Particle Identification Techniques

- Basic definitions and introductory remarks
- Ionization energy loss
- Time of Flight
- Cherenkov radiation
- Transition radiation

Advised textbooks:
R. Fernow, Introduction to Experimental Particle Physics, Cambridge University Press
R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
Complete event analysis (based on the reconstruction of conservation laws): 4-momenta of secondary particles

\[(\vec{p}, E)\]

Deflection in a magnetic field (+ sign of particle's charge)

Calorimetry (destructive measurement)

PID measurement

\[E = \sqrt{m^2 c^4 + \vec{p}^2 c^2}\]

“m” uniquely identifies the internal quantum numbers of the particle

Example:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (MeV/c^2)</th>
<th>Charge</th>
<th>Strangeness</th>
<th>J^p</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>938.27</td>
<td>+1</td>
<td>0</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>n</td>
<td>939.57</td>
<td>0</td>
<td>0</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>(\pi^+)</td>
<td>139.57</td>
<td>+1</td>
<td>0</td>
<td>0^-</td>
</tr>
<tr>
<td>(\pi^0)</td>
<td>134.96</td>
<td>0</td>
<td>0</td>
<td>0^-</td>
</tr>
<tr>
<td>(e^+)</td>
<td>0.511</td>
<td>+1</td>
<td>0</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>(\mu^+)</td>
<td>105.7</td>
<td>+1</td>
<td>0</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>K^+</td>
<td>493.7</td>
<td>+1</td>
<td>+1</td>
<td>0^-</td>
</tr>
<tr>
<td>K^0</td>
<td>497.7</td>
<td>0</td>
<td>+1</td>
<td>0^-</td>
</tr>
</tbody>
</table>
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E.Nappi
INFN-Bari

A Look at the Past

70’s: Hydrogen bubble chamber

1978: BEBC
A “Modern” Approach to PID

ALICE at LHC
(talk by Prof. Gerardo Herrera Corral)

Silicon trackers + TPC (PID with energy loss)

Ring Imaging Cherenkov detector

TOF

TRD

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Layers of silicon detectors with excellent position (0(10 µm)) and double track (0(100 µm)) resolution near the primary collision region

- detection of secondary vertices (short-lived strange and heavy flavor particles)
- impact parameter resolution $\sigma(r\phi) \sim 50$ µm for $p_t \sim 1$ GeV/c
- primary vertex resolution: $\sim 10$ µm
- momentum resolution improvement
- PID with energy loss

TPC, away from the interaction region, at more moderate particle densities

- tracking ($\delta p/p$ at the level of 1% for low momenta)
- PID with energy loss
PID Usefulness: Examples

No PID

One K identified

Two Ks identified

$\phi \rightarrow K^+K^-$

$m_\phi = 1020$ MeV/c$^2$

$$M = \text{invariant mass} = \frac{1}{c^2} \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_j p_j c\right)^2}$$

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Background Reduction

Examples: measurements of $D_0 \to K^+\pi^-$ and $D^- \to K^+\pi^+\pi^-$ at WA89 (OMEGA RICH)

and

$B \to \pi^+\pi^-$ at LHCb

(simulated data)
Measuring the Particle Velocity

\[ p = mc^2 \gamma \beta; \gamma = \frac{E}{mc^2} \] (Lorentz factor)

\[ \left( \frac{dm}{m} \right)^2 = \left( \gamma^2 \frac{d\beta}{\beta} \right)^2 + \left( \frac{dp}{p} \right)^2 \]

\[ \frac{dp}{p} \approx 0 \]

\[ m_1^2 - m_2^2 = p^2 \frac{\Delta \beta (\beta_1 + \beta_2)}{c^2 (\beta_1 * \beta_2)^2} \]

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

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Particle Identification Techniques

PID techniques are based on the detection of particles via their interaction with matter: ionization and excitation (Cherenkov light & Transition Radiation). The applicable methods depend strongly on the particle momentum (velocity) domain of interest.

