Particle identification using dE/dx from the CDC

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Outline

- Particle identification
- dE/dx basics: CDC structure, ionization, and universality
- Reconstruction and truncated mean
- dE/dx calibration
  - Overview of calibration constants
  - Electron calibration: run gain, wire gain, injection time, saturation
  - Hadron calibration: saturation, $\beta\gamma$ curve, resolution
- Conclusions

Note: I will not discuss dE/dx in the SVD which is done by others (some concepts are similar)

Particle Identification

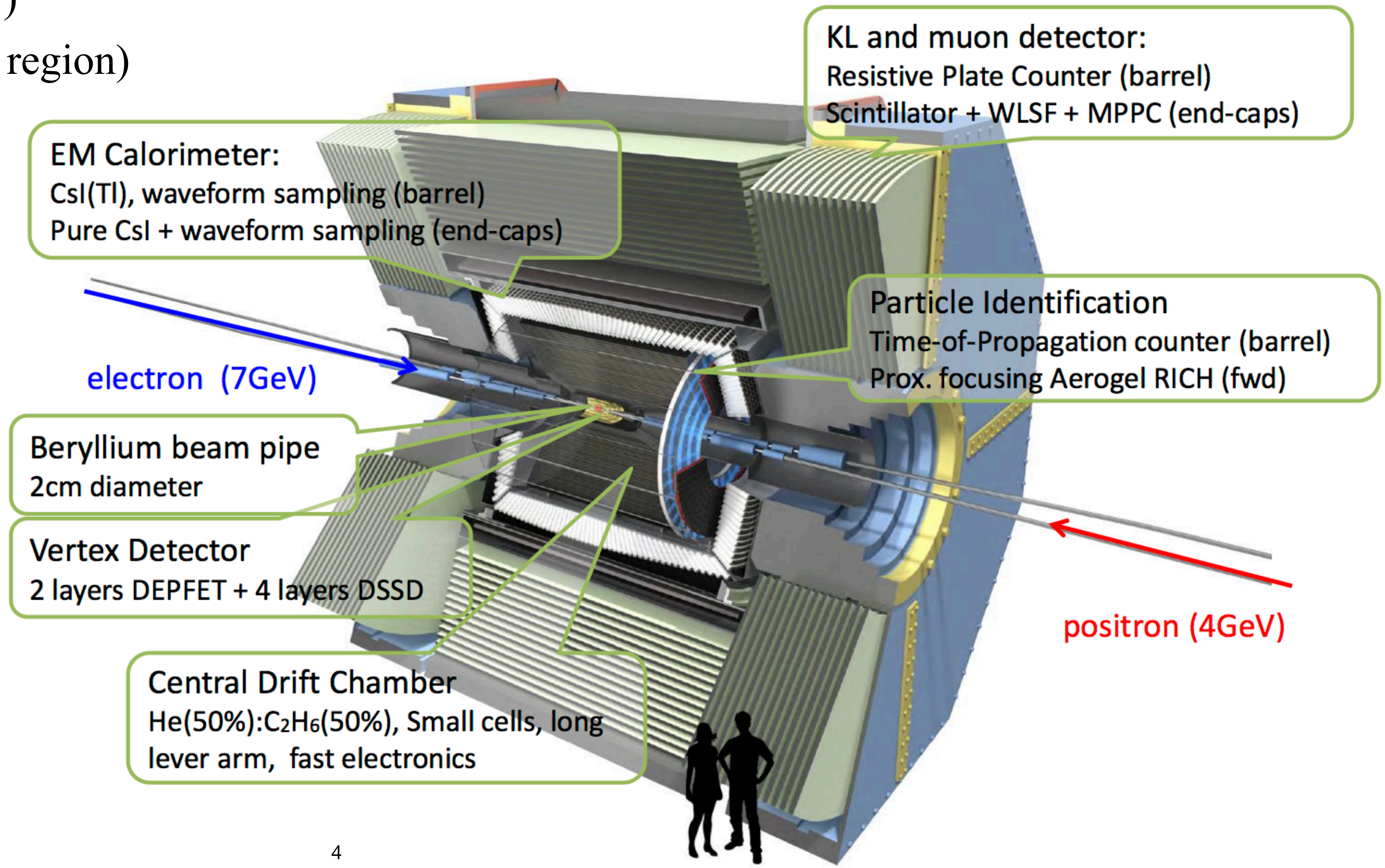
- **Particle identification** is a crucial part of several experiments in Particle physics.
  - **Goal: identify long-lived particles which create signals in the detector**
    - Charged: e, μ, K, π, p, d $\Leftarrow$ These are the domain of dE/dx!!!
    - Neutral: γ, ν, n, K_S, K_L
  - **Short-lived particles identified from their decay into long-lived particles.**
- Many common Particle identification technologies depend on particle velocity
  - **Time of flight (TOF):** directly measures velocity as time to travel a known distance.
  - **Cherenkov light detector:** use **optical sonic boom** of light produced when $\beta c = v > c/n$ in a material
  - **Specific ionization (dE/dx):** <u>Energy loss depends on velocity</u>
- **There are some special PID detectors, especially for leptons...**
  - **Electrons** deposit all their energy in EM Calorimeters (ECL)

    They make peaks in “E/p”: ECL energy over CDC momentum
  - **Muons** are the only highly penetrating charged particles: look for charged tracks after thick layers of steel (KLM)

Particle Identification in BelleII

- **Three** primary detectors for **hadron** identification:
  - Central Drift Chamber (CDC)
  - Time of Propagation Counter (TOP)
  - Aerogel RICH (ARICH in forward region)

- **Special** detectors for **lepton** identification:
  - Electromagnetic Calorimeter (ECL)
  - K_L and muon detector (KLM)



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
$He(50\%):C_2H_6(50\%)$, Small cells, long lever arm, fast electronics

Central drift chamber (CDC)

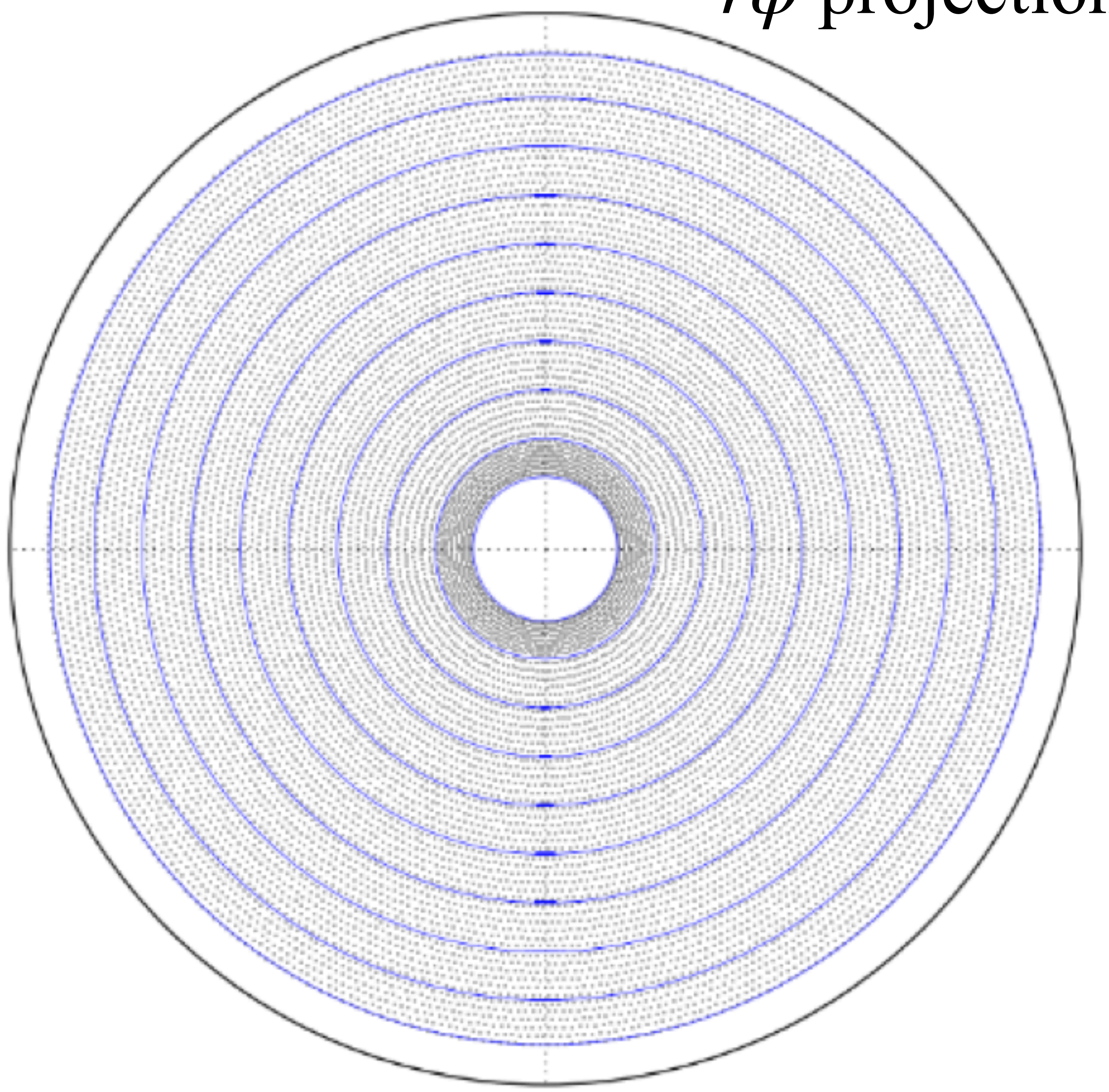
- **Three important roles of CDC in Belle-II**
    - Measure momentum of charged tracks.
    - <u>Particle identification (PID) using (dE/dx) measurements.</u>
    - used as trigger signals for charged particles.

The particles travel in helices:

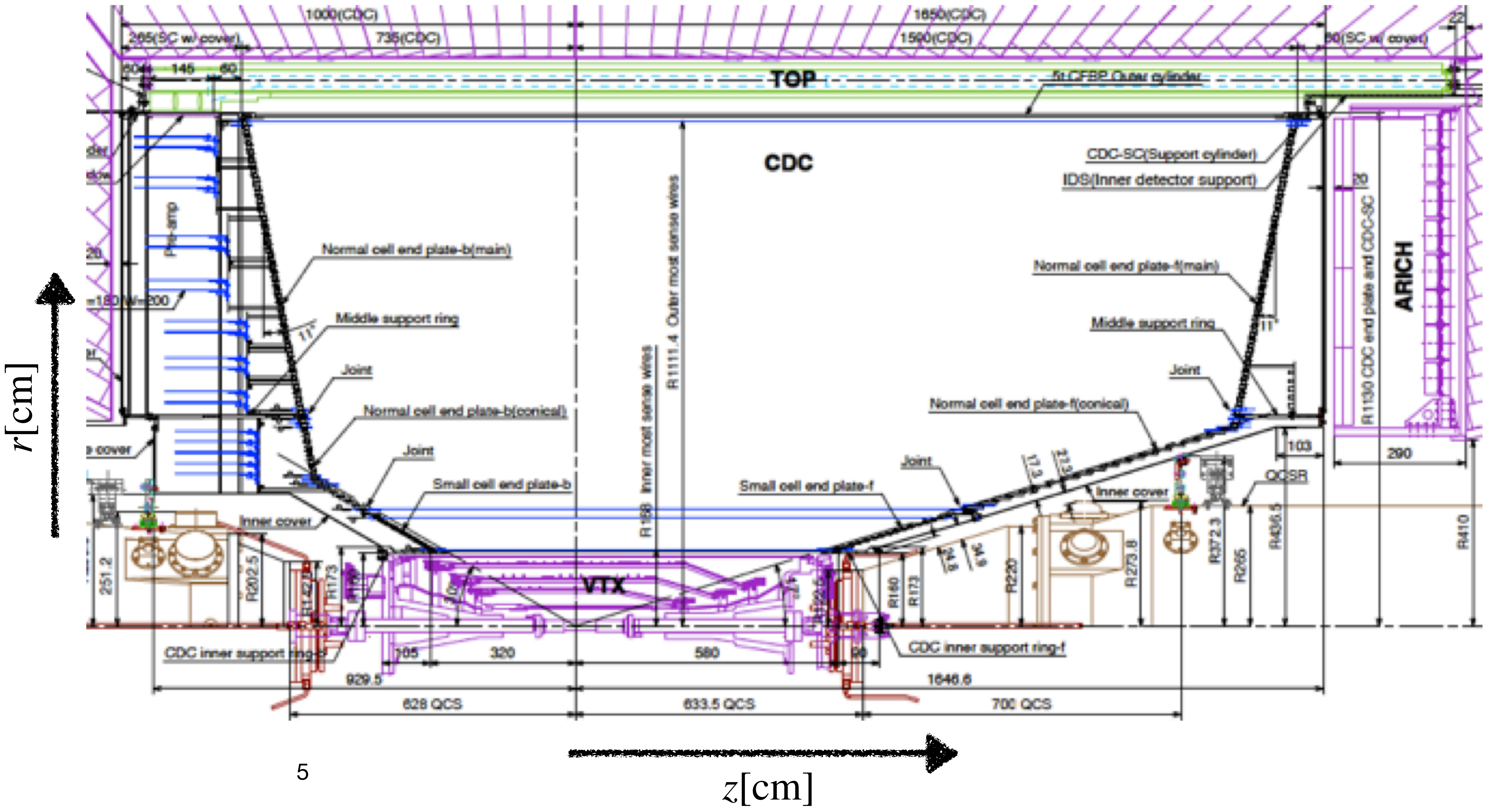
$$\frac{d\vec{p}}{dt} = q\gamma\,[\vec{\beta}\times\vec{B}]$$

