Instrumentation for Flavor Physics - Lesson II

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Outline

Lesson II

- Tracking detector
- Particle identification (PID) detectors
- Muon detectors

Tracking detectors

Tracking terminology

Stable charged particles: e,μ,π,K,p

Trajectory ≡ path of a charged particle (directional 1-D object in 3-space)

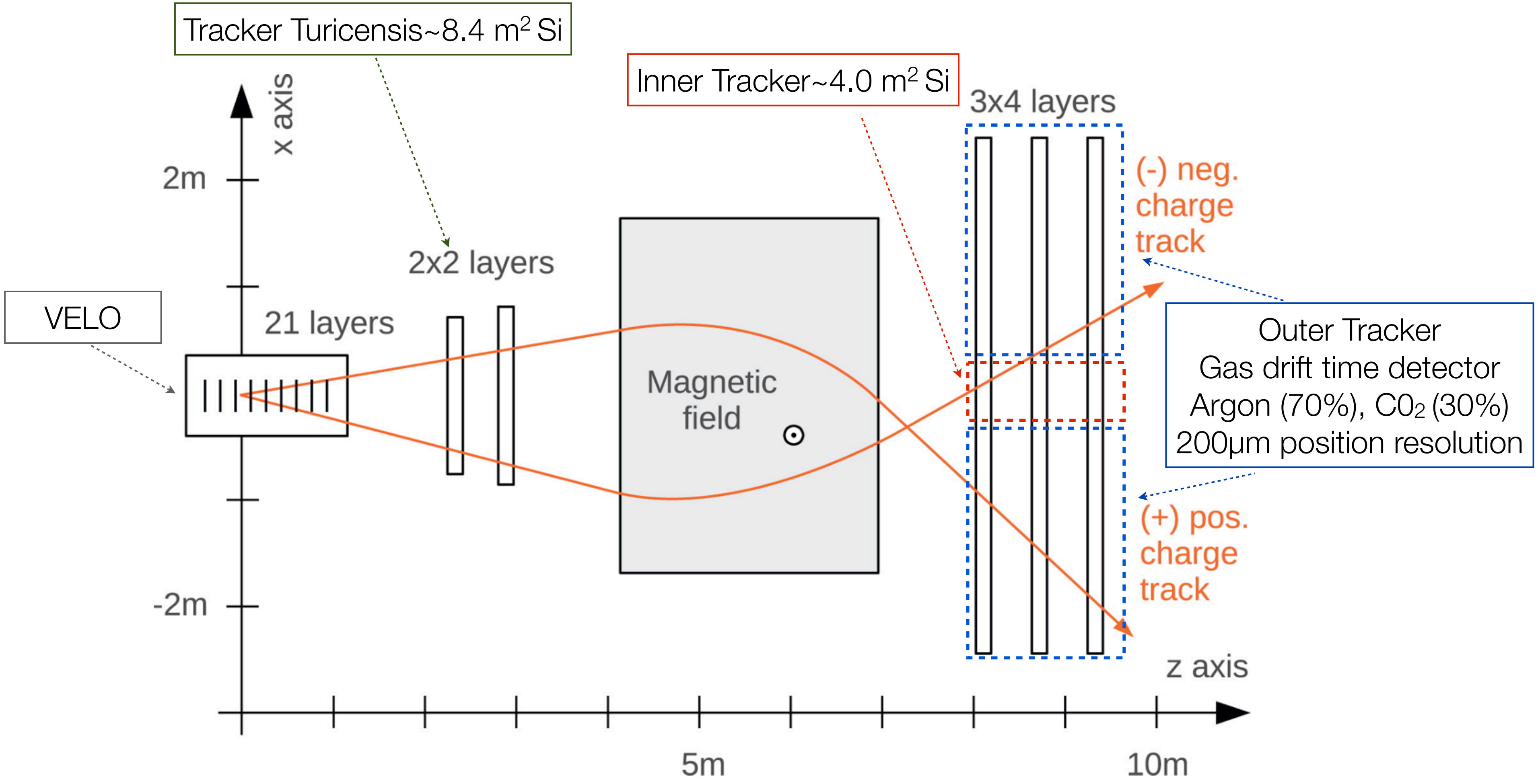
Tracking Detector ≡ highly-segmented detector capable of sensing a charged particle without greatly changing its **P**

Hit ≡ Position measurement in a single active element of a tracking detector

Track ≡ Collection of hits presumably from one particle, reconstructed to estimate the particle **P** and trajectory

LHCb spectrometer

Silicon Tracker: 500μm thick, single sided Si strip detector, pitch~200μm, vertical and stereo angle strips arrangement (x-u-v-x)=(0°,-5°,+5°,0°)

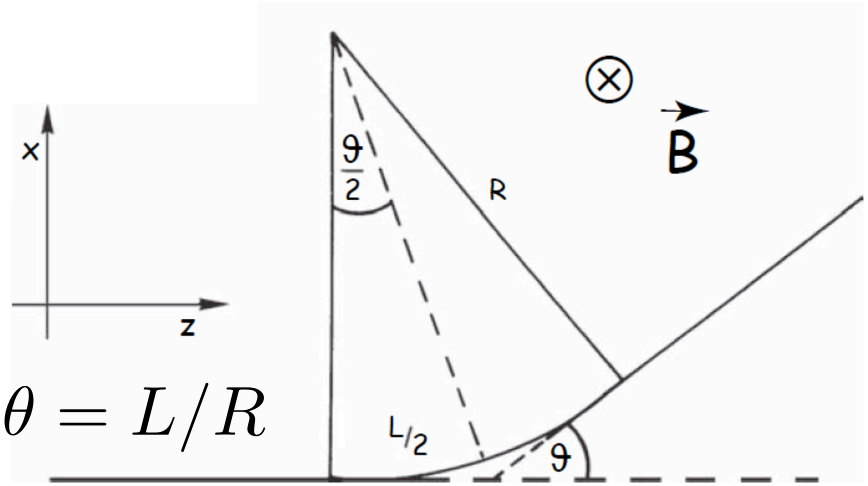


Magnetic spectrometer resolution

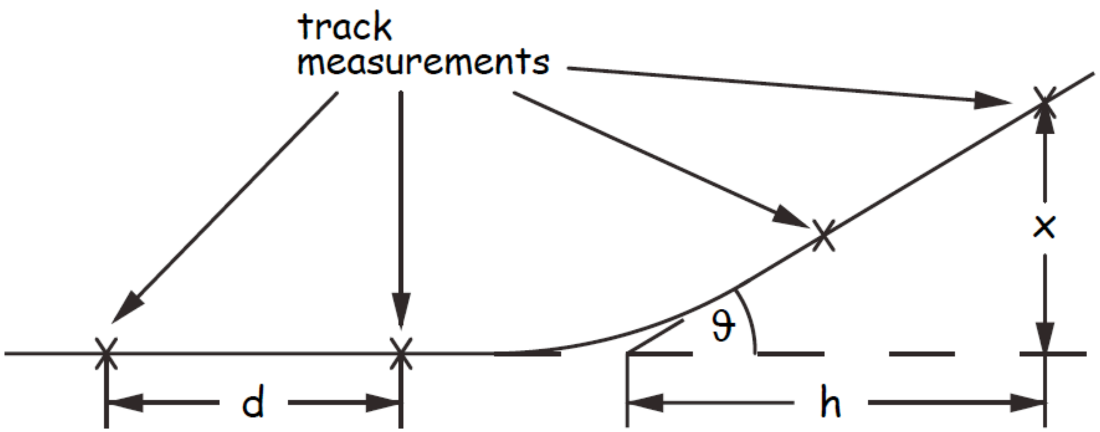
$$\vec{F} = q\vec{v} \times \vec{B} \ \rightarrow p = qRB$$

$$p = qBL/\theta$$

$$\frac{\sigma_p}{p} \sim \frac{\sigma_\theta}{\theta}$$



$$\theta = L/R$$



$$\theta \sim \frac{x}{h} \qquad \sigma_\theta \sim \frac{\sigma_x}{h}$$

$$\boxed{\frac{\sigma_p}{p} \sim \frac{\sigma_x}{h}\frac{p}{qBL}}$$

Effect of multiple scattering not considered yet

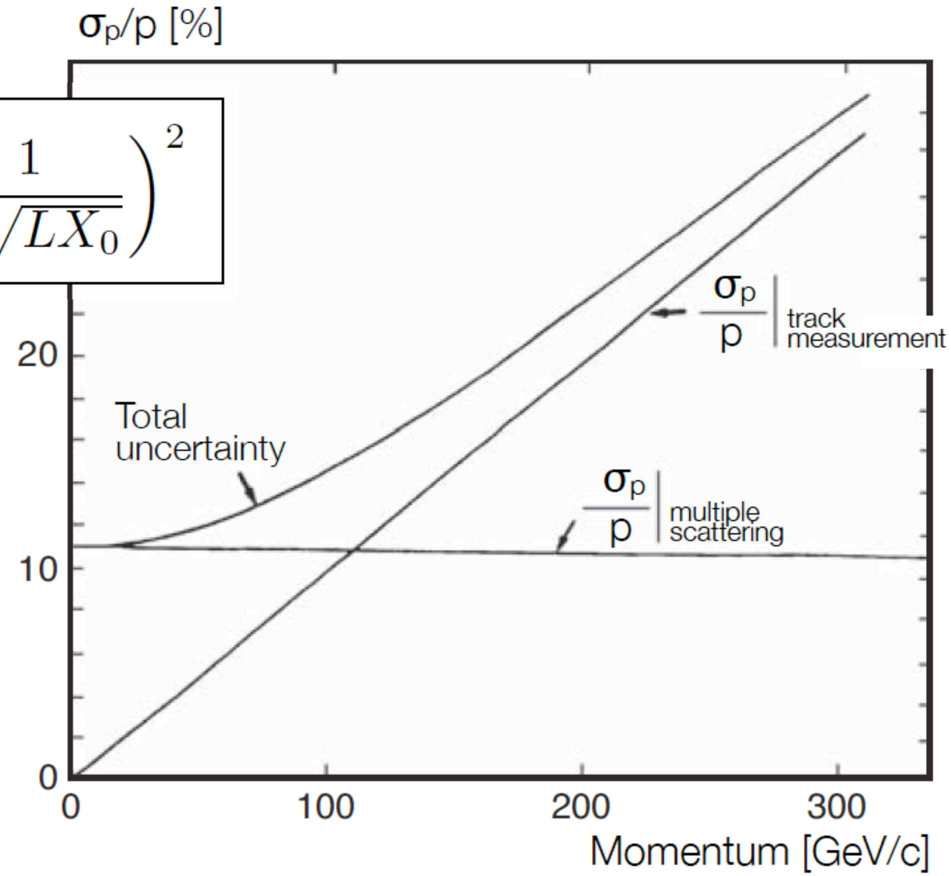
Magnetic spectrometer resolution

Multiple scattering contribution does not depend upon momentum

$$\left(\frac{\sigma_p}{p}\right)_{ms} \propto \frac{1}{\sqrt{LX_0}B}$$

[See PDG review of detectors]

$$\boxed{\left(\frac{\sigma_{p_t}}{p_t}\right)^2 = \mathrm{const} \cdot \left(\frac{p_t}{BL^2}\right)^2 + \mathrm{const} \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2}$$

