Calibrations at ICARUS and ML Perspective

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ICARUS Machine Learning Workshop @ Colorado State University

July 11th, 2023

Introduction

- The Calibration WG has been busy calibrating the detector since the beginning of cold commissioning at ICARUS
  - Drift velocity measurement
  - Tuning of electronics/field response
  - TPC energy scale (gain, recombination) and non-uniformities
  - Measurements of diffusion (D_T, D_L)
  - E field distortions, including space charge effects (SCE)
  - PMT calibrations (gain, timing, variations in light yield)
  - CRT calibrations (gain, timing)

Almost Finalized

Properly Resourced

Not Properly Resourced

- How well can we address these items? *That is, what is the level of residual data/MC disagreement we might expect?*
- The answer to this question is very relevant not just for ICARUS analyses, but the entire SBN physics program

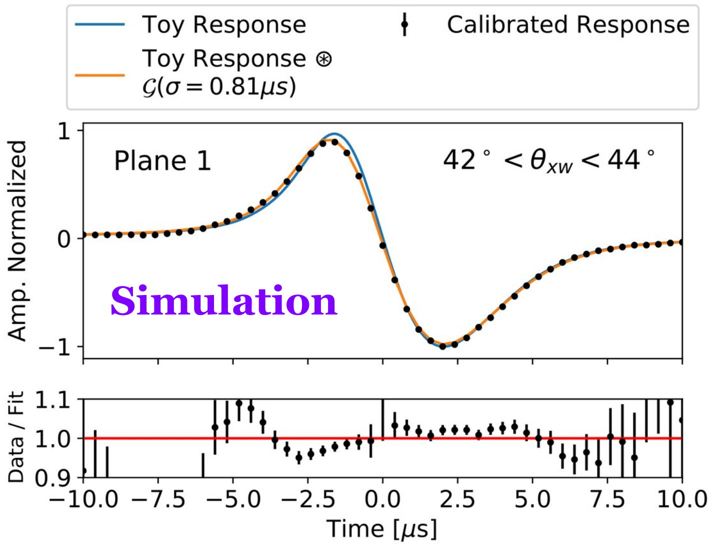
General Approach

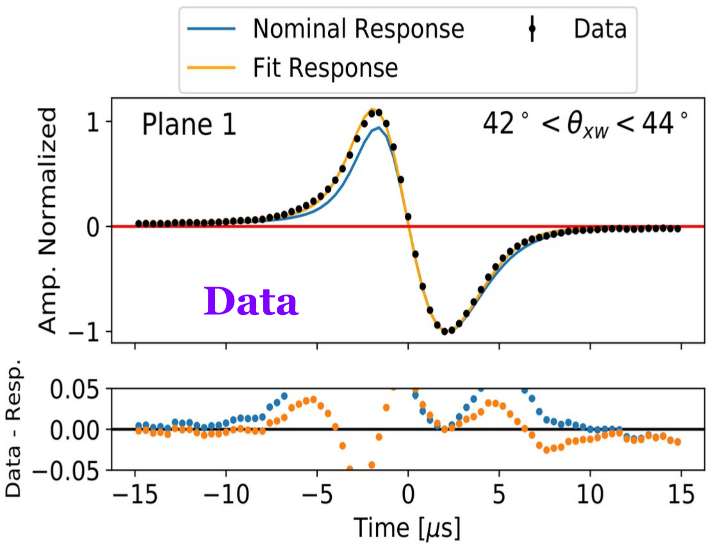
- Two important goals of detector calibration:
  - (1) Improve simulation to minimize data/MC bias
    - Example: modify TPC field response in MC to better match data
  - (2) Maximize performance of detector measurements
    - Example: change TPC deconvolution kernel to use measured field response in order to improve measured charge resolution
- In general, we should be more concerned with making a wrong measurement than making our "best" measurement
  - This prioritizes (1) over (2); start with (1), pursue (2) in longer term
- Both (1) and (2) are important to physics analyses:
  - More work on (1) → smaller detector systematics (can "cover" bias)
  - More work on (2) → high-level measurements more precise
- Work on (1) until detector systematics are subleading contribution, work on (2) until negligible to sensitivities

Logistics and Priorities

- First, let's consider logistical complications, and set our priorities accordingly
- Big bottleneck for experiment is how fast we can pull data from tape for processing
  - Want to do this as few times as possible
  - Cost is much higher if done later on in experiment (more data)
- Correspondingly, want to redo "stage-0" processing as infrequently as possible (output is more manageable to store)
- This prioritizes calibrations that would require reprocessing data through stage-0:
  - TPC electronics/field response tuning (impacts deconvolution)
  - PMT timing calibration (applied prior to creating OpFlash objects)
- Can store data on disk until this summer – handle by then!

TPC Signal Response Tuning

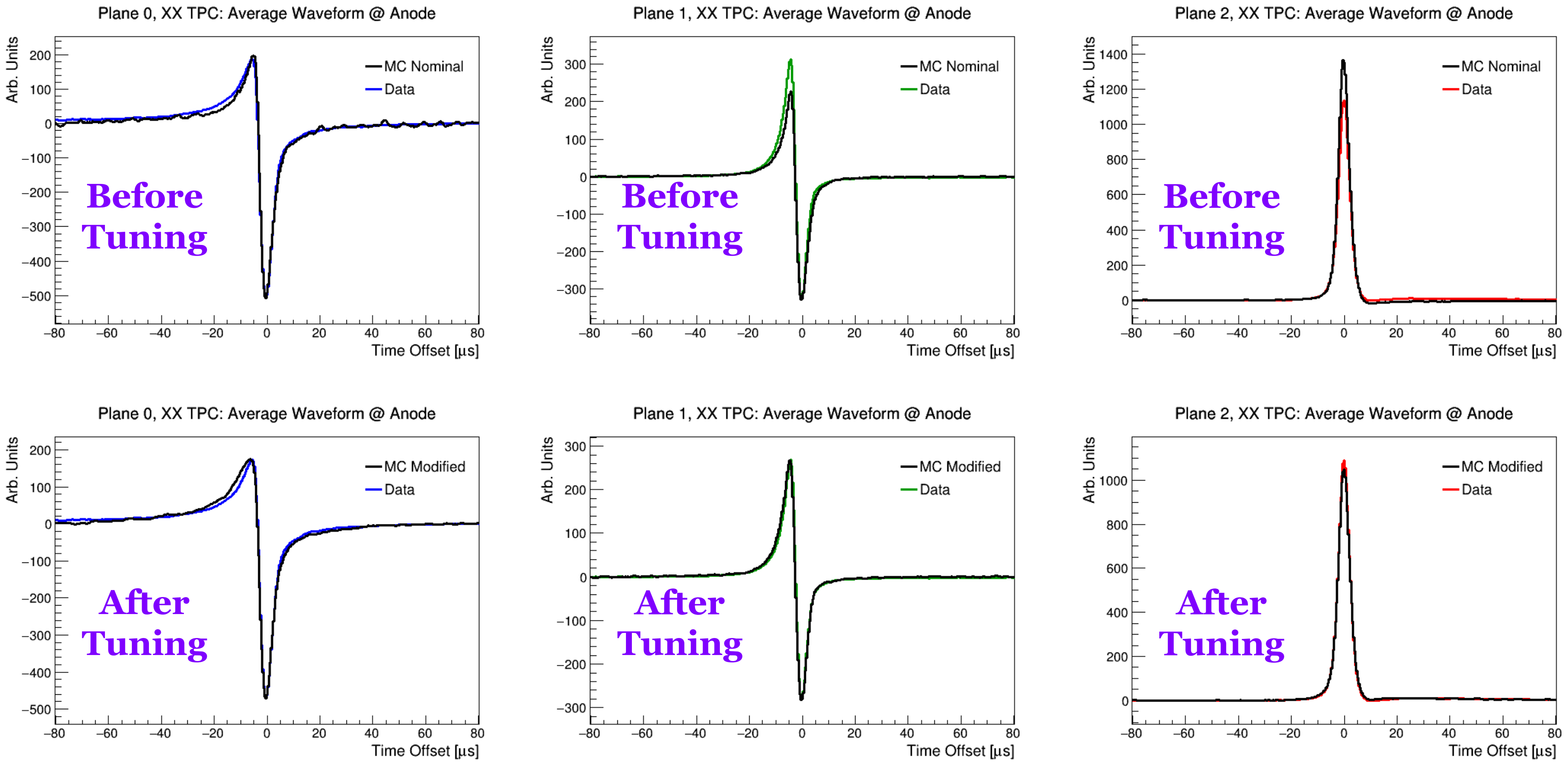




G. Putnam

- Brief summary of methodology:
  - Produce average signal waveforms in data, MC
  - Take toy MC model of signal response and use to extract amount of "smearing" due to noise as function of track angle
  - Fit same toy MC model to data, modifying electronics/field response to obtain data/MC agreement, including noise smearing
  - Produce MC sample using tuned signal response for validation
- See recent **talk** by Gray Putnam for more details

Response Tuning Results



- Much improvement in modeling of signal response after tuning – residual disagreement (particularly Induction 1) currently being addressed

TPC Gain/Noise Tuning

G. Putnam

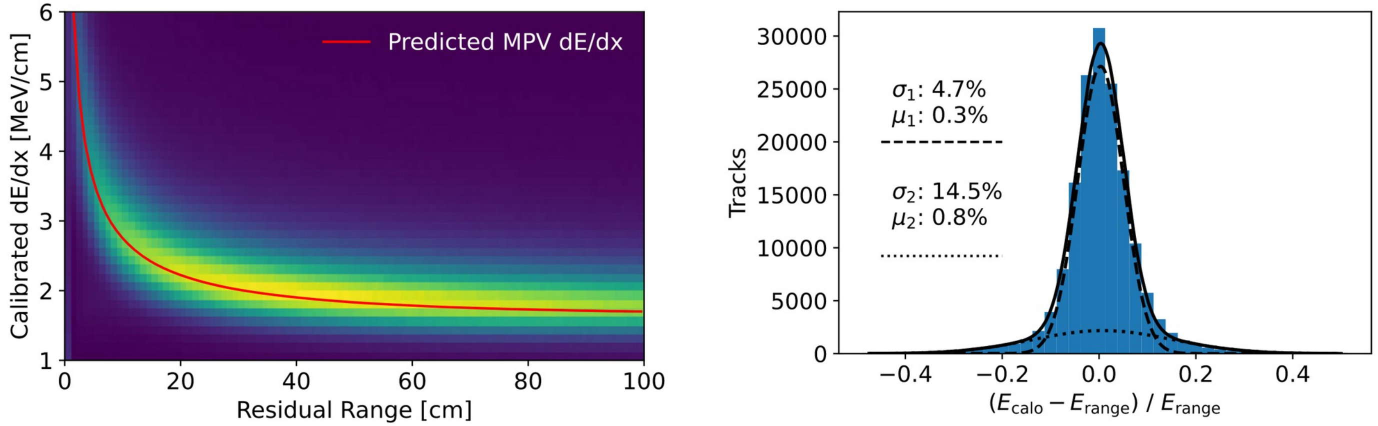
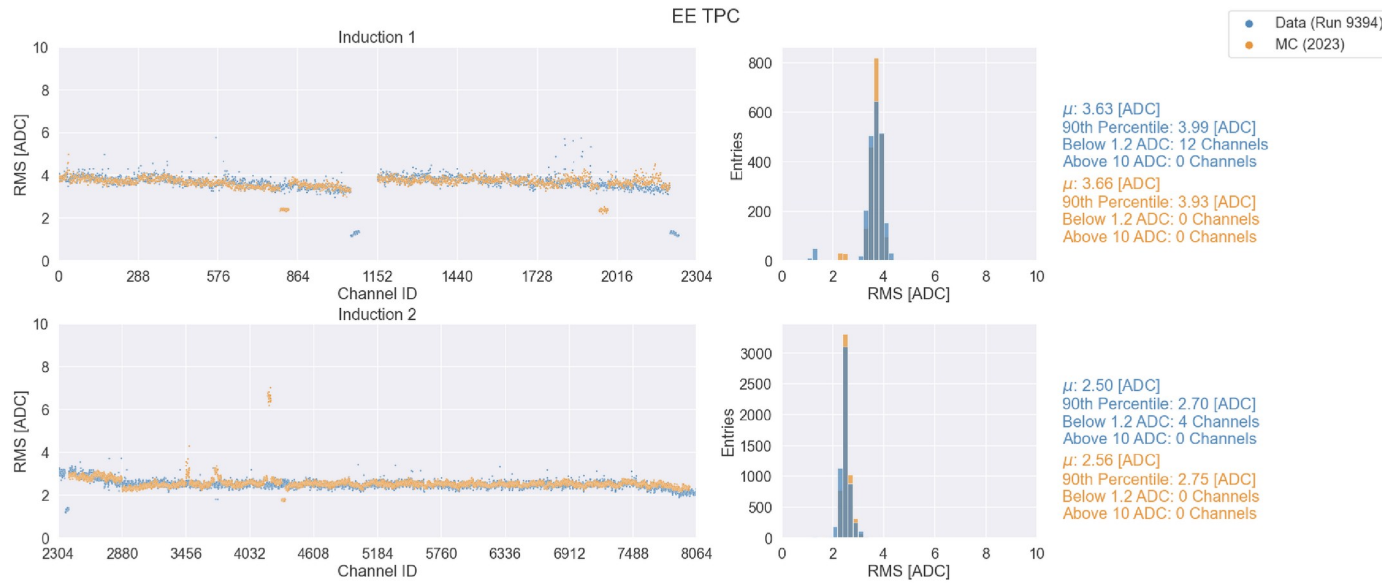


