Cherenkov detectors and particle identification

Graduate student Lecture

HighRR Lecture week

Sajan Easo
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Science & Technology
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Outline

- Part 1: Introduction:
  - *Particle identification (PID)*
- Part 2: Cherenkov detectors for PID
  - *Basic principles*
  - *Photon detectors*
- Part 3: Examples of Cherenkov detector systems
- Part 4: Techniques for PID, other than those using Cherenkov radiation

- Main focus on the principles that are useful for particle identification
- *Not Covered* : *PID using Calorimeters*
- *Further details* : *In the references listed*

Acknowledgements

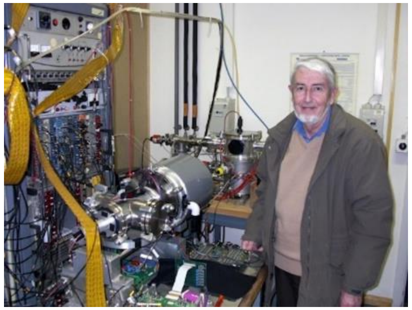
Many great scientists have written papers and given talks on the topic of Cherenkov detectors. I used material from some of these papers and talks for this lecture.

P.Cherenkov

T.Ypsilantis

J.Vavra

B.N.Ratcliff



J.Séguinot

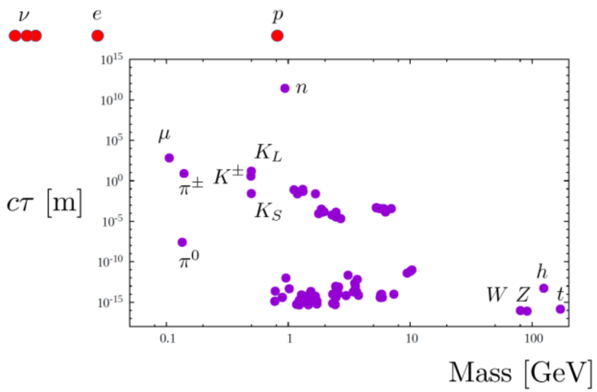
O.Ullaland

There are many others also.

The references to the papers are listed at the end of this lecture.

Introduction

- Particle identification is an important part of many experiments in high energy physics
  - These include accelerator based experiments and astroparticle experiments



- Types of particles :

  - Long-lived particles which create signals in a detector :
    - ➢ Use experimental techniques to find out if they are electrons, muons, protons, charged pions, charged kaons, photons etc.

  - short-lived particles : identified from their decays into long-lived particles
    example: D-mesons

  - quarks, gluons : these are normally inferred from the hadrons, jets of particles etc. that are created from them, using hadronization.

- This lecture: Identification of long-lived particles

Detector terminology

Tracking Detector : Directions of charged particles

They create hits create in silicon detectors, wire chambers etc.
They can also create photons
in scintillating fibres which in turn are detected by photon detectors.

Tracking Detector + Magnet : Charges and momenta of the charged particles
(Tracking system)

Measure of the bending of the particles in magnetic field
and use that to infer the momentum of the particle

Electromagnetic Calorimeter (ECAL) : Energy of photons, electrons etc.

Measure the energy deposited in the clusters of hits
they create, use the shapes of these clusters .

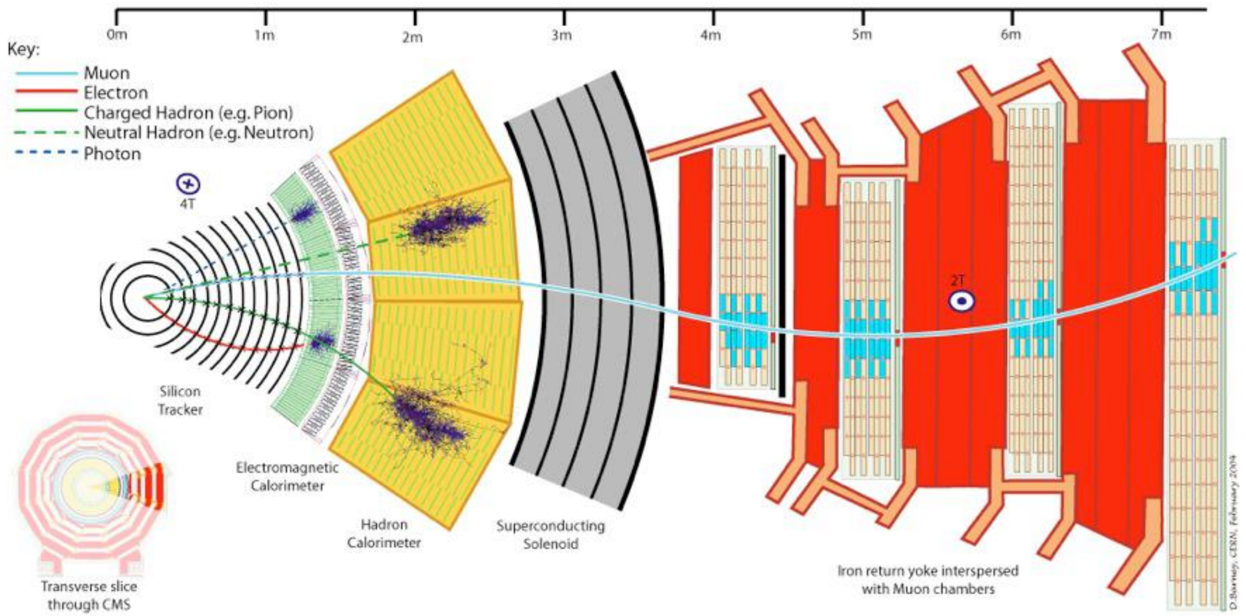
Hadronic Calorimeter (HCAL) : Energy of hadrons : protons, charged pions etc.

Measure the energy deposited in the clusters of hits, use the
shapes of these clusters

Muon Detector : Tracking detector for muons

Particle identification (PID) detector : Detectors dedicated for PID

Introduction



Some of the methods for particle identification:

Electron : ECAL cluster has a charged track pointing to it and its energy from ECAL is close to its momentum from Tracking system.

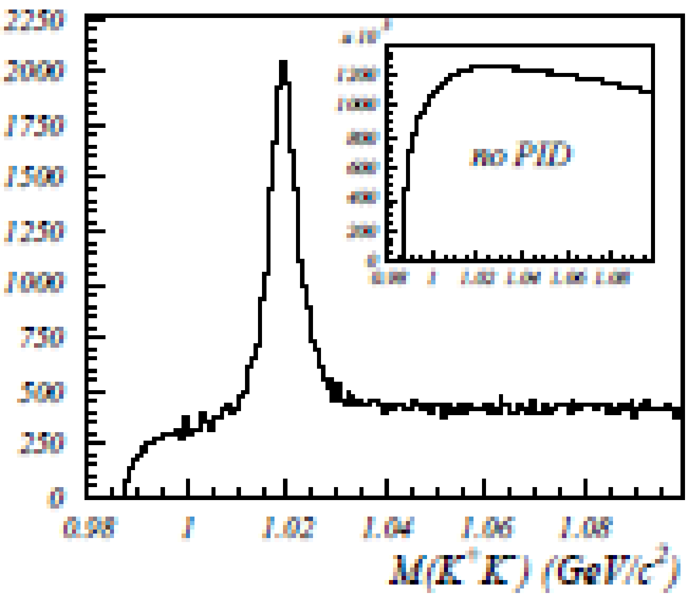
Photon : ECAL cluster has no charged track pointing to it.

photon conversion : photon creating $e^+ e^-$ *pair*
electron bremsstrahlung : electron emitting photons

Muon : Signals in the tracking system , muon chambers and calorimeters

Introduction

- Particle Identification (PID) detector:
  - To distinguish between charged kaons, charged pions, protons etc.
  - To separate charged pions from electrons
  - To distinguish between muons and electrons (in neutrino experiments)
  - Reduction of combinatorial backgrounds



$\phi \rightarrow K^+ K^-$ from HERAB

- These goals are achieved efficiently using Cherenkov detectors in many experiments.
- More examples and other types of PID detectors later in the lecture.
- Calorimeters and tracking detectors covered in other lectures.

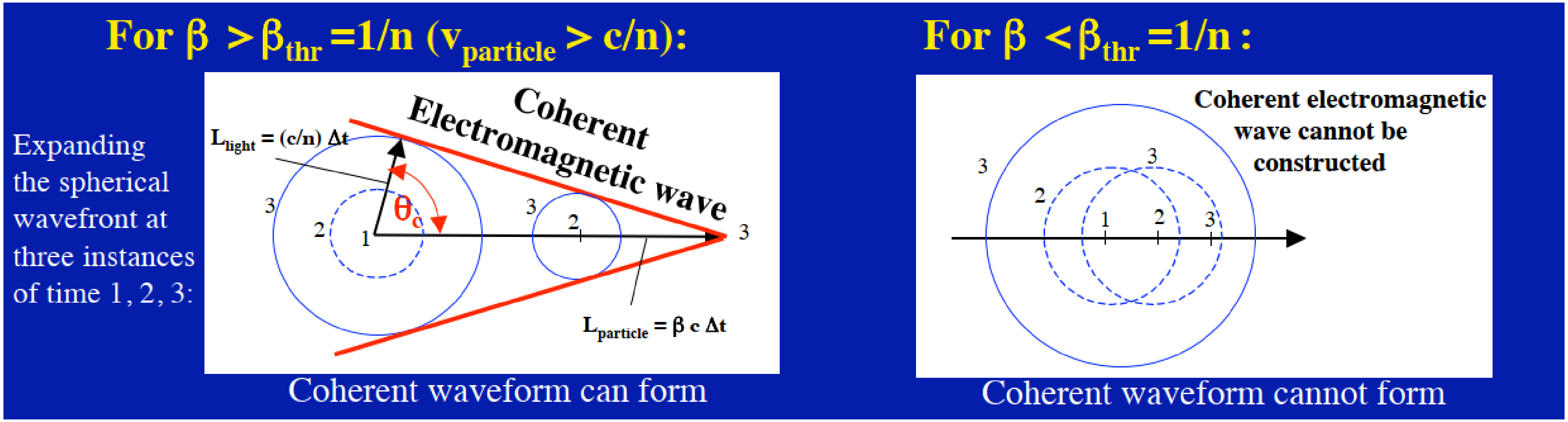
Cherenkov Detectors

- Cherenkov Radiation: General Ideas
- Brief History of the development of Cherenkov detectors
- Classification of Cherenkov detectors
- Photon detectors to detect Cherenkov Radiation
- Examples of large Cherenkov Detector systems

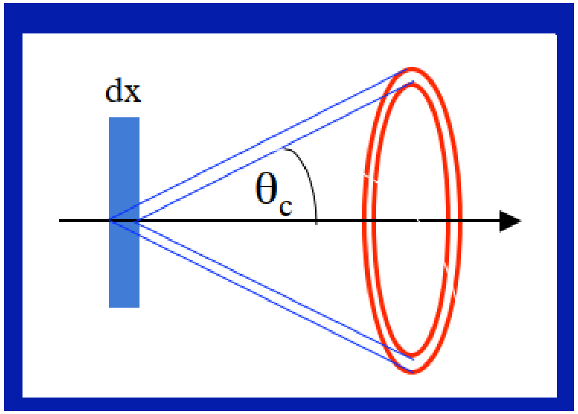
Basics of Cherenkov Radiation

In a medium, consider particle with speed v. Let speed of light = c_M in the medium
$\beta = v/c$, $n = c/c_M$, where c= speed of light in vacuum

For Cherenkov radiation, the speed of the particle should be such that
$\beta > \beta_{thr} = 1/n$



$\cos(\theta_c) = ((c/n)\Delta t) / (\beta c\, \Delta t) = 1/(n\beta)$

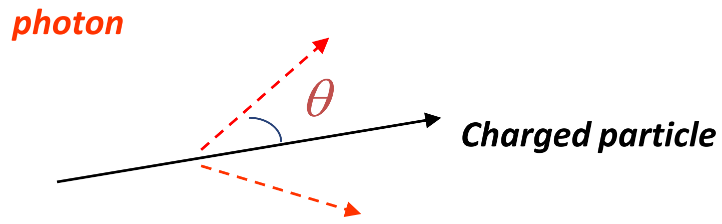


$\cos\theta_c = 1/n\beta$

$\theta=0$: Cherenkov threshold for the charged particle. At threshold, $\beta_{thr} = 1/n$

Here $n = n(\lambda)$, where λ= photon wavelength

Basics of Cherenkov Radiation



$\cos(\theta) = 1/(n\,\beta)$ where n = Refractive Index = $c/c_M = n(E_{ph})$

$$\beta = v/c = p/E = p/(p^2 + m^2)^{0.5} = 1/(1+(m/p)^2)^{0.5}$$

β= velocity of the charged particle in units of speed of light (c) vacuum
p, E ,m = momentum, Energy, mass of the charged particle.
C_M = Speed of light in the Medium (Phase velocity) ,
E_{ph} = Photon Energy, λ=Photon wavelngth.

- Theory of Cherenkov Radiation: Classical Electrodynamics by J.D.Jackson (Section 13.5)
- The energy radiated by the charged particle as Cherenkov radiation per unit length =

$$dE/dx = (Z/c)^2 \int_{\varepsilon(\omega) > 1/\beta^2} \omega\,(1-1/(\beta^2\,\varepsilon(\omega)))\,d\omega$$

Where ω= Frequency
$\varepsilon(\omega) = n^2$ = permittivity
assume permeability =1
Z= charge of the particle

Typical example: Charged particle with momentum of few GeV/c or more emitting Cherenkov photons with few eV of energy

Basics of Cherenkov Radiation

$\cos(\theta) = 1/(n\,\beta)$

$\theta=0$: Cherenkov threshold for the charged particle. At Threshold, $\beta = 1/n$

θ has Maximum in a medium when β almost = 1

⬄ p/m sufficiently high ⬄ Saturated tracks

θ is always less than 90 degree in standard materials

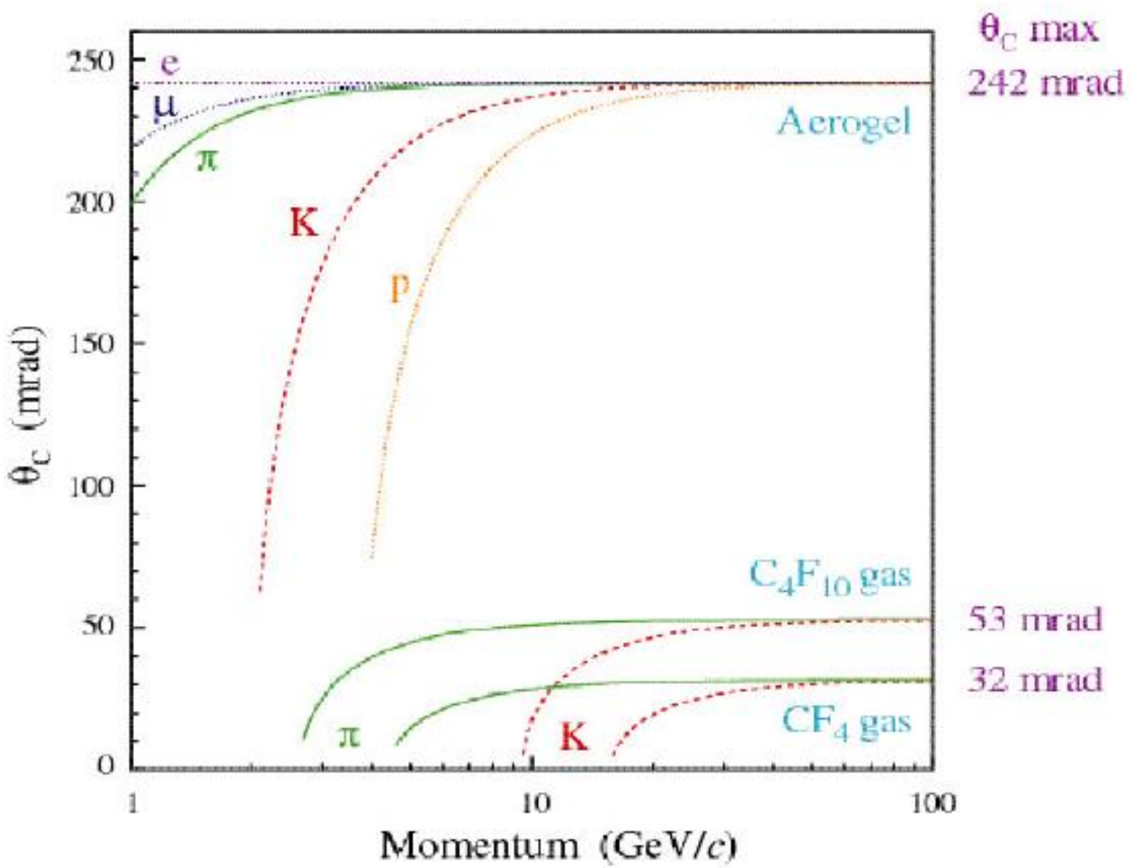
- Particle ID: θ (p,m) ; If we measure p and θ , we can calculate m and thus identify different particles

- Typically, in accelerator based experiments, momentum (p) is measured by a magnetic spectrometer (Tracking system+magnet)

- Cherenkov detectors: Measure θ : Resolution can be expressed in terms of ($\Delta\beta/\beta$)

Photonic Crystals: No Cherenkov Threshold and θ can be more than 90 degree.
Covered briefly at the end of this lecture: Reference: http://ab-initio.mit.edu/photons

Basics of Cherenkov Radiation



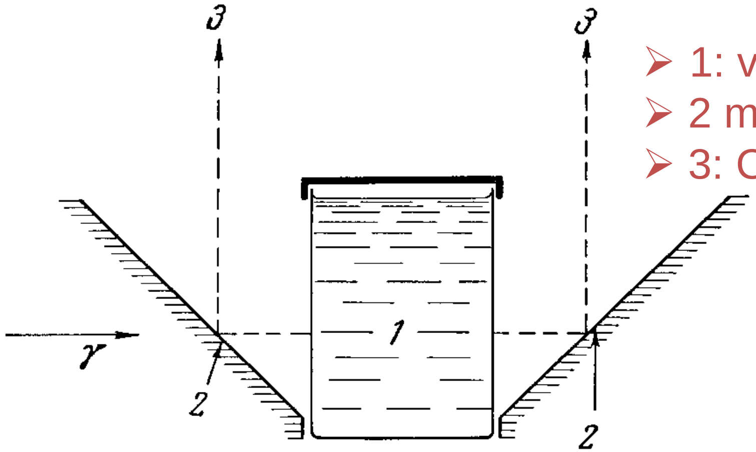
Cherenkov Angle vs Charged Particle Momentum

The separation between the plots for different particle types enables to discriminate between them.

Note on the History of Cherenkov Radiation

- The formula cos θ =1/nβ was already predicted by Heaviside in 1888
- ~1900: 'Blue glow' seen in fluids containing concentrated Radium (Marie & Pierre Curie)
- Pavel Alexeevich Cherenkov (1904-1990): Lebedev Physical Institute of the Russian Academy of Sciences.
- Discovery and Validation of Cherenkov Effect : 1934-37
- Full Explanation using Maxwell's equations: I.M. Frank and I.E. Tamm in 1937
- Nobel Prize in 1958: Cherenkov, Frank and Tamm.

History of Cherenkov Radiation



- 1: vessel with liquid
- 2 mirror
- 3: Cherenkov photons towards the photographic plate

Typical Apparatus used by Cherenkov to study the angular distribution of Cherenkov photons. (Incident γ ray produces electrons by compton scattering in the liquid).

P. Cherenkov established that:

- Light Intensity is proportional to the electron path length in the medium.
- Light comes only from the 'fast' electrons above a velocity threshold, in his Apparatus.
- Light emission is prompt and the light is polarized.
- The wavelength spectrum of the light produced is continuous. No special spectral lines.
- The angular distribution of the radiation, its intensity, wavelength spectrum and its dependence on the refractive index agree with the theory proposed by his colleagues Frank and Tamm.

Components of a Cherenkov Detector

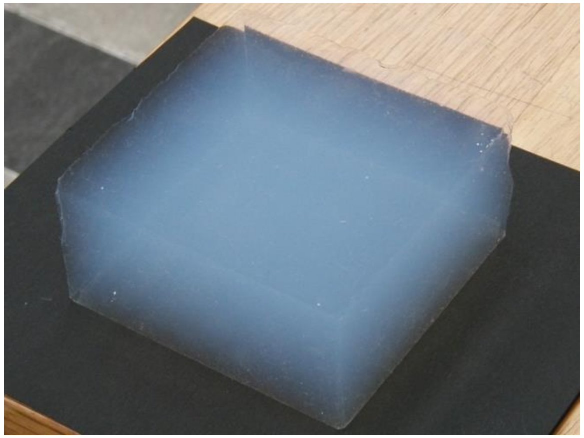
- Main Components:
  - Radiator : To produce photons
  - Mirror/lens/quartz bar etc. : To help with the transport of photons
  - Photon detector : To detect the photons

- Radiator: Any medium with a Refractive Index.

Example of radiators

Medium	n-1	γ_{th}	Photons/m
He (STP)	$3.5\ 10^{-5}$	120	3
CO_2 (STP)	$4.1\ 10^{-4}$	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

Aerogel: network of SiO_2 nano-crystals

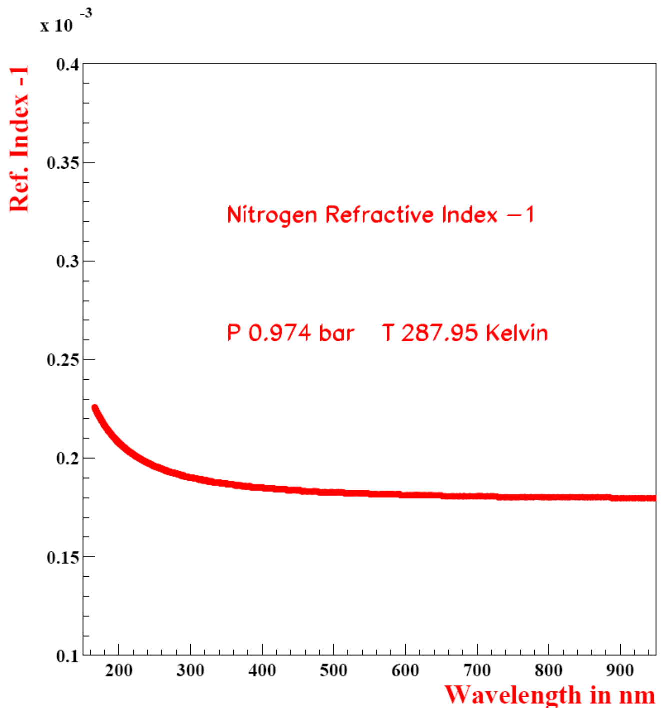


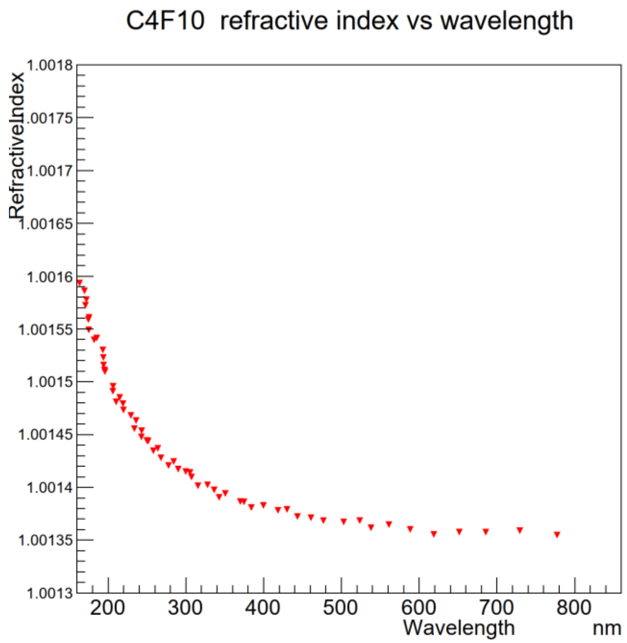
$$\gamma = 1/\sqrt{1-\beta^2}$$

- The atmosphere, ocean are the radiators in some Astro Particle Cherenkov Detectors

Photons from Cherenkov Radiation

- n= n(λ) : Different photons from the same charged track can have different Cherenkov Angles.(cos (θ)=1/n β)). This spread in angles gives rise to 'Chromatic Error' when measuring the average θ from a track.

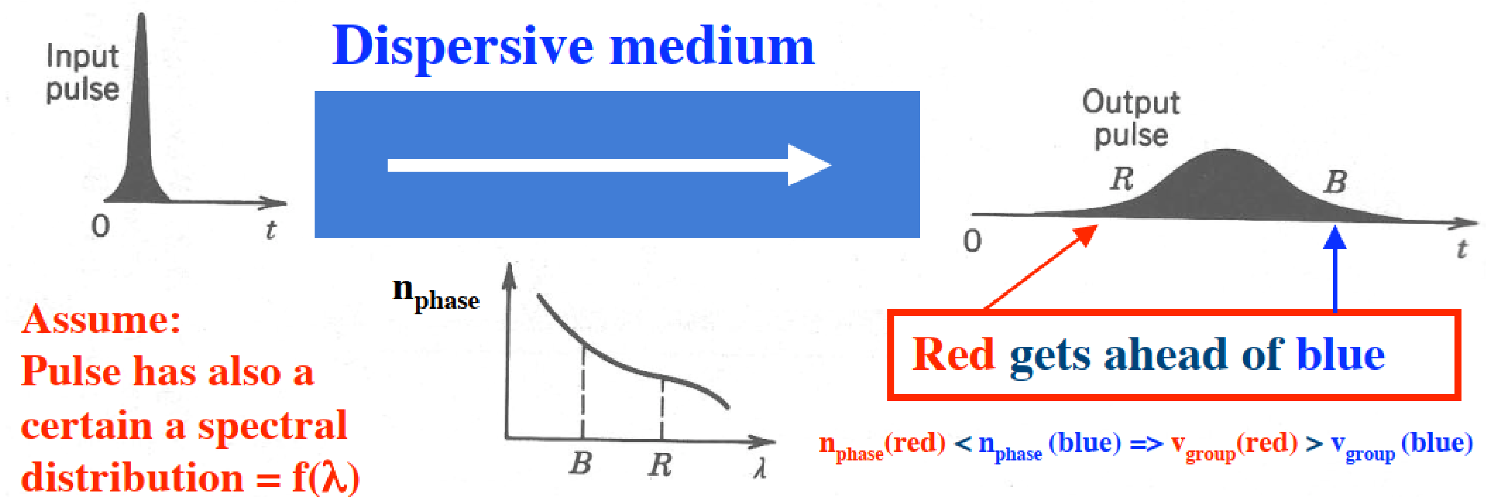




- To reduce the Chromatic error various methods have been tried:
  - Filter out the low wavelength photons before they reach the photodetector.
  - Appropriate choice of the radiator material
  - Recent development: Measure the variation in Time-Of-Propagation of photons (TOP) from their production point to the detection point. This can be used to correct for the Chromatic Error

Photons from Cherenkov Radiation

- Photon production depends on the phase velocity (v_{phase}) of photons
- Photon propagation depends on the group velocity (v_{group}) of photons



$$v_{group} = c \, / \, n_{group} = c \, / \, [n_{phase} - \lambda * dn_{phase}/d\lambda]$$

$$t \equiv TOP = L_{path} \, / \, v_{group} = L_{path} \, [n_{phase} - \lambda * dn_{phase}/d\lambda] / \, c \quad = \text{time-of-propagation}$$

$$dt = L \, \lambda \, d\lambda \, / \, c * (- \, d^2 n_{phase}/d\lambda^2)$$

Calibrate dt (variation TOP) with dθ (variation in Cherenkov angle) for the photons.
Measure the time of arrival at the photon detectors and correct for dθ
This assumes association between tracks and photons. (*Covered later in the lecture*)

Photons from Cherenkov Radiation

- Current photon detectors used for detecting Cherenkov light are sensitive to visible + part of UV. This part of the EM spectrum produced by the Cherenkov Radiation is the only range relevant for Cherenkov detectors. λ_{ph} ranges from 135 nm to 800 nm depending upon the photodetector.

- Number of photons produced by a particle with charge Z , along a Length L : (From Frank-Tamm theory)

$$N_{\mathbf{prod}} = (\alpha/hc)\, Z^{2}\, L \int_{E_1}^{E_2} \sin^{2}(\theta)\, dE_{ph}$$

where $\alpha/hc = 370\ eV^{-1}cm^{-1}$, $E_{ph} = hc/\lambda$.

- If the photons are reflected by a Mirrror with Reflectivity $R(E_{ph})$, are transmitted through a quartz window of Transmission $T(E_{ph})$ and then are detected by a photon detector with efficiency $Q(E_{ph})$

- Number of photons detected :

$$N_{\mathbf{det}} = (\alpha/hc)\, Z^{2}\, L \int R\, Q\, T\ \sin^{2}(\theta)\, dE_{ph}$$

$$= N_0\, L\, \sin^{2}(\theta_c)$$

(If we assume θ is almost constant = θ_c = Mean Cherenkov Angle)

- Figure of Merit of the detector = N_0 For example, $N_0 = 200\ cm^{-1}$ is a good value.

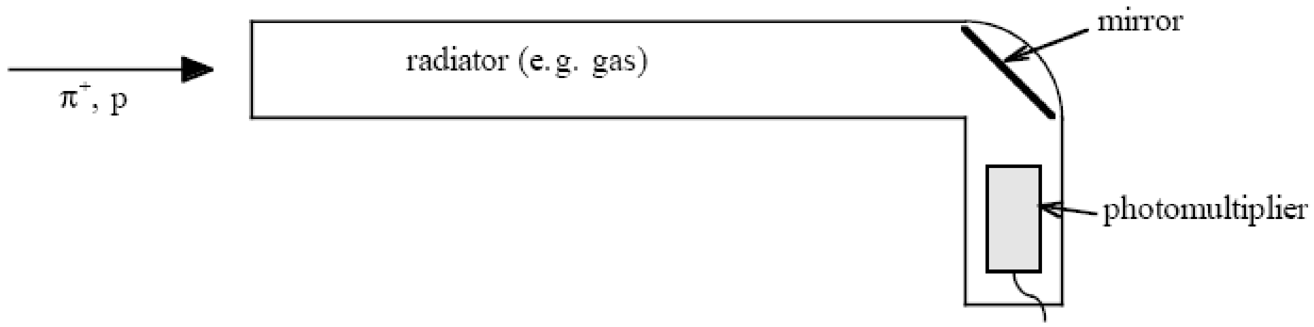
Classification of Cherenkov Detectors

- Cherenkov Detector Designs:
  - Threshold Counters
  - Imaging Counters:
    - Differential Cherenkov Detectors
    - Ring Imaging Cherenkov Detectors (RICH)
      - Detector for internally reflected light (DIRC) *covered later in the lecture*

- Types of photon detectors: (a) Gas Based (b) Vacuum Based (c) Solid State

- Applications:
  - In Accelerator Based High Energy Physics Detectors
  - In AstroParticle Physics Detectors

Threshold Cherenkov Counters



- Signal produced from only those particles which are above Cherenkov threshold.

- Basic idea: Yes/No decision, on the existence of the particle type.
  For this, count the number of photoelectrons detected (N_{det})

- In practice : Calibrate the number of observed photoelectrons or pulse heights to discriminate between particle types.

- For typical detectors: $N_o = 90\ \mathrm{cm}^{-1}$,

  N_{ph} per unit length of the radiator = $N_o * (m_1^2 - m_2^2)/(p^2+m_1^2)$

  At p= 1 GeV/c, N_{ph} per unit length = 16 /cm for Pions and 0 for Kaons.
  At p= 5 GeV/c, N_{ph} per unit length= 0.8 /cm for Pions and 0 for Kaons.

- Resolution : $\Delta \beta / \beta = \tan^2 \theta / (2 * \sqrt{N_{ph}})$

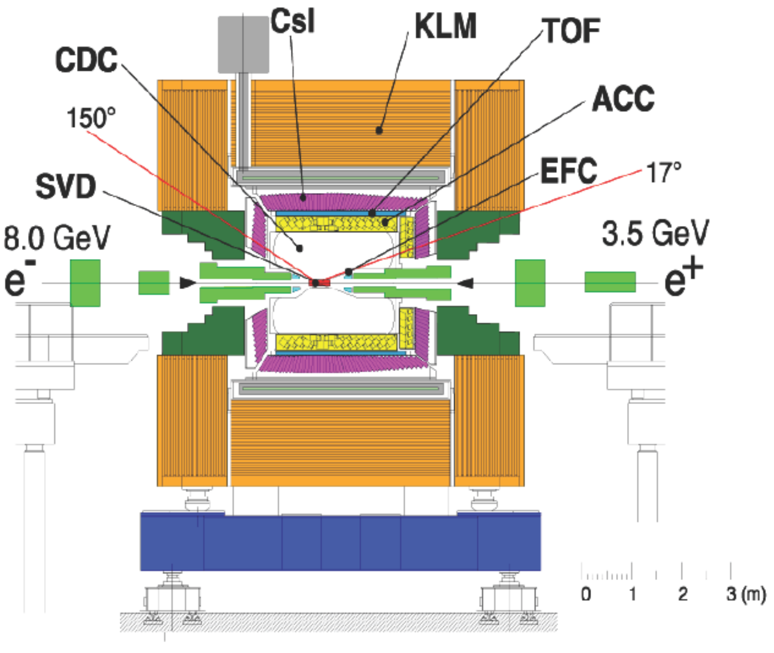
Threshold Cherenkov Detectors

- Can be used over a large area, for example : For secondary particles in a fixed target or Collider experiment.

- E691 at Fermilab: To study decays of charm particles in the 1980's

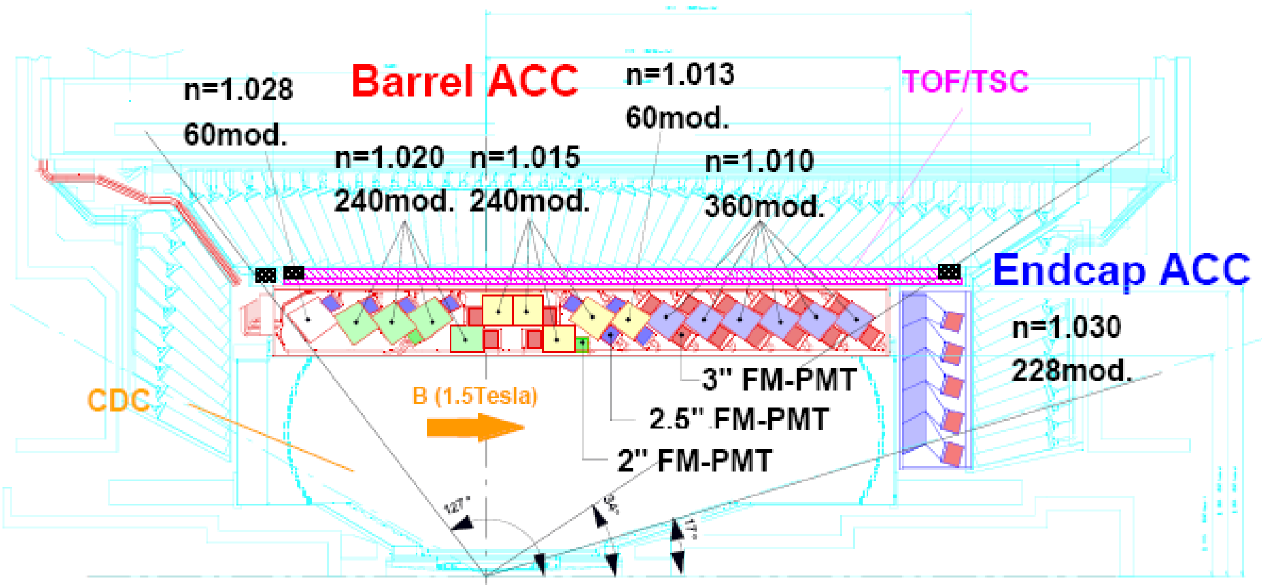
  $\Delta\beta/\beta = 2.3 * 10^{-5}$ using gas radiator.

- BELLE Experiment: To observe CP ciolation in B-meson decays at an electron-positron collider.

