Alignment of Gaps With Cosmic Rays

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ProtoDUNE Simulation and Reconstruction Meeting

November 14, 2018

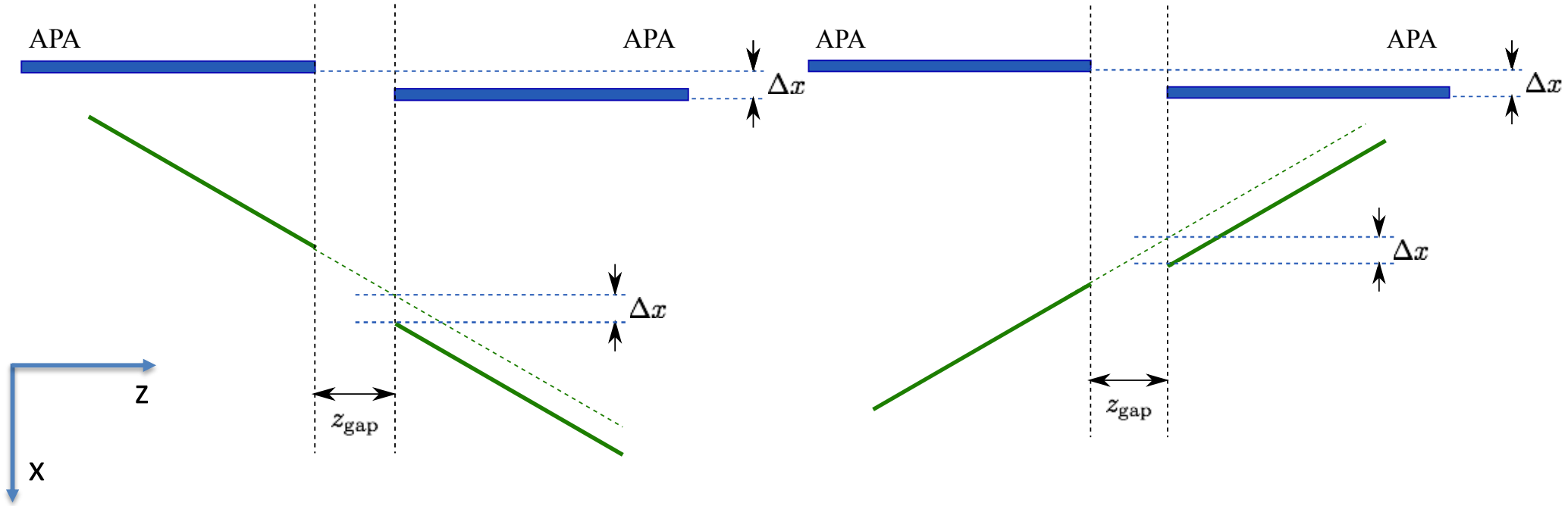
Alignment

- Nearly every detector in HEP is aligned with cosmic rays
- Elaborate examples:
  - CMS: http://arxiv.org/abs/0911.4022
  - ALICE: http://arxiv.org/abs/1001.0502
  - An ATLAS Ph.D. Thesis: Vincente Lacuesta Miquel
    http://inspirehep.net/record/1429422/
    And another: Regina Moles-Valls
    http://inspirehep.net/record/1339828/
    No specific mention of cosmic rays in either of these, but the idea's the same. Tracks from the collision point are copious at the LHC, but there are "weak directions"

Alignment Constants we Expect to Measure well in DUNE

Local deviations from nominal for inter-APA gaps
APA's seen from above, looking down a vertical gap

M. Wallbank's thesis:
http://inspirehep.net/record/1656784



Need positive Δx or positive Δz
to fix this track (really a combination)

Need positive Δx or negative Δz
to fix this track (really a combination)

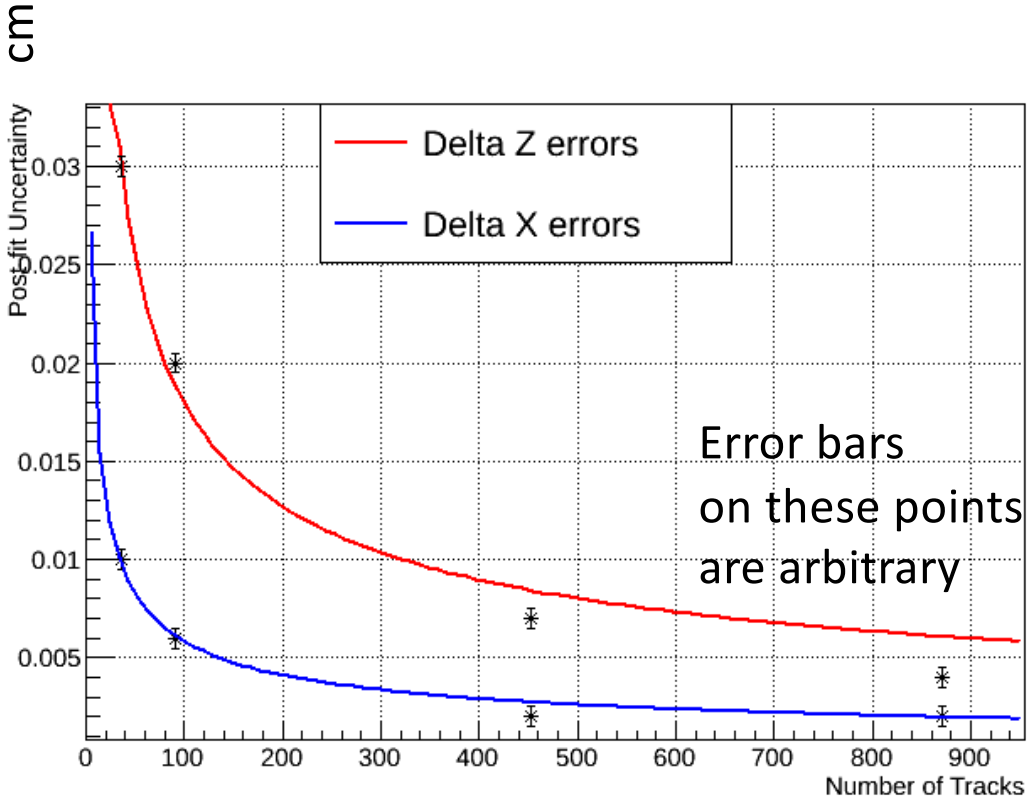
Vertical Gap Measurement Precision: 35-ton experience

- From Mike Wallbank's work on 35-ton measurements.
- Some gaps had more crossing tracks than others and are thus better measured.
- Assumes: Δx and Δz are constant along the length of the gap

$$\sigma_{\Delta z} = \frac{1.79\times10^{-1}\ \text{cm}}{\sqrt{N_{\text{tracks}}}}$$

$$\sigma_{\Delta x} = \frac{5.83\times10^{-2}\ \text{cm}}{\sqrt{N_{\text{tracks}}}}$$

Stat errors of order 10-50 microns



Gap Strategy: ProtoDUNE-SP

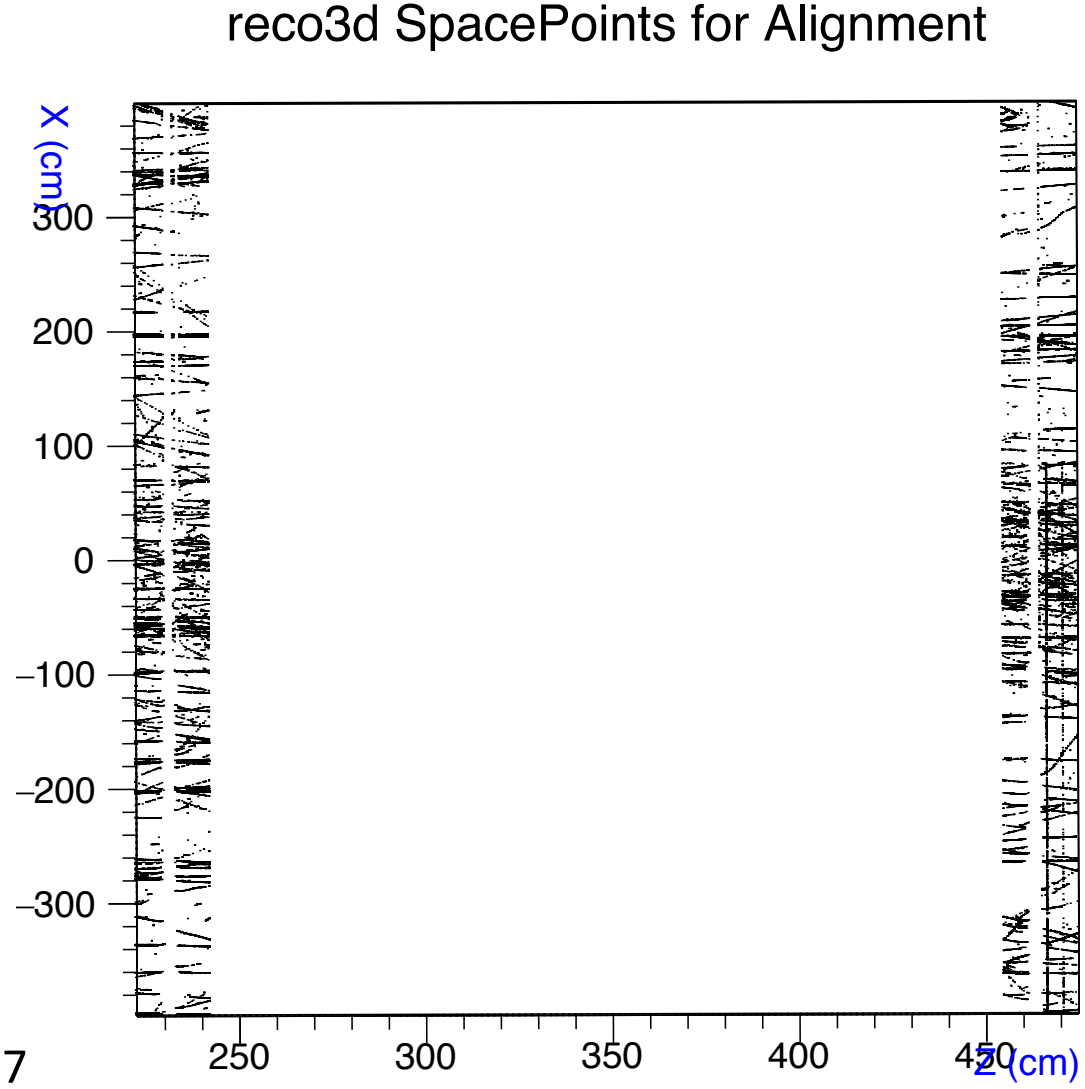
- Tracks aren't straight in liquid argon, so we select track stubs on either side of an APA gap.
- Use SpacePointSolver's SpacePoints as input data
- Any ProtoDUNE-SP run will do (need stable HV conditions) – plenty of cosmic rays and beam halo muons.
- Current cuts: select space points within 20 cm of a vertical gap, but not within 1 cm. (needs tuning).
- Cluster space points based on proximity into stub candidates.
- Fit lines in 3D. Require chisquared/DOF < 10 to reduce contaimination from crooked segments and overlapping/interacting particles.

Space Points Near Gaps: X vs Z

Older selection
with 10 cm
cut around gaps

Space point locations
are relative to nominal
geometry wire locations

No attempt made to assign
correct times – not really
necessary as segment pairs
come at the same time.

