TPC Alignment

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Workshop on Calibration and Reconstruction for LArTPC Detectors

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Introduction

- Large detectors are modular so we can build and assemble them

  My examples will come from DUNE (Far Detector, ProtoDUNE, 35t)

- "As-Built" components are close to, but not exactly at their nominal locations.

- Detector designers want requirements on tolerances.
  - Nominal gaps between components
  - Tolerances on differences between as built and nominal

- Detector is cooled down and filled with LAr
  - Components shrink and move
  - Not every piece may move the same amount. This is by design.
  - We need the (relative) locations and orientations of operating components.

Introduction

- Reconstruction in 3D space is relative to anode wire locations
- Field map is needed to interpret 2D information
- Measuring muon momentum from multiple scattering would give incorrect results if anode locations or field maps are not as assumed.
- Charge loss in gaps between Anode Plane Assemblies (APAs) depends on the size of the gaps
- May need to make fiducial volume cuts around gaps if we cannot reconstruct the primary vertex and the 2.5 cm of track/shower if it is in or near a gap.
- Source of systematic uncertainty. Need to calibrate and estimate uncertainties.

Alignment with Cosmic Rays

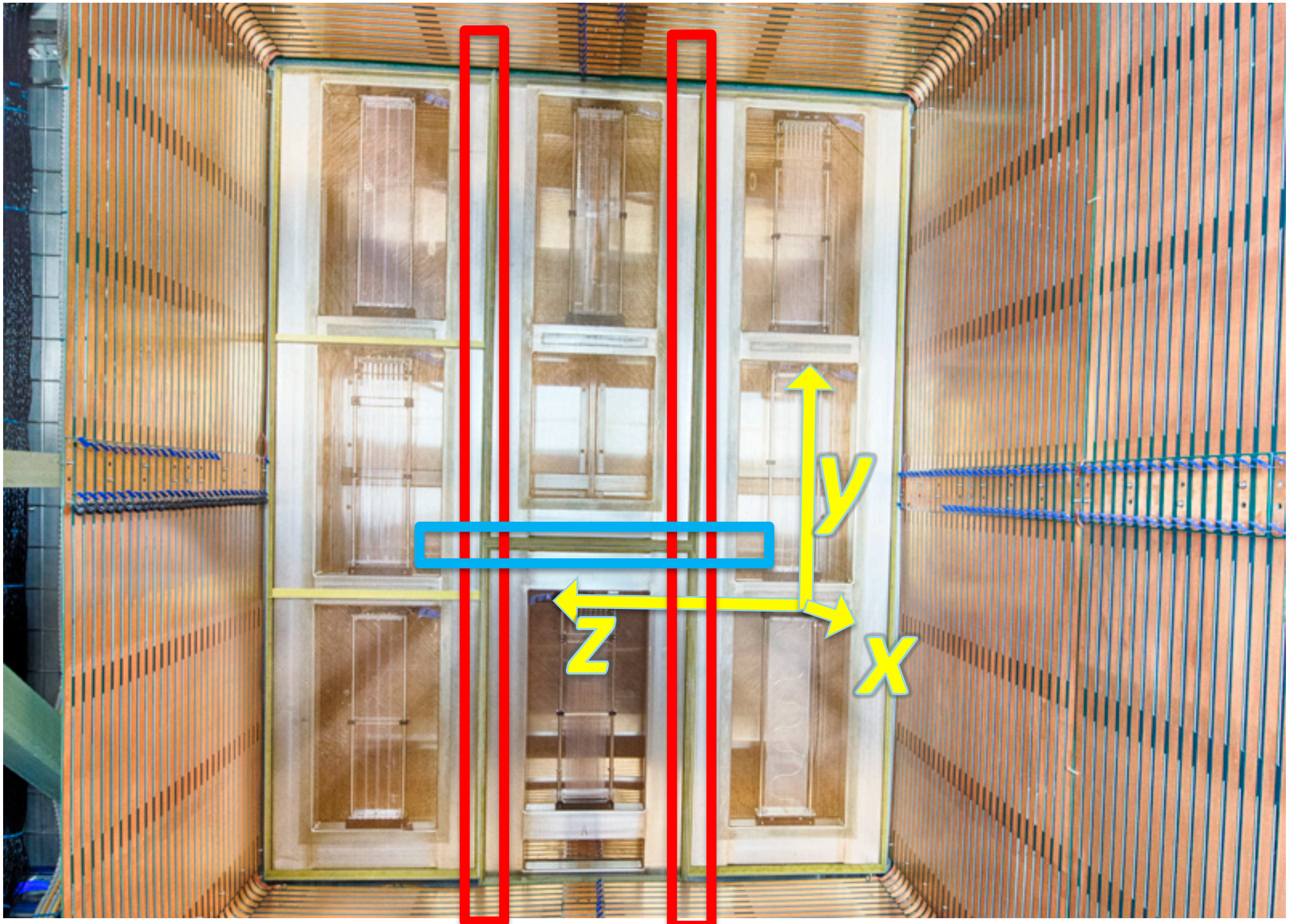
- Tracks that ought to be straight will not appear to be straight when reconstructed if the detector components are shifted or rotated with respect to their nominal positions.
- Relative positions and angles can be constrained, but not absolute positions.
- Some physics, e.g. multimessenger astronomy (Ice Cube's astrophysical neutrino → blazar) requires exquisite absolute alignment (0.5 degree).

Collider Detector Alignment 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"

35-ton APA Arrangement

Roughly cubical, ~2m on a side.



Z-Gaps in red

Horizont gap in blue

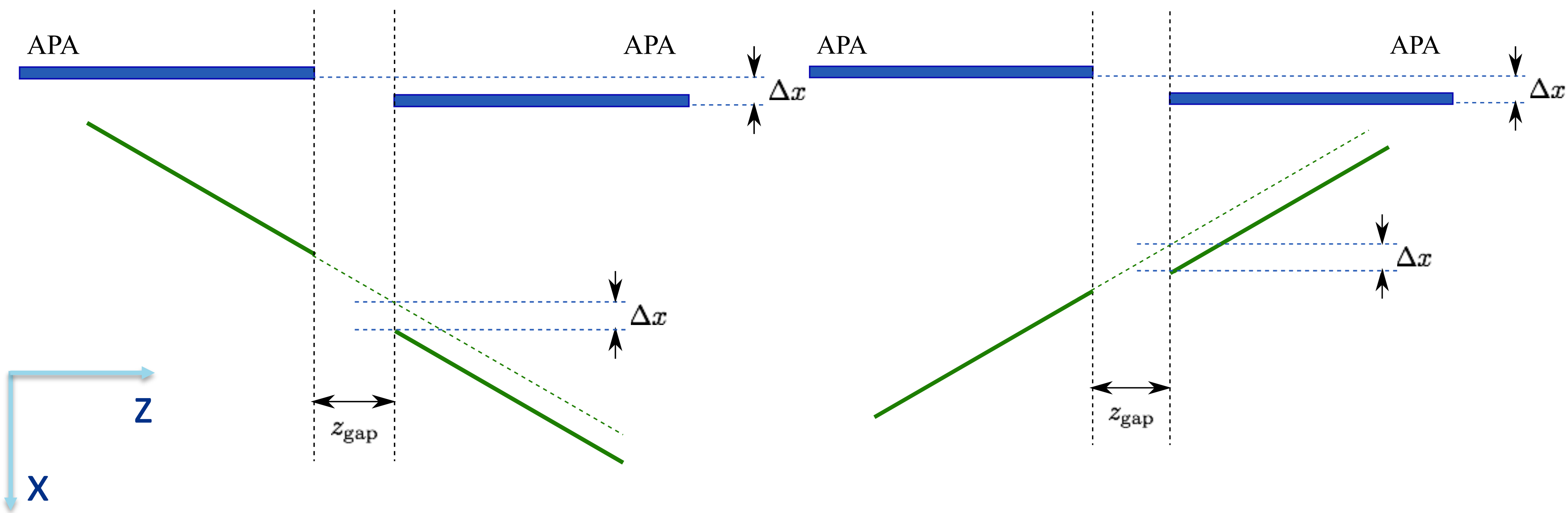
Alignment Constants we Expect to Measure well in DUNE

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)

Gap Measurement Strategy in 35t

- Select track segments on either side of the gap
- Track segments taken from hits between 1cm and 15 cm from a gap, with at least 10 hits
- Segment pairs must have an angle within 2 degrees of each other.
- Segments must have an angle steep enough to be able to constrain a gap parameter
- Summed chisquareds over segment pairs fit to lines, as a function of (dx,dz) from nominal.
- Only assumption: tracks are locally straight near a gap. Space charge is not a problem.

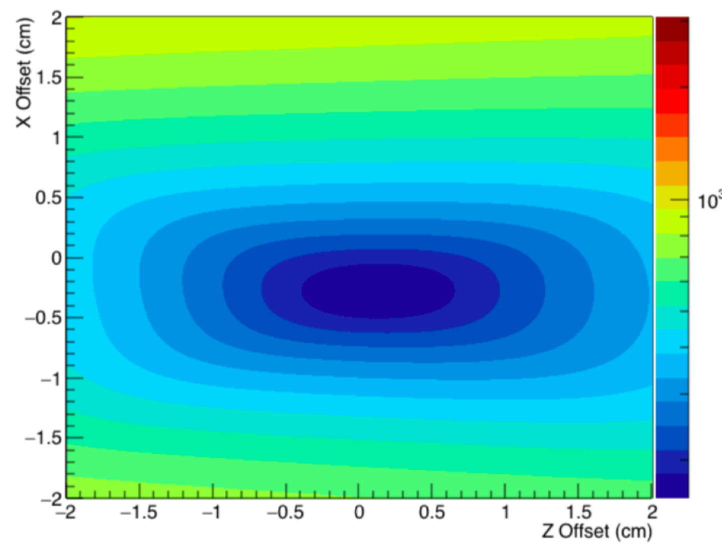


Fig. 7.14 The χ^2 distribution for all APA-gap traversing tracks in Δz-Δx space.