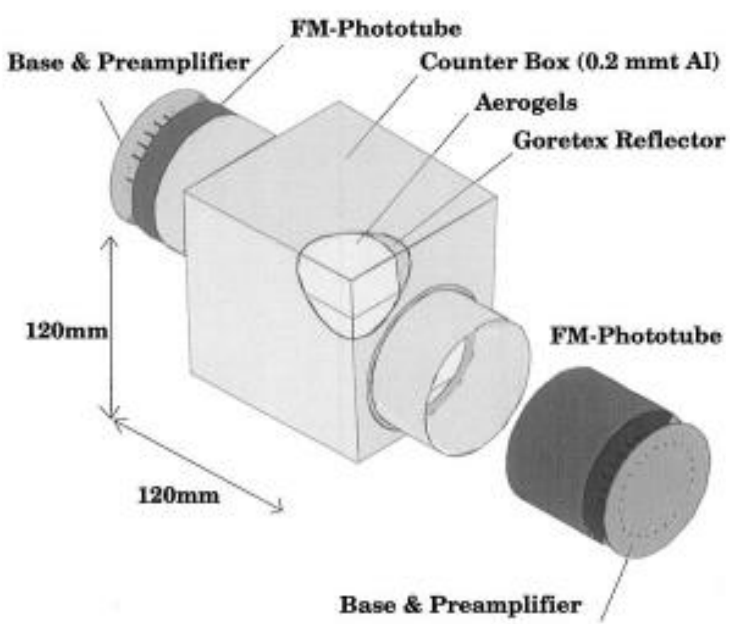


Threshold Counters

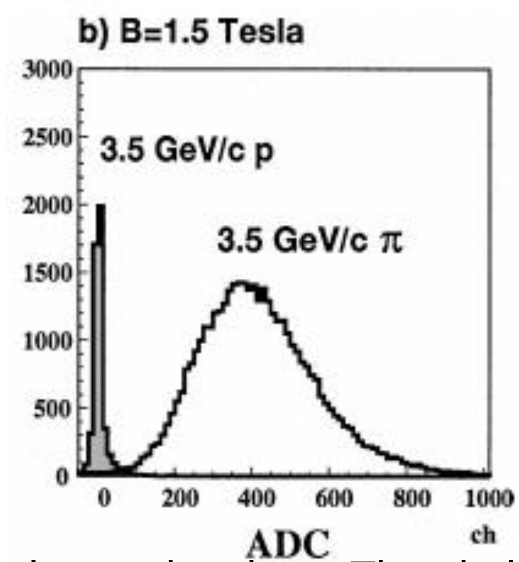
BELLE: Threshold Cherenkov Detector



- Five aerogel tiles inside an aluminum box lined with a white reflector(Goretex reflector)
- Performance from test-beam



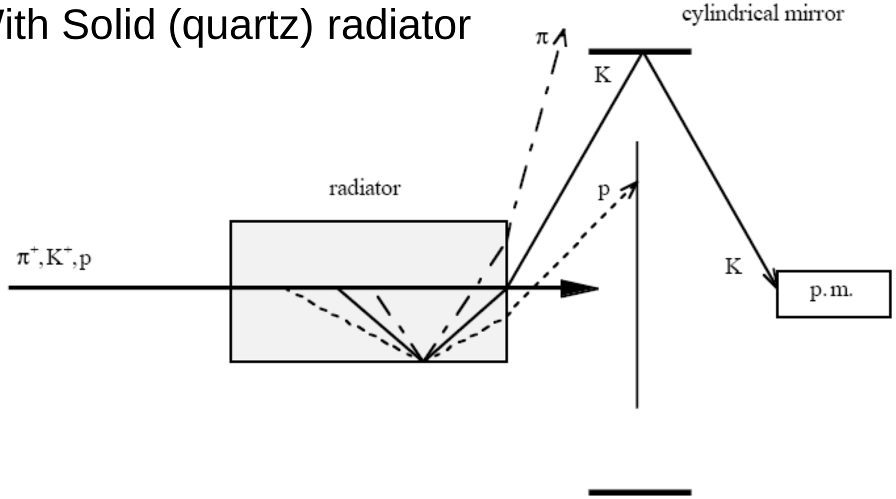
- Approx . 20 photoelectrons per Pion detected at 3.5 GeV/c
- More than 3σ separation



p below and π above Threshold

Differential Cherenkov Detectors

With Solid (quartz) radiator



- Very small acceptance in β and direction of the charged particle. (Narrow range in velocity and direction intervals).
- Mostly used for identifying particles in the beam lines.

Resolution:

- $\Delta\beta/\beta = (m_1^2 - m_2^2)/2p^2 = \tan\theta \quad \Delta\theta$

m_1, m_2 (particle masses)<< p (momentum)

- $\Delta\beta/\beta$ from 0.011 to $4 * 10^{-6}$ achieved.

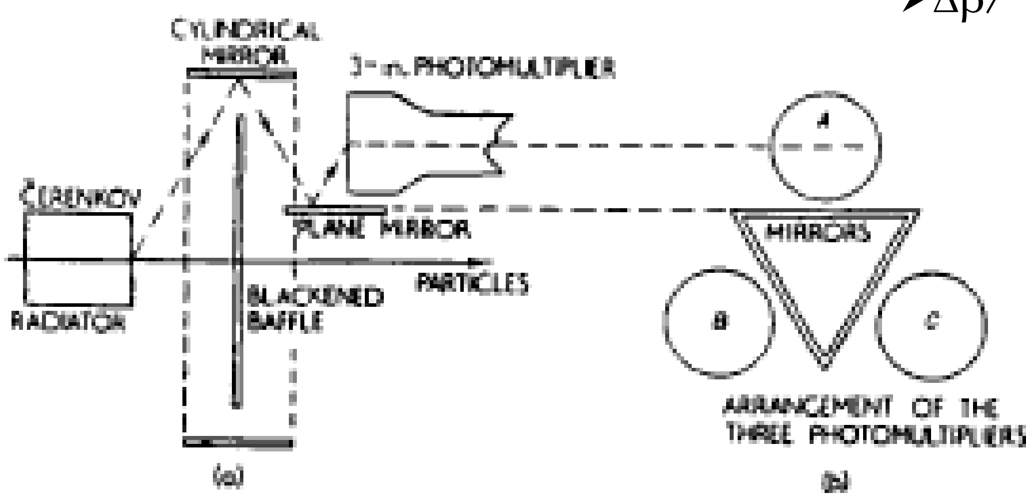
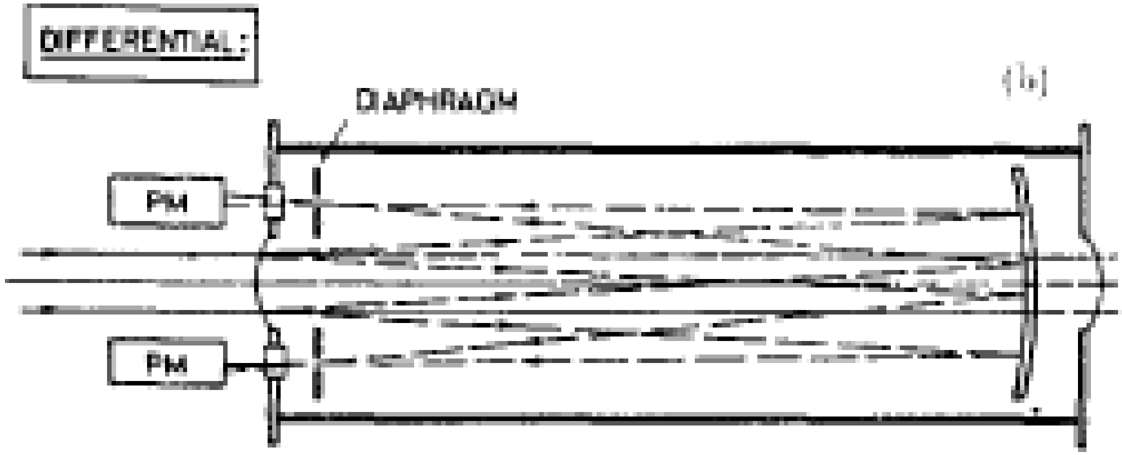


Fig. 2. The differential Cherenkov counter used in the antiproton discovery experiment: (a) side view; (b) end view.

- Discovery of anti-proton in 1955 by Chamberlain, Segre et. al. at Berkeley.
- Nobel Prize in 1959

Differential Cherenkov Detectors

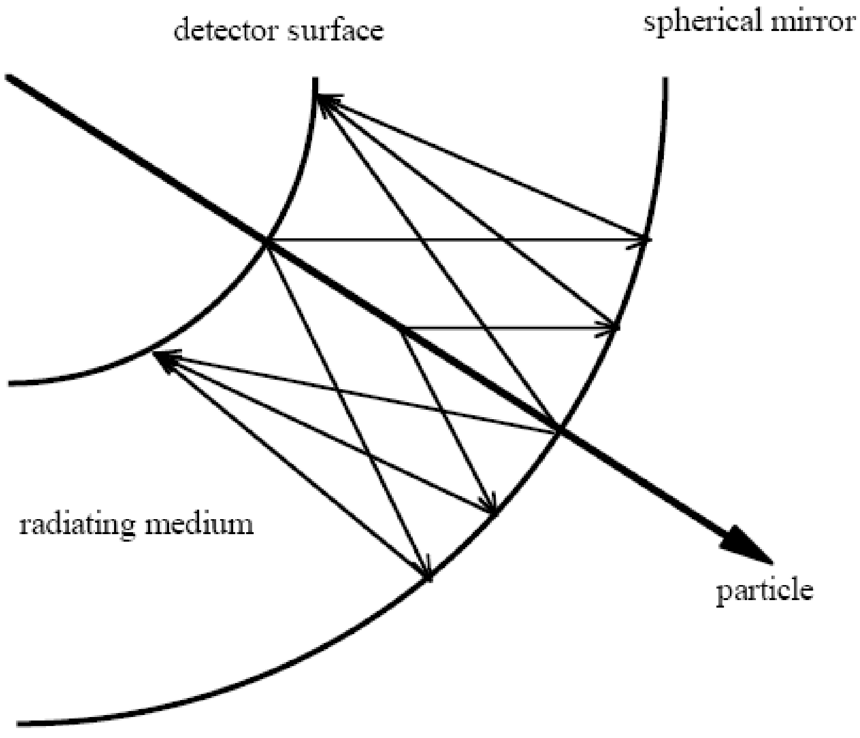


With a Gas radiator

Table 2
Some differential Cherenkov counters

Type	Year	Length [m]	Angle [mrad]	Gas	Range for ($\pi - K$) [GeV/c]	Remarks	Ref.
IHEP [1]	1968	5	23	He, N_2	< 100	no optical	
[2]		10	12		< 200	correction	[3]
DISC	1964	2	44	CO_2	< 100	corrected	[4]
FNAL DISC	1973	5.5	25	He	< 500 (< 100 for $\pi - \mu - e$)	Id.	[2]
CEDAR W	1976	3.25	31	N_2	< 150	Id	[5]
N		3.90	26	He	< 340		
HYPERON DISC	1972	0.3	120	SF_6	< 40 (< 100 for $\Sigma - p$)	Id.	[2]
For comparison:							
LDISC	1976	0.05	640	FC88 liquid	< 5	corrected high aperture	[6]

RICH Detectors



- Measures both the Cherenkov angle and the number of photoelectrons detected.
- Can be used over particle identification over large surfaces.
- Requires photodetectors with single photon identification capability.

RICH detectors

Resolution:

- $\Delta \beta / \beta = \tan(\theta) * \Delta\theta_c = K$ where $\Delta\theta_c = \langle \Delta\theta \rangle / \sqrt{N_{ph}} + C$

  where $\langle\Delta\theta\rangle$ is the mean resolution per single photon in a ring and C is the error contribution from the tracking , alignment etc.

- For example , for 1.4 m long CF_4 gas radiator at STP and a detector with $N_0 = 75\ cm^{-1}$
  $K = 1.6 * 10^{-6}$.

- This is better than similar threshold counters by a factor 125.
  This is also better than similar differential counters by a factor 2.
  Reason: RICH measures both θ and N_{ph} directly.
- RICH detectors have better resolution than equivalent differential and threshold counters.

- Let $u = \sin^2(\theta) = 1 - (1/n^2) - (m/p*n)^2$ for a particle with mass m and momentum p

  Number of standard deviations to discriminate between particles with masses, m_1 an m_2
  $= N_\sigma = (u_2-u_1) / (\sigma_u * \sqrt{N_{ph}})$ where σ_u : $\Delta\theta$ converted into the parameter u.
  ($\Delta\theta$ = error in single photon θ measurement)

- At momentum p ($=\beta$ E), $N_\sigma = \mathrm{sqrt}((m_2^2-m_1^2)/(2 * K * p))$, for $\beta \sim 1$

  This equation gives a general idea regarding number of σ separation achievable, during in the design of the RICH detectors. However it has limitations in giving a good prediction, in multi particle events with high occupancy.
  In practice, detailed simulations are carried out for detector design.
- One of the first large size RICH detector: in DELPHI at LEP.

Photon detection techniques

- The RICH detectors require capability to detect 'single photons'. This is more difficult than detection of photons in other detectors. (for example a simple camera, a calorimeter etc.)

- Types of Photon detectors:

  (a) Gas Based (b) Vacuum Based (c) Solid State

Detection of Photons

- Principle:
  - Convert Photons → Photoelectrons using a photocathode
  - Detect these photoelectrons using 'charged track detectors'.
  - Measure the position and (/or) time of photoelectrons in the tracking detector.

- General introduction to tracking detectors and silicon detectors is not covered in this lecture. However they are covered in other lectures this week.

- In this lecture, we focus on some of the aspects related to the detection of photoelectrons in Cherenkov Detectors.

- Gas based detectors:
  - **MWPC (Multi Wire Proportional Chambers)**
  - **GEM (Gas Electron Multiplier)**

- Vacuum based detectors: **PMT (Photomultiplier tubes)**
  HPD (Hybrid Photodiodes)

- Solid state detectors: Silicon photomultipliers

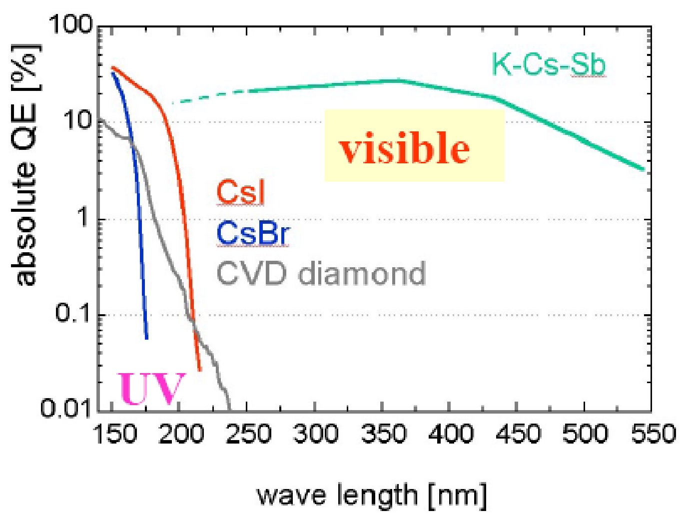
Photodetectors

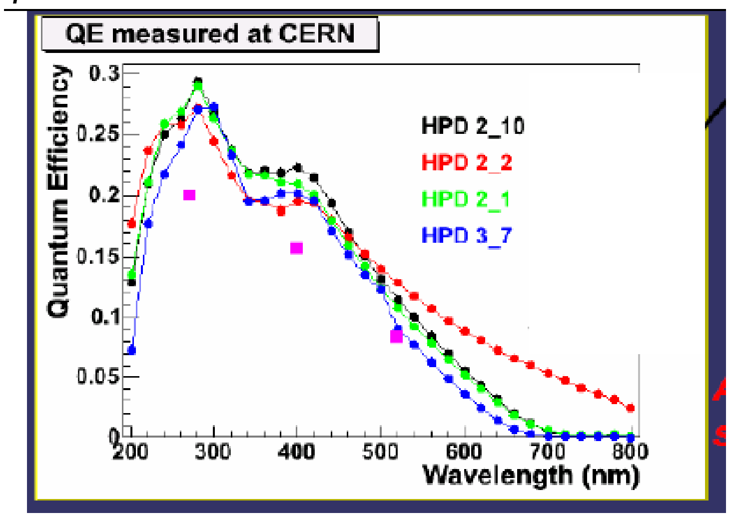
- Photon Conversion:
  - Photoelectric Effect : Photon energy to be above the ‘work function’ (**Einstein : Nobel Prize in 1921**).
  - Commercial alkaline Photocathodes: Bialkali , Trialkali (S20) , CsI etc. Alkali metals have relatively low ‘work function’.
  - There are also gases where the photon conversion takes place.
  - Different photocathodes are efficient at different wavelength ranges.
  - Quantum Efficiency (QE) : Fraction of photons converted to electrons

- Photon detection efficiency (PDE): Effective QE, that is measured

  $PDE = QE \times P_{trigger} \times \varepsilon_{PackingGeometry}$

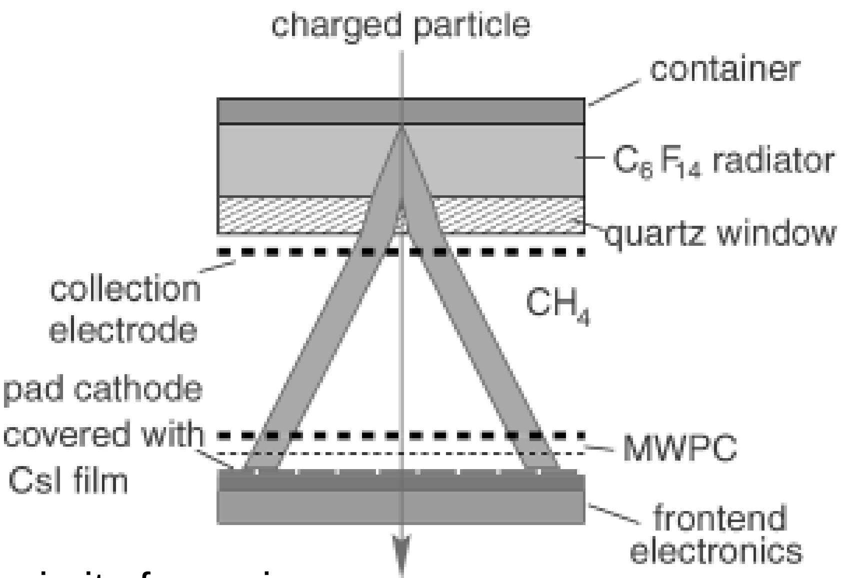
PackingGeometry refers to Active area fraction, for example due gaps between pixels
$P_{trigger}$ refers to where the electron is produced, for example in an SiPM.





Examples of S20- photocathodes

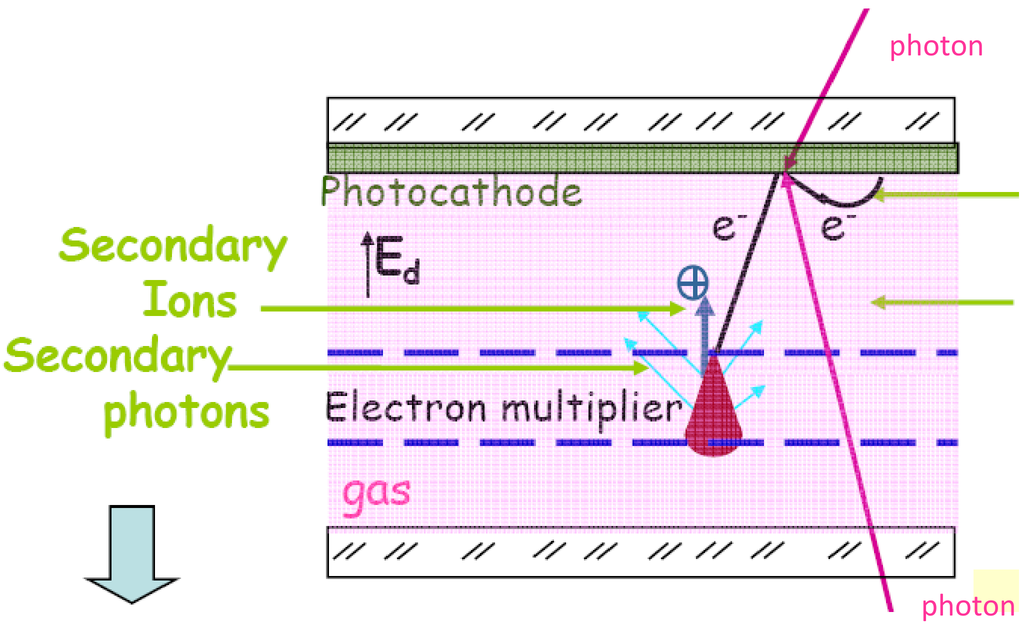
Photodetector with CsI photocathode



Proximity focussing

- Used in ALICE experiment at CERN: ALICE-HMPID
- Thickness of :
  - radiator = 10mm
  - quartz window= 5mm
  - MWPC gaps= 2 mm
  - Wire cathode pitch=2 mm
  - Anode pitch= 4 mm
  - anode diameter= 20 micron
  - pad size = 8*8 mm^2

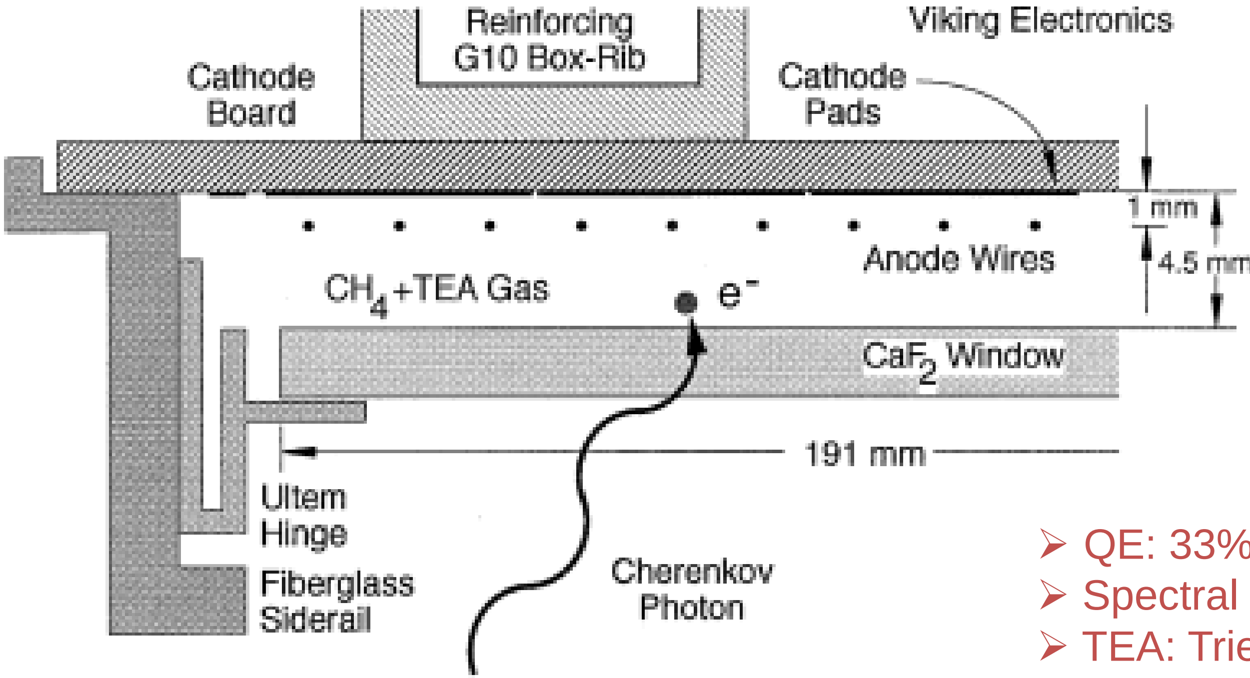
- Total detector area: 12 m^2
- Open geometry: using MWPC



Typical gain: 10^4

cause feedback: leading to loss of original signal info.

Gas Based Photon Detectors



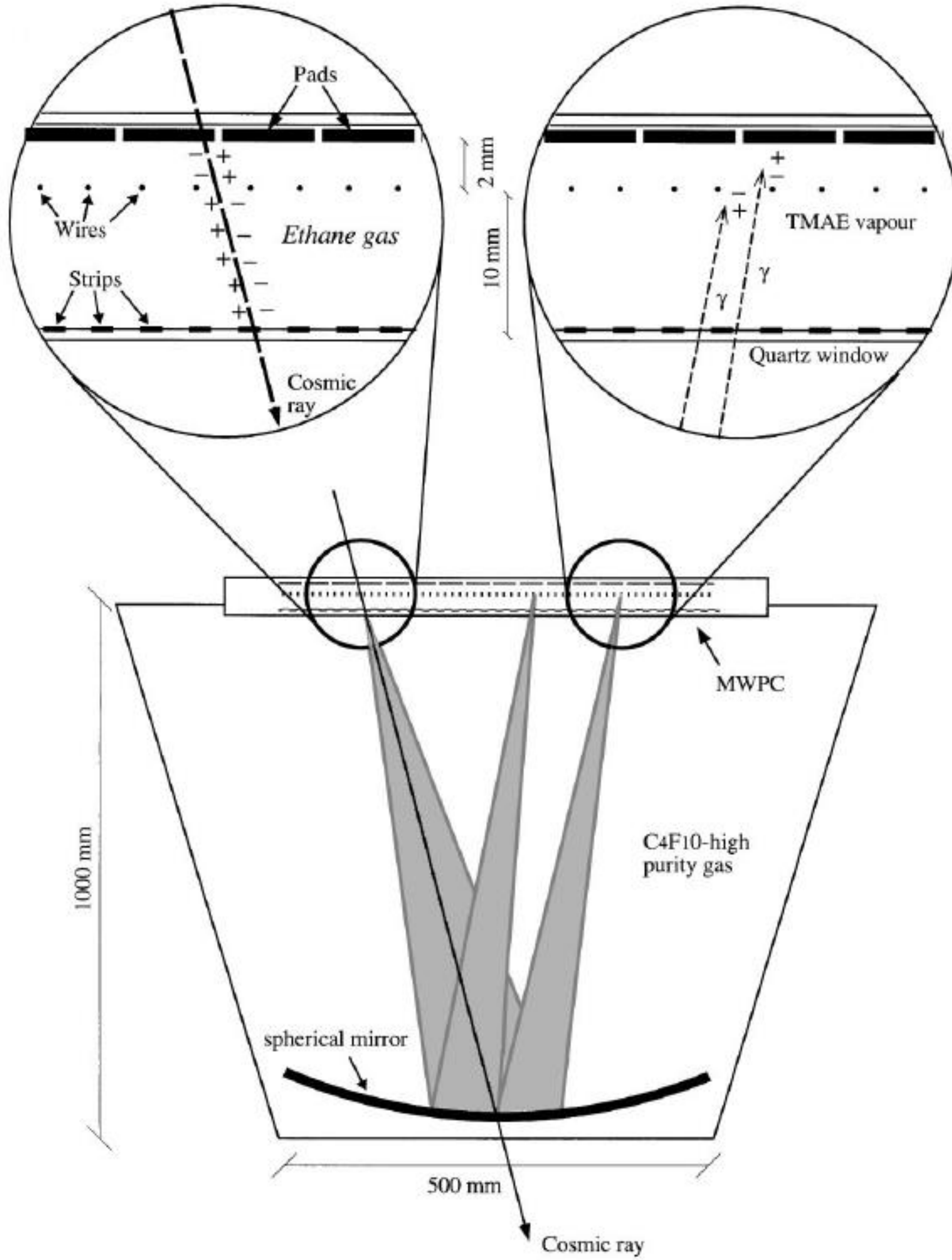
- QE: 33% at 150 nm
- Spectral Range: 135-165 nm
- TEA: Triethylamine

Photon Detector of the CLEO-III Cherenkov detector

- photon passes through the CaF_2 and converts to photoelectron by ionizing a TEA molecule.
- The photoelectron drifts towards and avalanches near the anode wires, theirby inducing a charge signal on the cathode pads.

Balloon Experiment:
RICH detector

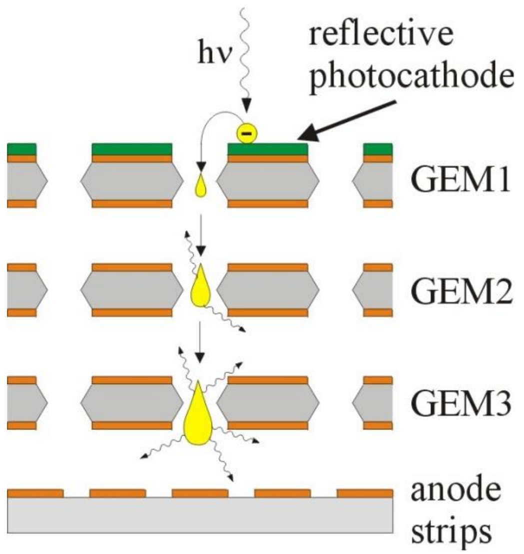
CAPRICE Experiment



TMAE:
(tetrakis(dimethylamino)
ethylene)

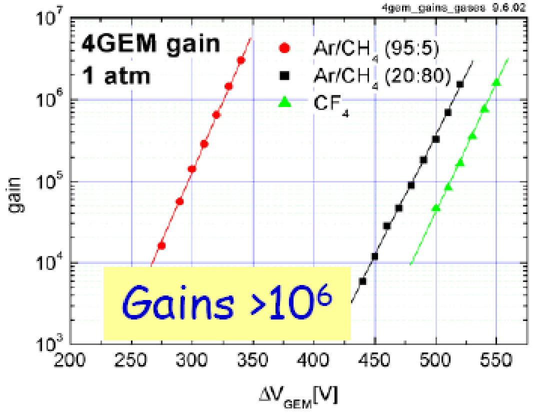
Recent Developments: Gas Based Photodetectors

GEM: Gas Electron Multiplier



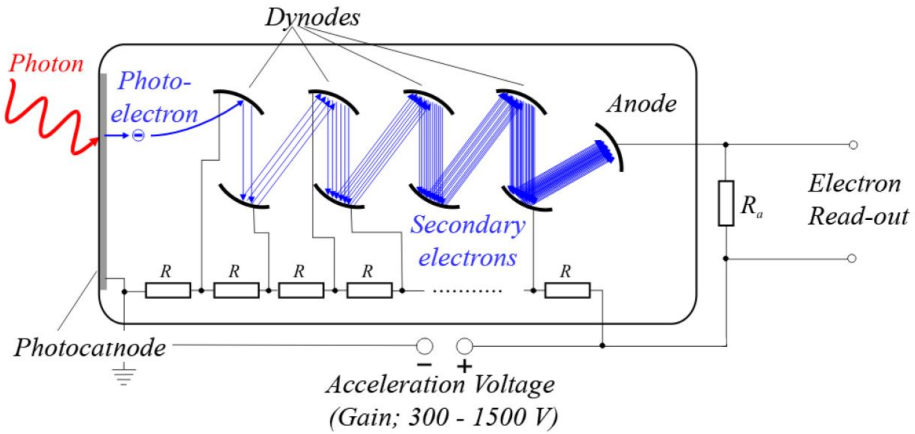
GEM with semi-transparent Photocathode (K-Cs-Sb)

- Photon and ion feed back reduced.
- Gated operation to reduce noise.
  (no readout outside a 'time window of signal')
- For now only closed geometry (in sealed tubes): Reduced fraction of useful area for photon detection (Active Area Fraction) compared to open geometry.

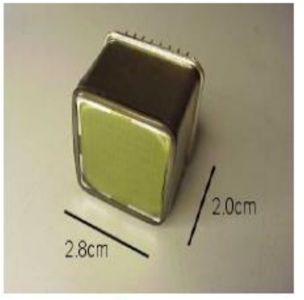


Vacuum Based Photodetectors

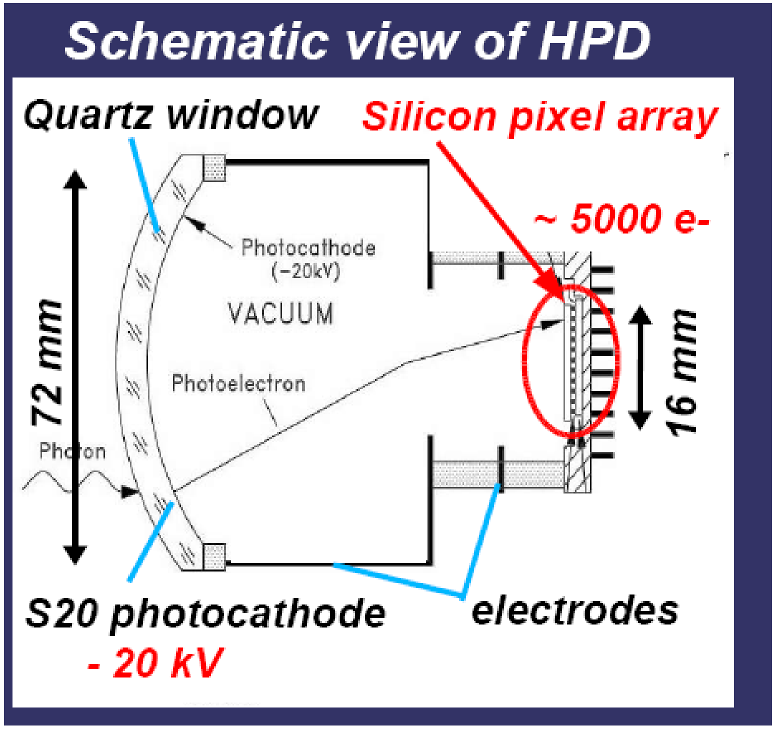
PMT schematic:



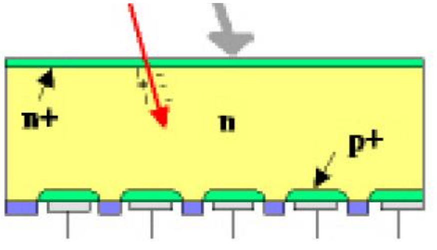
PMTs



MAPMT



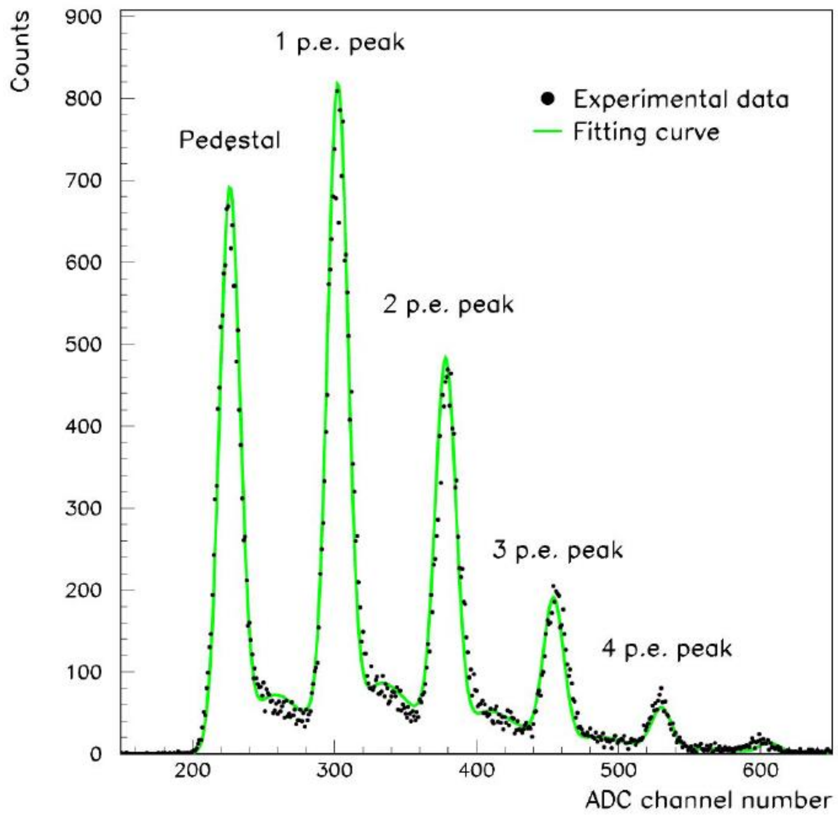
- PMTs Commercially produced: more info in www.sales.hamamatsu.com

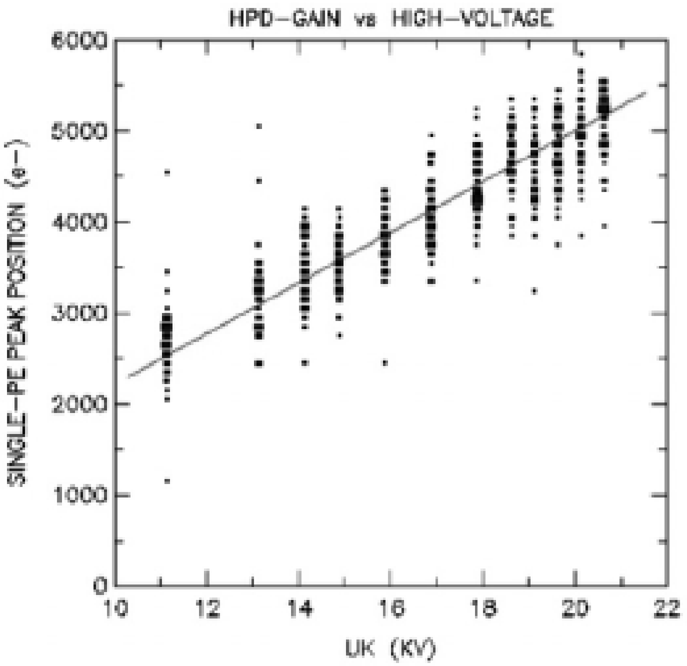


Silicon detector of HPD

HPD

Features of HPD





Signal pulse height spectrum of a 61-pixel HPD
Illuminated with Cherenkov photons

- Typical gain = 5000 (approx)
- Very low noise: typically, only a few hundred electrons

Features of the PMTs and HPDs

- PMT:
  - Typical Gain of MAPMT 300 K.
  - Excellent time resolution: ~ 150 ps
    (Ex: used in underwater Cherenkov detectors).
  - Active area fraction: 40 % - 75% : Fraction of effective detection area.
    This can be Improved with a lens, at the cost of a few photons at lens surface
  - Recent developments: Flat panel pmts with 89 % active area fraction.
    Recent photocathodes with >45% QE at 400 nm

- HPD:
  - Typical gain 5K, but quite uniform across different channels.
  - Excellent Single photon identification capability.
  - Active area fraction: 35→ 76 %

Comparison of photodetectors

- Choice of photodetector depends on the design of the Cherenkov detectors and constraints on cost etc.
- Gaseous:

Issues:

- Related to photon and ion feed back and high gains at high rate.
- Detection in visible wavelength range (for better resolution)
- There have been recent improvements in these areas

Advantages:

- Can operate in high magnetic field
- Lower cost for large size detectors compared to vacuum based detectors

- Vacuum based:

Issues:

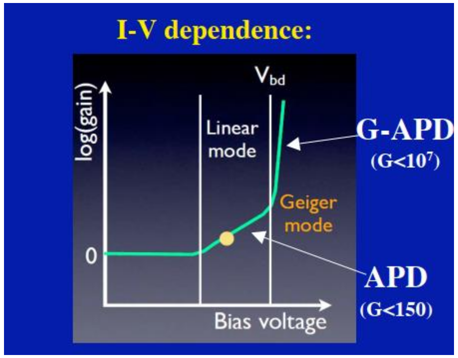
- Sensitivity to magnetic field
- cross talk between readout channels in case of PMTs
- Active Area Fraction
- There have been recent improvements in these areas

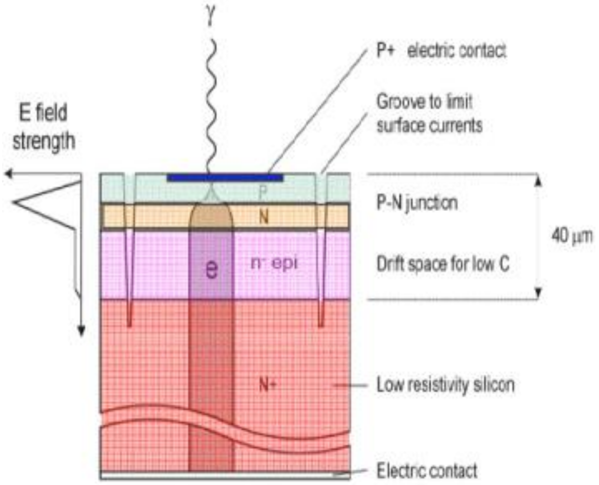
Advantages:

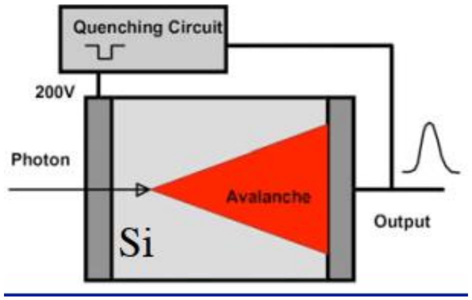
- Can easily operate at high rate (eg. LHC rates and higher).
- Operates also in visible wavelengths. (reduced chromatic error)
- Ease of operation at remote locations: underwater, in space etc.
- HPD: uniform gain over large number of tubes and small noise.

