Charged Particle ID in Belle II

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Jan Strube
Outline

• Background
  ▪ How to measure particle ID
• PID Detectors in Belle II
• Hands-on session
  ▪ Reconstruction of D* decays and study of PID performance
The Belle II detector
Density correction:
Density dependent polarization effect ...
Shielding of electrical field far from particle path; effectively cuts of the long range contribution ...
More relevant at high $\gamma$

For heavy particles ($m \gg m_e$):

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]$$

U. Tamponi
Using a sample of single particles, we can measure the degree of separation between different particle species.
Coverage of the tracking detectors

dE/dx is used also here, but the separation power is not excellent.
Cherenkov Detectors

When a charged particle in a medium moves faster than the speed of light in that medium, the particle emits Cherenkov radiation.
Properties of Cherenkov Radiation

\[ \frac{d^2 N}{dxd\lambda} = \frac{2\pi \alpha z^2}{\lambda^2} \left( 1 - \frac{1}{\beta^2 n^2(\lambda)} \right) \]

Integrate over sensitivity range: [for typical Photomultiplier]

\[ \frac{dN}{dx} = \int_{350\text{ nm}}^{550\text{ nm}} d\lambda \frac{d^2 N}{d\lambda dx} = 475 z^2 \sin^2 \theta_C \text{ photons/cm} \]

\[ \frac{d^2 N}{dEdx} = \frac{\alpha z^2}{hc} \sin^2 \theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2} \left( 1 - \frac{1}{\beta^2 n^2(E)} \right) \]
Endcap Particle ID

- Aerogel Ring Imaging Cherenkov Detector
- Two aerogel layers with different refractive indices (1.045/1.055) result in a sharper image
- $K/\pi$ separation for a wide momentum range (0.7 GeV – 4.0 GeV)
Coverage of the tracking detectors + ARICH

$p \text{ [GeV/c]}$

$\cos(\theta)$

- SVD Only
- SVD + CDC
- ARICH
ARICH reconstruction

- Likelihood is based on the comparison of expected photon patterns for a given particle type with the measured photon patterns.

\[
\mathcal{L}^h = \prod_{i \in \text{pixels}} p_i^h \\
\]

\[
p_i^h(m_i) = \exp(-n_i)n_i^{m_i}/m_i! \\
Poissonian probability for a pixel with \(n_i\) average hits to show \(m_i\) hits for this track
\]

In our case, the pixel is either hit (\(m_i=1\)) or not hit (\(m_i=0\))

\[
p_i(0) = \exp(-n_i) \\
p_i(1) = 1 - p_i(0) = 1 - \exp(-n_i)
\]
ARICH expected number of hits

Expected number of hits on pixel $i$

$$n_i = n_i^1 + n_i^2 + n_i^{bg}$$

Expected number of photons emitted from layer $r$

$$N_r = \frac{dN_{ch}}{dx} \lambda_{abs} (1 - \exp(-d/\lambda_{abs}))$$

Also possible photon loss on the edges and between aerogel tiles is taken into account to get $N_r$ detection efficiency in the track internal coordinate system.
Implementation of ARICH probabilities

We reconstruct \((\theta_i, \phi_i)\) of each photon hit in the track coordinate system (taking into account refractions).

Then we apply ray tracing from the emission point at the angle \((\theta^h_c, \phi_i)\) to the detection plane.

\[
\int_{\Omega_i} \frac{1}{2\pi} G(\theta, \theta^r_h, \sigma^r_h) d\theta d\phi
\]

\[
\int_{S_i} G(x, 0, \sigma_x) dx dy
\]
ARICH hit patterns

\[ N = \epsilon_{\text{acc}} \epsilon_{\text{det}} (N^1 + N^2) + N_{\text{bg}} \]

Detection efficiency

Ring acceptance

Number of photons from 1\textsuperscript{st} and 2\textsuperscript{nd} layer, respectively

Geometric acceptance of the Cherenkov ring

The expected number of photons depends on the particle hypothesis

After propagating 200 “dummy photons” at the expected \( \theta_{hc} \) and uniformly distributed in \( \phi \), we can just count how many fall on HAPDs

Expected number of photons in Cherenkov ring for 3 GeV pions vs. track position on the aerogel plane
From photon times to particle ID

The different reflections in the bar result – for a given incident position on the bar – in different photon arrival times in each channel.

