US Belle II Summer School:
Overview of the structure and uses of the Central Drift Chamber (CDC)

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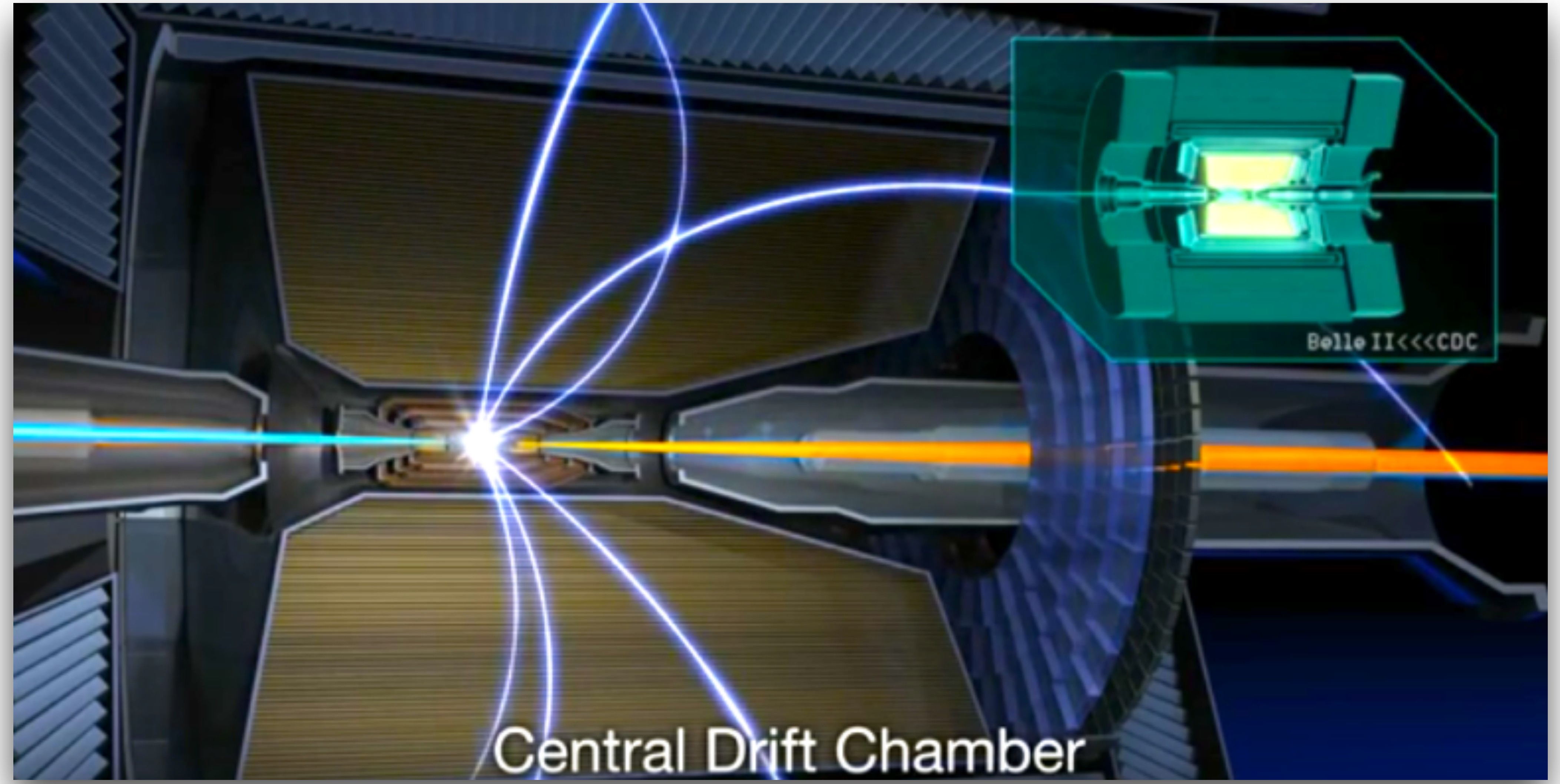
Outline

- Introduction to the CDC
  - General structure
  - Ionization and drift cells
  - Tracking
- Brief introduction to dE/dx
- dE/dx Calibration
  - Overview of calibration constants
  - Electron calibration: run and wire gains, drift distance, saturation
  - Full hadron calibration: saturation, beta-gamma curve, resolution
- Progress
- Conclusions

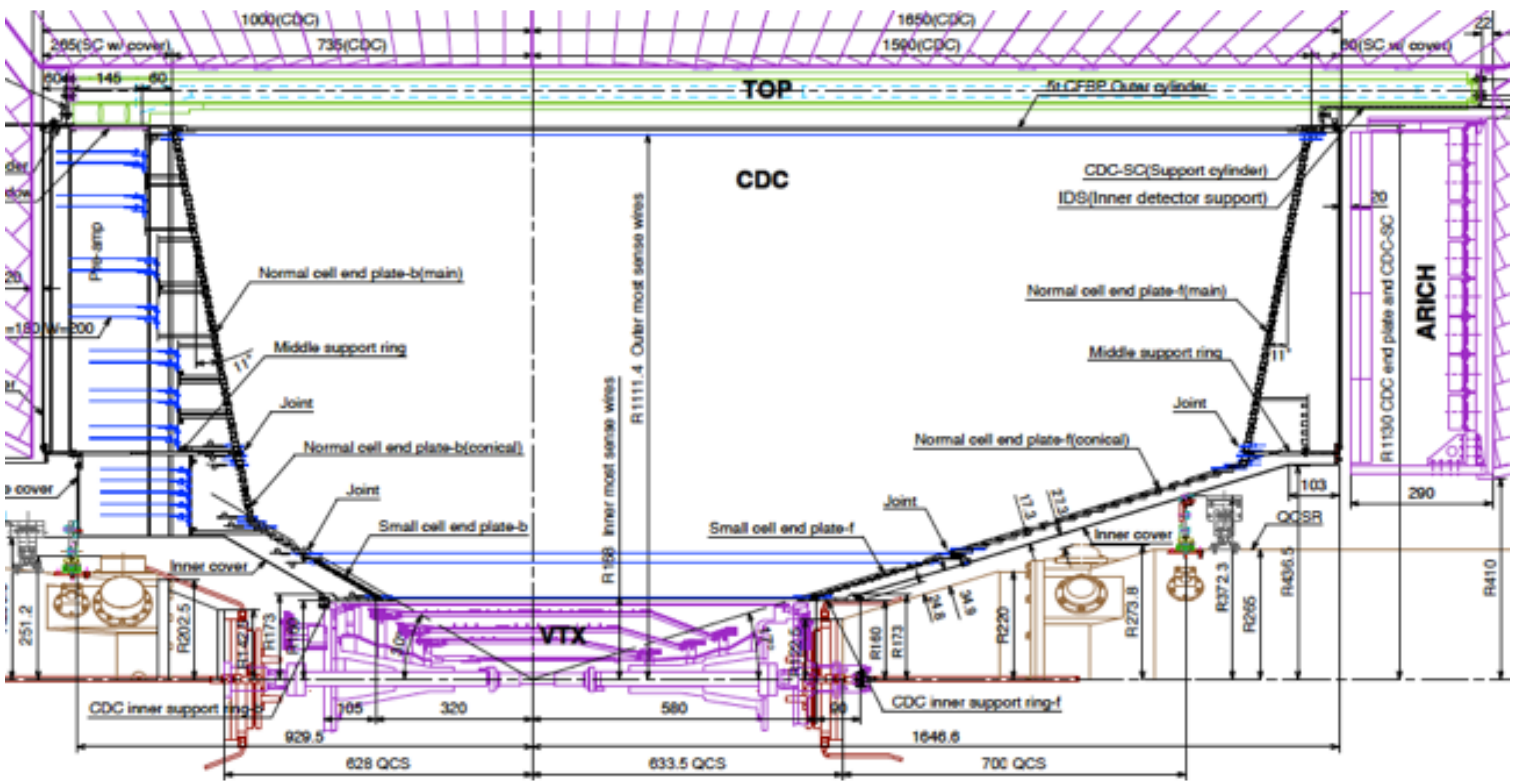
The Belle II Central Drift Chamber (CDC)

- The CDC plays three important roles
  - Reconstruction of charged tracks with precise momentum measurements
  - Particle identification using ionization energy loss (dE/dx) measurements
  - Efficient and reliable trigger signals for charged particles



Basic idea

- Roughly cylindrical gas-filled chamber with thin wires parallel to the primary axis
  - Charged particles ionize the gas along their flight path, giving up a small amount of kinetic energy (few keV/cm)
  - Ionization electrons drift through the gas and are amplified at the wires in avalanches at the wires



- Electrical signals with the location (which wire) and drift time of each hit are recorded

Belle II CDC structure

- Follows the general structure of the very successful Belle CDC
- Larger inner radius to make room for bigger VXD
- Less room needed for TOP than RICH: larger outer radius

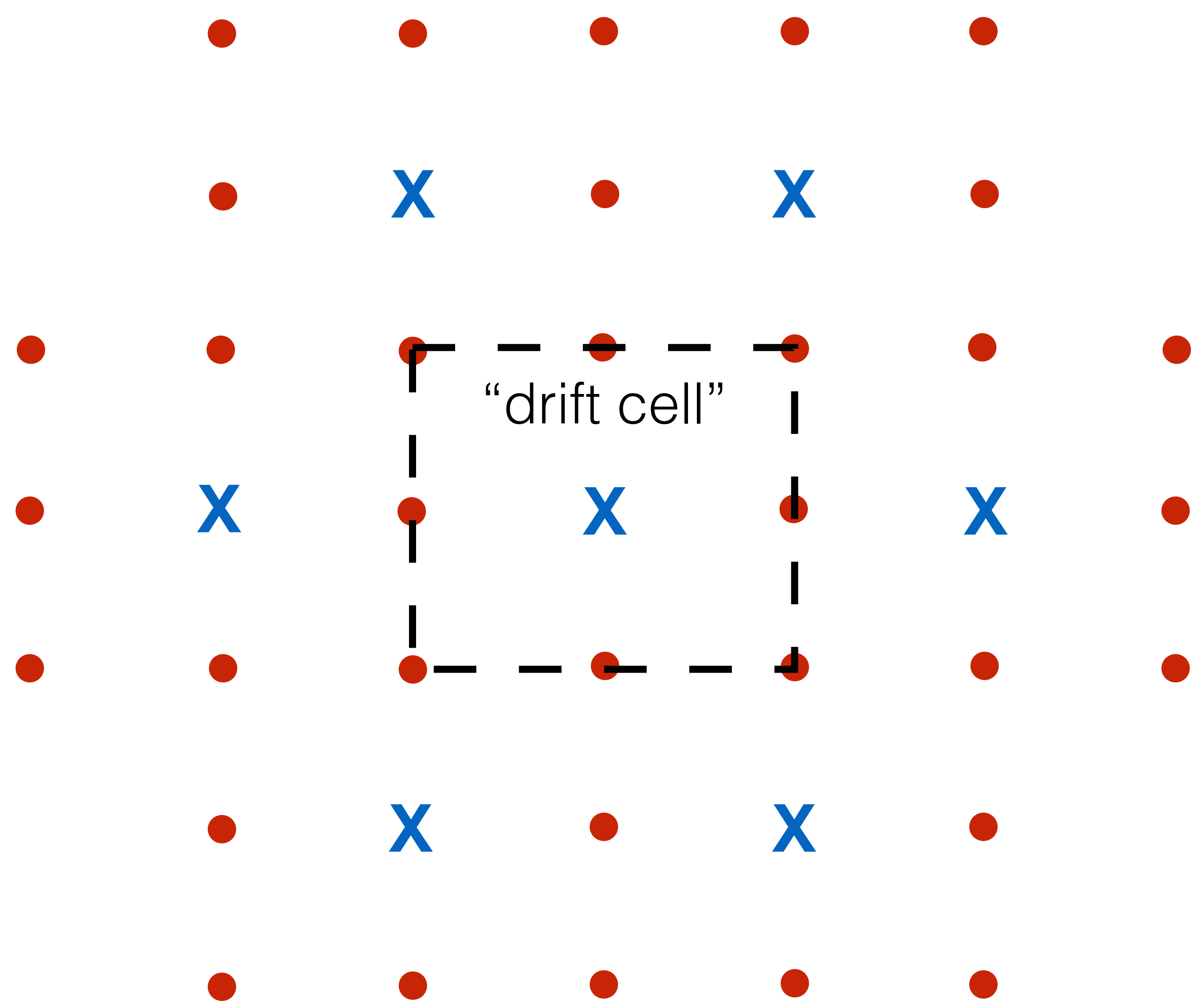
	Belle	Belle II
Radius of inner cylinder (mm)	77	160
Radius of outer cylinder (mm)	880	1130
Radius of innermost sense wire (mm)	88	168
Radius of outermost sense wire (mm)	863	1111.4
Number of layers	50	56
Number of sense wires	8,400	14,336
Gas	He–C_2H_6	He–C_2H_6
Diameter of sense wire (μm)	30	30

	Sense	Field
Material	Tungsten	Aluminum
Plating	Gold	No
Diameter (μm)	30	126
Tension (g)	50	80
Number of wires	14,336	42,240

- Try to keep the influence of gravitational sagging of the wires within the inherent mechanical resolution of the detector
- Tension in wires will cause deformation of endplates

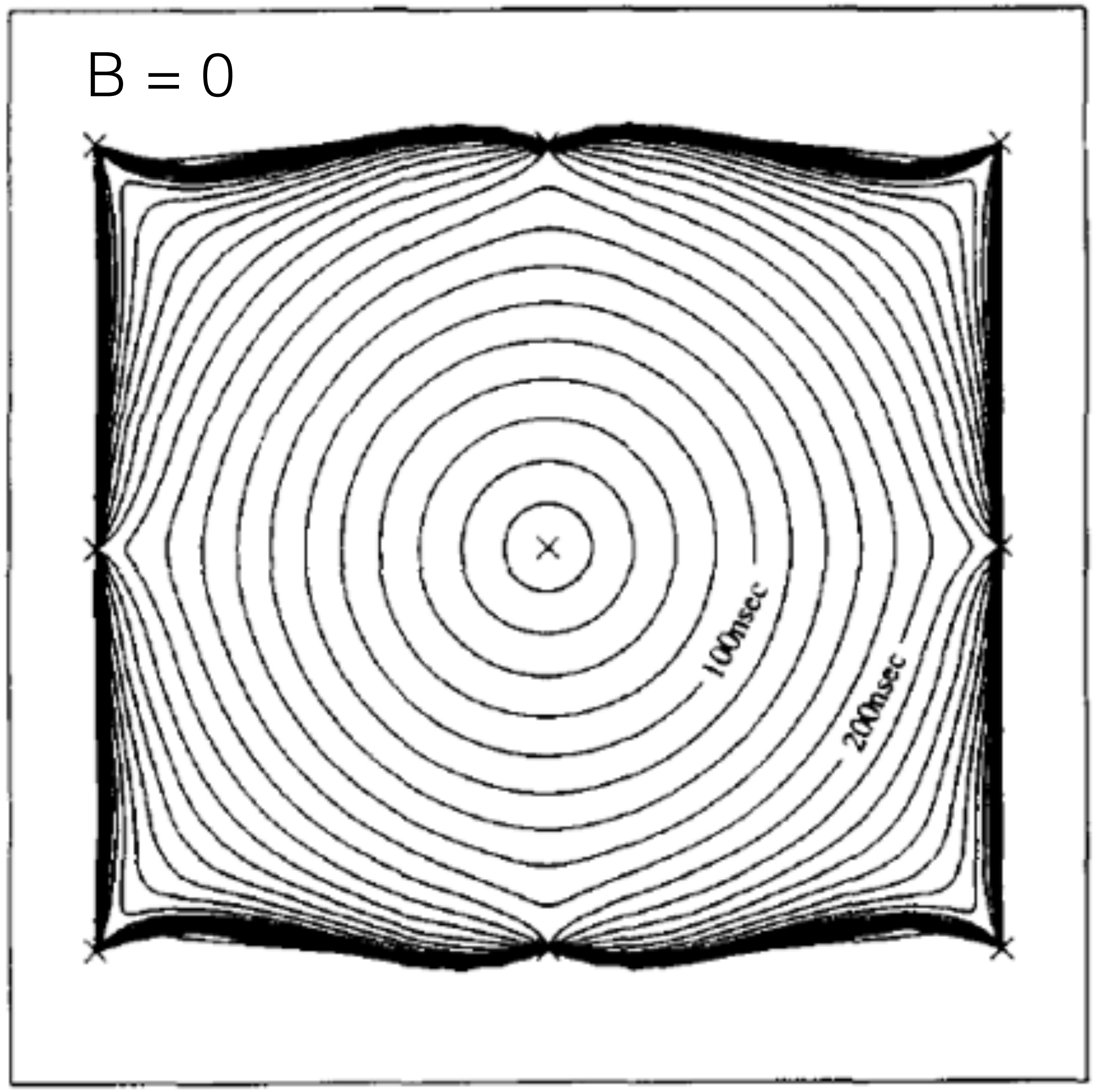
Drift cells

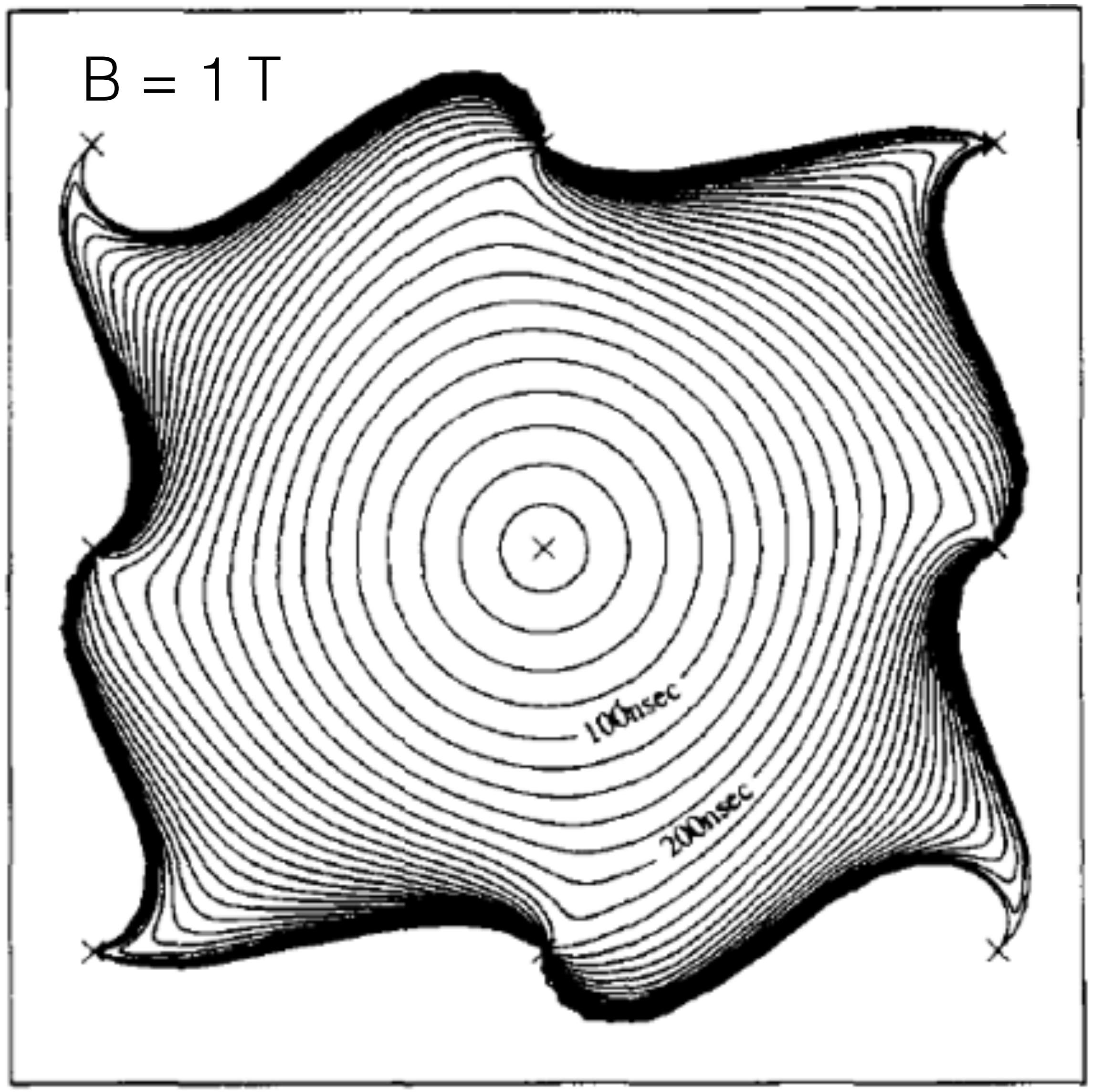
- CDC layers alternate between "field layers" and "sense layers"
  - Sense wires held at a large potential (anode)
  - Grounded field wires help to shape the electric field
- Electrons liberated by ionization drift toward the sense wires
  - Near the wires, the large electric field causes the electrons to gain enough energy per mean free path to ionize at the next collision
  - Detectable signal created by avalanche of electrons near sense wires



Drift cells

- Presence of magnetic field causes electron trajectories to curve
    - Changes the shape of isochrones (lines of equal drift time)