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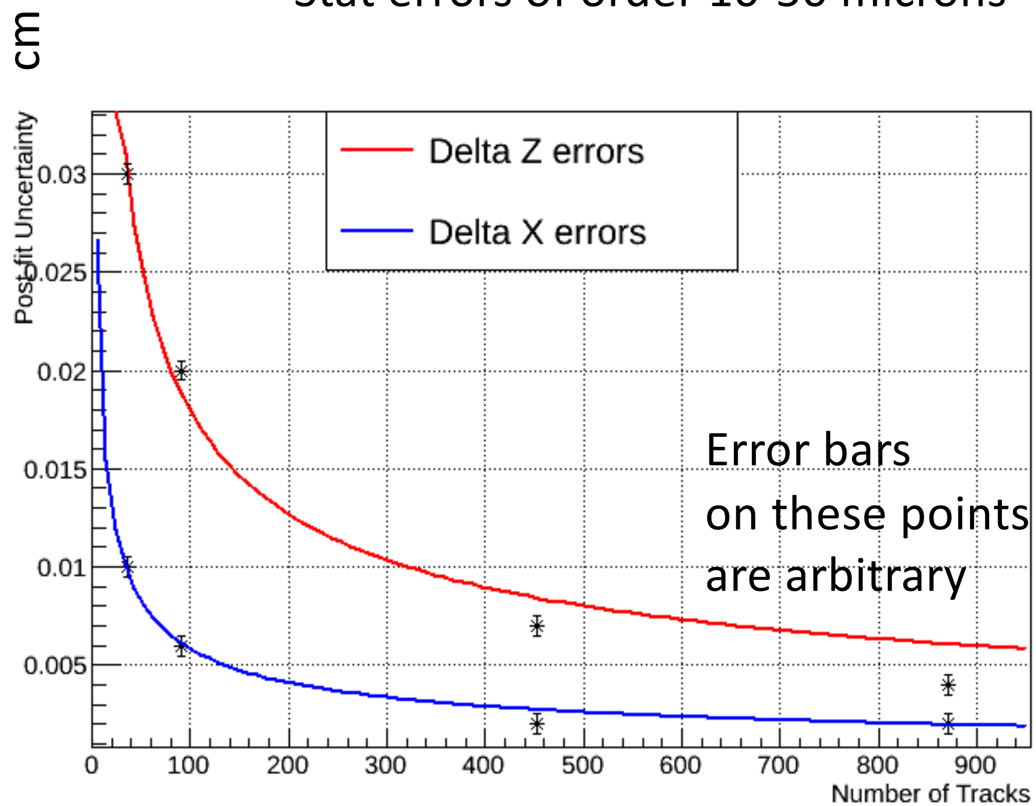
Vertical Gap Precision from 35t Cosmics

- 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



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Estimate of Angular Precision in the YZ plane

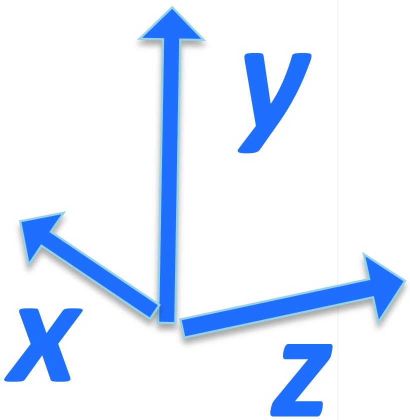
What if the gaps between the APA's aren't of uniform width?
What if the offsets along the drift field direction (*x*) vary with height (*y*)?

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:

$$\sigma\left(\frac{d\Delta z}{dy}\right) = \frac{\sqrt{2}\sigma_{\Delta z}(N_{\mathrm{tracks}}/2)}{3\ \mathrm{m}} \approx \frac{1.19\times 10^{-3}}{\sqrt{N_{\mathrm{tracks}}}}$$

$$\sigma\left(\frac{d\Delta x}{dy}\right) = \frac{\sqrt{2}\sigma_{\Delta x}(N_{\mathrm{tracks}}/2)}{3\ \mathrm{m}} \approx \frac{3.89\times 10^{-4}}{\sqrt{N_{\mathrm{tracks}}}}$$

ProtoDUNE-SP Layout



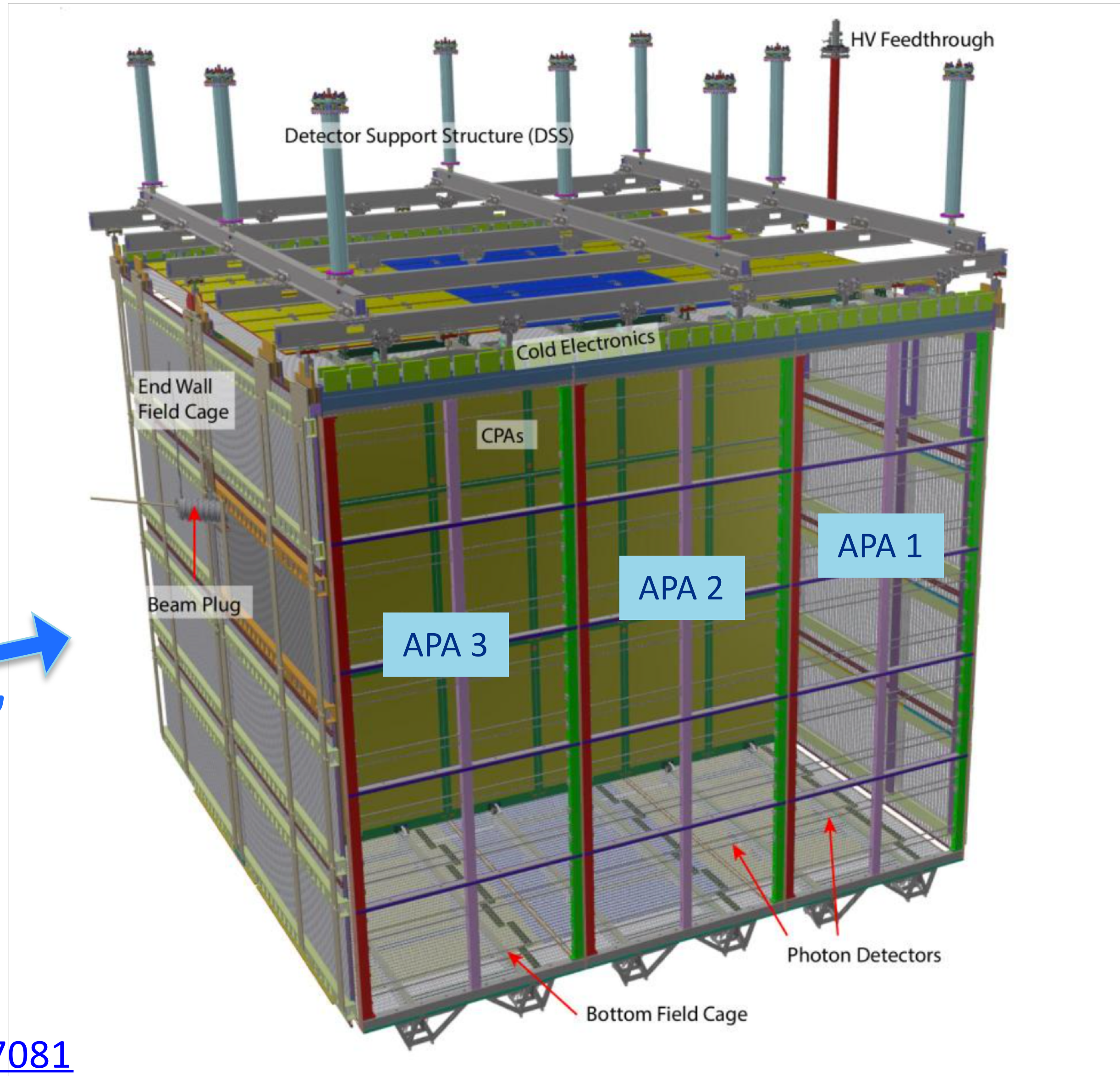


Figure 1.1: The major components of the ProtoDUNE-SP TPC.

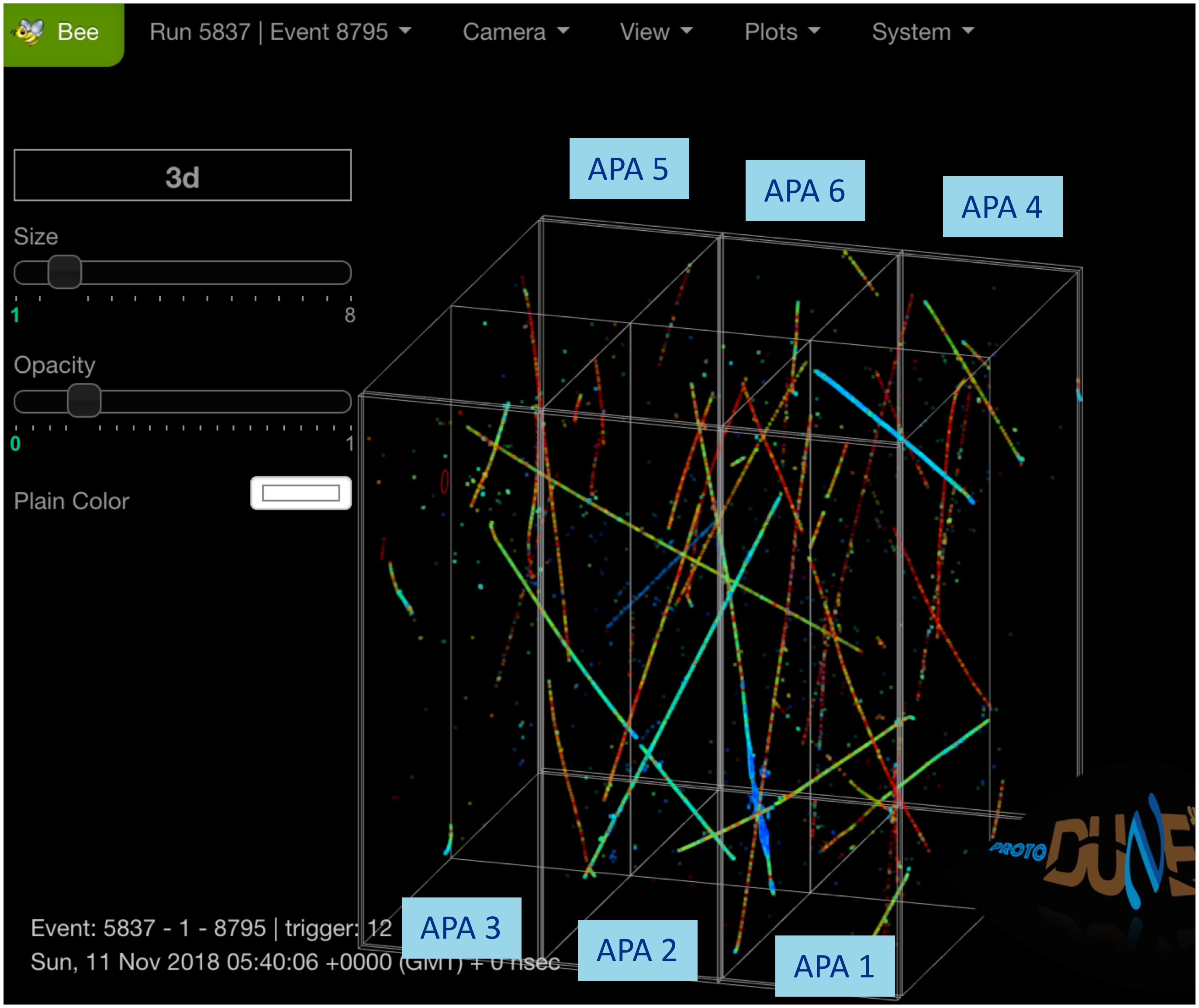
https://arxiv.org/abs/1706.07081
(ProtoDUNE-SP TDR)

A Typical Event in ProtoDUNE-SP

Bee event display by Chao Zhang and collaborators at BNL. Shows SpacePointSolver output in 3D

Time is arbitrary for cosmic rays.