The combined likelihood of all of the measured photons is the input to the PID.

Probability distribution for a given type, momentum, incidence.
An example of a Likelihood analysis in the iTOP

**Belle II TOP 2018 (Preliminary)**

$D^*$ kinematically tagged kaon

$p = 1.41 \text{ GeV/c}$

$\theta = 45.4^\circ$

Pion PDF

$\log L(\pi) = -265.83$

Kaon PDF

$\log L(K) = -250.81$

Proton PDF

$\log L(p) = -294.08$
Coverage of the tracking detectors and Cerenkov detectors (most of the PID system)
Electromagnetic interactions

- Photoelectric effect
  \[ \gamma + \text{atom} \rightarrow \text{atom}^+ + e^- \]

- Compton effect
  \[ \gamma + e \rightarrow \gamma' + e' \]

- Pair production
  \[ \gamma + \text{nucleus} \rightarrow e^+ e^- + \text{nucleus} \]

- Ionisation
  \[ \text{d}E/\text{dx} \rightarrow E \]

- Bremsstrahlung
  \[ \text{d}E/\text{dx} \rightarrow E \]
The signal processing in the ECL improved between Belle and Belle II

- **Shaper output** \( (\tau=1.0\mu s) \)

  - Gate width \( (\Delta t=100\text{ns}) \)
  - Signal charge
  - Charge-to-time converter (QTC)
  - Digitizer (TDC)
  - Amplitude

- **Waveform Digitizer, 1.76 MHz, 18 bit**

  - FPGA fits to extract **Amplitude** and **Time**
Pulse-Shape Discrimination (PSD)

- First time pulse shape discrimination (PSD) is used in an $e^+e^-$ collider experiment
- New variable based on a BDT trained (on MC) to separate photons and $K^0_L$ using all pulse shapes in a cluster
- Will be included in charged particle identification to improve muon vs. pion separation
Different stages of reconstruction in the ECL

Crystal energy

Shower (no timing selection)

Cluster (timing selection, \(E_{\text{Cluster}} > 20 \text{ MeV}\))

Belle II Simulation

Belle II Simulation

Belle II Simulation

Clustering

User analysis
Particles with low transverse momentum ($p_t < 0.5 \text{ GeV/c}$) do not reach our muon system:

→ Baseline particle identification depends on $E/p$ and is very poor.

→ Clustering itself difficult, since these particles leave long, charge dependent, trails in the calorimeter.
Deep learning methods to improve the PID in the ECL

- Approach under study:
  - No clustering
  - Extrapolate tracks to calorimeter
  - Analyse 5×5 pixel calorimeter images around impact crystal using convolutional networks
Coverage of all of the detectors surrounded by the solenoid magnet

For illustration, only. Do not use this plot to get some serious number

The d80Ld dominates the d electron identification.
The $K_0^L$ – Muon detector (KLM)

Endcap KLM: scintillator strips
(14 layers fwd, 12 layers bwd)

Barrel KLM:
Inner 2 layers: Scintillator strips
Outer 13 layers: RPC
(glass, not bakelite)

Angular resolution of hit from the IP: better than 10 mrad (4 cm)
FNAL scintillator for barrel

Scintillator strip

Wavelength-shifting fiber

Rubber spring

Connectors

1.3 x 1.3 mm²
667 pixels

Detect WLS-fiber light with Geiger-mode avalanche photodiode ("SiPM" or "MPPC")

1.3 x 1.3 mm²
2667 pixels

Rubber spring

Scintillator strip developed for T2K near detector operates in 1.5 T magnetic field rad-hard (>10⁸ year lifetime in KLM)

8-pixel threshold gives >99% efficiency

Wavelength-shifting fiber

Hamamatsu S10362-13-050C attached to one end of fiber (fiber is mirrored at the other end)
Coverage of the detectors in the Belle II experiment

The KLM dominates the muon identification.
Particle ID in Belle II analyses

Current implementation:

• Each subdetector measures the likelihoods for 6 basic species
  ▪ Electron
  ▪ Muon
  ▪ Pion
  ▪ Kaon
  ▪ Proton
  ▪ Deuteron

