Cherenkov Radiation and RICH Detectors

Basic expression of Ch radiation

History of the Ch radiation
and the RICH

What is a RICH ?

Physics for which you need a RICH

Ingredients of a RICH

Illustrative RICHes – geometry, radiators, photodetectors…
DELPHI
BaBar DIRC
LHCb

Large scale RICH systems:
- Super-K
- Icecube

Epilogue: a very quick look at transition radiation

Guy Wilkinson
HT 2014

Cherenkov Radiation in a Nutshell

Fundamental Cherenkov relation:

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

Both a *threshold* and thereafter, an *angular dependence* up to *saturation* (β=1)

Frank-Tamm relation:

$$\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 L \sin^2\theta_C$$

So number of photons will also increase with velocity (up to saturation)

History of Cherenkov Radiation

- Prediction of Cherenkov radiation: Heaviside 1888
- Discovery (by accident) : Pavel Cherenkov 1936

Cherenkov: 1905-1990

Radiation seen when uranyl salts exposed to radium source.

Sergey Vavilov was Cherenkov's supervisor, and hence Russians refer to Vavilov-Cherenkov radiation

- Explanation: Tamm and Frank 1937
- Experimental exploitation in HEP pioneered by Cherenkov himself

(Cherenkov, Tamm, Frank: Nobel Prize 1958)

Fathers of the RICH

Cherenkov :
1936 – discovery

1905-1990

Arthur Roberts: 1960 - first to propose exploiting ☺$_c$

1912-1994

Tom Ypsilantis: 1977- driving force behind practical RICH

1928-2000

What is a RICH ?

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

Measurement of ♌ from RICH, together with p, from tracking system, allow mass, and hence PID to be determined.

This is an excellent way of separating □ from kaons and protons

The simplest way to exploit Cherenkov radiation is to choose n such that heavy particles do not emit light. This works OK if p range narrow.

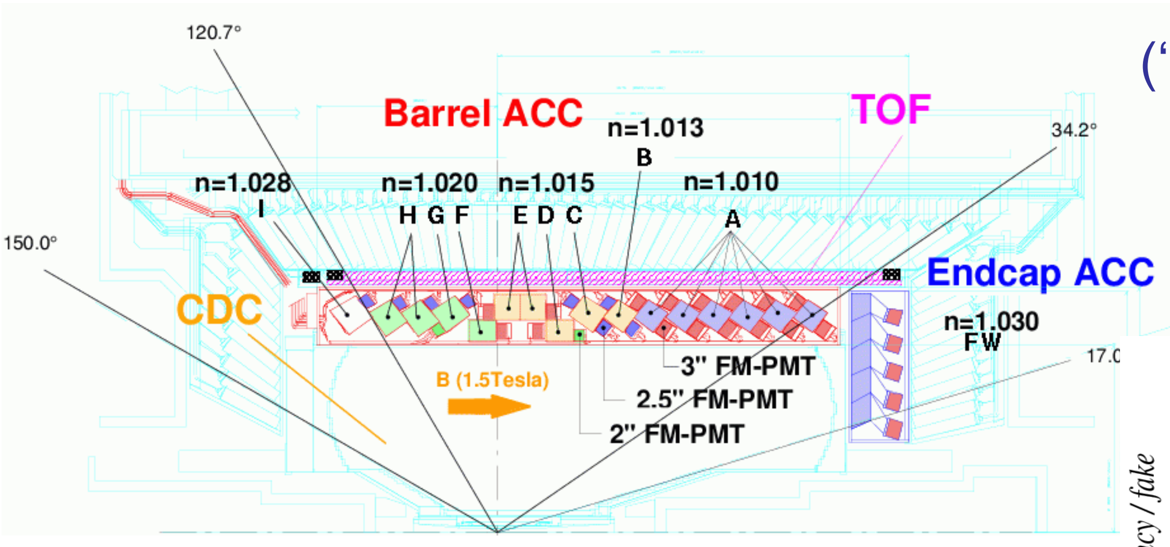
→Cherenkov counter (not a RICH!)

But if we want to do better, or if momentum is far from monochromatic, then we need to measure ☺$_C$. We have to image the ring. This is a RICH!

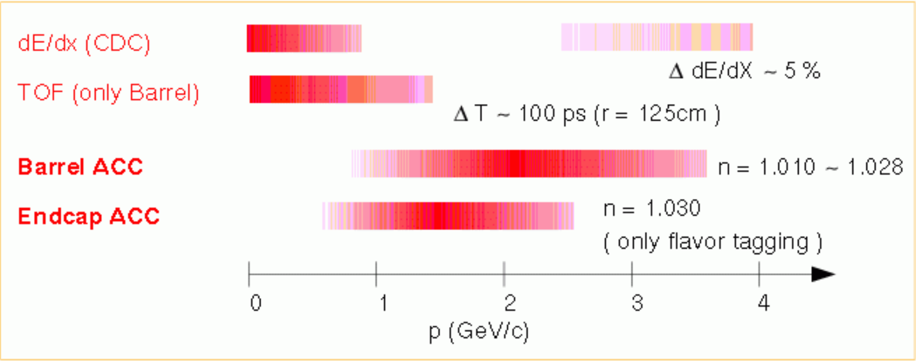
Belle Cherenkov Counter: not strictly a RICH!

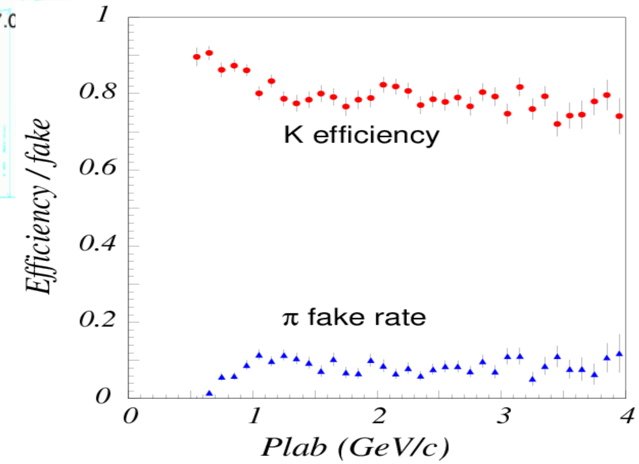
Cherenkov technique allows hadron PID even when ring not imaged → merely look for presence/absence of light. No light means heavy particle.

(‘veto’ or ‘threshold’ mode)



Amount of light seen can still be exploited.





This a viable approach if we do not need to cover a large range in p !

Experiments which need Hadron ID

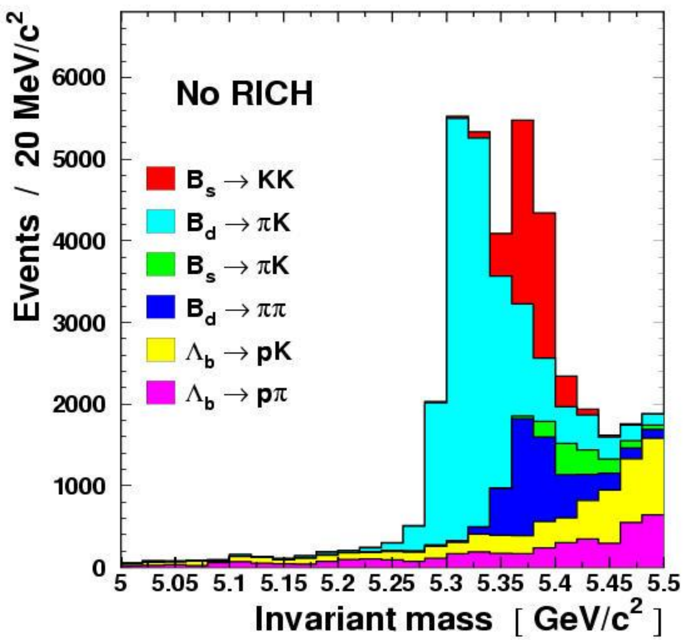
- B physics CP violation studies
- Hadron spectroscopy/exotic searches
- Large volume neutrino detectors (special case – see later)

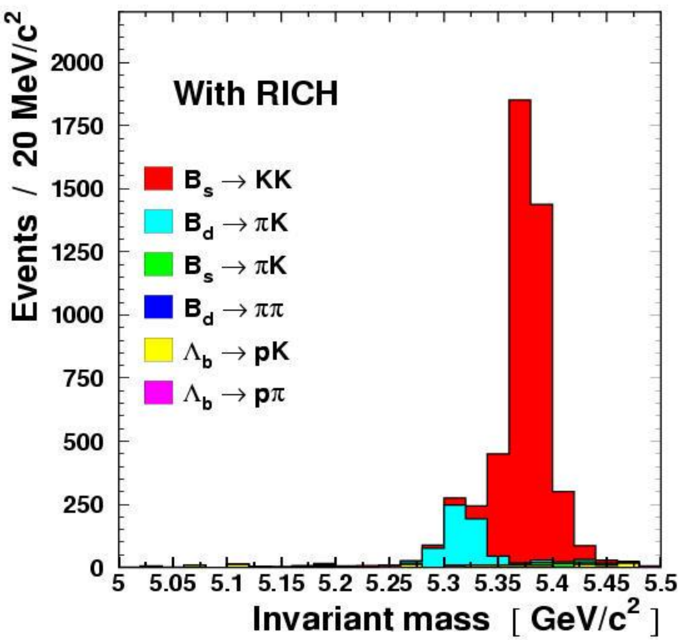
In all cases, benefit from imaging Cherenkov rings!

B (& D) Physics Requirements for PID

B physics CP violation experiments perform exclusive reconstruction of final states, with & without kaons (and protons). Hadron PID mandatory.

eg. selection of $B \rightarrow h^+h^-$ - below is an LHCb simulation study





Another example: kaon ‘flavour tagging’ – essential in CP measurements

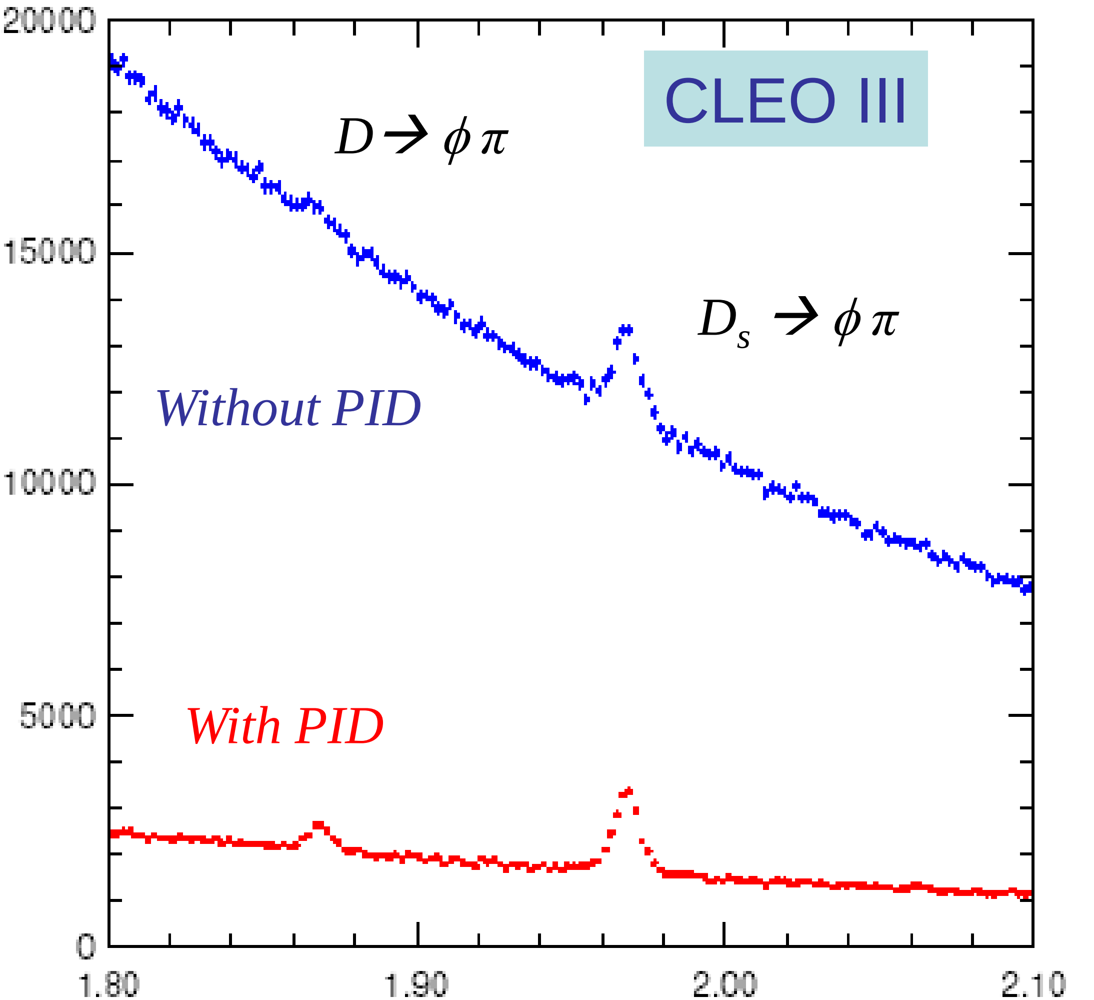
B (& D) Physics Requirements for PID

Suppress background from combinatorics.

In building up, eg.

B → D X → n □ K X

PID allows much cleaner reconstruction of intermediate charm mesons → cleaner B



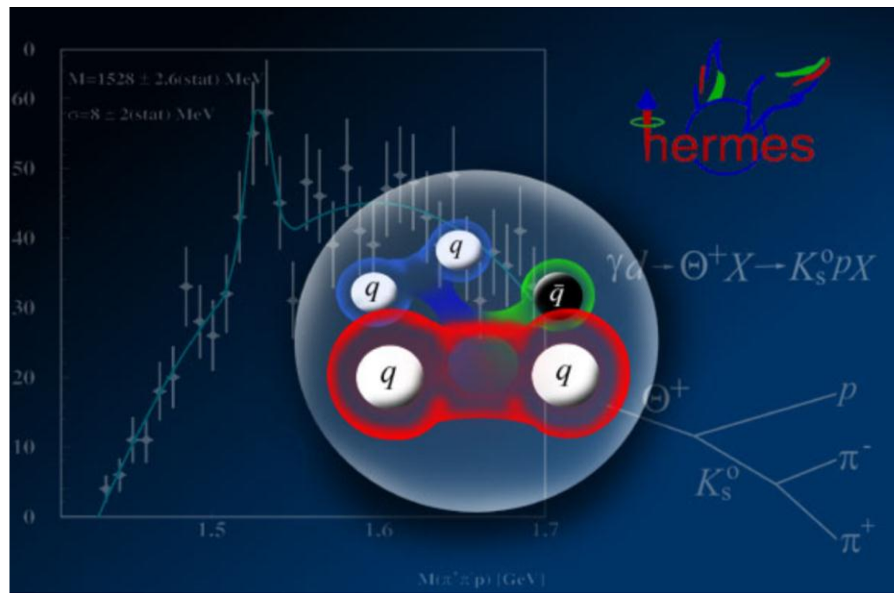
Spectroscopy / New Hadron Searches

An example: pentaquark search

$$\mathbf{e}^+ + \mathbf{D} \rightarrow \Theta^+ + \mathbf{X} \rightarrow \mathbf{K}_s^0\mathbf{p} + \mathbf{X} \rightarrow \pi^+ + \pi^- + \mathbf{p} + \mathbf{X}$$

Θ^+ identified in pK_s

RICH essential for background suppression



HERMES pentaquark signal

Peak at:

M= 1527 ± 2.3 MeV

σ= 9.2 ± 2 MeV

Significance:

$N_s^{2\sigma} / \sqrt{N_b^{2\sigma}} = 6.1$ (naïve)

$N_s / \delta N_s = 4.3$ (realistic)