Fig. 18 Calibrated collection plane dE/dx as a function of residual range for a selection of stopping muons in ICARUS cosmic muon data, including a comparison to the most-probable value (MPV) of dE/dx from stopping muons predicted from theory [36] (left); comparison of cosmic muon kinetic energy reconstruction by calorimetry, E_{calo}, and by range, E_{range}, showing little bias between the two methods for stopping muons in ICARUS cosmic muon data after the energy scale calibration is applied (right)

- Use known stopping muon dE/dx vs. residual range curve in order to tune TPC electronics gain – see **here**
  - Use ArgoNeuT recombination measurement as constraint (pull term) in fit, with TPC gain separately floating per TPC
  - Can repeat for all three planes (see next slides)
- Noise model in MC simulation tuned to match data
  - Close but likely imperfect – eventually replace with data overlays

TPC Gain/Noise Tuning

J. Mueller



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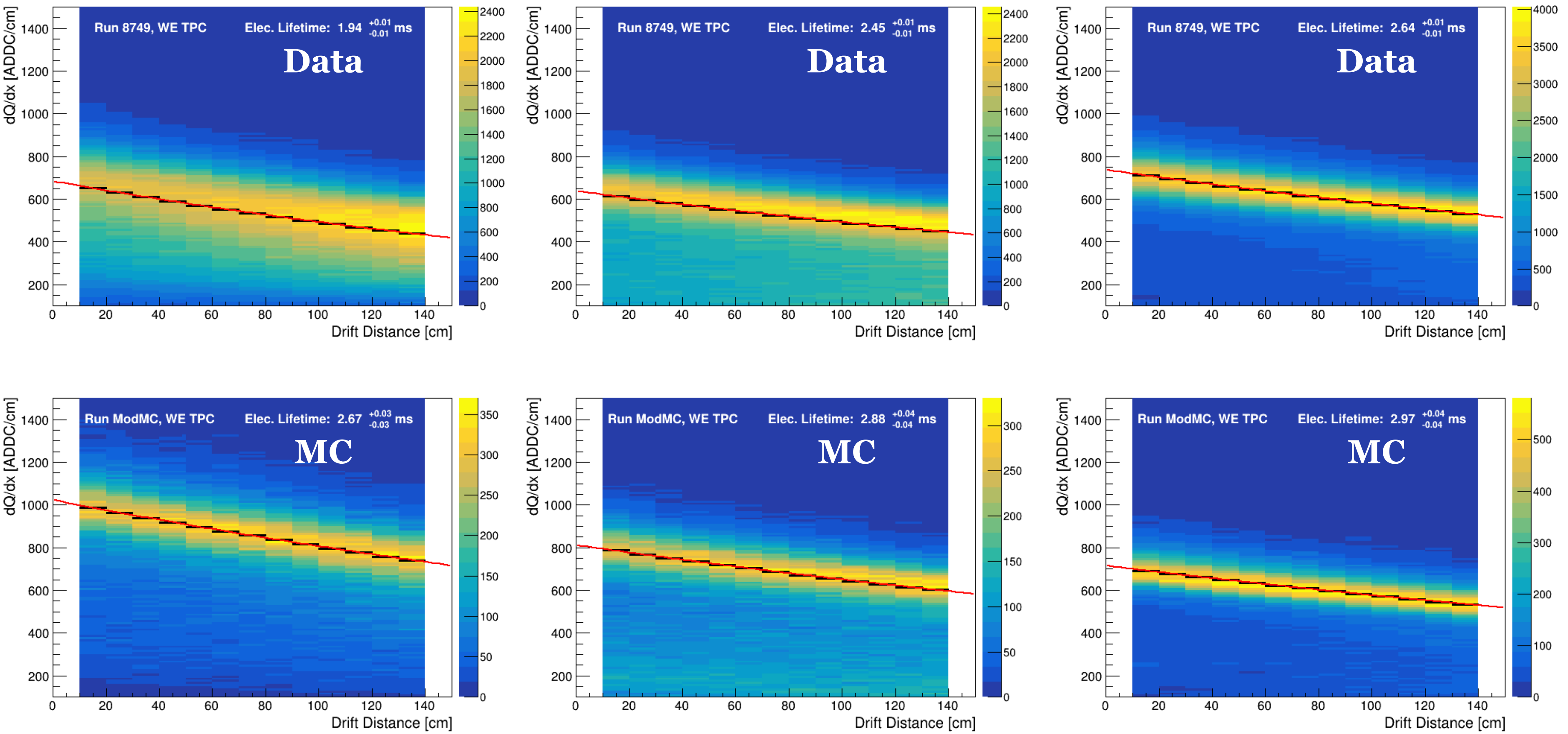
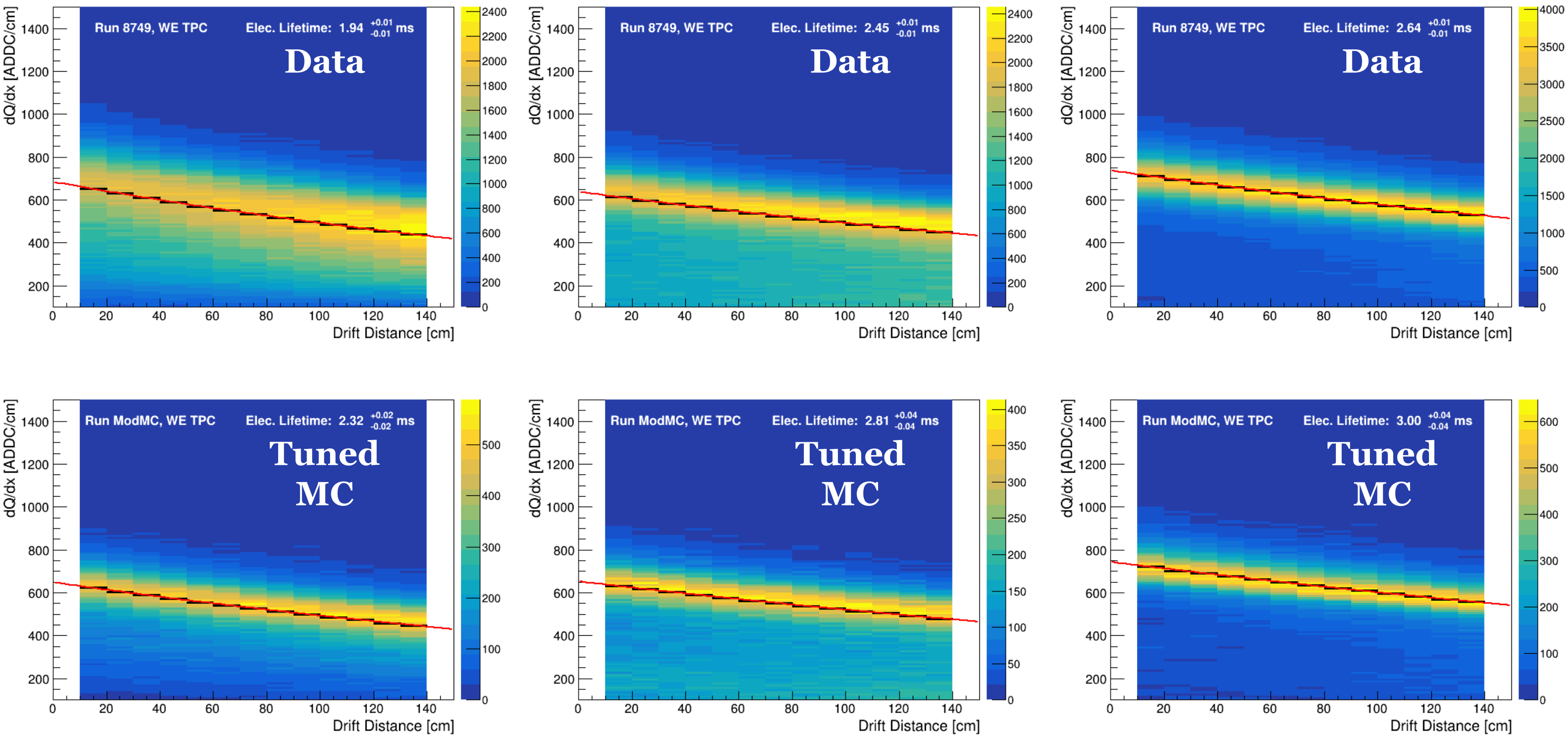
Gain Tuning Results



- Use cosmic muon tracks to adjust gain per-plane
- Data/MC agree well on Ind2/Col; Ind1 data/MC discrepancies from not modeling TPC response non-uniformity in MC

Gain Tuning Results



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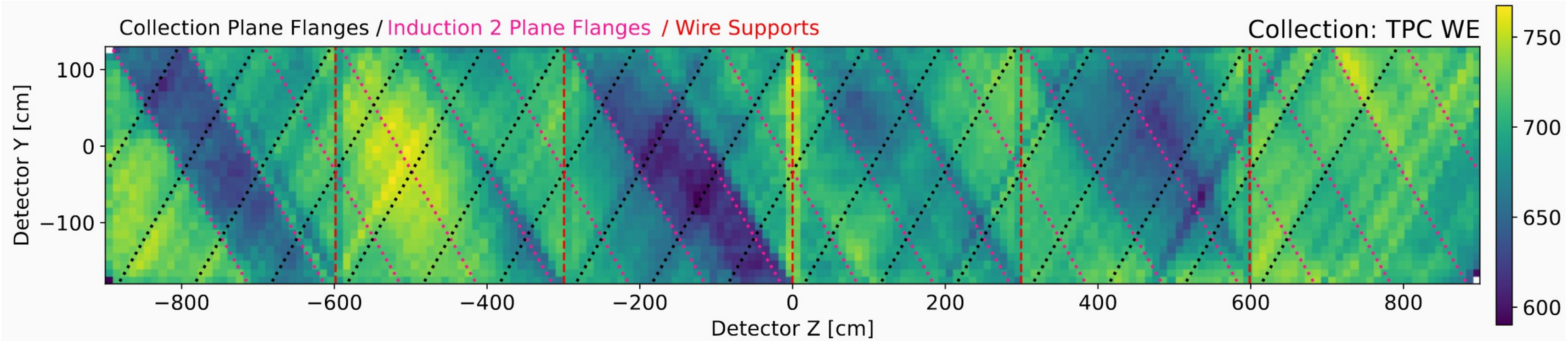
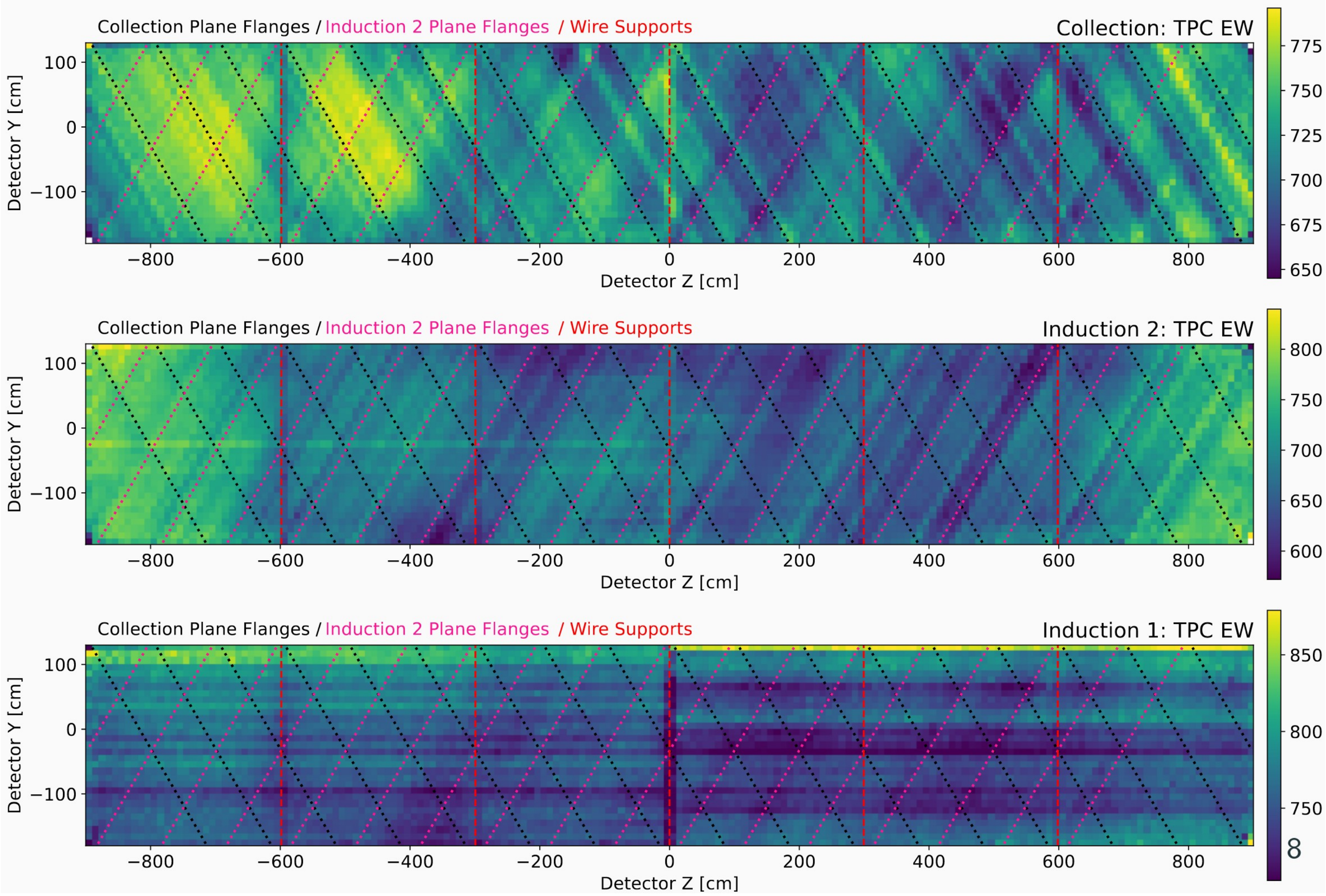
TPC Response Non-uniformity