• Particle ID for a given species is the combination for all detectors

\[
\log \mathcal{L}_\pi = \log \mathcal{L}^{SVD}_\pi + \log \mathcal{L}^{CDC}_\pi + \log \mathcal{L}^{TOP}_\pi + \log \mathcal{L}^{ARICH}_\pi + \log \mathcal{L}^{ECL}_\pi + \log \mathcal{L}^{KLM}_\pi
\]
Example: Particle separation in the iTOP detector

Belle II TOP 2018 (Preliminary)

\[ \int L \, dt = 90 \, \text{pb}^{-1} \]

- \( D^* \) kinematically tagged kaons
- Pion background not subtracted

Entries / 4 units of \( \Delta LL \)

\[ \Delta LL = \log L(K) - \log L(\pi) \] (TOP only)
Performance characterization

• Two basic concepts to characterize the performance of a detector
  ▪ Efficiency
  ▪ Purity
  ▪ Usually the likelihoods overlap, so deciding on a cut is always a trade-off between the two

• Some people like to quote a “fake-rate”. I find this confusing and will use only efficiencies
  ▪ The efficiency to correctly identify a particle of type A in a sample of mostly As
  ▪ The efficiency to erroneously identify a particle of type B in a sample of mostly As
    ✓ This latter term is sometimes called “fake rate”
    ✓ Except by people who confuse A and B…
Hands-on session

• In the hands-on session you will follow the steps to reconstruct the decay
  \[ D^* \rightarrow D_0 \; (K \pi) \, \pi \]

• The Kaons and pions can be very cleanly reconstructed without using particle ID, so this is a good channel to test the PID performance

• The notebook is making a couple of plots you can use to study the performance of the different detectors
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Backup
KLM

→ Muons do not interact that much (why?)
→ Muons are more likely than any other particle to survive the solenoid and the steel plates

ECL

→ Electrons are showering as photons are (why?)
→ Hadrons may leave distinctive signatures (hadronic showers)
Pulse-Shape Discrimination (PSD)

- Online FPGA waveform fits use photon templates only and provide time and amplitude fit results (2 variables).
- New: Exploit the fact that hadronic and electromagnetic scintillation components are different.
  - If crystal energy $E > 30$ MeV: Store waveform data (31 variables) and repeat fit offline with different templates.
- Third information from a crystal: PSD.

Sample Fit of Hadron Pulse in Collision Data

Belle II Phase 2 data – preliminary

S. Longo, ICHEP2018

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**Graph:**

- Data
- Offline Photon+Hadron Fit
- Photon Component
- Hadron Component

**Table:**

- Cell ID: 5590 (brl)
- $E_{\text{Total}} = 125$ MeV
- $E_{\text{Hadron}} = 54.01$ MeV
- $I_\text{fit} = 0.431$
- $\chi^2 = 29.3$ (NDF=27)
Binary or global PID?

A very simple example: a magic universe where only pions and kaons exist.

We observe a “kaon-like” signal.
What’s the probability for that particle to be a kaon?

\[
P(S \text{ is from } K) = \frac{P(K \text{ gives } S) \cdot P(K)}{P(K \text{ gives } S) \cdot P(K) + P(\pi \text{ gives } S) \cdot P(\pi)}
\]

Posterior probability

Prior probability
Binary or global PID?

The likelihood value is actually a proxy (i.e. is proportional) exactly to the conditional probability!

\[ P(S \text{ is from } K) = \frac{L(K) \cdot P(K)}{L(K) \cdot P(K) + L(\pi) \cdot P(\pi)} \]

\[ P(A) = \frac{L_A}{L_c + L_\mu + L_\pi + L_K + L_p + L_d} \]

→ Global and binary PID are simply different priors schemes
→ Non-trivial priors are not implemented yet
Performances

Few metrics are used to characterize the performances of a PID detector

→ **Efficiency:** ability to correctly assign the ID

\[ \varepsilon(K) = \frac{N(\text{K identified as K})}{N(\text{real K})} \]

Equal, by definition, to the “probability of a kaon to be called kaon”

→ **Mis-ID probability:** ability not to assign the incorrect ID

\[ \text{Mis-ID}(K) = \frac{N(\text{non-K identified as K})}{N(\text{non K})} \]

Equal, by definition, to the “probability for a non-kaon to be called kaon”

→ **Fake rate:** fraction of particles with the wrong ID

\[ F(K) = \frac{N(\text{non-K identified as K})}{N(\text{identified as K})} \]

Equal, by definition, to the “fraction of non-kaons in my collection of kaons”