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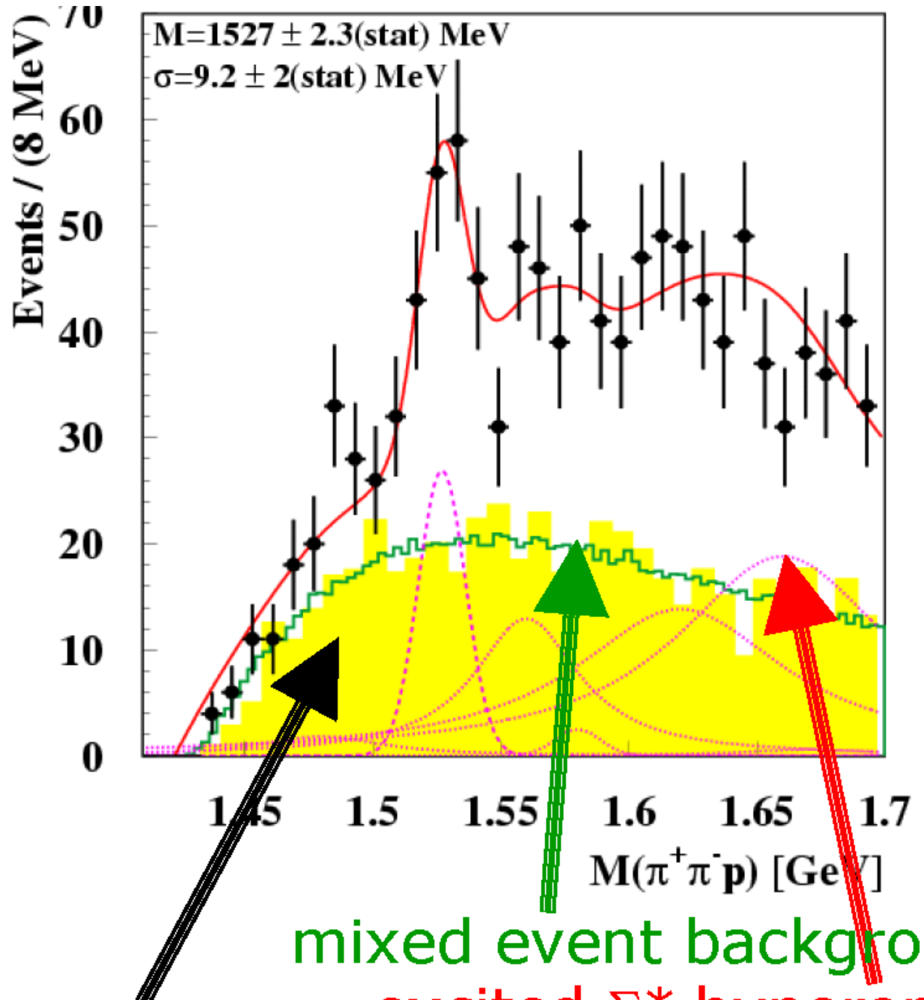


mixed event background

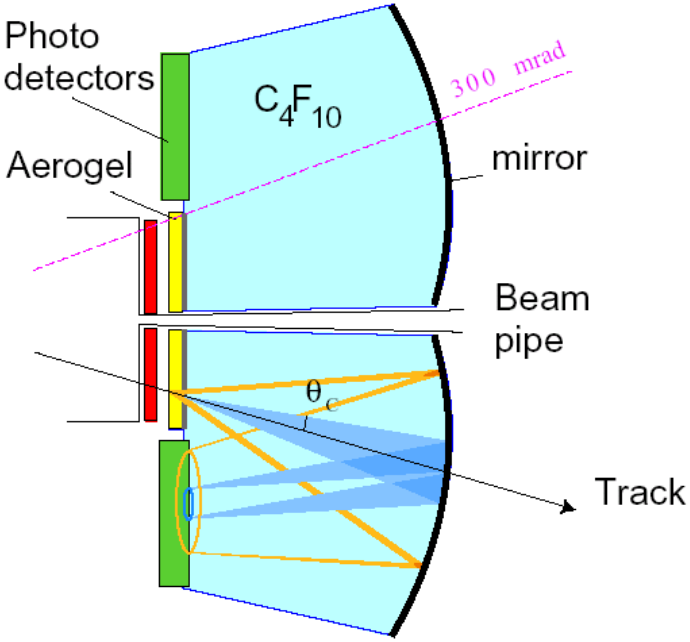
excited Σ* hyperons (not included in Pythia6)

PYTHIA6

Ingredients of a RICH

We need a radiator, a mirror and a photodetector.

Why do we need mirrors ?



1. Often to take light out of acceptance
2. Mirrors focus light. Without mirrors we would have a splodge.

But sometimes it is true we can survive without mirrors…

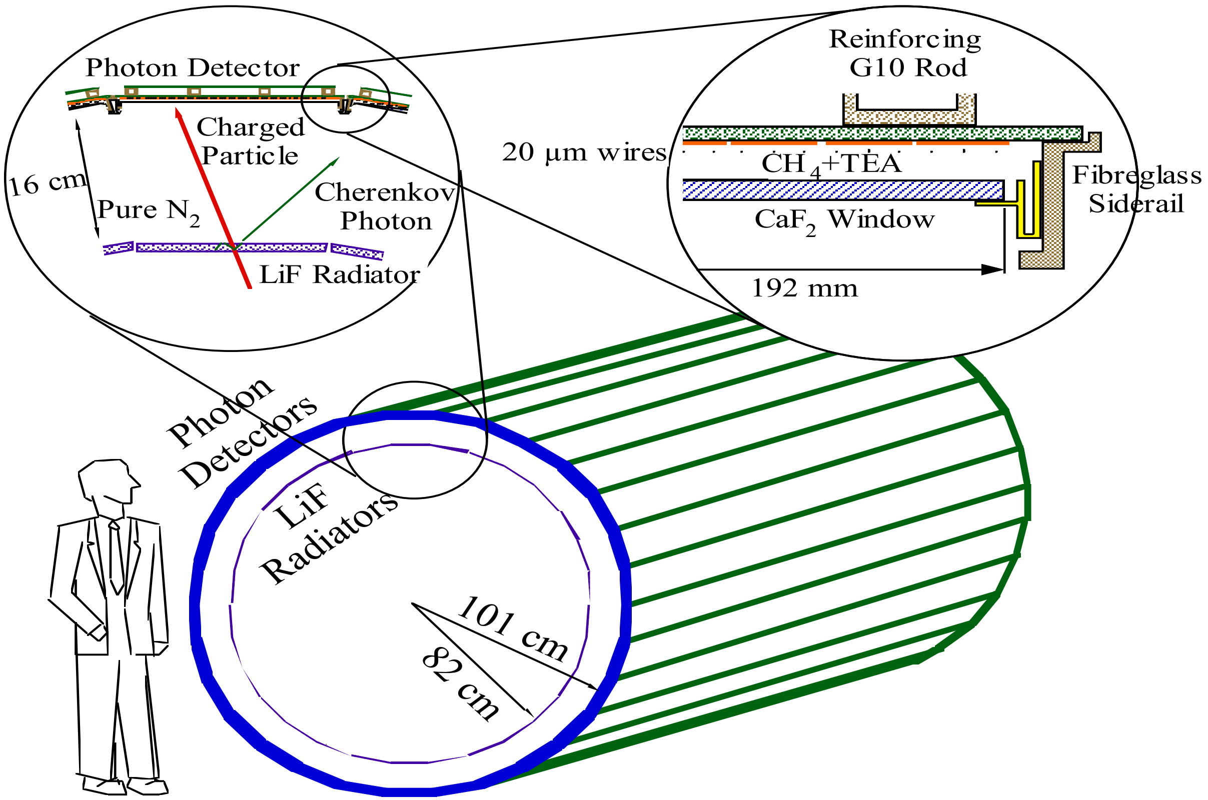
Proximity Focusing

If radiator is sufficiently narrow in extent, then light which emerges will be a ring, rather than a splodge.

This is *proximity focusing*.

Works with solid and liquid radiators, where we get plenty of photoelectrons.

CLEO III RICH



Considerations in Building a RICH

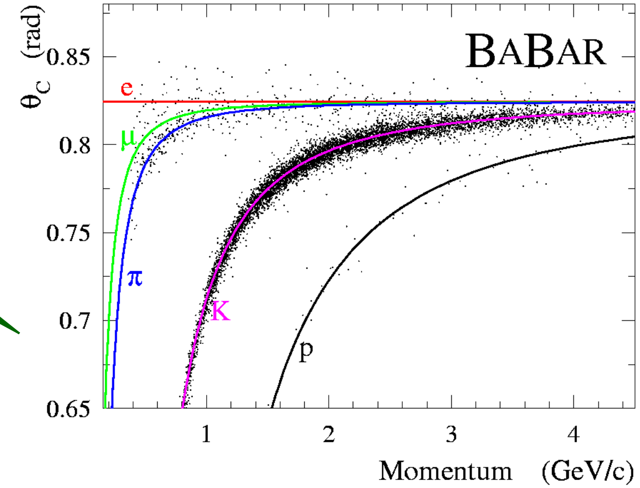
Want to optimise ring resolution.
Ring resolution determines how far in momentum PID extends.

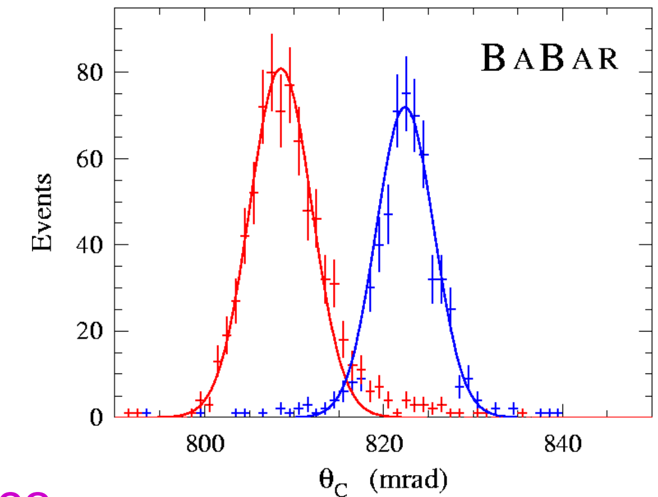
$$\sigma_{\theta_C}^{\text{ring}} = \sigma_{\theta_C}/\sqrt{N_{\text{pe}}}$$

Contributions to ϑ_C :

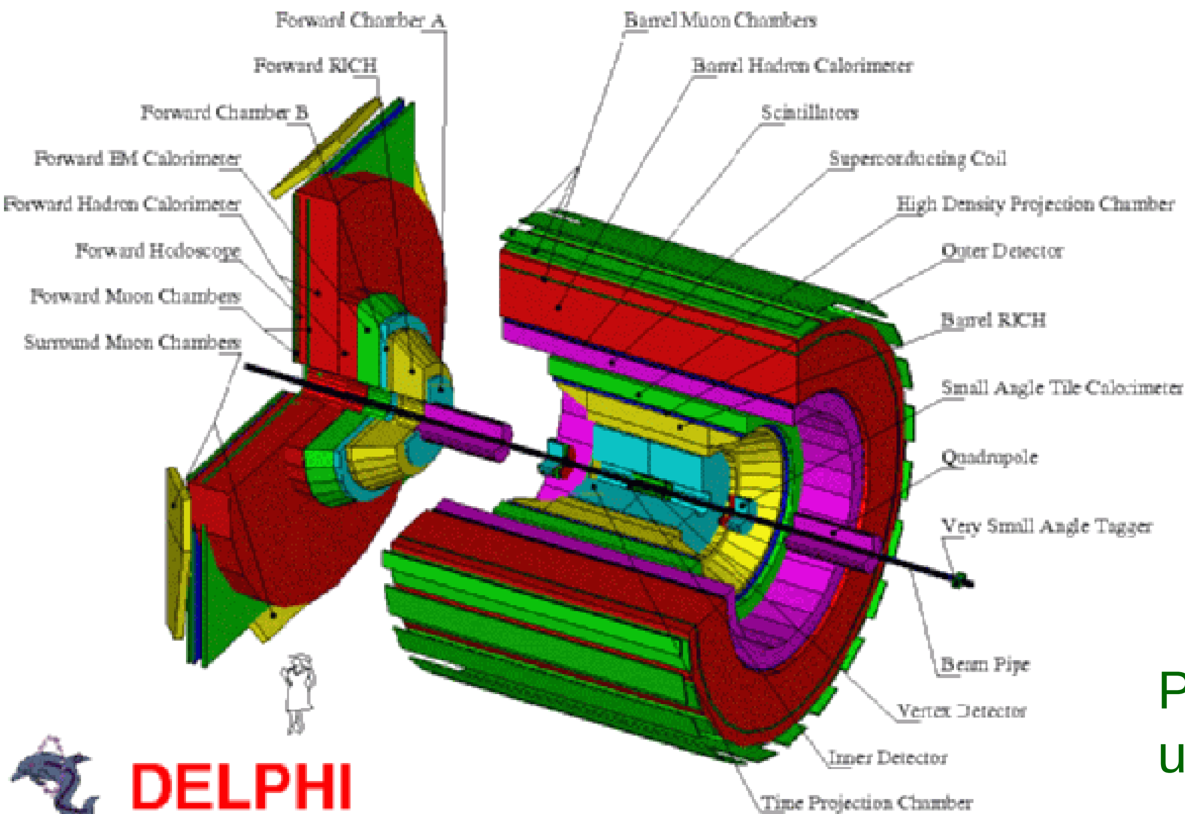
- Emission point error (how well the focusing works)
- Detection point error (the spatial resolution of the photodetector)
- Chromatic error – we will explain this later.

N_{pe} optimised through radiator choice & length, and photodetector performance.





DELPHI (1989-2000) RICH



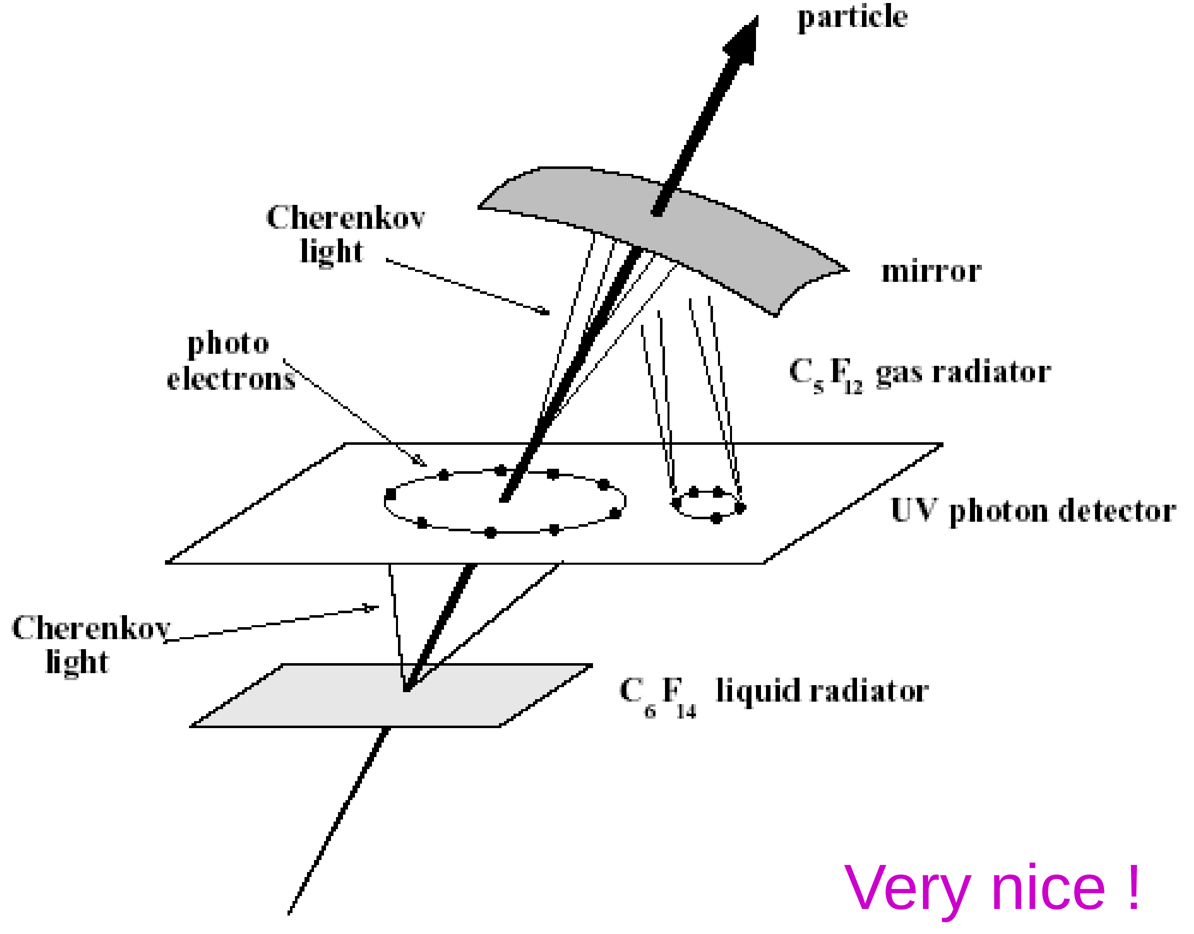
DELPHI

OMEGA, DELPHI & SLD were the first experiments to use RICHes in anger.

