Belle II Particle ID: 
dE/dx from the CDC

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Outline

Teaser: a nice dE/dx band plot

Quasi-Stable Particles
PID & Velocity

dE/dx Basics: CDC structure, ionization, universality

Reconstruction: Truncated means
Calibrations: Types & Plots of some calibration “constants”

Charge Asymmetries
Using dE/dx PID

Monte Carlo

Conclusions

NOTE: CMU [Jitendra Kumar & I] do all CDC dE/dx calibration, maintain reconstruction code, and supply the current “track-level” MC simulation of CDC dE/dx. I will not discuss dE/dx in the SVD which is done by others (some concepts are similar)
A classic dE/dx “band plot”

Separation is related to mass

“Blind spots” at band crossings

Best separation at lower momenta

Calibration goal: make bands narrow

CLEO-c Ultra-Clean Tracks

a previous experiment I worked on took data 2004-2008 or so…
**Quasi-Stable Particles I**

**Heisenberg:** \( \Delta E \Delta t > \hbar \) becomes \( \Gamma \tau \sim \hbar \sim (70 \text{ MeV}) \times (10^{-23} \text{ s}) \)

*short lifetime \( \tau \) implies uncertain rest-energy (mass) of order \( \Gamma \)

( notice the inequality disappears: Nature pushes Heisenberg to the limit! )

**Hadronic “resonances” (strong decay):** \( \Delta, K^*, \rho \) \( \Gamma \sim 100 \text{ MeV wide} \rightarrow \tau \sim 10^{-23} \text{ s} \)

**EM decays, quarkonia (suppressed strong):** \( \eta, J/\psi, \Upsilon \sim \text{keV to } \sim \text{MeV} \)

Even the “long-lived” \( \pi^0 \): \( \Gamma \sim 8 \text{ eV} \rightarrow 0.8 \times 10^{-16} \text{ s} \)

**Heavy quark hadrons (weak decays):** \( B, D, D_s, \Lambda_c \) \( \tau \sim 10^{-12} \text{ s} = 1 \text{ ps} \)

ALL very short lived!  *Short compared to what???*  \(< \text{beam pipe radius} \ldots \)

**Average Flight length before decay:** \( \tau \) is mean lifetime

\[
< L > = \gamma (\beta c) \tau = (\beta \gamma) (c \tau) = (p/m) c \tau = 1 \text{ ps} = 300 \text{ microns (\mu m)}
\]

**Useful connections:**

\[
\frac{E^2 - p^2 = m^2}{m^2} \Rightarrow \gamma^2 - (\beta \gamma)^2 = 1
\]

with \( \gamma = E/m \), \( \beta \gamma = p/m \), \( \beta = p/E \)

[ Also, realize that \( \beta, \gamma, \beta \gamma \) are all interchangeable: easy to calculate one from another… ]
Quasi-Stable Particles II

There are only a handful of “Quasi-stable” particles:

If \( \tau \sim 10^{-10} \text{s} \), then \( \langle L \rangle \sim 3 \text{ cm} \)

**Charged**: \( e, \mu, \pi, K, p, d \) \( \leftrightarrow \) These are the domain of \( \text{dE/dx} \) !!!

**Neutral**: \( \gamma, \nu, n, \Lambda^0, K_S, K_L \)

plus ~five more less-common “hyperons” = strange baryons (cousins of \( \Lambda^0 \)): \( \Sigma^+, \Sigma^-, \Xi^0, \Xi^-, \Omega^- \)

here, “d” = deuteron = bound pn (deuterium nucleus)

NOTE: the small number of quasi-stable particles helps with detector design!

There are only a few “old friends” to measure;
new particles typically decay inside the beam pipe (but not always…)
\( \Rightarrow \) we only see the familiar quasi-stable decays products

**This is how we planned in advance to discover the Higgs at the LHC**:
We knew how it would decay and we were old pros at measuring those decay products.
Particle ID and Velocity

Many common Particle ID technologies depend on particle velocity:

- **“Time of flight” (TOF)** directly measures velocity as time to travel a known distance (from interaction point to a piece of plastic scintillator, typically)
- **Cherenkov light detectors** use the “optical sonic boom” of light produced when \( \beta \frac{c}{c} = \frac{v}{c} > \frac{c}{n} \) in a material with index of refraction \( n \)
  a) Threshold mode: presence or absence of light \(< -- >\) velocity above or below threshold
  b) Ring-imaging: cone of light is at angle \( \cos \theta = \frac{c}{nv} = \frac{1}{(n \beta)} \)
  c) Time-of-propagation (TOP), which varies due to angle (See previous talk! Nice, newish idea…)
- **Specific Ionization \( (dE/dx) \)**
  Energy loss depends on velocity (and charge\(^2\), but usually = 1)