Covers $17^\circ < \theta < 150^\circ$ (polar angle)

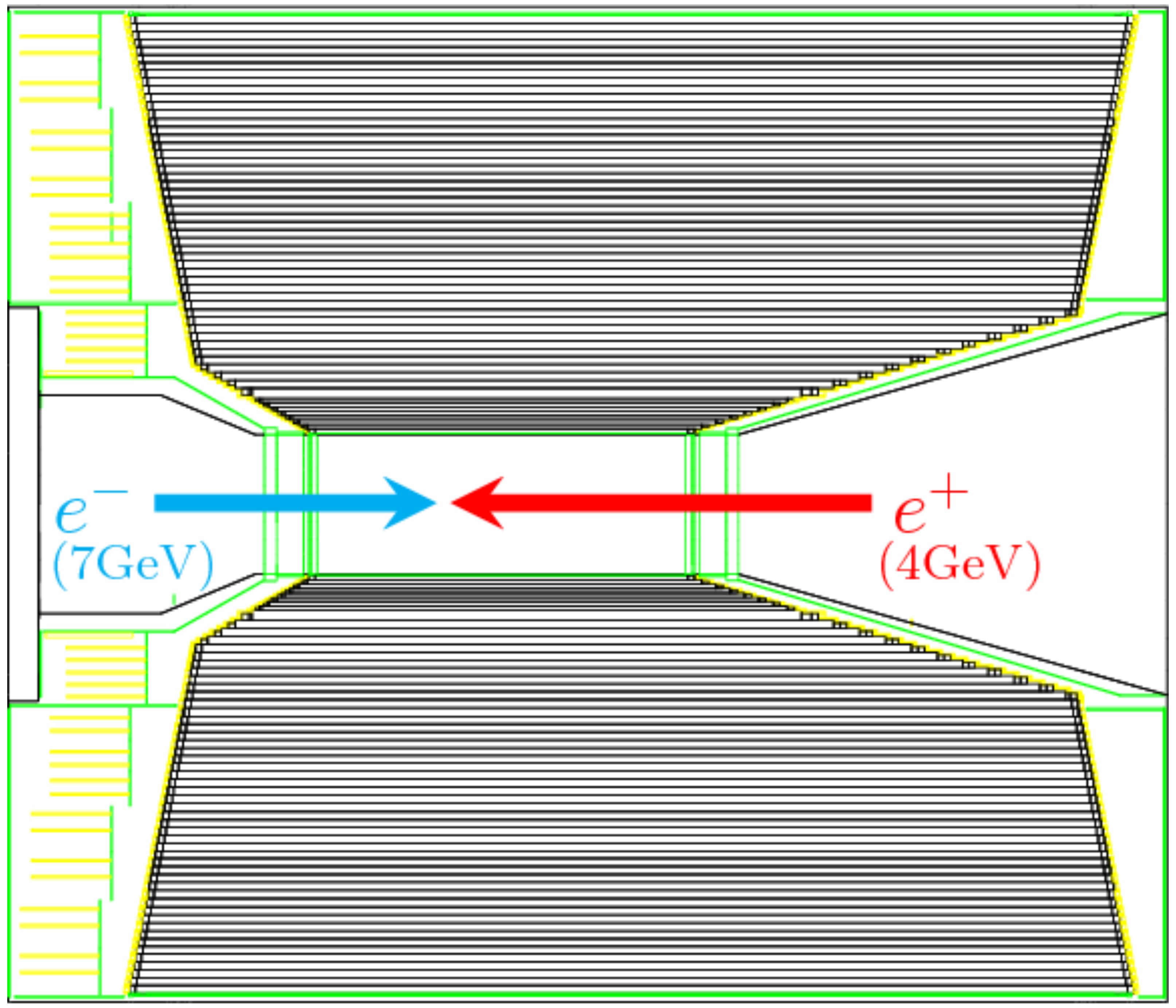
$r\phi$ projection



rz view

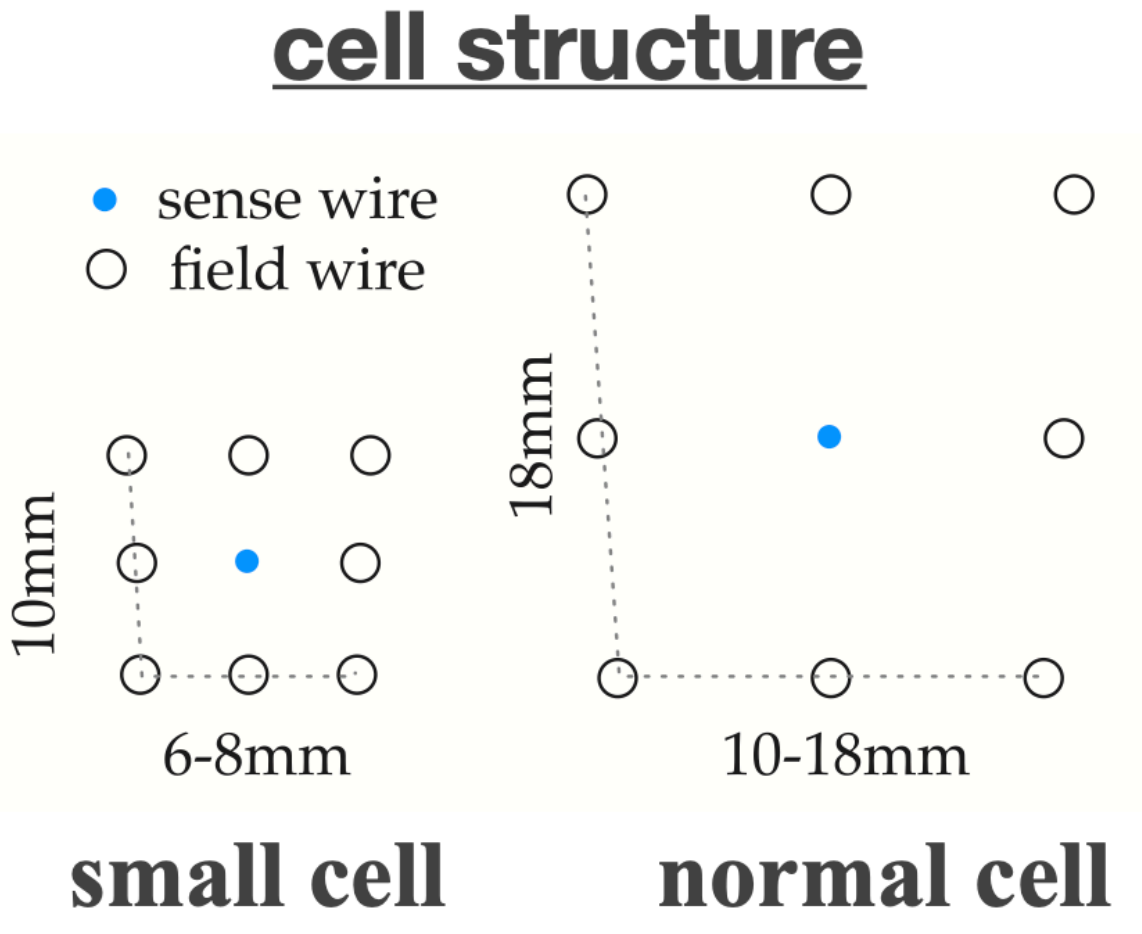


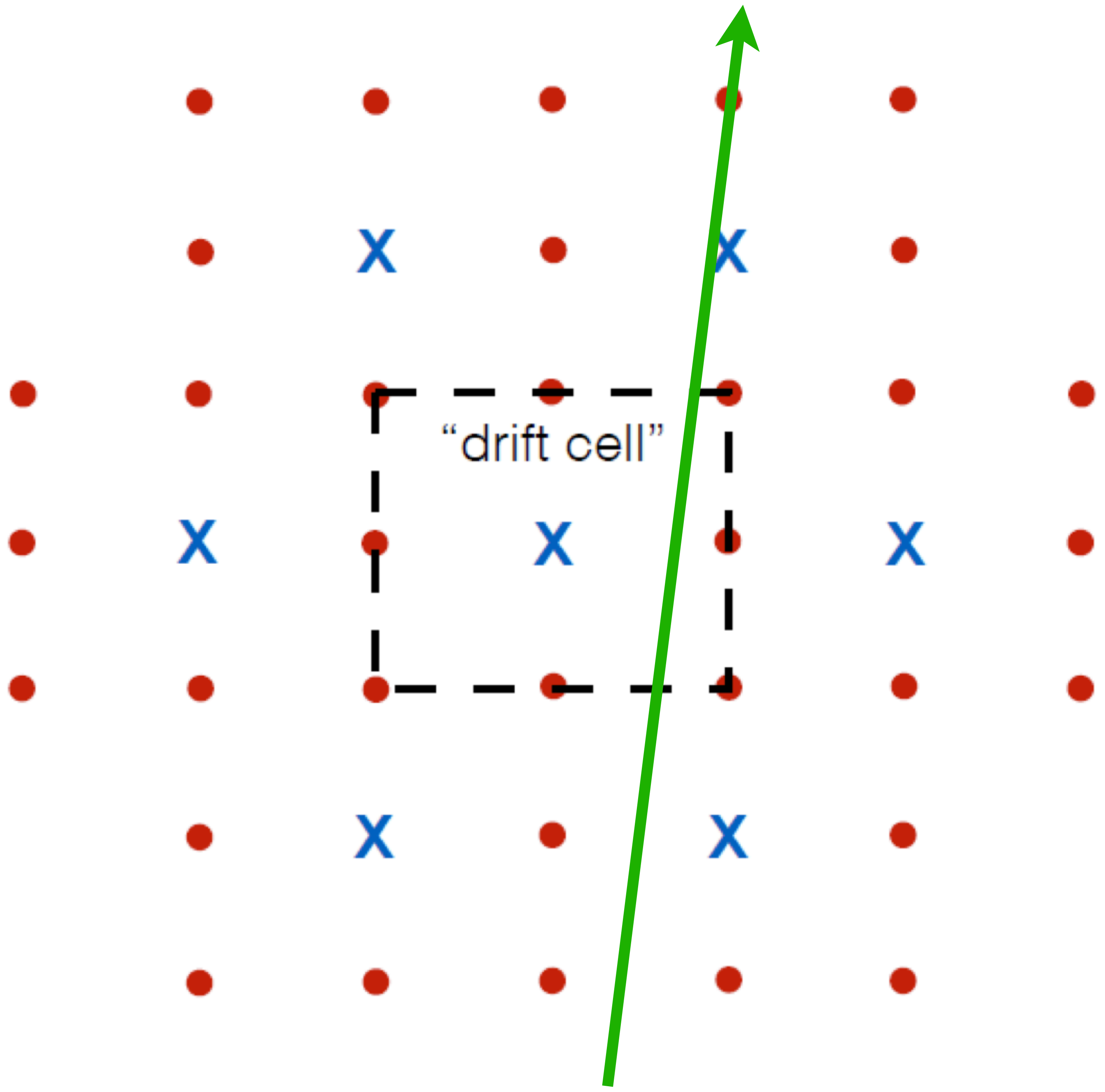
Belle II CDC structure



- Cylindrical shaped gas-filled drift chamber composed of
  - 56 layers (grouped to 1×8, 8×6)
  - 14336 thin wires (160 - 384 wires in layer).
- CDC layers alternate between **field wire** and **sense wire**.
  - **Sense wire** - large potential (anode)
  - **Field wire** - grounded

8 **field wires** surround each **sense wire** (but shared w/ other cells)





