Particle Identification

Graduate Student Lecture

Warwick Week

S. Easo, RAL
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Outline

- Introduction

- Main techniques used for PID (Particle Identification):
  - Cherenkov Detectors
  - Detectors using Energy Loss ($dE/dx$) from ionization and atomic excitation
  - Time of Flight (TOF) Detectors
  - Transition Radiation Detectors (TRD)

- Summary
  - Not Covered: PID using Calorimeters
  - Cherenkov Detectors: First part of the lecture
  - Focus on principles used in the detection methods.
Introduction

- Particle Identification is a crucial part of several experiments in Particle Physics. Identify Pions, Kaons, Protons, electrons, muons, tau etc.

- Tracking+Magnet: Measure the direction and momentum of charged particles
- Calorimeter: Measure the energy deposited in an Electromagnetic or Hadronic shower created by the particles.

- PID: (a) Use information from Tracking and Calorimeters alone.
  (b) Use additional information from ‘Particle Identification’ detectors.

- ‘PID’ detector:
  Reduction of combinatorial backgrounds

- More examples and other uses of PID detectors later in the lecture.
Cherenkov Detectors

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

\[ \cos(\theta) = \frac{1}{n \beta} \]

where \( n = \) Refractive Index = \( \frac{c}{c_M} = n(E_{\text{ph}}) \)

\[ \beta = \frac{v}{c} = \frac{p}{E} = \frac{p}{(p^2 + m^2)^{0.5}} = \frac{1}{\left(1 + (m/p)^2\right)^{0.5}} \]

\( \beta = \) 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) ,
\( E_{\text{ph}} = \) Photon Energy, \( \lambda=\)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 =

\[ \frac{dE}{dx} = \left(\frac{Z}{c}\right)^2 \int_{\varepsilon(\omega) > 1/\beta^2} \omega \left(1 - 1/(\beta^2 \varepsilon(\omega))\right) d\omega \]

Where \( \omega = \) 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

\[
\cos(\theta) = \frac{1}{(n \beta)}
\]

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

\(\theta\) has Maximum in a medium when \(\beta\) almost = 1 \(\iff\) p/m sufficiently high \(\iff\) Saturated Tracks

- Particle ID: \(\theta\) (p,m) ; If we measure p and \(\theta\) , we can Identify different particles with different m.

- Typically, in Accelerator based experiments, Momentum (p) is measured by a Magnetic Spectrometer : Tracking detectors and a Magnet.

- Cherenkov Detectors: Measure \(\theta\) : Resolution can be expressed in terms of \(\left( \frac{\Delta \beta}{\beta} \right)\)

Photonic Crystals: No Cherenkov Threshold and \(\theta > 90\) degree.

Not covered in this lecture: Reference: http://ab-initio.mit.edu/photons
Cherenkov Angle vs Charged Particle Momentum
Components of a Cherenkov Detector

Main Components:

- **Radiator**: To produce photons
- **Mirror/lens etc.**: To help with the transport of photons
- **Photodetector**: To detect the photons

Radiator: Any medium with a Refractive Index.

Aerogel: network of SiO₂ nano-crystals

Aerogel: network of SiO₂ nano-crystals

**Example of radiators**

<table>
<thead>
<tr>
<th>Medium</th>
<th>n-1</th>
<th>$\gamma_{th}$</th>
<th>Photons/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>He (STP)</td>
<td>$3.5 \times 10^{-5}$</td>
<td>120</td>
<td>3</td>
</tr>
<tr>
<td>CO₂ (STP)</td>
<td>$4.1 \times 10^{-4}$</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Silica aerogel</td>
<td>0.025-0.075</td>
<td>4.6-2.7</td>
<td>2400-6600</td>
</tr>
<tr>
<td>Water</td>
<td>0.33</td>
<td>1.52</td>
<td>21300</td>
</tr>
<tr>
<td>Glass</td>
<td>0.46-0.75</td>
<td>1.37-1.22</td>
<td>26100-33100</td>
</tr>
</tbody>
</table>

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

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

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

Typical Apparatus used by Cherenkov to study the angular distribution of Cherenkov photons. (Incident $\gamma$ 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.
n= n(\lambda): Different photons from the same charged track can have different Cherenkov Angles (\cos (\theta)=1/n \beta). This spread in angles gives rise to ‘Chromatic Error’ when measuring the average \theta.