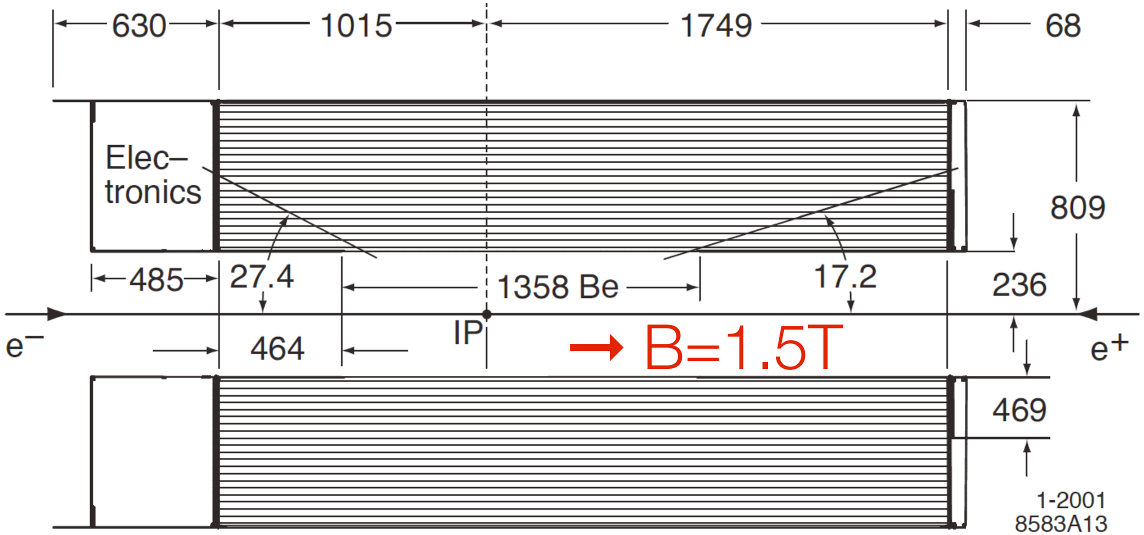


At LHCb, the momentum resolution is

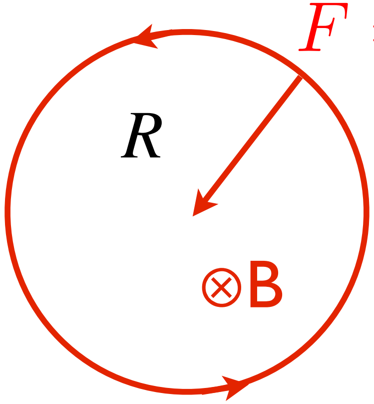
$$\frac{\sigma_p}{p} \sim (0.35 - 0.55)\%$$

for the range p=[1-140] GeV/c

Drift Chamber - BaBar DCH



$$\vec{F} = q\vec{v} \times \vec{B}$$



momentum ⇒ geometry (curvature)

$$\omega = 1/R = qB/p_t$$

Magnet+Tracking: magnetic spectrometer

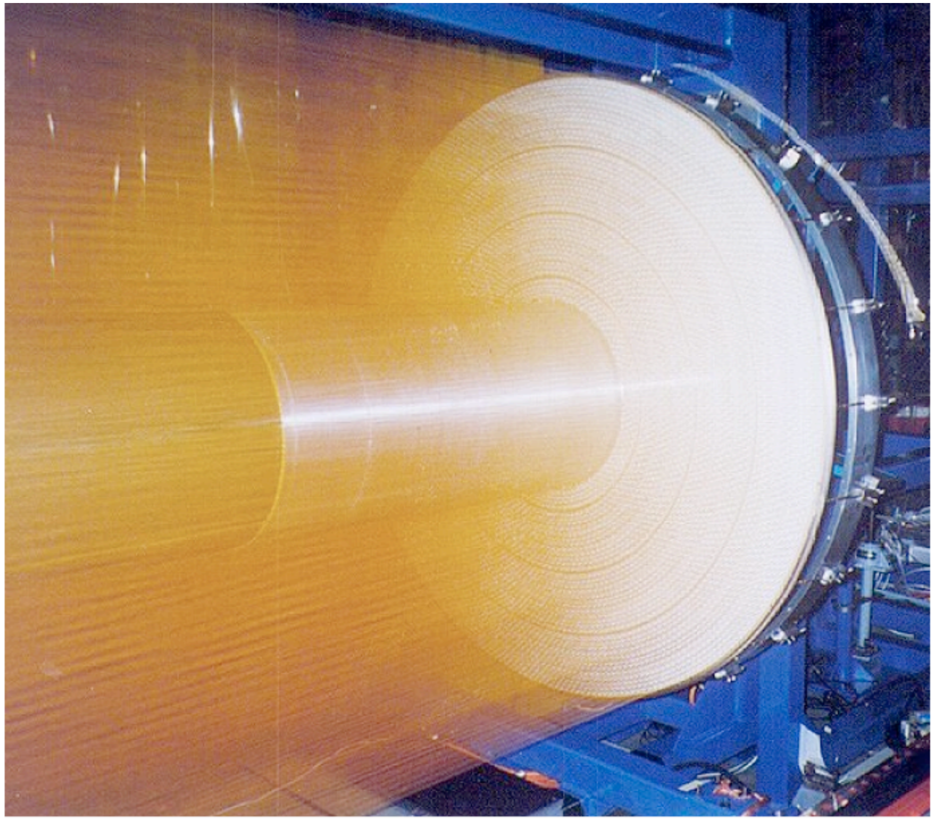
DCH is inside a solenoidal magnetic field B=1.5T

Momentum and angles measurements for charged tracks

40 layers of hexagonal cells providing spatial and ionization loss measurements

Helium-based gas mixture, low-mass wires

DCH components



Aluminum endplates

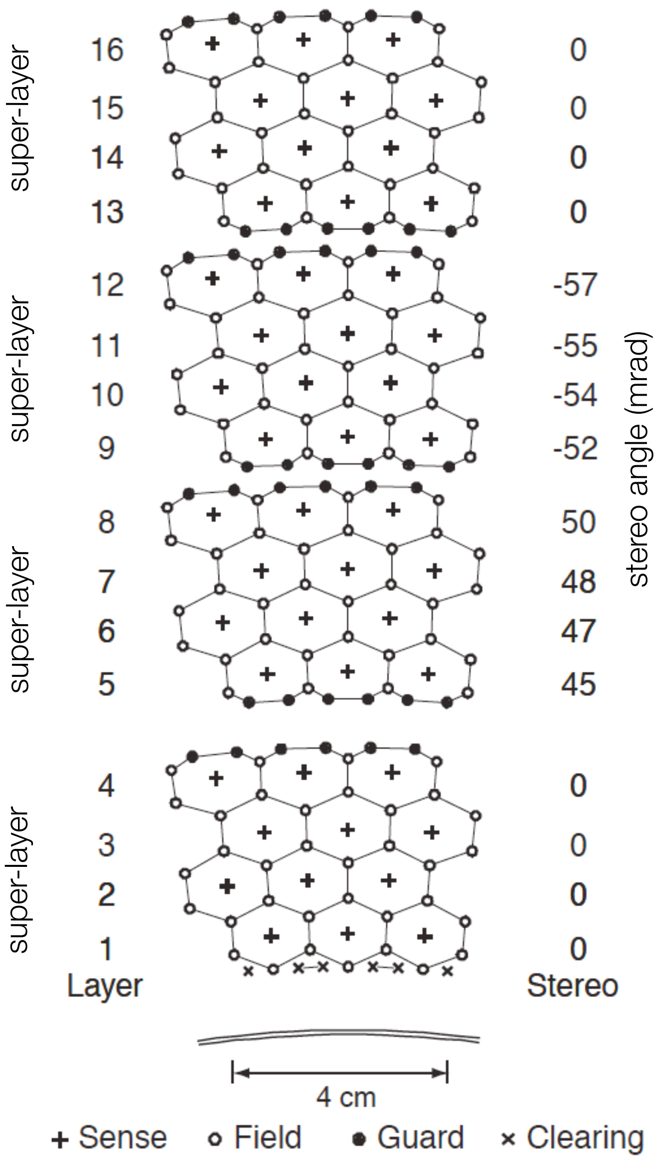
Inner (Be+Al) cylinder

Outer (Carbon Fiber) cylinder

5 m^3 gas volume
(Helium:Isobutane 80:20)

wires ~32 KNewton tension

DCH wires



7K hexagonal cells:

1 sense, 6 field wires

10 super-layers

40 layers

14 axial, 26 stereo

(α=±50mrad stereo angle)

$$\sigma_z \sim \frac{\sigma_{r,\phi}}{\sin\alpha} \sim \frac{140\mu m}{\sin\alpha} = \mathcal{O}(1)\mathrm{mm}$$

W-Re sense wires

∅=20μm, 1960 V

How does a DCH work?

Four stages:

- Ionization
- Gas amplification
- Electronic amplification + digitization
- Calibration and reconstruction

Ionization

Charged particles can ionize gas atoms

Helium provides most ionization

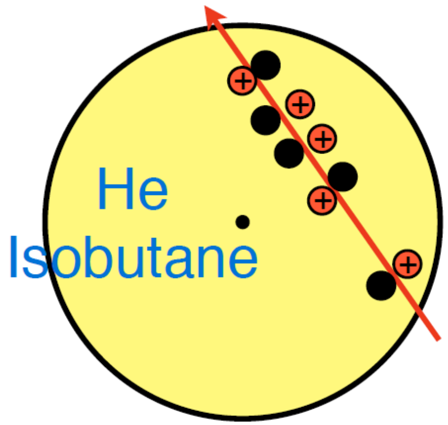
10x less absolute ionization than Argon

W_i=41eV for He (energy for electron/ion pair)

Isobutane absorbs photons (quencher)

prevents photoelectric electrons from cathode

keeps ionization local to particle trajectories



Drifting charges
due to electric field
Anode = wire

Gas amplification

Electrons and ions drift due to $\vec{E}$

$v \propto \mathbf{E}/m$, $v_e \sim 10^3\, v_{ion}$ ($v_e \sim 3\, v_h$ in Si)

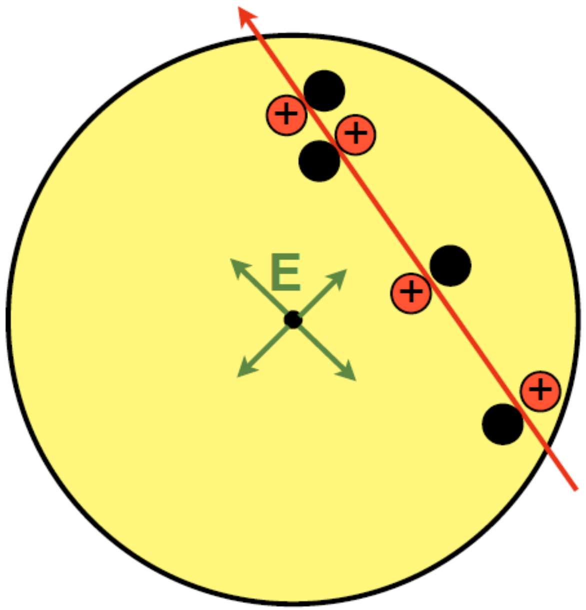
$\mathbf{E} \sim V/r$, electrons accelerate near the wire

When $E_e > E_{ionization}$ they ionize the gas, make more electrons (very close to the anode wire)

⇒ chain reaction

DCH Gain ~ 5×10^4

proportional mode: proportional to initial ionization produced in the detector



Signal amplification and timing

Electrons collected on wire in ~1ns

Electronic signal (voltage) appears on wires as ions drifts to field wires

≤1μs to see total charge

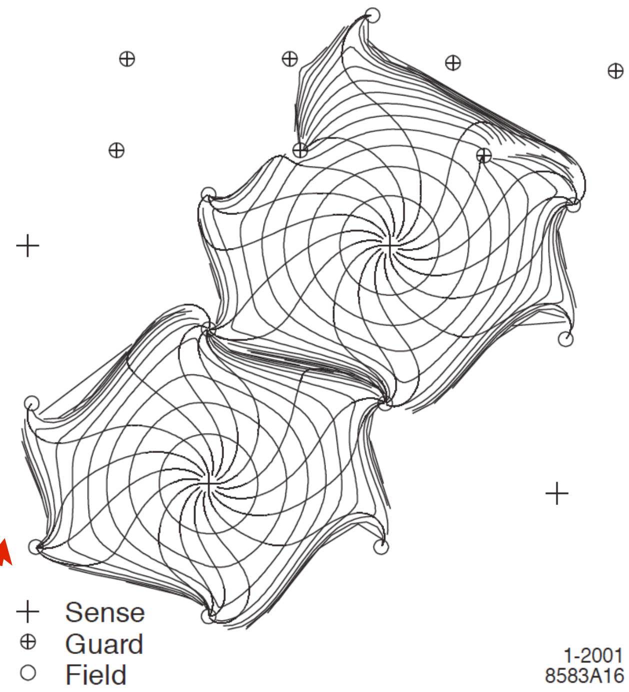
Signal shaping, amplification + digitization

FEE chip: 8 bit ADC (dE/dx), 1ns resolution
Time-to-digital converter (TDC) (tracking)

