Particle Identification

Lecture II: Detectors

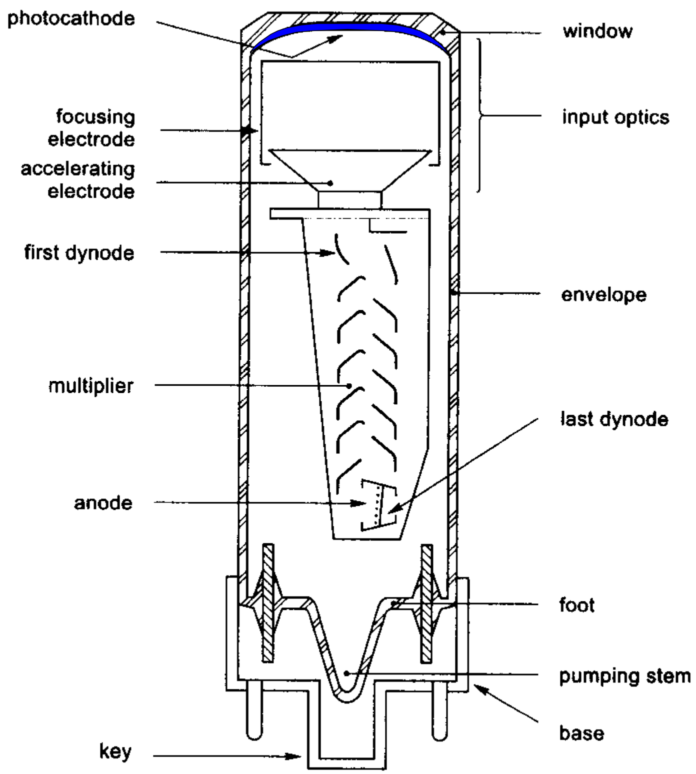
Charged hadron ID is based on the principles described in Lecture I
How are they applied in the design of actual detectors?

1. Photon detectors
2. Cherenkov detectors
3. RICH examples
4. Other PID devices

ICFA Instrumentation School, Bariloche, 19-20 January 2010

1. Photon detectors

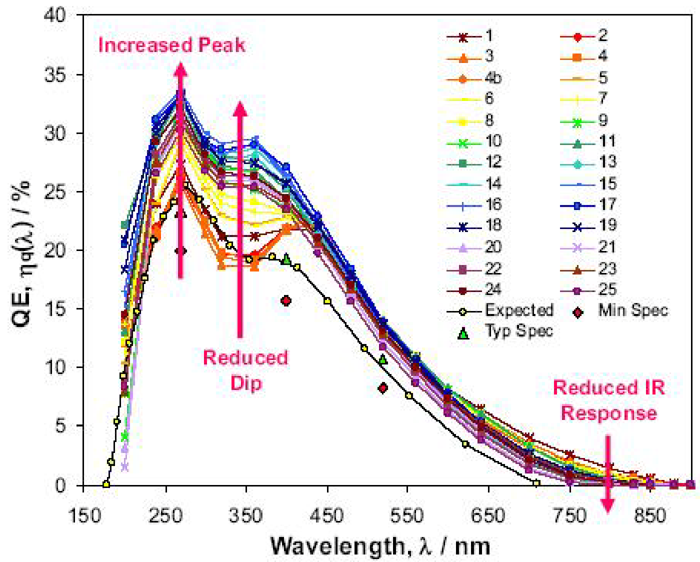
- Photon detection is necessary for many of the detectors performing particle identification
  Requirements: single photon sensitivity, high efficiency, good spatial granularity
- Incident photon is (usually) converted to an electron by the photoelectric effect in a *photocathode*, typically formed of a combination of alkali metals, eg Sb-Na-K-Cs
- The photoelectron signal needs to be amplified to give a measureable electronic pulse
- Achieved in traditional photomultiplier (PM) by dynode chain → multiplication of the charge at each dynode: eg if number of electrons is tripled on each stage of a 12 dynode chain
  → Gain = $3^{12} \sim 10^6$



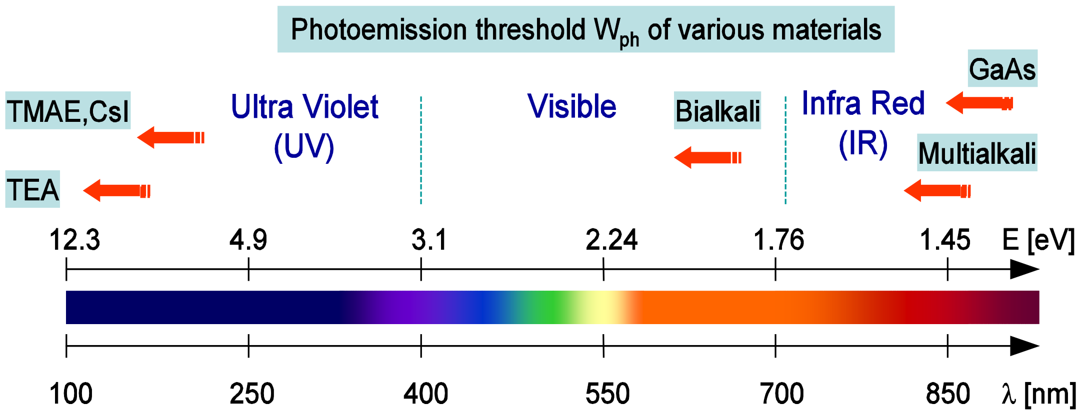
Photomultiplier (cross section)

Detection efficiency

- *Quantum efficiency*: probability that an incident photon produces a photoelectron Peak value is typically 20 – 30%
- Needs to be multiplied by the *collection efficiency*: the efficiency for detecting the photoelectron (typically 80 – 90 %)
- Photocathode type is chosen according to the desired spectral sensitivity:



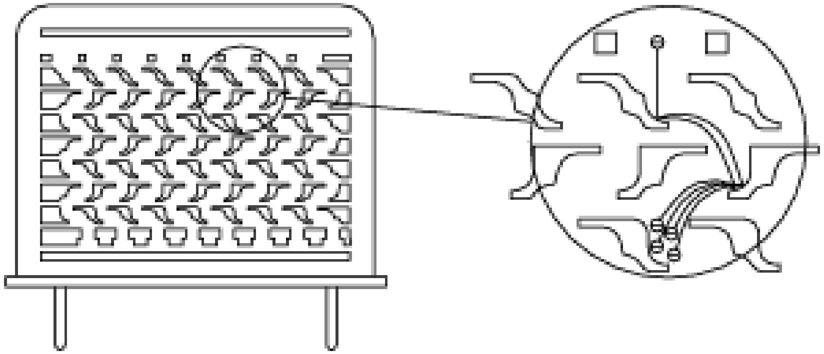
QE for tubes with multialkali photocathode



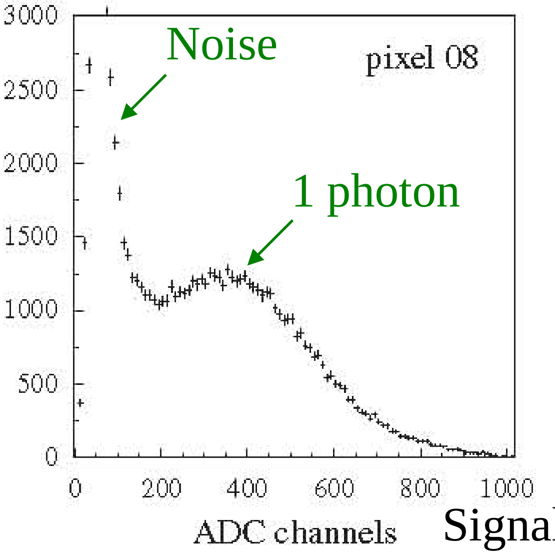
Remember: $E = hc/\lambda$
λ [nm] ≈ 1240 / E [eV]

Multianode PM

- The *multianode* photomultiplier is a marvel of miniaturization → up to 64 pixels in a single tube, each with size ~ 2×2 mm^2
- Dynode structure formed from a stack of perforated metal foils
- Signal width dominated by fluctuations in the charge multiplication of the first dynodes

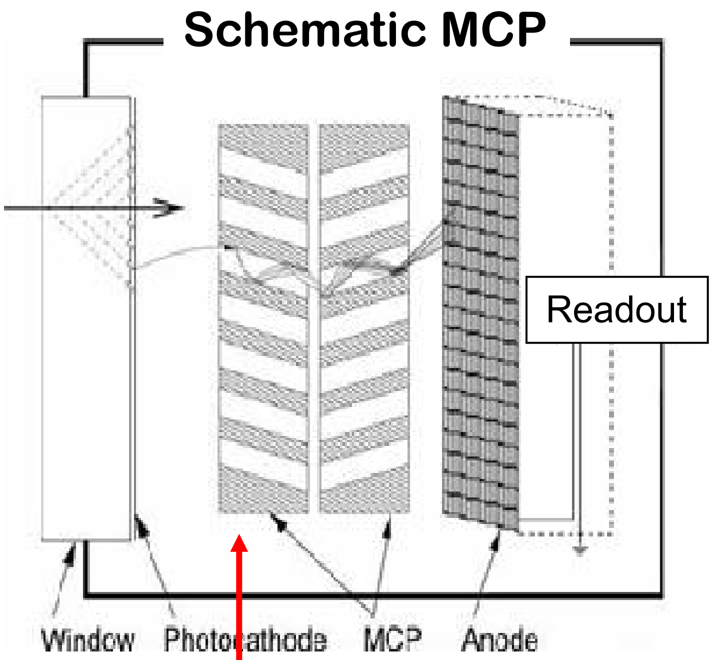


Multianode PM (Hamamatsu)



Micro-Channel Plates

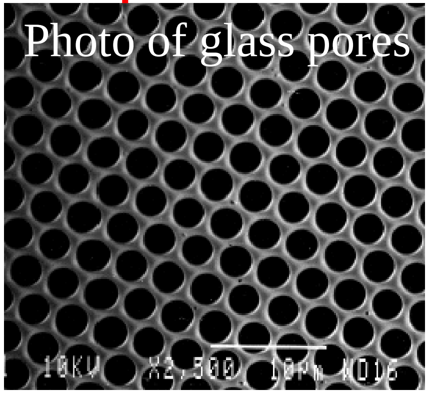
- Time Of Flight detectors would like timing precision at the *picosecond* (10^{-12} s) level
- 1 ps ≈ 0.3 mm for a relativistic particle
  → requires small feature sizes
- Micro-channel plate (MCP) photon detectors employ electron multiplication in small (~ 10 μm) pores, used in image intensifiers
- Timing precision of ~ 10 ps achieved



MCP detector (Photonis)

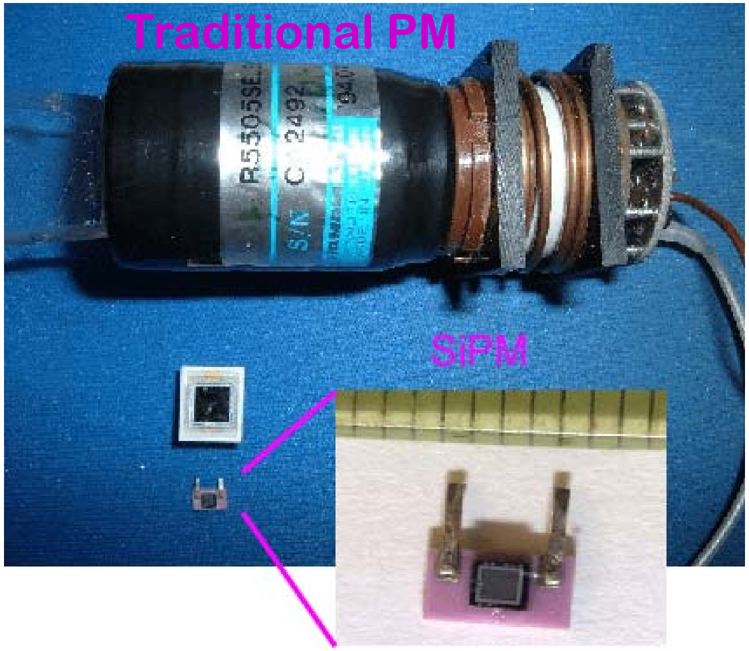
~ 6 cm width

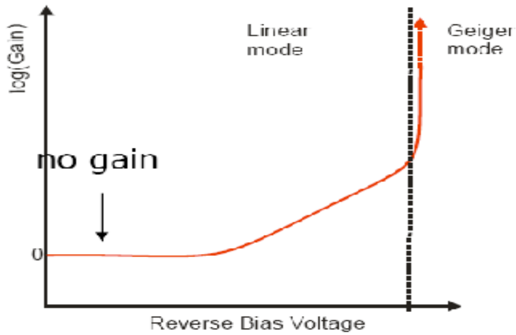
Up to 1024 anode pads

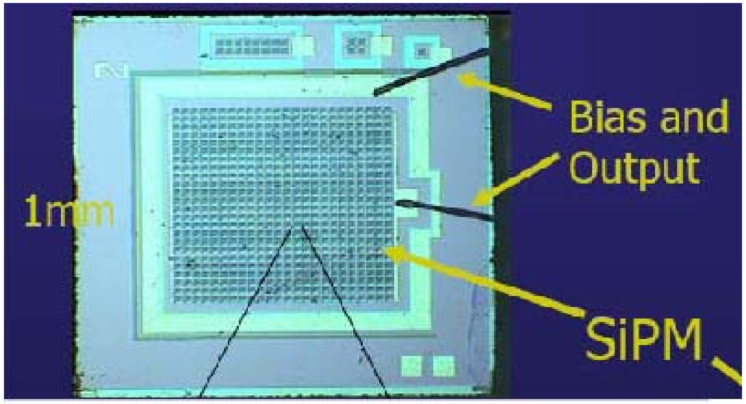


Silicon PM

- Fully solid-state photon detectors are a very active field of development
- Use a p-n junction in Geiger mode (above the breakdown voltage) → large gain, binary signal, long recovery
- An array of ~ 100 such elements is used to provide a single pixel
- *Advantages:* very compact, high quantum efficiency
  Disadvantages: high noise, n damage?