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 Time-Of-Propagation of photons to estimate their wavelengths and correct for the Chromatic Error.
  \[ \text{Time} = \frac{\text{PathLength in the detector}}{\text{Velocity}} \]
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. $\lambda_{ph}$ 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)

  \[ N_{\text{prod}} = \frac{\alpha}{hc} Z^2 L \int \sin^2(\theta) \, dE_{ph} \]

  where \( \frac{\alpha}{hc} = 370 \text{ eV}^{-1}\text{cm}^{-1} \), \( E_{ph} = \frac{hc}{\lambda} \).

- If the photons are reflected by a Mirror 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:

  \[ N_{\text{det}} = \frac{\alpha}{hc} Z^2 L \int R \, Q \, T \sin^2(\theta) \, dE_{ph} \]

  \[ = N_0 \, L \sin^2(\theta_c) \quad \text{(If we assume } \theta \text{ is constant } = \theta_c \text{ = Mean Cherenkov Angle)} \]

- Figure of Merit of the detector = $N_0$  
  For example, $N_0 = 200 \text{ cm}^{-1}$ 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)

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

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

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

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IHEP [1]</td>
<td>1968</td>
<td>5</td>
<td>23</td>
<td>He, N₂</td>
<td>&lt;100</td>
<td>no optical correction</td>
<td>[3]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>12</td>
<td></td>
<td>&lt;200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DISC</td>
<td>1964</td>
<td>2</td>
<td>44</td>
<td>CO₂</td>
<td>&lt;100</td>
<td>corrected</td>
<td>[4]</td>
</tr>
<tr>
<td>FNAL DISC</td>
<td>1973</td>
<td>5.5</td>
<td>25</td>
<td>He</td>
<td>&lt;500</td>
<td>Id.</td>
<td>[2]</td>
</tr>
<tr>
<td>CEDAR W</td>
<td>1976</td>
<td>3.25</td>
<td>31</td>
<td>N₂</td>
<td>&lt;150</td>
<td>Id.</td>
<td>[5]</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>3.90</td>
<td>26</td>
<td>He</td>
<td>&lt;340</td>
<td>Id.</td>
<td></td>
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<tr>
<td>HYPERON DISC</td>
<td>1972</td>
<td>0.3</td>
<td>120</td>
<td>SF₆</td>
<td>&lt;40</td>
<td>Id.</td>
<td>[2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( &lt;100 for $\pi-\mu-e$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( &lt;100 for $\Sigma-p$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>For comparison: LDISC</td>
<td>1976</td>
<td>0.05</td>
<td>640</td>
<td>FC88 liquid</td>
<td>&lt;5</td>
<td>corrected high aperture</td>
<td>[6]</td>
</tr>
</tbody>
</table>
Differential Cherenkov Detectors

- Very small acceptance in $\beta$ and direction of the charged particle. (Narrow range in velocity and direction intervals).

- From the Cherenkov angle ($\theta$) determine $\beta$.

- Mostly used for identifying particles in the beam lines.

- Resolution that can be achieved = $\frac{\Delta \beta}{\beta} = \frac{(m_1^2 - m_2^2)}{2 \, p^2} = \tan \theta \Delta \theta$

- \[ m_1, m_2 \text{ (particle masses)} \ll p \text{ (momentum)} \]

- At high momentum, to get better resolution, use gas radiators which have smaller refractive index than solid radiators. Have long enough radiators to get sufficient signal photons in the detector.

- To compensate for Chromatic dispersion ($n \left(E_{ph}\right)$), lens used in the path of the photons. (DISC: Differential Isochronous self-collimating Cherenkov Counter).

- $\Delta \beta/ \beta$ from $0.011$ to $4 \times 10^{-6}$ achieved.
Threshold Cherenkov Counters

- Signal produced from only those particles which are above Cherenkov Threshold. Basic version: Yes/No decision on the existence of the particle type.

- One counts the number of photoelectrons detected.

- Improved version: Use the number of observed photoelectrons or a calibrated pulse height to discriminate between particle types.