Signal time depend on ionization location

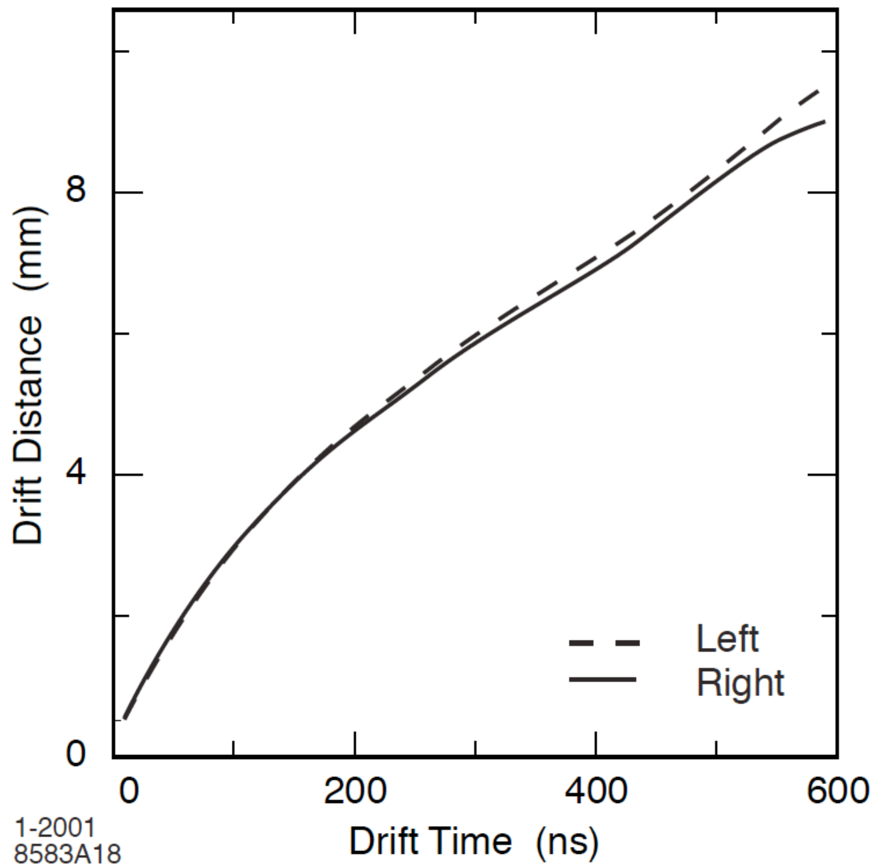
Interpret TDC as "distance to the wire" with time to distance calibration

Drift cell isochrones (100 ns steps)

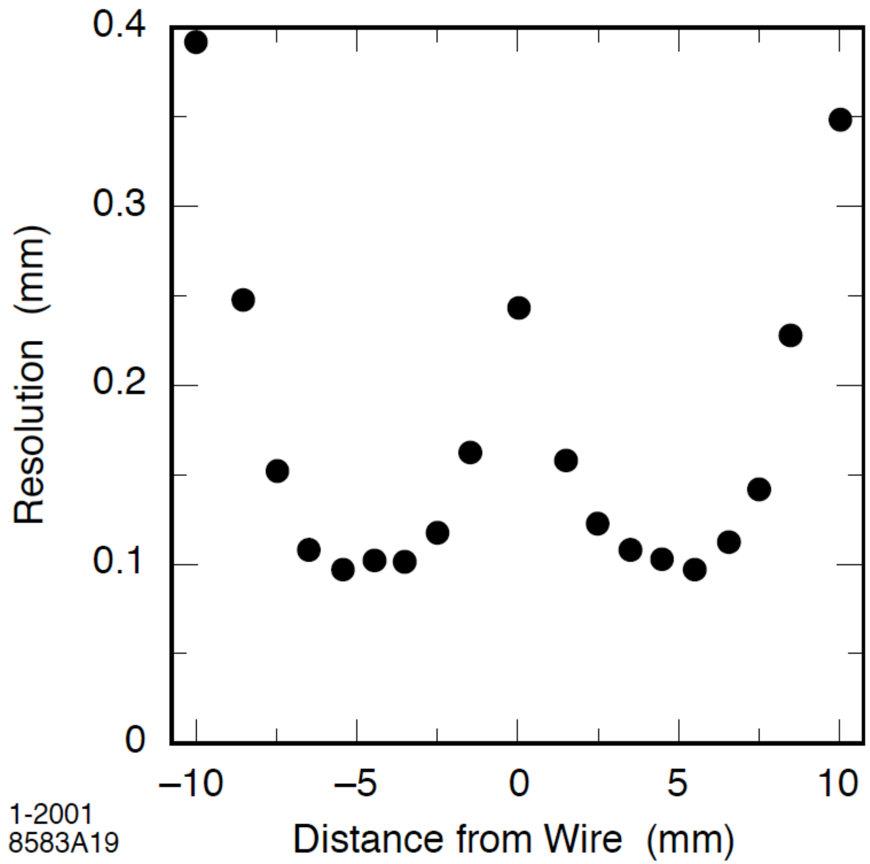


DCH Calibration

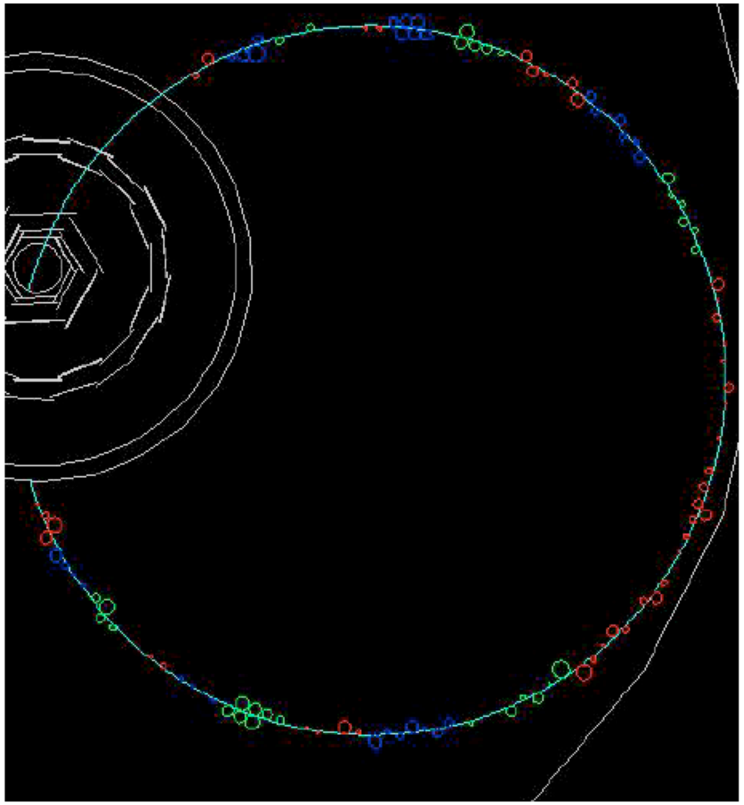
Time to distance calibration using control samples

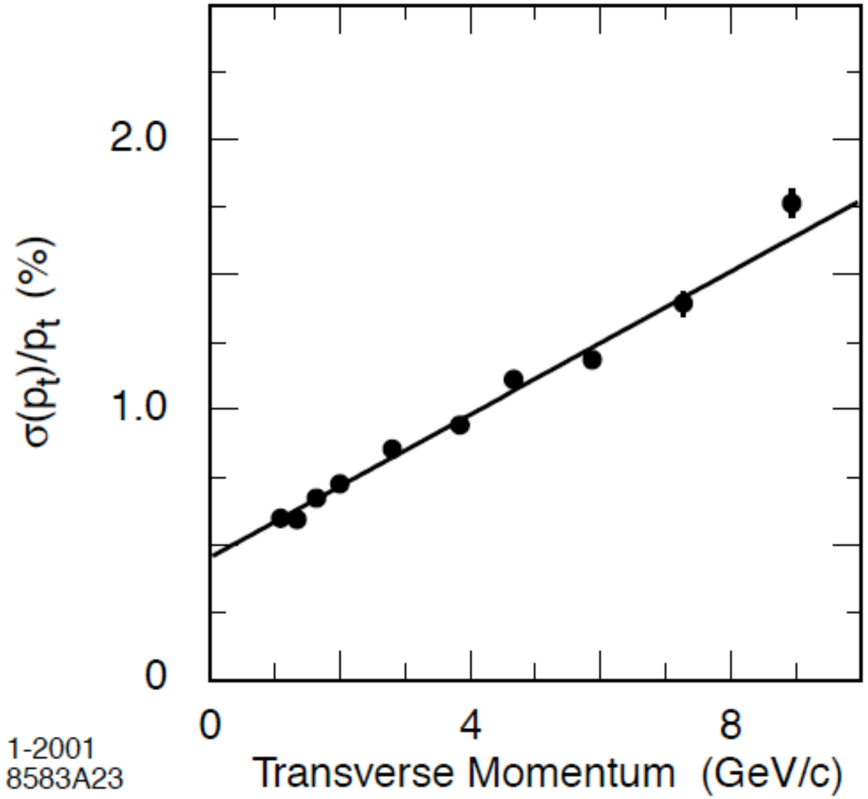


Position resolution vs drift distance



Tracking and momentum resolution





Distance to wire provide a 2D (x-y) constraint on the track position

Stereo views provide some z information

p_t resolution

$$\sigma_{p_t}/p_t = (0.13 \pm 0.01)\% \cdot p_t + (0.45 \pm 0.03)\%,$$

Exercises

1. Calculate the sagitta, s, for a muon (p=100 GeV/c) transversing a region (1m) with ⊥ magnetic field B=1.5T. Show that $\sigma_p/p = \sigma_s/s$.

2. What limits the time resolution of a proportional counter? Can you give an estimate of the maximum uncertainty in terms of wire spacing, d=1cm, and drift velocity, v_d=5cm/μs?

3. In a cylindrical proportional counter, the dominant signal is induced by the motions of electron or ions? Can you estimate the ratio of the two signal for a simple case with wire radius=10μm and cell radius 1cm?

4. If you wish to measure the momentum of a 10 GeV/c singly-charged particle to 1% accuracy, in a 2 T field, using a 1 m long magnet, how well do you have to know the exit angle (see figure in pag. 7)? Calculate the adequate spacing between detectors, to achieve this precision, if you use a gas detector with 200μm hit resolution and a silicon detector with 20μm hit resolution.

PID detectors

Particle identification - some examples

For charged particles, the momentum measurement is provided by the tracking system

$$p = \beta\gamma m_0 c \qquad \gamma = \sqrt{\frac{1}{1-\beta^2}}$$

By measuring the velocity of the particle, β, we can determine its mass

$$m_0 = \frac{p}{\beta\gamma c}$$

Measurement of velocity

Cherenkov angle $\quad \cos\theta_c = \frac{1}{\beta n}$

Time of flight $\quad \tau \propto \frac{1}{\beta}$

Energy loss $\quad \frac{dE}{dx} \propto \frac{z^2}{\beta^2}\ln(a\beta\gamma)$

I will not cover transition radiation detectors and calorimeters

Cherenkov radiation

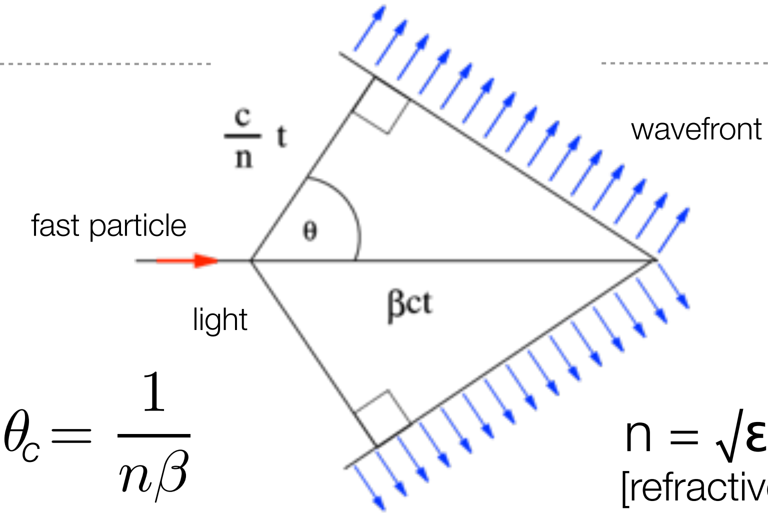
A charged particle in a medium that moves faster than the speed of light in the same medium generates Cherenkov radiation.

$$\beta c = v = c/n$$

$$v_{\mathrm{particle}} > c/n \Rightarrow \text{Cherenkov radiation}$$

n = refraction index
c/n = speed of light in medium

Electromagnetic shock wave is created. The coherent wavefront is conical and emitted at defined angle



$$\cos\theta_c = \frac{1}{n\beta}$$

[θ_C: Cherenkov angle]

$n = \sqrt{\varepsilon}$
[refractive index]

Cherenkov radiation

Energy loss by Cherenkov radiation very small compared to ionization (<1%)

Number of photons per unit length and per unit energy interval of the photon:

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370\ \sin^2\theta_c(E)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (z=1)$$

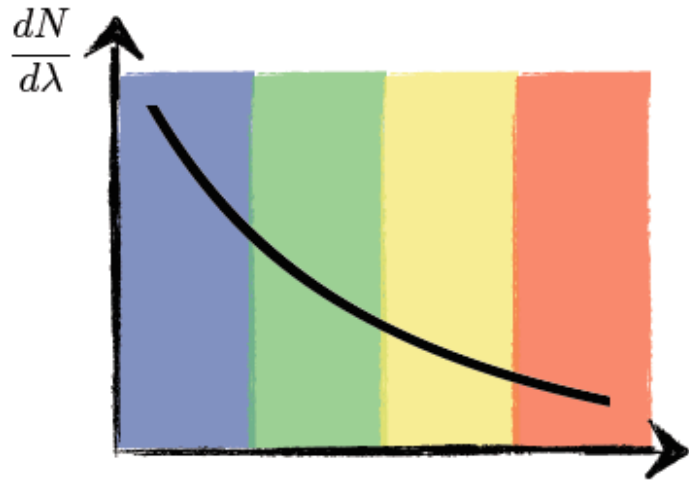
Equivalently:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