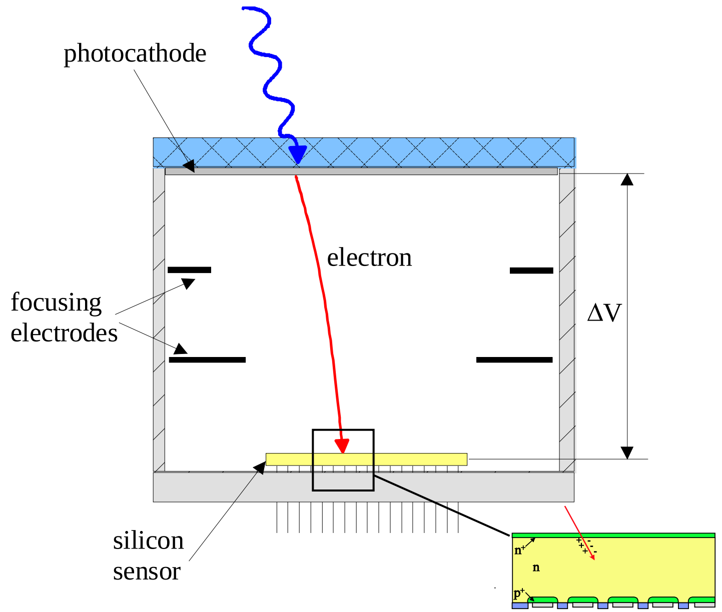
Hybrid Photon Detectors

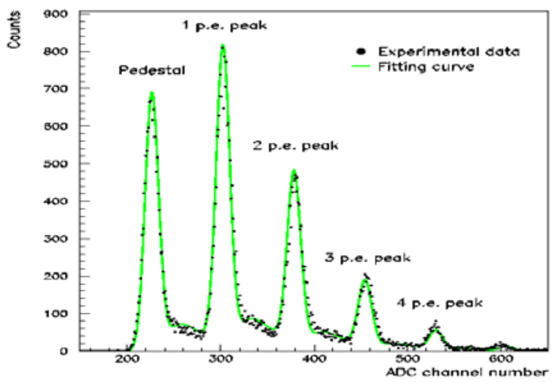
- Development from the photomultiplier: Instead of using a dynode chain to provide the amplification, accelerate the photoelectrons with electric field and use a silicon sensor as anode

- It takes 3.6 eV to create an electron-hole pair in silicon
  Using an accelerating voltage 20 kV
  → ~ 5000 e^- signal, enough to be detected using modern low-noise electronics

- *Advantages:* very good energy resolution (sensitivity to number of individual photons), silicon sensor can be segmented as required

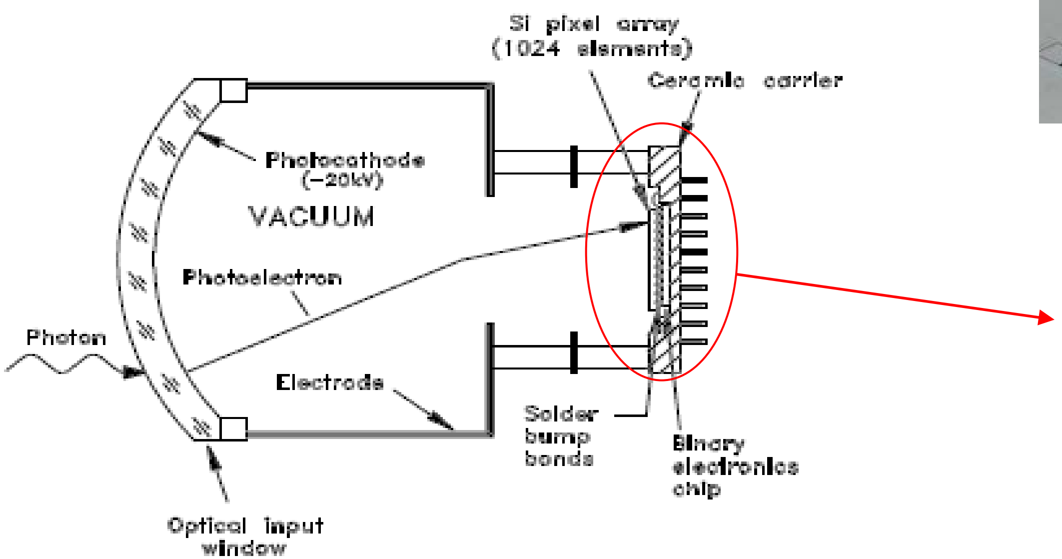
  Disadvantages: high voltage, ion feedback
  → requires very good vacuum

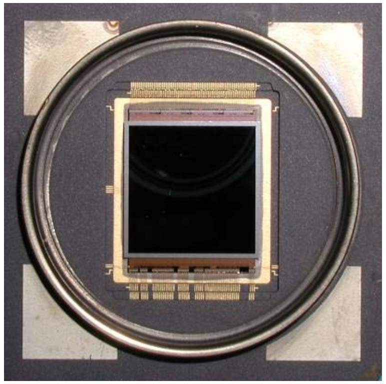




HPD example

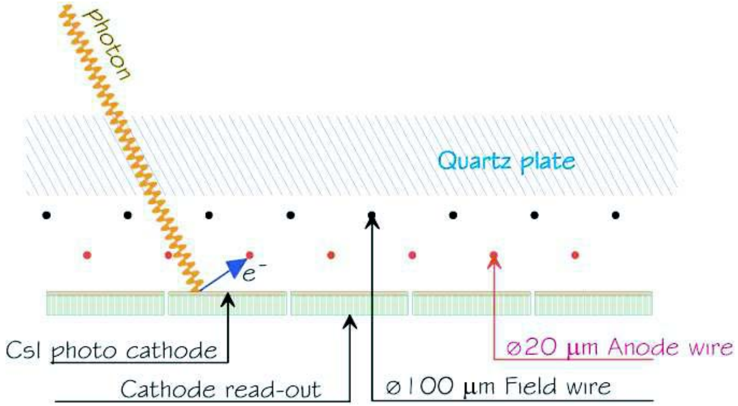
- HPDs developed for the LHCb RICH detectors in collaboration with industry
- 80 mm diameter tube has 1024 pixels
each ~ 2.5×2.5 mm^2 at the photocathode
Uses a silicon sensor with 32×32 pixel array, bump-bonded to a readout chip which can read out the signals fast enough for the LHC (25 ns)

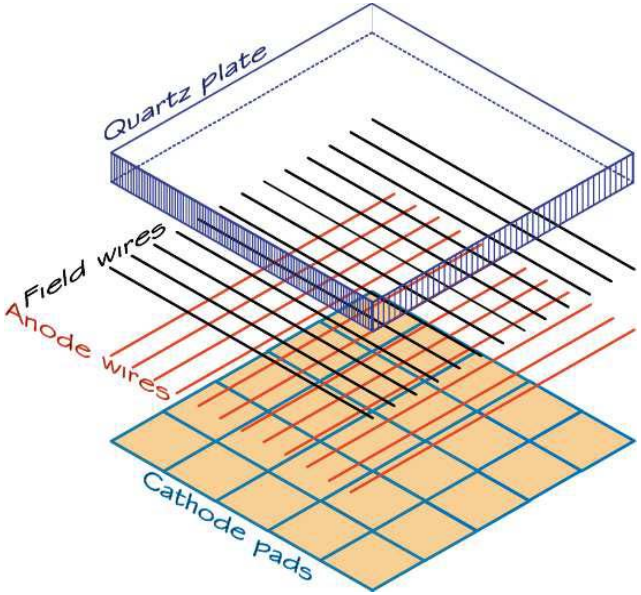


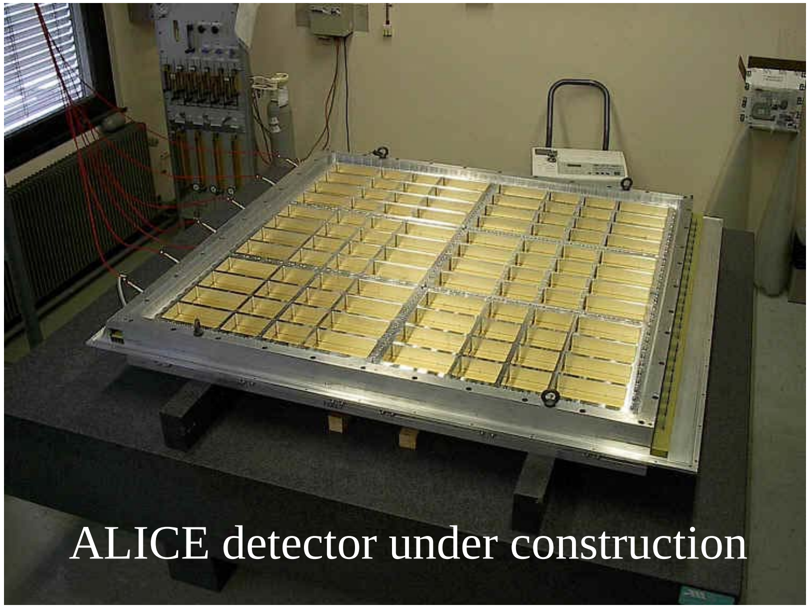


Gaseous photodetectors

- Alternative approach to photon detection using a wire chamber to detect the photoelectrons produced from a CsI layer
- Can cover large areas, low cost
  Typically suffer from higher noise







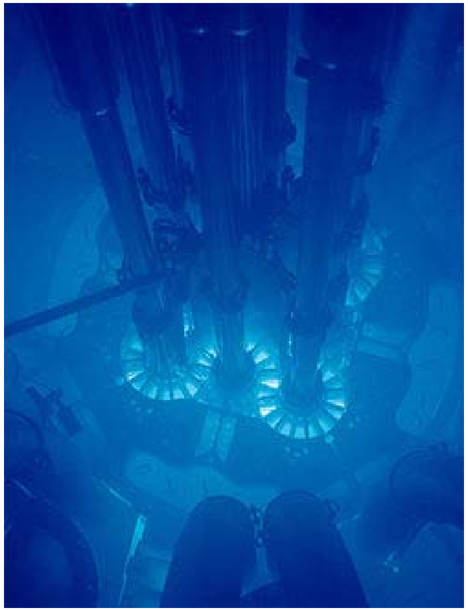
ALICE detector under construction

2. Cherenkov detectors

- Recall from first lecture: Cherenkov light is emitted with $\cos\theta_C = 1/\beta n$
- The light is produced equally distributed over photon energies, which when transformed to a wavelength distribution implies it is peaks at low wavelengths – it is responsible for the blue light seen in nuclear reactors
- The number of photons detected in a device is:

$$N_{pe} = \frac{\alpha^2 L}{r_e m_e c^2} \int \varepsilon \sin^2\theta_C \, dE, \text{ where } \frac{\alpha^2}{r_e m_e c^2} = 370 \text{ cm}^{-1}\text{eV}^{-1}$$

L is the length of the radiator medium
ε is the efficiency for detecting the photons

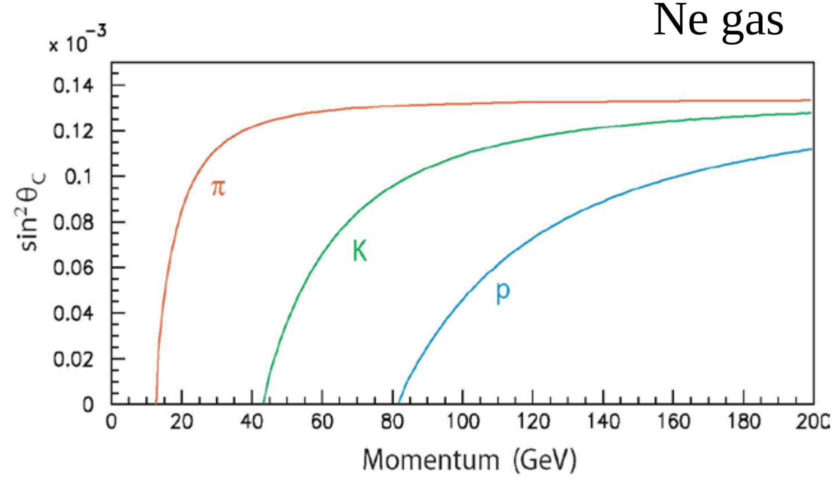


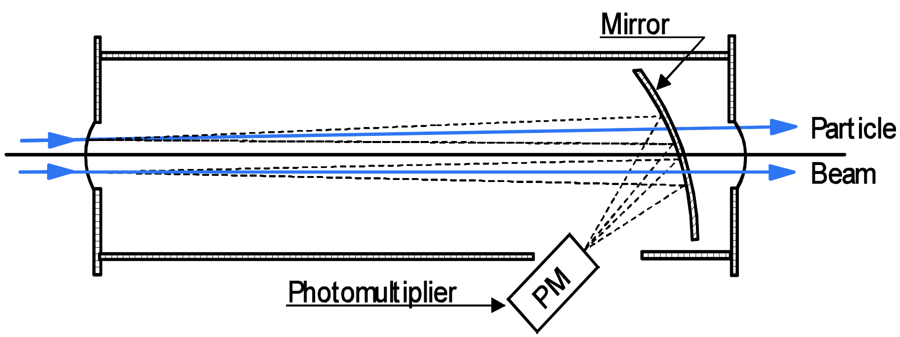
- There is a threshold for light production at $\beta = 1/n$
  - Tracks with $\beta < 1/n$ give no light
  - Tracks with $\beta > 1/n$ give light

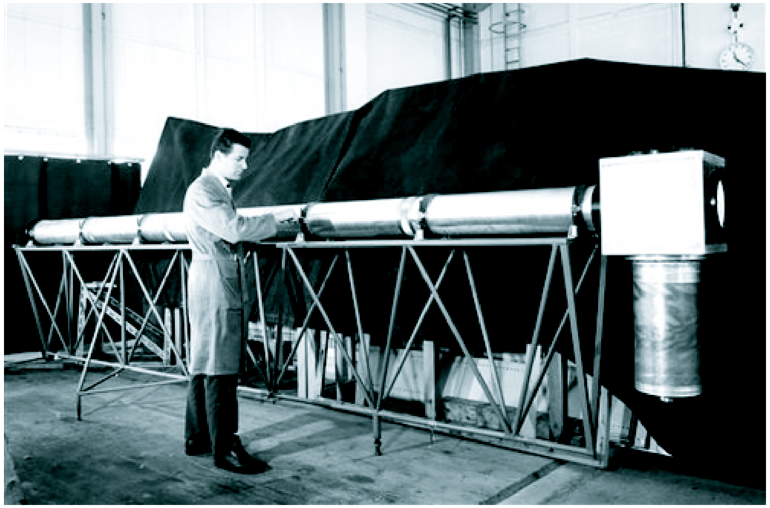
Threshold detectors

- This is the principle of “threshold Cherenkov detectors” which are useful to identify particles in a beam line (with fixed momentum)
  for example a 50 GeV π^+ beam with some 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