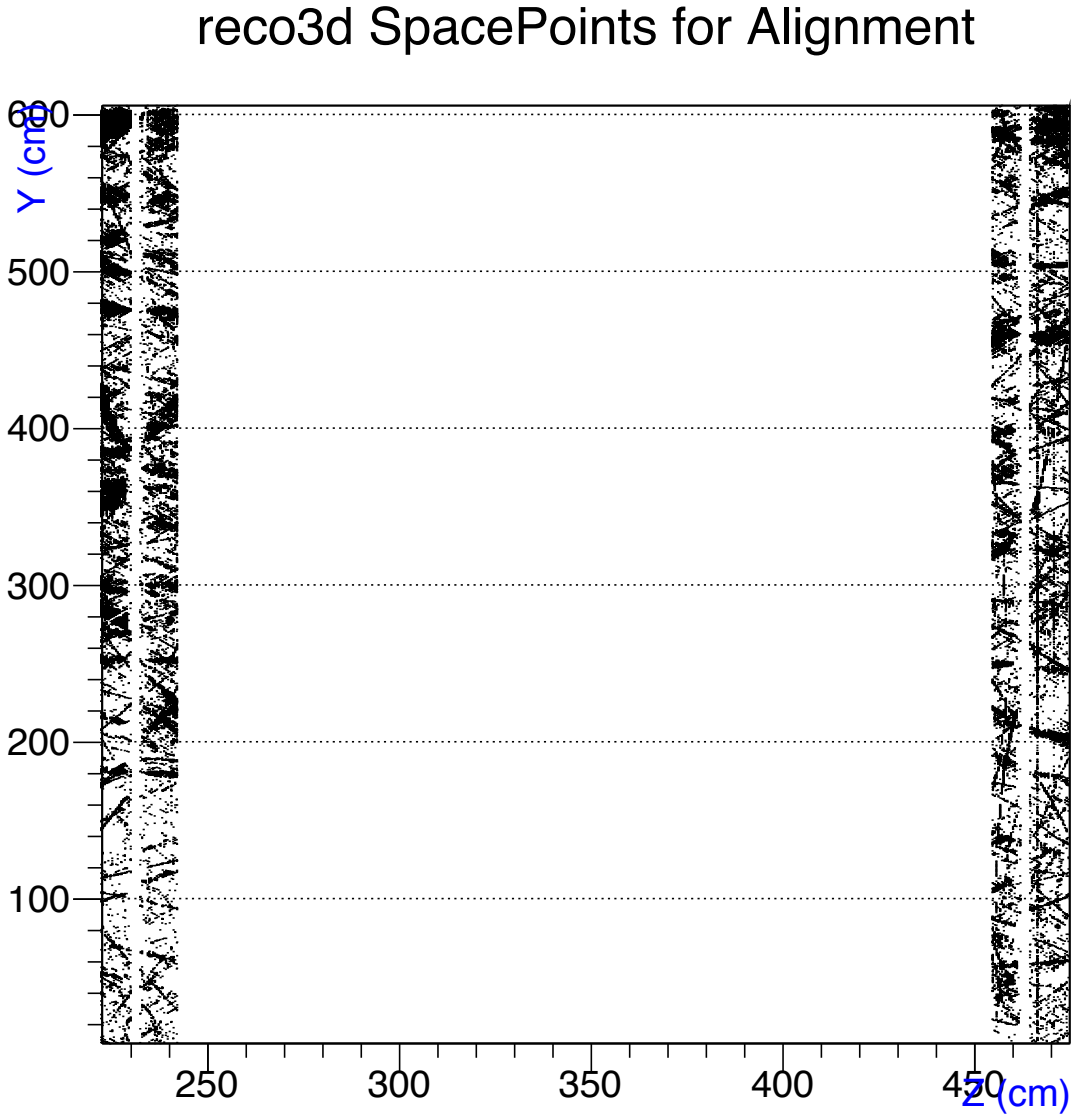


One file from Run 5177

Space Points Near Gaps: Y vs Z

More ambiguities seen in this view.

Beam halo muons in particular tend to be isochronous.

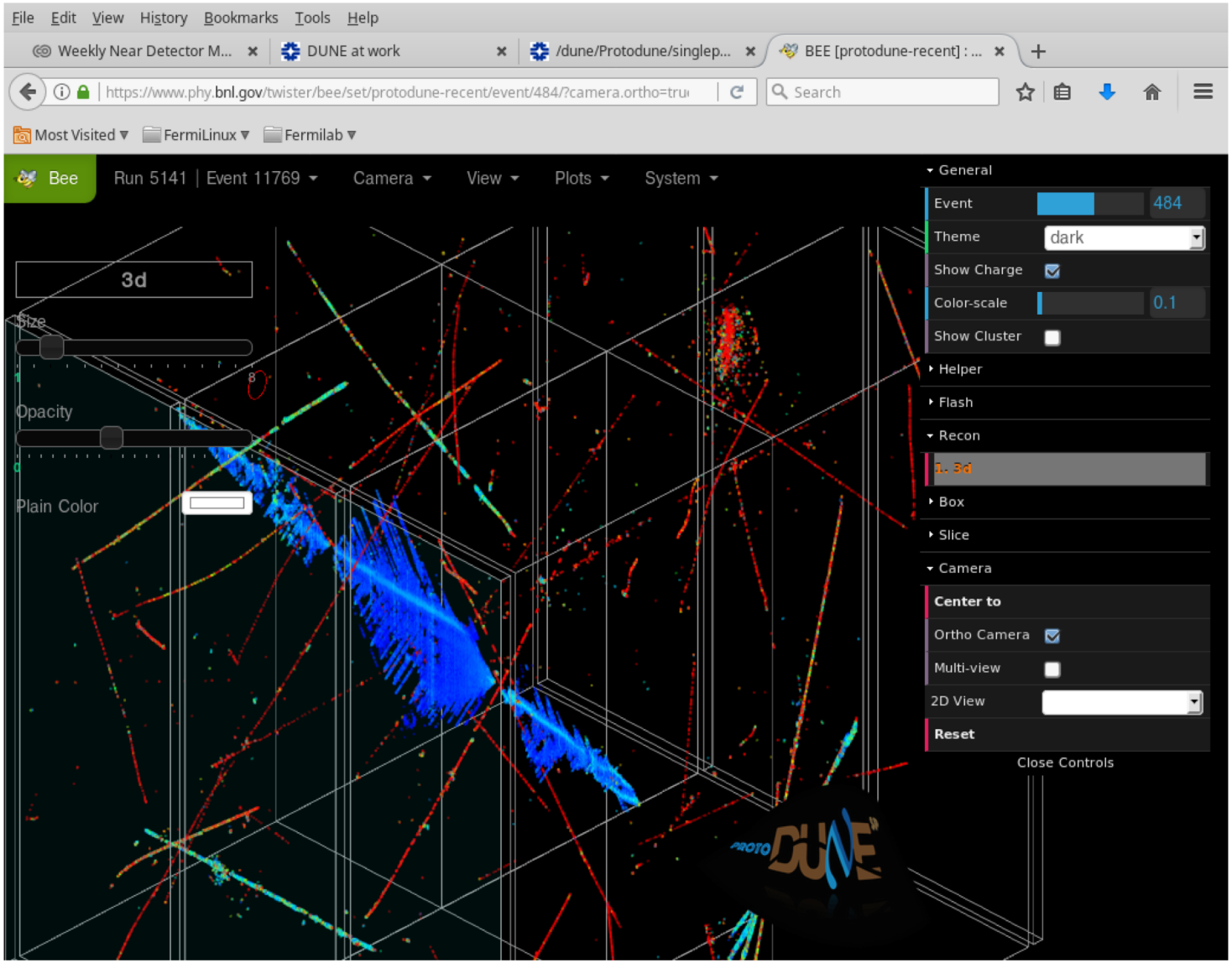


A Bee Event Display

Space points from isochronous tracks are spread out in Y.

Interesting aside: Density of possible space points clusters around a possible track trajectory, but it doesn't line up between APA's.

Possible timing misalignment between views?



Gap Strategy, Cont'd

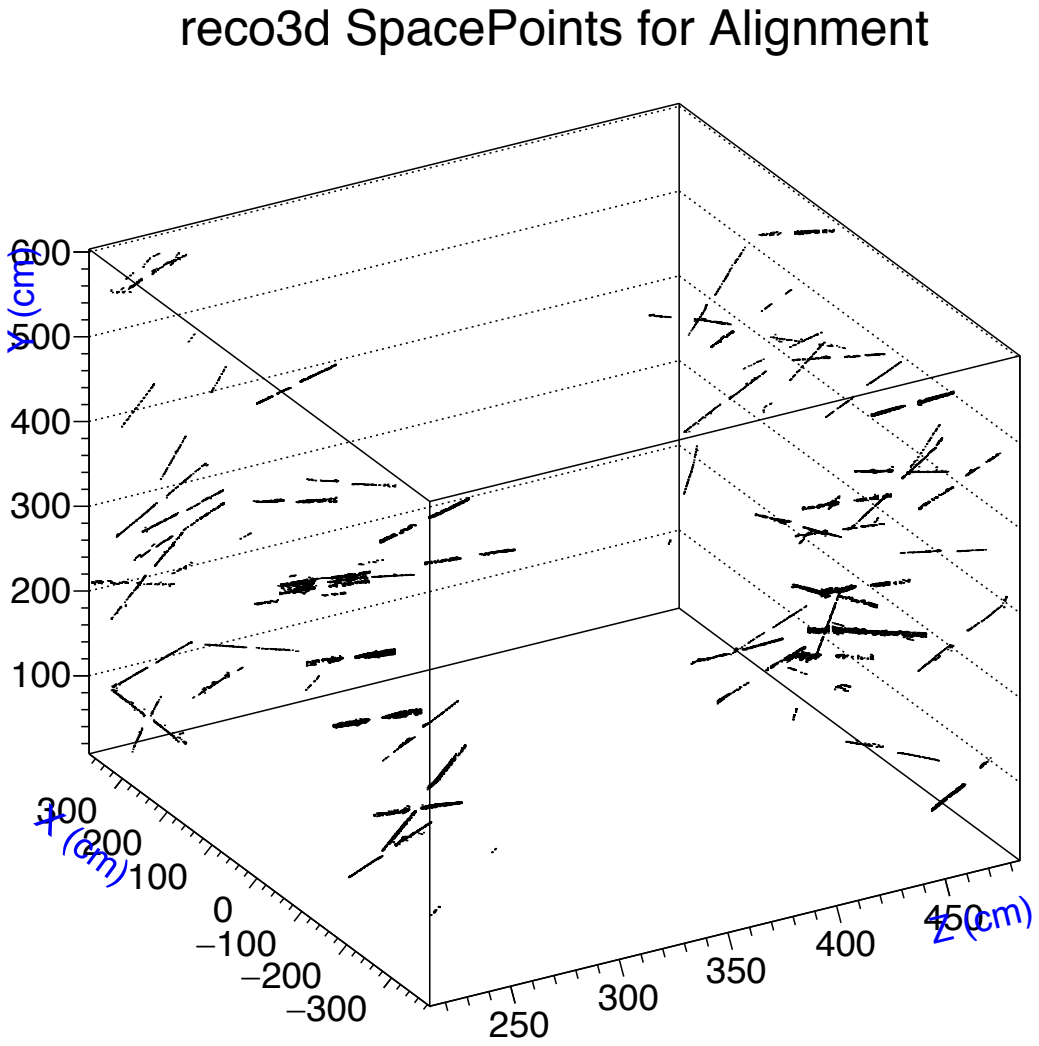
- Select pairs of track stubs on either side of the gap
- Abs(cos of angle between unit vectors of stubs) > 0.95
- Distance between starting point of one segment and the line of the other segment < 3 cm.

Selected Stub Pairs

Space points associated with stubs drawn.

