Particle Identification

Lecture II: Detectors

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

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

- Photon detection is necessary for many of the detectors performing particle identification. 

  **Requirements**: single photon sensitivity, high efficiency, good spatial granularity

- Incident photon is (usually) converted to an electron by the photoelectric effect in a **photocathode**, typically formed of a combination of alkali metals, e.g., Sb-Na-K-Cs

- The photoelectron signal needs to be amplified to give a measurable electronic pulse

- Achieved in traditional photomultiplier (PM) by dynode chain → multiplication of the charge at each dynode: e.g., if number of electrons is tripled on each stage of a 12 dynode chain → Gain = $3^{12} \sim 10^6$
Detection efficiency

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

\[ E = \frac{hc}{\lambda} \]

\[ \lambda \text{ [nm]} \approx \frac{1240}{E \text{ [eV]}} \]

 QE for tubes with multialkali photocathode
Multianode PM

- The *multianode* photomultiplier is a marvel of miniaturization → up to 64 pixels in a single tube, each with size \( \sim 2 \times 2 \text{ mm}^2 \)
- Dynode structure formed from a stack of perforated metal foils
- Signal width dominated by fluctuations in the charge multiplication of the first dynodes
Micro-Channel Plates

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

MCP detector
- (Photonis)
- ~ 6 cm width
- Up to 1024 anode pads
Silicon PM

• Fully solid-state photon detectors are a very active field of development

• Use a p-n junction in Geiger mode (above the breakdown voltage) → large gain, binary signal, long recovery

• An array of ~ 100 such elements is used to provide a single pixel

• *Advantages*: very compact, high quantum efficiency
  *Disadvantages*: high noise, n damage?
Hybrid Photon Detectors

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

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

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

- **Disadvantages:** high voltage, ion feedback → requires very good vacuum.
HPD example

- HPDs developed for the LHCb RICH detectors in collaboration with industry
- 80 mm diameter tube has 1024 pixels each $\sim 2.5\times2.5$ mm$^2$ at the photocathode
  Uses a silicon sensor with $32\times32$ pixel array, bump-bonded to a readout chip which can read out the signals fast enough for the LHC (25 ns)
Gaseous photodetectors

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

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

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

\( L \) is the length of the radiator medium
\( \varepsilon \) is the efficiency for detecting the photons
- There is a threshold for light production at \( \beta = 1/n \)
  - Tracks with \( \beta < 1/n \) give no light
  - Tracks with \( \beta > 1/n \) give light
Threshold detectors

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

- By choosing a medium with a suitable refractive index, it can be arranged that the $\pi$ will produce light, but the protons will not.
Ring imaging

- Threshold counters just give a yes/no answer, and are less useful when the tracks have a wide momentum range. However, more information can be extracted from the Cherenkov angle.

- From a classic paper by J. Seguinot and T. Ypsilantis [NIM 142 (1977) 377] the Cherenkov cone can be imaged into a ring, using a spherical mirror.

\[ r \approx R \theta_C / 2 \]

- Measuring the ring radius \( r \) allows the Cherenkov angle \( \theta_C \) to be determined.
RICH detectors

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

- A wide variety of materials are used as RICH radiators
- Refractive index selected according to the momentum region to be covered
- **Aerogel** \( (n = 1.03) \) is a very light material made from silica \( \text{SiO}_2 \), good for low momenta \( p < 10 \text{ GeV} \)
- \( \text{C}_4\text{F}_{10} \) \( (n = 1.0014) \), a fluorocarbon gas, good for intermediate momenta
- \( \text{CF}_4 \) \( (n = 1.0005) \) is used in RICH-2 for high momentum region \( p > 20 \text{ GeV} \)
- Fluorocarbon gases are chosen because they have a low chromatic dispersion i.e. \( n \) does not depend strongly on \( E_{\gamma} \)
Resolution

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

| Material         | CF₄  | C₄F₁₀ | Aerogel |
|------------------|------|-------|---------|
| L [cm]           | 167  | 85    | 5       |
| n                | 1.0005 | 1.0014 | 1.03    |
| θ_{c}^{max} [mrad] | 32  | 53    | 242     |
| ρ_{thresh}(π) [GeV]| 4.4 | 2.6   | 0.6     |
| ρ_{thresh}(K) [GeV]| 15.6 | 9.3   | 2.0     |
| σ_{θ}^{emission} [mrad]| 0.31 | 0.71  | 0.66    |
| σ_{θ}^{chromatic} [mrad]| 0.42 | 0.81  | 1.61    |
| σ_{θ}^{pixel} [mrad]| 0.18 | 0.83  | 0.78    |
| σ_{θ}^{track} [mrad]| 0.20 | 0.42  | 0.26    |
| σ_{θ}^{total} [mrad]| 0.58 | 1.45  | 2.00    |
| N_{pe}           | 19.1 | 35.3  | 6.9     |
Mirrors

- The optics of a RICH detector requires mirrors, with high reflectivity to avoid losing photons.
- Traditional construction uses a glass substrate, with coating of Al for the reflective surface and then MgF$_2$ or SiO$_2$ for protection. Reflectivity $\sim 90\%$.
- In applications where minimizing the material budget is important, carbon fibre or Be substrates are used.

eg the RICH-1 spherical mirror is made from carbon fibre, $\sim 1\% X_0$.
Detector plane