π-K identification ranges

<table>
<thead>
<tr>
<th>Method</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR+dE/dx</td>
<td></td>
</tr>
<tr>
<td>Cherenkov</td>
<td>electron</td>
</tr>
<tr>
<td>dE/dx</td>
<td>identification</td>
</tr>
<tr>
<td>TOF 150 ps</td>
<td>gas RICH</td>
</tr>
<tr>
<td>FWHM</td>
<td>liquid RICH</td>
</tr>
</tbody>
</table>

p (GeV/c)

DELPHI particle ID

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Efficiency & Contamination

\[ \text{efficiency} = \varepsilon_{A \rightarrow A} = \frac{N_{A-\text{identified}}}{N_{A-\text{total}}} \]

\[ \text{contamination} = \varepsilon_{B \rightarrow A} = \sum_{B, B \neq A} \frac{N_{B-\text{identified}}}{N_{A-\text{identified}}} \]

\( \rightarrow \) higher efficiency \( \rightarrow \) larger contamination

(Example: ALICE-ITS simulation)
N.B. in case of samples with different population: at a given separation power, the resulting contamination of the largest populated sample of particles in the other species will be larger by a factor equal to the ratio between the relative populations.
Energy Loss Mechanisms

Basic processes occurring when a charged particle traverses a medium being surrounded by a cloud of virtual photons that interacts with atoms in the medium

- ionization and excitation of the atoms of the medium (secondarily produced electrons could further ionize the medium)
- radiative phenomena
  - Cherenkov radiation
  - Transition radiation

Overall effect: the particle loses energy

Detection of the energy lost is the physical basis of many of the techniques used in charged particle detectors

Ionization trail: particle’s trajectory and velocity information
Charged Particle-Matter Interactions

Modern approach (unitary description in terms of matter properties): Allison and Cobb (1980)
- Charged particle moves in a dielectric medium through which virtual photons propagate
- The particle loses energy by doing work against the field created by the medium polarization

Photons are virtual, their energy and momentum are independent $E \neq pc$
- the integral must be performed over both energy and momentum separately
- virtual photon behaviour approximated with a combination of cross sections for the interactions of real photons allowing to perform the momentum integration for virtual photons

$$\frac{dE}{dx} = -n \int_0^\infty dE \int_0^E dp E \frac{d^2\sigma}{dEdp}$$

Density of atoms: $n = \rho N_A / A$

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**Ionization Energy Loss**

**Classical approach**: Bethe-Bloch equation modified to include the Fermi effect

**Average specific energy loss:**

\[
\frac{dE}{dx} = -0.3071 \frac{Z}{A} \rho \cdot t \frac{z^2}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_ec^2 \beta^2 \gamma^2 E_{\text{max}}}{I^2} - \frac{\beta^2}{2} - \frac{\delta}{2} - \frac{C}{Z} \right]
\]

- Valid only for particles with \(m > m_e\)
- \(dE/dx\) does not depend on \(m\) but on the charge \(z\)
- Non relativistic region: \(dE/dx \propto 1/\beta^2\)
  (more precisely as \(\beta^{-5/3}\))
- Minimum: at \(\beta \gamma = 3 \div 4\) (Minimum Ionizing Particle)
  \(\frac{dE}{dx}_{\text{mip}} \approx 1 \div 2\ \text{MeV}\ \text{g}^{-1}\text{cm}^2\)
- At high \(\beta \gamma\): \(dE/dx \propto \ln \gamma^2\) (relativistic rise)
- Density effect: \(\delta(\beta \gamma)\)
  (medium polarization reduces long range effects)
  - saturates at \(\beta \gamma_{\text{sat}}\):
    - 230 Ar
    - 68.4 CH₄
    - 55.3 C₂H₆
    - 42.4 C₄H₁₀
    - 5.6 Si

\[Z=\text{atomic number of the medium; } I \sim Z \cdot 12\ \text{eV}=\text{effective ionization potential; } E_{\text{max}} = \text{max energy transfer (} I \leq dE \leq E_{\text{max}}\text{)}\]
Particle ID using the specific energy loss $dE/dx$

\[ p = m \beta \gamma \]
\[ \frac{dE}{dx} \propto \frac{1}{\beta^2} \ln(\beta^2 \gamma^2) \]

\[ m \text{ from simultaneous measurement of } p \text{ and } dE/dx \]

\[ n_\sigma = \frac{dE_A/dx - dE_B/dx}{\sigma(dE_B/dx)} \]

