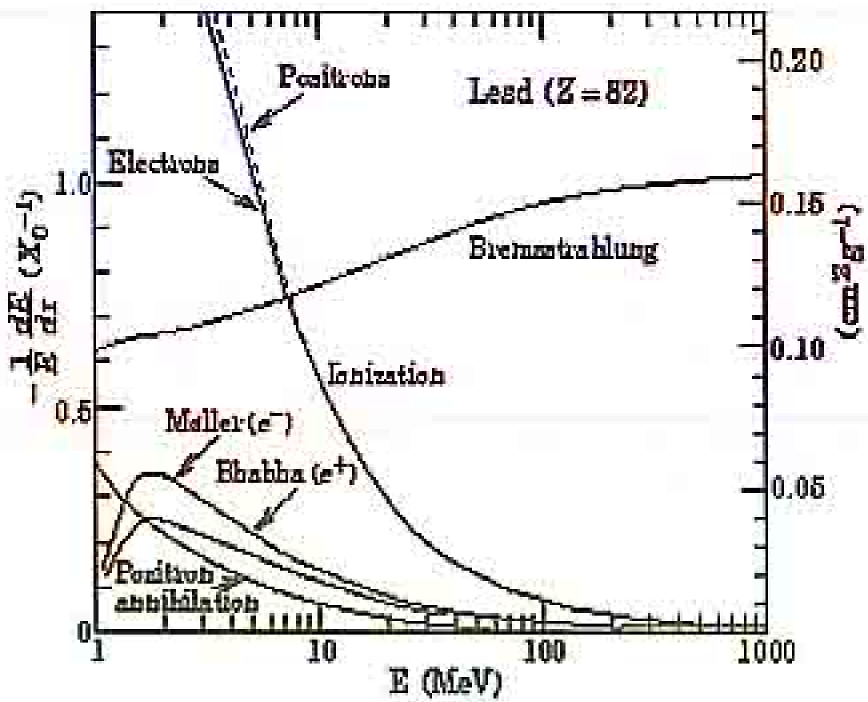
Electron/Positron Processes

- At low energies, ionisation dominates.
- At high energies, bremsstrahlung dominates.

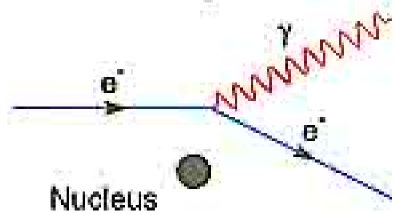
- Radiation length,

$$X_0 = \frac{716.4 g cm^{-2} A}{Z(Z+1)\ln(287/(\sqrt{Z}))}$$

Mean distance over which all but 1/e of energy is lost due to bremsstrahlung.



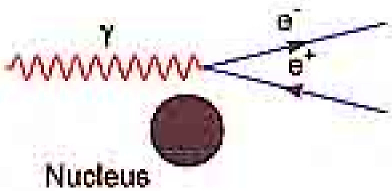
Bremsstrahlung



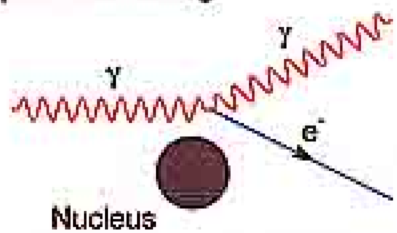
$$\left|\frac{dE}{dx}\right| \cong \frac{E}{X_0}$$

Photon Processes

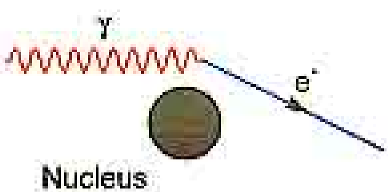
Pair Production

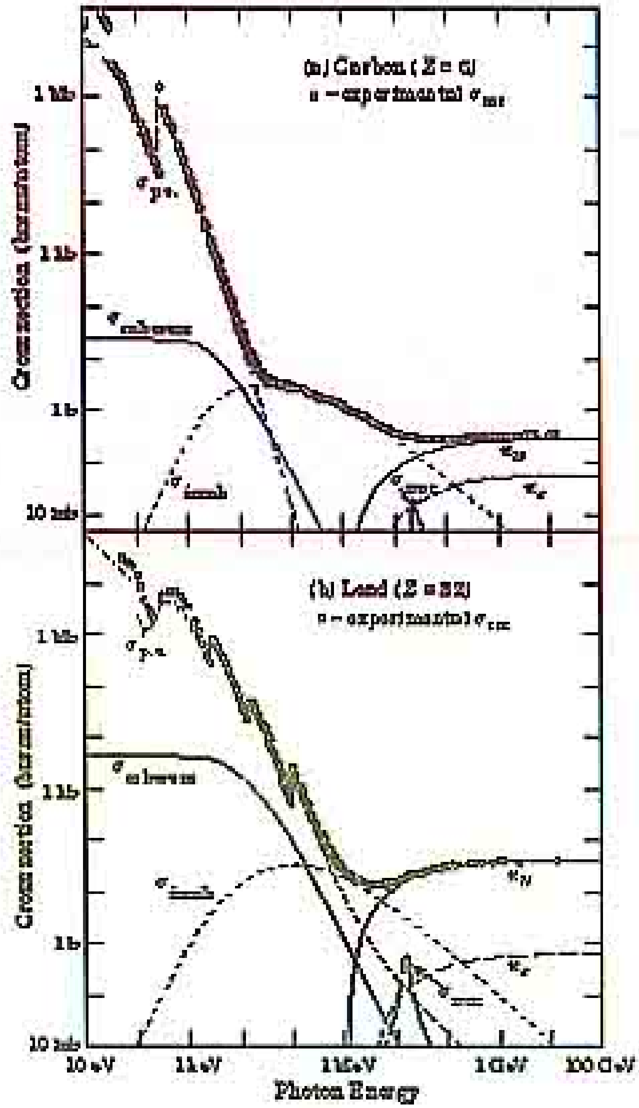


Compton Scattering



Photoelectric effect





Electromagnetic showers

* When a photon/electron/positron enters a crystal an electromagnetic shower is initiated.