Ne gas

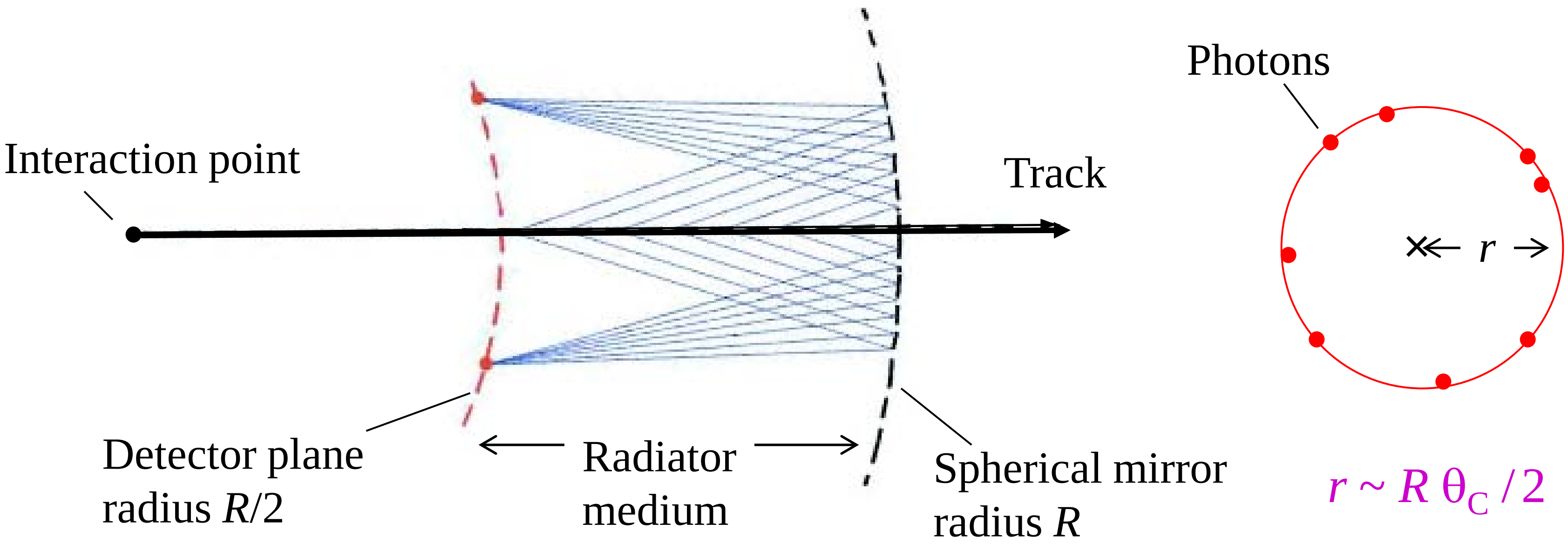






Ring imaging

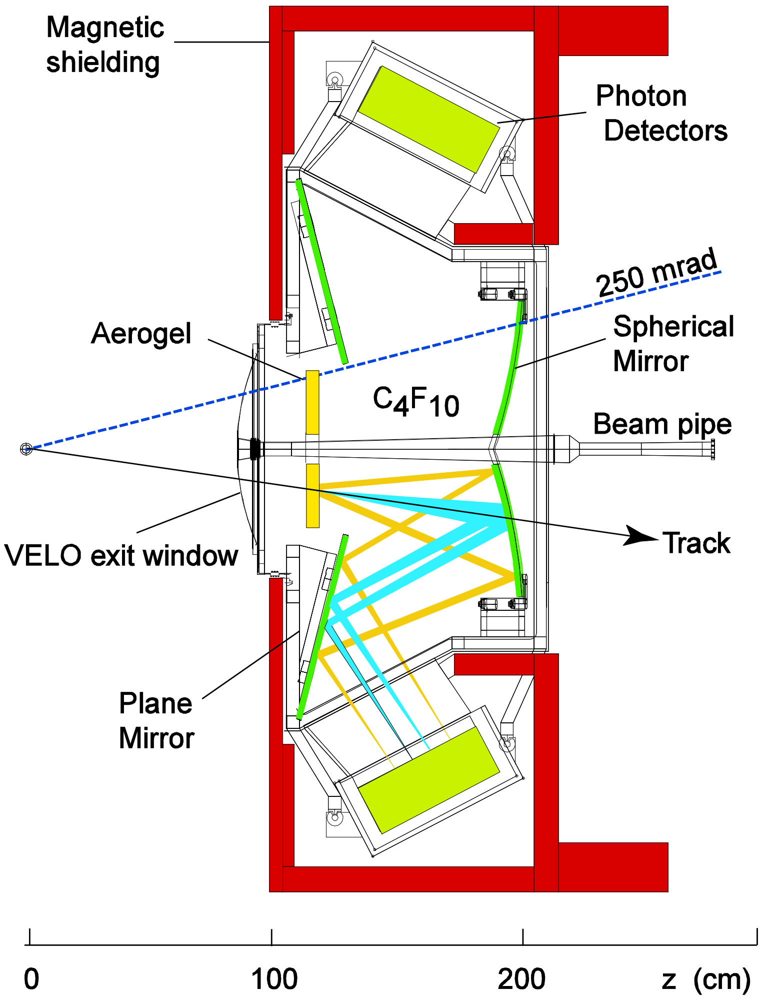
- Threshold counters just give a yes/no answer, and are less useful when the tracks have a wide momentum range
  However, more information can be extracted from the Cherenkov angle
- From a classic paper by J. Seguinot and T. Ypsilantis [NIM 142 (1977) 377] the Cherenkov cone can be imaged into a ring, using a spherical mirror



- Measuring the ring radius r allows the Cherenkov angle θ_C to be determined

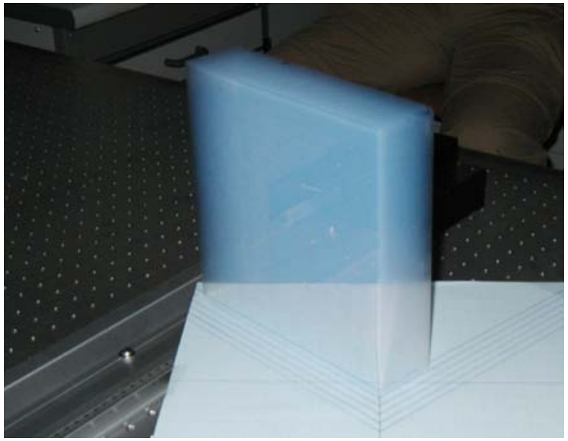
RICH detectors

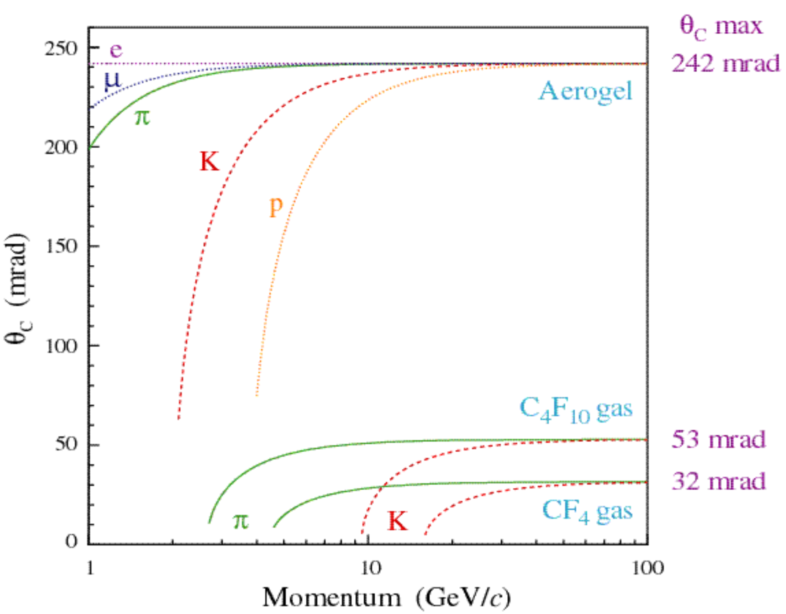
- “Ring-Imaging Cherenkov” → RICH
- Original concept has practical limitation: the photon detectors would be sited in the middle of the acceptance, their material would interfere with tracking/calorimetery
- Practical implementations typically use a tilted focussing mirror, to bring the ring images out of the acceptance
- Cross-section through RICH-1 of LHCb
- Makes use of two separate radiators: C_4F_{10} gas and silica aerogel (a solid)
A second (flat) mirror is used to limit the size of the detector along the beam axis



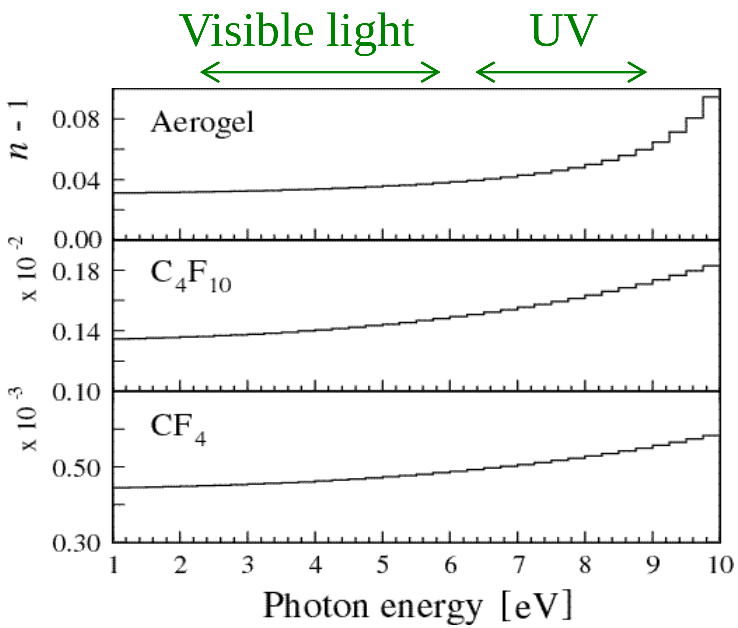
Radiators

- A wide variety of materials are used as RICH radiators
- Refractive index selected according to the momentum region to be covered
- **Aerogel** (n = 1.03) is a very light material made from silica SiO_2, good for low momenta $p < 10$ GeV
- **C_4F_{10}** (n = 1.0014), a fluorocarbon gas, good for intermediate momenta
- **CF_4** (n = 1.0005) is used in RICH-2 for high momentum region $p > 20$ GeV
- Fluorocarbon gases are chosen because they have a low chromatic dispersion i.e. n does not depend strongly on E_γ





Resolution

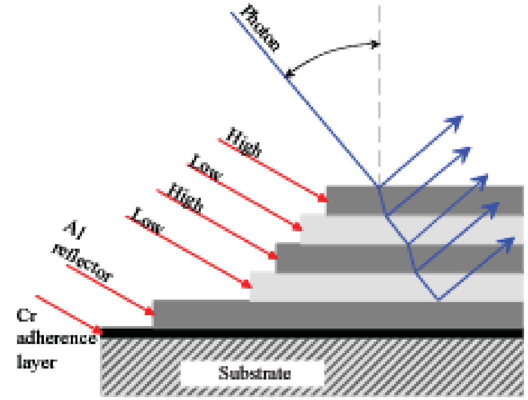


LHCb RICH

Material		CF_4	C_4F_{10}	Aerogel
L	[cm]	167	85	5
n		1.0005	1.0014	1.03
θ_c^{max}	[mrad]	32	53	242
$p_{thresh}(\pi)$	[GeV]	4.4	2.6	0.6
$p_{thresh}(K)$	[GeV]	15.6	9.3	2.0
$\sigma_\theta^{emission}$	[mrad]	0.31	0.71	0.66
$\sigma_\theta^{chromatic}$	[mrad]	0.42	0.81	1.61
σ_θ^{pixel}	[mrad]	0.18	0.83	0.78
σ_θ^{track}	[mrad]	0.20	0.42	0.26
σ_θ^{total}	[mrad]	0.58	1.45	2.00
N_{pe}		19.1	35.3	6.9

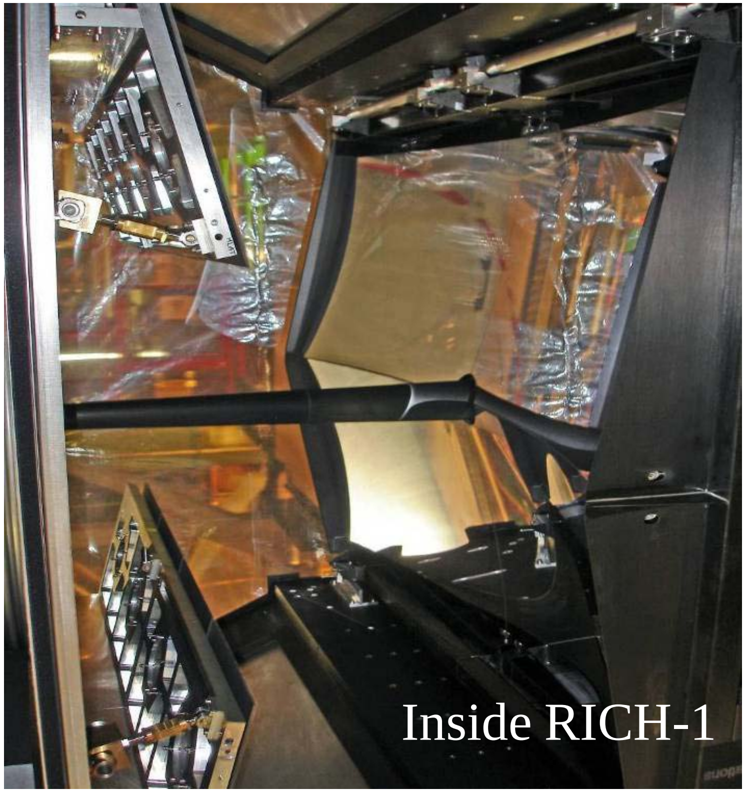
- Apart from chromatic dispersion, other factors that limit the resolution:
  - Imperfect focusing of the optics
  - Pixel size of the photon detector
- The overall resolution determines how high in momentum particles can be distinguished, since the increase in Cherenkov angle *saturates* so the radius for different *mass hypotheses* get closer together

Mirrors



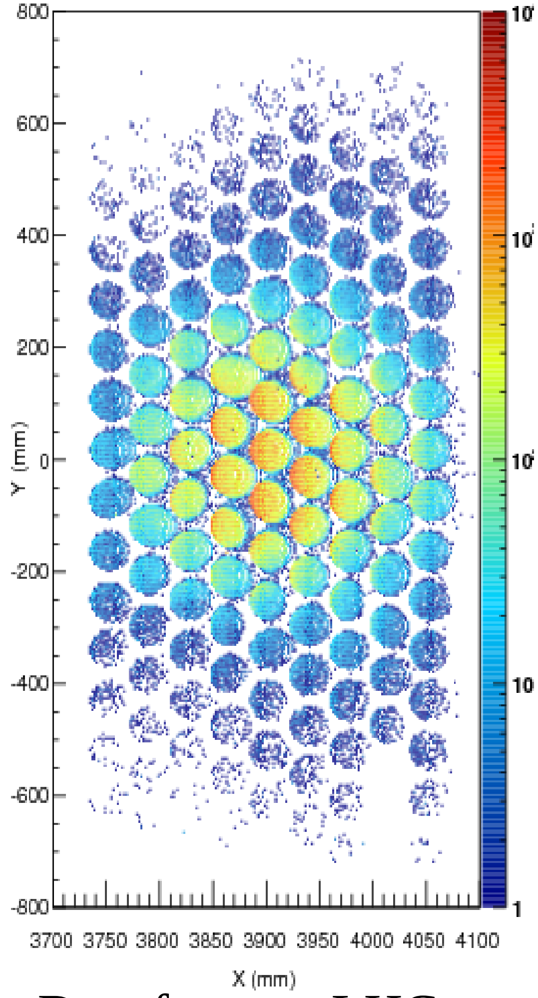
- The optics of a RICH detector requires mirrors, with high reflectivity to avoid losing photons
- Traditional construction uses a glass substrate, with coating of Al for the reflective surface and then MgF_2 or SiO_2 for protection Reflectivity ~ 90%
- In applications where minimizing the material budget is important, carbon fibre or Be substrates are used

