Cherenkov Radiation & RICH Detectors & TRD

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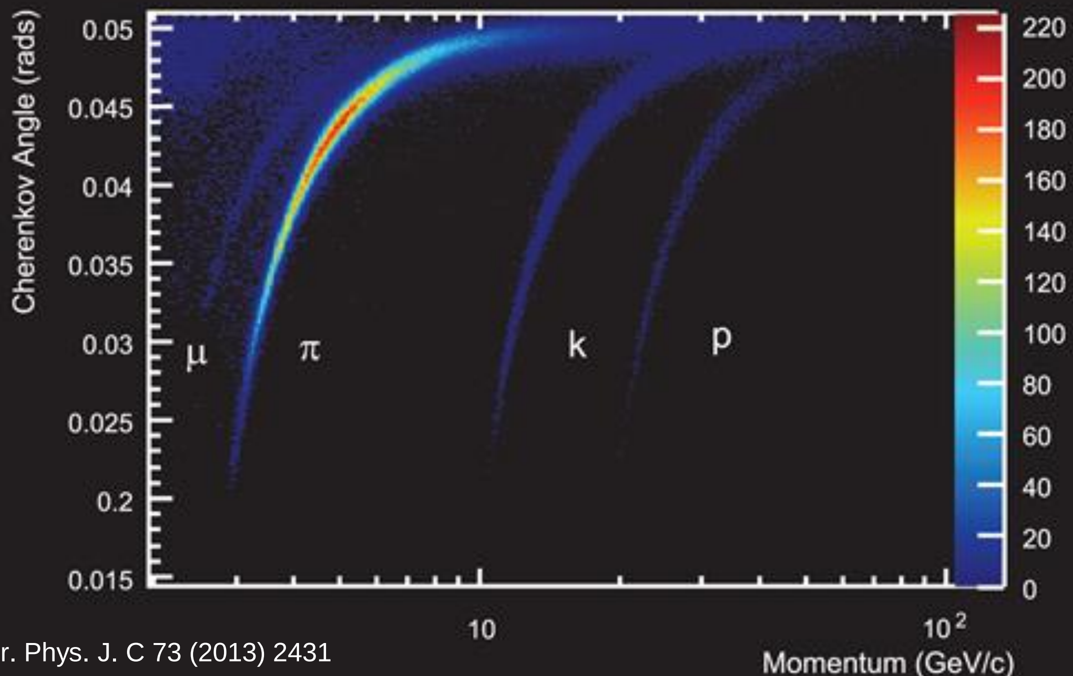
4/2/2021



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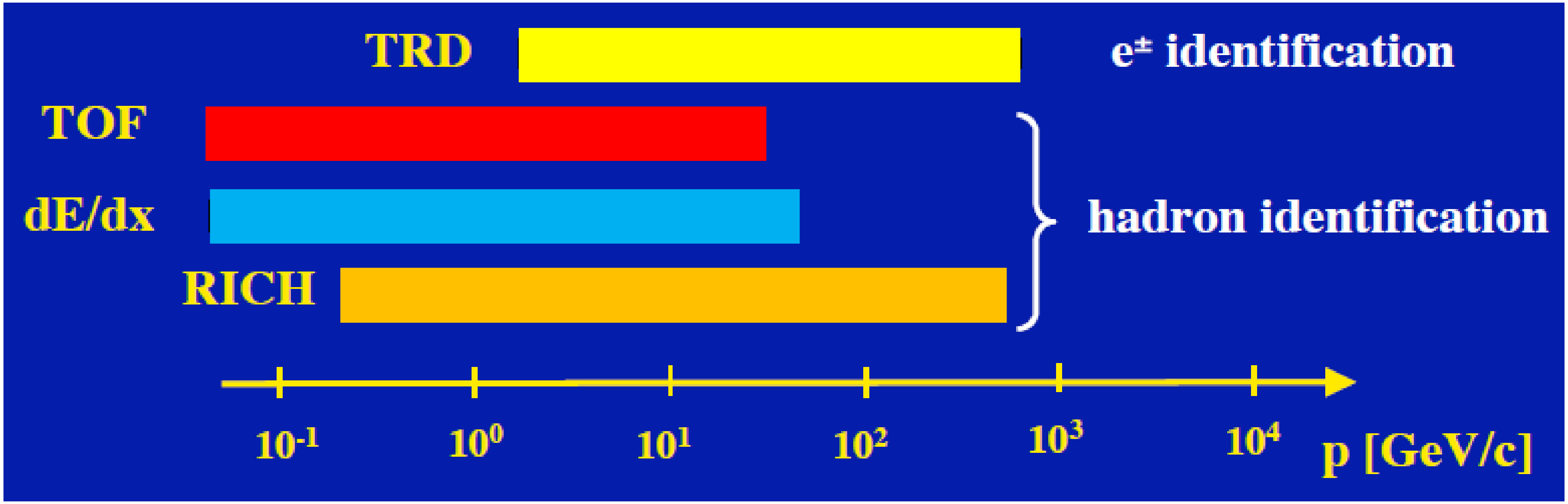
*** with many thanks to Donal Hill & Guy Wilkinson**

Reminder of PID techniques



- dE/dx & TOF work mainly in low momentum region
- RICH well established for general hadron identification (COVERED IN THIS LECTURE)
- TRD useful for $e^{\pm}$ identification at higher momentum (BRIEFLY IN THIS LECTURE)

History of Cherenkov radiation

Discovery: Pavel Cherenkov, 1936

Cherenkov: 1905-1990

Radiation seen when uranyl salts exposed to a radium source

Explanation: Tamm and Frank, 1937

Experimental exploitation in HEP pioneered by Cherenkov

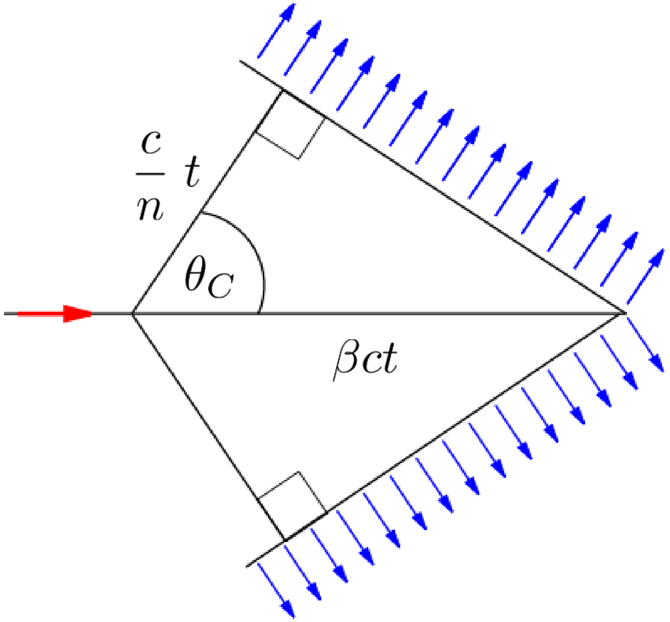
(Cherenkov, Tamm, Frank: Nobel Prize 1958)

Cherenkov Radiation in a Nutshell

Occurs when the speed of a charged particle is greater than the speed of light in the medium

Fundamental Cherenkov relation

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



Frank-Tamm relation

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

N_γ = no. of photons E = photon energy L= radiator length Z = particle charge

Get N_γ by integrating over E range acceptance of your detector

What is a RICH ?

RICH (Ring Imaging Cherenkov) detector

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

Measurement of θ_C from RICH, together with p from tracking system, allows mass (and hence PID) to be determined

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

Simple approach: choose n such that heavy particles do not emit light

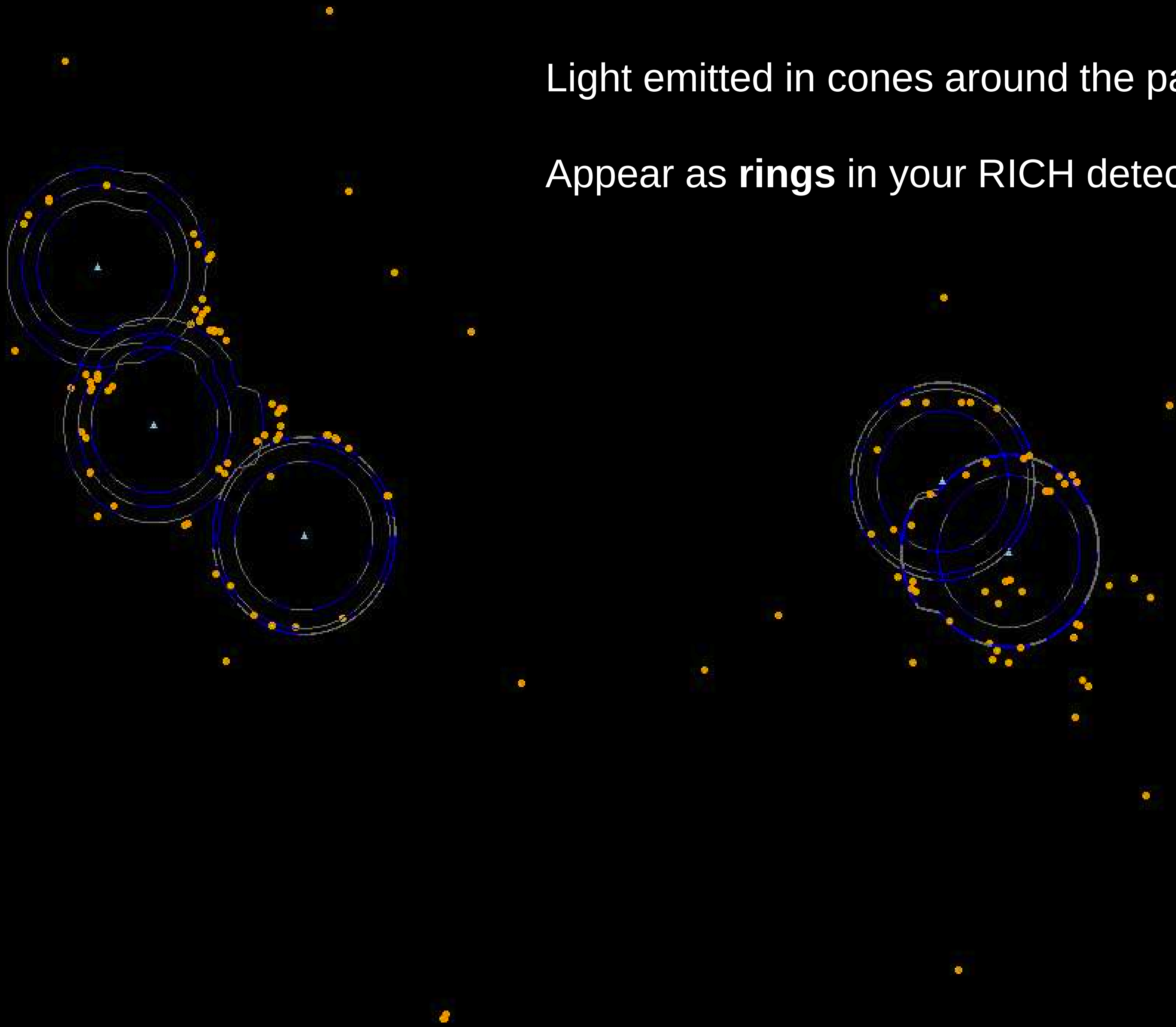
$\rightarrow$ Threshold Cherenkov counter (not a RICH!)

If we want to do better then we need to **measure θ_C**

How do we do this? Image the ring!
This is a **RICH (Ring Imaging Cherenkov) detector**

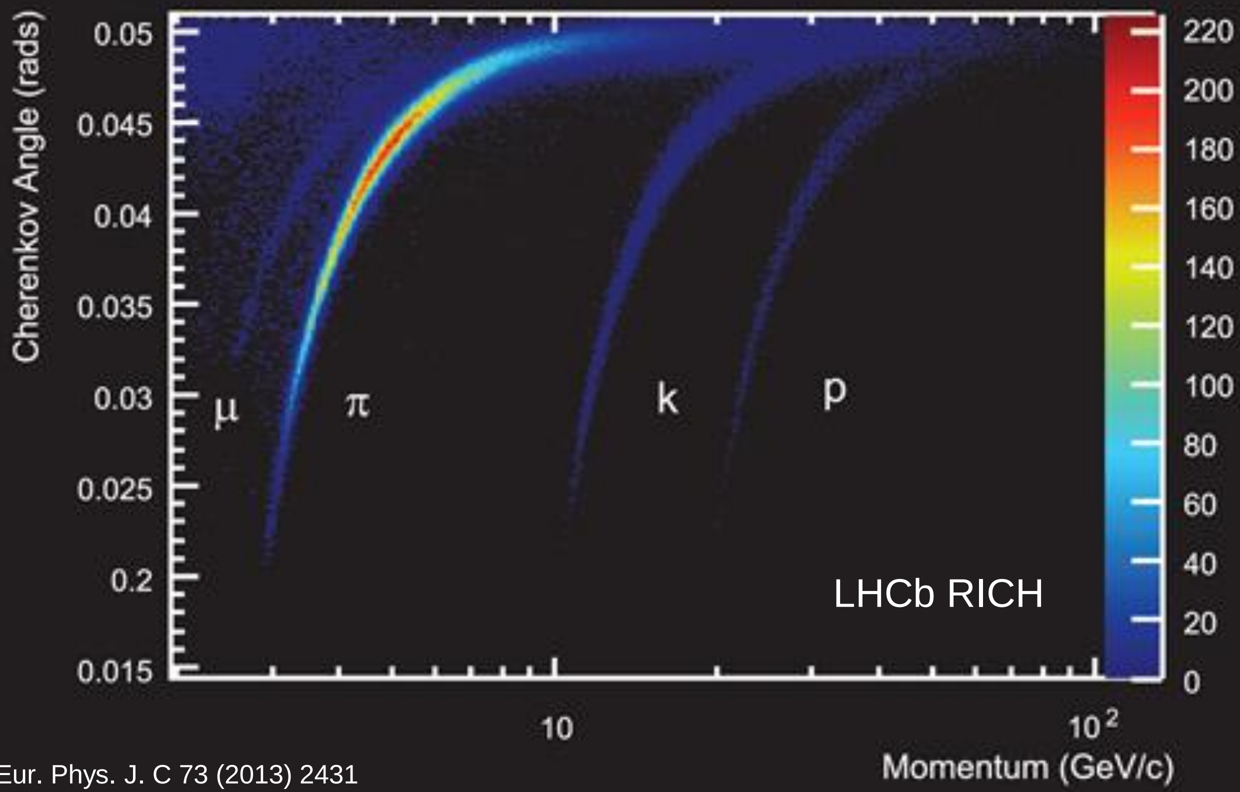
Light emitted in cones around the particle

Appear as **rings** in your RICH detector



Measure θ_c and p

Tells you which particle is which (PID)



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Who needs hadron ID ?

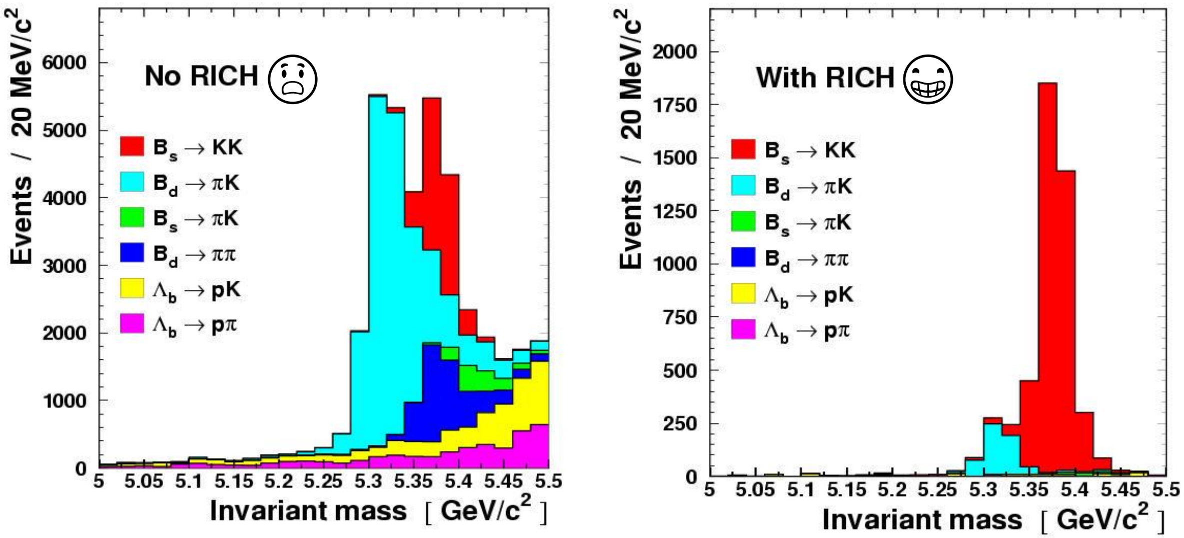
- B physics CP violation: $B \rightarrow DK$ and $B \rightarrow D\pi$
- Hadron spectroscopy / exotic searches
- Large volume neutrino detectors
  (special case discussed later)

Many other experiments would benefit (e.g. ATLAS/CMS)
but they have other good priorities for their space!