Integrate over sensitivity range:
[for typical Photomultiplier]

$$\frac{d^2N}{dx} = \int_{350\ \mathrm{nm}}^{550\ \mathrm{nm}} d\lambda \frac{d^2N}{d\lambda dx}$$

$$= 475\ z^2 \sin^2\theta_C\ \mathrm{photons/cm}$$



Cherenkov radiators

Minimal velocity for Cherenkov emission $\beta_{thr} = 1/n$

charged particles with $\beta < 1/n$ give no light
with $\beta > 1/n$ give light

Parameters of Typical Radiator

Medium	n	β_{thr}	θ_{max} [β=1]	N_{ph} [eV^{-1} cm^{-1}]
Air	1.000283	0.9997	1.36	0.208
Isobutan	1.00127	0.9987	2.89	0.941
Water	1.33	0.752	41.2	160.8
Quartz	1.46	0.685	46.7	196.4

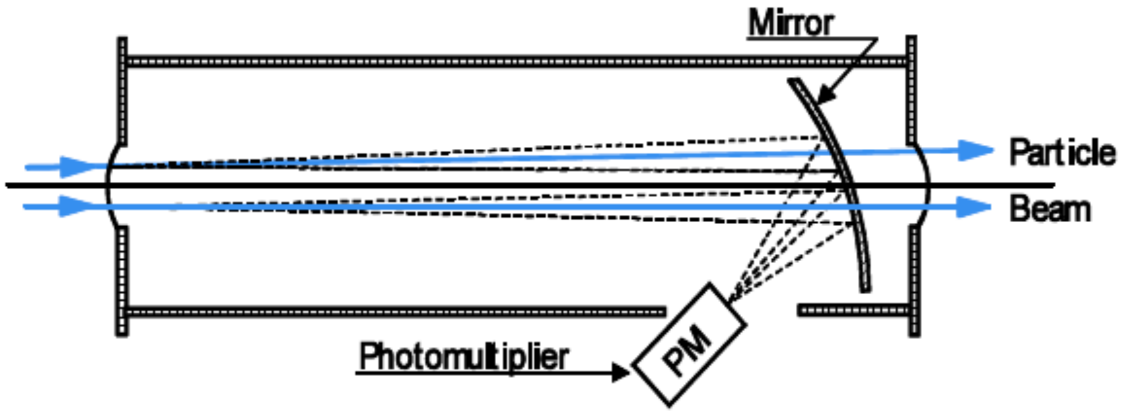
Gas radiators for high momentum particles $\mathcal{O}(10)$ GeV

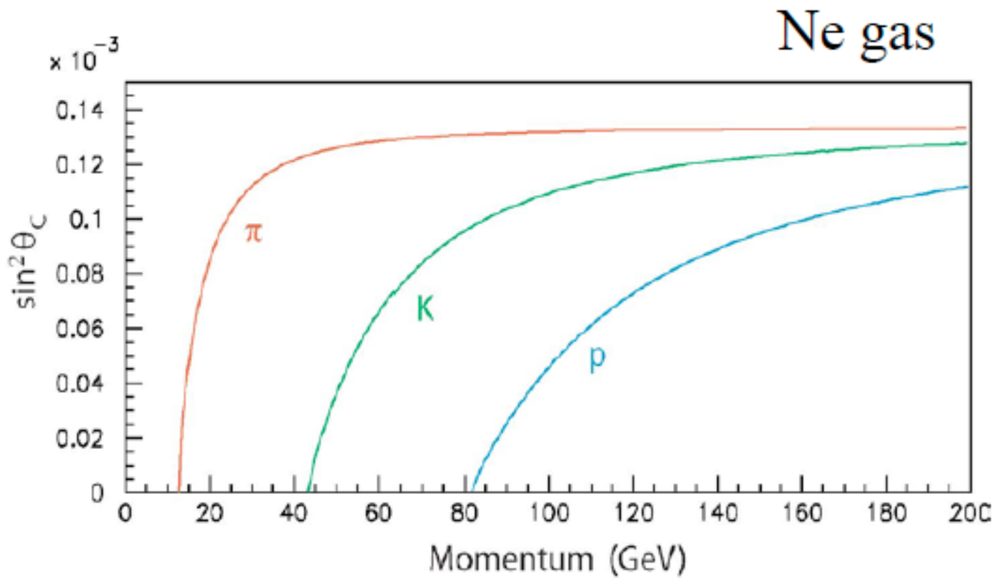
Solid radiators for low momentum particles $\mathcal{O}(1)$ GeV

Threshold Cherenkov counter

Useful to identify particles in a beam line (with fixed momentum). For example a 50 GeV π^+ beam with proton contamination

By choosing a medium with a suitable refractive index, it can be arranged that the π will produce light, but the protons will not





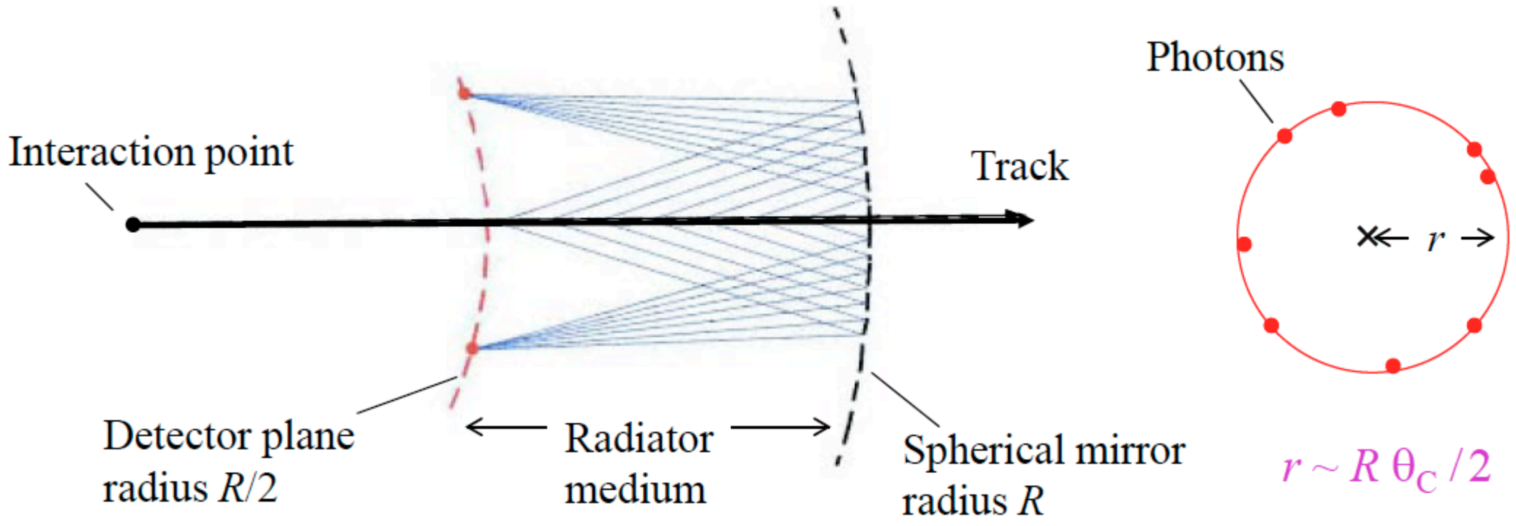
Ex: calculate the refractive index n for the above experiment.

Ring Imaging Cherenkov detector (RICH)

Proposed by Seguinot and Ypsilantis [NIM 142, 377 (1977)

The Cherenkov cone can be imaged into a ring using a spherical mirror

Requires large area photosensitive detectors (e.g. PMT arrays)

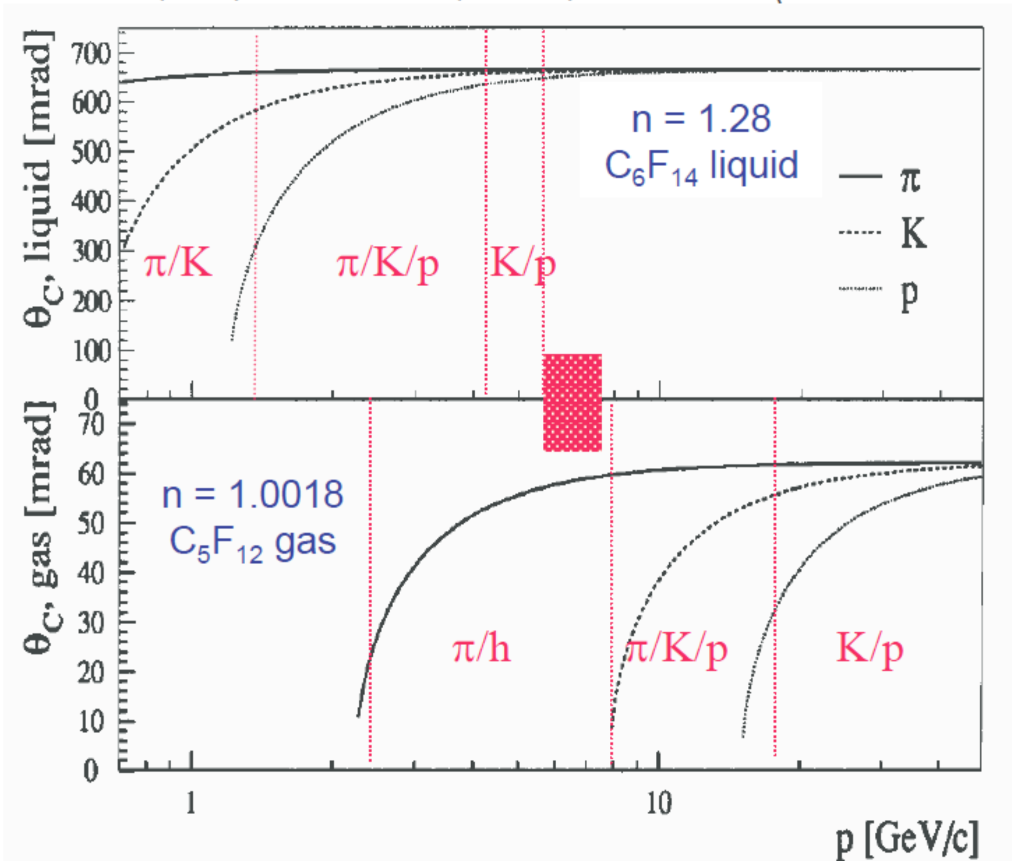


The Cherenkov angle θ_C is determined by measuring the radius of the ring r

First RICH detectors at collider experiments

$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right) = \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$

DELPHI and SLD: RICH with 2 radiators to cover a large momentum range for π/K/p separation 0.7-45 GeV/c



DELPHI

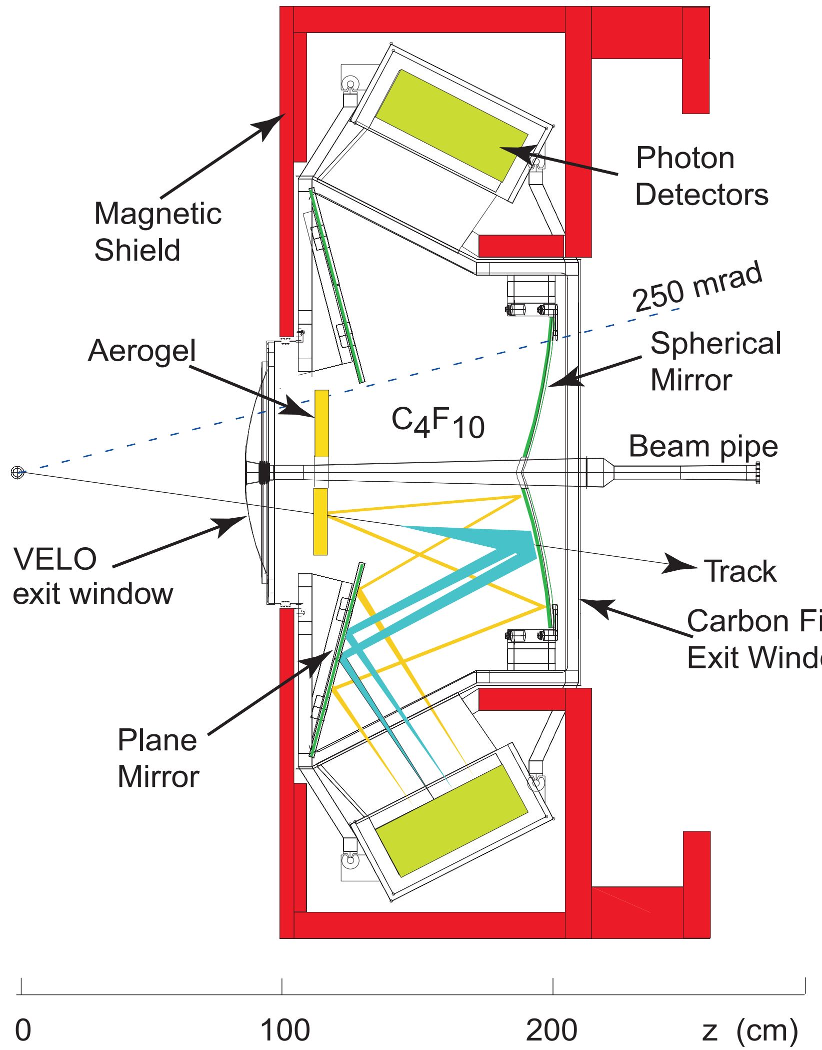
RICH in LHCb

RICH-1 and RICH-2 for different momentum range: [2-40] GeV/c, [15-100] GeV/c, respectively