- For typical detectors: \( N_o = 90 \text{ cm}^{-1} \).

\[
N_{ph} \text{ per unit length of the radiator} = N_o \times \frac{(m_1^2 - m_2^2)}{(p^2 + m_1^2)}
\]

At \( p = 1 \text{ GeV/c} \), \( N_{ph} \) per unit length = 16/cm for Pions and 0 for Kaons.

At \( p = 5 \text{ GeV/c} \), \( N_{ph} \) per unit length = 0.8/cm for Pions and 0 for Kaons.

- \( \Delta \beta / \beta = \tan^2 \theta / (2 \times \sqrt{N_{ph}}) \)
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
  \[ \Delta \beta/\beta = 2.3 \times 10^{-5} \] using gas radiator.

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

- BELLE: Continues to take Data.
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
- Measures both the Cherenkov angle and the number of photoelectrons detected.
- Can be used for particle identification over large surfaces.
- Requires photodetectors with single photon identification capability.
RICH detectors

- $\Delta \beta / \beta = \tan(\theta) \ast \Delta \theta_c = K$ where $\Delta \theta_c = <\Delta \theta> / \sqrt{N_{ph}} + C$

  where $<\Delta \theta>$ 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$^{-1}$
  $K = 1.6 \times 10^{-6}$.
  ($E=6.5$ eV, $\Delta E = 1$ eV)

  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 $\theta$ and $N_{ph}$ directly.

- RICH detectors have better resolution than equivalent Differential and Threshold counters.

- Let $u = \sin^2(\theta) = 1 - (1/n^2) - (m/p^n)^2$

  Number of standard deviations to discriminate between mass $m_1$ and $m_2$
  $= N_\sigma = (u_2-u_1) / (\sigma_u \ast \text{sqrt}(N))$ where $\sigma_u : \Delta \theta$ converted into the parameter $u$.
  ($\Delta \theta = \text{error in single photon } \theta \text{ measurement}$)

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

  This equation can be used in the design of the RICH detectors.

- One the first large size RICH detector: in DELPHI at LEP.
In this lecture, we focus on some of the aspects related to the detection of photoelectrons in Cherenkov Detectors.

- **Principle:**
  - Convert Photons \(\rightarrow\) 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 is not covered in this lecture.
  - Introduction to Silicon detectors already covered in another lecture of this series.

- 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

Examples of S20- photocathodes
Gas Based Photon Detectors

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

- Photon passes through the CaF₂ and converts to photoelectron by ionizing a TEA molecule.
- The photoelectron drifts towards and avalanches near the anode wires, thereby inducing a charge signal on the cathode pads.
Balloon Experiment:
RICH detector

TMAE:
(tetrakis(dimethylamino) ethylene)
Photodetector with CsI photocathode

- Used in ALICE experiment at CERN
- 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 mm²

- Total detector area: 12 m²
- Open geometry: using MWPC

Proximity focussing

Typical gain: $10^4$
Recent Developments: Gas Based Photodetectors

GEM: Gas Electron Multiplier

- 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.

GEM with semi-transparent Photocathode (K-Cs-Sb)
Vacuum Based Photodetectors

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

MAPMT

PMTs

Schematic of a photomultiplier tube coupled to a scintillator.
Features of HPD

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

- Band gap in Silicon = 3.16eV; Typical Max Gain = 20 keV / 3.16 eV = 5000 (approx)
Features of the PMTs and HPDs

- **PMT:**
  - Typical Gain of MAPMT 300 K.
  - Excellent time resolution: 125 ps for example (Ex: used in underwater Cherenkov detectors).
  - Active area fraction: 40 % : Fraction of effective detection area. This can be improved with a lens, but then one may lose some photons at the lens surface.
  - Recent developments: Flat panel pmts with 89 % active area fraction. New 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)

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

- **Vacuum based:**
  
  **Issues:**
  - Sensitivity to magnetic field
  - Cross talk between readout channels in case of MAPMTs
  - Active Area Fraction

  **Advantages:**
  - Can easily operate at high rate (eg. LHC rates and higher).
  - Operates also in visible wavelengths.
  - 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: APD, Silicon photomultiplier, HAPD, MCP etc.
Recent Developments: Silicon Photomultipliers

- Photon Detection Efficiency (PDE) for SiPM about 5 times that of ordinary PMT.
- Time resolution = ~100 ps.
- Works in magnetic field
- Gain = ~ $10^6$

- Reducing noise levels for single photon detection is still an issue and is being worked upon.
New Developments: Micro Channel Plate (MCP) Photon Detectors

Proximity focused MCP tube with 55um pixel readout

Photon

Quartz window and photocathode as HPD and MAPMT

50V/mm drift field

MCP cascade amplification (~1kV)

Bare readout chip array (no bump bonds)

Ceramic carrier with possible cooling built in

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

Cascade amplification similar in principle to a PMT

10um pores in an MCP
New Developments: Micro Channel Plates (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, but there are some solutions.