  eg the RICH-1 spherical mirror is made from carbon fibre, ~ 1% X_0

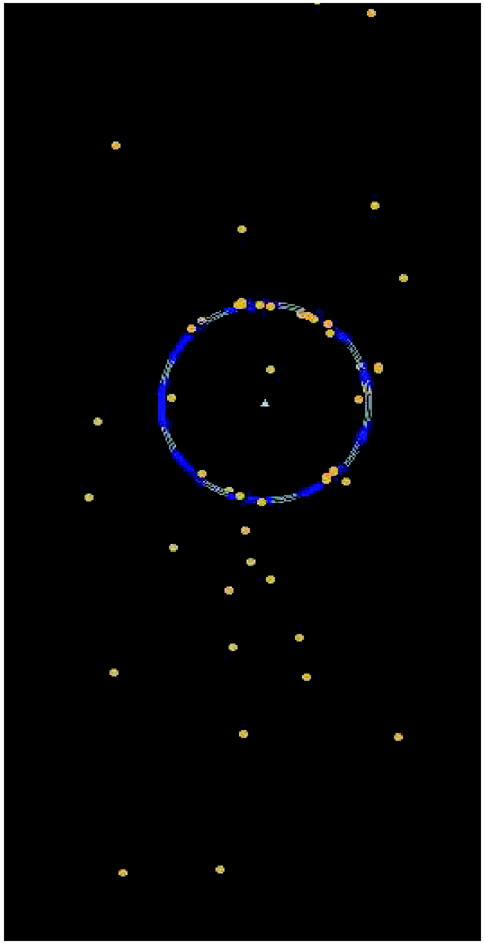

Inside RICH-1

Detector plane

Photo of installed HPDs



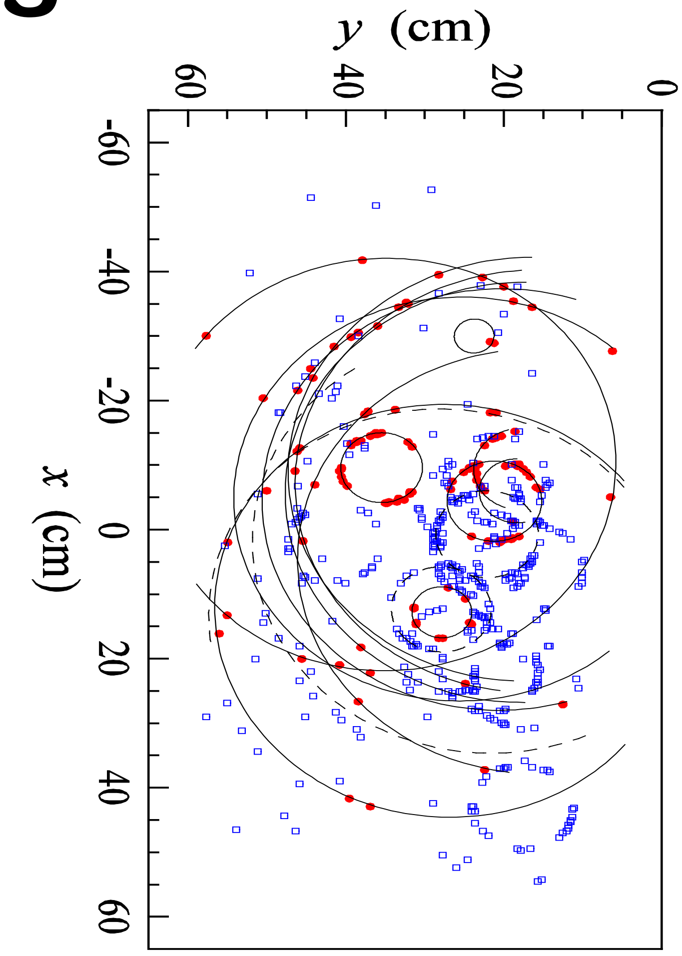
Data from an LHC run



Hits from single event

Pattern recognition

- In the busy environment of hadronic collisions (such as at the LHC) many tracks may pass through the detector → overlapping rings
- Deciding which hit belongs to which track requires *pattern recognition*
- Most approaches rely on the use of the track to seed the ring search:
  after transformation through the optics of the RICH, the track image will lie at the centre of the ring
- The ring search then corresponds to the search for a peak in the number of photon hits versus radius from the track



Simulated event in RICH-1

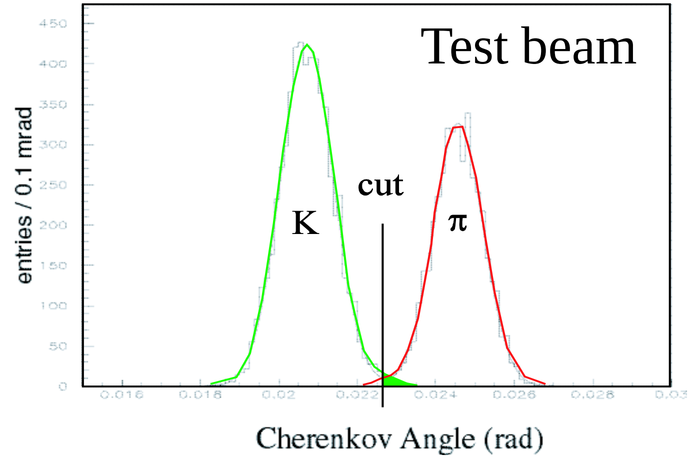
Large rings: aerogel, small: C_4F_{10}

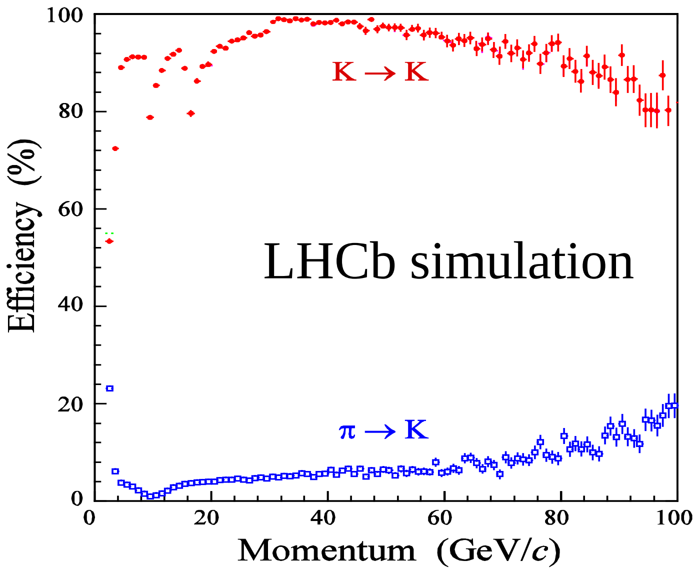
Particle separation

- Separating two particle types using the signal from a RICH detector is illustrated for K and π from a test beam
- ~ Gaussian response, $\sigma_\theta \sim 0.7$ mrad
  Peaks are separated by 4 mrad = 6 σ_θ

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

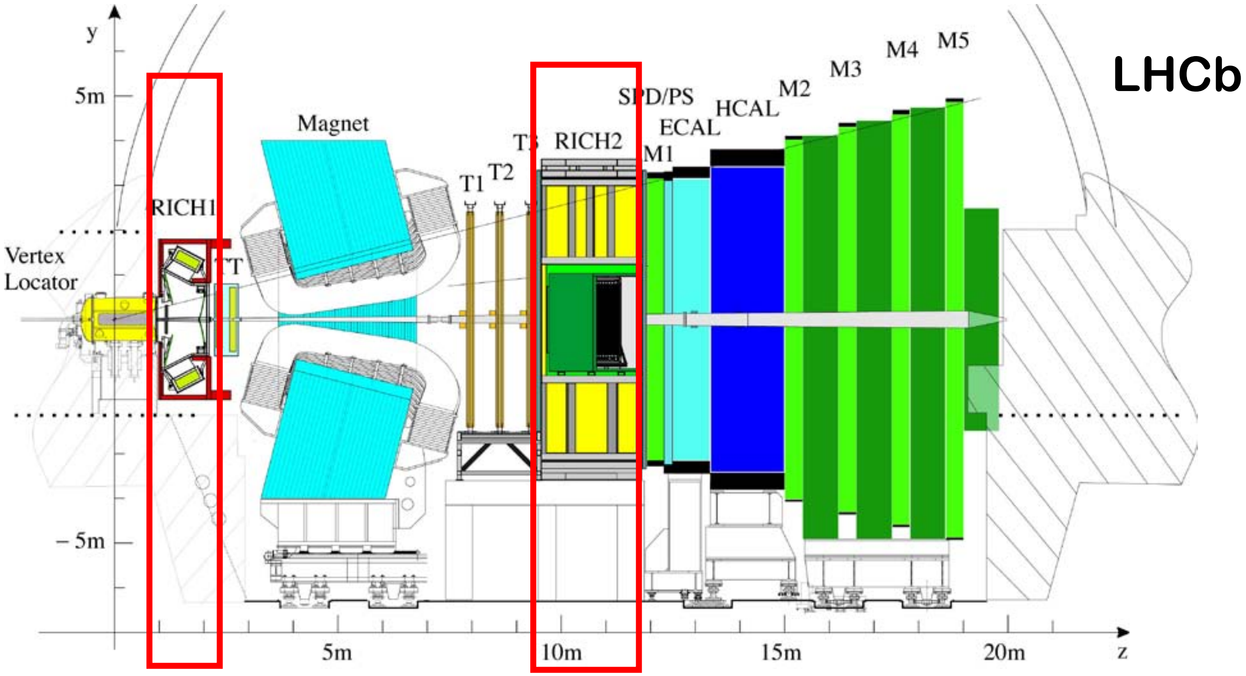
- Adjusting the position of the cut placed between the two peaks to identify a ring as belonging to a K or π gives a trade-off between *efficiency* and *misidentification*
- Studied in detail for the LHCb RICH system using Monte Carlo simulation





3. RICH examples

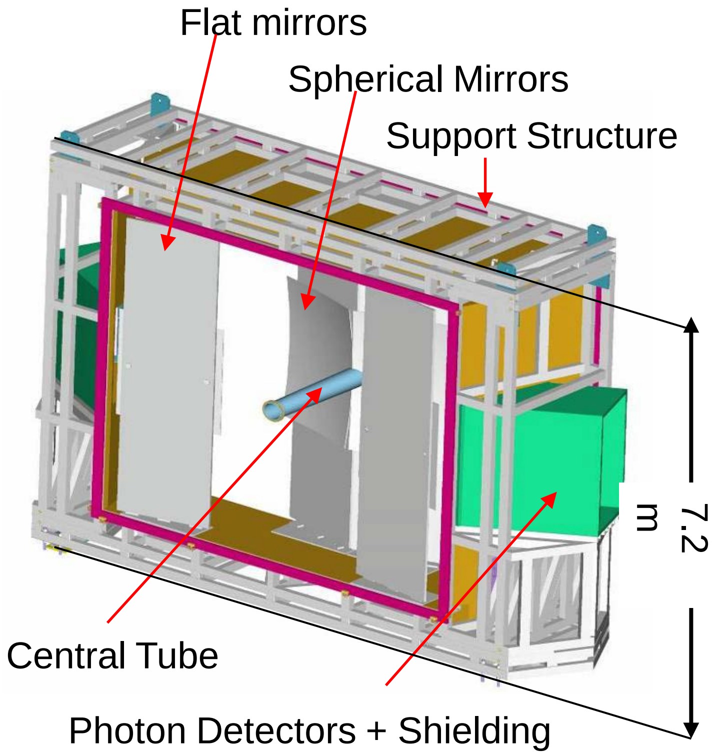
- A wide variety of experiments use RICH detectors:
  LHCb, ALICE, BaBar, COMPASS, SELEX, NA62, etc…
- Recall of the LHCb experiment:

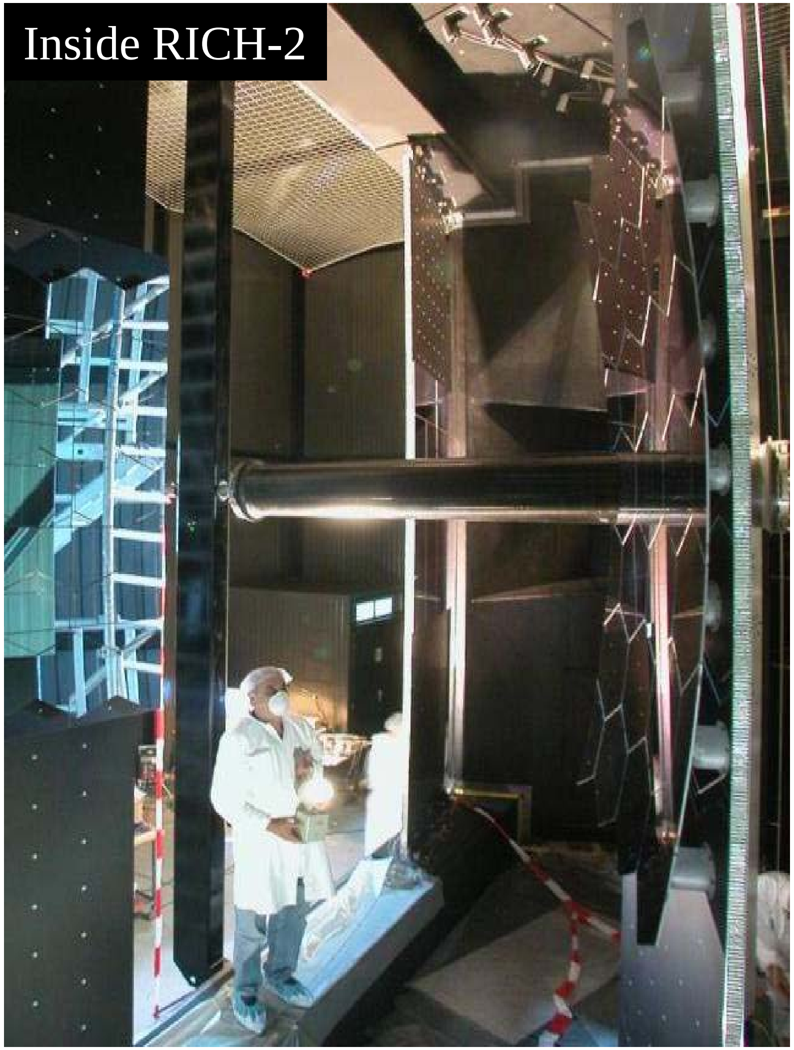


- RICH-1 already described, second RICH is for high momentum coverage

LHCb RICH-2

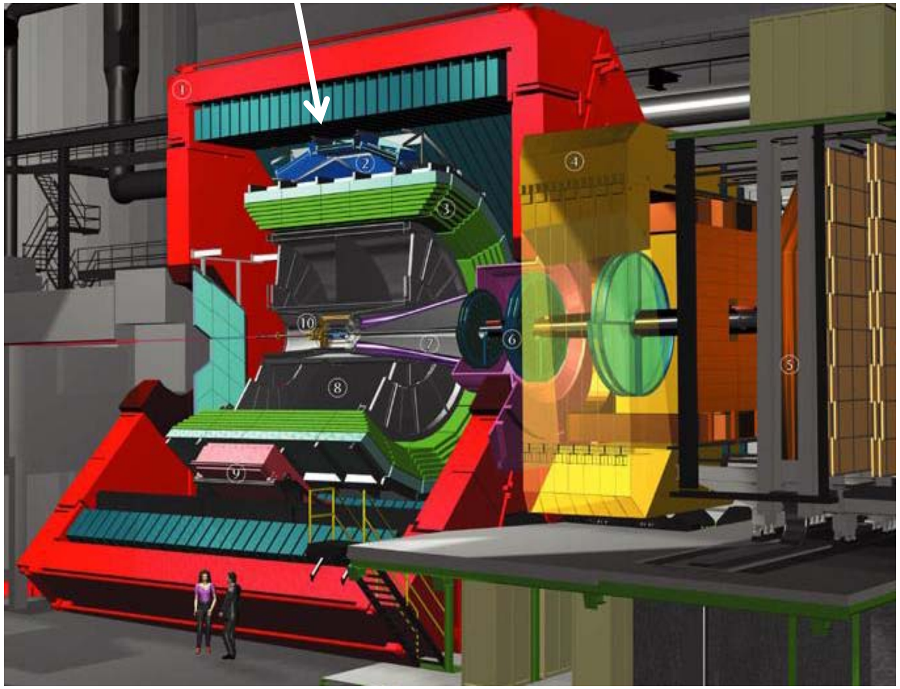
- Very large detector as sited downstream in the spectrometer
- Uses glass mirror substrates, CF_4 gas radiator