DELPHI/SLD RICHes (CRID) very similar.

Provided PID from low p up to 25 GeV or so.

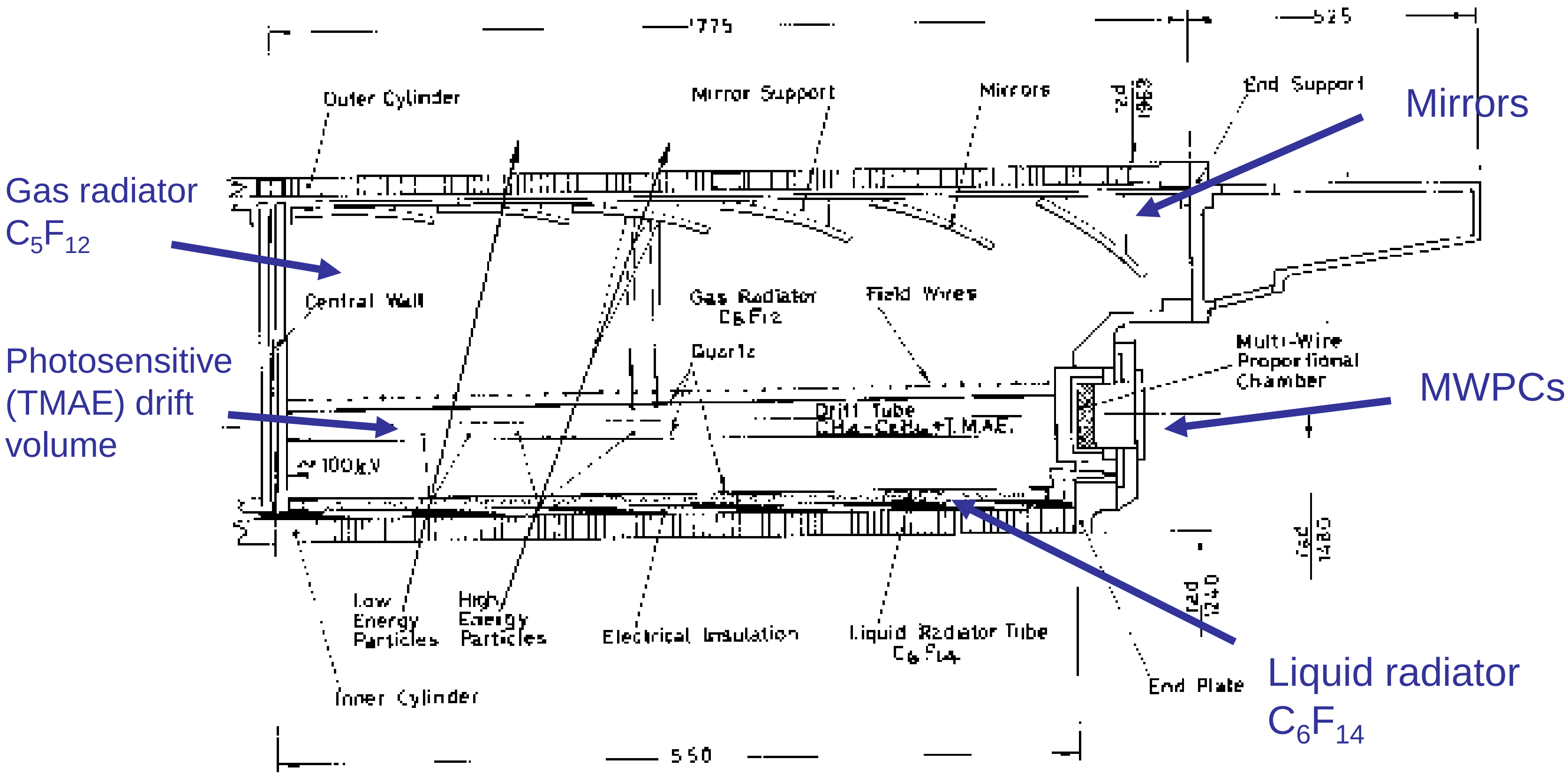
DELPHI/SLD RICH – the principle



Very nice !

DELPHI RICH – the reality

3 fluid system, mirrors and HV shoehorned into 70cm (inaccessible) gap



The horror, the horror!

TMAE / What was tough about DELPHI

What is this TMAE stuff ?

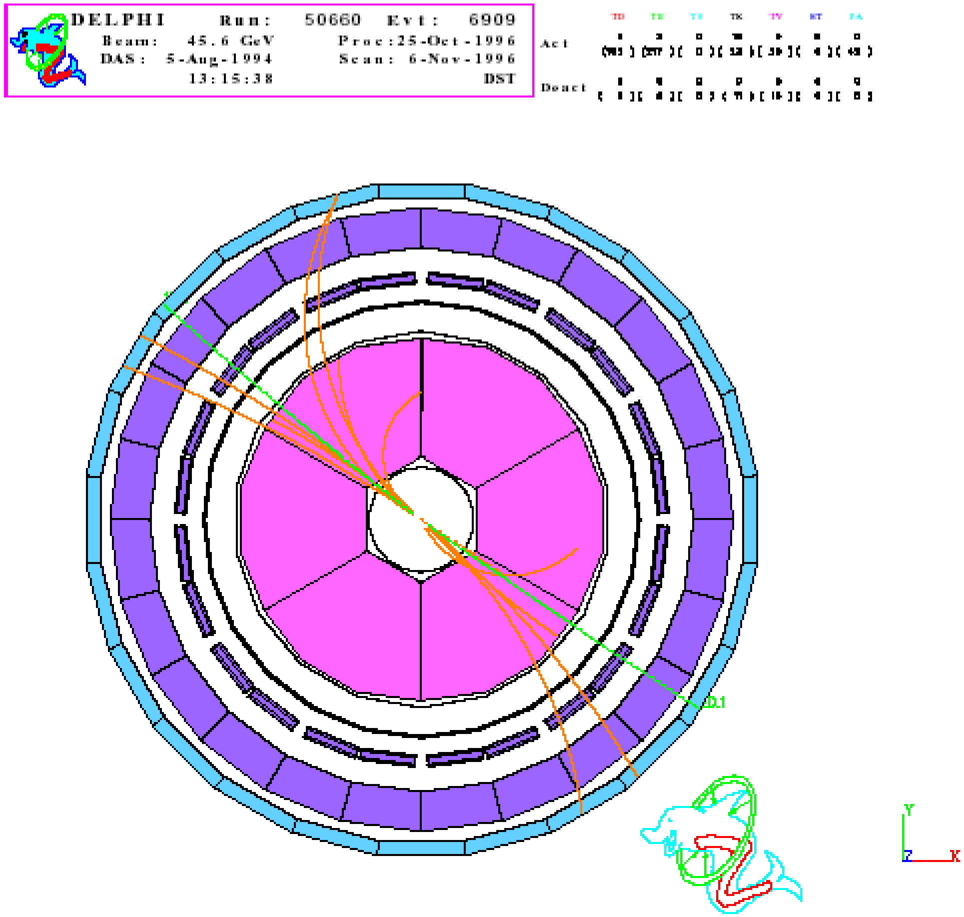
- Tetrakis dimethylamine ethylene
- Glows sickly green on contact with oxygen
  (“If it glows you’re screwed, if it doesn’t glow your screwed”
  from CRID group’s `Laws of TMAEDYNAMICS’)
- Sensitive in UV

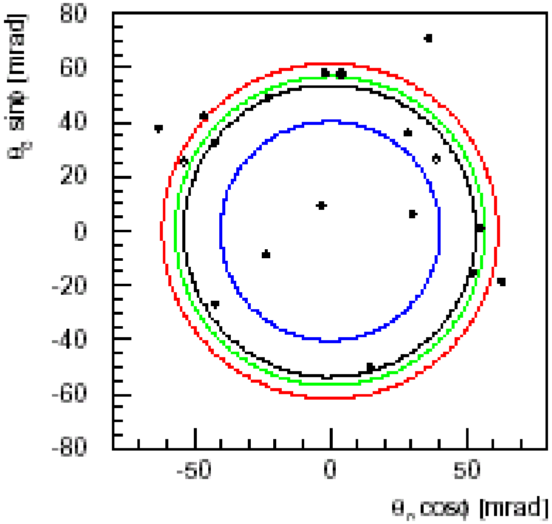
Some modest challenges of the DELPHI (& SLD) RICH (CRID):

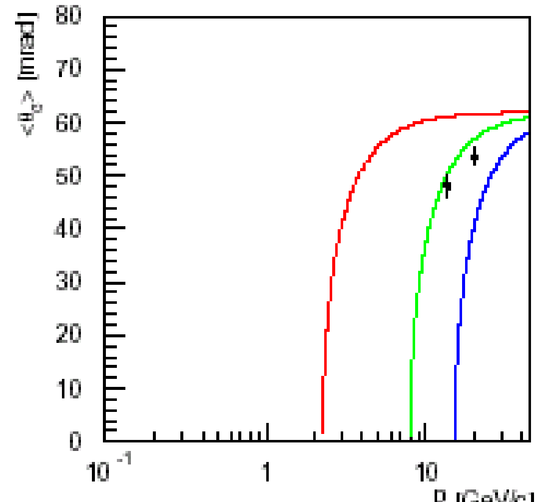
- Very limited and inaccessible space for 3 fluid system and mirrors.
- Need to keep gas radiator at 40 degrees to stop it condensing, whereas TMAE kept at 28 degrees (to optimise absorption length)
- Liberated photoelectrons have to drift 1.5 m (TPC technique)

Unsurprisingly, took a long time to commission. Not a plug and play detector. Many crises along the way. But when working it worked a treat!

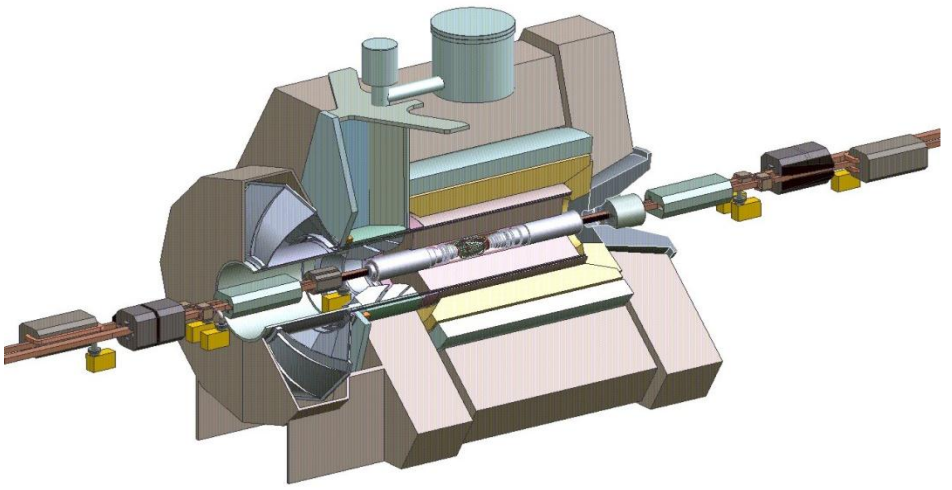
Tagging s-sbar jets







BaBar Detector of Internally Reflected Cherenkov Light (DIRC)



DIRC thickness:

8 cm radial incl. supports

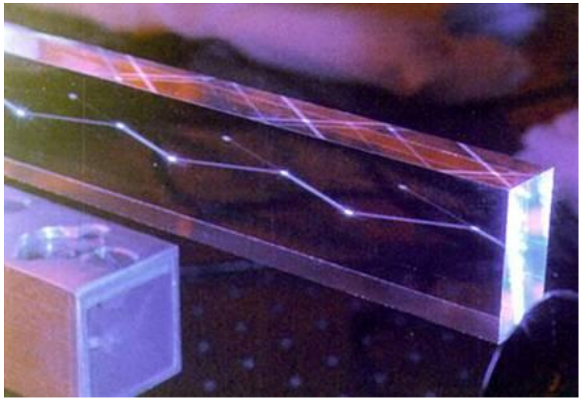
19% radiation length

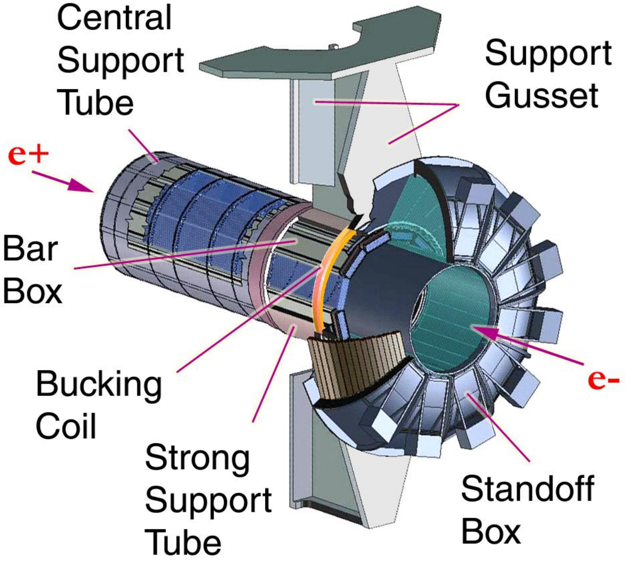
at normal incidence

DIRC radiators cover:

94% azimuth,

83% c.m. polar angle





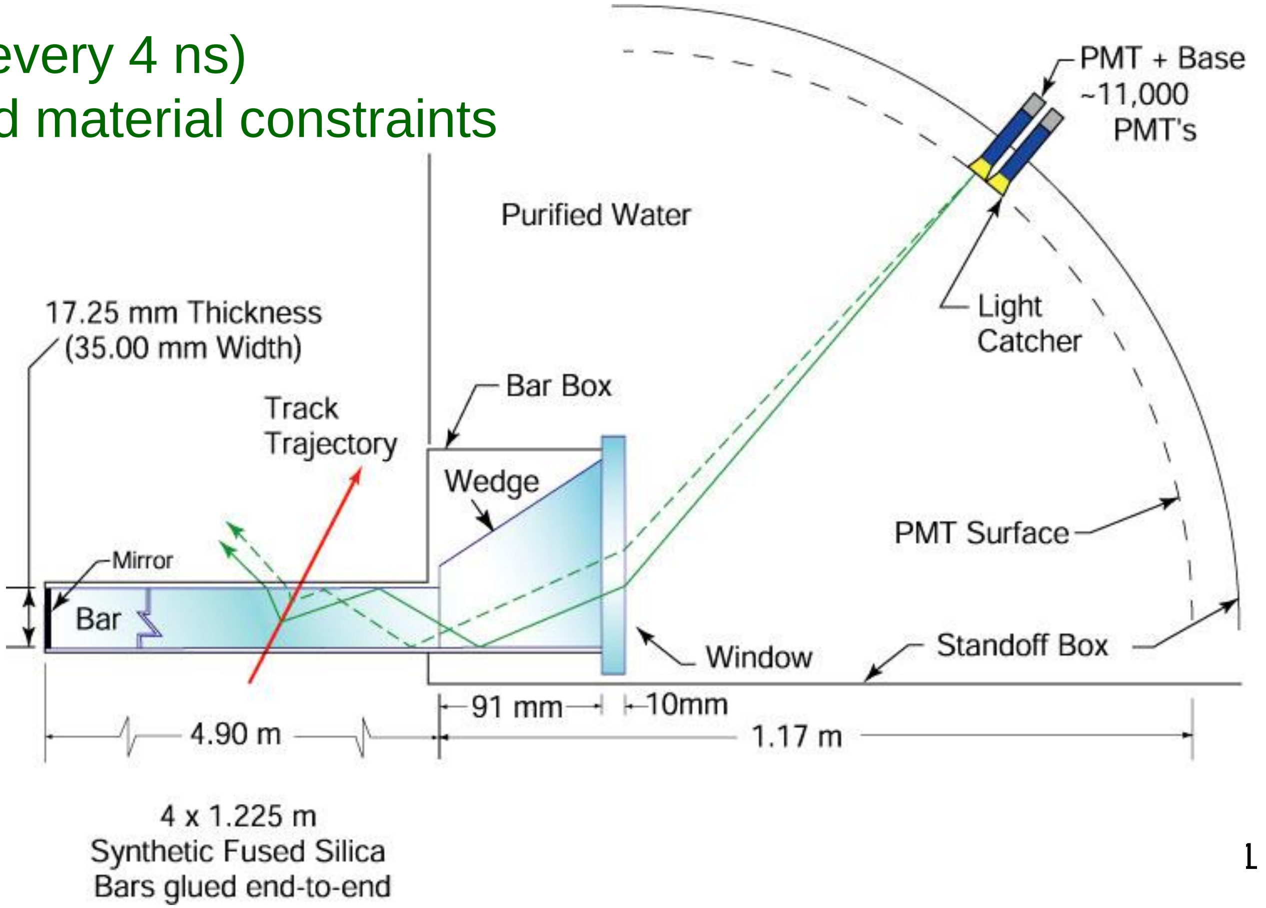
BaBar DIRC

BaBar PID requirements:

- π-K separation up to 4 GeV
- Low track density
- Must be fast (bx every 4 ns)
- Severe space and material constraints

DIRC an ideal solution!

PMTs provide adequate resolution



DIRC RECONSTRUCTION

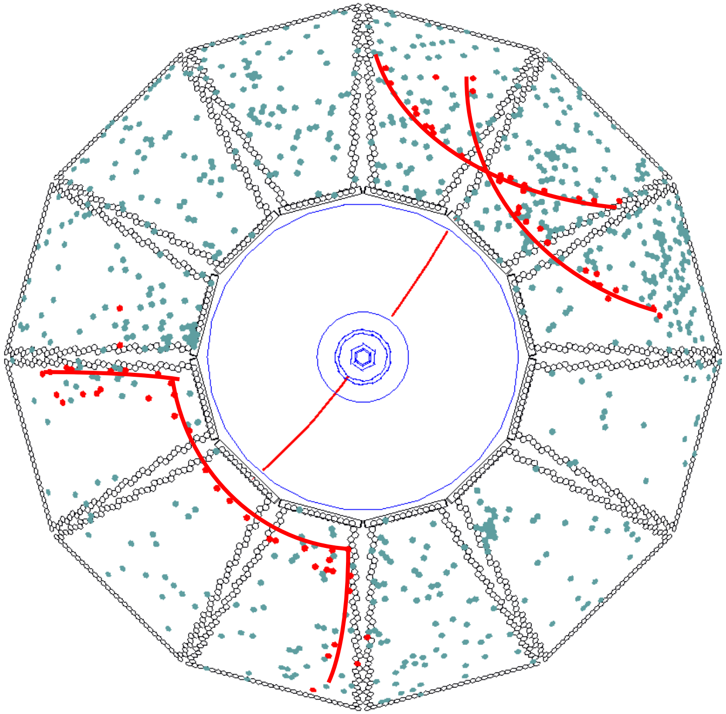
DIRC "Ring" images:

- limited acceptance for total internal reflection,
- reflection ambiguities (initial reflection up/down, left/right, reflection off mirror, wedge

  → up to 16 (θ_C, ϕ_C) ambiguities per PMT hit),
- toroidal detection surface,

→ Cherenkov ring images are distorted:

complex, disjoint images



Low energy photons from accelerator hit Standoff Box.

At current luminosity that causes rates of 80-200 kHz/tube.

80-200 kHz ⊗ 10,752 PMTs ⊗ ± 300 nsec trigger window

→ 500-1300 background hits (~10% occupancy)

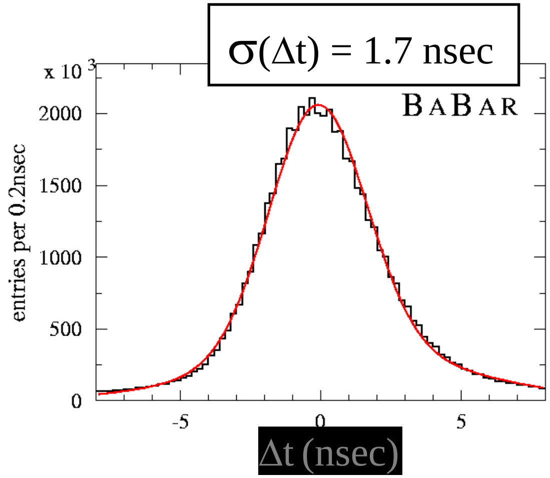
compared to

50-300 Cherenkov photons

Time information provides powerful tool to reject accelerator and event related background.

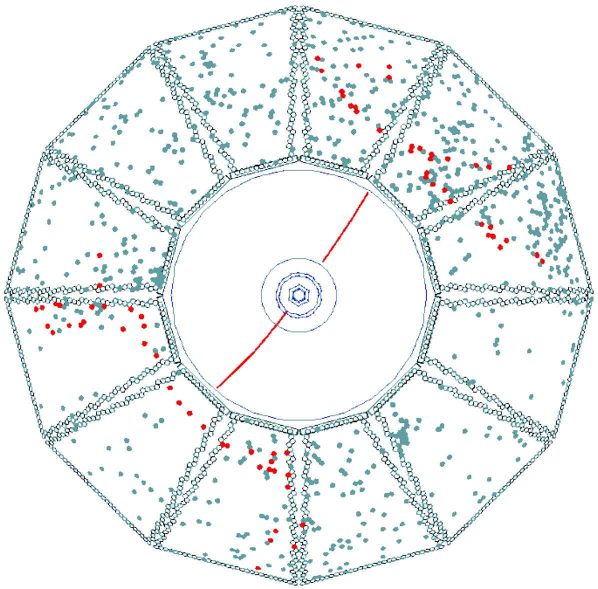
Calculate expected arrival time of Cherenkov photon based on

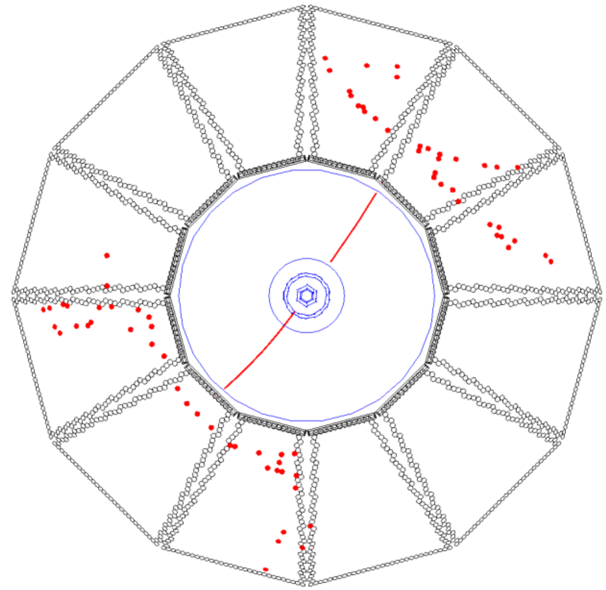
- track TOF
- photon propagation in radiator bar and in water



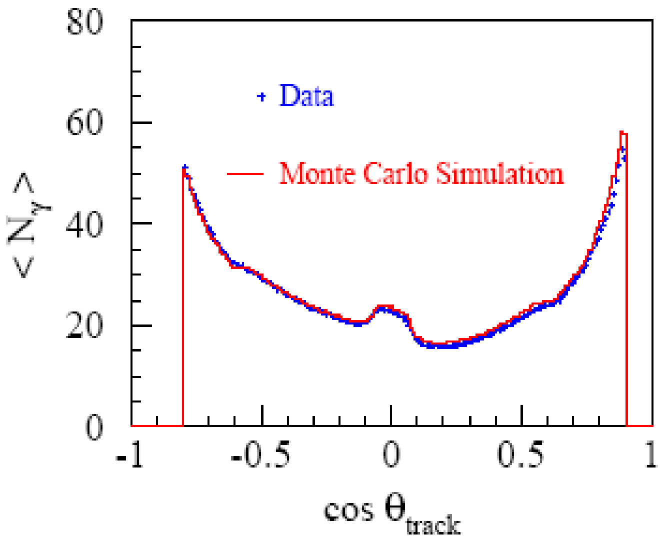
Δt: difference between measured and expected arrival time

± 300 nsec trigger window (~500-1300 background hits/event) → ± 8 nsec Δt window (1-2 background hits/sector/event)

