DUNE Far Detector Calibration with Cosmic Rays

Tom Junk

DUNE Far Detector Calibration Workshop

March 14, 2018

Many thanks for materials stolen without permission: Jonathan Asaadi, Bruce Baller, Sowjanya Gollapinni, Kevin Ingles, Vitaly Kudryavtsev, Kendall Mahn, Mike Mooney, Jen Raaf, Aidan Reynolds, Michelle Stancari, Matt Thiesse, Filippo Varanini, Erik Voirin, Mike Wallbank, Karl Warburton, Leigh Whitehead, Tingjun Yang

Early Years of DUNE

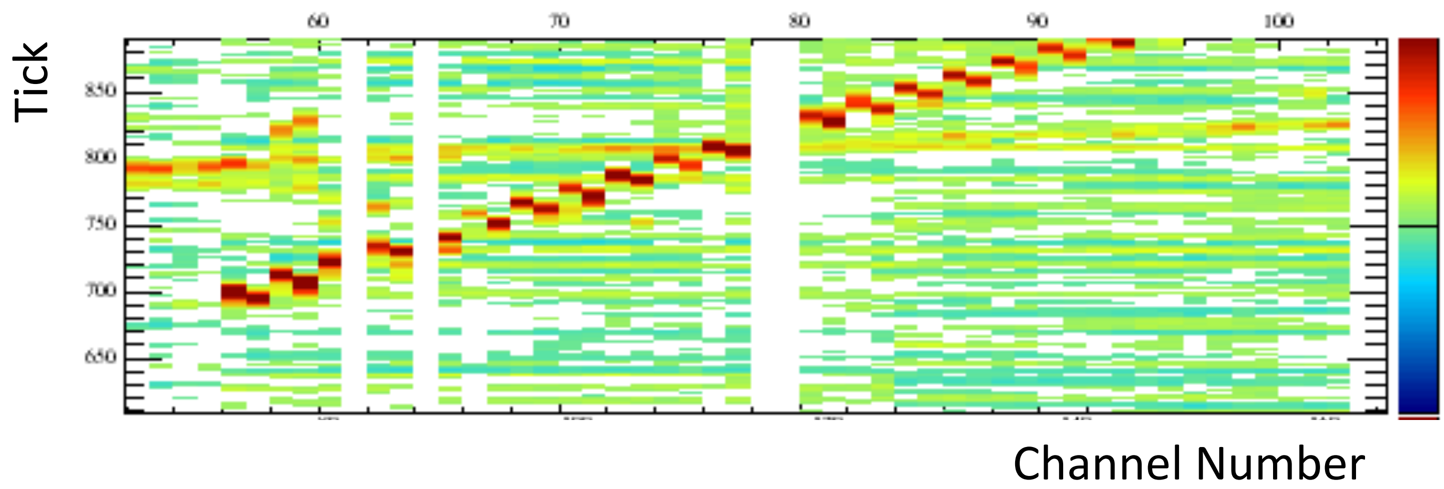
- Most data from most interactions will be from cosmic rays.
- ~1.5 million interactions per year per module (Sowjanya)

- Schedules shown so far have at least one FD module up and running at least one year before there is beam

- Commissioning, calibrating, atmospherics, exotics, possibly a SNB during that early period

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.



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"

An Elaborate Example: CMS muon tracker

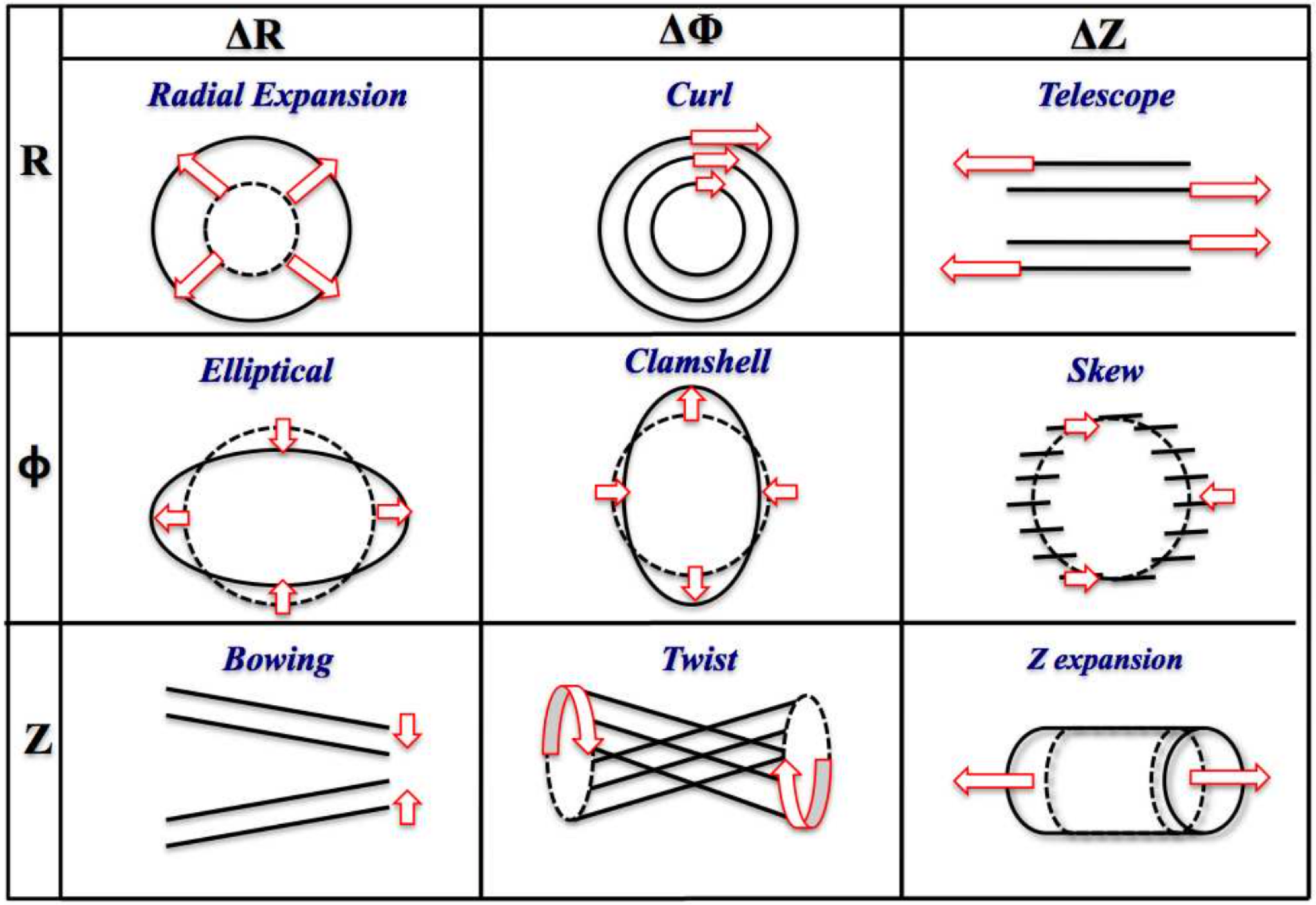
http://arxiv.org/abs/0911.4022

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.

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

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.

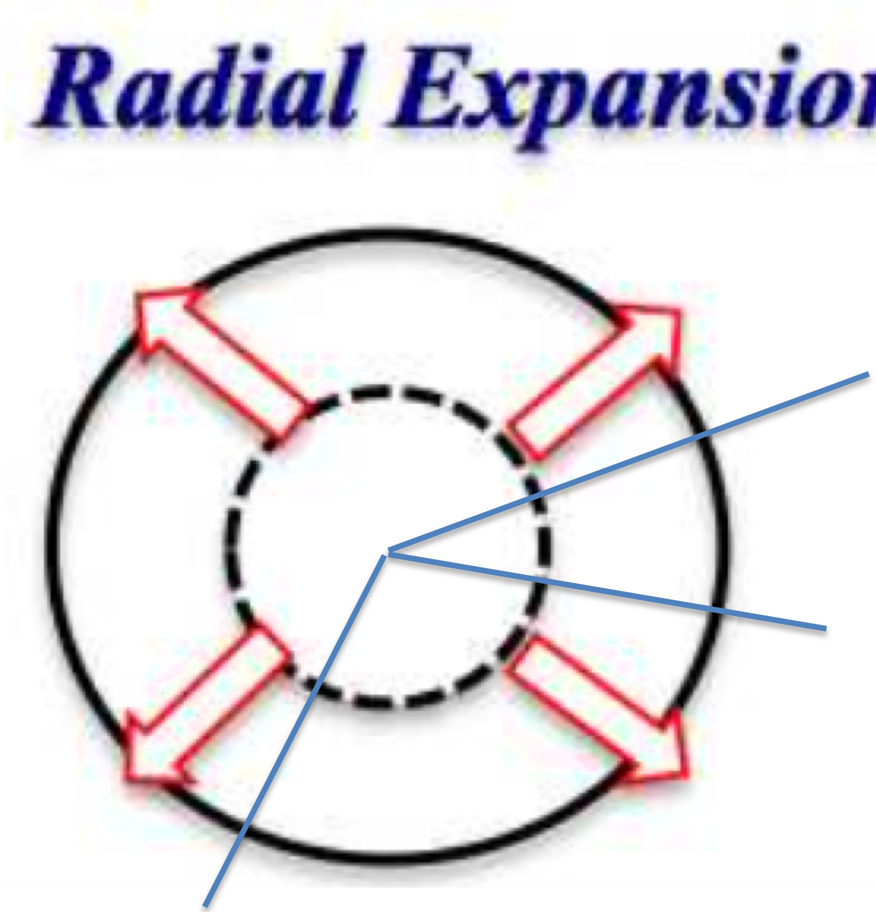
Examples of "Weak" Directions (ATLAS alignment)



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

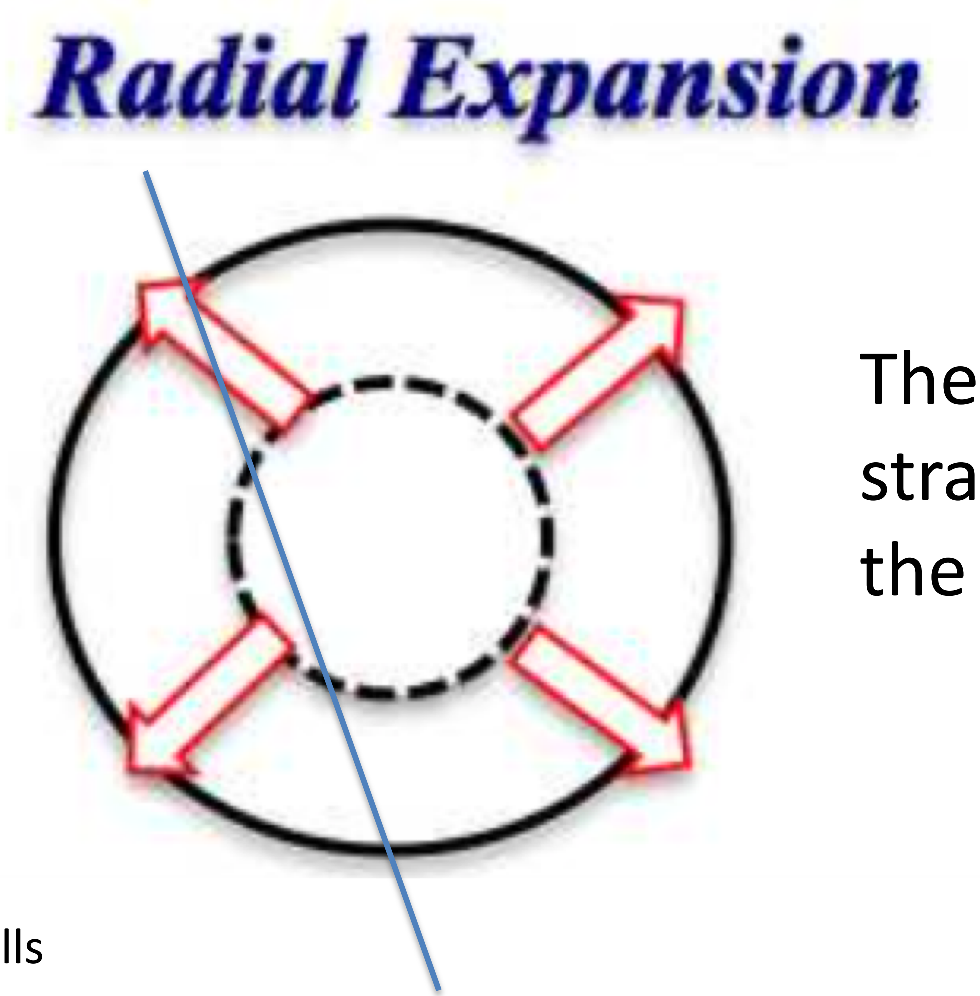


Tracks from the center of the detector don't constrain the radial size of the detector.

Expand the detector, and all the hits still fit!

Moles-Valls

Extra Constraint from Cosmics



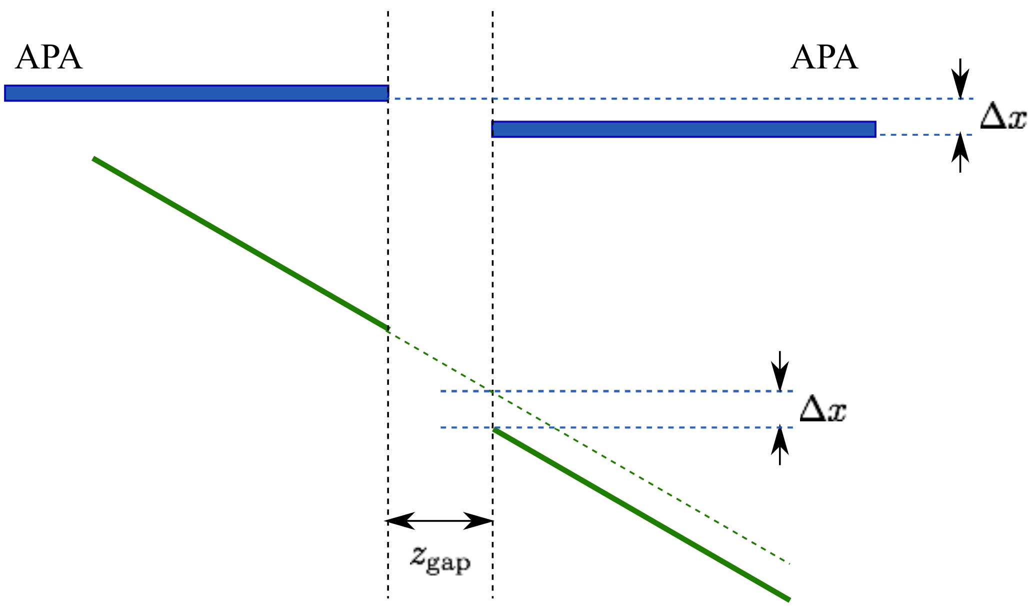
These tracks are no longer straight when you expand the detector.

