7 Particle Identification

Detectors for Particle Physics
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We know already several methods to identify particles:

- Distinguish particles by their different shower parameters (e.g. electrons from hadrons) → calorimeter

- Identification of **muons** as the only charged particles penetrating the hadron calorimeter → calorimeter

- Identify weakly interacting particles by “missing momentum” and “missing energy” (e.g. neutrinos) → hermetic calorimeter/detector systems

- Identification of long lived particles by the reconstruction of secondary vertices (e.g. particles containing a c or b quark, or a tau lepton) → precise silicon vertex detectors (following slide)
7.1 Identification of short lived Particles
e.g. by the DELPHI vertex detector

The precise extrapolation of the particle tracks toward the interaction point reveals the existence of two secondary vertices.

→ Identify this event as a decay of two B mesons bb(\bar{b}):
In typical physics analyses of high energy physics experiments the separation of particle types is more important than the absolute mass determination.

We know the long living (stable) secondary particles and their masses. Identification is needed!

Example for different (long lived) particle masses:

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>μ</th>
<th>π⁺⁻</th>
<th>K⁺, K⁻</th>
<th>p, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c²)</td>
<td>0.511</td>
<td>106</td>
<td>140</td>
<td>494</td>
<td>938, 940</td>
</tr>
</tbody>
</table>
Identify particles by determining the mass! The mass is deduced from a combination of two measurements:

• In high energy experiments one measurement is usually the **momentum** \( p \). The momentum of charges particles is calculated from the curvature of the particles track in a magnetic field.

• The second measurement is a variable depending on the particle velocity \((v, \beta, \gamma)\) or energy

→ combine the measurements and calculate \( m \).

\[
m = \frac{p}{\beta \gamma}
\]

\[
E^2 = p^2 c^2 + m^2 c^4
\]
Methods and instruments discussed in this chapter:

- Time of flight measurements
- Multiple ionisation measurements
- Cherenkov counters
- Transition radiation detectors
7.2 Particle Separation

Different methods for different momenta

Separation of π and K, length of detector needed:

Each method is only applicable in a certain kinematic region.
7.3 Time of Flight Measurements (TOF)
Momentum range

TOF is applicable for low energies only
e.g.: Separate $\pi$ from $K$ with 4 standard deviations, $\sigma_t = 0.3$ ns ($\Delta t = 4\sigma_t = 1.2$ ns)
$\rightarrow L \sim 3$ m at $p = 1$ GeV/c but already $L \sim 12$ m at $p = 2$ GeV/c
Determine the particles velocity by measuring the flight time in a defined length.

→ Flight time difference of two particles m₁, m₂ with equal momentum p:

\[ \Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c} \left( \sqrt{1 + \frac{m_1^2 c^2}{p^2}} - \sqrt{1 + \frac{m_2^2 c^2}{p^2}} \right) \]

\[ p = m\gamma = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}} \]

→ For relativistic particles p² >> m²c²:

\[ \Delta t \approx \frac{(m_1^2 - m_2^2)Lc}{2p^2} \]

Detectors used are mostly plastic scintillators, typical time resolution of about 0.1 – 0.3 ns (depends on counter size).

At equal \( \Delta t \) (time resolution) the length of the flight path L (detector length) increases quadratically with the particles momentum p.
Energy loss of particles (dE/dx) depends on momentum p (Bethe-Bloch formula). To overcome statistical fluctuations measure ionisation of one particle multiple times.

Total energy loss -dE/dx for different particles measured in the PEP4/9 TPC (Ar–CH4 = 80:20 @ 8.5 atm):

Carsten Niebuhr, DESY Summer Student Lecture, 2004
Difference of the mean energy loss for $\pi$ and K:

\[ \frac{|I_\pi - I_K|}{I_K} \]

Discrimination is easy at low momentum ($1/\beta^2$ range of Bethe-Bloch formula). At high momentum (relativistic rise) the difference is only a few % (5% at 100 GeV).
Multiple ionisation measurements are usually done in gas detectors, e.g. drift chamber, time projection chamber. (Some experiments use also the signals from the silicon sensors)

The measurement of the ionisation is done at the same time as the measurement of the particle tracks.

