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

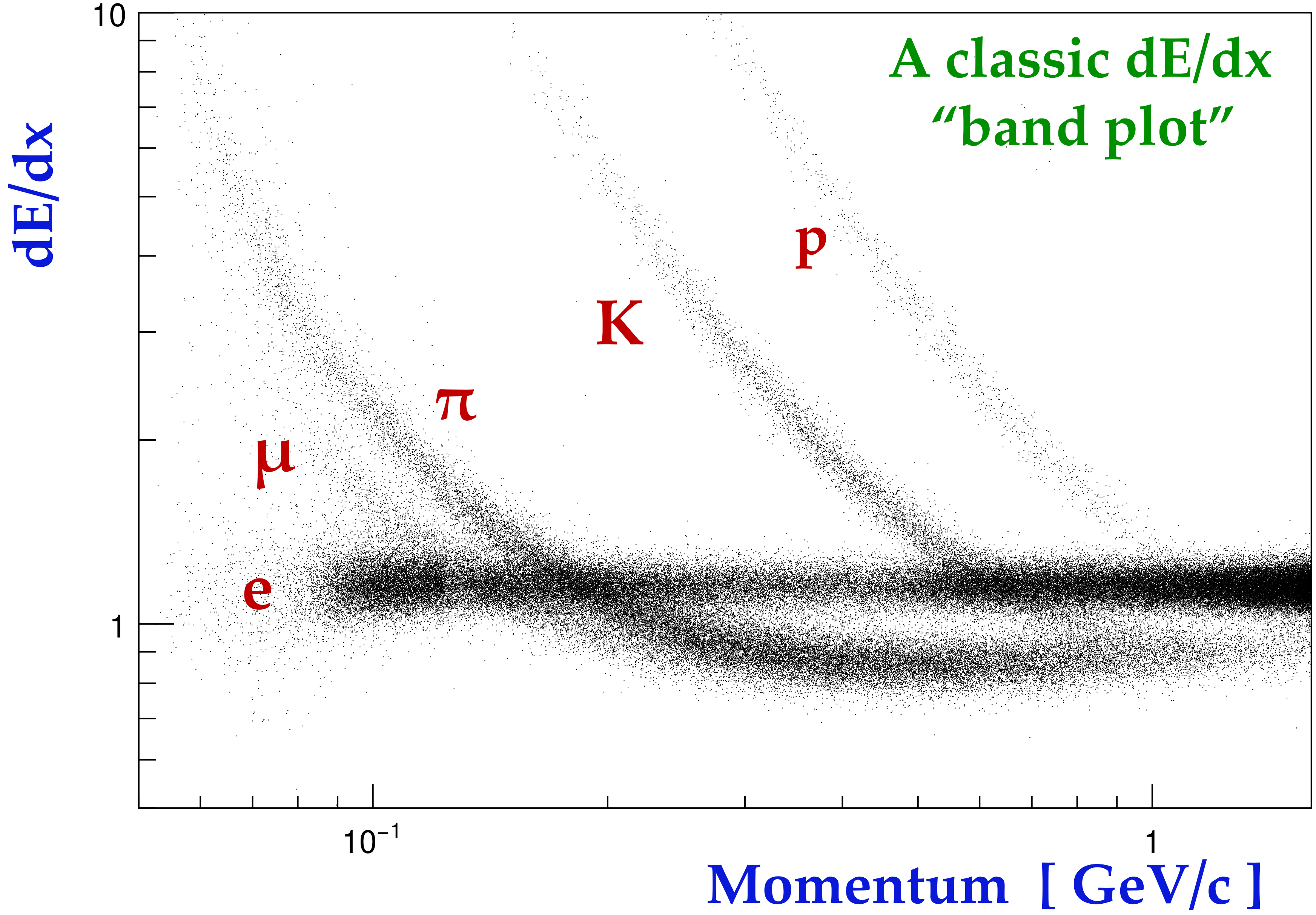
Monte Carlo

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)

CLEO-c Ultra-Clean Tracks

a previous experiment I worked on
took data 2004-2008 or so…



Separation is related to mass

"Blind spots" at band crossings

Best separation at lower momenta

Calibration goal: make bands narrow

Quasi-Stable Particles I

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

short lifetime τ *implies uncertain rest-energy (mass) of order* Γ

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

Hadronic "resonances" (strong decay): Δ, K^*, ρ $\Gamma \sim 100$ MeV wide → $\tau \sim 10^{-23}$ s

EM decays, quarkonia (suppressed strong): η J/ψ Υ ~ keV to ~ MeV

Even the "long-lived" π^0 : $\Gamma \sim 8$ eV → 0.8×10^{-16} s

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

ALL very short lived ! ***Short compared to what???*** **<< beam pipe radius …**

Average Flight length before decay: τ is mean lifetime

$< L > \ = \gamma\,(\beta c)\,\tau = (\beta\gamma)(c\tau) = (p/m)\,c\tau$ 1 ps = 300 microns (μm)

Useful connections: $(E^2 - p^2 = m^2)/\ m^2$ ➔ $\gamma^2 - (\beta\gamma)^2 = 1$

with $\gamma = E/m$ $\beta\gamma = p/m$ $\beta = p/E$

[Also, realize that β, γ, $\beta\gamma$ are all interchangeable: easy to calculate one from another…]

Quasi-Stable Particles II

There are only a handful of "Quasi-stable" particles:

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

Charged : e μ π K p d ← These are the domain of dE/dx !!!

Neutral : γ ν n Λ^0 K_S K_L

plus ~five more less-common "hyperons" = strange baryons (cousins of Λ^0) : Σ^+ Σ^- Ξ^0 Ξ^- Ω^-

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…)

→ *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 $\beta c = v > c/n$ 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 $\cos\theta = c/(nv) = 1/(n\beta)$
  - 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 Δr :   1.0 cm for layers 0-7 “inner”   1.8 cm for layers 8-55 “outer”

Measure time and charge:

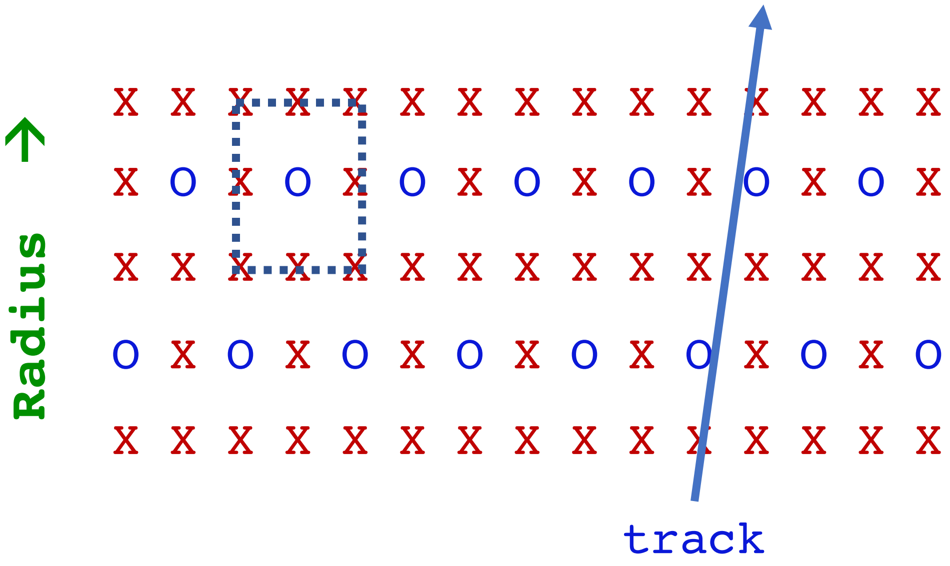
time of ionizations at “doca” (doca = distance of closest approach)

charge is total ionization inside “drift cell”, multiplied by “gas gain” near thin wire