Moles-Valls

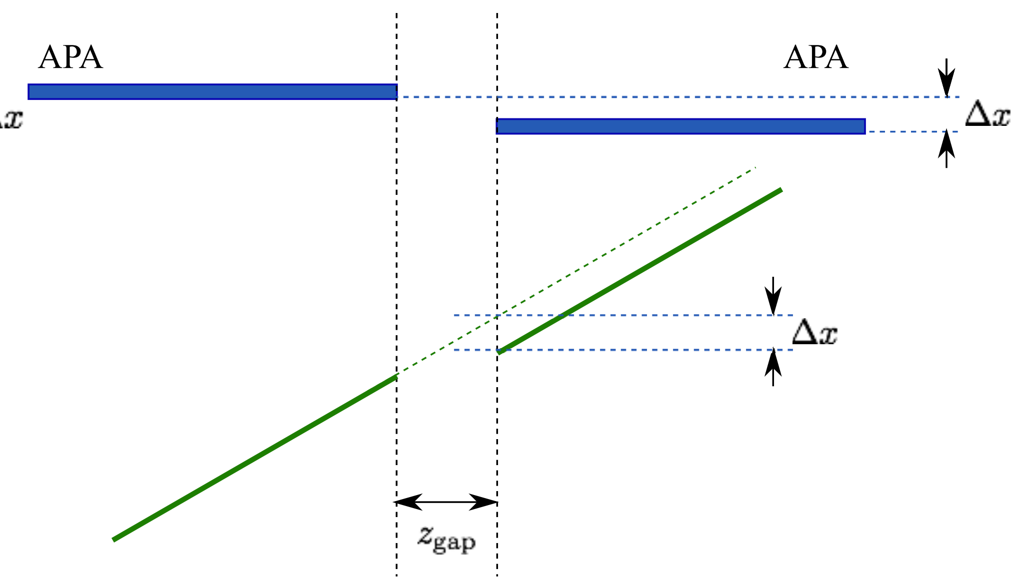
"Strong" Directions in DUNE

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

M. Wallbank



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)

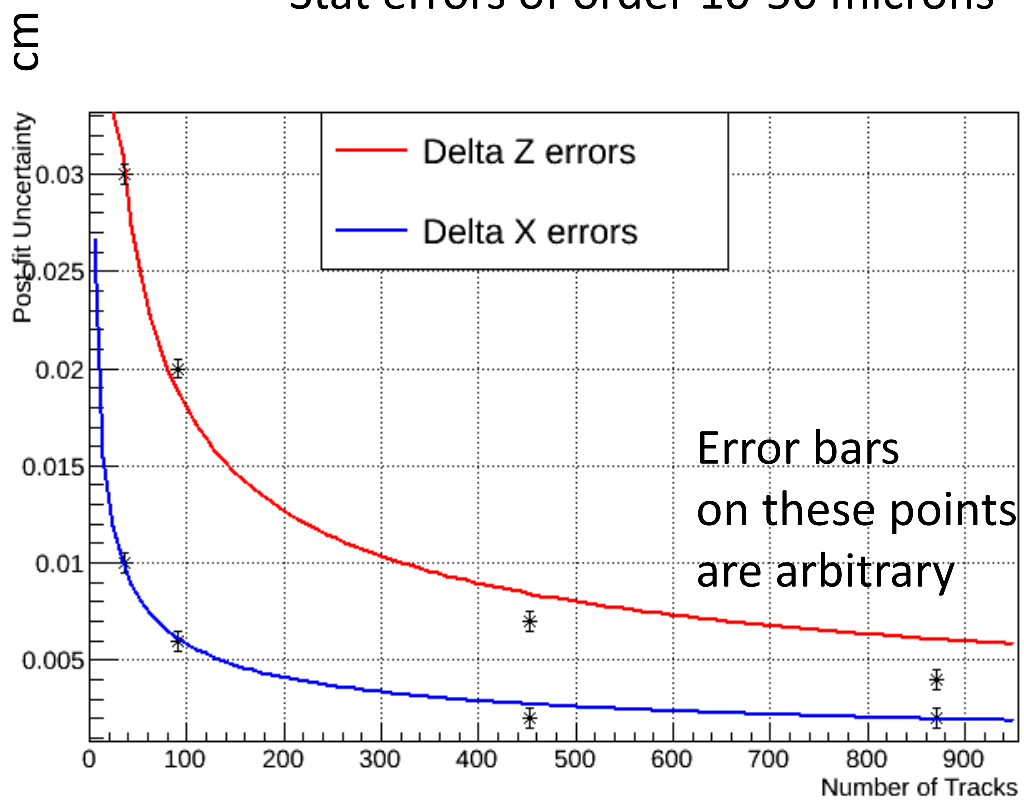
Vertical Gap Measurement Precision: 35-ton experience

- 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



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*)?

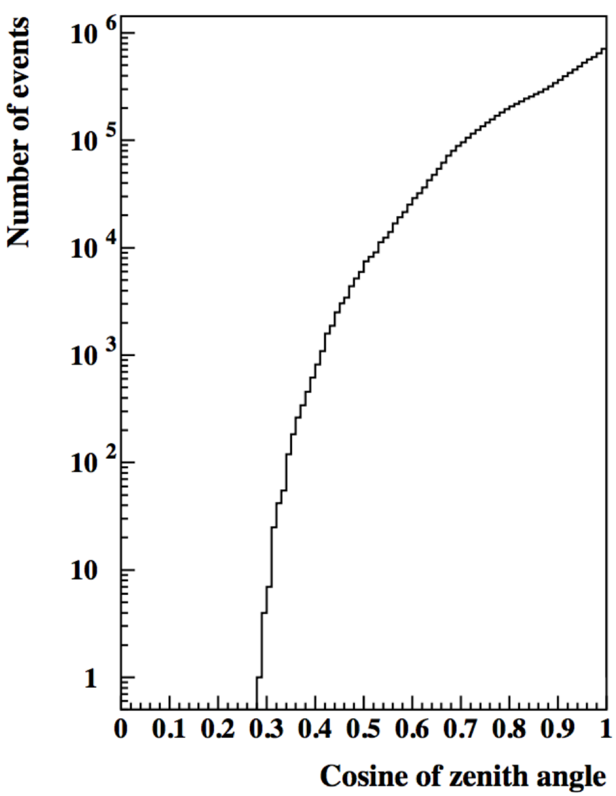
Repeat analysis in bins along *y* for each gap. Approximate analysis with two bins with centers 3 m apart and uncertainties for half as many tracks in each:

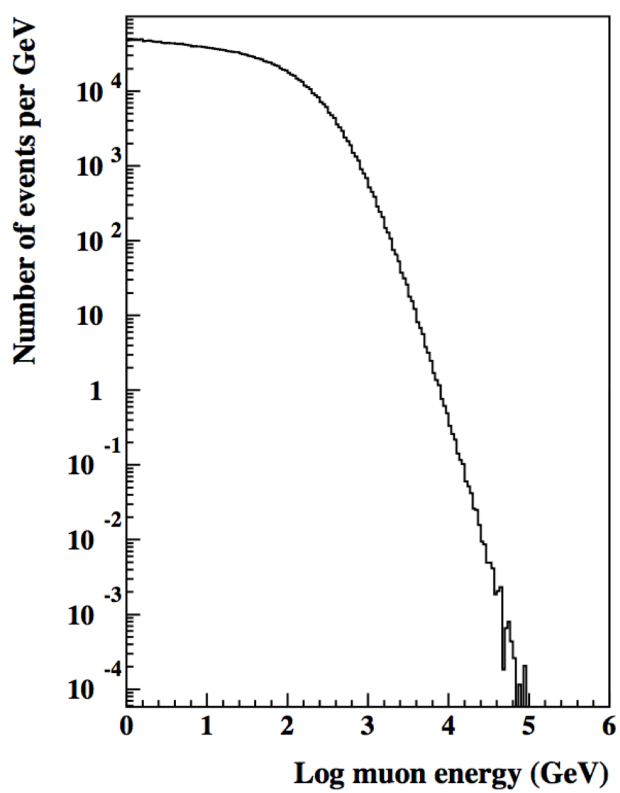
$$\sigma\left(\frac{d\Delta z}{dy}\right) = \frac{\sqrt{2}\sigma_{\Delta z}(N_{\text{tracks}}/2)}{3\text{ m}} \approx \frac{1.19\times 10^{-3}}{\sqrt{N_{\text{tracks}}}}$$

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

Muon Flux at the 4850' Level

- See DocDB 5505 for an approximate calculation based on Vitaly Kudryavtsev, Martin Richardson, J. Klinger, and Karl Warburton LBNE DocDB 9673-v1, and the calibration concept study document, DUNE DocDB 4769-v2





Estimate 4 cosmic rays per day per square meter at the 4850' level (DocDB 4769)

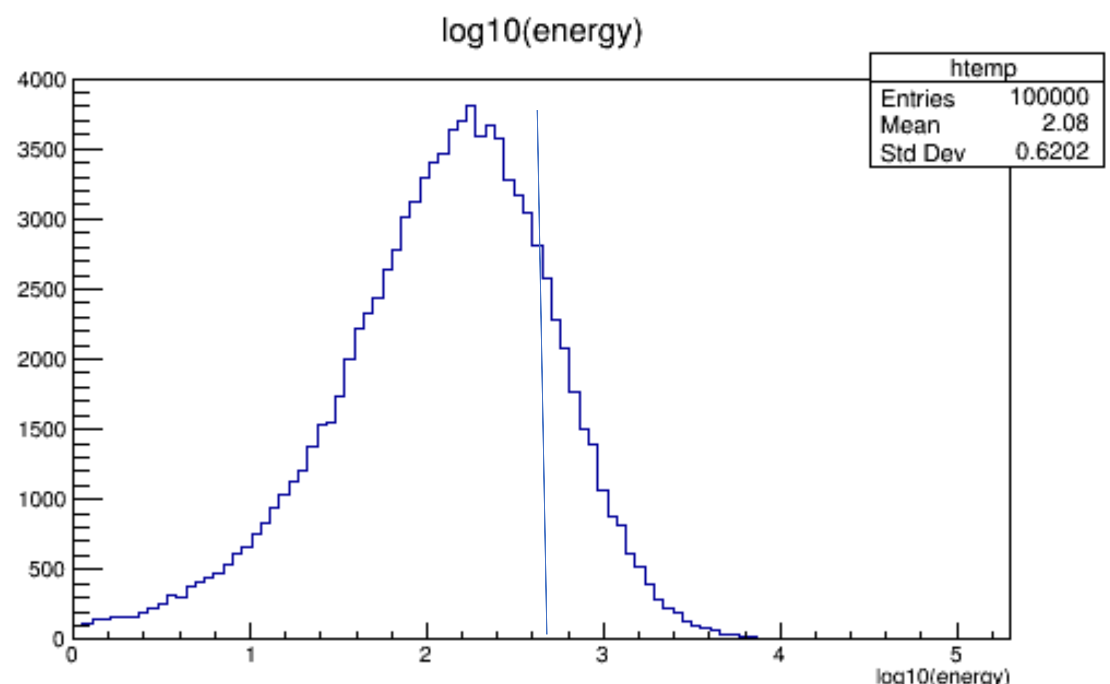
Syst. Uncertainty is ±20% in total rate. Shapes are uncertain too!

Fraction of Showering Muons

- No-shower cut: Critical Energy (energy at which radiative effects are more important than ionization) is 485 GeV in LAr. $\log_{10}(485) = 2.7$

Vitaly's plot was in muons per GeV (linear) on a log scale (!)

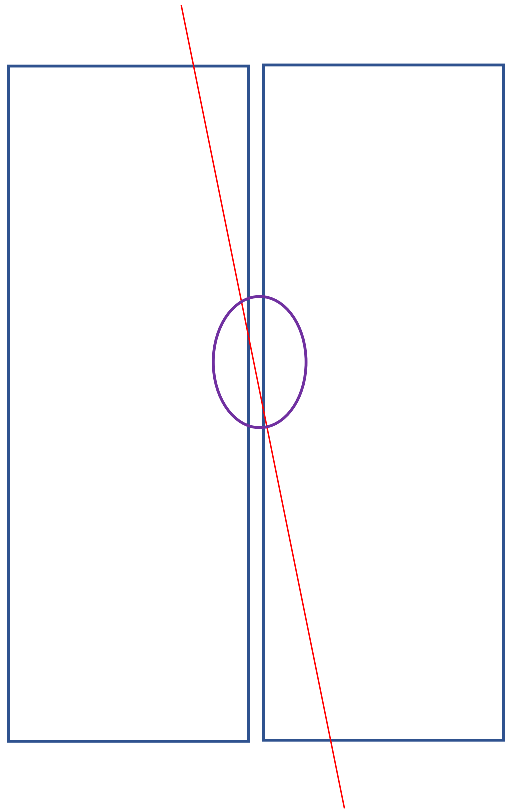
Estimate that 60% of muons don't shower significantly.



MUSUN Generator-Level Run: prodMUSUN_DUNE10kt.fcl with 100000 events

Estimating Rate of Muons Crossing Vertical Gaps: Angle

- Want 20 collection-plane hits on either side of the gap. 10 cm in both APA's + 5 cm for the gap (wild guess) – need 25 cm in z for 6m in y. Need 2.4° at least, more is better.
- From Vitaly's note: Average angle with respect to zenith: 26°.
- Assume 0.5 efficiency for having a steep enough angle. Most muons travel close to vertical.