Use a “thin” tilted focusing mirror to bring the images outside detector acceptance

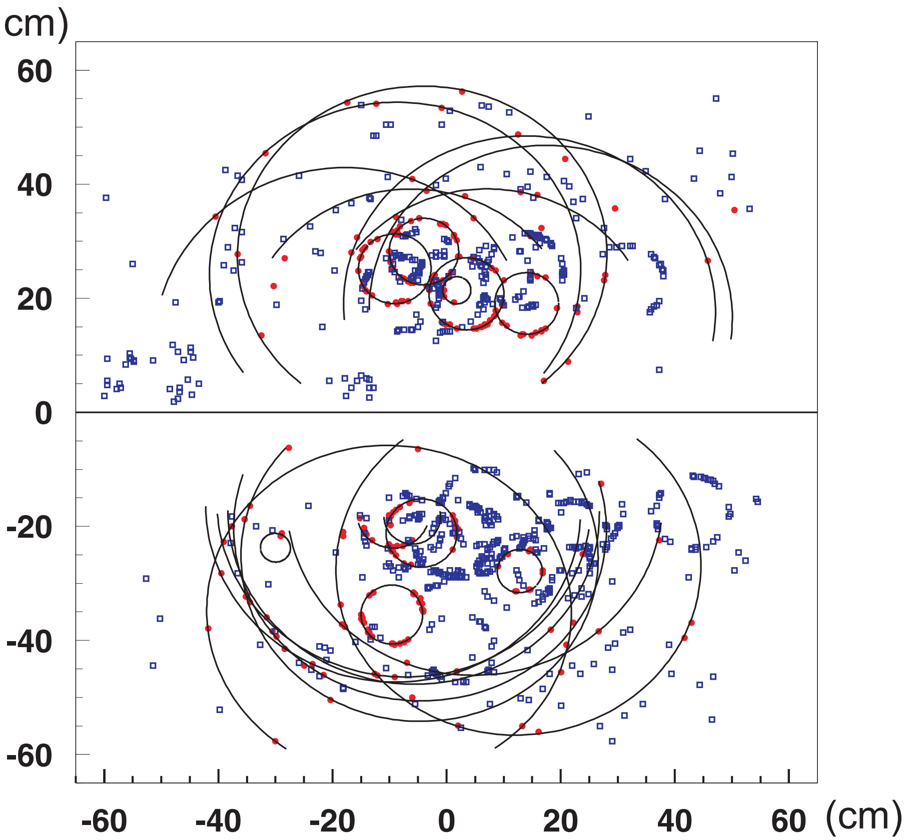
Use different radiators: Aerogel (n=1.03) for low momentum p<10 GeV/c, C_4F_{10} gas (n=1.0014) intermediate momentum, CF_4 gas (n=1.0005) in RICH-2 for high momentum p>20 GeV/c

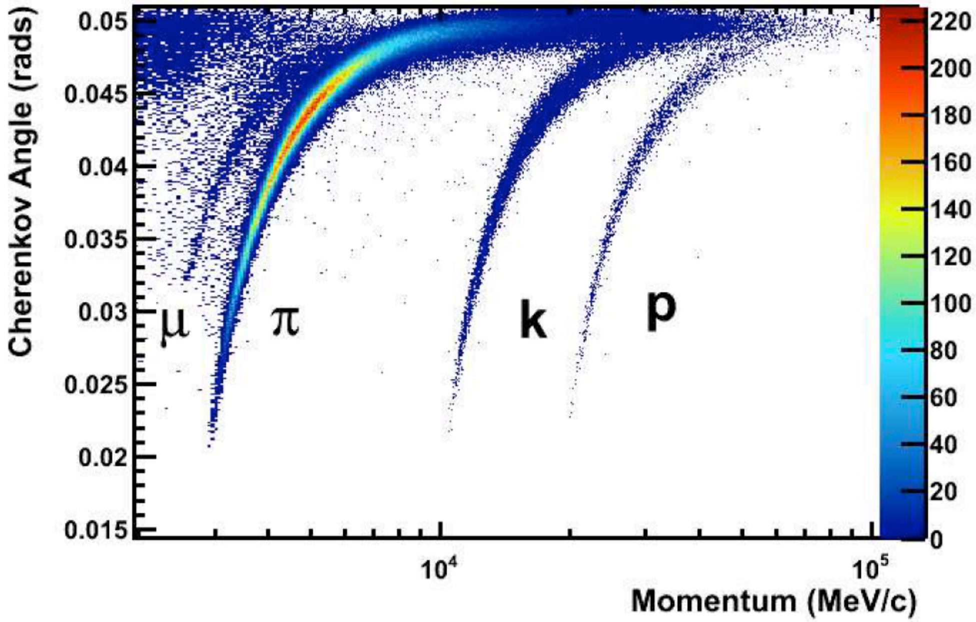
RICH-1cross section



Cherenkov angle reconstruction

Simulated event in RICH-1
Large (small) rings: Aerogel (C_4F_{10})
Multiple tracks generate overlapping rings→ pattern recognition

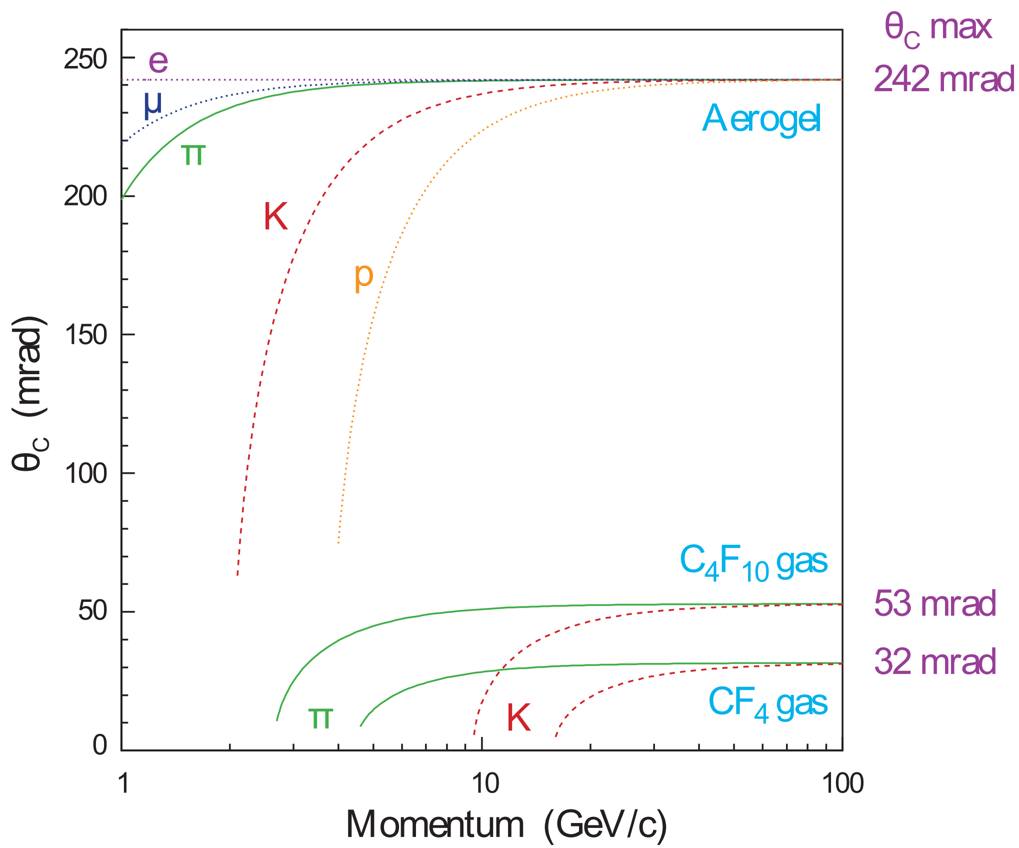




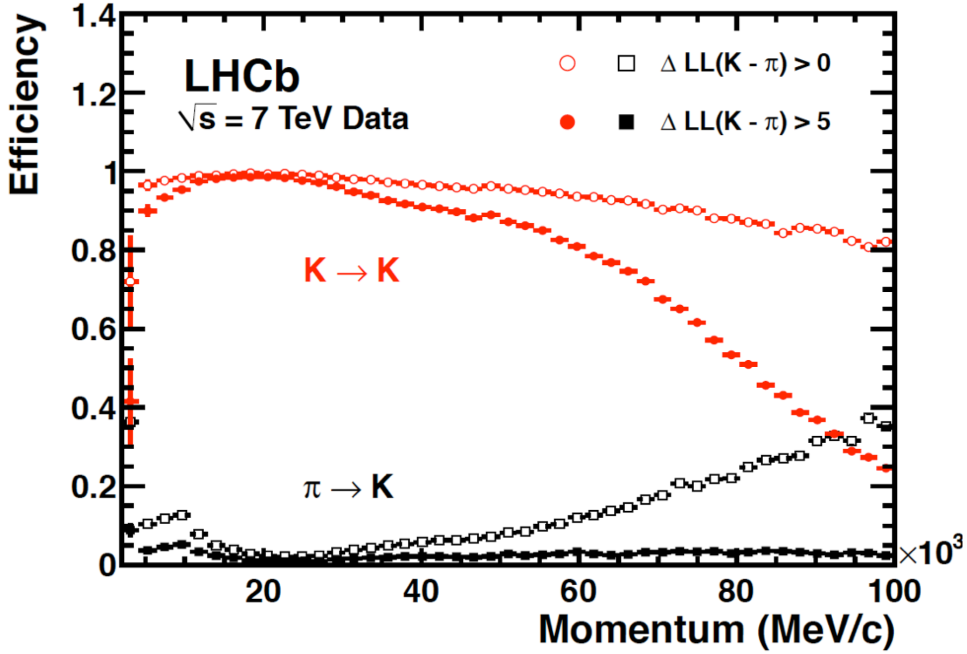
Reconstructed Cherenkov angle vs track momentum in C_4F_{10} radiator

RICH performance at LHCb

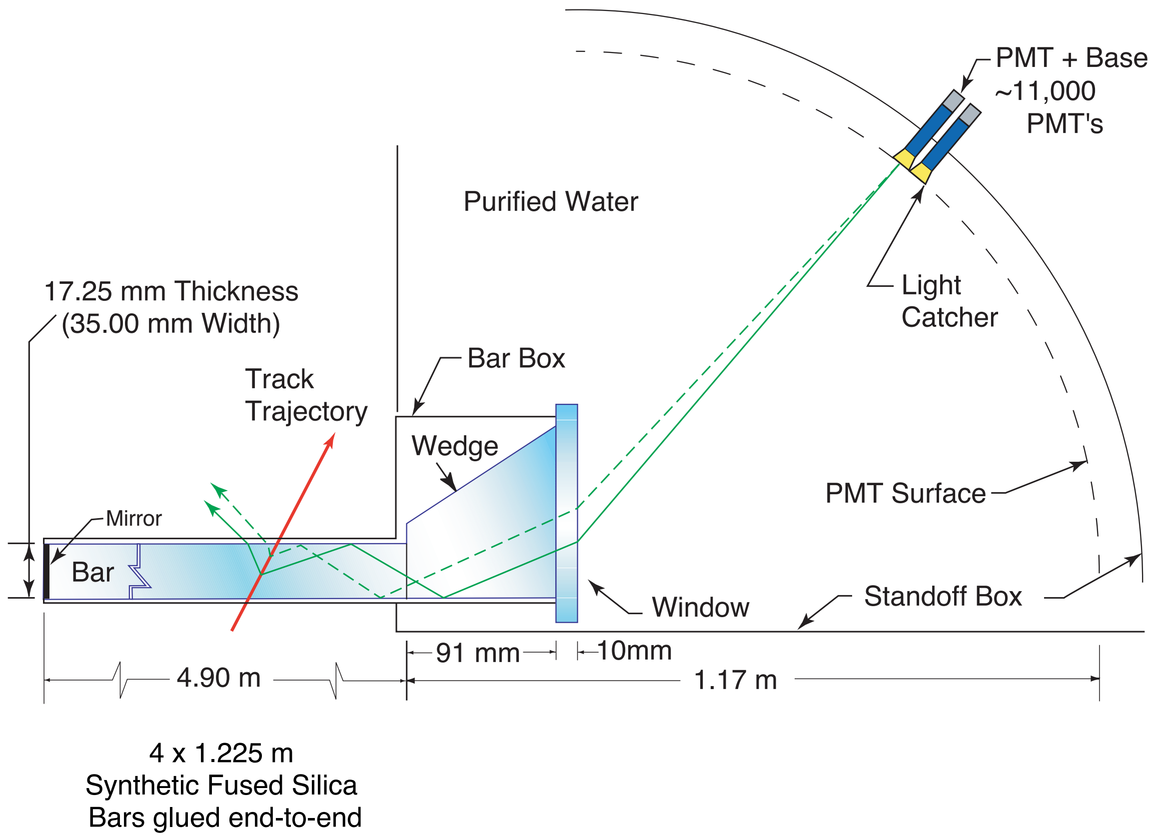
Cherenkov angle versus particle momentum for the RICH radiators