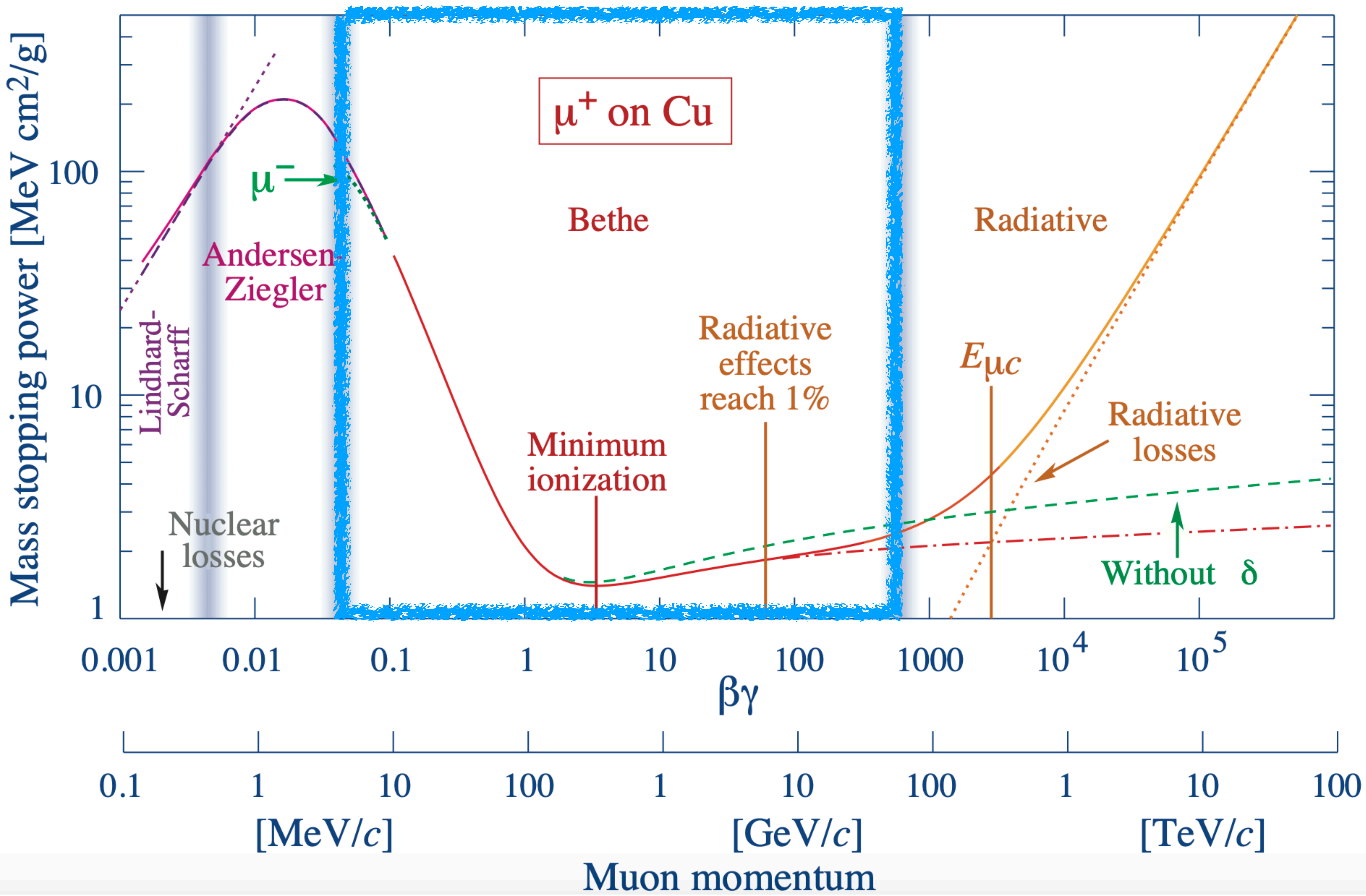
- Electrons liberated by ionization drift toward the anode (sense wires).
- Near the sense wires, the larger electric field causes the electrons to create avalanches and the signal is collected from sense wires.

dE/dx basics

Bethe-Block Formula $-\frac{dE}{dx} = Kq^2\frac{Z}{A\beta^2}\left[\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$

- Charged particles passing through matter can knock out electrons from atoms of the medium: **ionization.**
- The energy loss (dE/dx) is described by Bethe-Block formula.
- This can be used to identify particles, particularly at low momentum where dE/dx varies rapidly.
- **dE/dx has following properties:**
  - Independent of mass of incident particle.
  - Depends only on $\beta\gamma$ ($= p/m$)
  - Depends on the charge of incident particle squared.

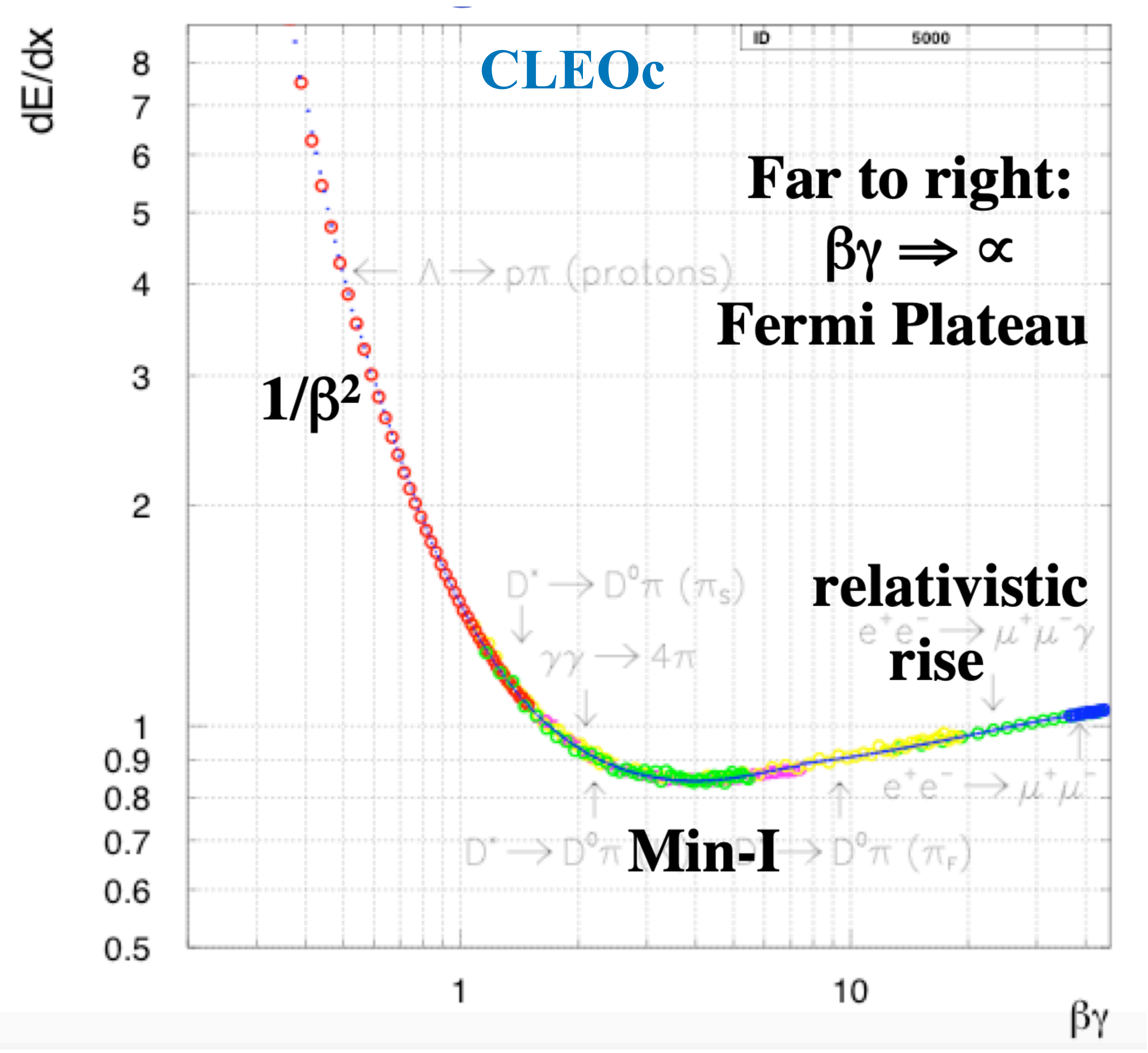
dE/dx momentum region



From PDG Review on
Passage of Particles through Matter

Universal dE/dx curve

- The dE/dx vs. βγ curve should be universal.
  - dE/dx depend only on βγ = p/m (Bethe-Bloch formula)



Four important *βγ* region of curve:

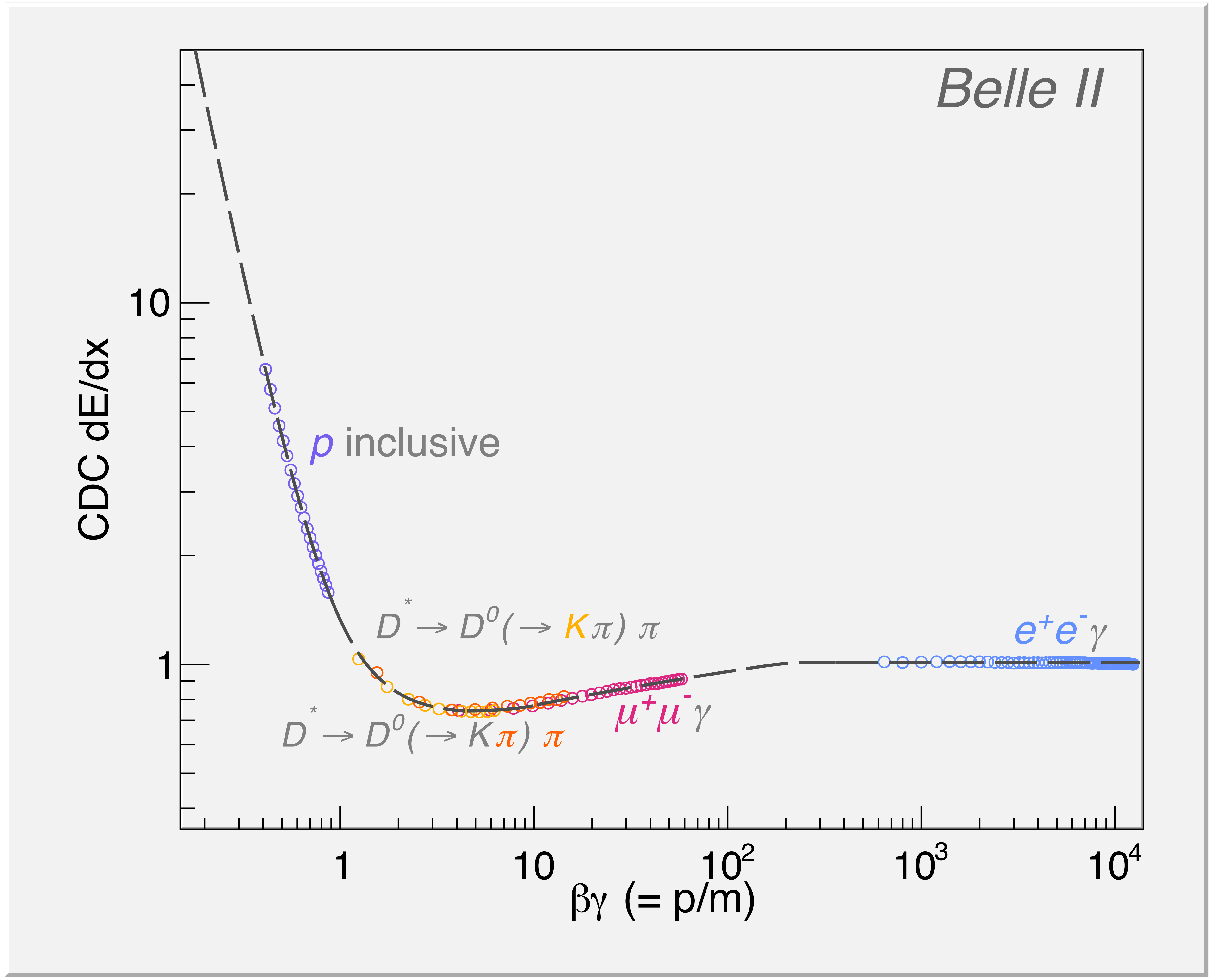
1. $1/\beta^2$ region at low βγ, where dE/dx ~ $1/\beta^2$
2. Min-I, minimum-ionization region near $\beta\gamma \simeq 4$
3. Relativistic rise, after Min-I (35% increases)
4. **Fermi plateau** at very large *βγ*

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

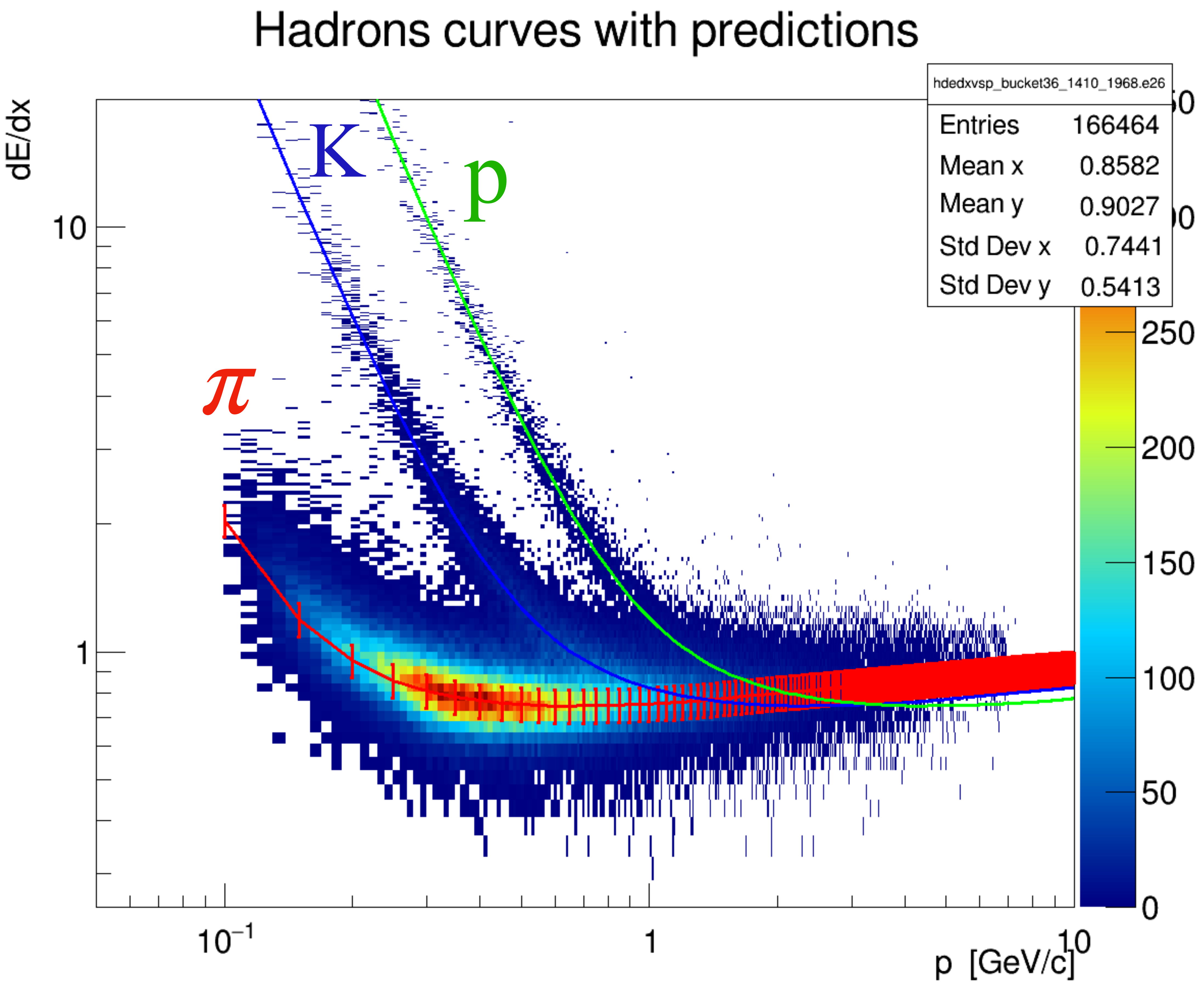
- All lie on one universal curve! ⇒ Only depends on βγ = p/m

dE/dx curve from Belle II data

dE/dx vs. βγ



- Mass of charged particles have definite discrete values.
  - Mass shifts the universal βγ curve to a series of parallel curves when plotted vs. p = βγm