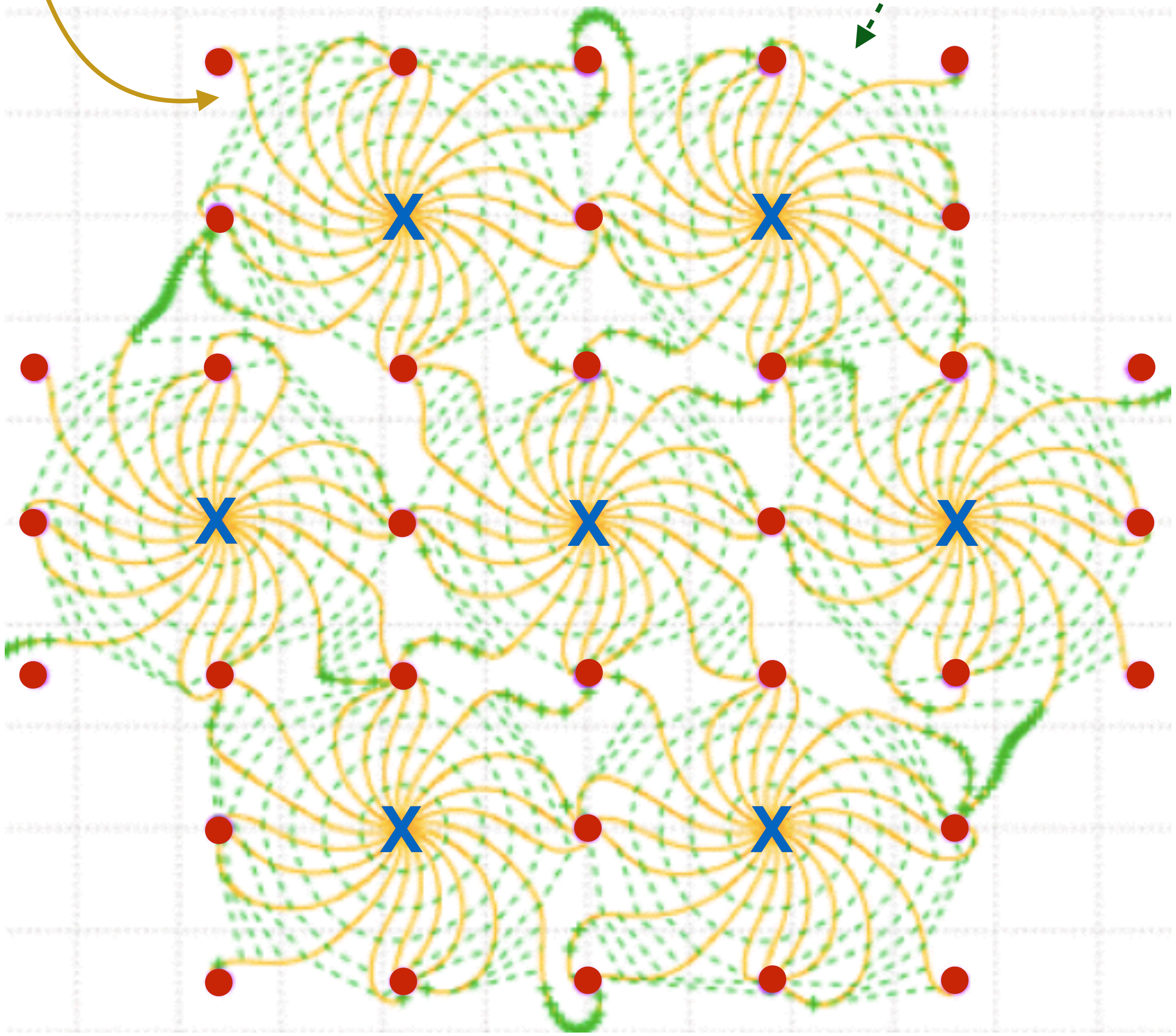




Plots from a drift chamber study [NIMA 330 (1993) 55-63]
Note: the right plot has the right gas for Belle II, but the wrong field (1.5 T)

Drift cells

- Presence of magnetic field causes electron trajectories to curve
  - Changes the shape of isochrones (lines of equal drift time)
  - Lorentz Angle: angle between drift path with and without B-field
  - Couples known asymmetries in the radial direction into the ϕ direction (important to properly calibrate!)
  - Degrades electron collection at cell edges
  - Also depends on the gas composition
  - Note: B-field can have a big effect on drift time!



Exercise: What are two sources of asymmetry in the radial direction?

Gas composition

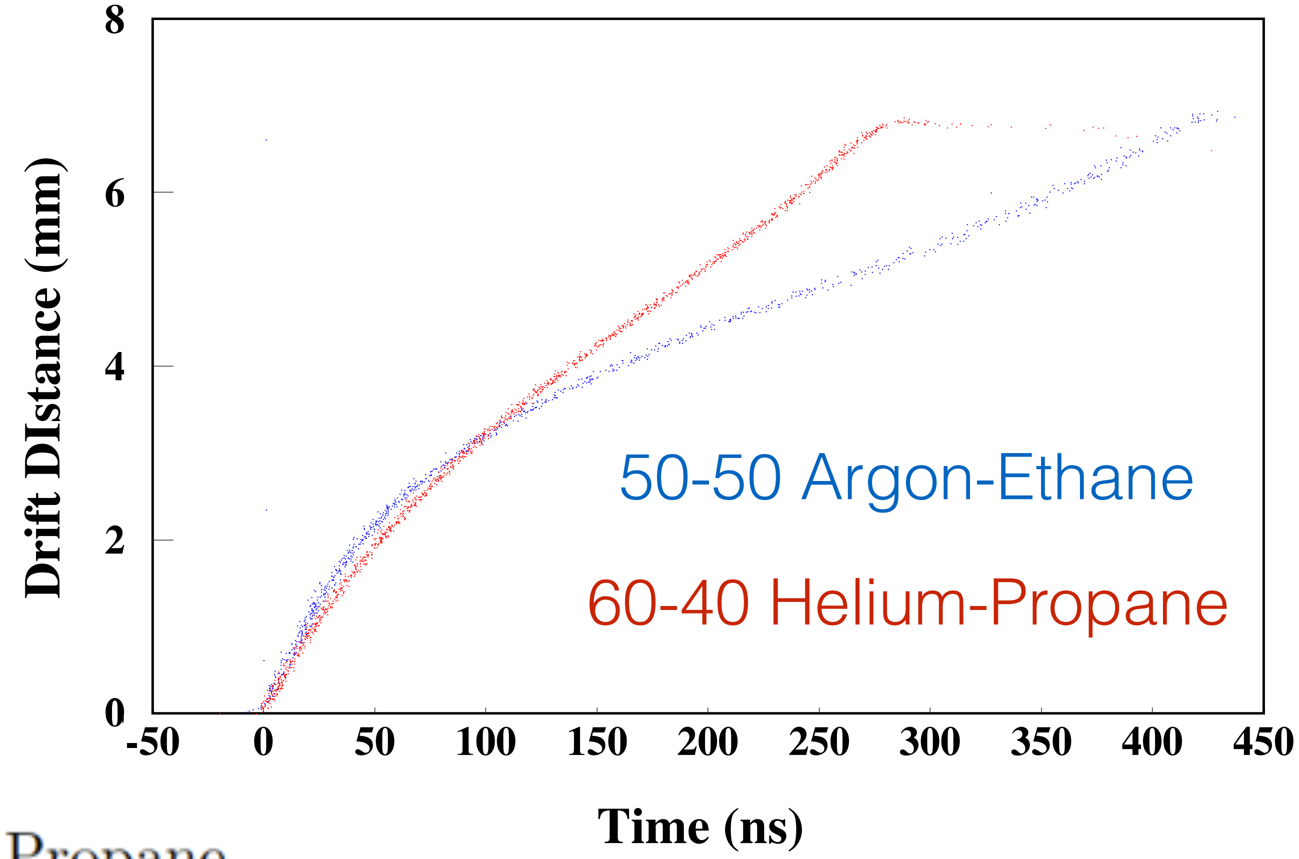
- Chamber momentum resolution: $\sigma_{P_t}/P_t = a \oplus bP_t$
  a. Gas should have a large radiation length, X_0, to reduce multiple scattering
  b. Should produce many primary ions (N_P), a fast drift velocity (V_d), and low diffusion (σ_d)

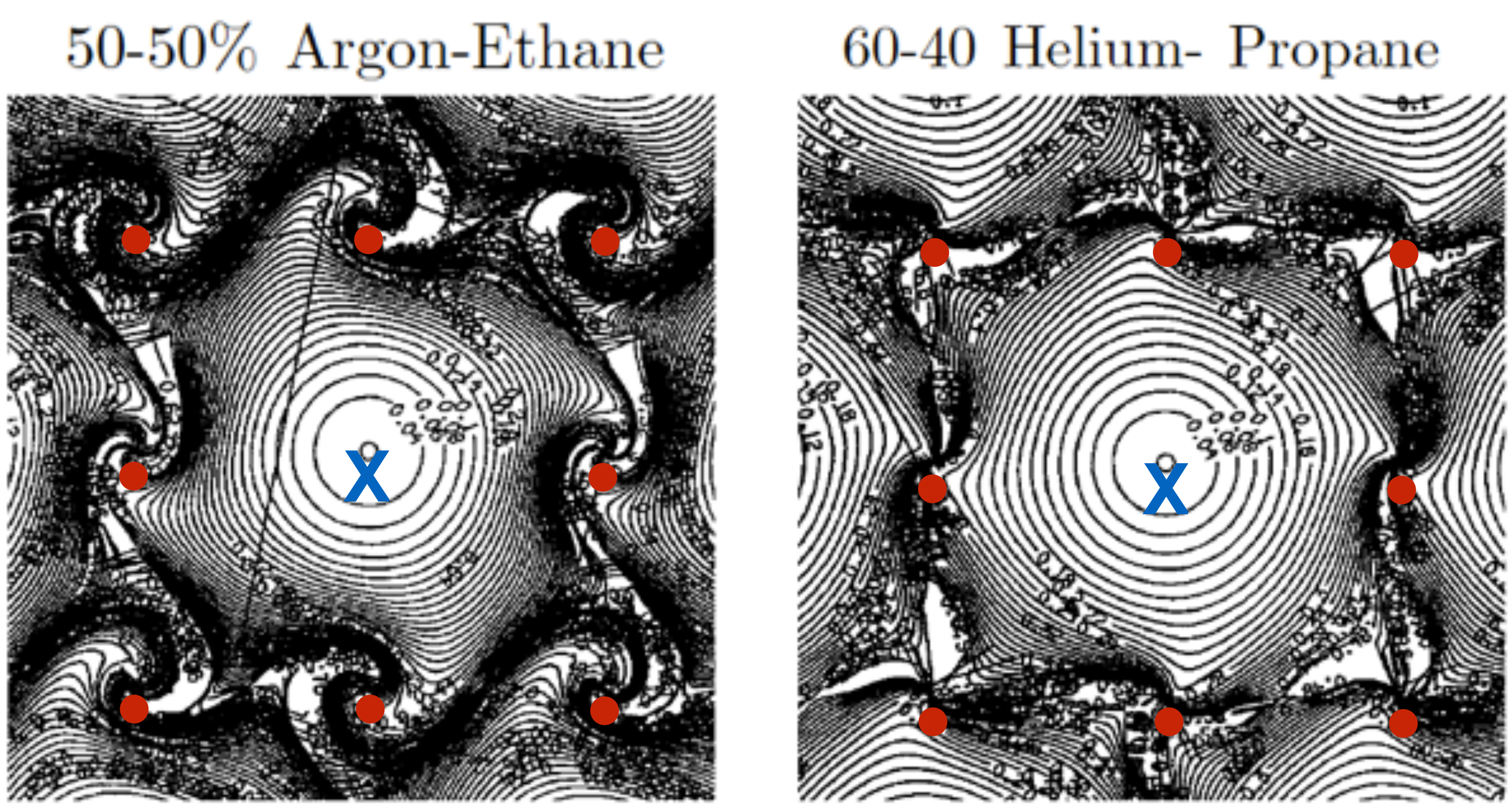
Gas	X_0 [m]	N_P [ions/ cm]	V_d [μm/ ns]	σ_d [μm/ √cm]	Used by
50-50 He-C_2H_6	686	25	30	143	Belle II
50-50 Ar-C_2H_6	178	34	45	140	CLEOII
60-40 He-C_3H_8	569	33	27	136	CLEOIII/c
80-20 He-C_4H_{10}	807	23	24	151	BaBar

- Must consider the Lorentz angle!

Gas composition

- Want a gas with a fast drift velocity, but with small Lorentz angle from magnetic field



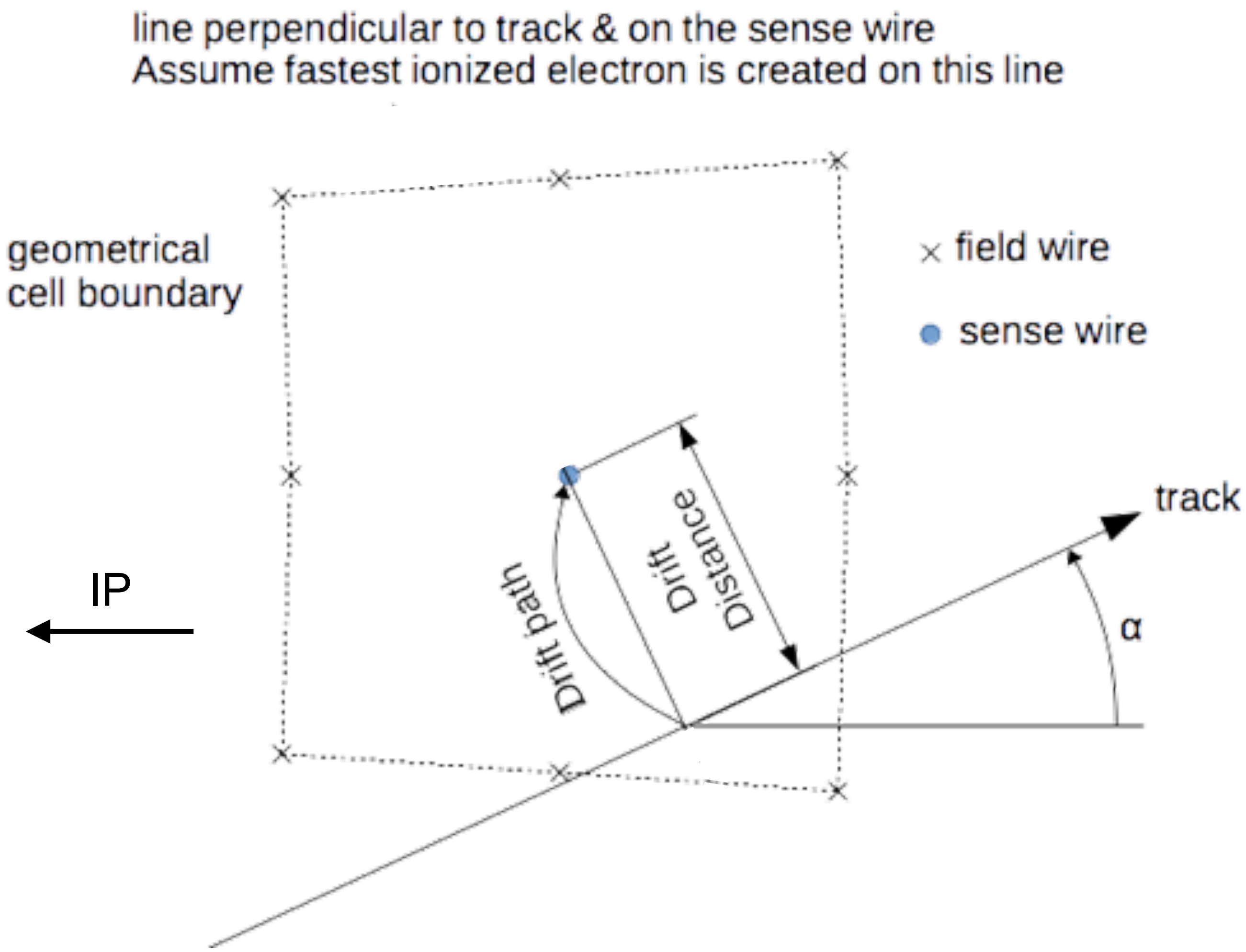


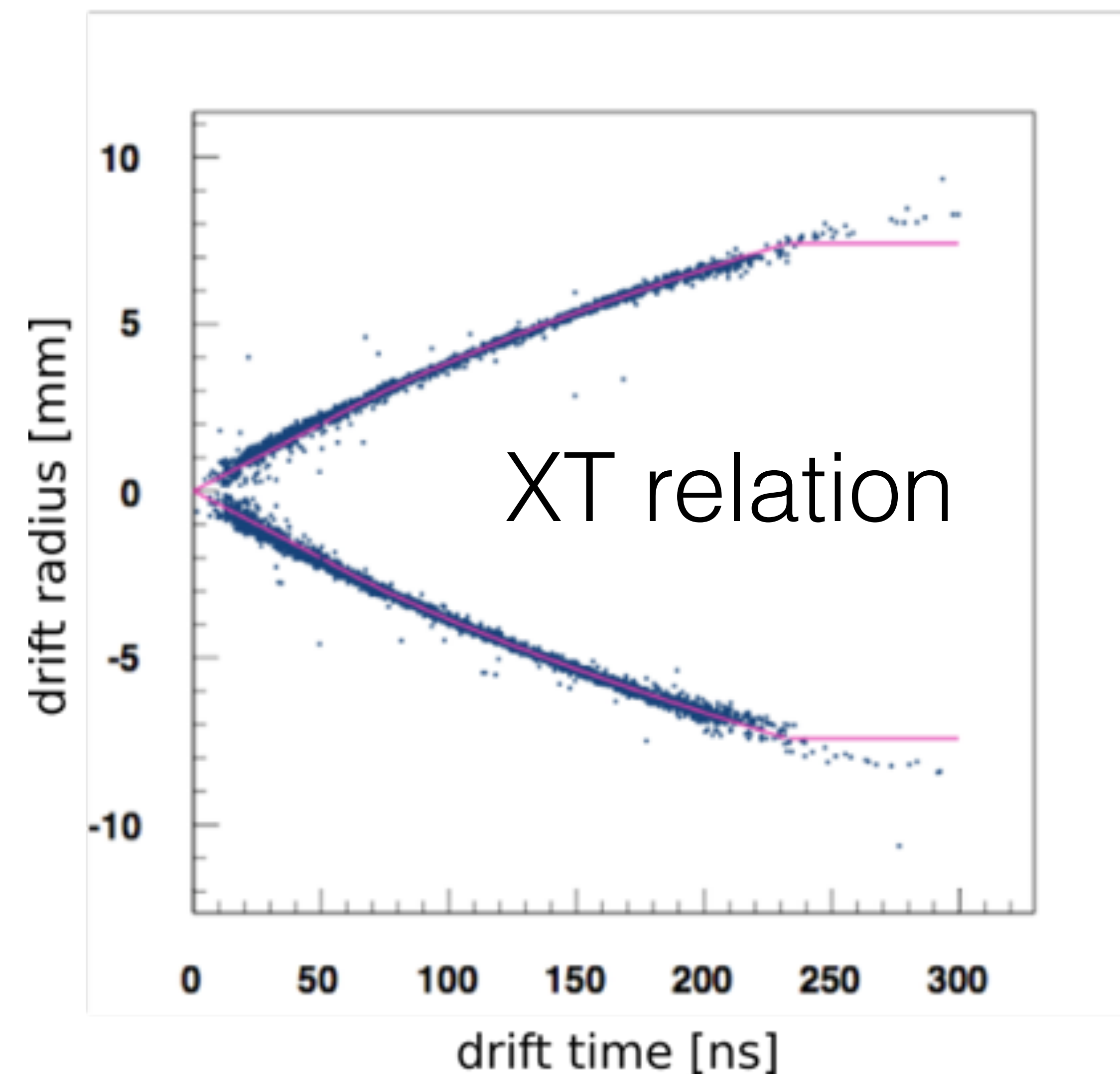
Example from CLEO

- Gain in drift time due to the Lorentz angle may actually make a bigger difference!