- Other Types and new developments: **Silicon photomultiplier, MCP etc.** for single photon detection

Recent Developments: Silicon Photomultipliers (SiPM)







- ➢ The Geiger mode operation needed for single photon detection

S10362-33 -059C MPPC

QE at 440nm (Silicone)	> 60 %
$P_{trigger}$ - trigger probability	80 - 90 %
Geometrical fill factor	78.5 %
PDE = Total fraction of detected photons (includes after-pulses & cross-talk !!!) *	~ 52 % @ 440 nm (HPK quote)
After-pulsing total rate	~ 20%
Operating voltage	70 ± 10 V
Terminal capacitance	320 pF
Pixel size	100 μm x 100 μm
Overall size & Sensitive size	~ 3.85 mm x 4.35 mm & 3 mm^2
Total Gain	~ 2.4 x 10^6
Noise rate (Single photoelectron threshold) *	~ 8 MHz
Transit time spread σ_{TTS}	< 100 ps

- ➢ Time resolution ~ < 100 ps.
- ➢ Works in magnetic field
- ➢ gain ~ 10^6
- ➢ Electric field ~ 3-5 x 10^5 V/cm

- ➢ Radiation hardness: sufficient for many applications, especially when single photon detection is not needed.

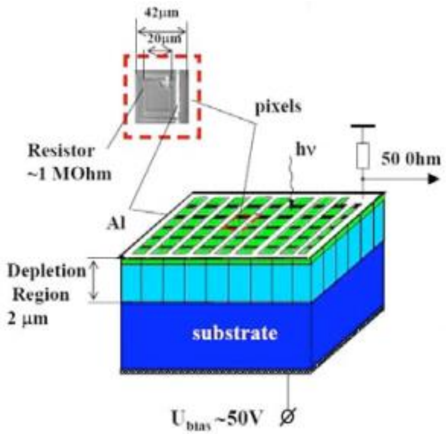
  Tests being done for single photon detection and in very high luminosity environments

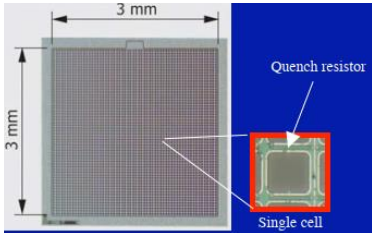
- ➢ Reducing noise levels for single photon detection is still an issue and it is being worked upon.

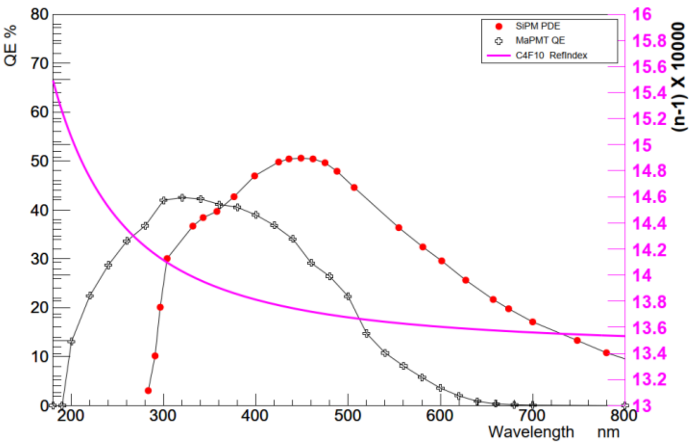
  One option: operate at very low temperatures to get a dark count rate < 100 kHz/mm^2

Recent Developments: Silicon Photomultipliers

Si-PM array







- Photon detection efficiency of SiPM is better than that of MaPMTs

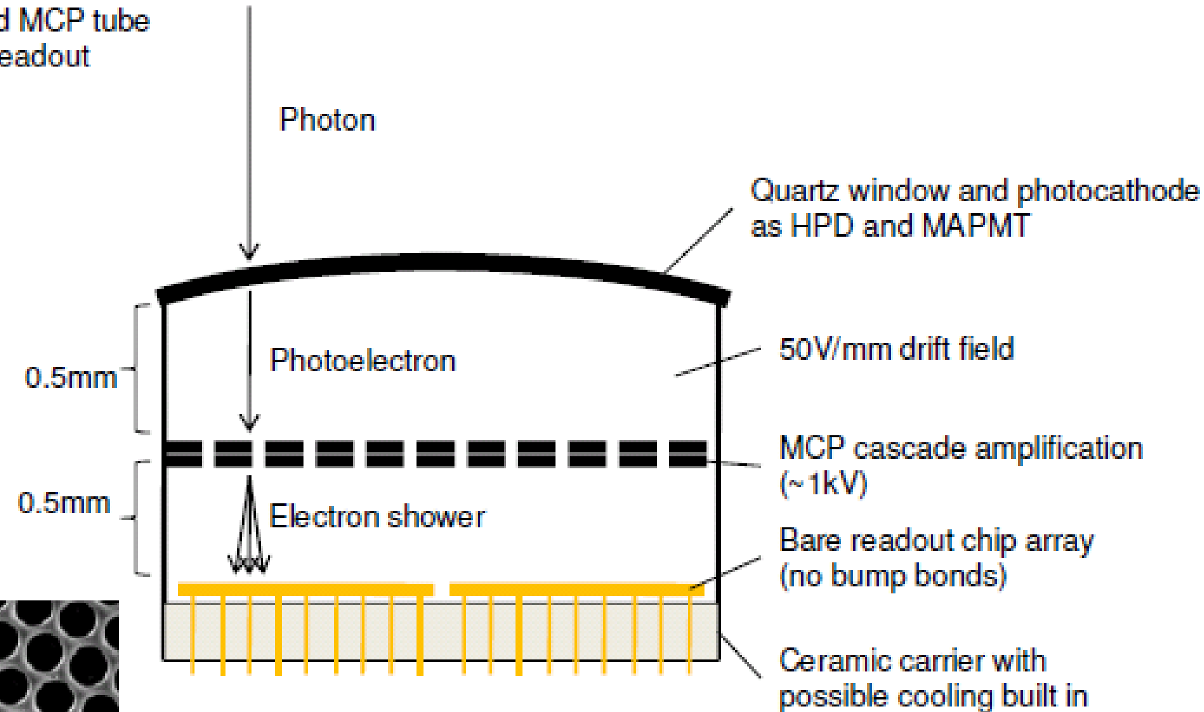
- Typical time resolution of SiPMs (<100 ps) is better than that of MaPMTs (150 ps)

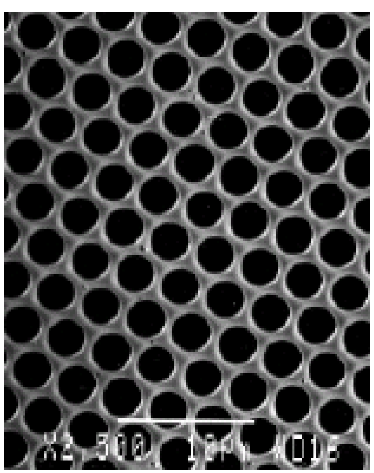
- A very active R & D is in progress to improve the properties of SiPMs.

Further info:
Sensors 2019,19(2),308

New Developments: Micro Channel Plate (MCP) Photon Detectors

Proximity focused MCP tube with 55um pixel readout

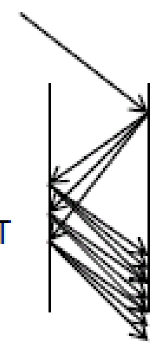




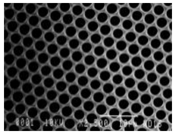
10um pores in an MCP

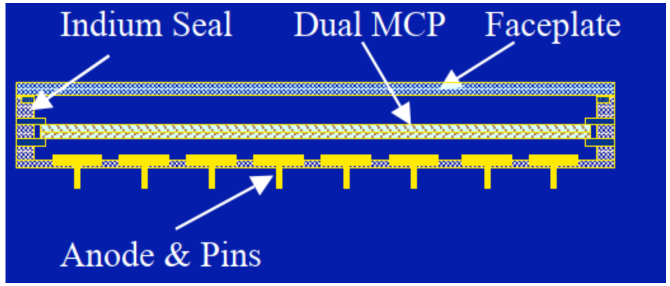
Tuning the lower drift field allows the electron shower profile to be well controlled

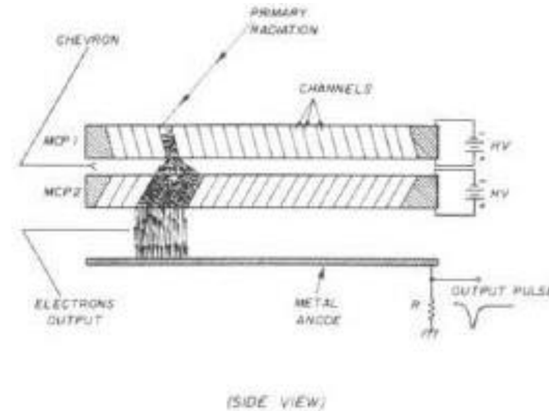
Cascade amplification similar in principle to a PMT



New Developments: Micro Channel Plates (MCP)

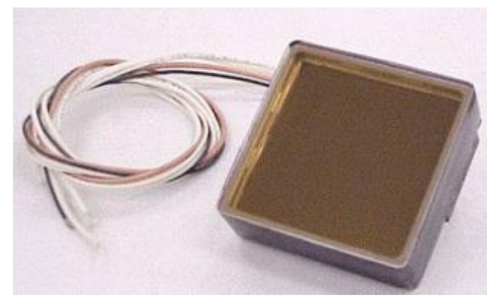






Typical Size:

- 2 mm thickness,
  51 mm X 51 mm active area.
- 10 micron pores separated by 15 microns
- Chevron: 8 degree tilt : To increase the gain and reduce ion-feed back
- Gain: ~ $5 * 10^5$
- Typically ~ 1000 channels per MCP.

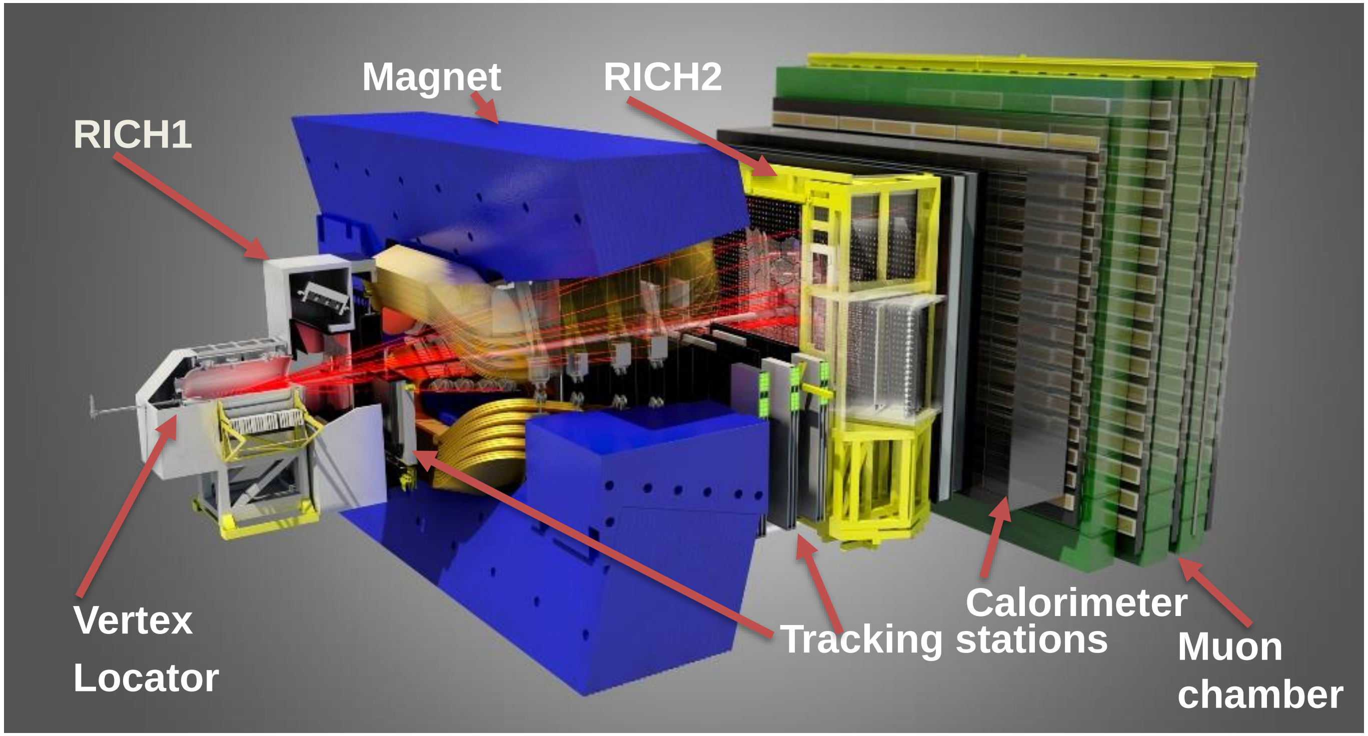


- Measure Space and time of the hits.
- Manufactured by industry (*Photonics for example*).
- Resolutions: Space: ~100 microns, Time: ~ 50 - 100 psec.
- Short flight path of photoelectrons: Resistant to magnetic fields up to 0.8 Tesla.
- Can work at 40 MHz readout rate.
- Can detect single photons (No noise from 'first dynode' as in MAPMT).
- Fast 'ageing' at large luminosity (eg: LHC) is an issue. However some solutions are being developed.

Examples of Cherenkov detector systems

- RICH in LHCb at CERN
- DIRC in BABAR at SLAC
- IceCube in Antartica

The LHCb Experiment



From 2015:

- pp : $\sqrt{s}$ = 13 TeV

Before 2015:

- pp : $\sqrt{s}$ = 8 TeV

Before 2012:

- pp : $\sqrt{s}$ = 7 TeV

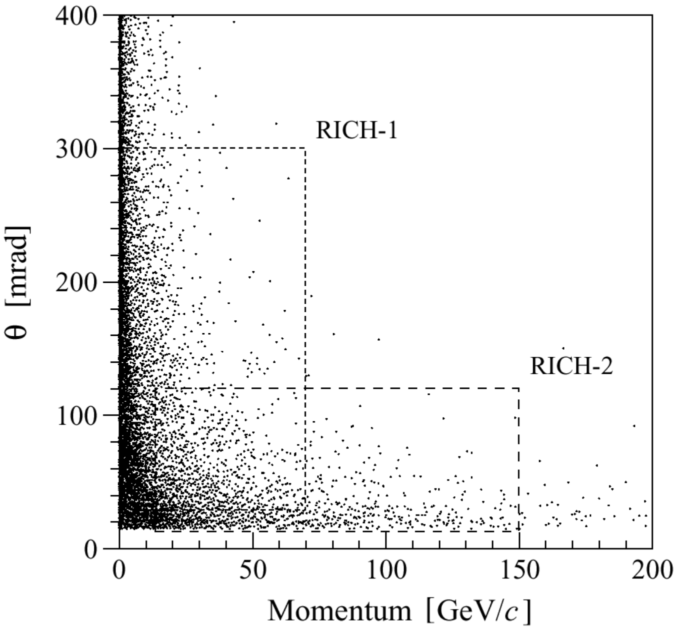
$2 < \eta < 5$, Forward spectrometer.
Overall acceptance ~ 10→300 mrad, Momentum range : 2-100 GeV/c

- Precision measurement of B-Decays and search for signals beyond standard model.

- Two RICH detectors cover the full momentum range .
  Until 2014, it had aerogel, C_4F_{10} gas and CF_4 gas as radiators.

LHCb-RICH original Design

RICH1: Aerogel L=5cm p:2→10 GeV/c
n=1.03 (nominal at 540 nm)
C_4F_{10} L=85 cm p: < 70 GeV/c
n=1.0014 (nominal at 400 nm)
Upstream of LHCb Magnet
Acceptance: 25→250 mrad (vertical)
300 mrad (horizontal)
Gas vessel: 2 X 3 X 1 m^3



Polar angle of charged tracks vs. their momentum

RICH2: CF_4 L=196 cm p: < 100 GeV/c
n =1.0005 (nominal at 400 nm)
Downstream of LHCb Magnet
Acceptance: 15→100 mrad (vertical)
120 mrad (horizontal)
Gas vessel : 100 m^3

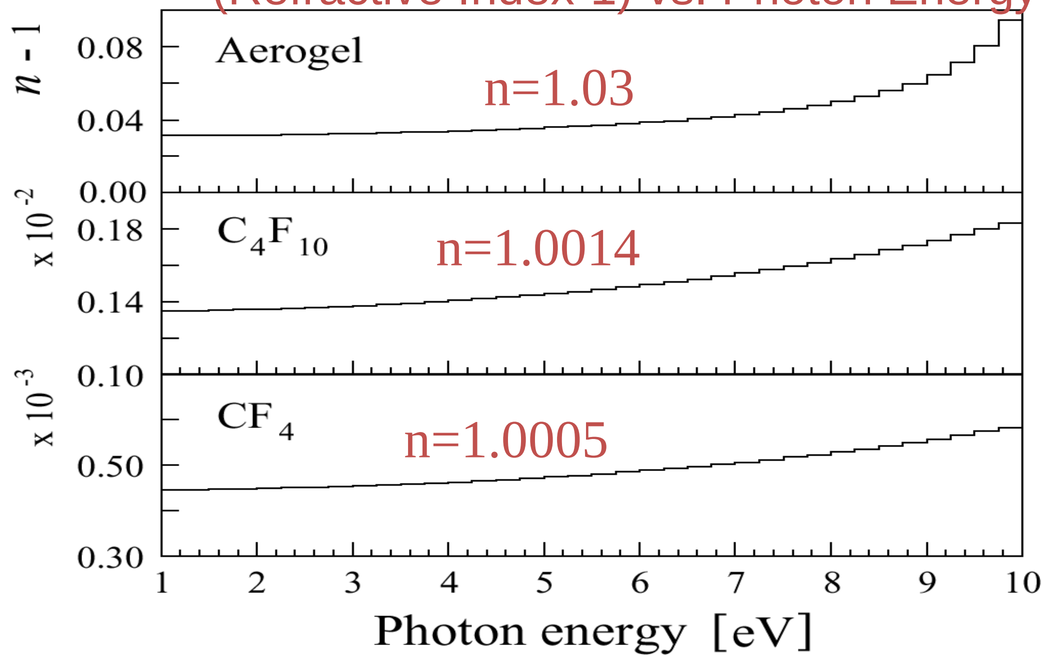
- Original version used HPDs as photon detectors.
- The design was upgraded in the last decade.
  At present, it uses MaPMTs as photon detectors.
  The aerogel was removed.

LHCb-RICH Specifications

RICH1: Aerogel 2→10 GeV/c
C_4F_{10} < 70 GeV/c

RICH2: CF_4 <100 GeV/c.

(Refractive Index-1) vs. Photon Energy

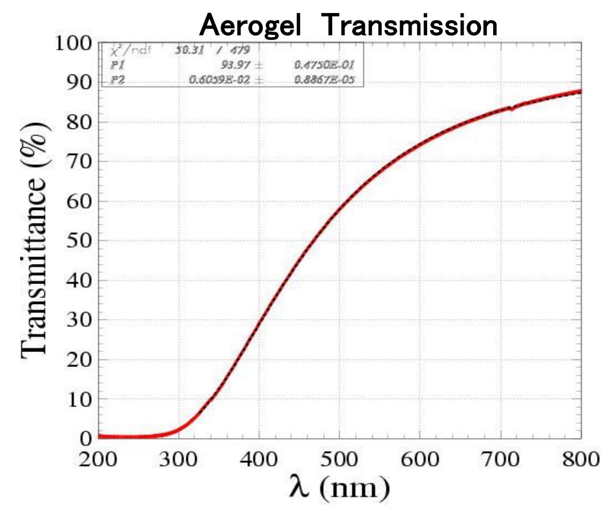


	Aerogel	C_4F_{10}	CF_4	
L	5	86	196	cm
θ_c^{max}	242	53	32	mrad
π_{Th}	0.6	2.6	4.4	GeV/c
K_{Th}	2.0	9.3	15.6	GeV/c

Aerogel: Rayleigh Scattering

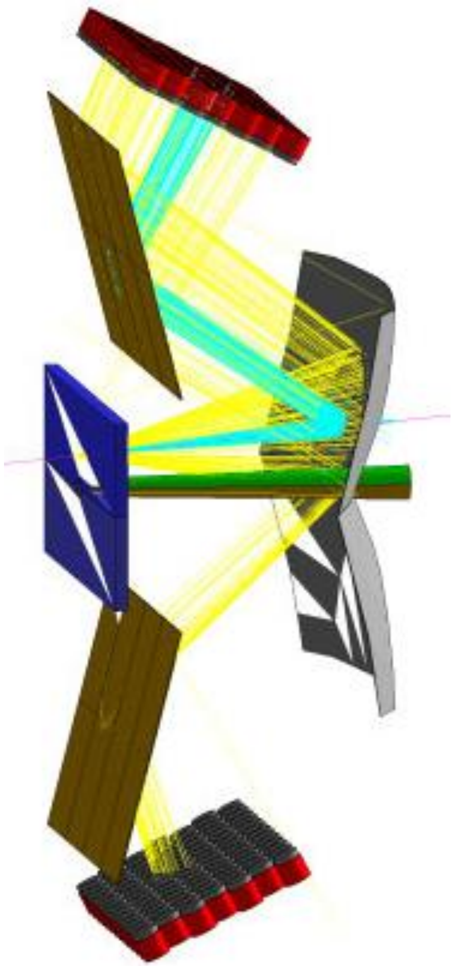
$$T = A\, e^{(-C\, t/\lambda^4)}$$

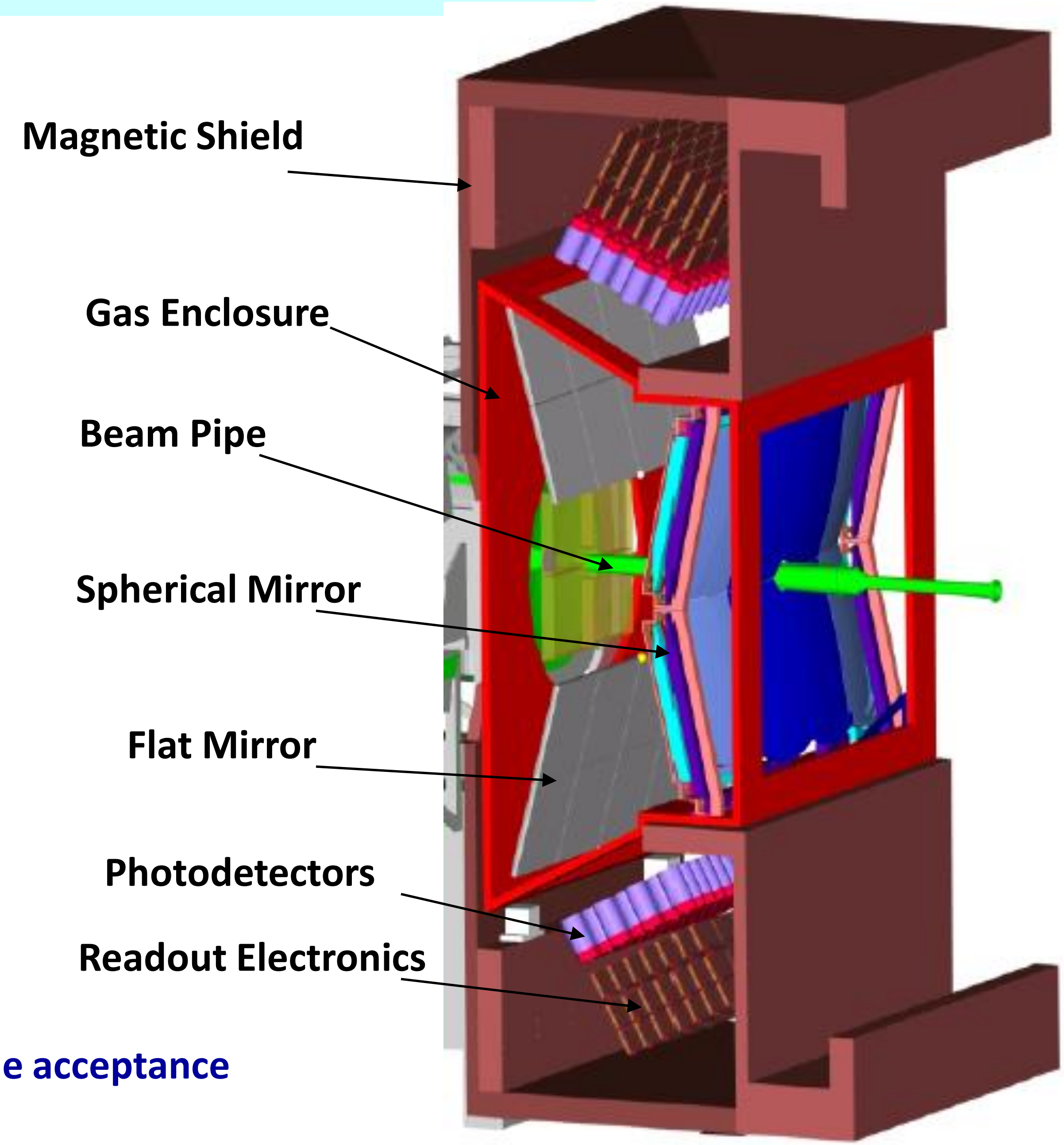
Typically: A= 0.94, C =0.0059 mm^4 /cm



LHCb- RICH1 SCHEMATIC

RICH1 OPTICS

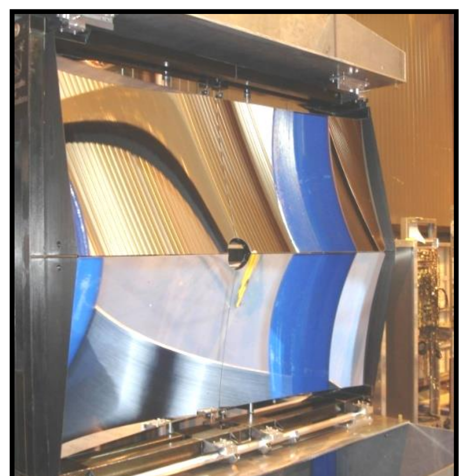




- Spherical Mirror tilted
  to keep photodetectors outside acceptance
  (tilt ~ 0.3 rad)

RICH1 Photos

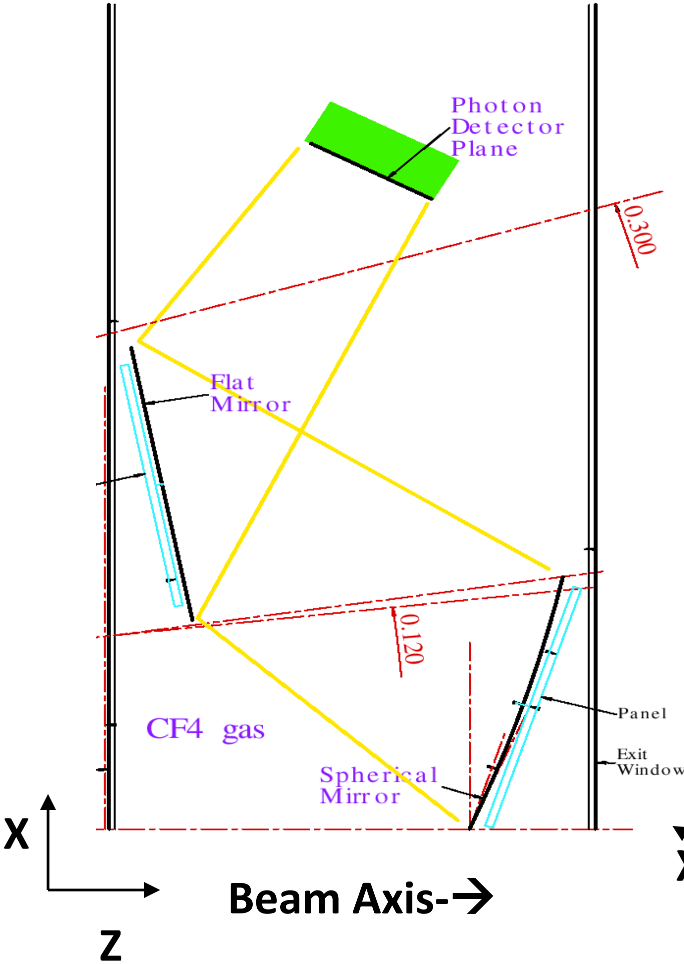
RICH1-HPDs

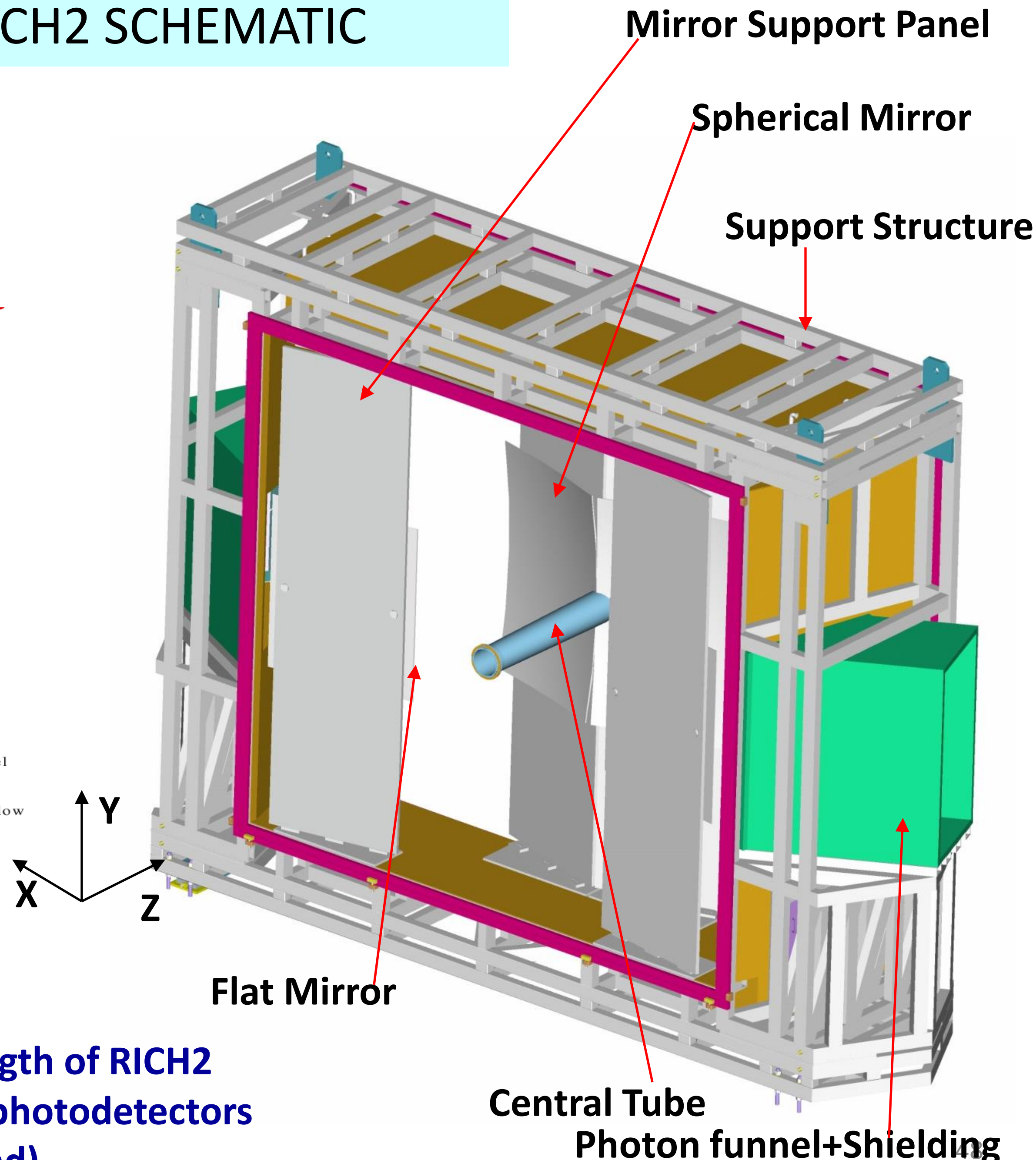


RICH1 mirrors

LHCb-RICH2 SCHEMATIC

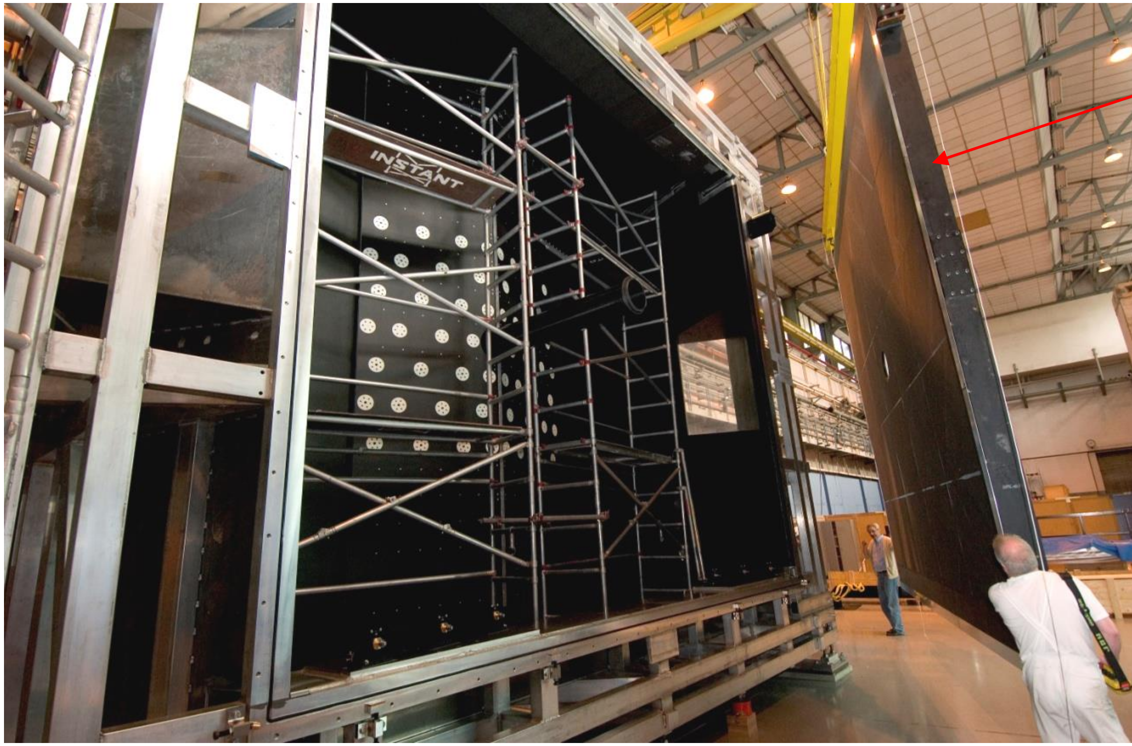
RICH2 Optics Top View





- Plane Mirrors to reduce the length of RICH2
- Spherical mirror tilted to keep photodetectors outside acceptance.(tilt=0.39 rad)