Kaon efficiency and pion misidentification rate vs momentum



Detector of Internally Reflected Cherenkov light (DIRC)



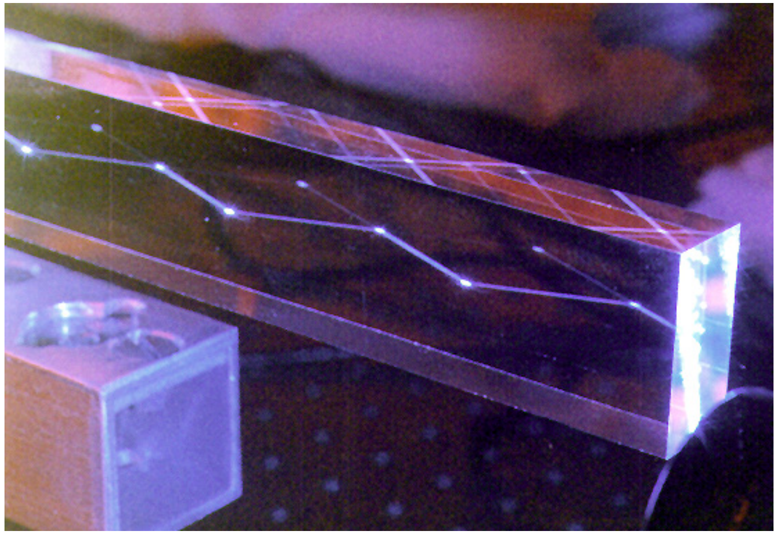
Ring imaging Cherenkov detector based on total internal reflection.

Preserving angle information due to precision surfaces

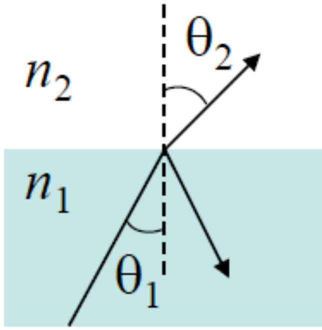
Long rectangular bars made from synthetic fused silica ("quartz") are used as both radiator and light guide.

Rings projected in water-filled standoff box (best match to quartz index), where photons are detected with an array of 10K PMTs

DIRC



Light internally reflected in DIRC bar



Law of refraction:

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$n_1 = 1.45$ (quartz)

$n_2 \approx 1.0$ (air)

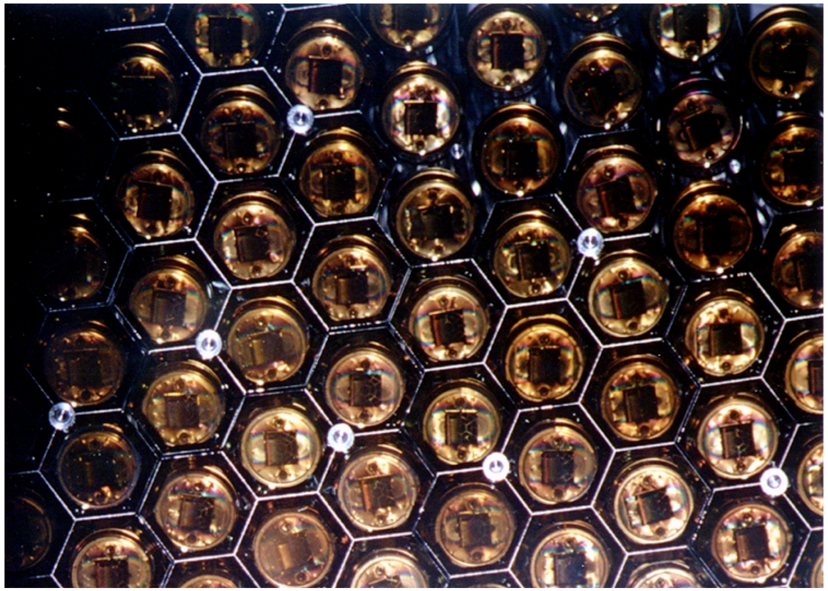
Total internal reflection

if $\theta_1 > \sin^{-1}(1/1.45) \approx 44^{\mathrm{o}}$

Typically, a charged track well above the Cherenkov threshold produces 20-60 photons

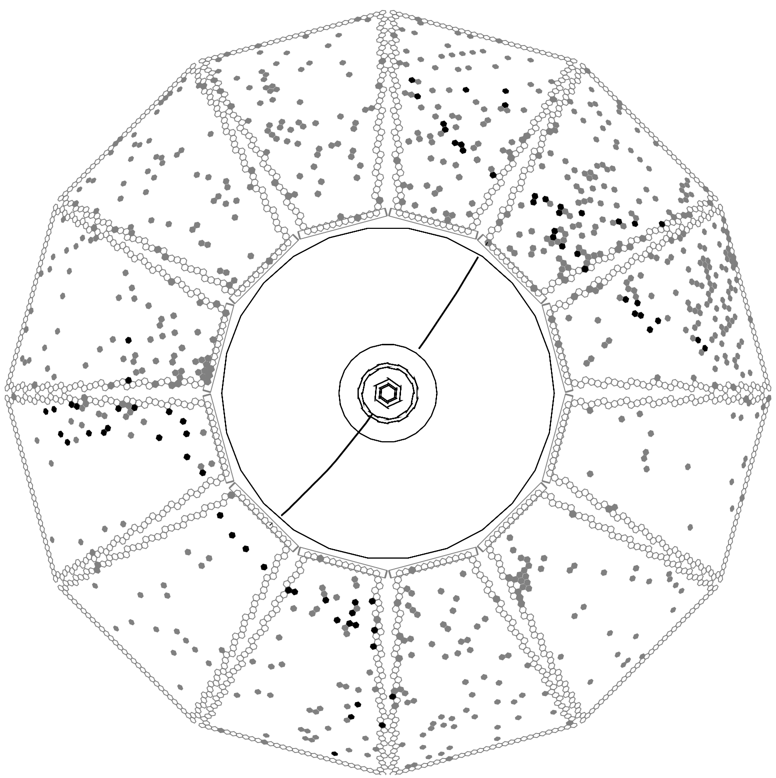
These are detected by an array of closely packed photomultipliers (PM's) in the Standoff Box

Very good precision in the measurement of the time (a few ns), required to reduce background

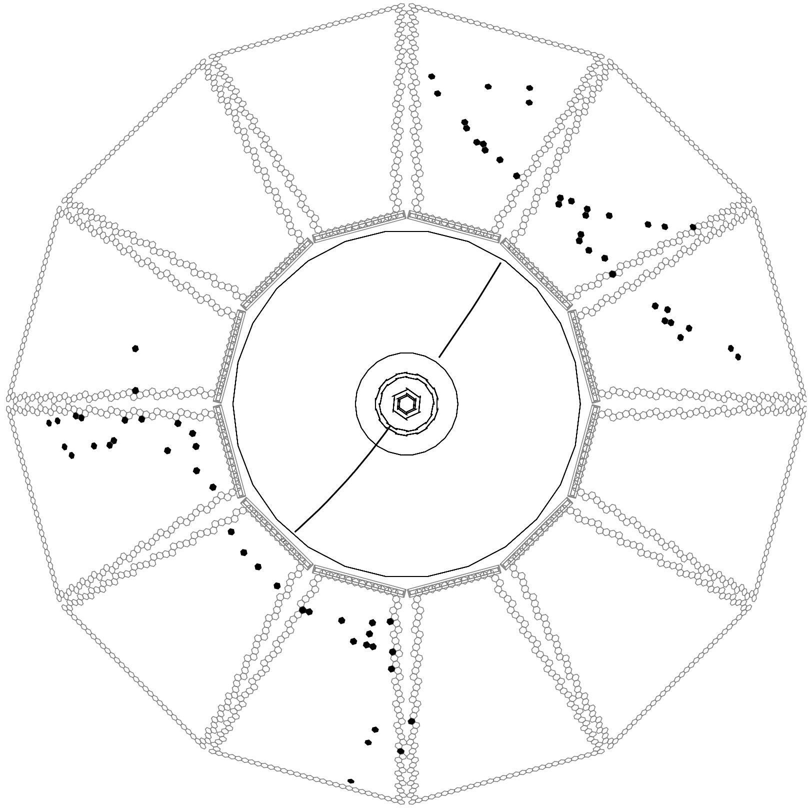


Reconstruction

Display of an $e^+e^- \rightarrow \mu^+\mu^-$ event reconstructed in BABAR with two different time cuts



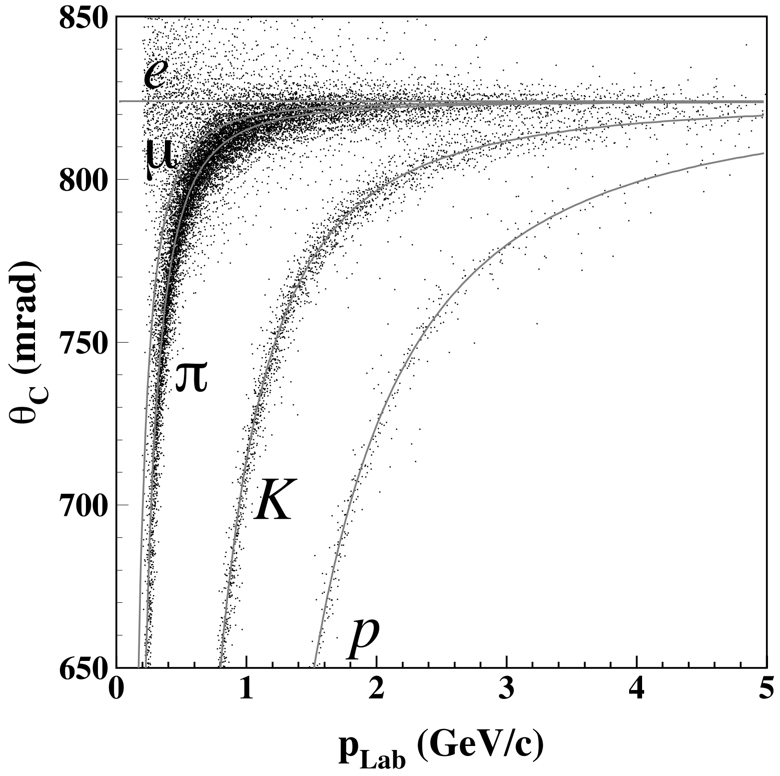
±300 ns window

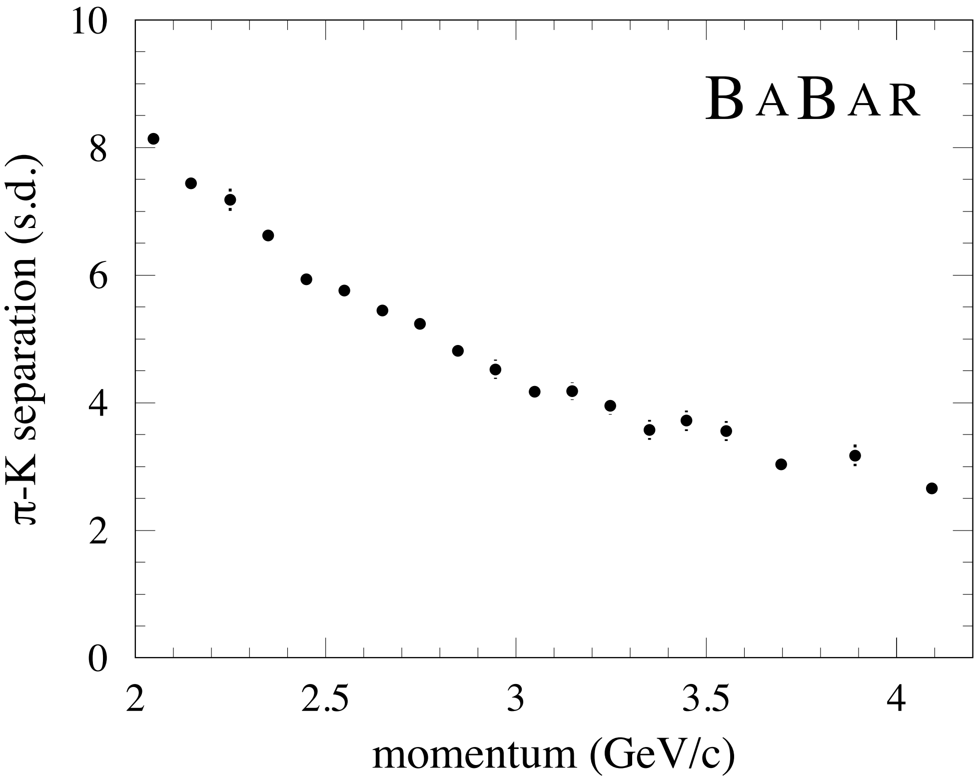


±8 ns window

Reduce background photons outside a fiducial time window around the trigger time
Signal patterns are conic sections rather than rings due to different geometry