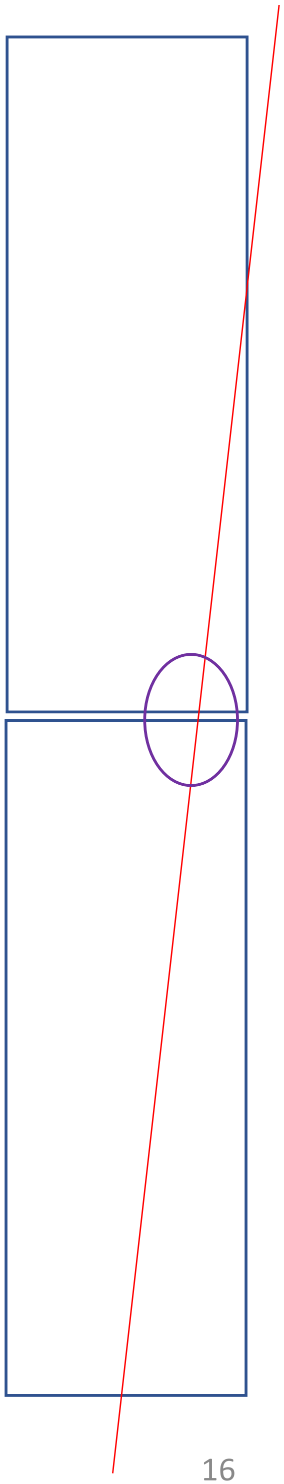


Estimating Rate of Muons Crossing Vertical Gaps: Flux

- Area of gap: 6m tall x 3.6 m in the drift direction.
- Average incident angle: 26°wrt vertical. Take tangent and divide by sqrt(2) for the *xz* projection.
- Get ~7.4 square meters projected area on the top surface.
- Divide by 2 again as muons passing near edges and corners of the gap are not useful.
- Four muons/day per square meter on top surface → ~four muons per vertical gap per day.
- Checked with MUSUN MC at generator level: 9 muons per gap per day

Estimated Rate of Muons Passing Horizontal Gaps

- Similar calculation – 2.5 m x 3.6 m in size (smaller), but angular requirements are less stringent. Can't be exactly vertical (otherwise saturate the collection-plane wires), but still useful for alignment. Nearly all muons pass a horizontal gap somewhere.
- Five useful muons per day per horizontal gap
- Checked with a MUSUN MC: 10/day horizontal gaps.

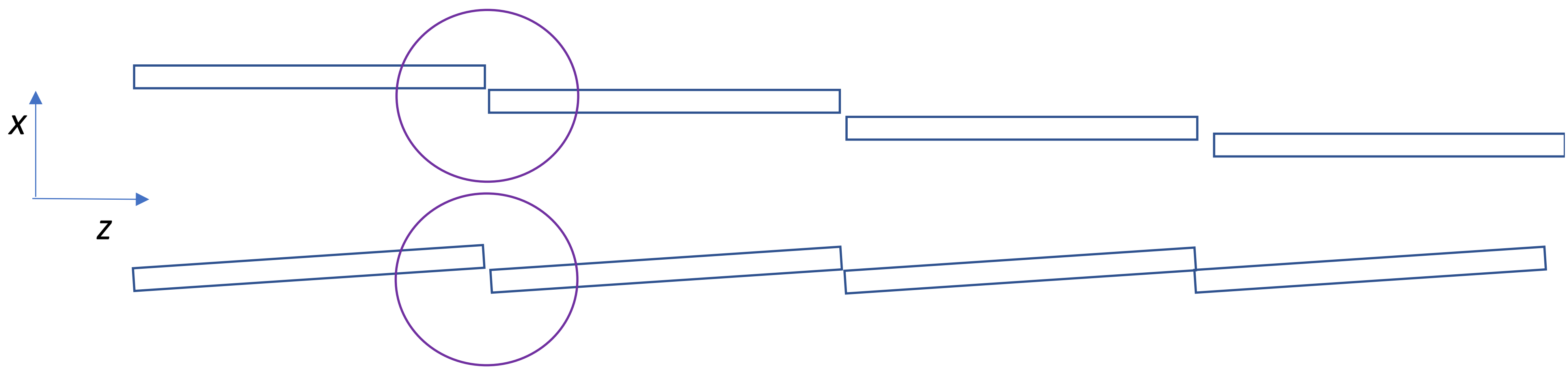


Estimated Rate of APA-CPA Crossers

- Use MUSUN sample to do this, and pick an APA in the middle of the detector
  - Rate of muons with 20 GeV < E < 400 GeV crossing an APA and the portion of the CPA on one side in its own TPC: 1/day
  - Rate of muons 20 GeV < E < 400 GeV crossing an APA and the portion of the CPA on one side in any TPC: 5/day
  - More with any TPC because upper-story APA and lower-story CPA section is now possible. Also the track can cross into other neighboring volumes.

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

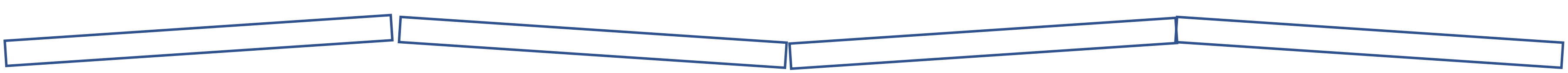
Other Difficult Distortions

View from top

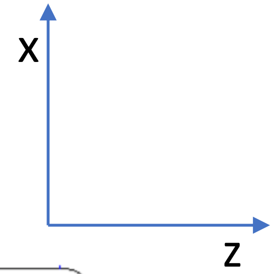
Bent APA's: Will a "flat" APA stay flat when cold?

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:



APA Alignment Pin and Slot



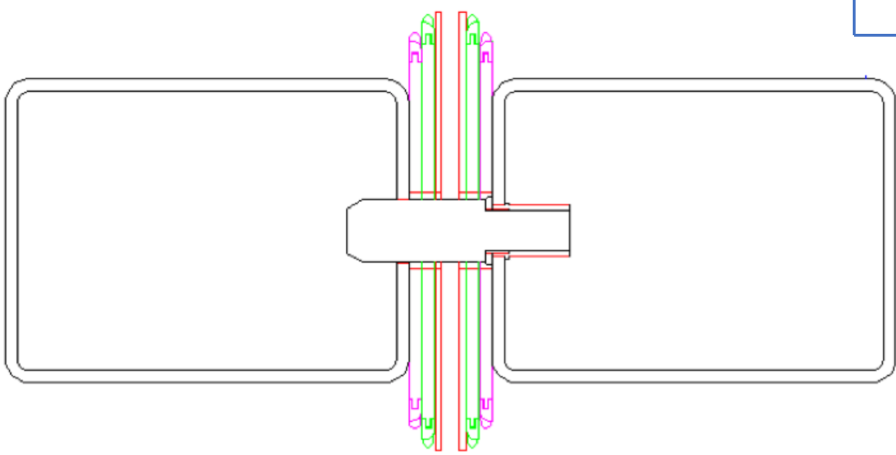
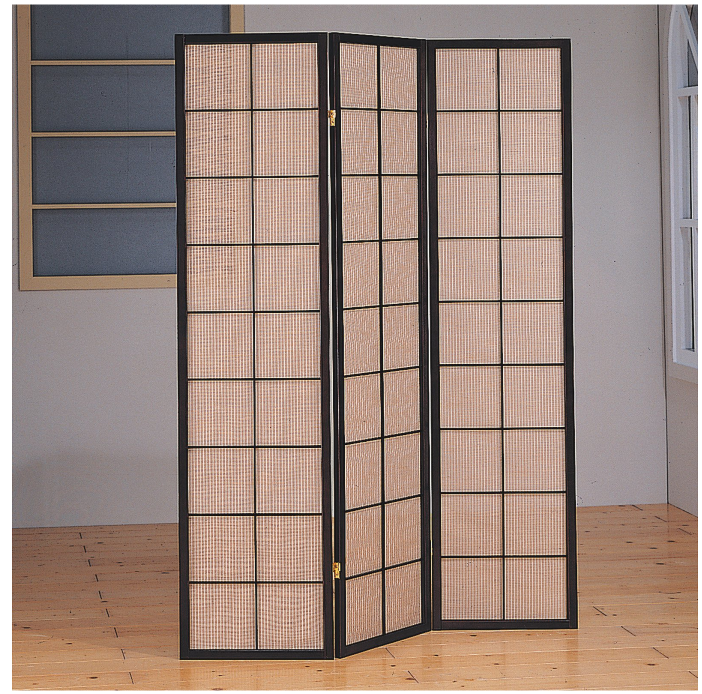


Figure 2.12: The pin/slot constraint. The pin screws into an insert in the outside frame member of one APA and engages a slot in the outside frame member of the adjacent APA.

- From the ProtoDUNE-SP TDR

Hopefully constrain this sort of distortion



- 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

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

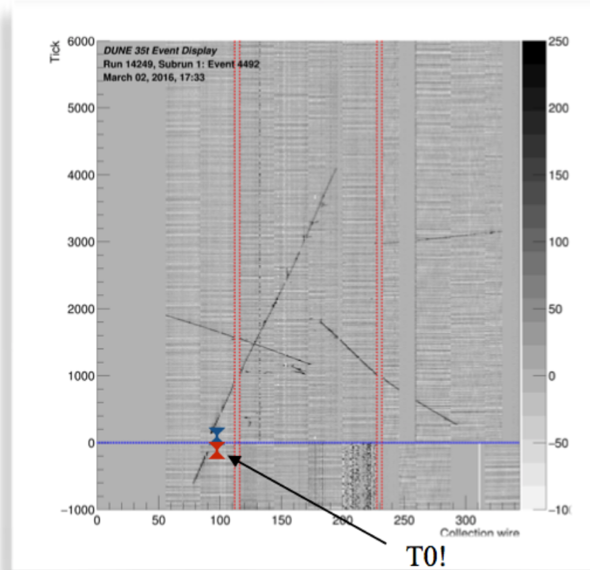
Karl Warburton has expressed interest!

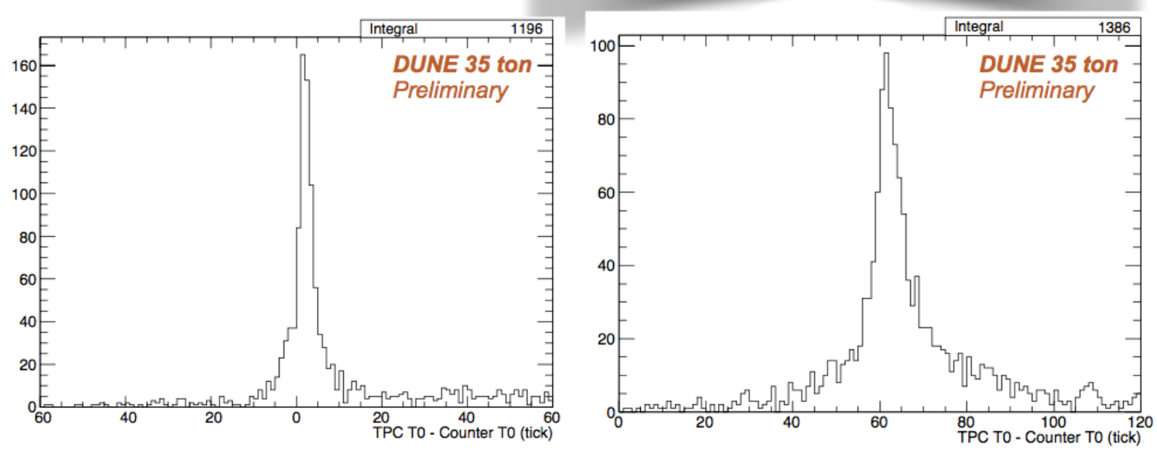
- Starting approach
  - Parameterize APA alignment parameters in terms of *x*, *y*, and *z* offsets, and roll, pitch, and yaw angles
  - Drift is always along the nominal *x* axis, even if the APA is rotated (pitch and yaw are assumed not to affect the drift direction)
  - Rotations are around the APA 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

M Wallbank

APA-Crossing Muons: T0 Measurement

- Only planned LArTPC experiment before the final DUNE far detector utilising APAs reading out multiple drift regions simultaneously.
- Can give unique handle on the event T0 directly from TPC data.
- Determined by minimising the residuals of a linear fit across the gap, as a function of various T0 hypotheses.
- Found timing offset between the counters and TPC data of ~62 TPC ticks (31 μs).
- Very useful calibration method; would never have found this offset otherwise.
- Also important for DUNE FD!





Difference between counter T0 and TPC-measured T0 in simulation (left) and data (right).