LHCb- RICH2 STRUCTURE

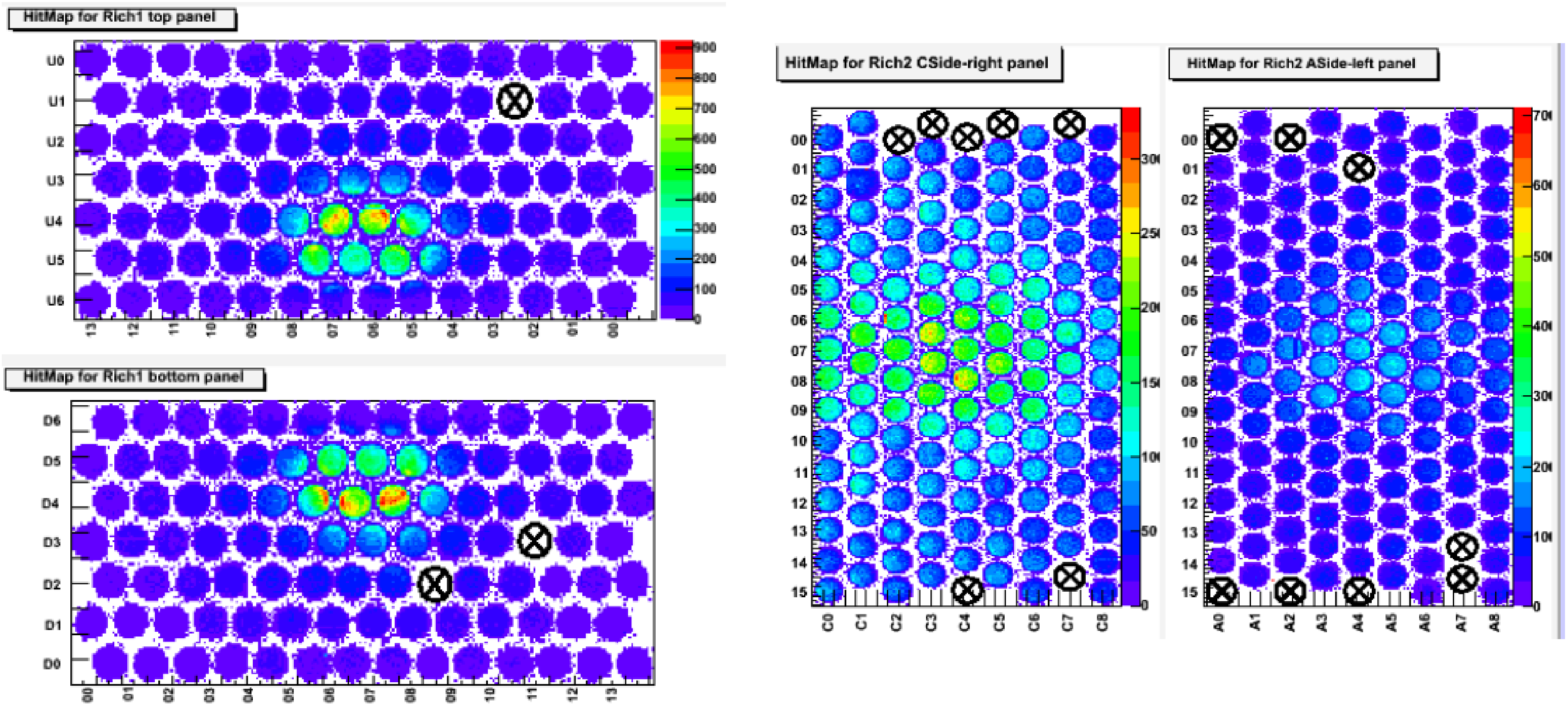


Entrance Window
(PMI foam between two
carbon fibre epoxy Skins)

RICH2

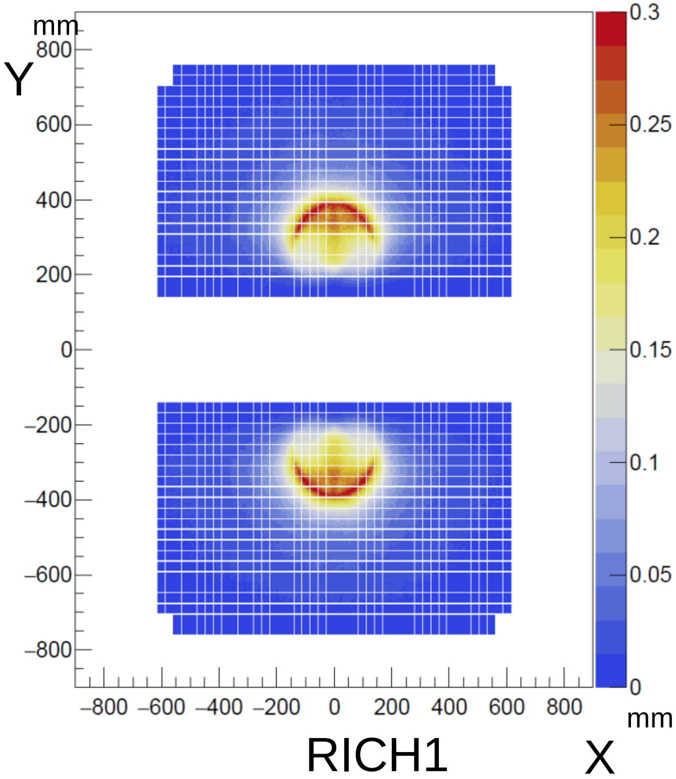
Typical Hits on LHCb-RICH HPDs

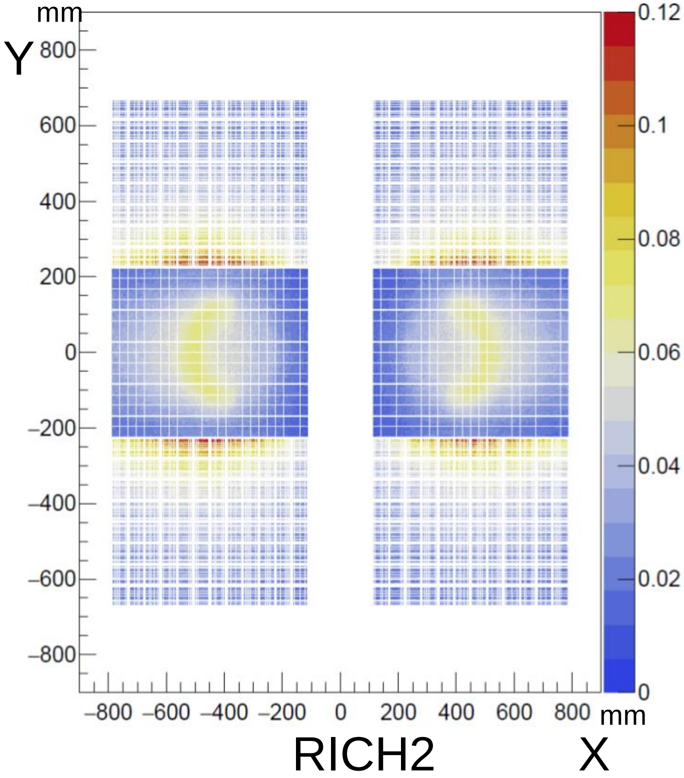
Early data in 2010



- ➢ LHCb-RICH collected data during 2010-2018 (RUN1, RUN2).
- ➢ The signals from the HPDs are subjected to time and space alignment.

RICH data from simulation for RUN3 in 2022

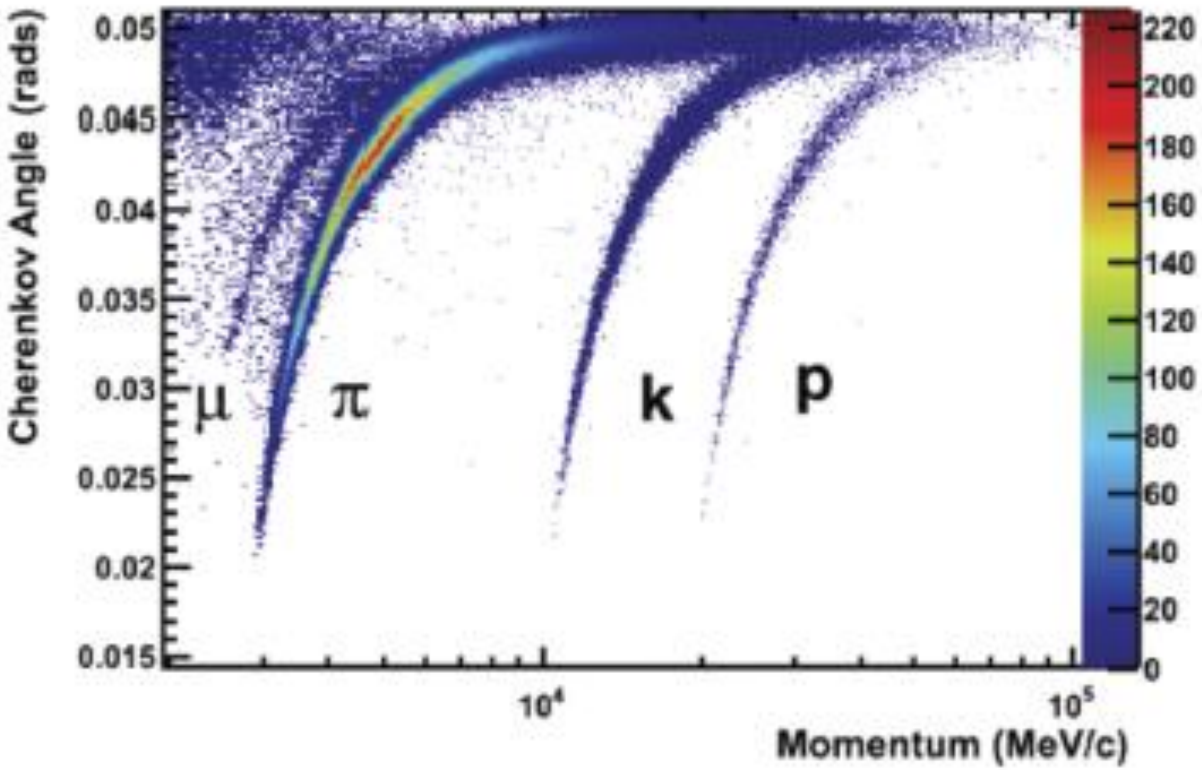




Y vs X of the hit coordinates on the detector planes, from simulations.

Performance of LHCb RICH

- From isolated Cherenkov rings from RICH1 in Real Data



Compare with the expectations plotted earlier.

LHCb-RICH performance from simulations: RUN2 and RUN3

RUN3 starts in 2022

Examples of Cherenkov Angle Resolutions and yields

Resolution (in mrad)	RICH1-2015 HPD, C_4F_{10}	RICH1-upgrade MaPMT, C_4F_{10}	RICH2-2015 HPD, CF_4	RICH2-upgrade MaPMT, CF_4
Chromatic	0.84	0.58	0.48	0.31
Pixel	0.60, PSF=0.86	0.44	0.19 PSF=0.29	0.19
Emission point	0.76	0.37	0.27	0.27
Overall Overall+Track	1.60 1.65	0.78 0.88	0.65 0.76	0.45 0.60
Yield	**32**	**42**	**24**	**22**

- Yield: Mean Number of RICH hits per saturated track (Beta ~1).

- Chromatic: From the variation in refractive index.
- Emission Point: Essentially from the tilt of the mirrors.
- Pixel Size: From the granularity of the pixels in HPD/MaPMT
- PSF (Point Spread Function): From the spread of the Photoelectron direction as it travels inside the HPD.

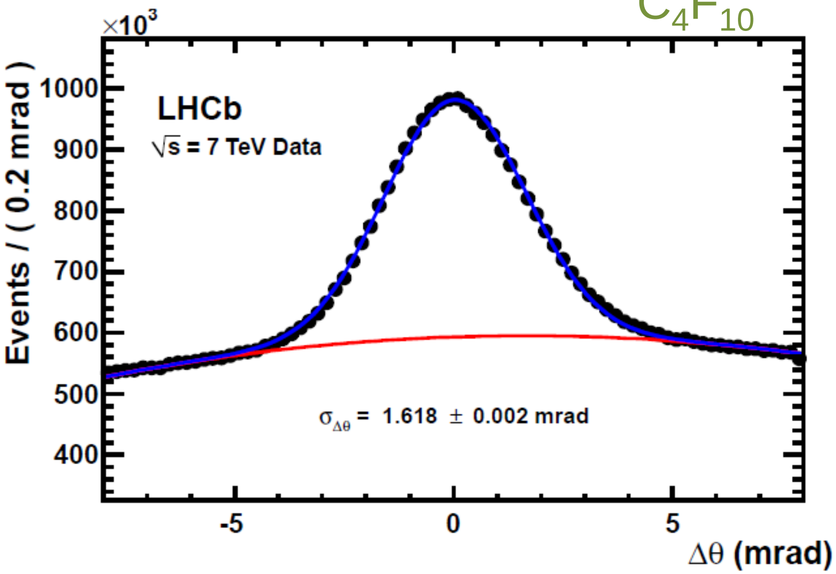
Ref: "*Overview of LHCb RICH Upgrade*", S.Easo, Nucl.Inst.Meth. A 876 (2017) 160-163

LHCb-RICH resolution

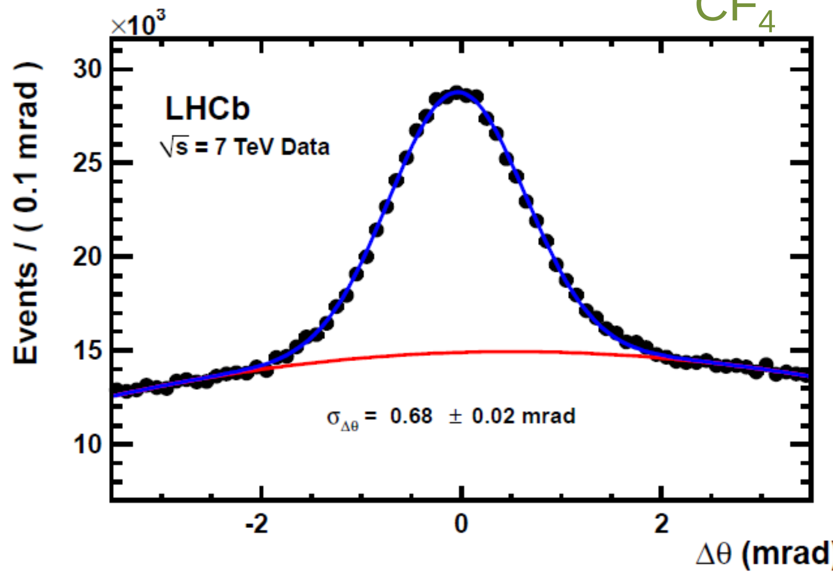
Single photon resolutions

Real Data 2011:

C_4F_{10}



CF_4



From simulation in 2011:
$\sigma_{\Delta\theta}$ = 1.53 mrad

From simulation in 2011:
$\sigma_{\Delta\theta}$ = 0.68 mrad

LHCb-RICH detector: data taking

- The refractive index (n) is dependent on
the pressure(P) and temperature (T) of the gas radiator.

$$(n-1) \quad \alpha \quad P/T$$

Hence it was required to monitor this continuously

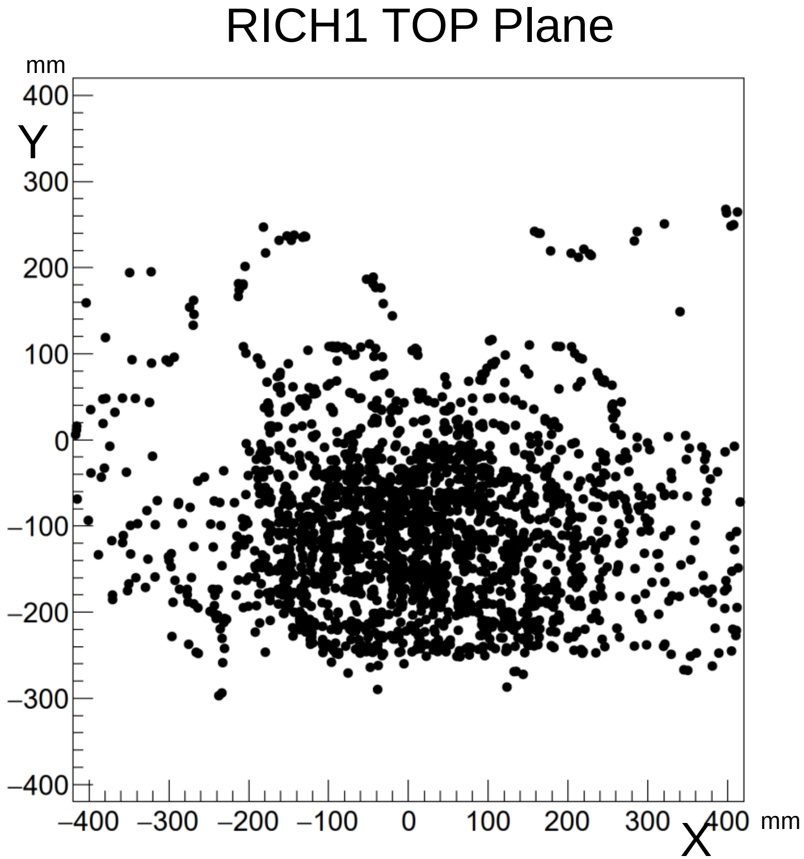
- The CF_4 scintillates. This creates additional photons which go in 4π directions and forms background to the signal photons.
A solution was found by mixing this gas with a small amount of CO_2.
The CO_2 essentially quenches most of the scintillation photons.

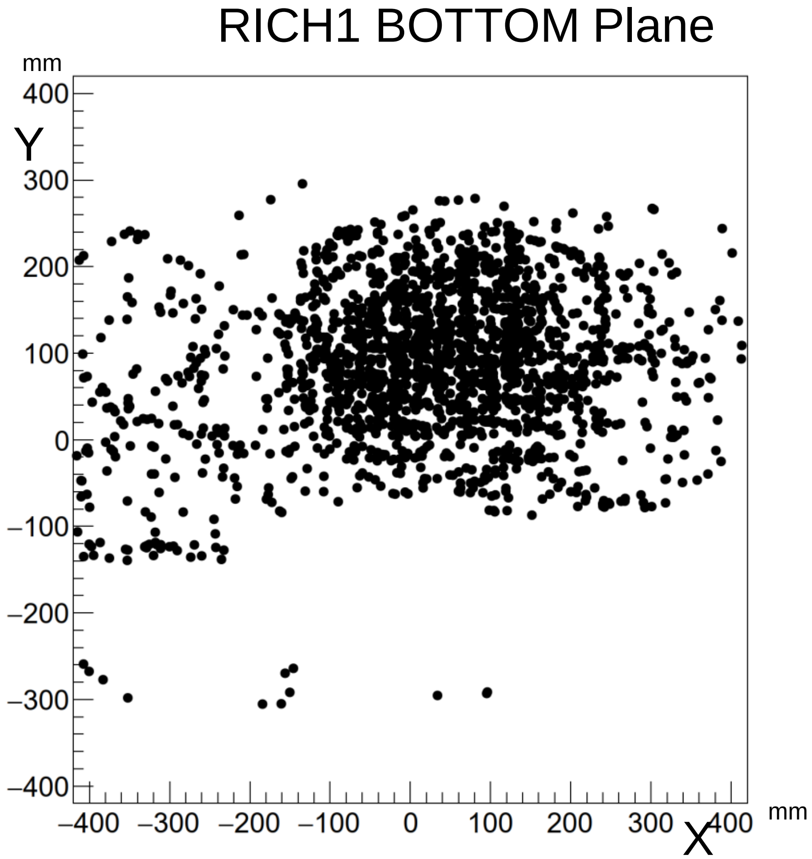
Here the scintillation is from a 'cascade-free' emission. The quenching happens due to a radiationless transition from a donor molecule to an acceptor molecule with a subsequent transmission in infrared wavelengths.

Ref: Nucl. Inst. Meth. A 791 (2015) 27-31

RICH data from simulation for RUN3

Singe event





- Y vs. X of the hit coordinates in the central region of the detector plane in a single event in RICH1.

- *Number of tracks ~ 215*
- *Number of RICH1 hits ~ 5300*

Pattern Recognition in accelerator based Cherenkov Detector

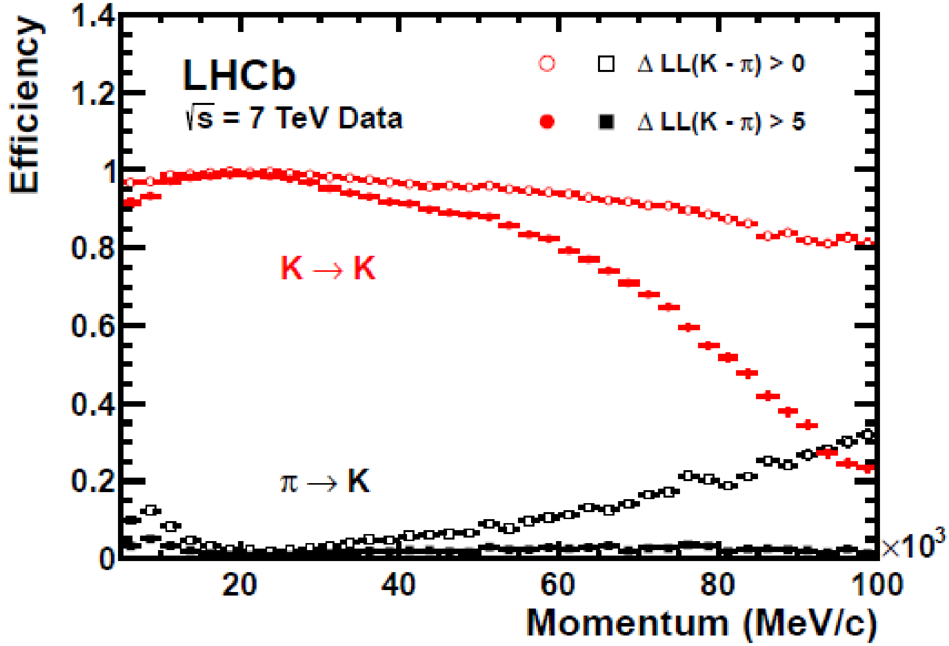
- Events with large number of charged tracks giving rise to several overlapping Cherenkov Rings on the photo detector plane.
  Problem: To identify which tracks correspond to which hits and then identify the type (e, p, π etc.) of the particle which created the tracks.

- Hough Transform:
  (used by ALICE at CERN)
  - Project the particle direction on to the detector plane
  - Accumulate the distance of each hit from these projection points in case of circular rings.
  - Collect the peaks in the accumulated set and associate the corresponding hits to the tracks.

- Likelihood Method:
  (used by LHCb at CERN)
  - For each of the track in the event, for a given mass hypothesis, create photons and project them to the detector plane using the knowledge of the geometry of the detector and its optical properties. Repeat this for all the other tracks.
  - From this calculate the probability that a signal would be seen in each pixel of the detector from all tracks.
  - Compare this with the observed set of photoelectron signal on the pixels, by creating a likelihood.
  - Repeat all the above after changing the set of mass hypothesis of the tracks. Find the set of mass hypothesis, which maximize the likelihood.

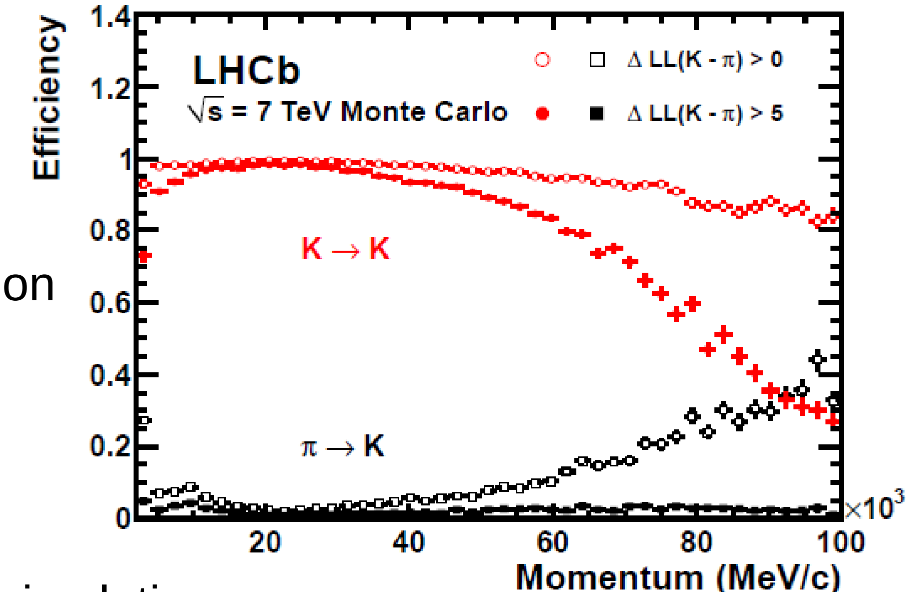
(Ref: R.Forty: Nucl. Inst. Mech. A 433 (1999) 257-261)

LHCb-RICH PID performance



Real data

Simulation

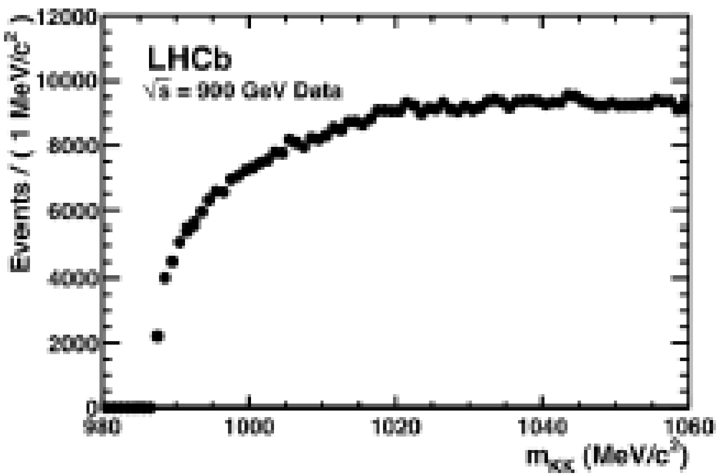


Red: Kaon identification efficiency
Black: Pion mis-identification probability
PID performance in D events (calibration channel)*

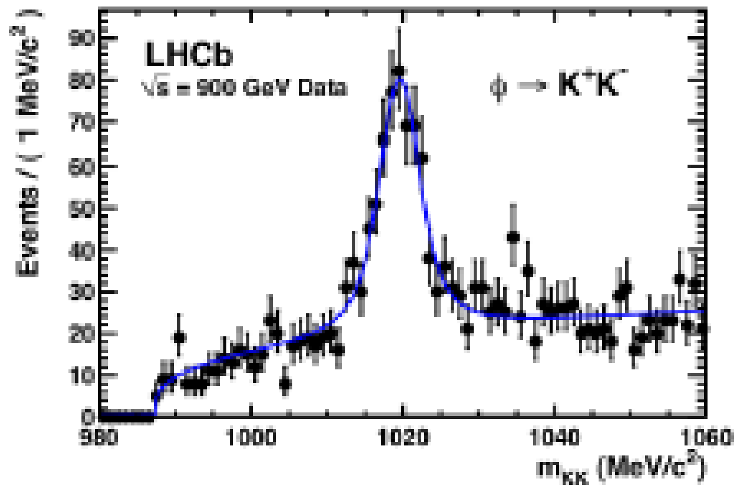
General agreement between real data and simulation

LHCb RICH Data in Physics Analysis

Without RICH data

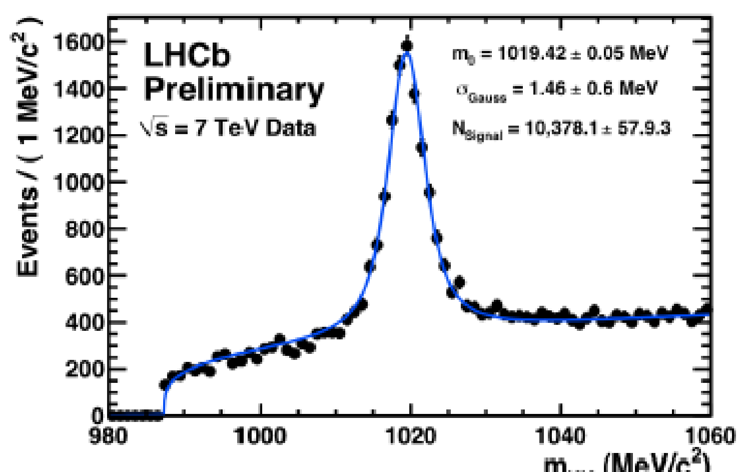


With RICH data



$\phi \rightarrow K^+K^-$

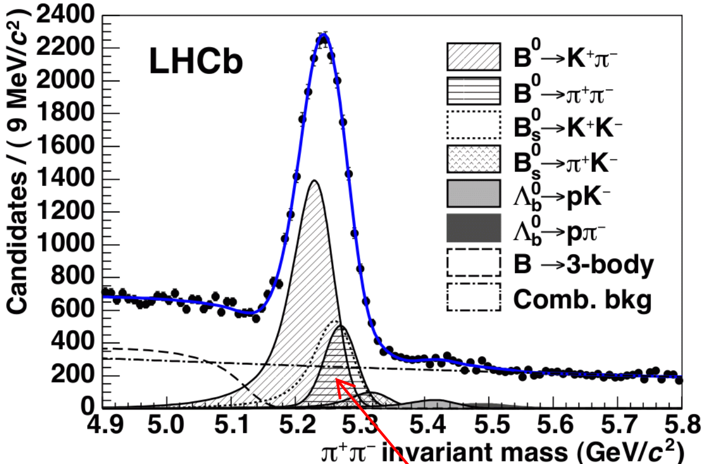
Status in 2011
using RICH data



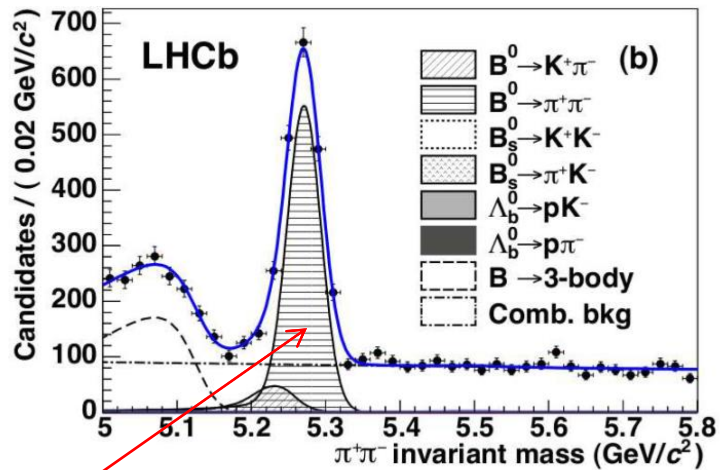
RICH data has been used in Physics analysis

RICH Detectors in LHCb

Real data from 2011



Before RICH PID



After RICH PID

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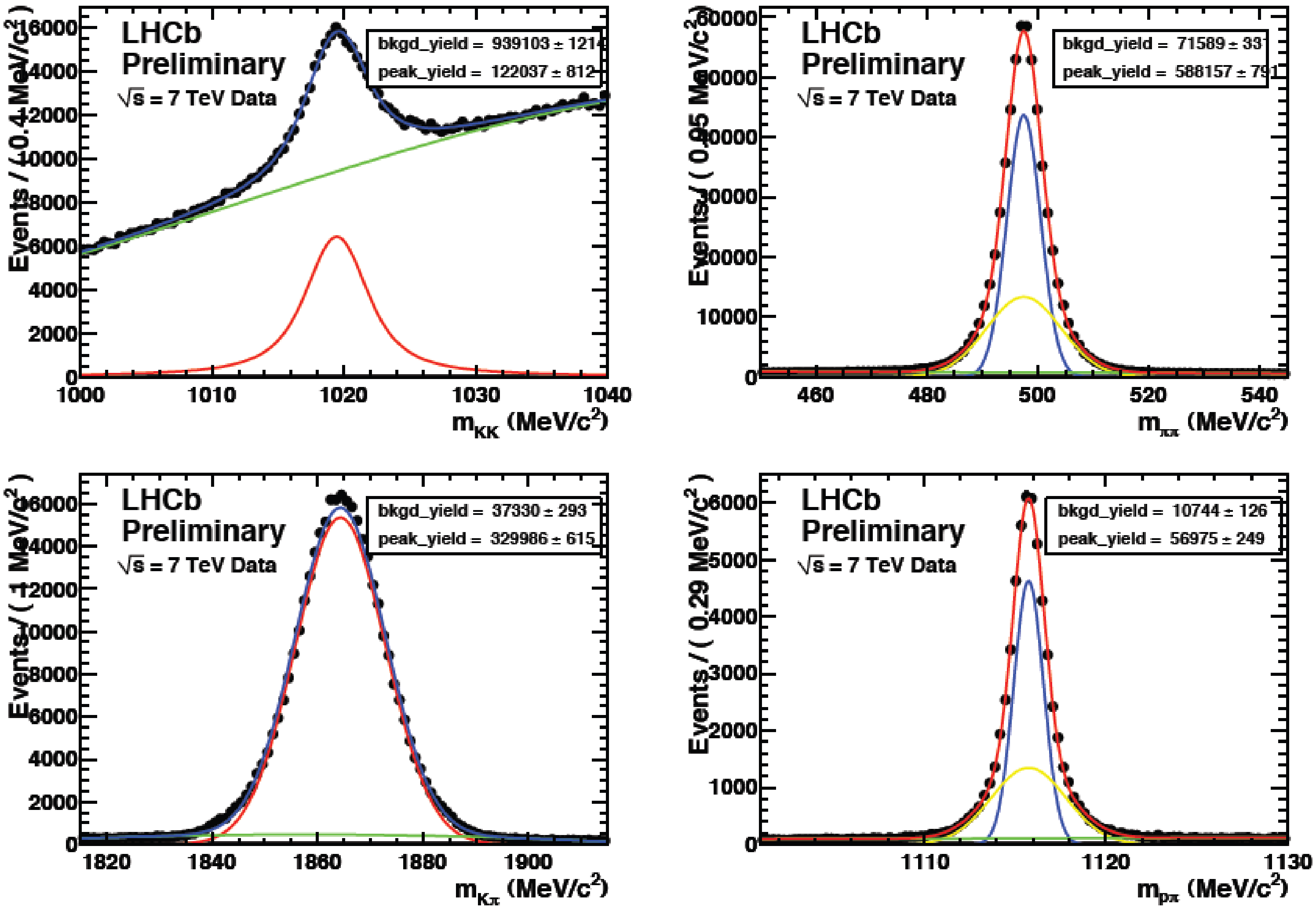
Without RICH PID, the $B^0 \to \pi^+\pi^-$ is completely dominated by $B^0 \to K^+\pi^-$

RICH PID useful for physics analysis

LHCb-RICH data in 2011

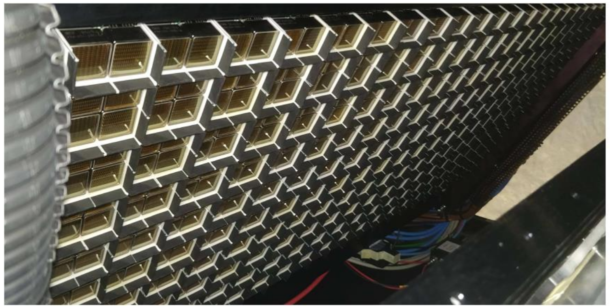


- Examples of signals for $\Phi \rightarrow KK$, $K_s \rightarrow \pi\pi$, $D \rightarrow K\pi$, $\Lambda \rightarrow p\,\pi$ obtained using RICH .
- The data from RICH are used for Physics Analysis.