Note there are some “special PID tricks”, especially for leptons…

- **Electrons** deposit all their energy in “EM Calorimeters” (EMC)
  They make peaks in “\( E/p \)”; EMC energy over momentum from B field curvature
- **Muons** are the only highly penetrating charged particles
  look for charges tracks after thick layers of steel (KLM)
- **Neutrinos** are “invisible”
  but we can infer them from apparent non-conservation of four-momentum
Belle II CDC Basics

56 layers of wires from 160 to 384 wires/layer 14,356 wires total
Cell height $\Delta r$ : 1.0 cm for layers 0-7 “inner” 1.8 cm for layers 8-55 “outer”

Measure time and charge:

time of ionizations at “doca” ($doca = distance of closest approach$)
charge is total ionization inside “drift cell”, multiplied by “gas gain” near thin wire

3:1 rectangular “cell” structure $\rightarrow$ 3 field wires (grounded) per 1 sense wire (+HV)
8 field wires surround each sense wire (but shared w/other cells)
[ 3:1 from 4 edge field wires shared by 2 cells, 4 corner fields by 4 cells: $4 \frac{1}{2} + 4 \frac{1}{4} = 3$ ]

X X X X X X X X X X X X X X X
X 0 X 0 X 0 X 0 X 0 X 0 X 0 X
X X X X X X X X X X X X X X X
0 X 0 X 0 X 0 X 0 X 0 X 0 X 0
X X X X X X X X X X X X X X X

X = field wires
O = sense wires 25 micron diameter

NOTE the “stagger” form one layer to next

Radius

track
dE/dx Basics

~25 (primary) ionization events per cm; about 2x as many total electron-ion pairs
Gas is 50%/50% Helium-Ethane (He for low mass! Most ionizations from ethane…)

“gas gain” near thin wire: about $10^4$ amplification “free pre-amplifier”

Near wire, E field is large: Drifting electrons gain enough energy in one mean free path
to ionize the next atom/molecule they collide with… gives a “chain reaction” multiplication
NOTE: E field $\sim \ln(r/r_0)$ near wire of radius $r_0$ (Gauss’ Law) $\Rightarrow$ use thin wires to get this gas gain!

Gas gain varies widely for each avalanche:
so resolution is worse than $1/\sqrt{N}$ from N primary ionizations

Use (lower) momentum at start of CDC (i.e., NOT $p$ at the interaction point)
Differ due to energy loss in material: mostly dE/dx again, but larger in a solid…

Many dE/dx effects depend on $\{ p, p_T = p \sin \theta, \cos \theta \}$
- Only 2 of these 3 variables are independent
- Important (radiative) Bhabha calibration samples have highly correlated $p, \cos \theta$: very different from physics analysis tracks
  $\Rightarrow$ Lots of correlations to keep in mind…
dE/dx Basics

From PDG Review on "Passage of Particles through Matter"

Complex set of phenomena, changes vs. momentum…

dE/dx momentum region is in the black frame
Universal dE/dx Curve

Different colors points: different particle types (i.e., different masses)

All lie on one universal curve!
→ Only depends on $\beta\gamma = p/m$

If we plot vs. mass instead:
get multiple copies of this curve, shifted left-right by mass ratios…

Min-I

$1/\beta^2$

relativistic rise

Far to right:
$\beta\gamma \Rightarrow \propto$

Fermi Plateau

[ CLEO III Data ]
Universal dE/dx Curve in Belle II Data

To prove we’re also doing this well

I used the CLEOIII plot since
it was already nicely labelled…
Belle II Hadronic Event Data

Compare to CLEO-c “teaser” plot:

- Poorer resolution, but huge luminosity difference! (noise…)
- Not using specially-selected samples! just “generic” hadron data:
  → has fewer leptons
  → pion band over-saturated
Reconstruction & Truncated Means

Two possible reconstruction methods

• “Hit Method”: Take a “truncated mean” of the list of corrected charges from each hit
• “Layer Method”: combine hits in each layer first, then take the “truncated mean”…this can reduce fluctuations of charge due to “clipping corners” of cells, etc.