3:1 rectangular “cell” structure → 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 (1/2) + 4 (1/4) = 3]



X = field wires

O = sense wires   25 micron diameter

NOTE the “stagger” form one layer to next

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 ~ $\ln(r/r_0)$ near wire of radius r_0 (Gauss' Law) → 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)

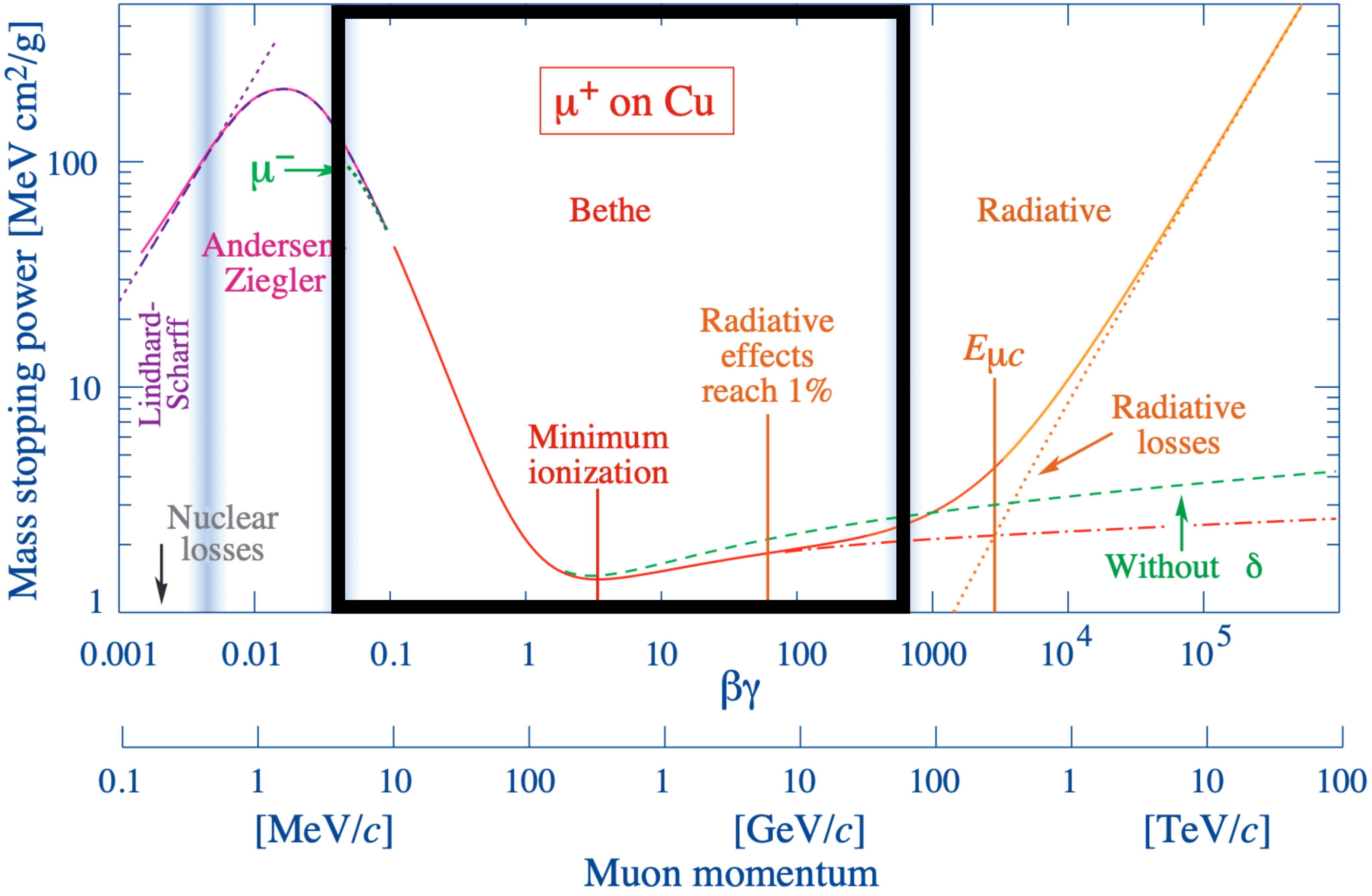
Differ due to energy loss in material: mostly dE/dx again, but larger in a solid…

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 θ:
  very different from physics analysis tracks

→ Lots of correlations to keep in mind…

dE/dx Basics



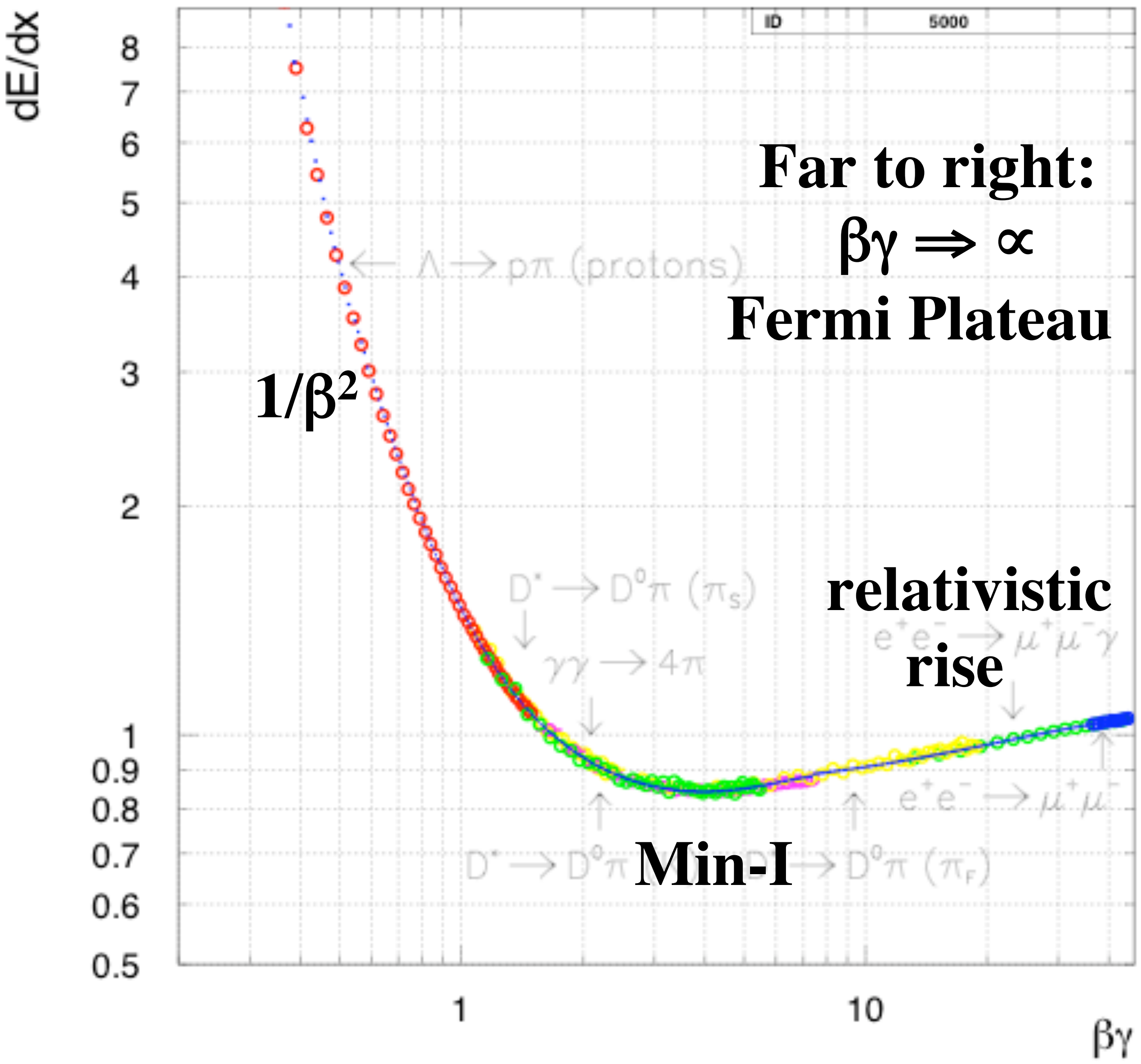
From PDG Review on “Passage of Particles through Matter”