- TPC signal response inhomogeneities observed by means of studying variations in extracted charge scale (dQ/dx MPV)
  - Range of variations across each TPC: **15-20%**
  - See previous **study** by G. Putnam
- Also TPC signal response waveforms show data/MC disagreement, likely another manifestation of same issue
  - See previous **study** by M. Mooney, previous slides
- Can correct inhomogeneities in charge scale after 3D hit reconstruction, include any signal shape variations in MC

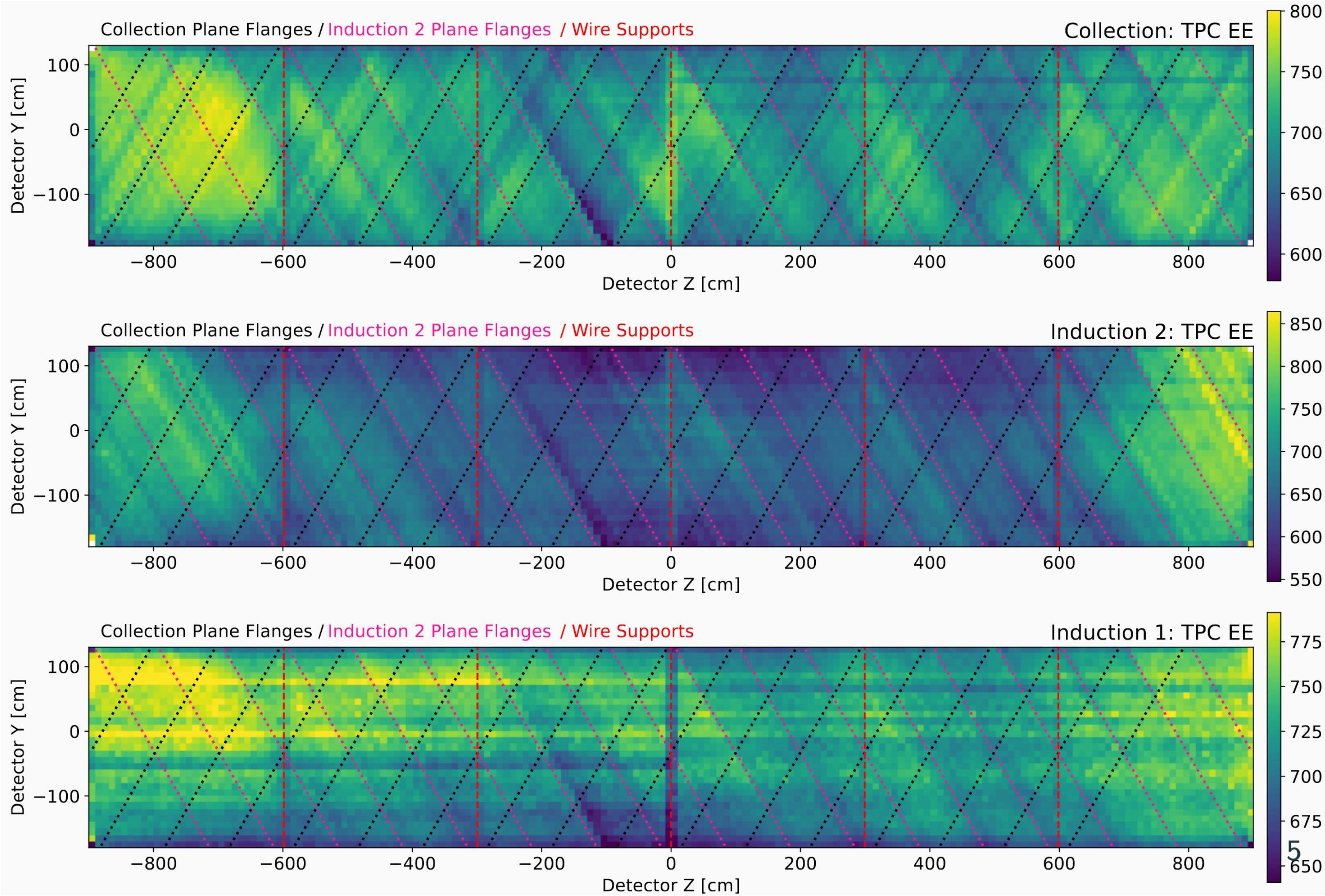
TPC EW Response