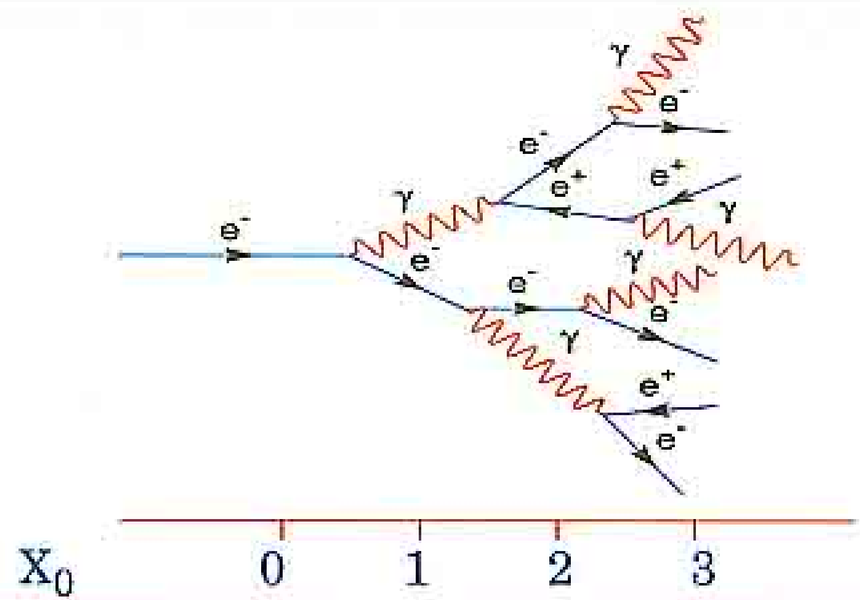
* A cascade of secondary photons, electrons and positrons produced by the particle interactions described previously.

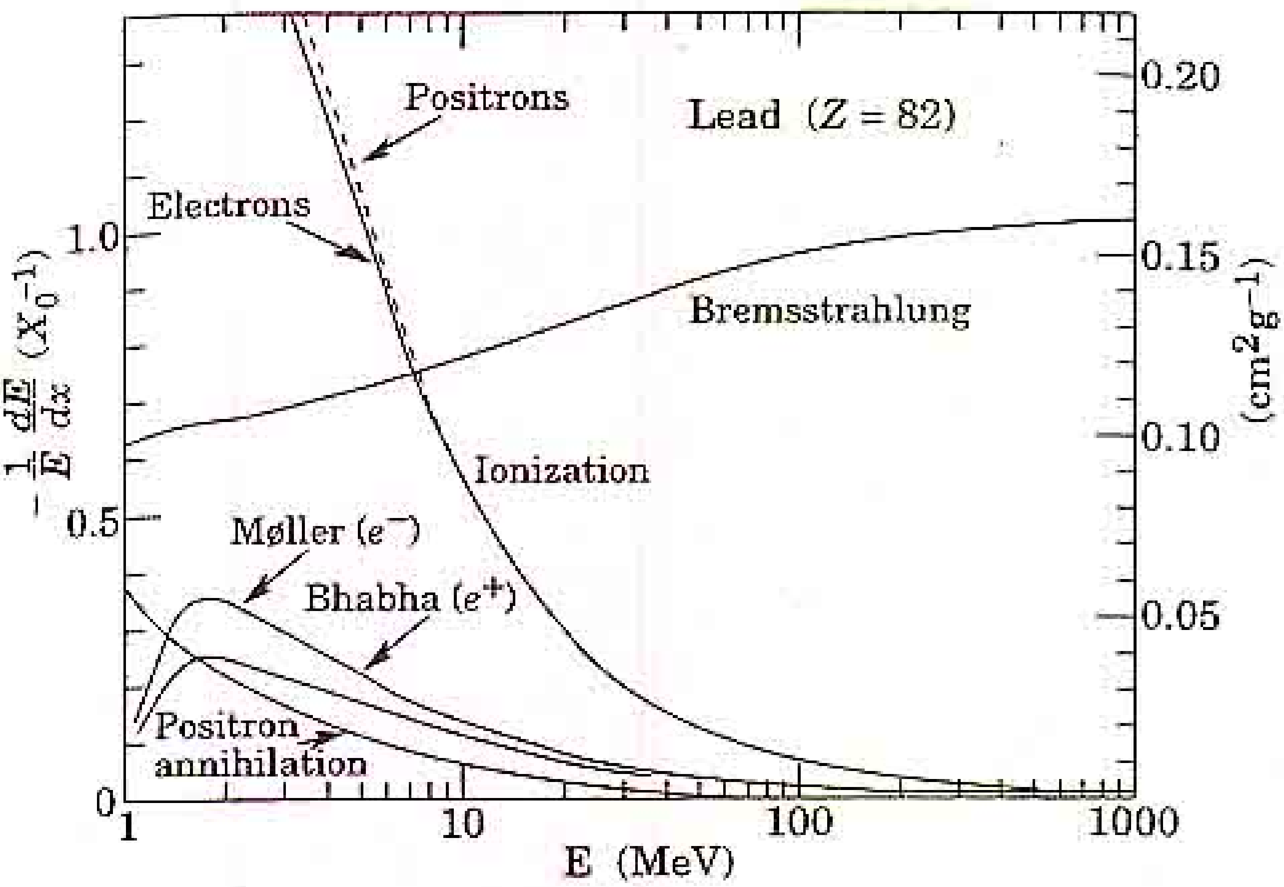
* Average shower properties described by simple model.