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 th gain and reduce ion-feed back
- Gain: ~ 5 * 10^5
- Typically ~1000 channels per MCP.

![Diagram of MCP](image)
- Precision measurement of B-Decays and search for signals beyond standard model.

- Two RICH detectors covering the particle momentum range $1 \rightarrow 100$ GeV/c using aerogel, $C_4F_{10}$ and $CF_4$ gas radiators.
LHCb-RICH 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 m³

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 m³
LHCb-RICH Specifications

RICH1: Aerogel  $C_4F_{10}$  $\rightarrow$ 10 GeV/c

$C_4F_{10}$  < 70 GeV/c

RICH2: CF$_4$  <100 GeV/c.

Aerogel  $C_4F_{10}$  CF$_4$

<table>
<thead>
<tr>
<th></th>
<th>Aerogel</th>
<th>$C_4F_{10}$</th>
<th>CF$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>5</td>
<td>86</td>
<td>196</td>
</tr>
<tr>
<td>$\theta_{c\text{max}}$</td>
<td>242</td>
<td>53</td>
<td>32</td>
</tr>
<tr>
<td>$\pi_{Th}$</td>
<td>0.6</td>
<td>2.6</td>
<td>4.4</td>
</tr>
<tr>
<td>$K_{Th}$</td>
<td>2.0</td>
<td>9.3</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Aerogel: Rayleigh Scattering

\[ T = A e^{-C \frac{t}{\lambda^4}} \]

Typically: $A=0.94$, $C=0.0059 \ \mu m^4/cm$
LHCb- RICH1 SCHEMATIC

RICH1 OPTICS

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

- Magnetic Shield
- Gas Enclosure
- Beam Pipe
- Spherical Mirror
- Flat Mirror
- Photodetectors
- Readout Electronics
- 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)
Typical Hits on LHCb-RICH HPDs

LHCb Preliminary data

- In 2010-11, LHCb-RICH continues to collect data.
- These data were aligned in space and time with the rest of LHCb. The particle identification performance was calibrated.
Examples of signals for $\Phi \rightarrow \Lambda\pi$, $K_s \rightarrow \pi\pi$, $D \rightarrow K\pi$, $\Lambda \rightarrow p\pi$ obtained using RICH.

The data from RICH used for Physics Analysis.
Example of LHCb-RICH PERFORMANCE

- Performance as seen in Simulated Data in 2006
- Yield: Mean Number of hits per isolated saturated track (Beta ~1).

<table>
<thead>
<tr>
<th>Components and Overall (mrad)</th>
<th>Aerogel</th>
<th>(C_4F_{10})</th>
<th>CF_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromatic</td>
<td>2.36</td>
<td>0.90</td>
<td>0.46</td>
</tr>
<tr>
<td>Emission Point</td>
<td>0.38</td>
<td>0.82</td>
<td>0.36</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>0.52</td>
<td>0.52</td>
<td>0.17</td>
</tr>
<tr>
<td>PSF</td>
<td>0.54</td>
<td>0.53</td>
<td>0.17</td>
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<tr>
<td>Overall RICH</td>
<td>2.53</td>
<td>1.44</td>
<td>0.66</td>
</tr>
<tr>
<td>Overall RICH+Tracks</td>
<td>2.60</td>
<td>1.60</td>
<td>0.70</td>
</tr>
</tbody>
</table>

- Chromatic: From the variation in refractive index.
- Emission Point: Essentially from the tilt of the mirrors.
- Pixel Size: From the granularity of the Silicon detector pixels in HPD
- PSF (Point Spread Function):
  From the spread of the Photoelectron direction as it travels inside the HPD, (from the cross focussing in the electron optics)
Red: From particles from Primary and Secondary Vertex
Blue: From secondaries and background processes (sometimes with no reconstructed track)
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, π, p 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.