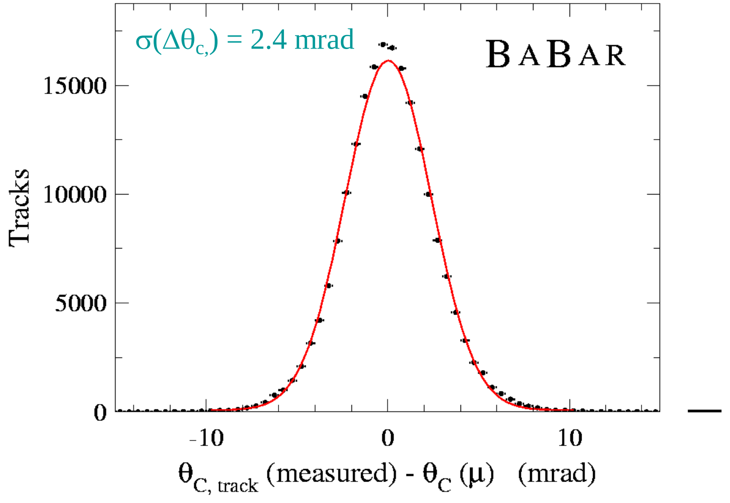




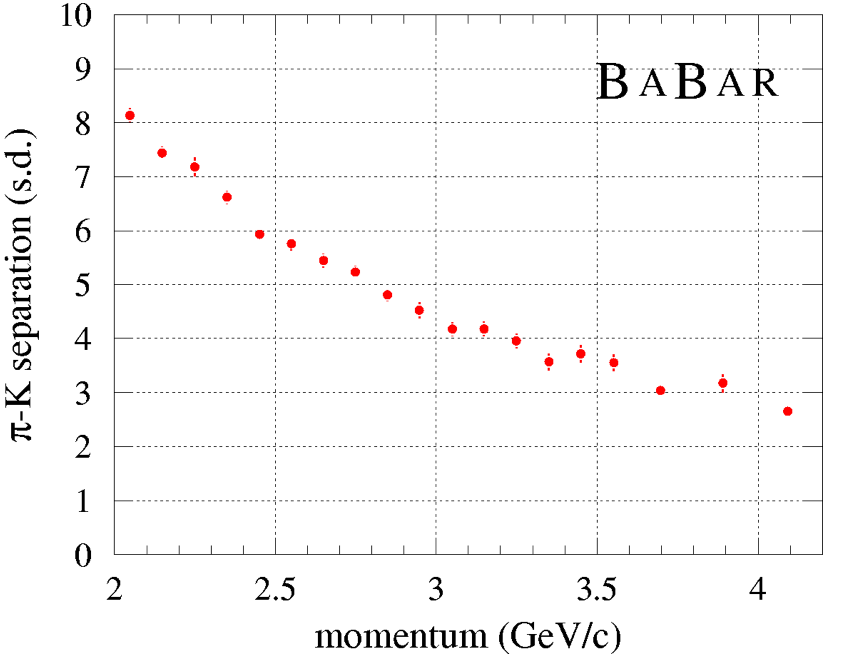
DIRC Performance



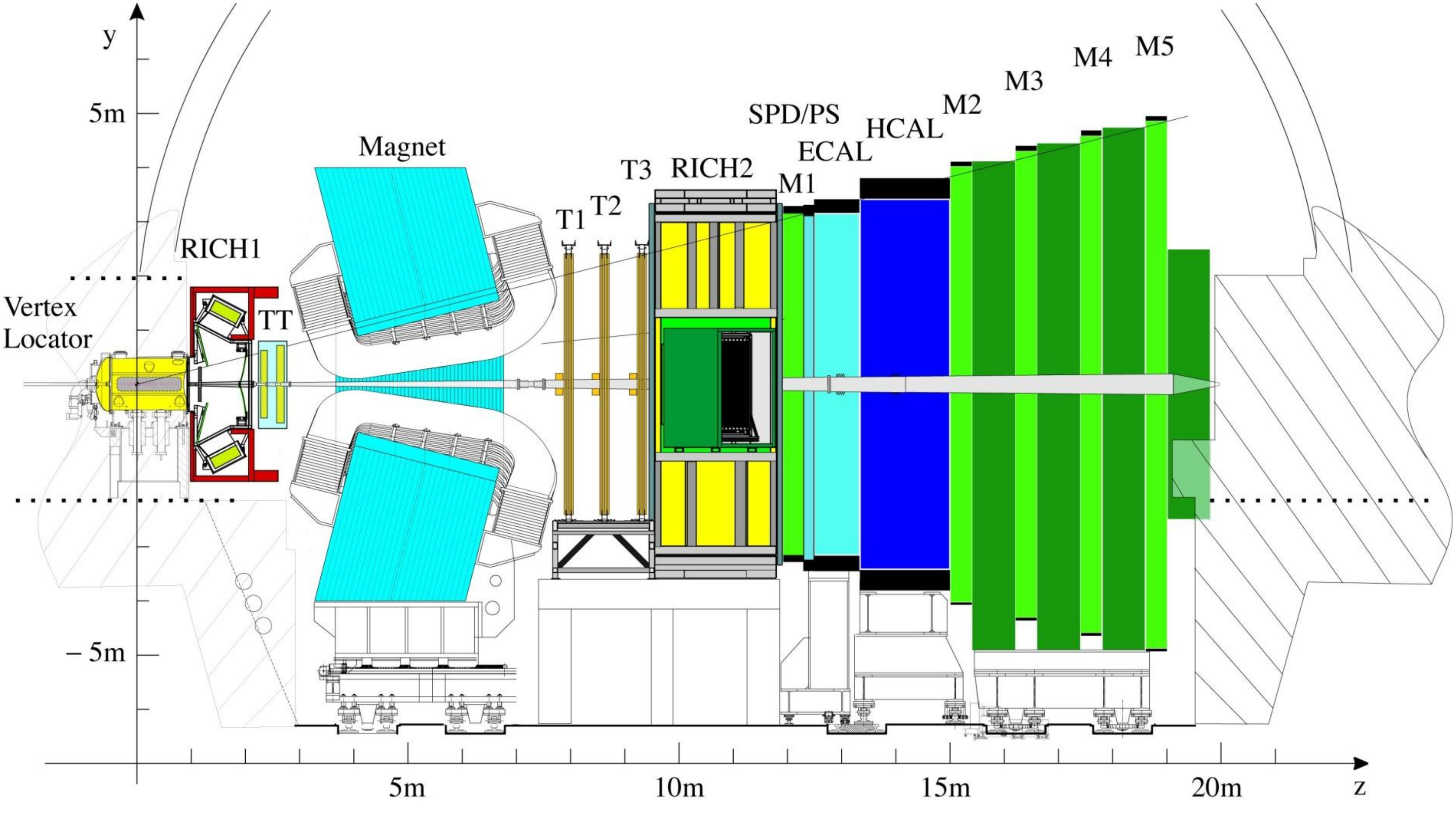
N_{pe} and resolution



π-K separation vs momentum

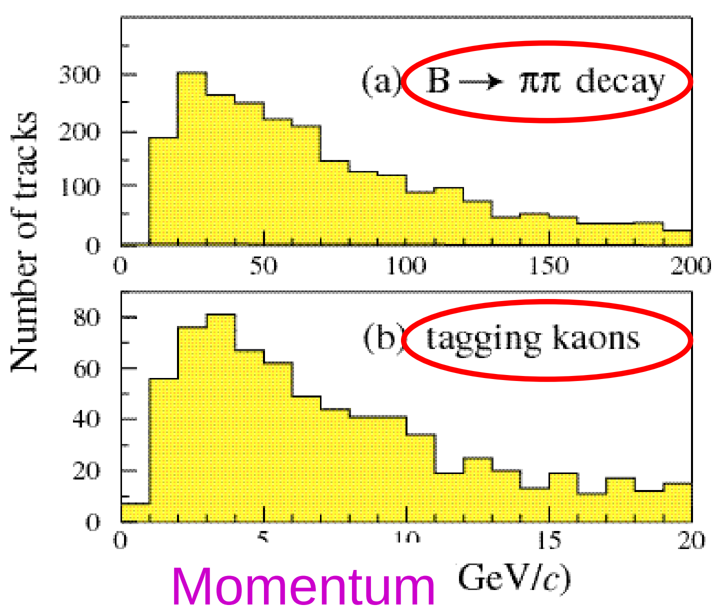


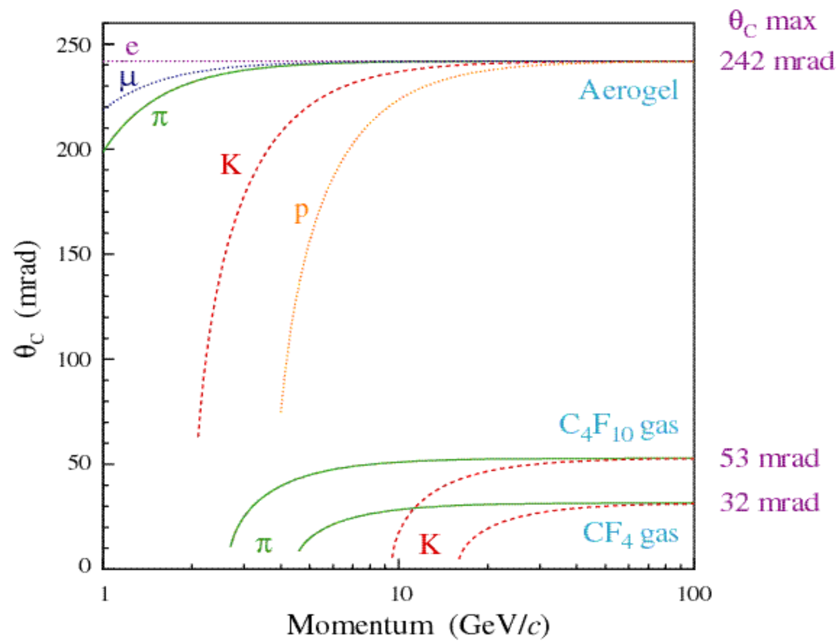
LHCb: a two RICH (3 radiator) detector



Why RICH? Why 3 radiators?

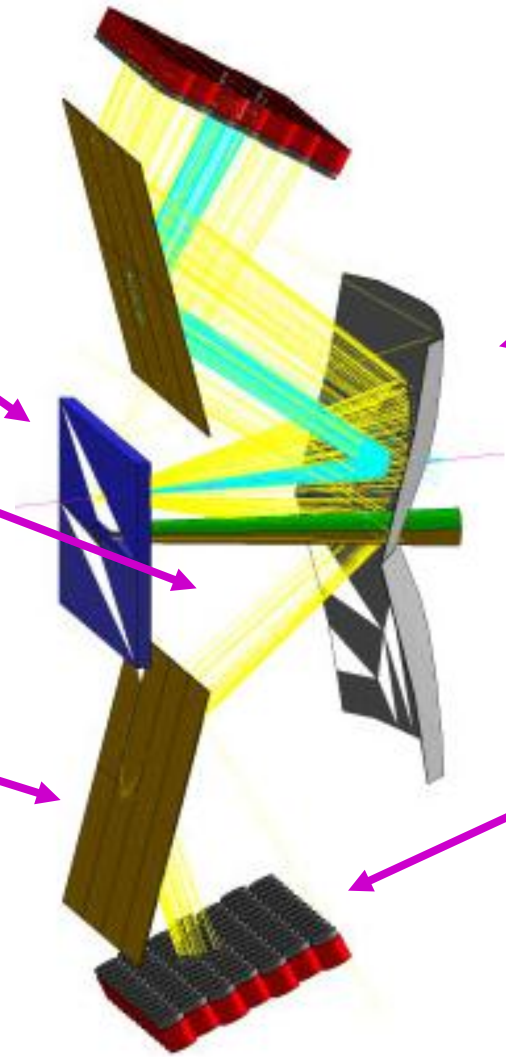
Physics requirements, and kinematics of b production, mean there is a big range in the momentum of the hadrons we wish to identify





Only suitable PID technique is RICH. Even then, three radiators are needed: Low p: aerogel ; middle p: C_4F_{10} ; high p: CF_4. Aim to span 2<p<100 GeV/c

LHCb RICH 1: a two-in-one detector



Aerogel

Gas volume

Flat Mirror

Spherical Mirror, tilted at 0.3 rad to keep photodetectors outside acceptance

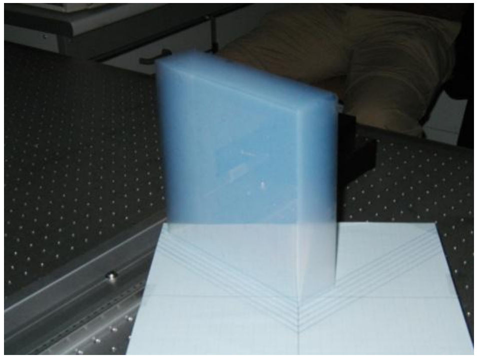
Photodetectors, enclosed in magnetic shielding box (not shown) to protect vs fringe field of dipole magnet

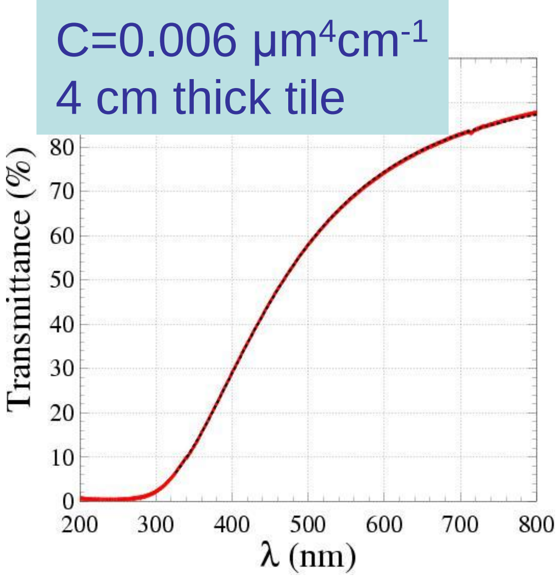
Aerogel as a RICH Radiator

Aerogel: a low density form a quartz.

Refractive index ~ 1.03. Well suited to low momentum π-K separation.

Used extensively in threshold counters, but not in RICHes (only operational example is HERMES)





The problem of Rayleigh scattering:

$$T = A\, e^{(-C\, t / \lambda^4)}$$

Scattering of photons limits transmission at low wavelength. Scattered photons → background.

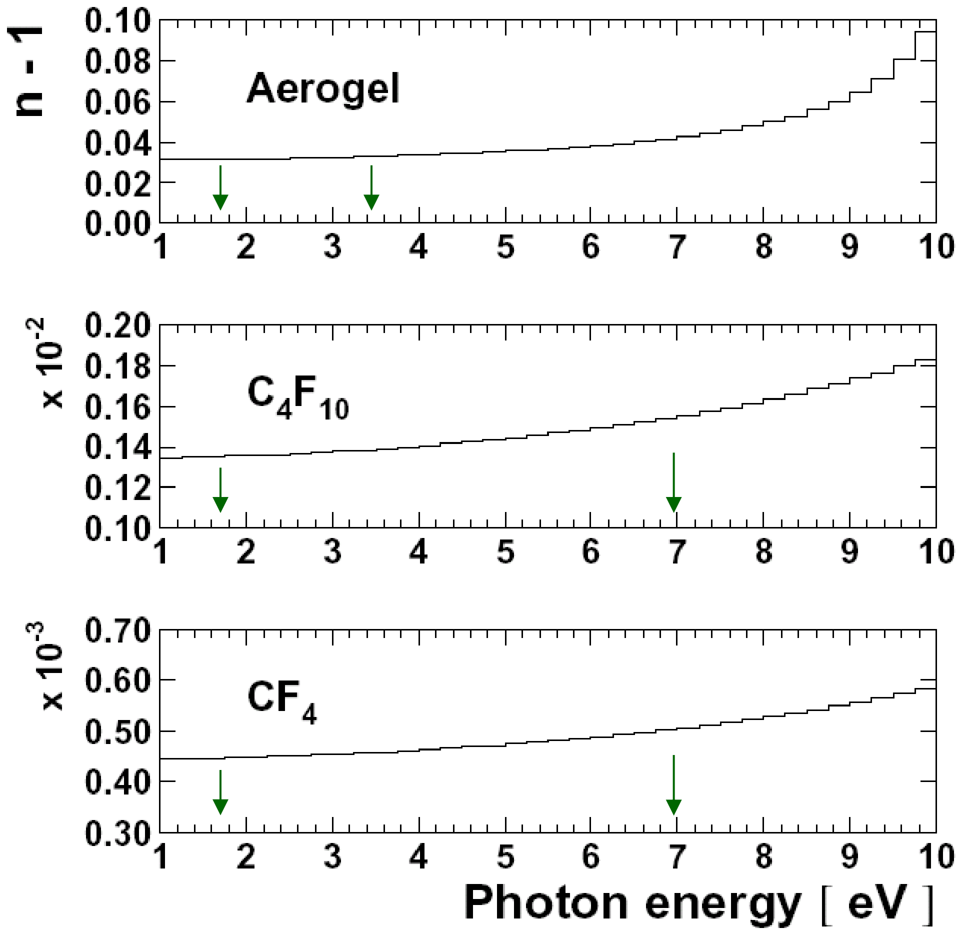
Aim for as clear samples as possible, which means low values of C (='clarity coefficient')

Chromatic Dispersion

A significant source of uncertainty in the Cherenkov angle determination, and one which is important for aerogel in particular, is that of chromatic dispersion.

Refractive index varies with wavelength/photon energy, and hence so will ϑ_c

Control this effect by limiting wavelength, as far as possible to visible. Do this with choice of photodetector technology &/or filters.



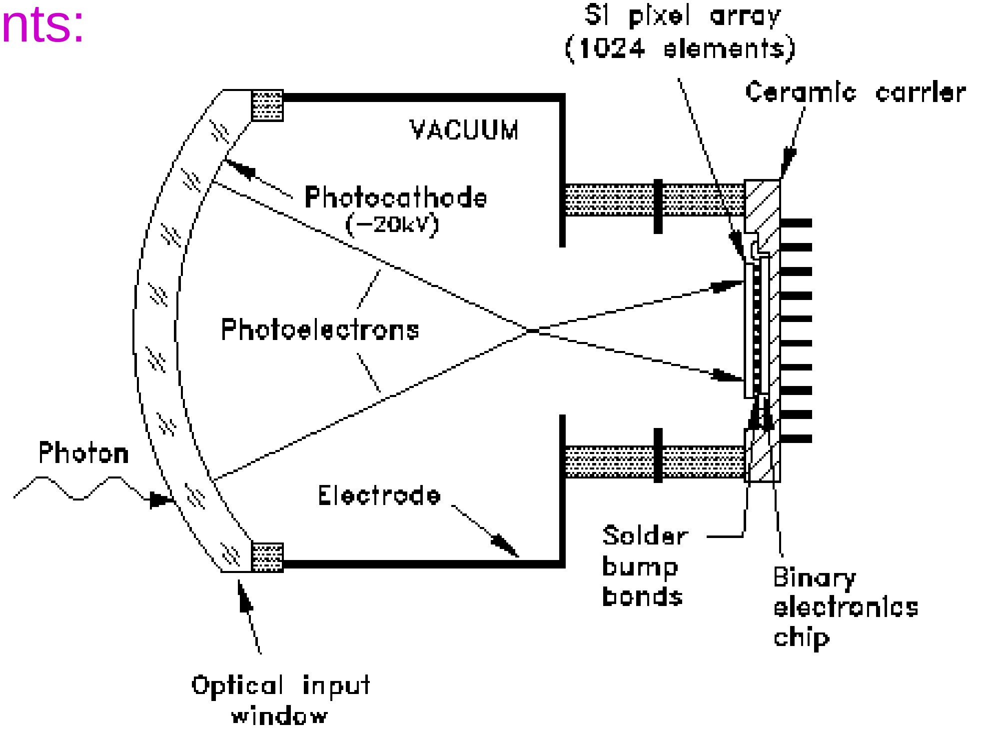
Visible light preferable to UV!

