EP228 Particle Physics

Topic 4
Particle Detectors

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Course web page
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Outline

1. Introduction
2. Bubble Chambers
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- See also:
  - http://www.cern.ch
  - http://en.wikipedia.org/wiki/Particle_Detectors
  - http://en.wikipedia.org/wiki/Large_Hadron_Collider
1. Introduction

- A particle detector is a device used to detect, track, and/or identify high-energy particles.
- Some detectors are also used to measure the energy and spin of a particle.
Detectors employed in HEP experiments record *position, arrival time, momentum, energy* and *identity* of particles.

**Charged particles** \( (e^\pm, p, K^\pm, \mu^\pm, \pi^\pm) \) can be detected through their ionisation in tracking chambers

* a measure of the curvature of the track in a magnetic field gives a measure of its momentum
* a measure of the rate of ionisation loss \( (dE/dx) \) can be used to determine its type

**Neutral particles** \( (\gamma, n) \) are detected via calorimeters, where their position and energy are measured.
We need charged particle tracking in HEP experiments to determine:

- # of charged particles produced in a reaction
- the identity of a charged particle
- the momentum of a charged particle

\[
\frac{mv^2}{R} = qvB \quad \rightarrow \quad p = mv = BqR \quad \rightarrow \quad p(\text{GeV}) = 0.3BR
\]

*B in Tesla and R in meter*
2. Bubble Chambers

- A bubble chamber consists of a vessel filled with a liquid (hydrogen or a mixture of neon and hydrogen at a temperature of about 30K) heated nearly to the **boiling point**.

- When the pressure on the fluid is suddenly dropped, the fluid becomes **overheated**. At this moment electrically charged particles are fired through the chamber.

- The charged particles collide with liquid molecules, and give up some of their energy to them. The particles may knock electrons away from the molecules, leaving them electrically charged. In the heated, charged atoms and molecules surrounding the particles' paths, the liquid boils and forms a series of minute bubbles of vapor.

- Therefore, the fluid begins to boil along the paths of the particles, developing tiny bubbles that can be **photographed**.

- The bubble chamber, invented by Donald Glaser in 1952.
- K - p collisions
- K - p collisions
- K - p collisions
- **V0 Decays**

The component of the momentum perpendicular to the original path of the neutral particle, $p_{\perp}$, is given by:

$$ p_{\perp} = p \sin \theta \implies \sin \theta = \frac{p_{\perp}}{p} $$

But from similar triangles:

$$ \sin \theta = \frac{\left(\frac{L}{2}\right)}{R} = \frac{L}{2R} \implies L = \frac{2R}{p} p_{\perp} $$

But the radius of curvature $R$ is determined only by the momentum of the particle and the strength of the magnetic field:

$$ Bqv = \frac{mv^2}{R} \implies p = (Bq)R $$

so

$$ L = \frac{2R}{BqR} p_{\perp} = \left(\frac{2}{Bq}\right) p_{\perp} $$

as required.
Question: How can we determine the momentum \( p \) if we know only \( x \), \( L \) and magnetic field \( B \)?
3. Ionisation Detectors

- Ionisation detectors are devices designed to measure the ionisation produced when an incident particle traverses some medium.

- As we mentioned before, when a charged particle traverses a medium of a detector, it ionises the medium and produces electron-ion pairs.

\[- \frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \]
4. Time of Flight Detectors

- The time of flight (TOF) describes the method used to measure the time that it takes for a particle, object or stream to reach a detector while traveling over a known distance ($L$).

- This method is usually limited to low-energy particles with momenta less than about $p = 4$ Gev/c
- \( L \): particles’ path between two counters
- \( t \): time to traverse \( L \)

\[
\text{particle speed} = v = \frac{L}{t}
\]

- For two different particles with the same momentum \( p \) time difference is

\[
\Delta t = t_2 - t_1 = \frac{L}{v_2} - \frac{L}{v_1} = \frac{L}{c} \left( \frac{1}{\beta_2} - \frac{1}{\beta_1} \right)
\]

\[
= \frac{L}{c} \left( \frac{E_2}{pc} - \frac{E_1}{pc} \right) = \frac{L}{pc^2} \left( [m_2^2 c^4 + p^2 c^2]^{1/2} - [m_1^2 c^4 + p^2 c^2]^{1/2} \right)
\]

- For known momentum and time, the mass and its resolution of a particle is given by:

**measured mass:**

\[
m = p \sqrt{\frac{c^2 t^2}{L^2} - 1}
\]

**mass resolution:**

\[
\frac{dm}{m} = \sqrt{\left( \frac{dp}{p} \right)^2 + \gamma^4 \left( \frac{dt}{t} \right)^2}
\]
Example 1: Calculate the minimum flight path necessary to distinguish pions from kaons if they have momentum 3 GeV/c and TOF can be measured with an accuracy of 200 ps.