Drift time measurement

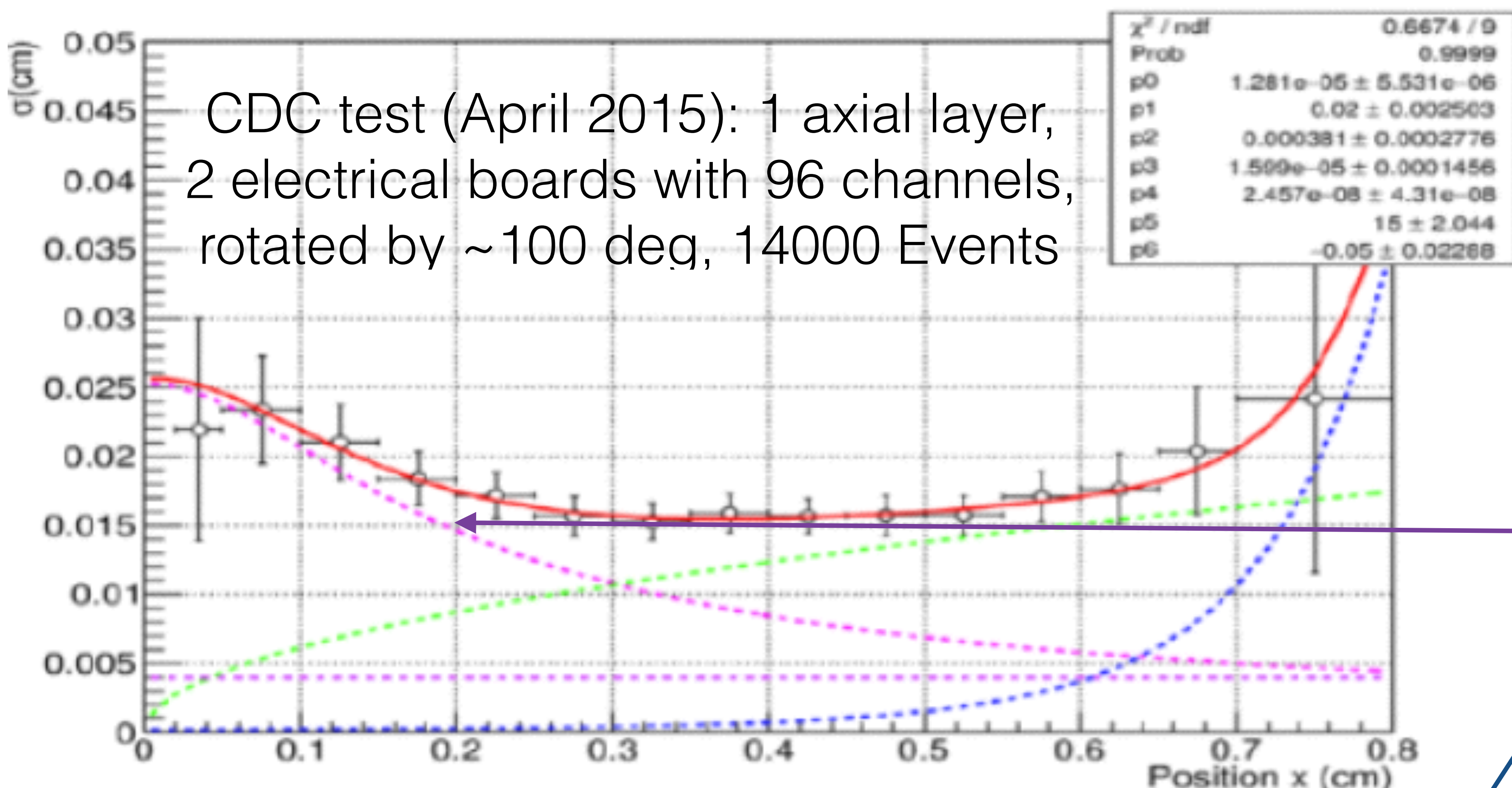
- Diffusion process of electrons through gas with characteristic drift velocity (average motion of electrons under an external electric field)
  - Time delay between ionization and detection at sense wire
  - From drift velocity of the gas, can determine the distance from the ionizing track to the sense wire within some resolution





Intrinsic resolution

- Production of electron/ion pairs is Poisson distributed
- Spatial resolution deteriorates due to statistical fluctuations in the primary ionization near the sense wire



- sigma at best region: ~155μm.
- From Monte-Carlo simulation: magnitude of sigma degradation 20-30 μm.

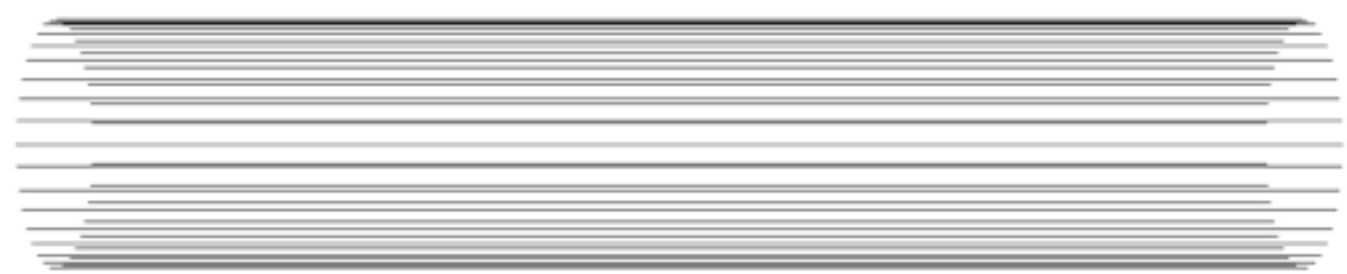
=> ***Sigma =~ 135 μm***

Ion statistics
Longitudinal diffusion
Electronics
???

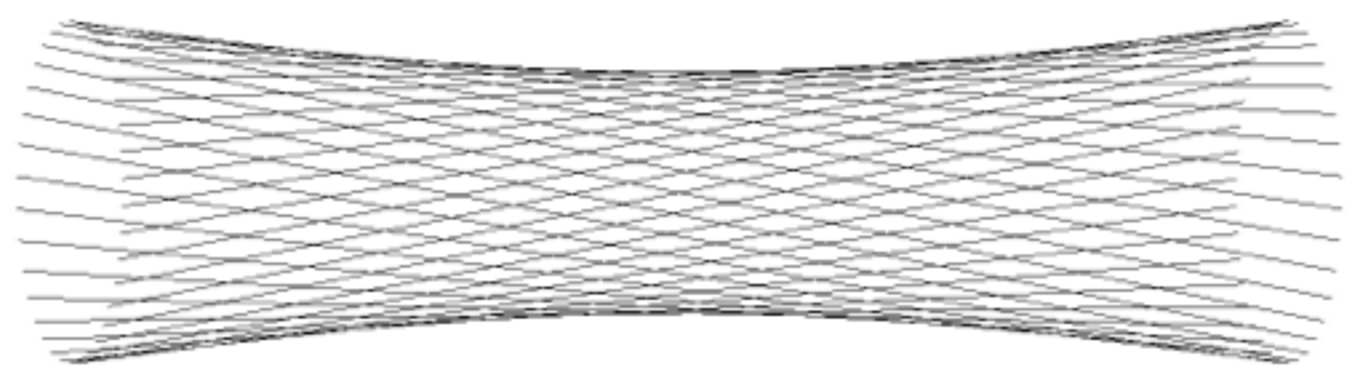
Exercise: What causes the deterioration near the cell boundaries?

Stereo layers

- Some layers have a stereo angle to obtain z information
  - A larger stereo angle provides better z resolution, but a large variation in the radial cell size along the z direction occurs in the boundary region between axial and stereo superlayers
  - Geometrical variations of cells are reduced by implementing half of the full stereo angle in the transition layers (a similar procedure was used in Belle)
  - The sense wire is then only ~1 mm closer to the field wire so a large gain variation is avoided



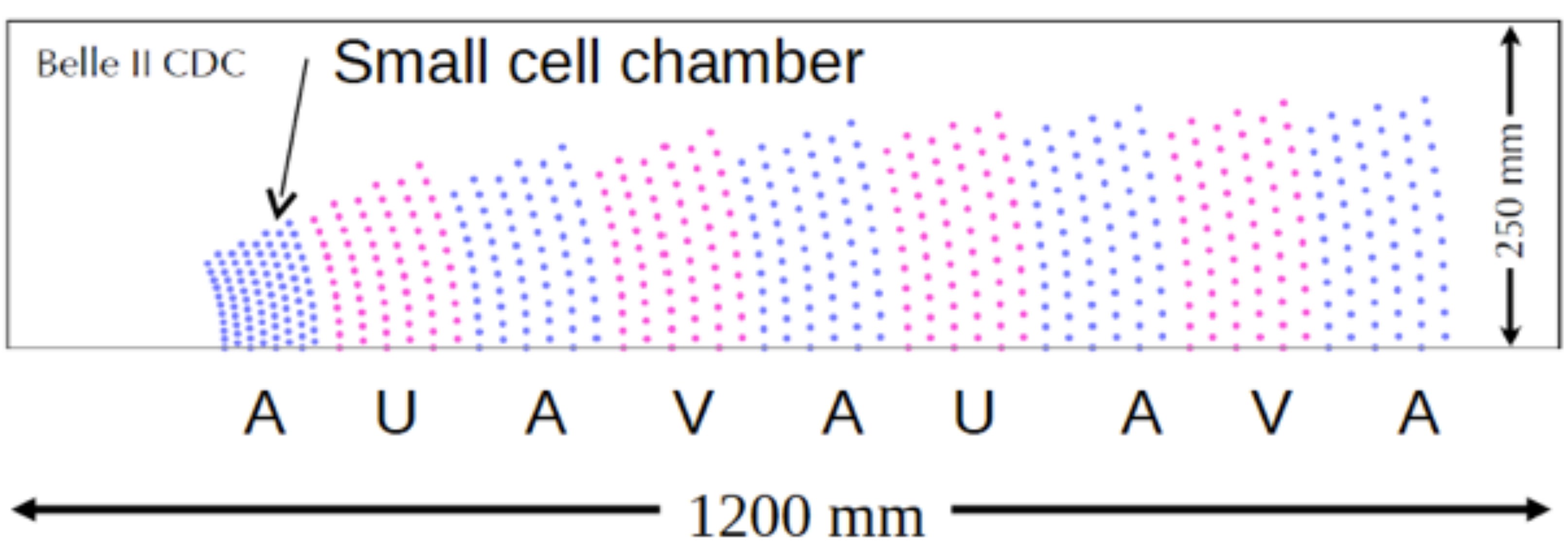
Axial layer



Stereo layer

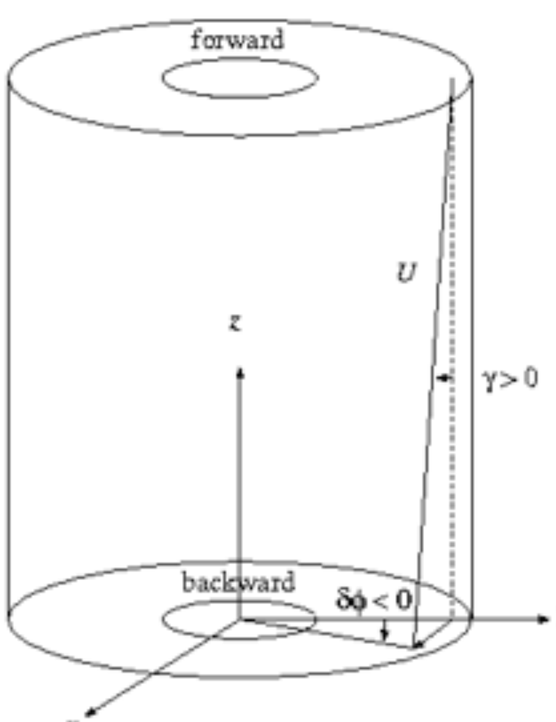
Superlayer structure

- Group layers with similar stereo angles into superlayers
  - Six layers in each superlayer, vs 3-4 layers each in Belle
  - Innermost and outermost super layers contain axial (A) layers, to match the shape of the inner and outer cylinders
  - Superlayers alternate between stereo (U or V) and axial layers
- Innermost superlayer is implemented separately as a small-cell chamber
  - Two additional layers with active guard wires to protect against high occupancy from beam backgrounds



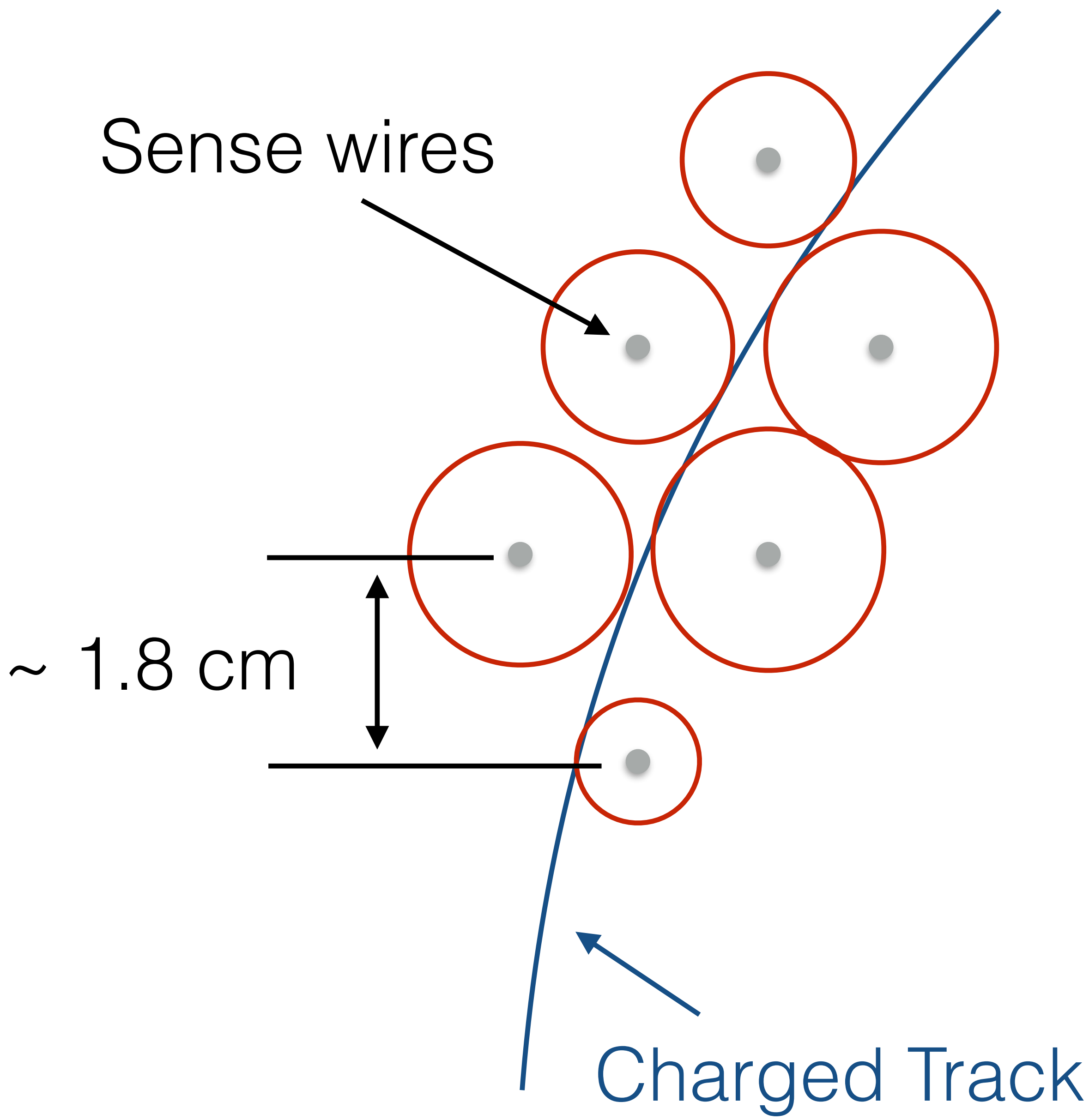
U: $\delta\phi < 0$

V: $\delta\phi > 0$



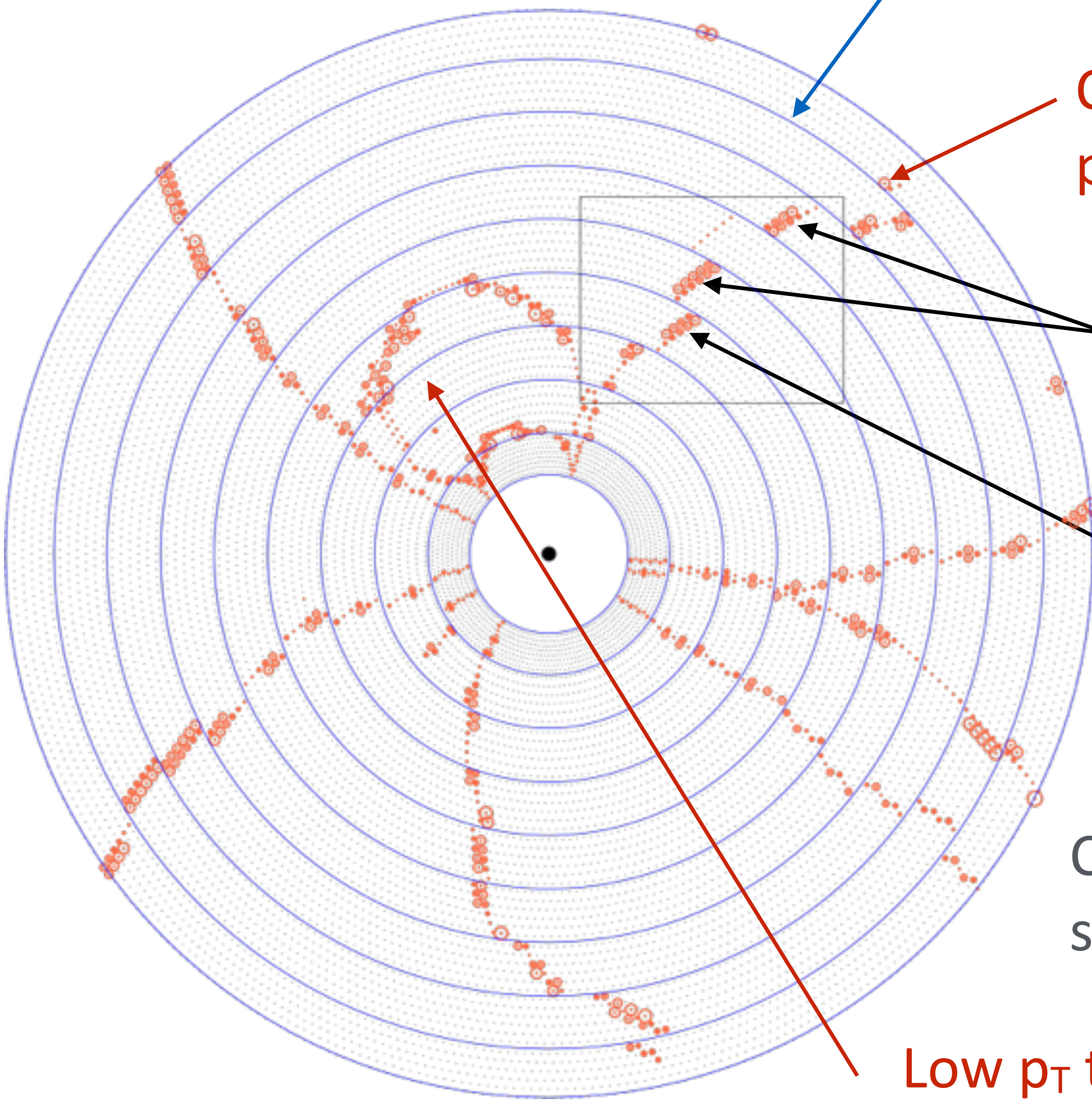
Very simplistic overview of tracking

- Localize a charged track to be on a ~135 µm resolution drift circle around wire



- Detector hits are collected into a track segments with pattern recognition algorithms
- An approximately helical fit is applied to the track segments, taking into account things like multiple scattering and ionization energy loss
- Track segments are merged into track candidates, which are then fitted to tracks with a particular mass hypothesis

Stereo layers



Superlayer boundaries

CDC Hits (size of circle proportional to drift time)

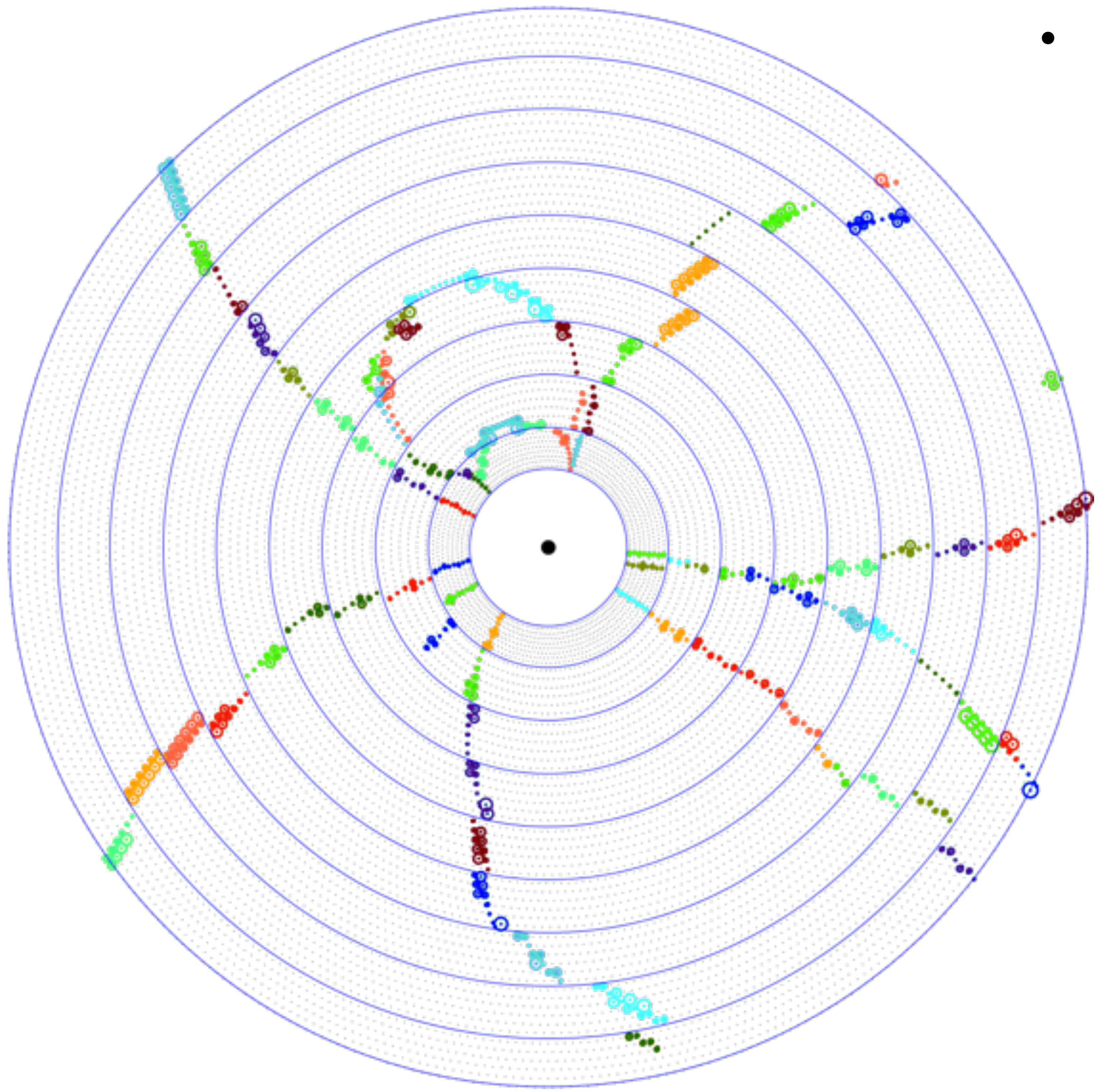
Hits in axial layers lie along the same trajectory