LHCb-RICH pattern recognition

Efficiency for identification and probability for misidentification vs Particle momentum

\[ m_{B_s} = 5.37 \text{ GeV/c}^2 \]
\[ \sigma_{B_s} = 13.8 \text{ MeV/c}^2 \]

\[ m_{B_s} = 5.42 \text{ GeV/c}^2 \]
\[ \sigma_{B_s} = 24.0 \text{ MeV/c}^2 \]

\[ B^0_s \rightarrow D_s^- K^+ \quad B^0_s \rightarrow D_s^- \pi^+ \]

(signal) (background)

After using RICH, background at 10% level from 10 times level

Particle Momentum (GeV/c) →

From simulations
**dE/dx detectors: Silicon based**

Energy loss by ionization

Bethe-Block formula (for $2 \gamma \ m/M << 1$)

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

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

M, p = mass, momentum of the traversing particle

Ref: NIMA 469(2001) 311-315

FWHM = 30-35 %
**dE/dx Detectors: Silicon based**

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

CMS Silicon tracker:

![CMS Silicon strip wafer](image-url)
**dE/dx Detectors: Drift Chambers**

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

Larger Landau fluctuations compared to those from Silicon detectors. So many measurements needed to get the average.

**BABAR Drift Chamber:**

Gas mixture 80% helium, 20% isobutane, 3500–4000 ppm water vapor, ~ 80 ppm O₂

Good \(\pi/K\) separation up to \(\sim 700\) MeV/\(\pi\)


\(dE/dx\) resolution \(\sim 7.5\%\)
**Time of Flight (TOF) Detectors**

- For a charged particle traversing a detector:

  
  \[ m = p \left( \frac{(c t/L)^2 - 1}{0.5} \right) \]

  - \( m = \text{mass}, \ p = \text{Momentum}, \ t = \text{time}, \)
  - \( L = \text{distance travelled}, \)
  - \( c = \text{speed of light in vacuum}. \)

  Typically, the mass resolution here is dominated by the time resolution, for example when \( dp/p = 1\% \) and \( dL/L = 0.001. \)

  For two particles, for \( p >> m, \)

  \[ c \Delta t = L \left( m_1^2 - m_2^2 \right) / \left( 2 p^2 \right) \]

  At very high momentum, \( \Delta t \) will be too small and become comparable to detector resolution; so particle misID shall occur.

  \[ n = \text{separation in standard deviations} = \frac{L(m_1^2 - m_2^2)}{2 p^2 c \Delta t} \]

  Typical values: \( L = 3.5 \text{ m}, \ \Delta t = 100 \text{ ps}, \) for \( 3 \sigma \) separation, \( P_{\text{max}} = 2.1 \text{ GeV/c} \)
New detectors reach somewhat higher momentum limit. Example: LHCb upgrade proposal has a detector at $L=10$ m with $\Delta t=15$ ps, reaching up to 10 GeV/c for $3\sigma$ $\pi$–$K$ separation.

Ref: NIM A 433 (1999) 542-553
**Time of Flight (TOF) Detectors**

Measurement of time: Using scintillators

Energy loss \((dE/dx)\) from the charged particle = 2 MeV/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 = 59 ps, 95 ps

Had a TPC to measure \(dE/dx\).

Too expensive for large areas.
**Time of Flight (TOF) Detectors**

ALICE at CERN: using MRPC (Multigap Resistive Plate Chamber)

Gas detector

Resistive plates made of glass.
2 X5 gaps: 250 µm
The resistive plates stop the avalanche development.

Use HPTDC (High Performance TDC)

Performance in testbeam

Time resolution = 50 ps
PID in 0.5->2.5 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 $e^{-\pi}$ separation in $0.5 \text{ GeV/c} \rightarrow 200 \text{ GeV/c}$.

