DUNE Far Detector Calibration with Cosmic Rays

Tom Junk

DUNE Far Detector Calibration Workshop

June 18, 2019

Many thanks for materials stolen without permission: David Adams, Jonathan Asaadi, Bruce Baller, Sowjanya Gollapinni, Kevin Ingles, Vitaly Kudryavtsev, Kendall Mahn, Mike Mooney, Ajib Paudel, Jen Raaf, Aidan Reynolds, Hannah Rogers, 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.
- ~1.3 million useful interactions per year per module

- 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

Uses of Cosmic Rays

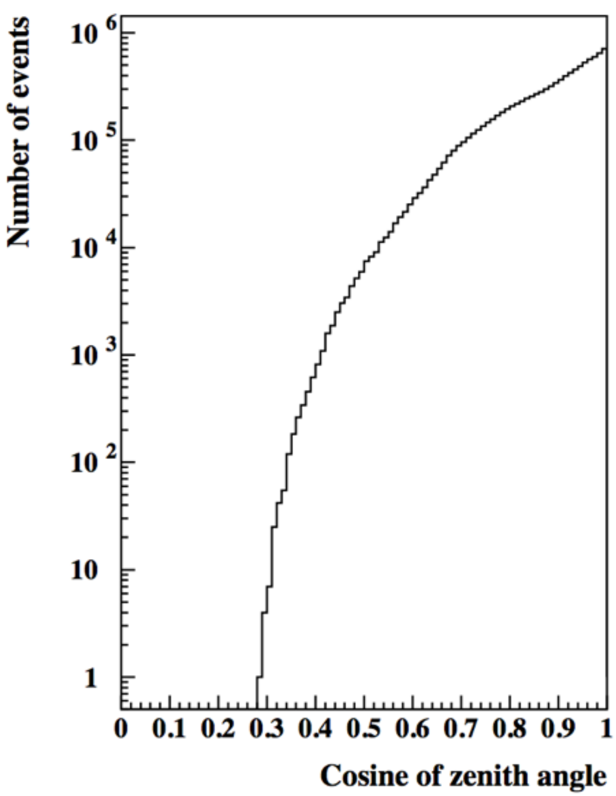
- Check the channel map
- Identify disconnected channels. The pulser only tests up to preamp input. Need to see physics signals. ^{39}Ar serves this role too.
- Calibrate pulse shapes – field response of the detector
- Measure electron lifetime (maybe ^{39}Ar can do this too)
- Measure dQ/dx uniformity across APA faces (channel calib). (^{39}Ar too)
- Calibrate dQ/dx --> dE/dx using known MIPs (^{39}Ar too)
- Measure drift velocity using Cathode-Anode Piercing Tracks
- Align the APAs and CPAs
- Calibrate charge and drift response in inter-APA gaps

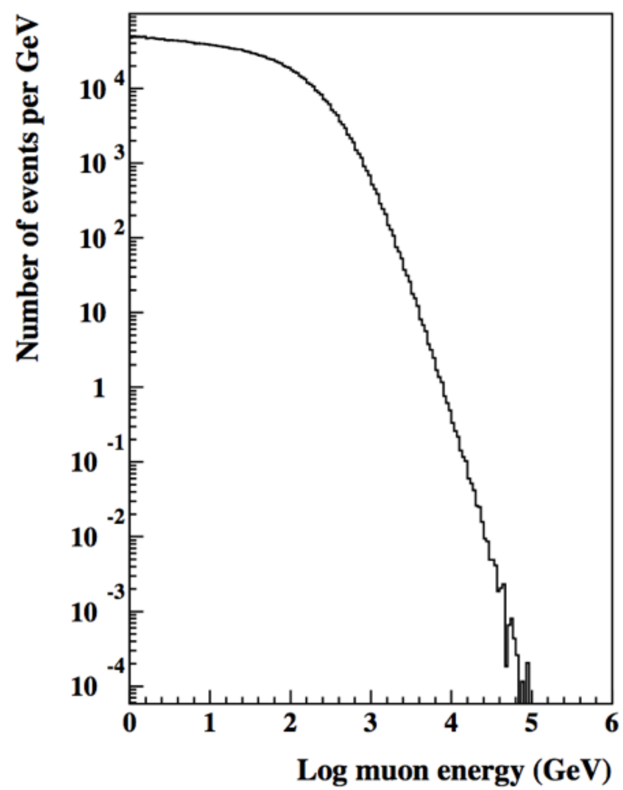
Uses of Cosmic Rays

- Characterize electric field nonuniformity
  - space charge (not expected for FD-SP but FD-DP will need to check)
  - field cage nonuniformities
- Test relative timing of TPC and photon detectors
- Explore saturation characteristics of front-end and ADC
- Measure long-range induction effects in the APAs (and FEMB effects)
- Michel electrons test the low-energy EM response

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)

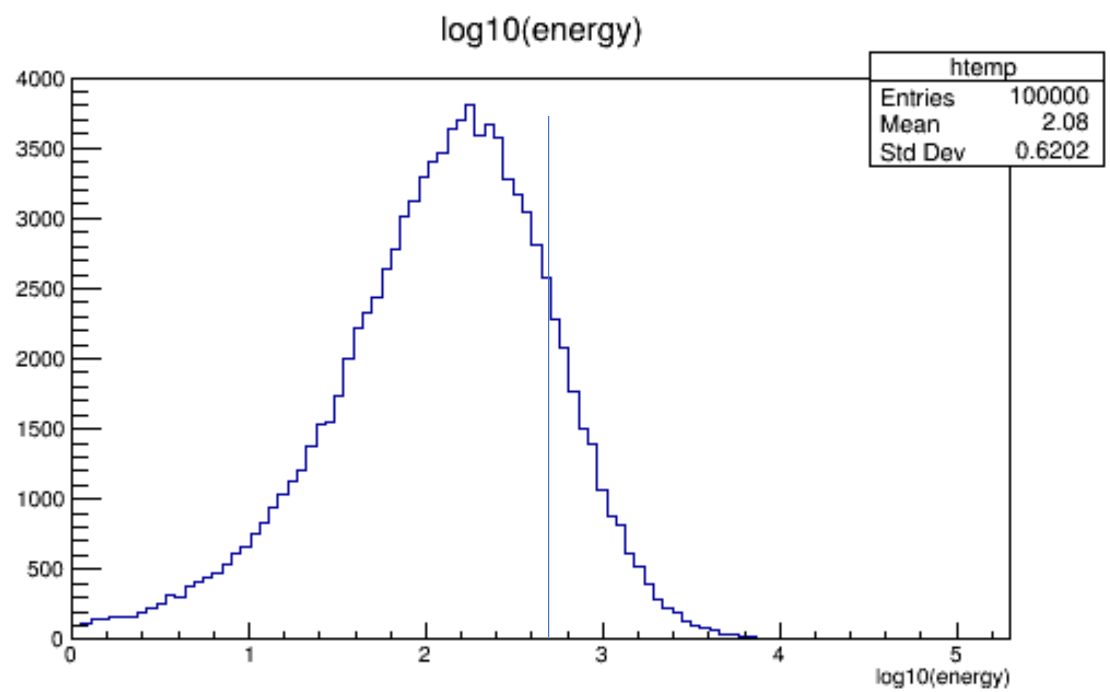
Syst. Uncertainty is ±20% in total rate. Shapes are uncertain too!

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

Rates For One DUNE Far Detector Module (SP)

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.

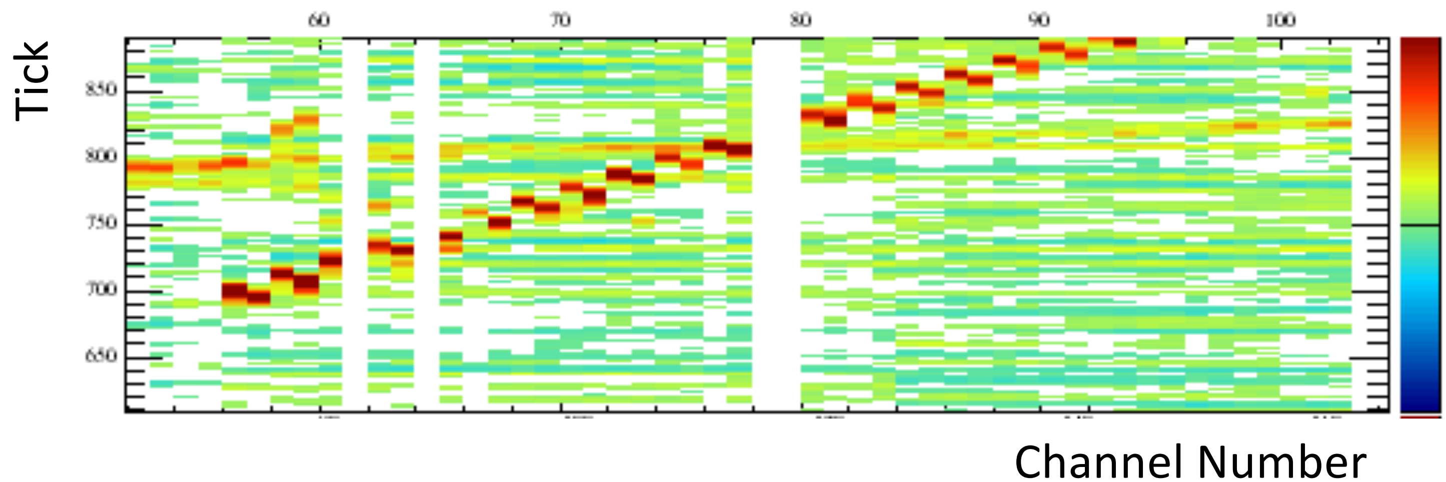
Sample	Annual Rate	Detector Unit
Inclusive	1.3×10^6	Per 10 kt module
Vertical-Gap crossing	3300	Per gap
Horizontal-Gap crossing	3600	Per gap
APA-piercing	2200	Per APA
APA-CPA piercing	1800	Per active APA side
APA-CPA piercing, CPA opposite to APA	360	Per active APA side
Collection-plane wire hits	3300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

Collection-plane channels get hit 10x per day. Induction-plane channels are hit more.

Some studies like checking for dead channels can use looser selections.

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.



- ProtoDUNE-SP channel map was correct on Day 1 of operations due to good communication and hard work.
- DUNE FD-SP map is likely just a scale-up. Cable swaps like this may be unlikely (all boards)
- Two days of cosmic ray data should suffice for this and also spot dead channels that stay dead. Intermittent channels are more difficult.

Staging Cosmic-Ray Measurements

- Cosmic ray rates are low at the 4850' level. 10x per collection-plane wire per day.
- For rapid measurements and stability checks, we will have to loosen up cuts. E.g. use photon detector timing to locate an event in *x* and not rely on anode-cathode piercing tracks
- Some measurements can be done inclusively by assuming uniformity of the detector.
  - e.g. assume lifetime is the same everywhere – get a number within an hour.
  - Relax the assumption to get a more differential measurement takes more data.
- Looking at average hit response on a channel takes a few days' data. Looking along length for shadows of other wires takes thousands of times more data.

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 2018 collab meeting.
- **35-ton prototype:** Matt Thiesse's Ph.D. Thesis: very difficult due to low signal/noise). Multi-track method.

ICARUS Lifetime Measurement

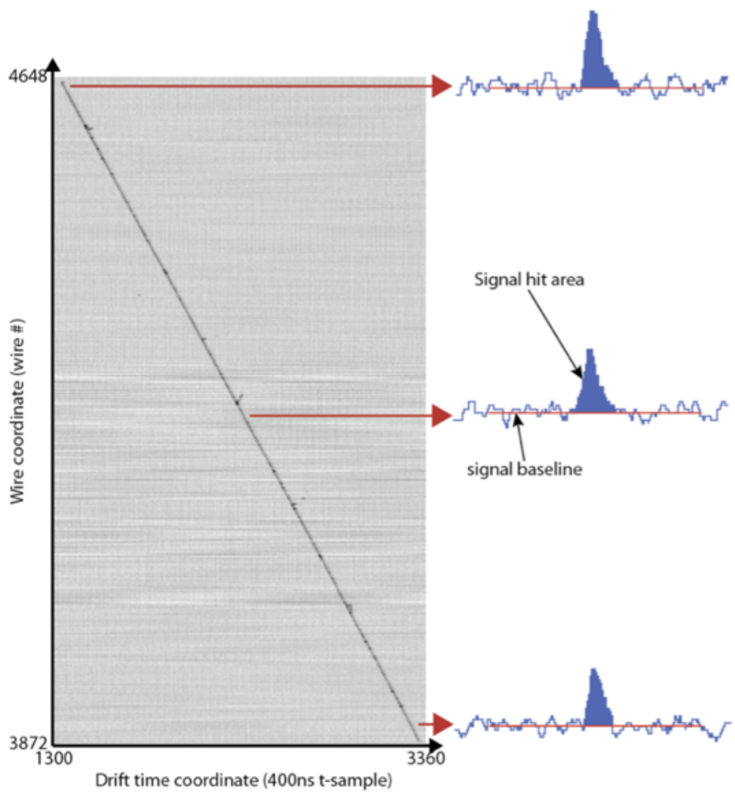


Figure 1. Example of a track used for purity measurement extending over 776 wires and 2060 t-samples, corresponding to a drift time of 824 μs. Signals of three different hits are also shown.

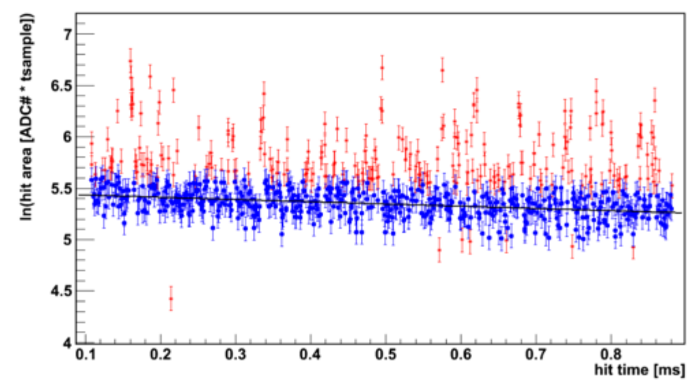


Figure 3. Pulse hit area as a function of the drift time for the track shown in Figure 1; in red star the $\sim$ 230 hits that are removed by the truncation method, in blue circle the $\sim$ 510 surviving hits. The linear fit of the logarithm of the hit signal vs. drift time used to extract the electron 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

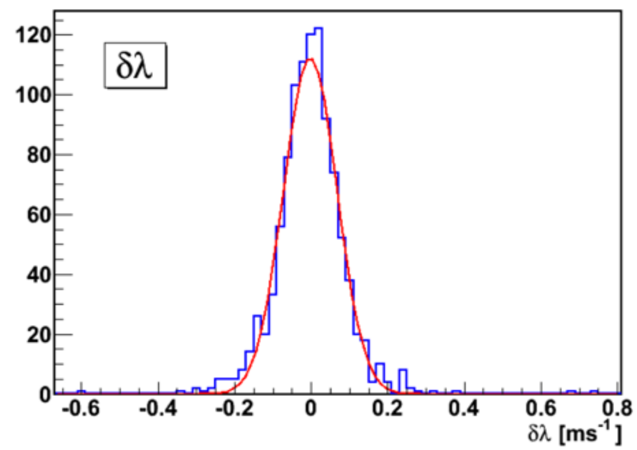


Figure 5. Distribution $\delta\lambda_T$ defined as the difference between the single-track λ_T measurements and the corresponding average value. The mean value and the width of the distribution obtained from the gaussian fit are (-0.0029 $\pm$ 0.0022) ms^{-1} and (0.07$\pm$ 0.002) ms^{-1} respectively.

$\lambda = 1/\tau$ 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

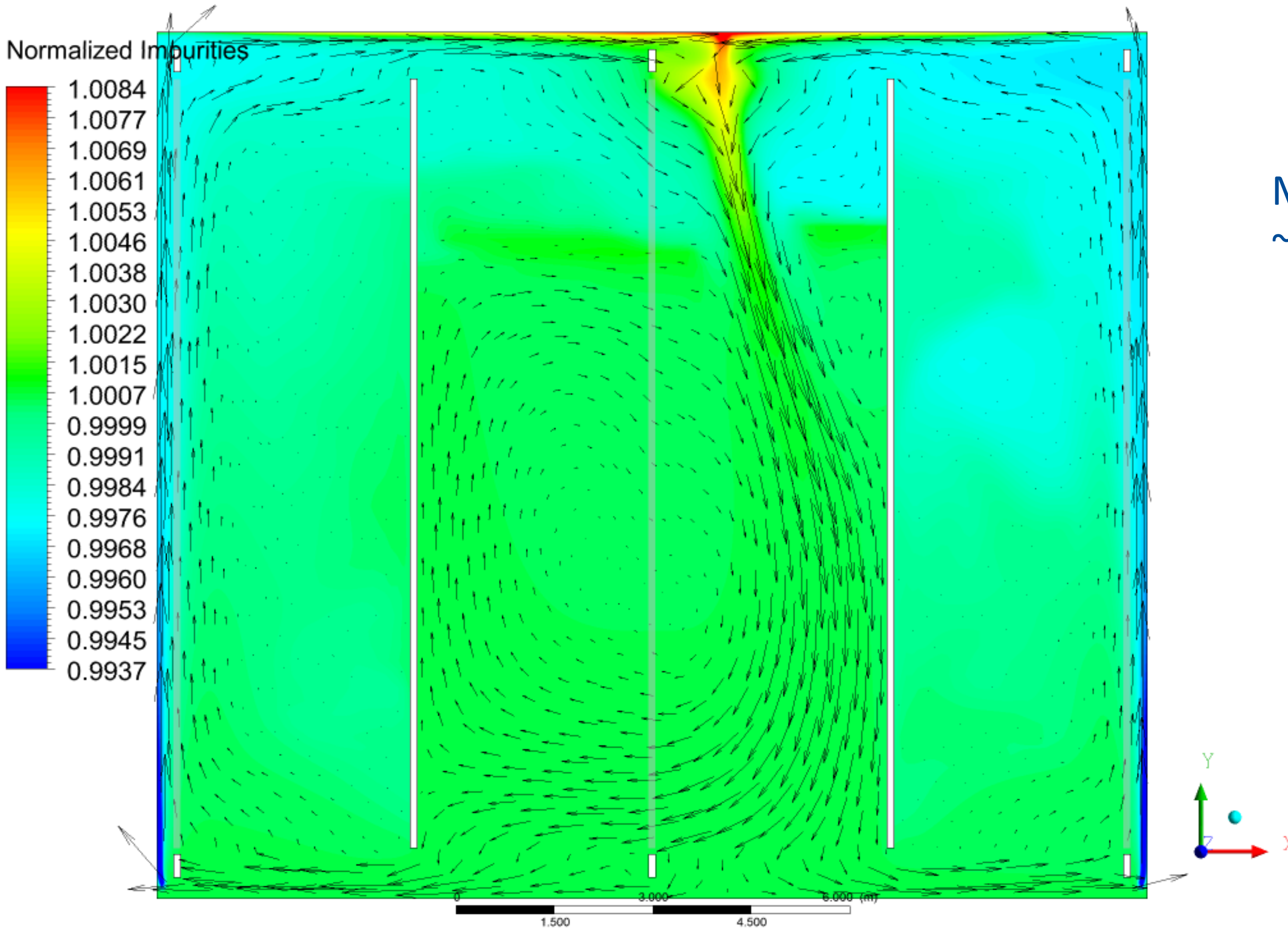
Five muons per day per APA, 1/day if you want the muon to go in the opposite CPA panels.