In practice, almost no difference in resolution: currently use layer method in Belle II

Truncation: remove non-Gaussian high-side tail (also low side: less important)
“the central limit theorem is too slow for us”

Rank-order measurements on track: drop lowest 5%, highest 25% of measurements

NOTE: the “cuts” are for the set of measurements on the current track, and NOT fixed values, since intrinsic dE/dx varies widely from Min-I to soft protons in $1/\beta^2$ rise)

→ Then take the simple average of the remaining corrected hit charges
“the mean of the truncated list”
Predictions & User Information

In addition to a well-calibrated measured $dE/dx$, we also need to provide:

- **Expected $dE/dx$** $I_{\text{pred}}$ Depends only on $\beta Y = p/m$
  - varies for each hypothesis due to $m$
- **Expected resolution** Depends on 3 variables: $I_{\text{pred}}$, #hits, sin $\theta$

The final result of $dE/dx$ reconstruction is:

- one “$\chi$” value for each of six hypotheses $\{ e \, \mu \, \pi \, K \, p \, d \}$
- These chi values are simply normalized deviations:
  $$\chi(\text{hyp}) = \left[ I_{\text{meas}} - I_{\text{pred}}(\text{hyp}) \right] / \text{resolution(hyp)}$$

Also convert to a log likelihood: $LL = -\chi^2 / 2$

- for ease of combining with other PID results
- assumes that results for $\chi$ follow a normalized Gaussian: $\exp[ -\chi^2 / 2 ]$
Resolution from Bhabhas \( (e^+ e^- \rightarrow e^+ e^-) \)

**Upturn at edges:**
- Fewer hits for steep tracks which exit the CDC endplate!

**Middle Cosine region**
- Overall “frown” shape due to increasing \( r-Z \) path length \( \sim \sin \theta \)
- Decrease near \( \cos \theta = 0 \) related to gas gain saturation (presumably)
Calibration Overview

Types of Calibrations we apply can be categorized in different ways:

- **Source of calib. data:** electrons, or “hadron” = e μ π K p
- **Basic effect corrected:** geometric path length; gains; etc.
- **Variation along track:** “global” = same for entire track vs. “local” = different for each hit

Table 1: Summary of the main steps for $dE/dx$ Calibration.

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>r-z path length</td>
<td>track geometry</td>
</tr>
<tr>
<td>r-φ path length</td>
<td>track and drift cell geometry</td>
</tr>
<tr>
<td>Scale Factor</td>
<td>$e^+e^-$</td>
</tr>
<tr>
<td>Run Gain</td>
<td>$e^+e^-$</td>
</tr>
<tr>
<td>Wire Gain</td>
<td>$e^+e^-$</td>
</tr>
<tr>
<td>2-D doca-ent. angle</td>
<td>$e^+e^-\gamma$</td>
</tr>
<tr>
<td>1-D ent. angle “clean up”</td>
<td>$e^+e^-\gamma$</td>
</tr>
<tr>
<td>Electron Saturation (&quot;CosCorr&quot;)</td>
<td>$e^+e^-$</td>
</tr>
<tr>
<td>Hadron Saturation</td>
<td>$(e), \mu, \pi, K, p$</td>
</tr>
<tr>
<td>$\beta\gamma$ curve parameters</td>
<td>$e, \mu, \pi, K, p$</td>
</tr>
<tr>
<td>Resolution parameters</td>
<td>$e, \mu, \pi, K, p$</td>
</tr>
<tr>
<td>Electronic readout non-linearity</td>
<td>hit</td>
</tr>
</tbody>
</table>

We now give a quick overview of the purpose of each type of calibration. More details are given later; this overview is for general orientation.

The ratio of the full 3-D path length to the 2-D (r-φ) length is given by $1/\sin \theta$. This is divided out via multiplication by $\sin \theta$, correcting for extra path length in the r-z view.

The path length through the naive geometric cell in the r-φ view can be calculated from track parameters and known drift cell geometry. It is then divided out. The philosophy behind separating this from the empirical r-φ corrections below is discussed later.

There needs to be some scale factor which takes us from ADC counts to a more useful value. As noted elsewhere, we normalize the Fermi plateau to 1 (as opposed to, say, physical units like keV/cm). Rather than bury this scale factor in the reconstruction code, we have an actual separate constants entity for it. One could absorb it into other places, such as the run gain. However, we make use of this independent knob to make the run gains be near 1.0, for convenience.

In practice, there is no detailed normalization convention. One typically sets an approximate round-number value early on, and very rarely changes it.

Run gains mostly account for changes in chamber pressure, which usually are maintained at a fixed $\Delta p$ above ambient atmospheric. That is, they correct for weather. At Belle II, the chamber will (mostly) be maintained at a constant pressure. “Mostly” encompasses at least two issues: technical difficulties, or a possible finite step to avoid an uncomfortably large $\Delta p$ (chamber to atmosphere) due to very large weather variations, in particular lows from storms.