Hybrid Photo-Diodes (HPDs)

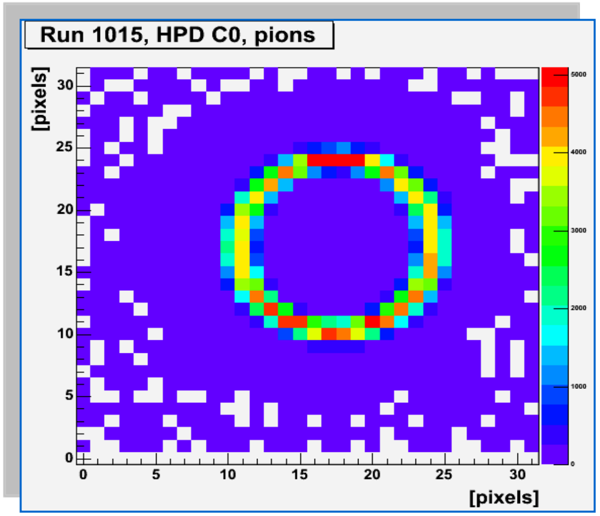
What kind of photodetector do we need for high performance PID at the LHCb? Requirements:

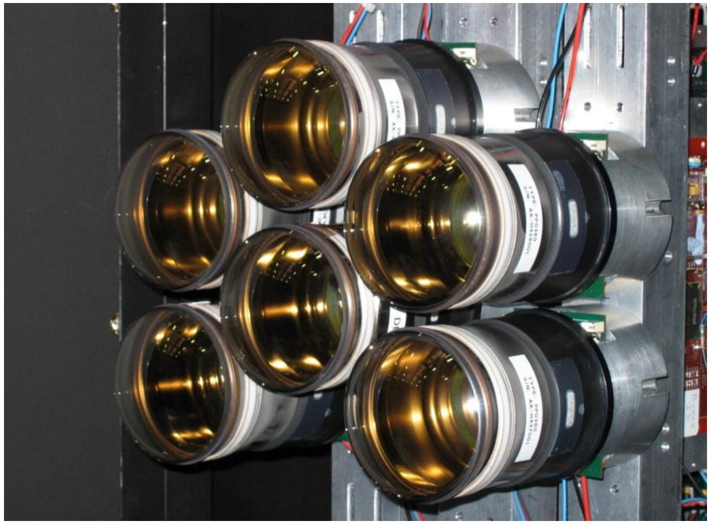
- Good single photon efficiency
- Sensitivity in visible
- Capacity to cover large area (several m^2)
- Good spatial resolution (order mm^2)
- High rate capabilities

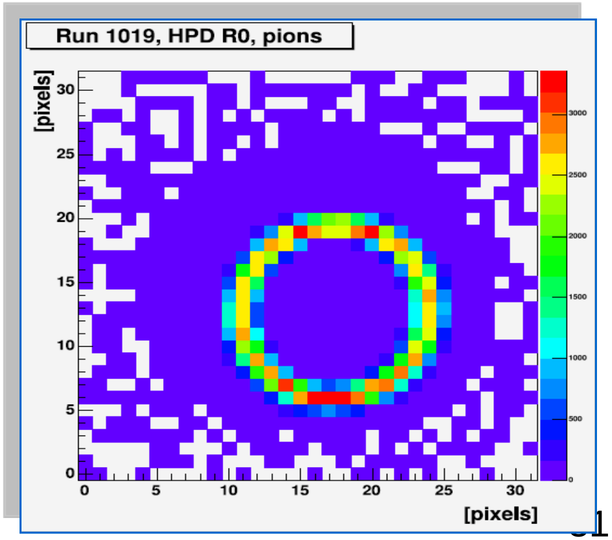
Solution – the HPD:



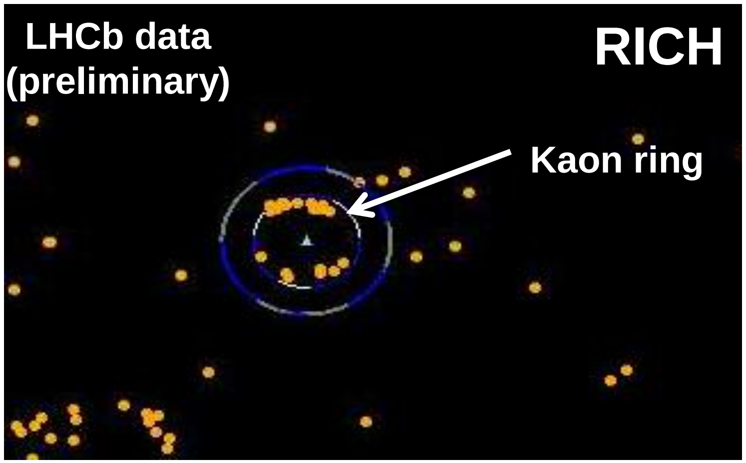
HPDs and Testbeam Results

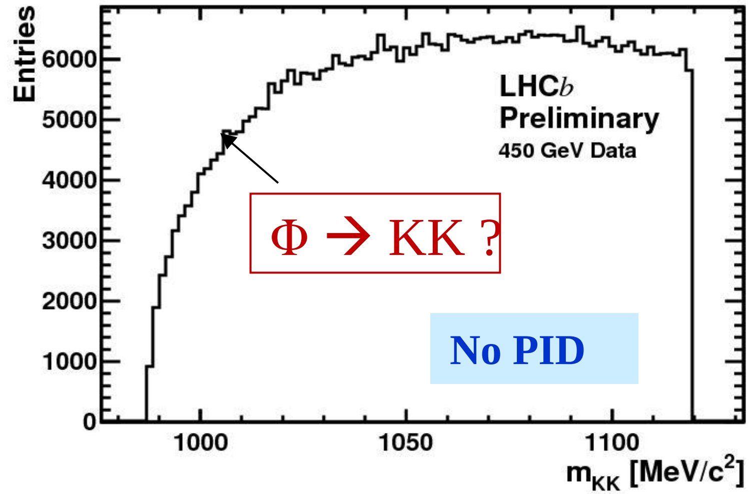


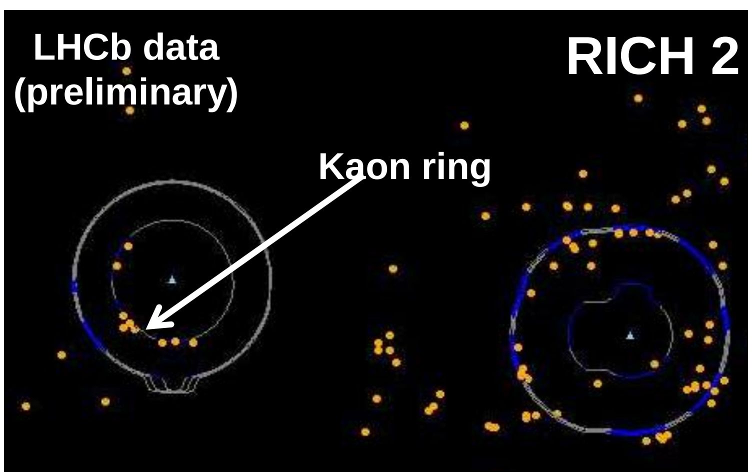


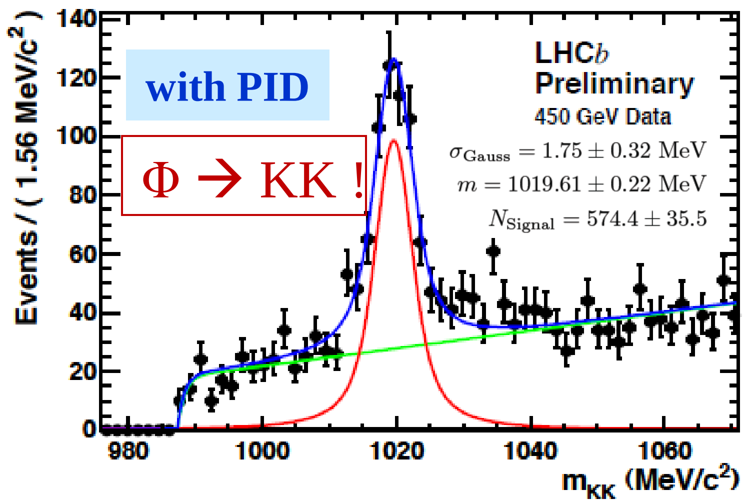


LHCb RICH already performed well with very first (2009) collision data





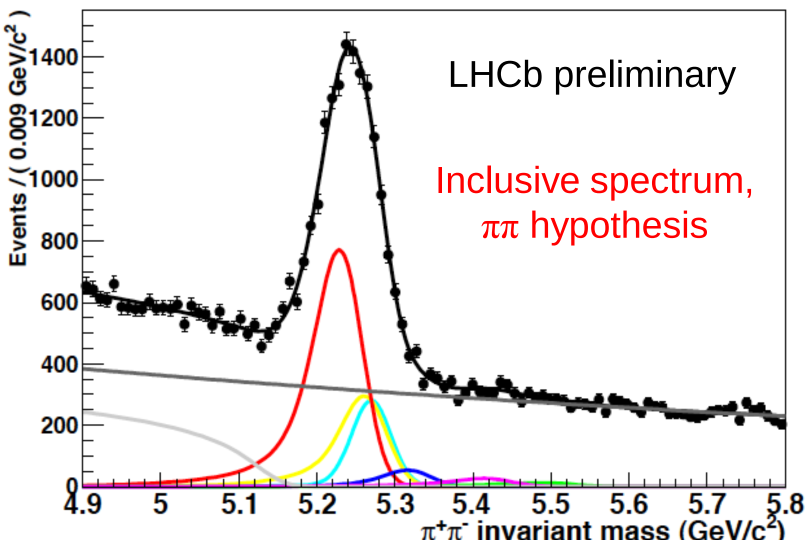




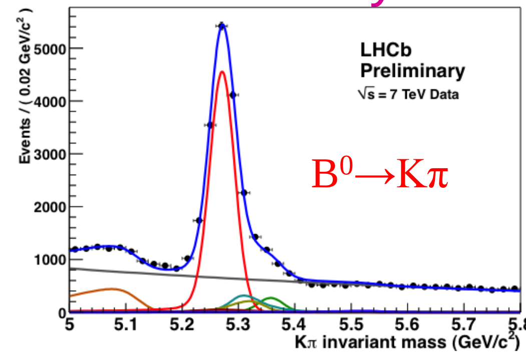
LHCb RICH: performance on ‘B→hh’

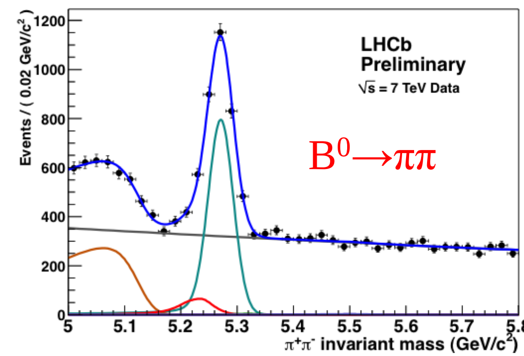
Two-body charmless B decays are central goal of LHCb physics. Significant contribution of Penguin diagrams provides entry point for New Physics

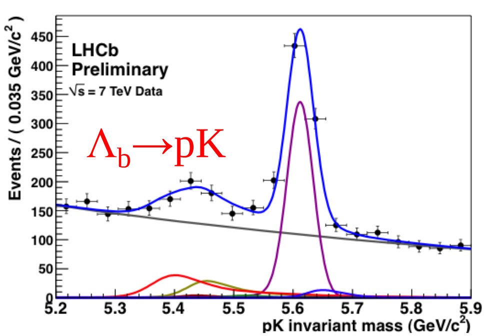
RICH critical to dig out contributing modes !

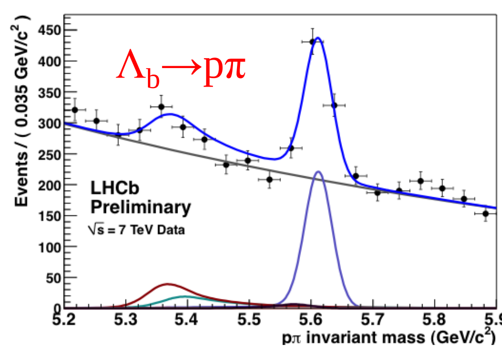


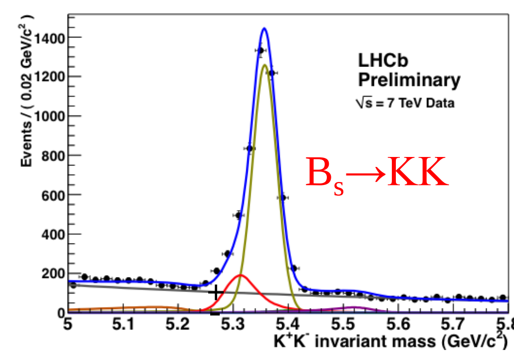
Deploy RICH to isolate each mode !







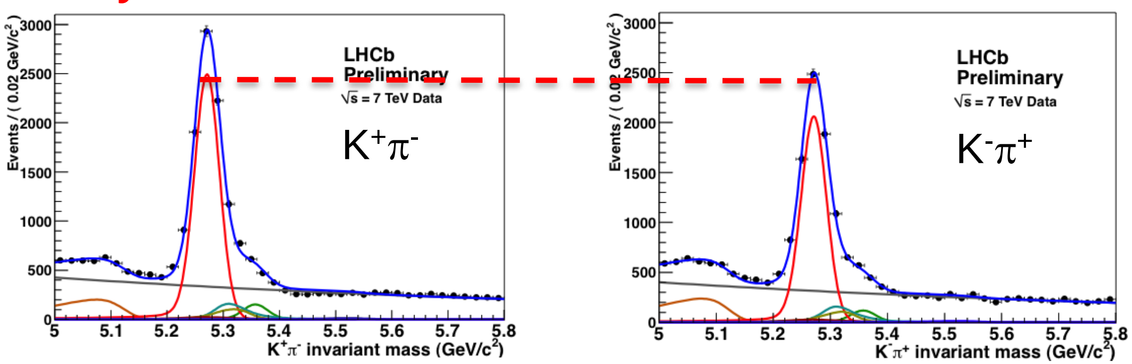




A closer look at $B_{d,s} \to K\pi$: direct CPV

Using RICH can measure CP violation in Kπ final state [LHCb-CONF-2011-042] :

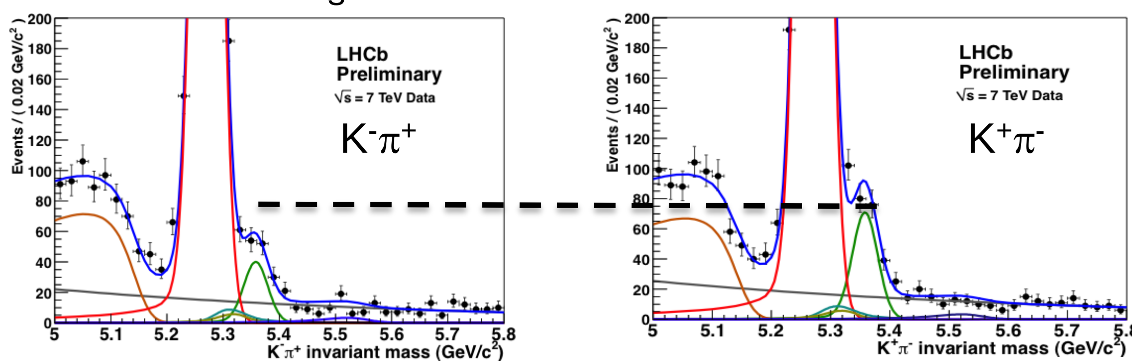
- Firstly look at $B^0 \to K\pi$



$$A_{CP}(B^0 \to K^+\pi^-) = -0.088 \pm 0.011(\mathrm{stat}) \pm 0.008(\mathrm{syst})$$

Most precise single measurement and first 5σ observation of CPV at a hadron machine !

- Now look at $B_s \to K\pi$



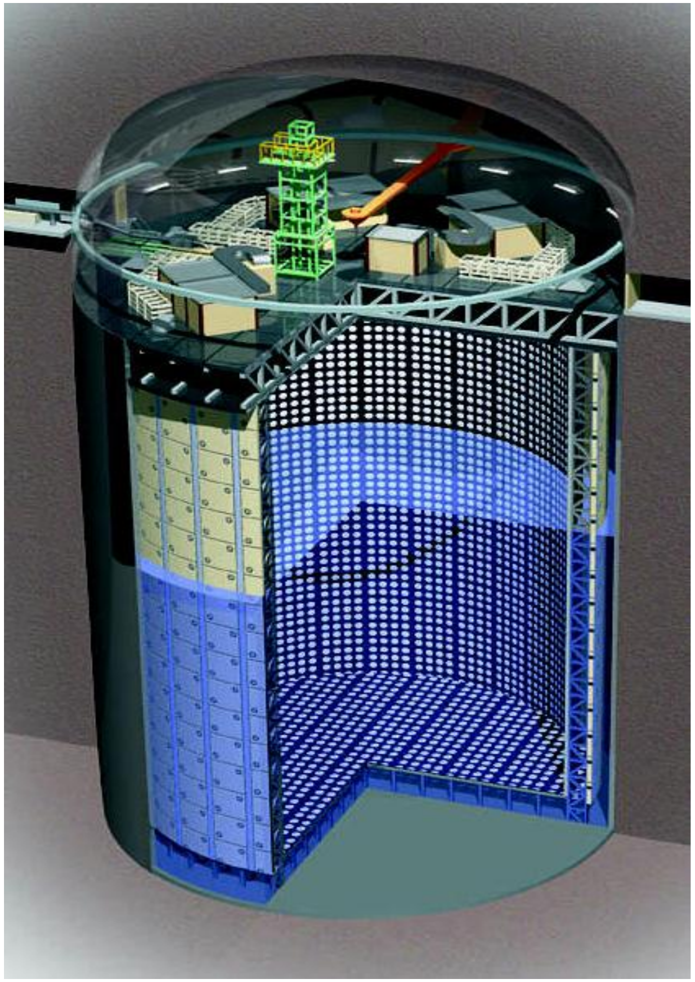
$$A_{CP}(B_s^0 \to \pi^+K^-) = 0.27 \pm 0.08(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

First evidence of CPV in B_s decays !