Offset from stereo layers related to z coordinate of particle trajectory

Charge of track determines sign of bend

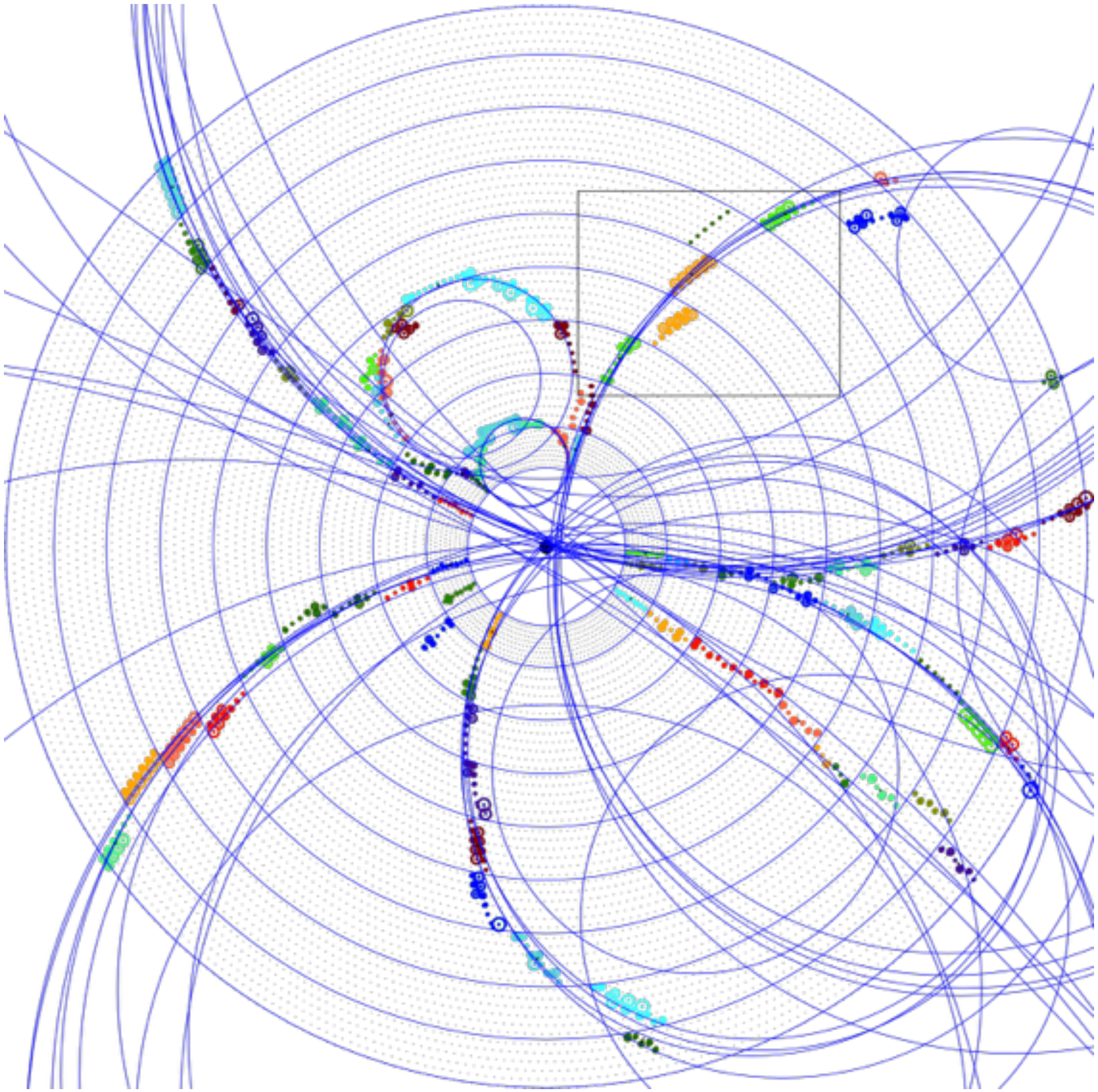
Low p_T tracks curl up inside the detector

Stereo layers



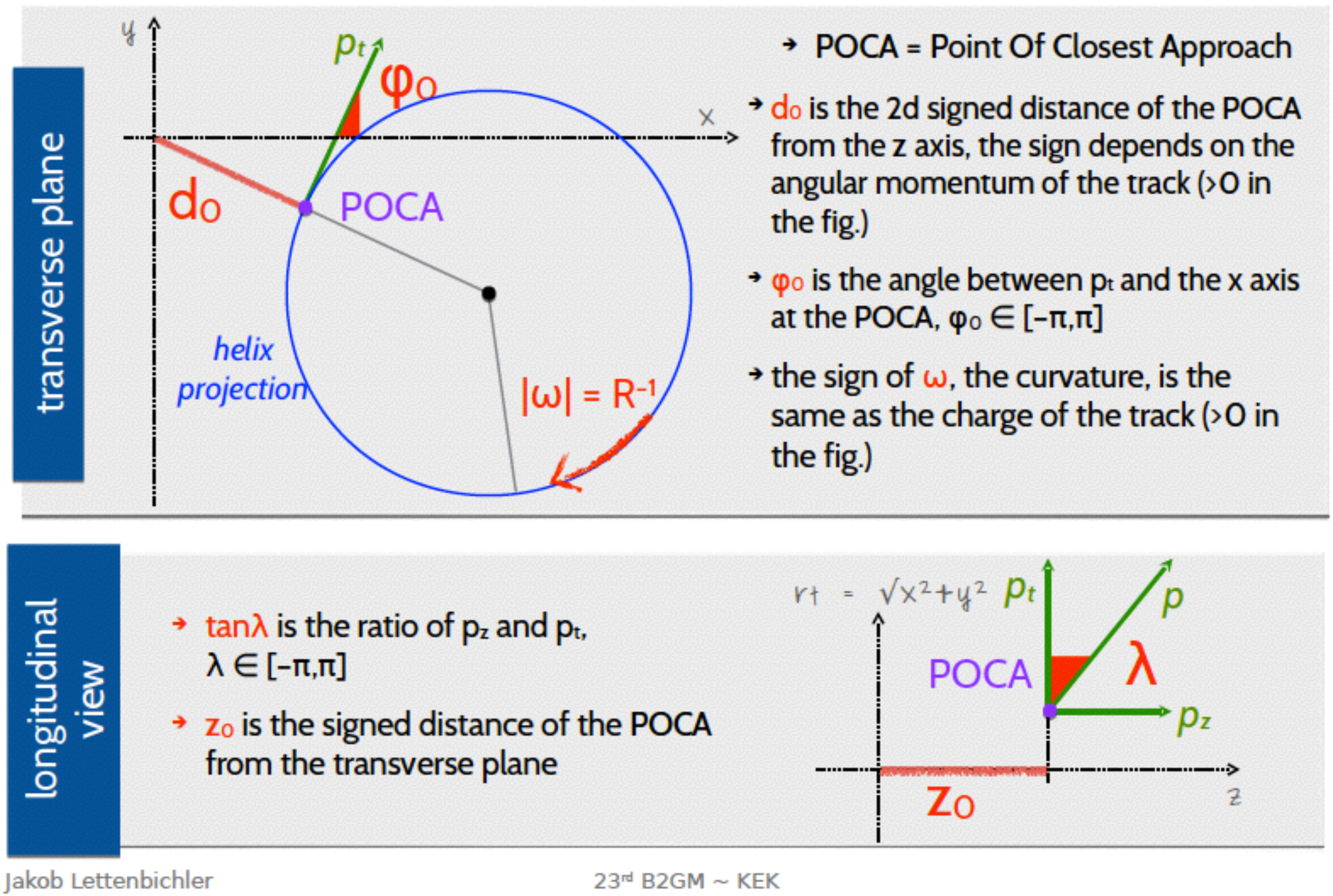
- Detector hits are collected into a track segments with pattern recognition algorithms

Stereo layers



- Circular fits to the track segments in axial layers
- Combine 2D circle trajectories with information from stereo layers to construct a track
- Fit tracks with a mass hypothesis (GENFIT)

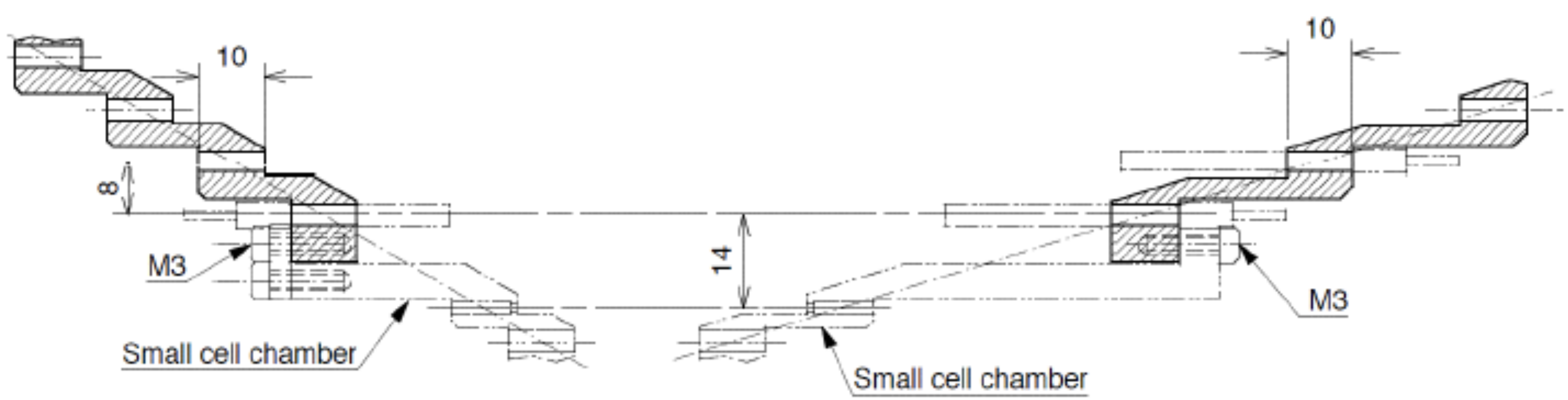
Track parameterization



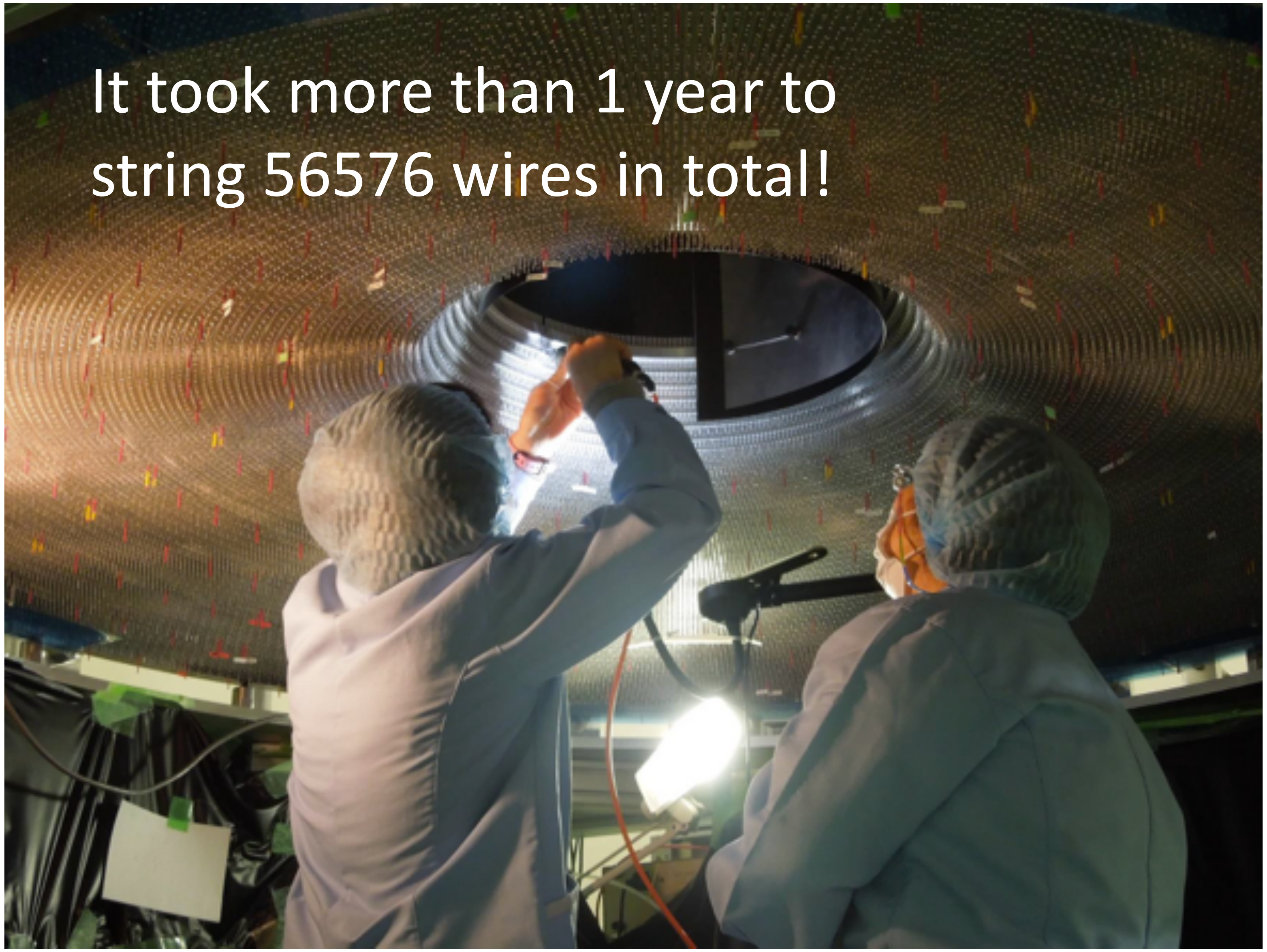
Note: we tend to use $\cos(\theta) = p_z/(p_z^2+p_t^2)^{1/2}$ instead of $\tan(\lambda)$ in calibration/analysis

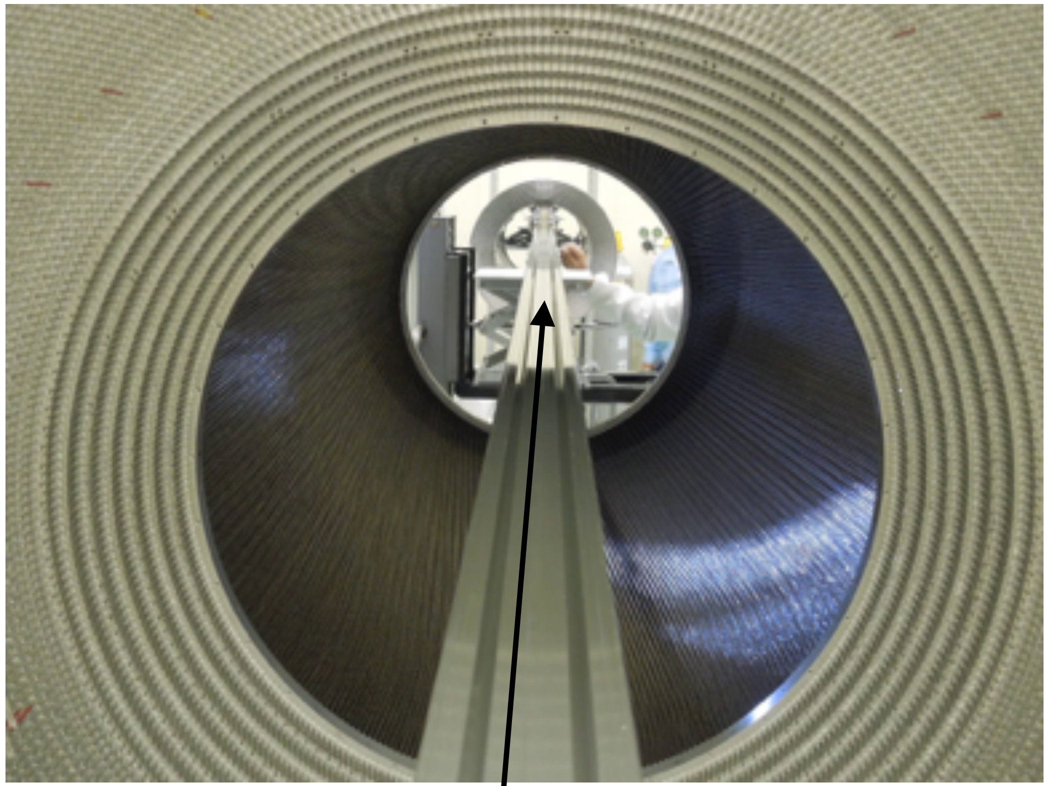
Support

- Outer cylinder (thickness: 5mm) supports most of the wire tension (~4 tons)
  - Tapered aluminum endplates are used for the outer region to reduce the deformation caused by wire tension (~factor of 2 relative to the Belle CDC)
- Inner cylinder (thickness: 0.5mm), much thinner to minimize the amount of material, supports the wire tension for the small-cell chamber
  - Conical endplates for the inner region to match the polar angular acceptance (17°-150°)
  - Step structure machined in endplate sections for easier and more precise drilling of holes for wire feedthroughs