Impurity Contour and Velocity @ Z=0

FD-SP
Near Mid-Plane

Erik Voirin

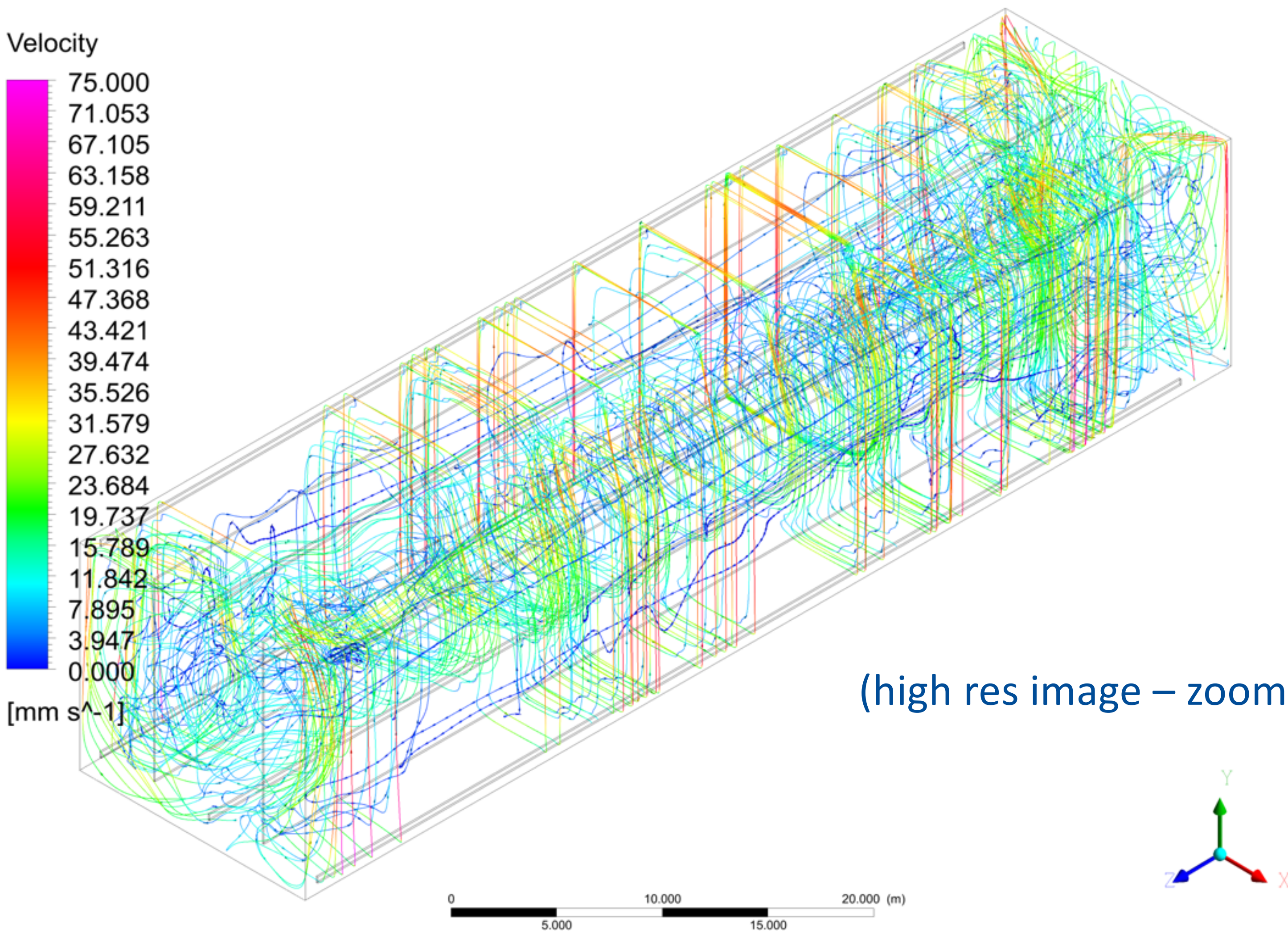
Max. variation ~2%



124 discharge ports

Velocity Streamlines

Erik Voirin,
DUNE DocDB 1046-v2

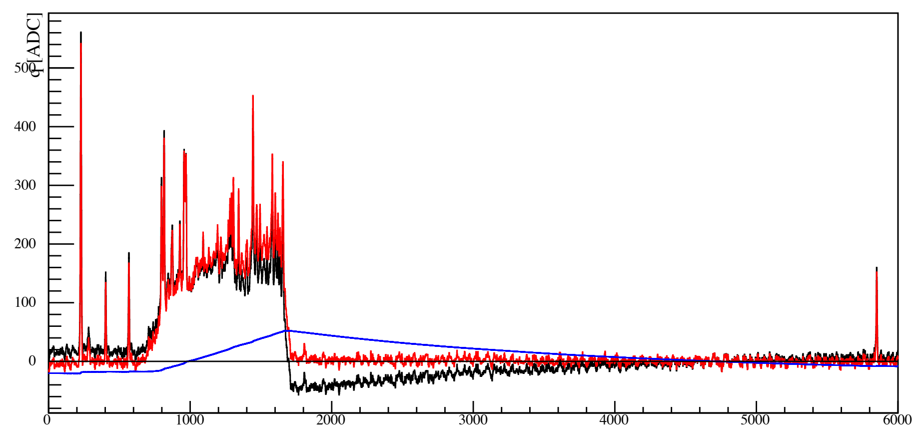


(high res image – zoom for detail)

124 discharge ports

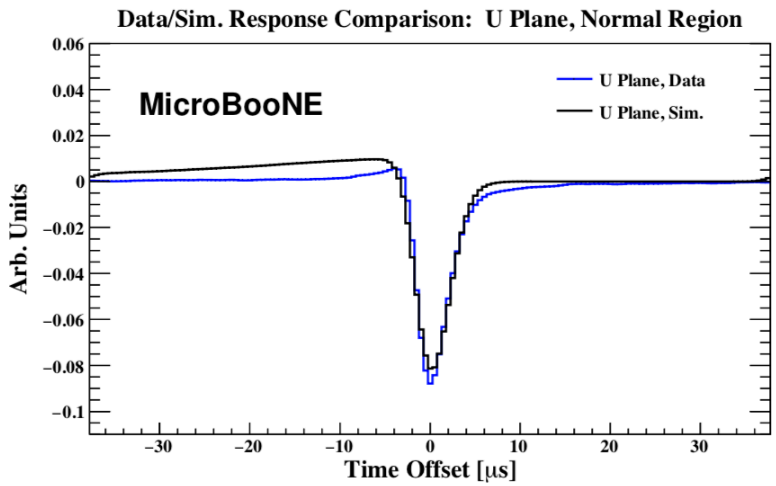
Pulse Shape Measurement

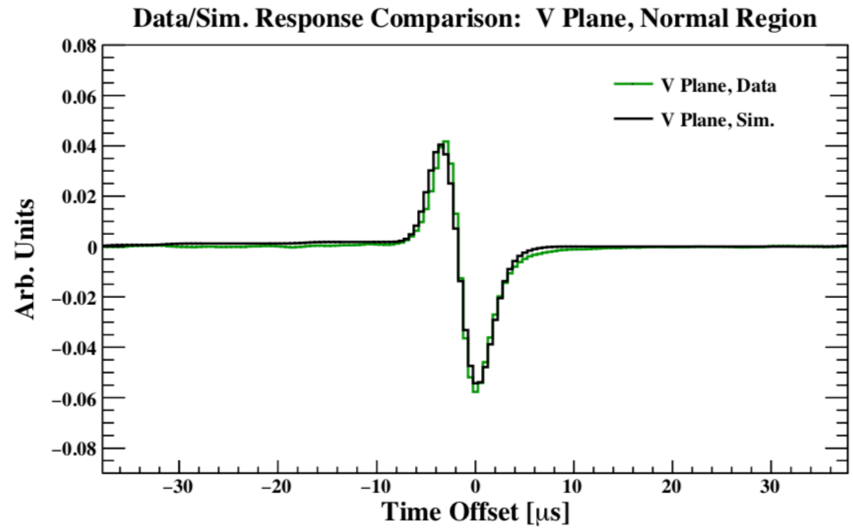
- Undershoot correction for AC-coupled electronics
  - can do with a pulser but better with cosmic-ray data
  - needs very little data to check – just need a few big signals
  - Electronics model is reliable, just need to check each channel
  - Imperfect pole-zero cancellation seen in MicroBooNE's preamp causing under- and overshoot.



- MIP response needs tracks perpendicular to wires. Easy for induction-plane wires, harder for collection-plane wires.

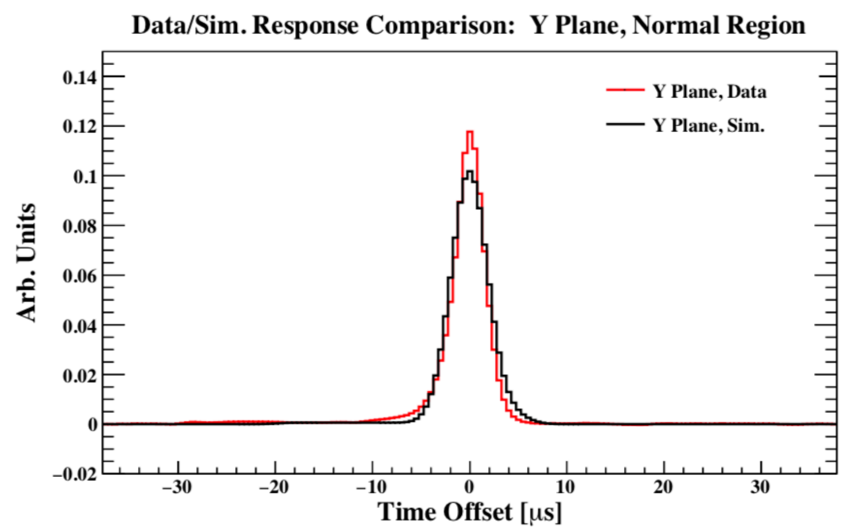
MicroBooNE Example – Calibrating Pulse Shapes



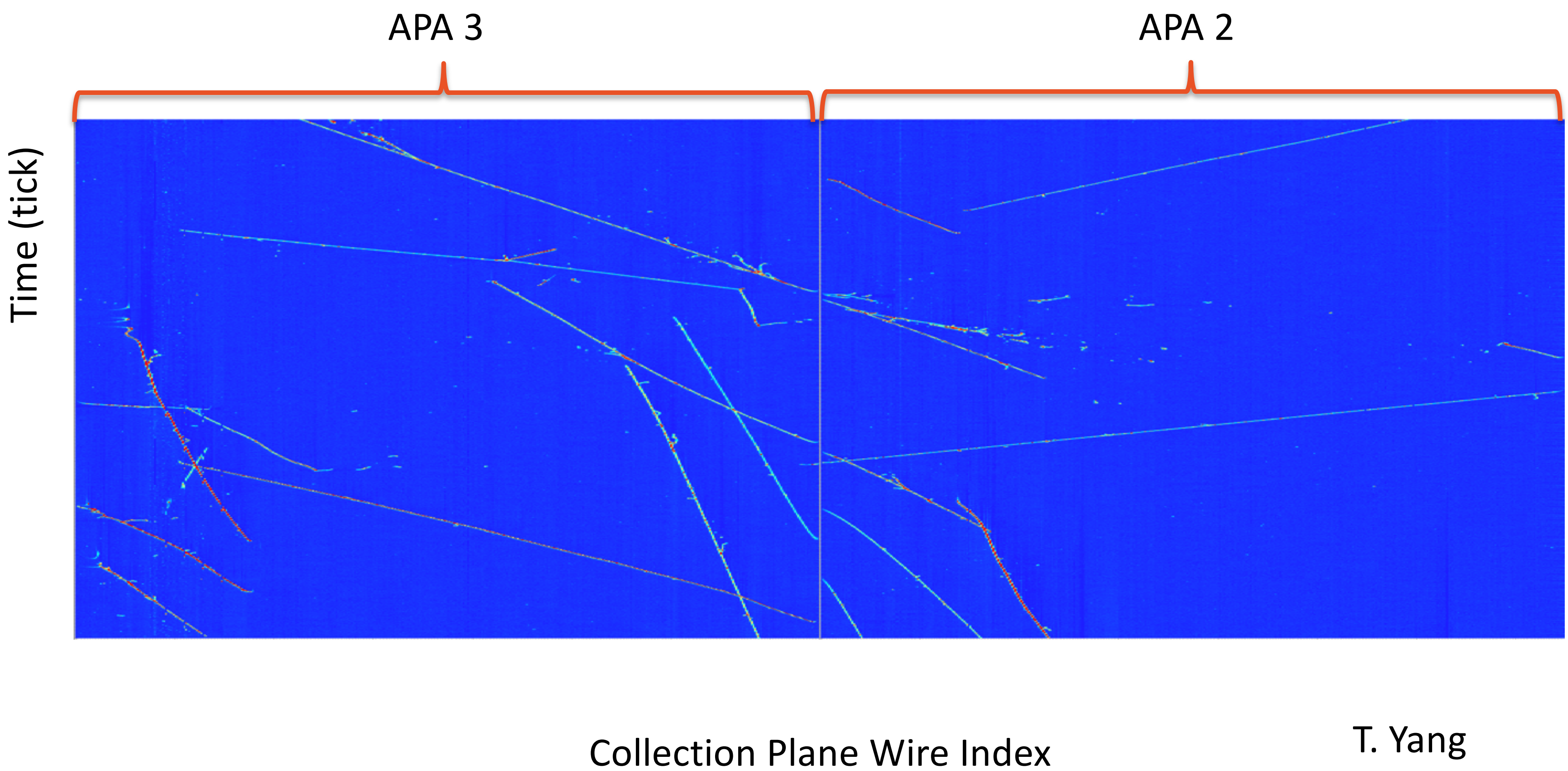


C. Adams *et al.*, JINST 13 (2018) no.07, P07007

MicroBooNE has no grid plane, so *U* is special.