Estimate of Uncertainty on t_0

- Width of core of data distribution in 35-ton: 2 μs. Half of the tracks are in the core, other half in the tails.

$$\sigma_{t_0} \approx \frac{2.8\ \mu s}{\sqrt{N_{\text{tracks}}}}$$

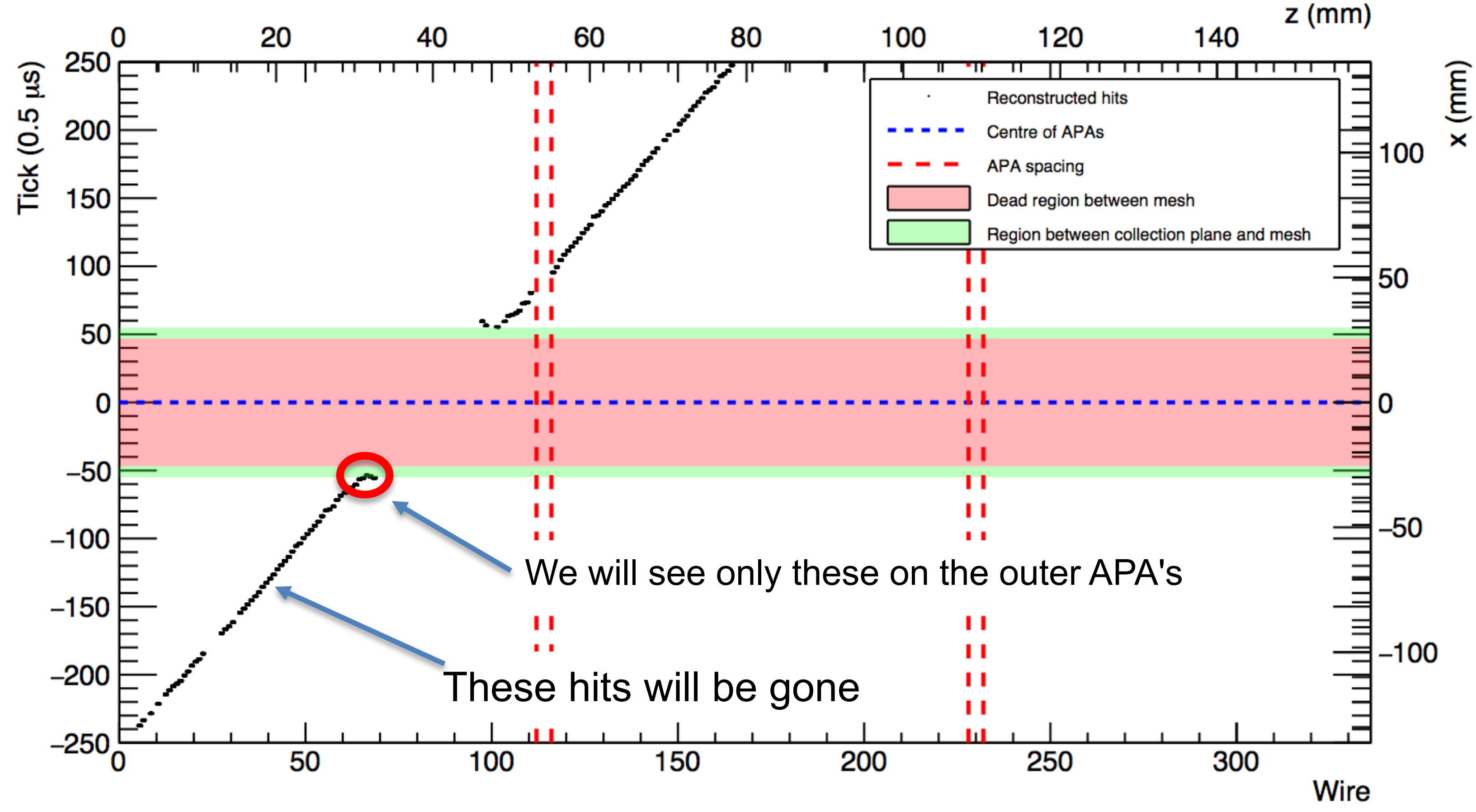
Here, N_{tracks} is the number of APA-crossing tracks.

You can average over the entire module or perform this APA-by-APA.

But only inner APA's.

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

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

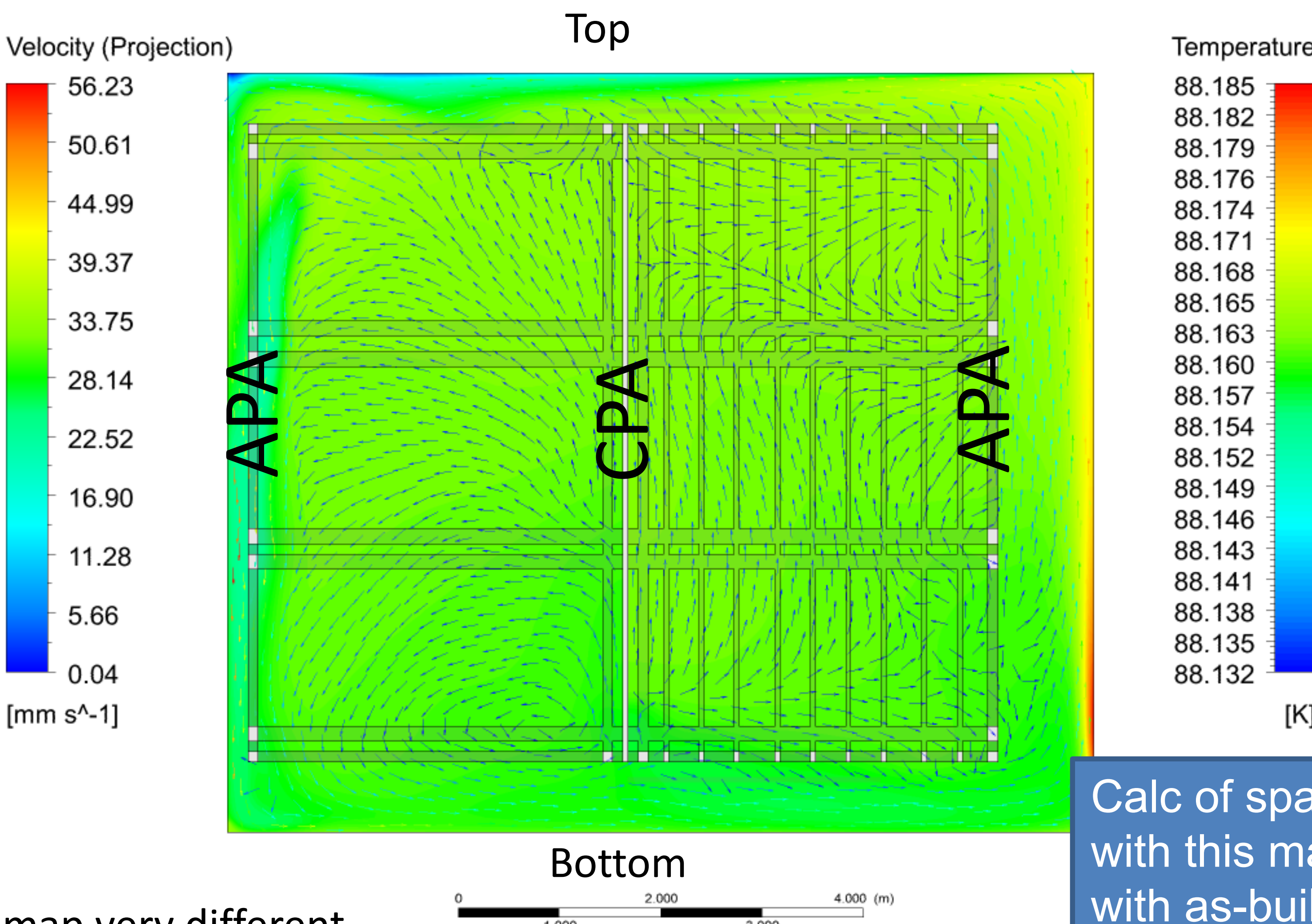


Cathode Piercers (single phase)

- Five muons per day per APA-sized cathode portion (four panels), if you require the muon also crosses an APA.
- Many more if the angle requirement is relaxed, just piercing the cathode and not an anode.
- Leigh Whitehead has an analysis that finds t_0 for cathode-piercing cosmic rays in ProtoDUNE-SP
- But it assumes symmetric space charge on either side of the cathode.
- Can find not only t_0 but can measure cathode flatness with enough crossers (assuming space charge is symmetric or negligible)

Temperature and Velocity @ X = 2m

Erik Voirin, DUNE DocDB 928-v1



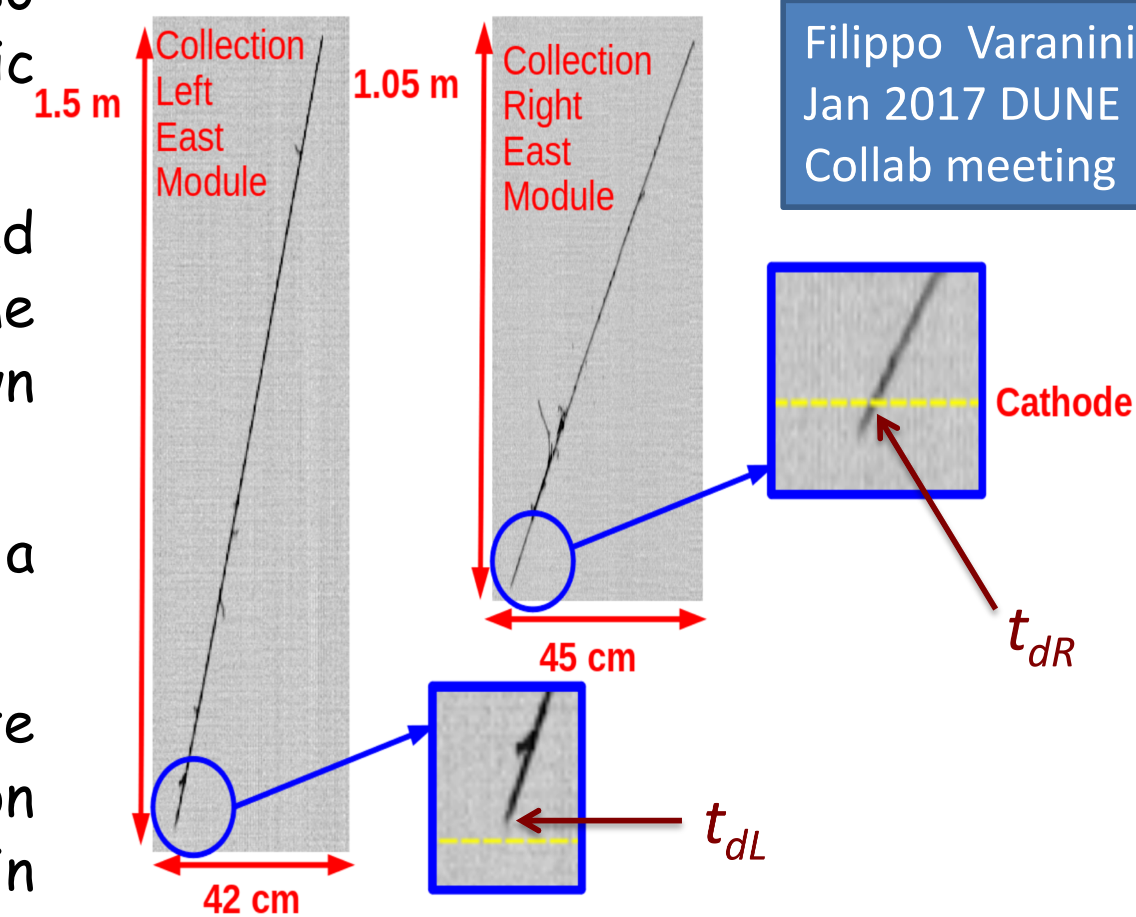
Calc of space charge with this map (updated with as-built cryo piping) is needed!

Fluid flow map very different on either side of the cathode

Indirect measurement of cathode distortions

- Cathode non-planarity can also be measured from data: cosmic μs crossing the cathode plane
- Measurement can be performed during run but takes a long time *underground* (results shown here refer to ~6 months)
- This measurement refers to a full and cold TPC
- The apparent drift coordinate of the point where the muon crosses the cathode plane in both TPC is considered t_{dR}, t_{dL}
- The difference $\Delta t_d = t_{dR} - t_{dL}$ is approximately proportional to the cathode distortion Δy in that point:

Filippo Varanini Jan 2017 DUNE Collab meeting



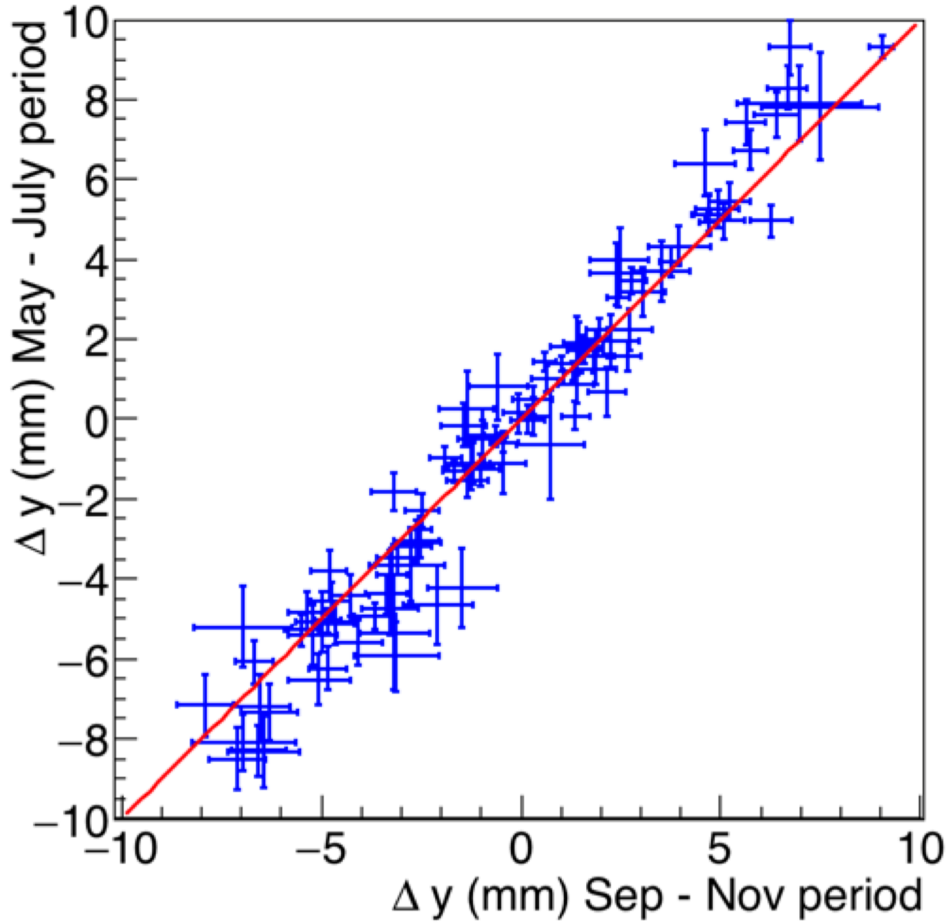
Yellow line marks nominal cathode position(Δy=0)

$$\Delta y \approx 1/3\, v_d \Delta t_d \qquad \sigma_{\Delta y} \sim 2mm$$

Time stability of cathode distortions

- Stability of the cathode distortions during run has been checked by the indirect method with cosmic muons
- The considered data-taking time has been subdivided in 2 equal periods (~3 months)
- No evidence of any change in local cathode distortions is found