3 ms readout time
~30-40 cosmic rays



ProtoDUNE-SP APA Alignment Pin and Slot

Provides some protection against this, but possibly not much

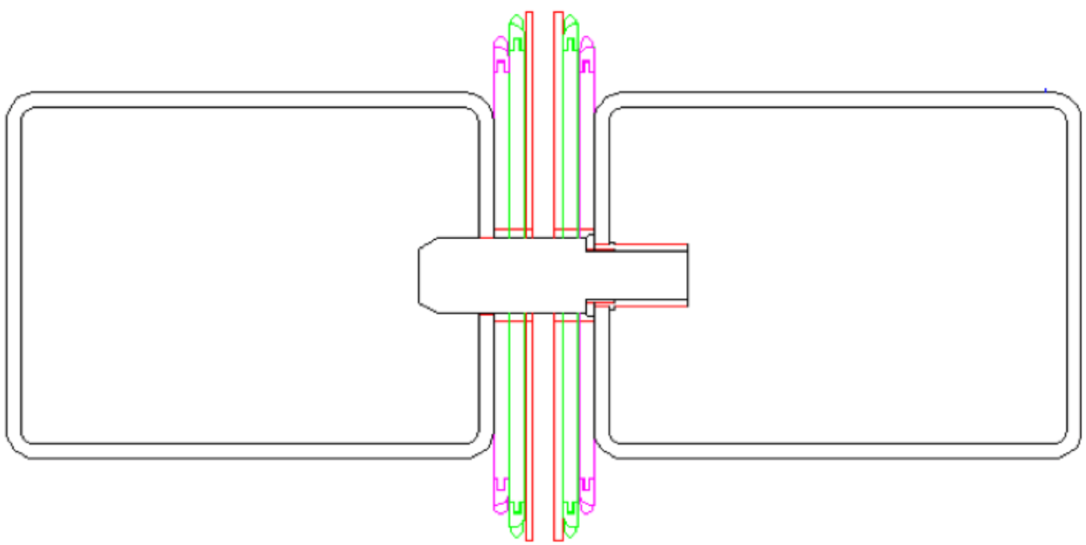
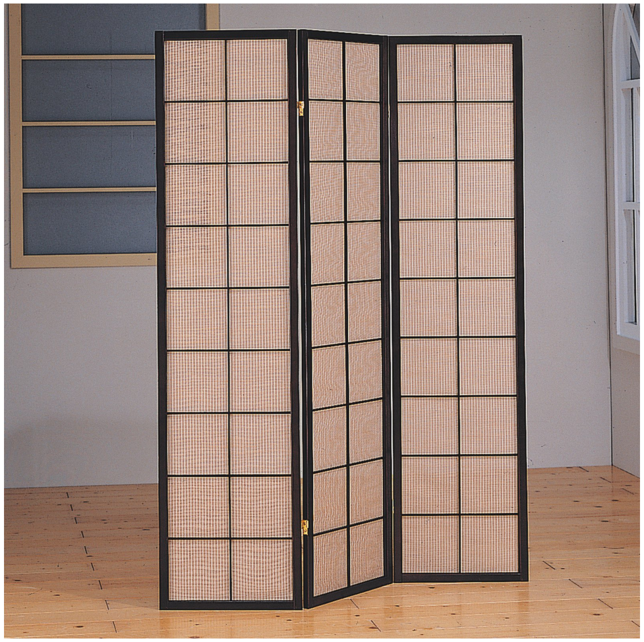
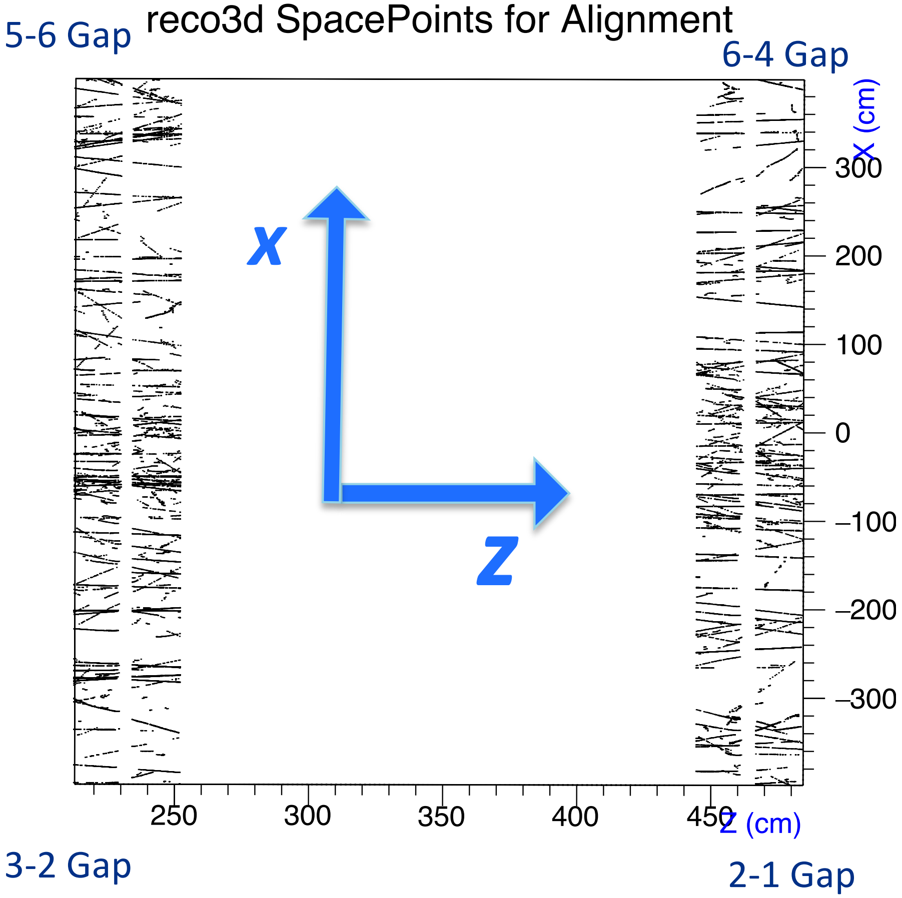


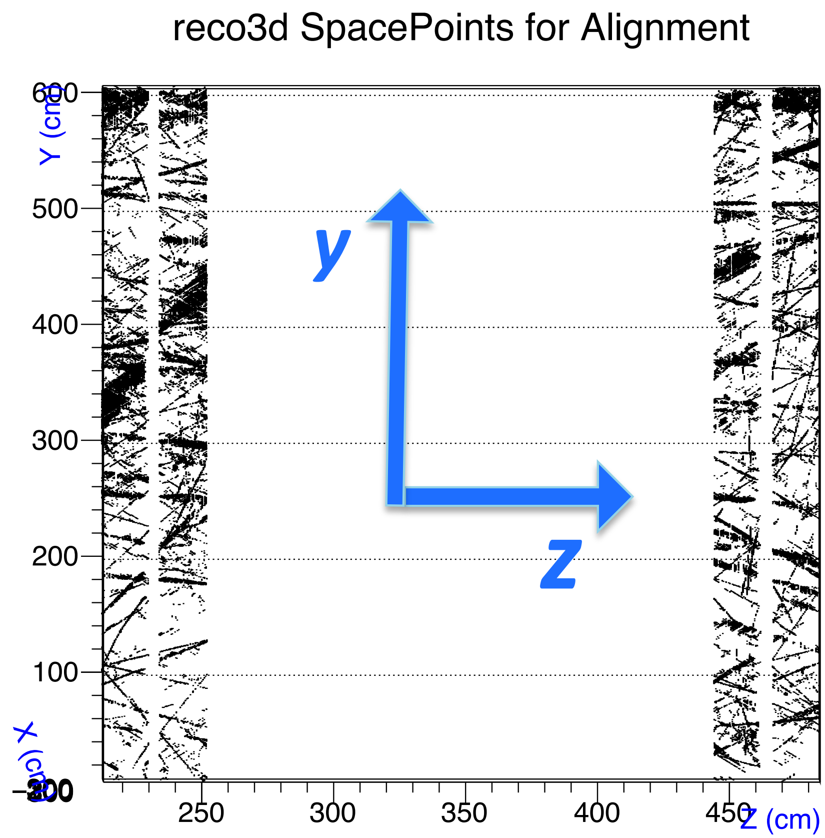
Figure 2.12: The pin/slot constraint. The pin screws into an insert in the outside frame member of one APA and engages a slot in the outside frame member of the adjacent APA.



All Stubs – One Data File from ProtoDUNE-SP

Select 3D space points for stubs: 1-20 cm from gap, must lie on a straight line.





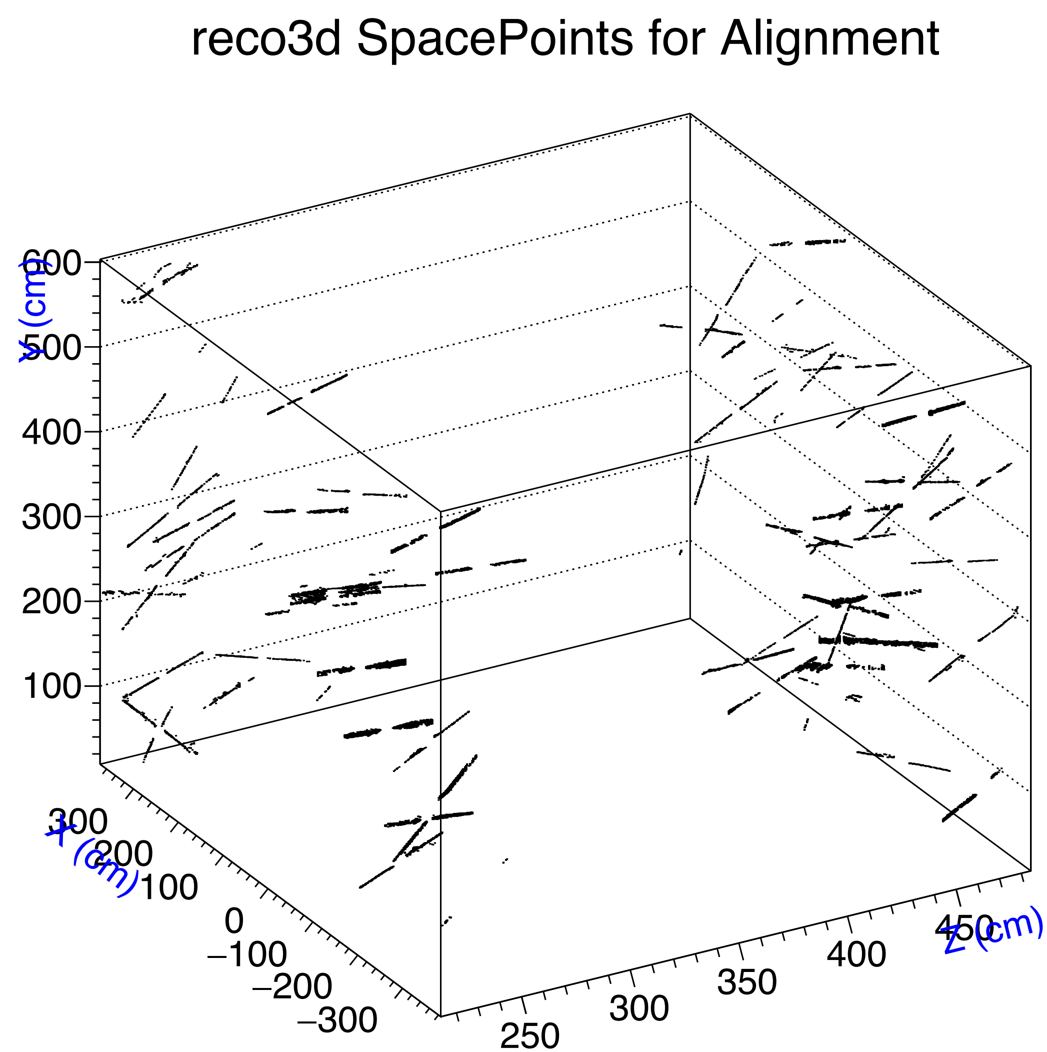
Each file contains ~41 triggers

Selected Stub Pairs

Stub pairs are associated with loose pointing miss-distance requirement.