Complex set of phenomena, changes vs. momentum…

dE/dx momentum region is in the black frame

Universal dE/dx Curve

[CLEO III Data]



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

$1/\beta^2$

relativistic rise

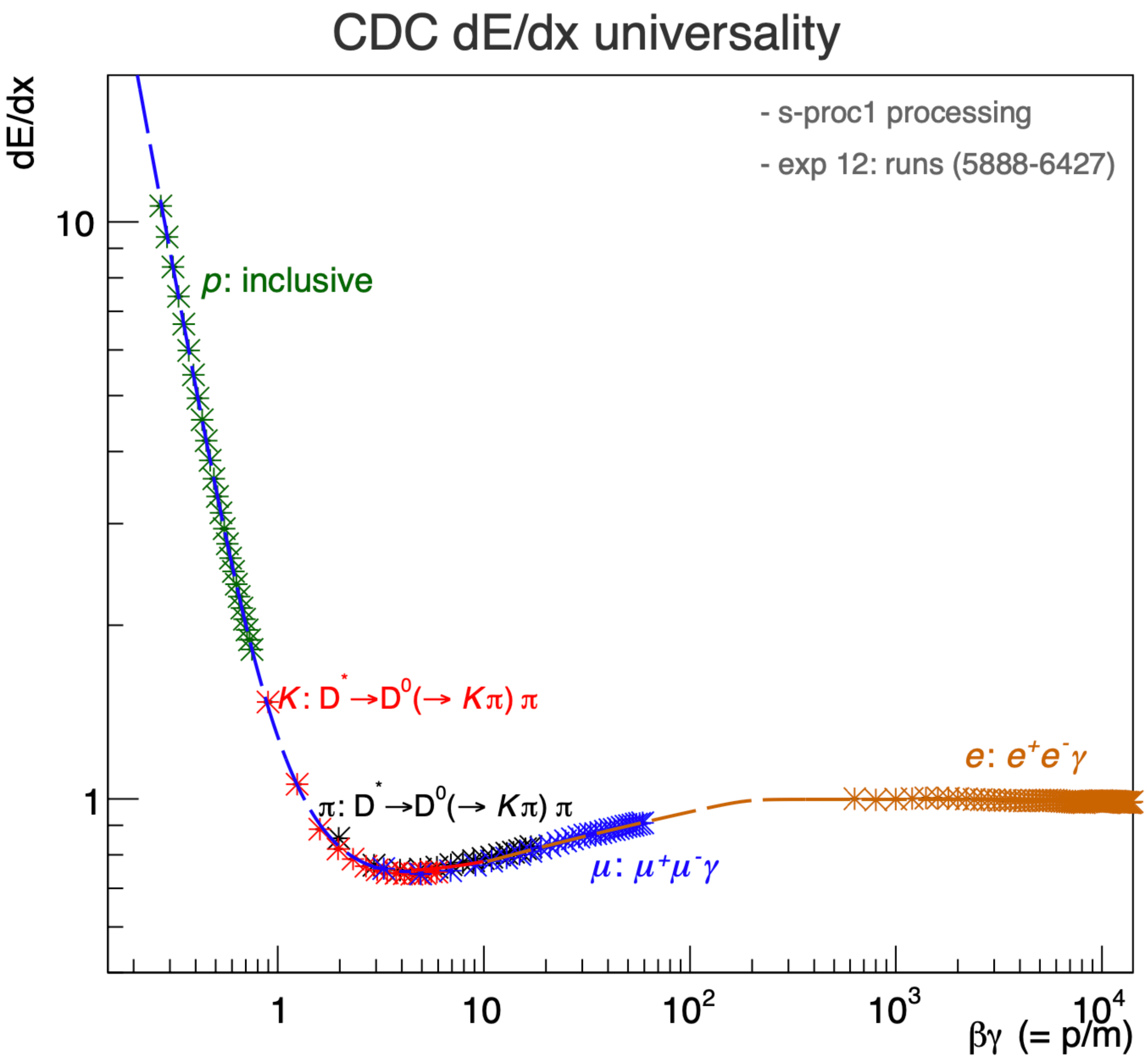
Min-I

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…

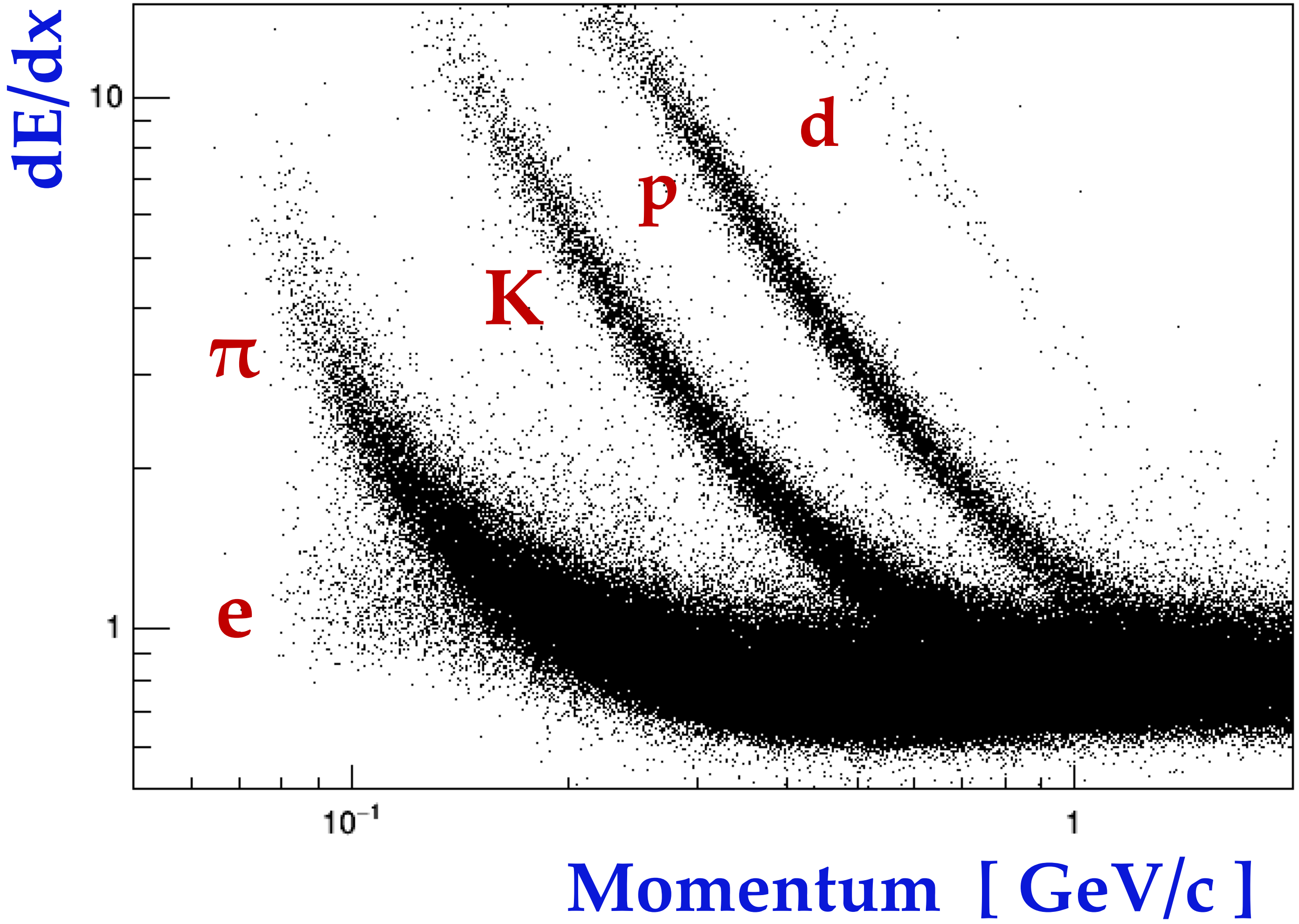
Universal dE/dx Curve in Belle II Data



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_pred   Depends only on $\beta\Upsilon = p/m$:
  varies for each hypothesis due to m
- Expected resolution   Depends on 3 variables: I_pred, #hits, sin θ