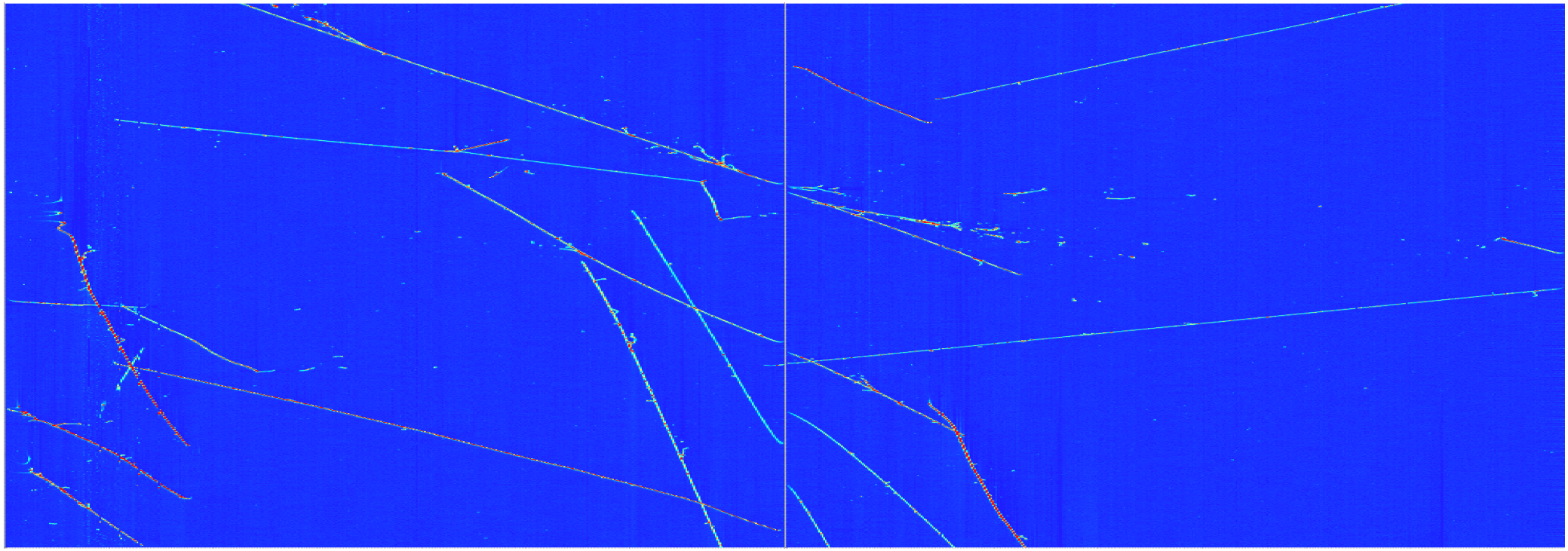
One file's worth of data from Run 5177

Surprisingly low efficiency for vertical-ish tracks. Mostly horizontal tracks pass my selections



An Event in the Collection View

Distortions seen near APA boundary. More apparent for steep tracks.
Gap in arrival times of charge for steep tracks. I suspect missing charge.



Event display tuned by Corey Adams, run by Tingjun Yang. Run 5439 Event 13.
APA's 3 and 2 (Beam Right, collection view).

Electron Diverter

Installed in beam-right APA's (1, 2, and 3)

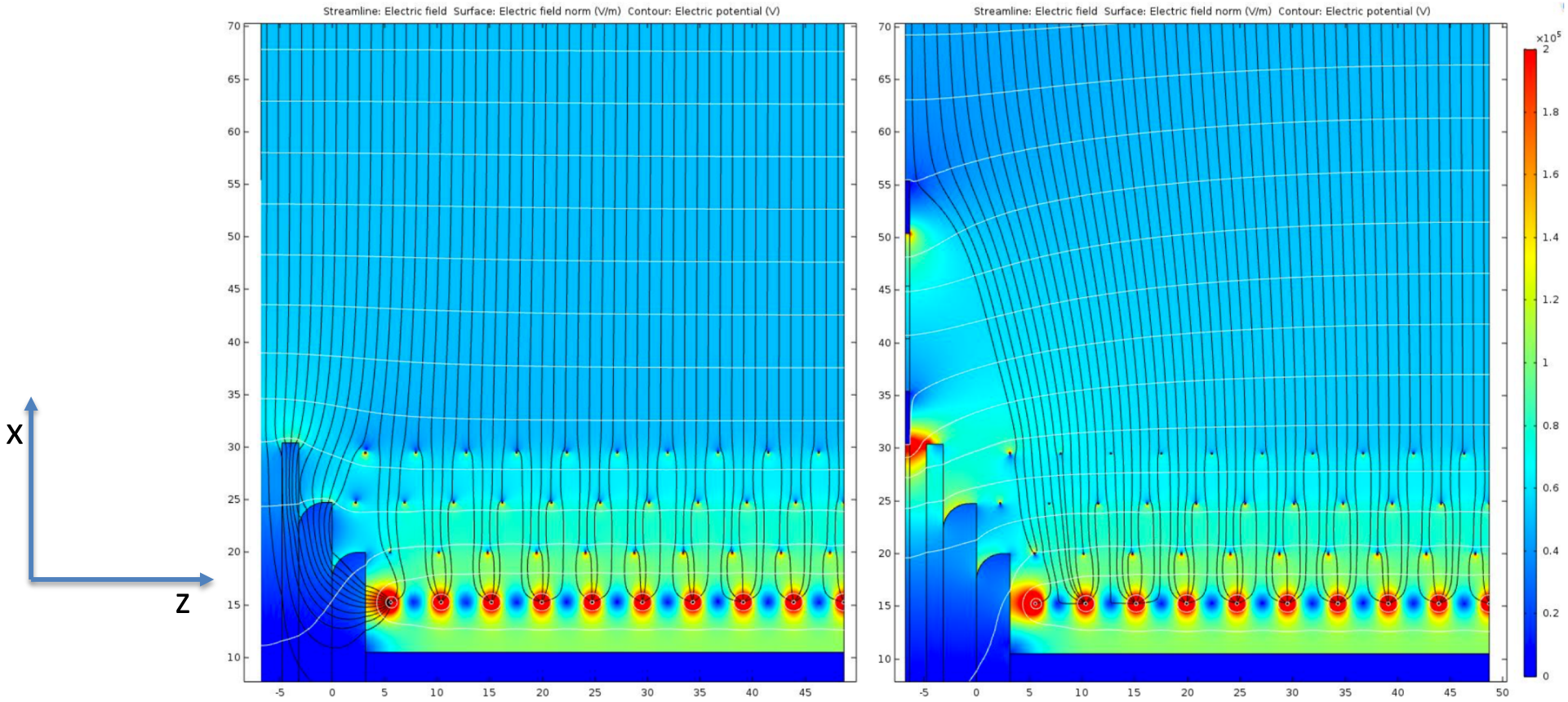


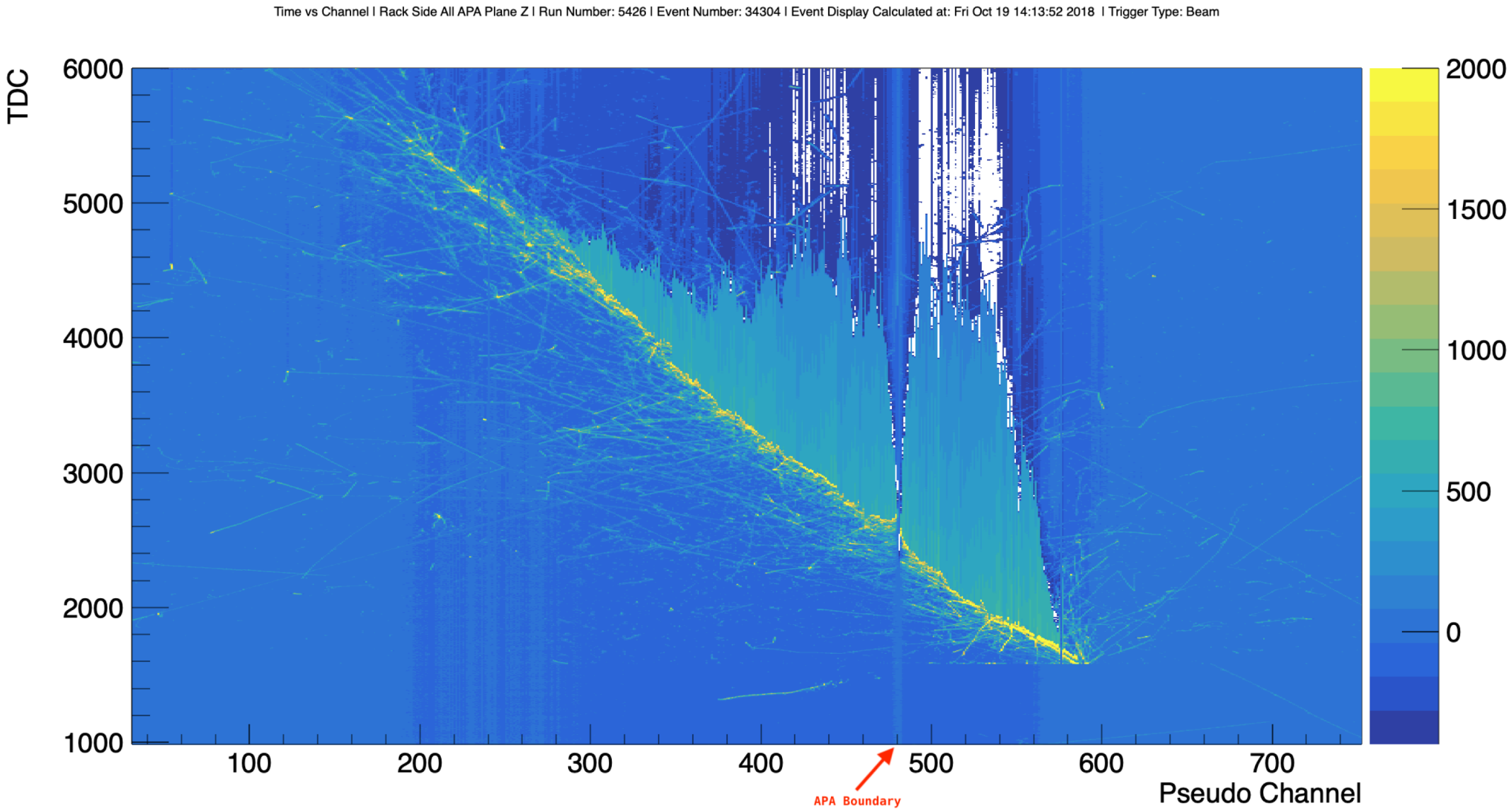
Figure 2.11: Left: field map of the region near the inactive gap of an APA without the electron diverter; Right: field map with the electron diverter in place. Electric field lines are shown in black, equipotential contours are in white, and electric field strength is represented in color gradient.

DUNE Doc 1794 (PD-SP TDR)

Effect on Showers

Noticed by Aidan Reynolds and James Pillow

"flatlands" saturation.



Fermilab DUNE

Gap Strategy

- Once pairs of segments have been selected, fit their space points jointly to a line in 3D as a function of
  - gap Δx and
  - gap Δz
- I scanned these from -1 cm to +1 cm in a 2D plane (possible correlations between measurements, but not if we have enough tracks).
- Plot sum of line-fit chisquareds in the (Δx, Δz) plane for each of the four gaps.
- Assumes no rotations for now, just translations.