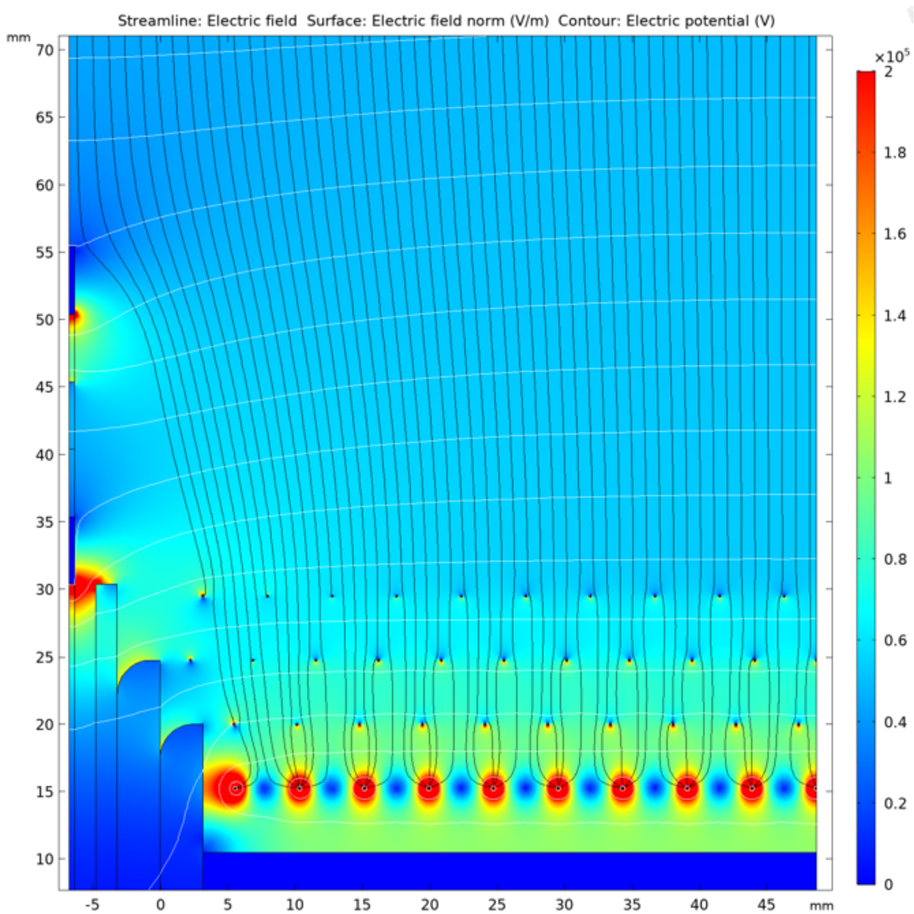
An Event in ProtoDUNE-SP



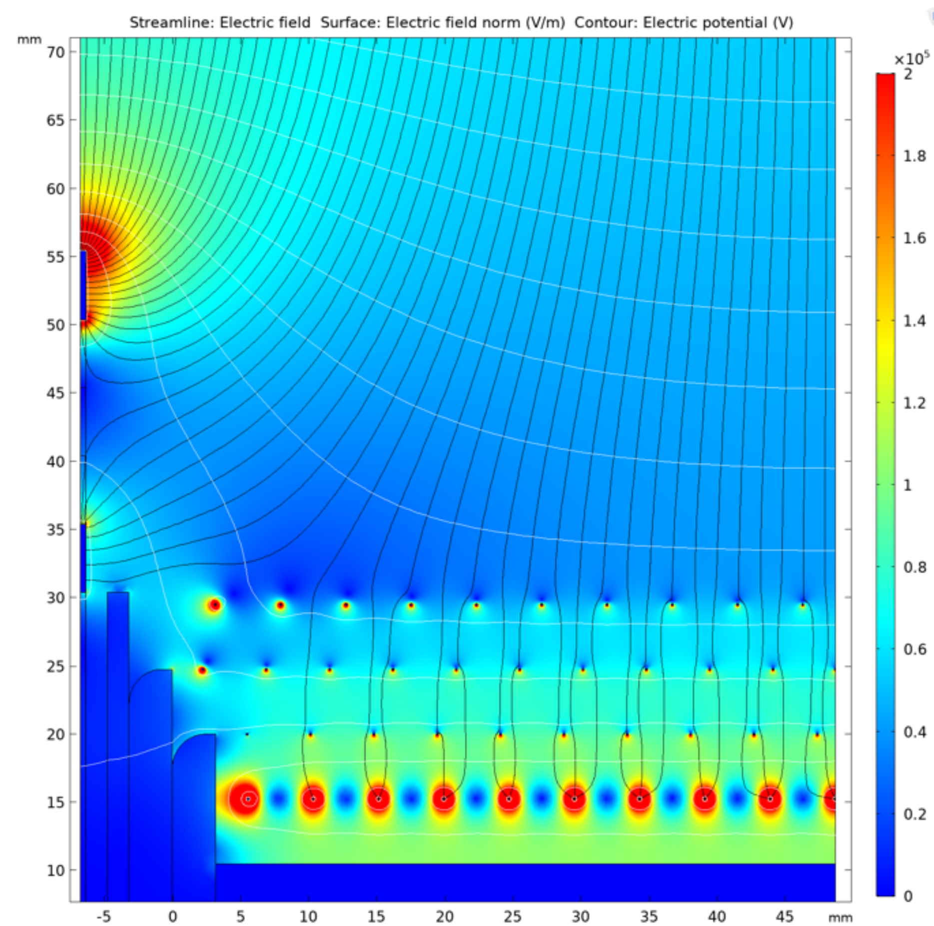
DUNE DocDB 10842

ProtoDUNE-SP Electron Diverter Field Predictions

Biased as designed

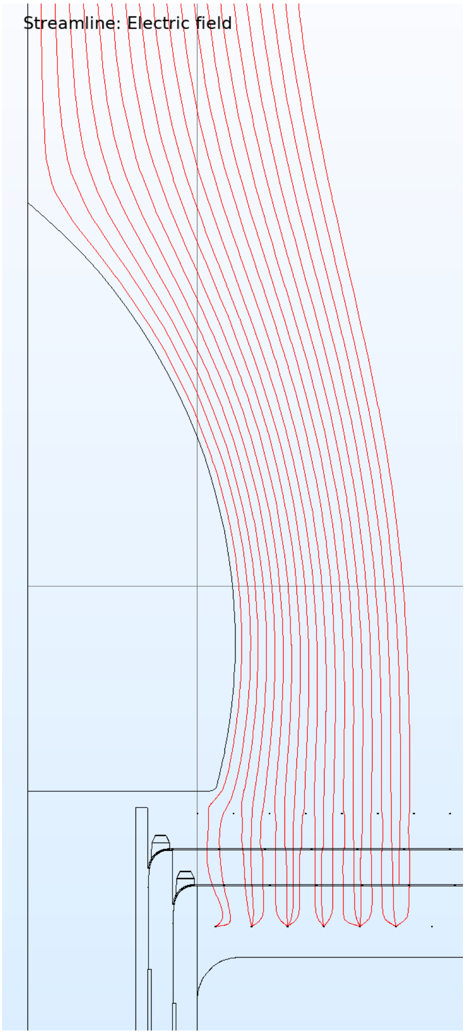


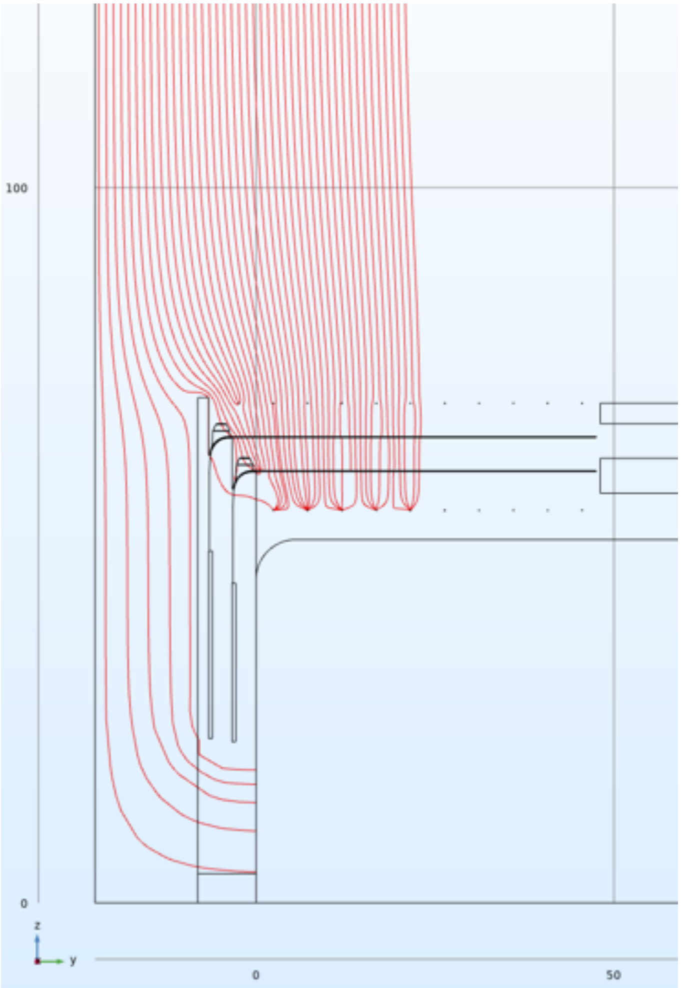
Grounded outer electrode



Passive Diverters or No Diverters

- Options under consideration

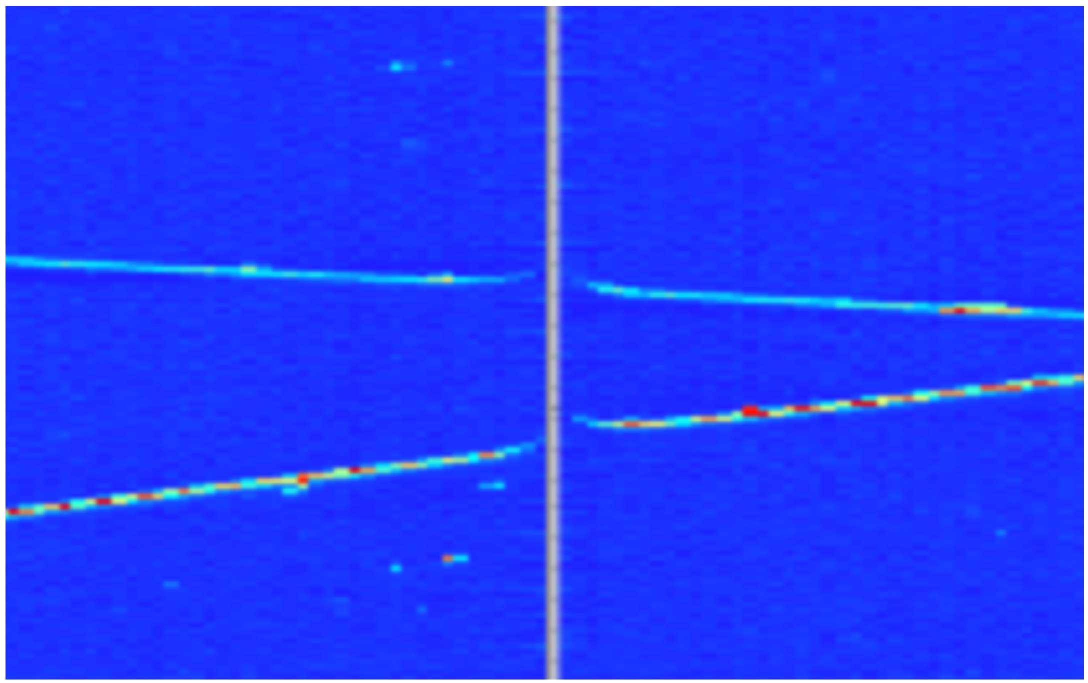




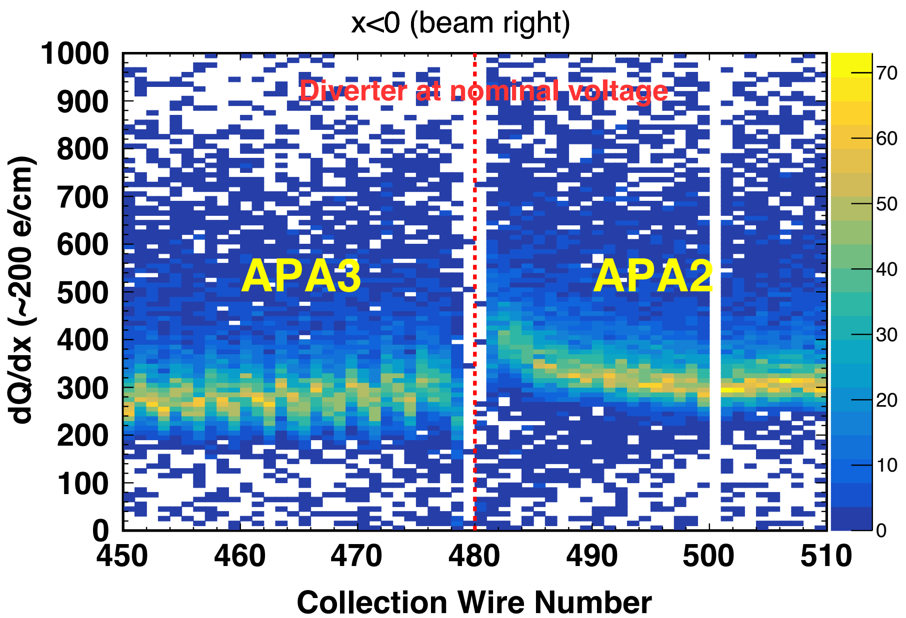
Calibrating Response in Gaps

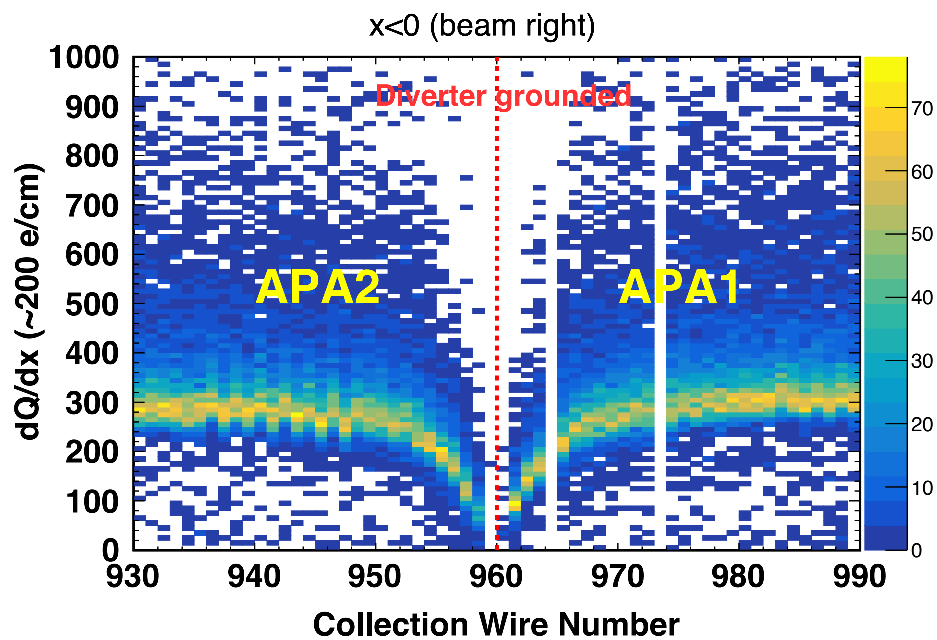
- Isochronous tracks – measure time delays
- Tilted tracks – measure spatial distortions

Electron Diverters grounded in this event.



dQ/dx uniformity near gaps



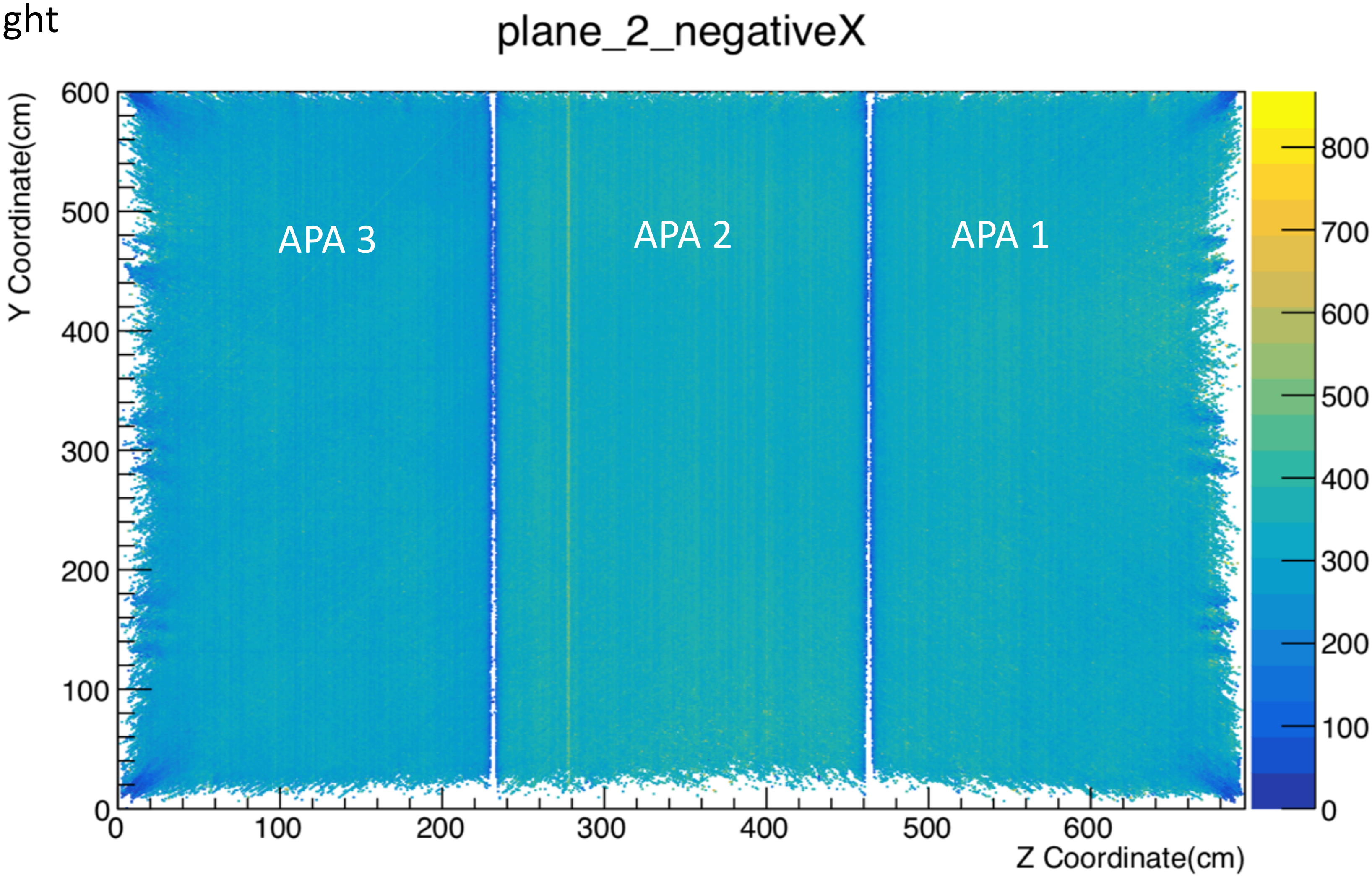


Diverter at nominal voltage.
note: APA 3's grid plane is charging up

Grounded Diverter
Note: One ASIC is a little different from the others.