The final result of dE/dx reconstruction is:

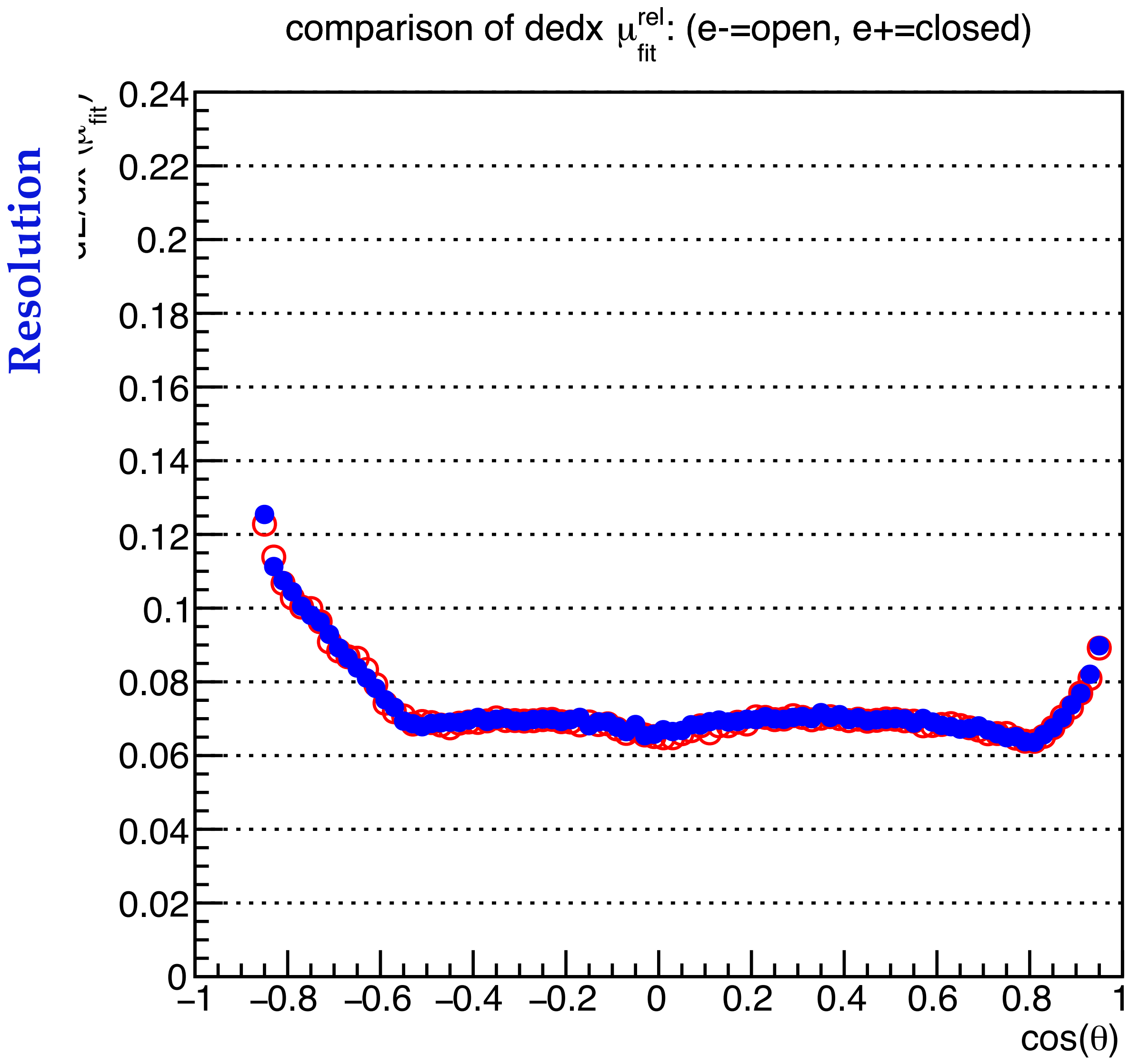
- one "χ" value for each of six hypotheses   { **e μ π K p d** }
- These chi values are simply normalized deviations:

$$\chi(\text{hyp}) = [\,\text{I\_meas} - \text{I\_pred(hyp)}\,] \,/\, \text{resolution(hyp)}$$

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

- for ease of combining with other PID results
- assumes that results for χ follow a normalized Gaussian: $\exp[\,-\chi^2/2\,]$

Resolution from Bhabhas (e+ e- → 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 ~ sin θ
- Decrease near cos θ = 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.