One file's worth of data from Run 5177

Alignment strategy:
For each value of (dx, dz) distortion from nominal, re-fit the space points in a stub pair in 3D to a single line segment. Add up χ^2 for all stub pairs. Plot $\sum\chi^2$ as a function of (dx,dz)



Fit Results – One File, Diverters Off

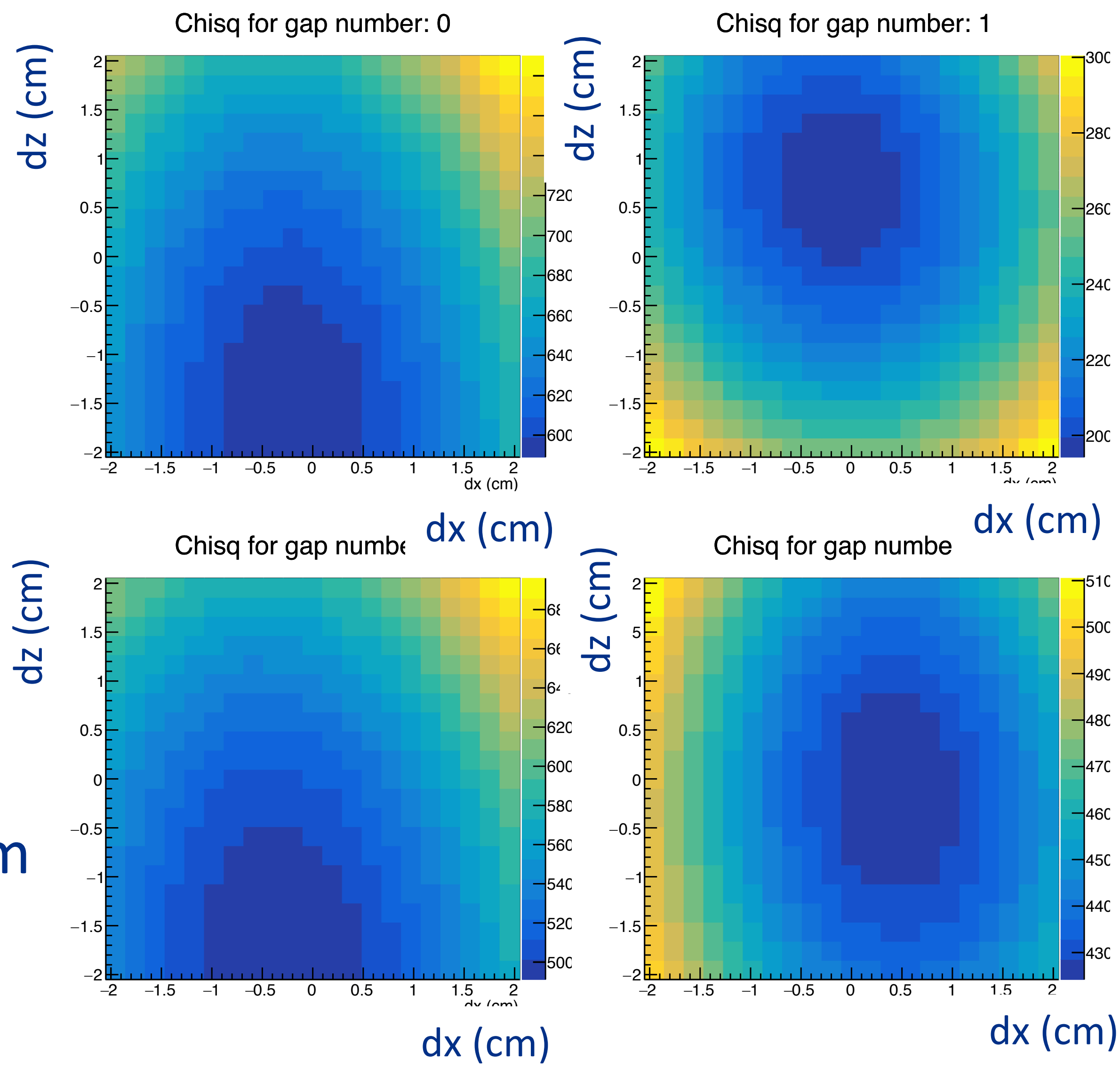
Nominal Δz between collection-plane wires 25.2 mm.

Beam Right Upstream

Beam Left Upstream

Beam Right Downstream

Beam Left Downstream

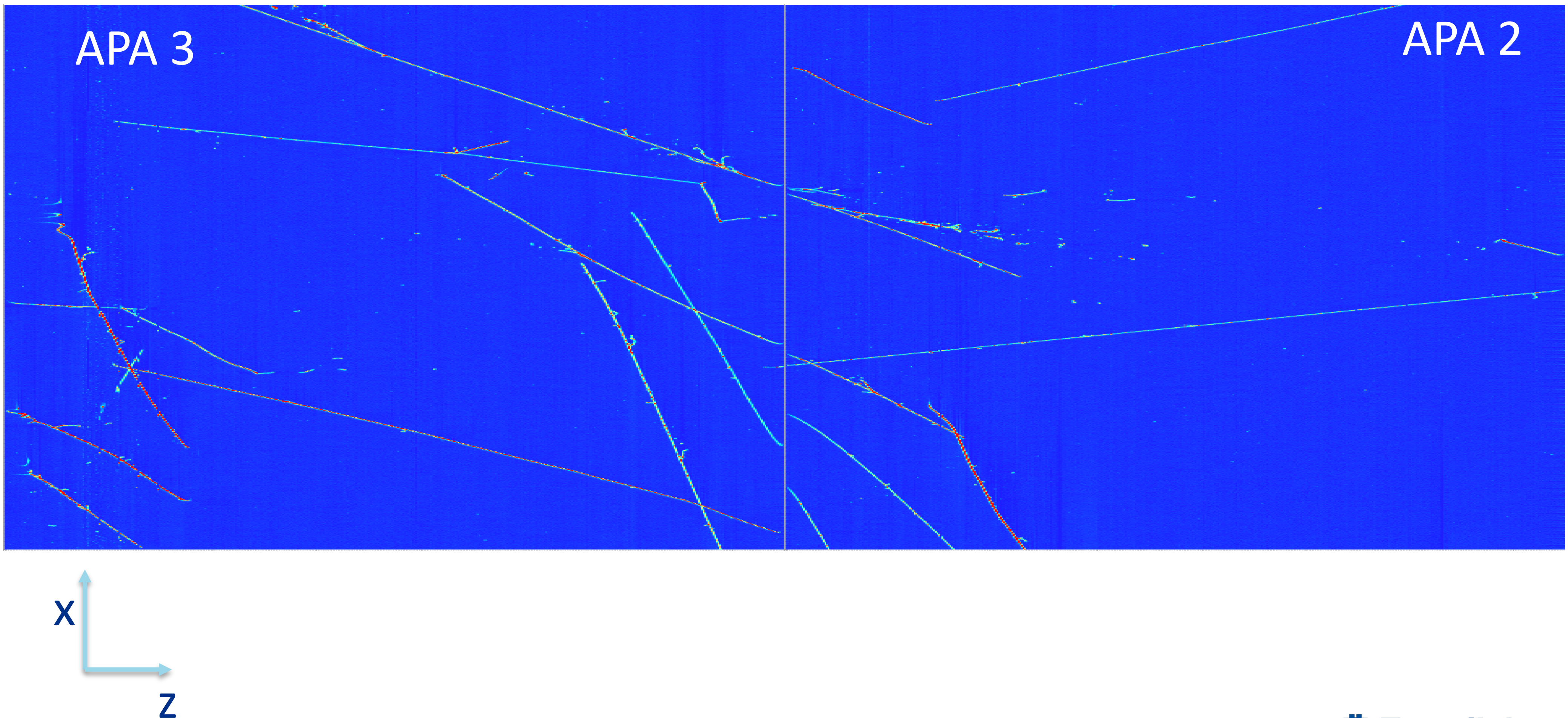


Fit prefers wider gaps with the diverters off.
Slightly narrow them when there are no diverters

Best-fit points shift when diverters are activated

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.



Electron Diverter

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

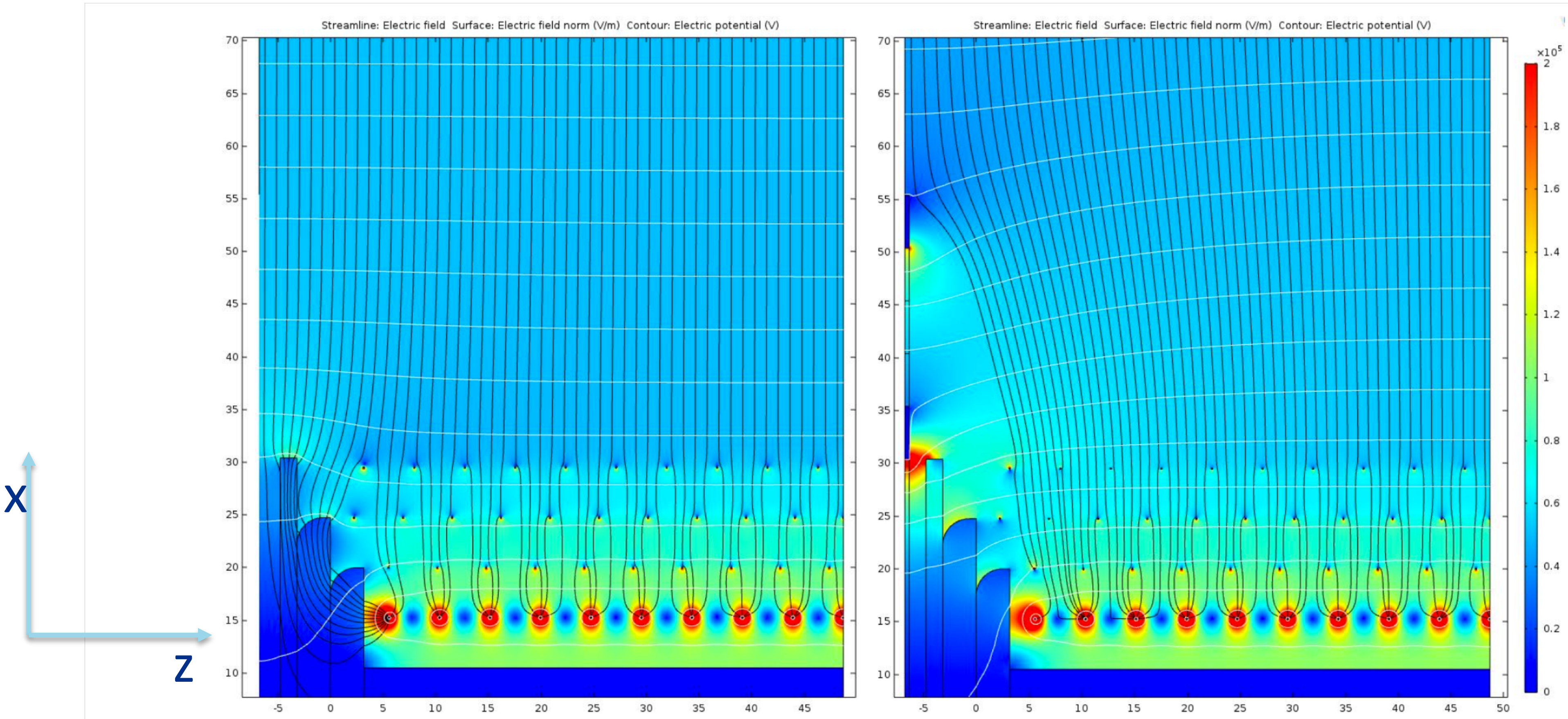
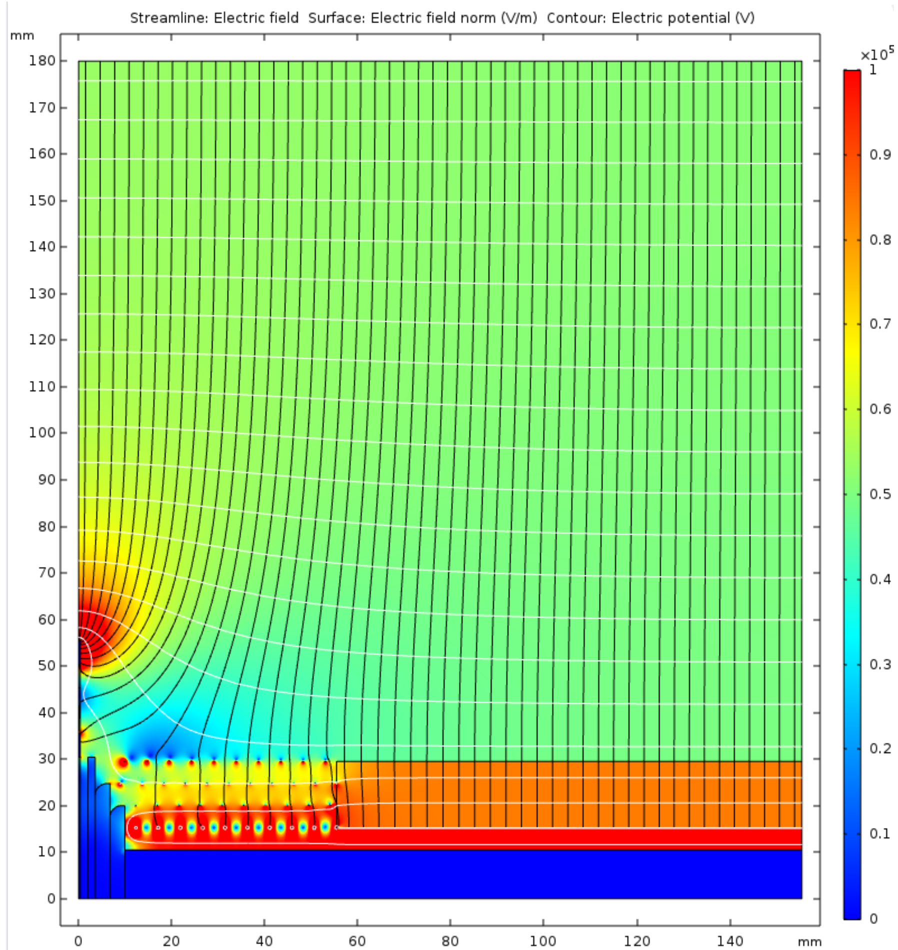