G. Putnam



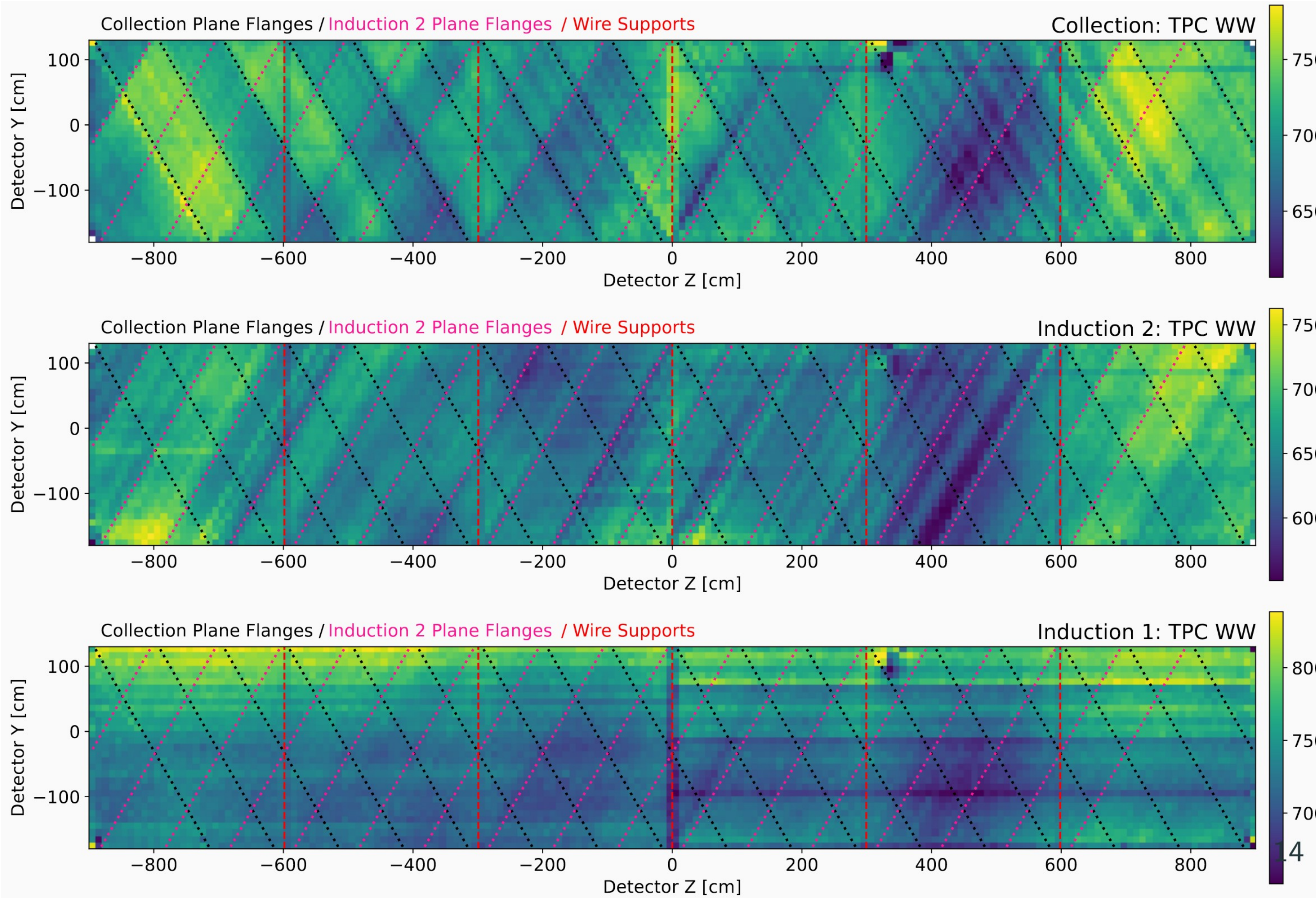
TPC EE Response

G. Putnam



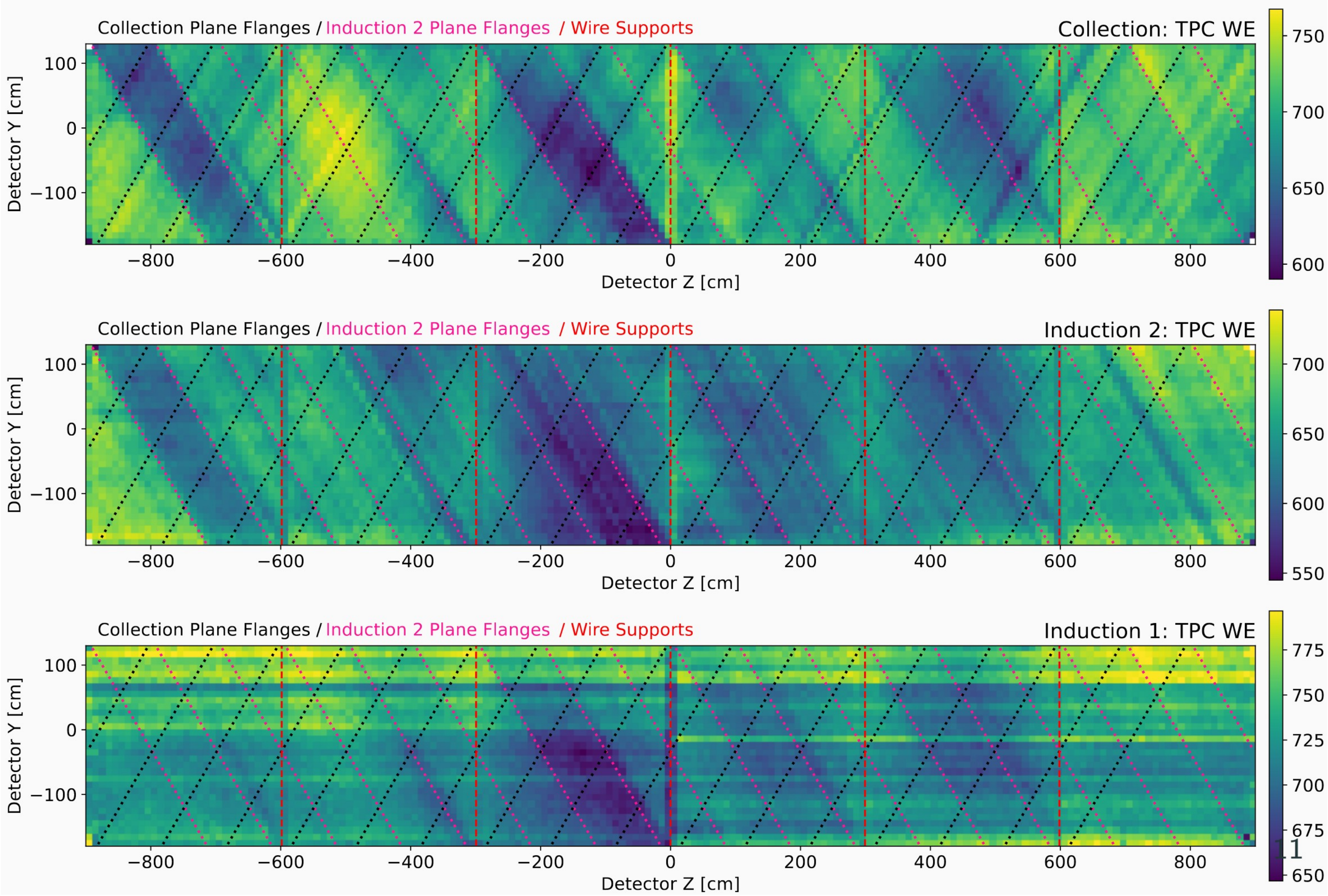
TPC WW Response

G. Putnam

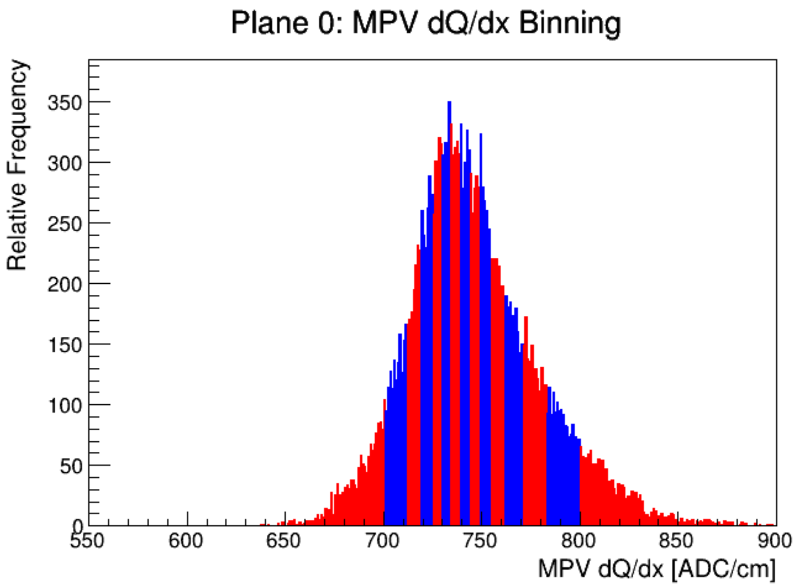


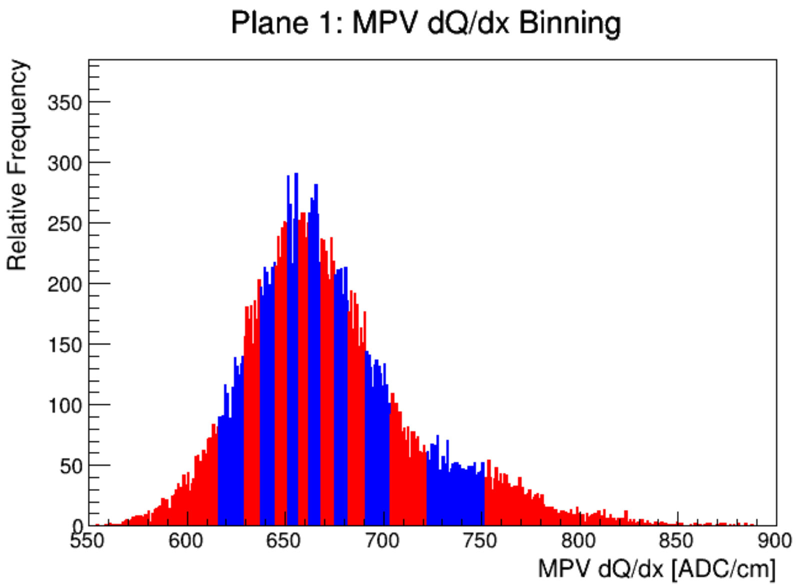
TPC WE Response

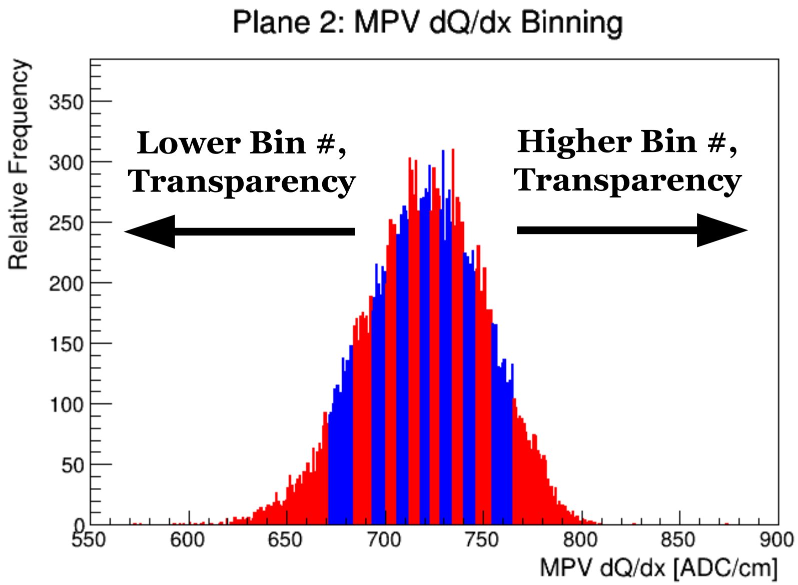
G. Putnam



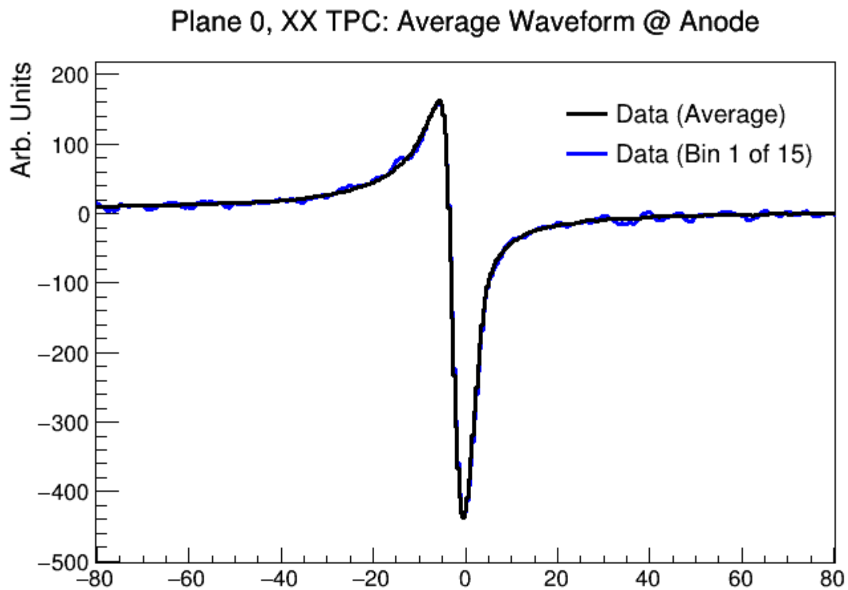
Binning in MPV dQ/dx

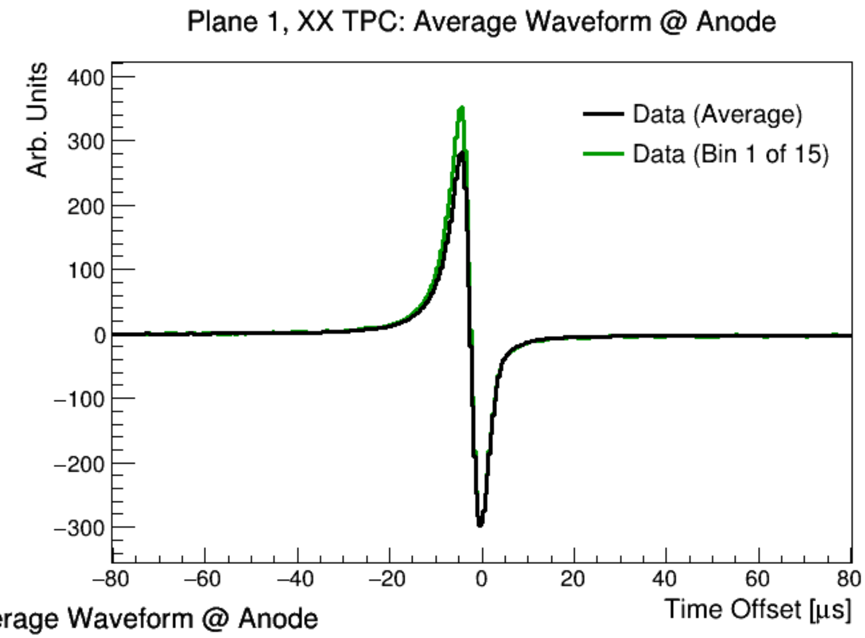


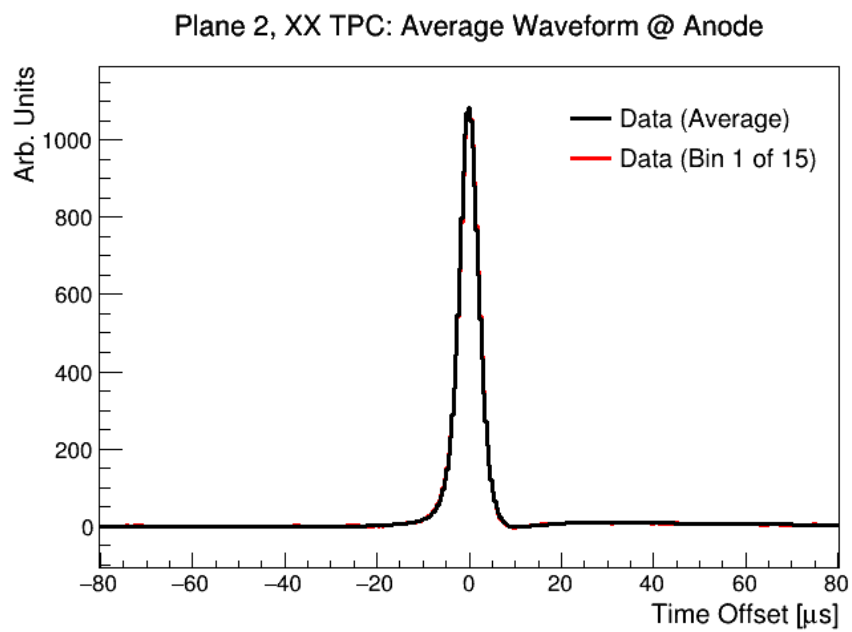




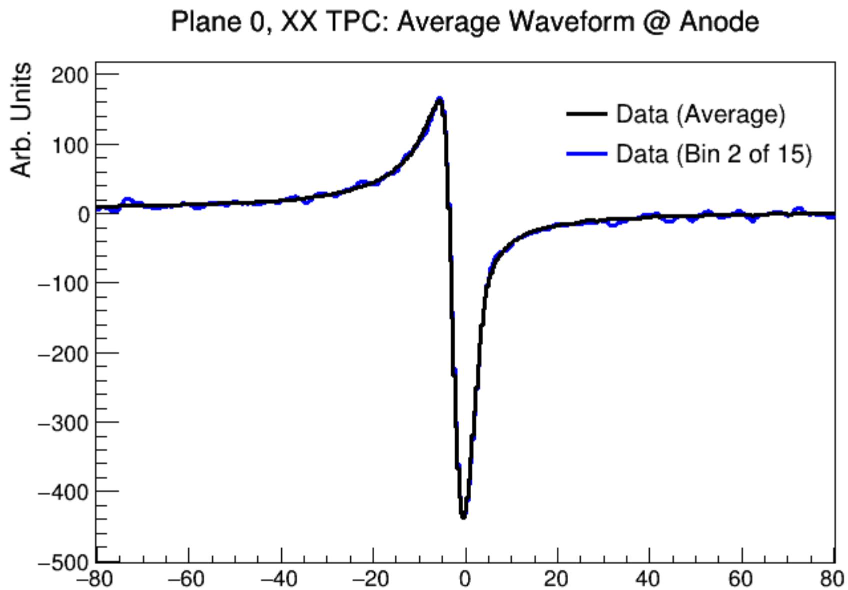
Spatial Study Results – Bin 1