	Calibration	Source	
path	r-z path length	track geometry	track
path	r-ϕ path length	track and drift cell geometry	hit
gain	Scale Factor	e^+e^-	track
gain	Run Gain	e^+e^-	track
gain	Wire Gain	e^+e^-	hit
~both	2-D doca-ent. angle	$e^+e^-\gamma$	hit
~both	1-D ent. angle "clean up"	$e^+e^-\gamma$	hit
gain	Electron Saturation ("CosCorr")	e^+e^-	track
gain	Hadron Saturation	$(e), \mu, \pi, K, p$	track
prediction	$\beta\gamma$ curve parameters	e, μ, π, K, p	prediction
Prediction	Resolution parameters	e, μ, π, K, p	Prediction
gain	**Electronic readout non-linearity**		hit

Geometric Path Length

rφ - Z View of Track

"Unwind" track helix so that the rφ curling is flat:

→ Get a straight line vs. Z

3-D Path length varies as 1/sin θ

Correction: divide by the (relative) path; i.e., just multiply by sin θ

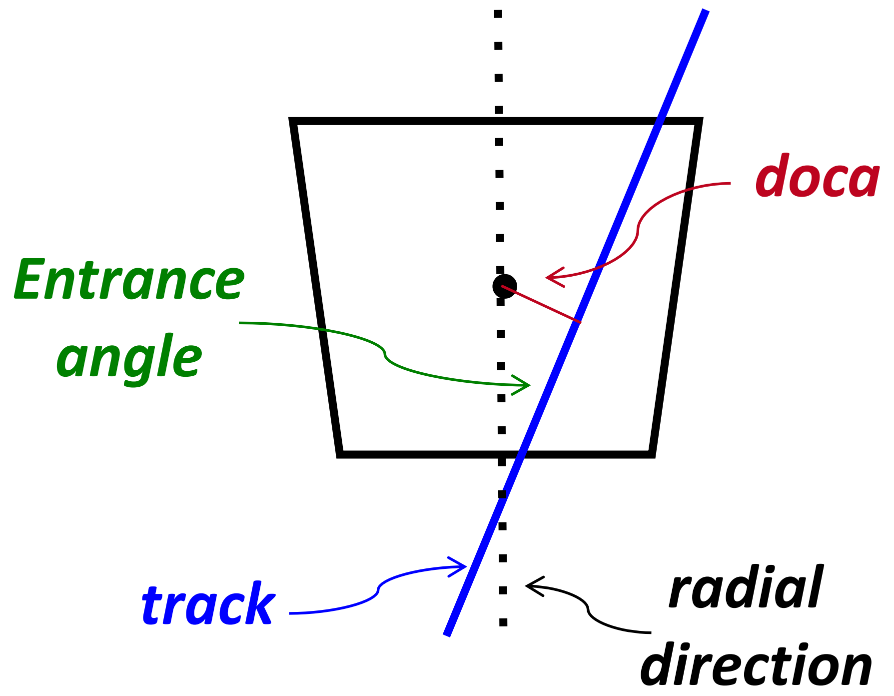
Correction for this r-Z path length effect

→ *Very large effect:*

- 1/sin θ varies from 1 to >3
- common to ALL hits !

r-φ View of drift cell

Cell Geometry



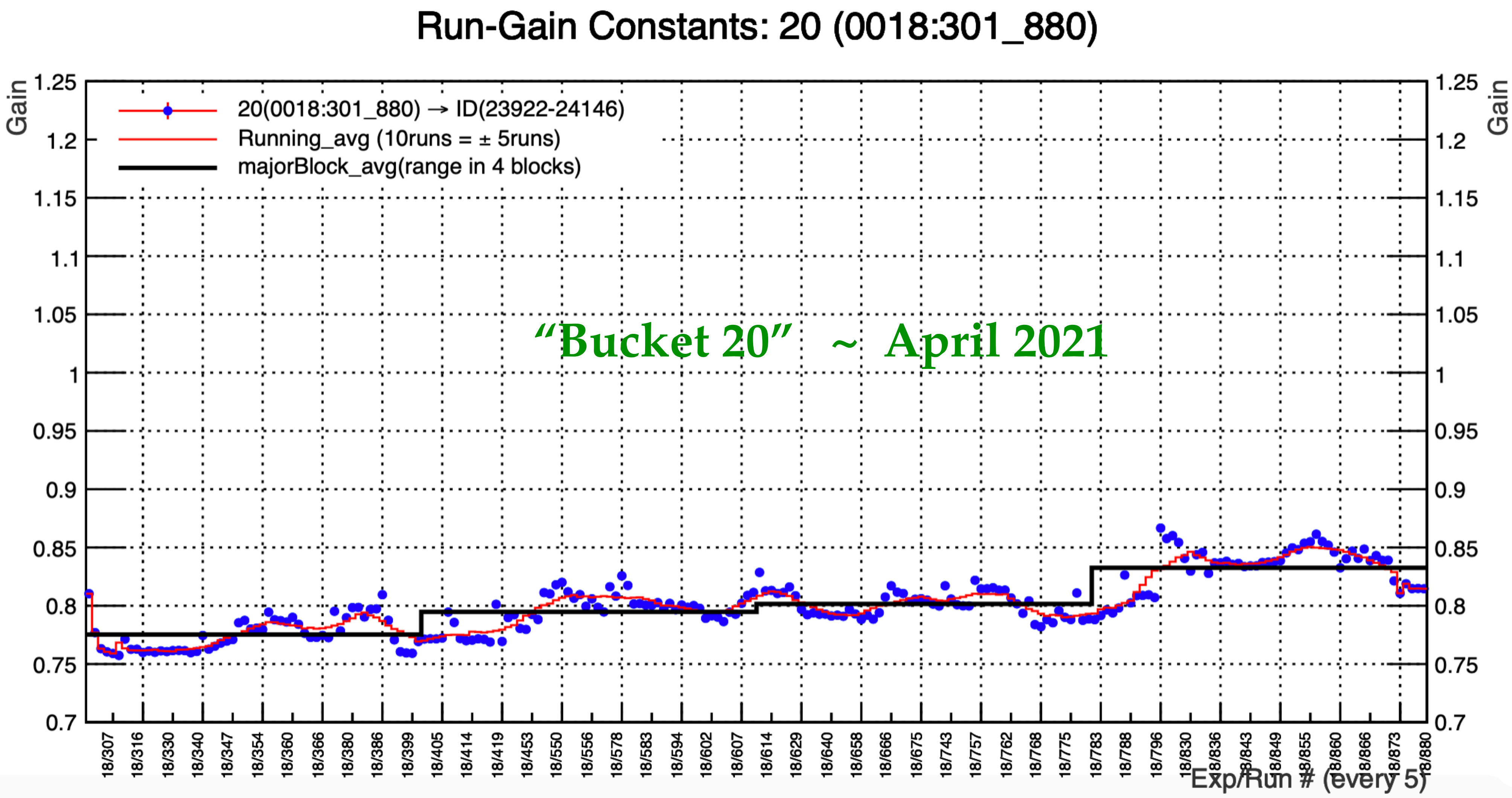
Correction for the 2-D r-φ path length

→ *Smaller effect: averages out over many hits*

Run Gains

one gain per data “run”