Ajib's Median dQ/dx Z plane (y,z)

Beam Right



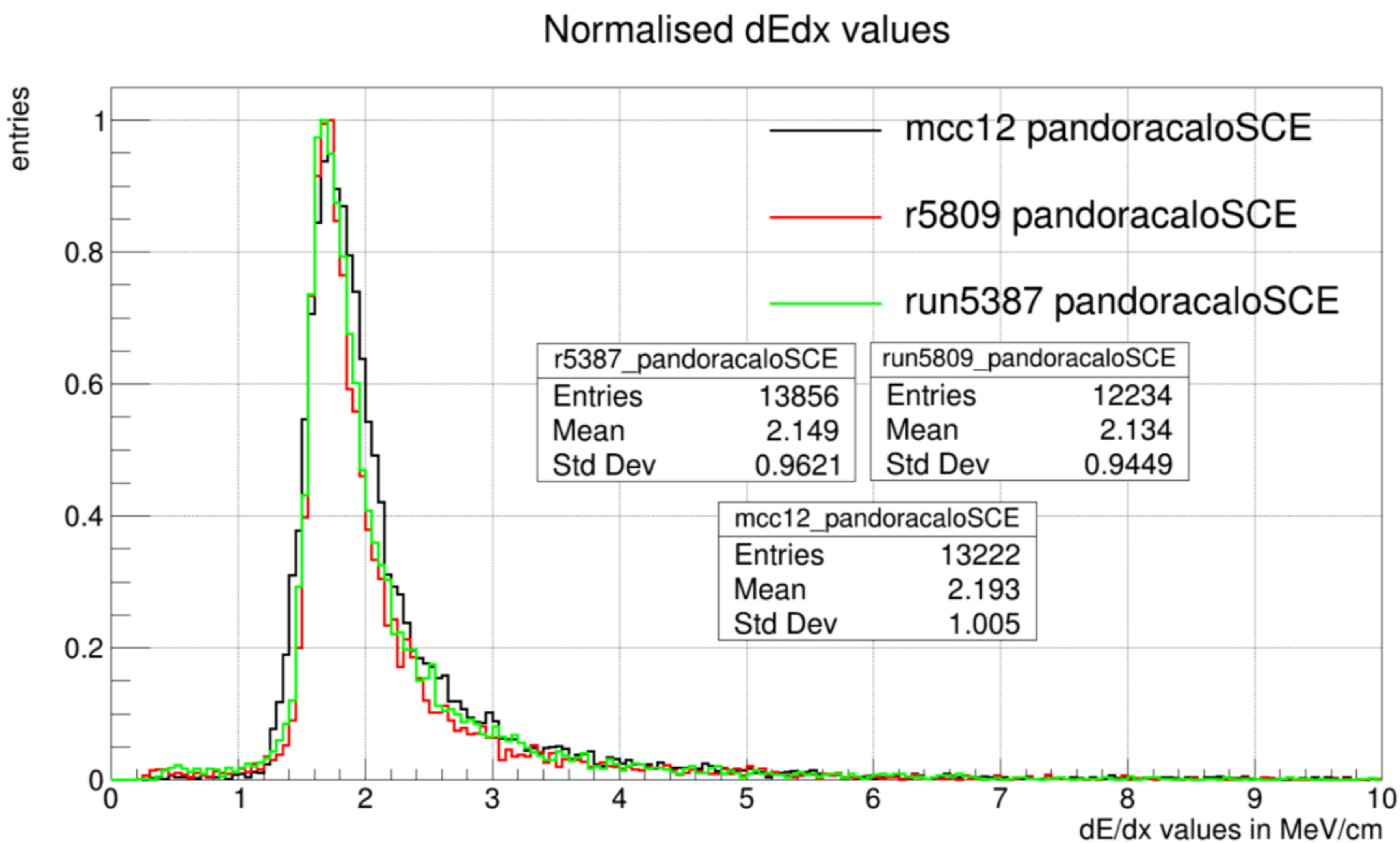
80,000 events used to fill histograms with this granularity in ProtoDUNE-SP

Calculated using Anode-Cathode Piercing Tracks

Ajib Paudel, June 12, 2019

dE/dx in data scaled to MC

dE/dx 1D histograms for mcc12, run5387, 5809

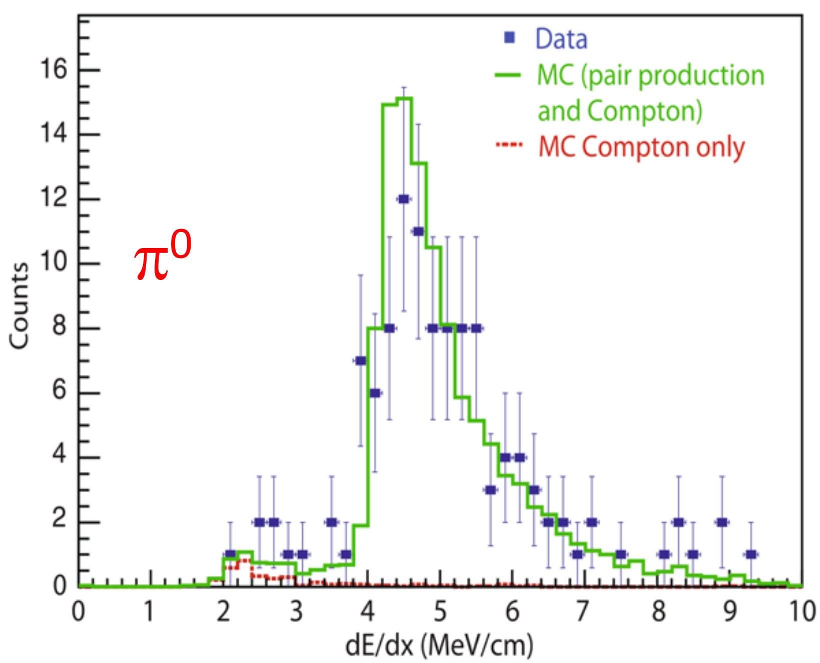


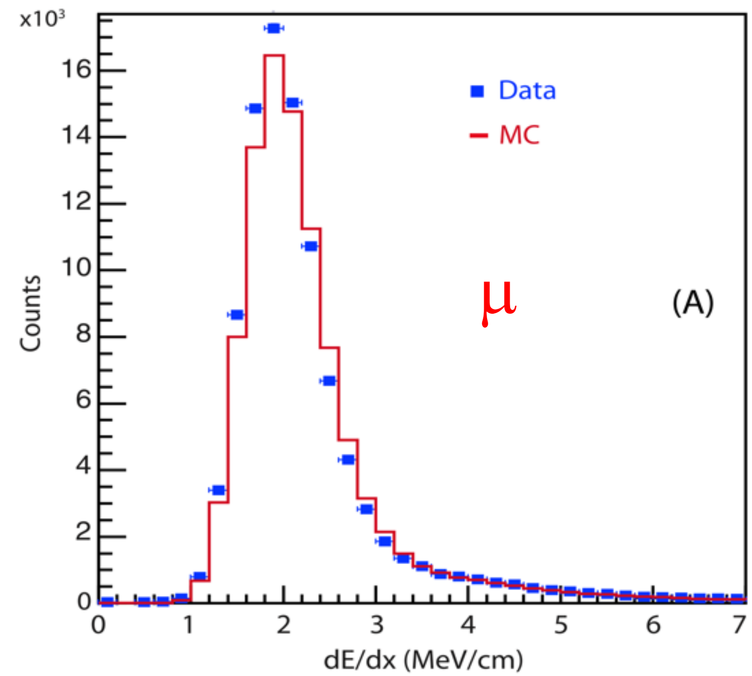
~a few thousand events should suffice if we assume detector is uniform

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



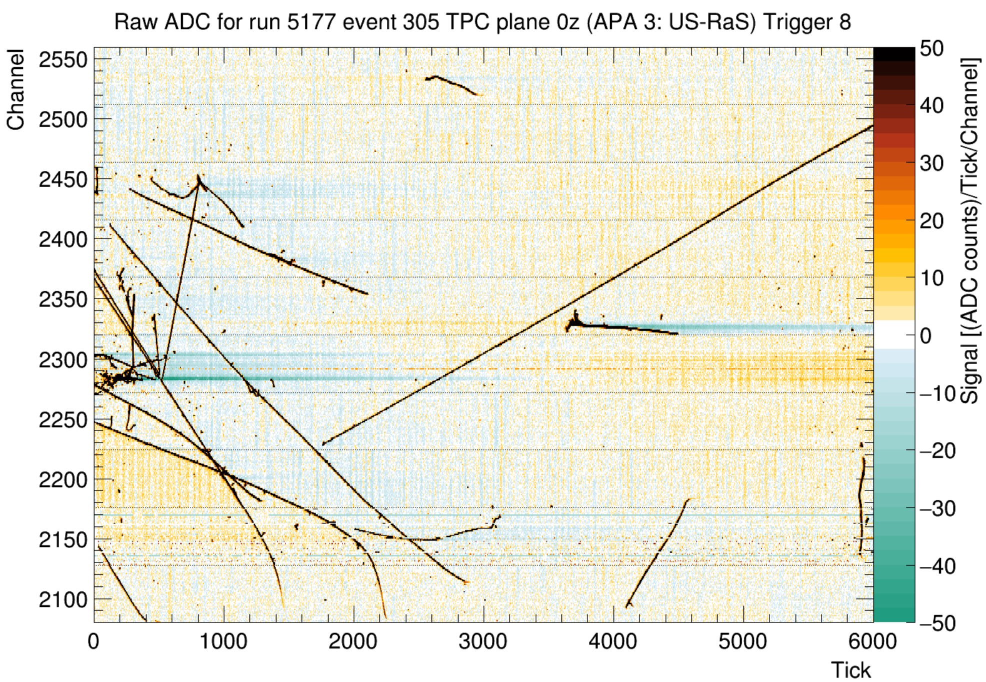


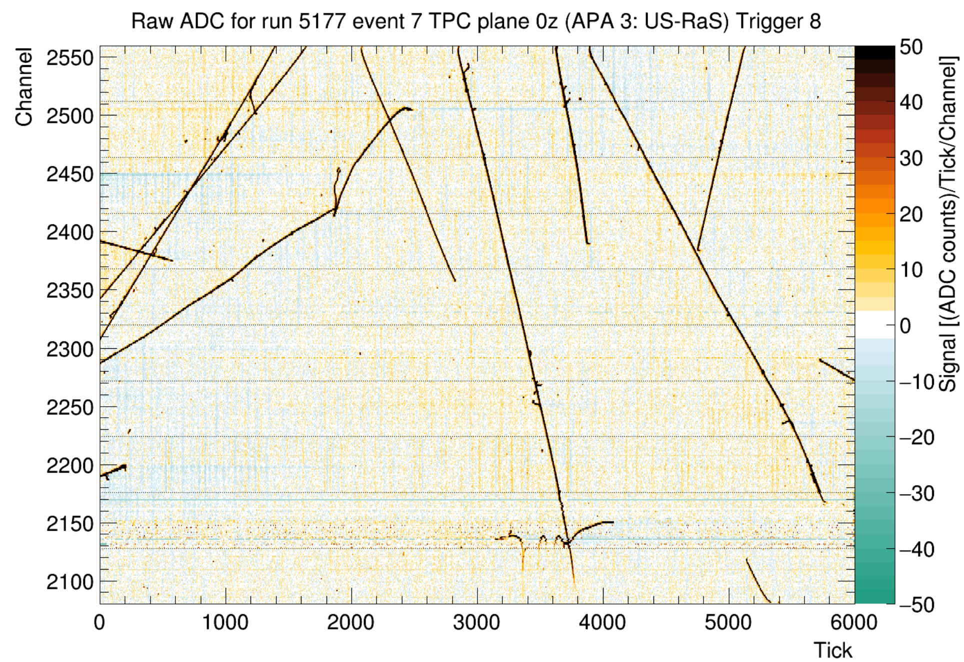
Beam neutrino data, not cosmic rays!

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

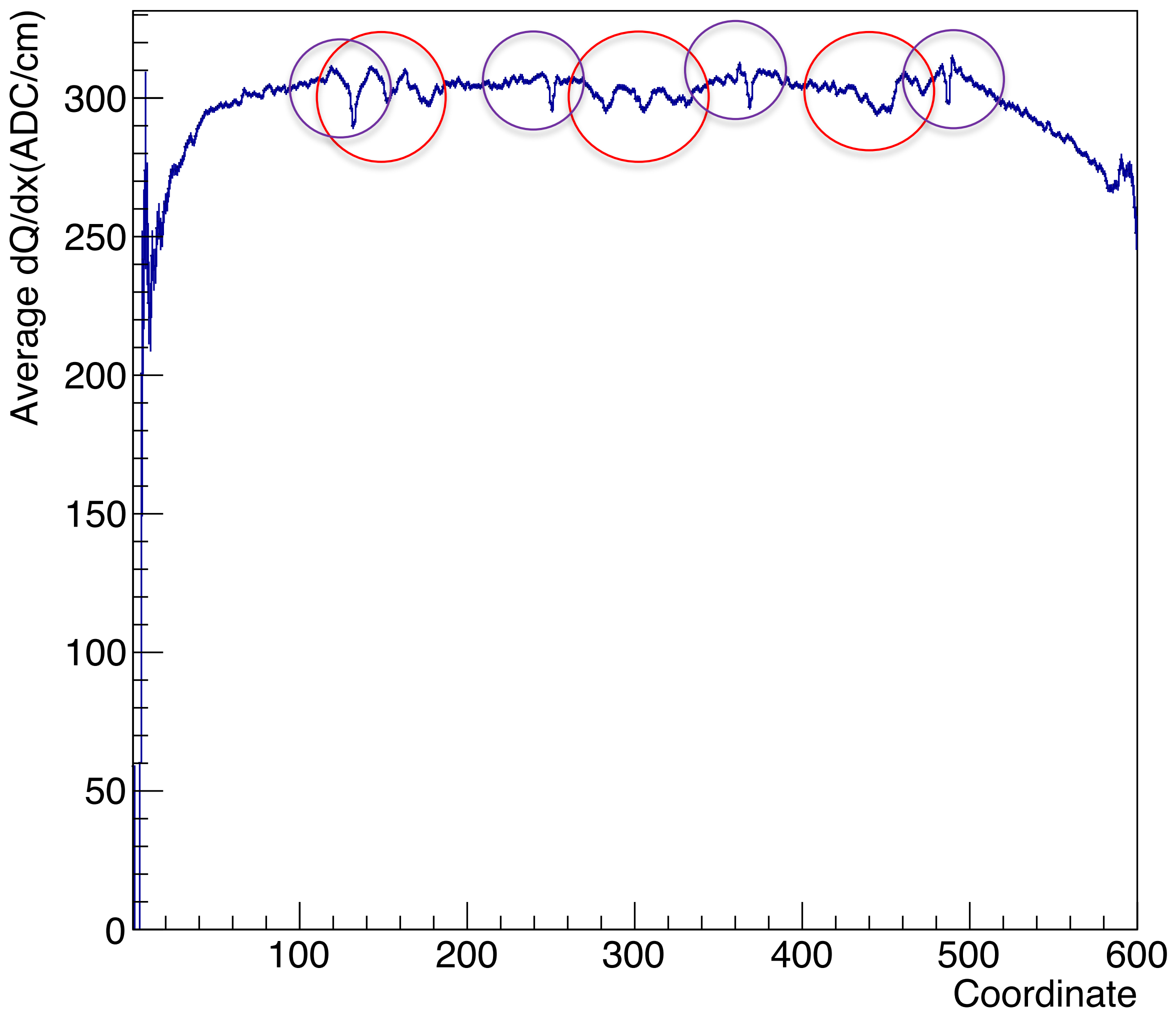
Electric Field Nonuniformities – Apparent in Individual Events