High atmospheric pressure could in principle give a negative $\Delta p$; one runs with $10$
**Geometric Path Length**

**r\(\phi\) - Z View of Track**

“Unwind” track helix so that the \(r\phi\) curling is flat:
→ Get a straight line vs. Z

3-D Path length varies as \(1/\sin \theta\)
Correction: divide by the (relative) path;
   i.e., just multiply by \(\sin \theta\)

Correction for this \(r-Z\) path length effect
→ Very large effect:
   • \(1/\sin \theta\) varies from 1 to >3
   • common to ALL hits!

**r-\(\varphi\) View of drift cell**

Correction for the 2-D \(r-\varphi\) path length
→ Smaller effect: averages out over many hits
Run Gains
one gain per data “run”

Follows variations in pressure, temperature, gas composition, HV drifts, etc.

Run-Gain Constants: 20 (0018:301_880)

“Bucket 20” ~ April 2021
Wire Gains
one gain per wire

zero gains = dead wires

Inner layers 0-7 have larger gain

Layer 8 is very non-square

Residual variations:
- electronics
- cell geometry
- high voltage
- ...
Gas Gain Saturation

r-Z of sloping track crossing a CDC layer
Dash-dot field wires define the ionization region for the solid field wire collecting the charge

Larger $\cos \theta$: less dense
Smaller $\cos \theta$: more dense

Leads to a decrease in gain for tracks near $\cos \sim 0$: a “dip”
- For electrons (constant ionization) we map this out very accurately this “anchors” the correction in the region of crossing $dE/dx$ bands
- For other tracks, we need to apply another correction since the “dip” changes shape as the intrinsic ionization changes (slow protons saturate even more!)
Gas gain saturation for electrons (i.e., ionization level of Fermi plateau)

Shape is fairly stable over time (due to pressure regulation)
Track-Level $dE/dx$

Current Monte-Carlo simulation of $dE/dx$ is done at the “Track Level”
- We use matching of reconstructed tracks to generator truth to determine the particle type
- We then create a smeared $dE/dx$ value based on our predicted means and resolutions
- The more perfect the high-level data calibration, the better the MC will agree
  (i.e., prediction goes through middle of data; dependences of resolution track well…)

Clearly, some effects cannot be captured by this method!

But it is easy to implement and works fairly well…

Note: this as the ONLY MC method ever used by CLEOIII and CLEO-c (data from 1999-2008)

Also, raw ADC values are separately simulated fairly well, since this has an effect on tracking

An effort to do hit-level MC via sampling histograms is in its early stages…
Sources Of Charge Asymmetries

Charge asymmetries: a very bad artifact for an experiment that has studies of CP violation (CPV) as a major goal!

Charge asymmetries in detector response = fake CPV !!!

Main sources of charge asymmetry:

- **Particle interactions in material**: detector is all matter; 100% CPV!
  A positive kaon and a negative kaon interact differently; largest effect at low momentum, smoothly decrease as p increases.

- **B-field effects on tracking**
  affects drift time of ionization electrons; get different #hits on tracks for different charges…

- **B-field effects on dE/dx**
  again, due to effect on drifting ionization electrons (details on next page)
Asymmetries: The “E-M Cell”

Intuition for cell effects:

* B field breaks reflection symmetry
* Rotational symmetry remains

B field means region of ionization that’s collected by a given wire is NOT the naïve geometric cell!

→ B makes electron drift paths curve!

Light square:

* Naïve geometric cell (field wires + straight lines)

Dark “scallop” shape

* “Electromagnetic cell”: accounts for B-field effects

Blue & Red tracks: opposite charges, and thus opposite entrance angles. Different path lengths (inside the dark scallop) giving different amounts of ionization to be collected at the sense wire
**Likelihood Ratios**

**Vertical axis:**

“pairwise” Likelihood ratio

\[ \frac{L_\pi}{(L_\pi + L_K)} \]

Plotted for “generic tracks”

Collapses to 0.5 at band crossing!

→ Tight cuts will “sculpt” the momentum spectrum

Effect “covered up” by other PID info

**BUT:** backwards angle tracks and many “low-momentum “curlers” have only dE/dx PID!
Likelihood Ratios

**Vertical: Likelihood ratio**

\[
L_\pi / (L_\pi + L_K + L_\mu)
\]

*Now the muon hypothesis is always close to the pion hypothesis:* so, the ratio tends to be smaller everywhere.

The 0.5 ratio near 0.5 GeV is the pion-muon band crossing…

**Momentum [ GeV/c ]**
dE/dx provides useful Particle ID in Belle II

We directly detect only a handful of “quasi-stable” particles
PID often uses velocity

A little understanding is helpful for users
  band crossings are important
  some tracks have only dE/dx (no TOP, ARICH)

Calibration improvements are still being made