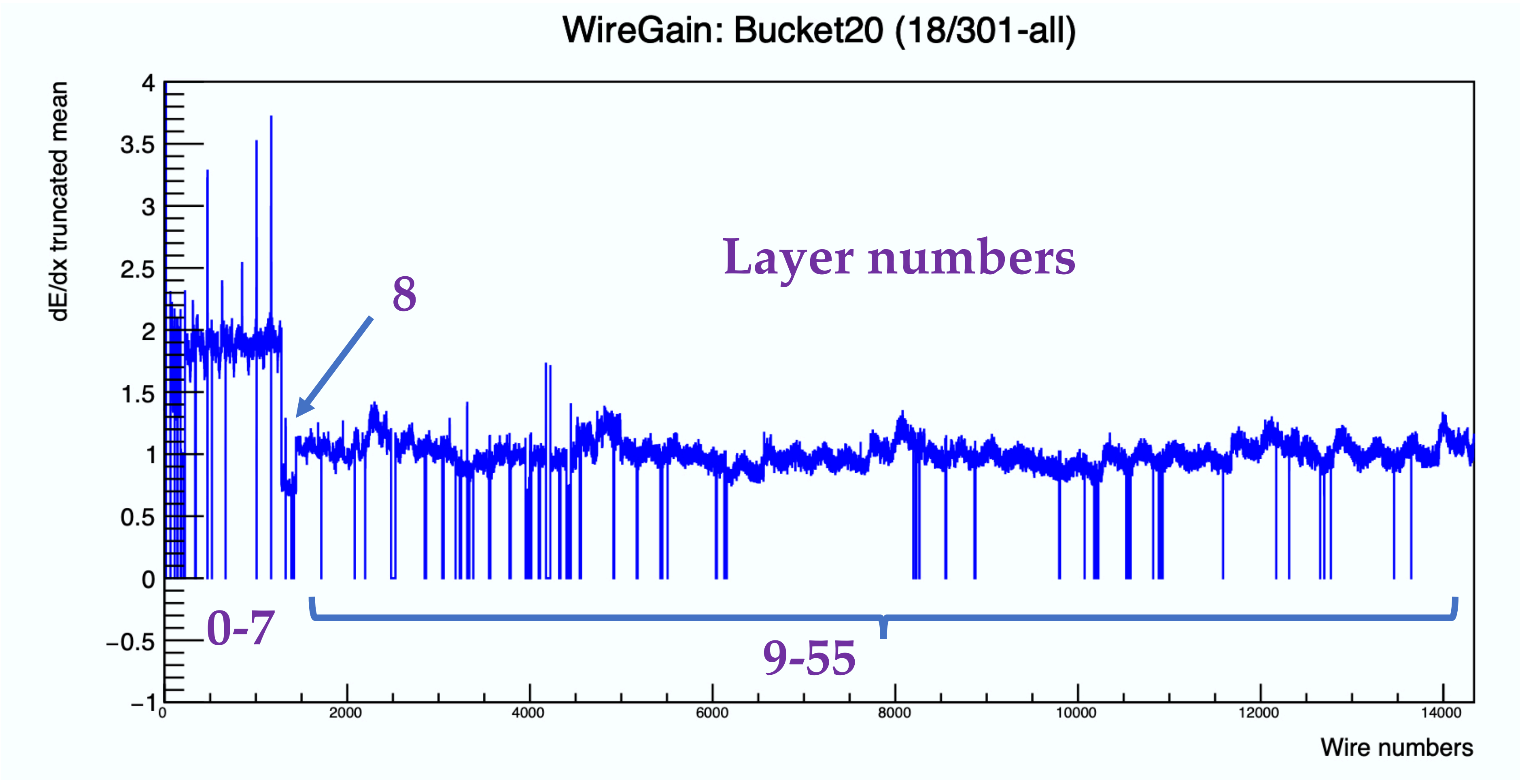
Follows variations in pressure, temperature, gas composition, HV drifts, etc.