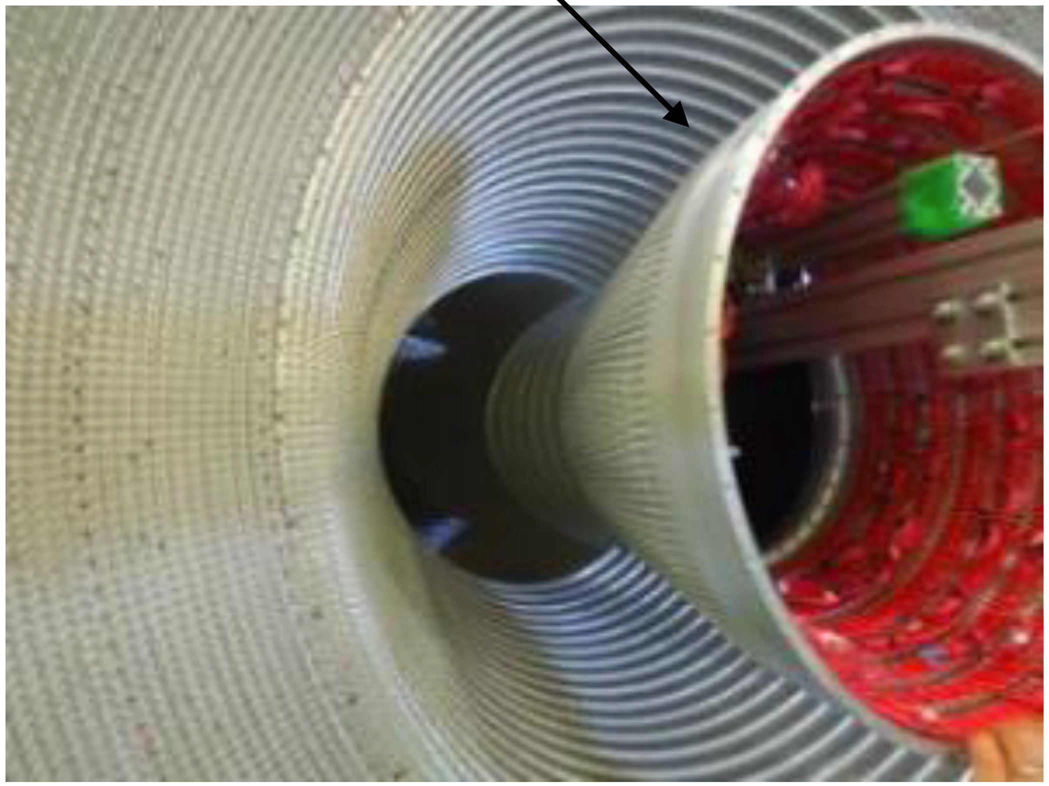


CDC wire stringing



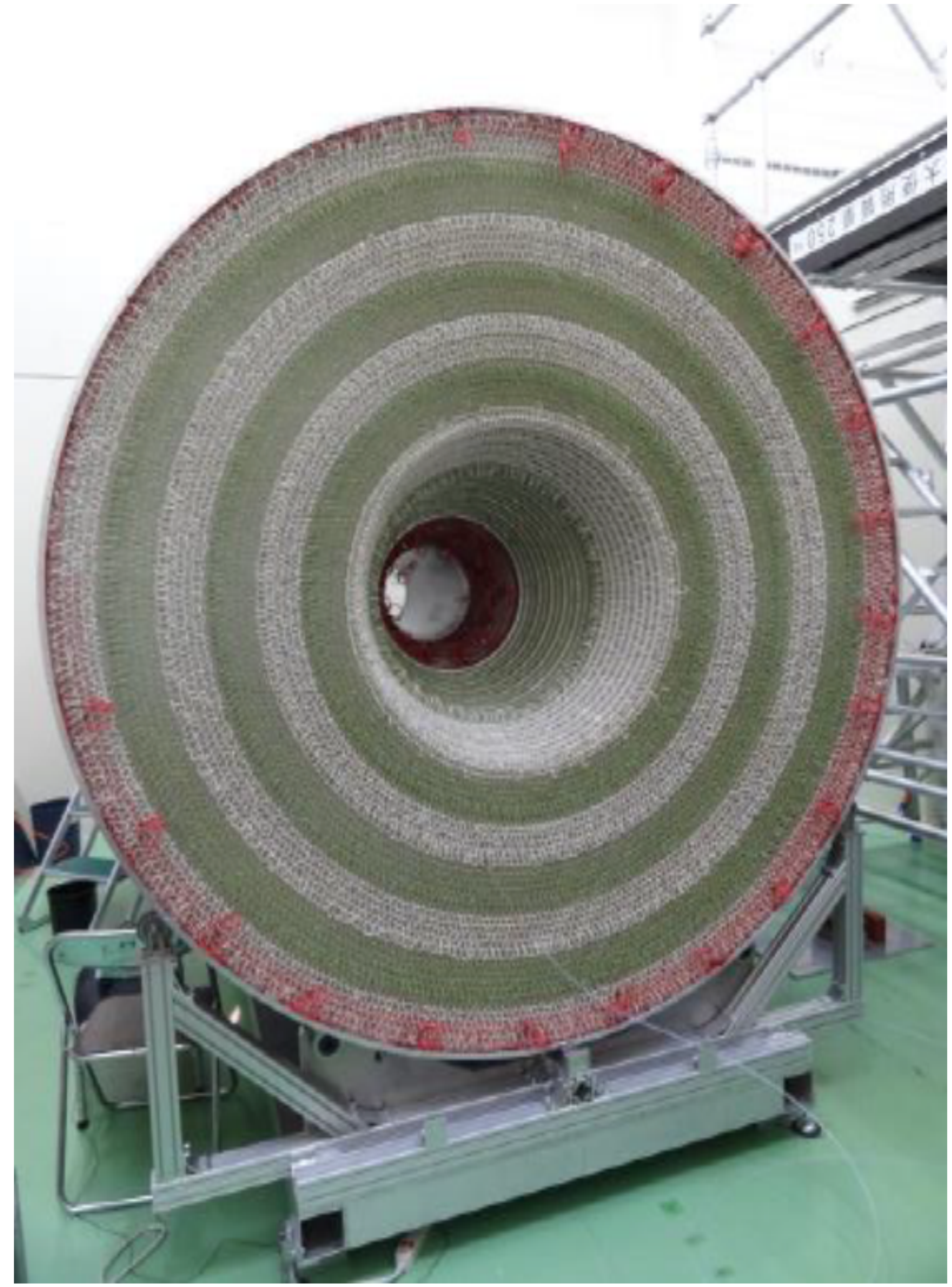


Small cell chamber installation



CDC cabling

HV cabling - forward side

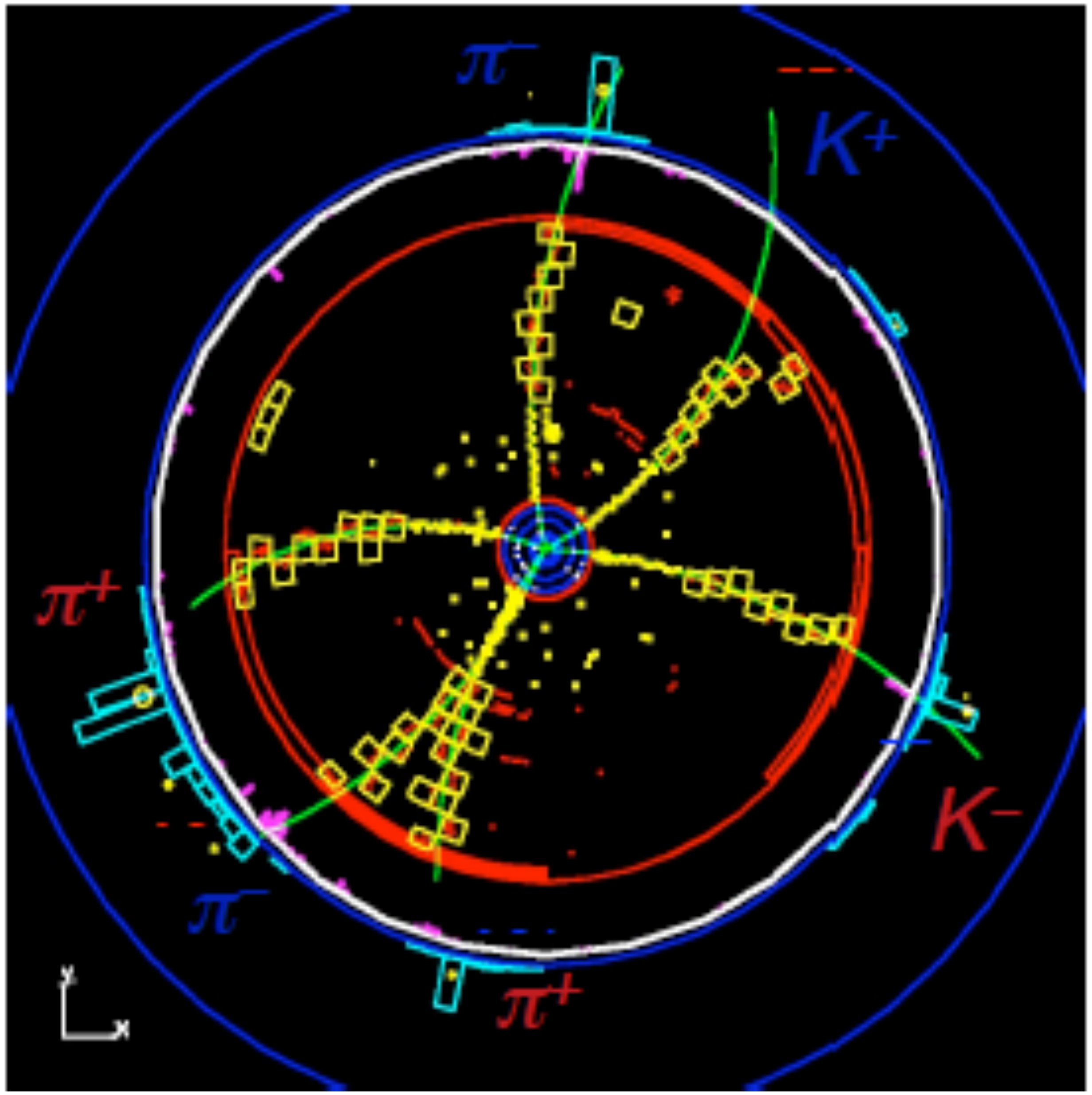


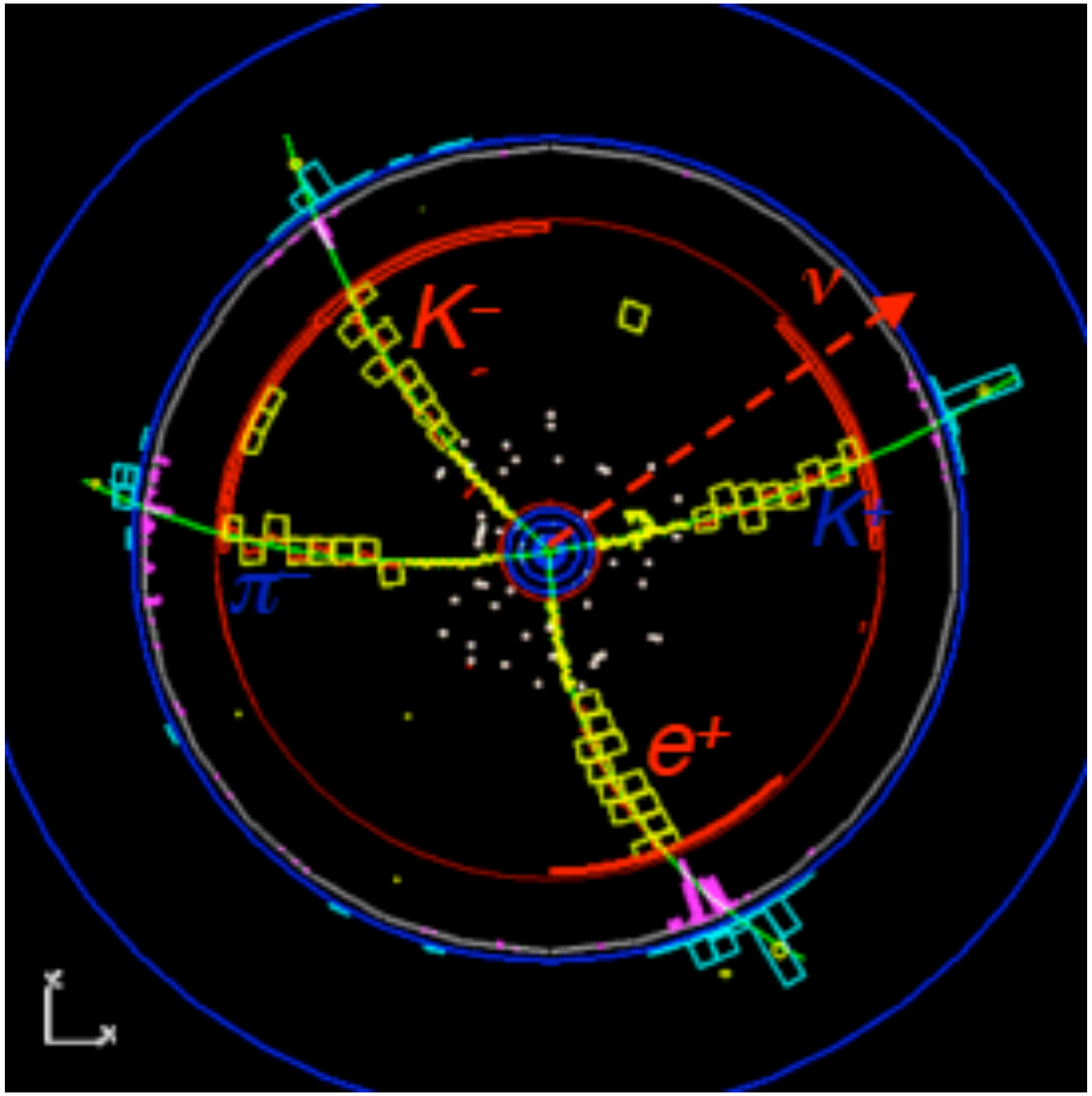
Ground cabling - forward side

Note: Many of the following plots are from CLEO-c

D-Tagging at CLEO-c

dE/dx: are tracks pions or kaons?



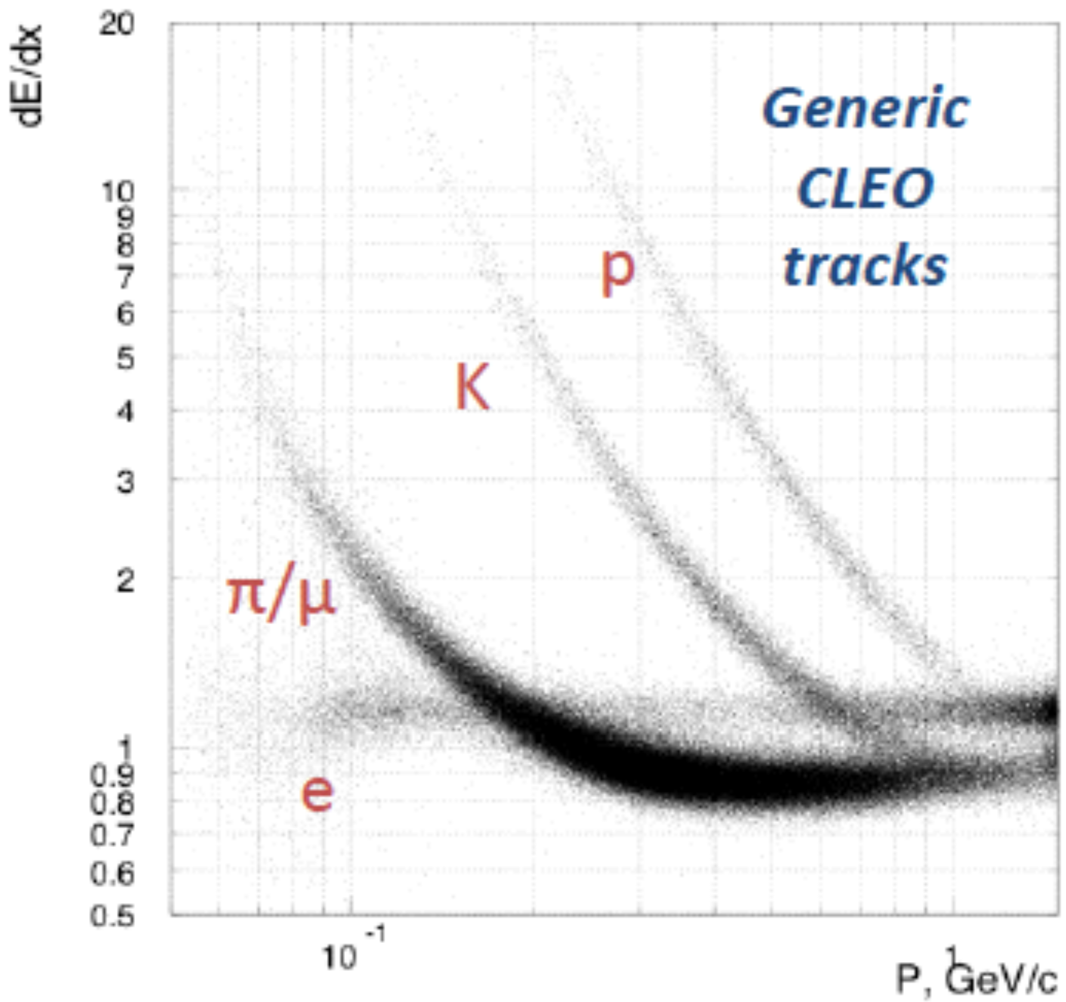


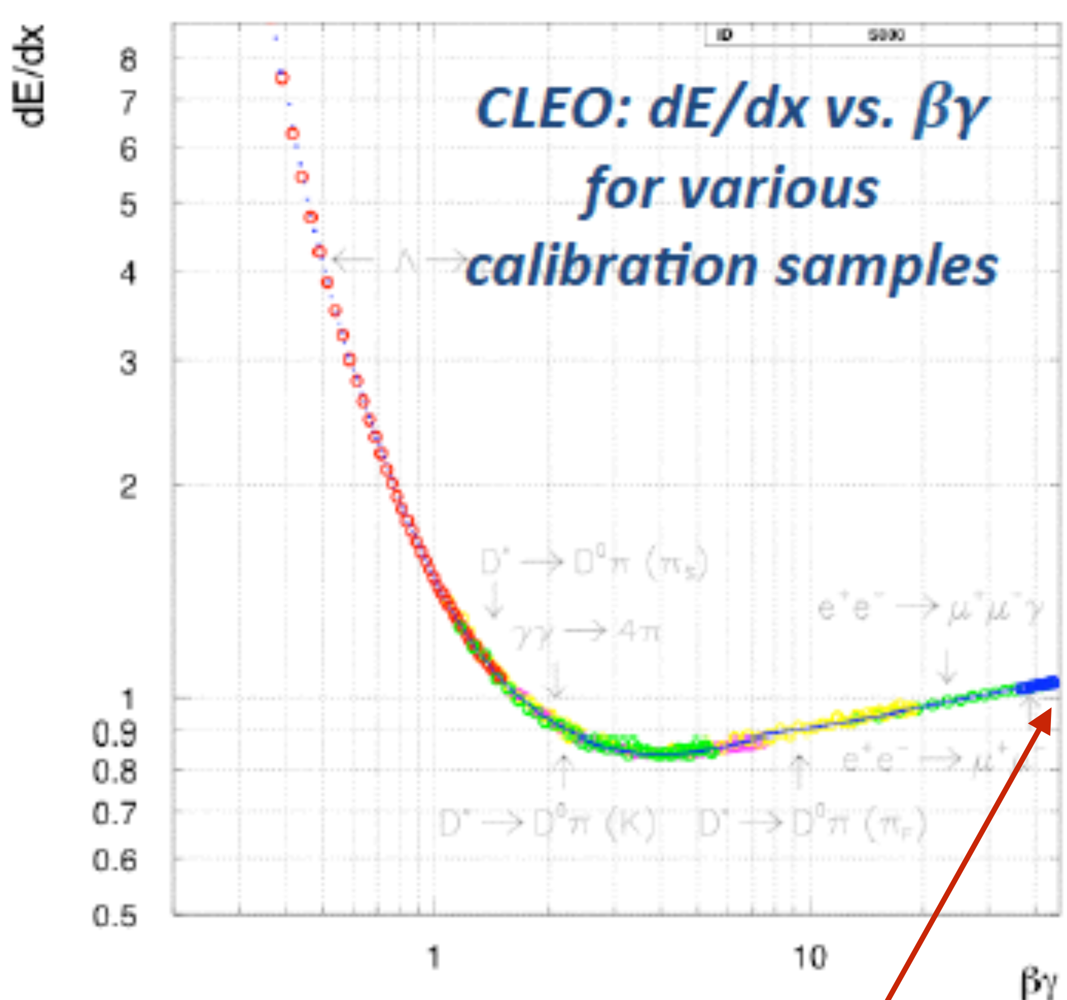
$K^- \pi^+ \pi^+$ vs. $K^+ \pi^- \pi^-$ $K^- e^+ \nu$ vs. $K^+ \pi^-$

CMU group (Briere) dE/dx experience: CLEO III, CLEO-c, BES III

Basic philosophy

- dE/dx should depend only on βγ = p/m (Bethe-Bloch formula)



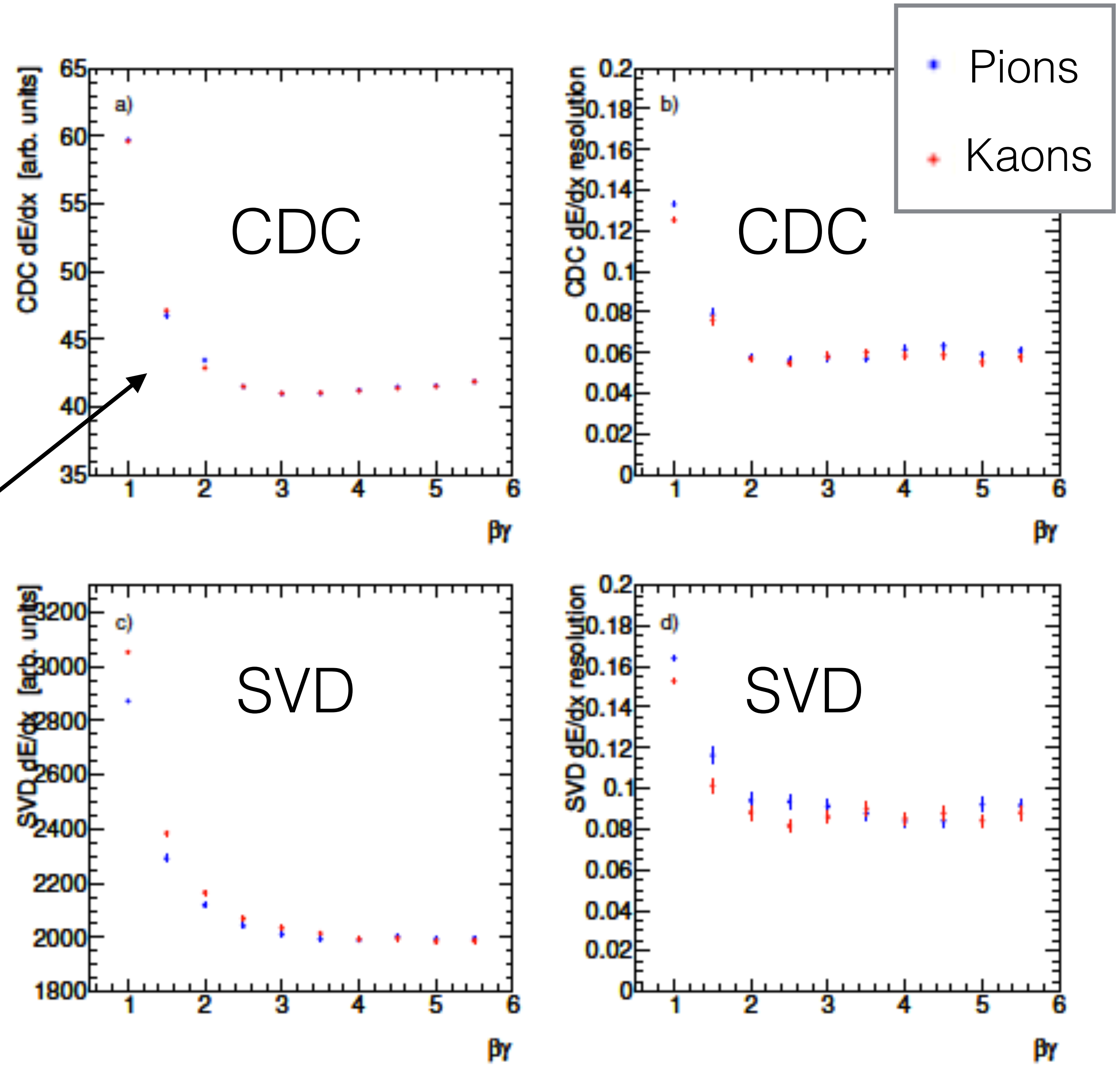


- Make this happen by doing low level calibrations well (not arbitrary high level corrections later)

Exercise: Why is it useful to set dE/dx to 1 for electrons?