B (and D) physics PID

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

e.g. select $B_s^0 \to K^+K^-$ for example [this is LHCb MC]



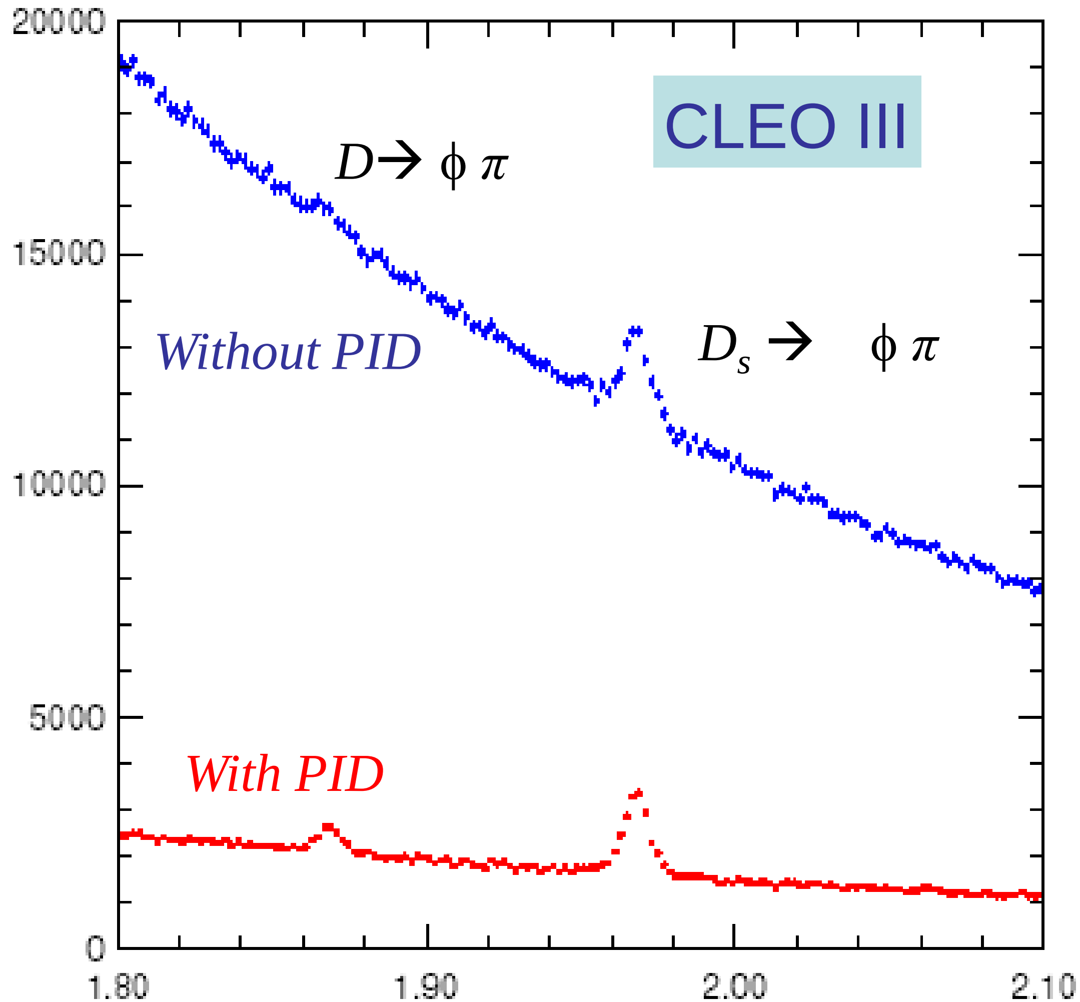
First, reconstruct everything as $B_s^0 \to K^+K^-$ (left)

Backgrounds from decays like $B^0 \to \pi^+ K^-$ reduced by RICH PID (right)

B (and D) physics PID

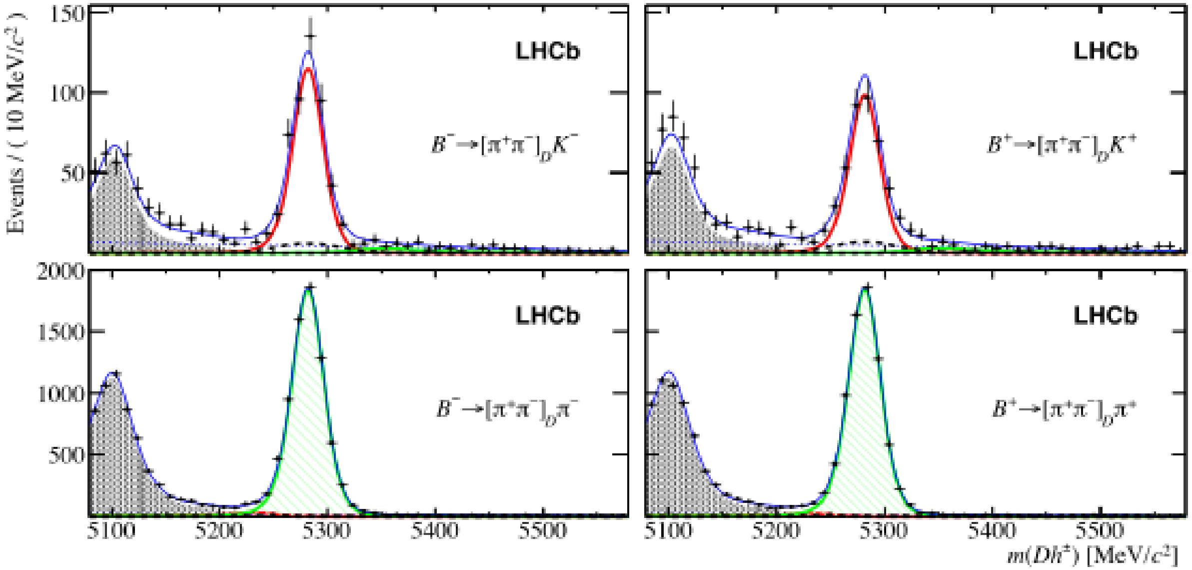
Suppress background from combinatorics.

PID allows much cleaner reconstruction of D (and B) mesons



B (and D) physics PID

Differentiate between B → DK and B → Dπ decays



Crucial in all attempts to measure CKM parameters e.g. γ

B → DK is sensitive to γ and is a precision SM standard candle

B → Dπ is much less sensitive – crucial to distinguish these decays

Ingredients of a RICH

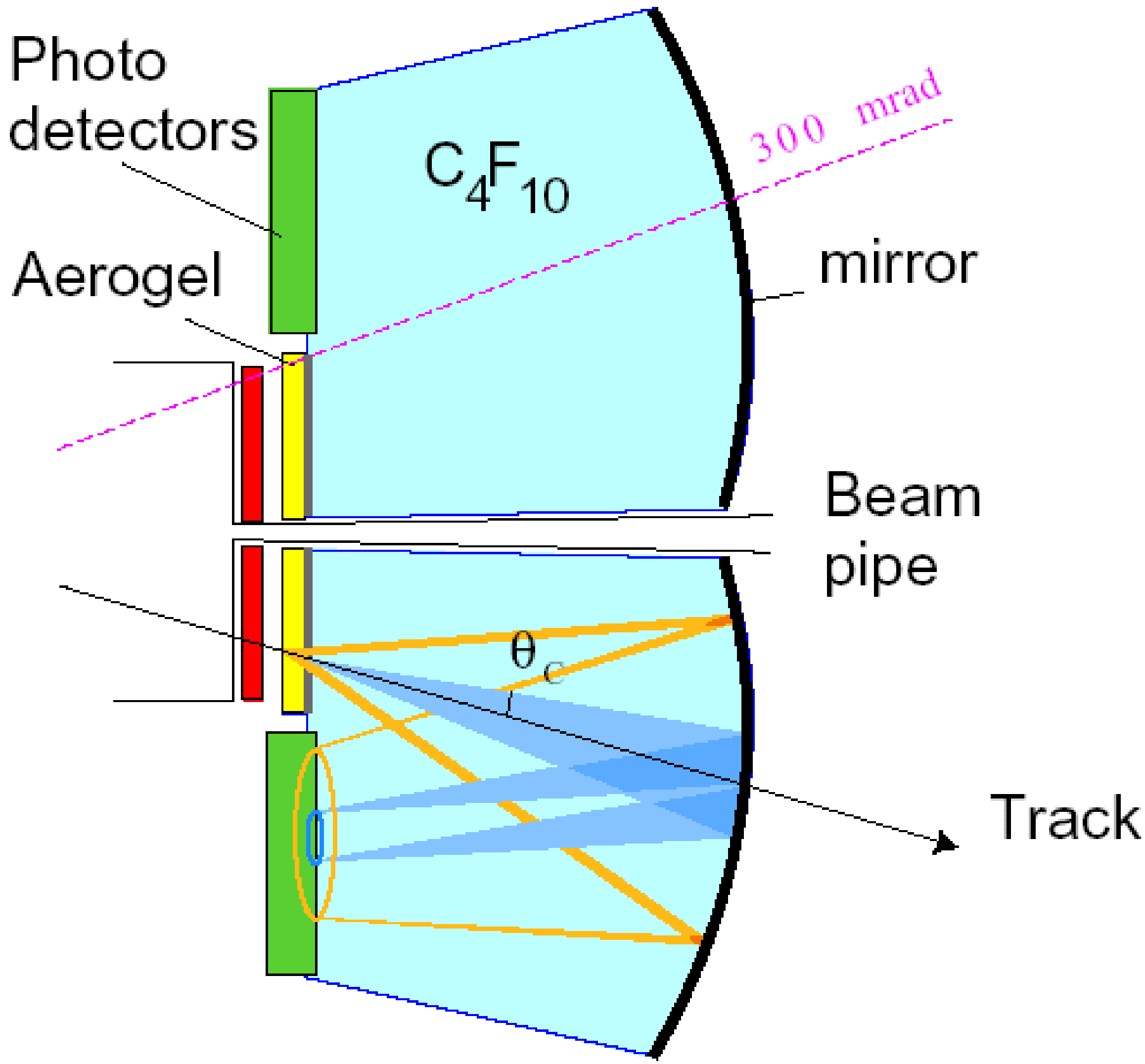
We need a **mirror**, a **radiator** and a **photon detector**

Why do we need mirrors?

1. Takes Cherenkov light **out of the detector acceptance**
2. **Focuses** the light - without mirrors we would have splodges

LHCb RICH1

(does lower p tracks, RICH2 covers higher p)



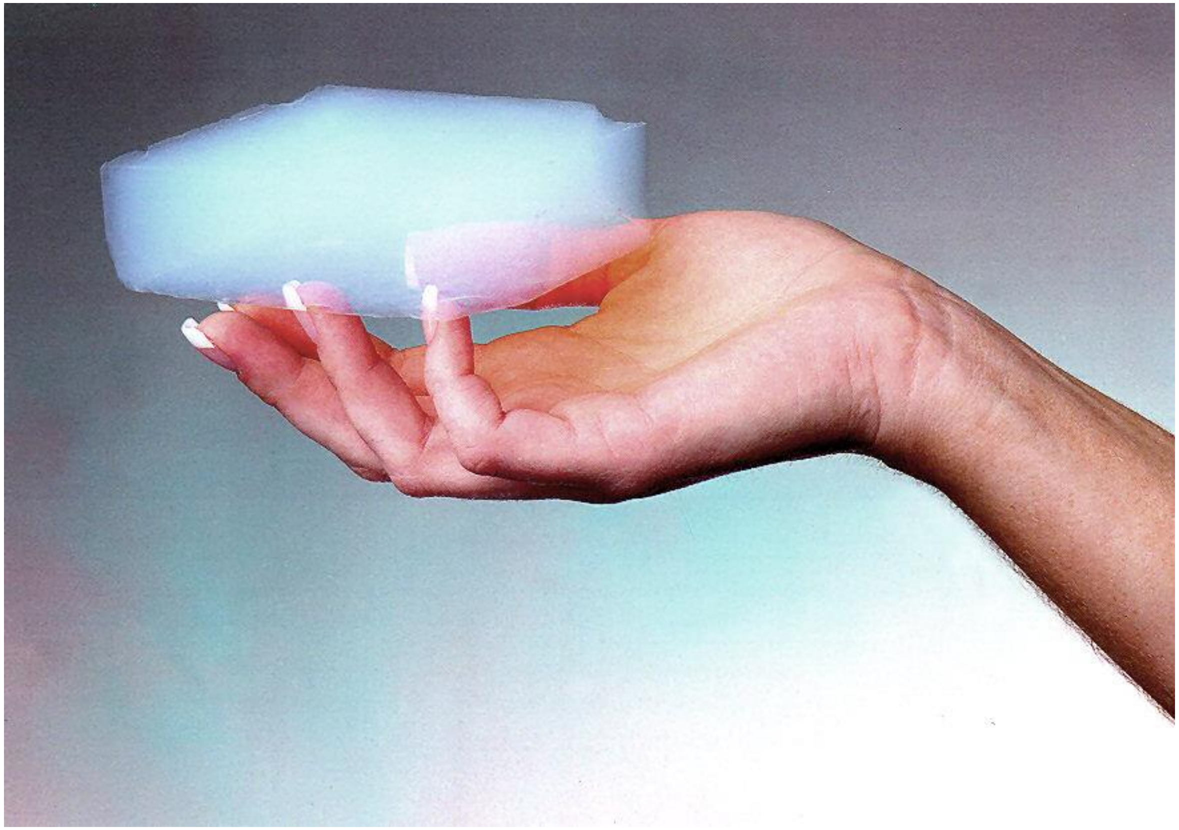
C4F10 gas is the radiator material

N.B. Aerogel was supposed to be useful for lowest momentum particles, but turned out to be unuseable due to the high particle occupancy in LHCb

It was removed before Run 2!

1) Aerogel: quartz-like material with extremely low density and relatively high refractive index (~1.03) giving PID up to ~10 GeV/c

2) Very difficult to handle (and hygroscopic) !