DIRC performance

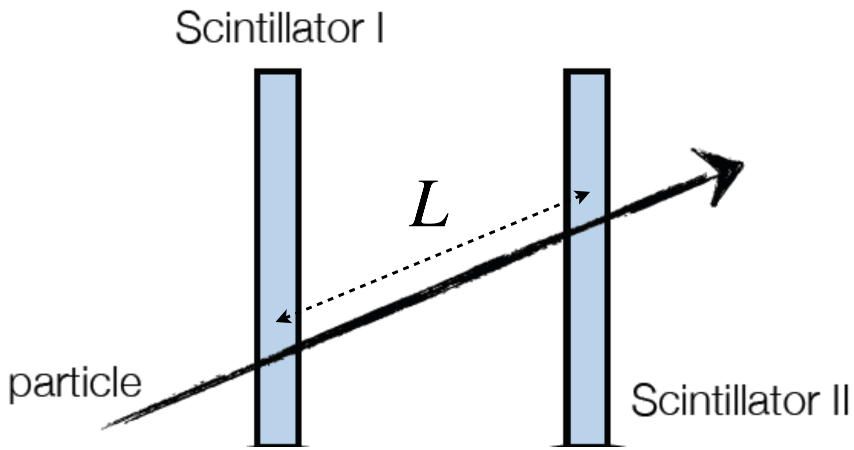




Excellent π/K separation over the kinematically allowed region at BaBar

Time Of Flight (TOF) detector

Measure signal time difference between two detectors with good time resolution [can use time of beam crossing as start signal]



Relativistic particles, $E \simeq pc \gg m_i c^2$:

$$\Delta t \approx \frac{L}{pc^2}\left[(pc + \frac{m_1^2 c^4}{2pc}) - (pc + \frac{m_2^2 c^4}{2pc})\right]$$

$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

Cherenkov counter, RPC : $\sigma_t \approx 40$ ps
Scintillator counter : $\sigma_t \approx 80$ ps

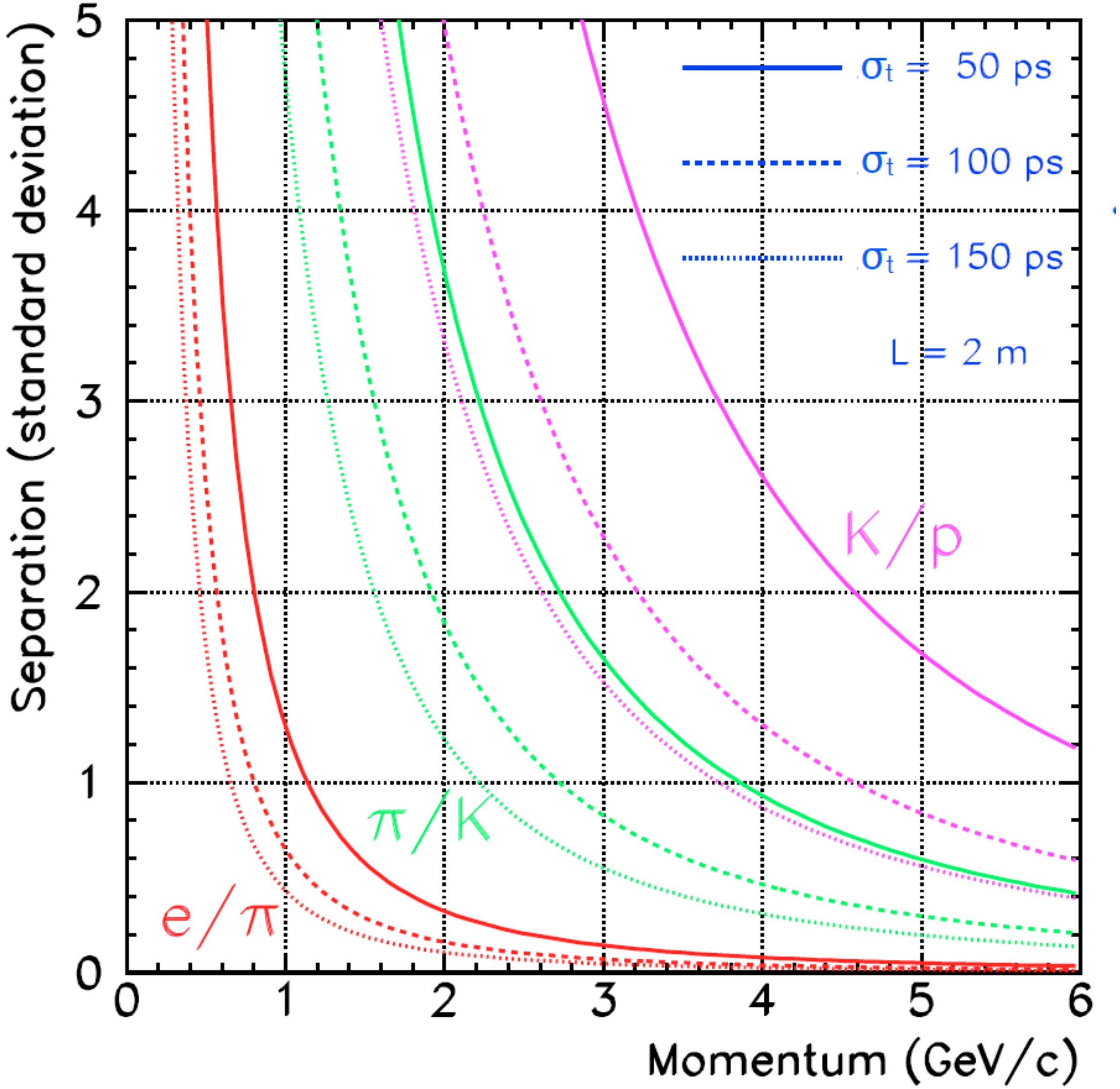
Number of standard deviation separation for a TOF and RICH detector

$$N_\sigma = \frac{|m_1{}^2 - m_2{}^2|\, d}{2\, p^2\, \sigma_t\, c} \quad \text{TOF}$$

$$N_\sigma = \frac{|m_1{}^2 - m_2{}^2|}{2\, p^2\, \sigma_\theta\, \sqrt{n^2 - 1}} \quad \text{RICH}$$

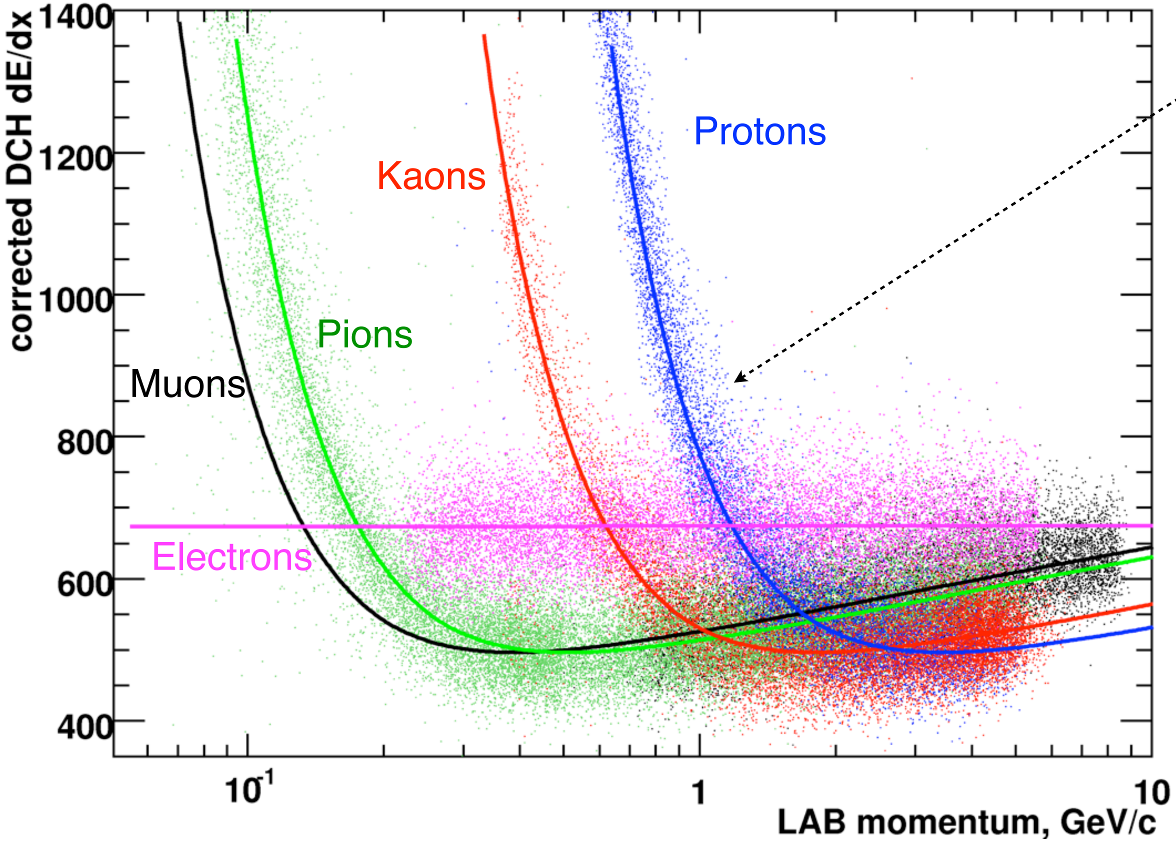
Factor $1/\sqrt{n^2 - 1}$ allows RICH to cover high momentum spectrum using appropriate radiators (n value close to 1)

TOF performance - example L = 2 m



dE/dx measurement - an example

Measured energy loss in BABAR drift chamber (DCH)



Bethe-Bloch distribution

Large Landau fluctuations: use many dE/dx measurements and truncate large energy-loss values “truncated mean”

dE/dx resolution~7.5%

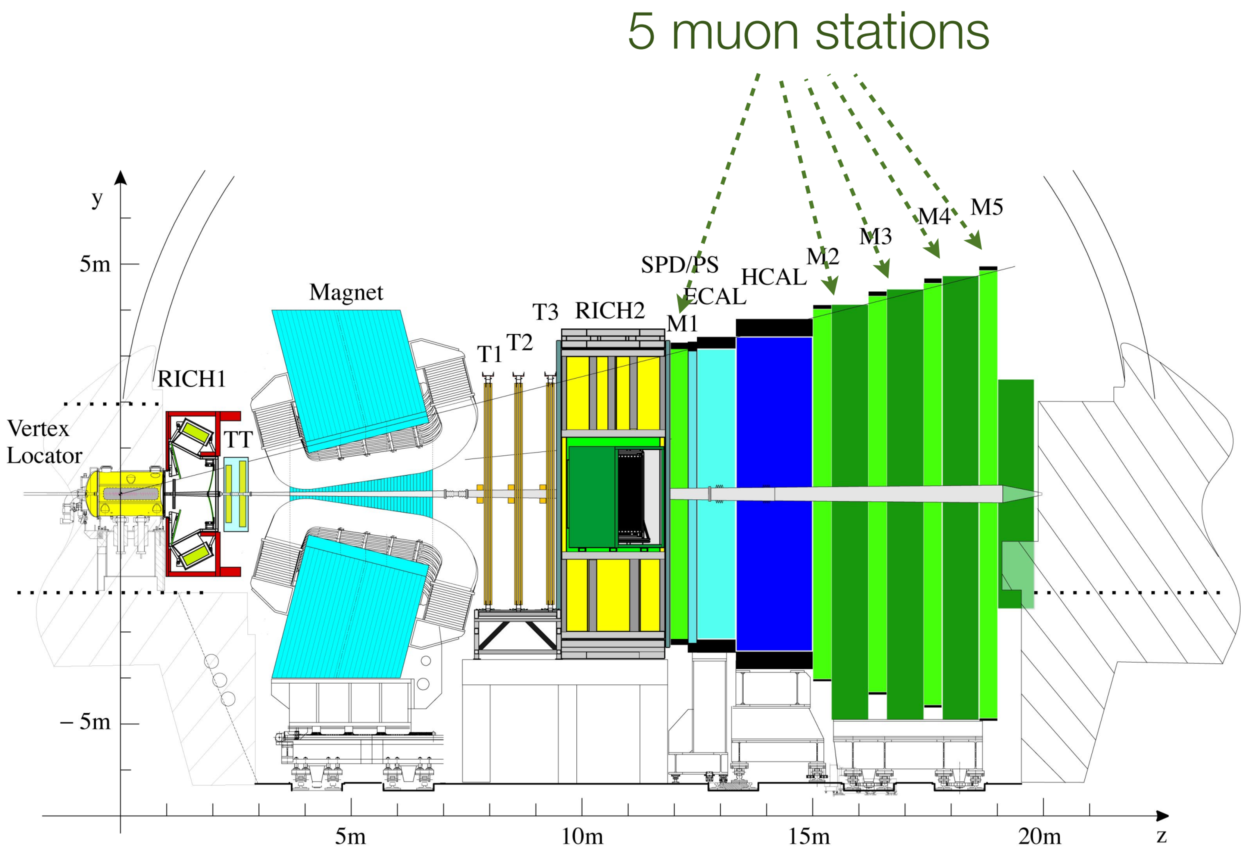
Excellent kaon-pion separation below 700 MeV/c, where the DIRC is not effective