Universality of dE/dx in basf2

- Ionization energy loss (dE/dx) determined from measurements in the CDC and VXD (only SVD by default, but could also add PXD)
  - Should depend only on β/γ = p/m (requires careful calibration in data)
  - Test with single particle samples at given βγ, uniformly distributed in ϕ, cos(θ)

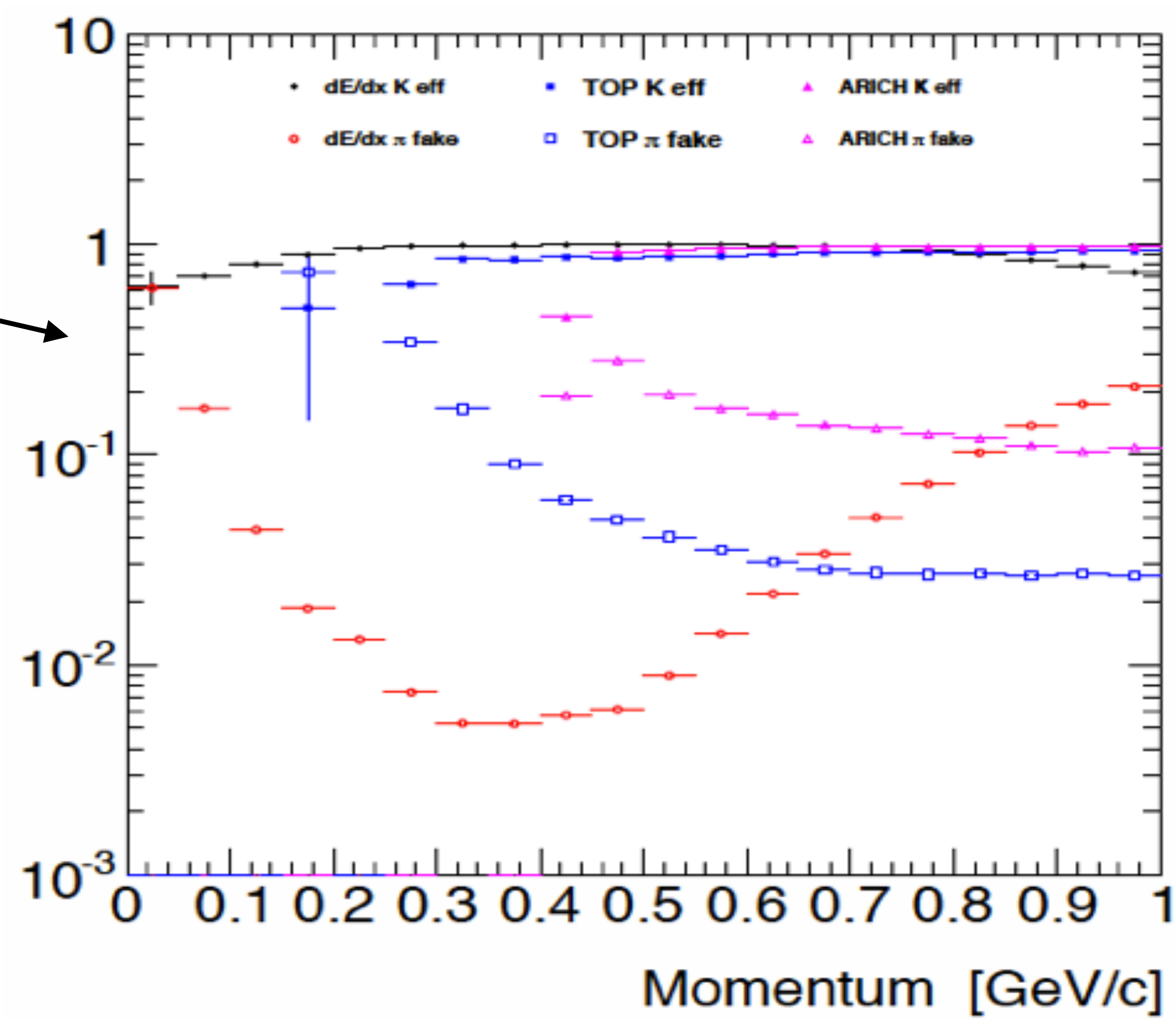


Exercise: Why is the shape different between CDC and SVD dE/dx measurements?

Usefulness of dE/dx

dE/dx measurements

- are "free" - come along with CDC measurements
  - Just need calibration, reconstruction software (our job)
- are inherently noise-immune (many measurements)
- provide very good separation at low momentum, where TOP and ARICH are less useful
  - Inclusive $c\bar{c}$ MC sample (minimal quality cuts)
  - Efficiency determined with ratio of events with L(α:β) > 0.5 to the total particle sample



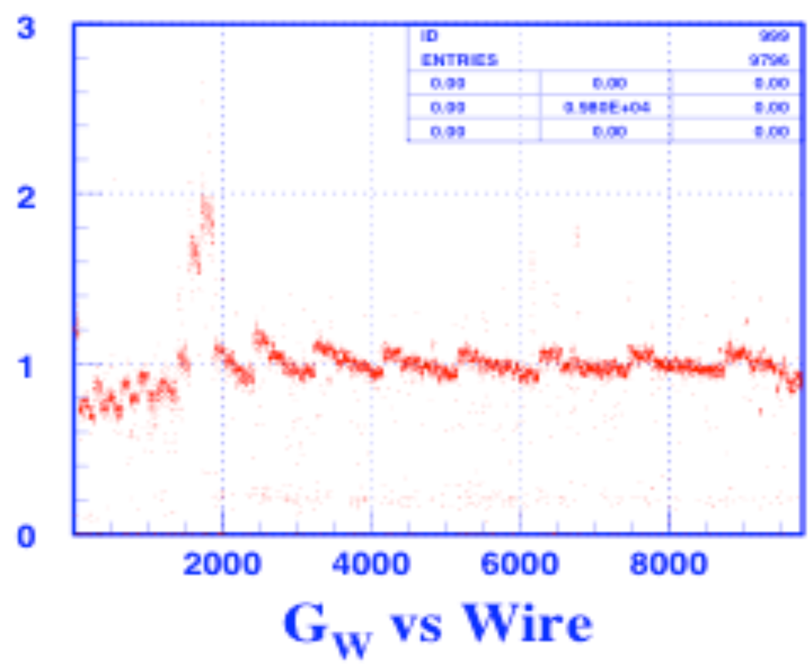
Primary calibration topics

Basic idea: variations and non-linearities in running conditions bias and degrade dE/dx measurements

- Wire gains
  - Same voltage different cell sizes, bad wires, electronics, …
- Run gains
  - Mostly due to pressure, i.e. weather
- Path length
- Saturation correction
  - Charge screening effect - depends on polar angle
- Prediction
  - Need universal βγ curve for predicted dE/dx mean
  - Also need predicted resolution (depends on θ, # of hits, dE/dx)

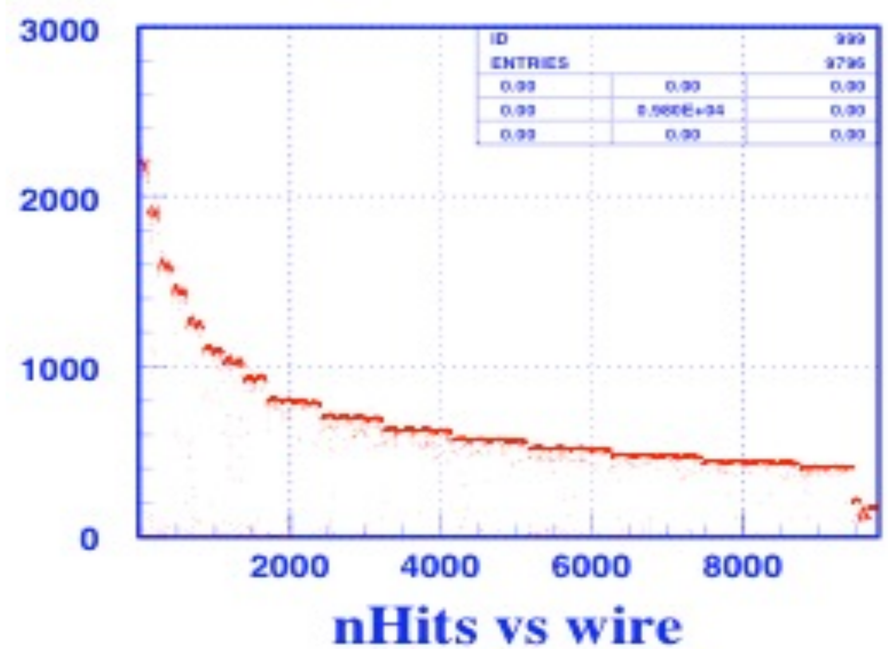
Note: terminology sometimes varies: *electron vs. hadron, hit-level vs. track-level*

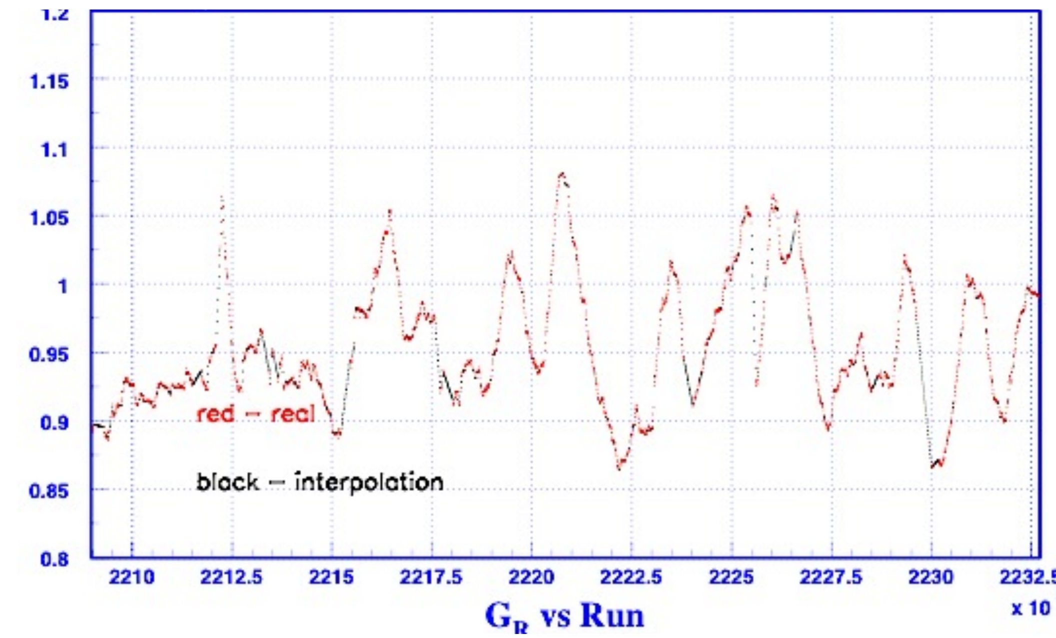
Overall wire gains and run gains



Wire Gains:

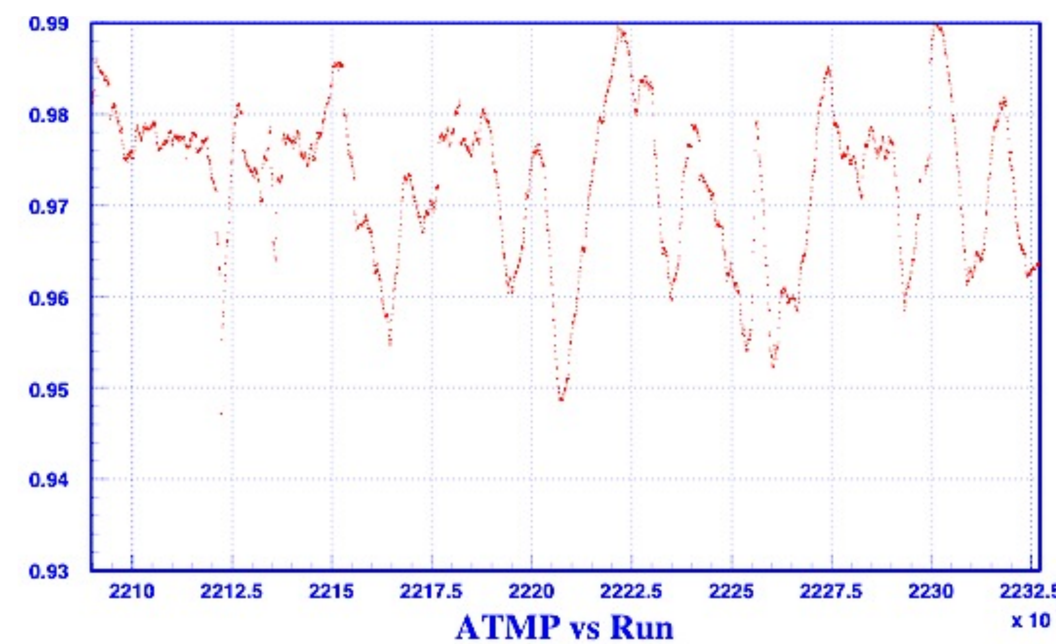
See superlayer structure in statistics and gains…





Run Gains:

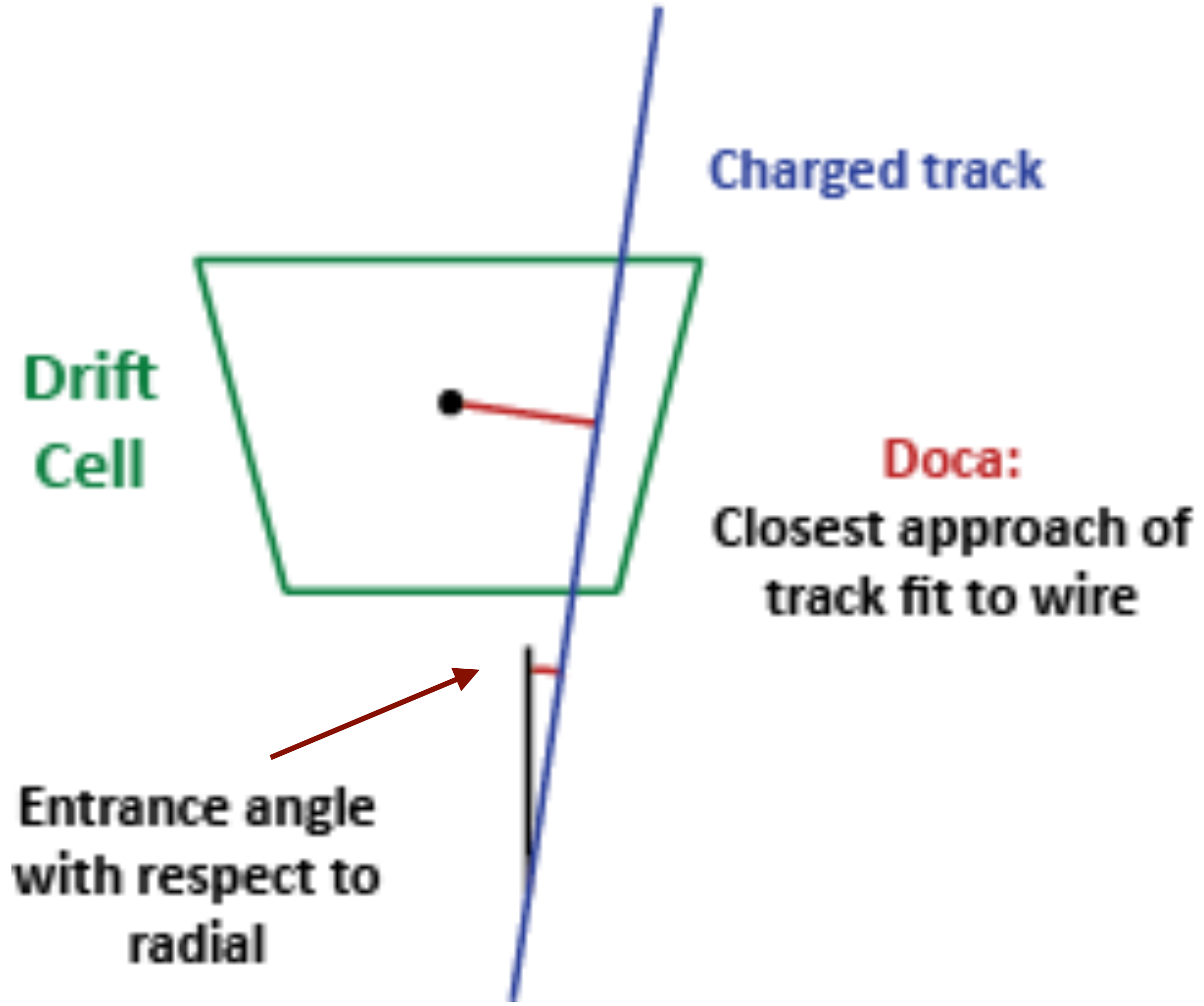
See anti-correlation with atmospheric pressure (pressure *not* used)



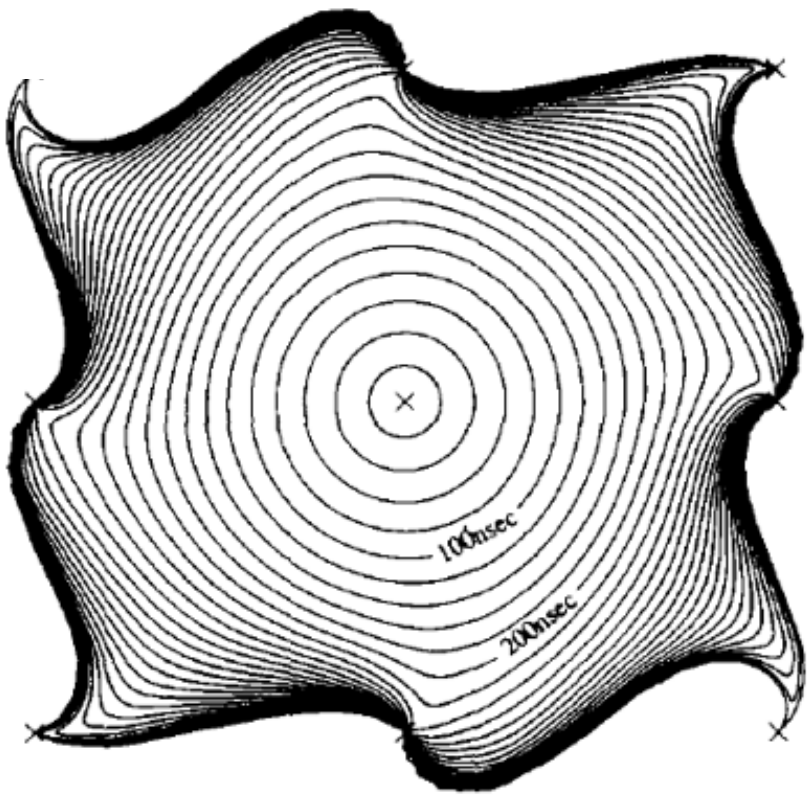
Geometrical r-φ path

- Charge collected depends on path through a cell in r-ϕ projection:
  - Doca: Distance of closest approach (track fit to wire)
  - Entrance Angle: angle of the track relative to the radial

- Geometrical (path length) correction factors out irregularity of drift cell shapes
  - Calculated from full track fit to all hits and nominal cell geometry
  - One correction for large cells and another for small cells
  - *Able to have geometry piece coded and ready before data* (reconstruction/modules/CDCDedxPID)



Empirical r-φ "cell corrections"



- Empirical 2-d corrections
  - *Only place to fight fake CP asymmetry*
  - Left-right drift-cell symmetry broken by B field
  - Entrance angles are correlated for a given track -> left/right tilts
- Some details:
  - Corrections performed with electrons
  - Correct in 2-dimensional bins of doca and entrance angle
  - Use radiative Bhabhas and γγ -> e^+e^- events
  - Final step: add 1-d correction versus entrance angle
    - Correlated among hits along track (unlike doca, imperfections do not average out over the track)
    - Important to remove charge asymmetry (*fake CP violation*!)

Exercise: Why are electrons useful for empirical corrections?
Why are radiative Bhabha and γγ events important?

Hit-level calibrations

Without r-ϕ corrections:

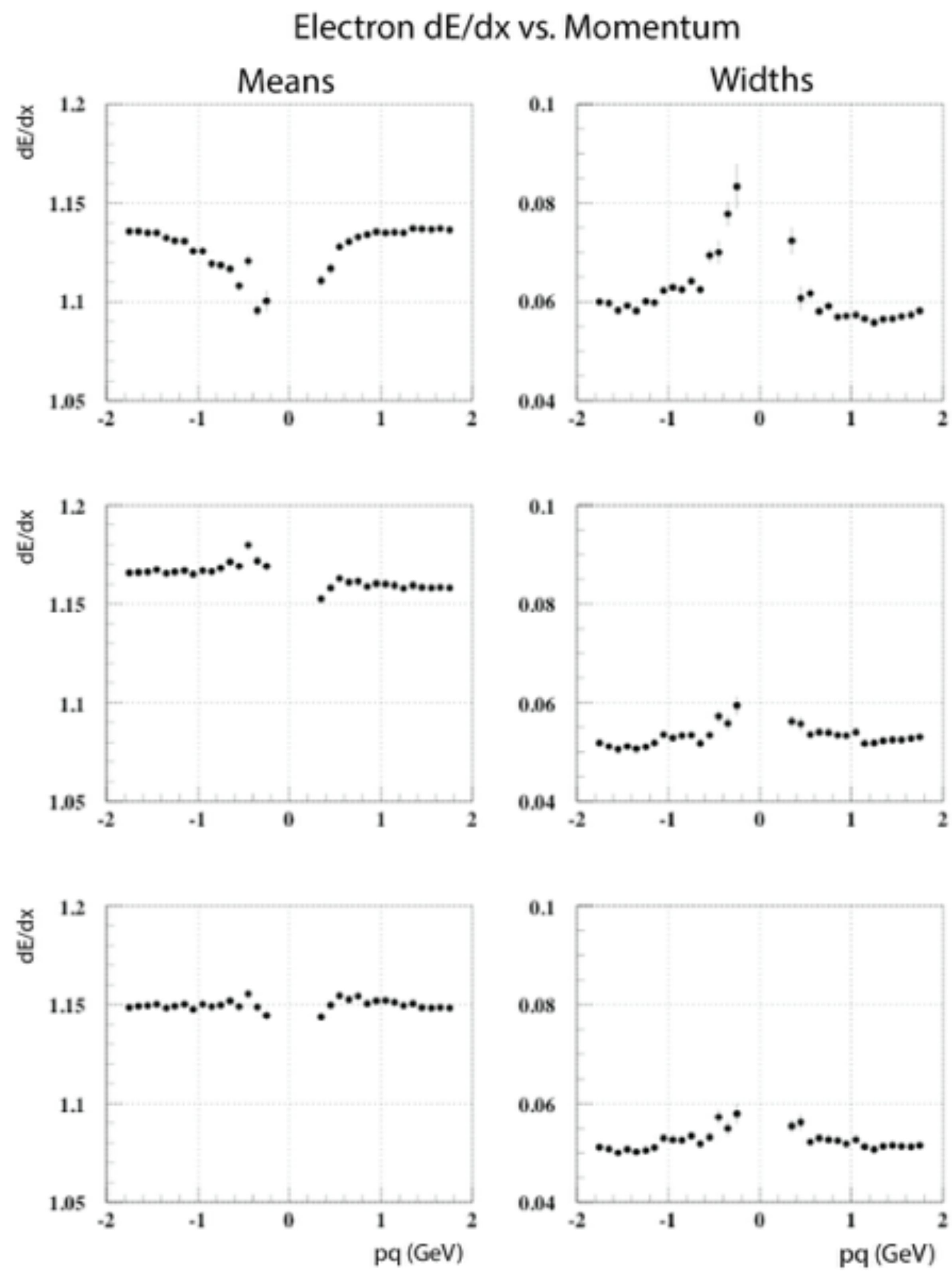
- Means not flat
- Widths can be large

Apply r-ϕ path length correction:

- Biggest correction comes here
- Note asymmetry!