Average dQ/dx vs Y

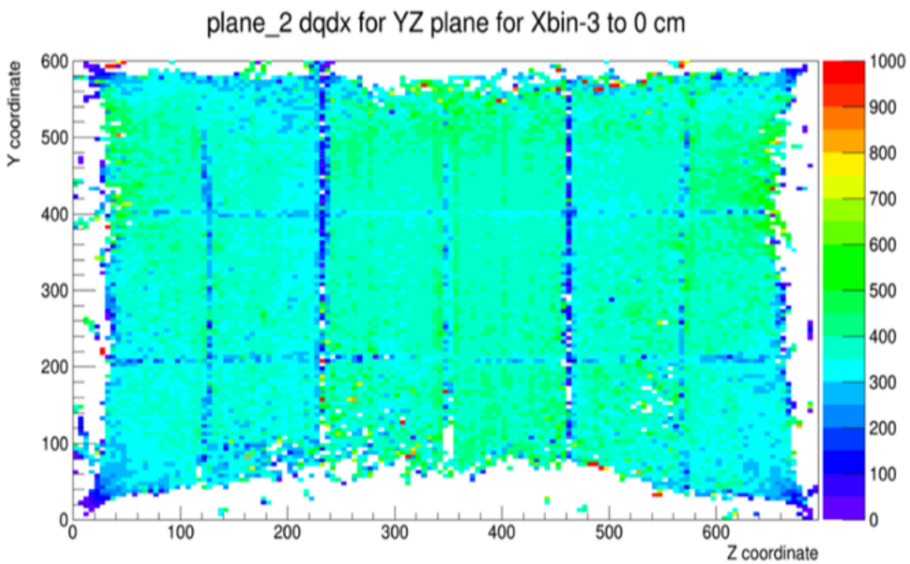
Four
Wire
Support
Combs

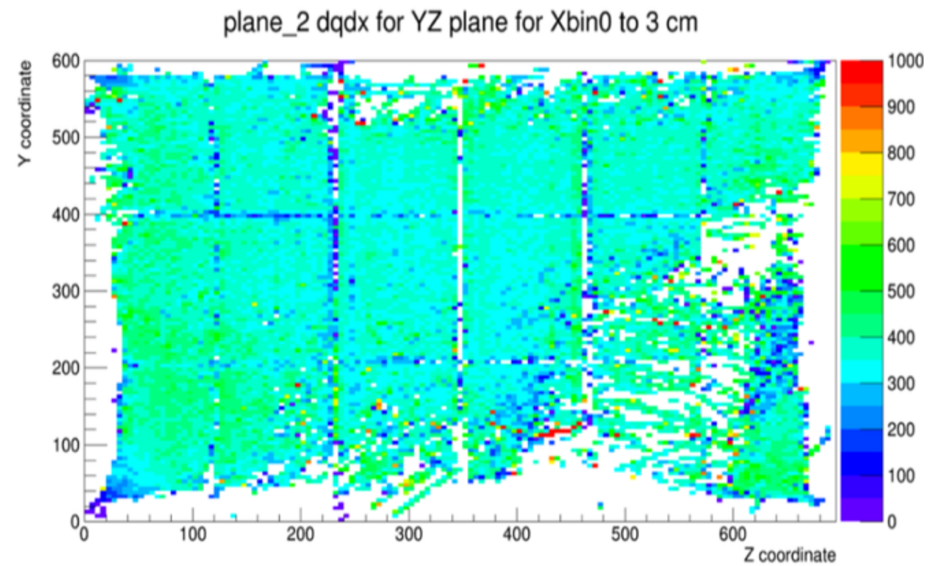


Three
Field
Cage
box-beam
Pairs

Ajib Paudel found the CPA pattern in his dQ/dx analysis

Shows expected pincushion distortion



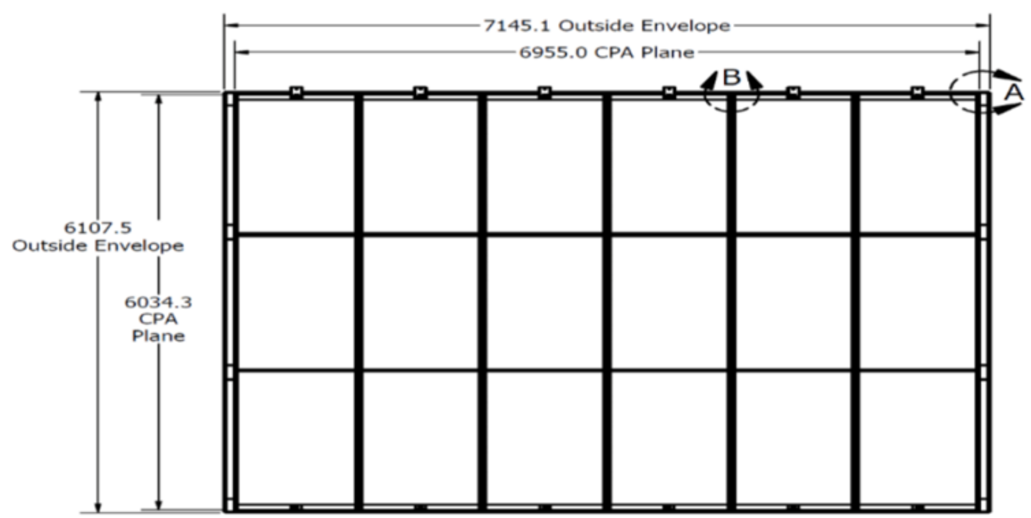


Top Left: dQ/dx distribution for beam right (0 to –3cm)

Top Right: dQ/dx distribution for beam left (0 to 3cm)

Bottom right:CPA frames from ProtoDUNE SP TDR

Plotting dQ/dx very close to CPA boundaries we can see the CPA array

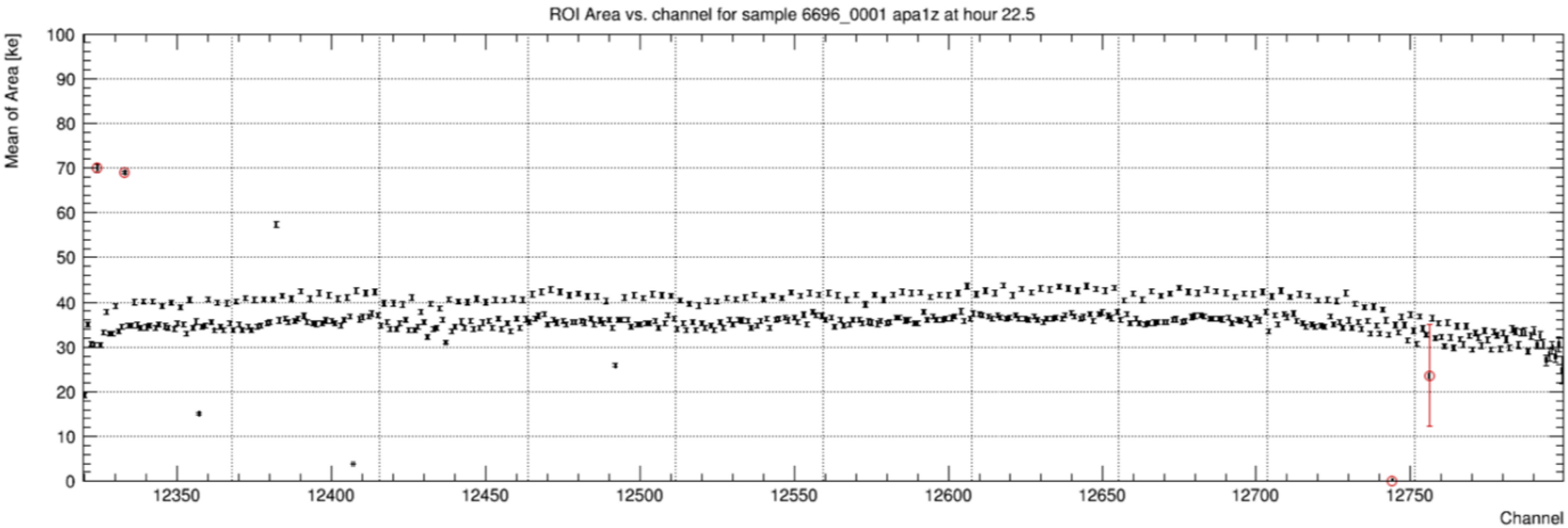


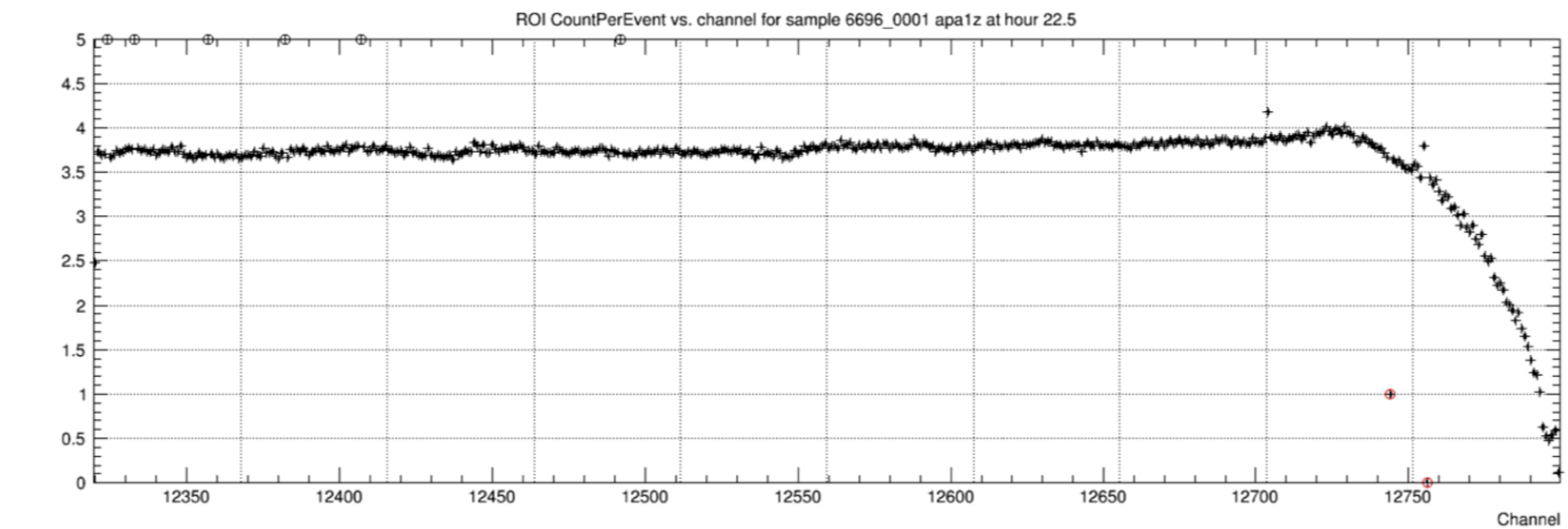
Need for Faster Monitoring

- ProtoDUNE-SP had an issue with APA 3's grid plane not being connected
- Charge-up time of several days in ProtoDUNE-SP. Grid not perfectly transparent while charging up.
- Affects dQ/dx means in a time-dependent way.
- Underground: fewer cosmic rays, and more capacitance on the grid plane (to reduce an induction effect seen in ProtoDUNE-SP)

22.5 hours

David Adams, March 2019





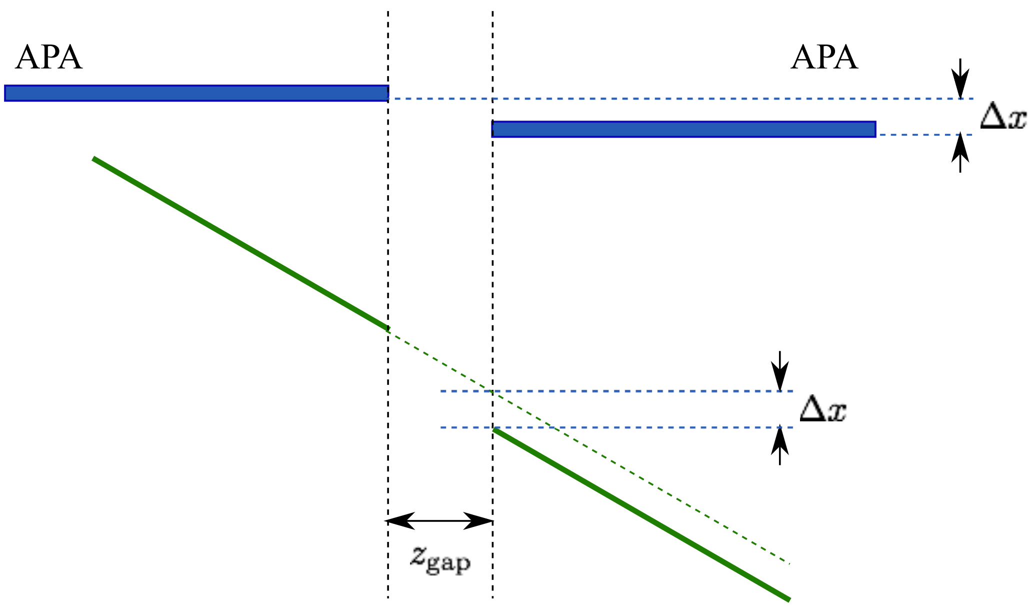
Alignment

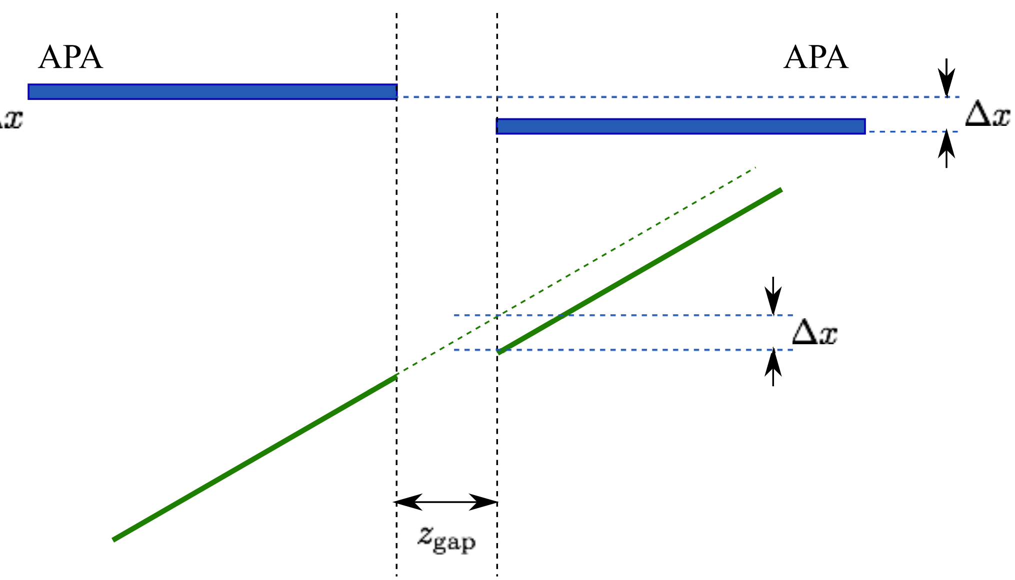
- Nearly every detector in HEP is aligned with cosmic rays
- Elaborate examples:
  - CMS: http://arxiv.org/abs/0911.4022
  - ALICE: http://arxiv.org/abs/1001.0502
  - An ATLAS Ph.D. Thesis: Vincente Lacuesta Miquel
    http://inspirehep.net/record/1429422/
    And another: Regina Moles-Valls
    http://inspirehep.net/record/1339828/
    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"

"Strong" Directions in DUNE

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

M. Wallbank

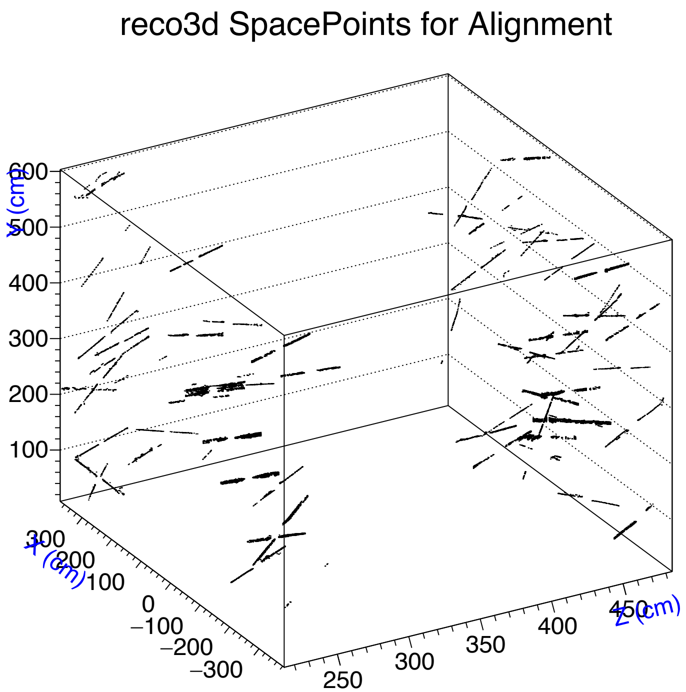


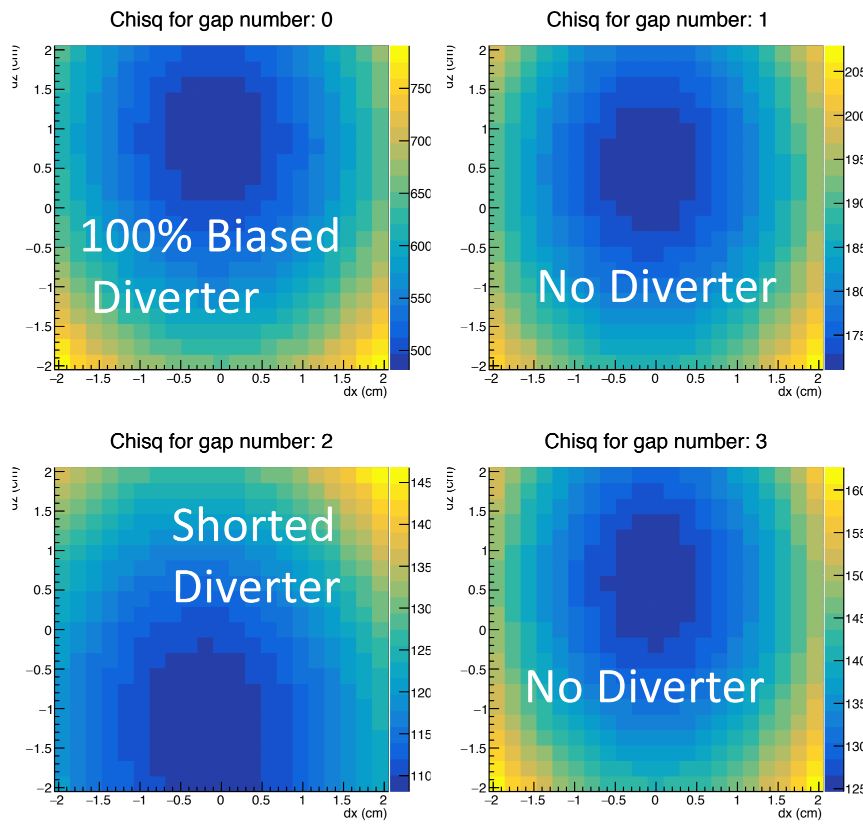


Need positive Δx or positive Δz
to fix this track (really a combination)