Considerations when building a RICH

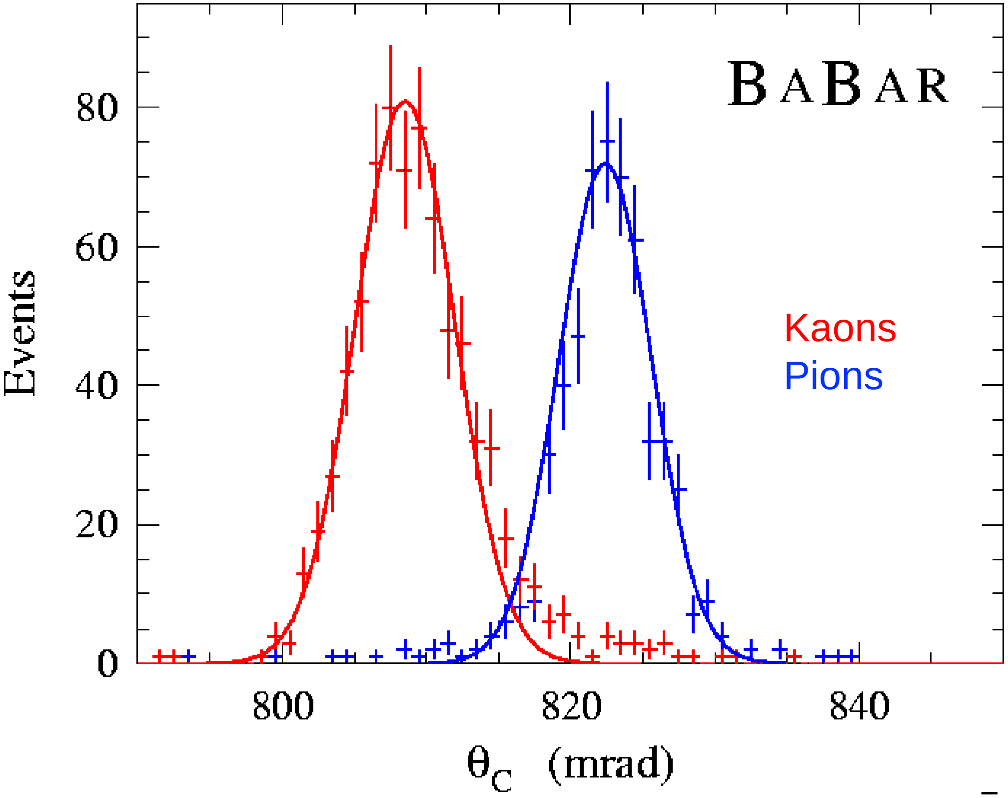
Optimise **ring resolution**, which determines how far in momentum we have PID

$$\sigma(\theta_C^{\rm ring}) = \sigma(\theta_C)/\sqrt{N_{pe}}$$

$\sigma(\theta_C^{\rm ring})$ Ring resolution – how well we measure photons.on ring

$\sigma(\theta_C)$ Single photon resolution (see below)

$\sqrt{N_{pe}}$ No. of photoelectrons



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

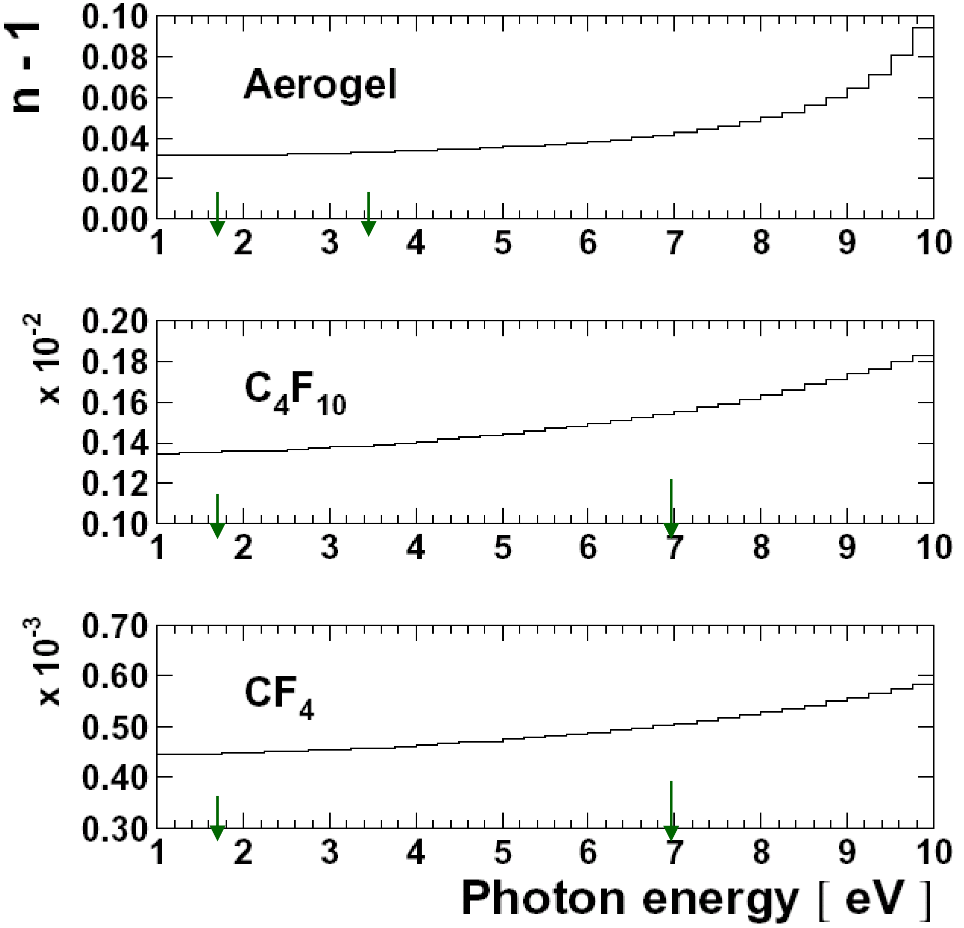
Chromatic dispersion

A significant source of uncertainty in the Cherenkov angle

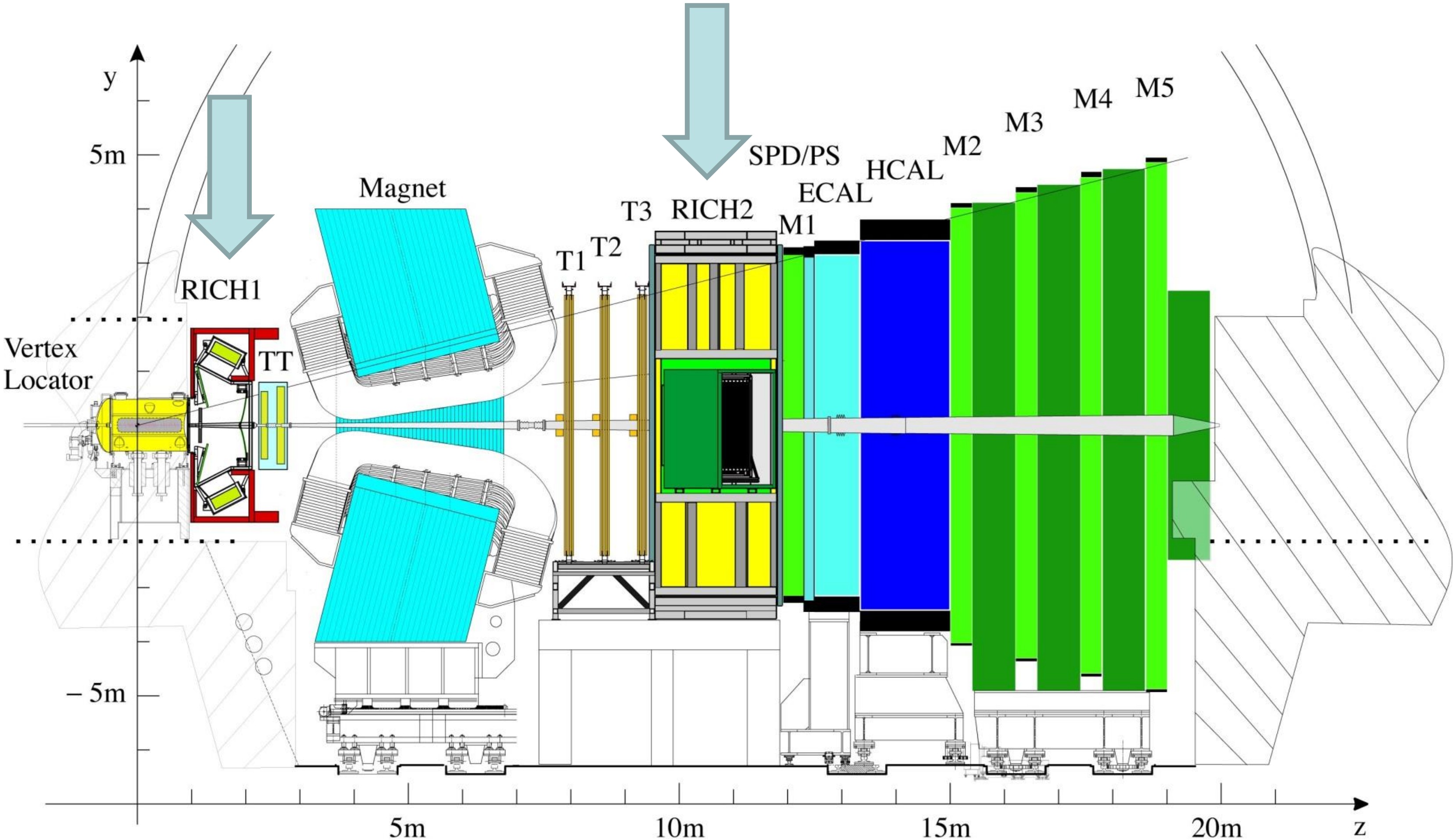
Refractive index varies with wavelength/photon energy, and hence so does θ_c

Control this by **limiting wavelength**.

Do this with choice of photodetector technology and/or filters.

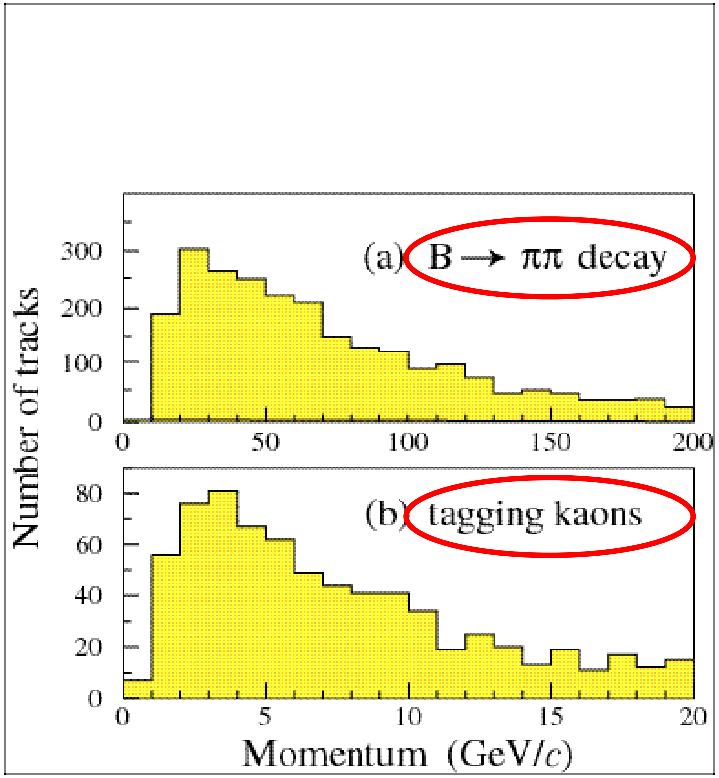


LHCb: a two RICH (2 radiator) detector



Why RICH? Why two 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, multiple radiators needed:

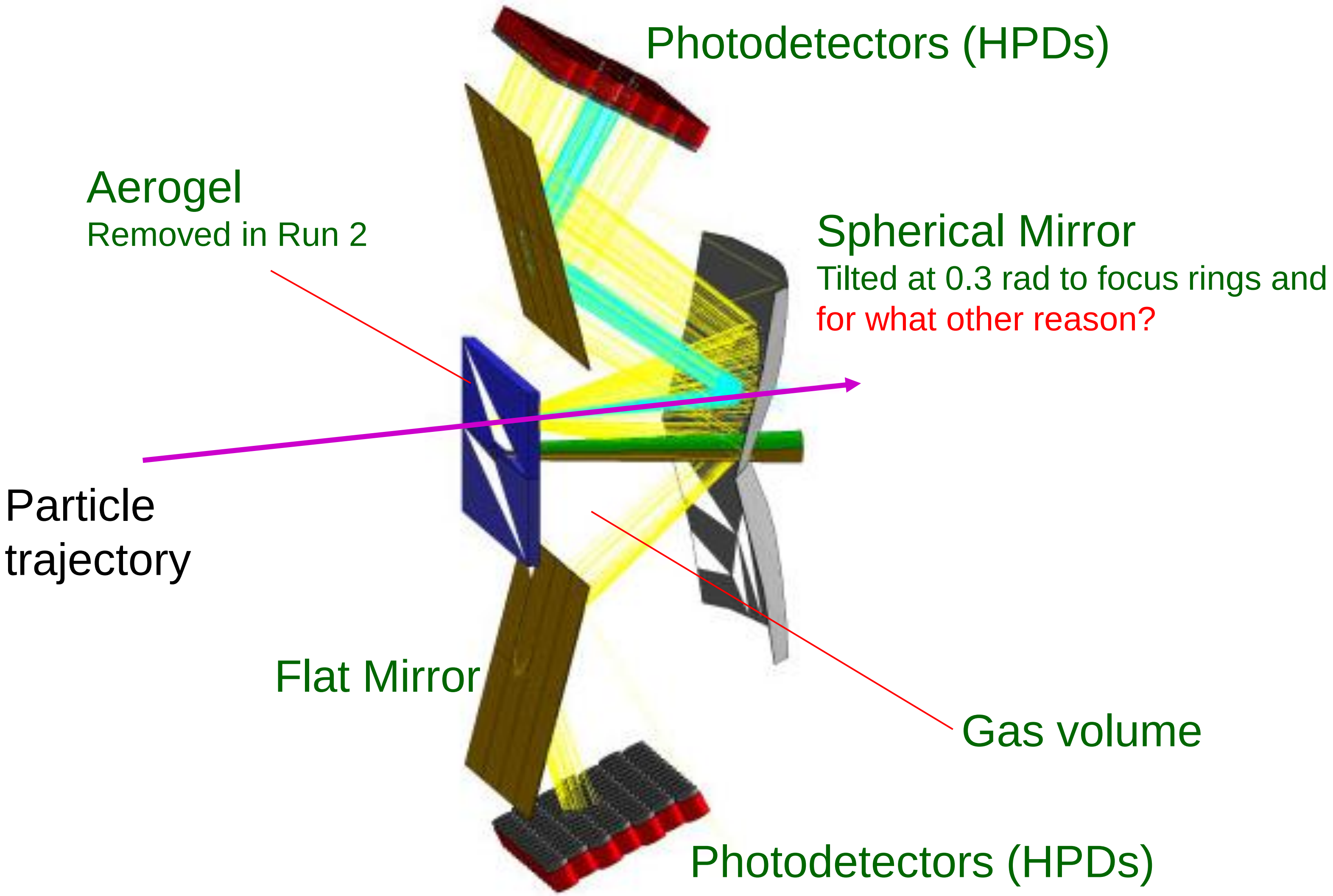
Low p: aerogel (now removed)

Central p: C_4F_{10}

High p: CF_4

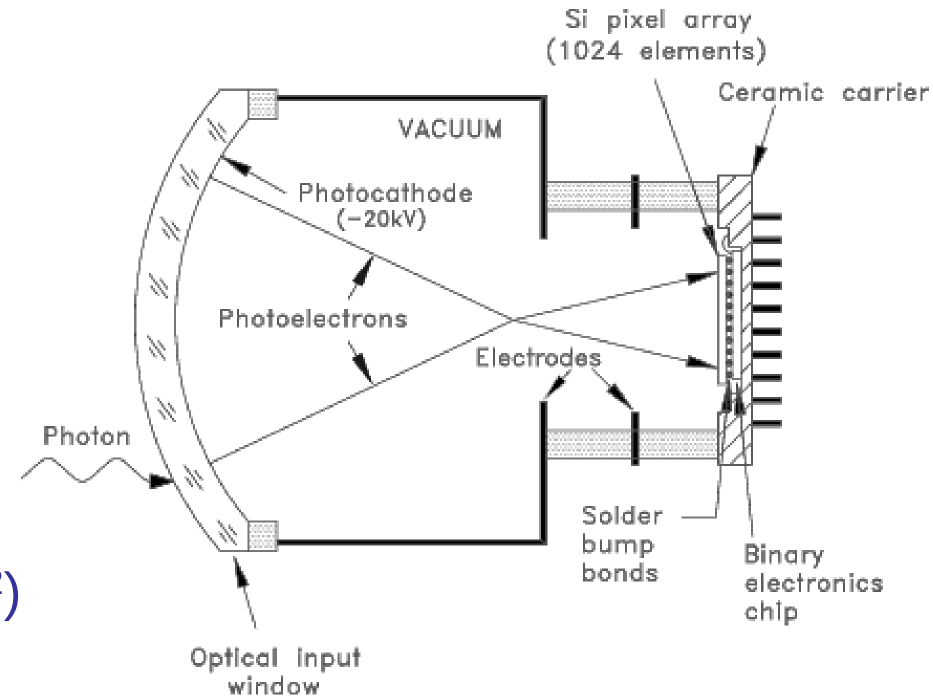
Covers 2 < p < 100 GeV/c

LHCb RICH 1 geometry



LHCb RICH: Hybrid Photon Detector (HPD)

- Good single photon efficiency (~30% max)
- Sensitivity in visible light
- Capacity to cover large area using lots of them (several m^2)
- Good spatial resolution (2 mm^2 pixels)
- High rate capabilities (1 MHz)