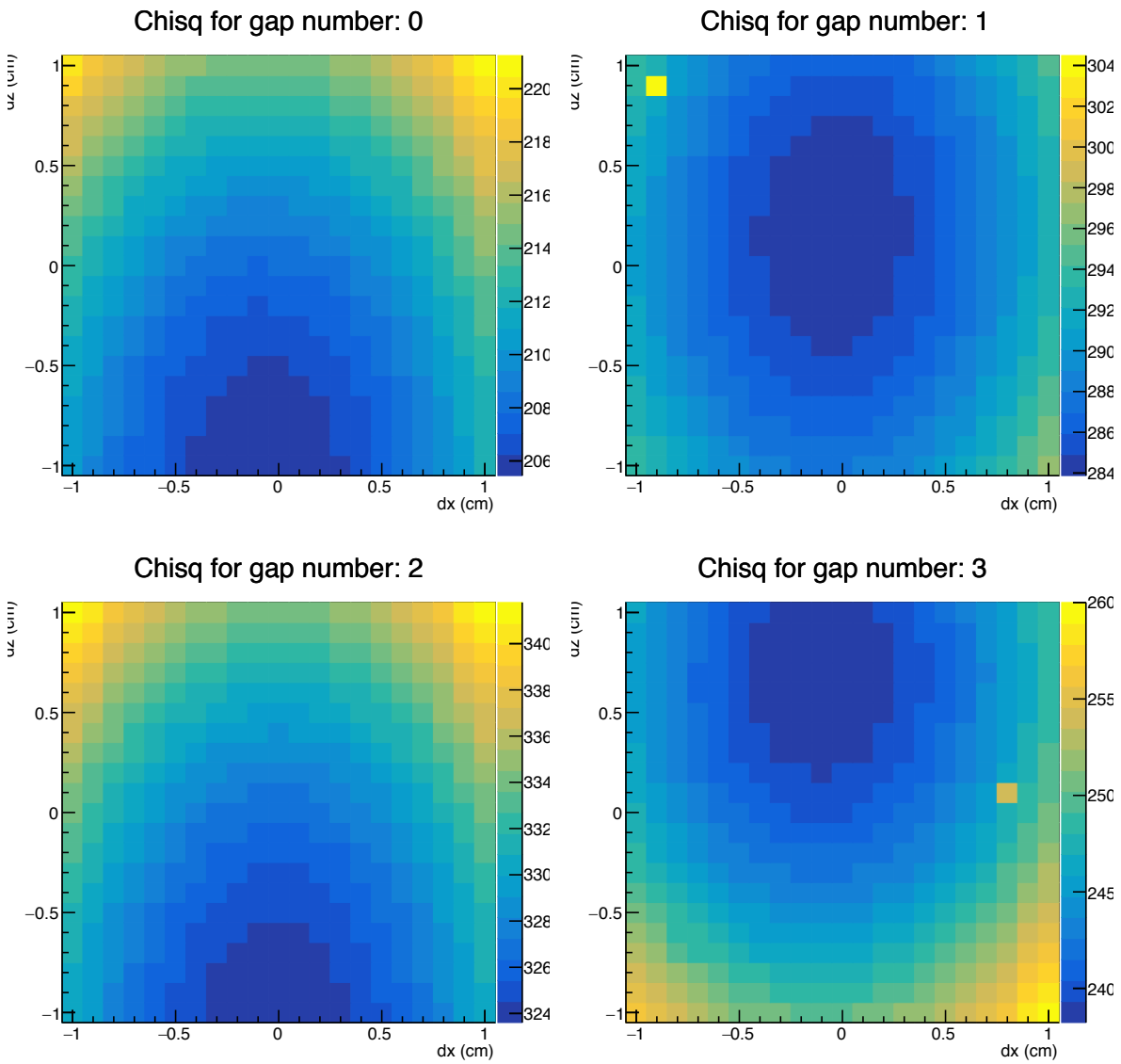
Chisquared vs dx and dz

Occasional fit failures give spots on pictures – some work to clean up

Gap numbering:

0: upstream, beam right
1: upstream, beam left
2: downstream, beam right
3: downstream, beam left

One file's worth of data in Run 5833.
Chisquareds not normalized (don't have right errors).
Strategy: use variations in fit values over many samples to determine uncertainties.



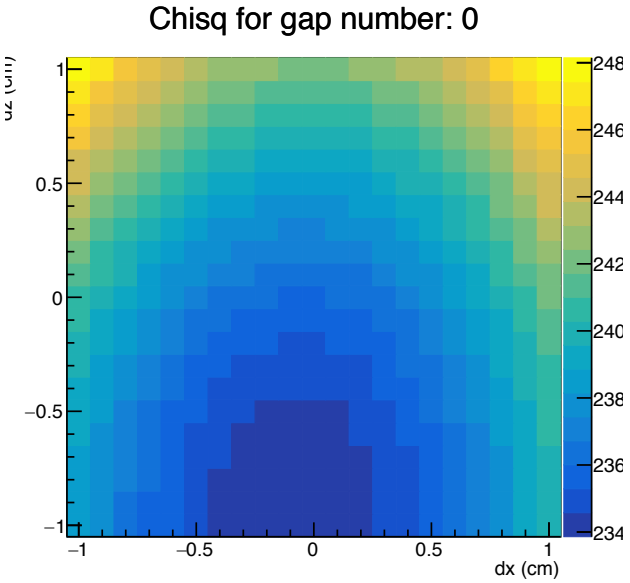
Another File of data

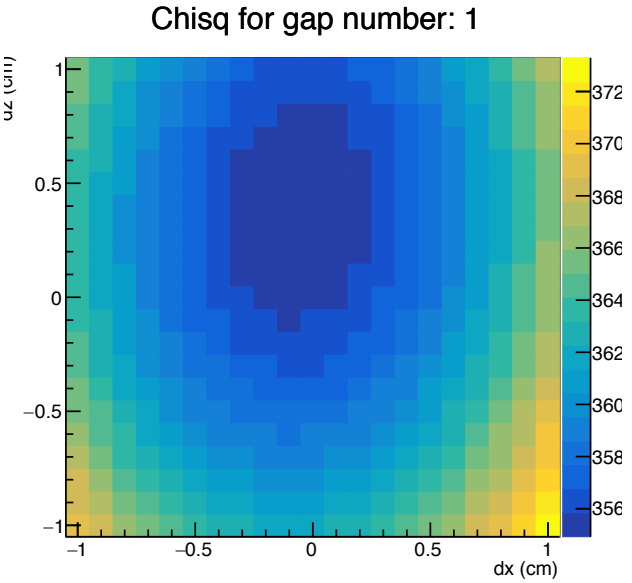
From Run 5834

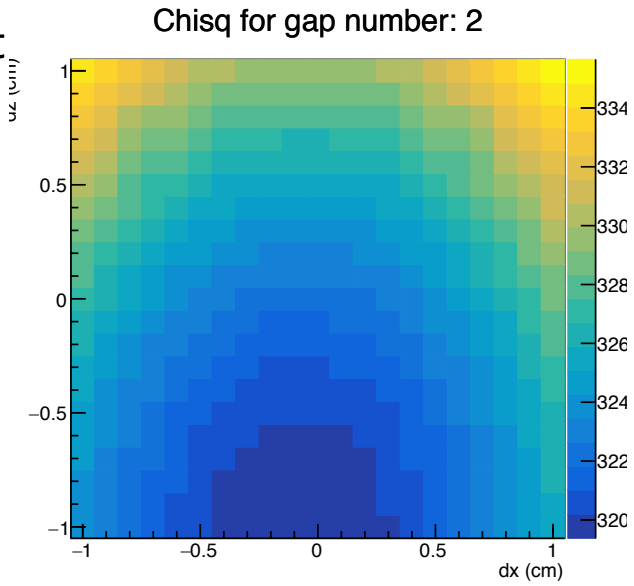
Gap numbering:

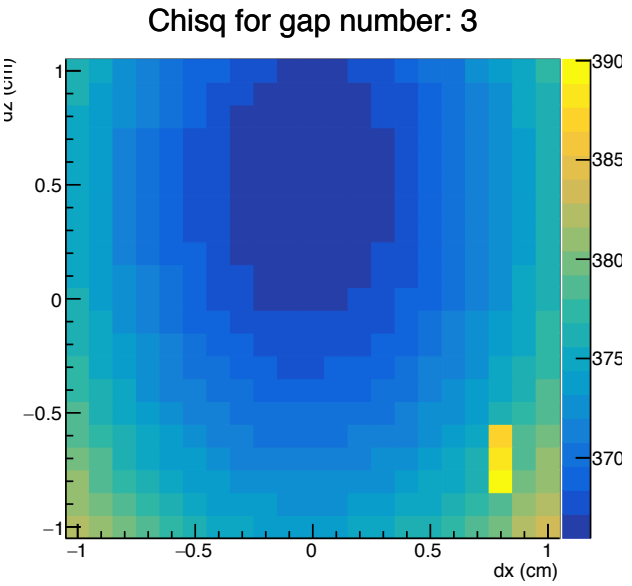
0: upstream, beam right
1: upstream, beam left
2: downstream, beam right
3: downstream, beam left

Mysterious shift in Z in the beam-right samples. Could be the diverters causing this.







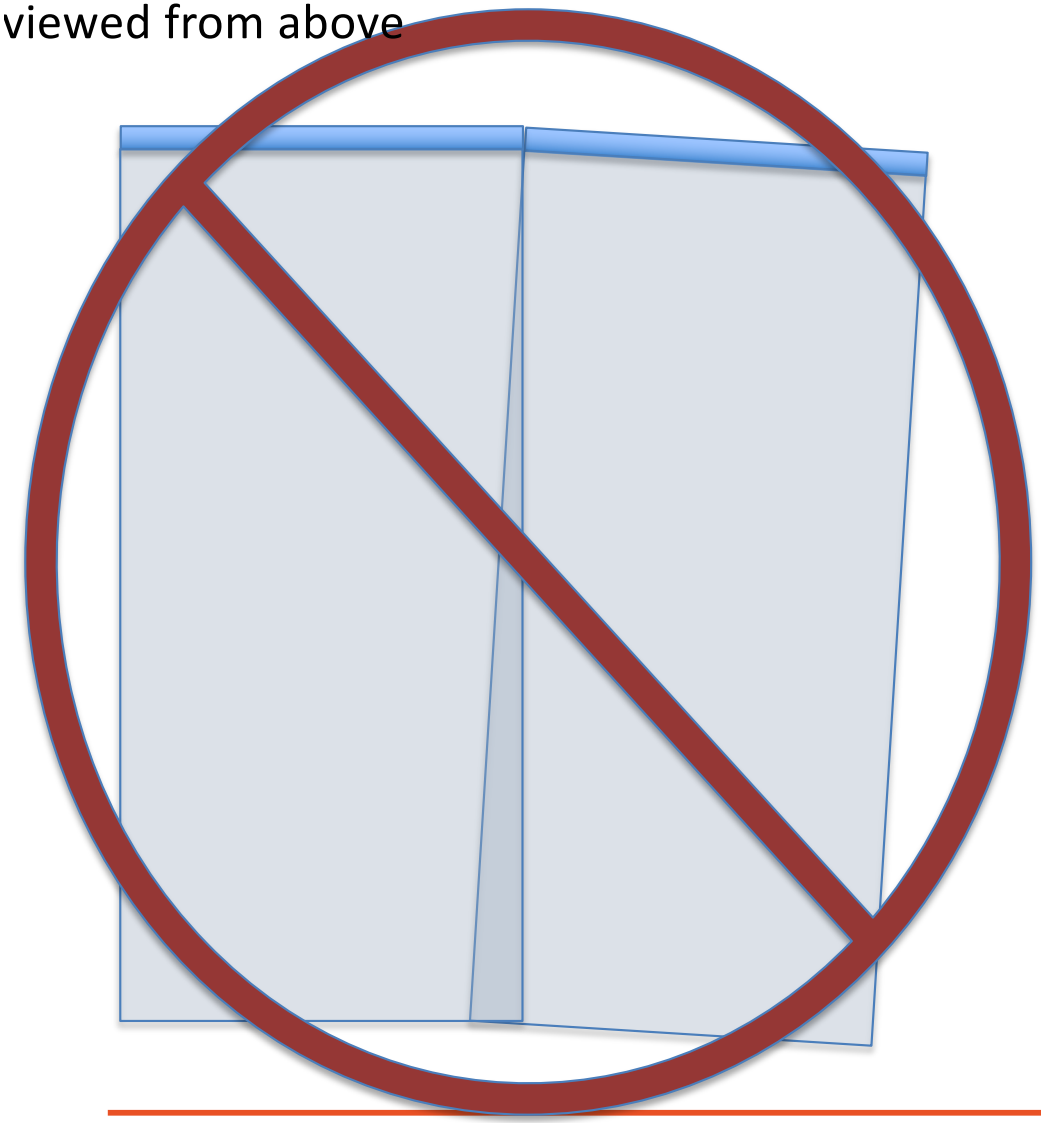


Status and Plans

- Analysis developed as a ROOT macro using gallery.
  - convenient, since it runs in an environment where adding a plot and iterating to see what's going on is quick.
- Some shortcuts taken (no geometry service for example, so APA boundaries hard-coded in). Configuration parameters not input nicely. Could be made into an art module.
- Sanity check – pretend the gaps are in the *middle* of an APA and fit for distortions. They should be zero.
- Need to figure out what the biases and uncertainties are
- Only studied (Δx, Δz) for four gaps, assuming constant (Δx, Δz) as a function of *y* for each gap.
- Measure Δy and rotations. Six parameters per APA.
- Some combinations of parameters will be poorly constrained (e.g. distance between beam-left and beam-right APA planes), at least with this method.
- Help is welcome! Patrick Tsang has expressed interest. I wanted to clean up my script and remove egregious bugs first – done!