Add empirical “cell corrections”:

- Before final 1-d correction (flattens meas further)



Note: electrons will be calibrated to 1, not 1.15 as in these CLEO-c plots

Track-level calibrations

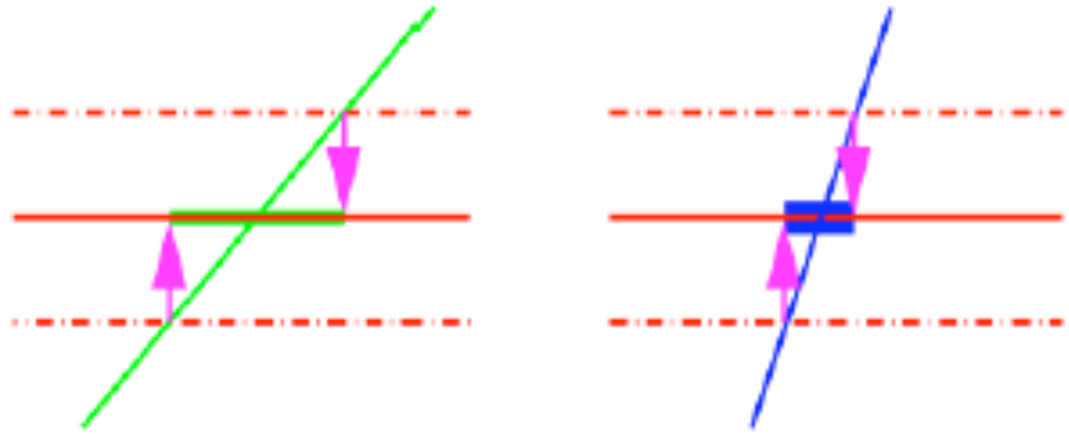
- r-z path correction:
  - Simple, no constants needed (actually part of geometry correction)
  - Divide by path length (1/sinθ)

- Saturation correction (difficult):
  - "Cosine" correction (for electron saturation)
  - General saturation correction (relative to electrons)
    - Hard to parameterize
  - Very accurate electron correction (anchors correction to be good near minimum ionization) plus relative correction ensures good accuracy near electron dE/dx:
    - 1-2x min-I is a critical region!

- Predicted means and resolutions:
  - Needed to form PID variables for users

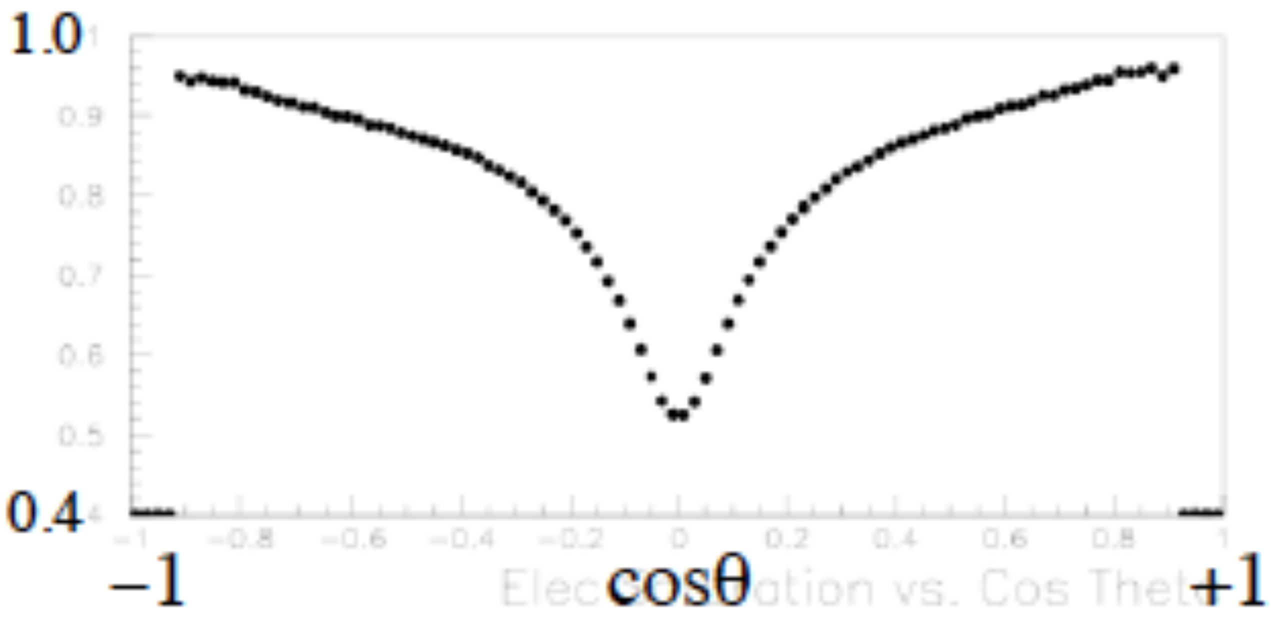
Gas-gain saturation

- Avalanche from early electrons screens wire:
  reduces local field and hence gas-gain for later electrons



- Key variable: D / (| cos θ | + δ) = charge/length: Q/ΔZ
- Density of charge along wire: D is measured dE/dx (after r-z path corr)
- δ ~ 0.1 accounts for natural spread of avalanche
  (i.e. density not infinite even if |cos θ| = 0!)
- Naïve spread of charge: 1/ΔZ ~ | tan θ |
  but the "D" we use is already scaled by sin θ for r-z path effect…

Gas-gain saturation



The shape of saturation effect for electrons

- Interpolate binned plot

Ideal, "true" value: I

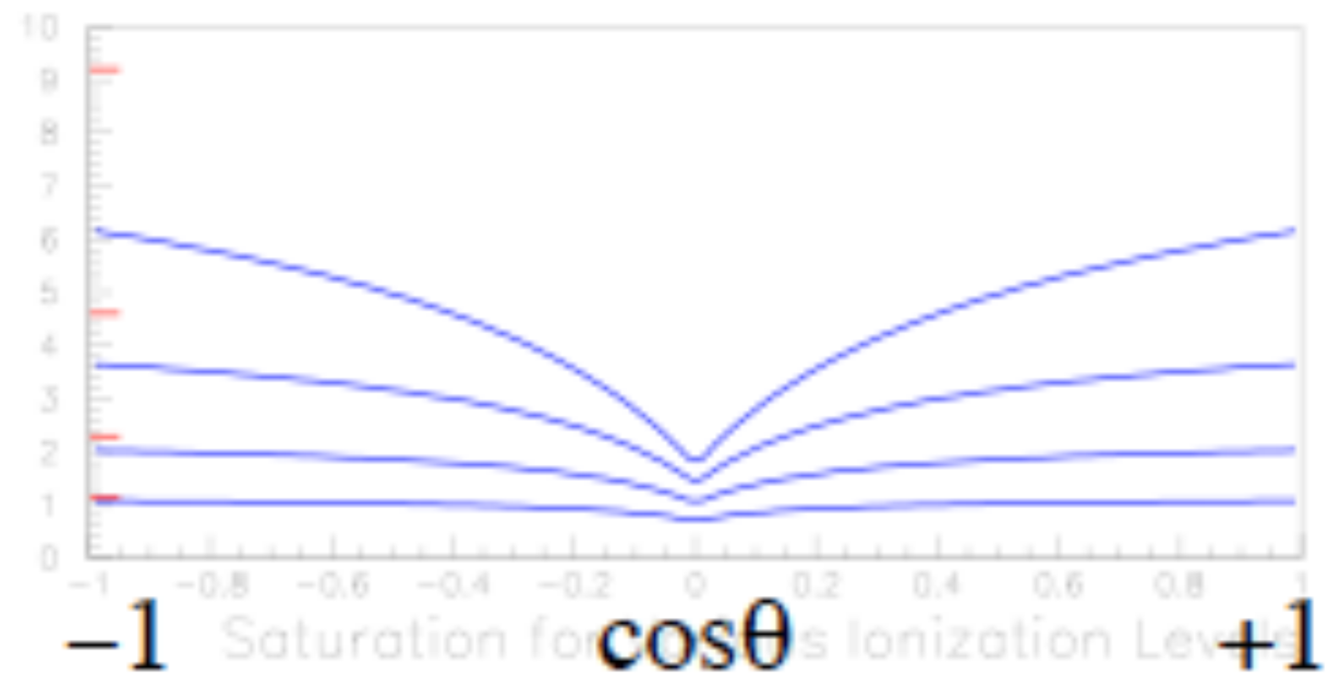
Measured value: D

Red ticks:

- 4 "I" values: each 2x previous
- D = I if no saturation

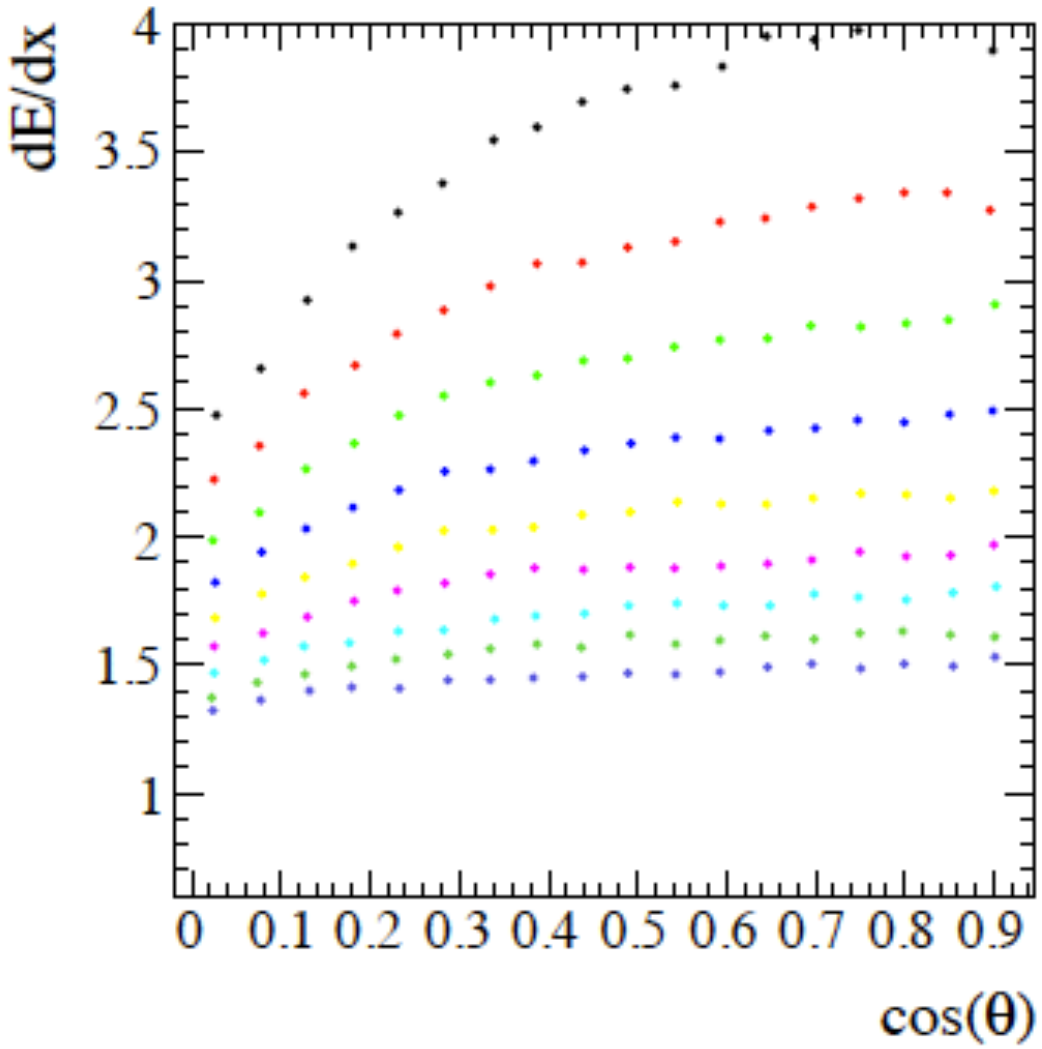
Blue curves:

- predicted D for each I

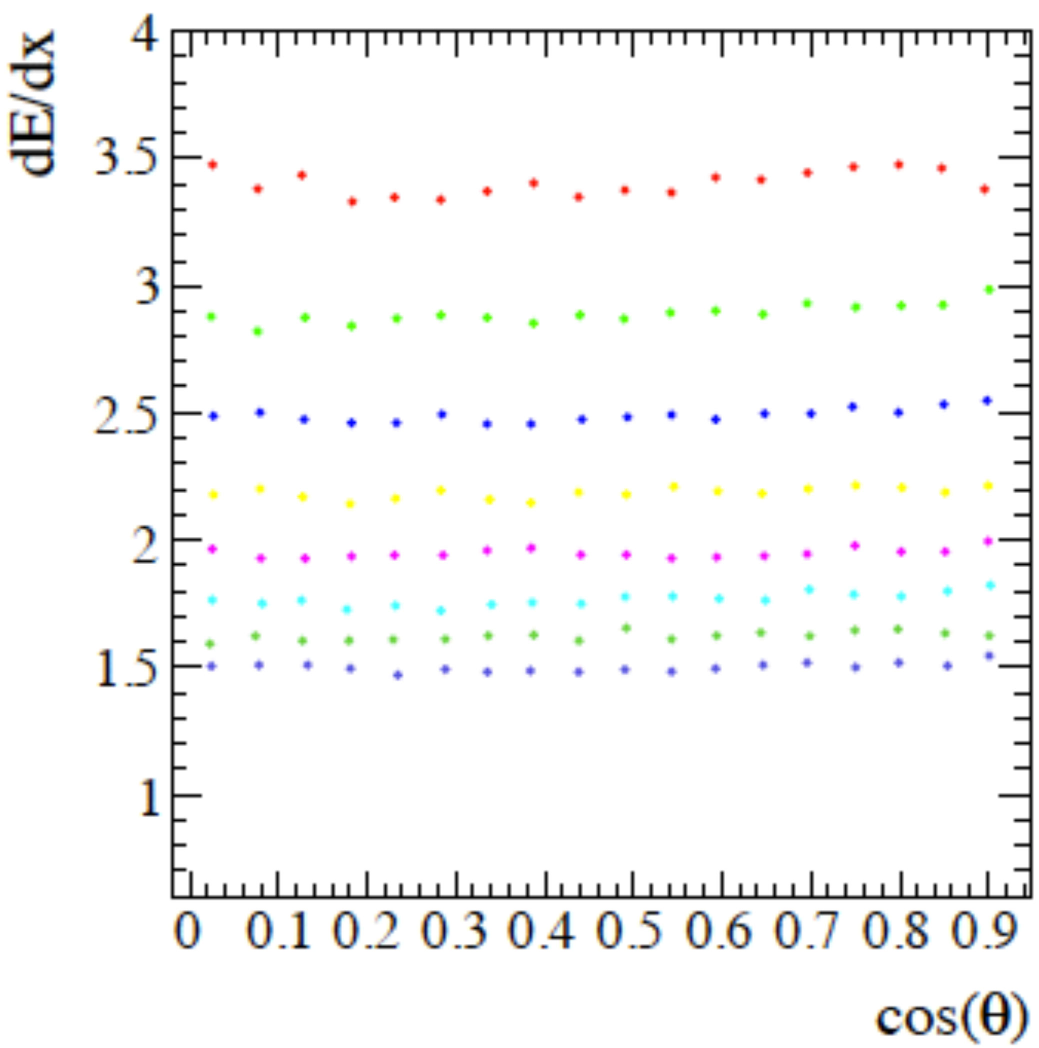


Gas-gain saturation

- Example from our dE/dx calibration tools *using real data from BESIII (protons)*



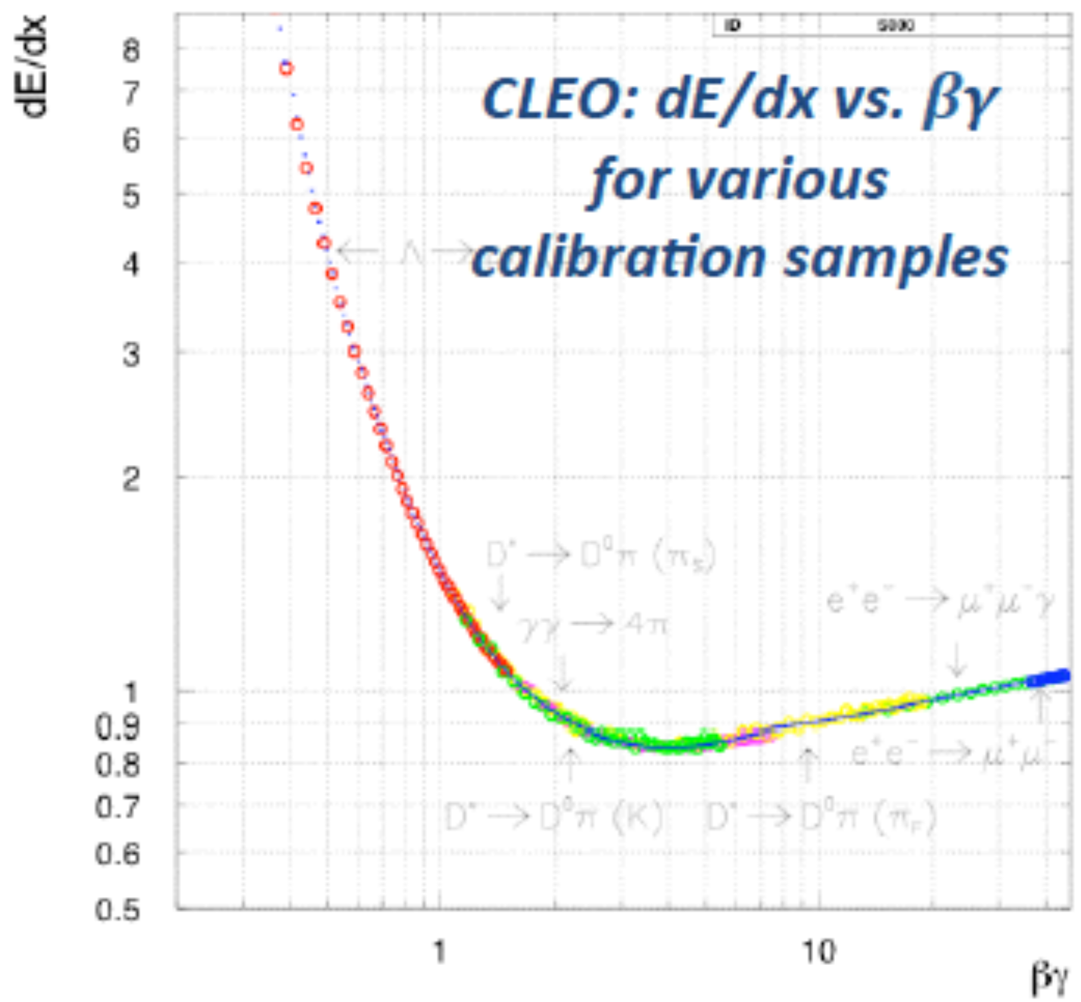
Before correction



After correction

Predicted means and resolutions

- Fit means to empirical functions in ~4 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:
  - $\sigma_I \sim f(I^{1/2})$ / [$g(\#\text{ of hits}^{1/2})\, h(1/\sin\theta)^{1/2}$]
  - Carefully fit for functions f, g, h
  - Iterate, fit for each with other two effects removed.
  - Need to be aware of finite bin-size effects (as with saturation work)
  - There is room for improvement here

Usage: “sigma” variables

- Currently, dE/dx PID uses look-up tables to determine likelihoods
- We plan to move to using parameterized means and resolutions (similar to what was done at CLEO-c and BESIII)
  - Obtain χ = (measured - expected) / resolution
  - Then χ^2 can be combined with -2 ln L from other detectors (TOP, ARICH) - resolution is approximately Gaussian