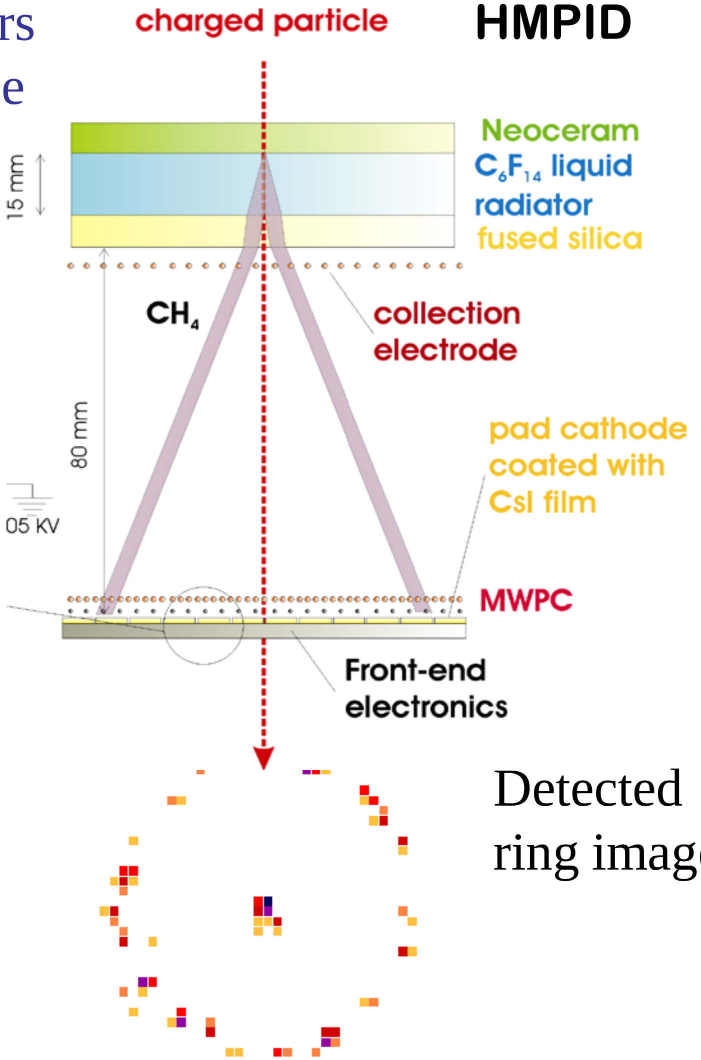




ALICE HMPID

- Uses liquid radiator, gaseous photon detectors
  "Proximity focusing" with stand-off distance
- Used for high-momentum PID, over only part of the solid angle

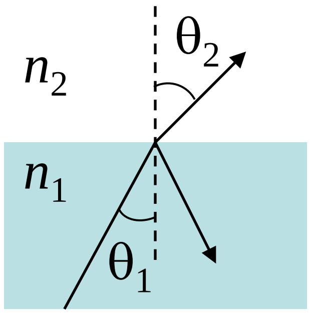




Detected ring image

DIRC detector

- Detector of Internally Reflected Cherenkov light (BaBar experiment) uses quartz as the radiator
- Light is trapped inside quartz bars by *total internal reflection* → takes up little radial space
- TIR preserves the angles of the photons Detection at end of bars using PM array



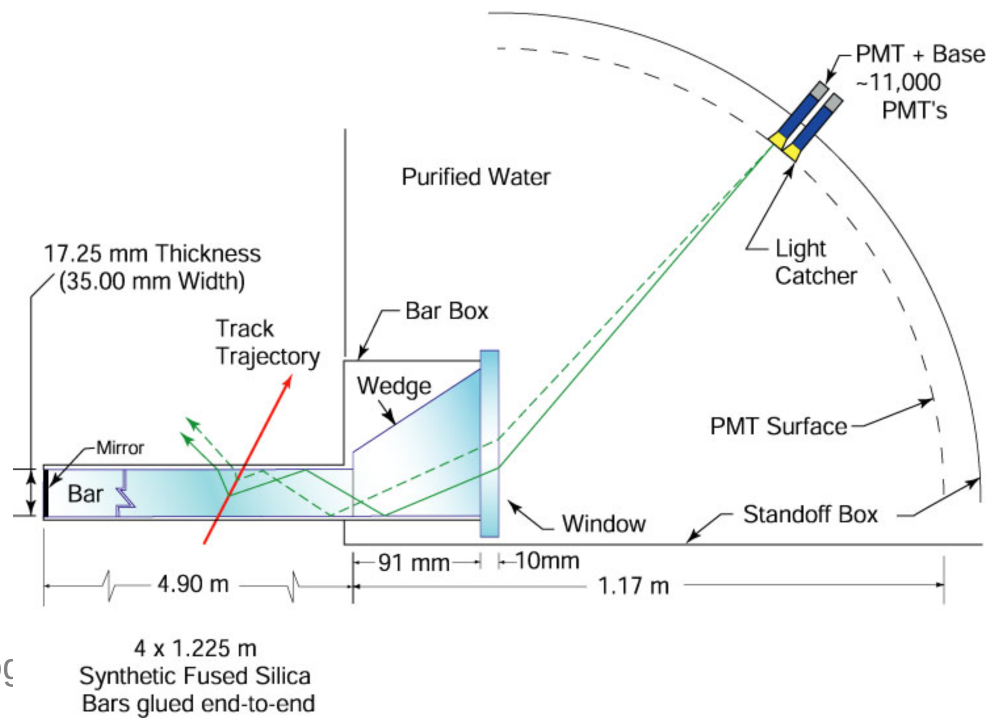
Law of refraction:

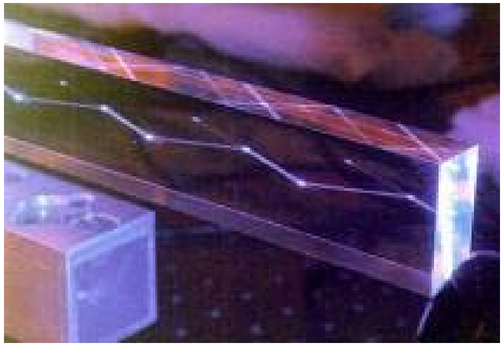
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$n_1 = 1.45$ (quartz)

$n_2 \approx 1.0$ (air)

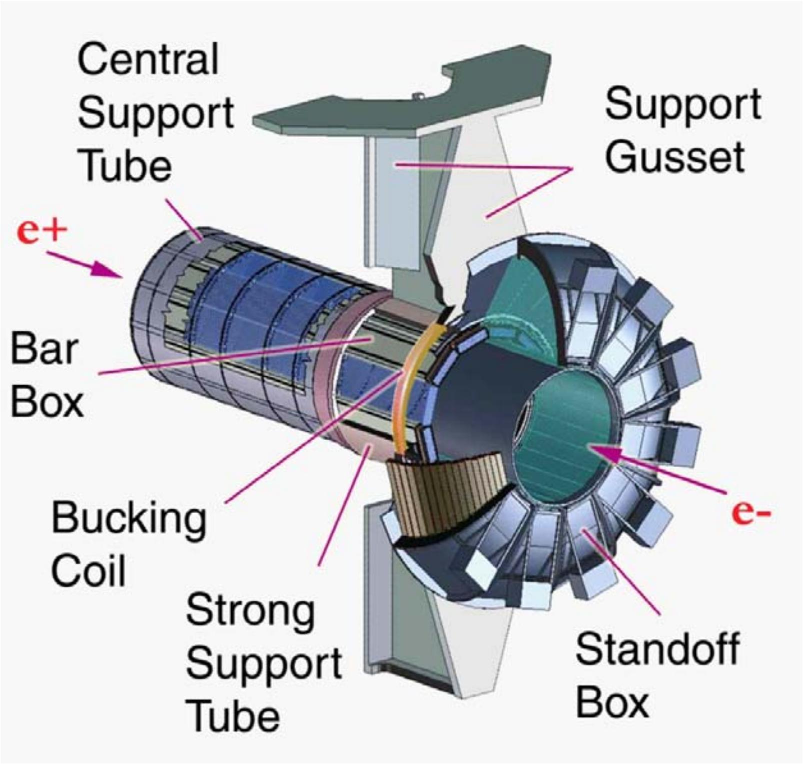
Total internal reflection if $\theta_1 > \sin^{-1}(1/1.45) \approx 44^{\circ}$

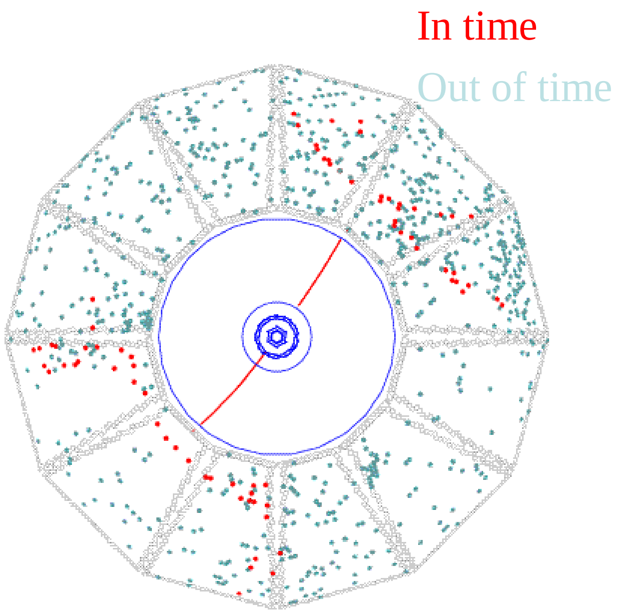


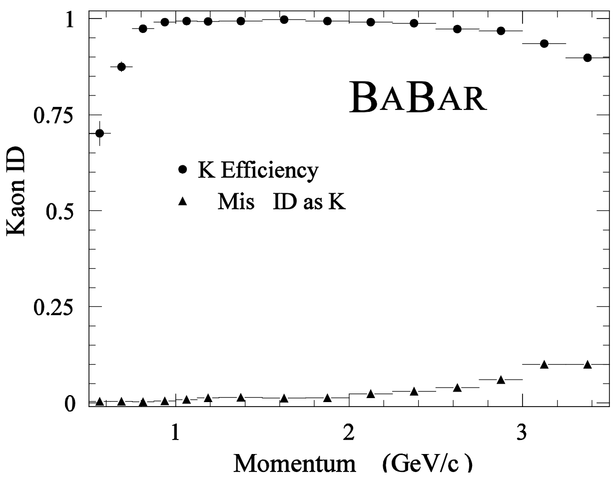


DIRC performance

- Due to different geometry, signal patterns are hyperbolic rather than rings
- Good performance at low momentum

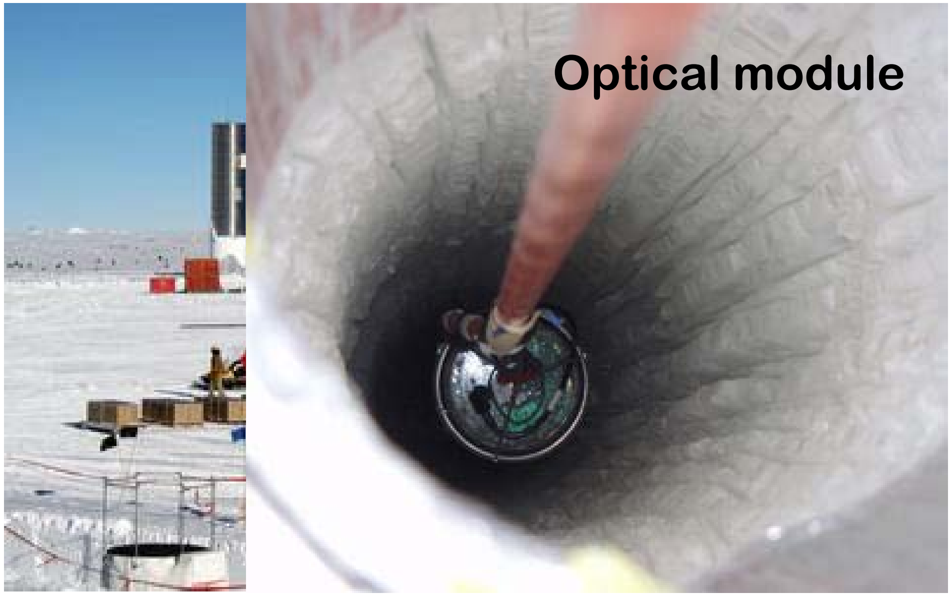


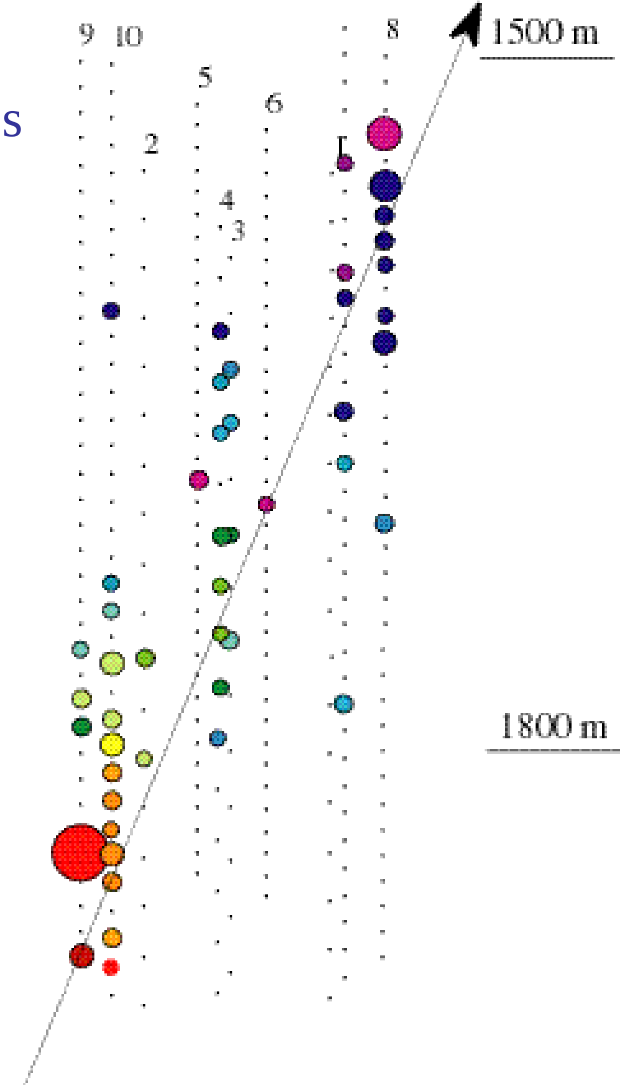




Ice-Cube

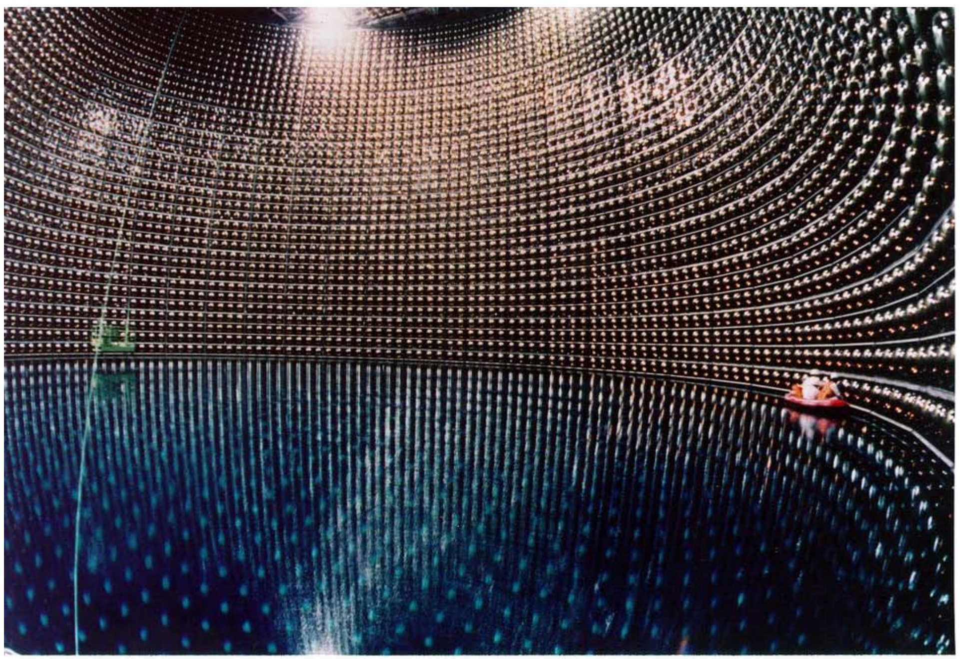
- Neutrino experiment in the ice of the South Pole, detecting Cherenkov light from up-going neutrinos that have traversed the earth, and then $\nu_\mu N \rightarrow \mu X$
- Others use similar technique with sea water as the target/radiator (ANTARES, NESTOR, etc)
- Very challenging deployment!