Particle ID reconstruction

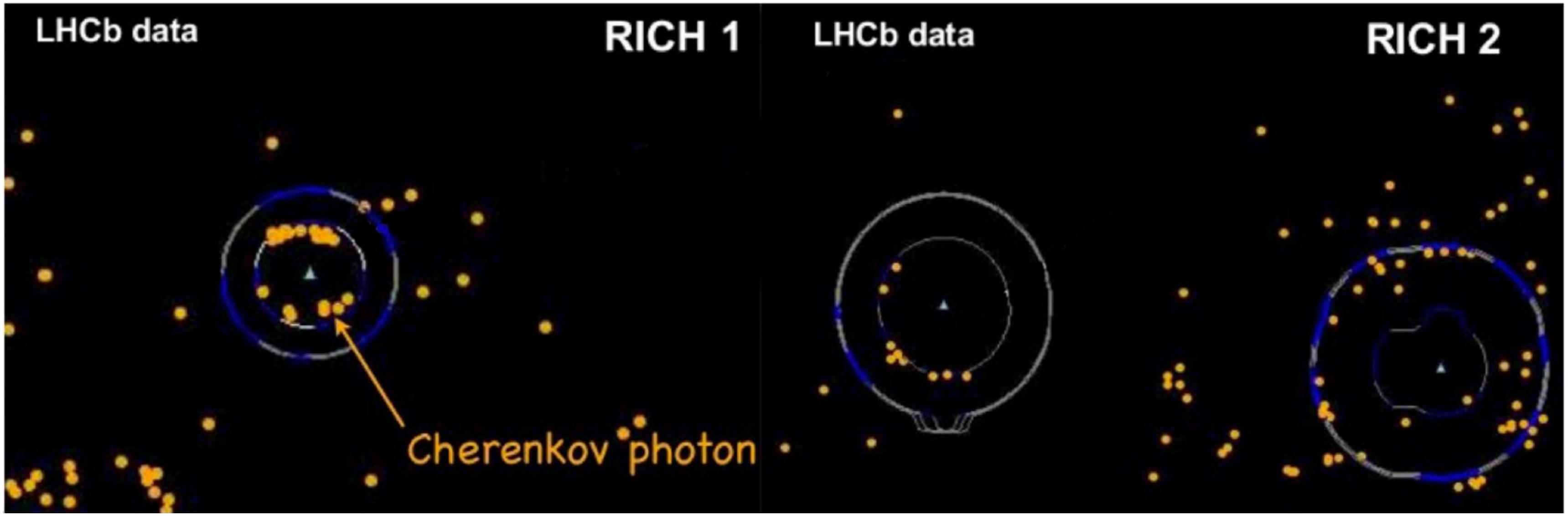
Data: **hits from Cherenkov photons cover many HPDs**

Fit the hits with rings – size of ring depends on momentum and mass

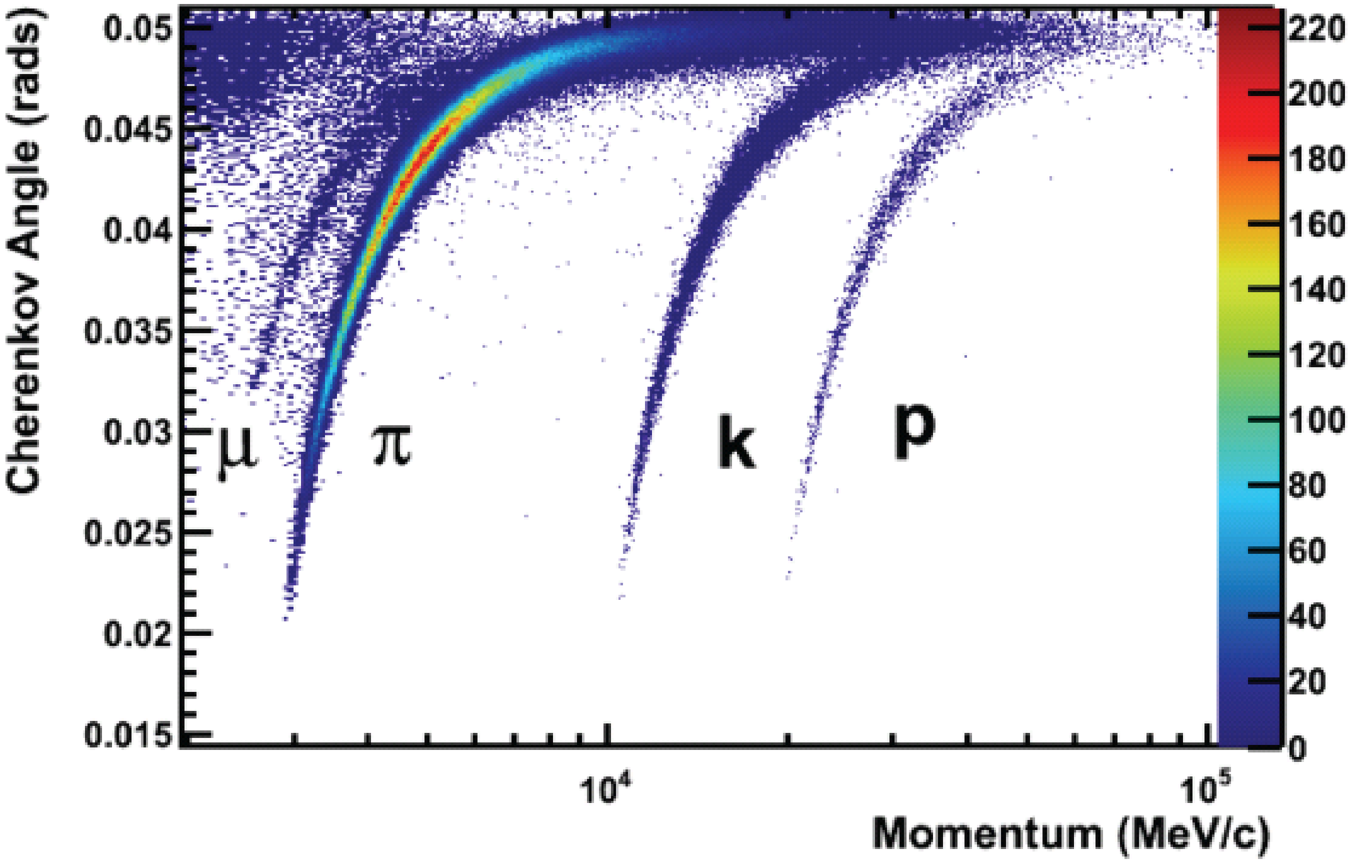
Momentum from tracking

Guess the mass → fit several rings, one for each of K, π, μ and p mass hypothesis

Fit quality tells us the likelihood of a track being K, π, μ or p

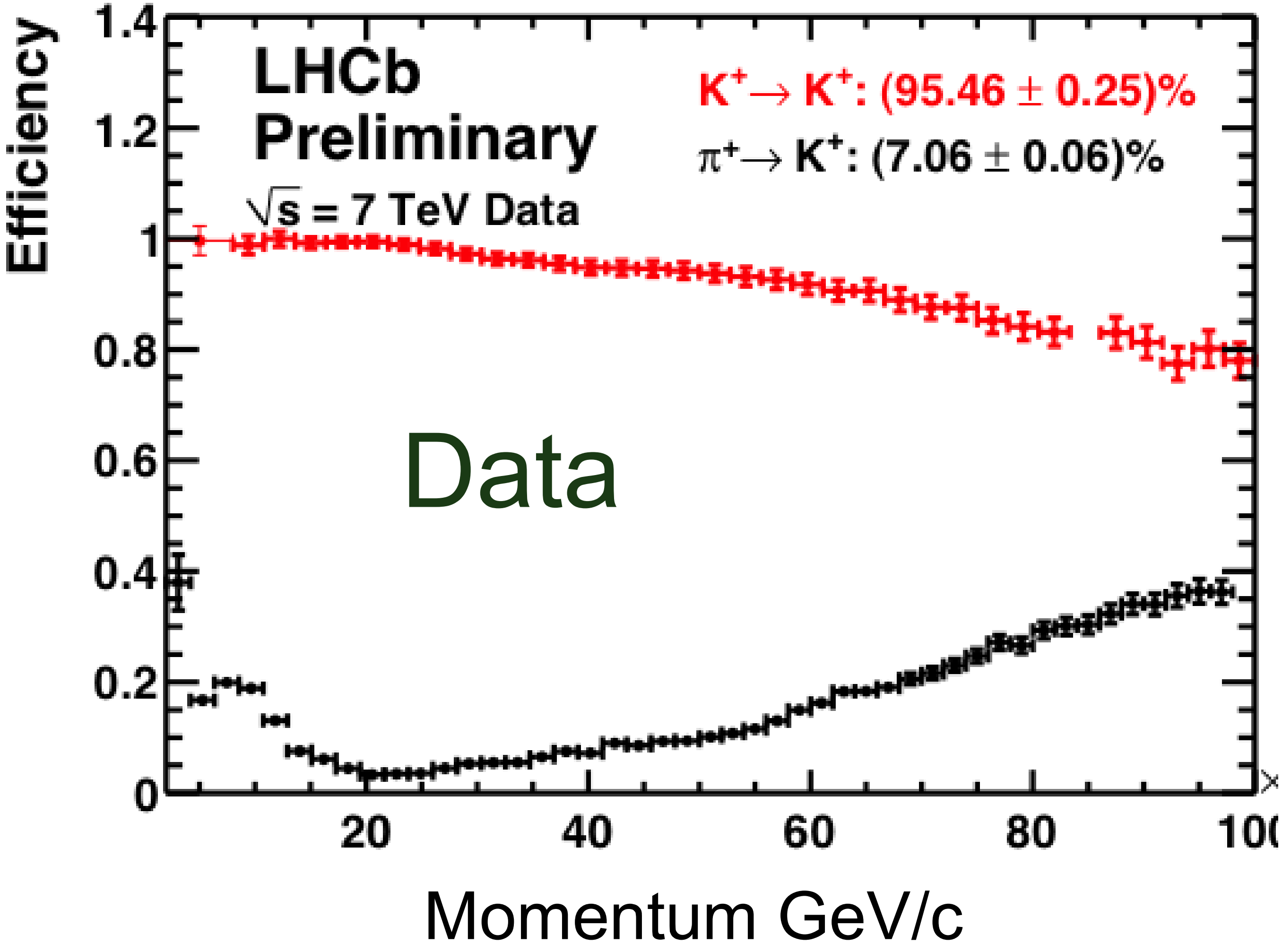


θ_C vs. momentum

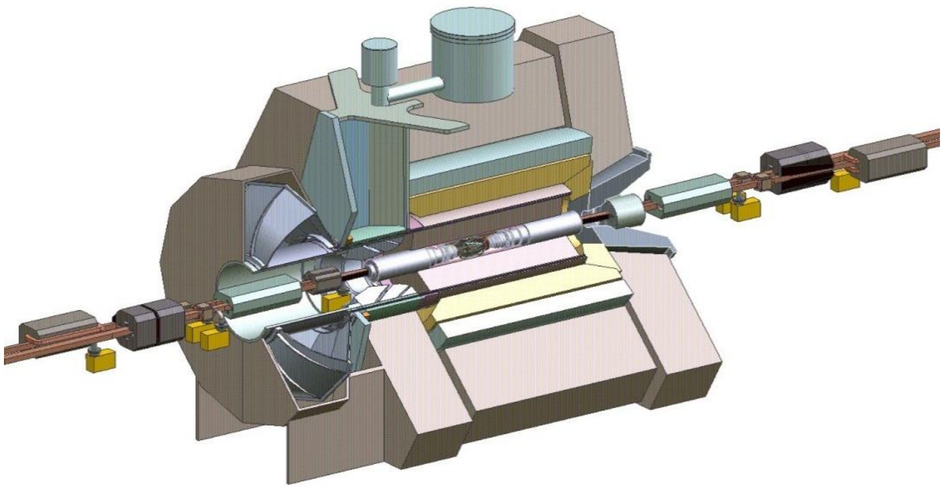


Excellent separation of curves for the different charged particle types

Performance

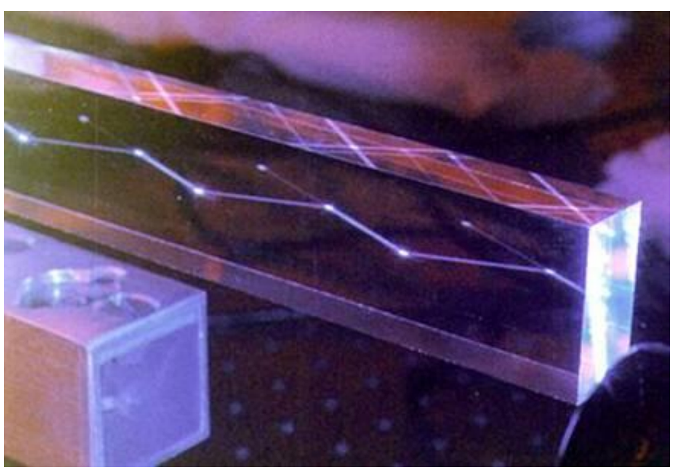


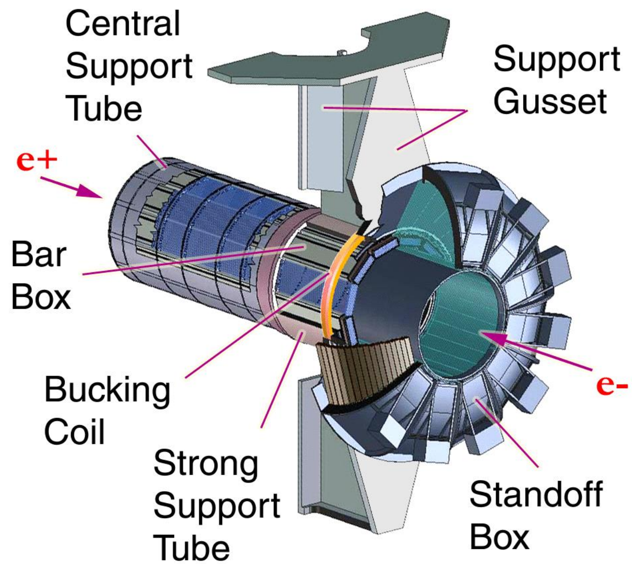
DIRC detectors : Detector of Internally Reflected Cherenkov Light (eg BaBar)



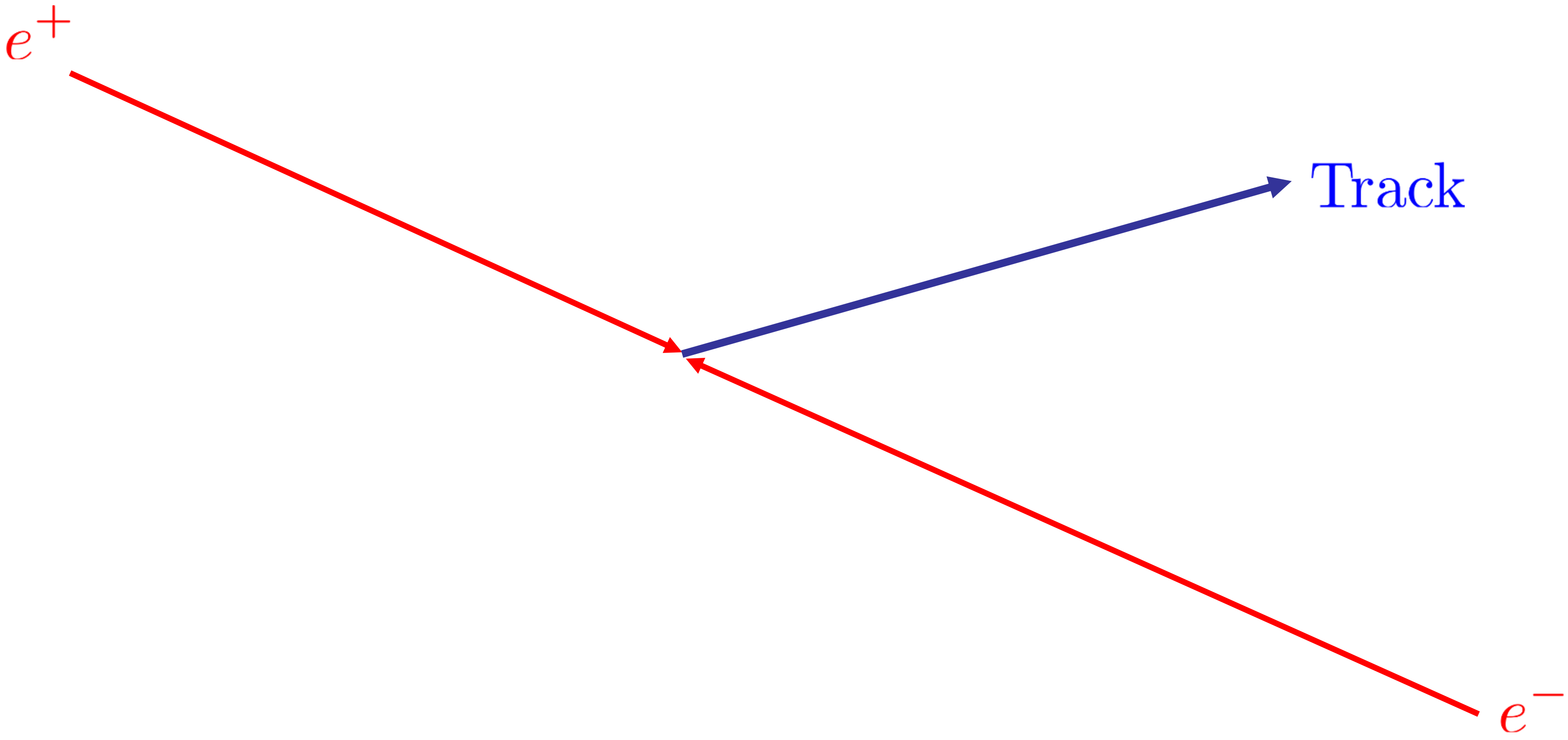
DIRC radiators cover:

94% azimuth
83% c.m. polar angle

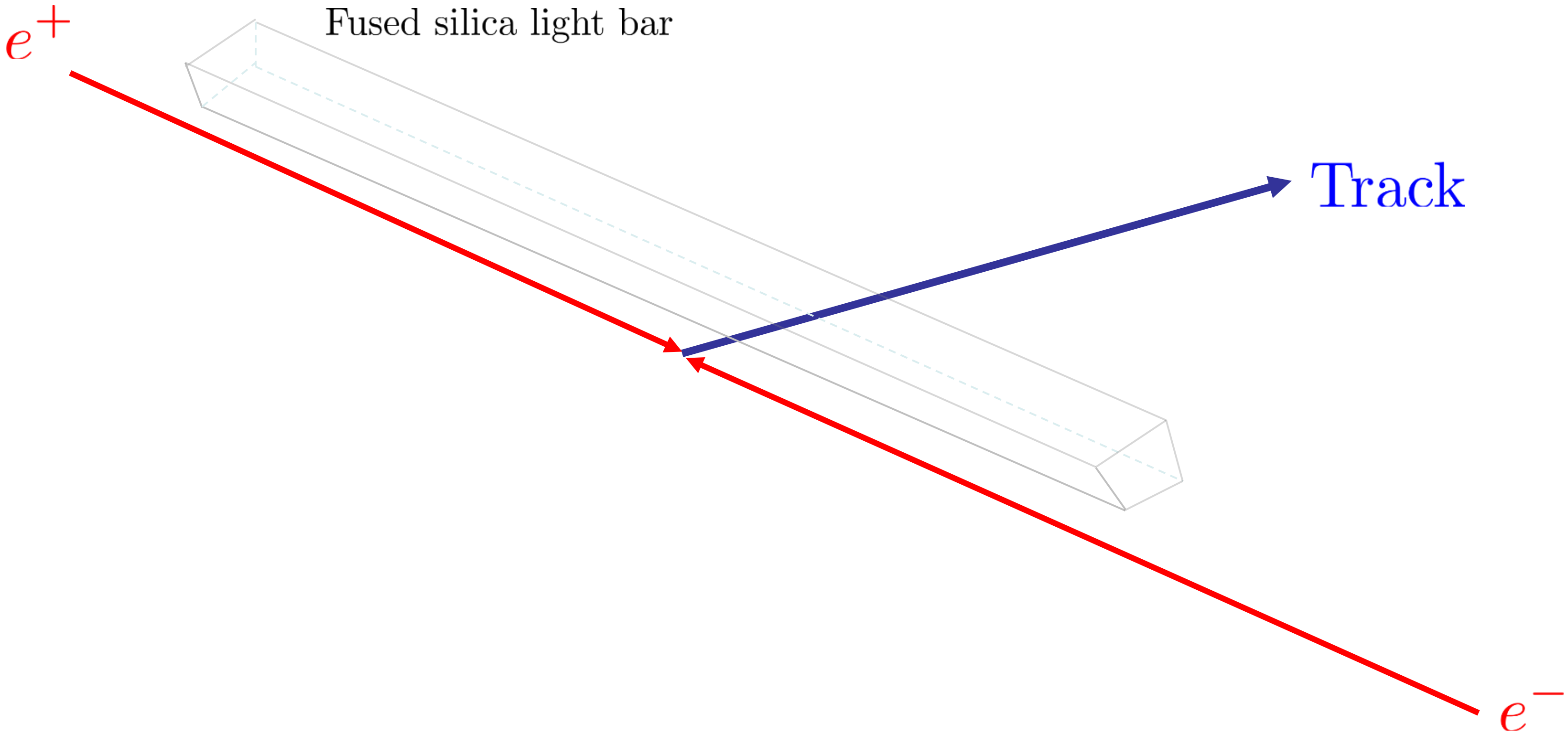




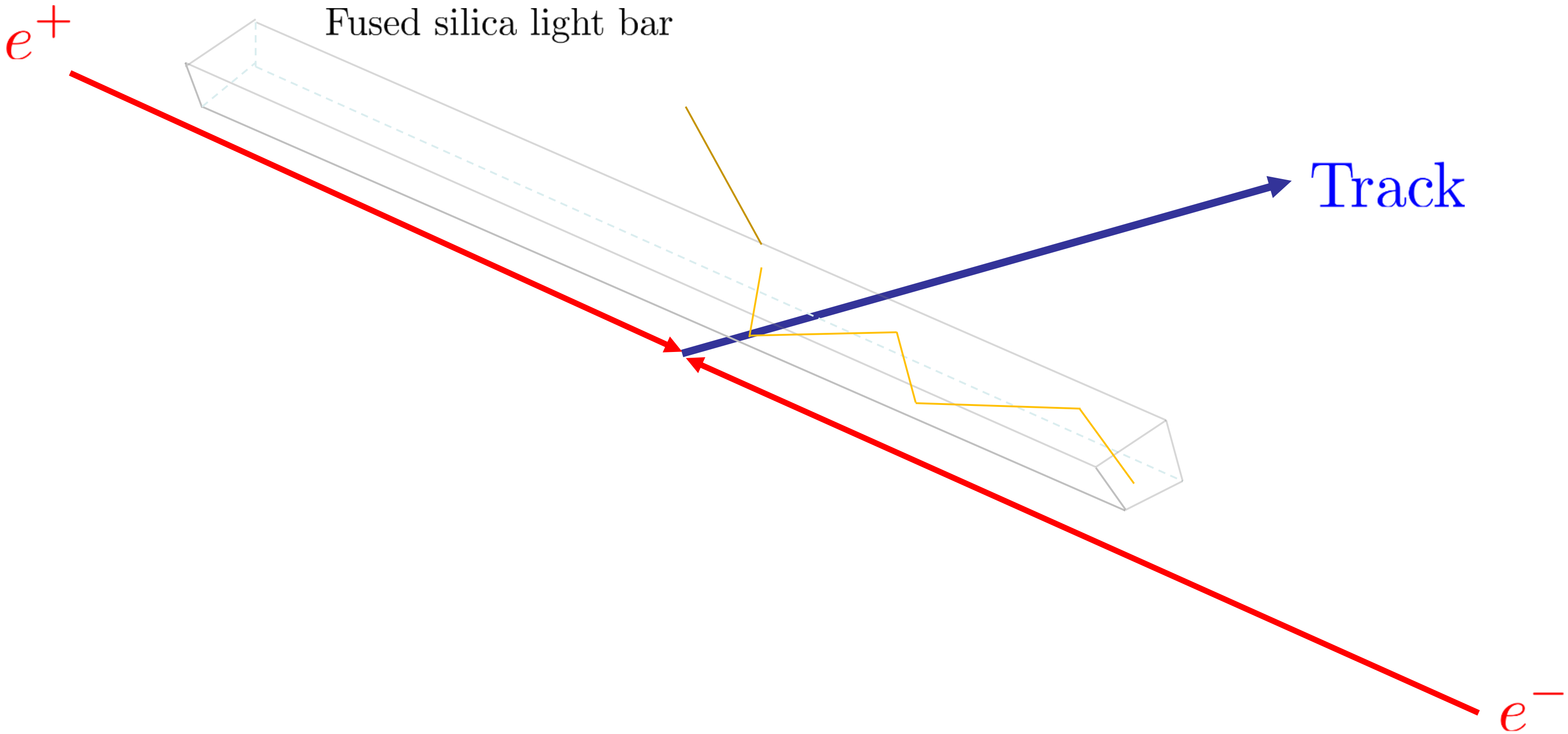
BaBar DIRC



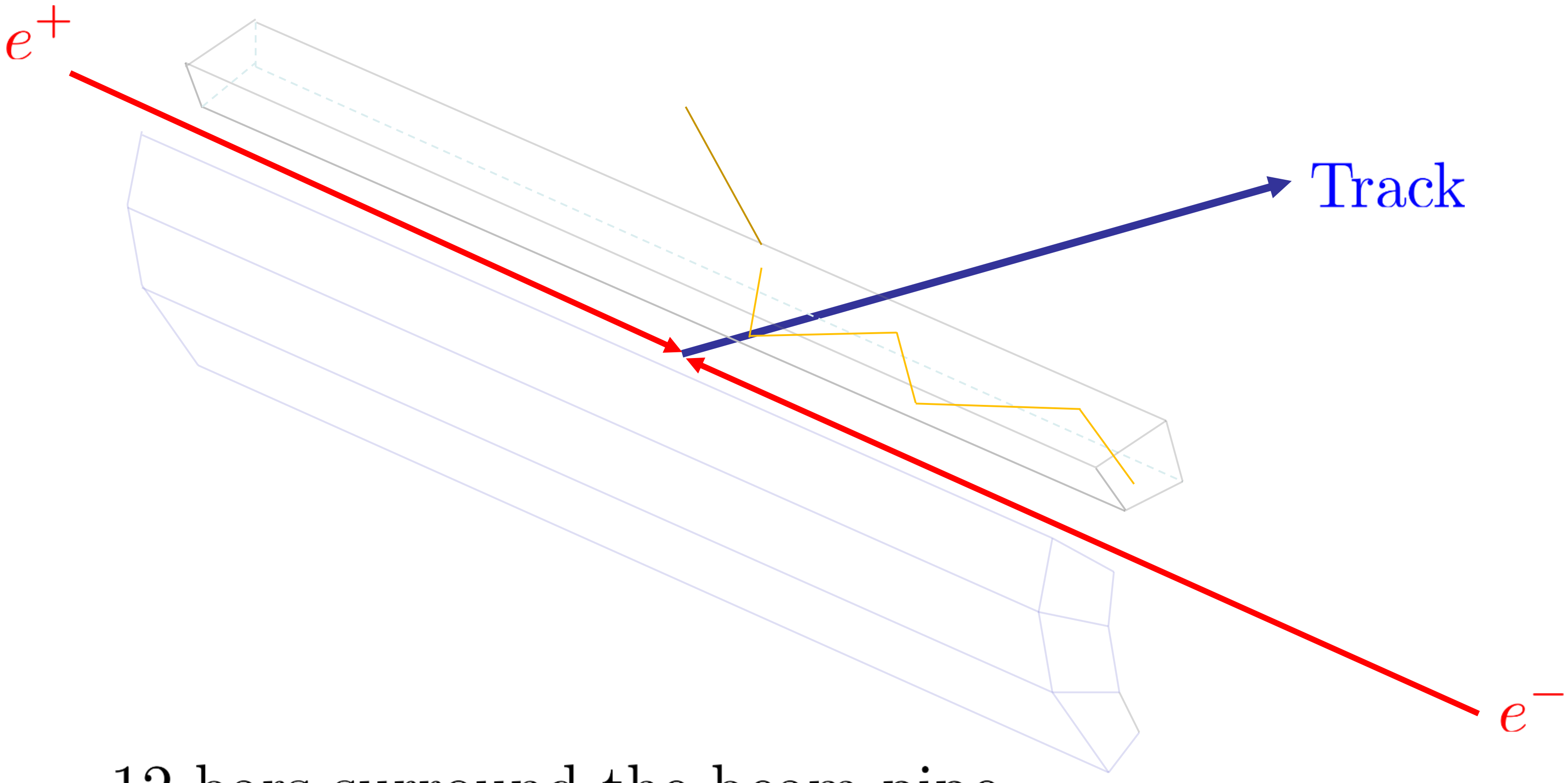
BaBar DIRC



BaBar DIRC



BaBar DIRC



12 bars surround the beam pipe

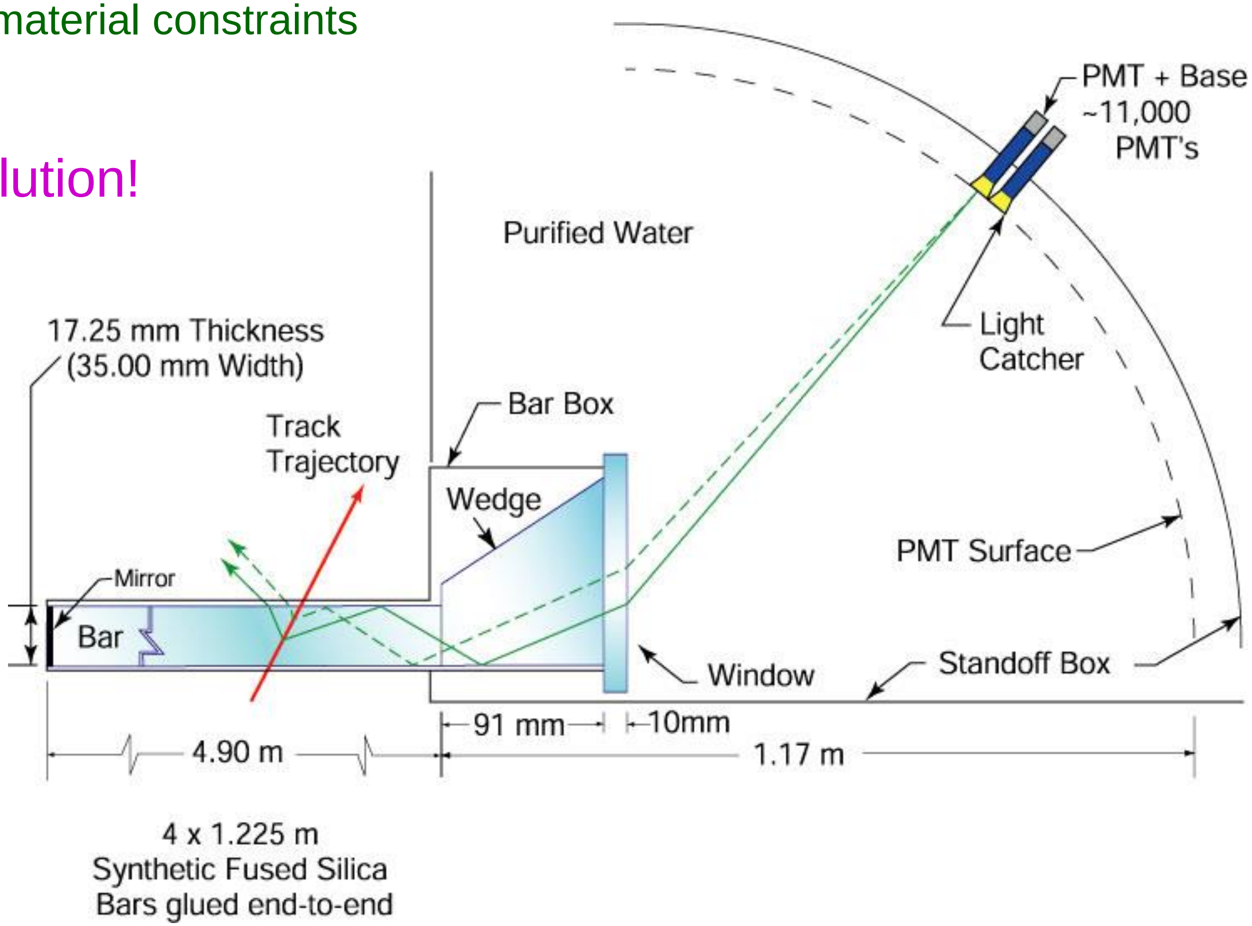
BaBar DIRC

BaBar PID requirements:

- π - K separation up to 4 GeV
- Must be fast (bunch crossing every 4 ns)
- Severe space and material constraints