Figure 2.11: Left: field map of the region near the inactive gap of an APA without the electron diverter; Right: field map with the electron diverter in place. Electric field lines are shown in black, equipotential contours are in white, and electric field strength is represented in color gradient.

https://arxiv.org/abs/1706.07081 (ProtoDUNE-SP TDR)

Electron Diverter when Off

- Diverters have 1.5 GΩ resistance to ground
- E-Field simulation form Bo Yu of grounded diverters
- Charge collects on diverter conductors
- Distorts out to 4 cm from gap.



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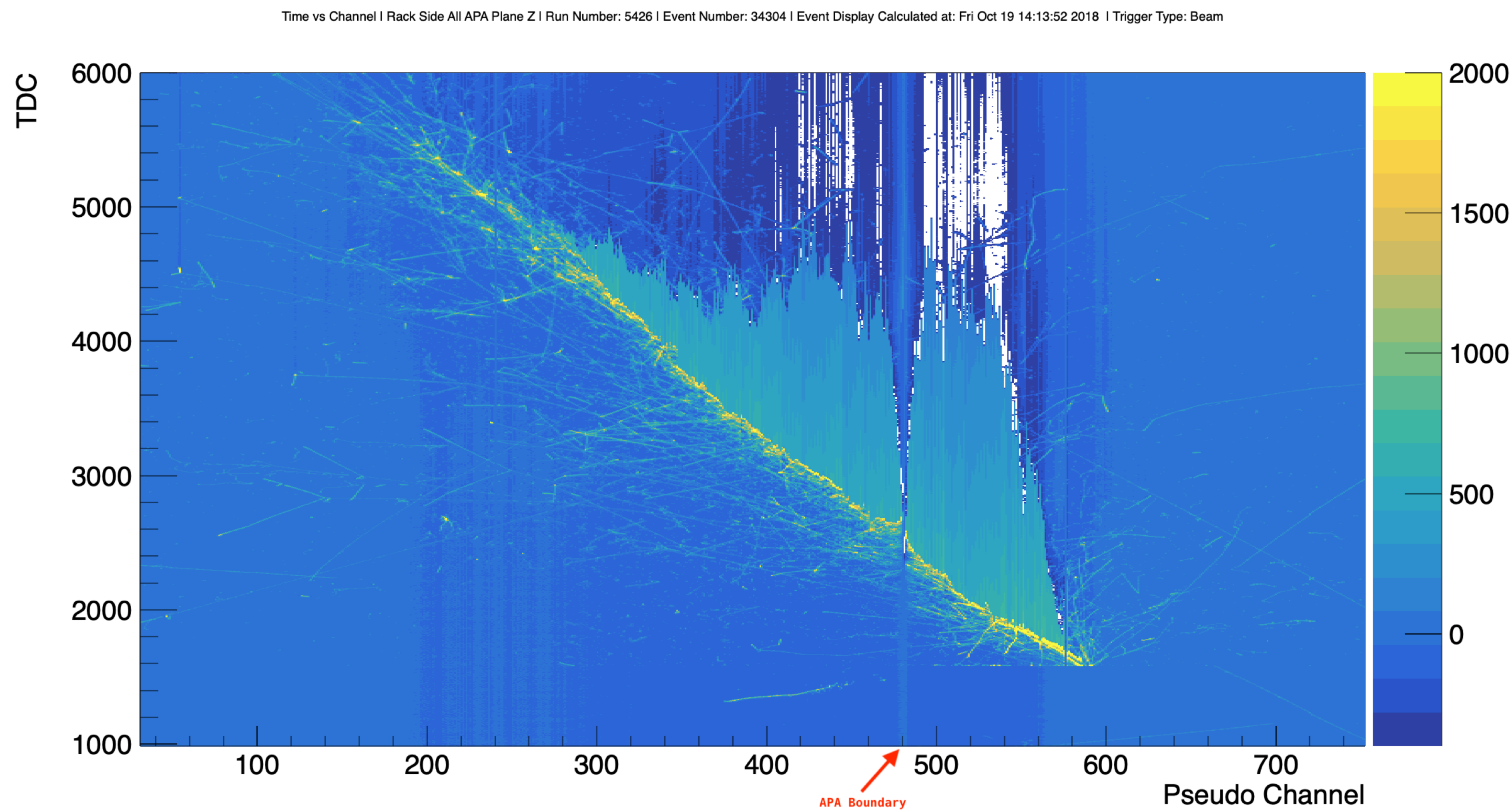
Effect on Showers



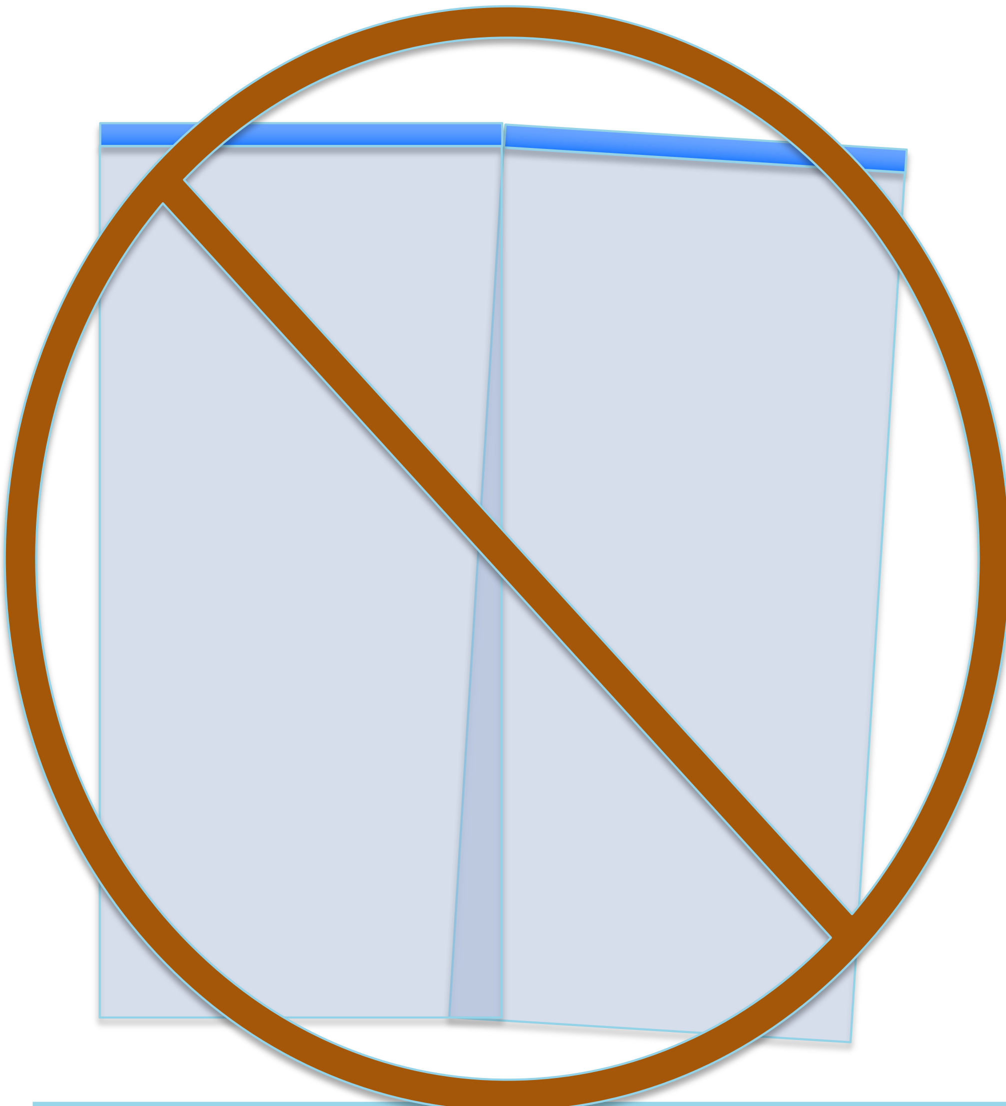
Towards a More General Alignment

- Tools are in place to fit line segment pairs across gaps
- Assuming the APA's are rigid bodies, each has six parameters:
  - Position: (*x*,*y*,*z*) of center
  - Angles: (roll, pitch, yaw)
- We have more than enough data – results will be systematics dominated when we are done.
- Some combinations are not measurable at all:
  - Global detector shift in position or angle (need external reference)
- And some are correlated with other unknowns:
  - Distance between Beam Left and Beam Right planes and the cathode can be done with APA-CPA piercing cosmics.
  - Dependence on assumptions of drift velocity and space charge.