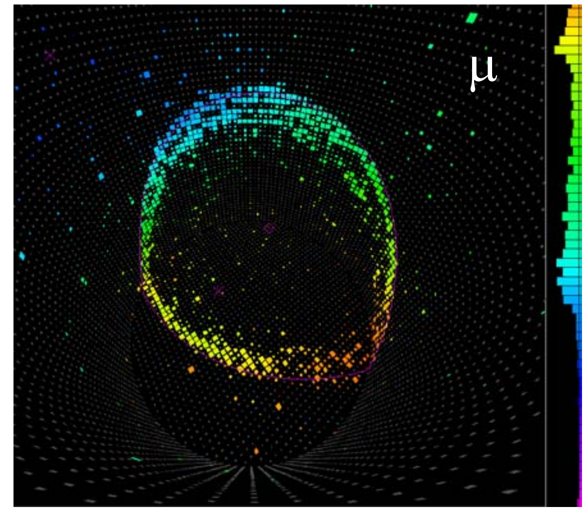


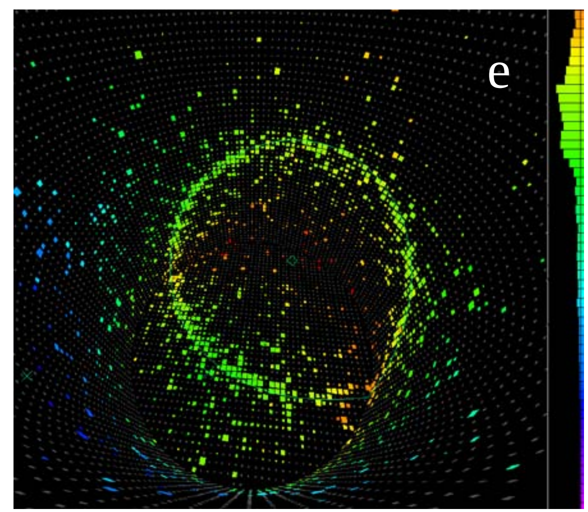


Super-Kamiokande

- Neutrino detector using water as the target and detector medium
- Clear separation (real data) of μ- and e-like rings (showering)
  Misidentification rate < 1%

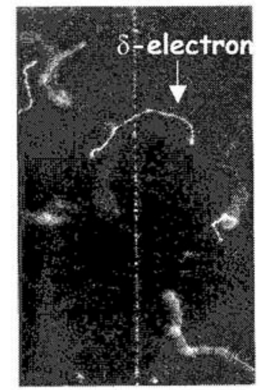


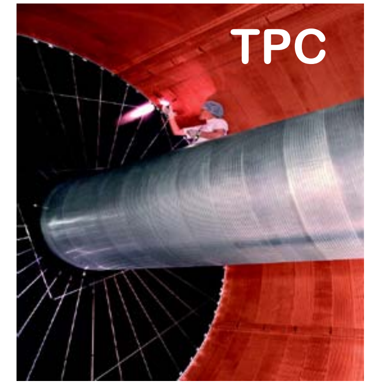


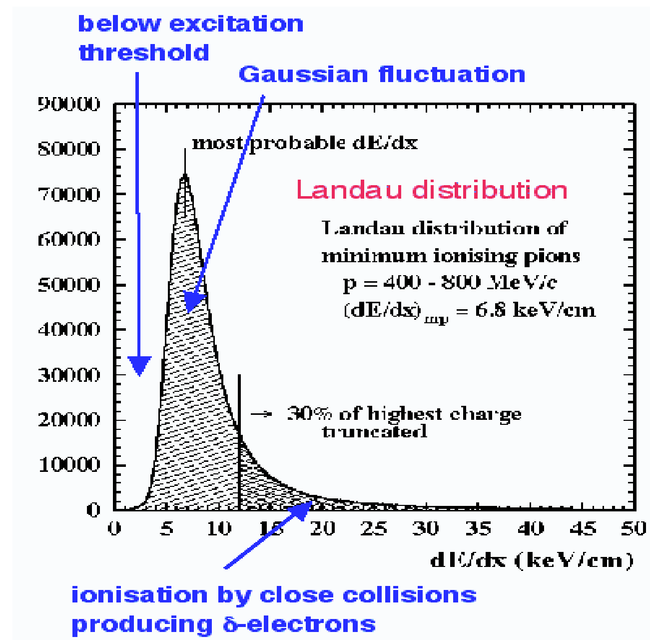


4. Other PID devices

- The other processes discussed earlier (ionization, Transition radiation and TOF) all have their own related detectors
- Ionization is used in ~ all tracking detectors (see the Tracking lectures)
  Tracking measures the *position* of ionization for particle ID measure the *amount (dE/dx)*
- This is subject to large fluctuations due to ejection of δ-electrons (Landau distribution)
- To avoid bias from the long tail, best to have many independent samples of the ionization, and perform a truncated mean
- Excellent *dE/dx* measurements achieved with TPCs (many samples) and silicon detectors (good energy resolution)

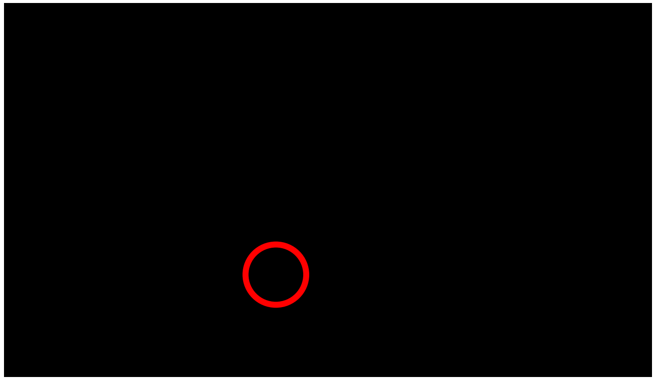


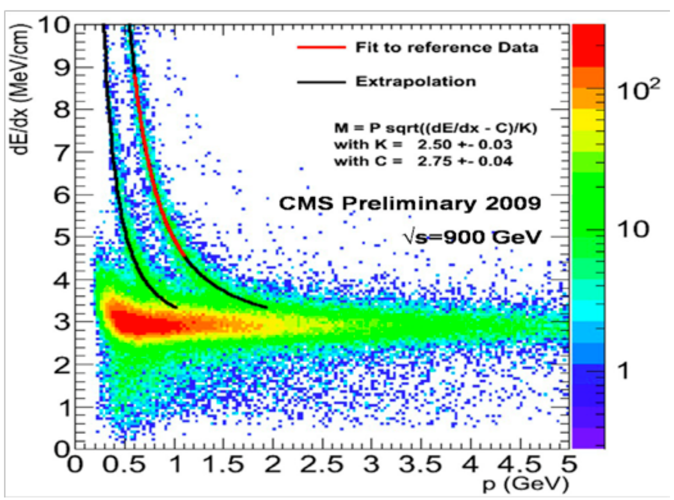


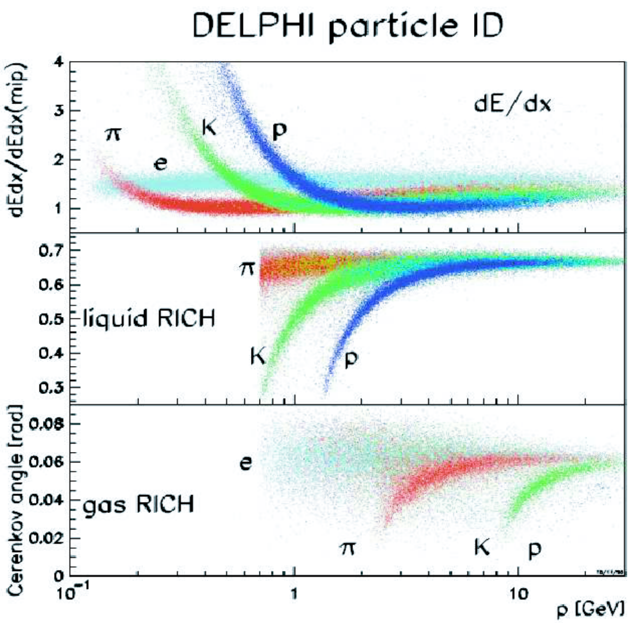


dE/dx performance

- Note that the *dE/dx* plot as a function of momentum has a lot of *overlap* regions between the different mass hypotheses → limits usefulness for those momenta
- Good separation for low momentum Combine with other detectors to cover full momentum range







Transition Radiation

- The Transition radiation energy emitted when charged particle crosses a boundary between vacuum and a medium with plasma frequency ω_p

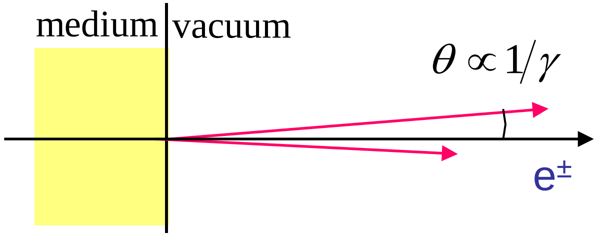
  $\Delta E = \alpha\, \hbar\omega_p \gamma / 3$, where α = fine structure constant ≈ 1/137

- $\hbar\omega_p$ depends on the electron density in the material
  ~ 20 eV for a low-Z material such as plastic (eg polypropylene)

  For a 10 GeV electron, $\gamma \sim 2 \times 10^4$, so $\Delta E \sim$ keV (X-ray energy)

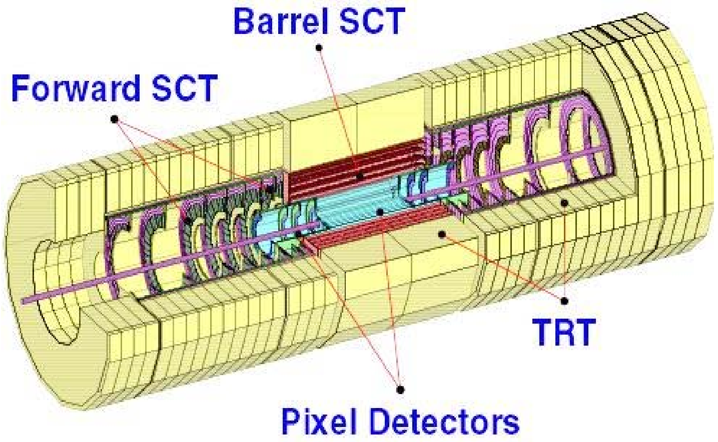
- Low probability of photon emission at one interface (~ 1%)
  so many layers of thin foils are used for the radiator
  Low Z is important to limit re-absorbtion of the radiation

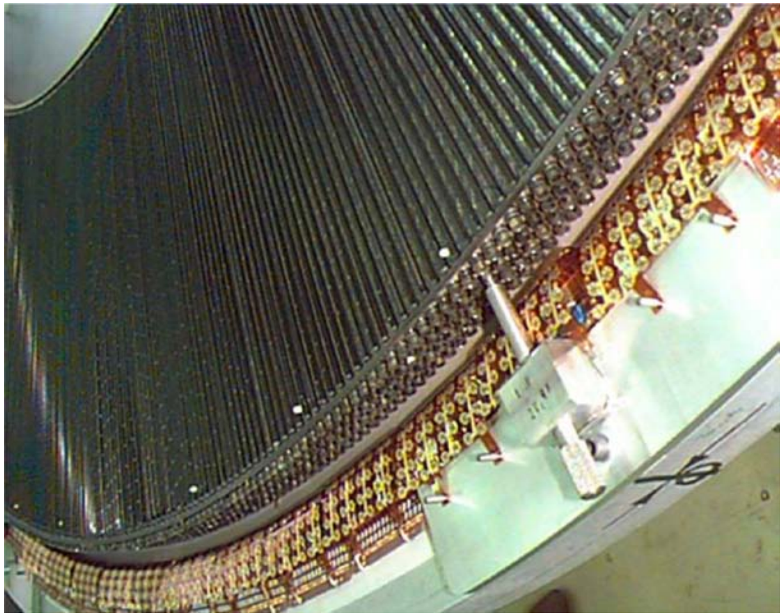
- Radiation emitted in the very forward direction, in cone of angle $1/\gamma$ around the particle direction
  → photons will be seen in same detector as the ionization from the track

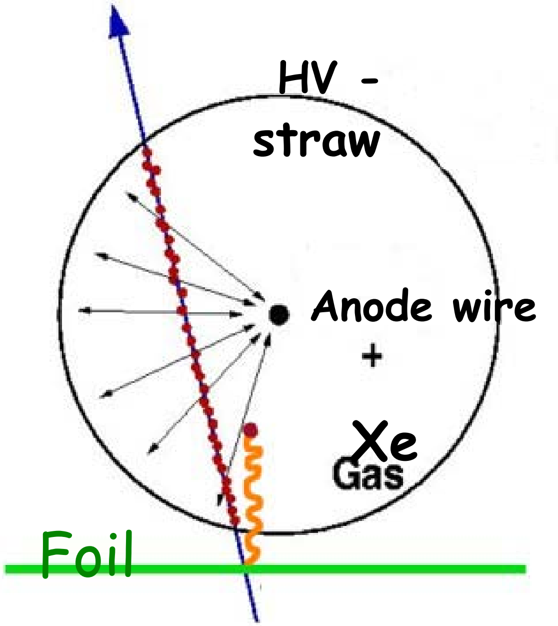


ATLAS TRT

- Transition Radiation Tracker: also acts as a central tracker using ~ 300 000 straw tubes
- 15 μm-thin polypropylene foils (radiator) interleaved with straws → transition radiation
- Xe as active gas for high X-ray absorption