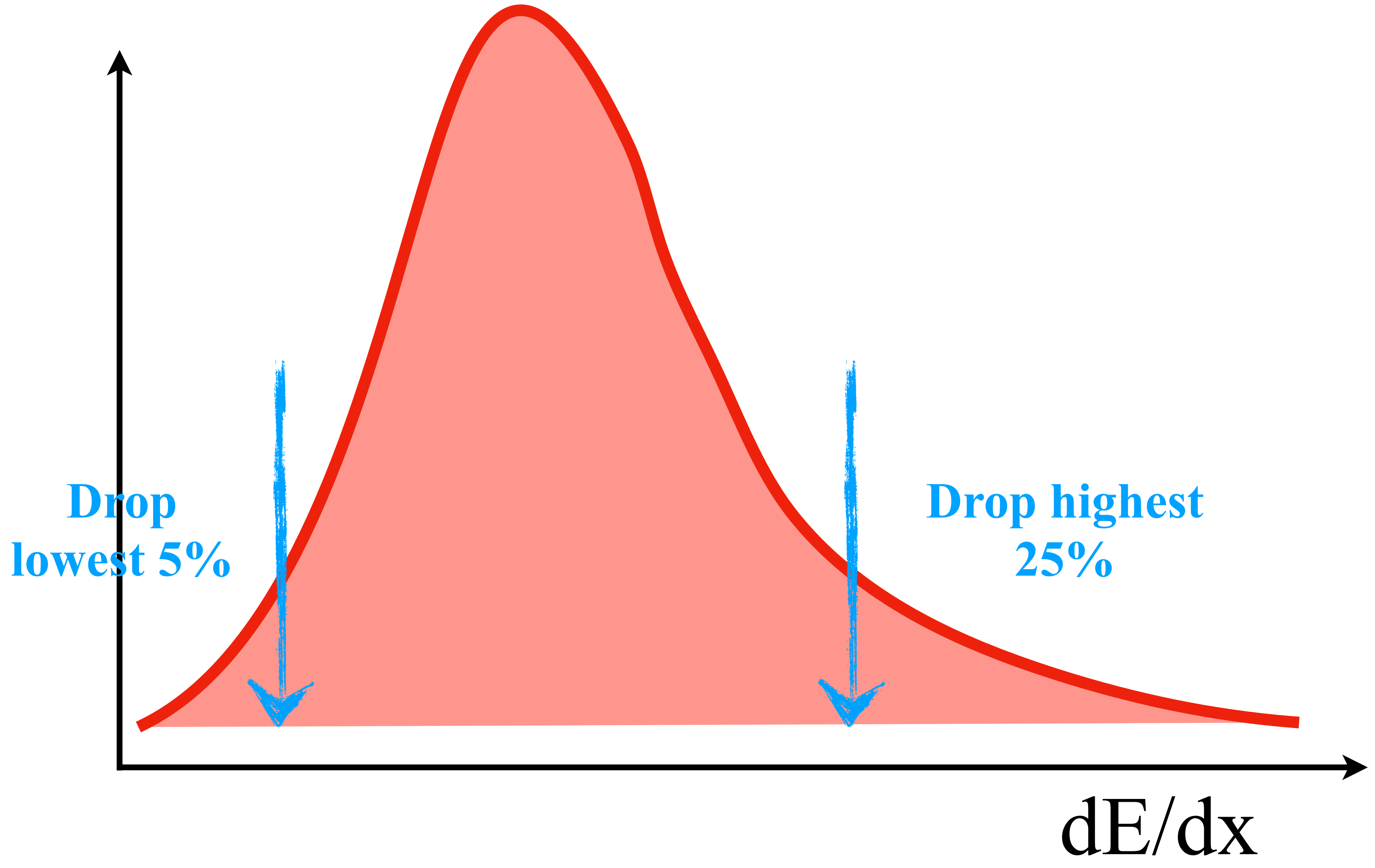
dE/dx vs. p

Reconstruction and Truncated mean

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”...

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)

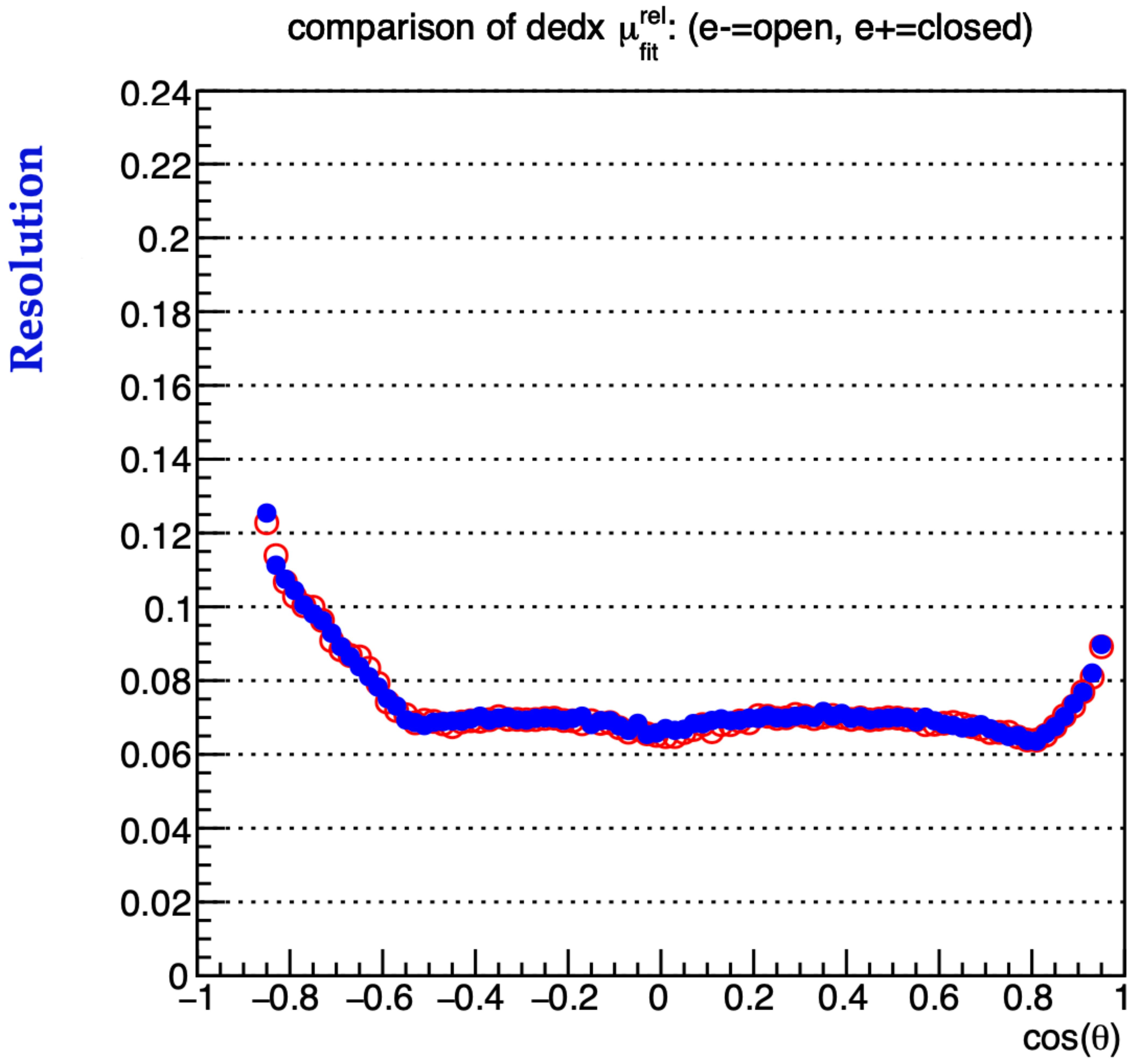
drop lowest 5%, highest 25% of measurements

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”

Resolution from Bhabha ($e^+e^- \to e^+e^-$)



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)

dE/dx calibration

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

- **Source of calibration 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**

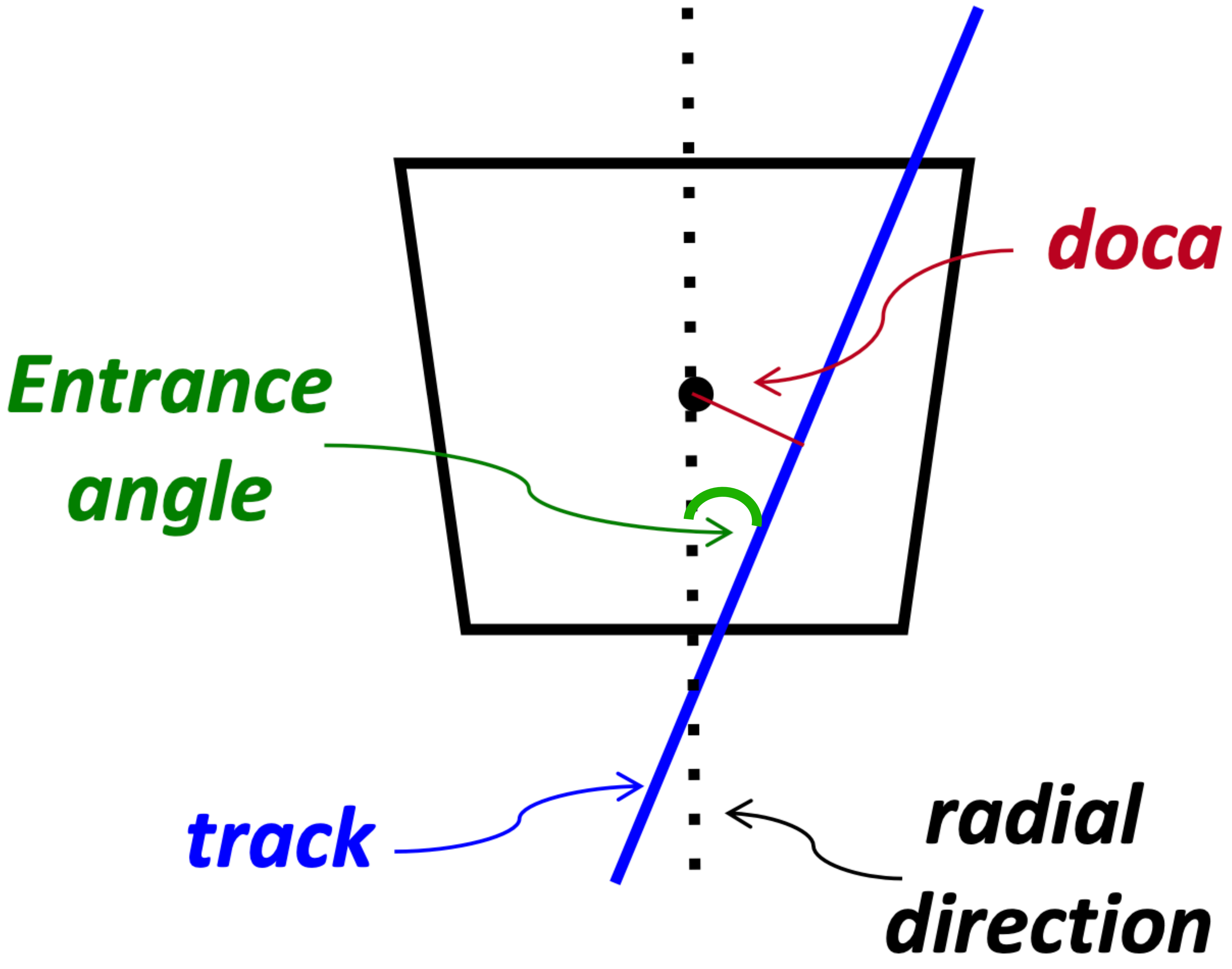
	Calibration	Source	
path	r-z path length	track geometry	track
path	r-ϕ path length	track and drift cell geometry	hit
gain	Scale Factor	e^+e^-	track
gain	Run Gain	e^+e^-	track
gain	Wire Gain	e^+e^-	hit
~both	2-D doca-ent. angle	$e^+e^-\gamma$	hit
~both	1-D ent. angle “clean up”	$e^+e^-\gamma$	hit
gain	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
gain	Injection time	e^+e^-	hit