Measurement in a TPC (PEP):
A charged particle travelling in matter (refraction index of n) with a velocity larger than the velocity of light in this material emits Cherenkov light.

★ Threshold velocity is:

\[ \beta_{\text{thr}} = \frac{1}{n}, \quad \gamma_{\text{thr}} = \frac{n}{\sqrt{n^2 - 1}} \]

- The Cherenkov light is emitted in a cone with opening angle: \( \cos \theta = 1/n\beta \)

- A saturation angle is reached at \( \beta = 1, \gamma = \infty \):
  \[ \cos \theta_{\text{max}} = 1/n \]
7.5 Cherenkov Counters

Principle

- Cherenkov detector in TASSO experiment
- Three different cherenkov thresholds
7.5 Cherenkov Counters
Properties of Cherenkov light

★ Cherenkov light is responsible for only appr. 0.1% of the energy loss.
★ Intensity of the produced Cherenkov light:

\[
\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2 \Theta = 370 (cm)^{-1} (eV)^{-1} L \sin^2 \Theta
\]

→ Number of photons produced per path length and energy interval is small.
★ Photon losses due to spectral sensitivity of photon detector, quantum efficiency of photon detector, transparency of the radiator, reflectivity of mirrors, etc. → typical value \( N_0 \sim 120\text{ eV}^{-1}\text{cm}^{-1} \)
7.5 Cherenkov Counters
Examples of different materials

Maximum Cherenkov angle and $N_{ph}$ for some radiator materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>$n$</th>
<th>$\Theta_{max}$ (deg)</th>
<th>$N_{ph}$ (eV$^{-1}$cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>1.000035</td>
<td>0.48</td>
<td>0.026</td>
</tr>
<tr>
<td>Air</td>
<td>1.000283</td>
<td>1.36</td>
<td>0.208</td>
</tr>
<tr>
<td>Isobutan</td>
<td>1.00127</td>
<td>2.89</td>
<td>0.941</td>
</tr>
<tr>
<td>Freon</td>
<td>1.233</td>
<td>35.8</td>
<td>126.6</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
<td>41.2</td>
<td>160.8</td>
</tr>
<tr>
<td>Quartz</td>
<td>1.46</td>
<td>46.7</td>
<td>196.4</td>
</tr>
<tr>
<td>BGO</td>
<td>2.15</td>
<td>62.3</td>
<td>290</td>
</tr>
</tbody>
</table>
7.5 Cherenkov Counters
Photon detectors

The following photon detectors are used for Cherenkov counters:

• Photo Multipliers (PM)
• Hybrid Photo Multipliers
• Wire chambers (DT, MWPC) with photo sensitive additives or CsI layer on the cathode
• GEM detectors with CsI photocathodes
• SiPM

![Diagram of Thick GEM and THGEM with UV photon and CsI photocathode]
7.5.1 Threshold Cherenkov Counters
Gas counters

The simplest Cherenkov counter for the discrimination of two particle types with different masses \((m_1, m_2)\) but the same momentum is a Threshold Cherenkov Counter: A tube filled with gas (e.g. He, CO\(_2\),...).

The light particle \(m_1\) travels above the Cherenkov threshold: \(v_1 > \frac{c}{n}\) □ signal !

The heavy particle \(m_2\) travels below the Cherenkov threshold: \(v_2 \leq \frac{c}{n}\) □ no signal

The refraction index and hence the threshold is adjusted by varying the gas pressure.
7.5.1 Threshold Cherenkov Counters

Aerogel counter

Alternatively use aerogel as radiator.
Aerogel (a form of $\text{Si}_x\text{O}_y$) with tuneable refraction index between $n=1.01 \ldots 1.13$.

Example Belle at KEK-B:

Threshold Cherenkov counters applied in collider experiments (e.g. Tasso, Petra):

Combination of several Threshold Cherenkov Counters with different refraction indices → discriminate between several particle types
Ring Imaging Cherenkov Counters (RICH) use also the information of the angle of photon emission. Geometry developed for collider experiments.