Fermi plateau is a few percents above the minimum in solid and liquid media, 50-70\% in high Z noble gases at STP -> PID in the relativistic rise region only possible in gases!

$\pi/K$ separation ($2\sigma$) requires a $dE/dx$ resolution of few percents

"cross-over" regions (as wide as $\pm 100$ MeV/c)

Ambiguities -> complementary PID mandatory

Average energy loss in 80/20 Ar/CH$_4$ (NTP)

(J.N. Marx, Physics today, Oct.78)
\[ \langle \frac{dE}{dx} \rangle \] is practically measured by evaluating \( \Delta E \) in a short interval \( \delta x \), but this is not necessarily the average energy lost in the given slice of material – the distribution shows large fluctuations and Landau tail.

Most interactions involve little energy exchange – the total energy loss from these interactions is a Gaussian (central limit theorem). Few interactions involve large energy exchange – Landau tail.

Because of the high energy tail, increasing the thickness of the detector or choosing high Z material does not improve \( \sigma(\frac{dE}{dx}) \). Indeed, the relative width of Gaussian peak reduces but the probability of high energy interaction rises – tail gets bigger.

B. Adeva et al., NIM A 290 (1990) 115
Samples must not be too many:
for each total detector length L, there exists
an optimal N

Rule of thumb: at least N=100 for a total track
length of 3-5 m/atm

(M. Aderholz, NIM A 118 (1974), 419)

Improve dE/dx resolution and fight Landau tails

Thick absorber: large chance of high energy δ ray production cancels the reduction
of fluctuations \( \rightarrow (dE/dx)_A - (dE/dx)_B < \) Landau fluctuations

Usual method of measuring dE/dx is:

- Choose material with high specific ionization
- Divide detector length L in N gaps of thickness T.
- Sample dE/dx N times
- Calculate truncated mean, i.e. ignore samples with (e.g. 40%) highest values
- Also pressure increase can improve resolution. Drawback: reduced relativistic
rise due to density effect!
Particle Separation

\[ N_{S.D.}(A; B) = \frac{dE / dx(A) - dE / dx(B)}{\sigma (dE / dx)} \]

- \( dE/dx \) resolution (A.H. Walenta et al. Nucl. Instr. and Meth. 161 (1979) 45)

\[ \sigma (dE / dx) \propto n^{-0.43 \div -0.47} (t \cdot p)^{-0.32 \div -0.36} \]

- \( n \): number of sampling layers,
- \( t \): thickness of the sampling layer (cm)
- \( p \): pressure of the gas (atm)

Remarks:
- \( \sigma \) does not follow the \( n^{-0.5} \) dependence owing to the Landau fluctuations;
- if the total lever arm \( (nt) \) is fixed, it is better to increase \( n \); so long as the number of produced ion-pairs is enough in each layer.
**TPC: basic principle**

**Time Projection Chamber → full 3-D track reconstruction**
- **x-y** from wires and segmented cathode of MWPC
- **z** from drift time -> precise knowledge of $v_D$ (LASER calibration + p,T corrections)
- **dE/dx**

**Drift over long distances → very good gas quality required**

**Gate open**

**Gate closed**

$\Delta V_g = 150$ V

**Space charge problem from positive ions, drifting back to medial membrane → gating**

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Tracker evolution

80’s: 6.4 TeV Sulphur - Gold event (NA35)