PMTs provide adequate resolution

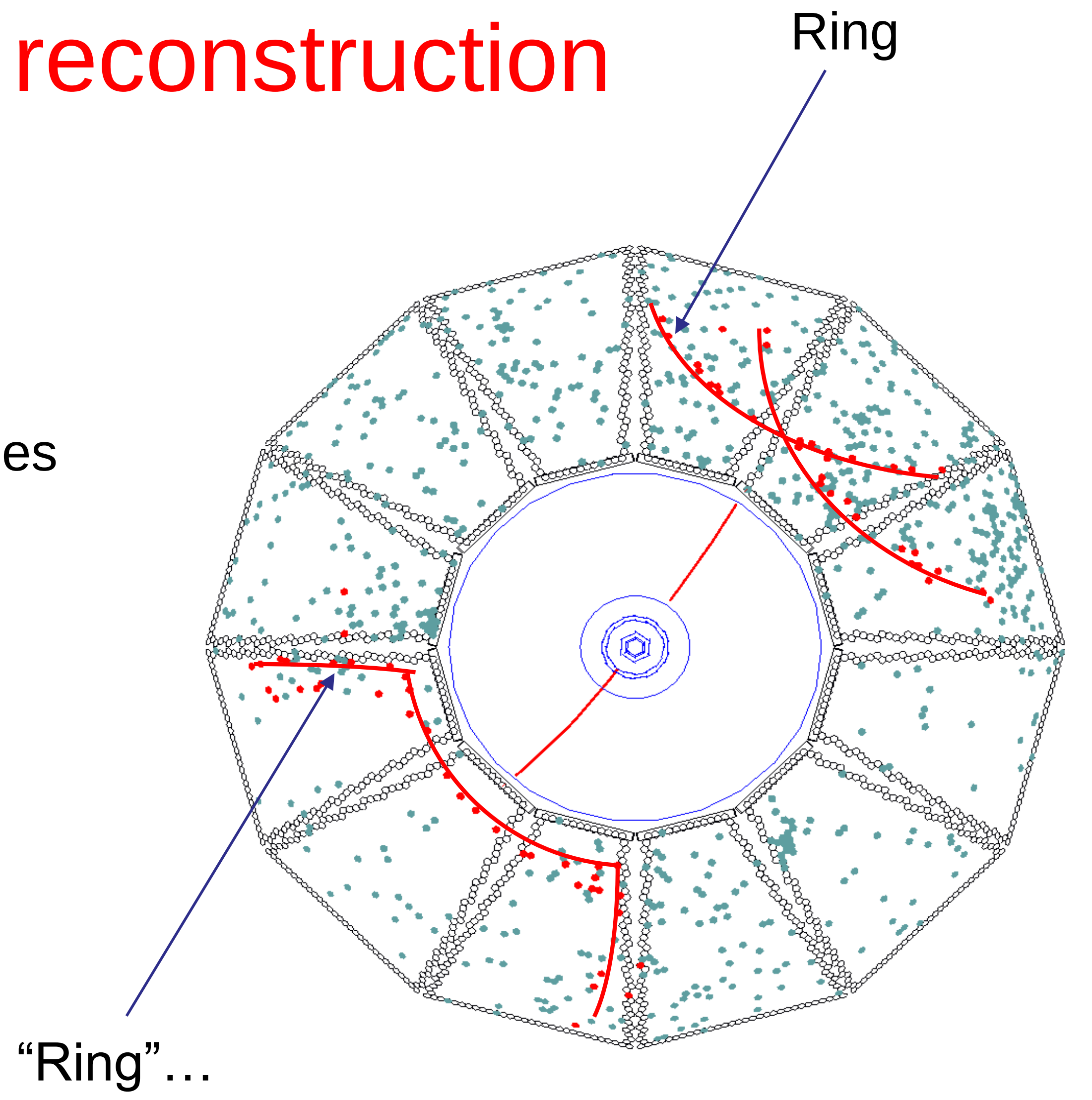
DIRC an ideal solution!



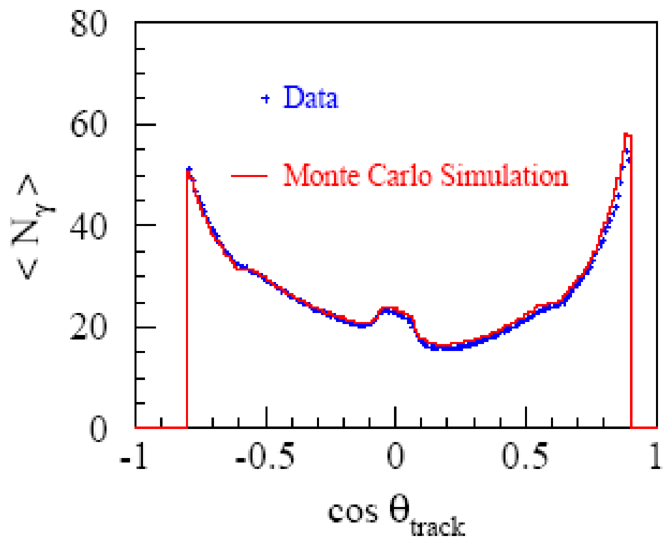
DIRC reconstruction

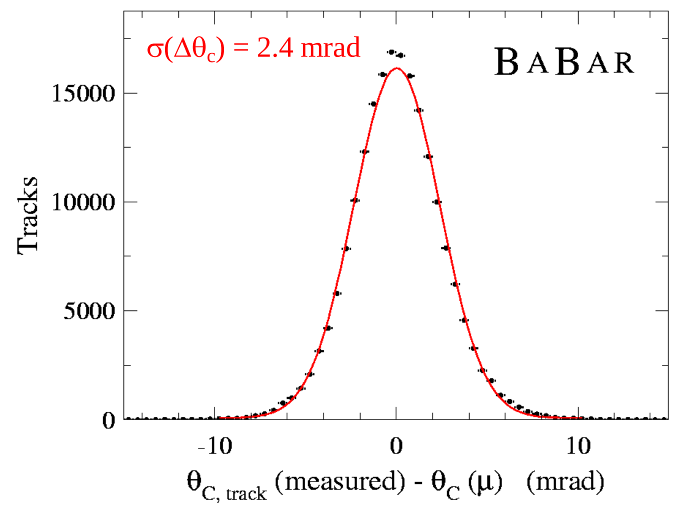
DIRC "ring" images

- Up to 16 reflection ambiguities
- Ambiguities per PMT hit
- Cherenkov ring images are distorted
- Complex, disjoint images



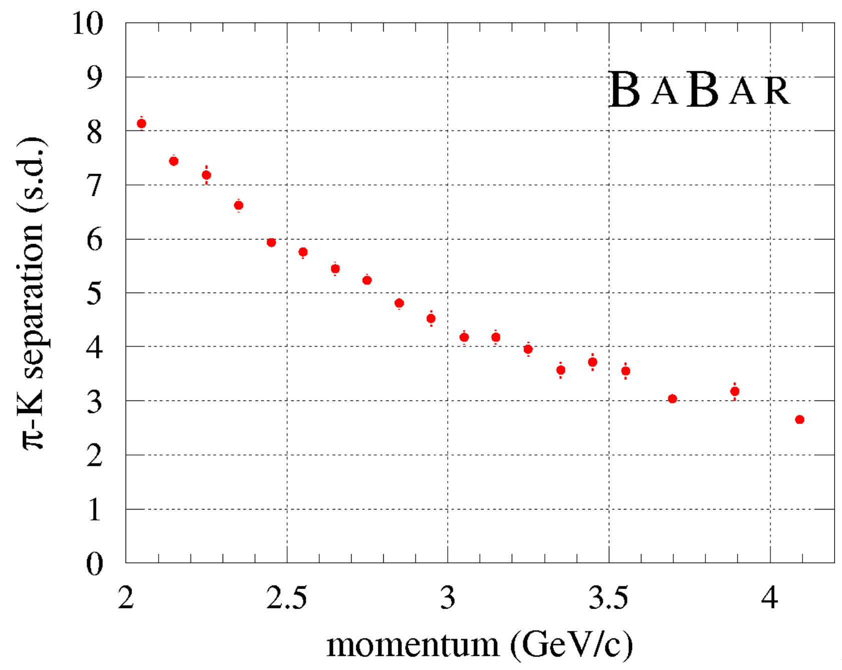
DIRC performance





N_{pe} and resolution

π - K separation vs momentum

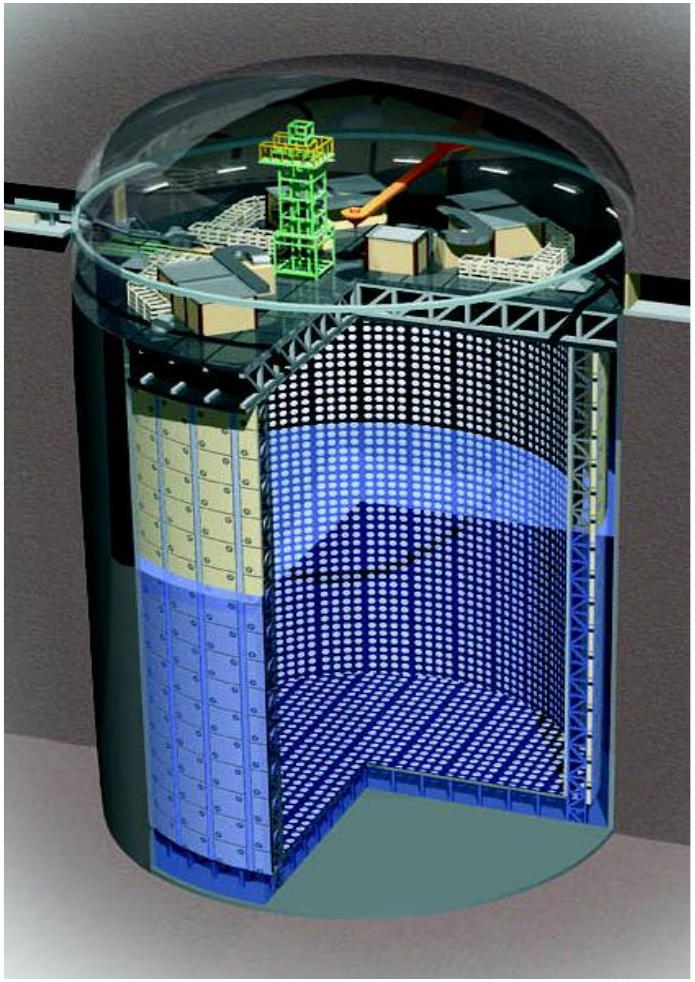


Large water volume neutrino detectors

Examples:

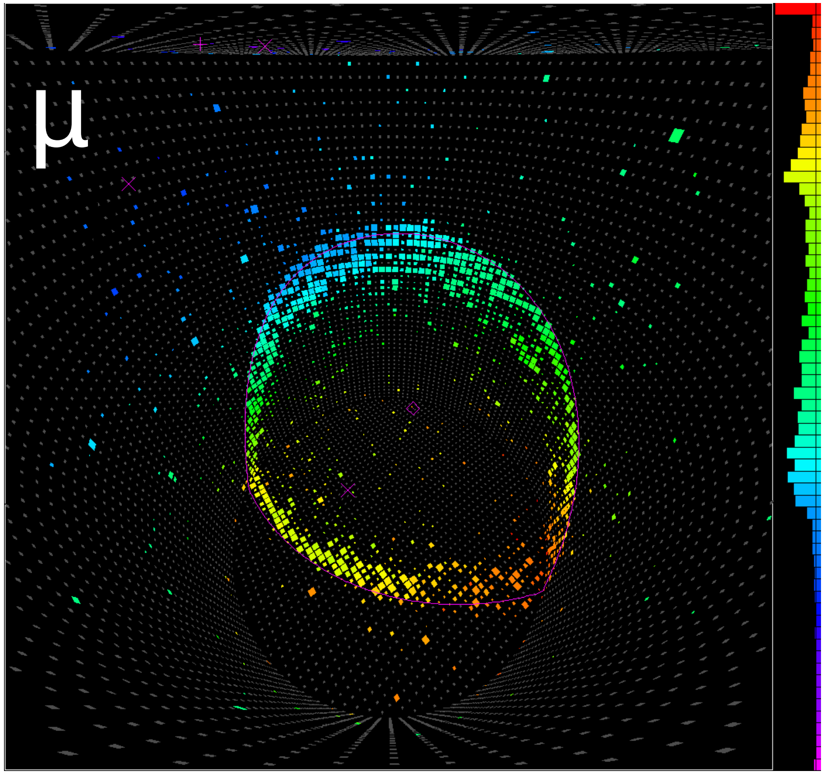
- SNO
- Super-Kamiokande
  - 50k tonnes H_20
  - 1 km underground

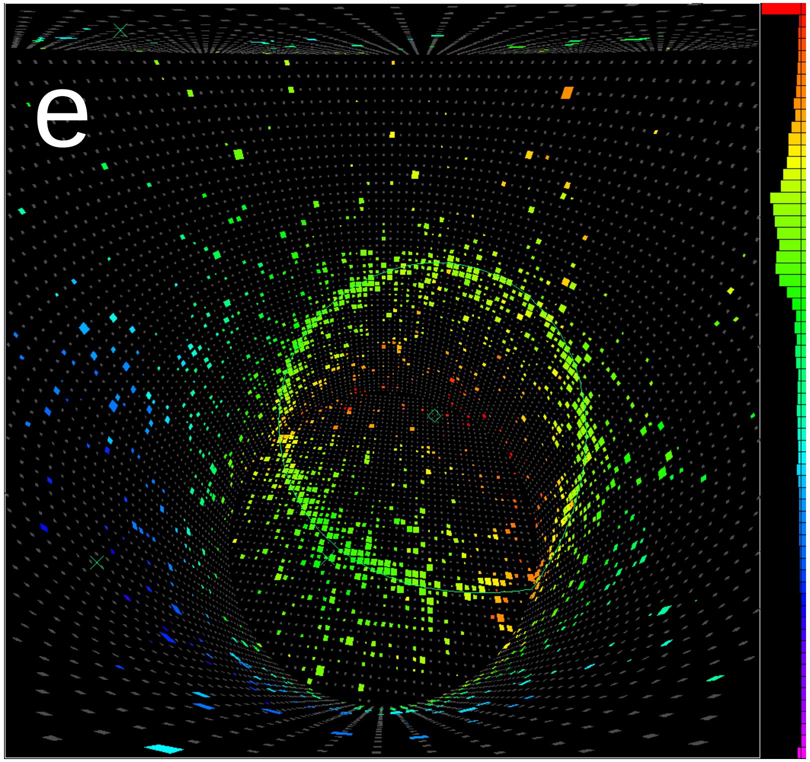
Cherenkov rings are an ideal technique for detecting $\nu \rightarrow \mu$, e



Cherenkov Rings in Super-K

Cherenkov light a perfect signature of a neutrino interaction





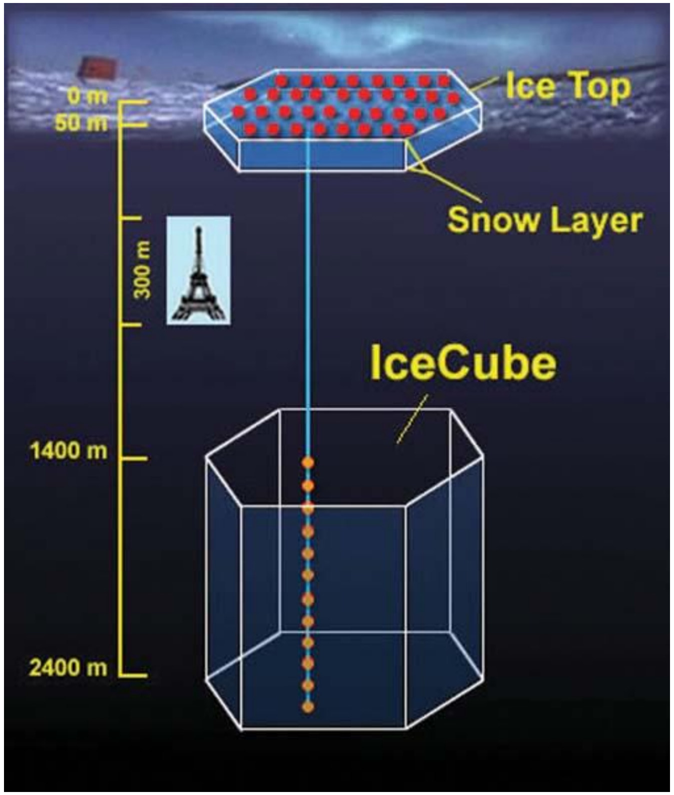
No momentum measurement

PID from **sharpness of ring** – muon is sharper, while electron showers

Timing response of PMTs necessary to determine particle direction

Ice Cube: a Cherenkov counter for studying high energy neutrinos (Antartica)