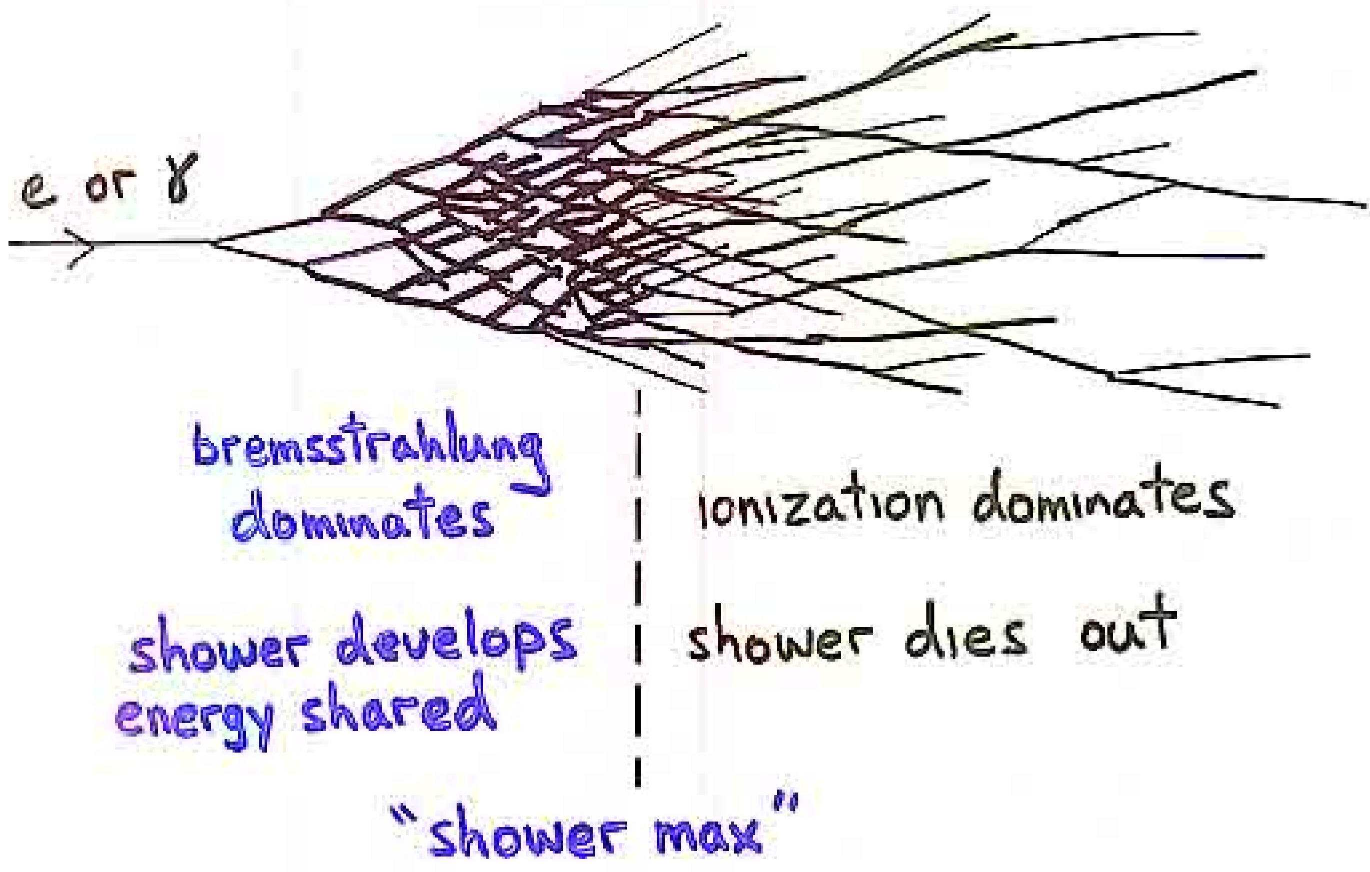
* Define the scale variables:

$$t = \frac{x}{X_0}$$

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




Positrons
Lead (Z = 82)
Electrons
Bremsstrahlung
Ionization
Møller (e^-)
Bhabha (e^+)
Positron
annihilation
$-\frac{1}{E}\frac{dE}{dx}$ (X_0^{-1})
(cm^2g^{-1})
E (MeV)
0
0.5
1.0
0.05
0.10
0.15
0.20
1
10
100
1000