Full explanations and the derivations from Maxwell’s equations:
NIMA 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

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

where

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

$\xi_i = \omega_i / \omega_i$, $\omega_i =$ plasma freq of medium $i$
Transition Radiation Detectors (TRD)

Integration the previous equation, one can get, for $\xi_g = 0$, 

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

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

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

$\rho =$ density, $Z =$ atomic weight, $A =$ atomic number

For example, for $\omega_f = 0.02$ keV and $\gamma = 5000$, most of the photon energy is in the range $10$ keV $< \omega < 100$ keV (ie. $0.1 \omega_c < \omega < \omega_c$

where $\omega_c =$ 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 $\omega_c = 100$ 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)

• The minimum thickness of the foils and air gaps are determined by the size of the ‘formation zone’ and the interference effects. (typically foils can be 10-20 µm 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.

Example: HELIOS experiment (NA34)

Drift space=10 mm,
Anode space=6 mm
Drift time=0.5 → 1 µ s
May use FADC or discriminators
Transition Radiation Detectors (TRD)

ATLAS Transition Radiation Tracker

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)
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 current Accelerator based experiments and Astro Physics 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.

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
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.

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);
- …
Search for:
- Neutrinos $\rightarrow$ muons
- High energy Gamma and other Cosmic rays $\rightarrow$ Air showers
- Ultra high energy Gamma ($>10^{19}$ eV) $\rightarrow$ 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.
Neutrino Detection

Angle between the $\mu$ and $\nu$ direction =

\[ \theta \leq \frac{1.5 \text{ deg.}}{\sqrt{E_{\nu} \text{[TeV]}}} \]

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

- Typically $1\gamma$ / PMT
- 40 m from $\mu$ axis

- Measure position and time of the hits.
ANTARES Experiment in the sea.

La Seyne-sur-Mer, France

Optical Module

Hamamatsu PMT:
Size: 10 inch

Glass pressure Sphere.
Design Specifications

- Fully digital detector concept.
- Number of strings – 75
- Number of surface tanks – 160
- Number of DOMs – 4820
- Instrumented volume – 1 km³
- 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(10⁷) 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

$\nu_\mu$ from CC interactions

$\nu_e$ from CC or $\nu_x$ from NC interactions

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

All signals from Cherenkov Radiation.

$E_\mu = 10$ TeV

$\sim 300$ m for $>\text{PeV}$ $\nu_\tau$
EXTRA SLIDES
• 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 $6m^3$ 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 $\sim 1.5$ns, $\sim 30$mm diameter)

• **DIRC** is a 3-D device, measuring: $x$, $y$ and **time** of Cherenkov photons, defining $\theta_c$, $\phi_c$, $t_{\text{propagation}}$ of photon.
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):

\[ \sigma(\Delta \theta_c) = 2.4 \text{ mrad} \]

Track Cherenkov angle resolution is within \(~10\%\) of design.
Kaon selection efficiency typically above 95% with mis-ID of 2-10% between 0.8-3 GeV/c.
New Development: Focussing DIRC

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

\[ v_{\text{group (red)}} > v_{\text{group (blue)}} \]

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

→ Future DIRC needs to be smaller and faster:

- Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10
- Faster PMTs reduce sensitivity to background.

Additional benefit of the faster photon detectors:
- Timing resolution improvement: \( \sigma \sim 1.7 \text{ns (BABAR DIRC)} \rightarrow \sigma \leq 150 \text{ps (~10x better)} \)
  which allows measurement of photon color to correct the chromatic error of \( \theta_c \)
  (contributes \( \sigma \sim 5.4 \text{ mrad in BABAR DIRC} \))

Focusing mirror effect:
- Focusing eliminates effect of the bar thickness (contributes \( \sigma \sim 4 \text{ mrad in BABAR DIRC} \))
- However, the spherical mirror introduces an aberration, so its benefit is smaller.

Ref: NIMA 595(2008)104-107
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$^{-1}$
Fluorescence → Array of water → Cherenkov detectors

Principle of Auger Project
The Pierre Auger Observatory

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

- 1600 surface stations
  1.5 km spacing
  over 3000 square kilometers

- Fluorescence Detectors:
  4 Telescope enclosures, each with 6 telescopes.
- Installation of the Cherenkov detectors are continuing and data taking started.
- First set of results are published
LHCb Pattern Recognition

Particle Identification using the likelihood method.

(From Simulations )
Energy loss by muons \( \frac{dE}{dx} : \) Bethe-Block Formula

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

Ionisation Constant for material

Density correction

\[
T_{\text{max}} \approx 2m_e c^2 \beta^2 \gamma^2
\]

Max energy in single Collision.