LHCb-RICH upgrades

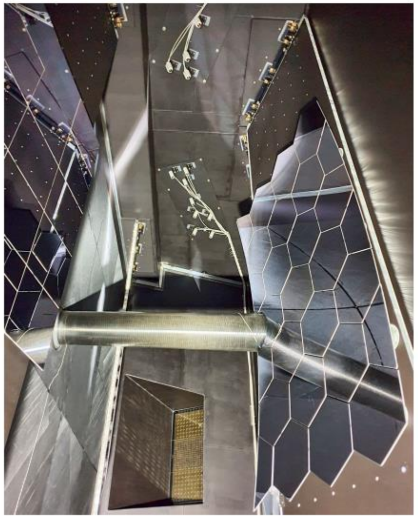
Recent upgrades:

- Installed arrays of MaPMTs as photon detectors.
- Improved the optics geometry for RICH1.
- These improve the resolutions and yields of the photons in the two detectors
- The reconstruction software for PID, is running online



Arrays of MaPMTs in RICH1

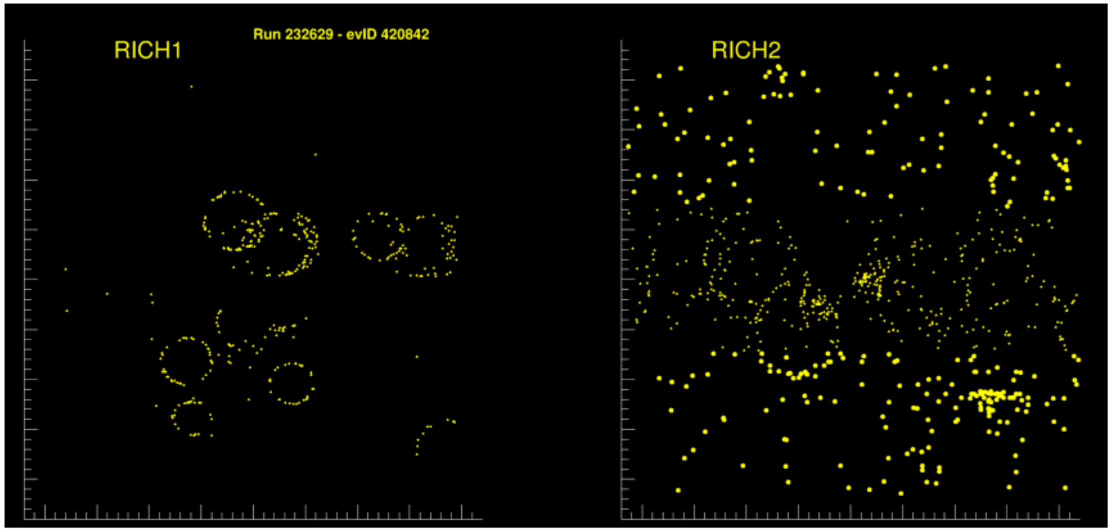
Arrays of MaPMTs in RICH2



RICH2 mirrors

LHCb-RICH upgrades

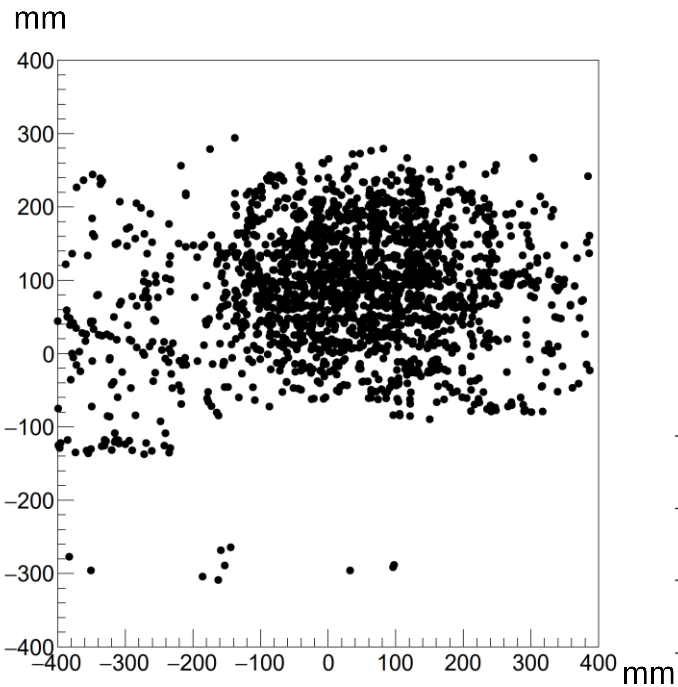
- Starting to collect data with the new system:



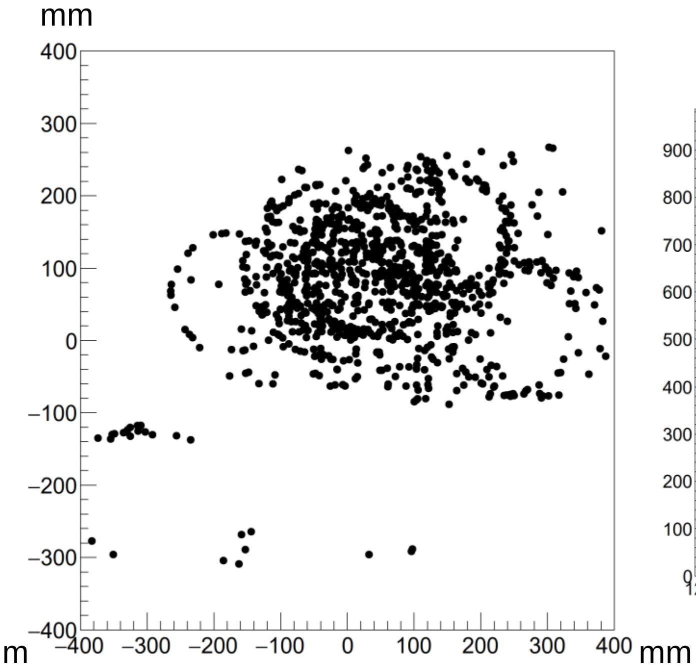
- Future upgrades are also being planned:
  - Usage of fast timing with new readout chips and new types of photons detectors to obtain a resolution below 100 ps
  - Improvement in all other aspects of the system, including the optics
  - Usage of modern GPUs for simulation and reconstruction

LHCb: Hit distribution from simulations

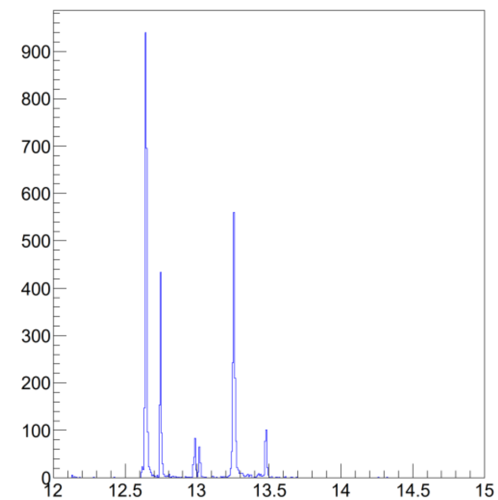
Single event



All time slots 12-15 ns



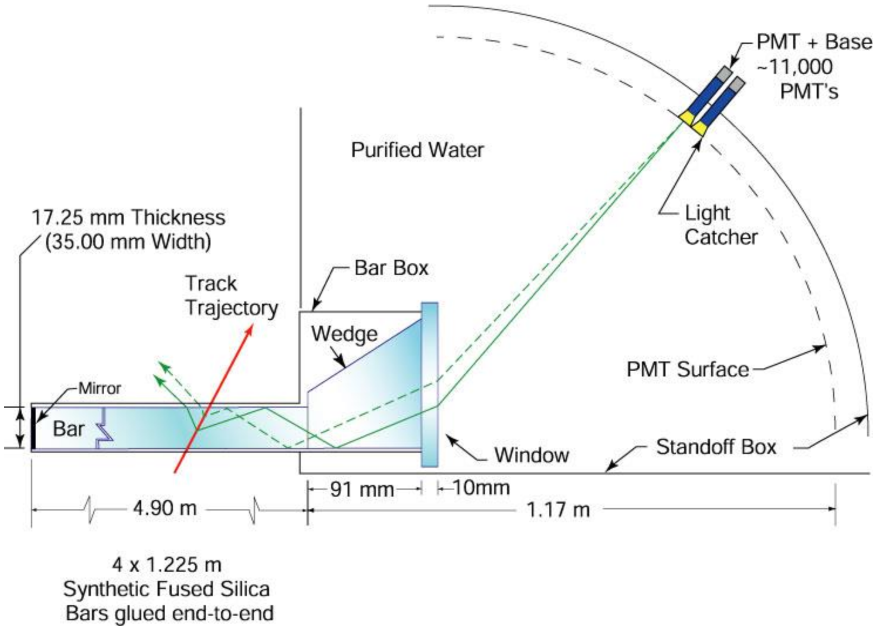
Time slot 12.6-12.7 ns



RICH1 hit time

- Fast timing can help to improve the RICH performance.
- This is planned for the future upgrade of these detectors

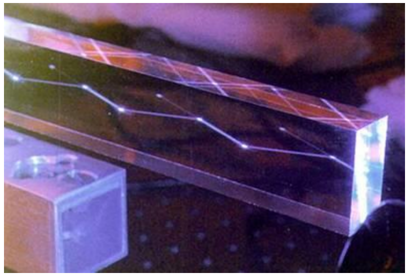
DIRC PRINCIPLE

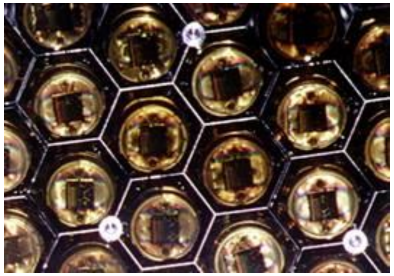


- If $n > \sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.
- Radiator and light guide: Long, rectangular Synthetic Fused Silica ("Quartz") bars (*Spectrosil*: average $\langle n(\lambda) \rangle \approx 1.473$, radiation hard, homogenous, low chromatic dispersion)
- Photons exit via wedge into expansion region

(filled with $6 m^3$ pure, de-ionized water).

- Pinhole imaging on PMT array (bar dimension small compared to standoff distance). (10,752 traditional PMTs ETL 9125, immersed in water, surrounded by hexagonal "light-catcher", transit time spread ~1.5nsec, ~30mm diameter)
- DIRC is a 3-D device, measuring: x, y and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$ of photon.





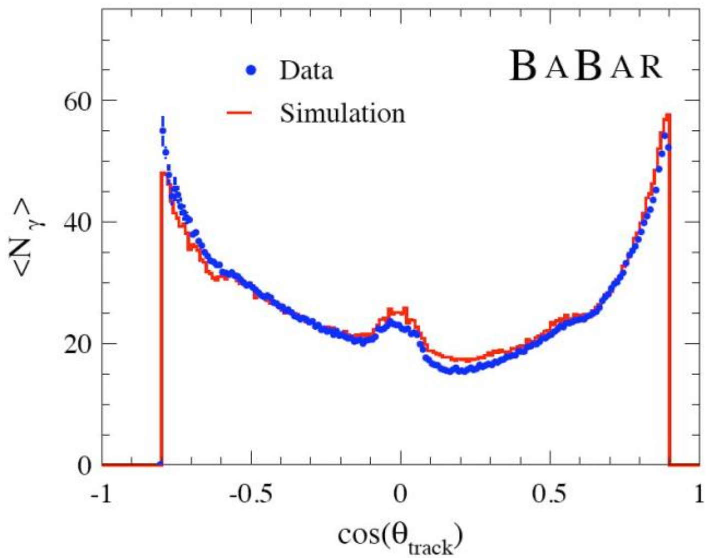
DIRC detector

Photon detector:

Cherenkov radiator:

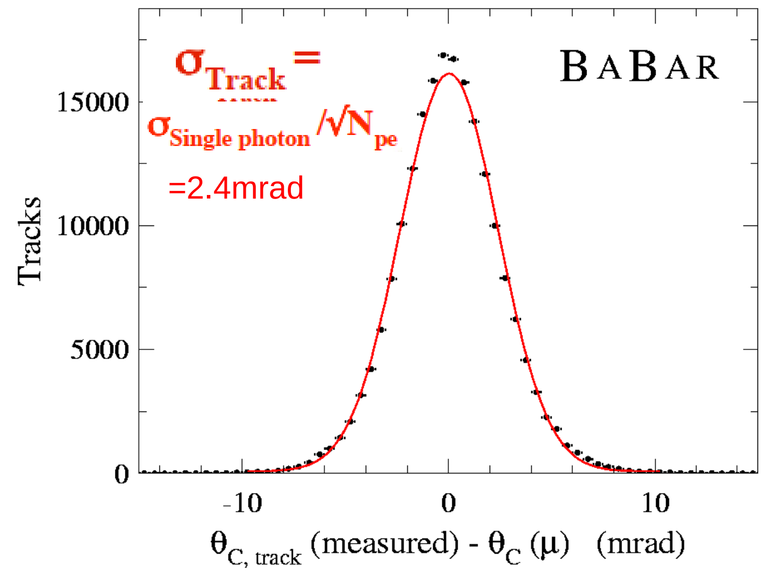
- **Bar dimensions (glued out of 4 segments): 488 cm x 3.5 cm x 1.7 cm**
- **~11,000 1 inch dia. ETL PMTs, sitting in water to minimize the photon loss.**

Number of Cherenkov photons per track (di-muons) *vs.* polar angle:

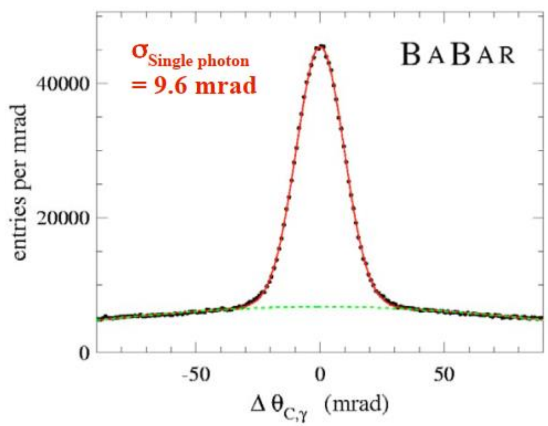


Between 20 and 60 signal photons per track.

Resolution of Cherenkov angle fit per track (di-muons):



$\sigma(\Delta\theta_c) = 2.4$ mrad



Track Cherenkov angle resolution is within ~10% of design

$$\sigma_{\theta c}^{tot} = \sqrt{[(\sigma_{\theta c}^{ext.\ track})^2 + (\sigma_{\theta c}^{prod})^2 + (\sigma_{\theta c}^{trans})^2 + (\sigma_{\theta c}^{imaging})^2 + (\sigma_{\theta c}^{align})^2]} \sim 9.6 \text{ mrad}$$

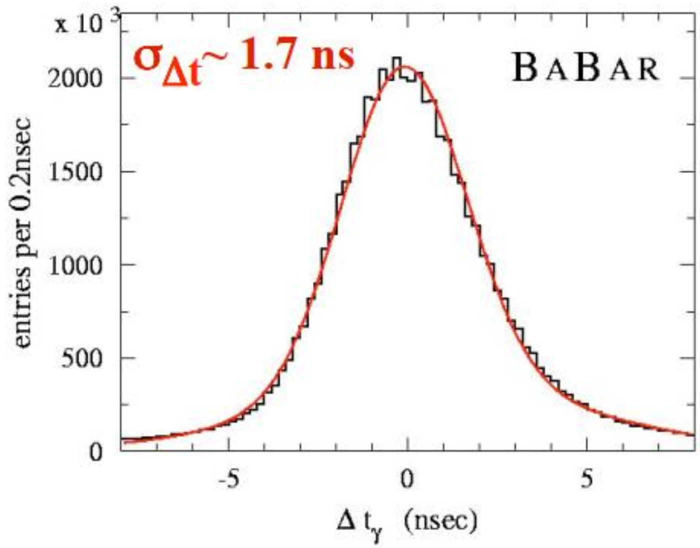
- ~ $f(\theta_{track})$ ~1mrad
- ~ f[chromatic error, multiple scatt.~1/(βp)] ~5-6 mrad
- ~ f(bar imperfections) ~2-3 mrad
- ~ f(bar size, pixel size) ~6-7 mrad
- ~ f(alignment) <1 mrad

- **Imaging error (pixels and bar size) and the Chromatic errors dominate.**

DIRC PERFORMANCE

DIRC time resolution:

Difference between measured and expected time:



- This helps to reduce the background
- However, in order to correct for chromatic corrections, further improvement needed. In recent years R&D to achieve this goal was performed.

$$\Delta t = t_{measured} - t_{expected} = TDC_{Start:\ bunch\_to} - (TOF_{track} + TOP_{bar\_expected} + t_{offsets})$$

$$\sigma_{\Delta t}^{tot} = \sqrt{[(\sigma_{\Delta t}^{ext.\ trigger})^2 + (\sigma_{\Delta t}^{TDC})^2 + (\sigma_{\Delta t}^{det\ TTS})^2 + (\sigma_{\Delta t}^{TOF})^2 + (\sigma_{\Delta t}^{TOP})^2]} \sim 1.7\ ns$$

~ f(ref. time for TDC) ~1ns

TDC resolution ~0.5/√12 ns

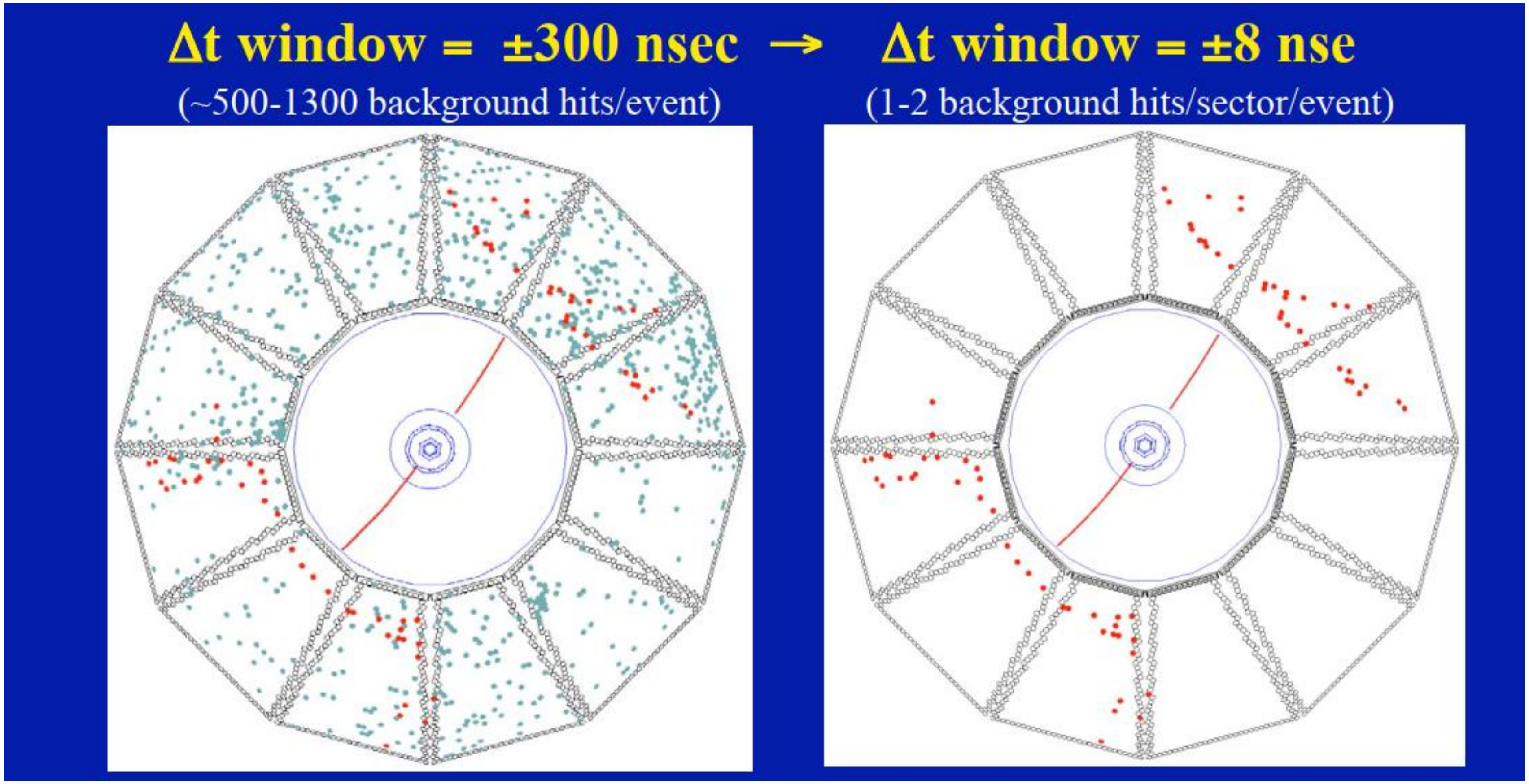
PMT TTS ~1.5 ns

~ f(track TOF) - small

~ f(bar imperfections, alignment) ~1ns

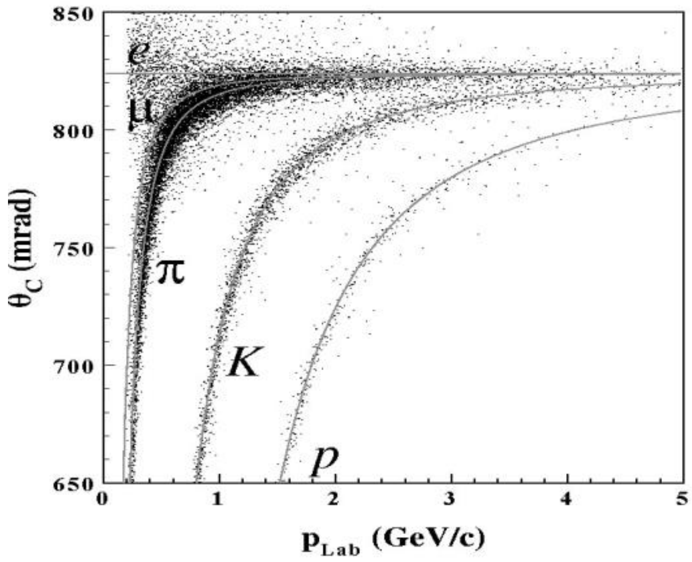
DIRC performance

Background reduction from fast timing:

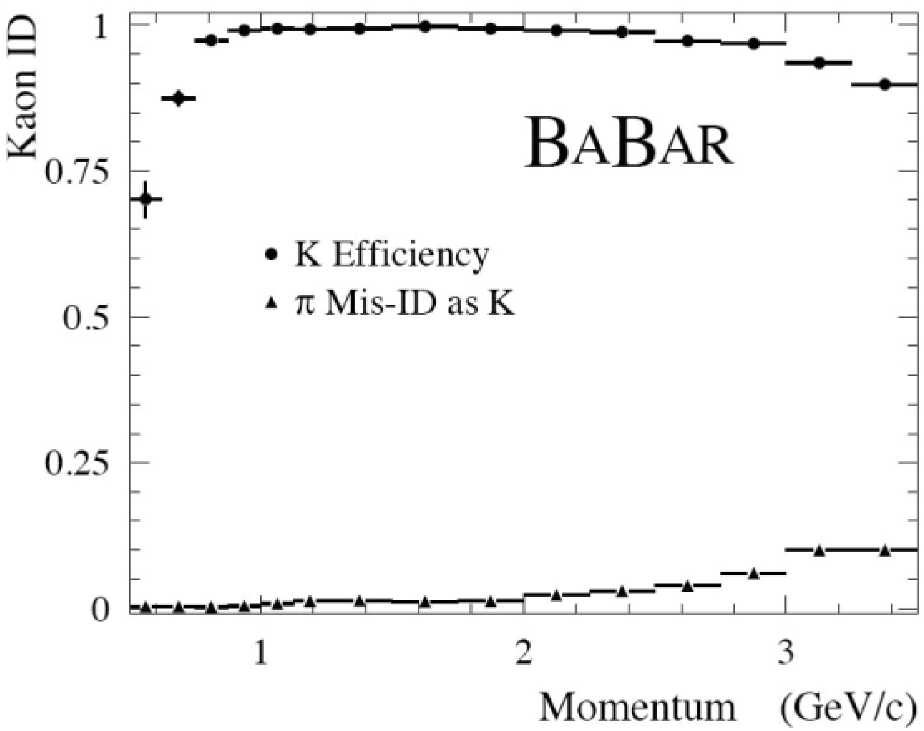


The cut on Δt helps to reduce background and avoid forward-backward ambiguity.

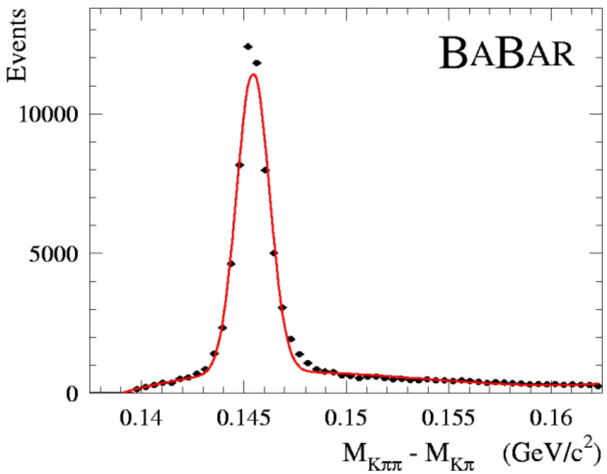
DIRC PERFORMANCE



Kaon selection efficiency typically above 95% with mis-ID of 2-10% between 0.8-3GeV/c.



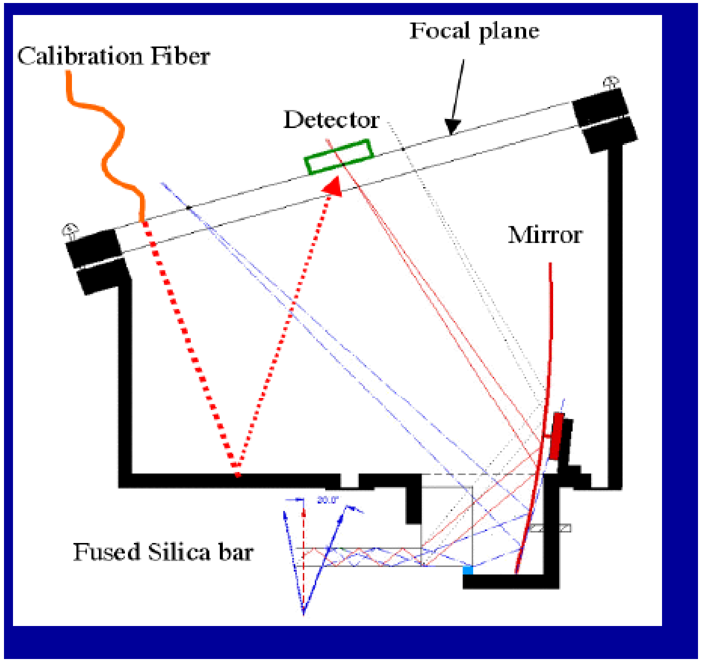
Kaon selection efficiency for $\mathcal{L}^{K} > \mathcal{L}^{\pi}$



$D^{*-} \rightarrow D^{0} \pi^{-}$

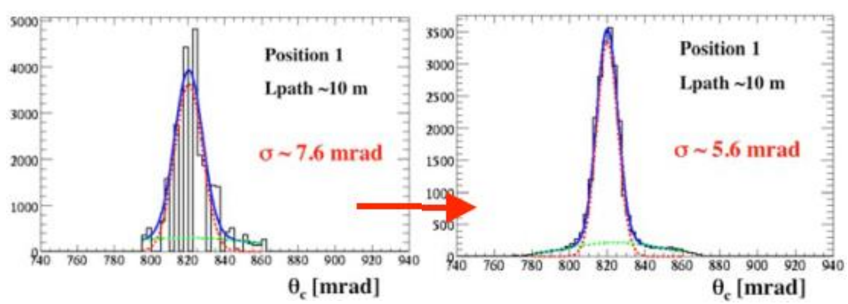
$\hookrightarrow K^{-} \pi^{+}$

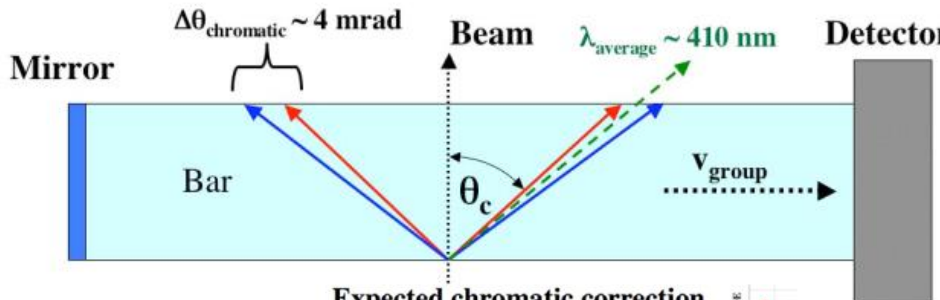
New Development: Focussing DIRC

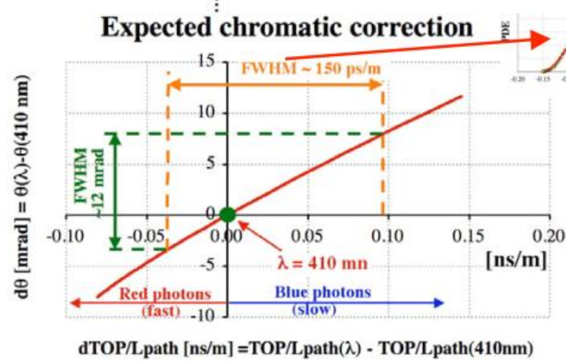


$v_{group}(red) > v_{group}(blue)$

- Red photons arrive before blue photons
- Time of Propagation= PathLength/ v_{group}
- Correct for Chromatic error from the measurement of time of propagation.







- Size of the expansion volume reduced
- Chromatic error reduced
- Needs photon timing resolution $\sigma \sim 200$ ps

Ref: NIMA 595(2008)104-107

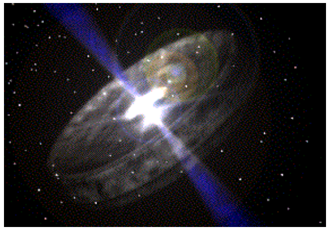
Cherenkov Detectors in Astro Particle Physics

Goal: Contribute to the understanding of our Universe.

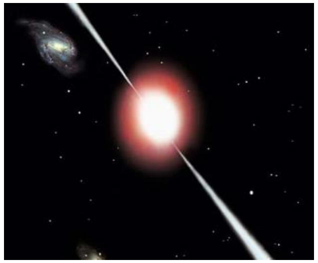
- **Understanding production mechanism ('cosmic accelerators') of HE cosmic rays ;**
- **Study very energetic galactic / extragalactic objects : SN remnants, microquasars, GRB, AGN,…;**
- **Search for Dark matter (wimps)**
- . . .

SNR

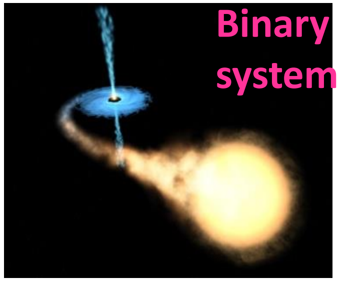
AGN



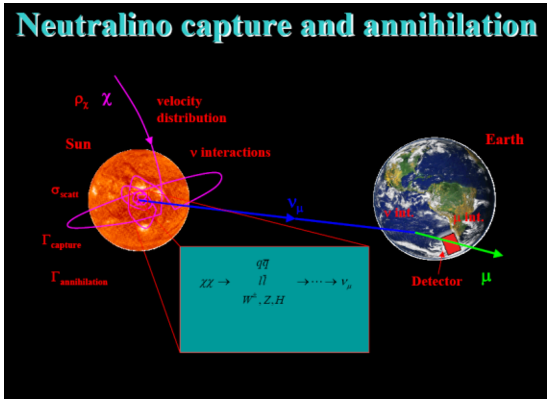
GRB



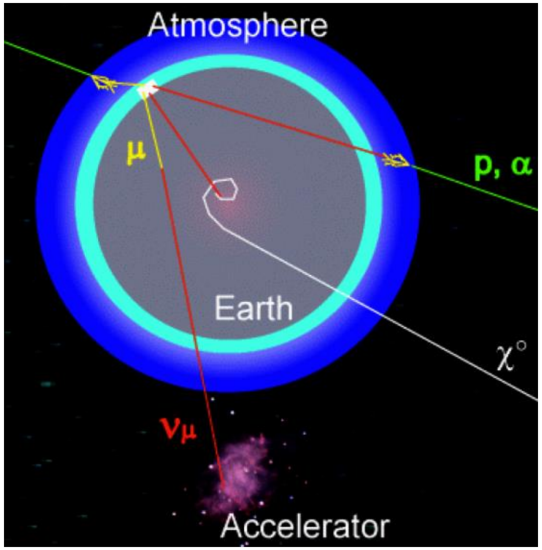
Micro-quasars

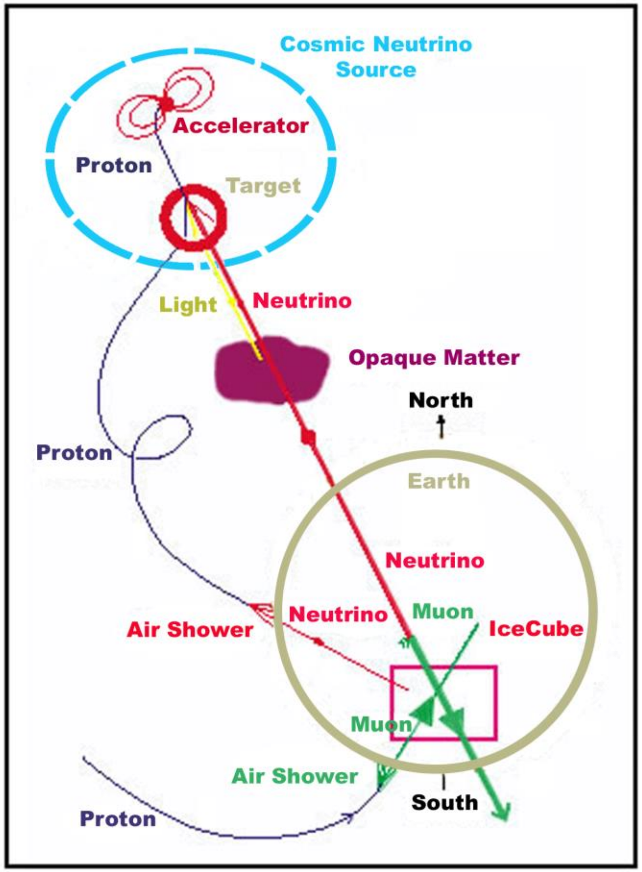


Binary systems



Astro Particle Physics

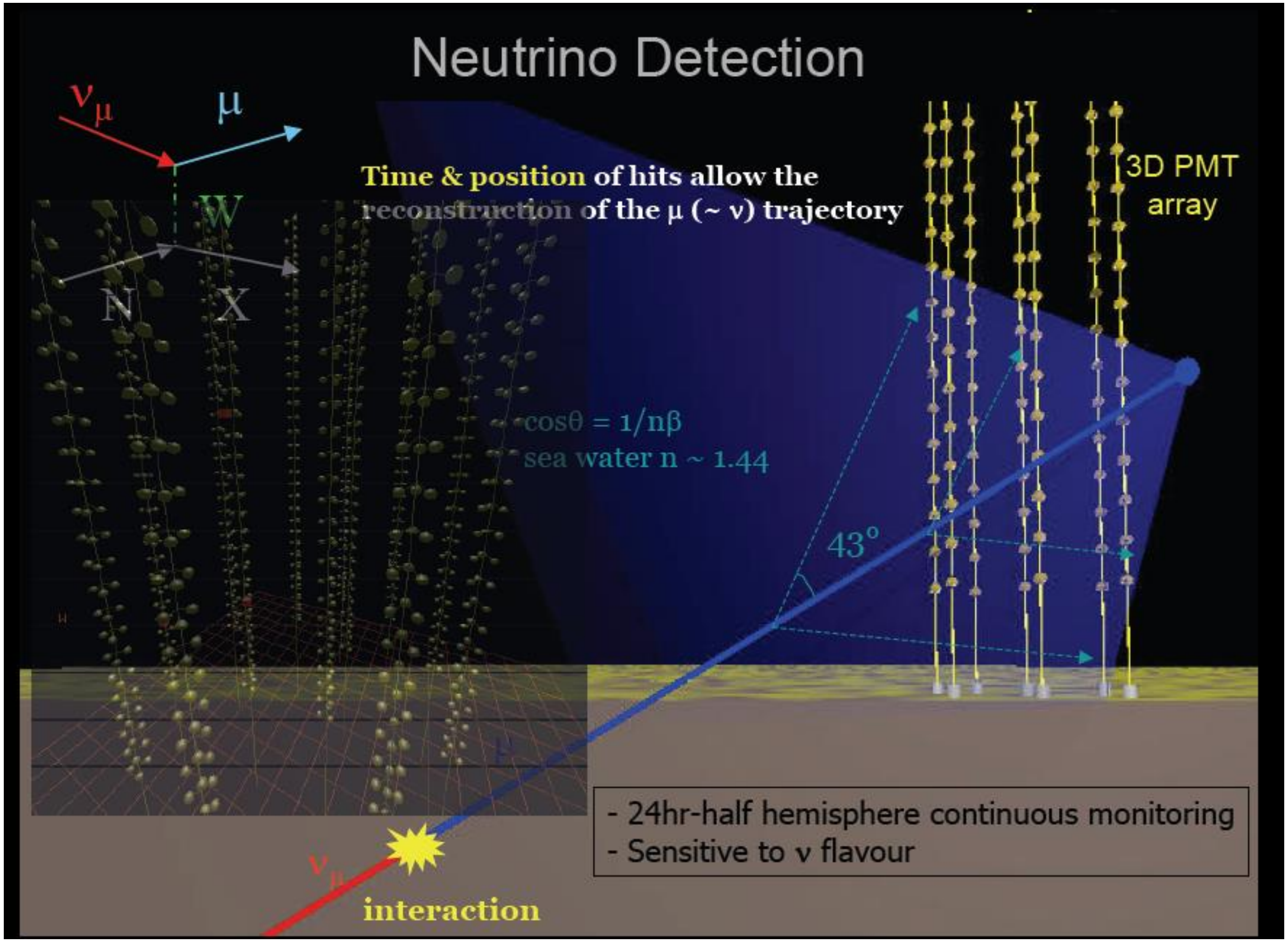




Search for :
- ➢ Neutrinos → muons
- ➢ High energy Gamma and other Cosmic rays → Air showers
- ➢ Ultra high energy Gamma (> 10^{19} eV) → Air showers