Photo of installed HPDs

Data from an LHC run

Hits from single event

Roger Forty

Particle ID (Lecture II)
Pattern recognition

• In the busy environment of hadronic collisions (such as at the LHC) many tracks may pass through the detector → overlapping rings

• **Deciding which hit belongs to which track requires *pattern recognition***

• Most approaches rely on the use of the track to seed the ring search: after transformation through the optics of the RICH, the track image will lie at the centre of the ring

• The ring search then corresponds to the search for a peak in the number of photon hits versus radius from the track

Simulated event in RICH-1
Large rings: aerogel, small: $C_{4}F_{10}$
Particle separation

• Separating two particle types using the signal from a RICH detector is illustrated for K and π from a test beam

• \( \sim \) Gaussian response, \( \sigma_\theta \sim 0.7 \) mrad
Peaks are separated by 4 mrad = 6 \( \sigma_\theta \)

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

• Adjusting the position of the cut placed between the two peaks to identify a ring as belonging to a K or π gives a trade-off between efficiency and misidentification

• Studied in detail for the LHCb RICH system using Monte Carlo simulation
3. RICH examples

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

- Recall of the LHCb experiment:

  - RICH-1 already described, second RICH is for high momentum coverage
LHCb RICH-2

- Very large detector as sited downstream in the spectrometer
- Uses glass mirror substrates, CF$_4$ gas radiator

![Diagram of RICH-2 components: Flat mirrors, Spherical Mirrors, Support Structure, Central Tube, Photon Detectors + Shielding, Inside RICH-2]
ALICE HMPID

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

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

Law of refraction:
\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

- \( n_1 = 1.45 \) (quartz)
- \( n_2 \approx 1.0 \) (air)

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

*Diagram showing the internal reflection process and detector setup.*

*Image of DIRC detector with dimensions and materials.*
**DIRC performance**

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

![DIagram of DIRC](image)
Ice-Cube

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

Optical module
Super-Kamiokande

- Neutrino detector using water as the target and detector medium
- Clear separation (real data) of $\mu$- and e-like rings (showering)
  Misidentification rate < 1%
4. Other PID devices

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

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

- The Transition radiation energy emitted when charged particle crosses a boundary between vacuum and a medium with plasma frequency $\omega_p$
  \[ \Delta E = \alpha \hbar \omega_p \gamma / 3, \] where $\alpha = \text{fine structure constant} \approx 1/137$

- $\hbar \omega_p$ depends on the electron density in the material
  $\sim 20 \text{ eV}$ for a low-$Z$ material such as plastic (e.g., polypropylene)

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

- Low probability of photon emission at one interface ($\sim 1\%$)
  so many layers of thin foils are used for the radiator

Low $Z$ is important to limit re-absorption of the radiation

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

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

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

Simulated $B^0 \rightarrow J/\psi K_S^0$ event

High threshold hits identify electrons

5.5 keV
0.2 keV

Readout pulse
4. Time Of Flight

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

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

Scintillator hodoscope

Readout with PMs
Resistive Plate Chambers

- Fast thin-gap parallel plate detectors were proposed as alternative to scintillators, for low-cost, large-area TOF systems.
- Signal comes from ionization in the gas between the plates.
  High resistivity of the plates required (> $10^{10} \, \Omega \text{cm}$) to limit discharge area.
- *Multigap* RPCs use a stack of equally-spaced resistive plates with voltage applied to external surfaces.
- Pickup electrodes on external surfaces (resistive plates transparent to fast signal).
  Inner plates stop avalanche development → avoid sparks, and high dead time.
ALICE MRPC

- Made from stacks of 1 mm glass plates, each with 5 gas gaps of 250 µm
- Gas used is a complicated mixture: $\text{C}_2\text{F}_4\text{H}_2 + \text{SF}_6 + \text{C}_4\text{H}_{10}$
- Timing resolution as good as 70 ps has been achieved
TOF performance

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

\[ N_\sigma = \frac{|m_1^2 - m_2^2| \cdot d}{2 \cdot p^2 \cdot \sigma_t \cdot c} \quad \text{(TOF)} \]

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

\[ N_\sigma = \frac{|m_1^2 - m_2^2|}{2 \cdot p^2 \cdot \sigma_\theta \cdot \sqrt{n^2 - 1}} \quad \text{(RICH)} \]

- However, in that case there is an “amplification” factor of \(1/\sqrt{n^2 - 1}\) which allows RICH detectors to reach high momentum coverage (with a suitable \(n\))

- Combination of TOF with \(dE/dx\) can help remove ambiguities:
TORCH concept

- I am currently working on the design of a new concept for Particle ID for the upgrade of LHCb (planned to follow after ~ 5 years of data taking)
- Uses a large plate of quartz to produce Cherenkov light, like a DIRC But then identify the particles by measuring the photon arrival times Combination of TOF and RICH techniques → named TORCH

- Detected position around edge gives photon angle ($\theta_x$) Angle ($\theta_z$) out of plane determined using focusing Knowing photon trajectory, the track arrival time can be calculated
Proposed layout

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

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

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

• Transition radiation is useful in particular for electron identification

• Cherenkov detectors are in widespread use. Very powerful, tuning the choice of radiator

• Ionization energy loss is provided by existing tracking detectors but usually gives limited separation, at low $p$

• Time Of Flight provides excellent performance at low momentum. With the development of faster photon detectors, the range of TOF momentum coverage should increase

• There is still room for new ideas, for the next generation of experiments. Maybe one of your ideas?