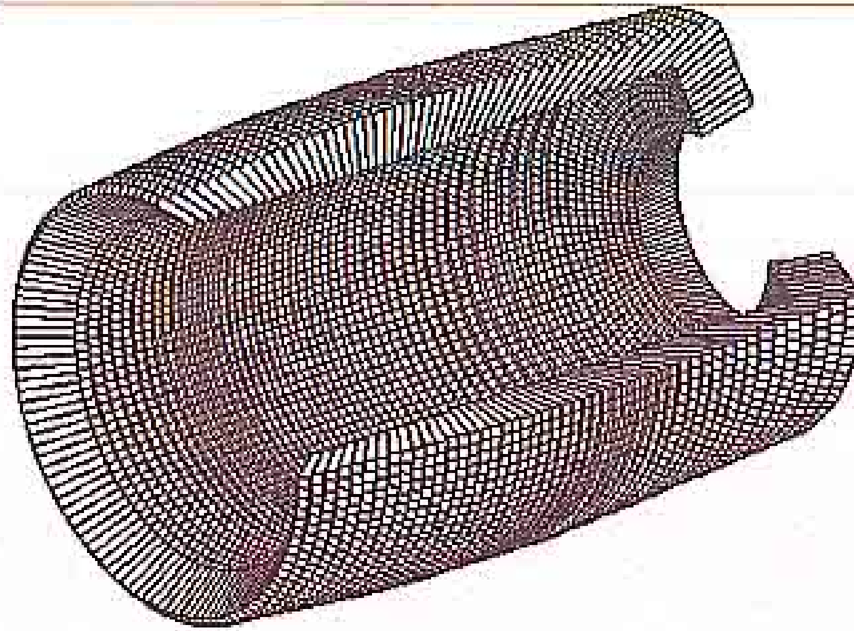

e or γ
bremsstrahlung
dominates
shower develops
energy shared
ionization dominates
shower dies out
"shower max"

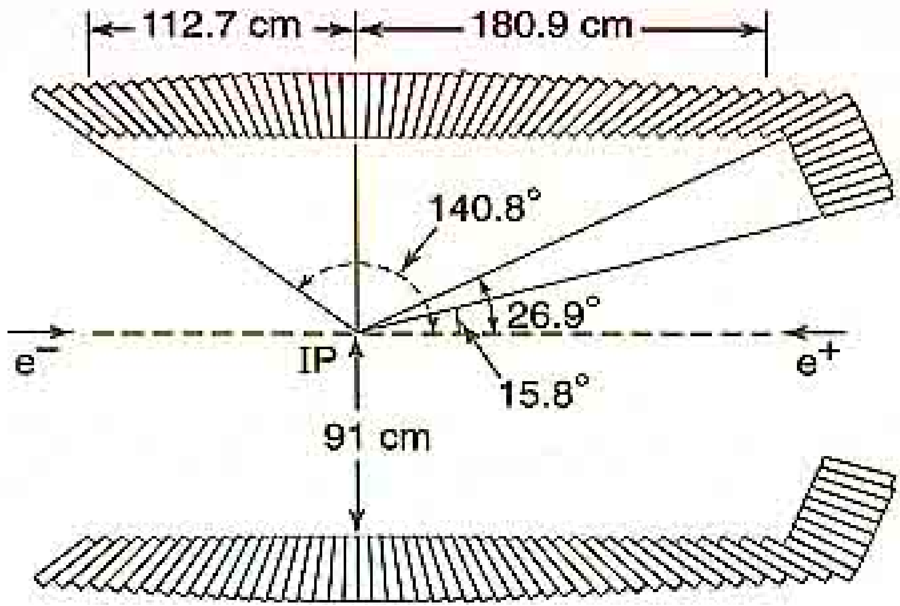
BABAR CsI (Tl) Calorimeter

EMC located asymetrically about interaction point.
Non-projective crystal geometry by15-45 mr in θ - minimise lost photons.