Solution

$$\Delta t = \frac{L}{pc^2} ([m_2^2c^4 + p^2c^2]^{1/2} - [m_1^2c^4 + p^2c^2]^{1/2})$$

$$\Delta t = \frac{L}{c} ([1 + m_2^2c^4 / p^2c^2]^{1/2} - [1 + m_1^2c^4 / p^2c^2]^{1/2})$$

$$200 \times 10^{-12} s = \frac{L}{3 \times 10^8 m/s} ([1 + 0.494^2 / 3^2]^{1/2} - [1 + 0.140^2 / 3]^{1/2})$$

Solving for $L$:

$$L = 4.8 m$$
Example 2: The momentum of a particle is measured as \( p = 2.0 \pm 0.1 \) GeV/c. If the time to travel the distance \( L = 6.0 \) m in TOF detector, whose time resolution is \( dt = 10.0 \) ps, is measured as \( t = 20.05 \) ns, determine the mass of and the mass resolution for this particle.

Solution

\[
m = p \sqrt{\frac{c^2 t^2}{L^2}} - 1 = 2 \sqrt{\frac{(3 \times 10^8)^2 (20.05 \times 10^{-9})^2}{5^2}} - 1 = 0.1415 \text{ GeV/c}^2
\]

\[
dm = m \sqrt{\left(\frac{dp}{p}\right)^2 + \gamma^4\left(\frac{dt}{t}\right)^2}
\]

\[
= 0.1415 \sqrt{\left(\frac{0.1}{2}\right)^2 + (14.2)^4 \left(\frac{10.00 \times 10^{-12}}{20.05 \times 10^{-9}}\right)^2} = 0.0158 \text{ GeV/c}^2
\]

Therefore: \( m = 141.5 \pm 15.8 \text{ MeV/c}^2 \) (charged pion)
5. Cherenkov Detectors

- If the velocity of a charged particle is larger than the velocity of light in the medium $v > c/n$ (n: refractive index), it emits ‘Cherenkov Radiation’ with cone angle
  \[
  \cos \theta_c = \frac{1}{n\beta} \quad (\beta = v/c)
  \]

- Number of photons generated ($N$) per unit length ($dx$) can be found from for the wavelength (lambda) is given by:
  \[
  \frac{d^2 N}{dx d\lambda} = \frac{2\pi \alpha}{\hbar c^2 \lambda^2} \left( 1 - \frac{1}{\beta^2 n^2} \right) \quad (\alpha = 1/137, \; \hbar = c = 1)
  \]
Example 3: Calculate number of generated photons/cm for the visible light (400-700 nm) in water (n=1.33) for charged particle of velocity beta ~ 1.

Solution

\[
\frac{dN}{dx} = \int_{400\text{nm}}^{700\text{nm}} \frac{2\pi}{137} \left(1 - \frac{1}{1.33^2}\right) \frac{d\lambda}{\lambda^2} = 215 \text{ photons / cm}
\]
Example 4: Compare Cherenkov angles of the pions and kaons of momentum \( p = 1 \text{ GeV/c} \) in water (n=1.33).

**Solution**

\[
p^{\text{kaon}} = p^{\text{pion}} = 1 \text{ GeV/c} \quad \rightarrow \beta^{\text{pion}} = 0.99034 \quad \text{and} \quad \beta^{\text{kaon}} = 0.89657
\]

\[
\cos \theta_c^{\text{pion}} = \frac{1}{(1.33)(0.99034)} = 0.7592 \quad \rightarrow \theta_c^{\text{pion}} = 40.6^o
\]

\[
\cos \theta_c^{\text{kaon}} = \frac{1}{(1.33)(0.89657)} = 0.8386 \quad \rightarrow \theta_c^{\text{kaon}} = 33.0^o
\]
6. Calorimeters

For electrons and photons of high energy, a dramatic result of the combined phenomena of *bramsstrahlung* and *pair production* is the occurrence of cascade showers.