- Data as presented to users:
  - 5 variables: $\chi_X = (dE/dx_{meas} - dE/dx_{exp}) / \sigma_{pred,X}$ ($X = e,\mu,\pi,K,p$)
  - *We would also like to include enough information in the mDST format for users to make their own plots*
    - Truncated means, momentum valid in CDC (not IP!), # of hits, …?
    - Should not require much memory

Other useful information

- Belle II dE/dx page
  - https://confluence.desy.de/display/BI/Physics+DEdx
  - Links to old talks, documents, etc.
  - List of open questions and discussion topics

- Belle II Combined Performance physics working group
  - https://confluence.desy.de/display/BI/Physics+CombinedPerformance
  - Status of reconstruction algorithms, recent performance benchmarks, etc.
  - Intended to improve collaboration and coordination of reconstruction/ performance topics
    - Reconstruction algorithms, performance benchmarks, calibration methods, data flow, and eventually systematics
    - Please let me know if you are working on any of these topics
  - https://confluence.desy.de/display/BI/Physics+DataPreparation
  - *Lots of work to be done!*

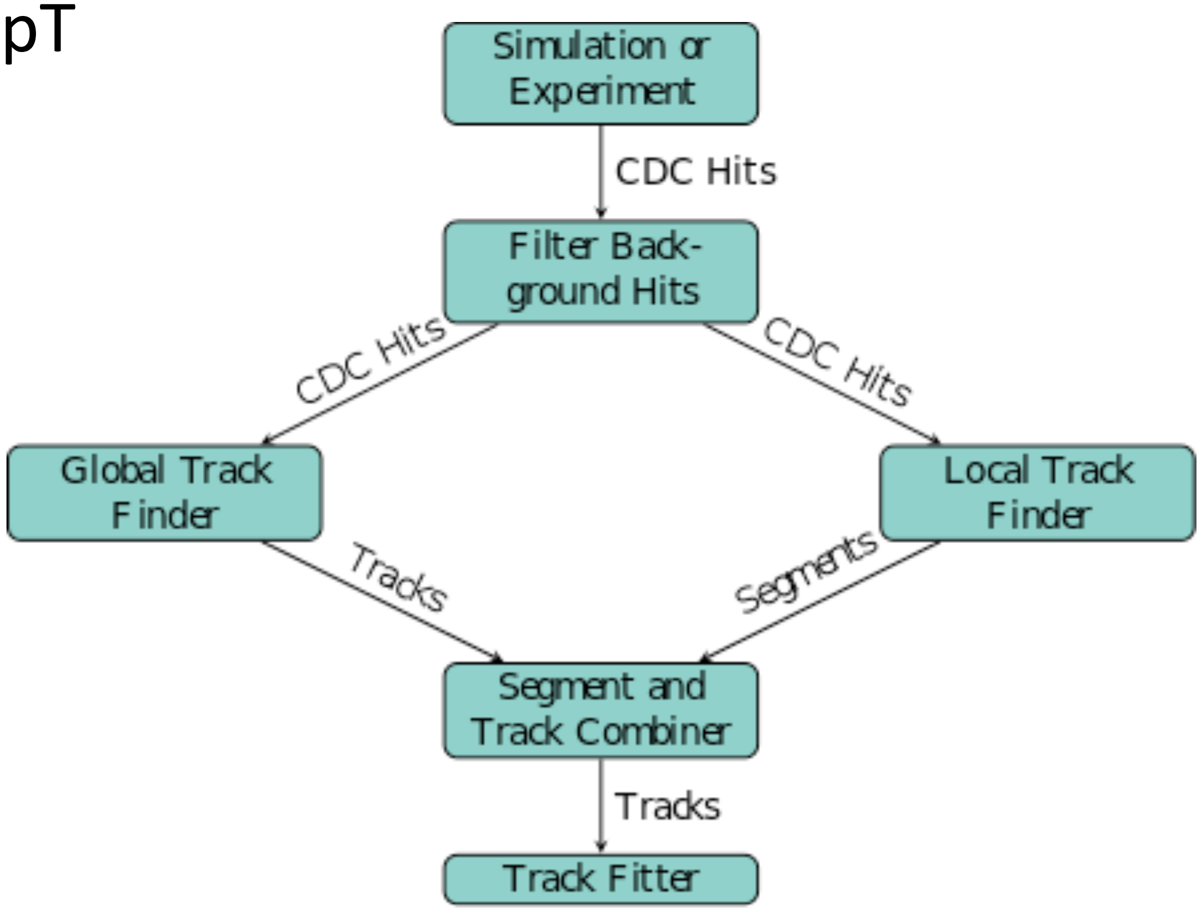
Summary

- The Belle II CDC is important for tracking, PID, and trigger
  - Based on successful predecessor at Belle
  - Cosmic ray testing in progress
  - Installation in Fall 2016
- dE/dx reconstruction and calibration is good shape
  - Detector response and PID performance seems reasonable
  - Calibration scheme becoming more clear
  - Many useful tools in place or under development

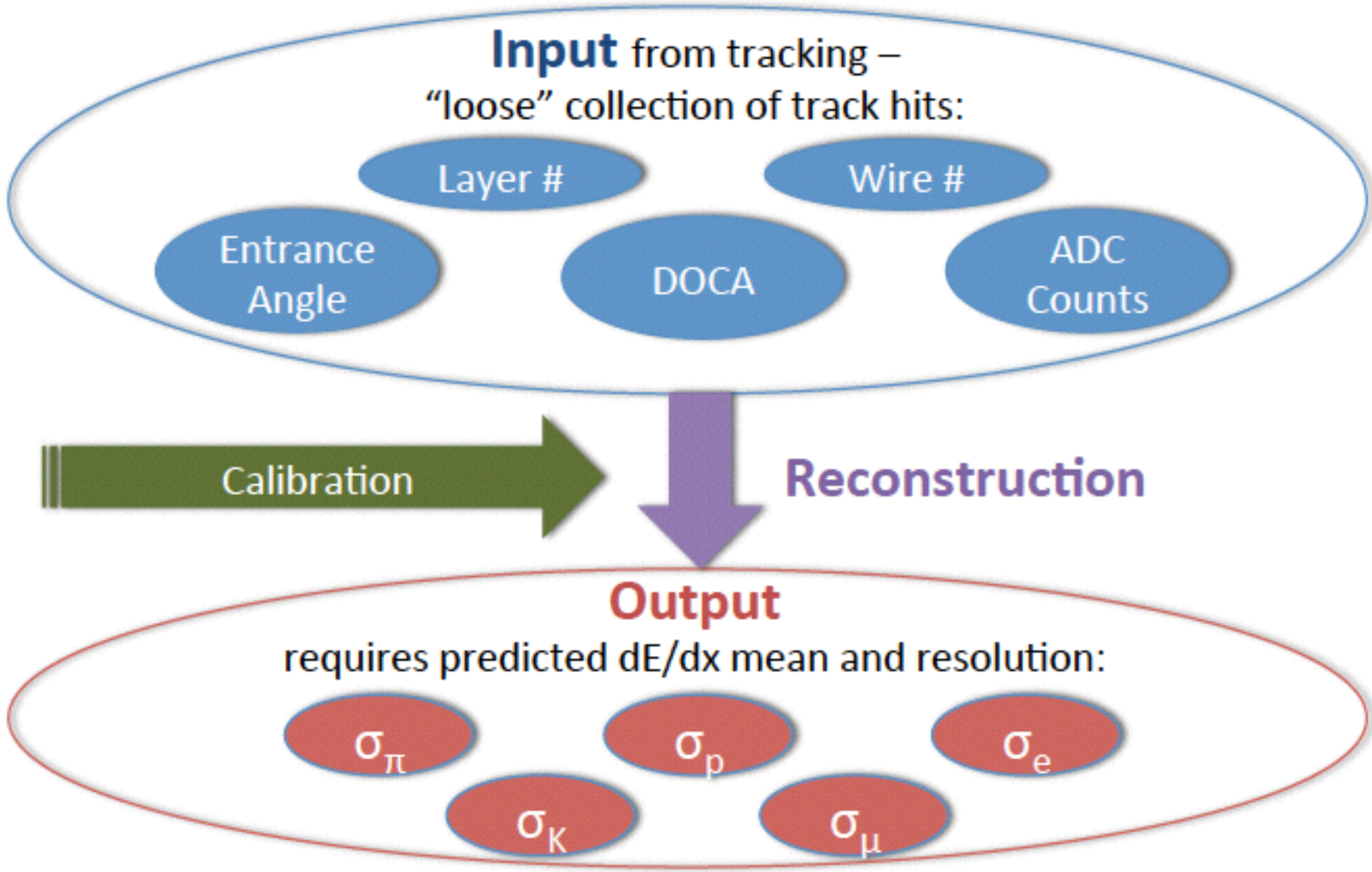
Extra

Track finding

- Algorithms for track candidates out of CDC hits
  - Global track finder (Legendre) uses all hits at once by applying a mathematical transformation to the hit positions
    - Apply different transformations for axial and stereo hits
    - Fast and highly efficient for high-pT tracks coming from the IP and can cope with missing hits
  - Local track finder (Automaton) searches for segments and tracks using a cellular automaton
    - Robust to energy losses
    - Especially important for tracks not coming from the IP
- Tracks and segments from the two algorithms are combined and sent to the track fitter (GENFIT)



dE/dx reconstruction overview



Five values (one for each candidate mass) of deviation from expected dE/dx measurement – may be used for building a PID χ^2/likelihood value for example

Overview of all dE/dx "constants"

Electrons

Wire Gain: Same voltage different cell sizes, bad wires, electronics, …
Run Gain: Atm. pressure changes, provides overall stability of dE/dx means
"DocaEnt": Empirical hit correction, path length from track crossing cell in r-ϕ
"Cosine": Saturation correction for electrons - function of cos θ only

Pre-recon

Hadrons

Saturation: Saturation relative to electrons (non-linear – depends on dE/dx)
Mean: Predicted mean to calculate # of std. dev. from hypothesis
Resolution: Predicted resolution to calculate # of std. dev. from hypothesis

Post-recon

Based only on nominal geometry: path length of track in r-ϕ, r-z projections

Not normally varied (relevant parameters not calibrated – not included above):
amount of truncation, ADC count to charge conversion

Possible additional effects

Residual Run Gain: Re-adjust gain after other correction to guarantee consistency
Residual Cosine: Small adjustment to avg. "Cosine" – also depends on track Q
Number of Hits: Correct mean for bias due to quantization of truncation
"Run Saturation": Most complex! Run gain correction biases saturation

Scope of CMU efforts

- We are committed to handling all aspects of CDC dE/dx calibration
  - Skims of calibration samples, code to extract constants, etc.
  - Natural for us to also assume responsibility for dE/dx reconstruction software, where calibrations are applied

- We are also willing to do more:
  - Willing to help with Monte Carlo
    - *Can do a track-level version by ourselves, if desired*
    - Need additional collaborators to lead a hit-level MC but we can certainly be involved
  - Looking into sharing skims for SVD calibration

- We are also involved in performance monitoring and data production
  - Currently coordinating the *Combined Performance* physics working group

Discussion topics

- MC issues
  - Sources of dE/dx resolution (ionization statistics, gas gain variations (individual avalanches), magnetic effects in r-ϕ path length, imperfect calibration, gas gain saturation, …
  - Current GEANT MC will do some of these well
  - Likely need a data-driven hit-based MC for best performance (This is a lot of work! Also hard to complete without data)
    - Several US groups willing to advise, but task should fall primarily on another (US?) group
  - Track-level MC (only MC for CLEOIII, CLEO-c): possible starter?

Discussion topics

- Adding dE/dx info to mDST format?
    - Truncated means, momentum valid in CDC (not IP!)
    - Should not require much memory

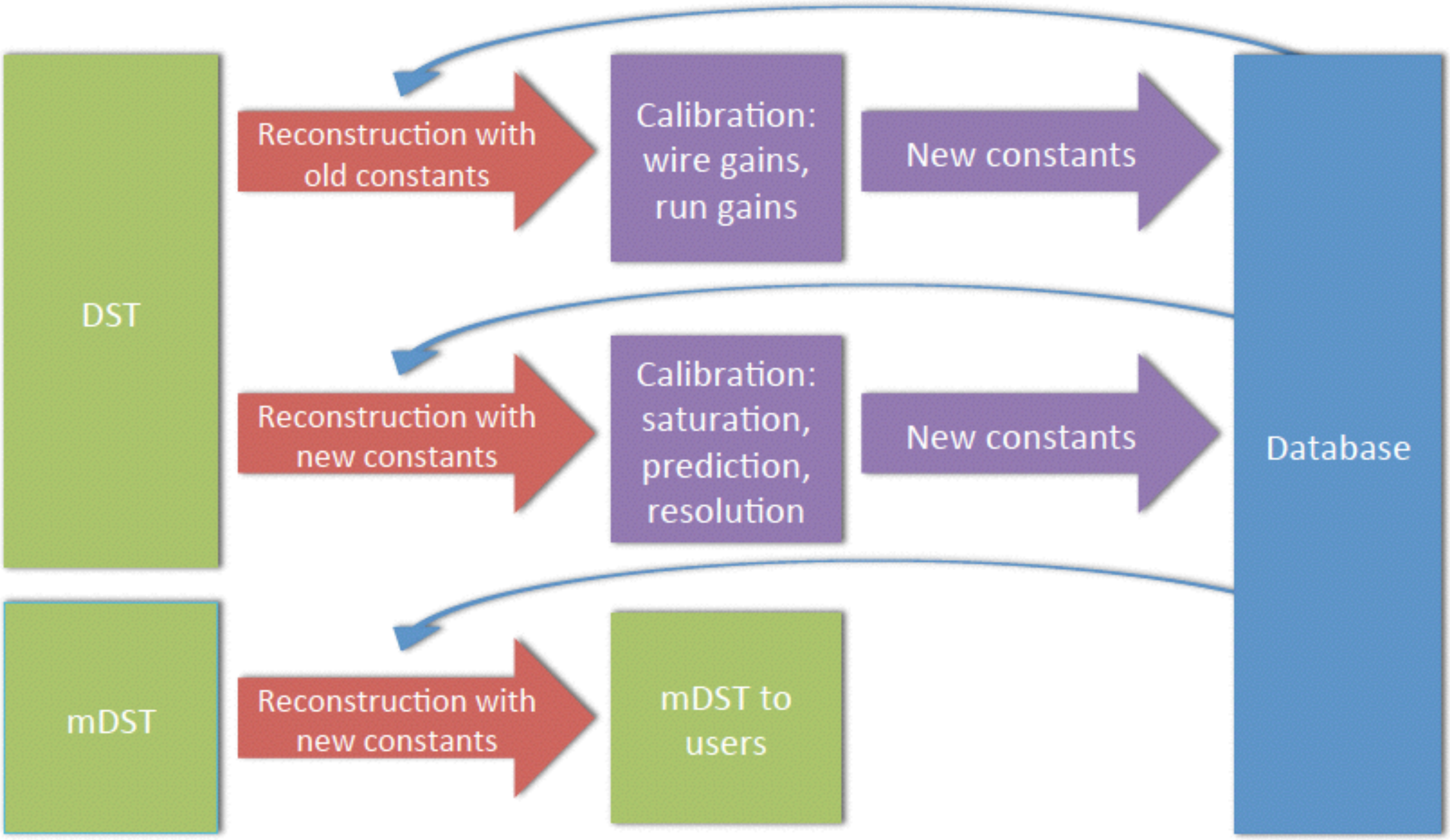
- Data flow (see following slides)
  - When should constants be applied?
    - Apply track-level calibration during reconstruction or at analysis phase?
    - Hit-level calibration is available earlier
  - Need larger set of hits than likely will be used in final track fitting
  - Is it possible to get dedicated queues and storage for calibration
    - It will take time to provide final calib. to users
  - Calibration sample sharing

dE/dx calibration samples

- Skim code needed to obtain clean samples:
  - Bhabha, radiative bhabha, γγ -> ee
  - Dimuons, radiative dimuons
  - γγ -> 4π
  - D^0 -> Kπ (with or without D* tag?)
  - Ξ -> $\pi^+\Lambda^0$ ($p\pi^-$), or untagged Λ

- Skim integration
  - Data flow issues should be discussed with appropriate parties
  - Possible sharing of samples with others
  - https://belle2.cc.kek.jp/~twiki/bin/view/Physics/DataPreparation

Data flow


DST
Reconstruction with old constants
Calibration: wire gains, run gains
New constants
Reconstruction with new constants
Calibration: saturation, prediction, resolution
New constants
Database
mDST
Reconstruction with new constants
mDST to users

Improvements over the Belle CDC

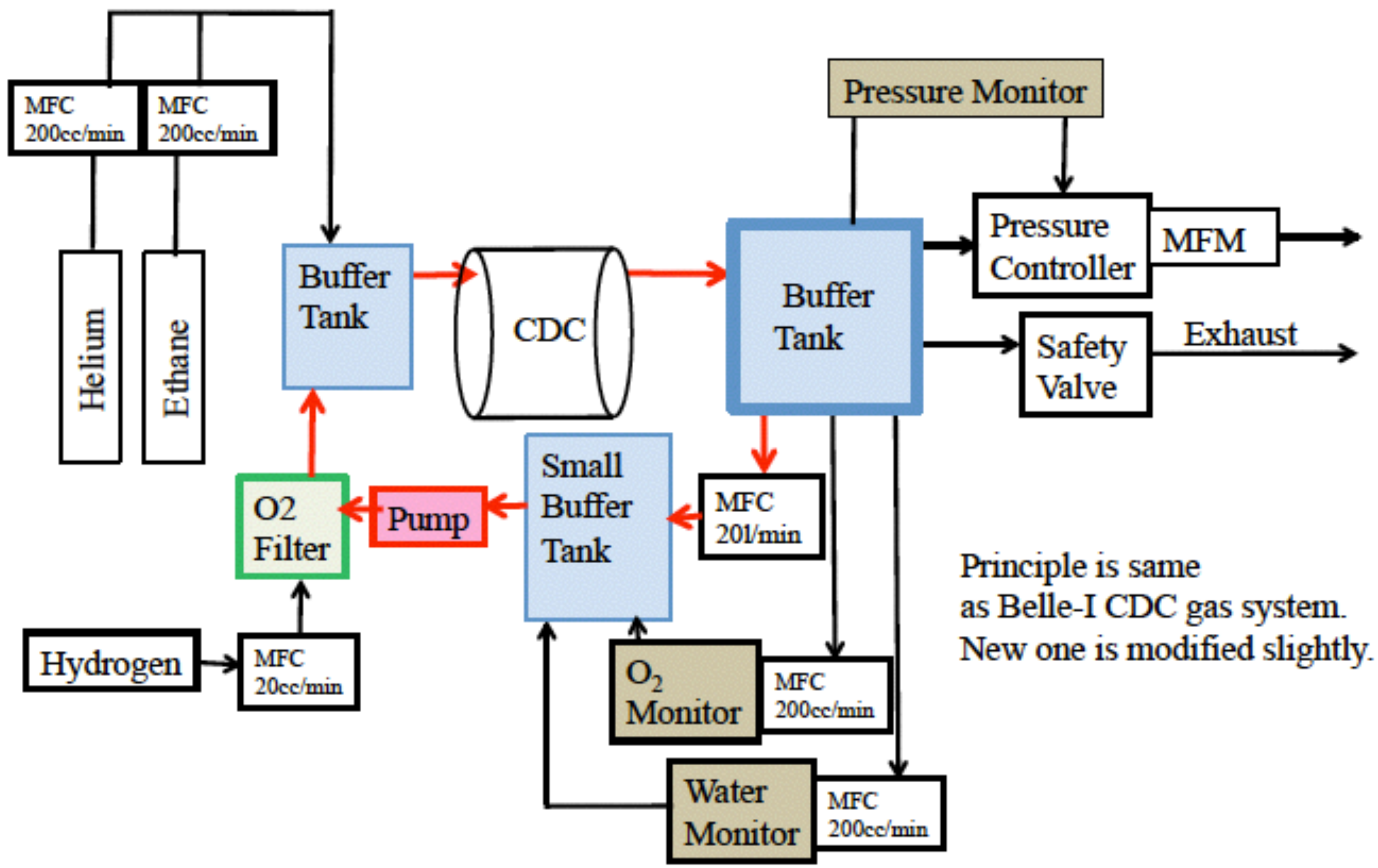
- New readout electronics system must handle higher trigger rates with less deadtime
  - Front-end electronics, located near the backward endplate, send digital signals to the electronics hut through optical fibers
    - ASIC chips incorporate amplifier, shaper, and discriminator
    - Drift time measured with a TDC, implemented in an FPGA, which also controls the slow FADC (~30 MHz) that measures the signal charge

Structural details

Superlayer	Layers	Cells per layer	Radius (mm)	Stereo angle (mrad)
Axial 1	8	160	168.0 - 238.0	0
Stereo U2	6	160	257.0 - 348.0	67.9 - 69.3
Axial 3	6	192	365.2 - 455.7	0
Stereo V4	6	224	476.9 - 566.9	-55.3 - -64.3
Axial 5	6	256	584.1 - 674.1	0
Stereo U6	6	288	695.3 - 785.3	63.1 - 70.0
Axial 7	6	320	802.5 - 892.5	0
Stereo V8	6	352	913.7 - 1003.7	-68.5 - -74.0
Axial 9	6	384	1020.0 - 1111.4	0

Gas system

- Mixed gas fed into the detector at a rate of one full volume every two days
  - Removes oxygen from the CDC gas volume
  - Fresh gas fed in at 1/10 the full circulation rate (reduce cost)



CDC calibrations

- Alignment of endplates and hole positions
  - ~120 μm shift in some hole positions due to earthquake during drilling!
  - Wire tensions (wire sag: ~200 μm at the center of the chamber)
- Timing offsets: “t0”
- X-T relation
  - Most important calibration
  - Dependent on incident angle, polar angle (new for Belle II)
- Propagation delay in wire
- Time walk correction