$$-0.775 \leq cos(\vartheta) \leq 0.962 \quad \text{(lab)}$$

$$-0.916 \leq cos(\vartheta) \leq 0.895 \quad \text{(CM)}$$



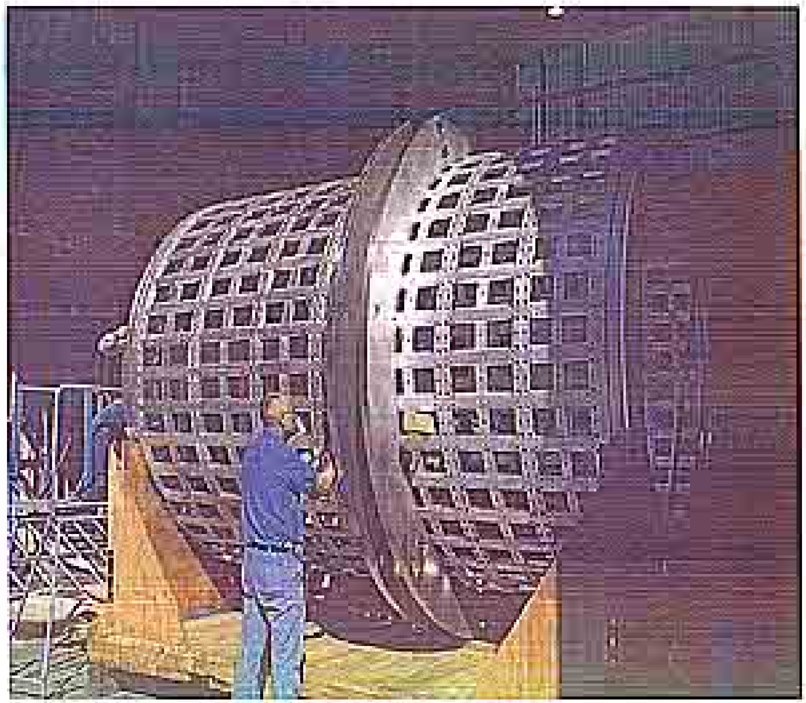


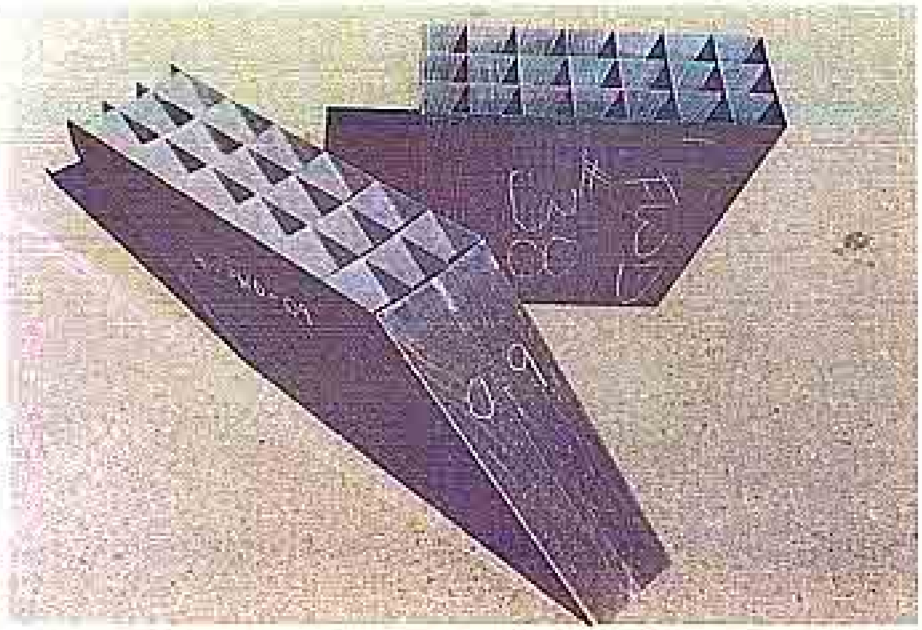
Barrel:

$$-0.916 \leq cos(\vartheta) \leq 0.715 \quad \text{(CM)}$$

5760 crystals.
48 θ rows, each with 120 crystals in φ.
280 modules of 3*7 crystals.
(except for last row - 6 crystals in θ)