F. Varanini



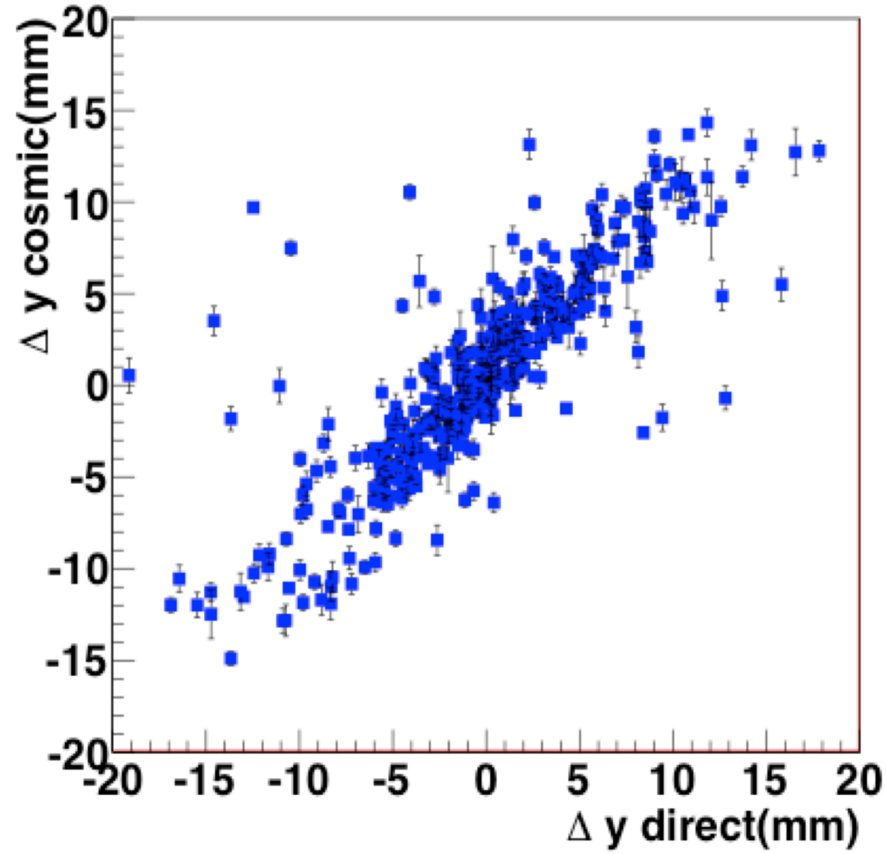
Cathode plane binned in pixels – need to map out distortions by cathode position

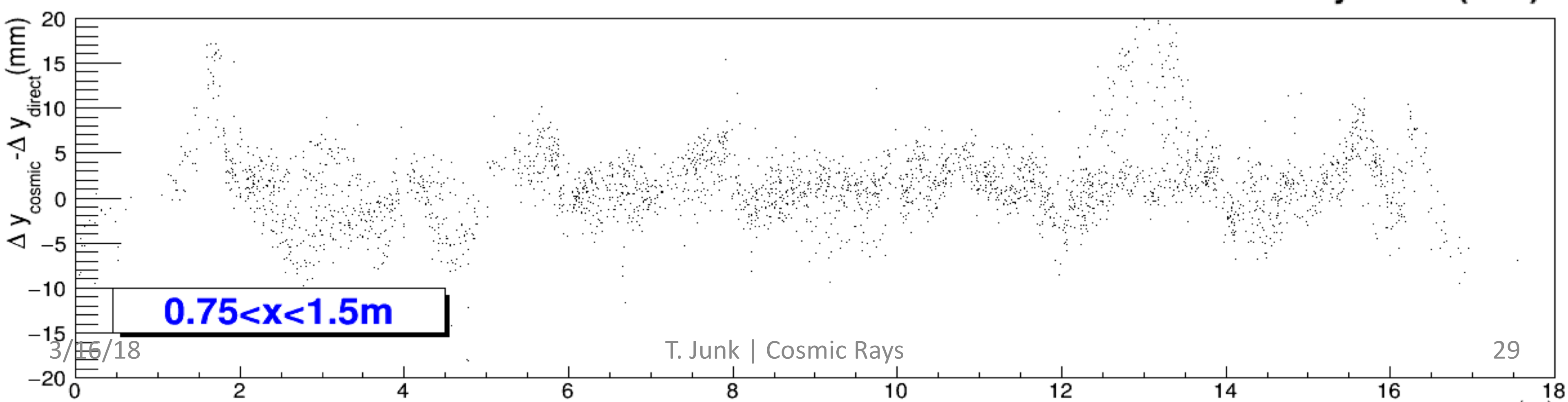
Comparison of direct/indirect measurements

- Results from the two measurements of cathode distortion are largely well correlated
- A few exceptions, localized in 1/2 panels. show no correlation or even anticorrelation. Might be related to mechanical "flipping" of panels

"Direct" = warm laser measurements

F. Varanini

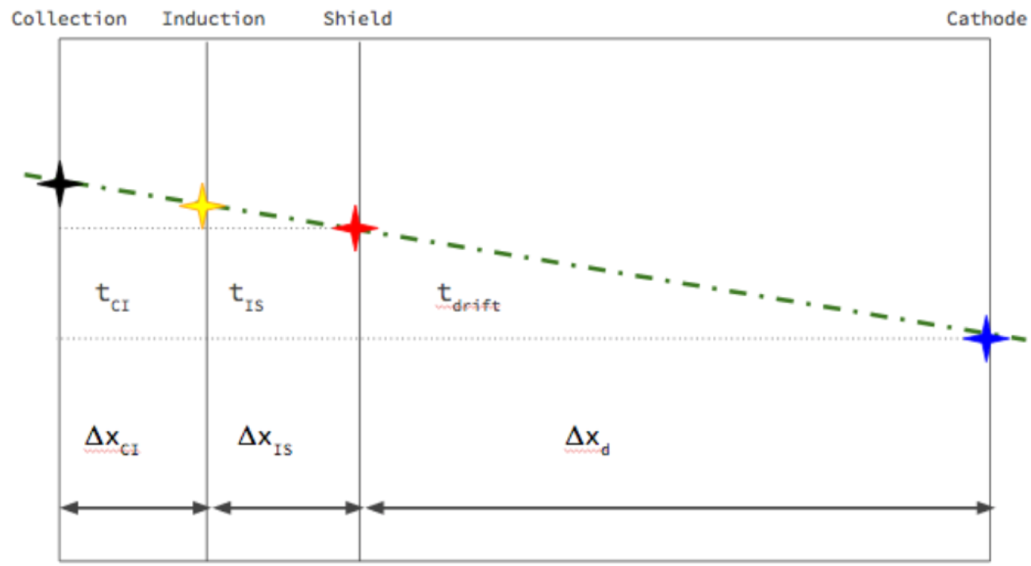




Once you know how far the cathode is from the anode, you get:

Drift Velocity by Anode-Cathode Piercing Tracks

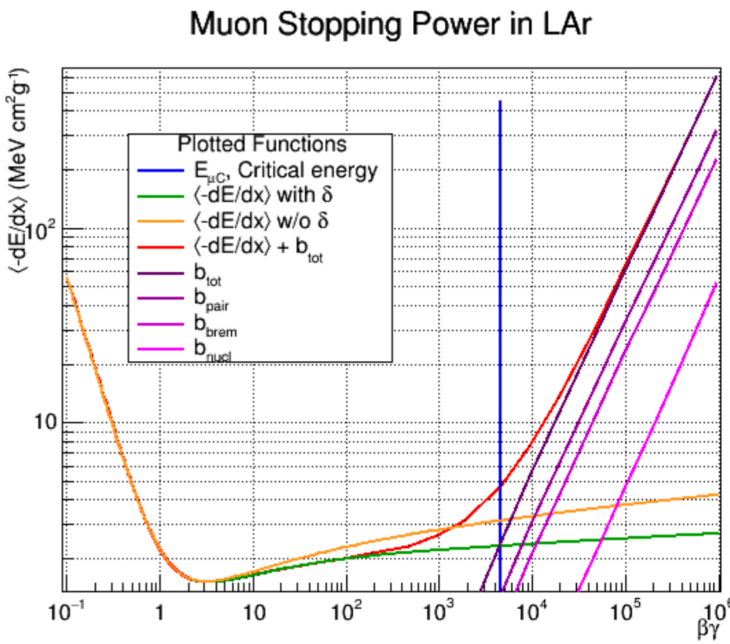
J.Raaf, J. Asaadi, LArIAT



- Use tracks that cross both anode and cathode
  - Span full drift distance of TPC
    - Latest hit spatially well-defined [at cathode], earliest hit at induction
    - Larger uncertainty in this measurement, due to width of hit time distribution and correction for faster drift in gap from shield to induction
    - Independent of absolute E field knowledge/assumptions, since drift time is just difference of earliest and latest hit times
  - Drift velocity = t_{drift} x distance
    - Measured drift time: $311.1 \pm 2.4\ \mu s$ → $v_{drift} = 1.51 \pm 0.1\ mm/\mu s$

dE/dx Calibration with MIPs

- MicroBooNE has an analysis of the uniformity of detector response using tracks
- Need t_0-tagged tracks
  - shouldn't be a problem in the FD. Tricky in ProtoDUNE-SP; even harder in ProtoDUNE-DP
- Absolute precision calibration of MIP scale complicated by the energy dependence and need to model the energy spectrum.
- Better measurement from stopping muons
  30/day/10 kt (Sowjanya)
  Michels -> stopping electron dE/dx

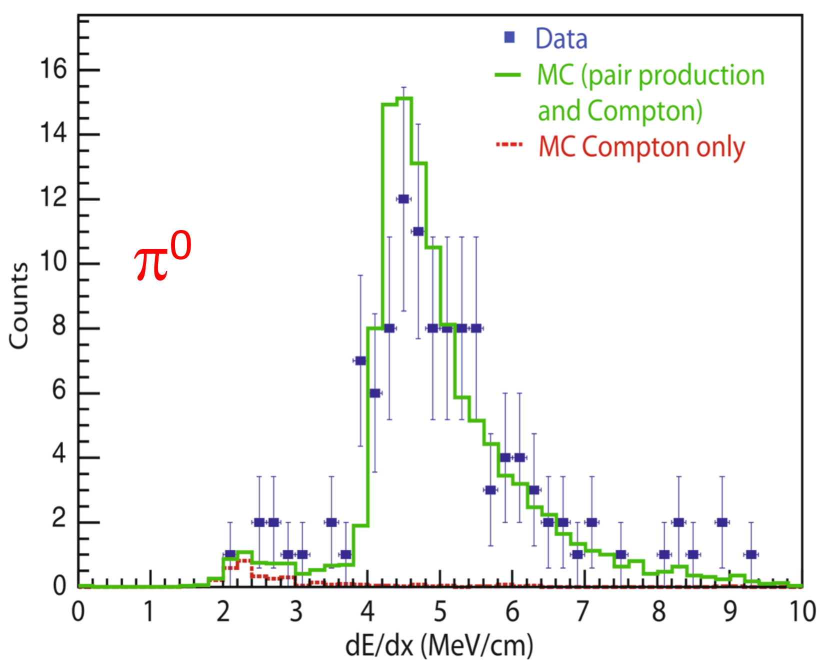


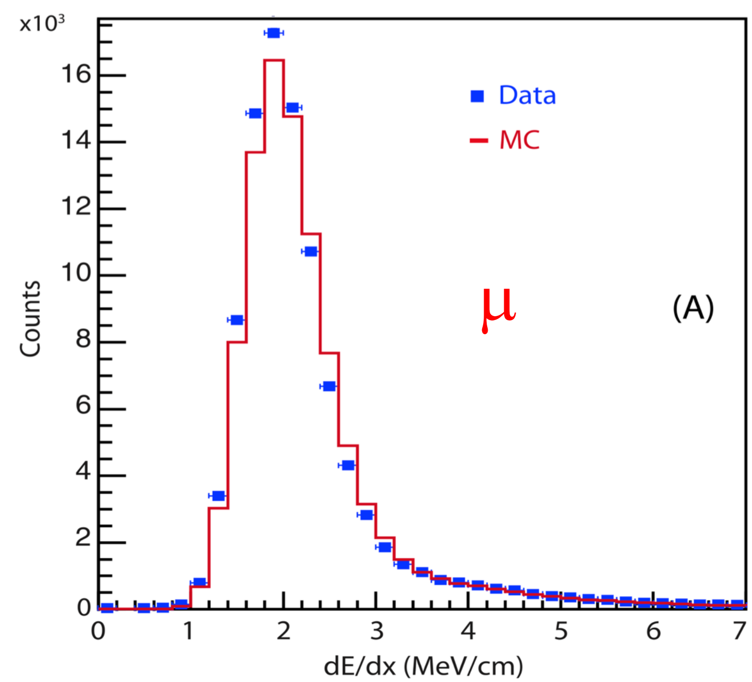
K. Ingles

dE/dx comparison

- Ionization density distributions from different physical samples in CNGS data are compared with MC expectations:
  - Low energy showers from isolated secondary π^0 show good agreement
  - Stopping muons from ν_μCC interactions of CNGS neutrinos show a small (~2.5%) underestimation

F. Varanini





Beam neutrino data, not cosmic rays!

Trying to do this with cosmic rays is harder – energy spectrum is less well known

M. Antonello et al., Eur. Phys. J. C (2013) 73:2345

Lifetime Measurement

- Tracks that leave hits at different distances from the APA provide a calibration sample for the lifetime.
- **ICARUS:** https://arxiv.org/abs/1409.5592 **(JINST 9 (2014) no.12, P12006)**
- **MicroBooNE:** https://arxiv.org/abs/1710.00396 (Varuna Meddage conf. proceedings, DPF 2017)
  - DUNE lifetime analysis module implemented for ProtoDUNE-SP for running in the nearline monitor
  - Uses APA-CPA piercers
- **LArIAT:** Single-track and multi-track methods – see Jen's talk at the January collab meeting.
- **35-ton prototype:** Matt Thiesse's Ph.D. Thesis: very difficult due to low signa/noise). Multi-track method.