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

Alignment results – ProtoDUNE-SP





Run	ED23 Voltage			Gap 0 (ED23)		Gap 1		Gap 2 (ED12)		Gap 3	
	Inner (V)	Outer (V)	Frac. nom.	Δx (cm)	$\mathbf{\Delta z}$ **(cm)**	Δx (cm)	Δz (cm)	Δx (cm)	Δz (cm)	Δx (cm)	Δz (cm)
5177	0	0	0%	-0.15 ± 0.09	$\mathbf{-1.46 \pm 0.23}$	-0.34 ± 0.12	0.63 ± 0.22	-0.20 ± 0.10	-1.22 ± 0.44	0.29 ± 0.10	0.05 ± 0.30
5941	-650	-1150	50%	-0.15 ± 0.05	$\mathbf{0.10 \pm 0.20}$	-0.10 ± 0.06	0.63 ± 0.15	-0.24 ± 0.12	-1.27 ± 0.06	-0.05 ± 0.05	0.49 ± 0.13
5925	-975	-1725	75%	-0.10 ± 0.06	$\mathbf{0.78 \pm 0.11}$	0.00 ± 0.00	0.49 ± 0.17	-0.15 ± 0.05	-0.73 ± 0.42	0.00 ± 0.00	0.63 ± 0.12
5924	-1300	-2300	100%	-0.10 ± 0.06	$\mathbf{1.32 \pm 0.12}$	-0.10 ± 0.06	0.73 ± 0.15	-0.15 ± 0.05	-1.03 ± 0.15	0.00 ± 0.00	0.68 ± 0.06
5930	-1625	-2875	125%	0.0 ± 0.5	$\mathbf{1.56 \pm 0.5}$	-0.15 ± 0.05	0.63 ± 0.12	-0.20 ± 0.08	-1.37 ± 0.21	0.00 ± 0.00	0.51 ± 0.26

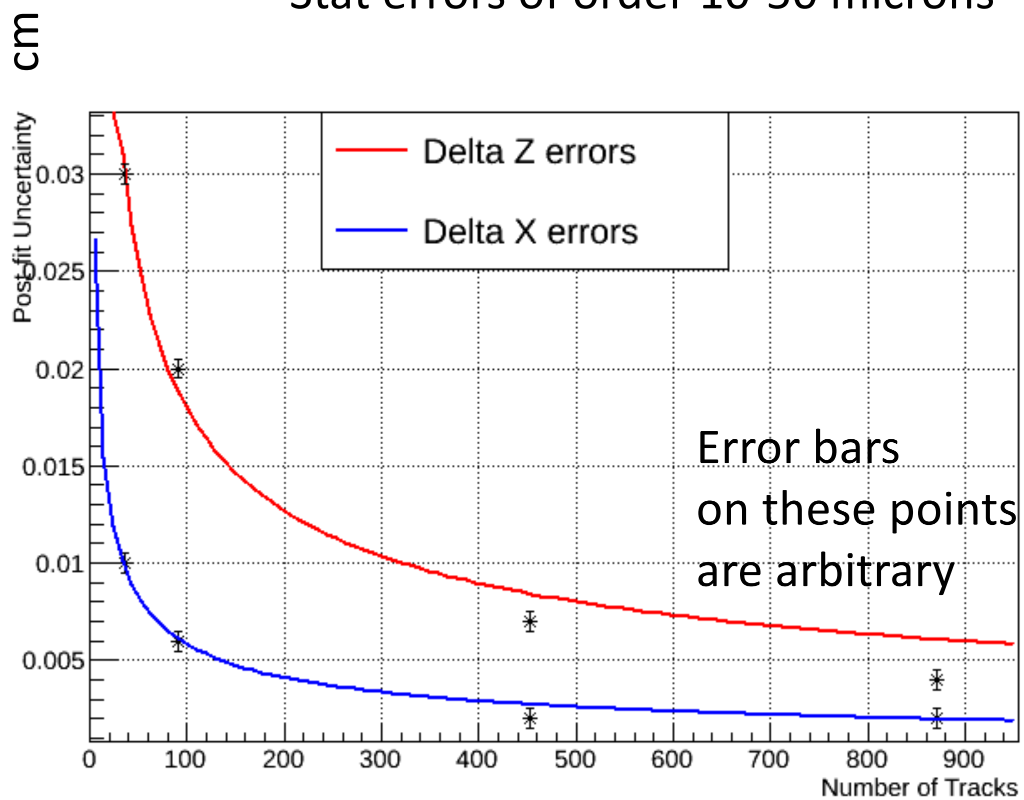
Vertical Gap Measurement Precision: 35-ton experience

- 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

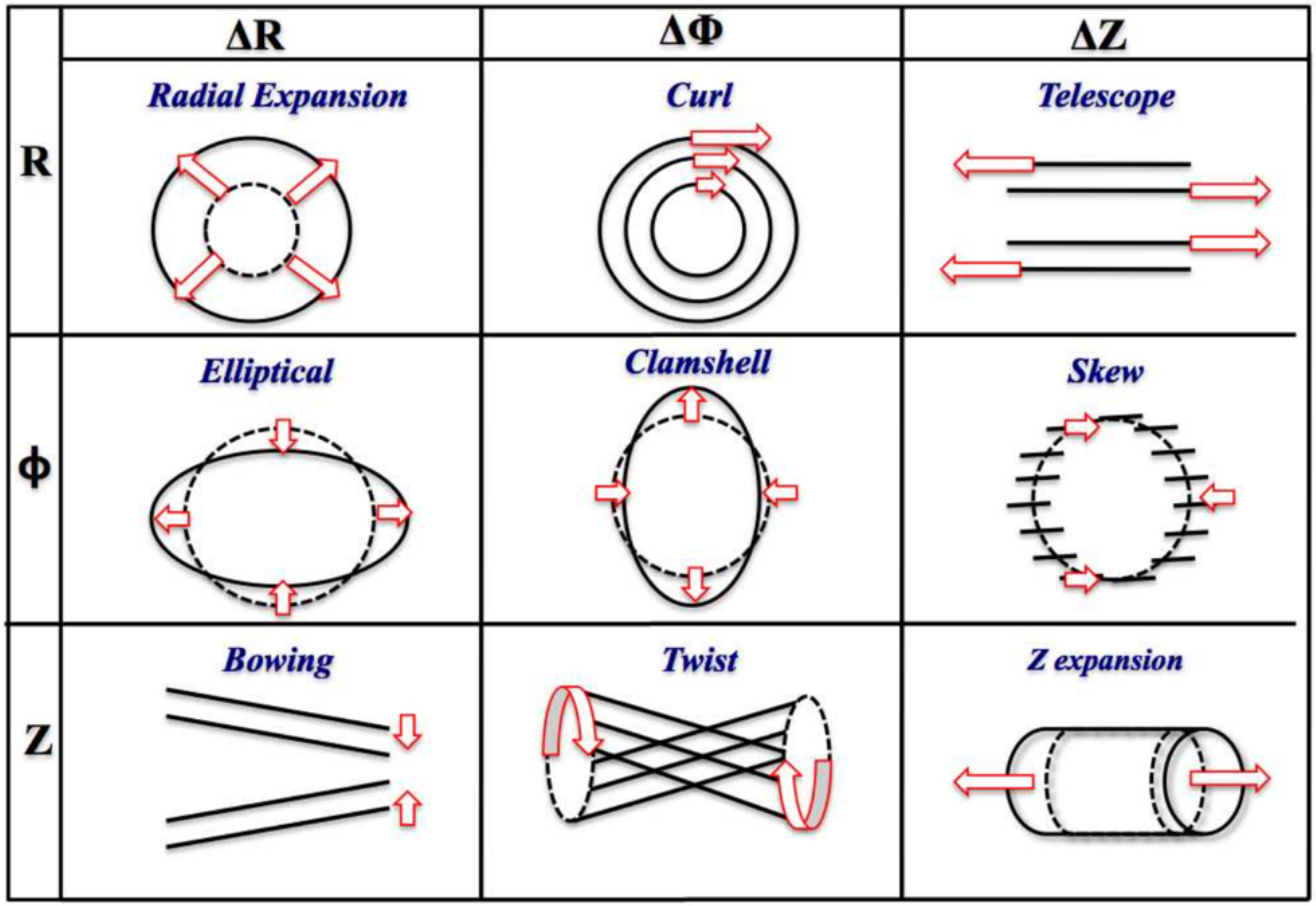
- What if the gaps between the APA's aren't of uniform width?
- What if the offsets along the drift field direction (*x*) vary with height (*y*)?

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:

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

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

Examples of "Weak" Directions (ATLAS alignment)

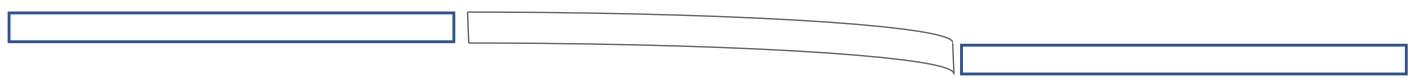


From Moles-Valls' thesis.

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

Difficult Distortions to Constrain

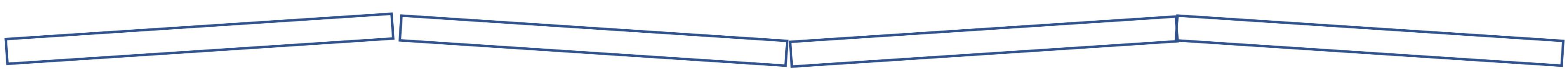
Bent APA's: Will a "flat" APA stay flat when cold?



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.

Cosmic rays are good at measuring *local relative* changes in positions (local in X, Z) and not good at absolute positioning

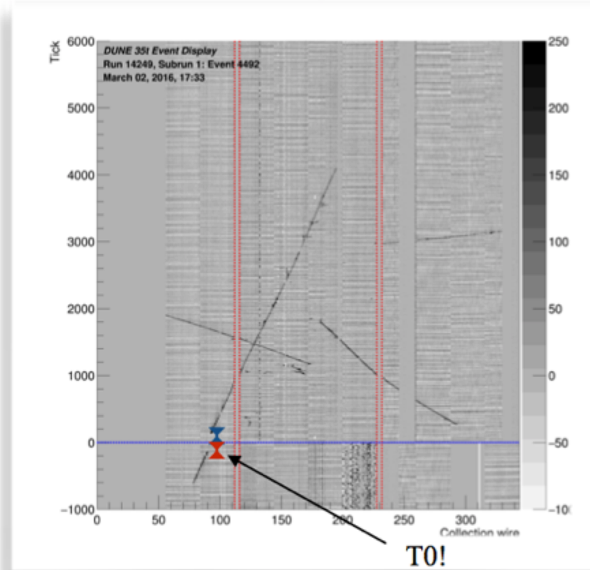


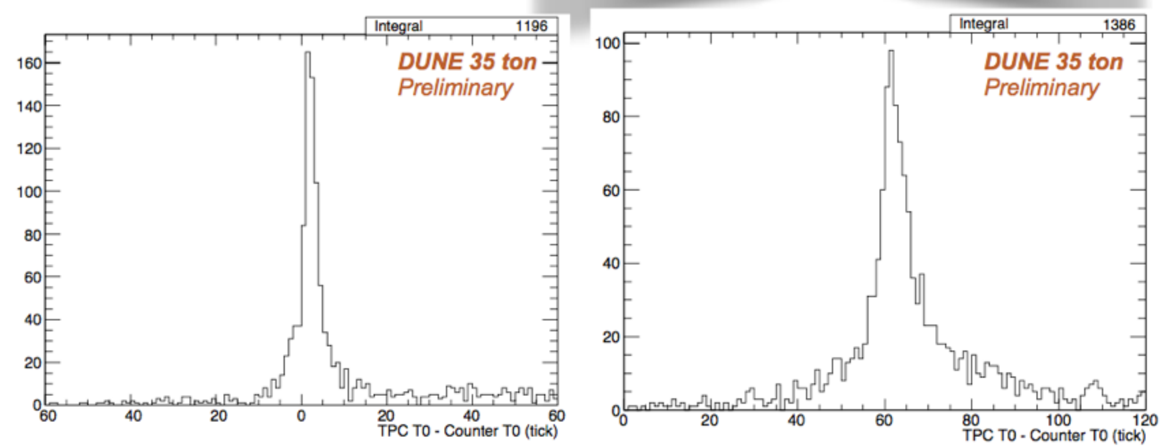
What is the magnitude of this that would escape our notice?

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.

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

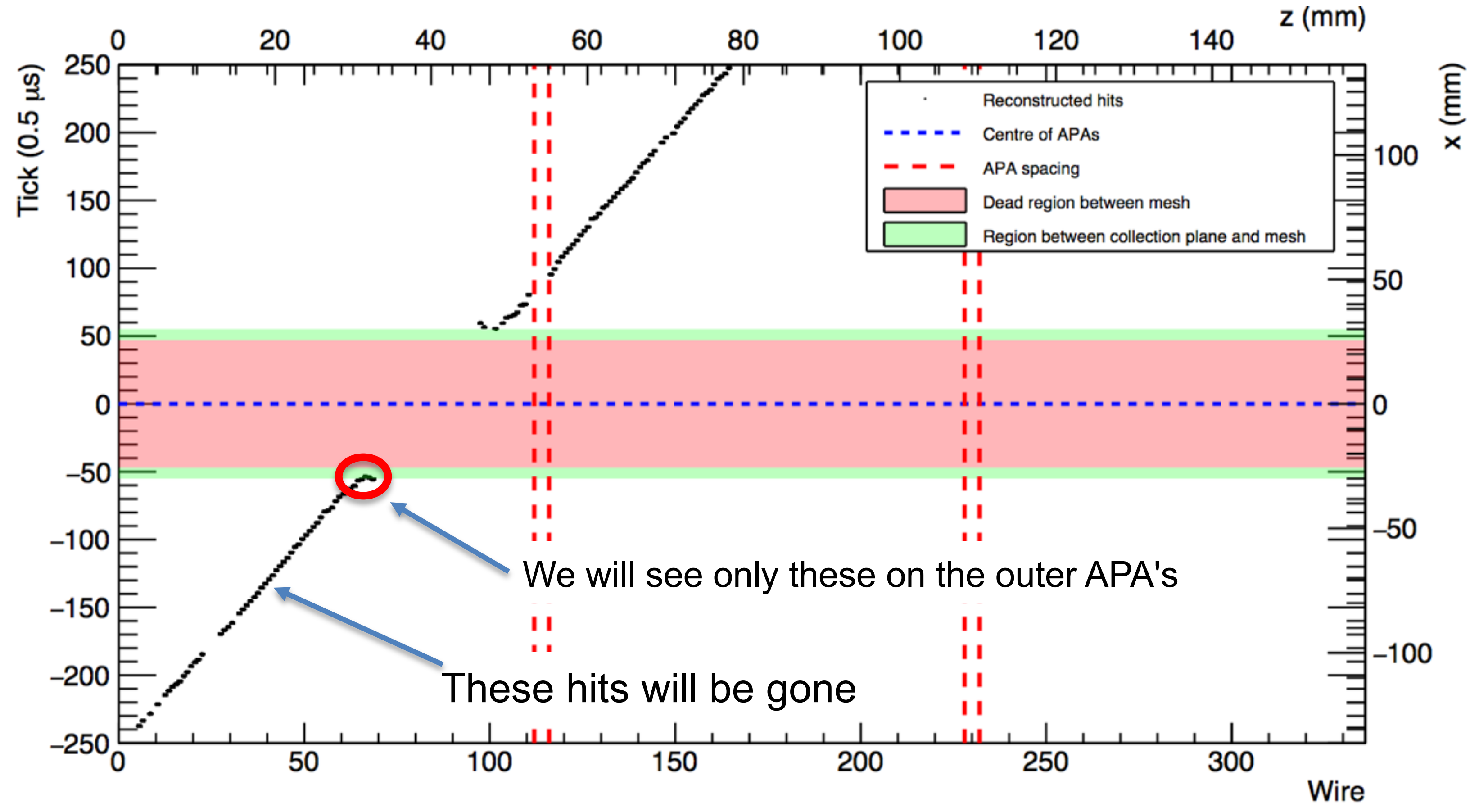
Here, N_{tracks} is the number of APA-crossing tracks.