Weighs 23.5 metric tonnes.

Calorimeter





Modules made from 300 μm CFC, and supported from the rear by an aluminium strongback. Mounted in an aluminium support cylinder-supported off coil. Cooling and cables located at the back of the modules.

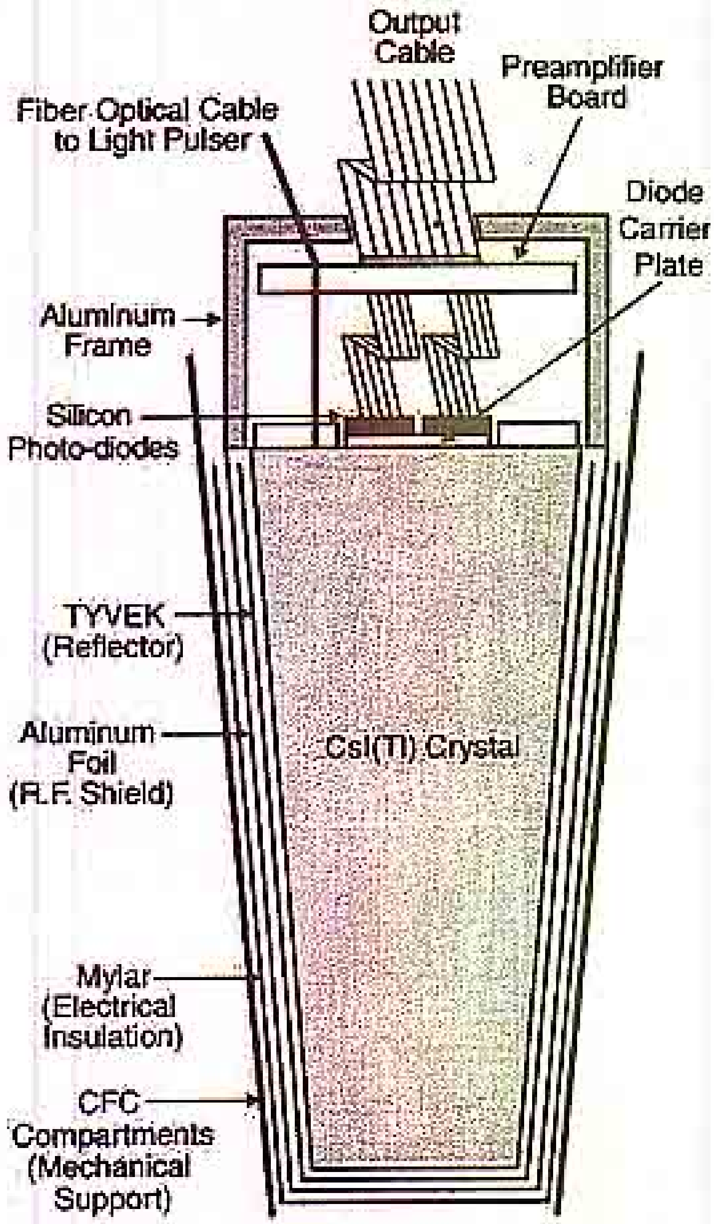
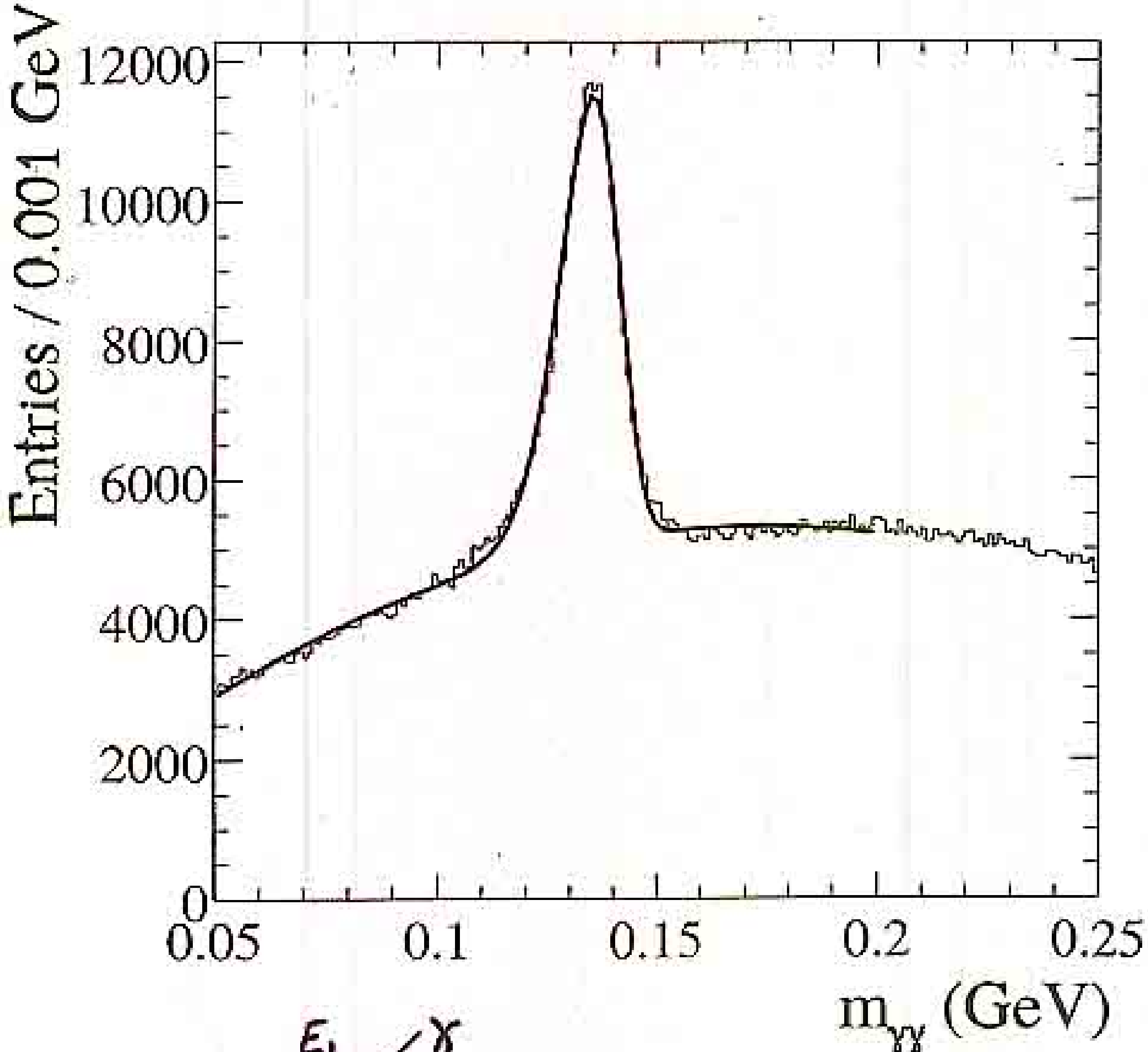
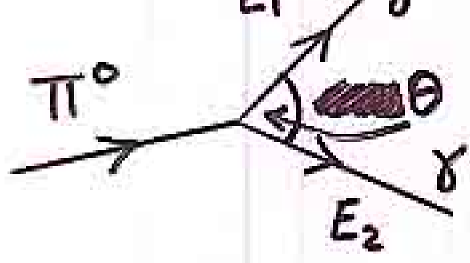