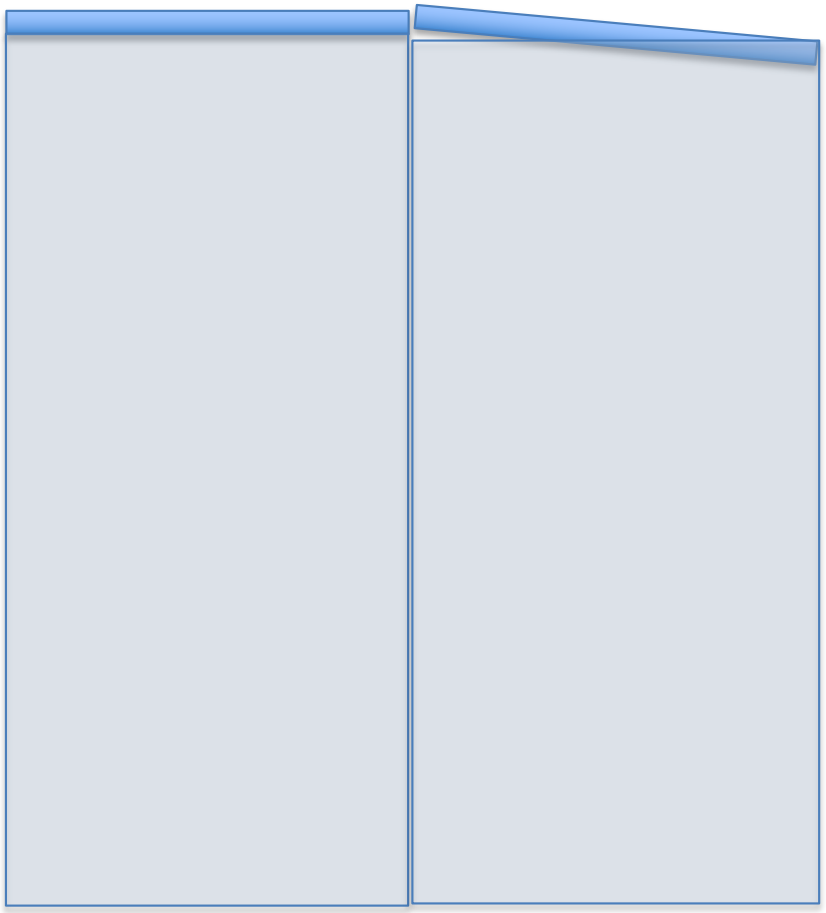
Effect on the Drift Due to Rotations

viewed from above



Electrons should still drift mostly in the *x* direction, but have their arrival times distorted.

position distortions may be more noticeable for tracks that go near the APA's



Effect on the Drift

- Field distortions due to misaligned cathode and anode planes are expected to be localized near the distorted element.
- Go far away from the distorted panel/APA, and the field should be asymptotically uniform. May need to do a calculation to see just how local this is
- But – electron arrival time distortions occur for charge drifting from anywhere in the drift volume due to field distortions at the anode
- And cathode field distortions only affect tracks close to the cathode.

A Project to Estimate the impact on physics

Maggie Greenwood has started this task.

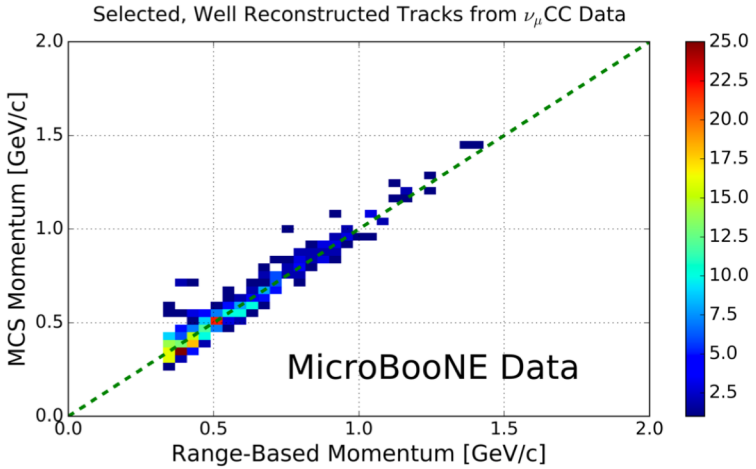
- Need a hit-shifter module
  - Inputs a collection of hits (e.g. GausHitFinder) and outputs shifted hits
  - Easiest distortions – just change the hit times based on hit position
  - More difficult distortions – change channel numbers
  - APA Rotations about the Y axis: Delta-t is a function of Z
  - APA rotations about the Z axis: Delta-t is a function of y
  - APA rotations about the X axis: No Delta-t but hits move from one channel to another.
  - "Crumple" mode is plausible – vanishing steps in position but angles are offset.
  - Need to use the BackTracker to get the (x,y,z) position of the charge that produced the hit in order to figure out what Y is.
  - Consistently shift hits in all three views so the 3D reco isn't tripped up artificially
- Run reco on shifted hits.
  - Some reco algs adjust hits (only using hit info or do they go back to recob::Wire?)
  - Find new residuals for MCS muon momentum. Biased and wider.
  - See how much the CVN veCC selection efficiency/energy reco is affected

Extras

Connection to physics:

Muon Momentum from Multiple Scattering

- Recent examples:
  - ICARUS: https://arxiv.org/abs/1612.07715 (JINST 12 (2017) no.04, P04010)
  - MicroBooNE: https://arxiv.org/abs/1703.06187 (JINST 12 (2017) no.10, P10010)



Selected beam neutrino-induced muon candidate tracks

- A DUNE FD module is 12 meters top to bottom, taller than MicroBooNE is long. 2.5 GeV muon or less will stop in DUNE.

APA Alignment Pin and Slot

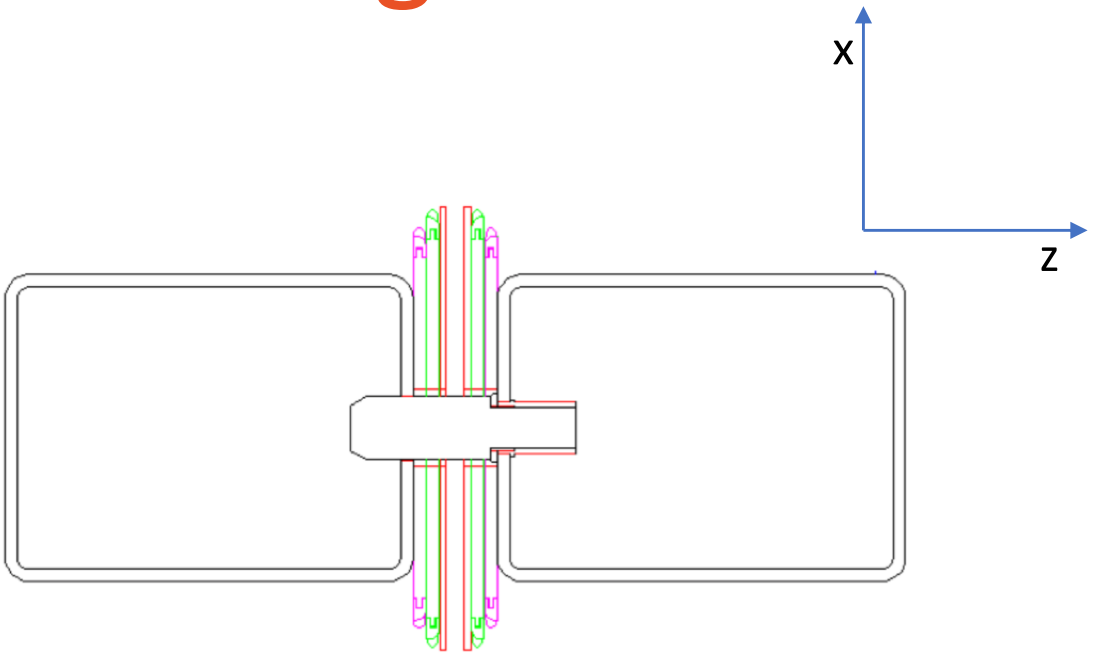
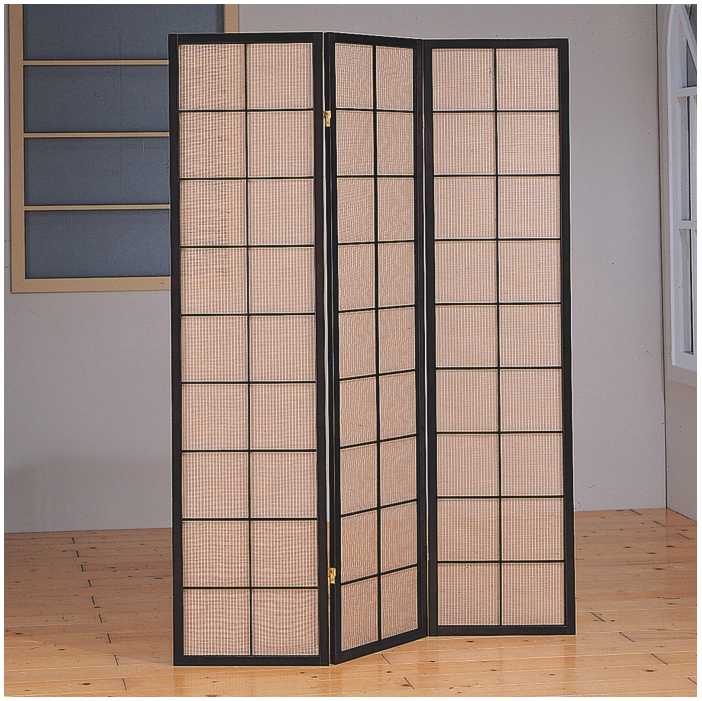


Figure 2.12: The pin/slot constraint. The pin screws into an insert in the outside frame member of one APA and engages a slot in the outside frame member of the adjacent APA.

Might have some constraint on this sort of distortion



- From the ProtoDUNE-SP TDR

- Provides a One-Dimensional Position Constraint (X but not Y or Z, unless they are locking).
- Provides a One-Dimensional Angular constraint if the slot is tight (roll in the above picture)
- A series of pins provides an additional angular constraint (pitch)
- On the figure above, roll and pitch are constrained but not yaw.
- Manufacturing tolerances: With the pins engaged, wires can still be offset in ways we can measure.
- 35-ton Prototype was assembled without Alignment pins and slots

Other Difficult Distortions (FD)

View from top

Bent APA's: Will a "flat" APA stay flat when cold?