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

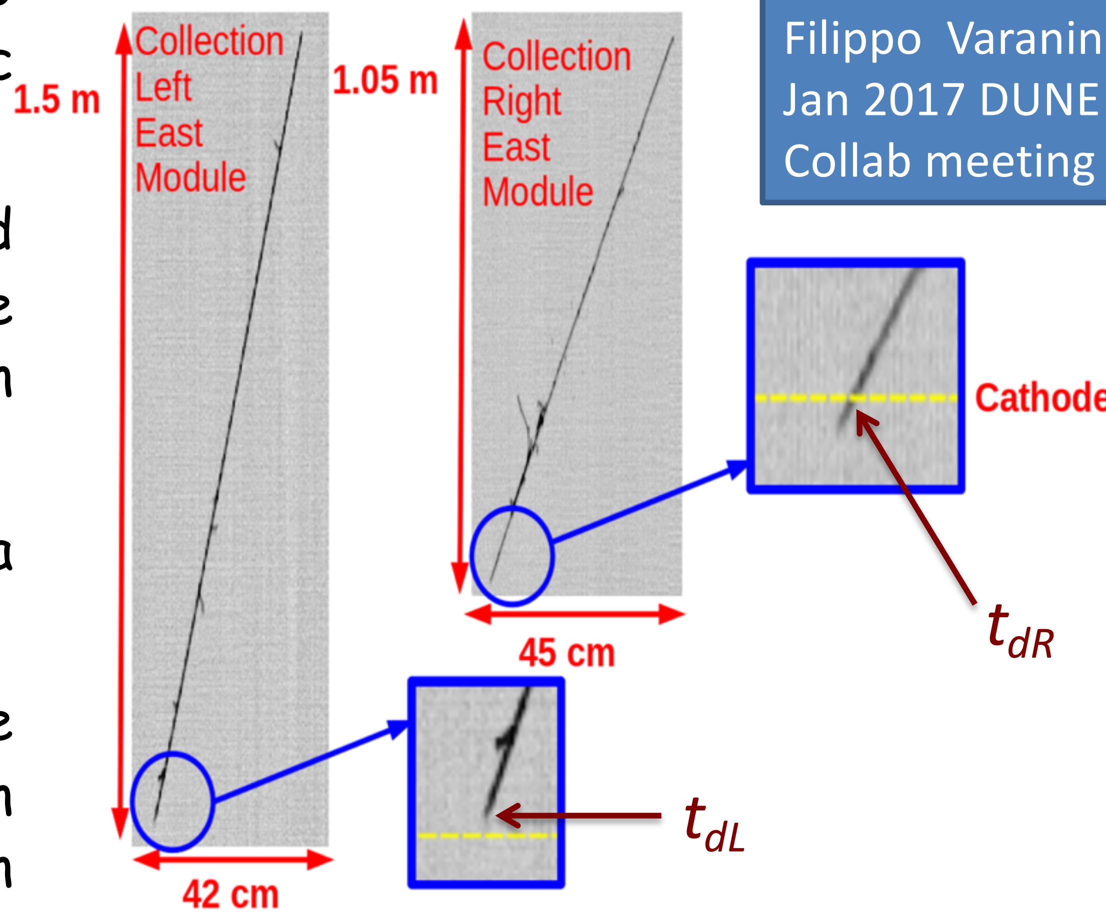


Measurement of cathode distortions in ICARUS

- 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:

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

Filippo Varanini
Jan 2017 DUNE Collab meeting

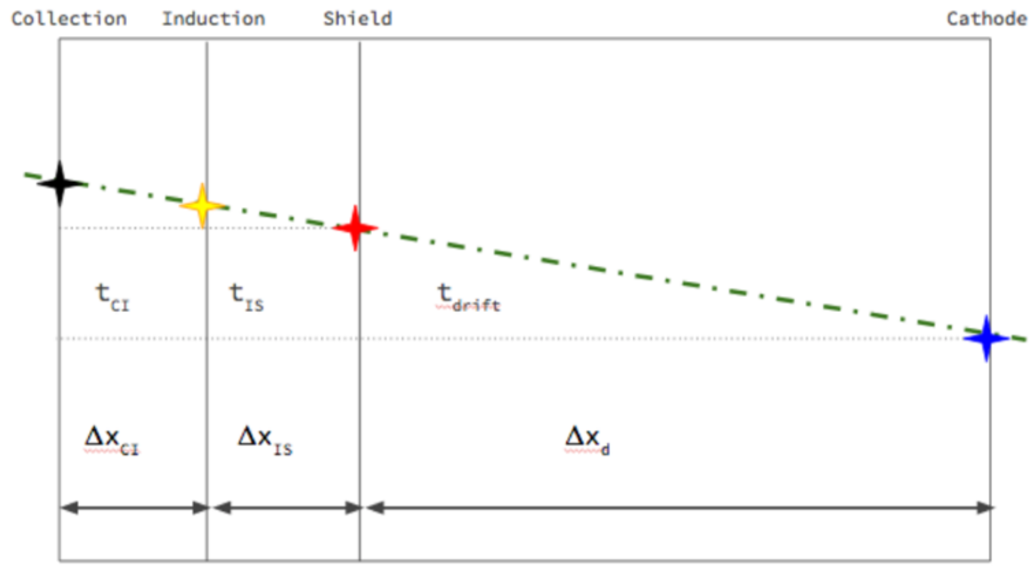


Yellow line marks nominal cathode position(Δy=0)

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

Drift Velocity by Anode-Cathode Piercing Tracks

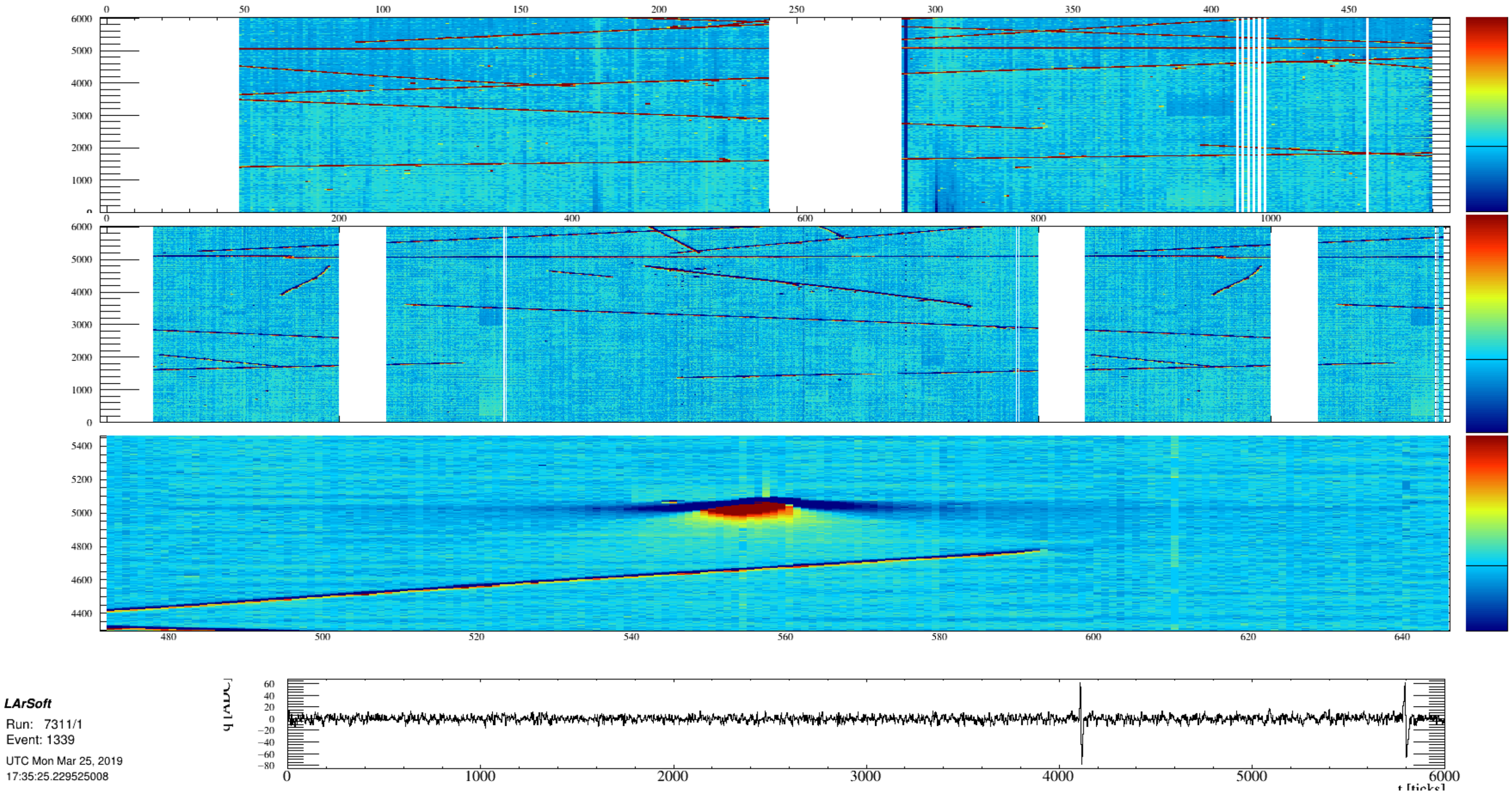
J.Raaf, J. Asaadi, LArIAT



- 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: $311.1 \pm 2.4\ \mu s$ → $v_{drift} = 1.51 \pm 0.1\ mm/\mu s$

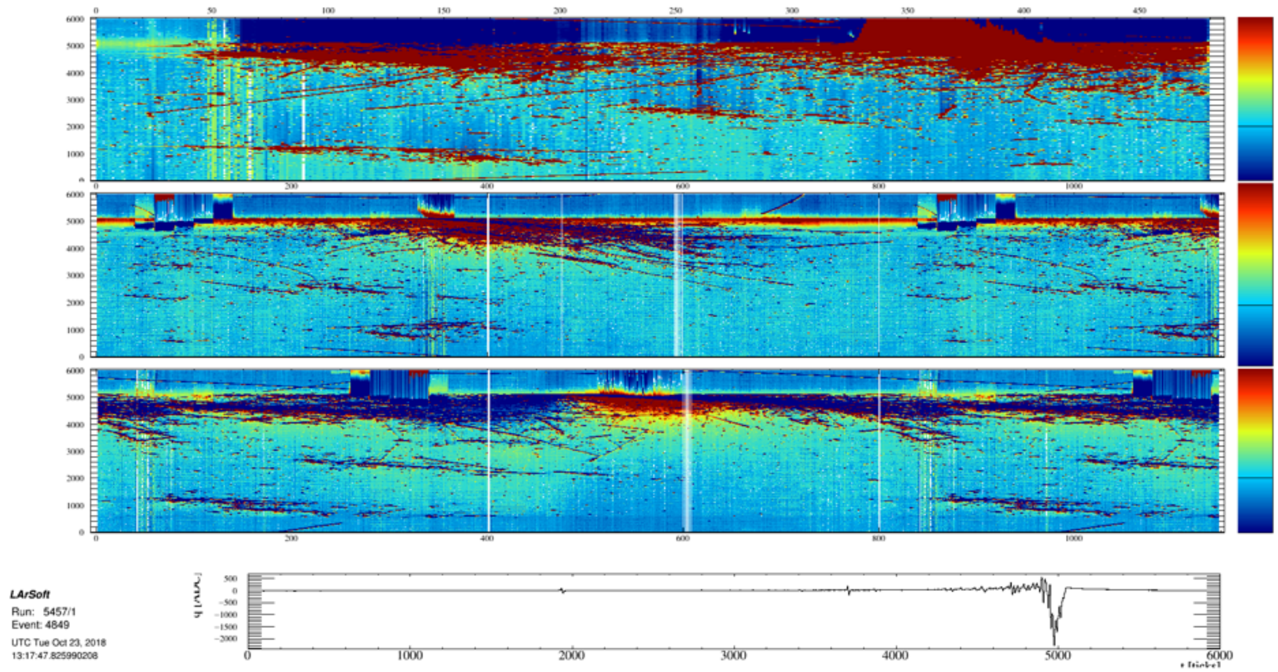
LArIAT Calibration Lessons Learned, J. Raaf Jan. 31, 2018

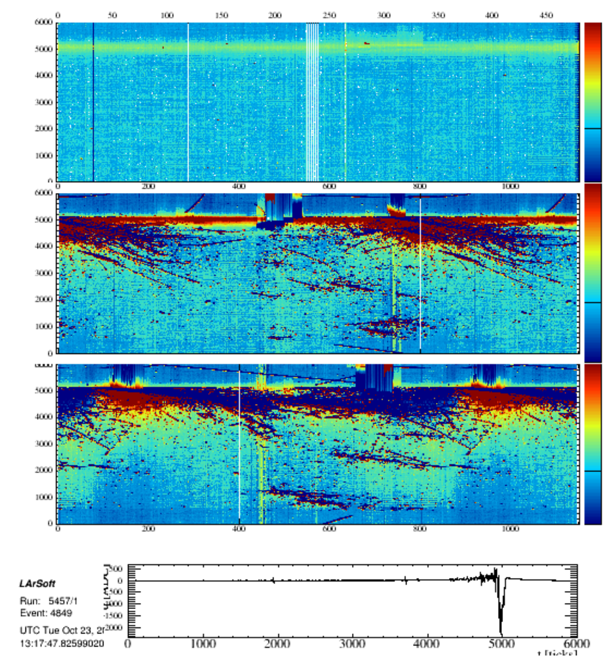
A Track in ProtoDUNE-SP that runs along U Wires



Unipolar induced charge over a span of hundreds of wires.
Can be used to calibrate 2D field response.

We can learn from big showers





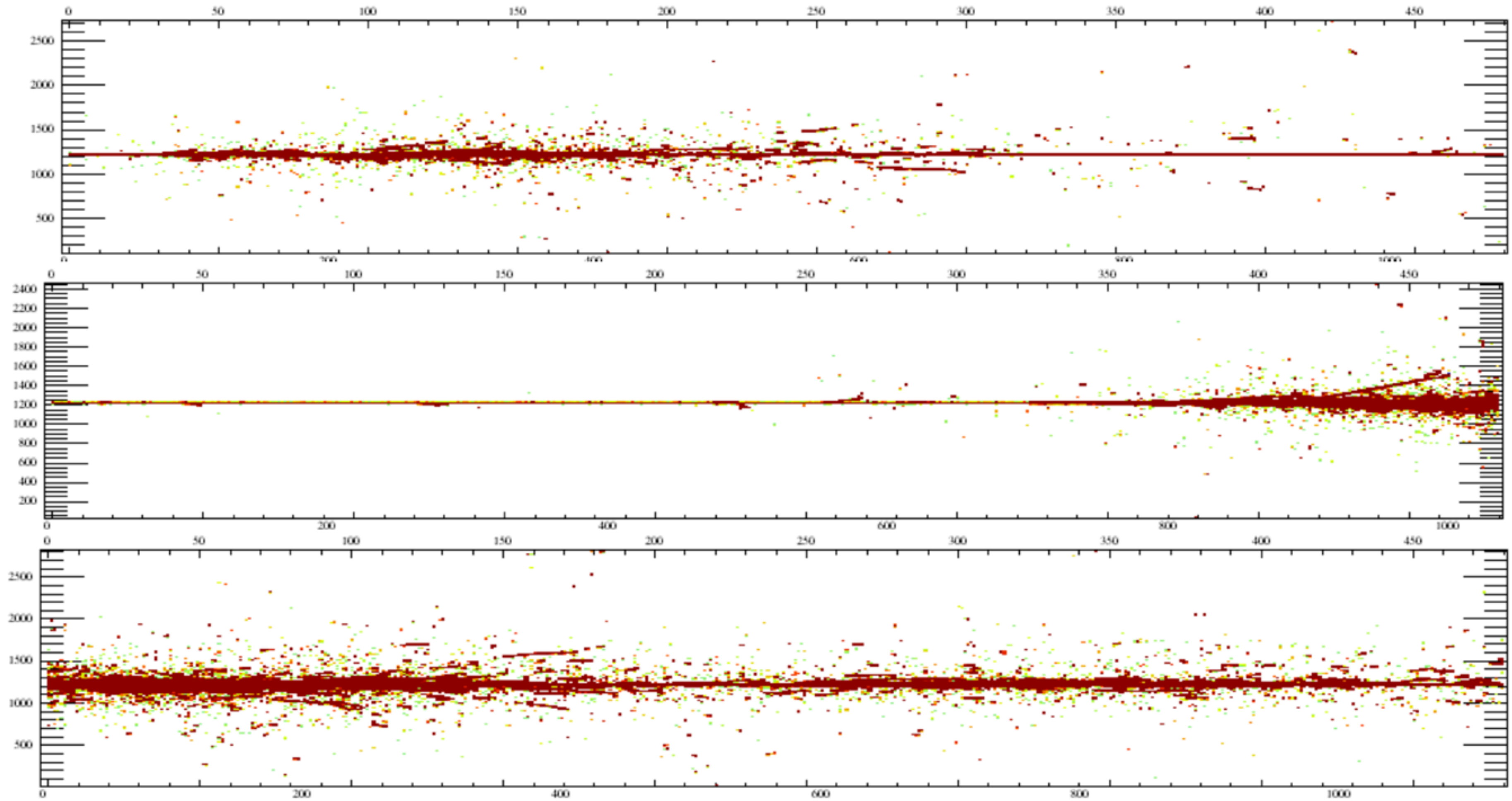
Front-end saturation, induction on back-side collection-plane wires due to wrapping of induction-plane wires, FEMB-localized effects.

Space Charge

- Space charge from cosmogenic sources not expected to be significant in FD-SP
- Space-charge effects in ProtoDUNE-SP and ProtoDUNE-DP are large – proportional to the cosmic-ray rate and the cube of the drift time
- More than 20 cm of lateral distortion in hits in ProtoDUNE-SP
- 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). Mike Mooney and Hannah Rogers have done a great job calibrating this with cosmics.
- Broken Field Cage resistor has an effect on the field that can be measured in a similar way to space charge

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 – mostly bremsstrahlung
- Some π^0's: 1300/module/year
- Spectrum of EM energy loss is model dependent.
  - energy spectrum of cosmic rays entering detector not perfectly known
  - interactions of high-energy muons with argon atoms

- Michels from stopping muons (11000 stopping muons per module per year) can help constrain EM energy reco
- Delta rays

ICARUS π^0 Invariant Mass Reco

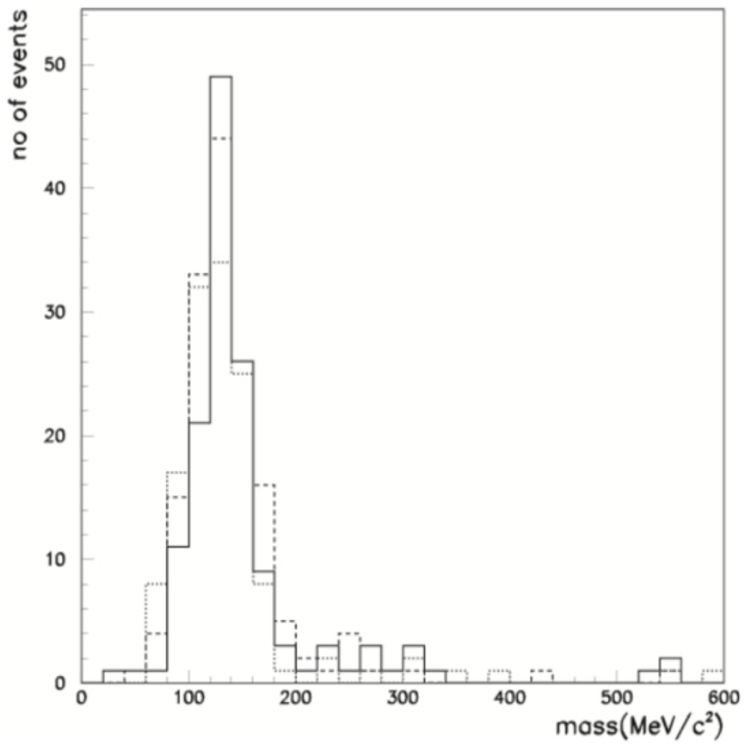


Fig. 7. (γ,γ) invariant mass distributions (solid, dotted and dashed lines) of three different laboratories involved in the data analysis.