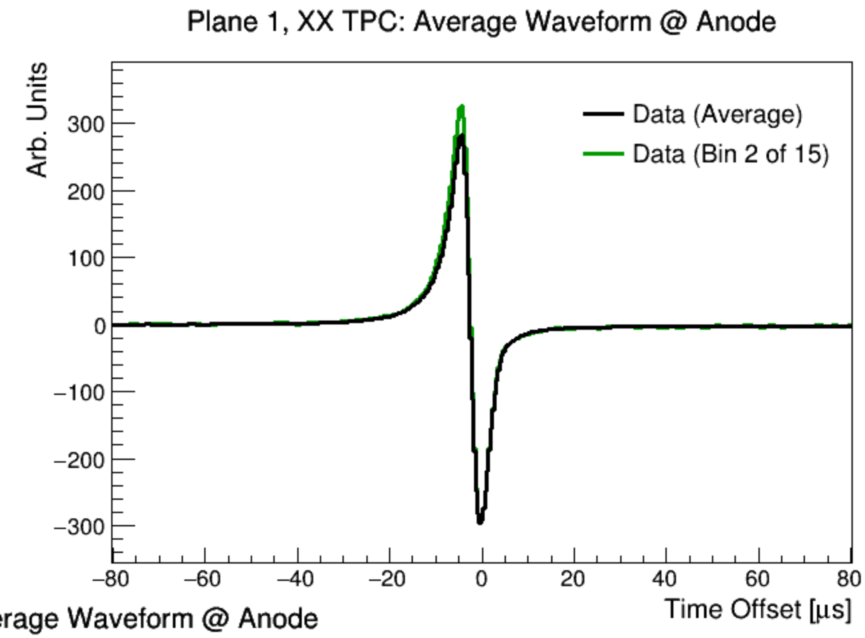


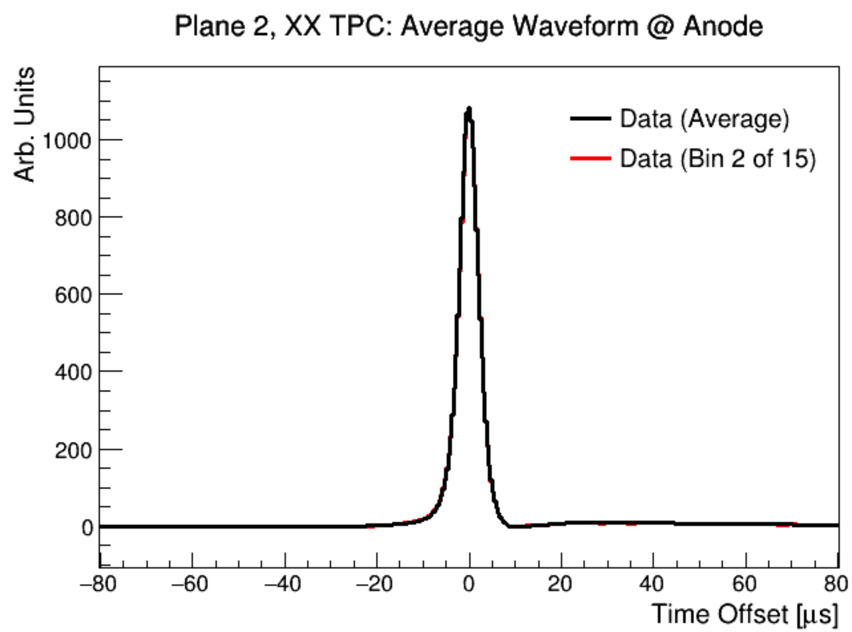




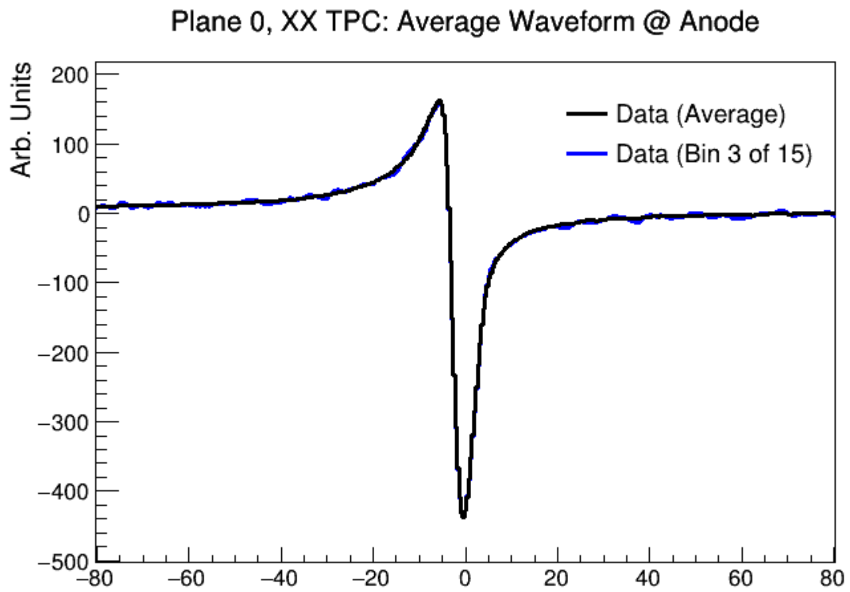
Spatial Study Results – Bin 2

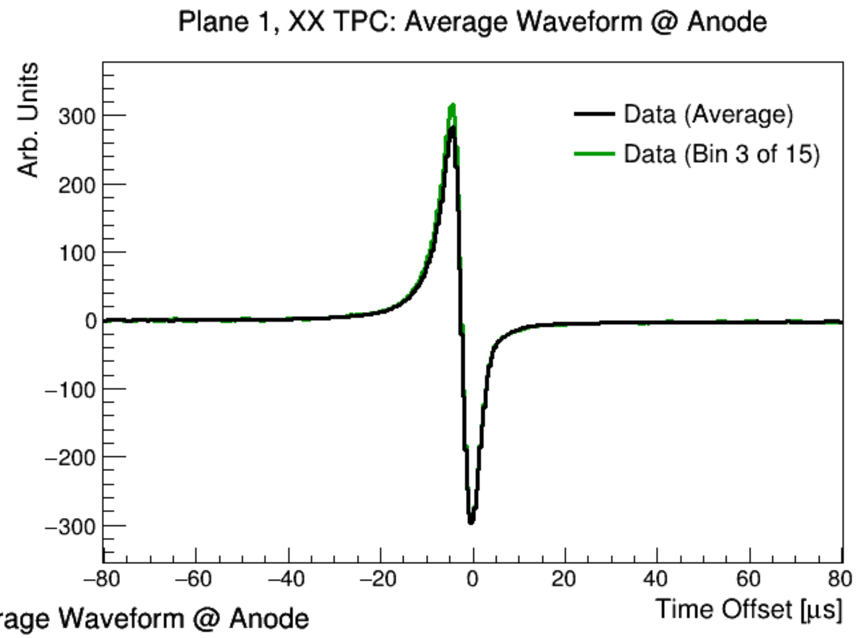


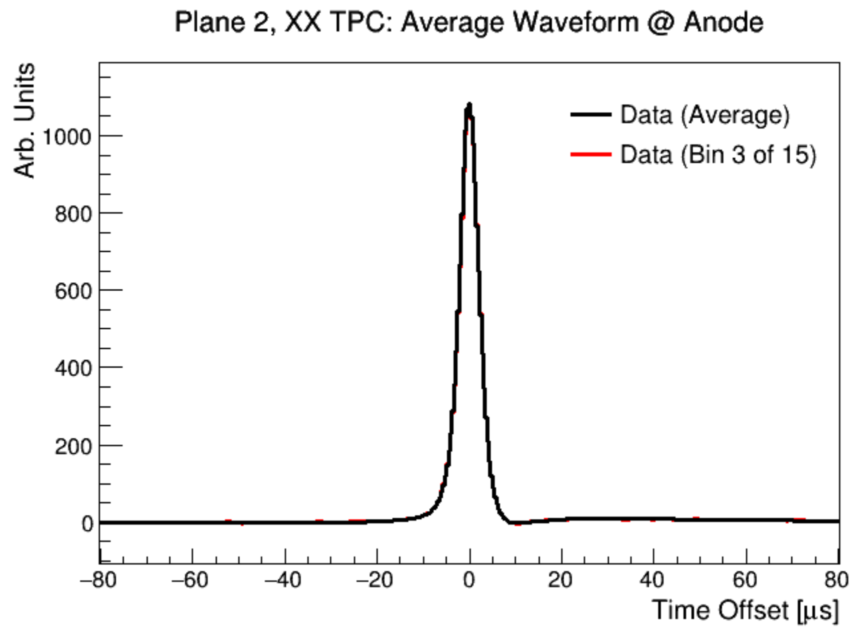




Spatial Study Results – Bin 3







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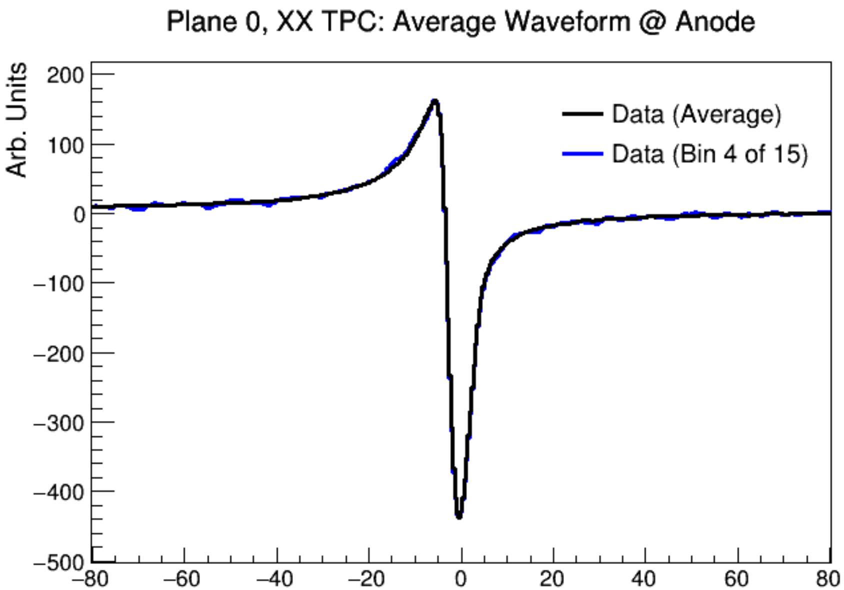

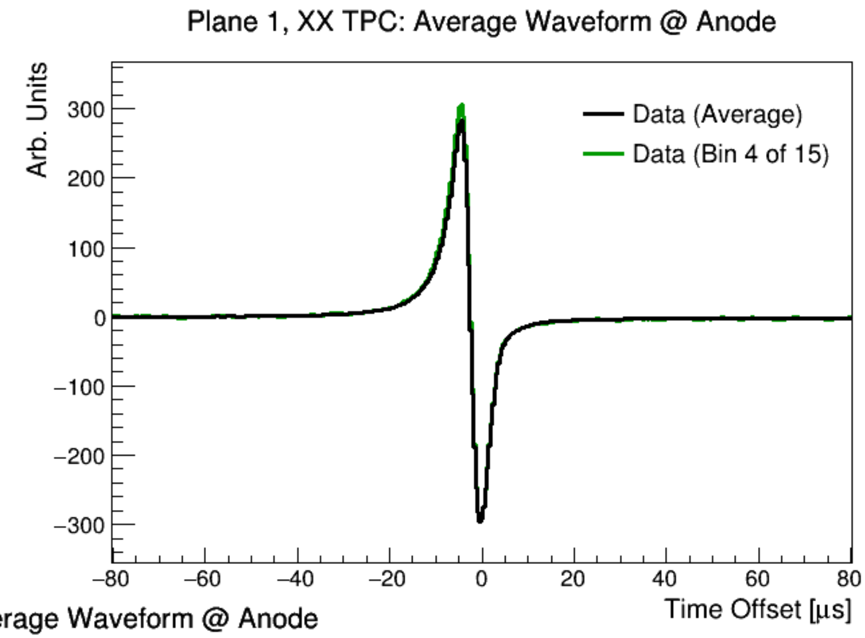

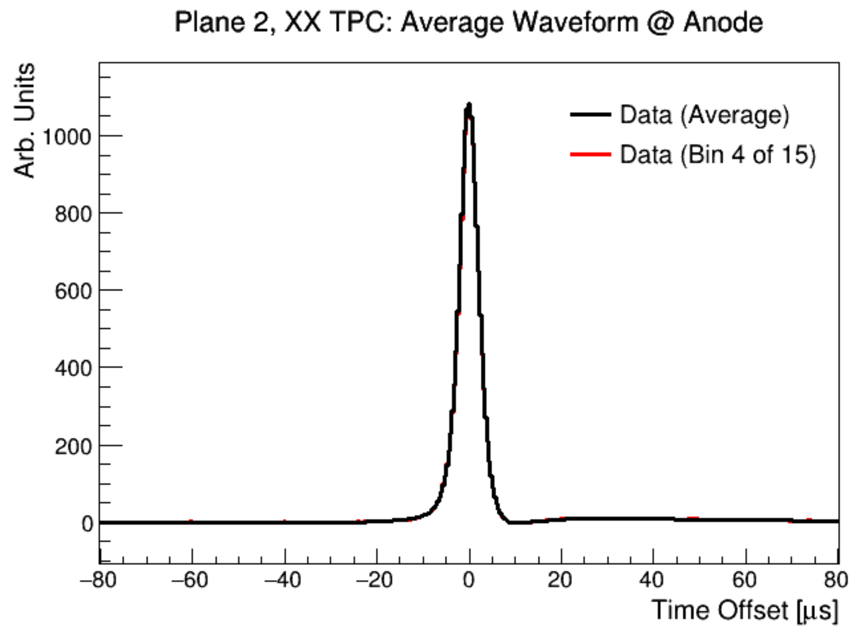

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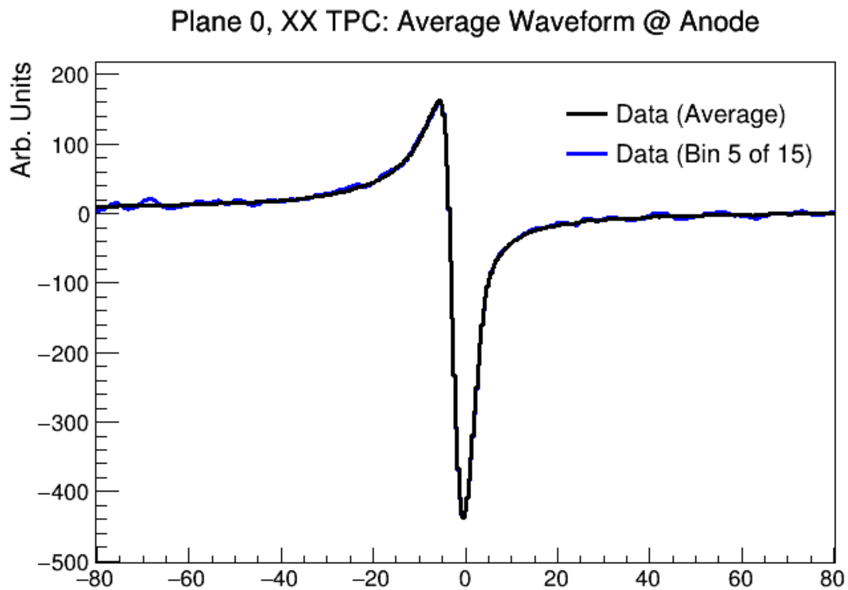