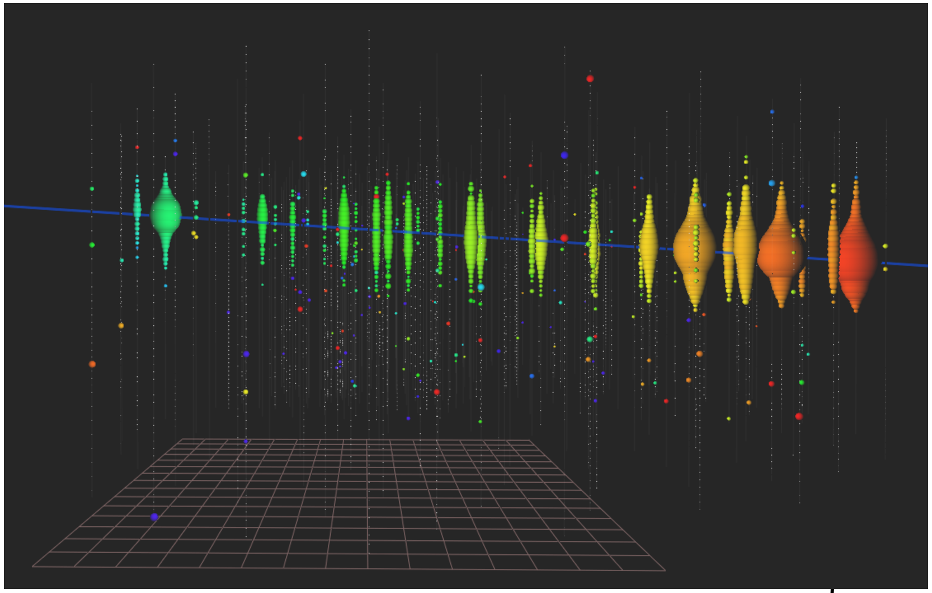
Ice Cube



Neutrino interacts with ice and creates a high energy muon / electron

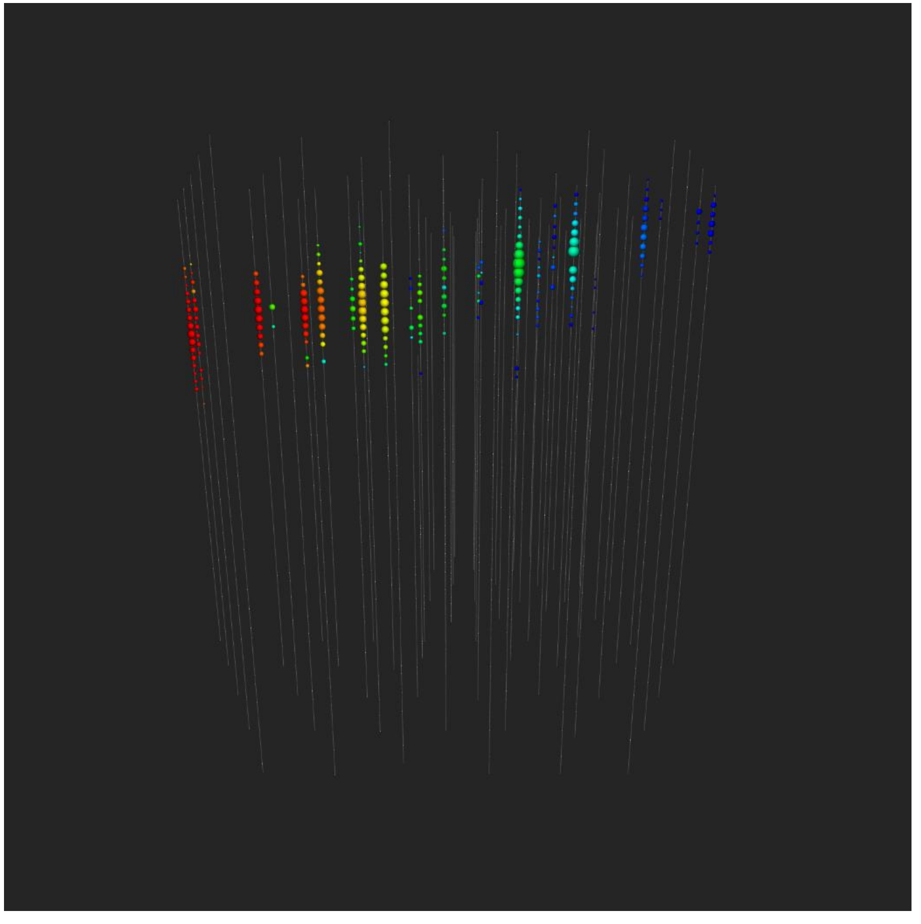
Particle radiates Cherenkov light as it travels, which is picked up by the array of optical sensors

Arrival time of Cherenkov light at the sensors gives the particle direction

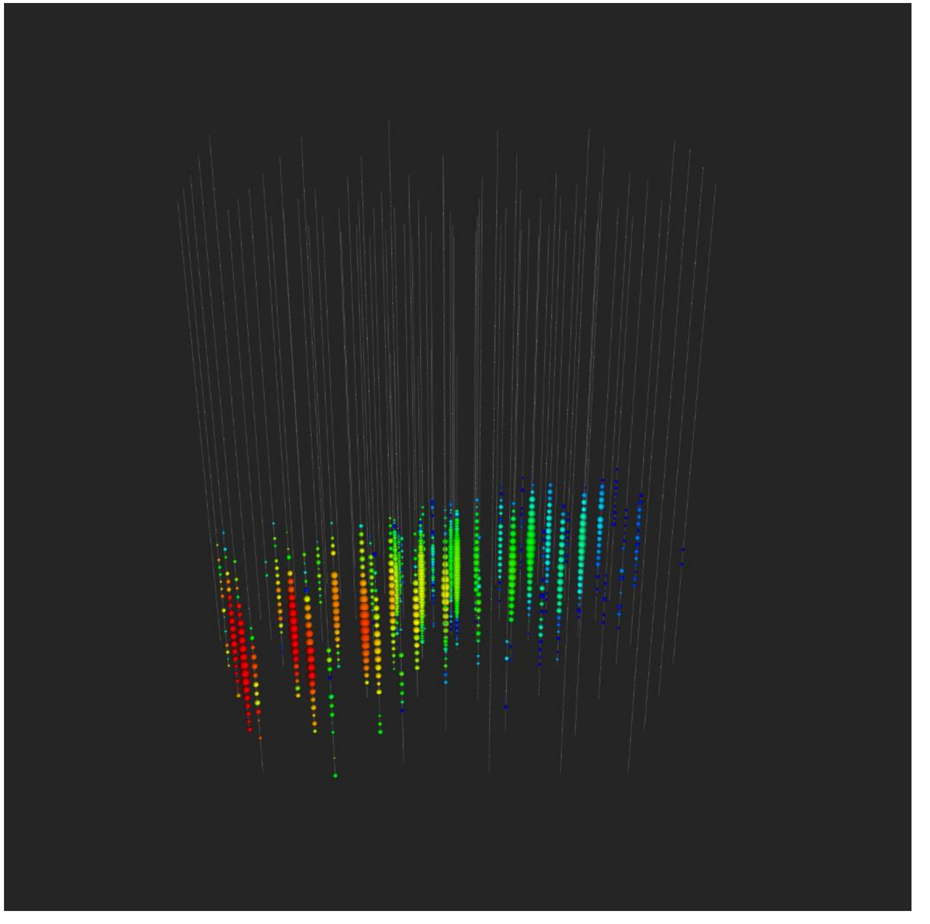


Hit Multiplicity = Energy Measurement

$E_{\mu} = 250\ \mathrm{TeV}$

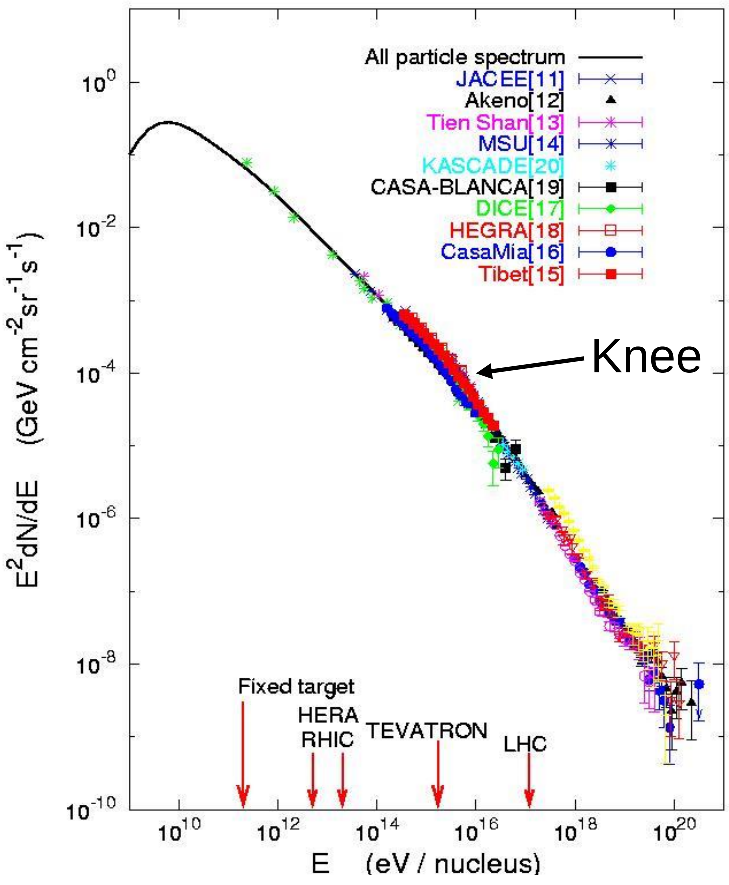


$E_{\mu} = 660\ \mathrm{TeV}$



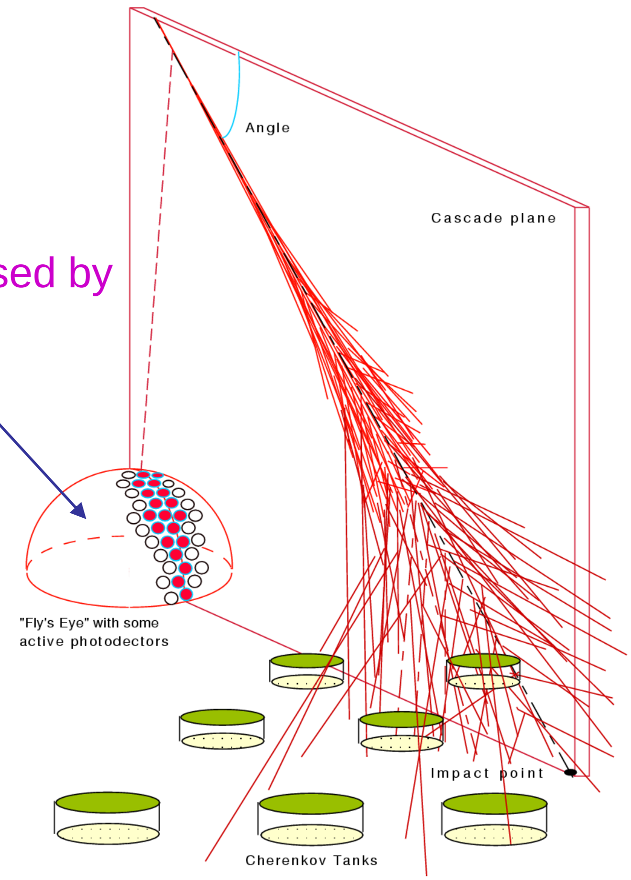
These are muons passing through IceCube

Pierre Auger – Search for ultra high energy cosmic rays



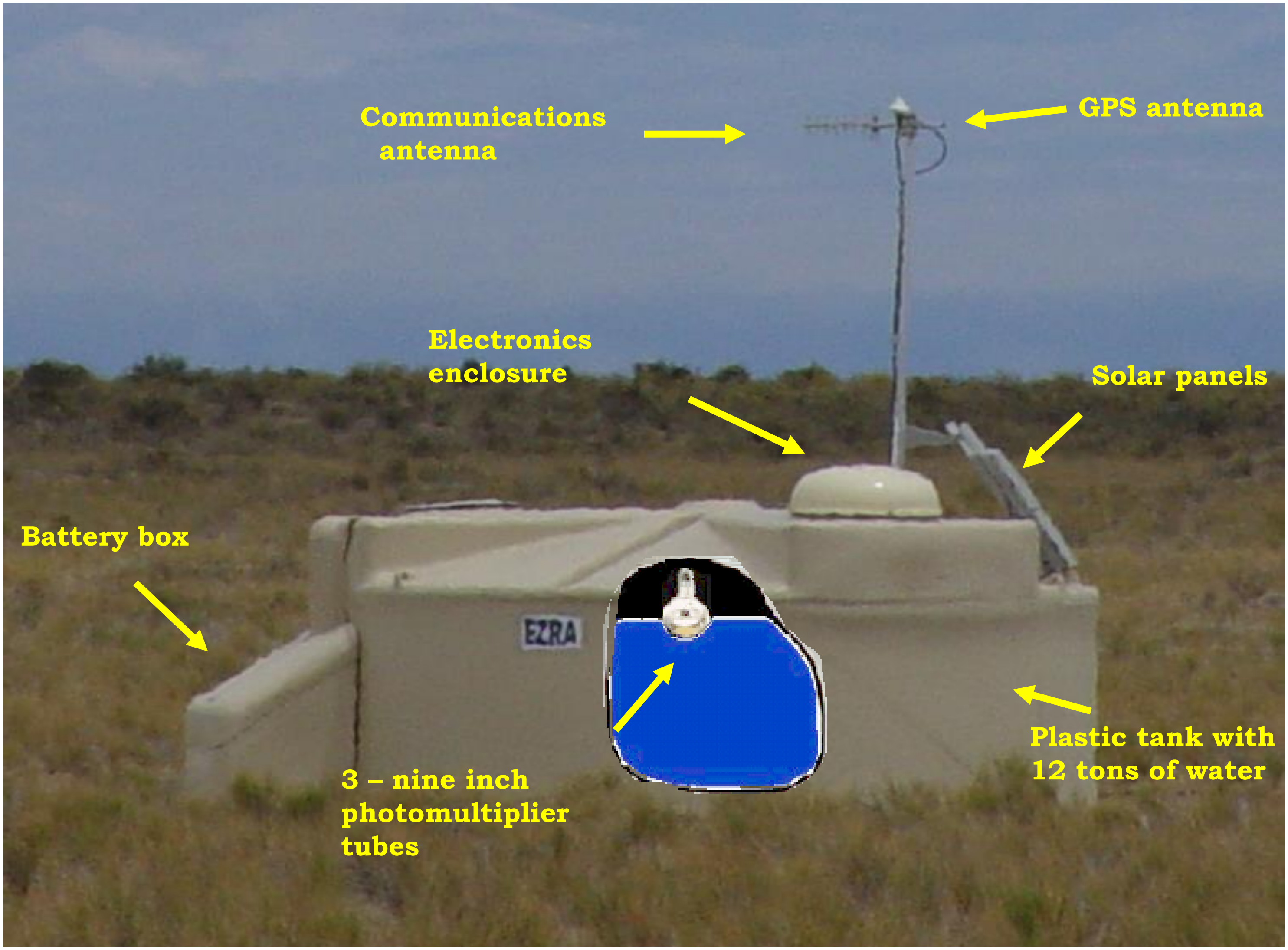
Air

24 fluorescence telescopes – measure nitrogen fluorescence caused by shower particles



Ground

1600 water Cherenkov detectors


Communications antenna
GPS antenna
Electronics enclosure
Solar panels
Battery box
EZRA
Plastic tank with 12 tons of water
3 – nine inch photomultiplier tubes

A quick look at transition radiation detectors

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

Brief example:

ATLAS TRT

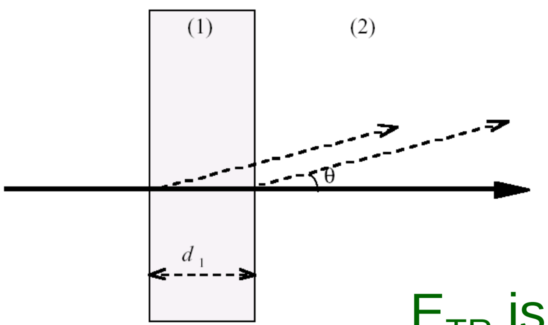
For more information:

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

Basics of Transition Radiation

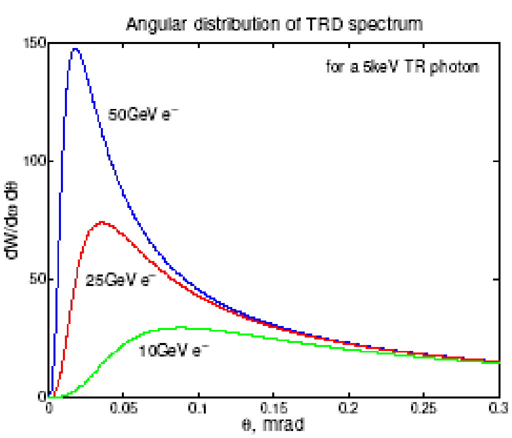
Transition radiation emitted when particle moves across interface of 2 media with different dielectric constants (predicted in 1946 by Ginzburg and Frank)

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



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

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

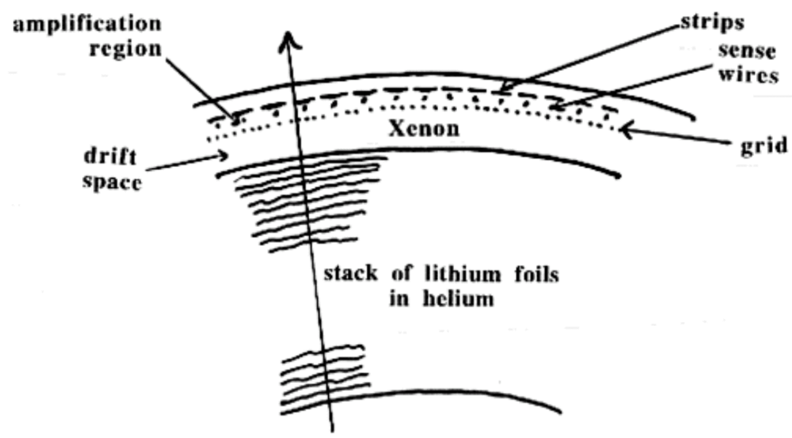
3) Total energy radiated proportional to γ !