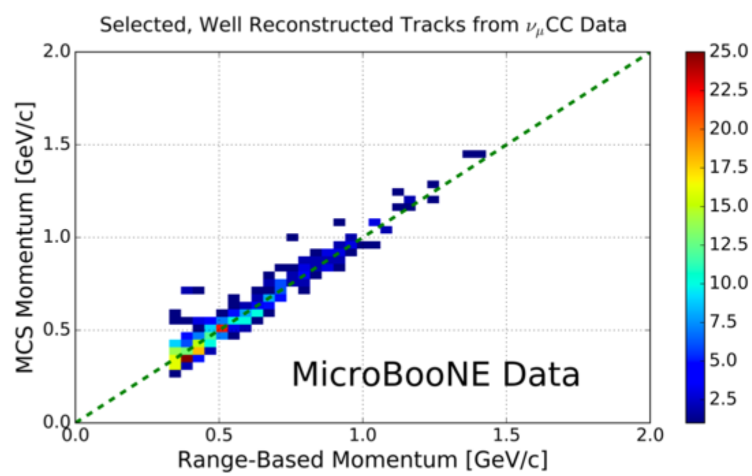
ICARUS Collab.
arXiv:0812:2373

212 Candidate Events, Pavia Surface Run

Extras

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.

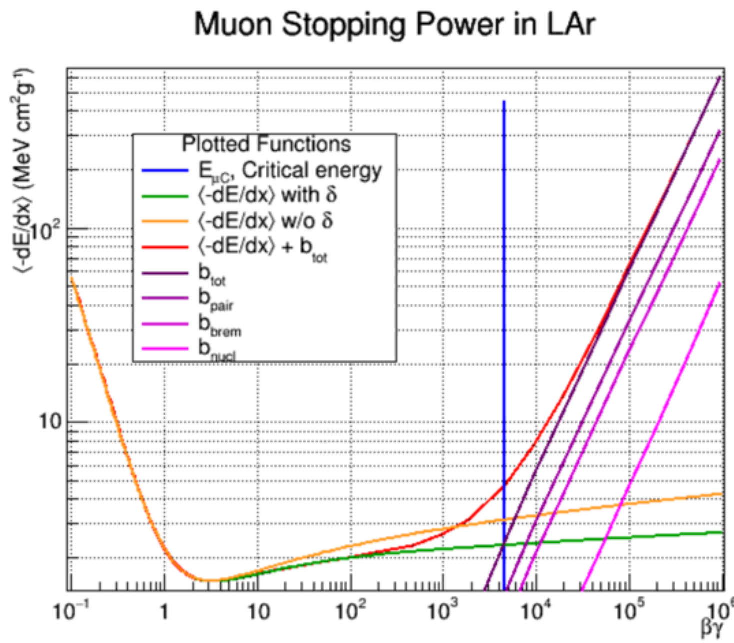
Recombination vs Angle

- 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.

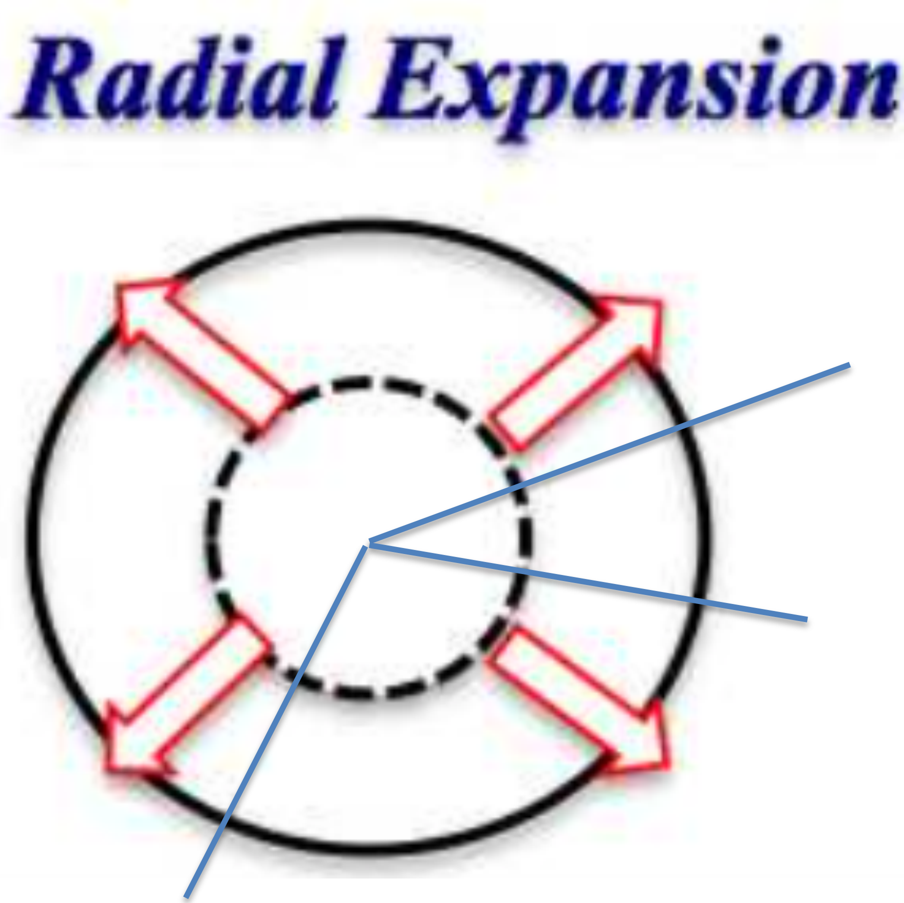
dE/dx Calibration with MIPs

- 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

Example: Radial Expansion is a Weak Direction

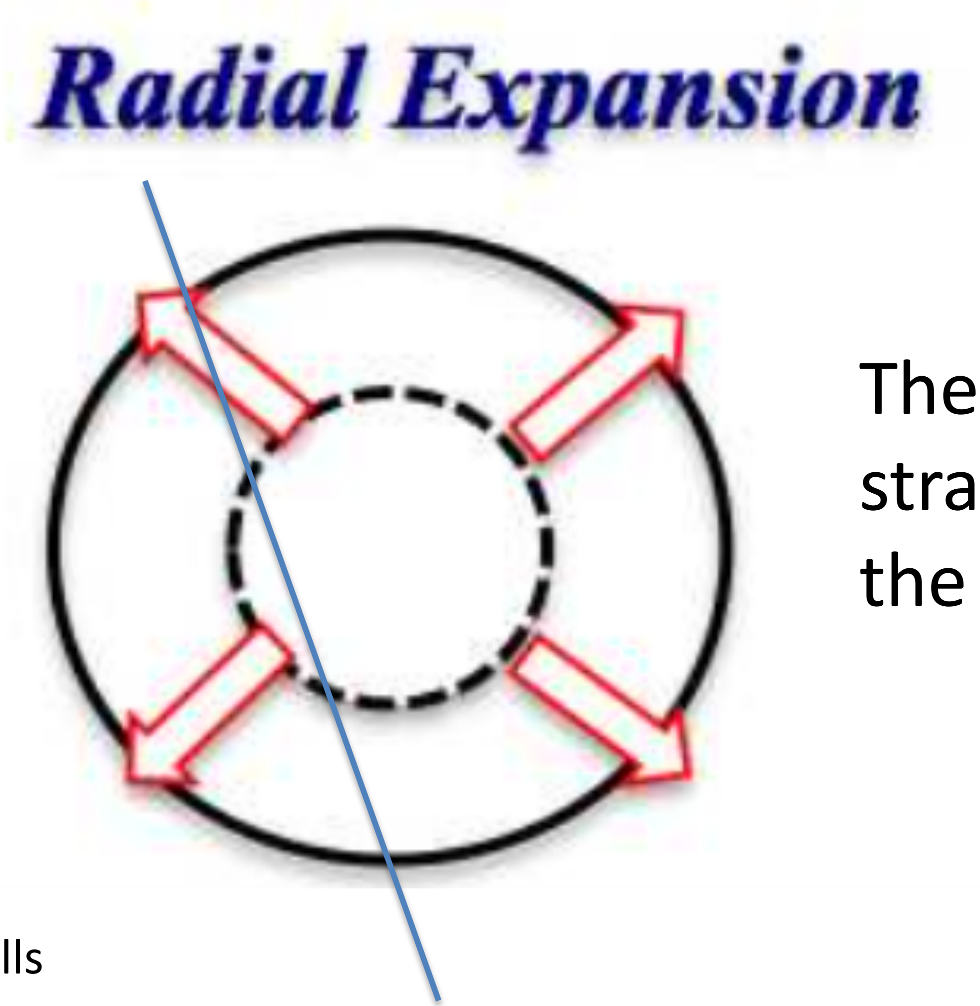


Tracks from the center of the detector don't constrain the radial size of the detector.

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

An Elaborate Example: CMS muon tracker

http://arxiv.org/abs/0911.4022

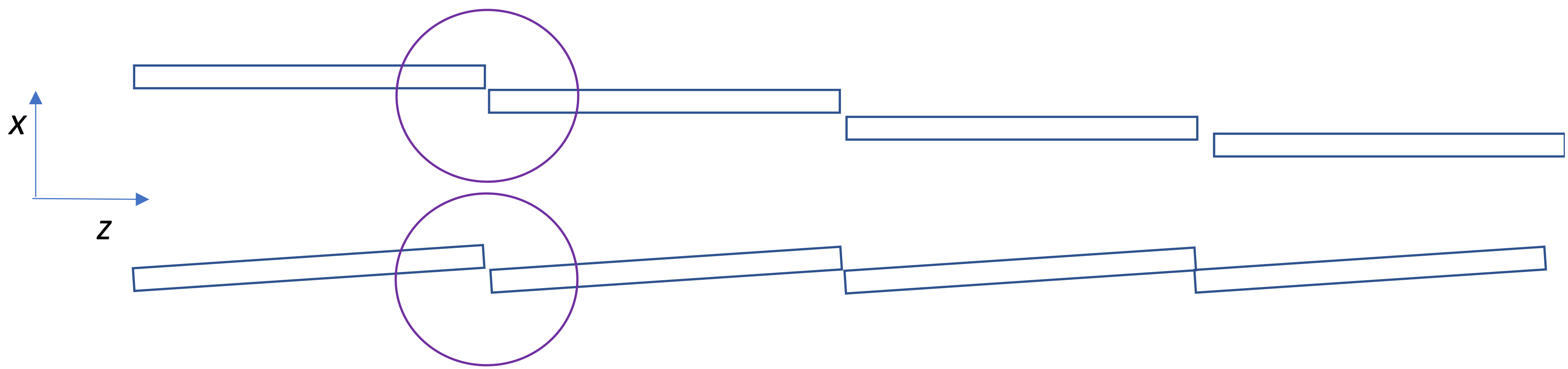
Essentially a sum of track-fit chisquareds as a function of alignment parameters (offsets and angles). Add to that survey constraints which keep the fit from wandering off in "loose" directions.

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

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.

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

APA Alignment Pin and Slot

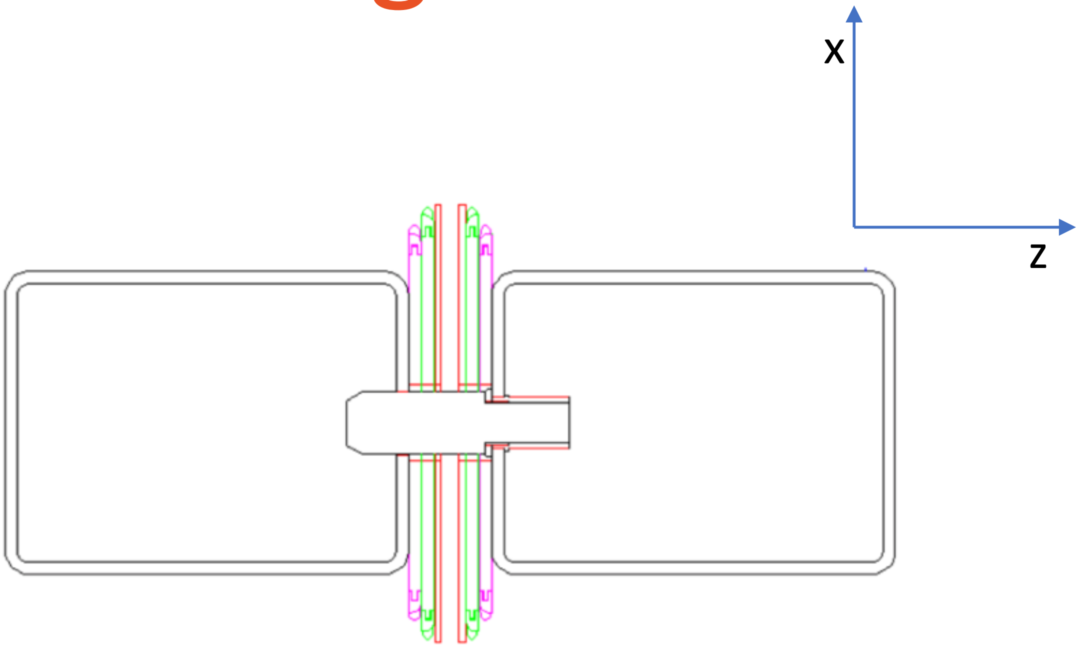
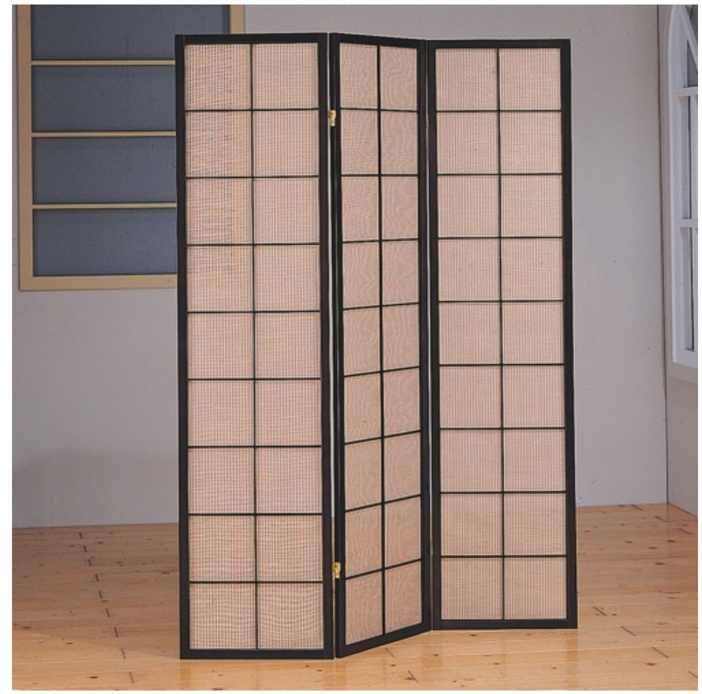


Figure 2.12: The pin/slot constraint. The pin screws into an insert in the outside frame member of one APA and engages a slot in the outside frame member of the adjacent APA.

- From the ProtoDUNE-SP TDR

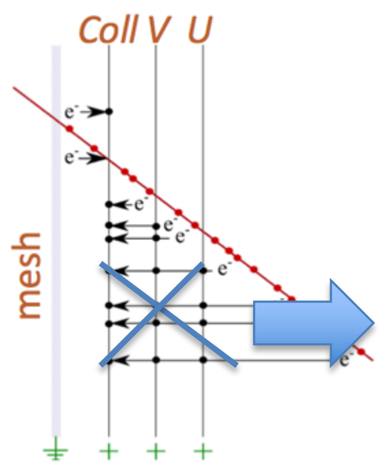
Hopefully constrain this sort of distortion



- 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

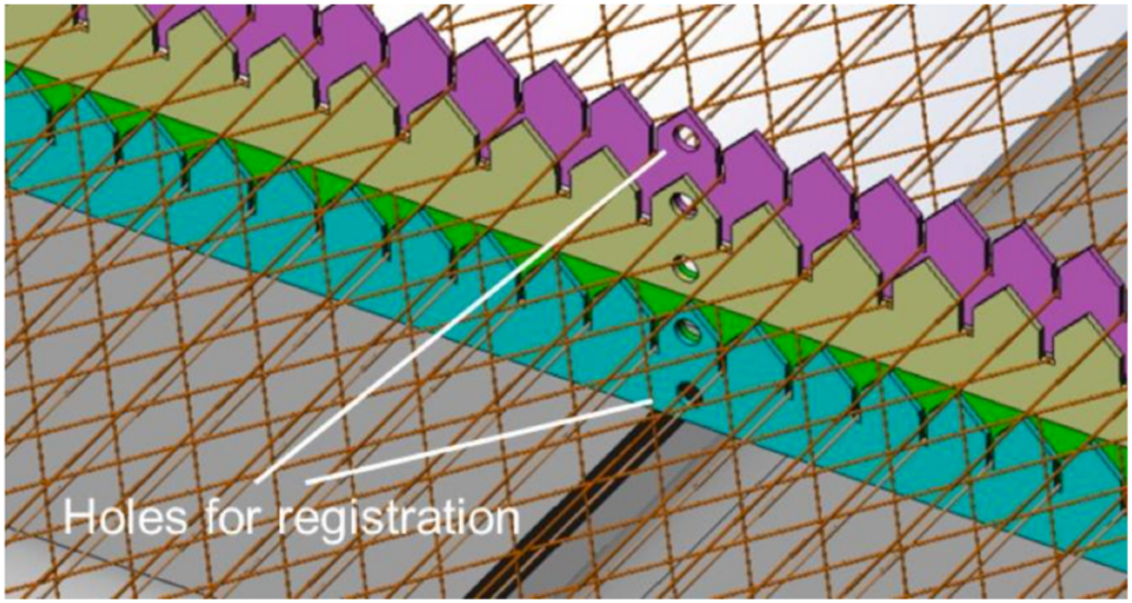
Hits on the Outer Side

- 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



Wire Support Combs

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

Field Cage Beams and Wire Support Combs

From Kevin Wood's Collab Meeting Talk Sep 2018