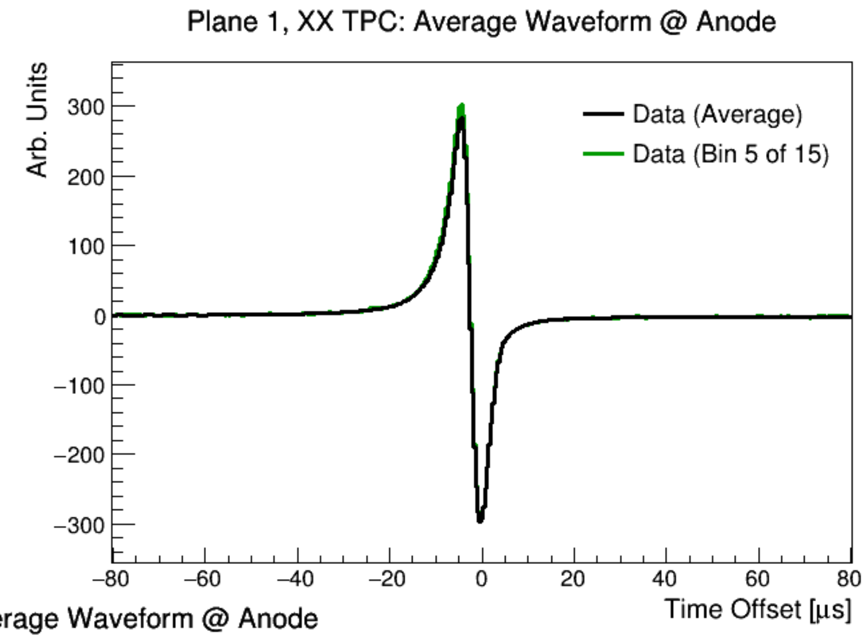

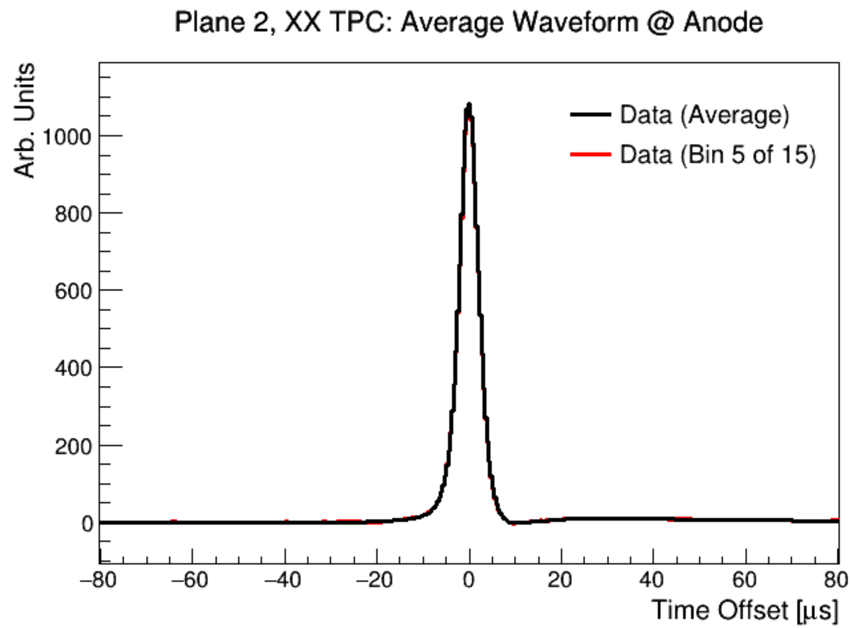

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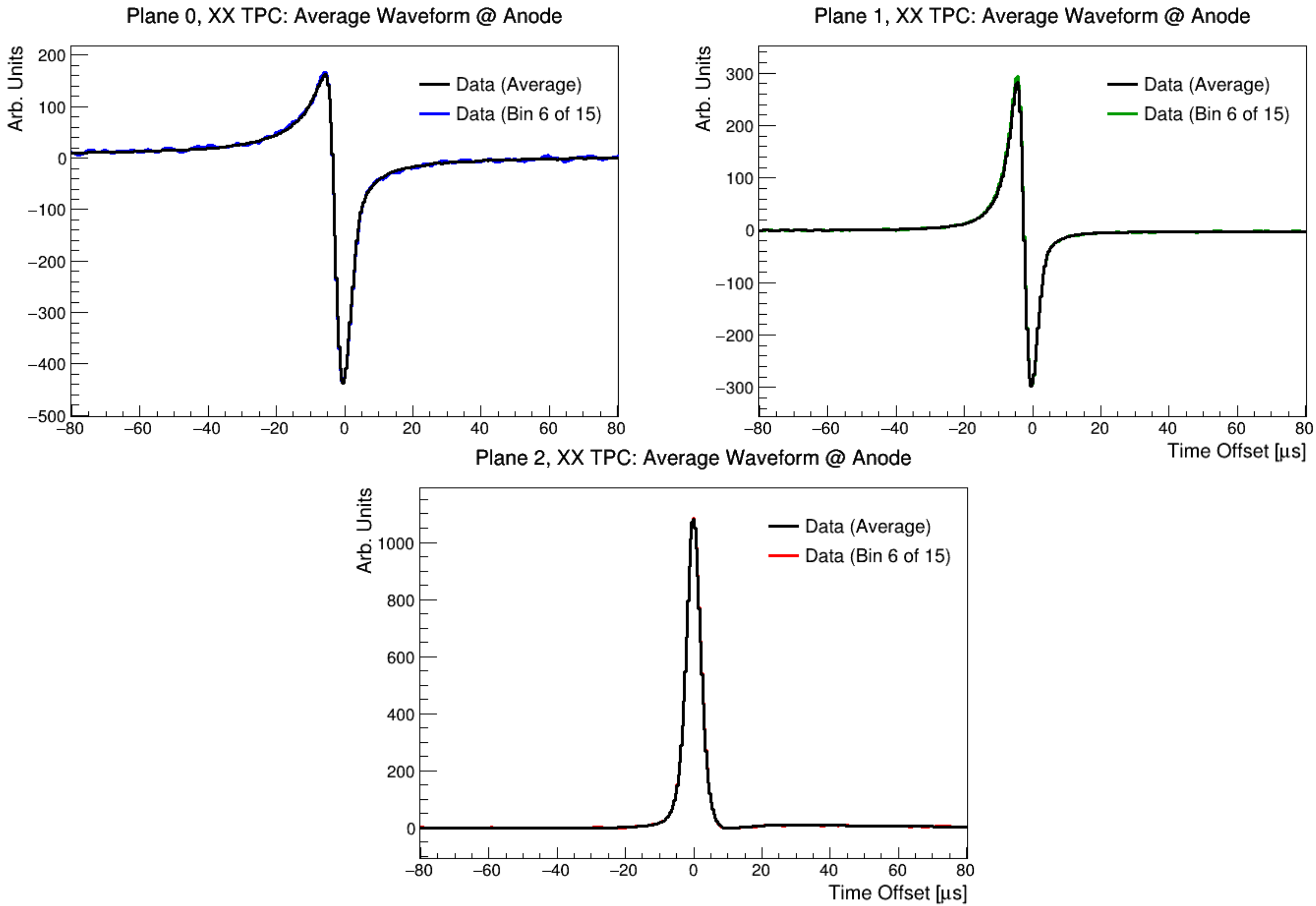
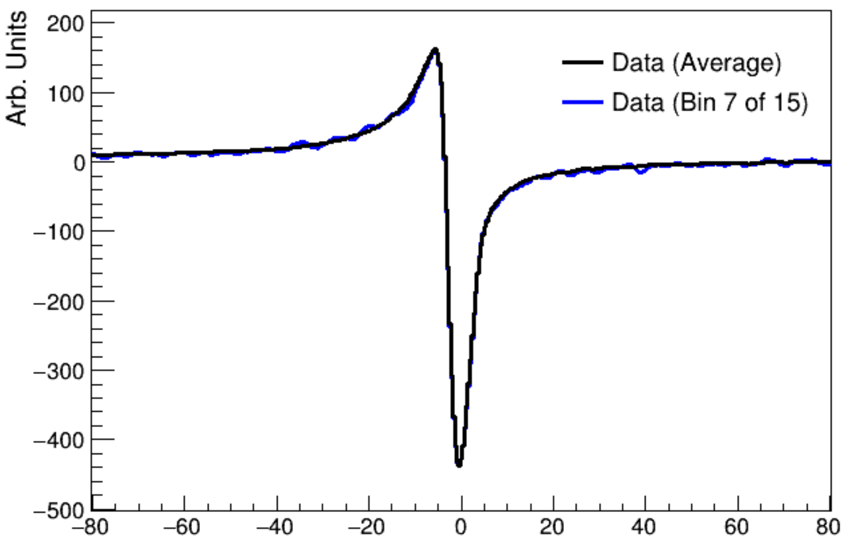
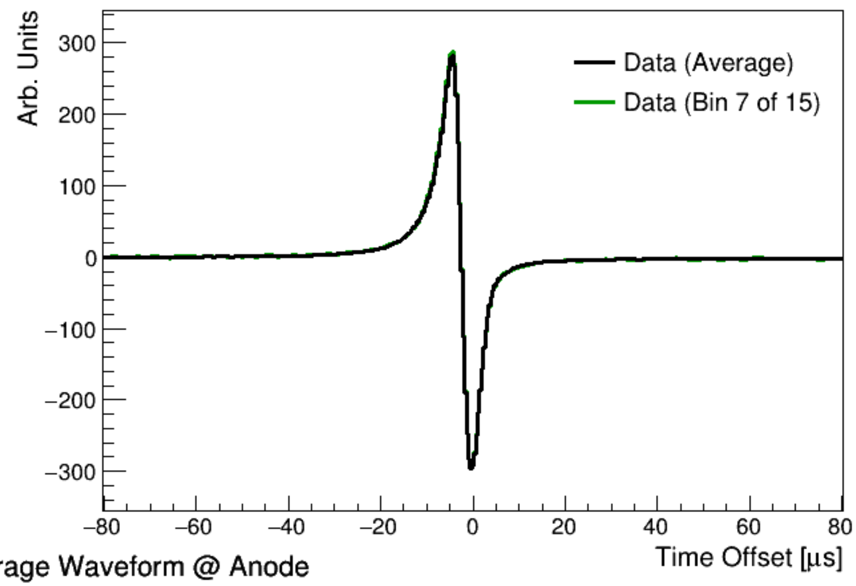


Spatial Study Results – Bin 7

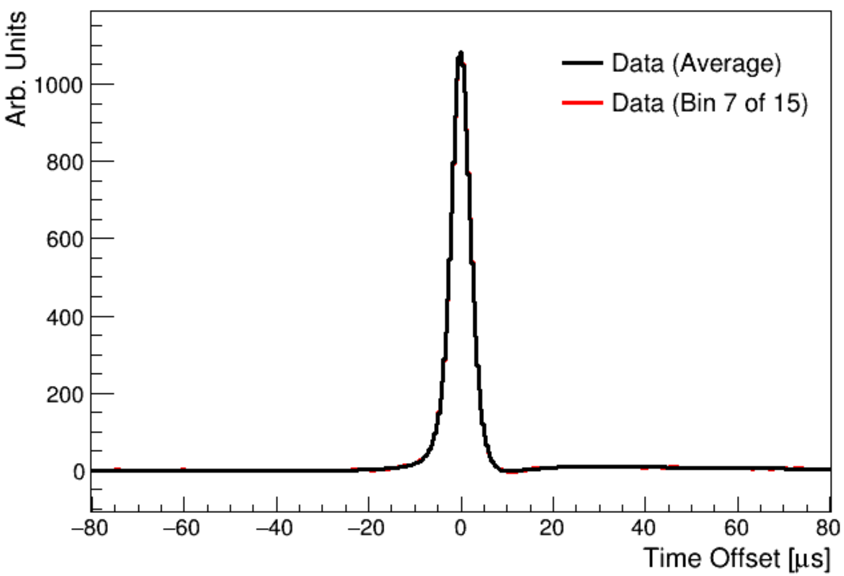
Plane 0, XX TPC: Average Waveform @ Anode



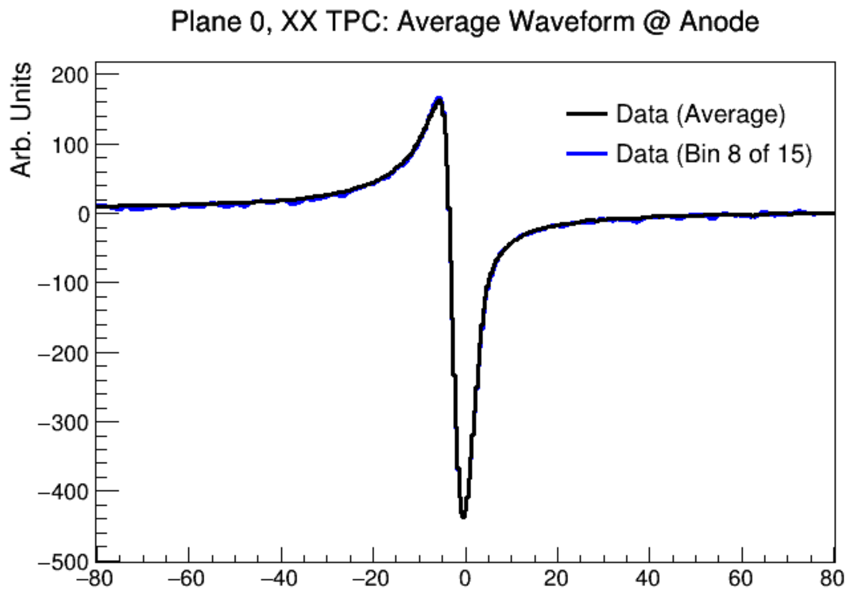
Plane 1, XX TPC: Average Waveform @ Anode

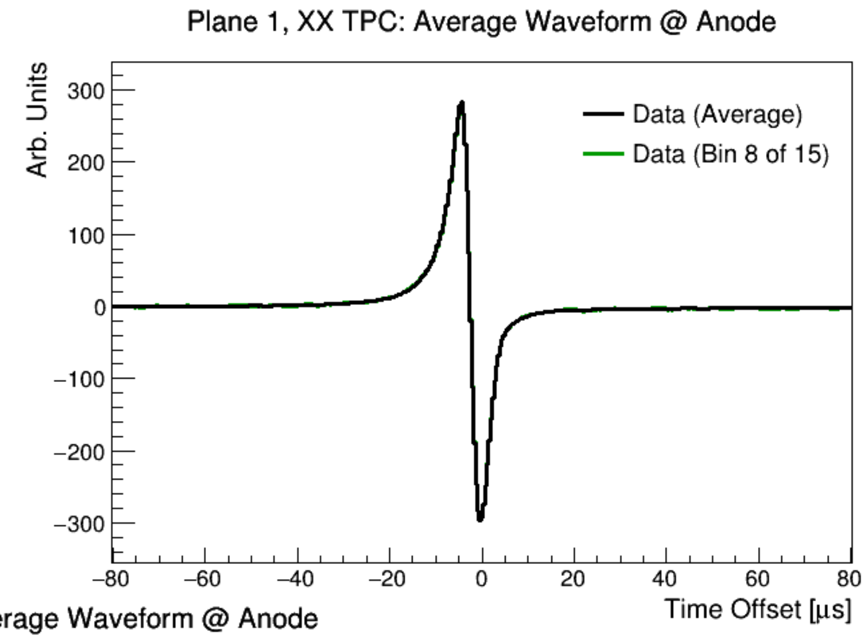


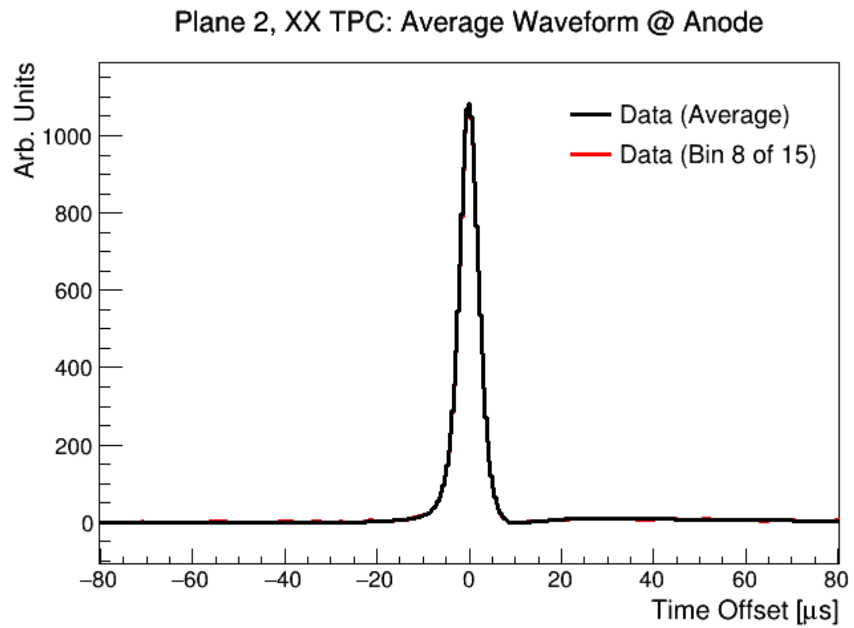
Plane 2, XX TPC: Average Waveform @ Anode