★ Photons generated in the (gas) radiator are reflected by a mirror

★ A photo detector is placed in the focal plane

→ ring of photons is mapped onto the photo detector
In solid or liquid radiators the number of photons produced per path length \( \frac{dN_{\text{ph}}}{dL} \) is much larger than in gases

→ radiator is thin

Proximity focusing
(no mirrors needed):

\[ \tan \varphi = \frac{R}{L} \]
7.5.2 Ring Imaging Cherenkov Counters
Example: The DELPHI Rich
7.5.2 Ring Imaging Cherenkov Counters

Example: The DELPHI Rich

Configuration of the DELPHI barrel RICH::

- Gas radiator
- Photo detector
- Liquid radiator
Two radiators used for the DELPHI RICH:
  - Gas radiator: $C_5F_{12}$
  - Liquid radiator: $C_6F_{14}$ (1 cm thick)

<table>
<thead>
<tr>
<th></th>
<th>Boiling point °C</th>
<th>$n$ (40°C)</th>
<th>$\gamma_{th}$</th>
<th>$\Theta_{max}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_5F_{12}$</td>
<td>28 (1 atm)</td>
<td>1.00176</td>
<td>16.9</td>
<td>3.40</td>
</tr>
<tr>
<td>$C_6F_{14}$</td>
<td>57</td>
<td>1.283</td>
<td>1.6</td>
<td>38.77</td>
</tr>
</tbody>
</table>

Photo detectors:
- UV sensitive Drift Chamber (75% CH$_4$ + 25% C$_2$H$_6$ + TMAE)
- TMAE: photosensitive additive
7.5.2 Ring Imaging Cherenkov Counters

Example: The DELPHI Rich - 4

Signals from a single event:

- **Liquid radiator:**

- **Gas radiator**:

accumulated events:

* Circle shows computer fit to detected photons
7.5.2 Ring Imaging Cherenkov Counters  
**Example: The LHCb RICHes**

Same principle but different geometry:

3 radiators: (aerogel, CF$_4$, C$_4$F$_{10}$)

Photodetektor: Hybrid PMT
7.5.3 Detector of Internally Reflected Cherenkov Light (DIRC)

Alternative geometry to measure the angle of the Cherenkov light in a collider experiment.
Example: DIRC at the experiment BaBar:
A charged particle traversing the boundary of materials with different dielectric constants $\varepsilon$ emits transition radiation.

- The total emitted energy $E_{\text{tot}}$ is proportional to $\gamma$
  - only fast electrons and positrons emit transition radiation
  - used for the identification of electrons and positrons

- The numbers of photons emitted per transition is very small
  - many transitions (boundaries) are needed

- The angle of emission is small $\Theta \sim 1/\gamma$

- Photons from the transition radiation are very close to the particle track
A possible detector geometry is an assembly with many hundred foils or a foam type material forming the radiator followed by photon detector (e.g. a multi wire proportional chamber).

To differentiate between the ionisation of the particle track and the signal from the transition radiation a gas with large $Z$ is used, e.g. Kr ($Z=36$), Xe ($Z=54$).

$\rightarrow$ optimise the ratio of signals

transition radiation + track / track only
To avoid absorption of the transition radiation (X ray) in the radiator itself low Z material is preferred.

Examples for radiator materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li (foils)</td>
<td>3</td>
</tr>
<tr>
<td>C (fibres)</td>
<td>6</td>
</tr>
<tr>
<td>Polyäthylen, Polypropylen (foils, foam)</td>
<td>6</td>
</tr>
<tr>
<td>Mylar (fibres)</td>
<td>8</td>
</tr>
</tbody>
</table>
Discrimination of $\pi$ from electrons:
electrons produce ionisation + transition radiation, $\pi$ ionisation only.

K. Kleinknecht, Detektoren für Teilchenstrahlung, B.G. Teubner, 1992
Measurement or particle tracks and discrimination of electrons from $\pi$

Radiator: polypropylene-polyethylene fibres (19 µm)
Detector: „Straw tubes“ embedded in radiator
Cross section of tubes 4 mm
Gas $\text{Xe/CO}_2/\text{O}_2$ 70%/27%/3%
7.6 Transition Radiation Detectors
Example: The ATLAS Transition Radiation Tracker - 2

Bilder: Präsentation F. Martin VCI2007