Large water volume neutrino detectors

Examples:

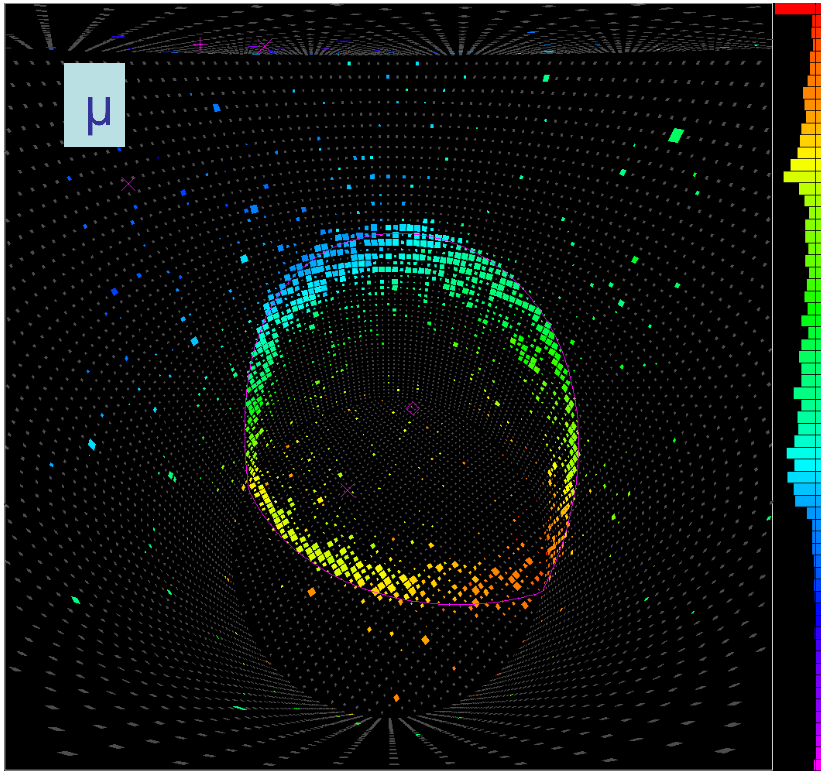
- SNO
- Super-Kamiokande
  50 k ton H_20
  1 km underground

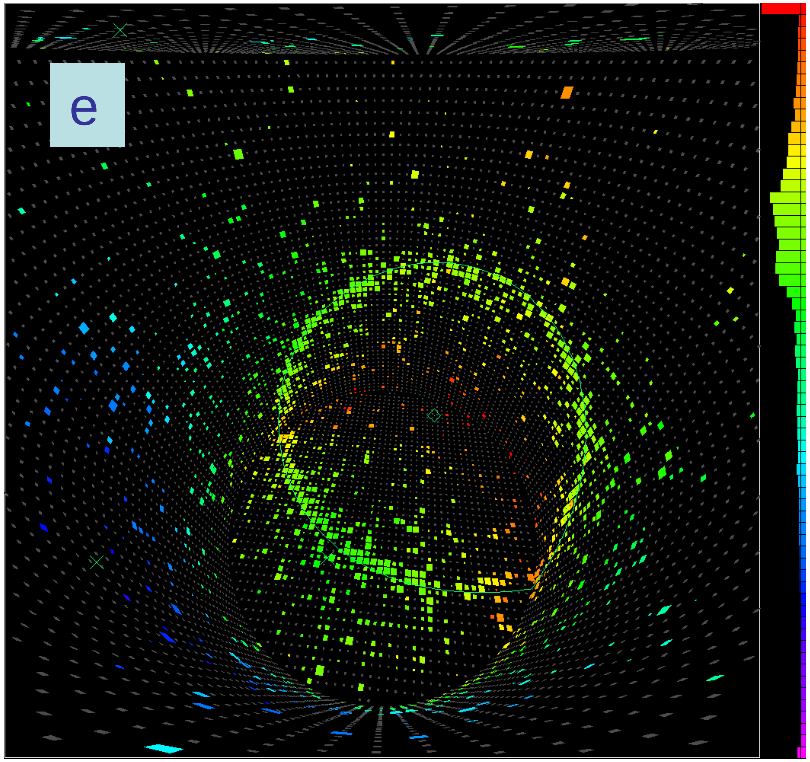


Cherenkov rings are an ideal technique for detecting $\nu \rightarrow \mu$, e

Cherenkov Rings in Super-K

Cherenkov light a perfect signature of a neutrino interaction in water.



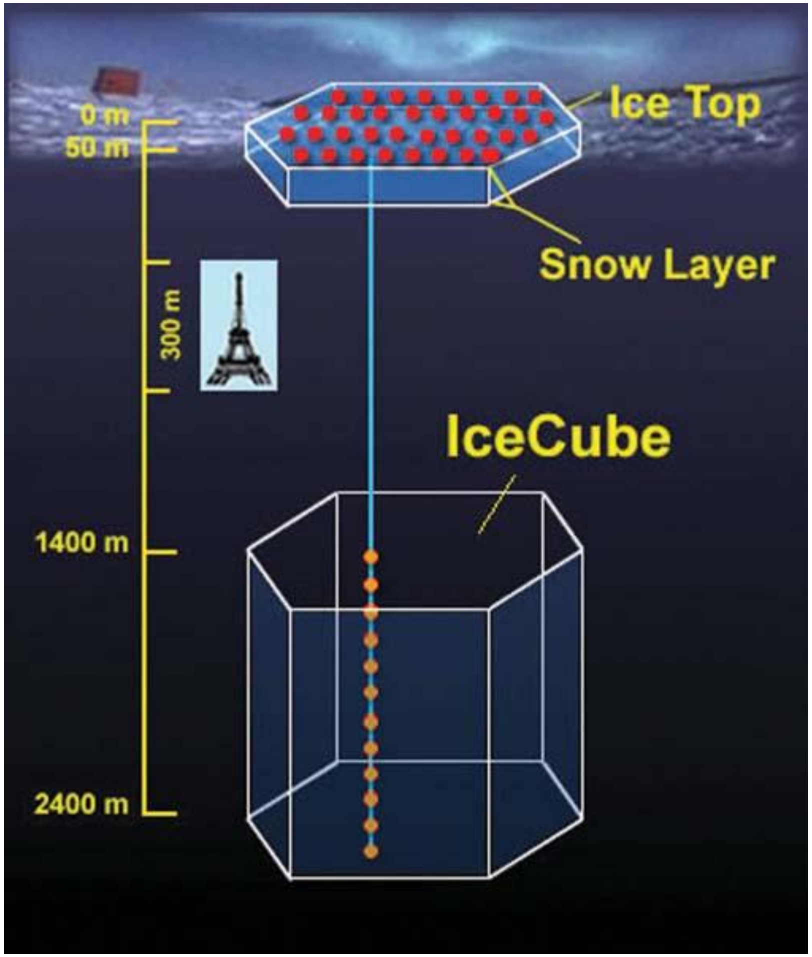


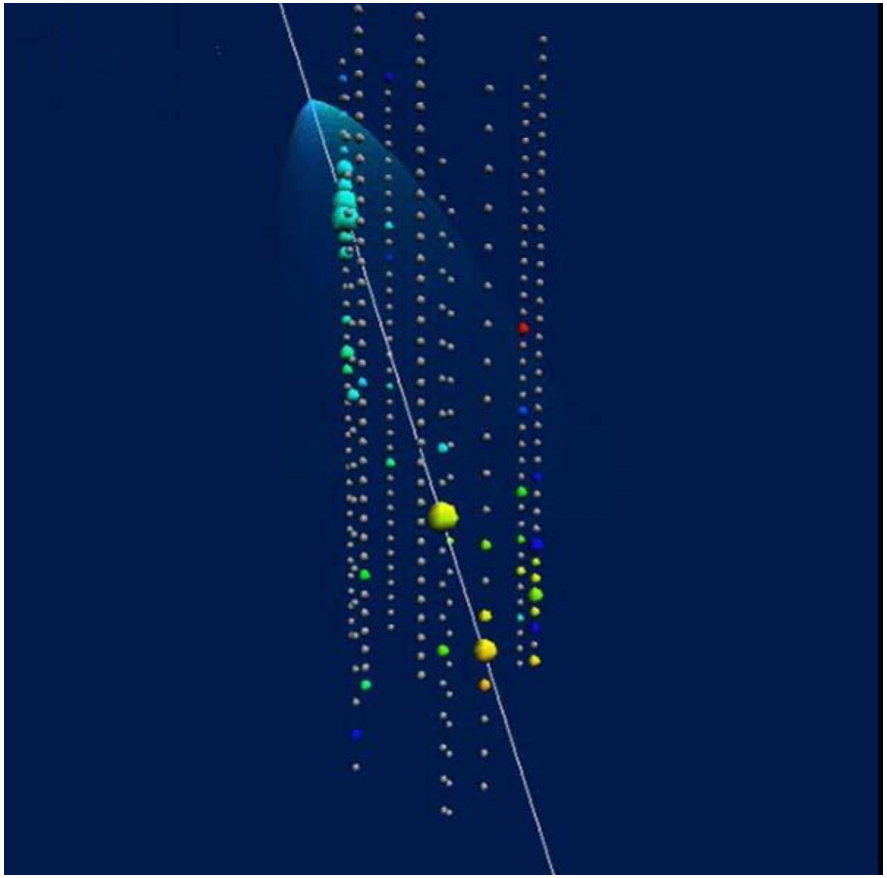
No momentum measurement, so PID performed from sharpness of ring.
Timing response of PMTs necessary to determine particle direction.

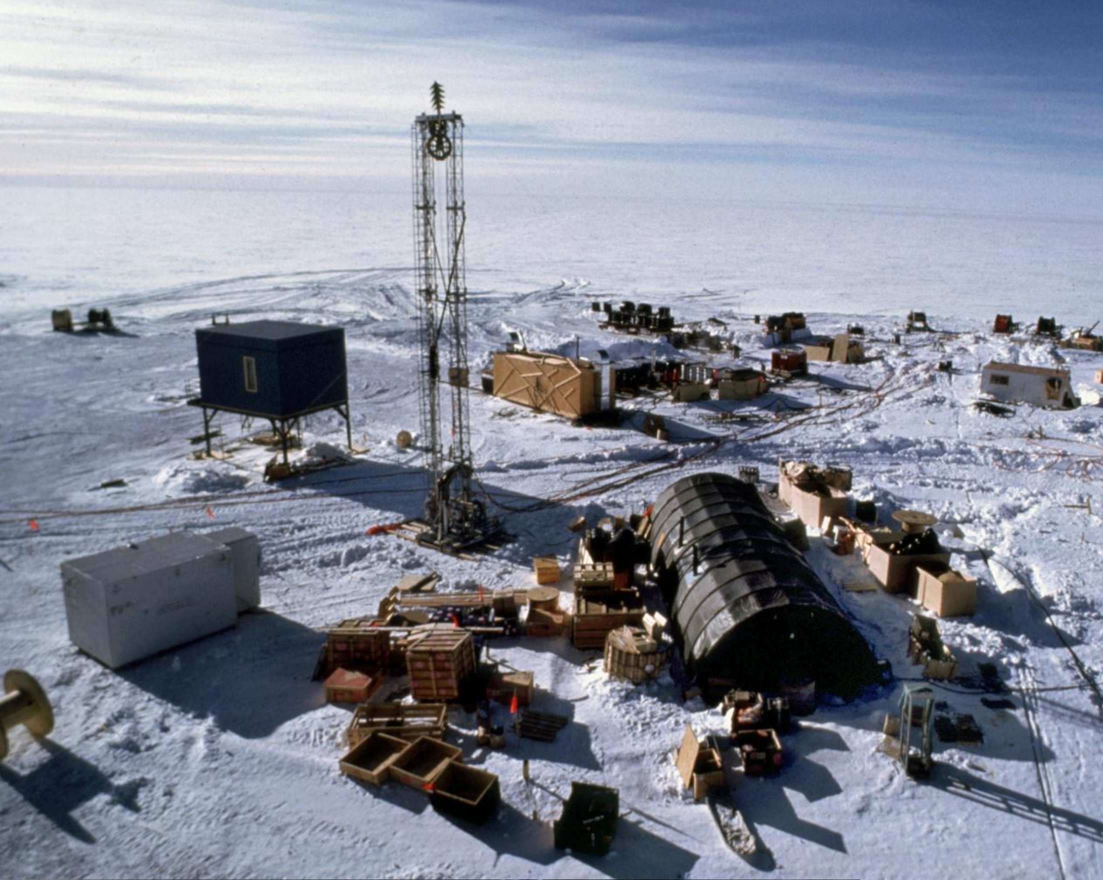
Whoops!