Path length correction

- **Charge collected depends on path through a cell in r-φ projection:**
  - **Doca**: **D**istance **o**f **c**losest **a**pproach (track fit to wire)
  - **Entrance Angle**: angle of the track relative to the radial

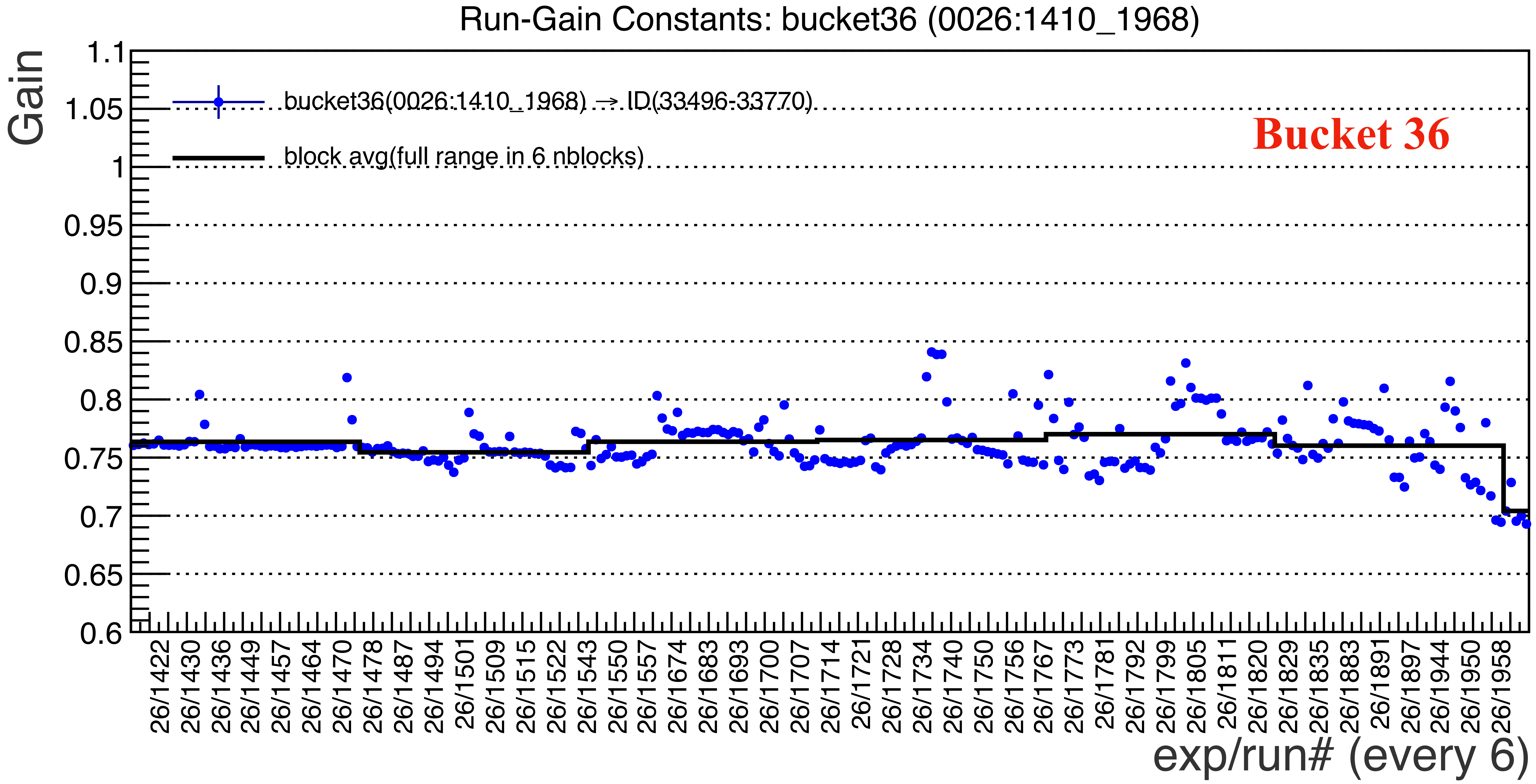
- **Geometrical (path length) correction:**
  - $r - z$ **view of track**:
    - ◉ 3-D path length varies as $1/sin\theta$
    - ◉ **Correction**: divide by the path length i.e. just multiply by $sin\theta$
  - $r - \phi$ **view of drift cell:**
    - ◉ Calculated from full track fit to all hits and nominal cell geometry
    - ◉ One need separate correction factor for each layer

Cell Geometry



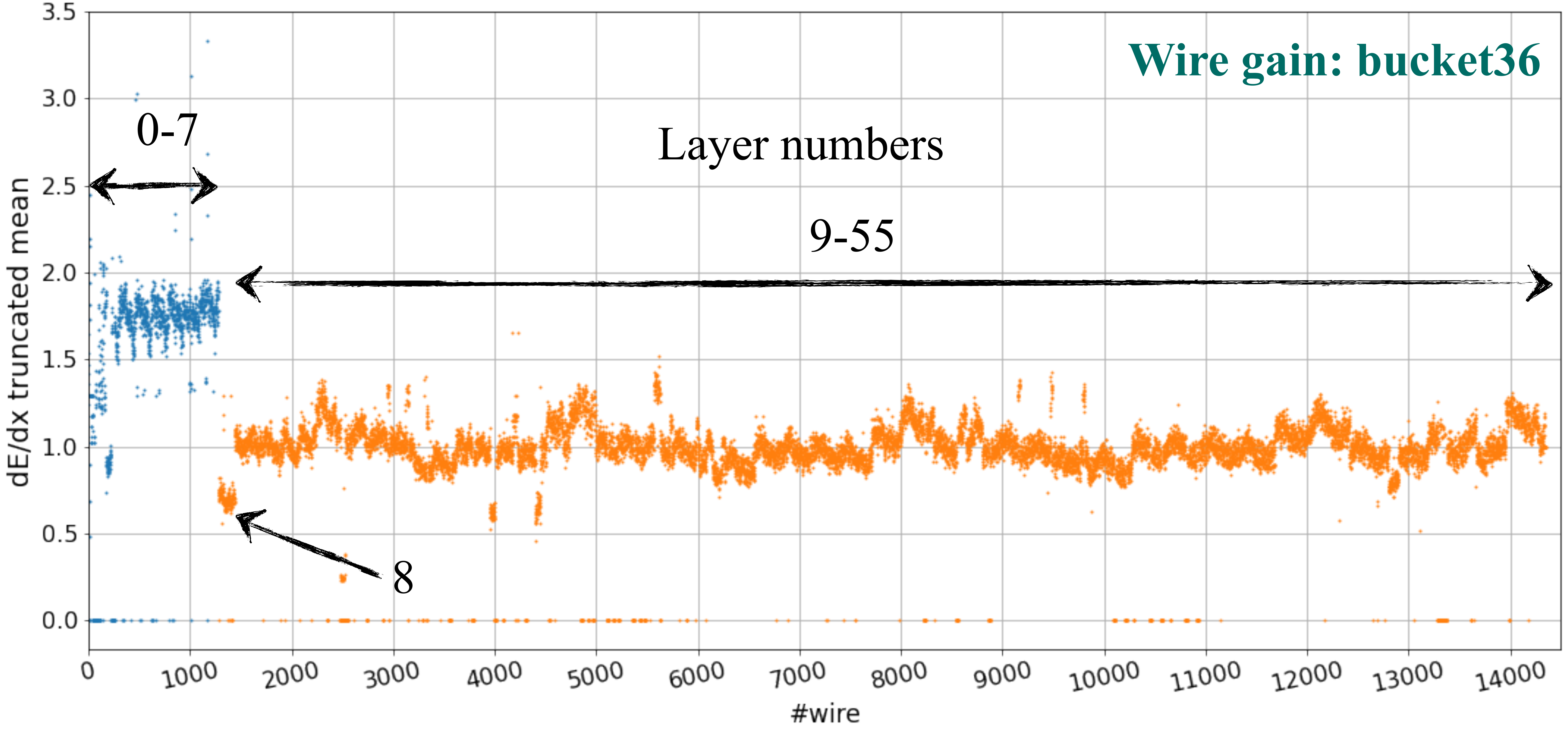
Run gain

- Run gain is calculated as fit mean of dE/dx distribution from each run (bhabha tracks)
- **Run gain changes because instabilities of CDC**
    - Gas composition (incl. water vapor)
    - Temperature
    - Pressure



Wire gain

- Wire gain is calculated as truncated mean of dE/dx distribution for each wire (14336).
- One needs to account for bad wires, bad electronics cards, voltage issues..…



zero gains = dead/bad wires

Inner layers 0-7 have larger gain

Layer 8 is very non-square

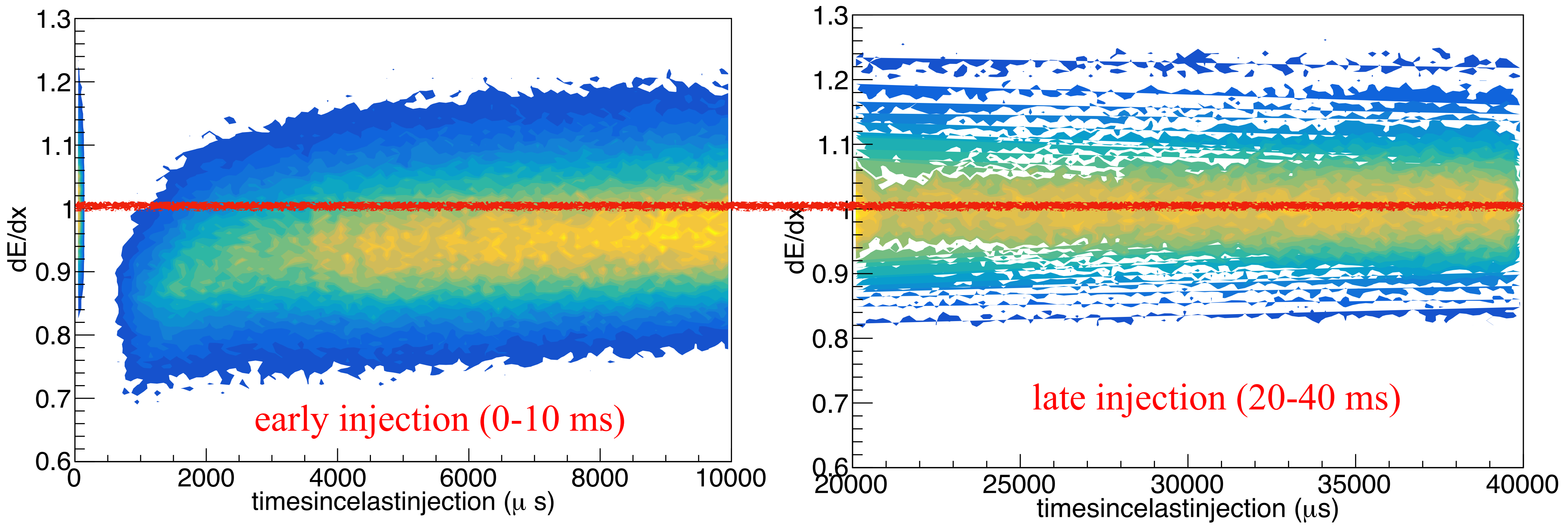
Time since last injection

New

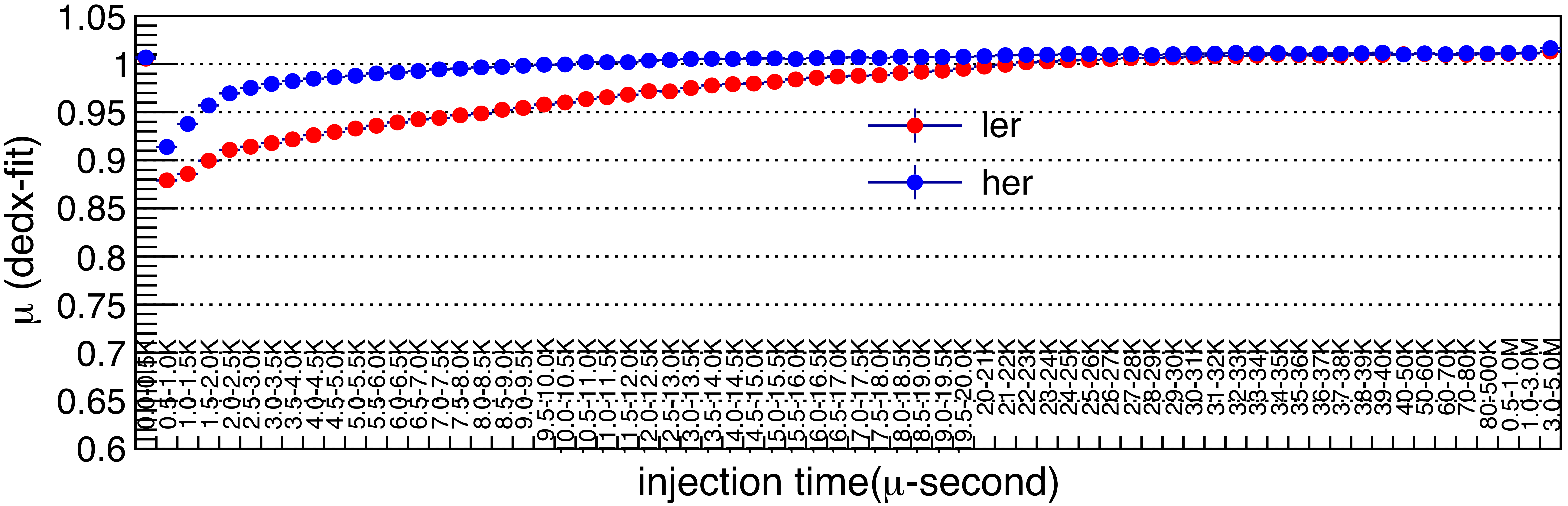
Dependency of dE/dx gain and resolution for early time since last beam injection and it further depends

- which ring had injection (LER and HER).
- on data period (experiments/run or buckets) or beam background conditions.