Transition Radiation & HEP Applications

Dependence on γ makes TR an attractive method of PID, particularly for discriminating between electrons and hadrons at higher energy. Works over wide momentum range.

Experimental challenges:

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



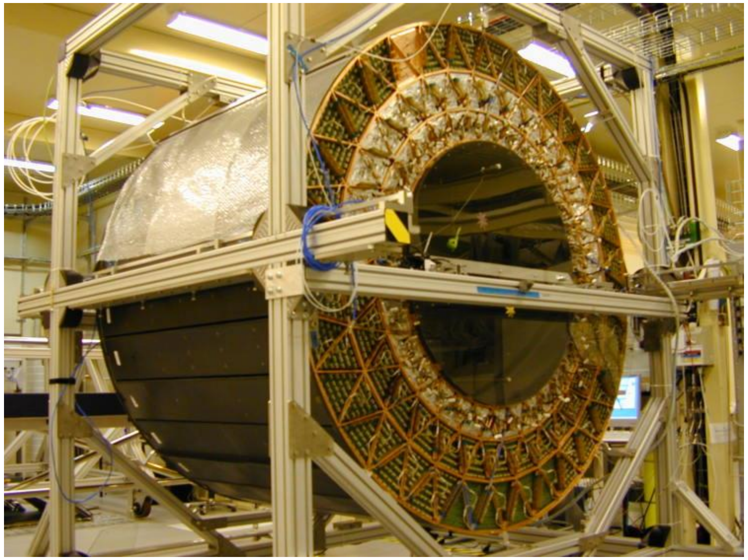
2) Forward peaking means that almost always X-rays and primary particle are seen by same detector. Generally one detects particle dE/dx and TR together. So must distinguish sum of energy from dE/dx alone, or look for clusters specifically associated with absorption of the X-rays.

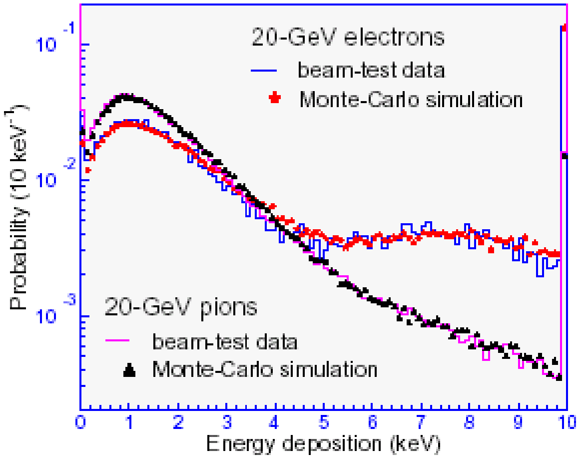
ATLAS Transition Radiation Tracker

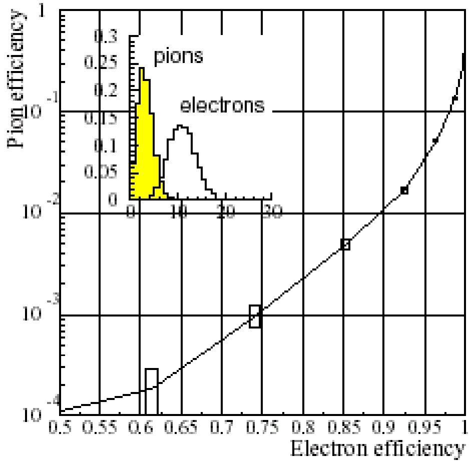
Part of the ATLAS Inner Detector.

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

Layers of xenon-filled straw tubes interleaved with polypropylene foils.



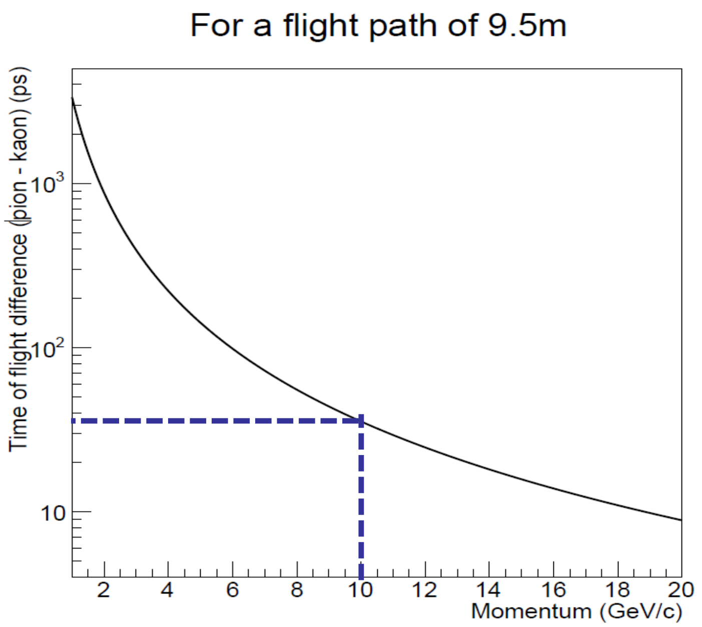


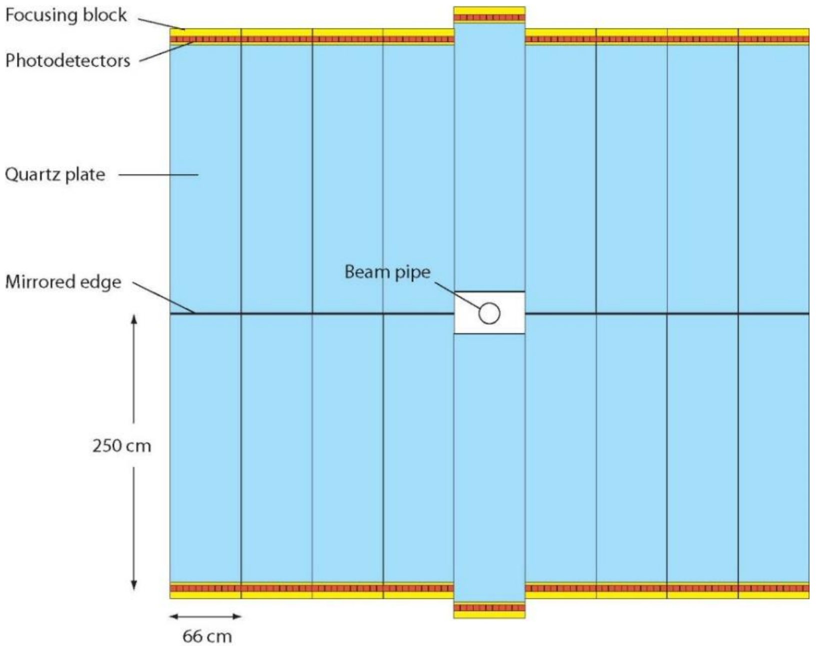


Can suppress pions by a factor of about 100, for 90% electron eff.

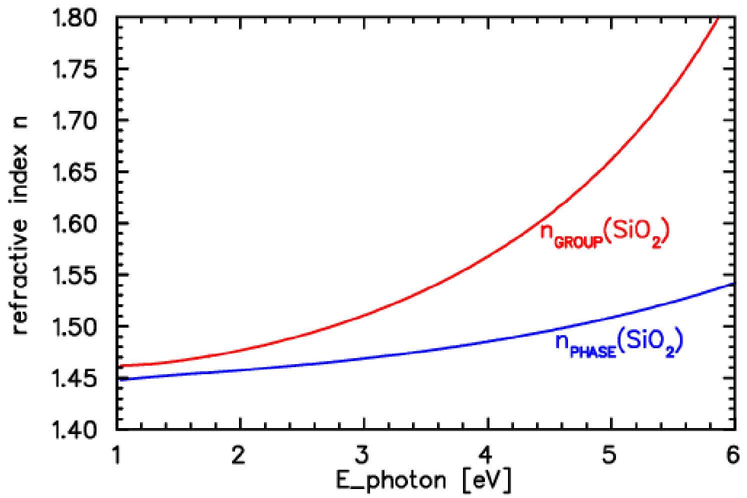
DIRC RICH to measure Time of Flight (TORCH)

- To achieve positive identification of kaons up to p ~ 10 GeV/c, ΔTOF (π-K) = 35 ps over a ~10 m flight path → need to aim for ~ 10-15 ps resolution per track
- Cherenkov light production is prompt → use a plane of quartz (~30 m^2) as a source of fast signal
- Cherenkov photons travel to the periphery of the detector by total internal reflection → time their arrival by Micro-channel plate PMTs (MCPs)
- The ΔTOF requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons)





Principles of the TORCH detector

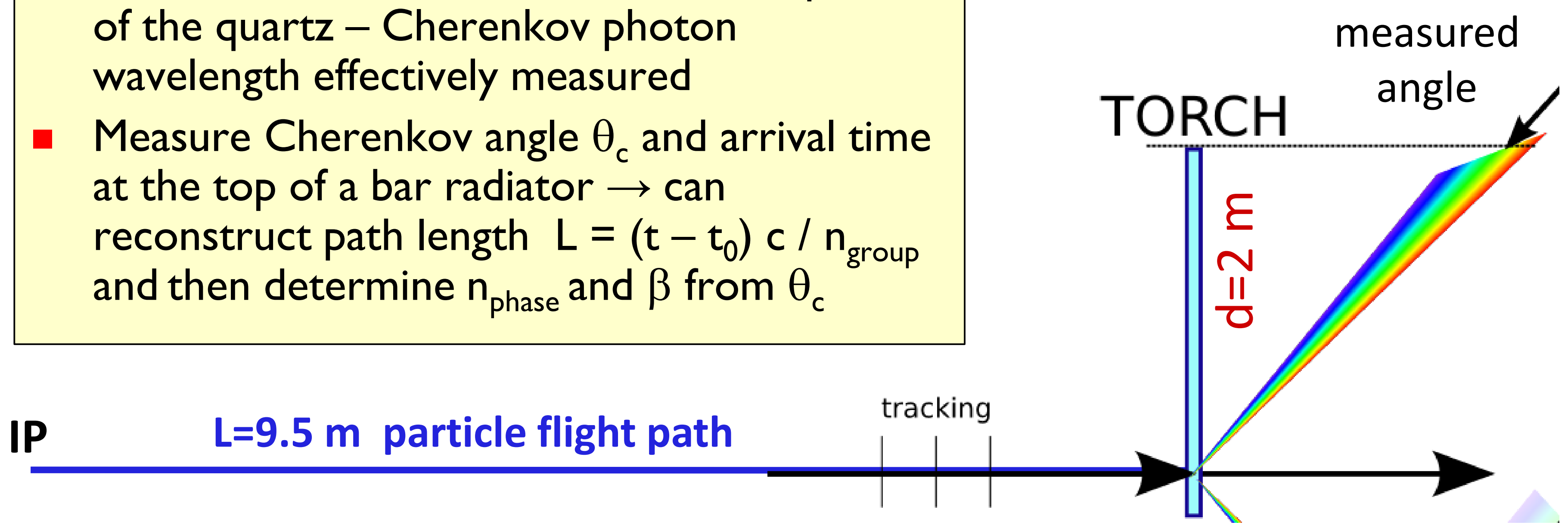


Cherenkov angle : $\cos\theta_c = (\beta\, n_{phase})^{-1}$

Time of propogation : $t = L / v_{group} = n_{group} L / c$

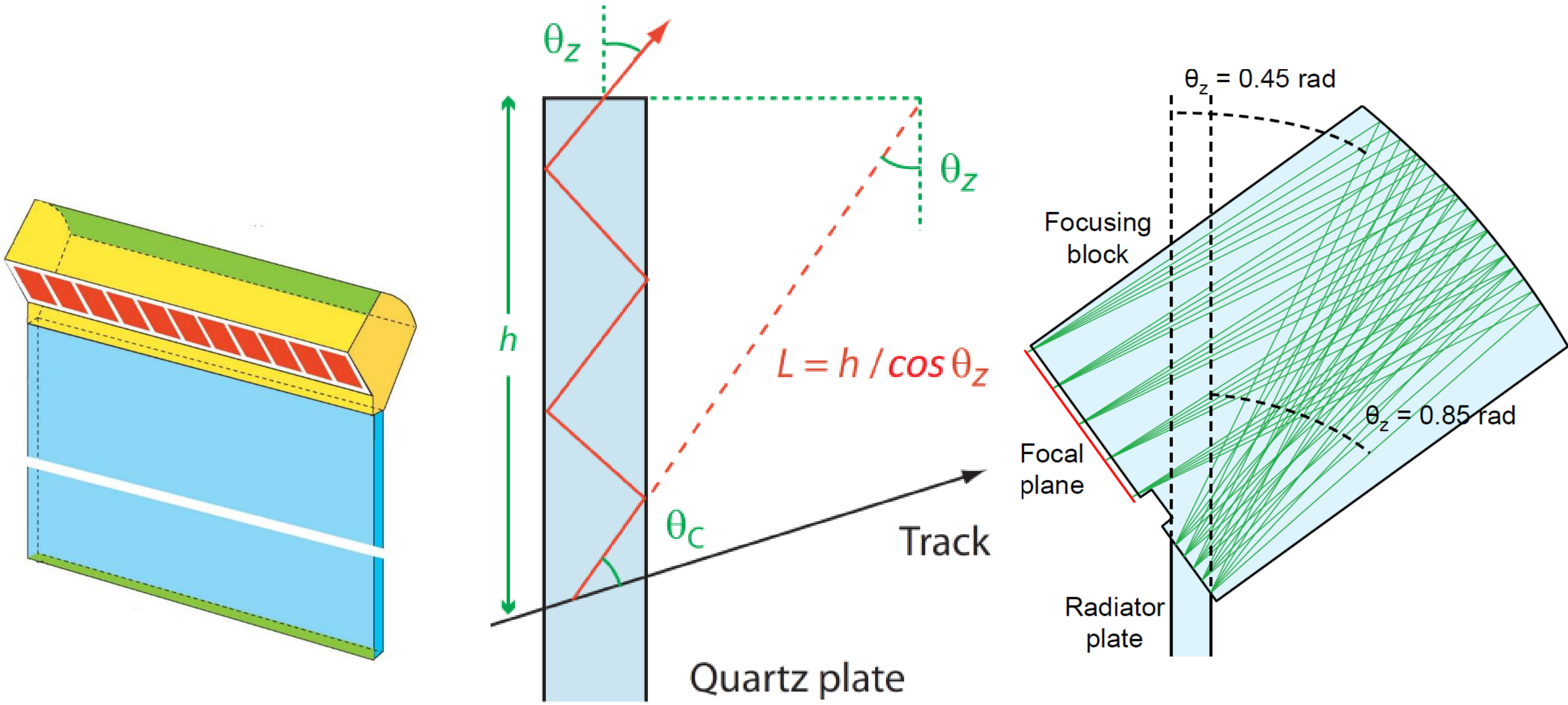
$n_{group} = n_{phase} - \lambda\, (dn_{phase}/d\lambda)$

- Need to correct for the chromatic dispersion of the quartz – Cherenkov photon wavelength effectively measured
- Measure Cherenkov angle θ_c and arrival time at the top of a bar radiator → can reconstruct path length $L = (t - t_0)\, c / n_{group}$ and then determine n_{phase} and β from θ_c



Basics of the TORCH design

- Measure *angles* of photons: then reconstruct their path length L, correct for time of propogation
- From simulation, ~1 mrad precision required on the angles in both planes for intrinsic resolution of ~50 ps



Conclusions

In the old days, RICHs were tricky!

> "Very often this technique is criticised as being too difficult and not reliable. We admit that in some senses this is true…"
>
> Tom Ypsilantis, co-discoverer of the antiproton

But today we know how to build them:

- B physics experiments
- Neutrino detectors
- Cosmic ray observatories

Cherenkov (and TR) detection is and will remain a vital tool in the armoury of experimental HEP!