ICARUS Lifetime Measurement

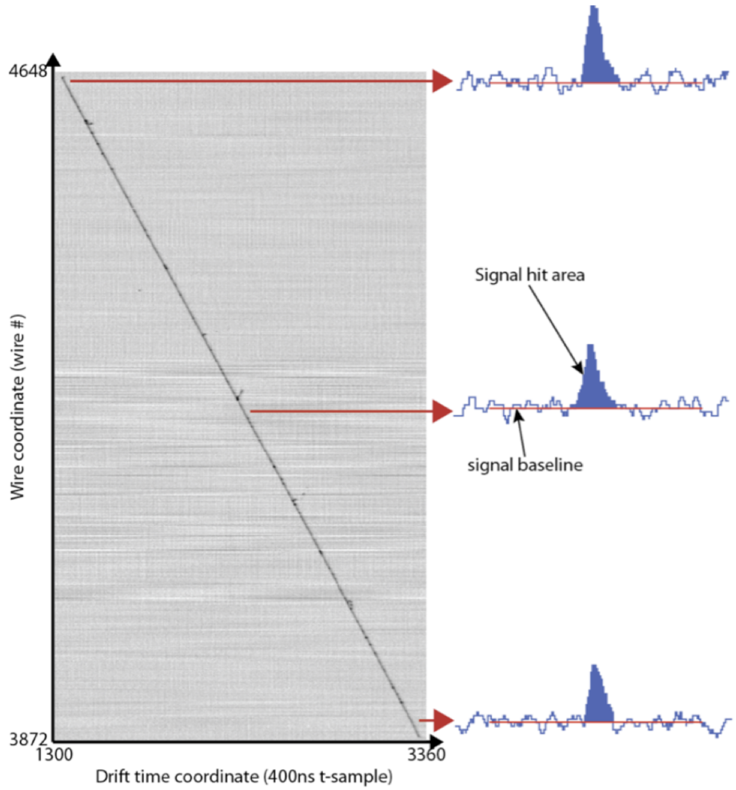


Figure 1. Example of a track used for purity measurement extending over 776 wires and 2060 t-samples, corresponding to a drift time of 824 μs. Signals of three different hits are also shown.

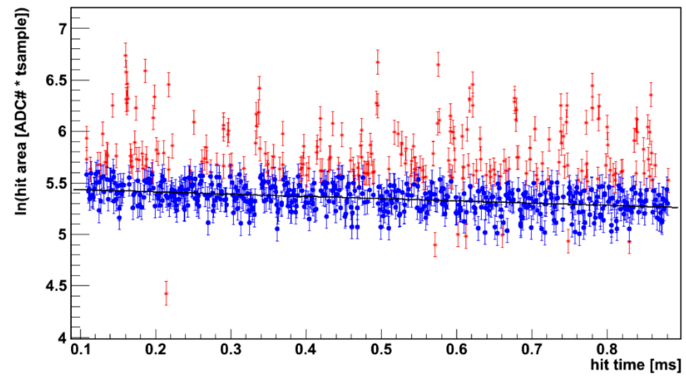


Figure 3. Pulse hit area as a function of the drift time for the track shown in Figure 1; in red star the $\sim$ 230 hits that are removed by the truncation method, in blue circle the $\sim$ 510 surviving hits. The linear fit of the logarithm of the hit signal vs. drift time used to extract the electron signal attenuation is also shown (black line): for this event λ_T = (0.212 $\pm$ 0.022) ms^{-1}.

Truncated means get more information out of Landau (convoluted with Gaussian) hit charges

Precision of Lifetime Measurement

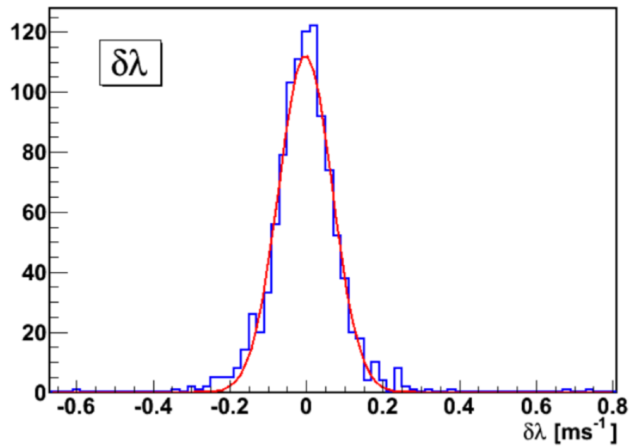


Figure 5. Distribution $\delta\lambda_T$ defined as the difference between the single-track λ_T measurements and the corresponding average value. The mean value and the width of the distribution obtained from the gaussian fit are (-0.0029 $\pm$ 0.0022) ms^{-1} and (0.07$\pm$ 0.002) ms^{-1} respectively.

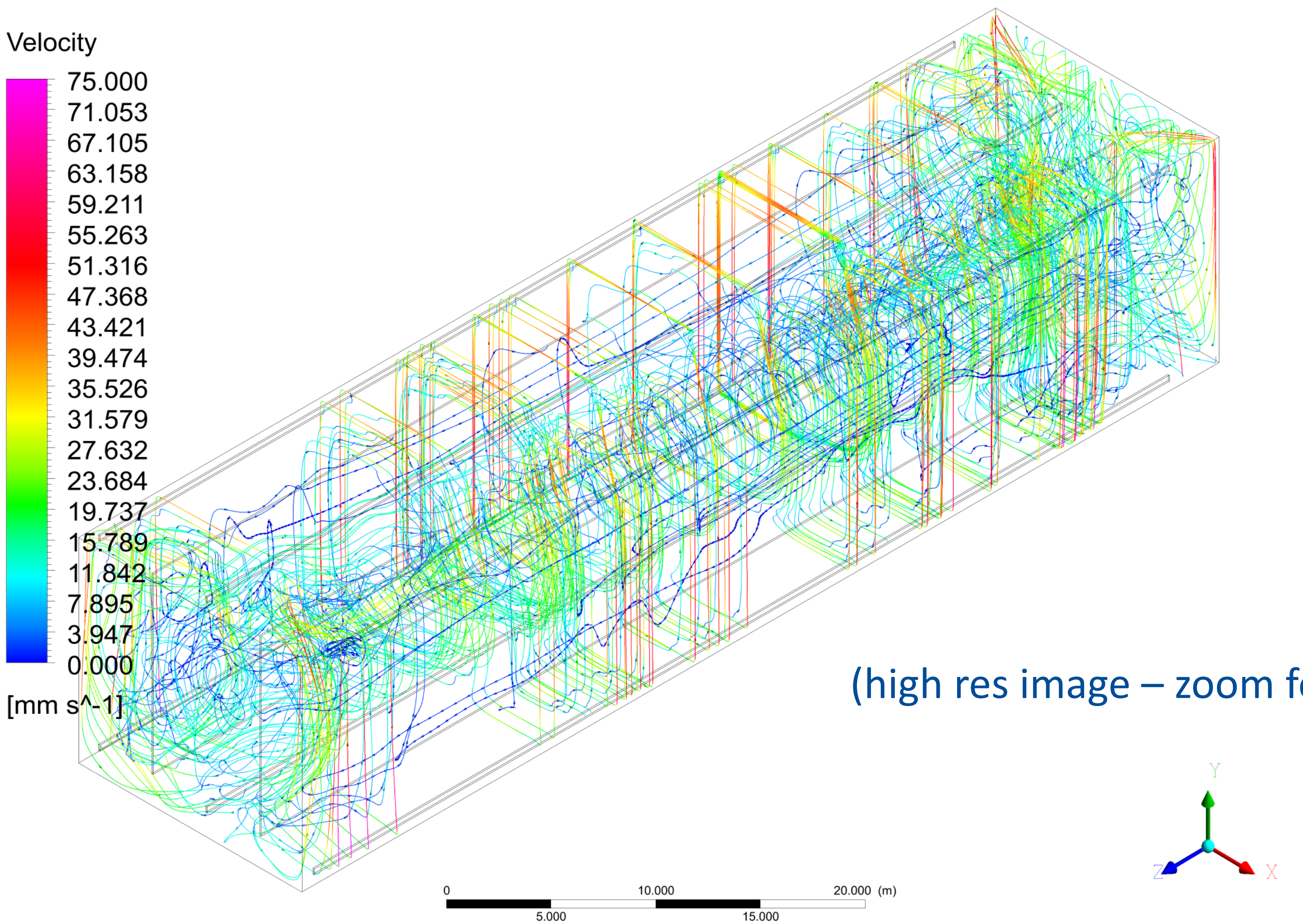
λ=1/τ is a more natural variable as the uncertainties don't depend on τ

For a 3 ms lifetime, one gets about a ±30% measurement of the lifetime for each track

Five muons per day per APA, 1/day if you want the muon to go in the opposite CPA panels.

Velocity Streamlines

Erik Voirin,
DUNE DocDB 1046-v2



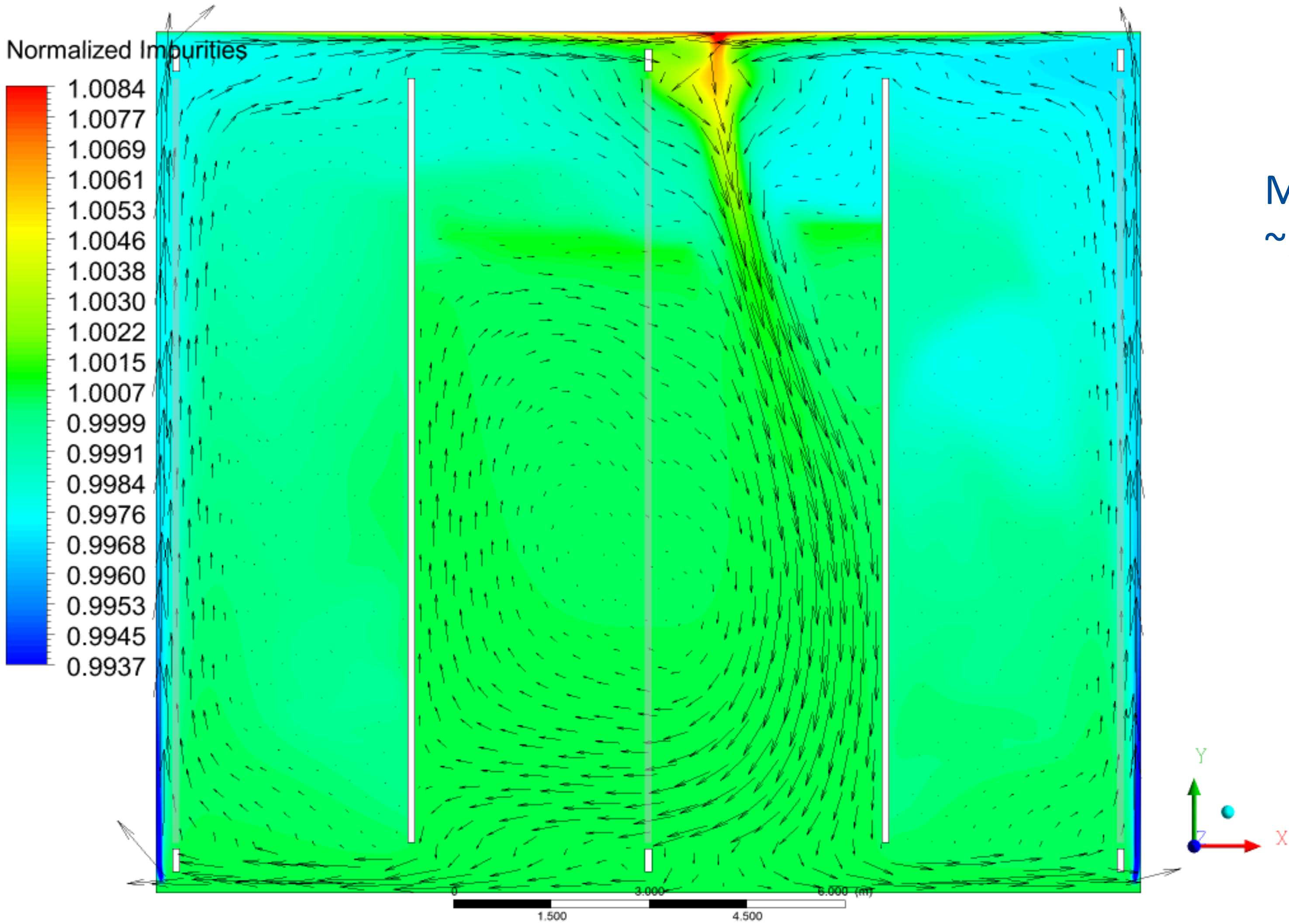
(high res image – zoom for detail)