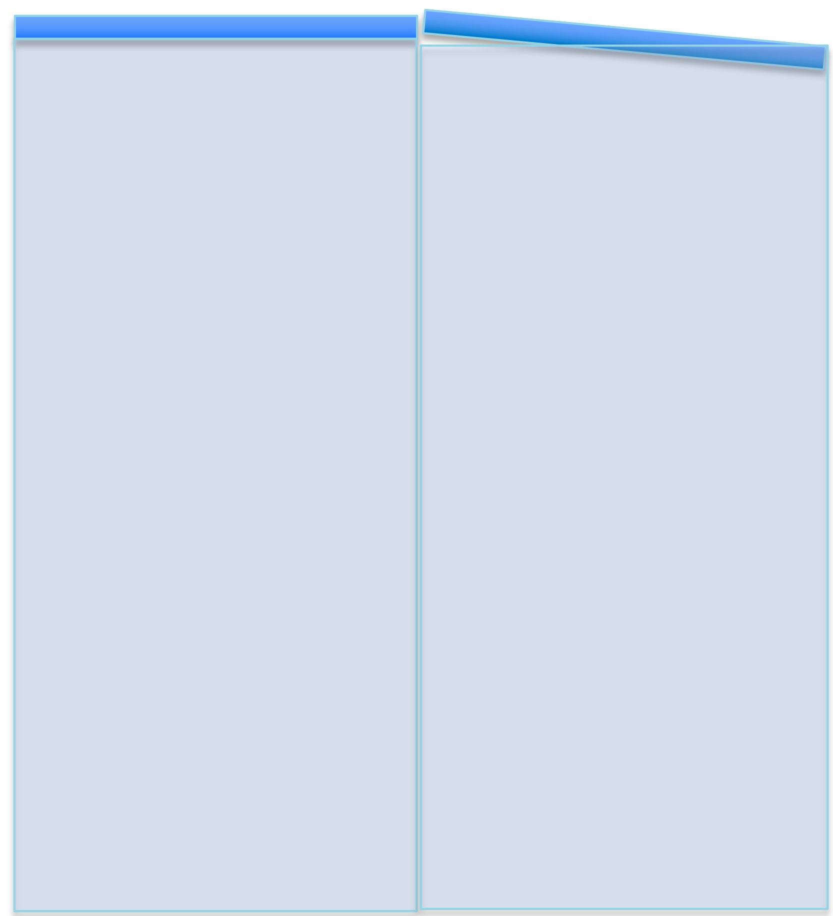
Effect on the Drift Due to Rotations

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

viewed from above



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



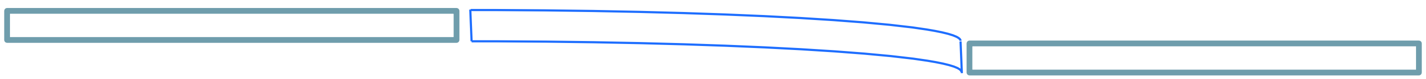
Extrapolating to the DUNE Far Detector (Single Phase module)

Table 4.2: Annual rates for classes of cosmic-ray events described in this section assuming 100% reconstruction efficiency. Energy, angle, and fiducial requirements have been applied. Rates and geometrical features apply to the single-phase far detector design.

Sample	Annual Rate	Detector Unit
Inclusive	1.3×10^6	Per 10 kt module
Vertical-Gap crossing	3300	Per gap
Horizontal-Gap crossing	3600	Per gap
APA-piercing	2200	Per APA
APA-CPA piercing	1800	Per active APA side
APA-CPA piercing, CPA opposite to APA	360	Per active APA side
Collection-plane wire hits	3300	Per wire
Stopping Muons	11000	Per 10 kt module
π^0 Production	1300	Per 10 kt module

Difficult Distortions to Constrain

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



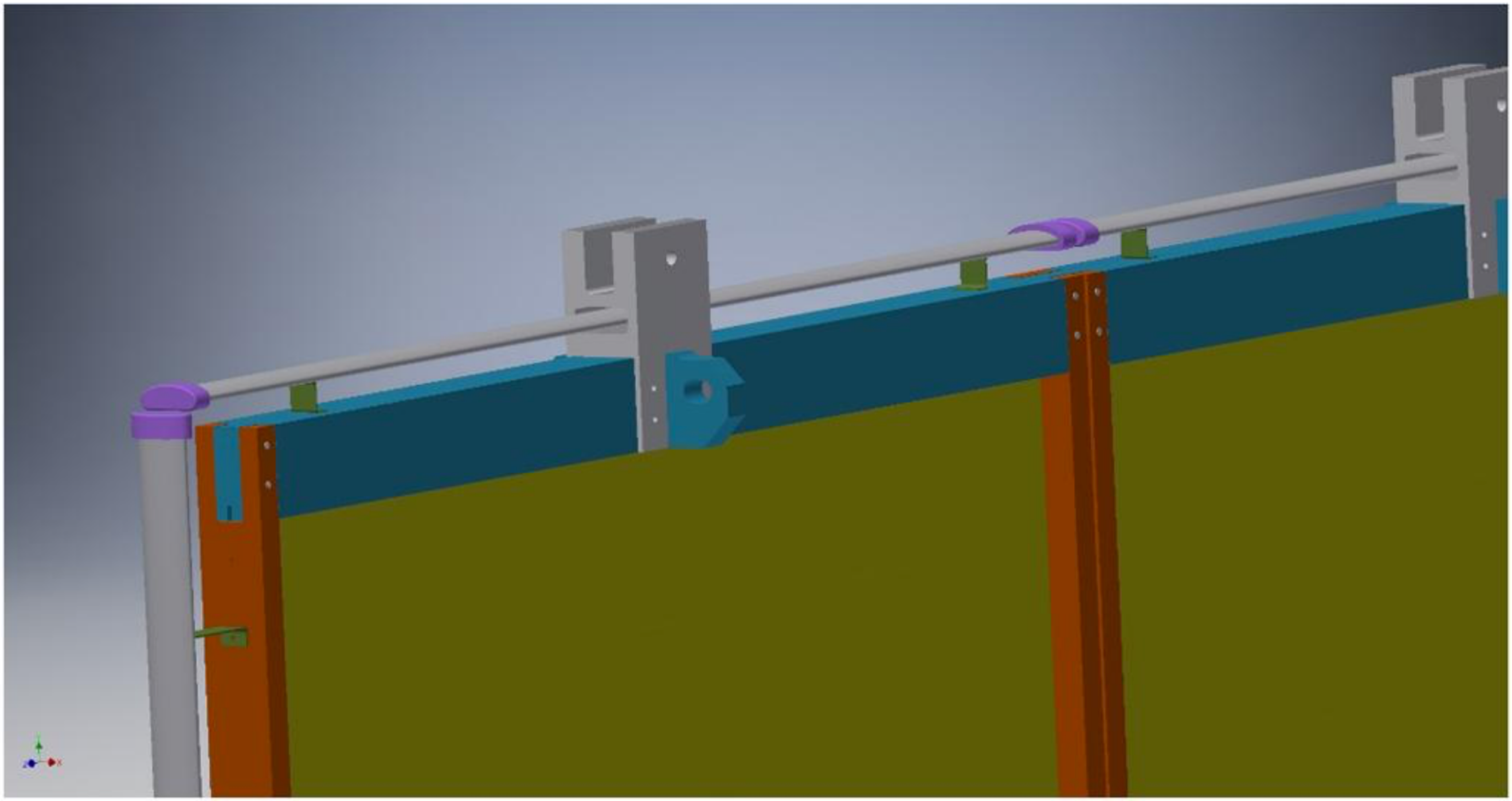
Bending of APA's:

- 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.
- Space charge can make long-range alignment constraints difficult.

What is the magnitude of this that would escape our notice?

CPA Geometry

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



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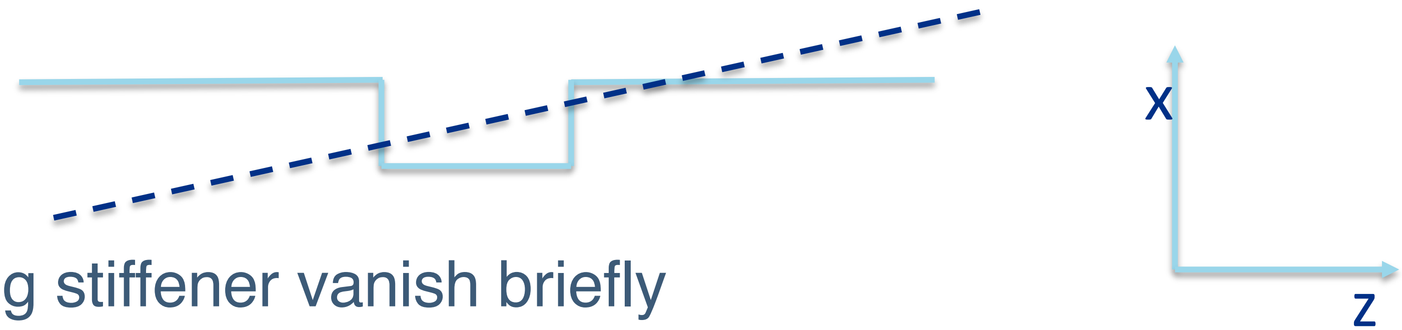
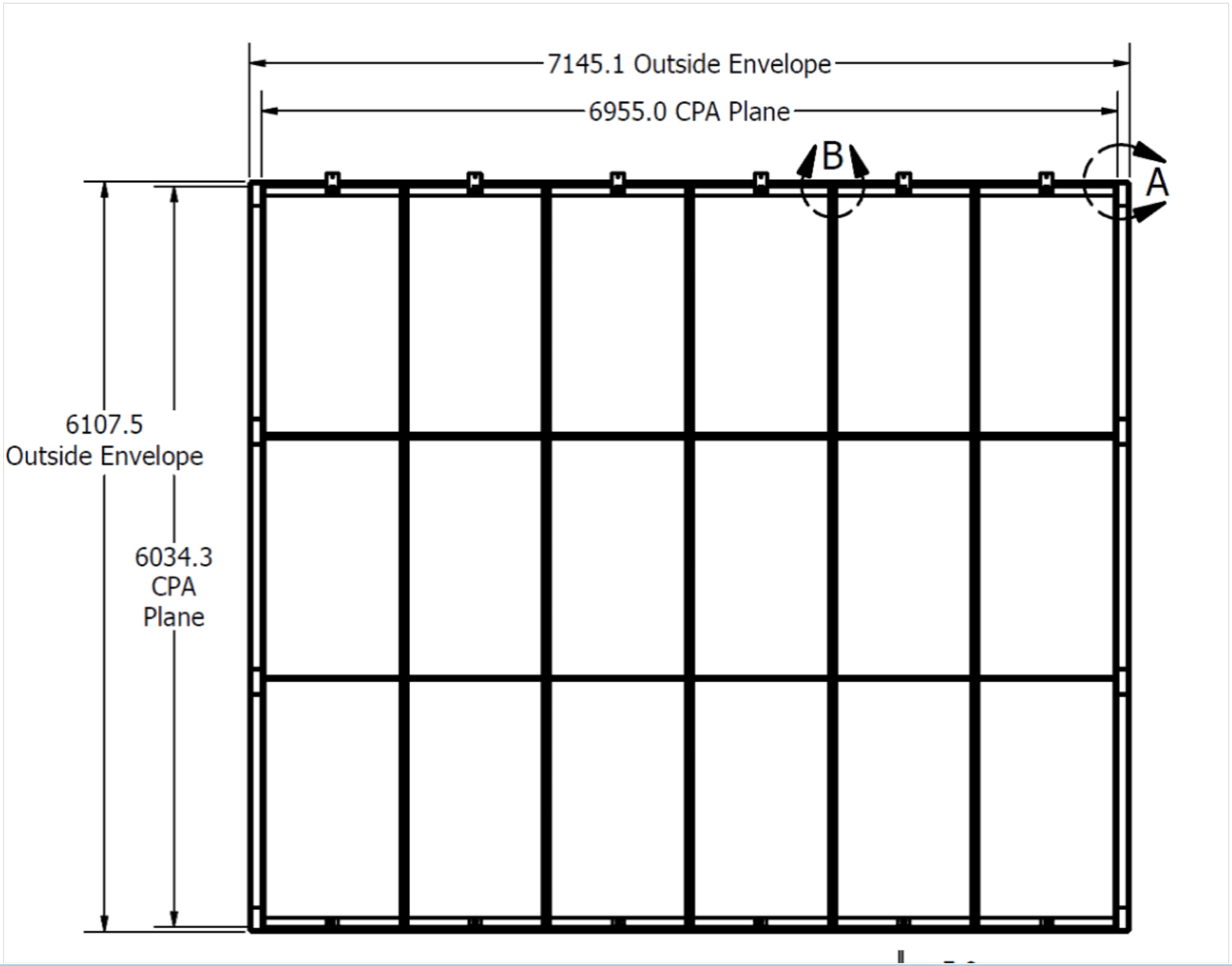
CPA Stiffener Bars/Panel Frames

- 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...