Neutrinos: Advantages:
- Neutral : Hence Weak interaction only
- Neutrinos point back to the astrophysical production source
  - Unlike photons which interact with CMB and matter
  - or protons: which also undergo deflection by magnetic fields

Disadvantages:
- Rate of arrival very low. Hence need very large detectors.
- Using the Ocean , ice in Antartica etc. as Cherenkov radiators



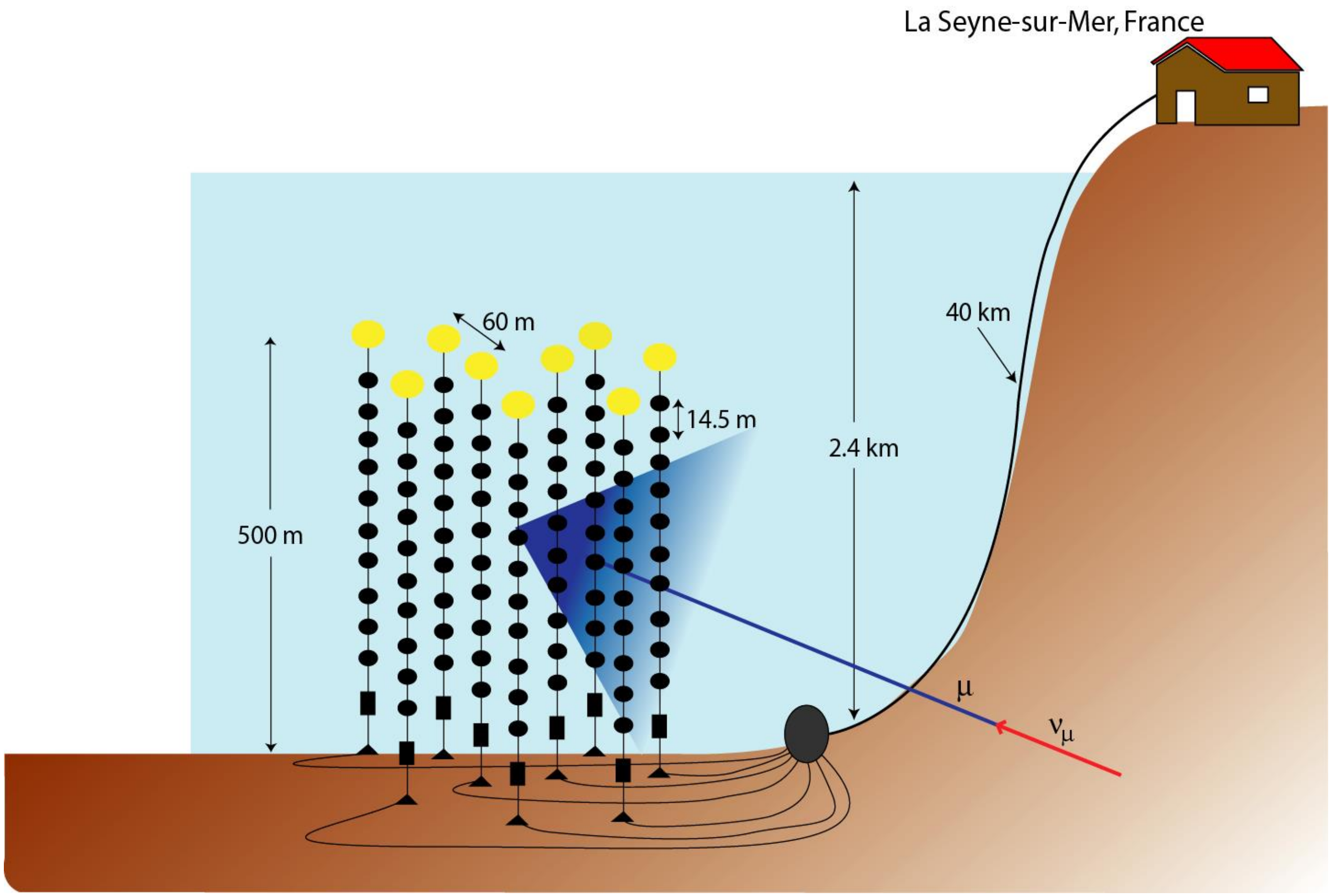
- **Typically 1γ / PMT 40 m from μ axis**

- Measure position and time of the hits.

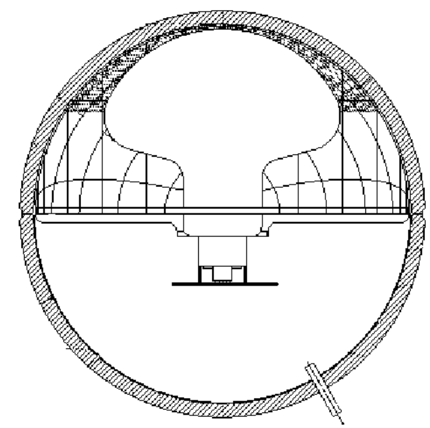
Angle between the directions of μ and ν = $\theta \leq \frac{1.5\,\text{deg.}}{\sqrt{E_\nu\,[\text{TeV}]}}$

Importance of Timing Resolution
c in water ~ 20 cm/ns
Chromatic dispersion ~ 2 ns (40 m typ. Path)
(PMT TTS σ ~1.3ns) so detector not dominant source of error

ANTARES Experiment in the sea



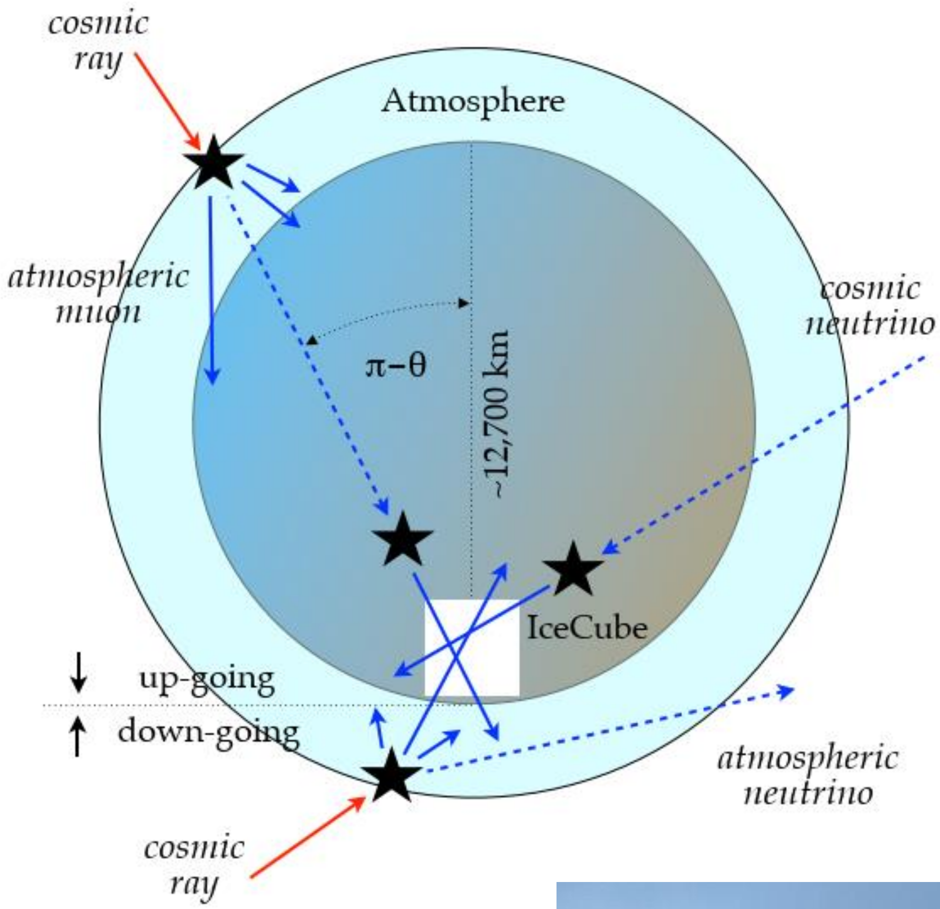
Optical Module



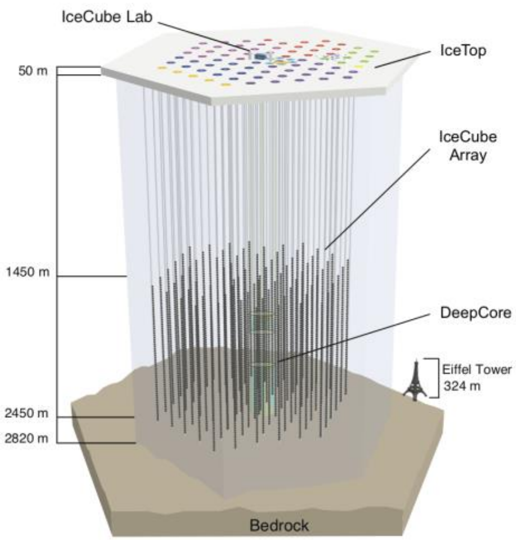
Hamamatsu PMT :
Size :10 inch

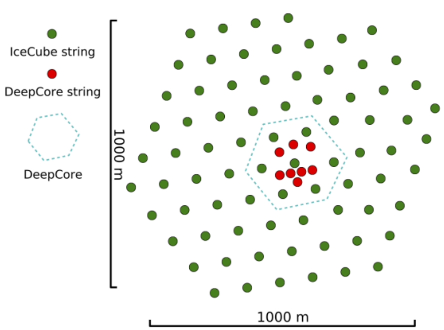
Glass pressure Sphere.

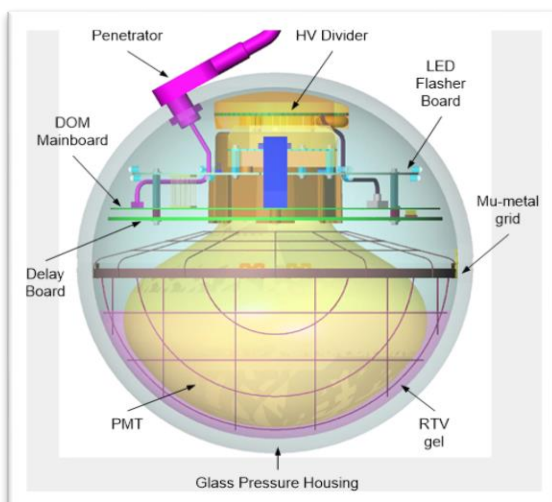
IceCube Experiment in Antartica



IceCube Experiment





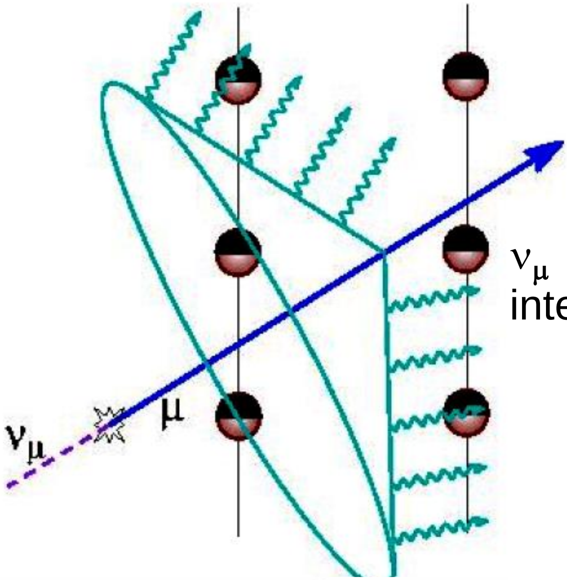


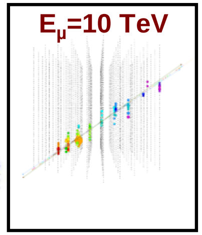
Design Specifications

- Fully digital detector concept.
- Number of strings – 75
- Number of surface tanks – 160
- Number of DOMs – 4820
- Instrumented volume – 1 km^3
- Angular resolution of in-ice array < 1.0°

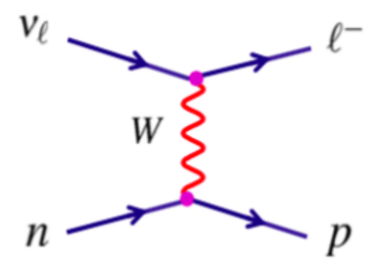
- Fast timing: resolution < 5 ns DOM-to-DOM
- Pulse resolution < 10 ns
- Optical sens. 330 nm to 500 nm
- Dynamic range
  - 1000 pe / 10 ns
  - 10,000 pe / 1 us.
- Low noise: < 500 Hz background
- High gain: O(10^7) PMT
- Charge resolution: P/V > 2
- Low power: 3.75 W
- Ability to self-calibrate
- Field-programmable HV generated internal to unit.
- 10000 psi external

Ice Cube/AMANDA Event signatures :   All signals are from Cherenkov Radiation.

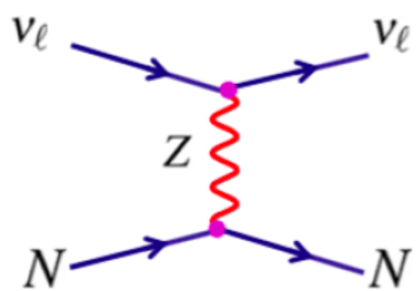




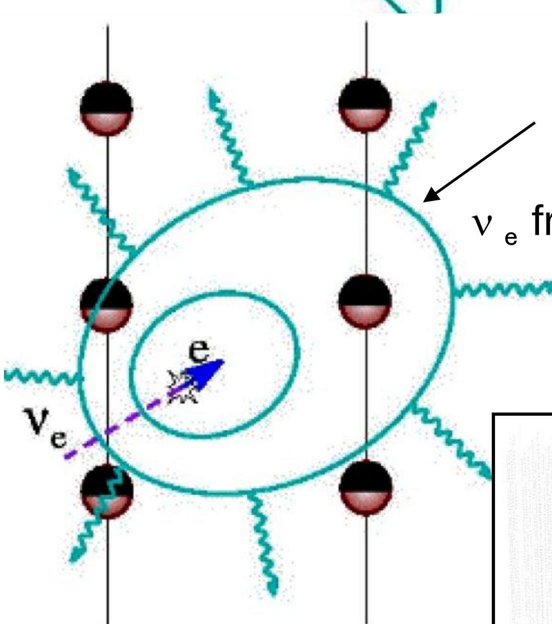
ν_μ from CC interactions



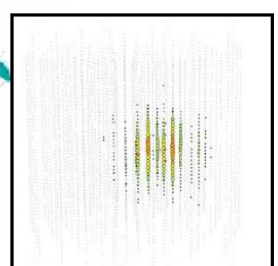
Charged Current (CC) interaction reveals the flavor from the outgoing charged lepton

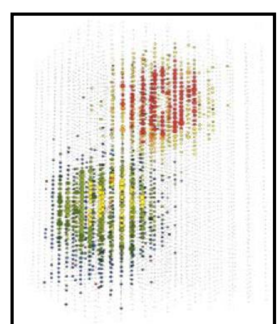


Neutral Current (NC) interactions mediated by Z boson is indistinguishable for the 3 flavors



ν_e from CC (also ν_τ or NC interactions)





$\nu_\tau \rightarrow \tau \rightarrow \mu$

~300m for > PeV ν_τ

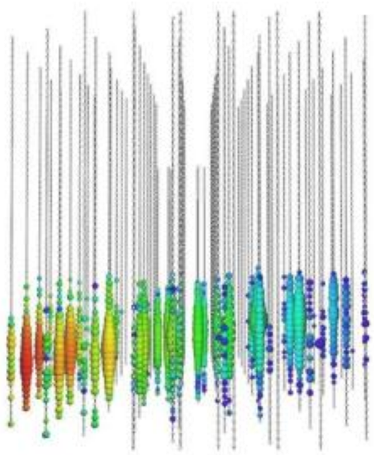
IceCube event signatures

Every DOM gets about 500-800 hits per second, mainly from dark counts. Hits from Physics events are ~1 order of magnitude lower.
After trigger, per year:

- 10^{10} events caused by atmospheric muons
- 10^{9} events caused by noise
- 10^{5} events from atmospheric neutrinos
- A **handful** of very high energy events likely to be of astrophysical origin

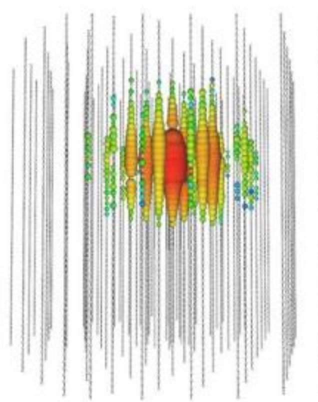
Tracks:

Mainly ν_μ CC interactions or atmospheric muons



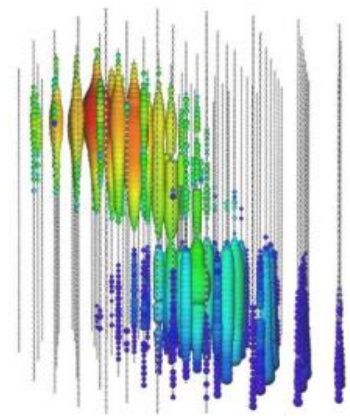
Cascades:

Mainly ν_e, ν_t CC as well as NC interactions

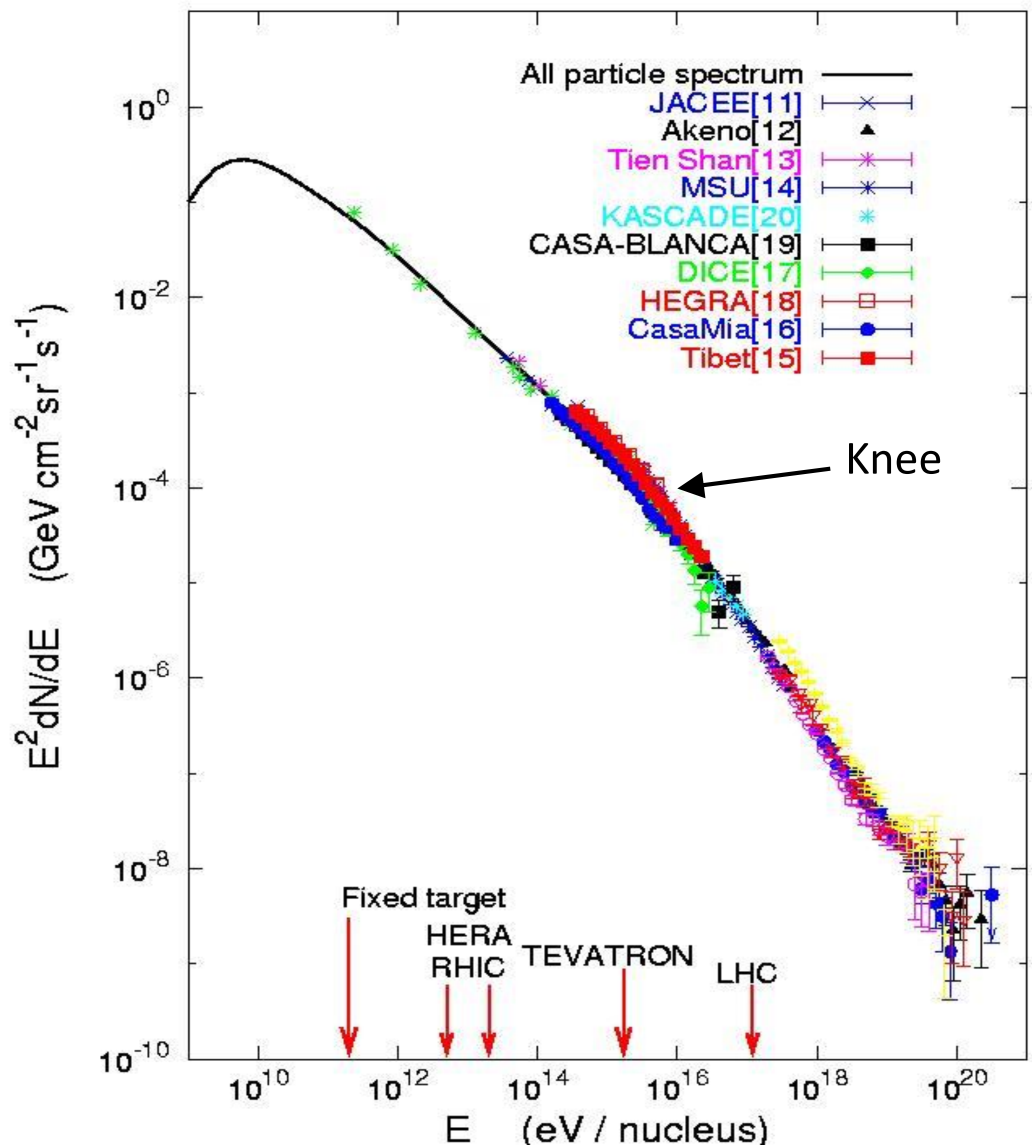


Double Bang:

Very high energy taus with second decay shower (~ 50 m /Pev)



High Energy Cosmic Ray Spectrum.

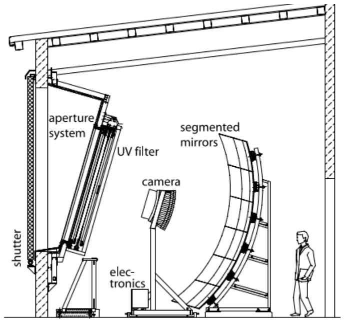


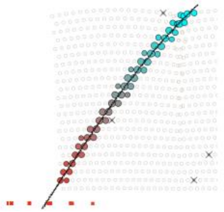
- Measure the Energy Spectrum
- Determine the Arrival Direction distribution etc.

- Composed of Baryons, photons, neutrinos etc.

$>10^{19}$ eV
1 km^{-2} $year^{-1}$ sr^{-1}

Principle of Auger Project

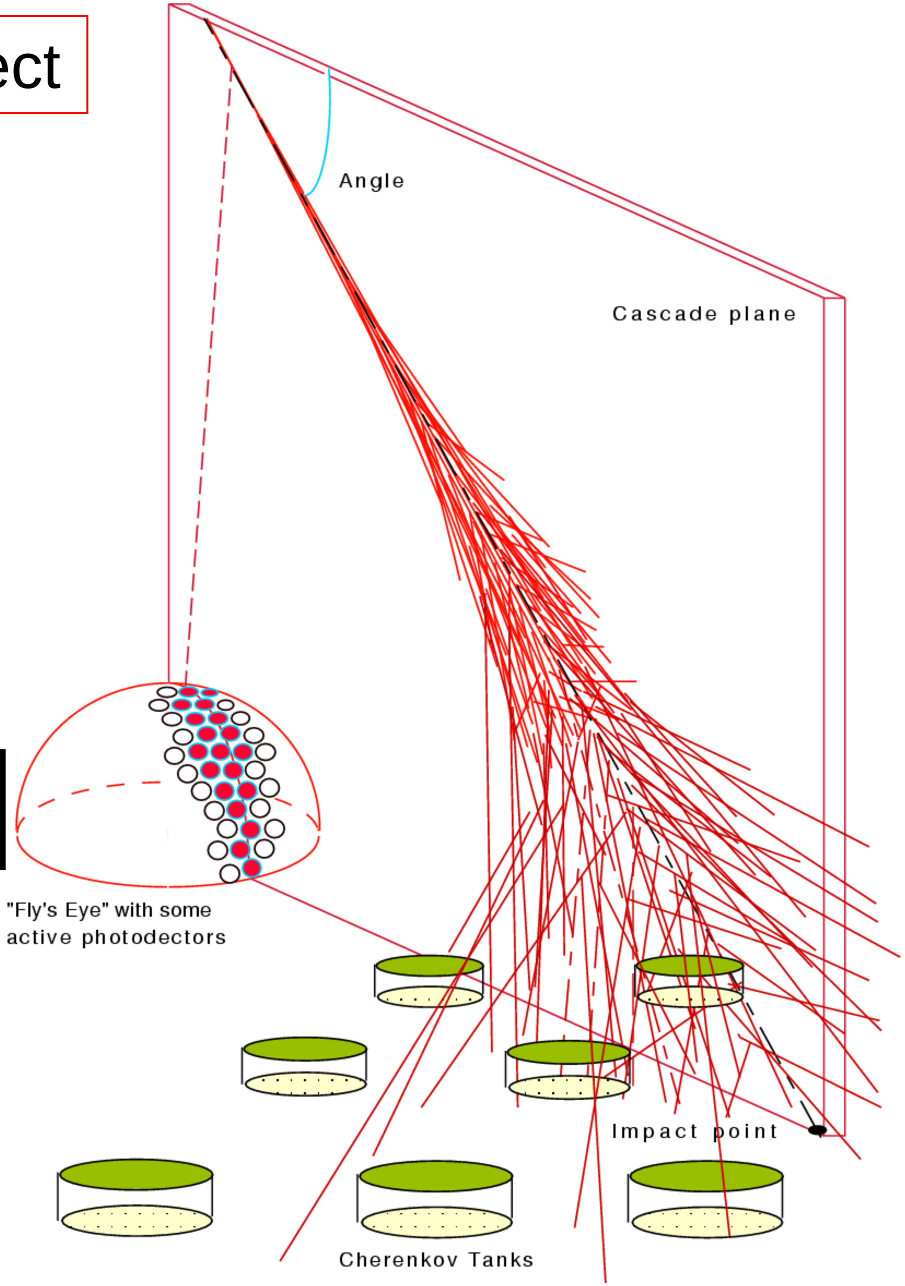


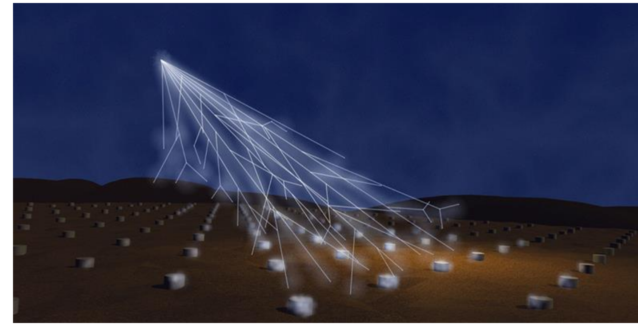


Fluorescense detector and signal

Fluorescence →

Array of water Cherenkov detectors →





The Pierre Auger Observatory

38° South, Argentina, Mendoza,
Malargue 1.4 km altitude, 850

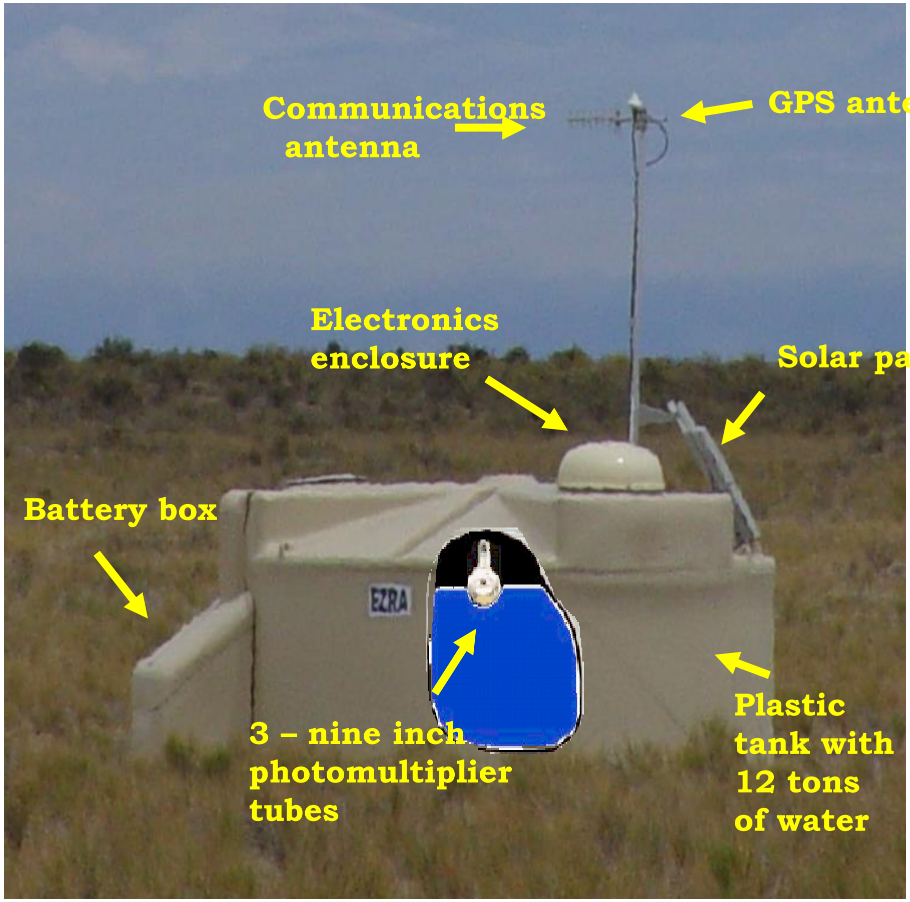
Argentina
Australia
Bolivia*
Brasil
Czech Republic
France
Germany
Italy
Poland
Mexico
Slovenia
Spain
United Kingdom
USA
Vietnam*

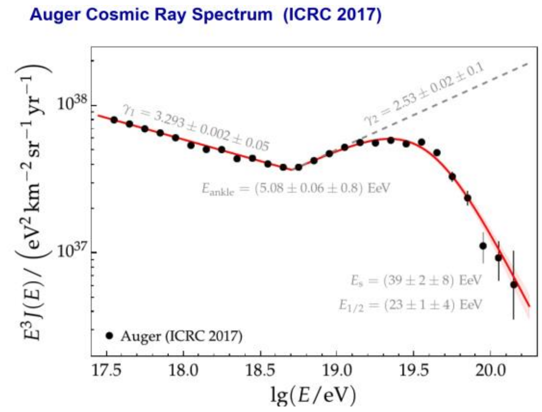
PIERRE AUGER OBSERVATORY

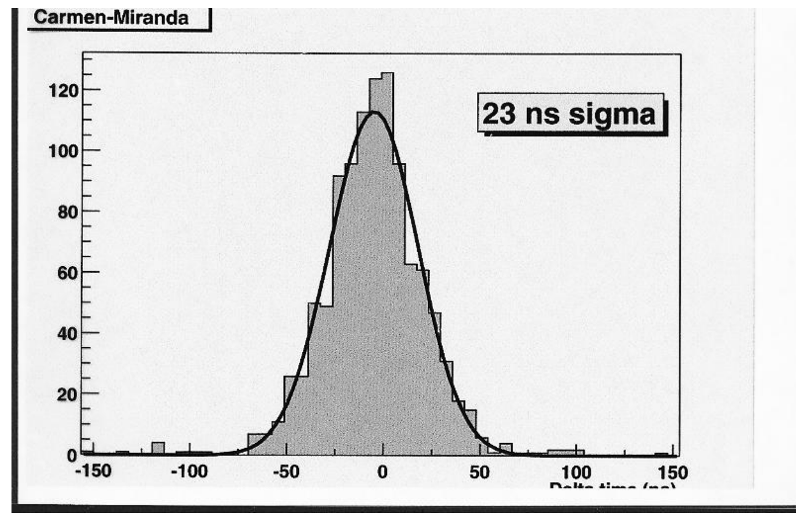
- 1600 surface stations
  1.5 km spacing
  over 3000 square kilometers

- Fluorescence Detectors:
  4 Telescope enclosures,
  each with 6 telescopes.

AUGER Project: Water Cherenkov Detector







Time difference between
test signals from nearby detectors

- . First set of results are published

Some other techniques for PID

- Techniques using energy loss (dE/dx)
- Time-of-Flight detectors
- Transition radiation detectors

Momentum ranges for PID detectors

Typical ranges:

- Hadron PID over large momentum range (1-100 GeV/c) with high resolution :
  - RICH with different radiators in different momentum range
  - Requires large radiator length at high momenta
    In the future photonic crystals may reduce the radiator length ?

- PID in the 1-5 GeV/c range : DIRC (using Cherenkov effect), detectors using energy loss (dE/dX) .

- PID in the 1-6 GeV/ range : Time of flight (TOF) detectors
  In the future up to 10 GeV/c.

- Electron-pion separation (0.5 – 200 GeV/c range) : Transition radiation detectors (TRD).

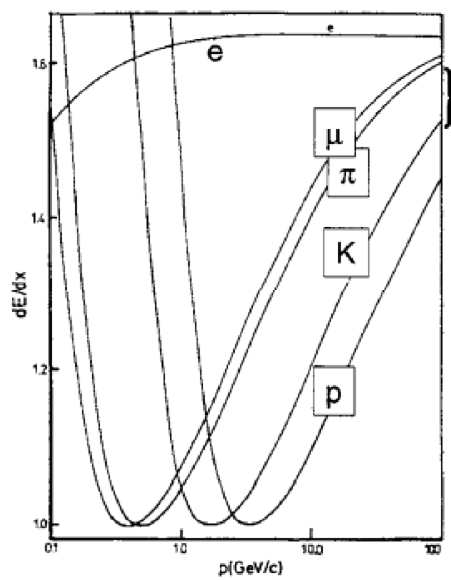
- PID in the TeV range (Astro particle detectors) : Cherenkov effect from secondary particles which are at relatively lower momentum.

dE/dx PID technique

dE/dx : Energy lost per unit length by the particle due to various processes like ionization

$$N_\sigma = [dE/dx(m_1) - dE/dx(m_2)] / \sigma(dE/dx)$$

- Calculated first by Bethe-Bloch in the 1930's.