Fig. 62. A schematic of the wrapped CsI(Tl) crystal and the front-end readout package mounted on the rear face. Also indicated is the tapered, trapezoidal CFC compartment, which is open at the front. This drawing is not to scale.



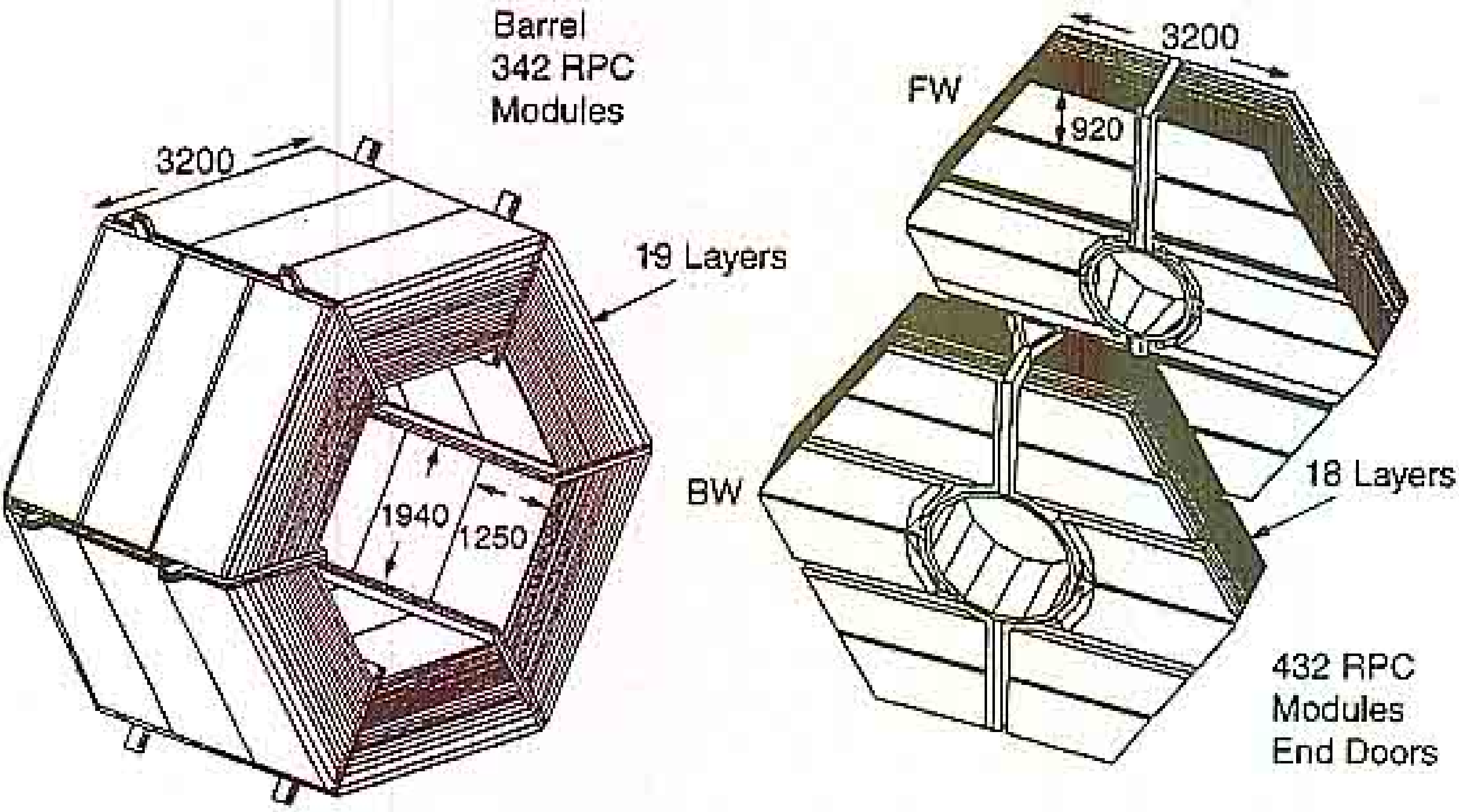


$$m_{\gamma\gamma}^2 = 2E_1E_2(1-\cos\theta) \overset{?}{=} m_{\pi^0}^2$$

(from $E^2 = p^2c^2 + m^2c^4$ with $c=1$)

Instrumented Flux Return (IFR)

Outermost detector – muons (μ), K^0_L



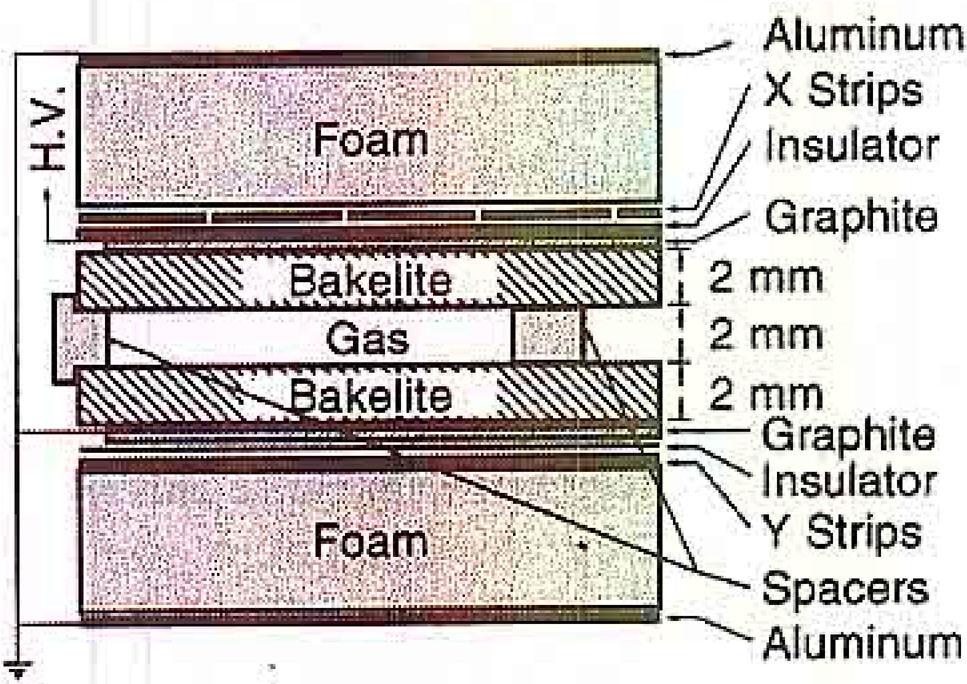
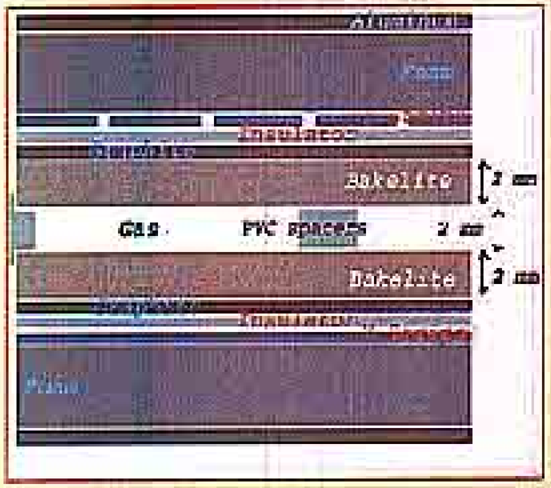


Fig. 74. Cross section of a planar RPC with the schematics of the high voltage (HV) connection.