1.0 = nominal electron

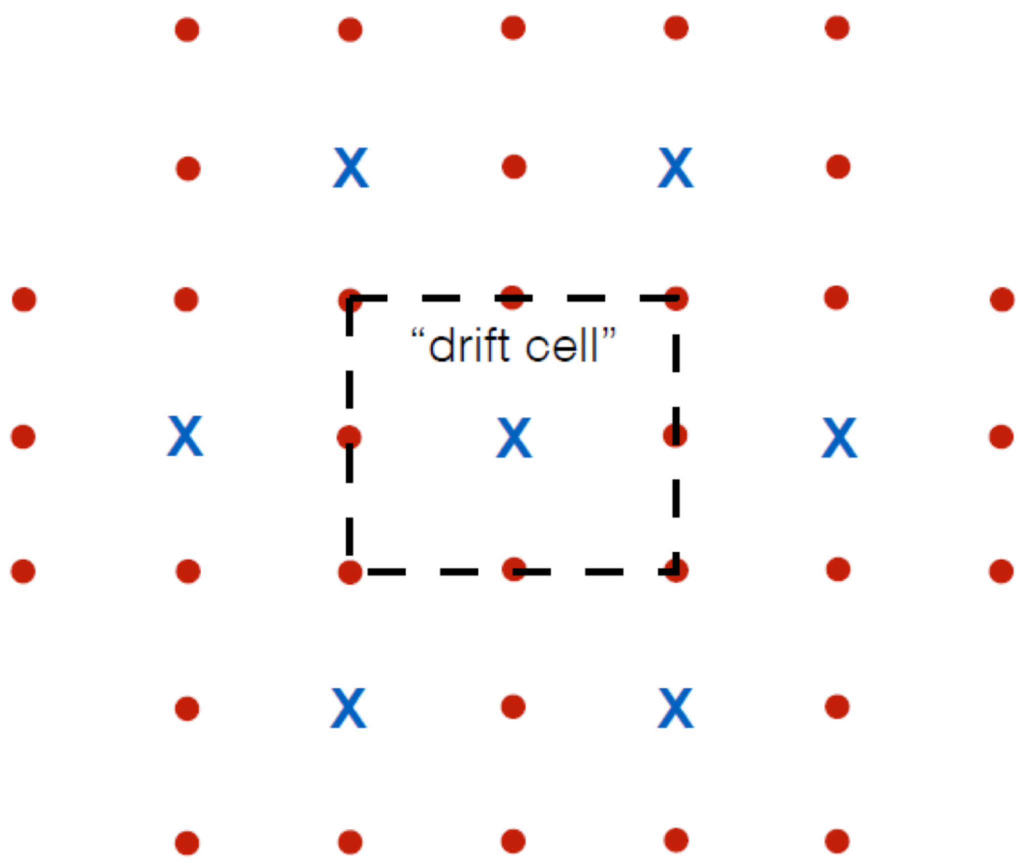


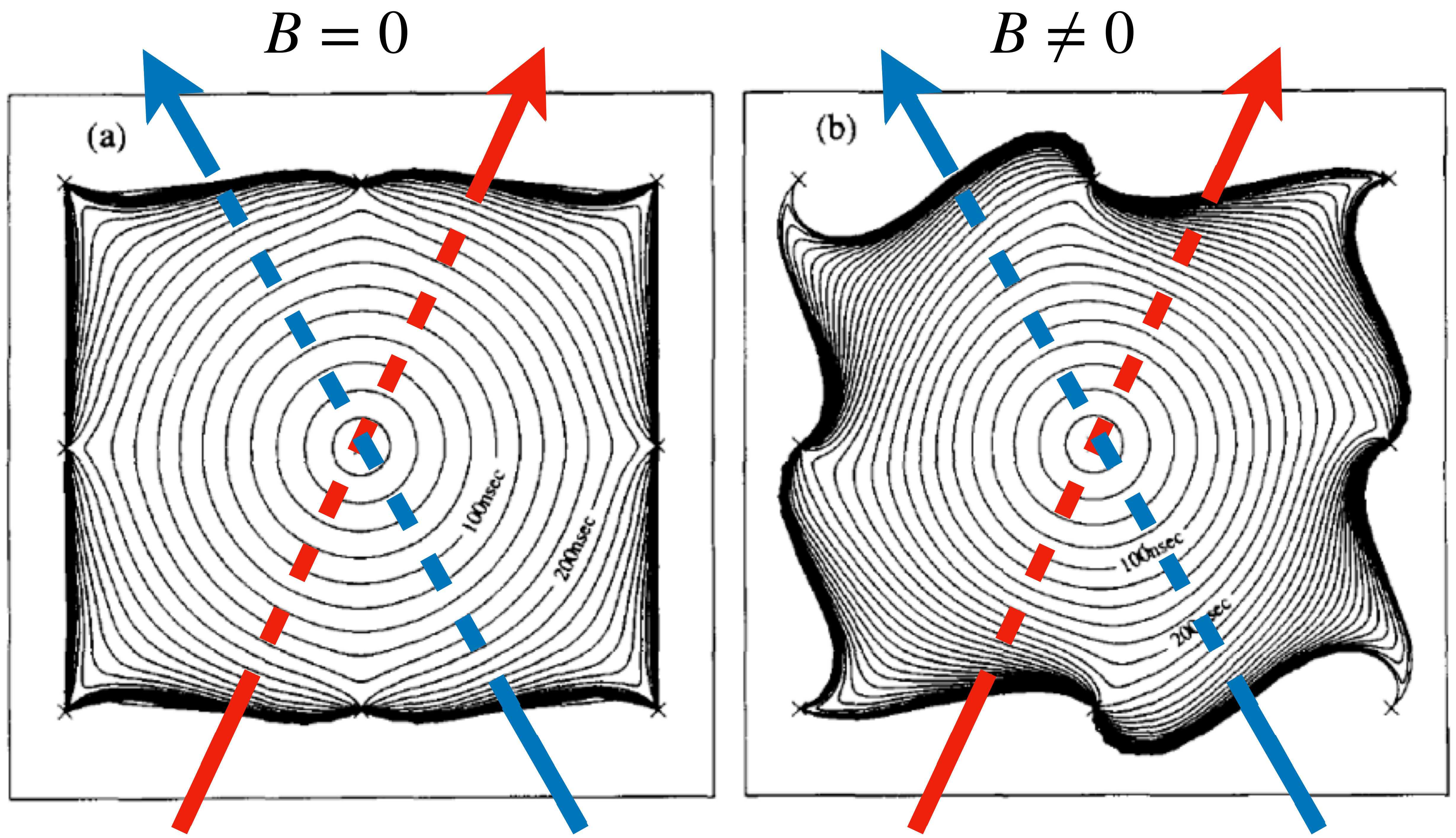
Gain is calculated as fit mean of dE/dx distribution in injection time bins for run grouped.



Empirical $r - \phi$ cell correction

- Left-right drift-cell symmetry broken by B-field
- Sign of charge determines the sign of entrance angle.
- Correct in 2-dimensional bins of **doca** and **entrance angle**
- 1-d correction versus entrance angle is applied further
  - Correlated among hits along track
  - Important to remove charge asymmetry (fake CP violation)





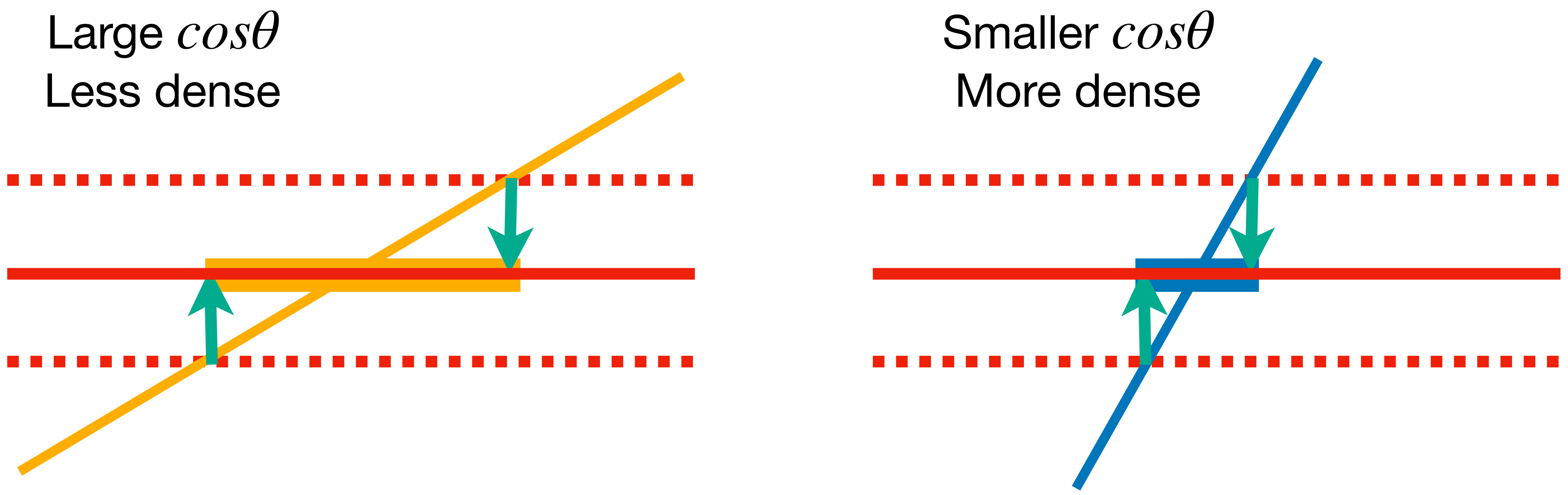
Presence of magnetic field causes electron trajectories to curve

Blue and Red tracks: opposite charges and thus opposite entrance angles. Different effective path lengths give different amounts of ionization to be collected at the sense wire.

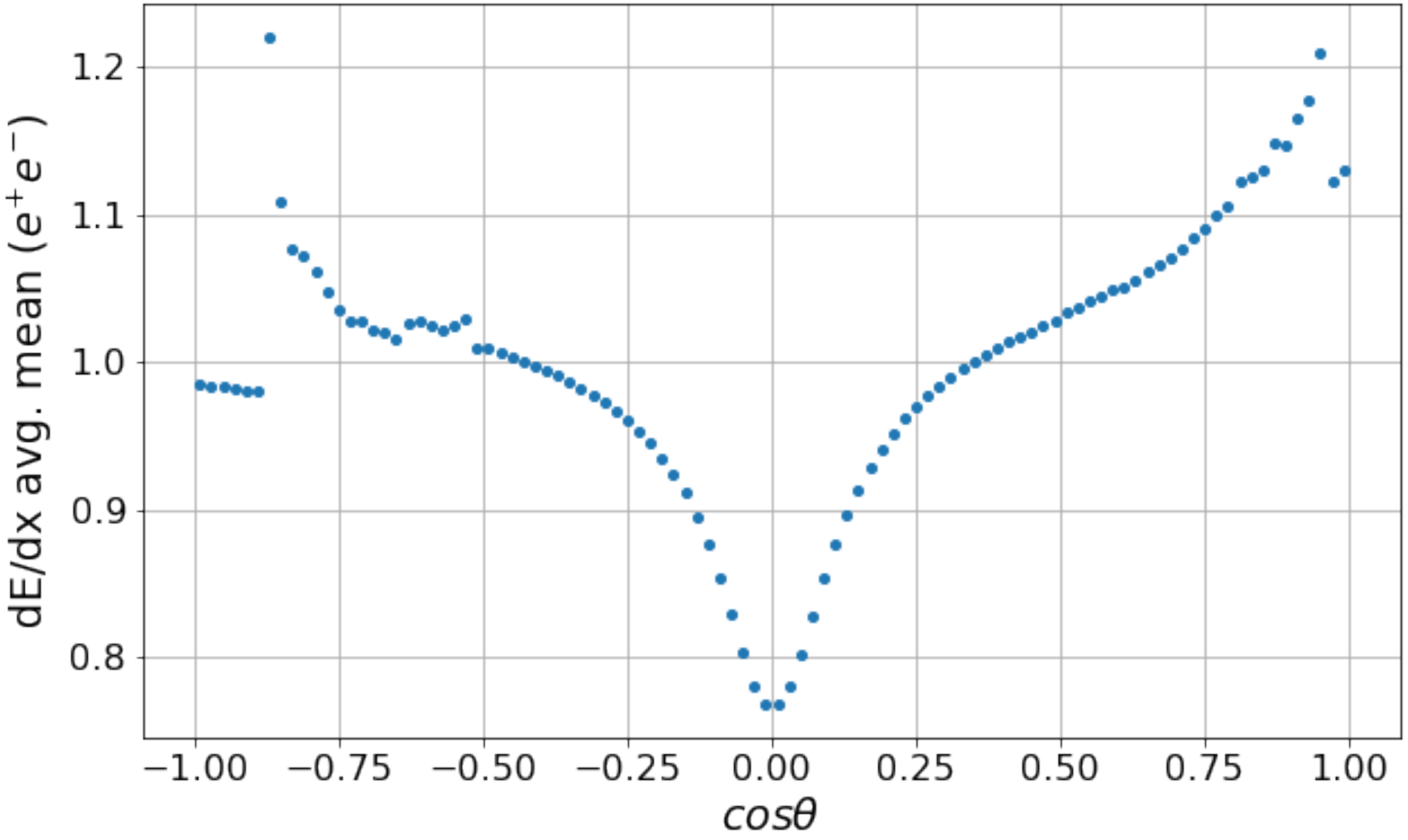
Gas gain saturation

Avalanche from early electrons screens wire:

Leads to a decrease in gain for tracks near *cosθ* ~ 0: a “dip”

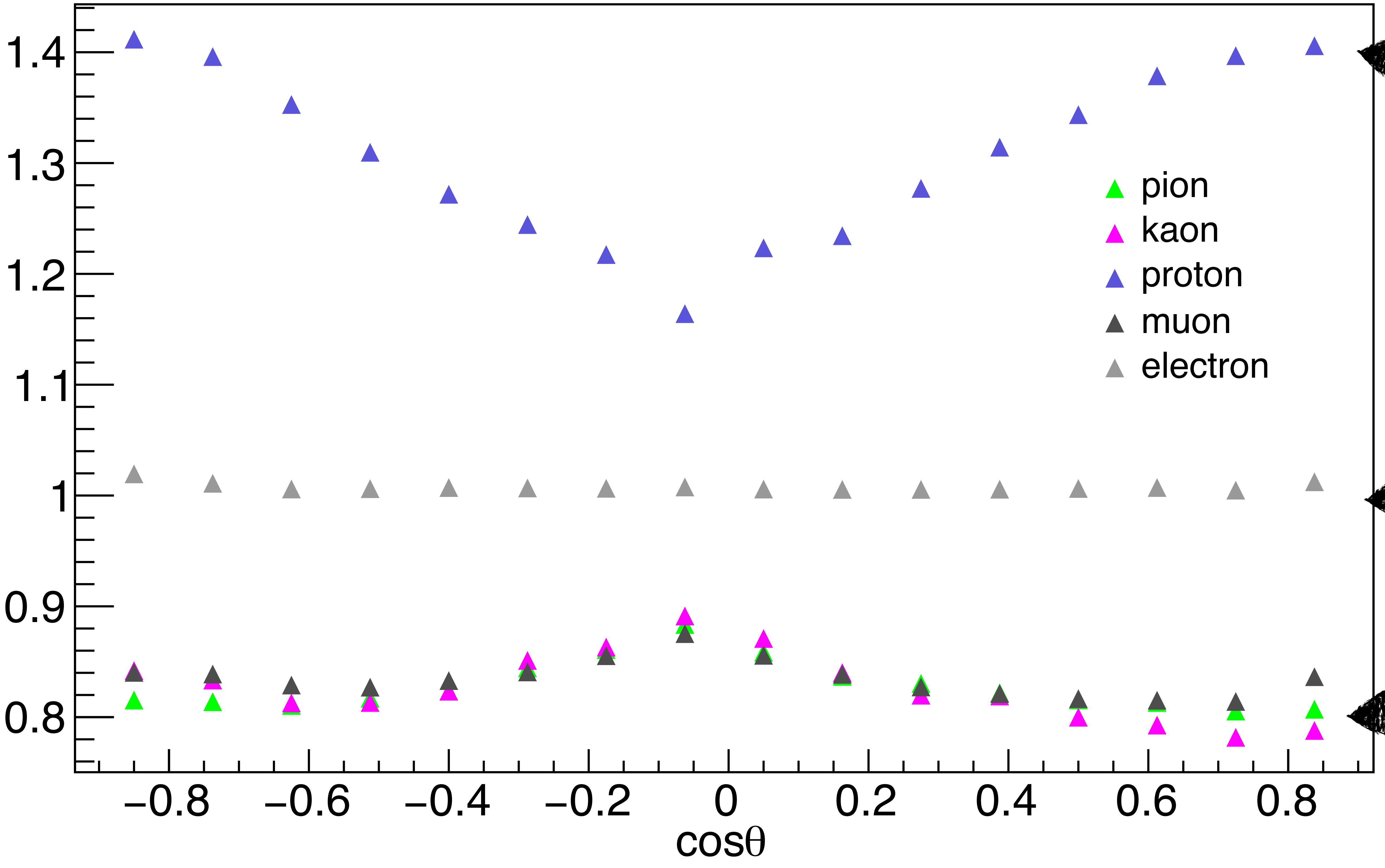


- For **electrons** (constant ionization) we map this out very accurately
  - this “anchors” the correction in the region of crossing dE/dx bands, where we need best resolution
- For **other tracks**, we need to apply another correction since the “dip” changes shape
  - An intrinsic ionization changes (slow protons saturate even more)



Gas gain saturation

- **Key variable:** $\frac{D}{|cos\theta| + \delta}$ = charge/length
- Density of charge along wire: D is measured dE/dx (after all path correction)
- $\delta \sim 0.1$ accounts for natural spread of avalanche
  - density not infinite even if $|cos\theta| = 0$



$1/\beta^2$ region
Under corrected

Fermi-plateau region
Electrons

Min-I region
Over corrected

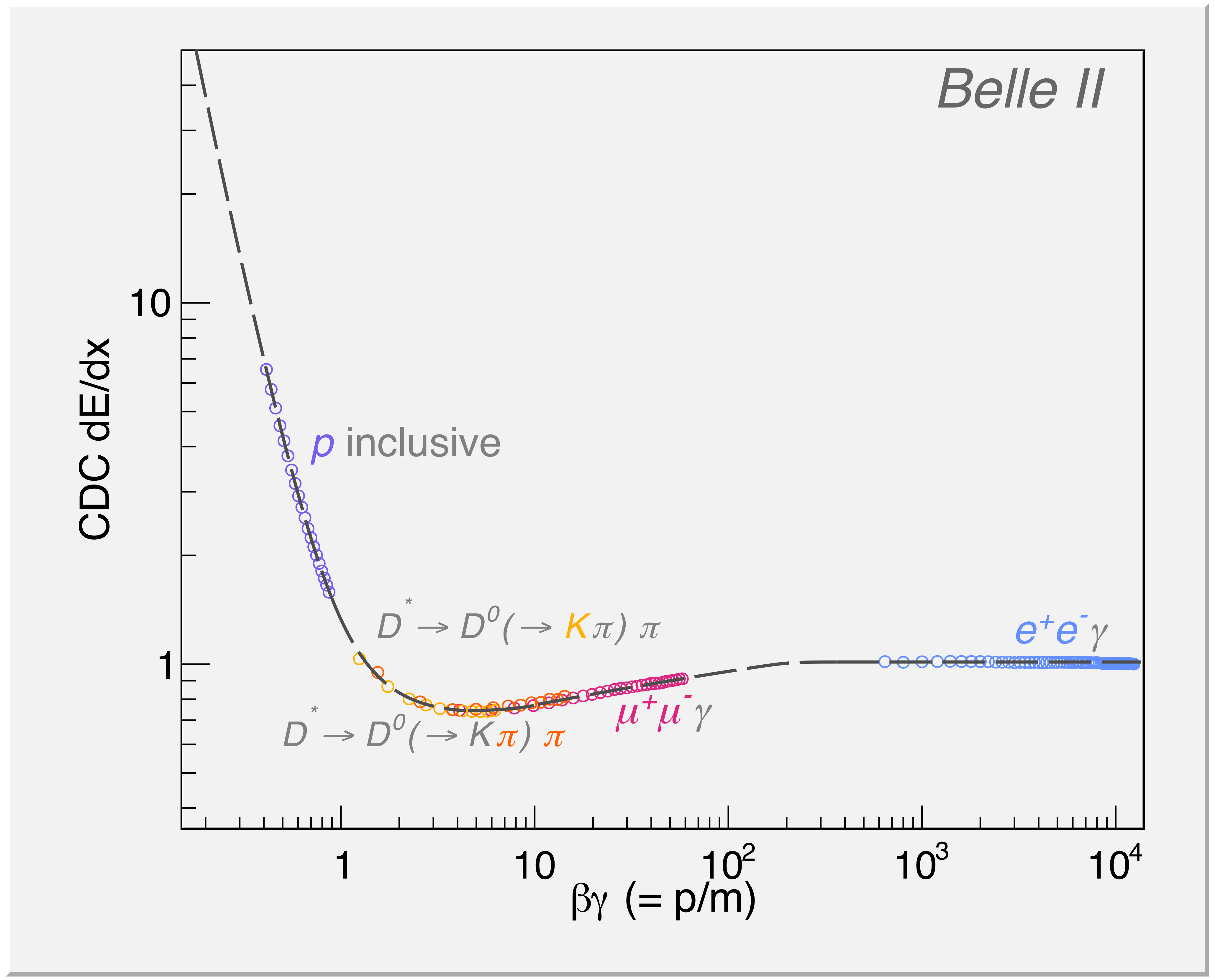
Predicted mean and resolution

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

- Expected dE/dx: I_pred Depends only on $\beta\gamma = p/m$
- Expected resolution Depends on 3 variables: I_pred, #hits, $cos\theta$

Fit means to empirical functions in ~3 regions of $\beta\gamma$

- In general, fits with polynomials often become poor at edges
- Therefore, fit to data beyond intended range of use!
    - for example, fit $\beta\gamma$ from 0.5 - 3.5 to get values for 1.0 - 3.0



Resolutions are a bit more complicated:

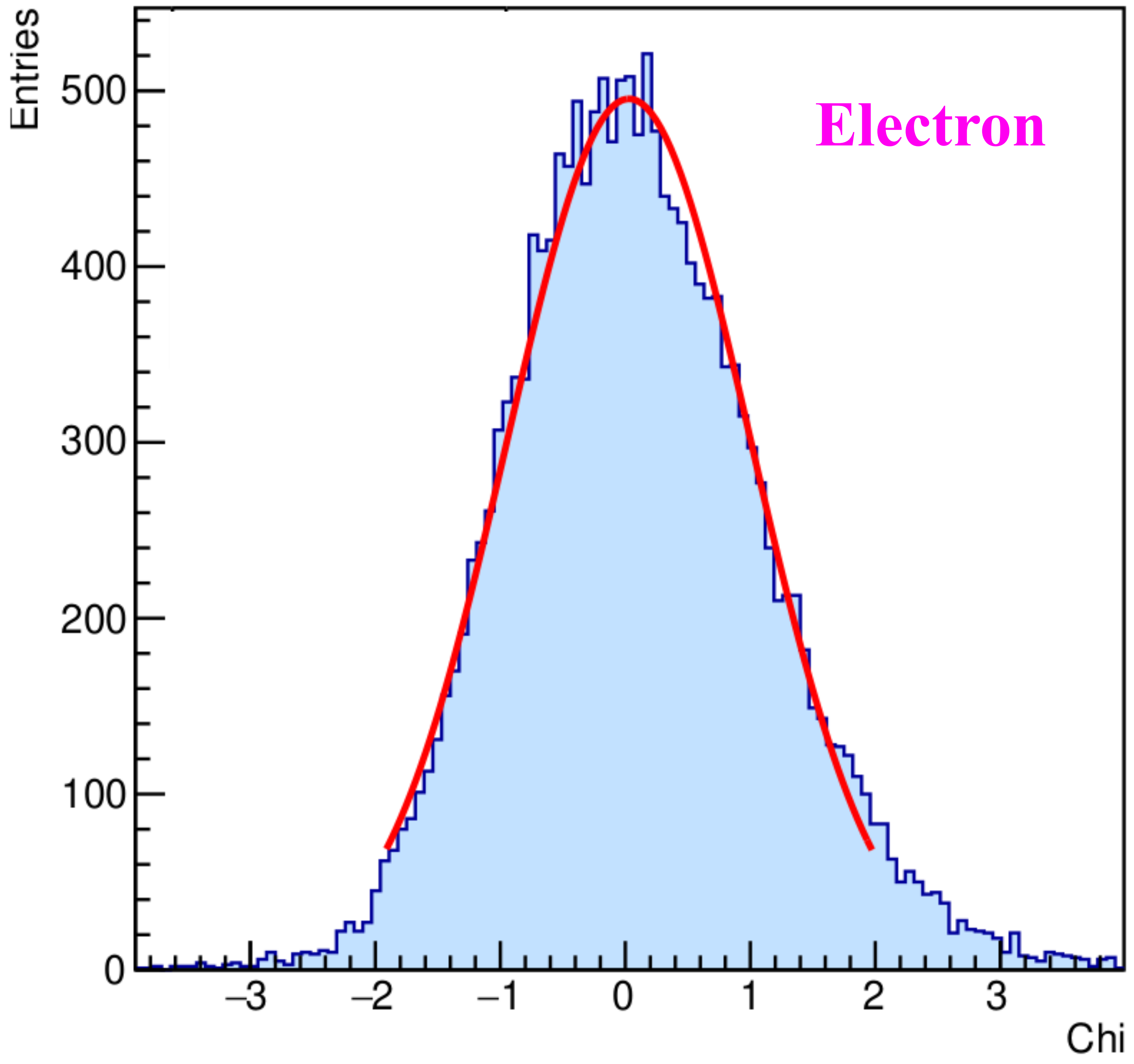
- $\sigma_I \sim f(I)\ g(nhit)\ h(cos\theta)\ m(time)$
- Carefully fit for ***functions*** f, g, h, m.
- Iterate, fit for each with other three effects removed.