“Bucket 20” ~ April 2021

Wire Gains

one gain per wire



zero gains
= dead wires

Inner layers 0-7
have larger gain

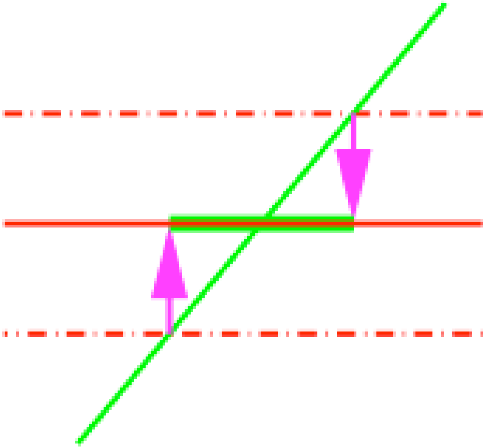
Layer 8 is very
non-square

Residual variations:
- electronics
- cell geometry
- high voltage
- …

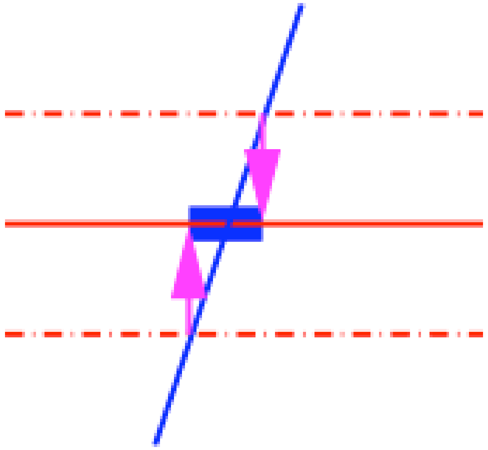
Gas Gain Saturation

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 cosθ:
less dense

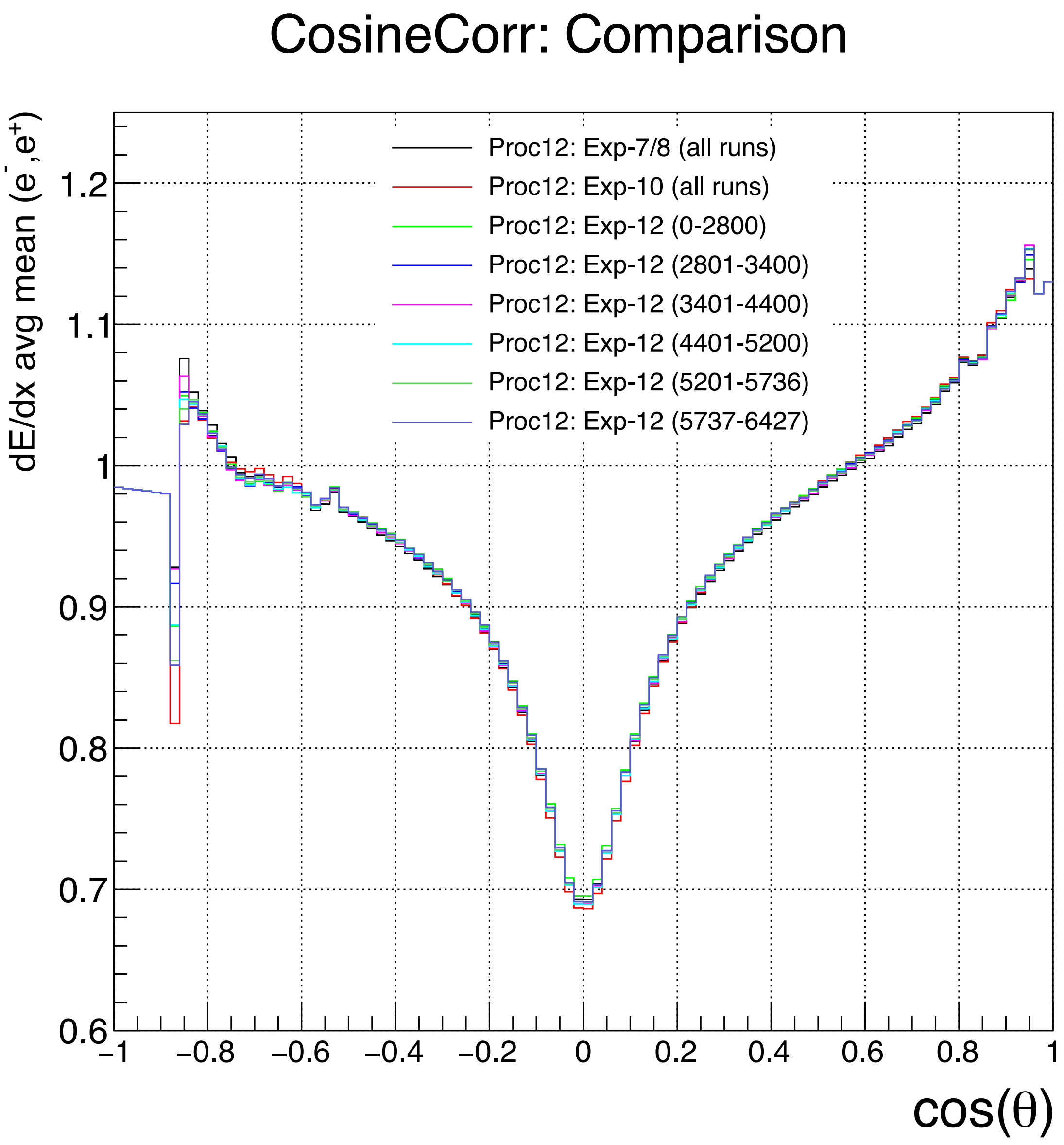


Smaller cosθ:
more dense

Leads to a decrease in gain for tracks near cos ~ 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!

“Cosine” Correction



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

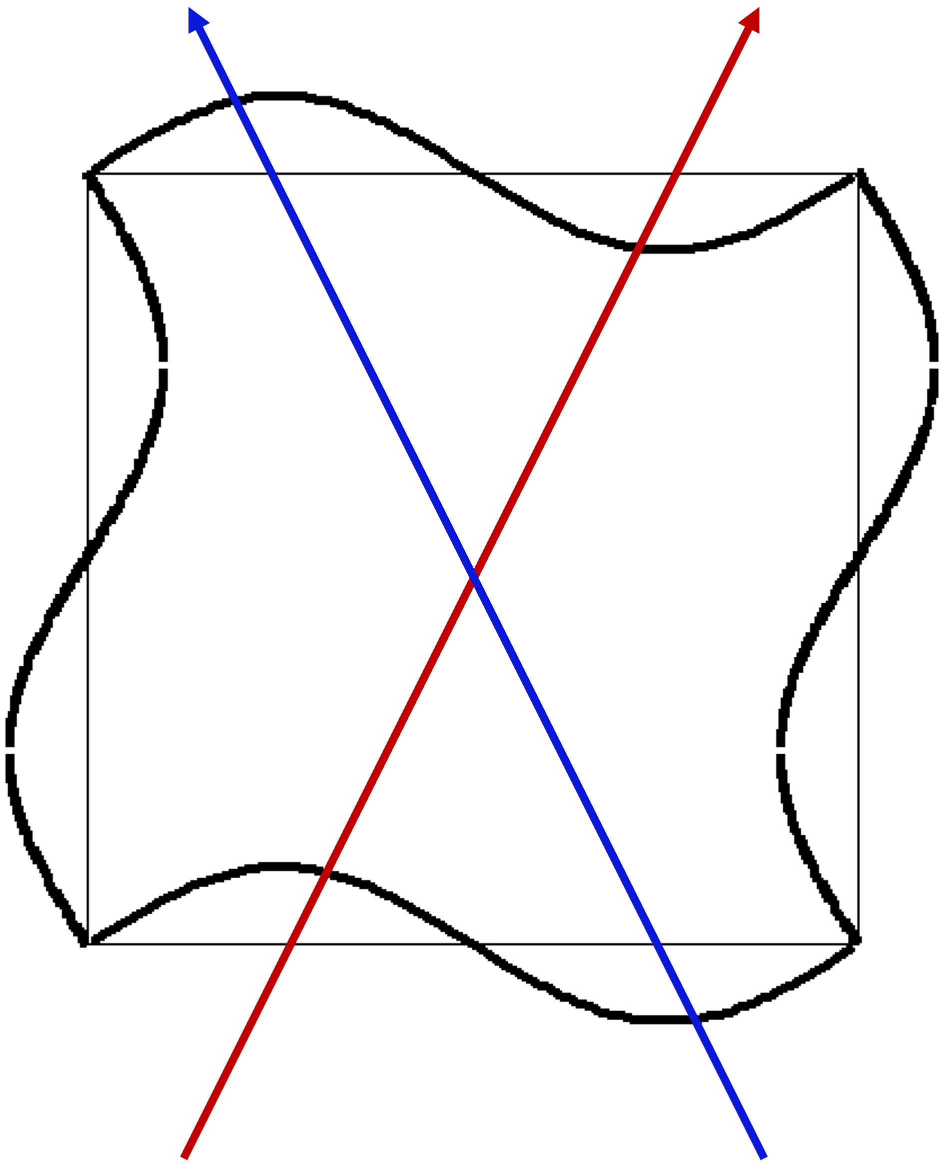
Charge asymmetries: a very bad artifact for an experiment that has studies of CP violation (CPV)as a major goal !