Average energy loss for e,μ,π,K,p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

π/K separation (2σ) requires a dE/dx resolution of < 2.5%

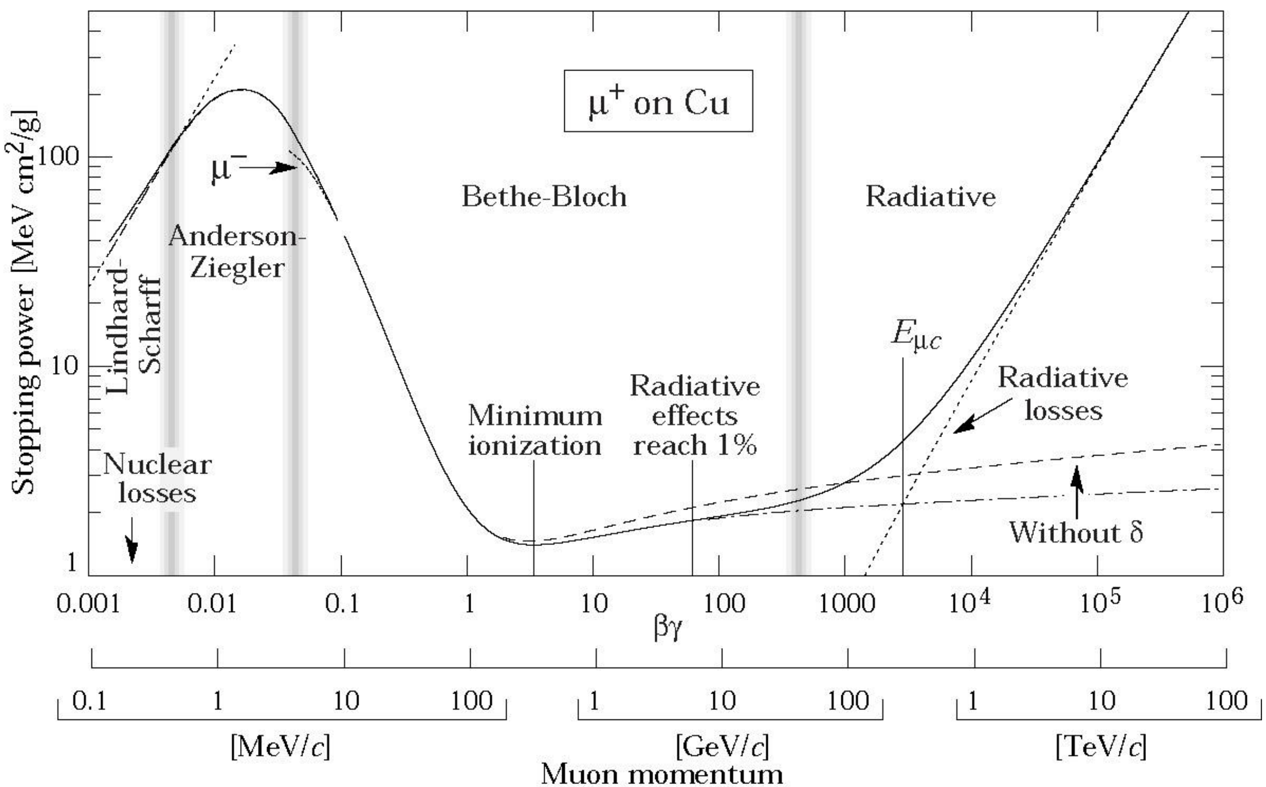
Energy loss : Bethe-Bloch formula for dE/dx

$$-\frac{dE}{dx}(\mathrm{eV cm^2 g^{-1}}) = Kq^2 \frac{Z}{A\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Ionisation Constant for material

Density correction

Example for muons:



$$T_{\max} \approx 2m_e c^2\beta^2\gamma^2$$

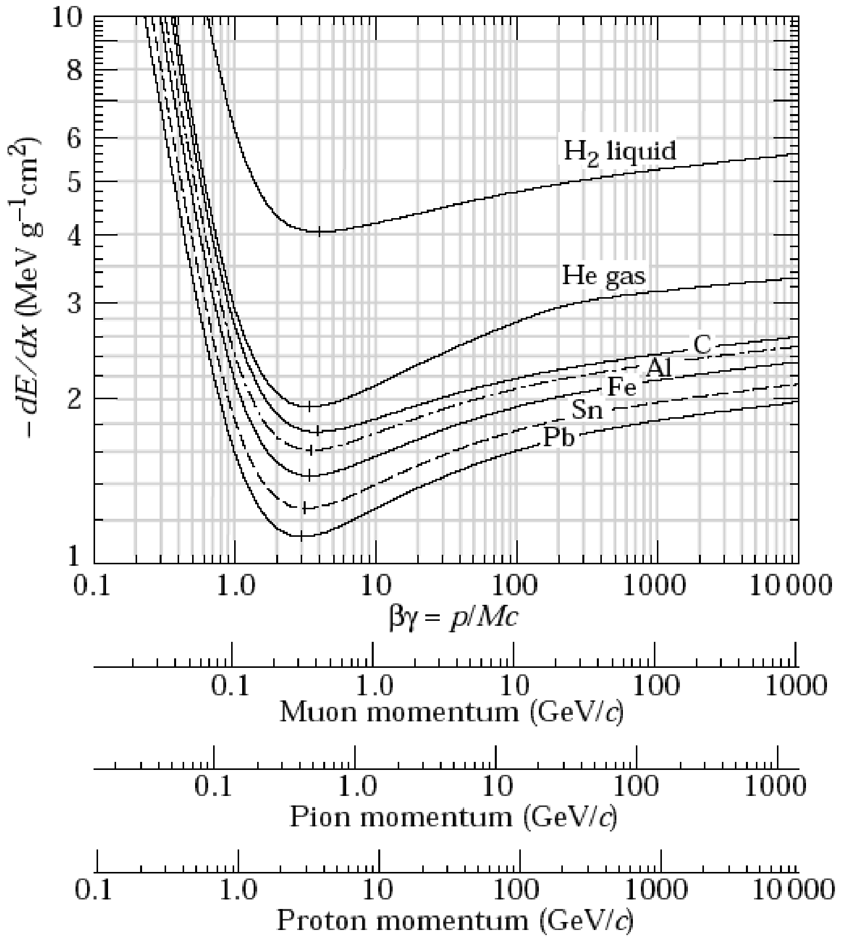
Max energy in single collision.

$K = 4\pi N r_e^2 m_e c^2$

Ref: PDG chapter on passage of particles through matter

dE/dx detectors: Silicon based

Energy loss by ionization



Ref: NIMA 469(2001) 311-315

Bethe-Bloch formula (for $2\gamma\ m_e/M << 1$)

$$\frac{dE}{dx} = \frac{4\pi N e^4}{mc^2\beta^2} z^2 \left(\ln \frac{2mc^2\beta^2\gamma^2}{I} - \beta^2 \right)$$

For $0.2 < \beta < 0.9$, $dE/dx \sim (M/p)^2$

M,p= mass, momentum of the traversing particle

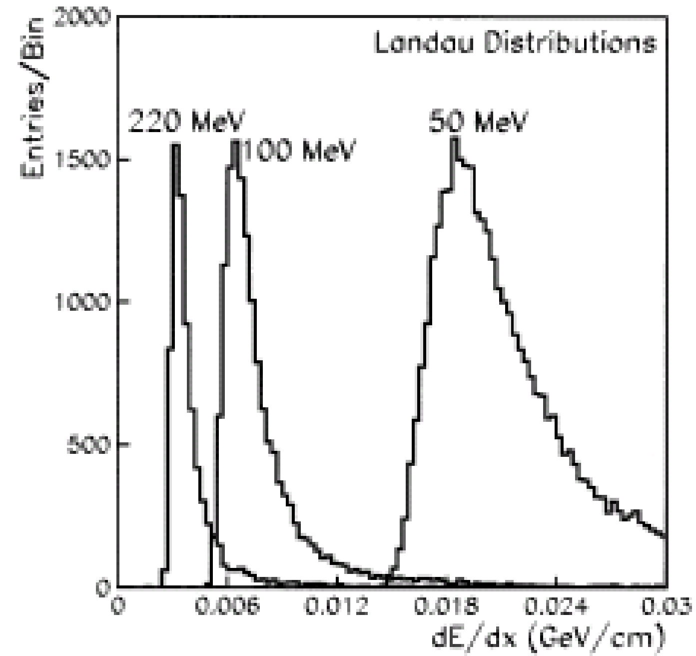


Fig. 1. Landau ⟨dE/dx⟩ distributions for pions of momenta 220, 100 and 50 MeV going through 300 μm of silicon.

FWHM= 30-35 %

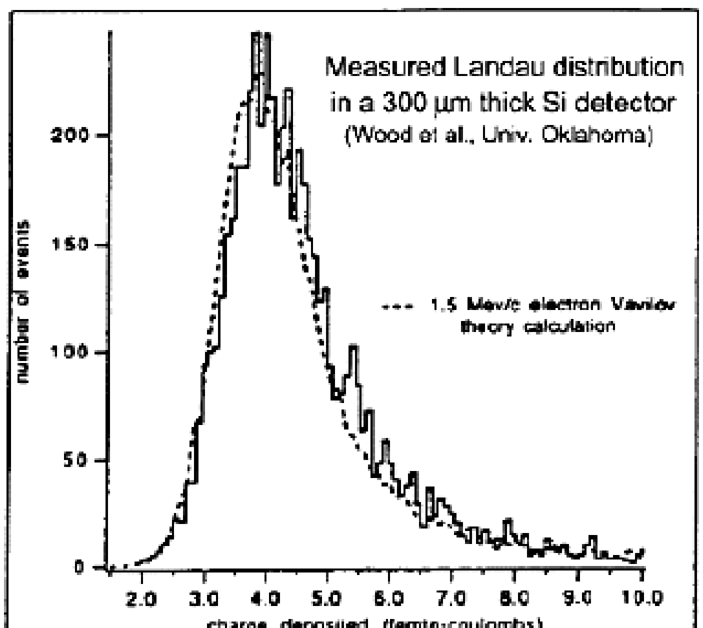
dE/dx detectors: Silicon based

For minimum ionizing particles in silicon ,

dE/dx ~ 39 keV/100 μm

An energy deposition of 3.6 eV will produce one e-h pair

Hence, in 300 μm we should get a mean of 32k electron-hole (e-h) pairs. The most probable value is ~0.7 of the mean of the landau distribution.



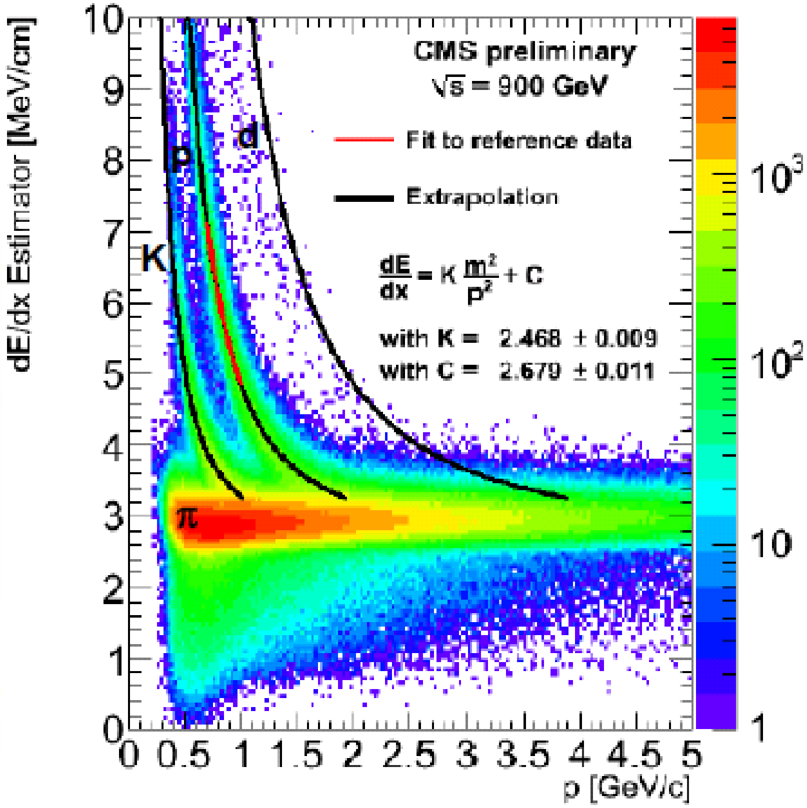
Hence we expect to get, 22K e as signal.

Typical S/N at LHC = 17/1
In practice the most probable value is estimated from measurements from different silicon layers.

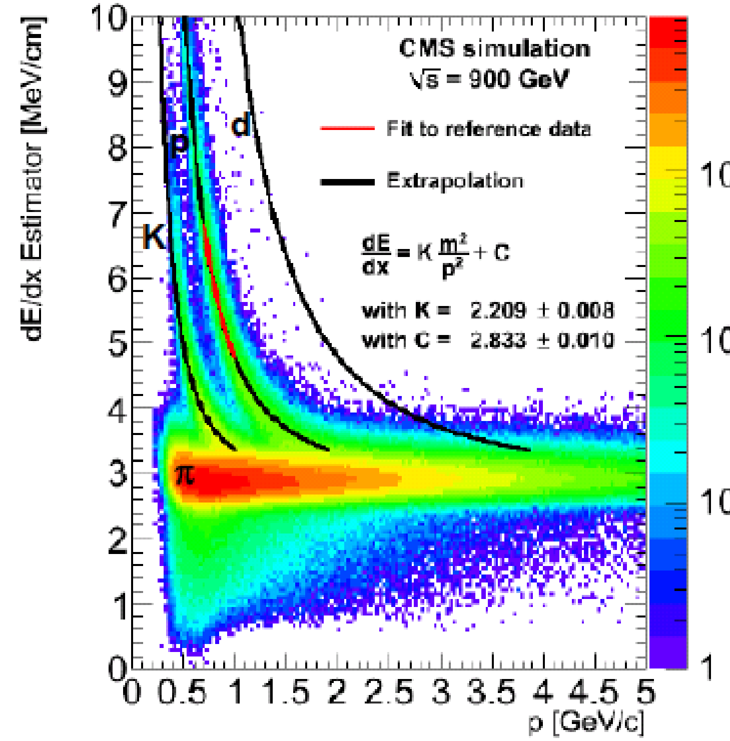
dE/dx Detectors : Silicon based

- Each Silicon sensor gives a single dE/dX measurement.
- Estimate the Most Probable Value from several (10-25) measurements (Truncated Mean: Ignore upper 40%)

CMS Silicon tracker:



Data



MC

CMS Silicon strip wafer

dE/dx Detectors: Drift Chambers

- Larger Landau fluctuations compared to those from silicon detectors. Hence many measurements needed to get the average.
- Bethe-Bloch formula with Sternheimer parametrization of the density function:

$$\frac{dE}{dx} = -0.3071\,\frac{Z}{A}\,\rho\, t\,\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 E_{cut}}{I^2} - \frac{\beta^2}{2} - \frac{\delta}{2}\right]$$

where

Z	is atomic number of medium,
A	is atomic mass of the medium,
ρ	is density of the medium,
t	is sample thickness,
m_e	is mass of electron,
I	**is mean excitation energy of the medium,**
E_{cut}	**is maximum kinetic energy which can be given to a free electron in a single collision,**
δ	**is density correction due to polarization of the medium.**

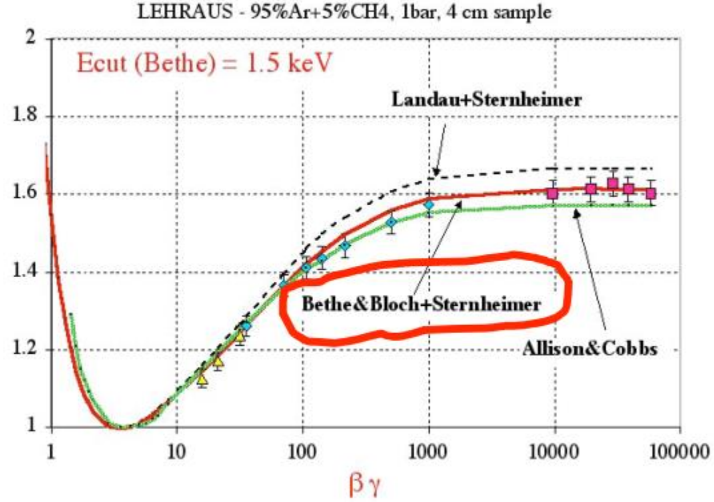
Sternheimer parametrization of density function δ:

$$\delta = 0 \qquad \text{for} \quad X = \ln\beta\gamma < X_0$$

$$\delta = 4.606(X - X_a) + \frac{4.606(X_a - X_0)}{(X_1 - X_0)^3}(X_1 - X)^3 \qquad \text{for} \quad X_0 \le X < X_1$$

$$\delta = 4.606(X - X_a) \qquad \text{for} \quad X > X_1$$

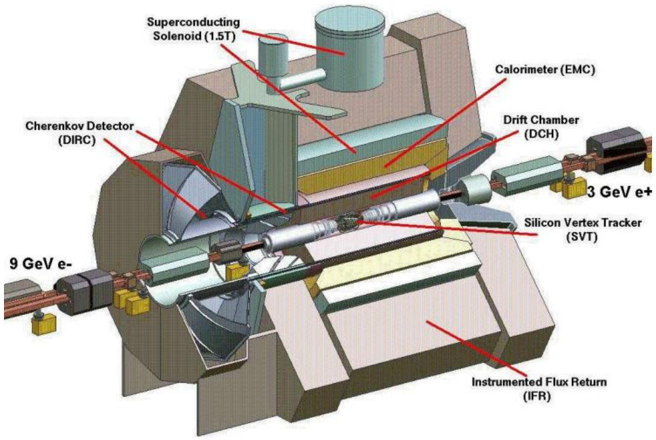
An example of dE/dx parametrization



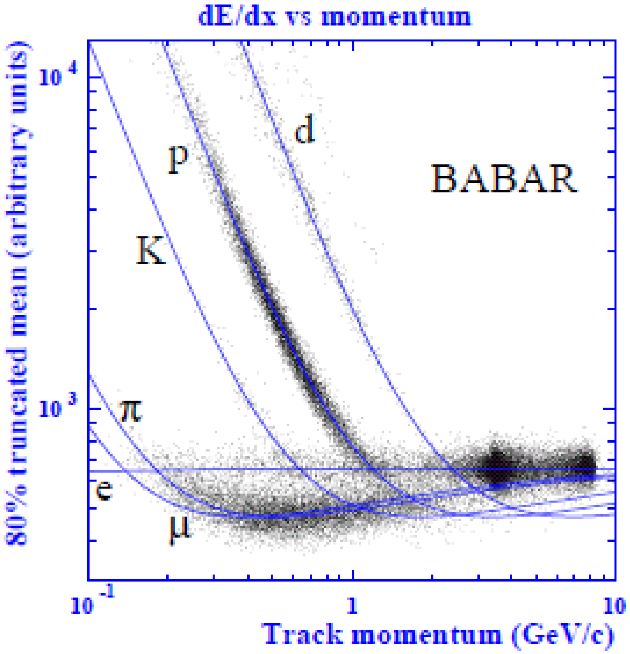
Mean ionization potential = I ~ (10 eV) * Z
Electron density = $n_{el} = N_A * Z * \rho/A$

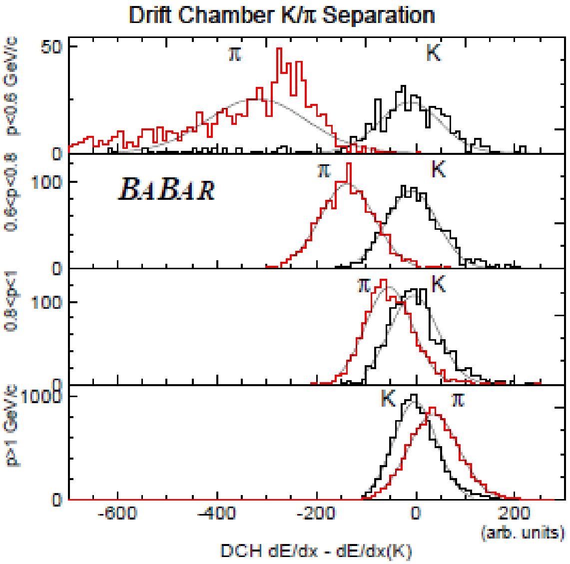
dE/dx Detectors: Drift Chambers

BABAR Drift Chamber:



Gas mixture 80% helium, 20% isobutane, 3500–4000 ppm water vapor, $\sim$ 80 ppm O_2





Good π/K separation up to $\sim$ 700 MeV$/c$.

Ref: IEEE-TNS VOL:47 , NO:6, Dec2000.

dE/dx resolution $\sim$ 7.5%

Time of Flight (TOF) Detectors

m=mass, p=Momentum, t=time,
L= distance travelled,
c=speed of light in vacuum
Using SI units

- For a charged particle traversing a detector:

using $L = v\,t$, $\beta = v/c = p/E = p/\left(p^2 + (mc)^2\right)^{0.5}$

t (= TOF) measured, is related to the mass of the particle

Typically, the mass resolution here is dominated by the time resolution , dp/p ~ 1% and dL/L ~ 0.001.

For two particles, with mass m_1 and m_2 for $p \gg m_1, m_2$

$$\Delta t = (L_{path}/c) * (1/\beta_1 - 1/\beta_2) = (L_{path}/c) * [\sqrt{(1+(m_1 c/p)^2)} - \sqrt{(1+(m_2 c/p)^2}] = \sim (L_{path} c/2p^2) * (m_1^2 - m_2^2)$$

The expected particle separation = $N_\sigma = [(L_{path} c/2p^2) * (m_1^2 - m_2^2)] / \sigma_{Total}$

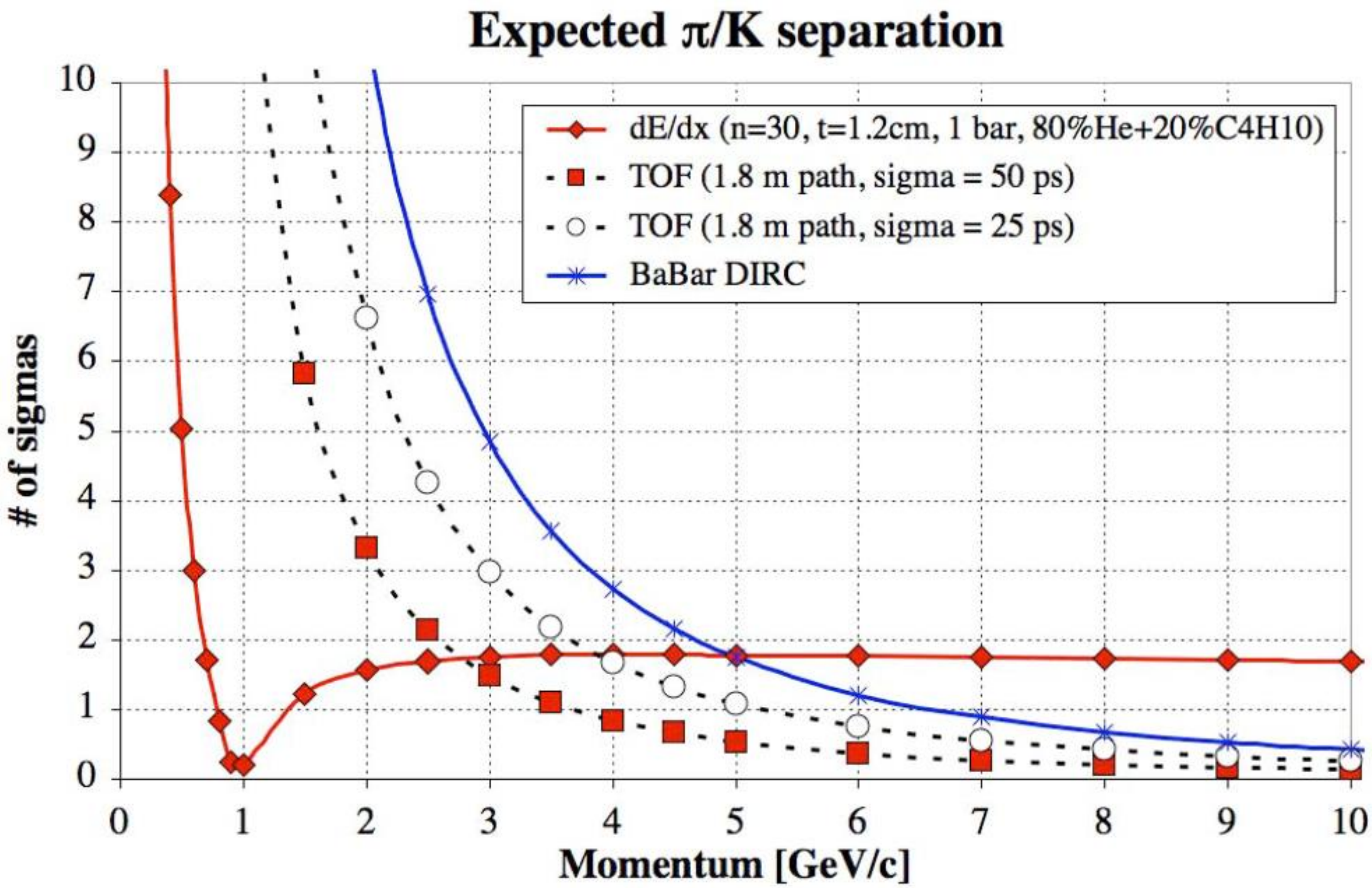
where σ_{Total} has many contributions :

$$\sigma_{Total} \sim \sqrt{ [(\sigma_{TTS} / \sqrt{N_{pe}})^2 + (\sigma_{Chromatic} / \sqrt{N_{pe}})^2 + \sigma^2_{Electronics} + \sigma^2_{Track} + \sigma^2_{T0}] }$$

At very high momentum, Δt will be too small and become comparable to detector resolution.

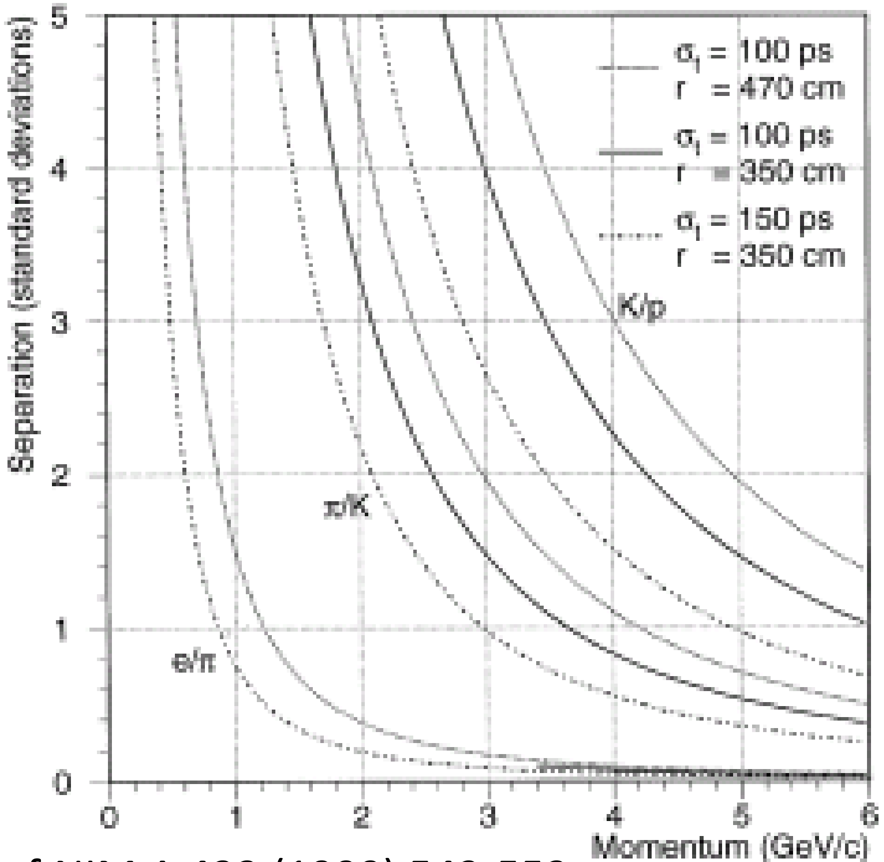
An example: L= 1.8 m, σ_{total}=25 ps, for 3 σ separation for π/K at p = 3 GeV/c

Comparison of dE/dx and TOF methods for BaBar DIRC/Super-B



These are ideal level of separations.
The TOF methods was used mostly for PID below 2-3 GeV/c

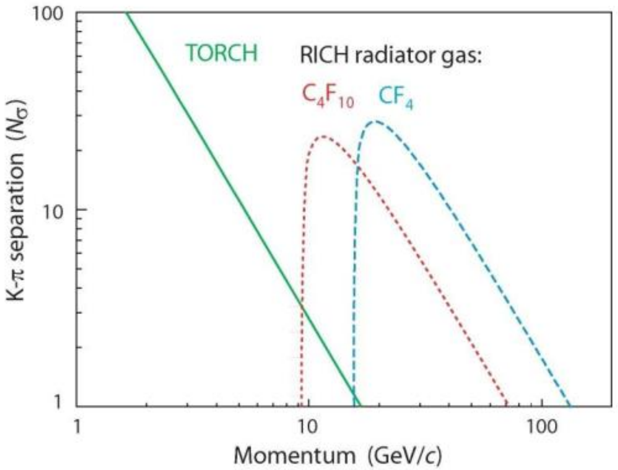
Time of Flight (TOF) Detectors



Ref:NIM A 433 (1999) 542-553

- New detectors reach somewhat higher momentum limit.
  Example: LHCb upgrade proposal has a detector named TORCH.
  It is proposed to be placed at L ~ 10 m with Δ t=40 ps, reaching up to 10 GeV/c for 3σ π–K separation.

Isolated tracks (TOF only)



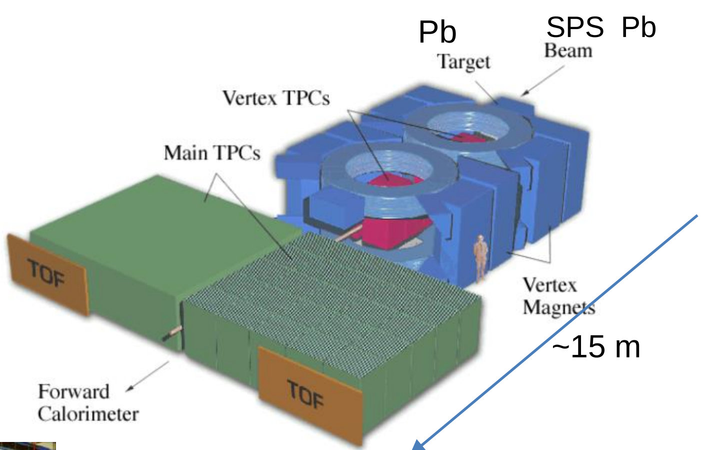
Time of Flight (TOF) Detectors

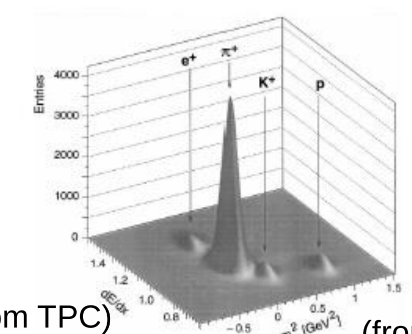
Measurement of time: Using scintillators

Energy loss (dE/dx) from the charged particle= 2MeV/cm
This energy is re-emitted as optical photons in UV. (Approx 1 photon/100 eV)
Too small attenuation length and low yield.
Fluorescent material added to scintillator so that the photon re-emitted at longer wavelengths (ex: 400 nm) longer attenuation length (ex: 1 meter) and high yield . These photons collected by a PMT. (0.002 pe per emitted photon)

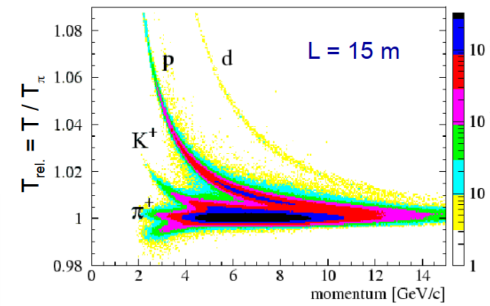
NA 49: Heavy ion expt, Scintillator thickness=2.3 cm, time resolutions up to 59 ps.
It had a TPC to measure dE/dx.

- 23 mm (thick) x 34 mm (hight) x 60/70/80 mm (length)
- Scintillators: Bicron BC-418 (TOF-R)
  polysterene +4% p-terphenyl (TOF-L)
- Al foil wrap of scintillators





TOF



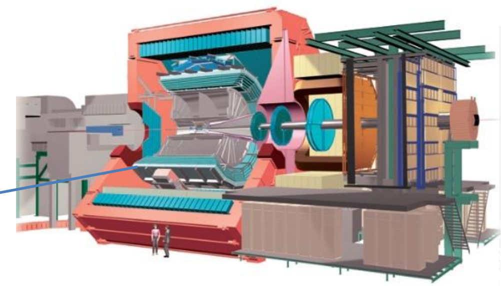
TOF

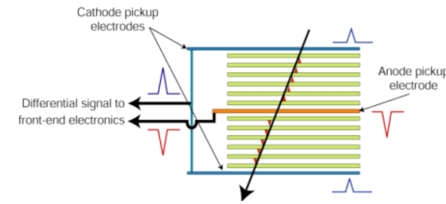
For kaons up to 6 GeV/c

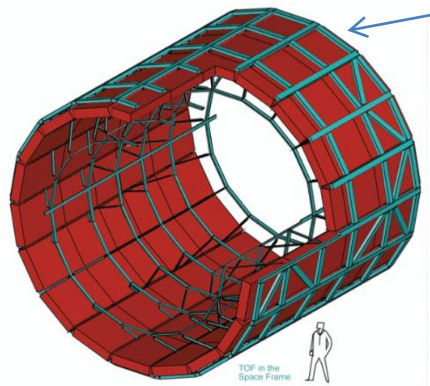
Ref: CERN-EP/99-001

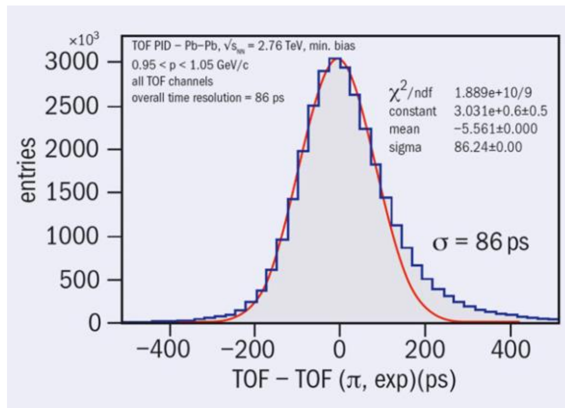
Time of Flight (TOF) Detectors

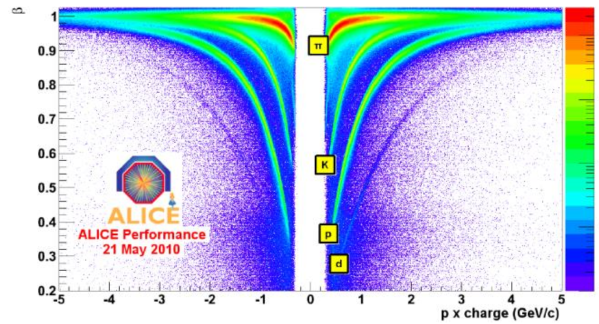
ALICE at CERN: using MRPC
(Multigap Resistive Plate Chamber)
Gas detector
at a radius of 3.6 m with 150 m^2 area





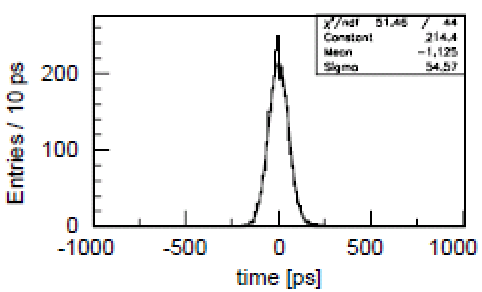




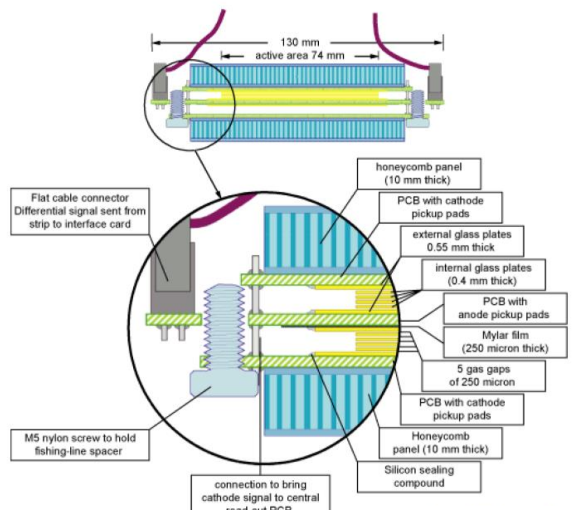


Resistive plates made of glass.
2 X5 gaps : 250 m m
The resistive plates stop the avalanche development, but transparent to the fast signal.

Use HPTDC
(High Performance TDC)



Performance in testbeam
Time resolution= 50 ps

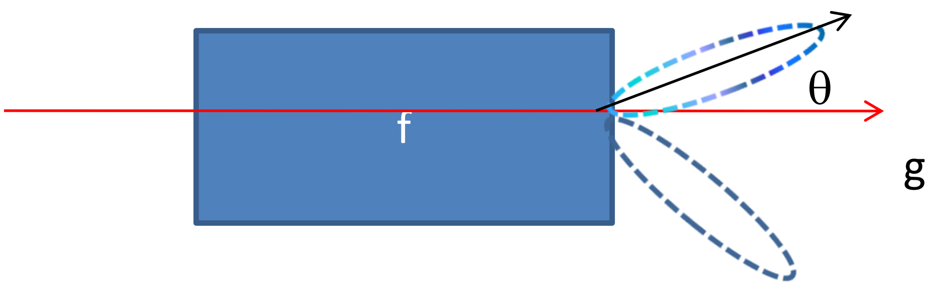


PID best in 0.5->2.5 GeV/c
2σ K-π separation up to 5 GeV/c

Transition Radiation Detectors (TRD)

- Transition Radiation: Radiation in the x-ray region when ultra relativistic particles cross the boundary between 2 media with different dielectric constants.
- Mainly for e-π separation in 0.5 GeV/c → 200 GeV/c.