124 discharge ports

Impurity Contour and Velocity @ Z=0

FD-SP
Near Mid-Plane

Erik Voirin



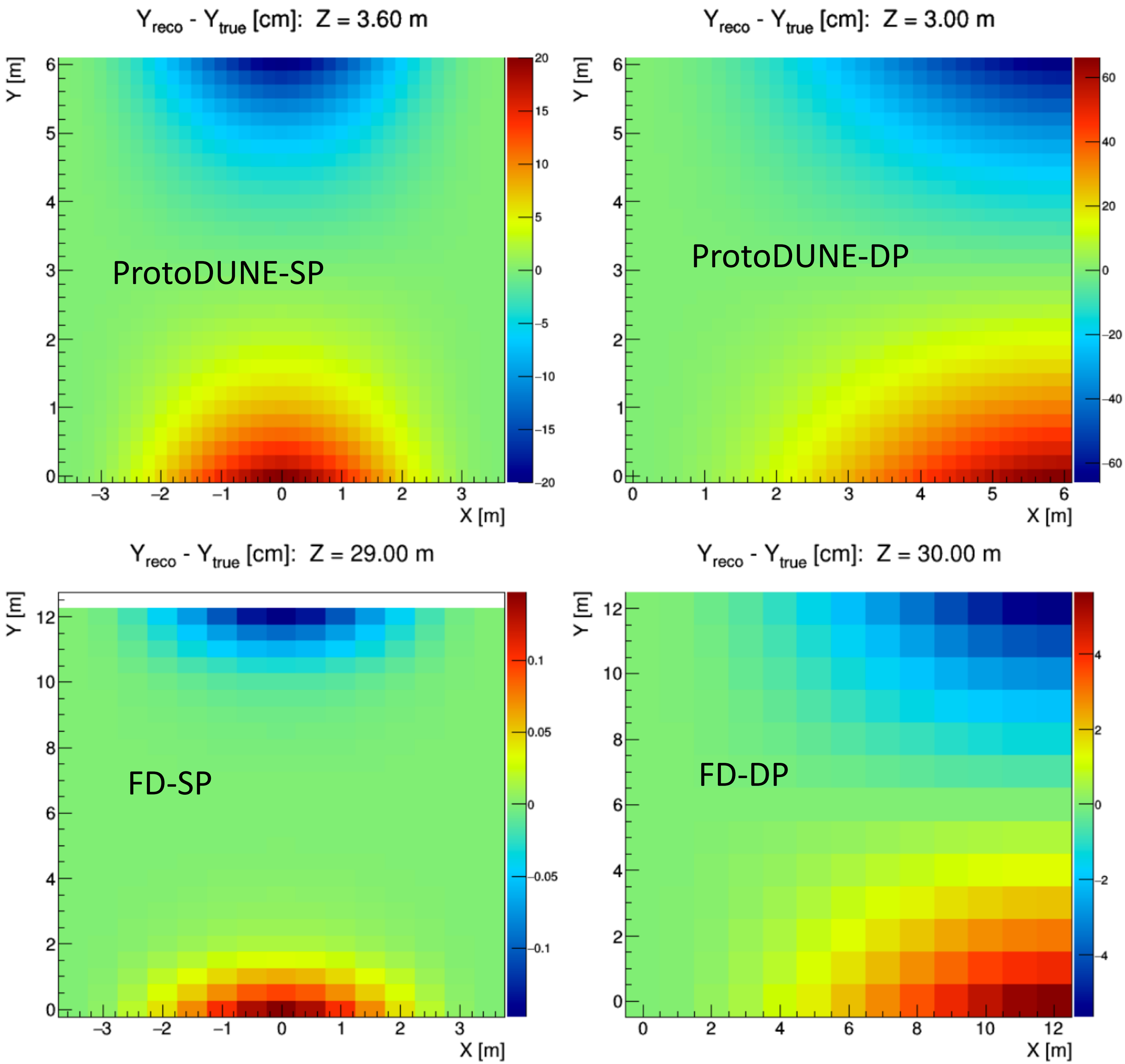
Max. variation ~2%

124 discharge ports

Space Charge

- Space charge from cosmogenic sources not expected to be significant
- Space-charge effects in ProtoDUNE-SP and ProtoDUNE-DP expected to be quite large – proportional to the cosmic-ray rate and the cube of the drift time
- Up to 20 cm of lateral distortion in hits in ProtoDUNE-SP due to cosmic-ray-induced space charge.
- Beam-induced space charge not yet estimated.
- Calibration of space charge in ProtoDUNEs needed to be able to extrapolate measurements to the FD (e-field distortions affect recombination for example, and thus the EM energy scale).
- Broken Field Cage resistor has an effect on the field that can be measured in a similar way to space charge

Space Charge induced distortions in apparent vertical position of a hit.



Mike Mooney

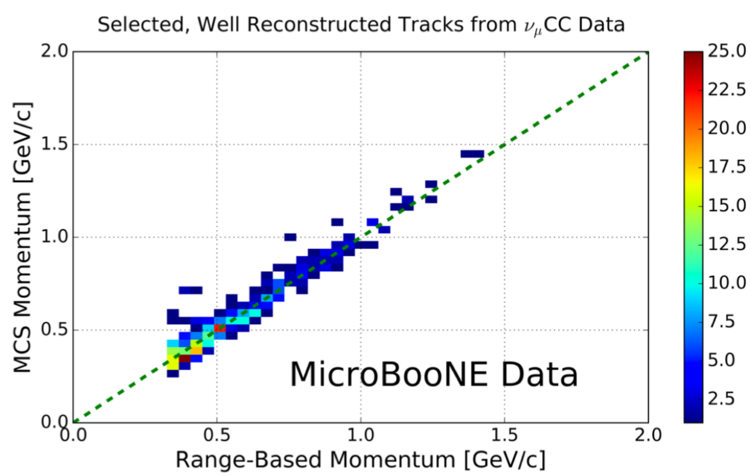
Recombination vs Angle

- Same analysis as the MIP scale analysis, except binned in the angle with respect to the electric field.
- Cosmic rays are depleted at horizontal angles
- Even rock muons from the beam are depleted at angles that point along the electric field.
- Energy spectrum of cosmic rays will depend on angle though!
- Need stopping muons if you want precise, absolute scale.

Michels provide electron information, but are tricky – a fraction the energy is scattered about in little deposits not connected to the track. Should be do-able.

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)**

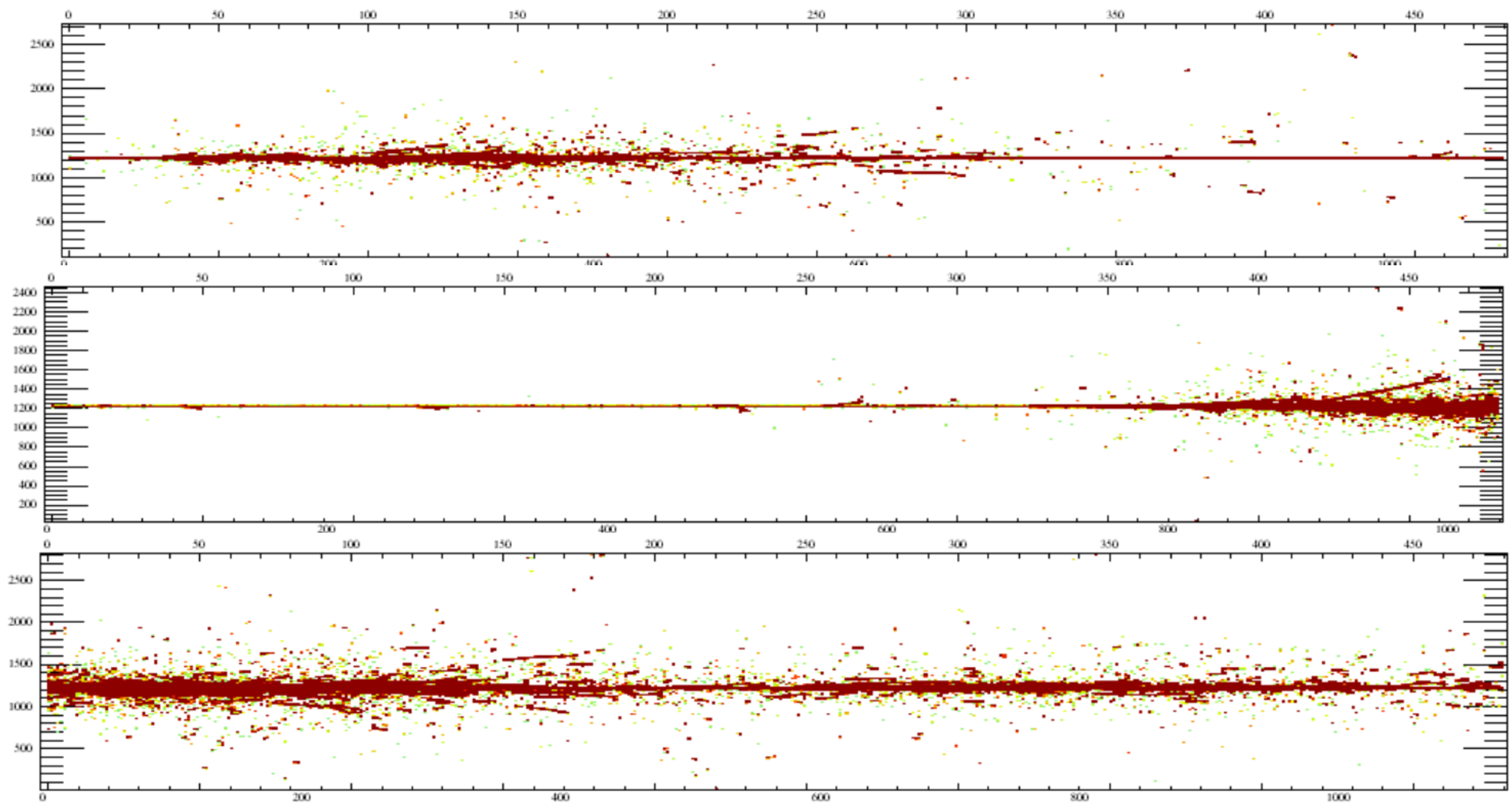


Selected beam neutrino-induced muon candidate tracks

- 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.

More Speculative: EM Showers

K. Ingles: 10 TeV horizontal muon simulated in the FD



EM Showers

- Cosmic rays will be the most abundant source of EM showers in the DUNE FD
- Some π^0's (if memory serves, possibly one in 1000 cosmic ray events has one), but mostly bremsstrahlung and pair production
- Spectrum of EM energy loss is model dependent.
  - energy spectrum of cosmic rays entering detector
  - interactions of high-energy muons with argon atoms
- We measure EM energy deposits though.
- Is there any information in that? Showers have lots of stopping electron tracks in them, but they are overlaid with many blips.

ICARUS π^0 Invariant Mass Reco

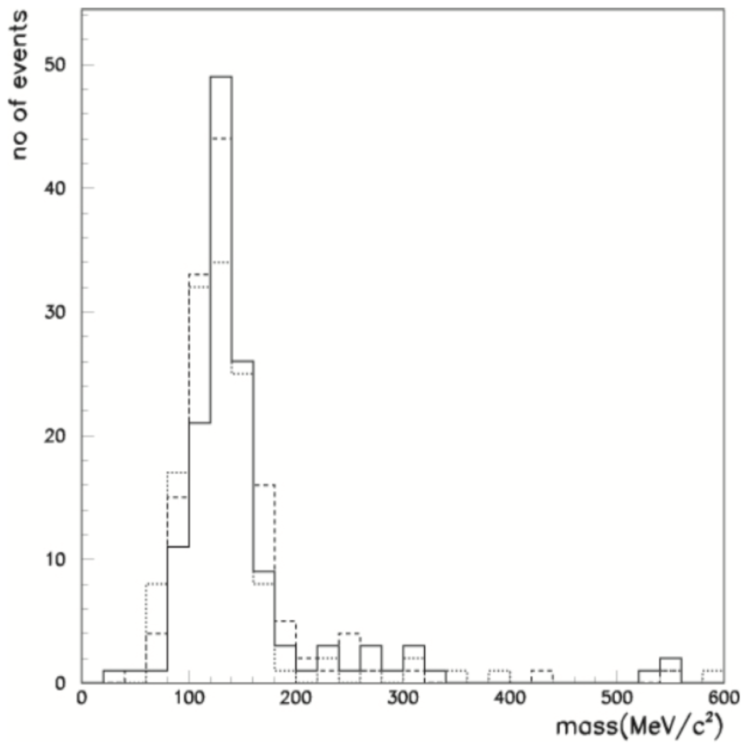


Fig. 7. (γ,γ) invariant mass distributions (solid, dotted and dashed lines) of three different laboratories involved in the data analysis.

ICARUS Collab.
arXiv:0812:2373

212 Candidate Events, Pavia Surface Run

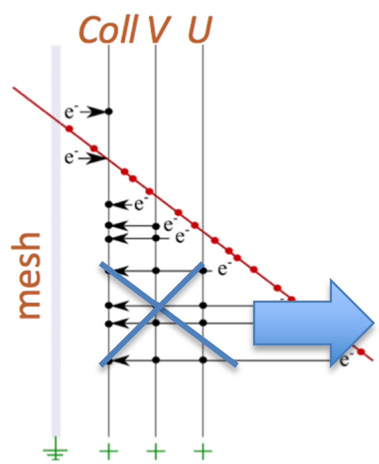
Summary of Approx. Rate Info

- Cosmic-ray rate per year in 4 modules: 3M
- Cosmic rays passing through 1 meter horizontal at the 4850' level: 4/day
- Average muon energy: 283 GeV
- Fraction of non-showering muons: ~60%
- Vertical-gap crossers (non-showering): 4 to 9 per day per gap
  - The once every 2-3 days per wire in Sowjanya's talk was for APA-CPA crossing muons
- Horizontal-gap crossers (non-showering): 5 to 10 per day per gap
- Cathode-Anode piercing tracks: 5/day per APA side (no requirement on which cathode it hits)
- Stopping muons: 30/day/10kt

Extras

Hits on the Outer Side

- Electric field drifts electrons away from the APA, towards the cryostat wall
- Hits made inside the wire planes will still be there, but they will have different pulse shapes (asymmetric induction-plane signals)
- Samples of these hits can be selected for study



Electron Diverter

To be installed between "some" of the APA's in ProtoDUNE-SP to determine if they should be included in DUNE FD-SP