Separation at to the 2σ level at higher momentum (3 GeV/c)

Muon detectors

Muon system - LHCb

Provide information for L0 trigger and offline muon identification



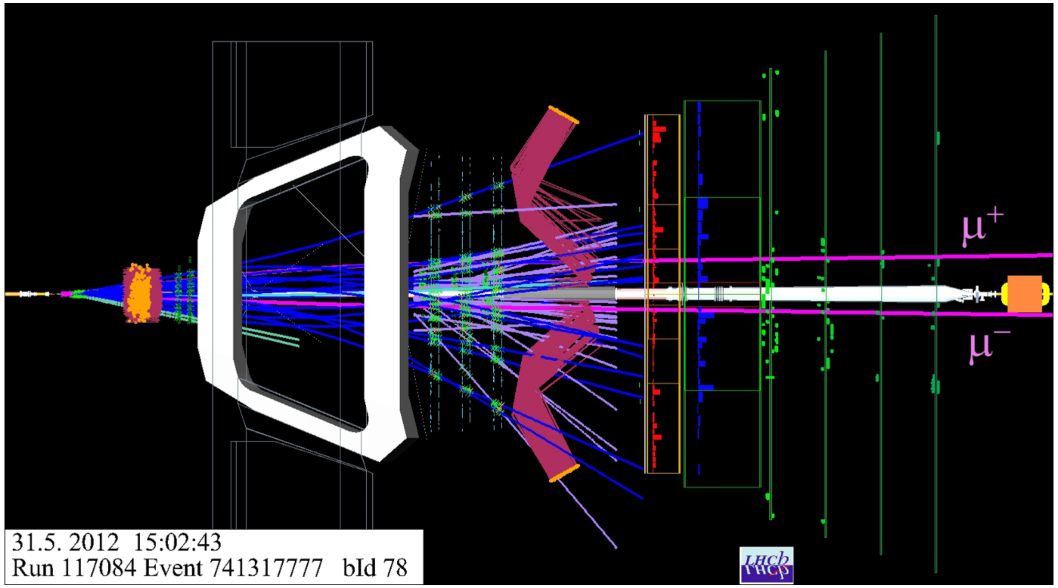
Minimum ionizing particles; penetrates thick iron absorbers (80cm); measure signal behind complete detector

5 stations M1-M5 (for a total active surface of 435 m^2) separated by iron filters (iron is only permeable to energetic muons)

1368 Multi-Wire Proportional Chambers and 24 triple GEM (Gas electron Multiplier) detectors (in the M1 region close to the beam) with spatial X-Y readout

Performance - LHCb

$B_s \to \mu^+\mu^-$ rare decay a candidate event



A track is a candidate muon when has hits in a minimum number of stations (2-4 depending on momentum value)

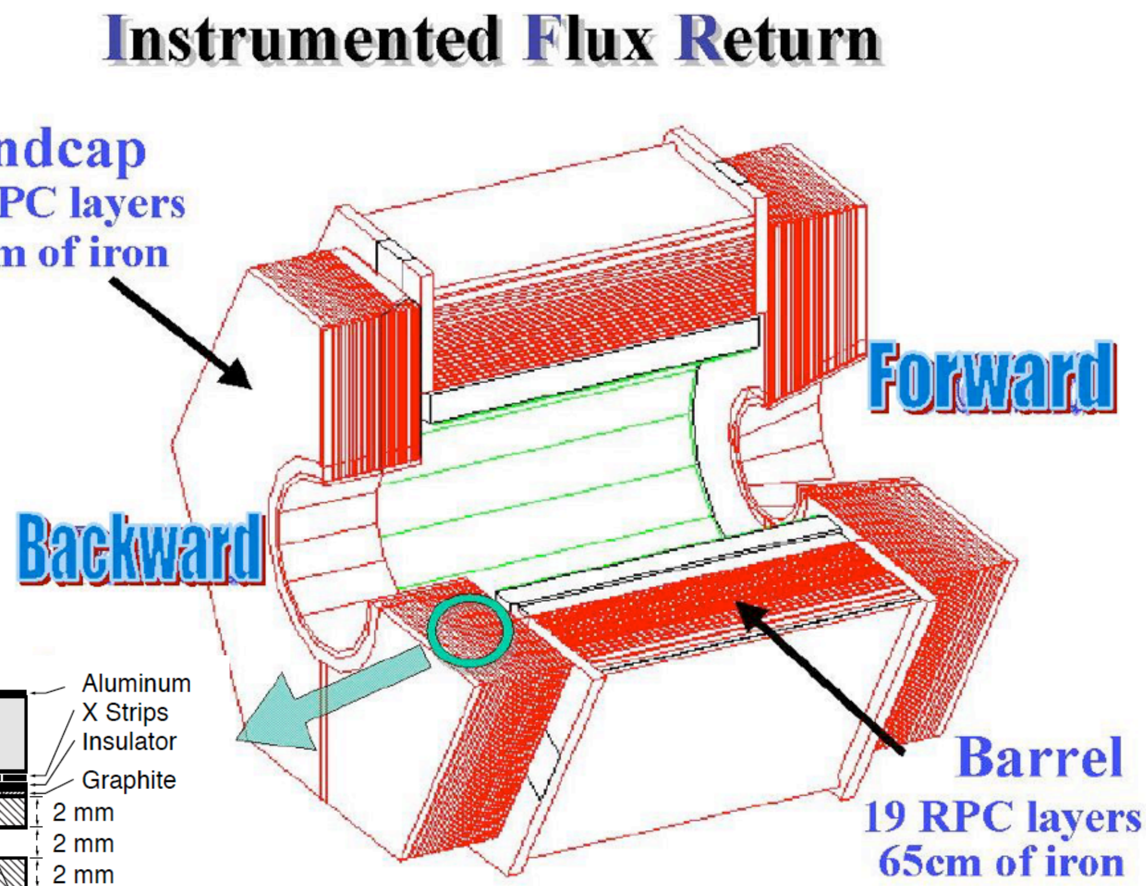
Acceptance ~20% for muons from inclusive b semileptonic decays

Muon p>6GeV/c to cross 5 stations (~20 X_0)

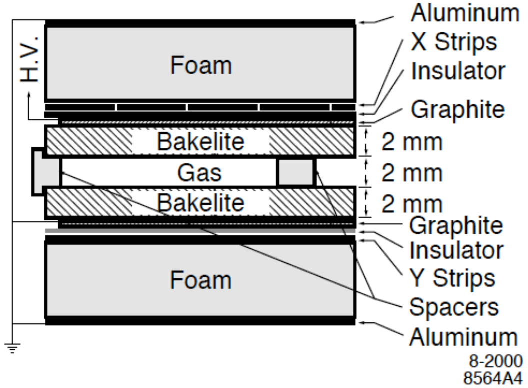
Muon ID efficiency ~97% with 1-3% $\pi \to \mu$ misidentification

Instrumented Flux Return (IFR)- BaBar

Original design: for muon and K_L detection

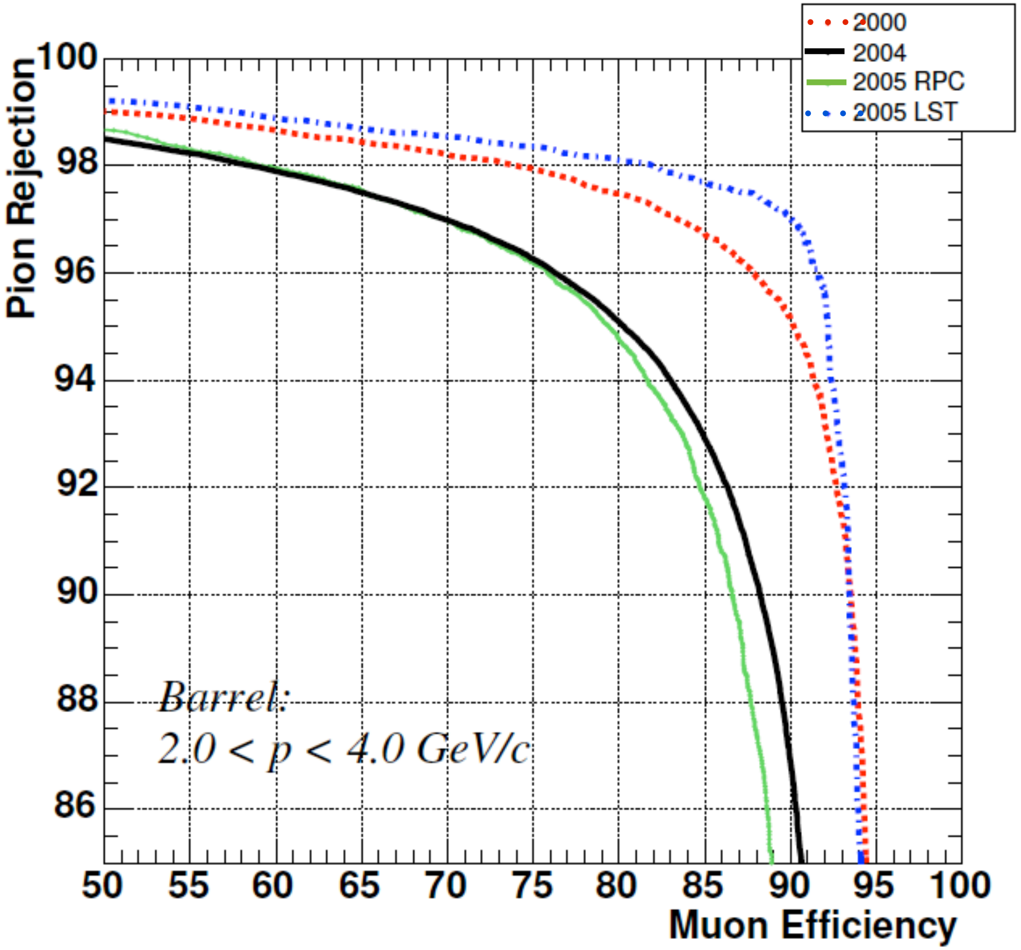


RPC: Resistive Plate Chamber



Gas: Argon (57%), Freon (electronegative gas) (39%), Isobutane (4%)
HV ~8 kV, position resolution few mm

Performance - BaBar



Muons with p>1 GeV/c are likely to cross the entire IFR while hadrons are stopped within the first layers

Decays in flight ~2% $\pi \rightarrow \mu$ misidentification

Serious degrading of RPC efficiencies during time: quality of chambers and operations under high temperatures

Barrel replaced with Limited Streamer Tubes (LST) and Forward Endcap with new RPC of better quality

Exercises

1. A Cherenkov counter based on nitrogen gas is located on a charged particle beam with momentum 20 GeV/c. The dependence of the refractive index on the pressure P is $n=1.3 \cdot 10^{-9}P$ (Pa). Calculate the range of P for which the Cherenkov emits light for π but not for K.
2. What are the Cherenkov angles for electrons and pions of 1 GeV/c for a radiator with $n = 1.4$? What will be the ratio of the number of radiated photons for incident electrons and pions?
3. What is the fraction of charged pions decaying in flight within L=4m if p=3GeV/c? If L=20m and p=40GeV/c?