Bending of APA's:

- More difficult with cosmics than steps at the gaps
- Does not violate alignment pin constraints (others do, but manufacturing imperfections can result in systematic offsets)
- Multiple scattering means that single tracks cannot be relied on to extract bending information. A large ensemble of them might be able to tease something out. But more z coverage per track helps.
- Or just a slightly crumpled curtain: -- Also: Vertical crumple mode? What holds the bottom of the bottom APA in place?

What is the magnitude of this that would escape our notice? +- 1 cm/APA perhaps?

An Elaborate Example: CMS muon tracker

http://arxiv.org/abs/0911.4022

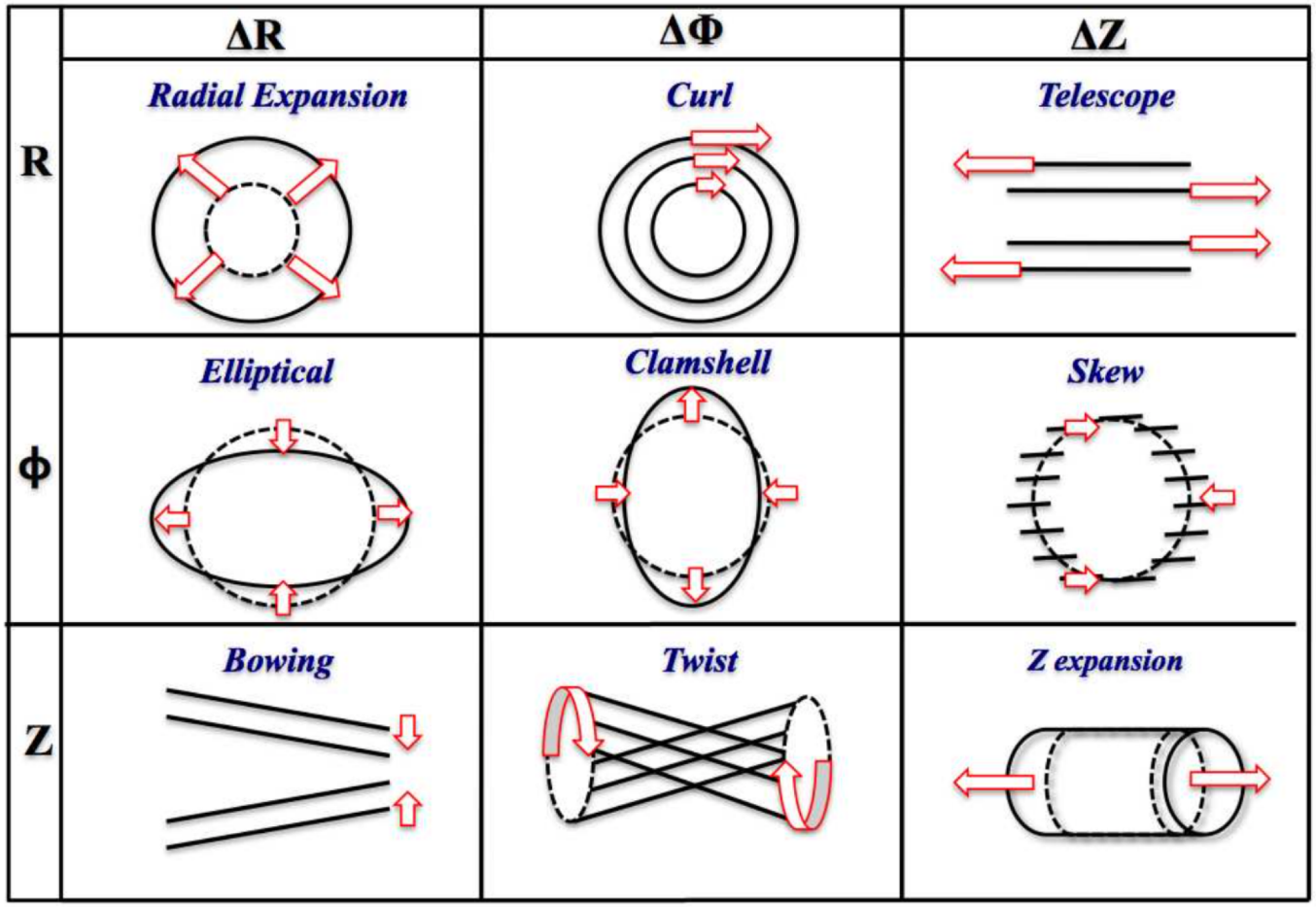
Essentially a sum of track-fit chisquareds as a function of alignment parameters (offsets and angles). Add to that survey constraints which keep the fit from wandering off in "loose" directions.

$$\chi^2 = \sum_{i}^{\text{layers}} \sum_{j}^{\text{tracks}} \left(\Delta\vec{x}_{ij} - A_j \cdot \vec{\delta}_i - B_i \cdot \delta\vec{p}_j\right)^T (\sigma_{\text{hit}}{}^2)_{ij}^{-1} \left(\Delta\vec{x}_{ij} - A_j \cdot \vec{\delta}_i - B_i \cdot \delta\vec{p}_j\right)$$

$$+ \sum_{i}^{\text{layers}} \sum_{k}^{\text{targets}} \left(\Delta\vec{\xi}_k - C_{ik} \cdot \vec{\delta}_i\right)^T (\sigma_{\text{survey}}{}^2)_k^{-1} \left(\Delta\vec{\xi}_k - C_{ik} \cdot \vec{\delta}_i\right) + \lambda \left| \sum_{i}^{\text{layers}} \vec{\delta}_i \right|^2 , \quad (1)$$

The total chisquared is quadratic in its parameters and minimizing it is a matrix inversion.
Another method in the paper uses non-Gaussian constraints and runs MINUIT.
Some hints at selecting well-formed track segments may be clues of things we have to do too.
This example has only two displacements and two angles per rigid detector piece due to the strip geometry. We'll probably do ours in 3D.

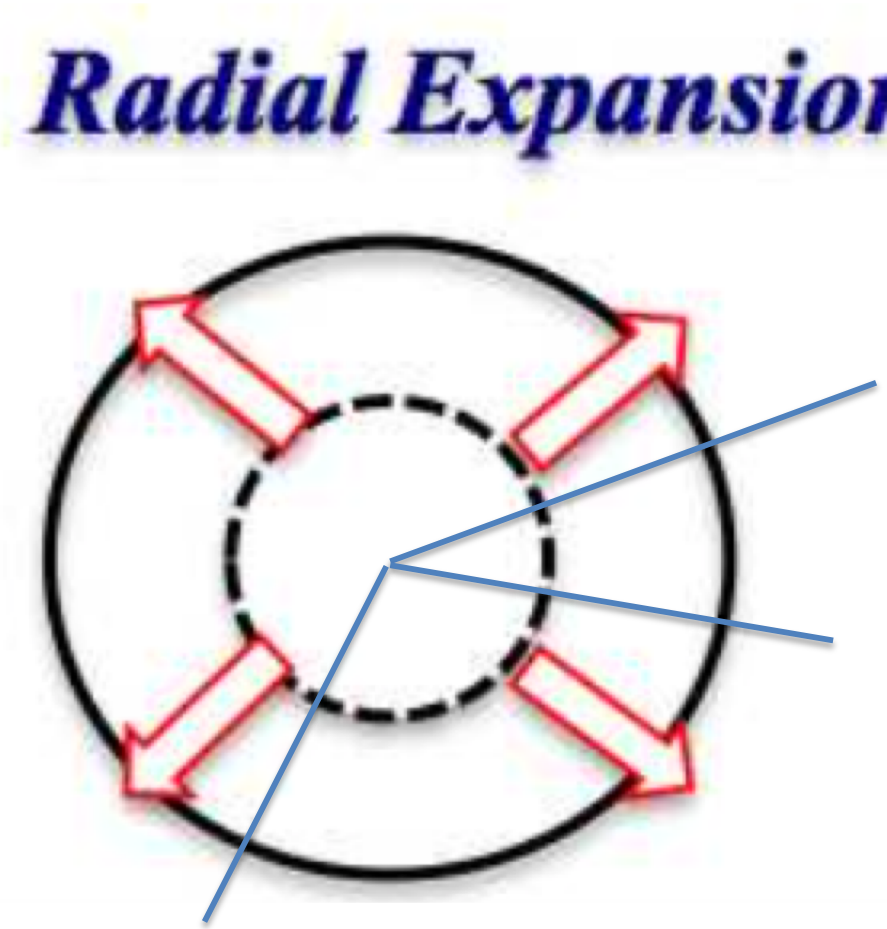
Examples of "Weak" Directions (ATLAS alignment)



From Moles-Valls' thesis.

Figure 4.4: Schematic picture of the most important weak modes for the ATLAS Inner Detector barrel.

Example: Radial Expansion is a Weak Direction

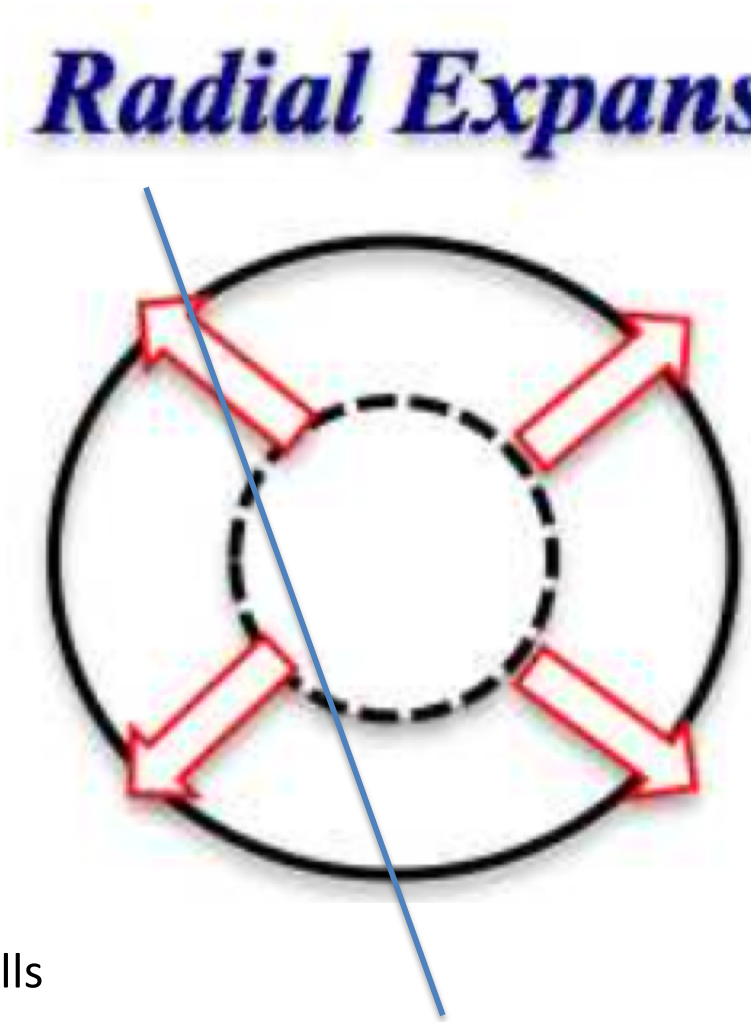


Tracks from the center of the detector don't constrain the radial size of the detector.

Expand the detector, and all the hits still fit!

Moles-Valls

Extra Constraint from Cosmics



These tracks are no longer straight when you expand the detector.