Spatial Study Results – Bin 8







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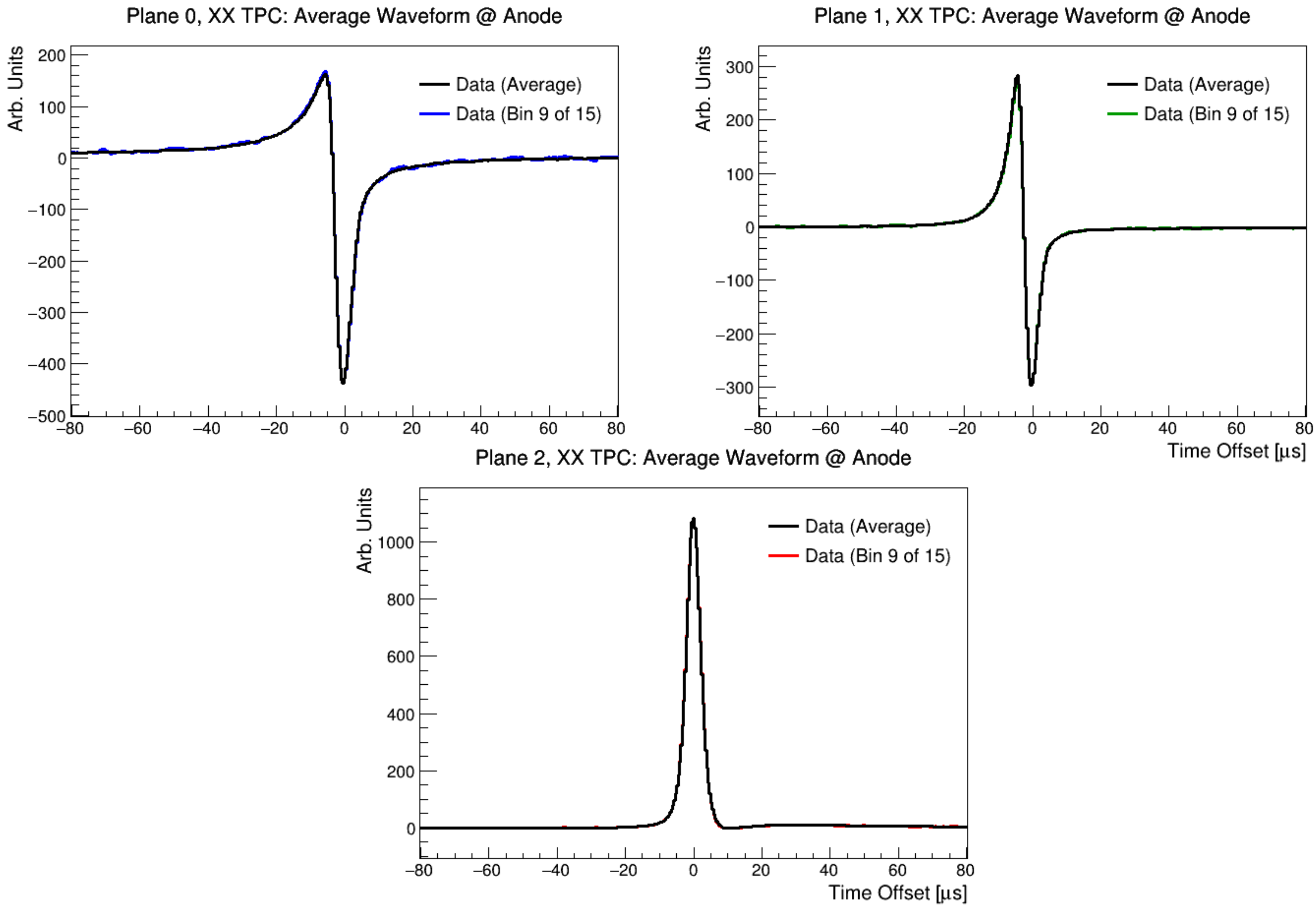

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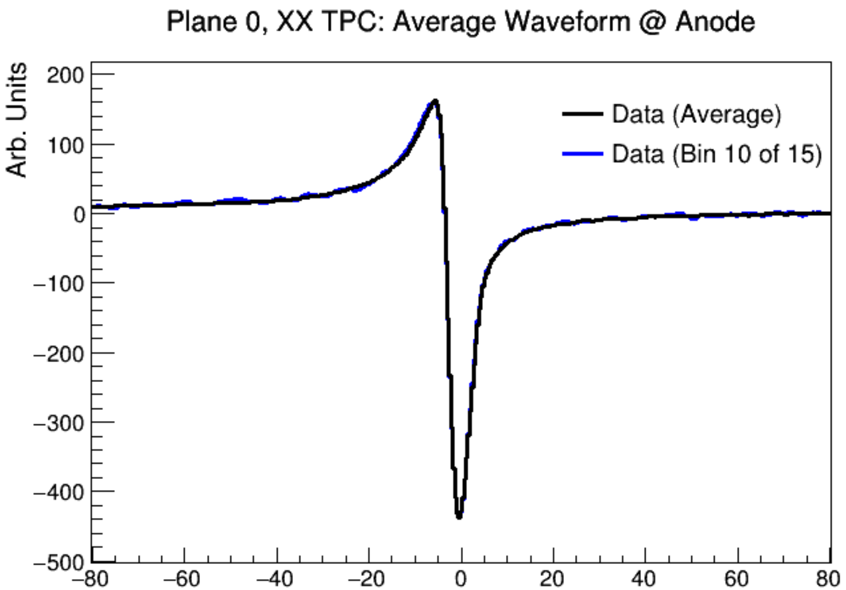