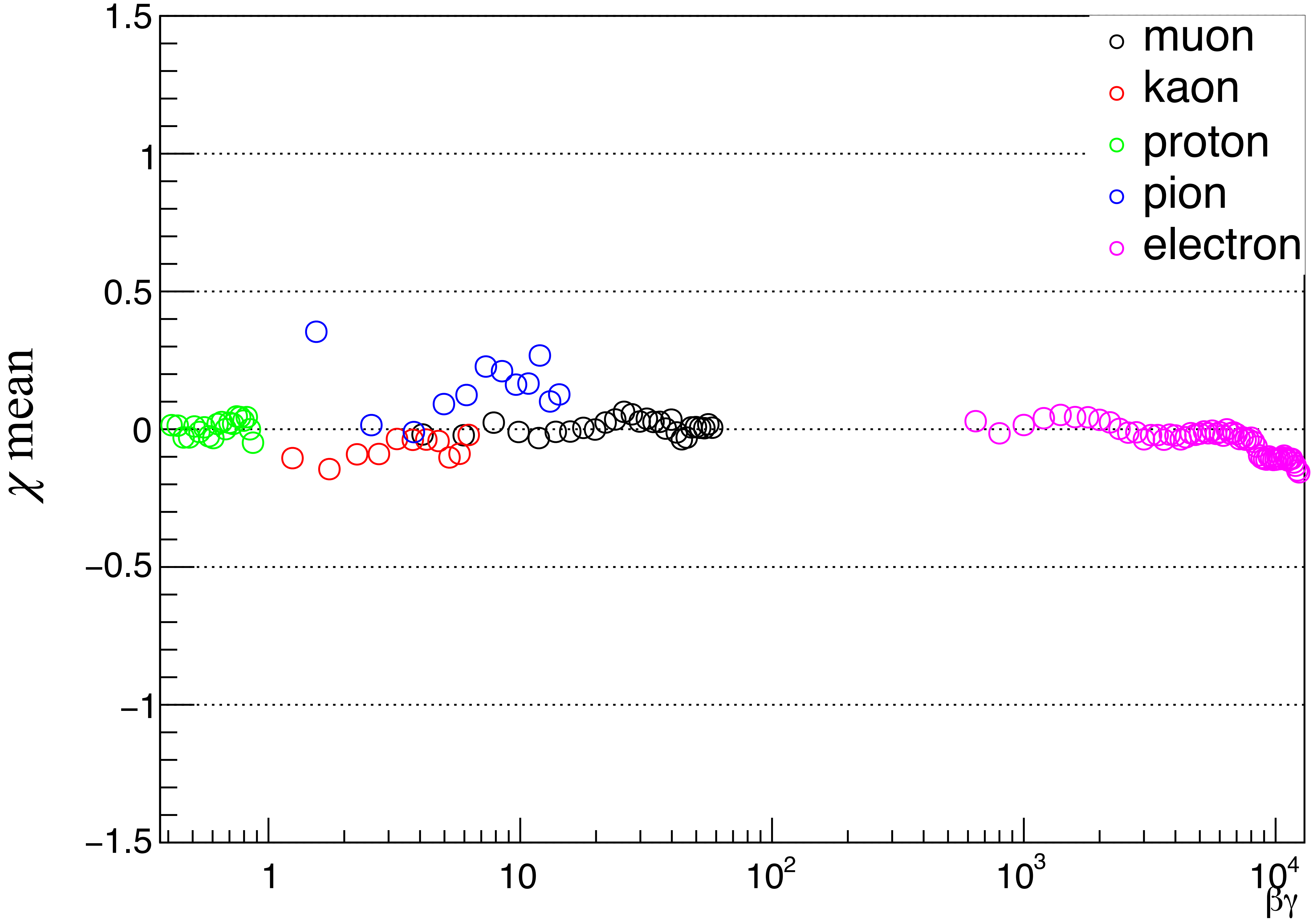
User information

The final result of dE/dx reconstruction is:

- one "χ" value for each of six hypotheses { e μ π K p d }

$$\chi(\text{hyp}) = \frac{I_{\text{meas}} - I_{\text{pred(hyp)}}}{\text{resolution(hyp)}}$$





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: $\exp[-\chi^2/2]$

Likelihood Ratios

Vertical axis:
“pairwise” Likelihood ratio

$L_\pi/(L_\pi + L_K)$

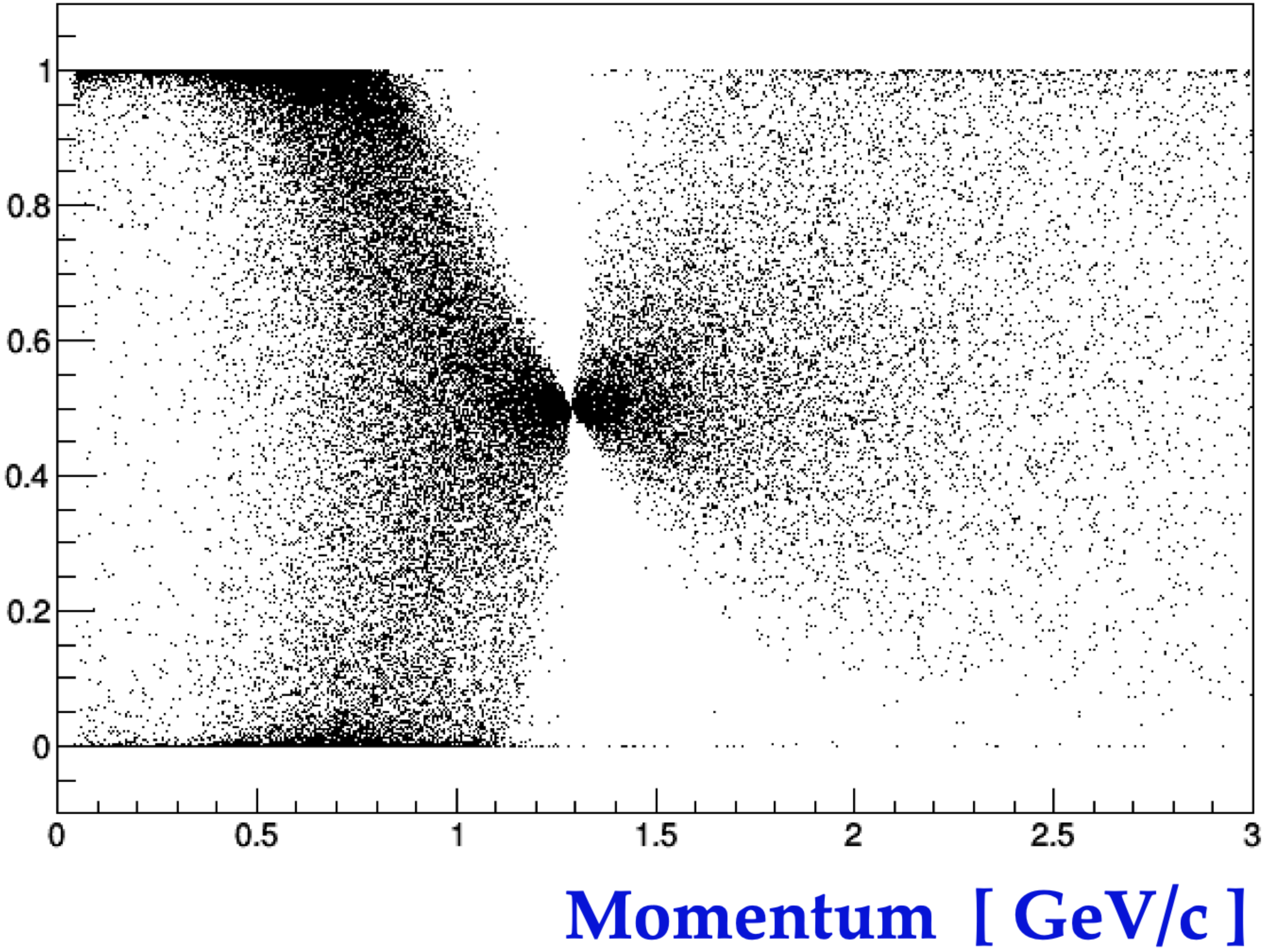
Plotted for “generic tracks”

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 !



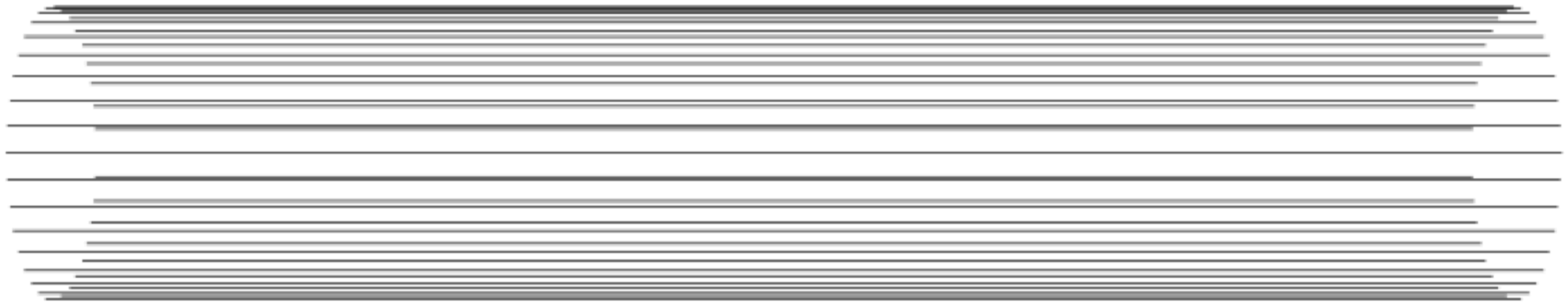
Summary

- The Belle II CDC is important for tracking, PID, and trigger.
- dE/dx provides useful Particle ID in BelleII.
- dE/dx reconstruction and calibration is good shape.
  - Detector response and PID performance seems reasonable.
  - We continue to work on improvements.

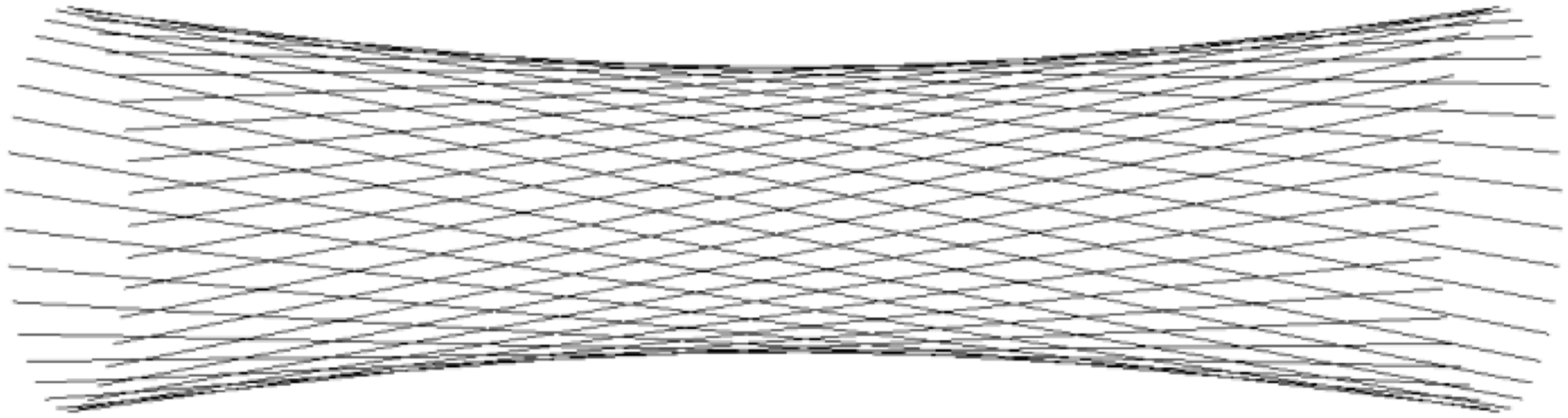
Backup

Axial and stereo layers

If wire is along the beam line:
how to differentiate between $z = z_1$ and $z = z_2$?



(a) An axial wire layer - sense wires are parallel to the beamline



(b) A stereo wire layer - sense wires are skewed to the beamline (exaggerated)

Different combinations of wires are hit for different z, due to skew.

Layer structure

Superlayer	Type	# of layers	# of wires /layer	Radius, mm	Stereo angle, mrad
1	A	8	160	168.0 – 238.0	0 – 0
2	U	6	160	257.0 – 348.0	45.4 – 45.8
3	A	6	192	365.2 – 455.7	0 – 0
4	V	6	224	476.9 – 566.9	-55.3 – -64.3
5	A	6	256	584.1 – 674.1	0 – 0
6	U	6	288	695.3 – 785.3	63.1 – 70.0
7	A	6	320	802.5 – 892.5	0 – 0
8	V	6	352	913.7 – 1003.7	-68.5 – -74.0
9	A	6	38