A Test Pattern on the ProtoDUNE CPA



Look for gaps in CPA-crossers

The reco image will tell us about space charge

Extras

Effect on the Drift

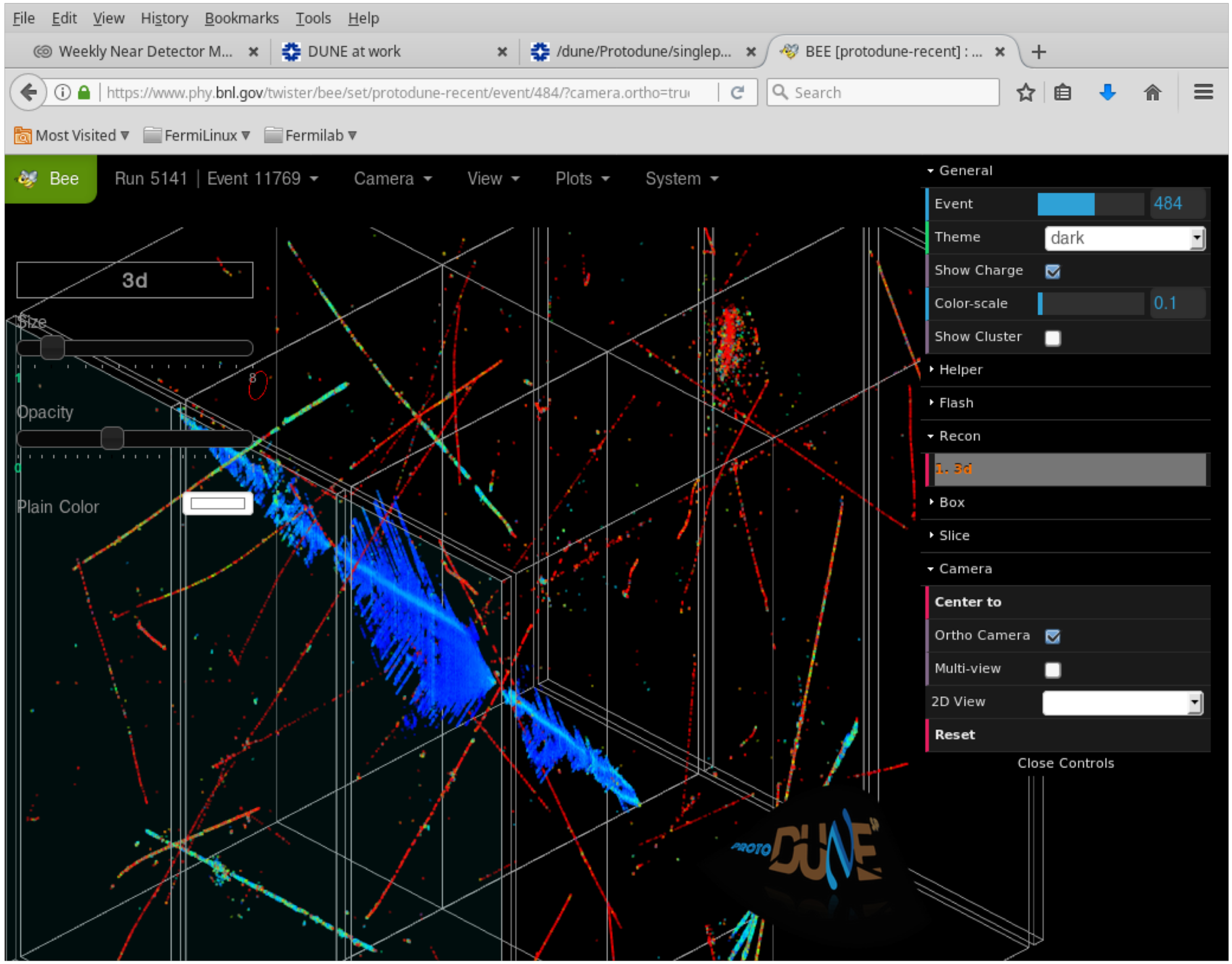
- Field distortions due to misaligned cathode and anode planes are expected to be localized near the distorted element.
- Go far away from the distorted panel/APA, and the field should be asymptotically uniform. May need to do a calculation to see just how local this is
- But – electron arrival time 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 Bee Event Display

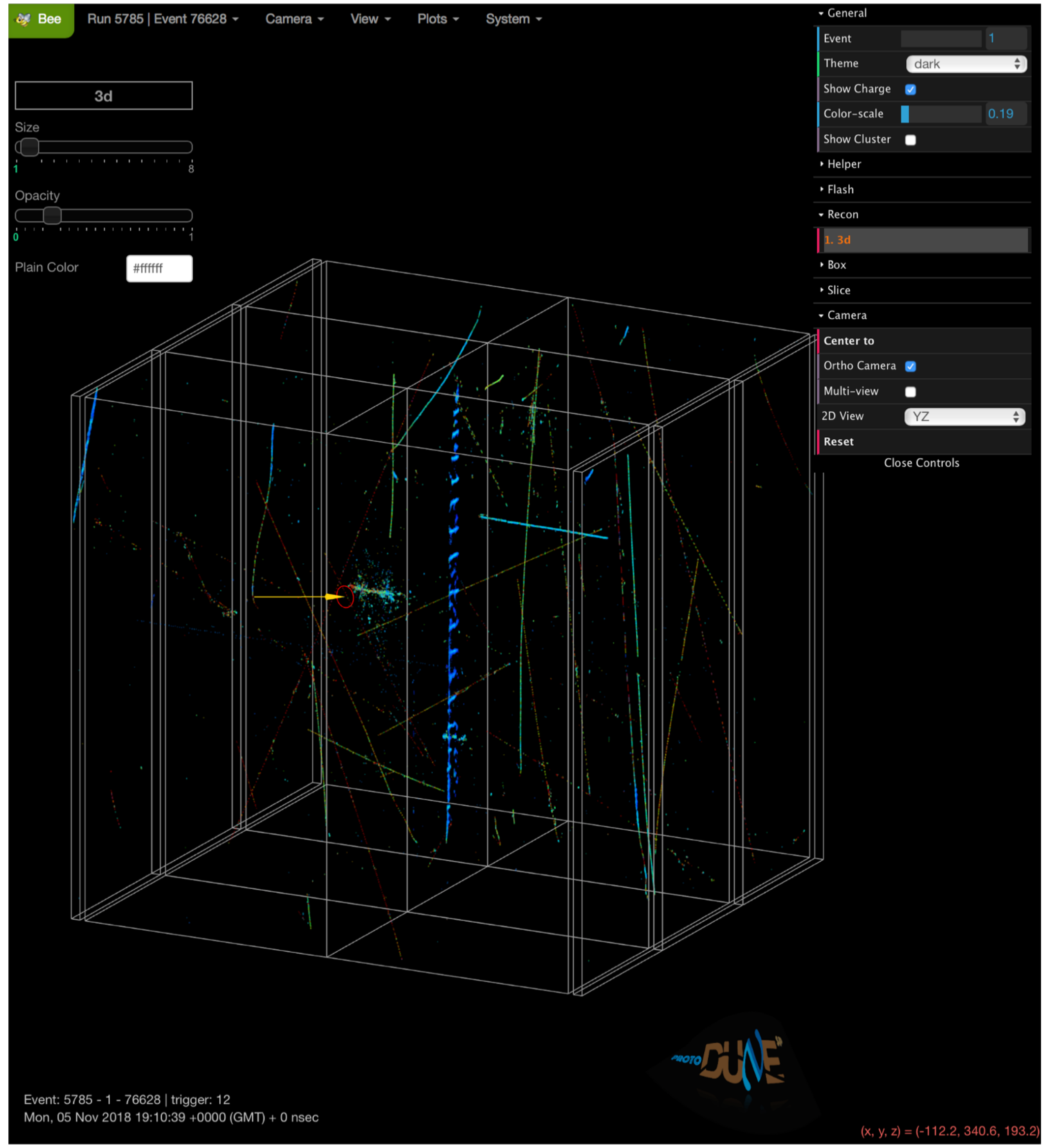
Space points from isochronous tracks are spread out in Y.

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?