Hardware Description (5)

- **Resistive Plate Counters: (used at L3, and Belle)**



- **Total RPC areas:**
  - **Barrel:** 1320 m^2
  - **Endcaps:** 1100 m^2

- **From the middle outwards - the 2 mm gap is filled with an Argon-Freon-Isobutane based gas mixture (gas mixture - spark quenching, safety requirements)**
- **PVC spacers (*0.8 cm²* area) placed in *10 cm-square grid* ensure RPC planarity, & gas gap (hence also field) remains constant.**
- **Two Bakelite plates with bulk resistivity in range 8-800 giga ohm cm, (coated on outside with thin layer of graphite, surface resistivity around 10 kohm cm^{-2}) and a 300 micron PVC insulating film, enclose this gap.**
- **A high (8 kV nominal) potential is applied between the graphite layers. (*Al* grounded)**

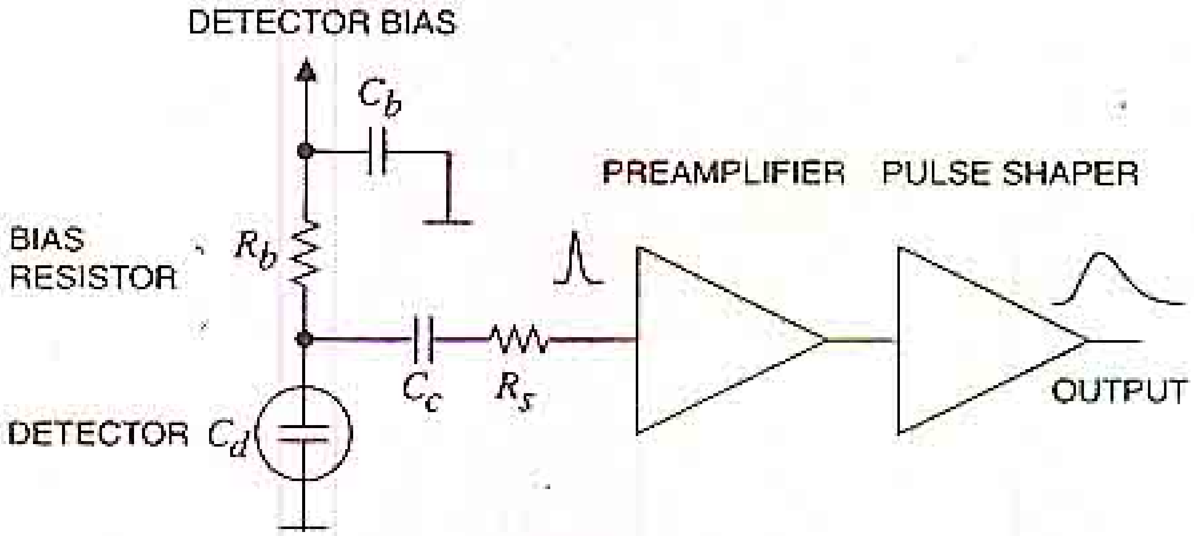
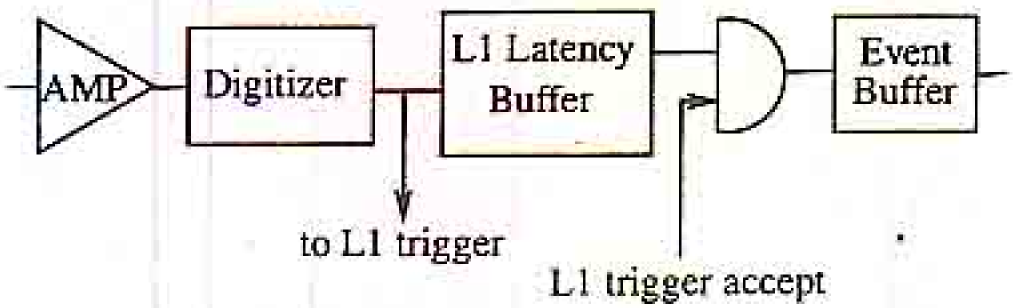


Figure 24.9: Typical detector front-end circuit.



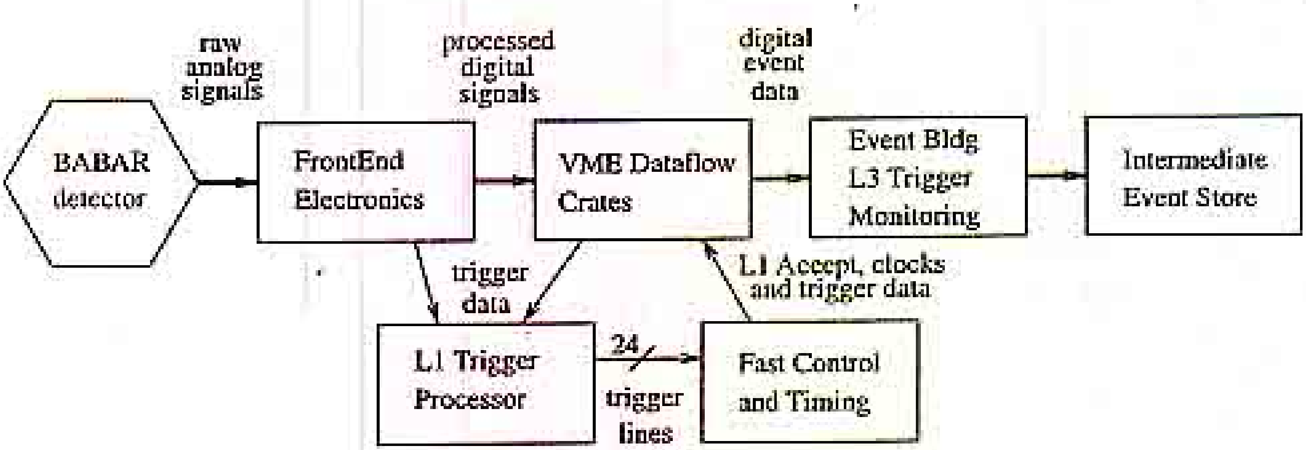


Fig. 5. Schematic diagram of the data acquisition.