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:

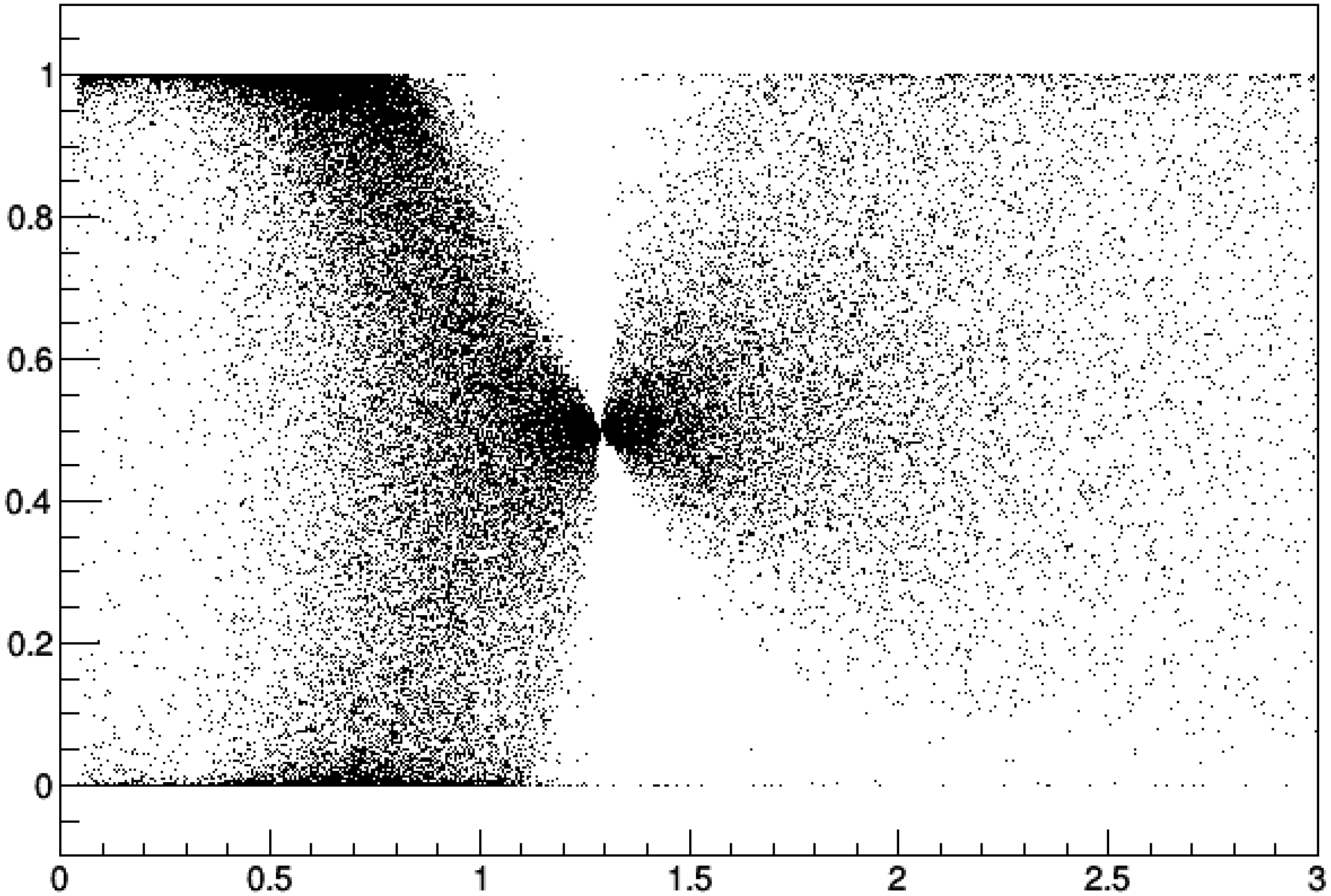
- Naïve geometric cell (field wires + straight lines)

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



Momentum [GeV/c]

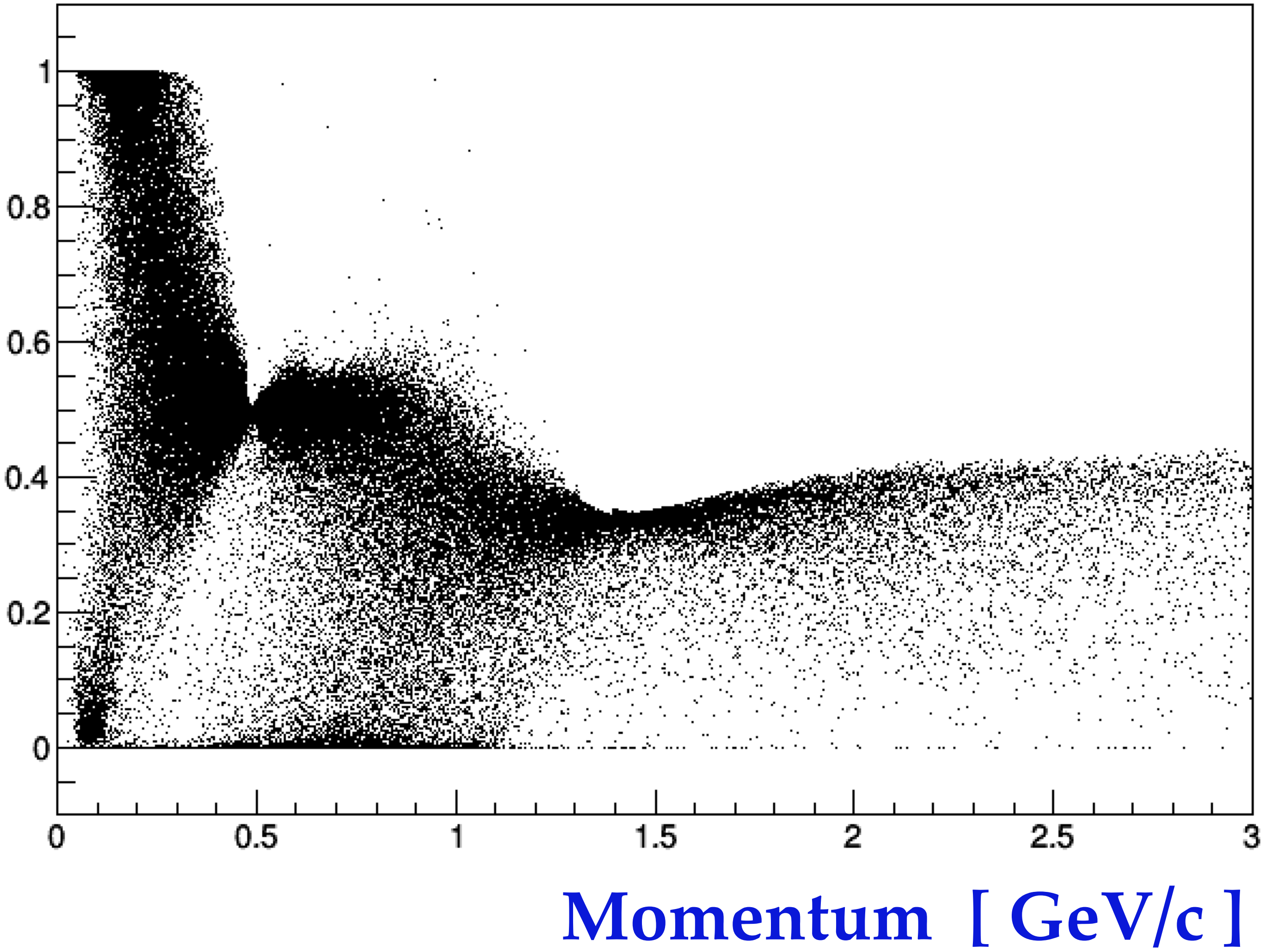
Vertical axis:
"pairwise" Likelihood ratio
$L_\pi / (L_\pi + L_K)$

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…

CONCLUSIONS

dE/dx provides useful Particle ID in BelleII

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