A "Ladder" Event



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.

$$\chi^2 = \sum_i^{\text{layers}} \sum_j^{\text{tracks}} \left(\Delta\vec{x}_{ij} - A_j \cdot \vec{\delta}_i - B_i \cdot \delta\vec{p}_j\right)^T ({\sigma_{\text{hit}}}^2)^{-1}_{ij} \left(\Delta\vec{x}_{ij} - A_j \cdot \vec{\delta}_i - B_i \cdot \delta\vec{p}_j\right)$$
$$+ \sum_i^{\text{layers}} \sum_k^{\text{targets}} \left(\Delta\vec{\xi}_k - C_{ik} \cdot \vec{\delta}_i\right)^T ({\sigma_{\text{survey}}}^2)^{-1}_k \left(\Delta\vec{\xi}_k - C_{ik} \cdot \vec{\delta}_i\right) + \lambda \left|\sum_i^{\text{layers}} \vec{\delta}_i\right|^2 , \quad (1)$$

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)

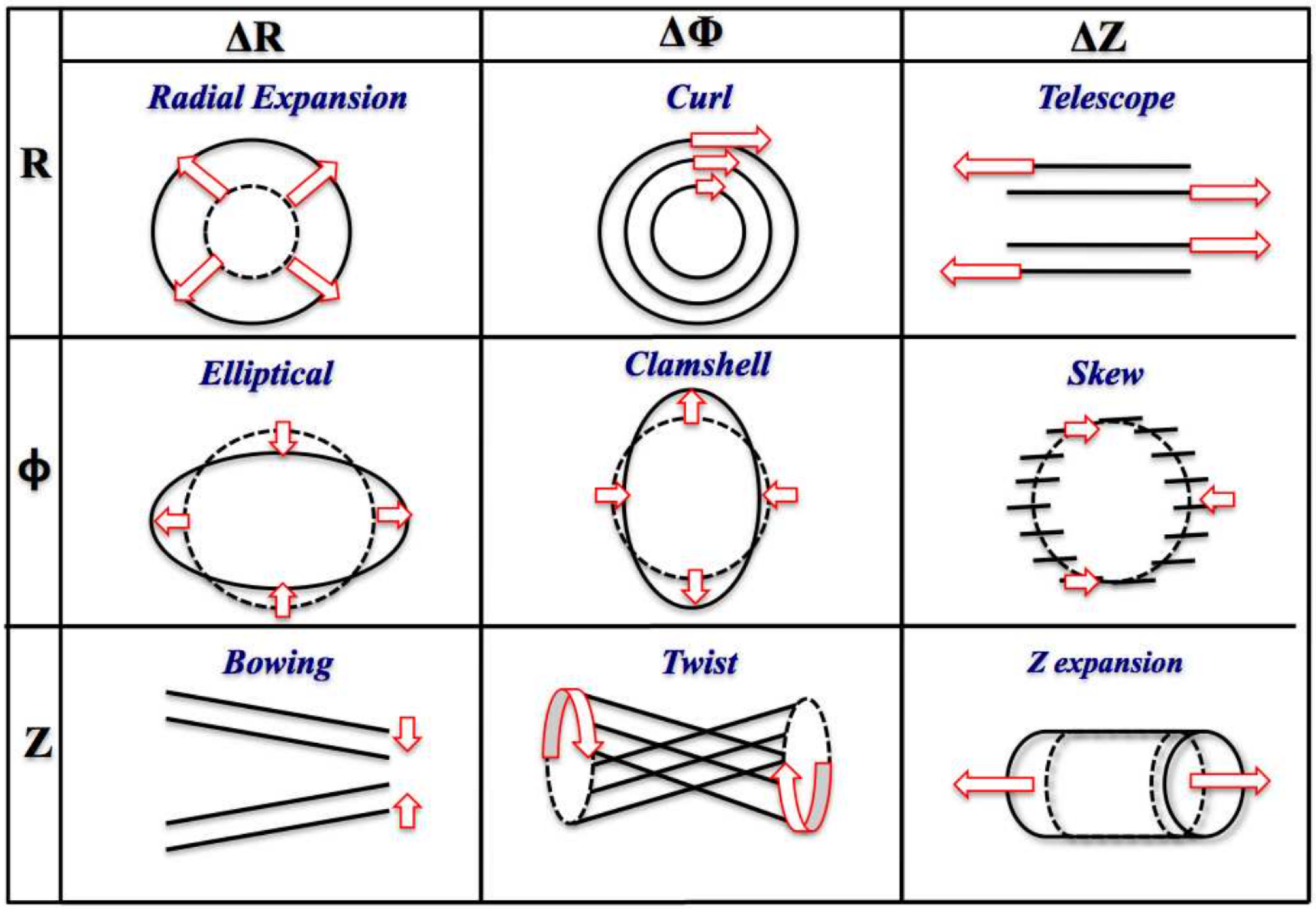
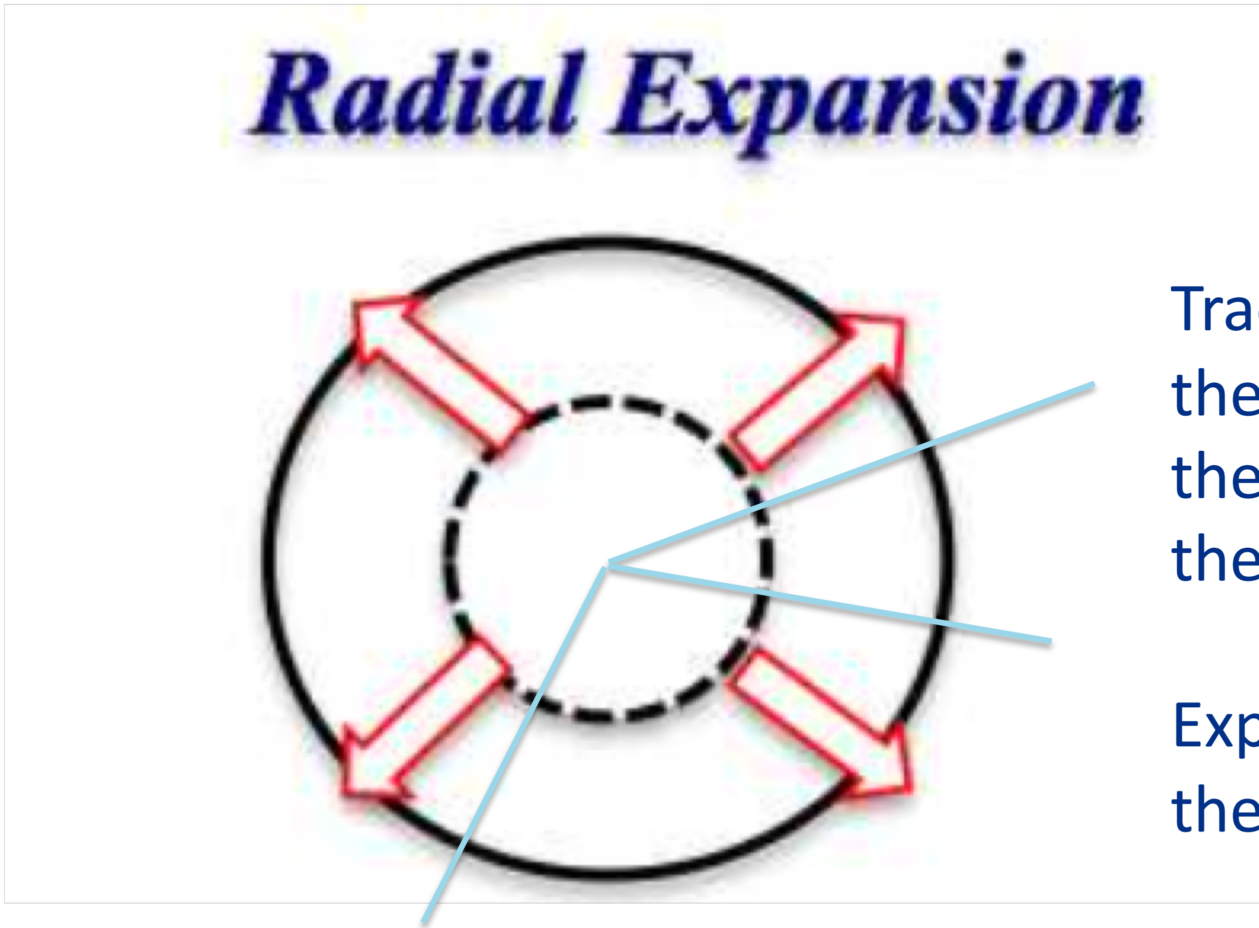


Figure 4.4: Schematic picture of the most important weak modes for the ATLAS Inner Detector barrel.

From Moles-V
thesis.

Example: Radial Expansion is a Weak Direction

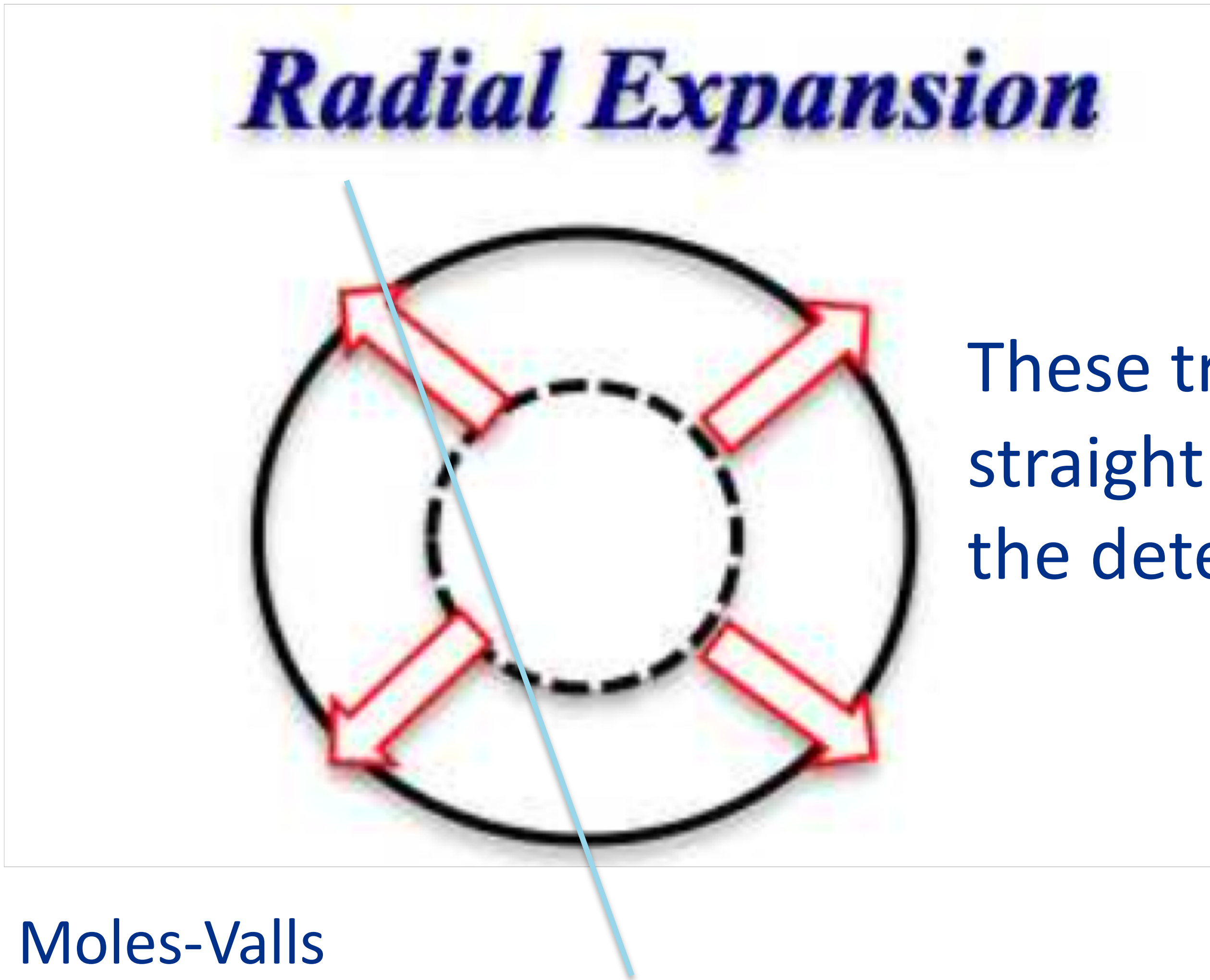


Tracks from the center of the detector don't constrain the radial size of the detector.

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 non-uniformly

Moles-Valls

Collaborations / Partnerships / Members 28pt Bold

BOSTON UNIVERSITY

UNIVERSITY OF MINNESOTA

LEWIS UNIVERSITY

KANSAS STATE UNIVERSITY

NORTHWESTERN UNIVERSITY

UNIVERSITÀ DI PISA

PURDUE UNIVERSITY

RICE

UCIrvine University of California, Irvine

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THE UNIVERSITY OF CHICAGO

Duke UNIVERSITY