A parent electron will radiate photons, which converts to pairs, which radiate and produce fresh pairs in turn, the number of particles increasing exponentially with depth in the medium.
7. Big Detectors

- Different particle types interact differently with matter e.g. photons do not feel a magnetic field.
- *Therefore, we need different types of detectors to measure different types of particles.*
The ALEPH Detector used between 1989-2000 at LEP
The ALEPH Detector
Recorded ALEPH Events

\[ Z \rightarrow e^+ e^- \]

\[ Z \rightarrow \mu^+ \mu^- \]

\[ Z \rightarrow q \bar{q} \]
LHC Detectors
LHC

lhc-olay.mpg

Large Hadron Collider

ATLAS Detector
Four Main Parts of ATLAS

- **Inner tracker**
  Measures the momentum of the charged particles

- **Calorimeter**
  Measures the energies of particles

- **Muon Spectrometer**
  Measures the energy of muons

- **Magnet System**
  Supplies the magnetic field to bend the charged particles for measuring p.
ATLAS Inner Tracker

- **Pixel Detector**
  - Closest the collision point
  - Gives 3D and 3 sp with resolution $\delta = 15 \, \mu m$
  - 1750 (60 mm x 20 mm) modules
  - 80 million pixels

- **SemiConductor Tracker: SCT**
  - Gives 3D 4 sp with resolution $\delta = 20 \, \mu m$
  - 780 (6 mm$^2$) semiconductor strips

- **Transition Radiation Tracker: TRT)**
  - Gives 2D 36 sp ($\delta = 170 \, \mu m$)
  - 370,000 straw tubes
  - Gas detector Xe(70%), CO$_2$(30%)
  - Identifies $e$ and $\pi$
ATLAS Calorimeter

The calorimeter measures the energies of charged and neutral particles. It consists of metal plates (absorbers) and sensing elements. Interactions in the absorbers transform the incident energy into a "shower" of particles that are detected by the sensing elements.

*In the inner sections of the calorimeter, the sensing element is liquid argon. The showers in the argon liberate electrons that are collected and recorded.*

*In the outer sections, the sensors are tiles of scintillating plastic. The showers cause the plastic to emit light which is detected and recorded.*
ATLAS Moon Spectrometer
Here, muons are detected and their momentums are are measured with high precision.

ATLAS Magnets

*Solenoid:* provides a uniform magnetic field of $B = 2\, \text{T}$ and bends the charged particles to measure their momentums.

*Toroid:* provides a non-uniform magnetic field to measure the momenta of the charged particle escaping from the calorimeters.
8. Exercises

1. Explain the operating principle of the Cherenkov detector.

2. Explain the operating principle of the Calorimeter.

3. (a) A radioactive source emits alpha-particles with kinetic energies of 4 MeV. What must be the value of an applied magnetic field so that the radius of curvature of the orbit of the alpha-particles is 10 cm? (b) Do the same calculation for electrons and protons of the same kinetic energy.

4. Estimate the minimum length of a gas (with $n = 1.0003$) Cherenkov counter which could be used in threshold mode to distinguish between pions and kaons with momentum 20 GeV/c. Assume that 200 visible photons (400-700 nm) need to be radiated to ensure a high probability of detection.
5. What are the Cherenkov angles for electrons and pions of 1 GeV/c for a radiator with \( n = 1.4 \)? What will be the ratio of the number of radiated photons for incident electrons and pions?

6. If the time resolution of each of two counters (of a TOF detector) that are 2 m apart is 0.2 ns, calculate to better than 10% accuracy the momentum at which the system will just be able to resolve a pion from a kaon.

7. Prove that for a particle in a magnetic field \( B \) (in Tesla) and having radius \( R \) (in meter) and charge \( e \), its momenta (in GeV) is given by:

\[
p(\text{GeV}) = 0.3BR
\]

8. In the figure in Page 11, the measured values \( x = 0.1 \) m and \( L = 1 \) m and the magnetic field \( B = 1.5 \) T are given. Determine the particle momentum \( p \).