Antartica

Ice Cube: a Cherenkov Counter for Studying High Energy Neutrinos

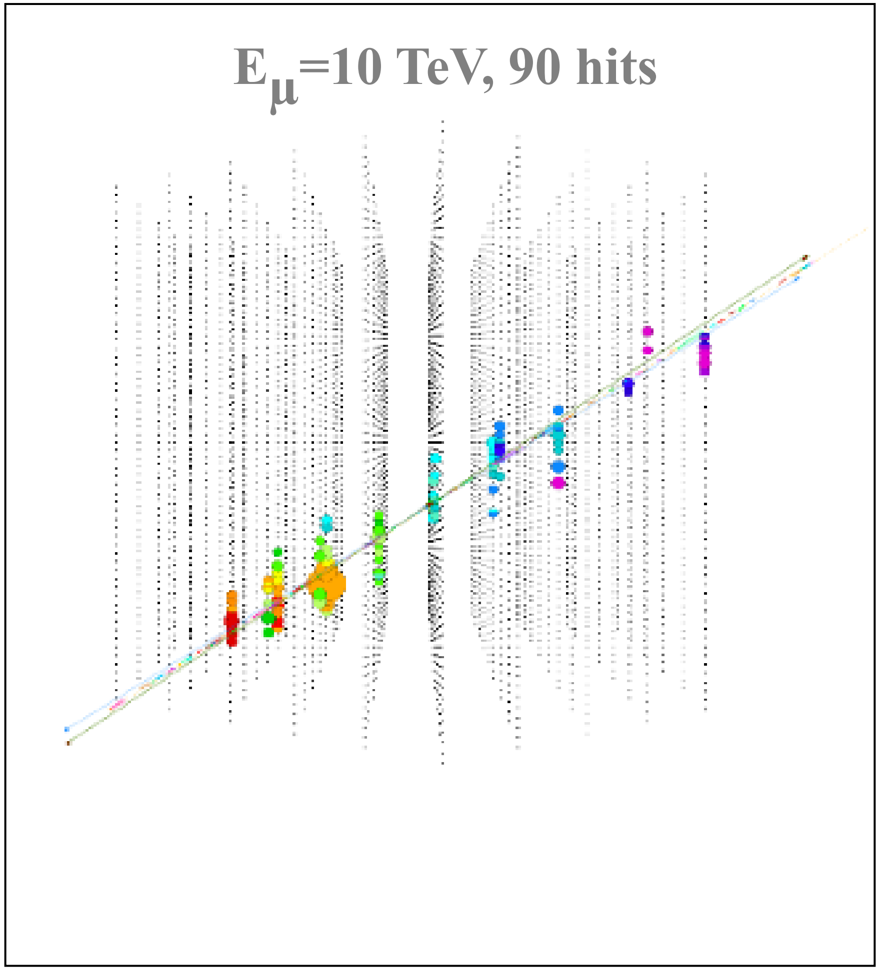


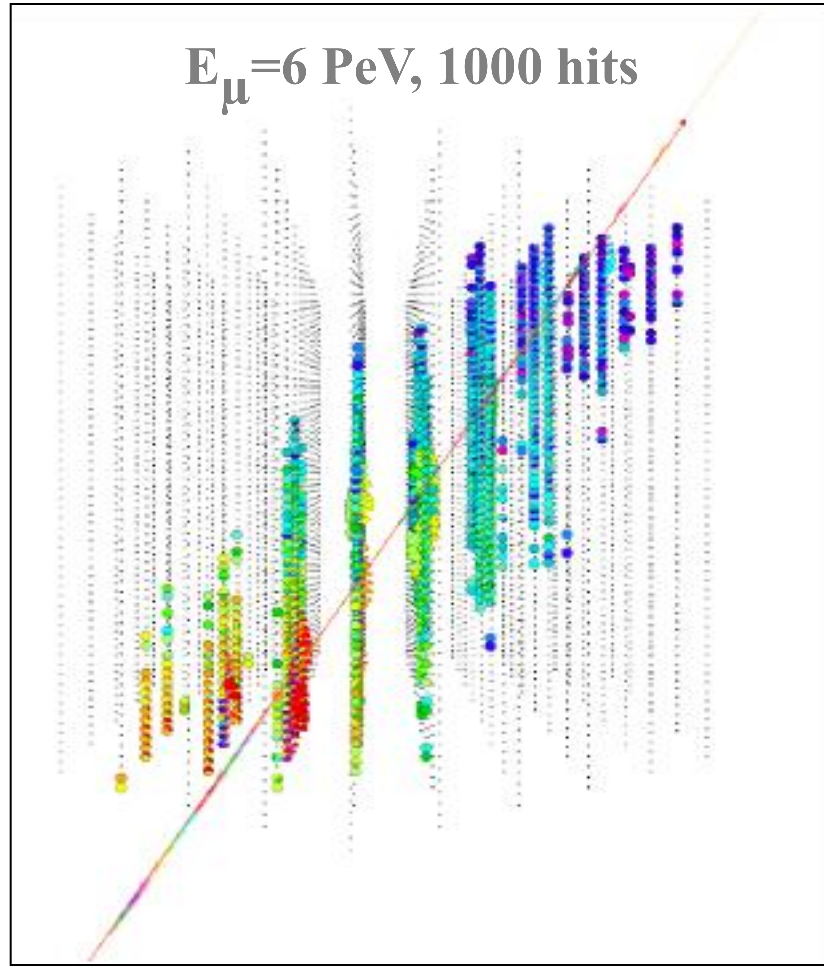




AMANDA Deployment

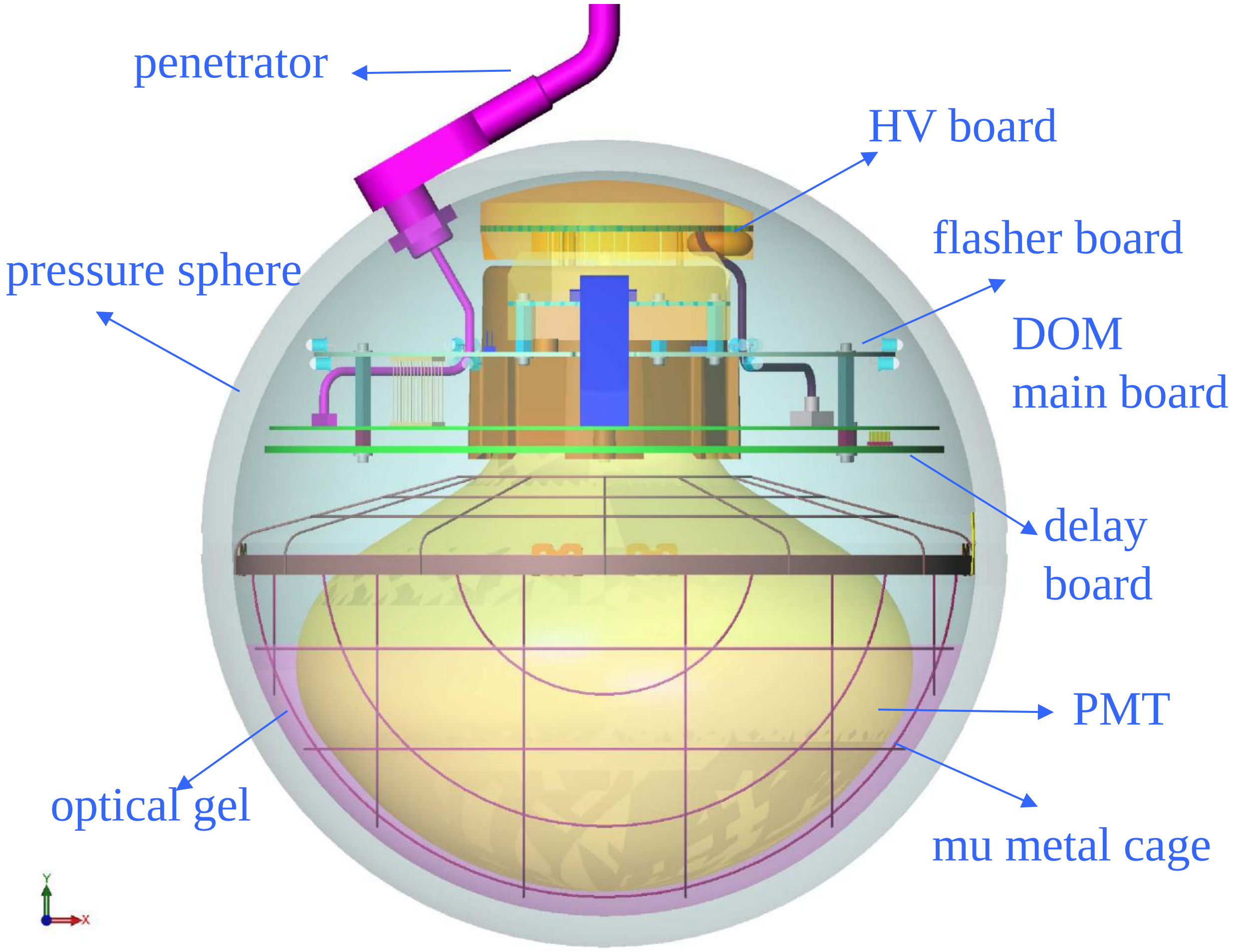
Hit Multiplicity →Energy Measurement





Photodetectors for Ice Cube

optical sensor
10 inch Hamamatsu R-7081



- records timestamps
- digitizes waveforms
- transmits to surface at request via digital communications
- can do local coincidence triggering
- design requirement Noise rate ~1 kHz
- SN monitoring within our Galaxy

RICH Conclusions

RICHes are tricky! Only build one if you absolutely need to.

> "Very often this technique is criticised as being too difficult and not reliable. We admit that in some senses this is true…"
>
> Tom Ypsilantis

But sometimes you absolutely need to:

- B Physics Experiments
- Spectroscopy

Cherenkov detection is a vital tool in armoury of experimental HEP: RICH detectors, neutrino detectors, …

Epilogue: a superficial look at transition radiation detectors

What is transition radiation and what is its use in HEP ?

Brief examples:

1) ATLAS TRT
2) AMS TRD

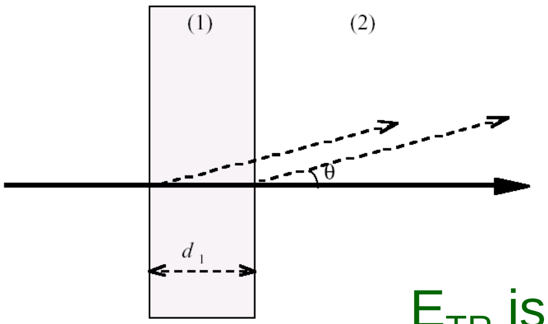
For more information:

Boris Dolgoshein, 'Transition Radiation Detectors',
Nuclear Instruments and Methods A326 (1993) 434-469

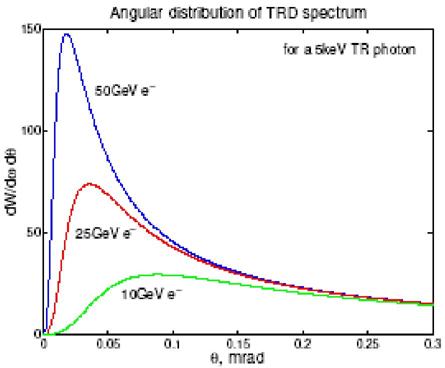
Basics of Transition Radiation

Transition radiation emitted when particle moves across interface of 2 media with different dielectric constants (predicted in 1946 by Ginzburg and Frank)

Consider ultra-relativistic particle passing through thin foil of material (1) in environment of material (2), then differential distribution of radiation is:



$$\frac{d^2E_{TR}}{d\omega\, d\Omega} = \frac{h\alpha}{\pi^2}\left(\frac{\theta}{\gamma^{-2}+\theta^2+\left(\omega_{p1}/\omega\right)^2} - \frac{\theta}{\gamma^{-2}+\theta^2+\left(\omega_{p2}/\omega\right)^2}\right)\times 4\sin(\varphi_1)$$



E_{TR} is energy of radiation; ω is angular frequency; ω_p is plasma frequency ; Θ is angle of emission. Φ_1 is phase angle, due to interference between boundaries.

Characteristics of transition radiation:

1) Forward peaked

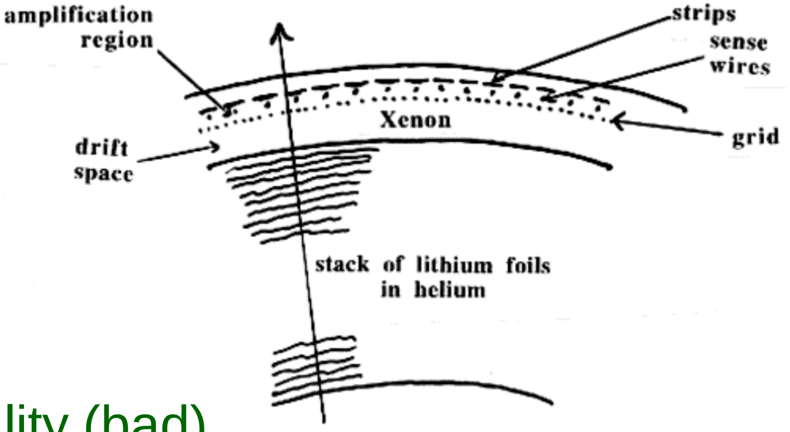
2) X-rays

3) Total energy radiated proportional to γ !

Transition Radiation & HEP Applications

Dependence on γ makes TR an attractive method of PID, particularly for discriminating between electrons and hadrons. Used for non-destructive electron identification (cf. calorimeter). Works over wide momentum range.

Experimental challenges:



1) Radiation very feeble.
   So require many foils (usually lithium or polyethelene)

   Interference and absorption effects lead to low γ threshold (good) and to saturation – loss of γ proportionality (bad)

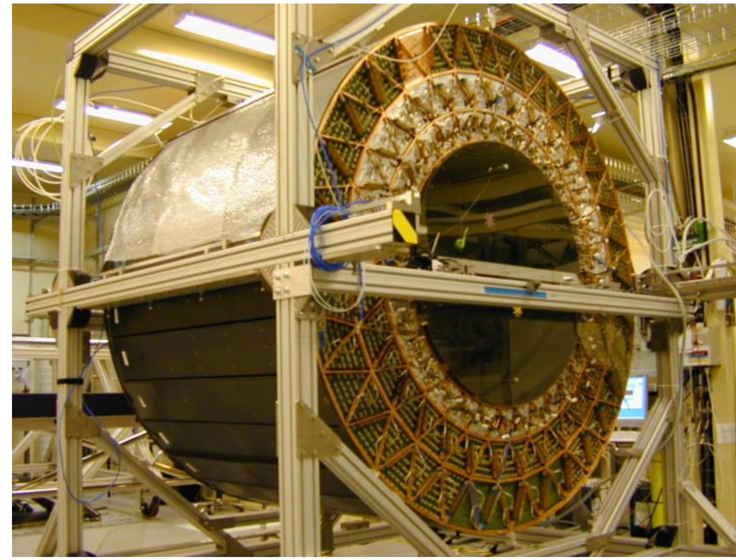
2) Forward peaking means that almost always X-rays and primary particle are seen by same detector. Generally one detects particle dE/dx and TR together. So must distinguish sum of energy from dE/dx alone, or look for clusters specifically associated with absorption of the X-rays.

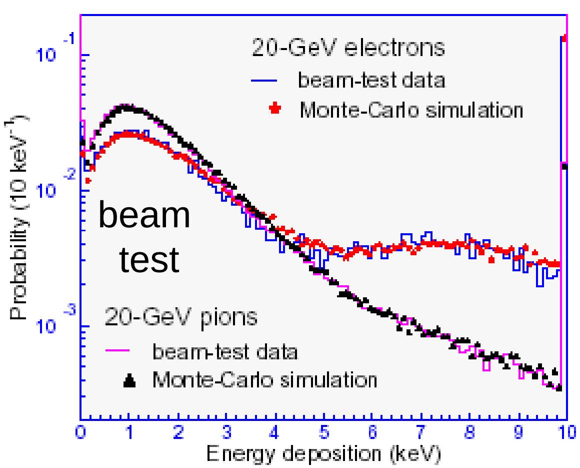
ATLAS Transition Radiation Tracker

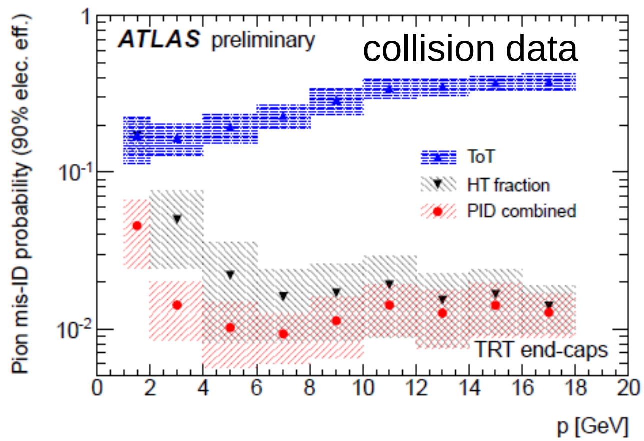
Part of the ATLAS Inner Detector.

Provides combined tracking, with standalone pattern recognition and electron identification.

Layers of xenon filled straw tubes interleaved with polymer fibres (and foils in endcaps).





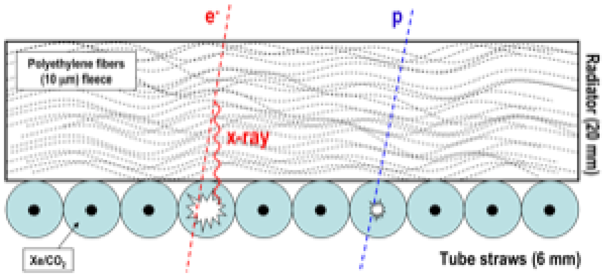


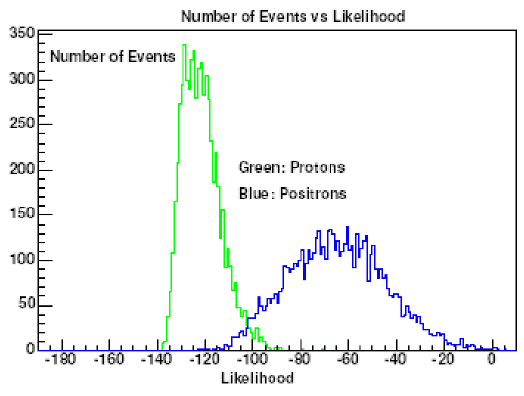
Can suppress pions by a factor of about 100, for 90% electron eff.

AMS TRD

Purpose: to look for positrons and suppress proton background by factor of 10^6 . To be achieved by combined TRD / ECAL system.

20 layers of polypropylene radiator and proportional straw tubes (Xe)





90% e-id efficiency for 0.1% contamination