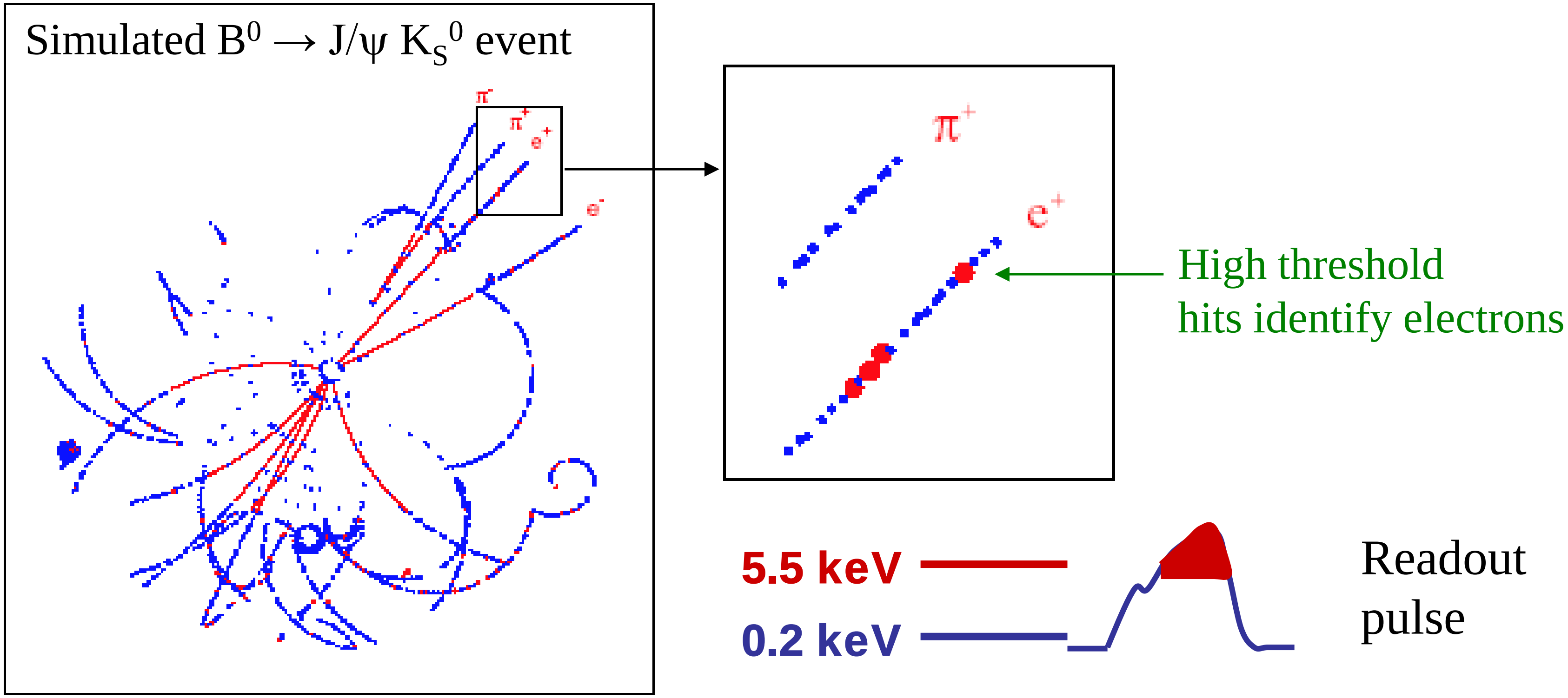




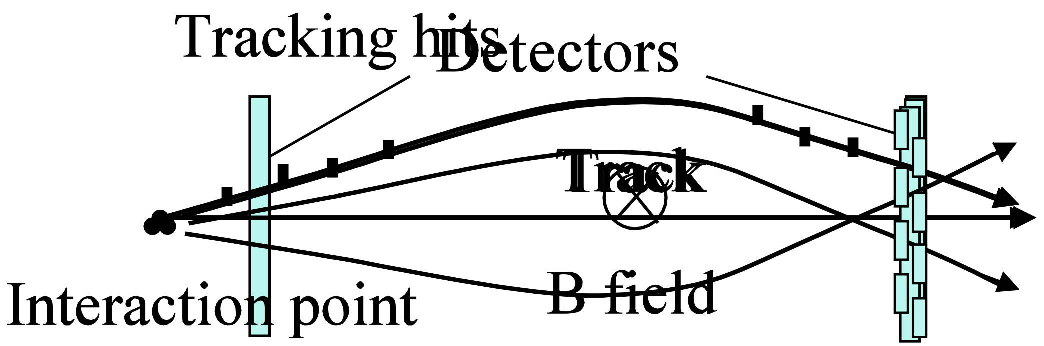


TRT information

- Energy deposition in the straw is the sum of ionization loss (~2 keV) and the larger deposition due to transition radiation absorption (> 5 keV) $\rightarrow$ use two thresholds in the readout electronics



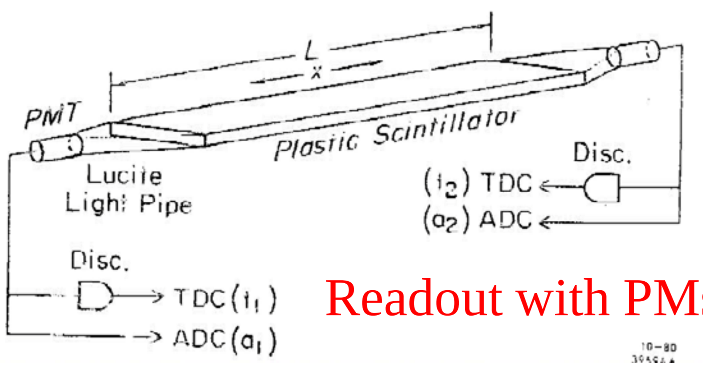
4. Time Of Flight



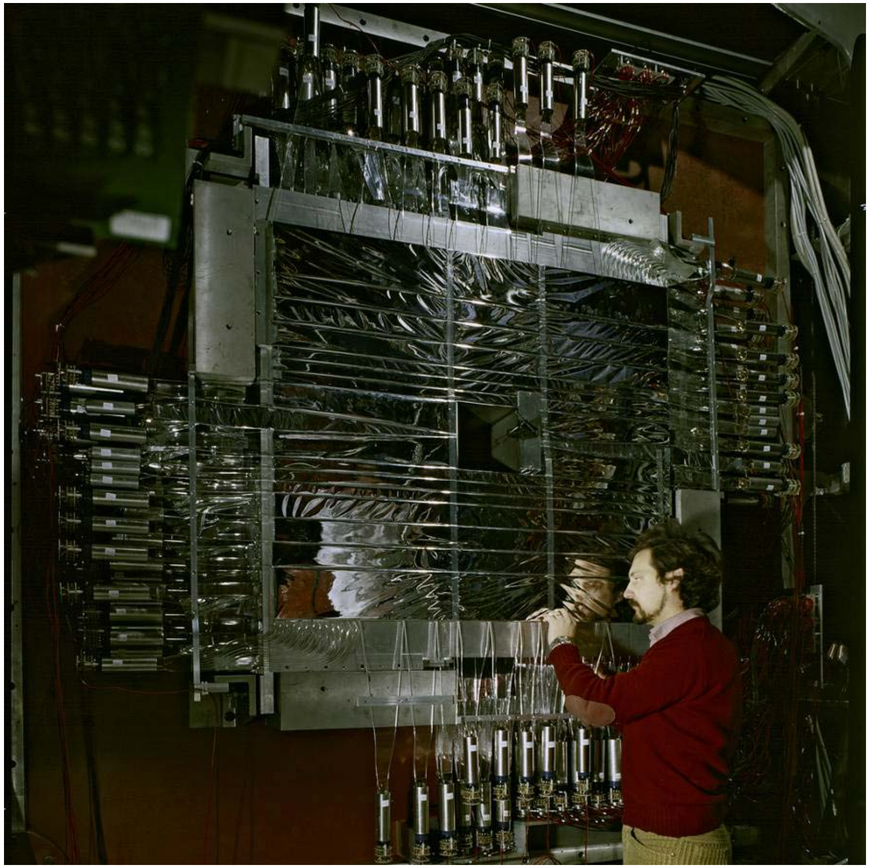
- Recall simple concept, measuring time difference between two detectors
- Can simplify by using time of beam crossing to provide the "start" signal
- Due to magnetic field, tracks are not straight lines
  $\rightarrow$ need to use tracking to determine actual path length
- Multiple tracks would give rise to ambiguous solutions
  $\rightarrow$ detector is segmented according to the expected track multiplicity
- This is the basic layout for TOF *hodoscopes* made of scintillator bars

TOF detectors

- Traditional approach to TOF uses scintillator hodoscopes (see the Scintillator lecture)
- Organic scintillators provide light on a timescale of ~ 100 ps (Inorganic are slower)
- Resolution improves if light yield increased, as can average over the detected photons arrival times



Readout with PMs



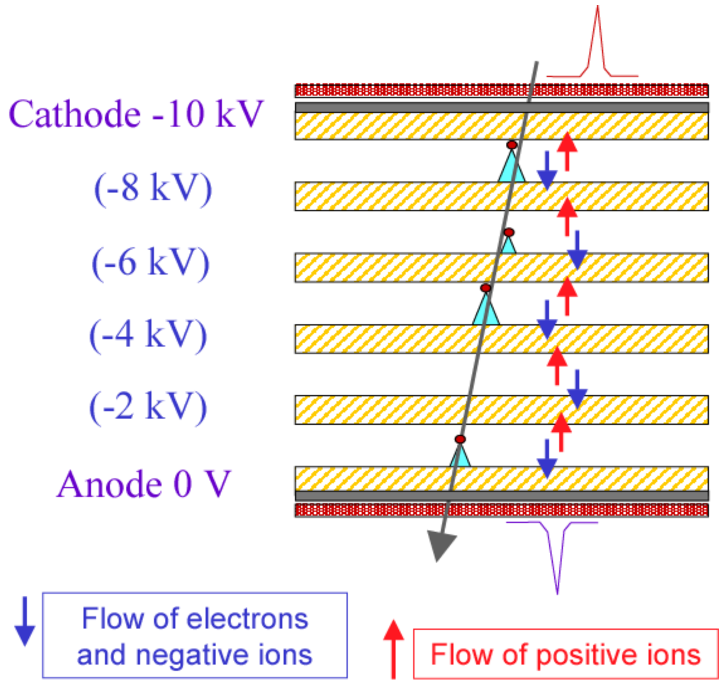
Scintillator hodoscope

Resistive Plate Chambers

- Fast thin-gap parallel plate detectors were proposed as alternative to scintillators, for low-cost, large-area TOF systems
- Signal comes from ionization in the gas between the plates

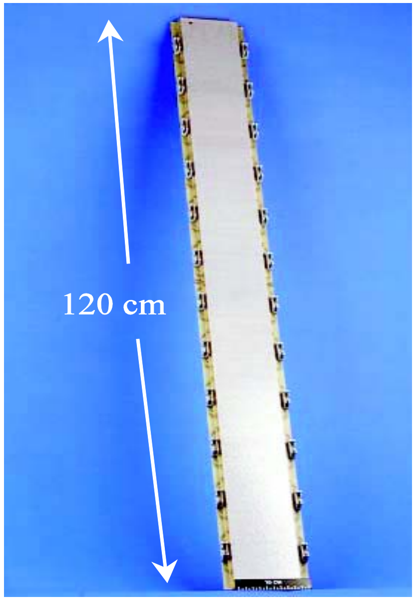
  High resistivity of the plates required (> $10^{10}\ \Omega$cm) to limit discharge area
- *Multigap* RPCs use a stack of equally-spaced resistive plates with voltage applied to external surfaces
- Pickup electrodes on external surfaces (resistive plates transparent to fast signal)

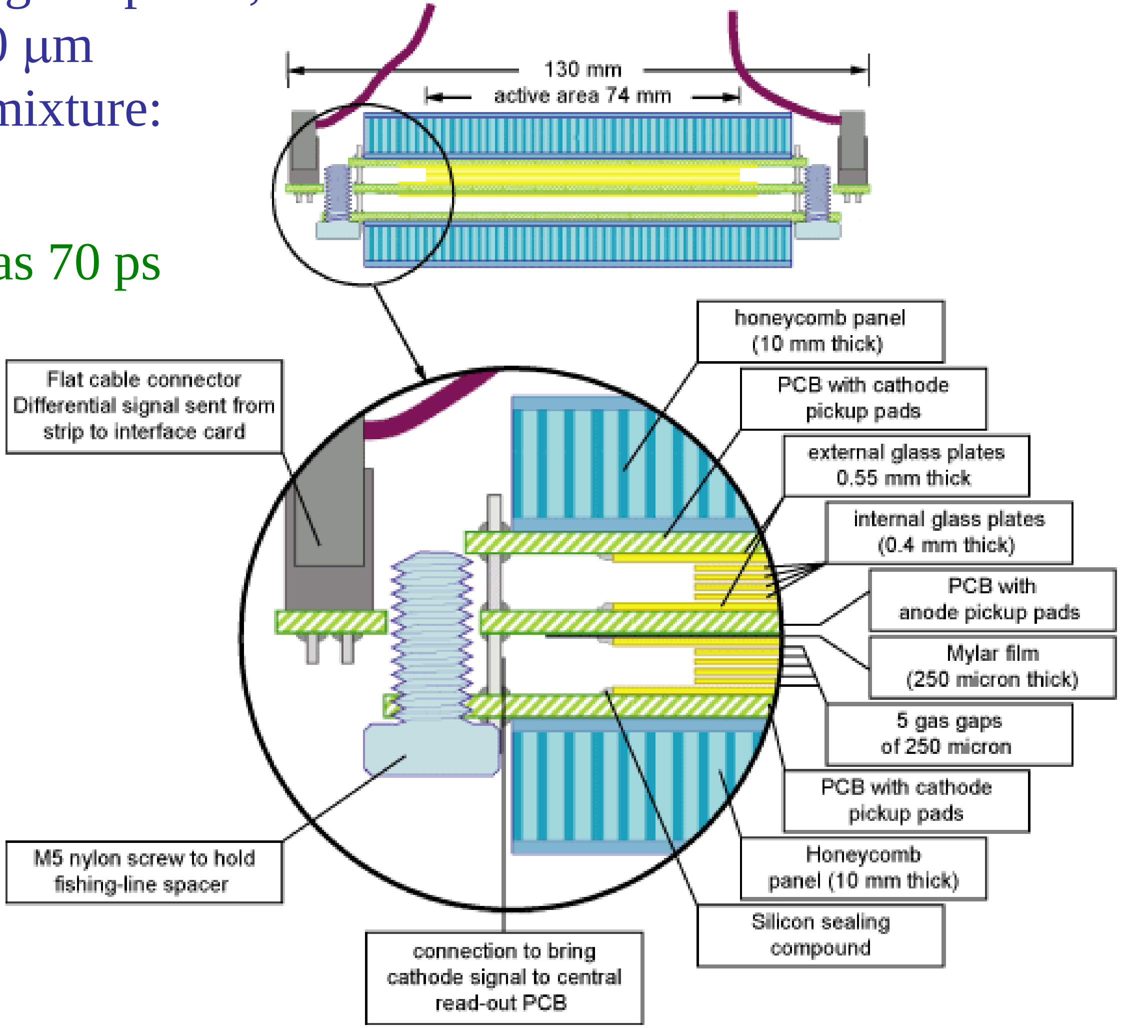
  Inner plates stop avalanche development → avoid sparks, and high dead time



ALICE MRPC

- Made from stacks of 1 mm glass plates, each with 5 gas gaps of 250 µm
  Gas used is a complicated mixture:
  $C_2F_4H_2 + SF_6 + C_4H_{10}$
- Timing resolution as good as 70 ps has been achieved