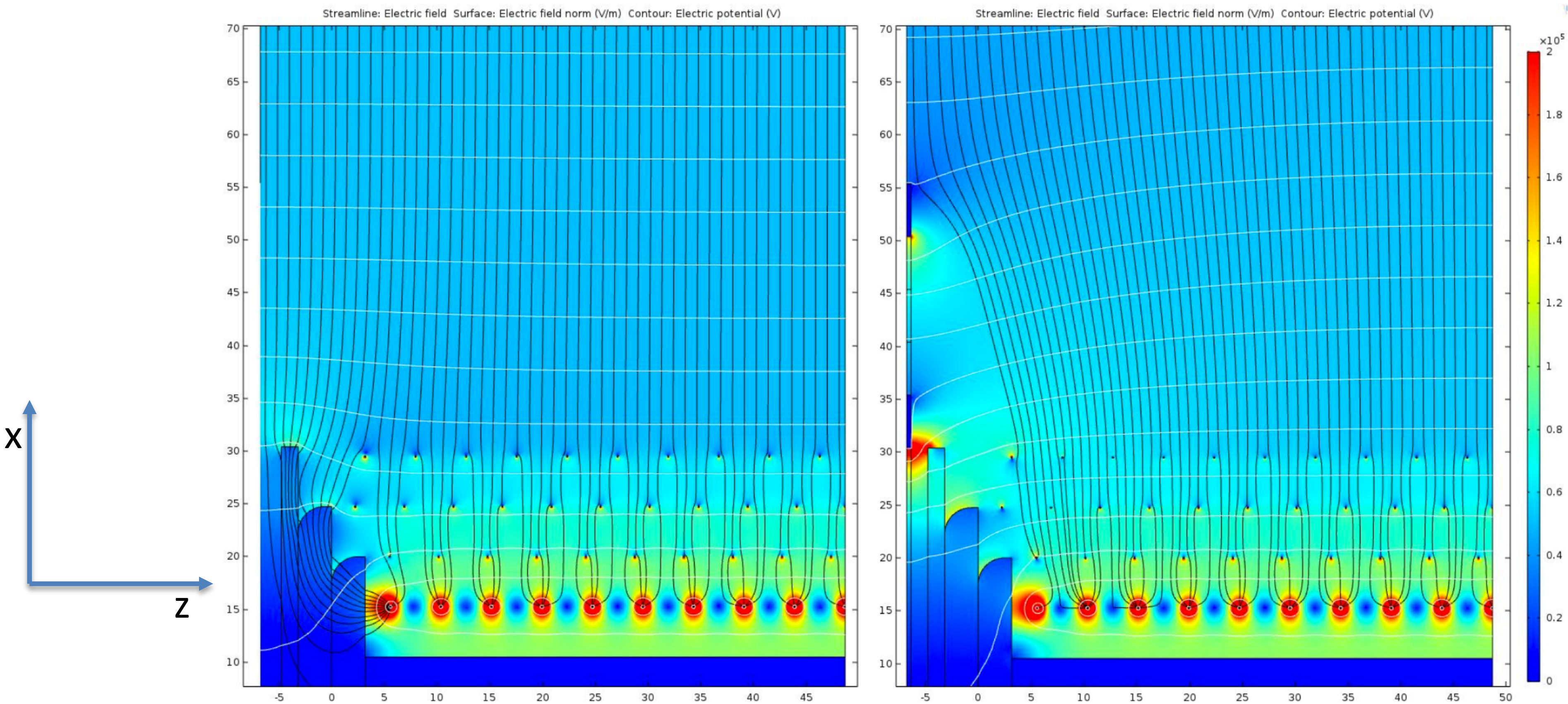
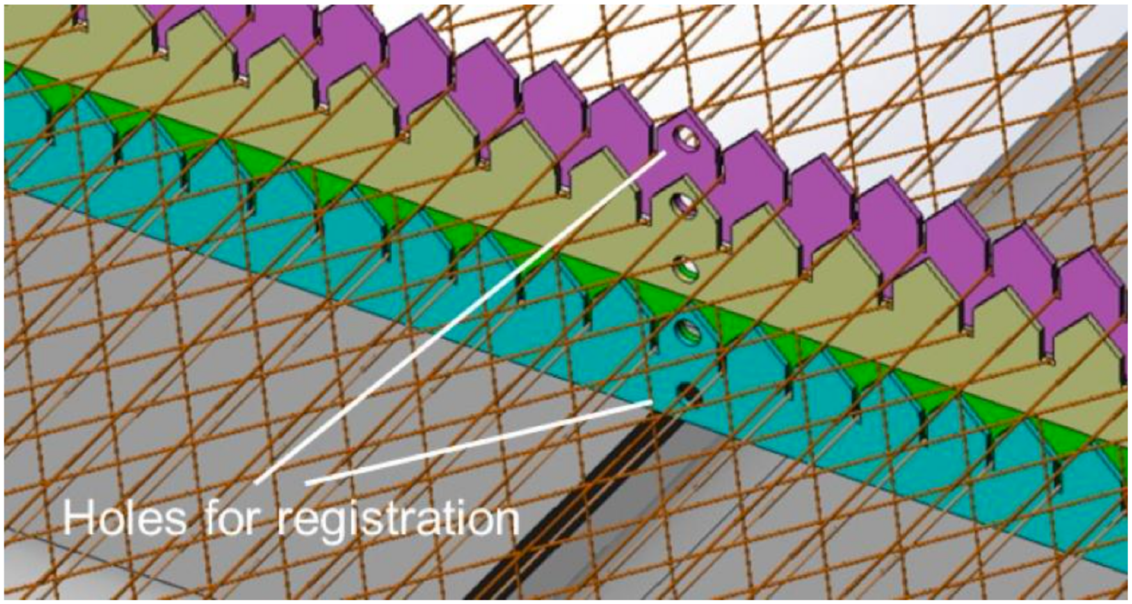


Figure 2.11: Left: field map of the region near the inactive gap of an APA without the electron diverter; Right: field map with the electron diverter in place. Electric field lines are shown in black, equipotential contours are in white, and electric field strength is represented in color gradient.

DUNE Doc 1794 (PD-SP TDR)

Wire Sag

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

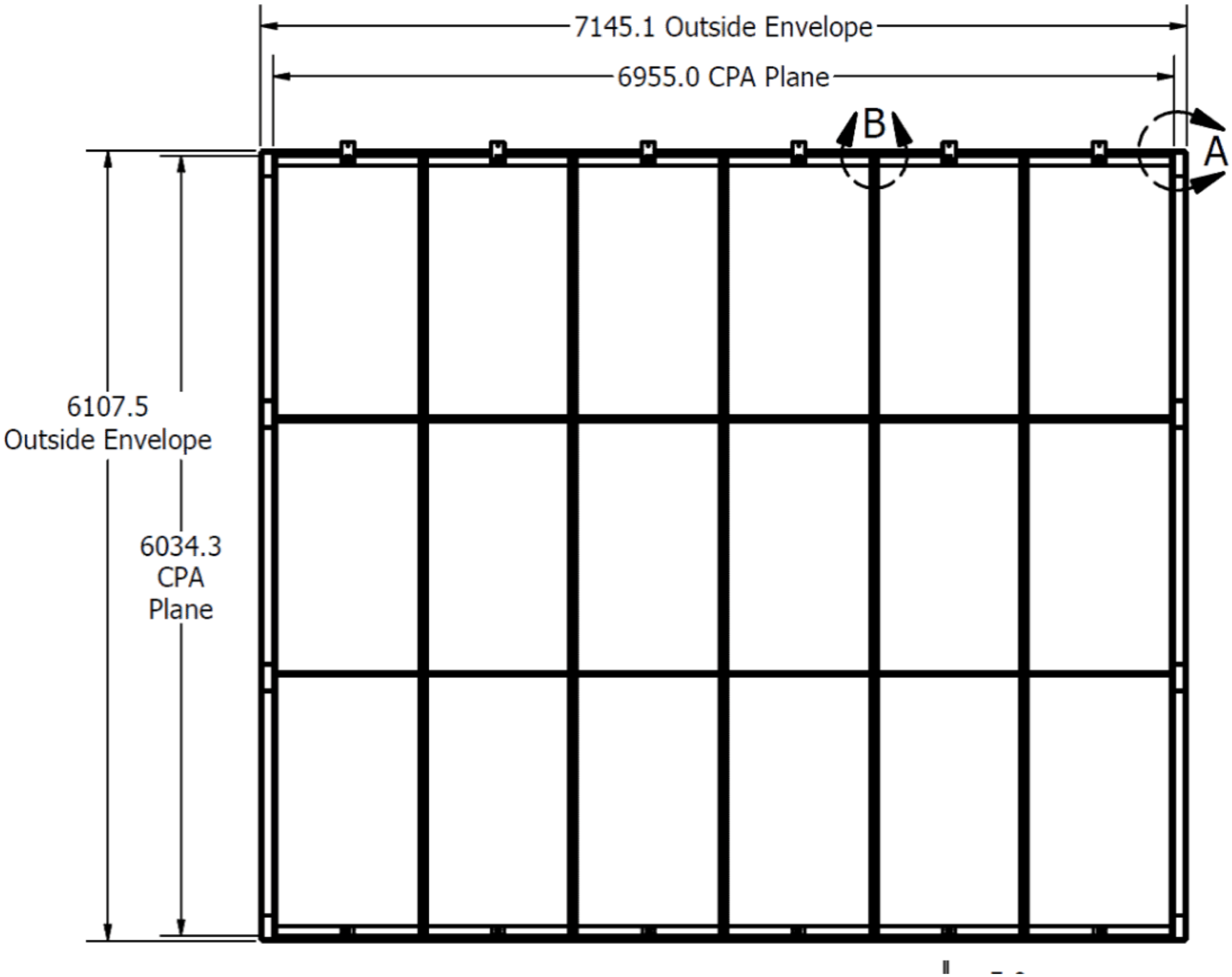


ProtoDUNE-SP TDR

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



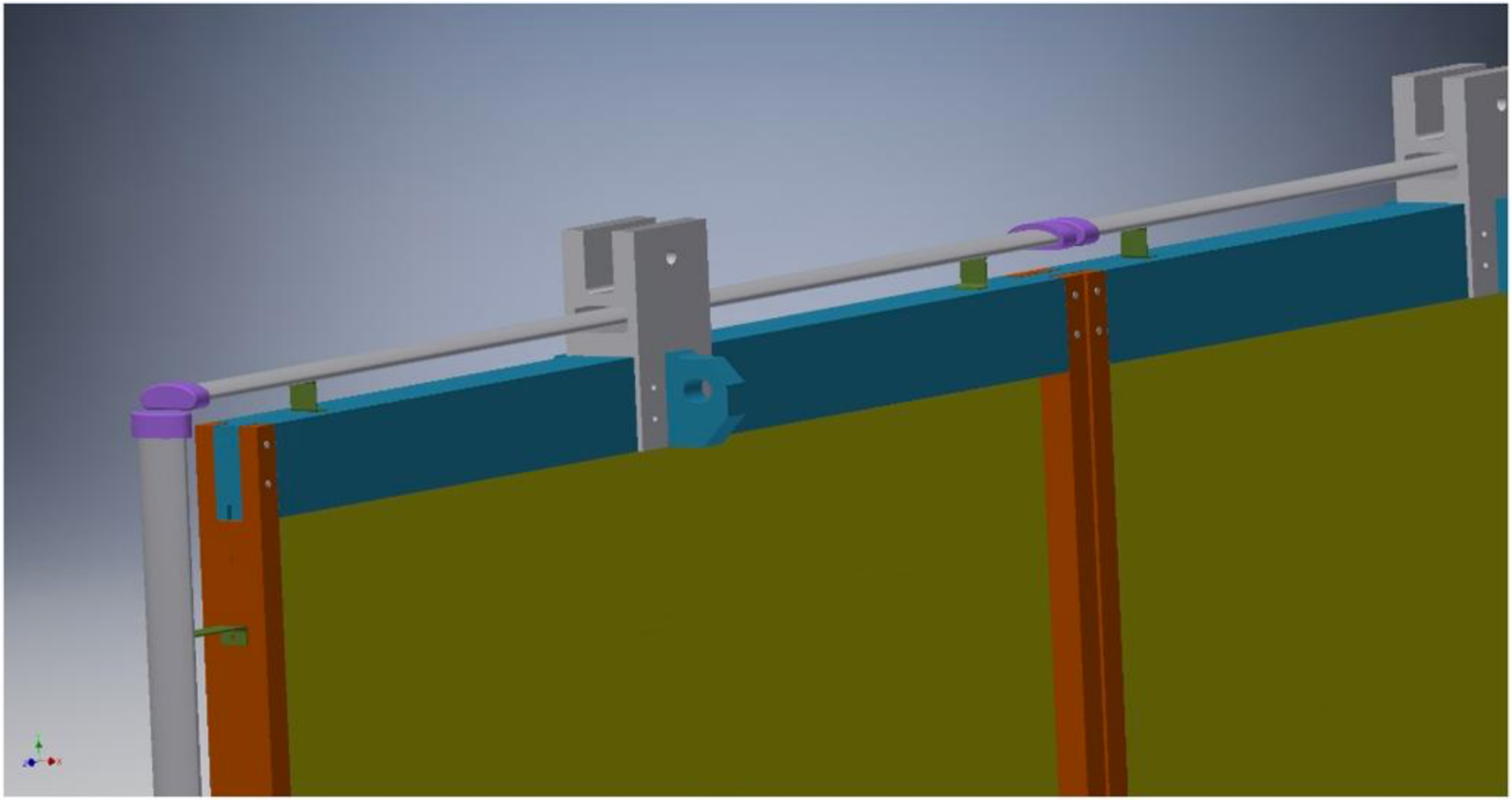
Can we "X-ray" the frames with tracks?

Look for gaps in CPA-crossers

The reco image will tell us about space charge

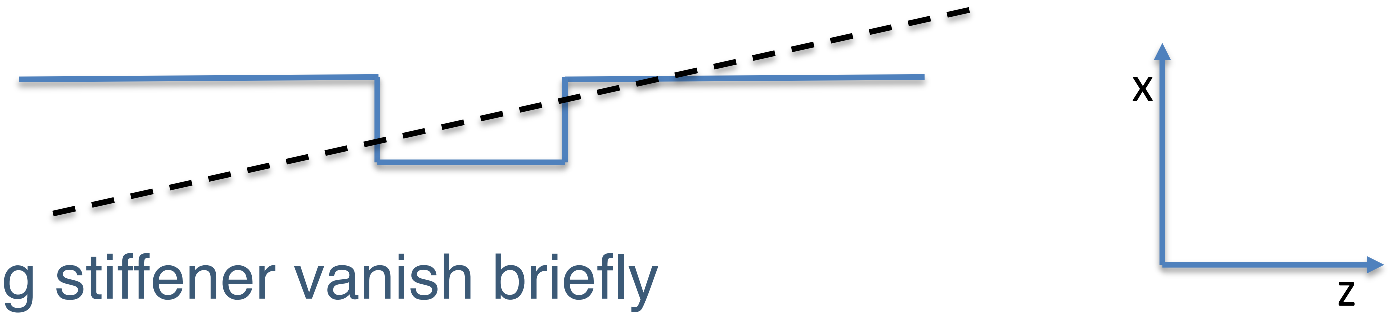
CPA Geometry

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...