Moles-Valls

Requirement from Astronomy

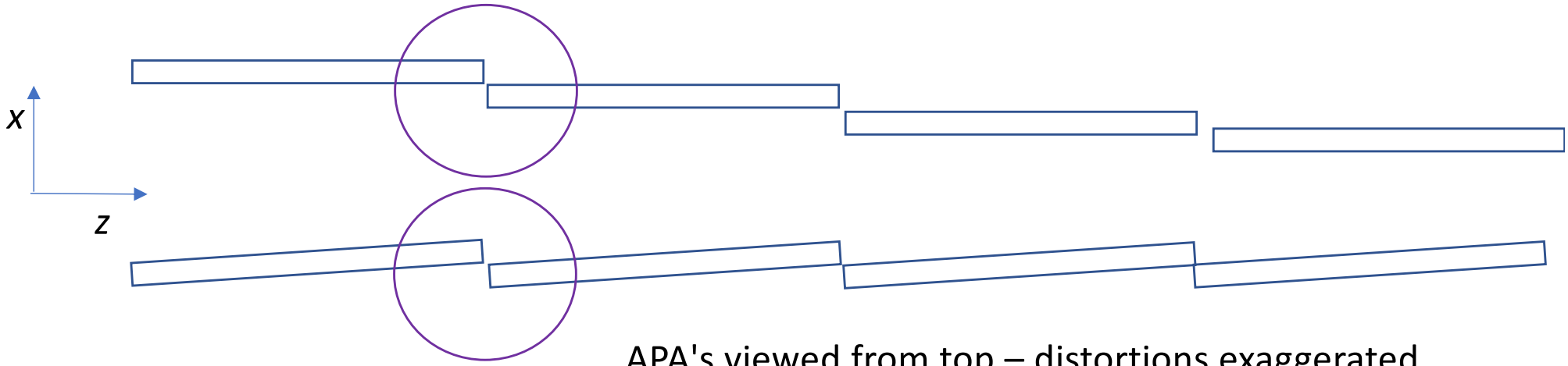
- Ice Cube's very nice very-high-energy muon from an astrophysical neutrino was pointed at a blazar with 0.5 degree accuracy
- Absolute orientation of detector elements at this level is important if we want to play this game
- Ice Cube or Hyper-K may win just based on size, but we have finer segmentation, so maybe we can win in some way that depends on that.

A Tool from Andrzej

- Andrzej Szelc says he has started on a simple tool to simulate misalignment in LArSoft. Most of the hooks are in a private branch.
- Not ready until second half of August (coming soon).
- We will need the flexibility to inject plausible misalingment scenarios. (6x150 parameters just for the APA's, but many combinations of these will be constrained with cosmics).

Local vs. Global Alignment

- We measure gap offsets in *x* and *z* easily.
- But muons only sample a small amount of *x* and *z* at a time – mostly travel in the *y* direction.
- How to tell these kinds of distortions apart with cosmics? Cosmic rays sample local patches of (*x*,*z*) and are best at seeing step discontinuities

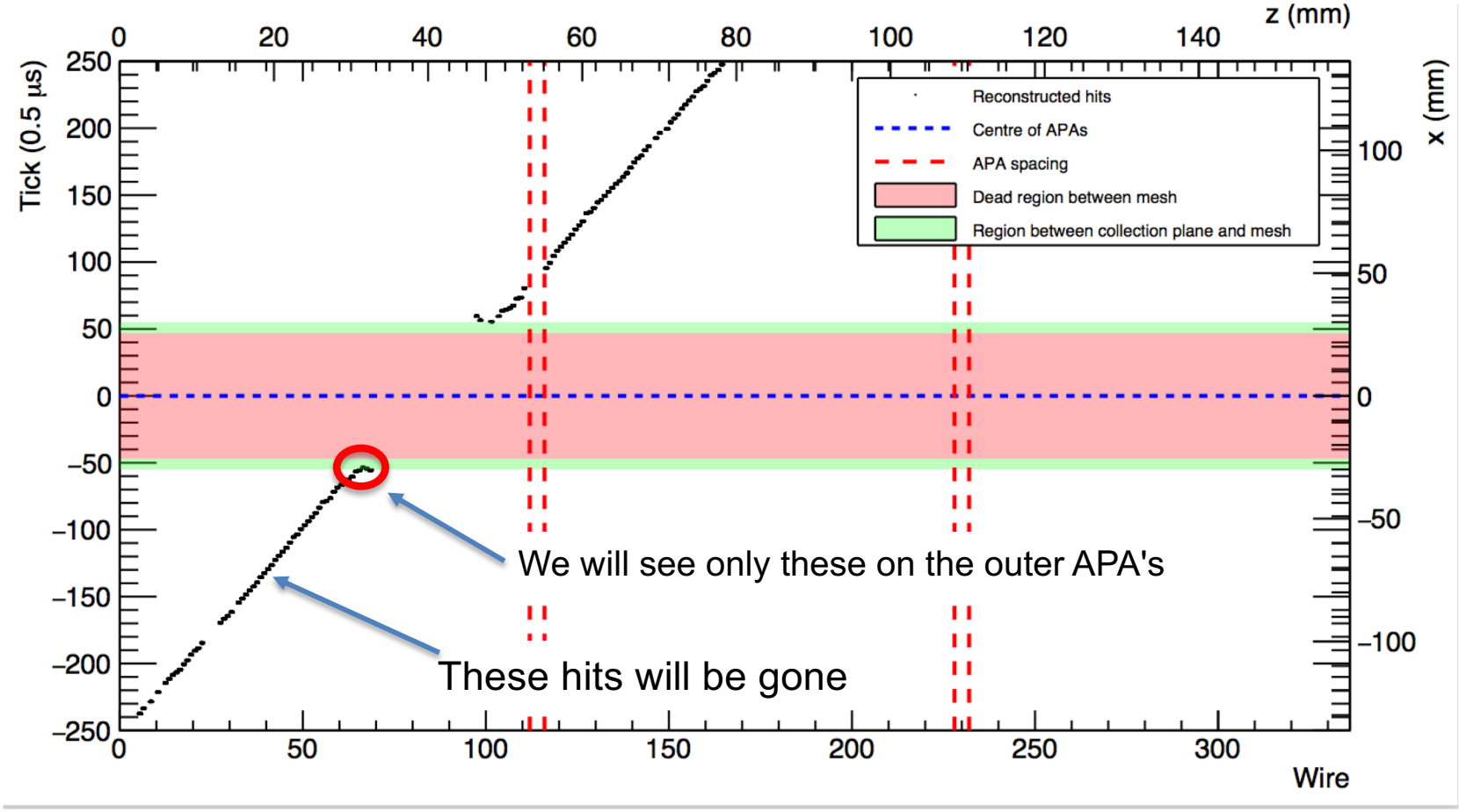


APA's viewed from top – distortions exaggerated

steps: tens of microns of precision. Angles – less so

Outer APA's Contribution (ProtoDUNE-SP) and FD

- With a mesh, you get a couple of hits on the far side



Measuring Angles

- What if the gaps between the APA's aren't of uniform width?
- What if the offsets along the drift field direction (*x*) vary with height (*y*)?

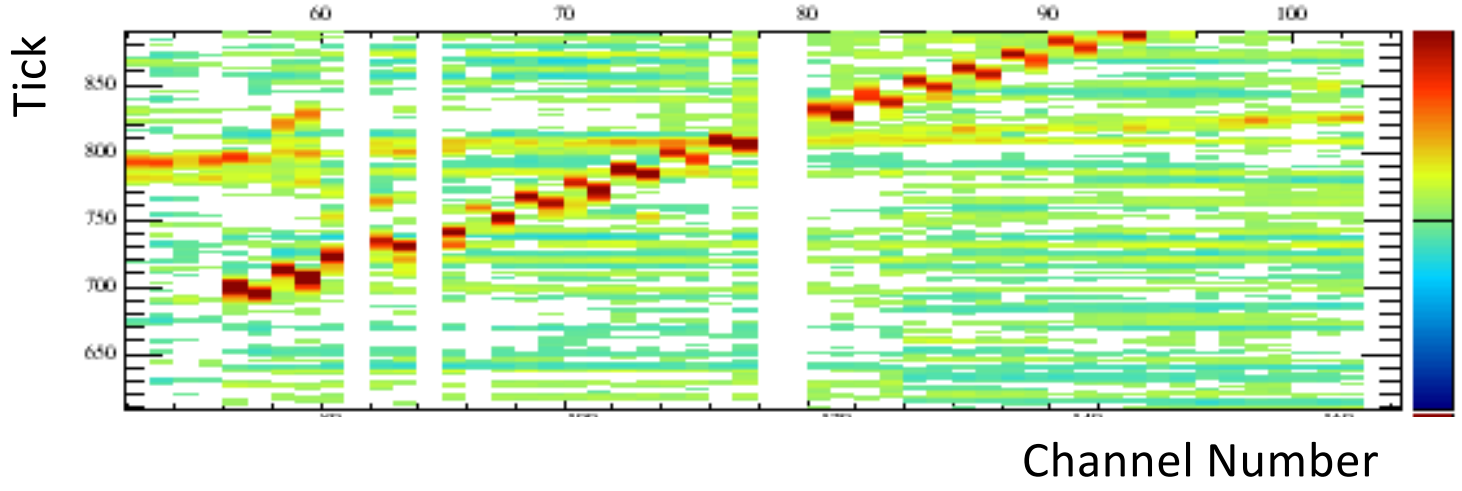
Repeat analysis in bins along *y* for each gap. Approximate analysis with two bins with centers 3 m apart and uncertainties for half as many tracks in each:

$$\sigma\left(\frac{d\Delta z}{dy}\right) = \frac{\sqrt{2}\sigma_{\Delta z}(N_{\text{tracks}}/2)}{3\text{ m}} \approx \frac{1.19\times10^{-3}}{\sqrt{N_{\text{tracks}}}}$$

$$\sigma\left(\frac{d\Delta x}{dy}\right) = \frac{\sqrt{2}\sigma_{\Delta x}(N_{\text{tracks}}/2)}{3\text{ m}} \approx \frac{3.89\times10^{-4}}{\sqrt{N_{\text{tracks}}}}$$

Validating/Fixing the Channel Map

- Some flaws in the channel map are obvious once you have straight tracks.
- Example from 35-ton running: even and odd collection-plane channels were swapped (ribbon cable?)
- Not the only possible flaw. If we get all the channels backwards, straight tracks may still look straight.
- Swap U and V views – can test with timing.

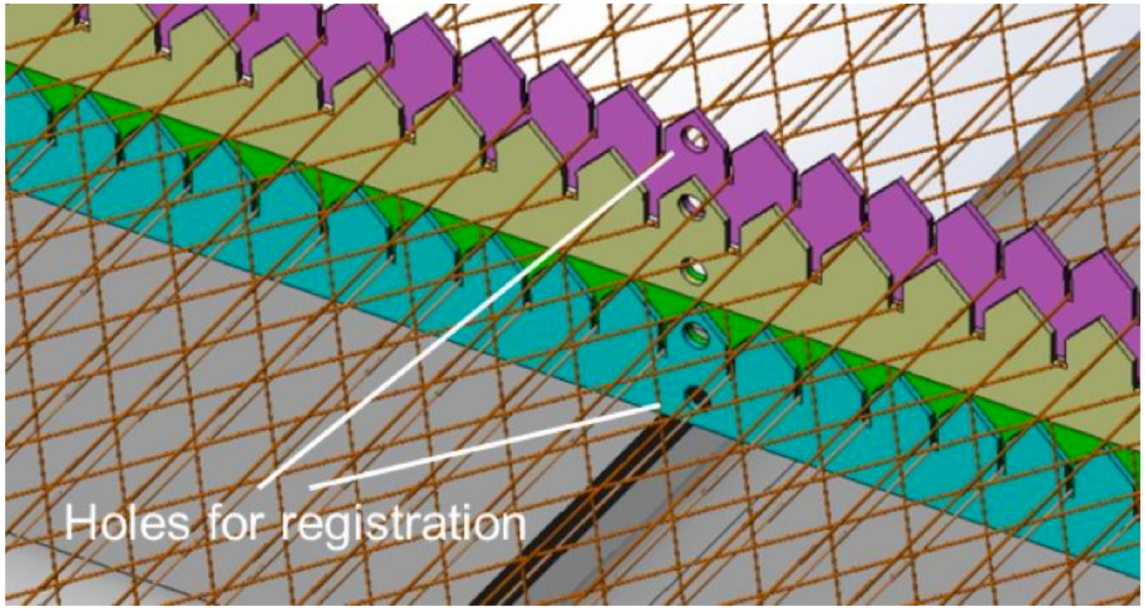


Status

- I started looking at the MUSUN sample using Gallery.
  - Fully simulated and reconstructed
  - DUNE single-phase FD module
  - Indexed here: http://dune-data.fnal.gov/mc/mcc9/index.html
- Starting approach
  - Parameterize APA alignment parameters in terms of *x*, *y*, and *z* offsets, and roll, pitch, and yaw angles
  - Drift is always along the nominal *x* axis, even if the APA is rotated (pitch and yaw are assumed not to affect the drift direction)
  - Rotations are around the APA center point. Roll: around *x*, Pitch: around *z*, Yaw: around *y*
  - look at PMTRACK's space points
  - Identify strings of space points on either side of horizontal or vertical gaps ⟸ I got to here
  - Fit a 3D line to space points and require chisquared/DOF not to exceed a cut.
  - match up strings on either side of a gap
  - fit a 3D line to the pairs and add chisquareds together.
  - Explore the chisquared sum as a function of the APA alignment parameters. See which coordinate combinations are well constrained and which aren't

Wire Sag

Support combs placed so that the maximum unsupported run is 1.6 m.