TOF performance

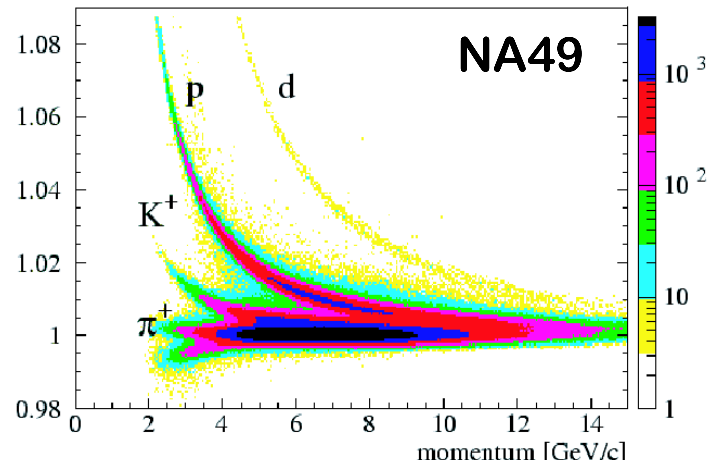
- The number of standard deviations separation for a time of flight detector is

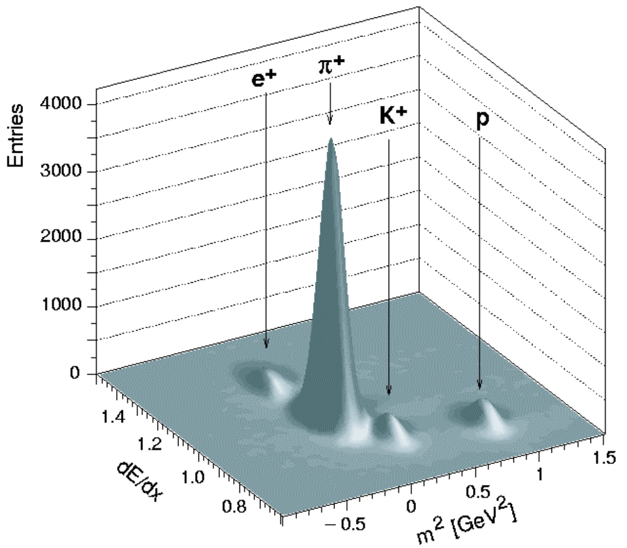
$$N_\sigma = \frac{|m_1^2 - m_2^2|\, d}{2\, p^2\, \sigma_t\, c} \qquad \text{(TOF)}$$

- Note the similarity to the expression for RICH detectors from before:

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

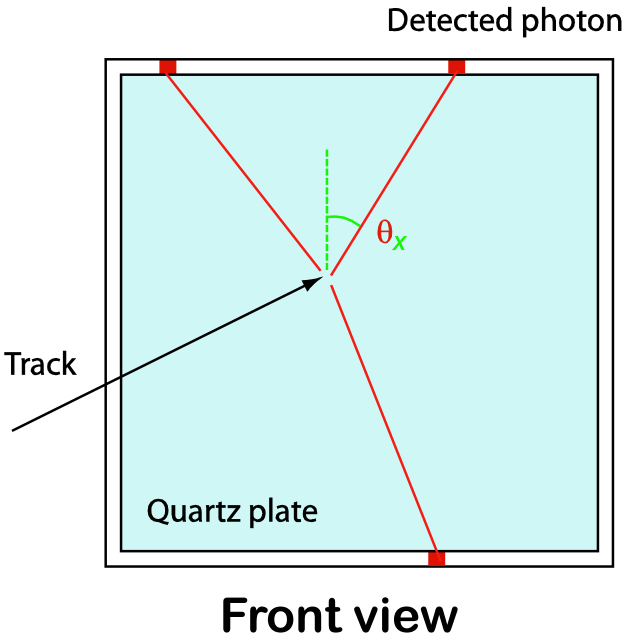
- However, in that case there is an "amplification" factor of $1/\sqrt{n^2-1}$ which allows RICH detectors to reach high momentum coverage (with a suitable n)
- Combination of TOF with *dE/dx* can help remove ambiguities:

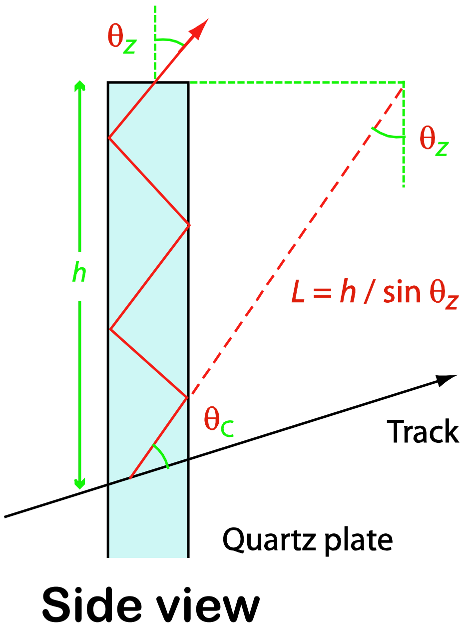




TORCH concept

- I am currently working on the design of a new concept for Particle ID for the upgrade of LHCb (planned to follow after ~ 5 years of data taking)
- Uses a large plate of quartz to produce Cherenkov light, like a DIRC
  But then identify the particles by measuring the photon arrival times
  Combination of **TO**F and **RICH** techniques → named TORCH
- Detected position around edge gives photon angle (θ_x)
  Angle (θ_z) out of plane determined using focusing
  Knowing photon trajectory, the track arrival time can be calculated

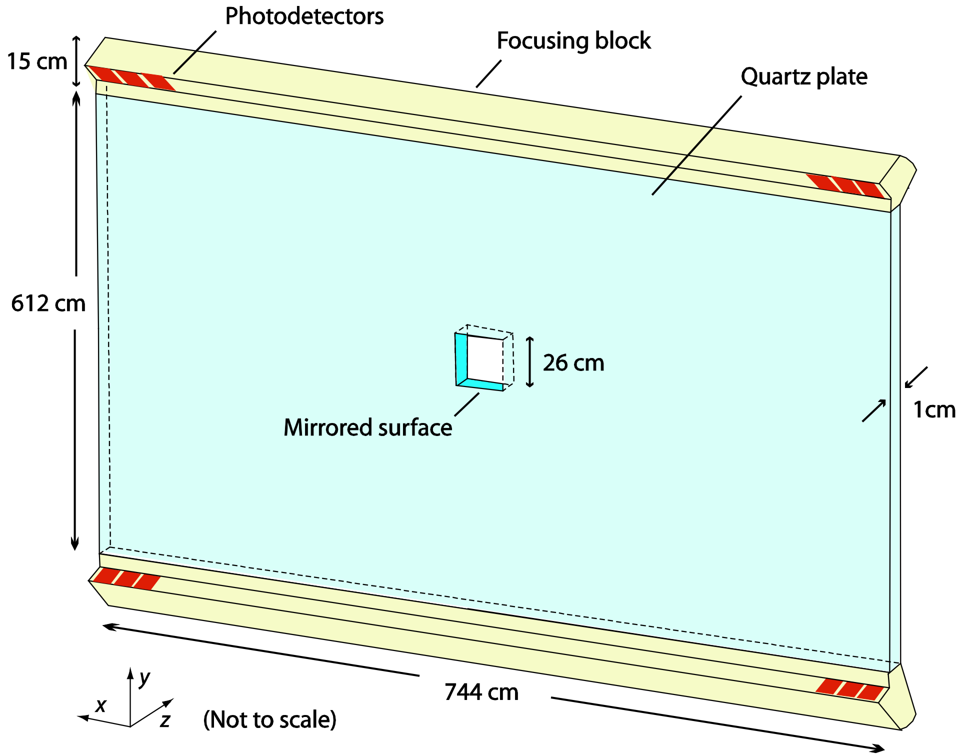




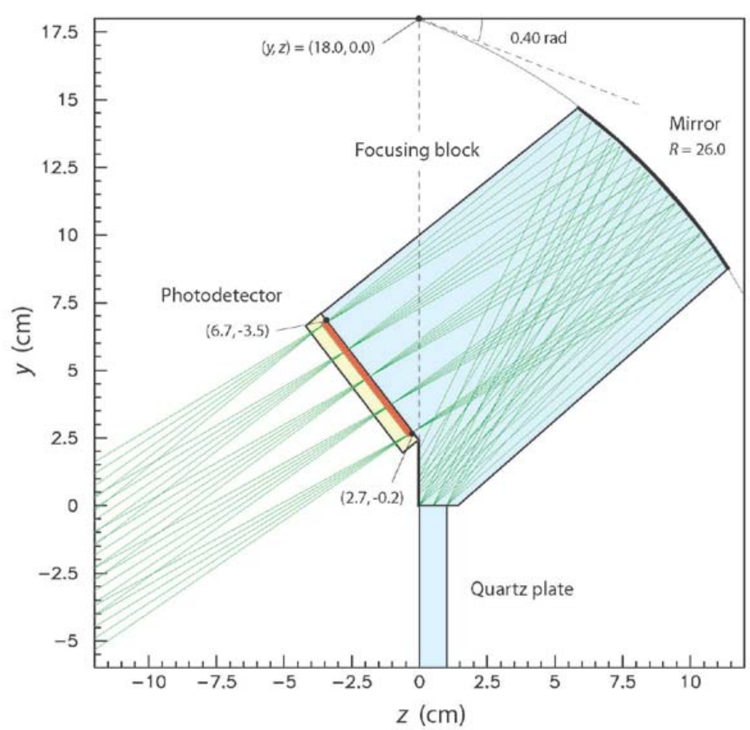
Proposed layout

- Optical element added at edges to focus photons onto MCP detectors
  It converts the angle of the photon into a position on the detector

Schematic layout

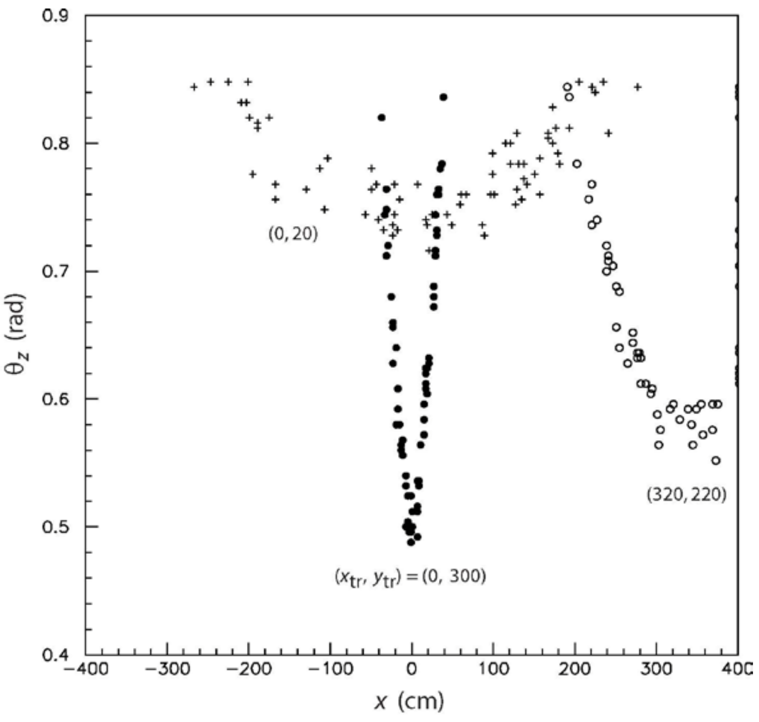


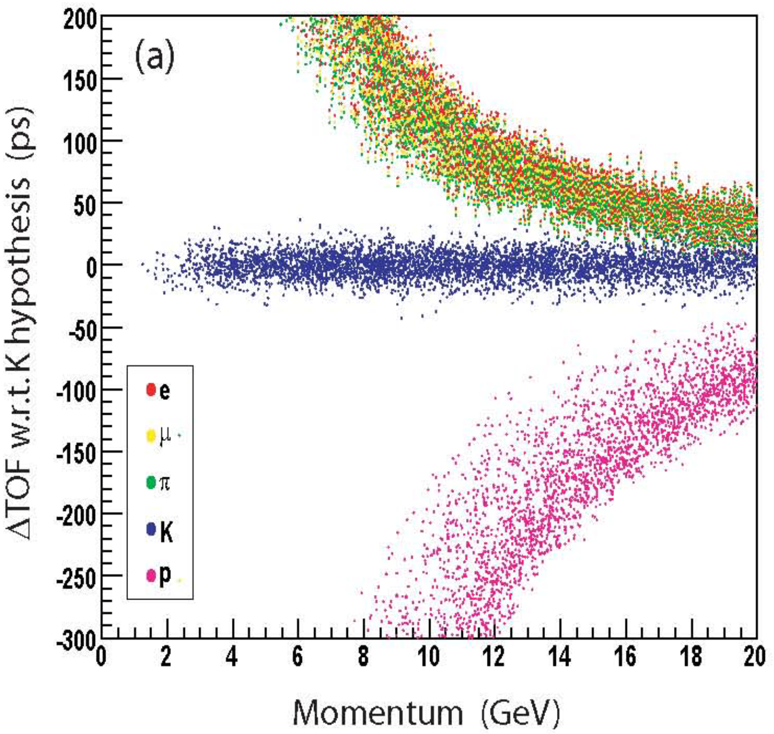
Focusing element



Predicted performance

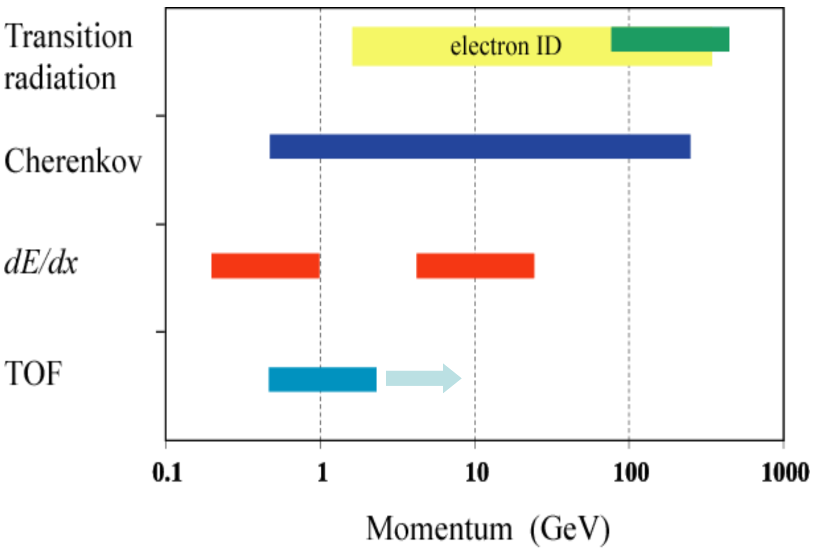
- Pattern recognition will be a challenge, similar to a DIRC
- Assuming a time resolution per detected photon of 50 ps,
  the simulated performance gives 3σ K-π separation up to > 10 GeV
  Will need to be confirmed with an R&D program using test detectors





Summary

- There is a wide variety of techniques for identifying charged particles



- **Transition radiation** is useful in particular for electron identification
- **Cherenkov** detectors are in widespread use Very powerful, tuning the choice of radiator
- **Ionization** energy loss is provided by existing tracking detectors but usually gives limited separation, at low *p*
- **Time Of Flight** provides excellent performance at low momentum With the development of faster photon detectors, the range of TOF momentum coverage should increase
- There is still room for new ideas, for the next generation of experiments Maybe one of *your* ideas?