2000: STAR

TPC

STREAMER CHAMBER

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- Gas: P10 (Ar-CH₄ 90%-10%) @ 1 atm, 50,000 Liters
- Voltage: -31 kV at the central membrane
  148 V/cm over 210 cm drift path

Self supporting Inner Field Cage:
Al on Kapton using Nomex honeycomb; 0.5% rad length
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Two-track separation 2.5 cm
Momentum Resolution < 2%
Space point resolution ~ 500 μm
Rapidity coverage |\( \eta \) | < 1.5

A Central Event
Typically 1000 to 2000 tracks per event into the TPC
PID via $dE/dx$ with the STAR TPC

$dE/dx$ PID range:
- ~ 0.7 GeV/c for $\pi$
- ~ 1.0 GeV/c for K/p

Gas: P10 (Ar-CH$_4$ 90%-10%) @ 1 atm

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ALICE TPC

Field Cage Inner Vessel

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gas volume
88 m³
drift gas
90% Ne - 10% CO₂

6x10⁵ channels, corresponding to 6x10⁸ pixels in space

Central membrane frame
$N_{ch}(-0.5<\eta<0.5)=8000$

\[ \sigma \frac{dE}{dx} = 10\% \]
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Drift Velocity Control:
- Lasers for coarse value
- Fine adjustment from tracking

TPC: experimental issues

- mechanical tolerances (gain and electrical field)
- stability of high voltage power (gain)
- space charge effects (track distortion)
- gating efficiency (background)
- temperature, pressure (drift velocity)

Drift Velocity vs. Pressure:

![Drift Velocity Graph](image)

- Drift Velocity (cm/µs) vs. Pressure (mbar)
- Examples from STAR
\[
\sigma \left( \frac{dE}{dx} \right)_{\text{calc}} = 0.41 n^{-0.43} (t \cdot p)^{-0.32}
\]

<table>
<thead>
<tr>
<th>Type</th>
<th>n</th>
<th>t (cm)</th>
<th>p (bar)</th>
<th>Gas</th>
<th>Calc.(%)</th>
<th>Meas.(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>52</td>
<td>1.5</td>
<td>1</td>
<td>He/C_2H_6 = 50/50</td>
<td>6.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Babar</td>
<td>40</td>
<td>1.4</td>
<td>1</td>
<td>He/C_4H_{10} = 80/20</td>
<td>7.5</td>
<td>7.2</td>
</tr>
<tr>
<td>CLEO II</td>
<td>51</td>
<td>1.4</td>
<td>1</td>
<td>Ar/C_2H_6 = 50/50</td>
<td>6.4</td>
<td>5.7</td>
</tr>
<tr>
<td>ALEPH*</td>
<td>TPC</td>
<td>338</td>
<td>0.4</td>
<td>Ar/CH_4 = 90/10</td>
<td>4.6</td>
<td>4.5</td>
</tr>
<tr>
<td>PEP*</td>
<td>TPC</td>
<td>183</td>
<td>0.4</td>
<td>8.5</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>OPAL*</td>
<td>Jet ch.</td>
<td>159</td>
<td>1.0</td>
<td>4 Ar/CH_4/iC_4H_{10} = 88.2/9.8/2</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>MKII/SLC*</td>
<td>Drift ch.</td>
<td>72</td>
<td>0.83</td>
<td>1 Ar/CO_2/CH_4 = 89/10/1</td>
<td>6.9</td>
<td>7.0</td>
</tr>
</tbody>
</table>

* Data from M. Hauschild (NIM A 379(1996) 436)

- Higher pressure gives better resolution, however, the relativistic rise saturate at lower $\beta \gamma$. $\Rightarrow$ 4 – 5 bar seems to be the optimal pressure
- Higher content of hydro-carbons gives better resolution (Belle and CLEO II).
  $\Rightarrow$ Landau distribution (FWMH); 60% for noble gas, 45% for CH_4, 33% for C_3H_6