Particle Identification

Many types of particles

- not just kinematics ($\vec{p}$, $E$) important to measure
- need their identity
  - leptons: $e$, $\mu$, $\tau$
  - neutral: $\gamma$, $\pi^0$, $\eta$, ...
  - charged hadrons: $\pi^\pm$, $K^\pm$, $\rho^\pm$, ...
  - weakly interacting: $\nu$, $\bar{\nu}$, ...

Each particle species has a unique combination of

- charge $z$
- mass $m$
- form of interaction (EM, strong, weak)

If known $\vec{p}$ or $E$, then a measure of $\beta$

Provides mass constraint

Sedimentation or distillation yields $z$ measure

Shower properties $\Rightarrow m$ or $e^+ / e^-$ or $\nu / \bar{\nu}$, hadrons
Some Measurements (example)

Radius of curvature, $\rho$, of charged particle track in $B$-field

$$\rho \propto \frac{1}{\beta} = \frac{y \mp ce}{\beta}$$

Measuring time of travel (time-of-flight)

$$\tau \propto \frac{1}{\beta} \quad \text{or} \quad \theta_{\text{rad.}} = \frac{1}{\beta}$$
$$\text{or} \quad \theta_{\text{cor}} = \frac{1}{\beta}$$

A measure of kinetic energy

$$E_k = (y-1)mc^2$$

This gives 3 relations in 3 unknowns

$m, z, (\beta, \gamma)$

- can identify mass and charge
Types of Interactions

Requires material sensitive to distinction

\[ M_\mu - M_\nu \quad \text{AND} \quad Z_\mu = Z_\nu \]

But when incident on a large mass

\[ \mu^- \quad \text{and} \quad \pi^+ \rightarrow \mu^- \]

\[ \text{hadronic shower} \]

Several \( \pi^- \)

Very different behaviors allow discrimination

Consider a photon and an electron

\[ e^- \quad - \text{similar showers} \quad - \text{difference in } \Delta E/\Delta x \]

\[ \gamma \quad - \text{hadronic showers} \]

\[ \text{Several } \pi^- \]
Timing Applications - Scintillators

Nanosecond (or better) timing resolution an important capability

Time-of-flight (TOF)

- use for low momentum particles
- can use to identify particle mass

Measure time of traversal between two points

\[
\tau_{1,2} = L \left( \frac{1}{\beta} \right) = \text{"TOF"}
\]

Comparing the TOF for two different particles of same momentum

\[
\Delta \tau = \text{TOF}_A - \text{TOF}_B = \frac{L}{c} \left( \frac{1}{\beta_A} - \frac{1}{\beta_B} \right)
= \frac{L}{p c^2} (E_A - E_B) \quad \text{(where } p c = \beta E)\]

\[
\Delta \tau = \frac{L c}{2 p^2} \left( m_A^2 - m_B^2 \right) \quad \text{where } p c \gg mc^2
\]

and expand

\[
E = \sqrt{p^2 c^2 + mc^2} \approx mc^2 + \frac{1}{2} \left( m_A^2 - m_B^2 \right) \left( \frac{1}{\beta_A^2} - \frac{1}{\beta_B^2} \right)
\]

\[
\Delta \tau \propto \frac{1}{p^2} \quad \text{(small for large momenta)}
\]
Scintillator device

- can obtain time resolution of 10-100 ps
- for a 1 m (≈ L) detector + 0.1 ns resolution:
  - PK separation up to 1 GeV/c
- for a 10 m detector: Δτ ≈ 4 ns
- can now go to several GeV

Spark Chambers

\[ ΔV > \text{breakdown voltage} \]

Operate detector so ionization leads to avalanche, and then
- then conducting plasma channel between electrodes
- sudden rise in current \( \Rightarrow \frac{dV}{dt} \text{ large} \)
  - can trigger on this signal

→ Resistive Plate Chambers (RPCs)

- similar: reduce gas pressure
  - operate in avalanche mode
  - trigger in same way (abrupt \( \frac{dV}{dt} \))
Ionization Measurements

Consider a drift chamber setup

\[ \Delta V \]

- gives momentum-dependent ionization measurement

- for some gases, \( \frac{dE}{dx} \) rises by 50%-60% for momenta from 0.1 to 100 GeV/c (Ar - xenon)

Want to maximize difference (DS) in \( \frac{dE}{dx} \) in region of relativistic rise between 2 species
- gaseous detectors have smaller density change
- very difficult to separate \( \pi + \mu \) at same momentum \( \Rightarrow (\Delta n + D \text{ too small}) \)

Resolving power = \( DS / \sigma_{dE/dx} \)
Fluctuations in energy loss

- Large random fluctuations
  - Can be bigger than total size of relativistic shell: 30% - 100%
  - Mean large overlaps in E² distributions
  - Inefficient discrimination

Potential remedies
- Higher density reduces rise size
- Increase gas sample thickness
- Sample ionization many times

Example: Several planes of drift regions

Reduces resolution, but still have large tail from Č rays

- Don’t highest energy loss measurements
  - “Truncated mean”

- Many measurements can get σ ≈ 5%
  - Roughly \( \sigma \propto \frac{1}{\sqrt{N}} \) (N = # measurements)

Pure hydrocarbons better than noble gas mixtures (95% Ar, 5% CH₄)
- But smaller relativistic shell
Likelihood Calculation

When we omit high energy less measurements:

- lose information: $dE/dx$ in some layers
- bias overall measurement

One way around: use all information more carefully

Consider histogram of $dE/dx$ for a $\pi^+$

$P_{\pi^+}(dE/dx)$ is probability
take in bin $dE/dx$ to $dE/dx + 

- "probability density function"

For some particle $x$: calculate overall probability from $N$ measurements, to be a $\pi^+$

$$P = \frac{1}{N} \prod_{i=1}^{N} P_{\pi^+}(A_i)$$

$A_i$ are $N$ measurements of $dE/dx$

Similarly

$$P = \frac{1}{K} \prod_{i=1}^{K} P_k(A_i)$$
We then calculate the overall relative "likelihood" to be a \( \Pi \) as

\[
L = \frac{P_m}{P_m + P_k}
\]

This distribution will have values from 0...1.

For \( K \),

For \( M \),

\[
\text{for } K \quad \text{and} \quad \text{for } M
\]
Transition Radiation Detectors

General structure
- many foils of high dielectric
- a gas ionization detector

For extremely high $\gamma$ particles (e$^+$):
- see charge from transition radiation (TR)
  and from ionization

For more massive particles (e.g., hadrons):
- just observe $dE/dx$
Example: ATLAS Transition Radiation Tracker (TRT)

370K kapton straw tubes

- conduction film on kapton walls
- cathode

- anode: 30um gold-plated tungsten wire

- polypropylene foils as radiator

Gas: 70:20:3 as Xe; CO₂; O₂

- high X-ray absorption cross section

As a tracker: use drift time to obtain coordinates
- 1 anode 6-130um

Particle Identification:

- based on measured energy deposited
  - TR ~ 8-10 keV
  - MIP ~ 2 keV

- may define threshold such that
  \( \frac{T}{T_{\text{fail}}} = \frac{T}{T_{\text{pass}}} \)

\( @ 90\% (e(e) \rightarrow 1.2\% e(\gamma)) \)

Sufficient