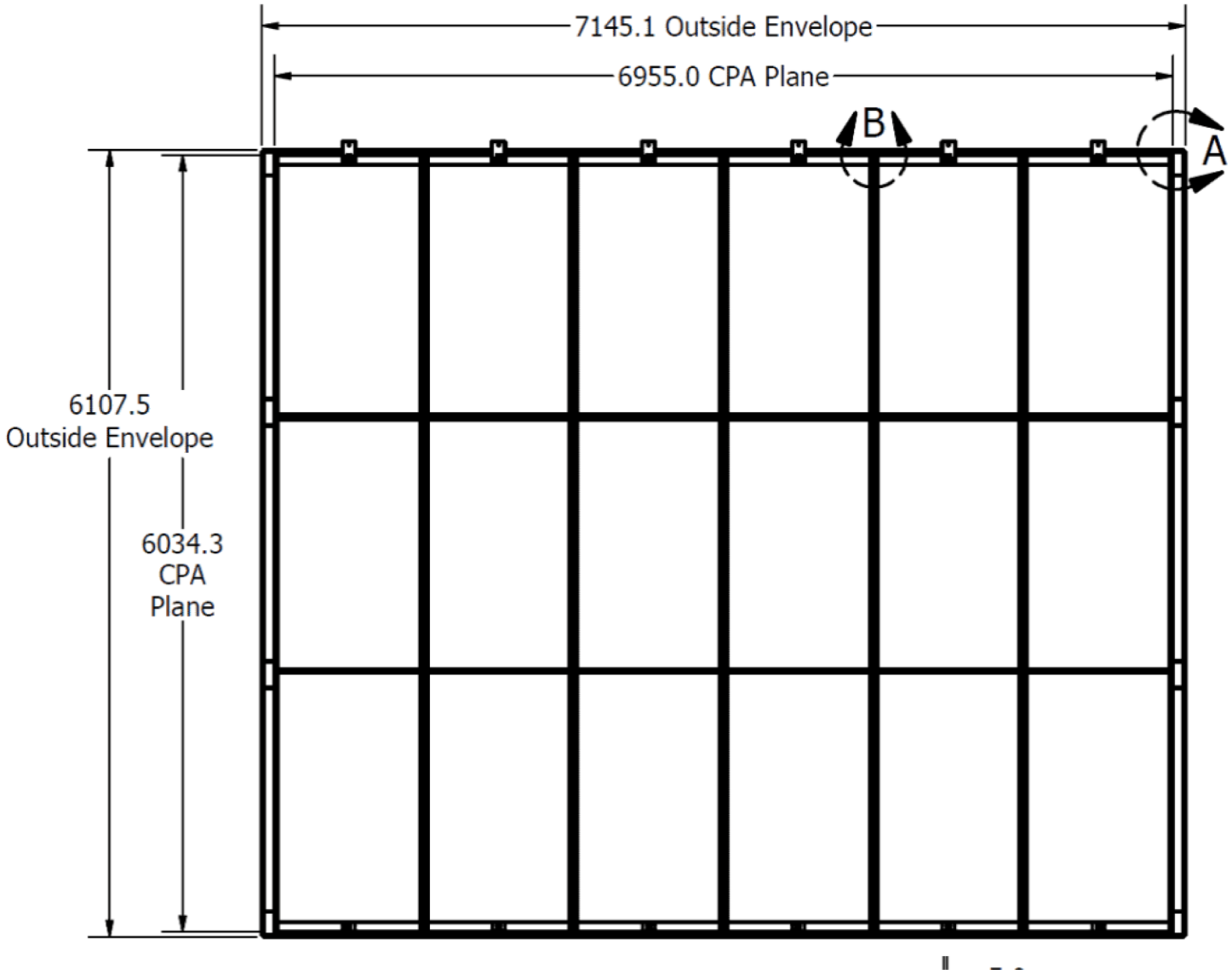


ProtoDUNE-SP TDR

The nominal wire tension is 5 N but even the 1.6-m-long wires could fall to 3 N of tension before the wire, held horizontally, would deviate 150 microns – one wire diameter. During operation the wires are either vertical or 35.7° from vertical, so the actual deviation would be less.

Ed. comment: Thermal expansion of comb vs. APA frame could cause deviations larger than 150 microns

A Test Pattern on the CPA



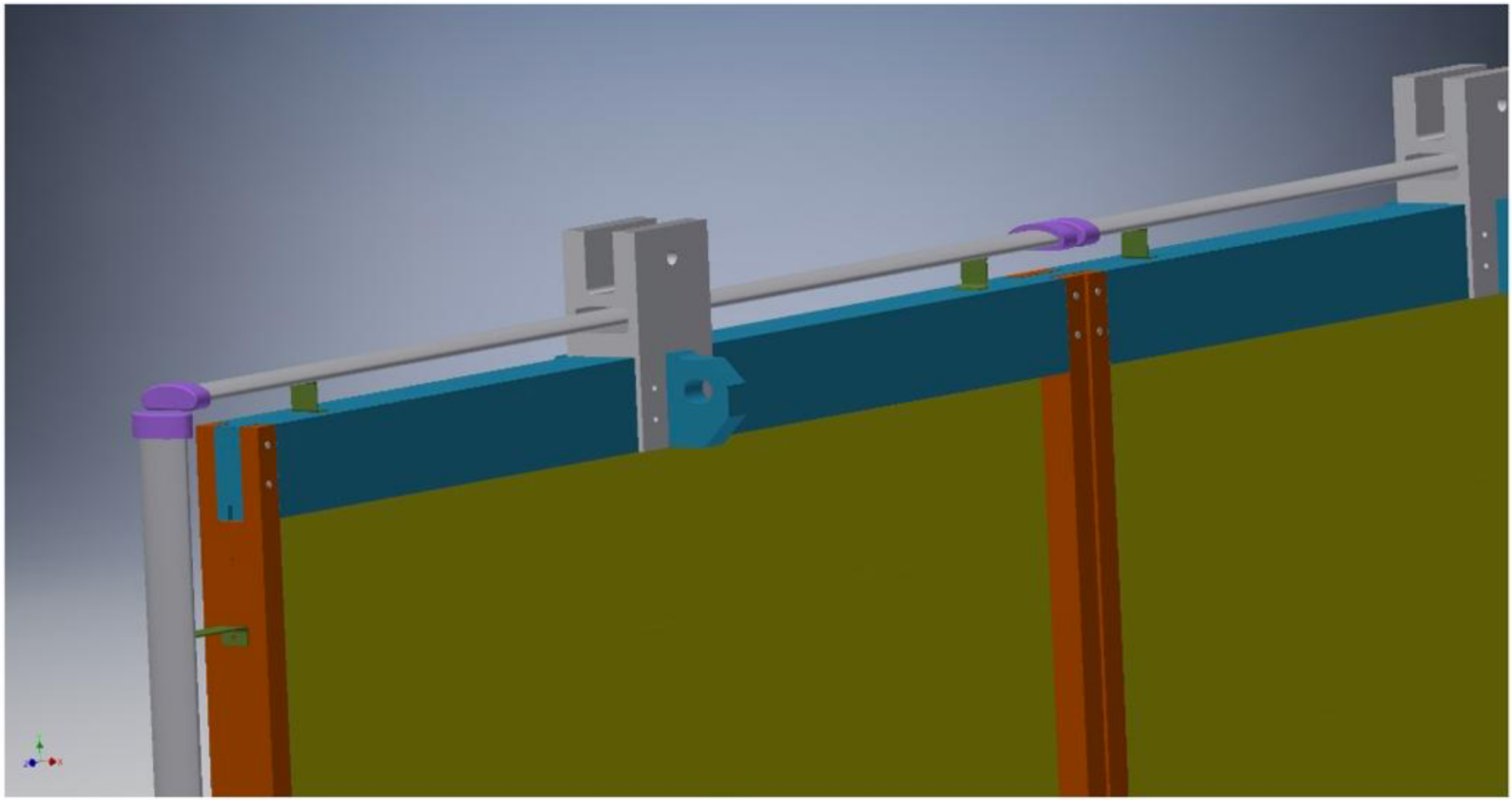
Can we "X-ray" the frames with tracks?

Look for gaps in CPA-crossers

The reco image will tell us about space charge

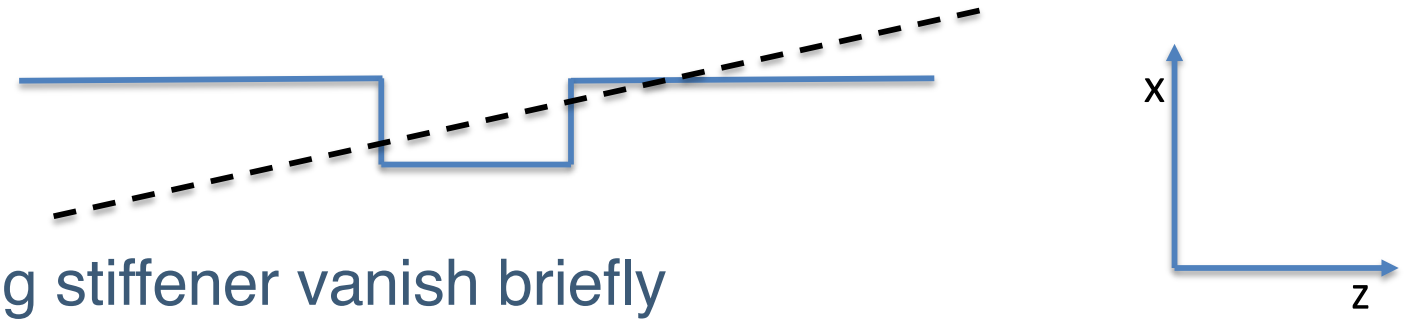
CPA Geometry

Stiffner bars protrude about 1 inch into the drift volume.
Resistive strips shapes the field so they don't distort the field.



CPA Stiffener Bars/Panel Frames

- Built into the 35-ton CPA
- S/N not adequate to do detailed studies of hits near the CPA in 35-ton – hit efficiency tailed off



- Tracks crossing stiffener vanish briefly
- Low-field region in concave corners -- less charge produced
- Can be used as a fiducial mark for space-charge distortion measurements. Can make an image of this at the anode?
- But you need lots of tracks passing through the bars. ProtoDUNE but not DUNE perhaps...