Full explanations and the derivations from Maxwell's equations:
Nucl. Inst. Meth. A 326 (1993) 434-469 and references there in.



- The radiation is peaked at a small angle $\theta = 1/\gamma$.

The intensity of the radiation (after some approximations) becomes

$$\frac{d^2W}{d\omega\, d\theta} = \frac{2\alpha}{\pi} f_0(\theta)$$

where

$$f_0(\theta) = \theta^3 \left(\frac{1}{\gamma^{-2} + \theta^2 + \xi_g^2} - \frac{1}{\gamma^{-2} + \theta^2 + \xi_f^2} \right)^2 ,$$

$\xi_l = \omega_l / \omega$, ω_l=plasma freqency of medium l

Transition Radiation Detectors (TRD)

Integrating the previous equation, one can get , for ξ_g =0,

$$W_{TR} = 2.43 \times 10^{-3}\ \omega_f\ \gamma$$

Here $\gamma = E/m$ of the particle. This makes PID possible by measuring W. Lighter particle give larger signal

ω_f = plasma frequency = 28.8 $(\rho\ Z/A)^{0.5}$ eV

ρ=density, Z=atomic weight, A=atomic number

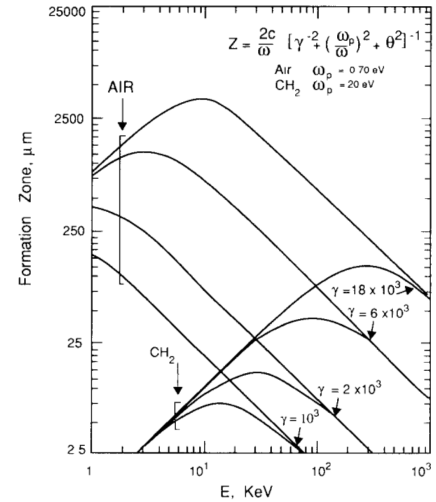
For example, for ω_f = 0.02 keV and γ =5000, most of the photon energy is in the range 10 keV< ω <100 keV (ie. 0.1 ω_c < ω < ω_c where ω_c = cut-off frequency).

Number of photons produced=

$$N(>\omega) = \frac{\alpha}{\pi}\left\{\ln\frac{\omega_c}{\omega}\left(\ln\frac{\omega_c}{\omega} - 2\right) + \frac{\pi^2}{12} + 1\right\}.$$

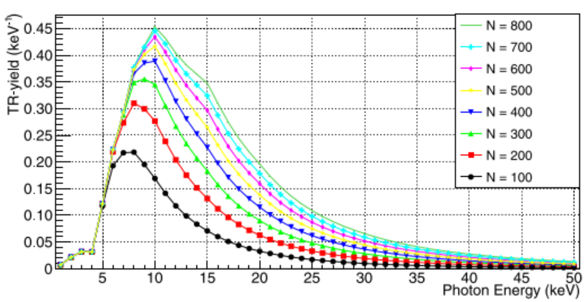
For ω_c =100 keV and $\omega=1$ keV, N= 0.03 for a single surface.
Hence to get sufficient number of photons , large number of interfaces are used : a stack of many foils with gaps in between.

Transition Radiation Detectors (TRD)



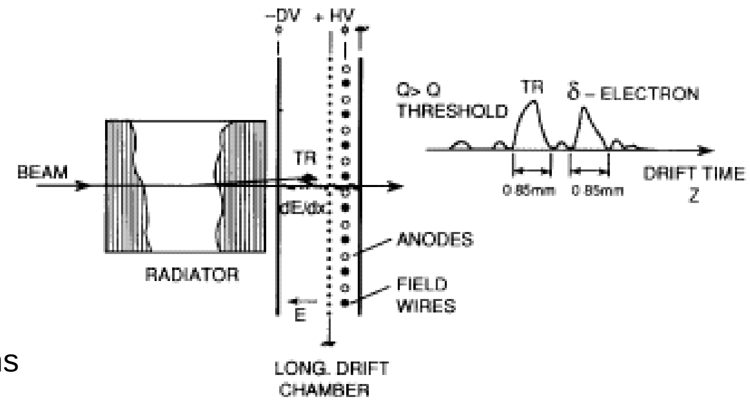
Formation zone: For relativistic particles,
most of the energy is emitted from within a small region of size $R = \gamma^2 c/\omega$ next to the interface.

- The minimum thickness of the foils and air gaps are determined by the size of the 'formation zone' and the interference effects.
  (for example, foils can be 10-20 μ m thick and are made of polypropelene)
- Behind a TRD foil stack there is a MWPC or drift chamber where the TRD signal is detected along with the signal from the charged track.



TR photon energy for 2.5 GeV/c electrons for different number of foils

Ref. Nucl.Inst.Meth A 962 (2020) 163723

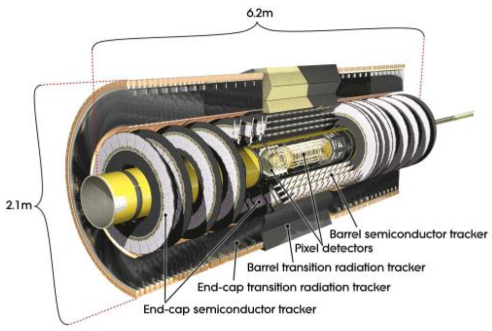


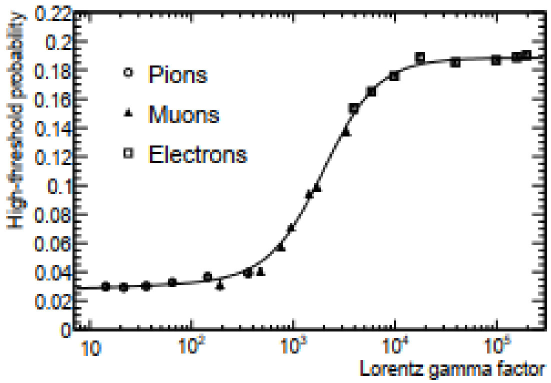
Drift space=10 mm,
Anode space=6 mm
Drift time=0.5→1 μ s
May use FADC
or discriminators

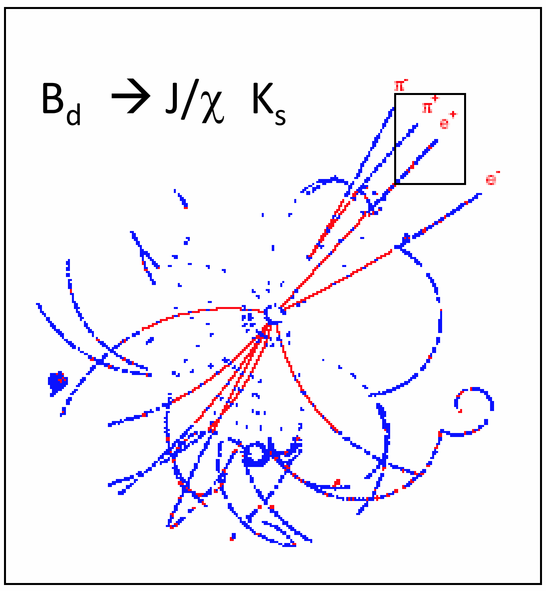
Example: HELIOS experiment (NA34)

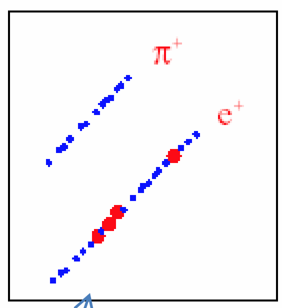
Transition Radiation Detectors (TRD)

ATLAS Transition Radiation Tracker





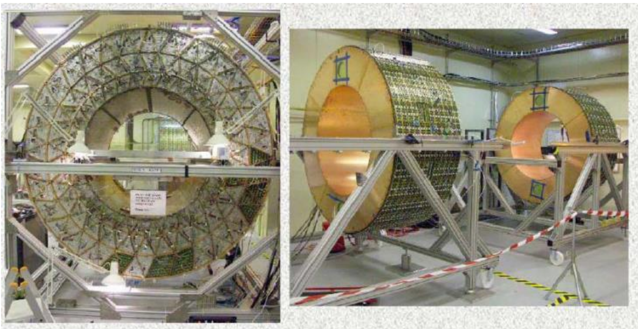




Blue dots: ionizing hits

Red dots : TR hits

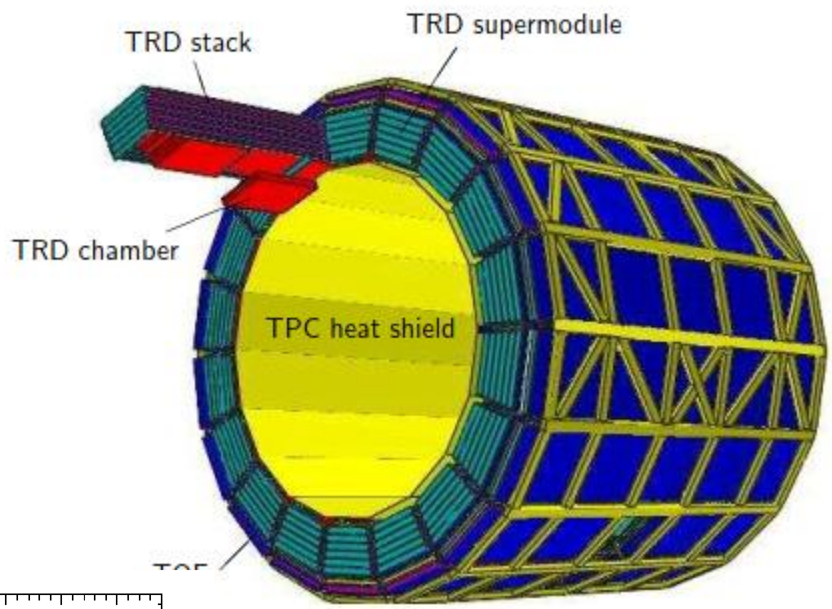
Barrel and endcap TRT

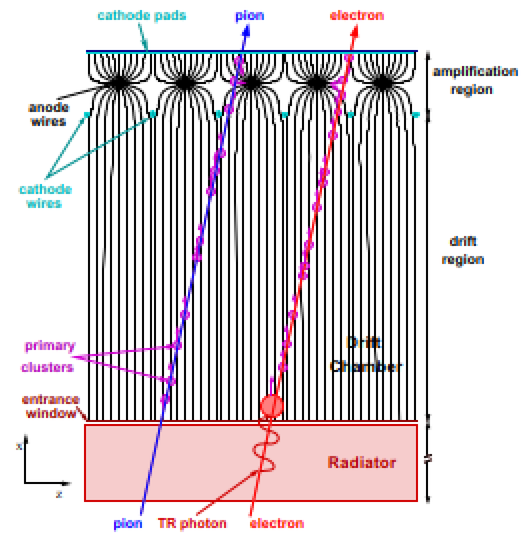


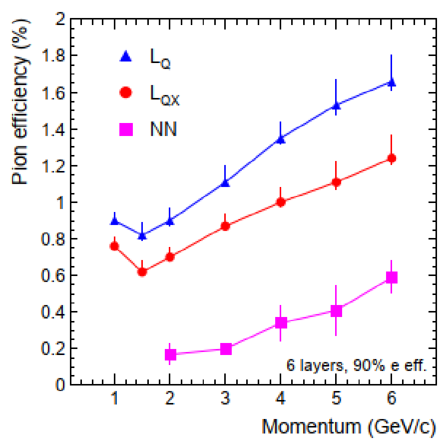
In an average event, energy deposit from:
Ionization loss of charged particles ~ 2.5 keV
TR photon > 5 keV.
(Photon emission spectrum peaks at 10-30keV)

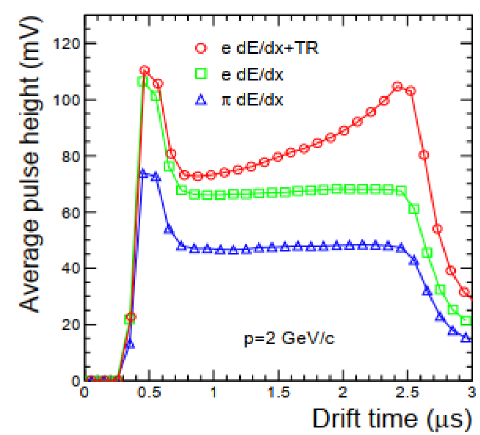
Transition Radiation Detectors (TRD)

ALICE TRD









Momentum=2 GeV/c

For 90% electron identification efficiency,
pion rejection probability (mis-id)
using three different methods

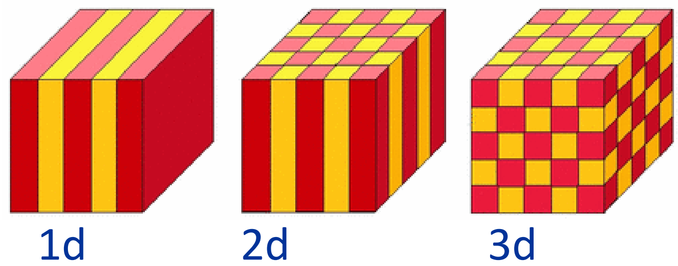
Photonic crystals as radiators

Concept:

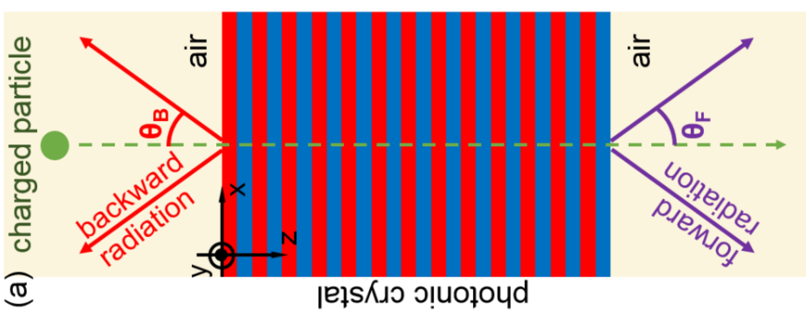
- Assemble materials to produce the desired ‘effective refractive index’
- Requires designing photonic crystals from transparent dielectrics

Example of natural photonic crystal

Photonic crystals:



- Typically made from two materials with different refractive indices, in alternating layers.
- The magnitude of layer thickness is similar to that of the photon wavelengths.
- Production of layers as thin as optical wavelengths, feasible in recent years.
  This creates the current interest in using the crystals, as radiators



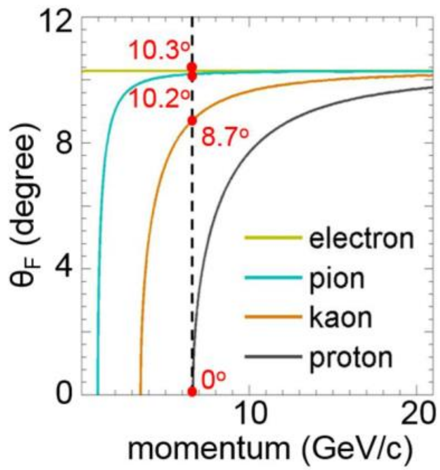
Resonance Transition Radiation :

- *Has the features of conventional Cherenkov radiation*
- *Both forward and backward radiation are possible*

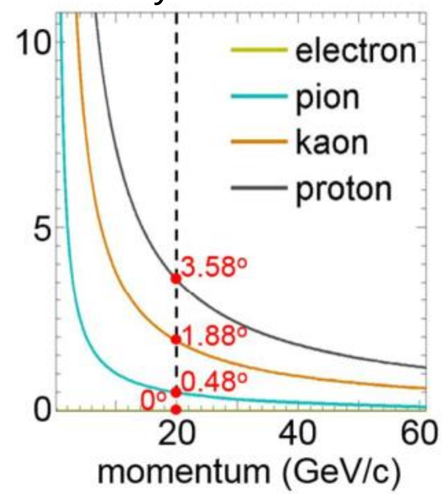
Nature physics 14, 816-821 (2018)

Photonic crystals as radiators

Example of forward configuration with 1d crystal



Example of backward configuration with 1d crystal



- Can be configured for different momentum ranges
- This can result in radiators which are onlly few mm thick.

Topics for R&D:

- The periodicity of the crystal structure can cause chromatic error. Many options to mitigate this are being investigated.
  - *Use materials with anisotropy which can compensate for achromaticty*
  - *Use filters to limit the wavelength range*

- Improving photon yield, ensure radiation hardness etc.

Summary

- The field of Particle identification detectors is an evolving field.
- They have contributed to some of the important discoveries in High Energy Physics in the last 50 years and they continue to be a crucial part of some of the recent experiments.
- The RICH detectors offer excellent particle identification capability for the hadrons since they can be designed to have very good single photon Cherenkov angle resolution and large photoelectron yield. Recent advances in photodetectors enhance the capability of these detectors.

- The particle ID using dE/dx, time-of-flight and Transition Radiation detectors continue to provide particle identification in different experiments.
- Particle identification is a crucial part of some of the Astroparticle physics experiments and long base line neutrino experiments

References

Acknowledgement: Thanks to all the authors of the papers from which the material for this lecture has been compiled.

For information on Cherenkov detectors:

(1) http://pdg.lbl.gov

(2) T. Ypsilantis et.al. Nucl. Inst. Meth A (1994) 30-51

(3) J.Vavra : Lecture : Super-B Particle identification systems (2009)

(4) M.Ahlers, F.Halzen : Opening a New Window onto the Universe with IceCube: arXiv:1805.11112 [astro-ph.HE] (2018)

(5) B.Dey et.al. Design and performance of the Focusing DIRC detector arXiv:1410.0075 [physics.ins-det]

(6) Adinolfi,M. et.al (LHCb-RICH collaboration)
Performance of the LHCb RICH detector at the LHC
Eur.Phys. J. C 73 (2013) 2431

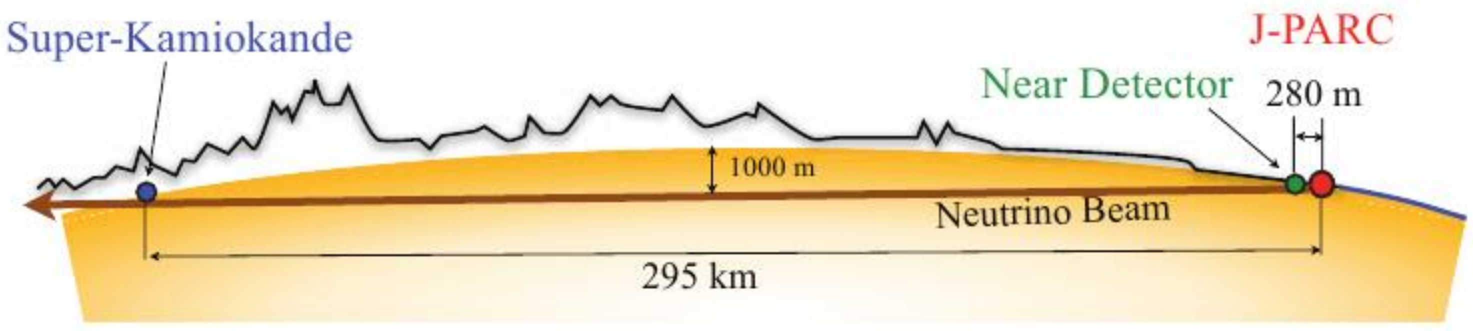
The Lord of the Rings

Photons from ice and sea under the sky,
  Photons from vast water tanks in halls of stone,
Photons from the atmosphere in an insect's eye,
  Photons from aerogels, light, clear, blown,
Photons from liquids, gases, crystals flying by,
  Photons from fused silica expanding on a cone.
In RICH detectors where PID truths lie.
  One Ring to rule them all, One Ring to find them,
  One Ring to bring them all, correlate, and bind them
In RICH detectors where PID truths lie.

(From B.N.Ratcliff, Nucl. Inst. Mech. A 501(2003) 211-221)

EXTRA SLIDES

Long Base Line Experients: T2K

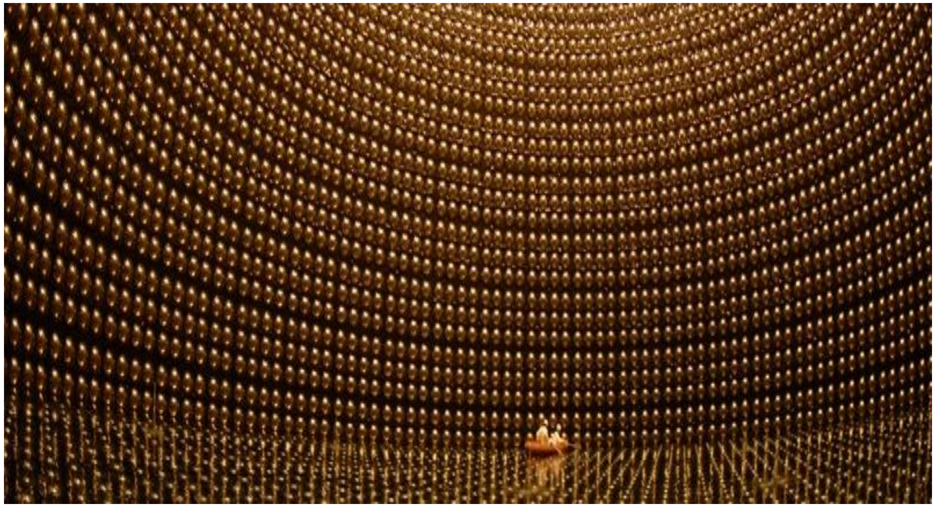


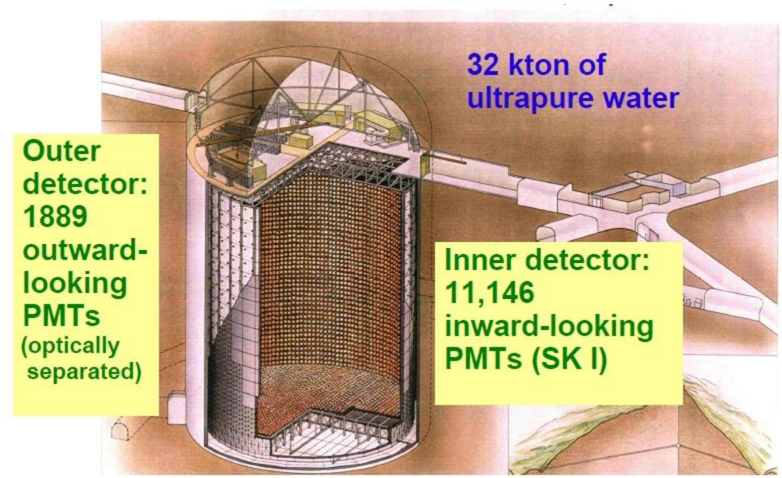
Neutrino production: Protons incident on graphite target to create pions, which decay into μ and $\nu_{\mu.}$ The muons and and any remaining protons and pions are stopped by a second layer of graphite; but the ν_μ pass through towards SuperK.

Beam energy: Centered around 600 MeV (to maximize the oscillation probability into ν_ε).

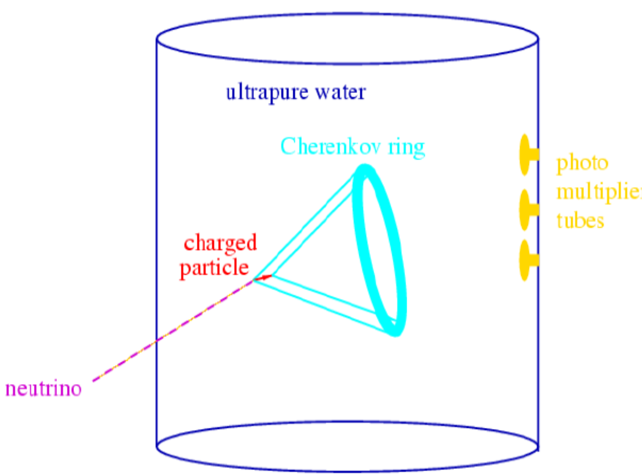
Far-detector: underground to reduce cosmic rays.

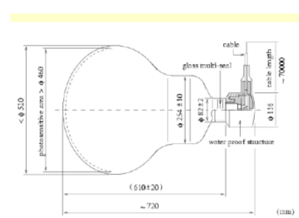
Super-K water cherenkov detector





40 m high, 17 m radius.





PMT-schematic

Super-K Cherenkov signals

- ν_e/ν_μ strike nuclei in H_2O, produce e^-/μ^- via weak charged-current (CC) interactions.

The leptons create Cherenkov light in the water.

Energy threshold $$E_{th} = \frac{m}{(1 - 1/n^2)^{1/2}}$$

(in water)

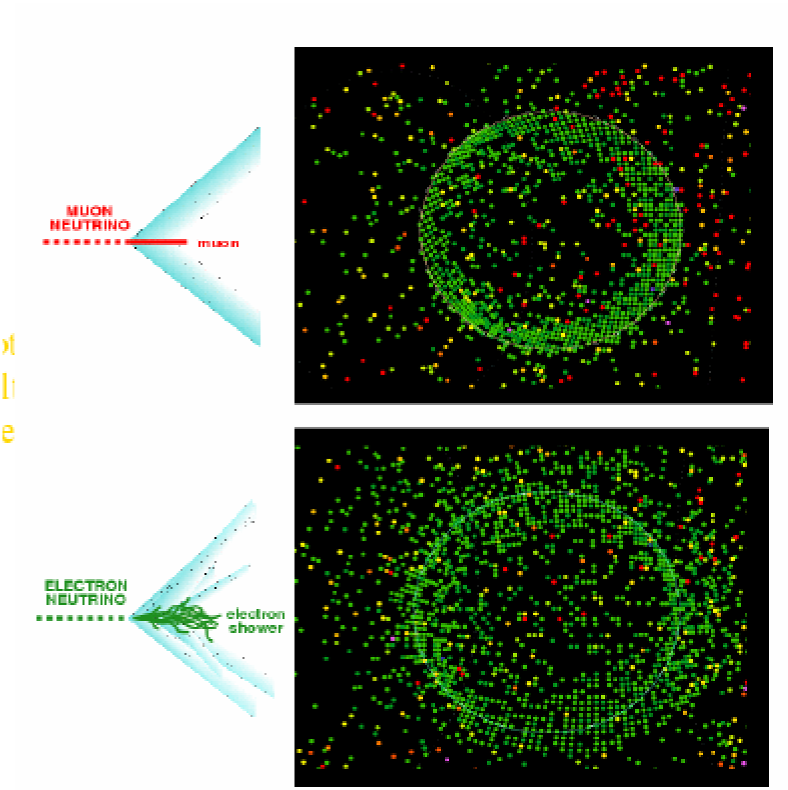
- e; p > 0.6 MeV/c
- m; p > 120 MeV/c (muon)
- π; p > 160 MeV/c
- K; p > 563 MeV/c
- p; p > 1,070 MeV/c

+ ~50MeV to identify a Cherenkov ring.

$\theta_c = 42^0$ for relativistic particle in water

$\beta \sim 1$

Super-K signals



Each dot represents a PMT hit by light

Measure the charge and time of each pulse. From this estimate :

(a) energy of the charged particle.
(Charge α number photons
α energy loss)

(b) position (vertex) of the interaction.

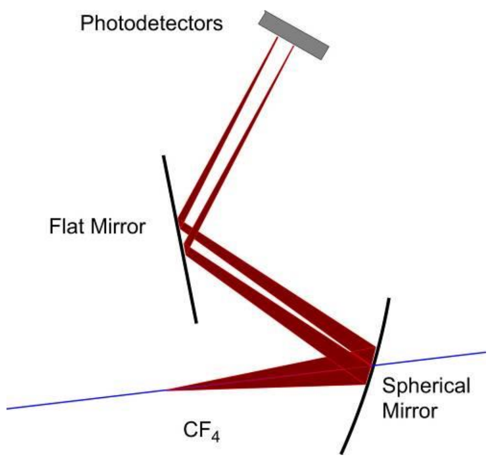
(c) direction of the charged particle.

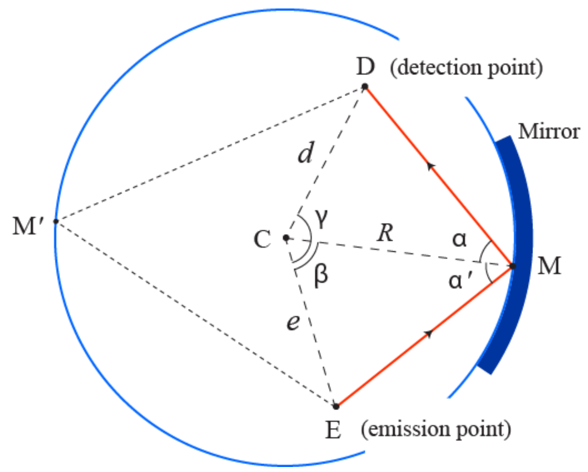
Muons create sharp rings,
Electrons scatter and shower and hence create ‘fuzzy’ rings.

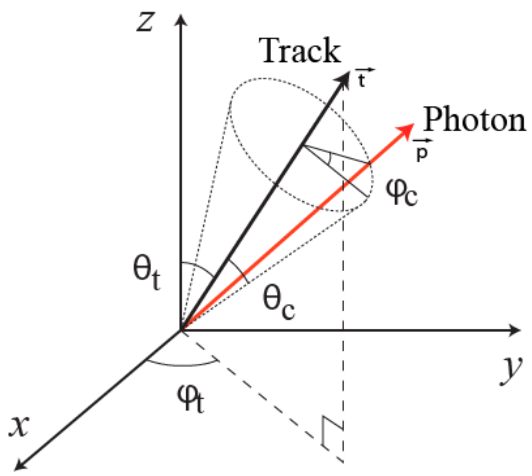
LHCb-RICH pattern recognition

Cherenkov angle reconstruction:

reconstructing the Cherenkov angle for each hit and for each track in the region of interest, assuming all photons are originating from the mid point of the track in the radiator.







Find the reflected point with respect to the flat mirror.
Use the fact that for the spherical mirror, the detection point (D), center of curvature (C), the reflection point (M) and the emission point (E) are on the same plane. Use D,C,E to solve for the reflection point M.

The Cherenkov angle is the angle between EM and the track direction.

Cherenkov angle reconstruction:

$$(Rd_y + 2ed_x \sin\beta)\ \cos\beta = R(e + d_x)\sin\beta + ed_y(1 - 2\sin^2\beta)$$

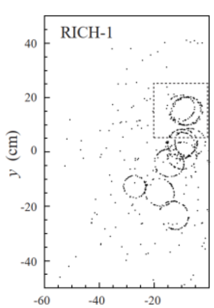
Squaring both sides and rearranging the terms, one gets a quartic equation to solve for sin β. With the solution, one determines the point M

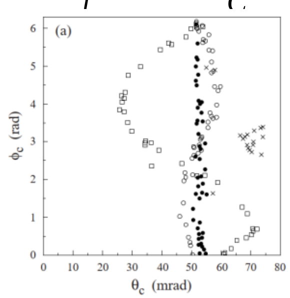
$$\cos\Theta_C = \vec{p}\cdot\vec{t}$$

$$\cos\phi_C = \frac{\cos\Theta_t \cos\Theta_C - \cos\Theta_p}{\sin\Theta_t \sin\Theta_C}$$

Here $\vec{p}$ = photon emission direction
= $\vec{EM}$

$\vec{t}$ = track direction





Reconstructed Cherenkov angles. The solid points are for the angles from the true track which created the hit

Brief description of the global algorithm for PID

- Project each charged track to the detector plane and select all RICH hits which are around each track projection, within the maximum possible Cherenkov radius.

- Create combinations of tracks and RICH hits.

  These constitute candidates for the 'photons' that created the hits.
  Determine the Cherenkov angles for these 'candidate photons'.

- For all the combinations of tracks and particle type hypotheses, determine the 'expected signals' on each MaPMT pixel and their uncertainty.

  This is done using a 'fast simulation' procedure.
  The average level of background expected for each MaPMT pixel is also added to this.

- The 'expected signal' is compared with the signal from 'candidate photons' in Cherenkov angle space. This is used to accumulate the 'likelihood' for each combination of tracks and particle type hypotheses.

  This enables to find the combination with the best 'likelihood'.

- The results on PID for each track are quoted in terms of the logarithm of likelihood ratios.

Ratio = likelihood for a particle type hypothesis / likelihood for pion hypothesis.

The algorithm runs in the Cherenkov angle space

Local algorithm
Each track is taken in turn.

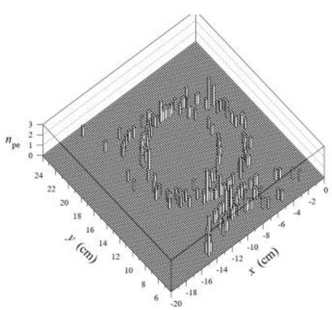
$$\ln \mathrm{L} = \sum_i \ln\left(1 + \frac{1}{\sqrt{2\pi}\sigma_\Theta \kappa} \exp\left[-\frac{(\Theta_i - \Theta_x)^2}{2\sigma_\Theta^2}\right]\right)$$

Θ_i : calculated emission angle for hit i
Θ_x : expected angle for hypothesis x
σ_Θ: angular resolution
κ: hit selection parameter

Global algorithm: This is actually used by LHCb these days
The likelihood is constructed for the whole event:

$$\ln \mathrm{L} = -\sum_{\text{track } j} \mu_j + \sum_{\text{pixel } i} n_i \ln\left(\sum_{\text{track } j} a_{ij} + b_i\right)$$

a_{ij}: expected hits from track j in detector/pixel i
$\mu_j = \Sigma_i\, a_{ij}$
n_i: hits in detector i
b_i: expected background in detector i



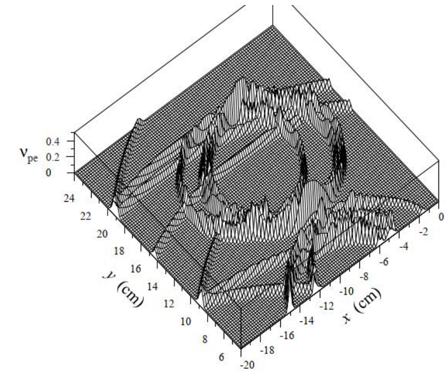
Observed number of photoelectrons in each pixel a small region on detector plane

Ref: "*RICH pattern recognition in LHCb*", *R.Forty Nucl.Inst.Meth. A 433 (1999) 257-261*

LHCb-RICH pattern recognition

The probability distribution expected for signal photoelectrons:

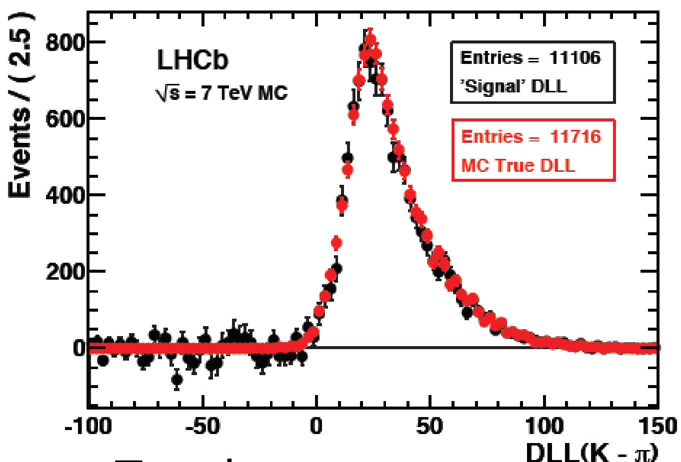
$$f_{h_j}(\theta,\phi) = \frac{1}{(2\pi)^{3/2}\,\sigma(\theta)}\,\exp\left[-\frac{1}{2}\left(\frac{\theta-\theta_c(h_j)}{\sigma(\theta)}\right)^2\right]$$



Expected number of photoelectrons in a small region on detector plane

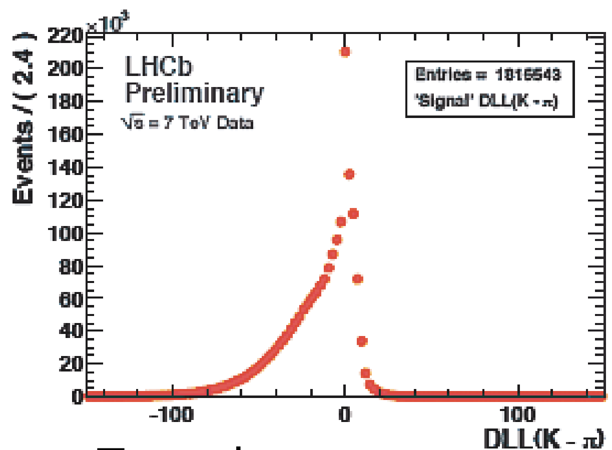
- The result of the algorithm is expressed in terms of

$$\Delta \ln \mathrm{L}_{K\pi} = \ln \mathrm{L}(K) - \ln \mathrm{L}(\pi)$$



True kaons

$$\Delta \log \mathcal{L}(\mathrm{K}-\pi)$$



True pions