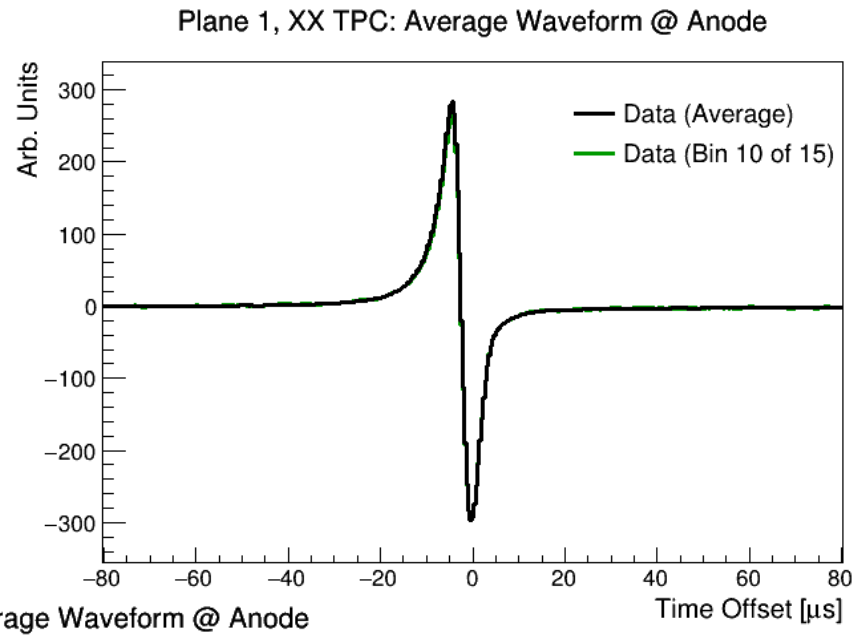

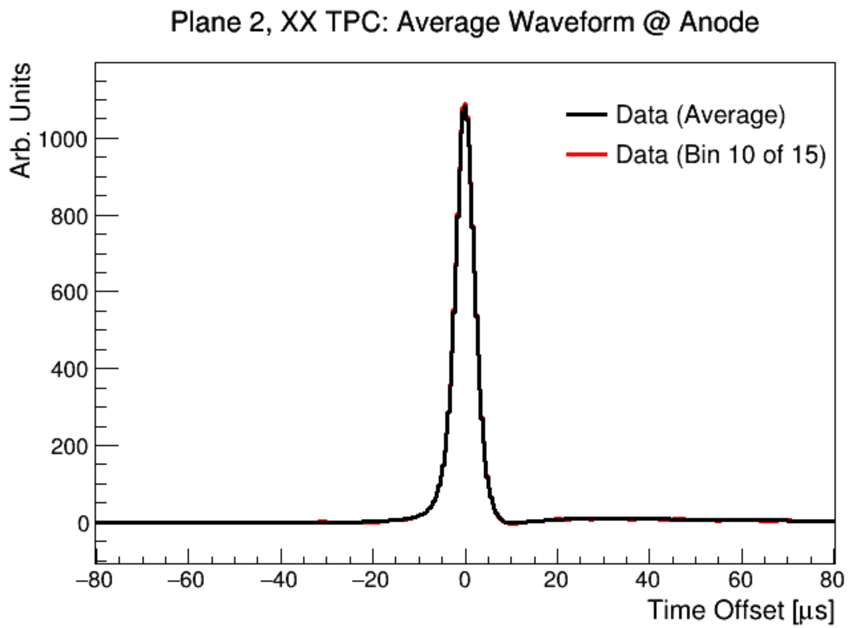

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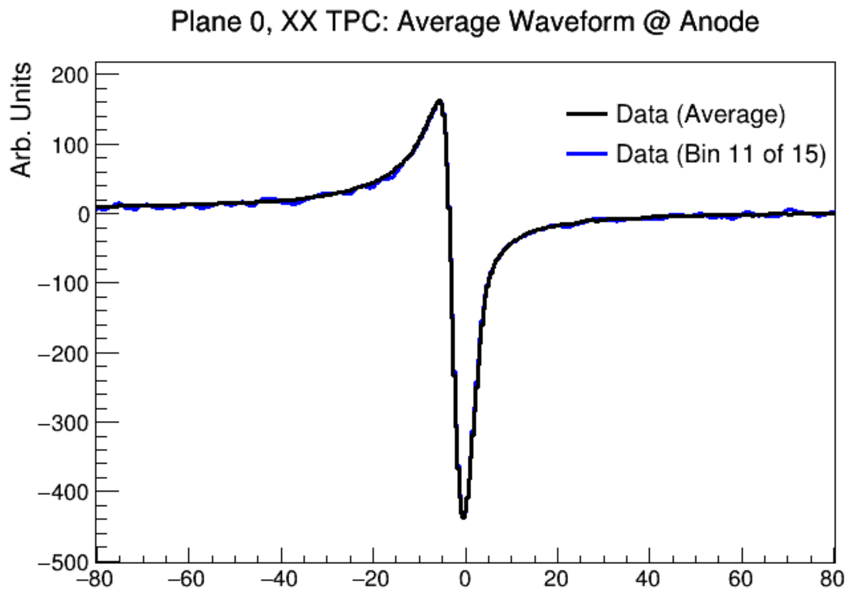
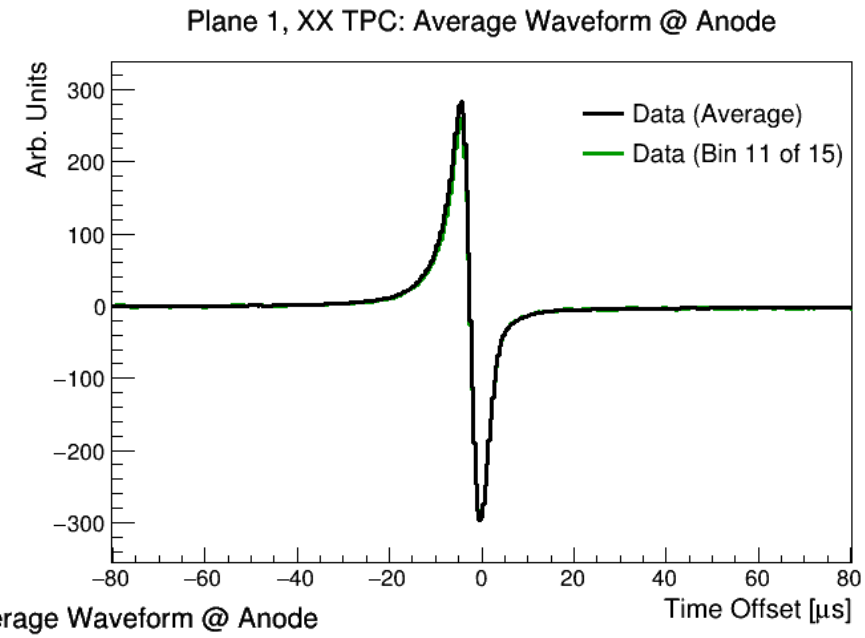
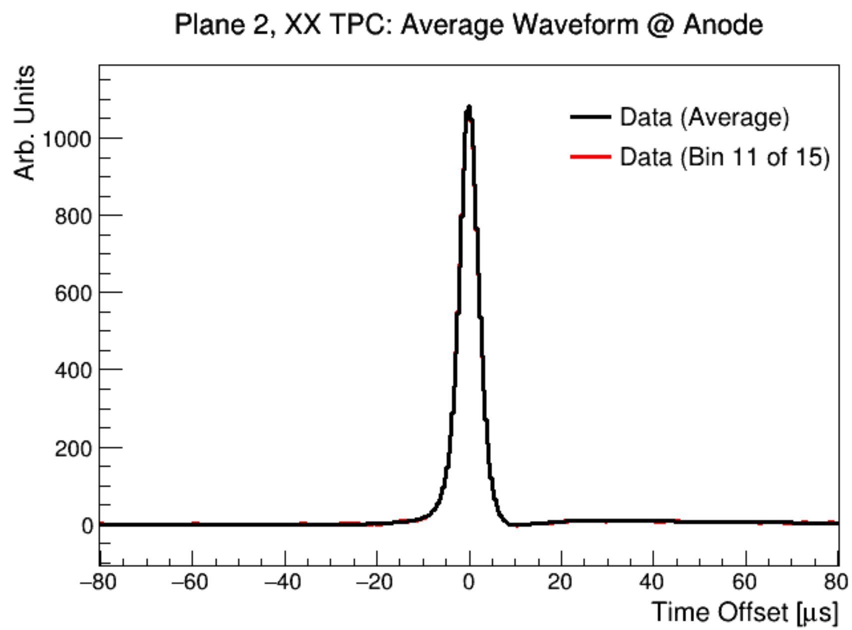
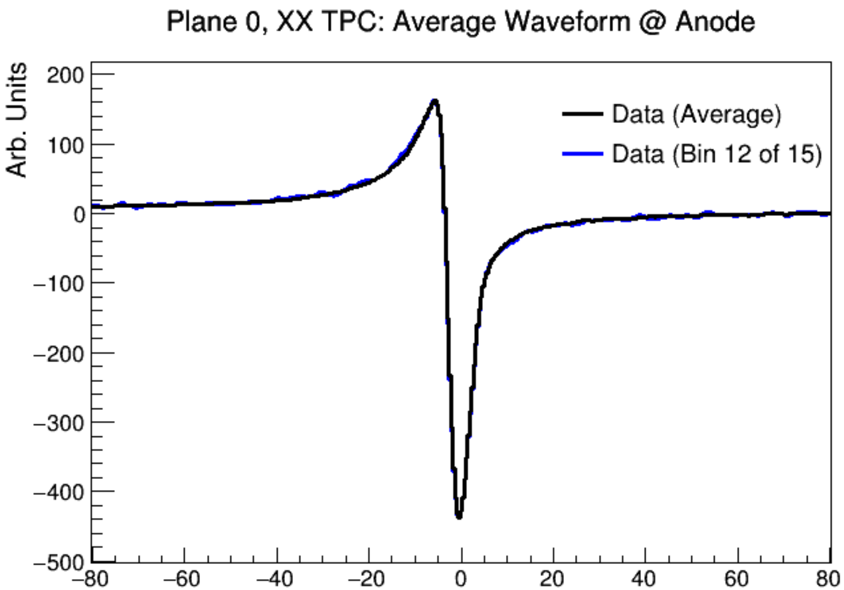
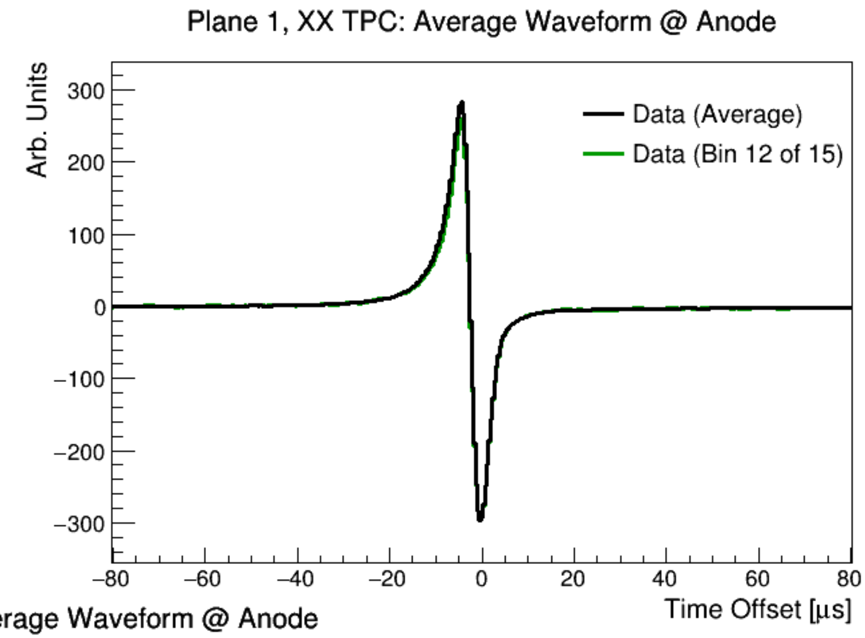


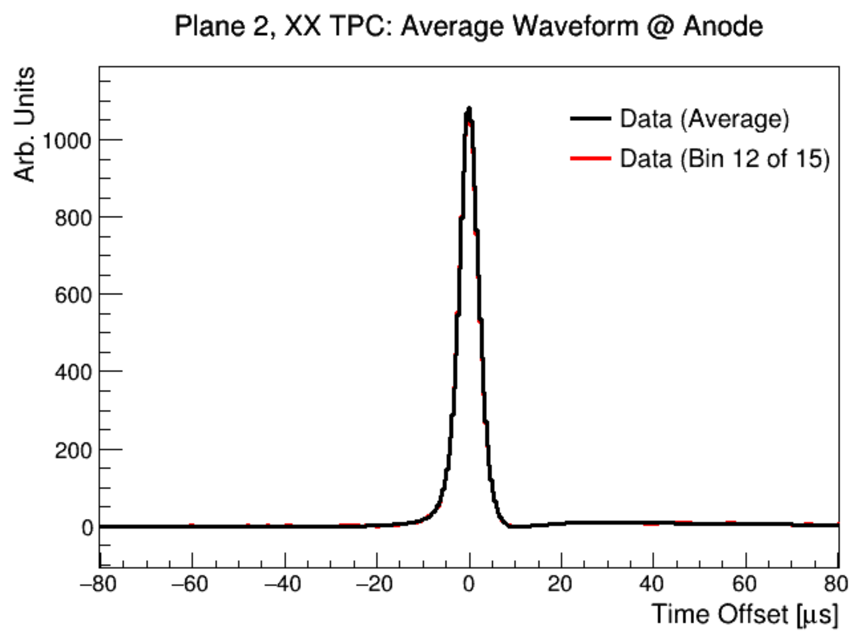




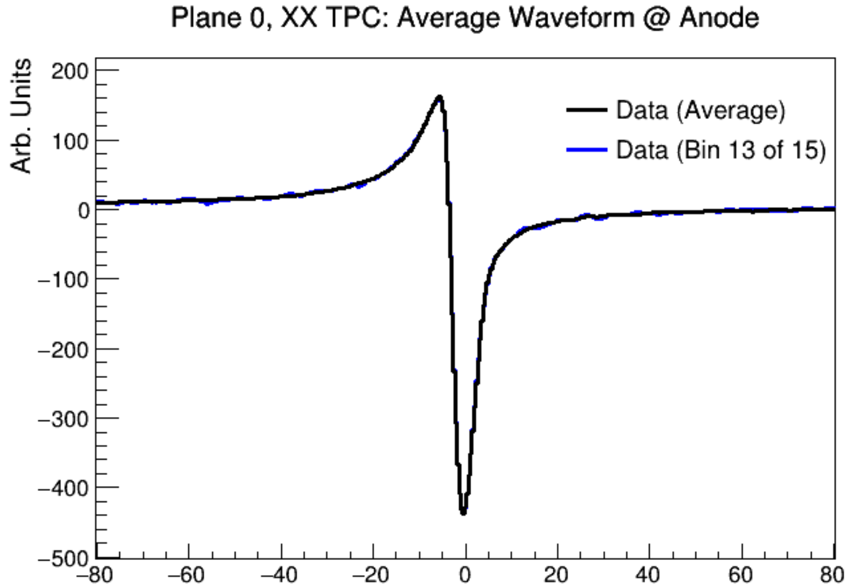
Spatial Study Results – Bin 12

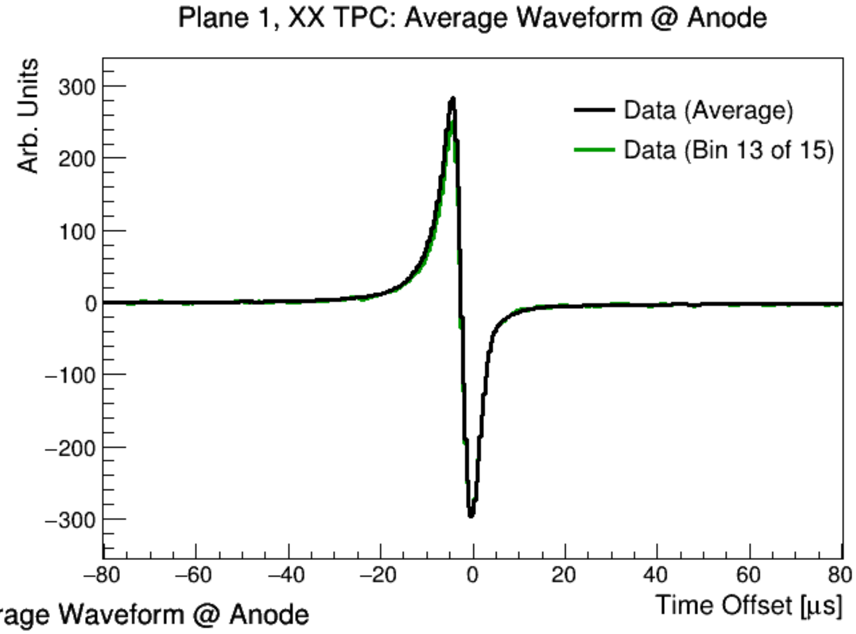


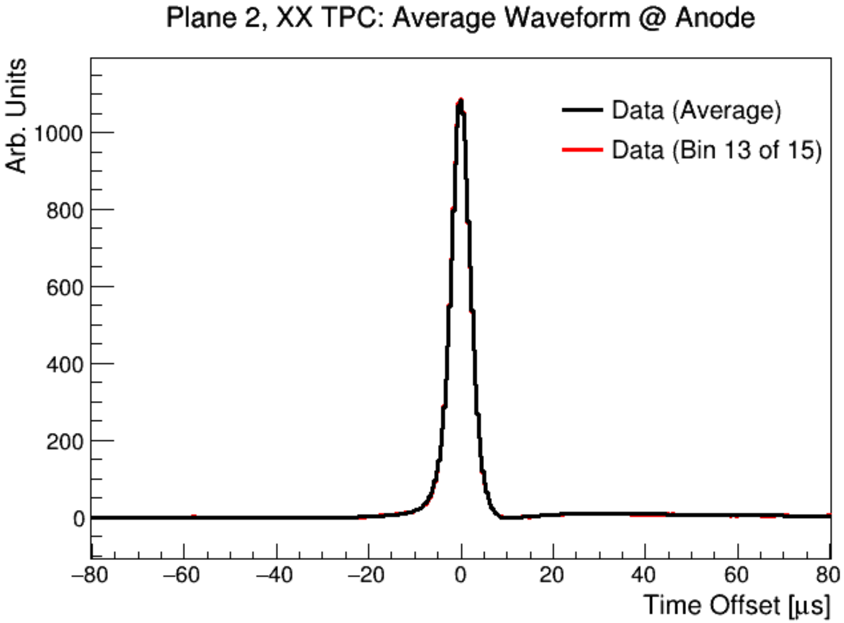




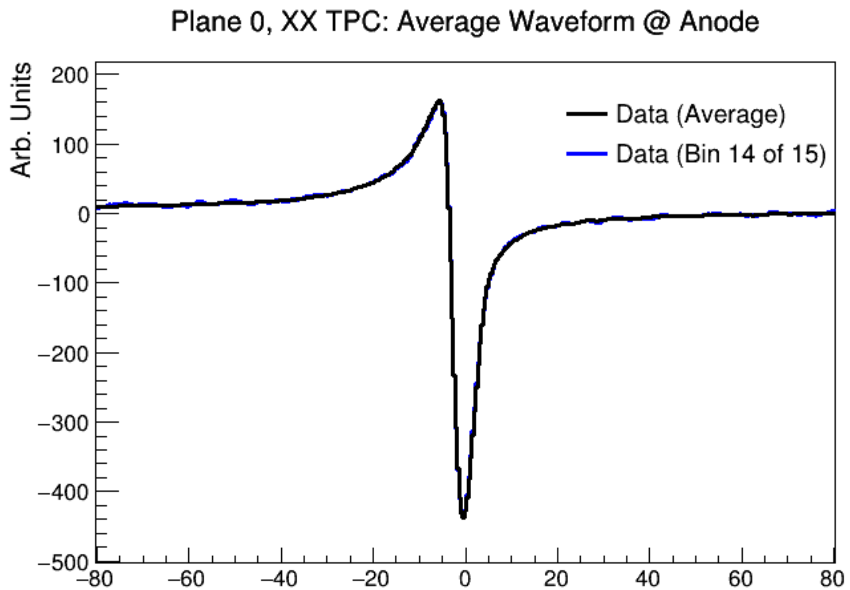
Spatial Study Results – Bin 13

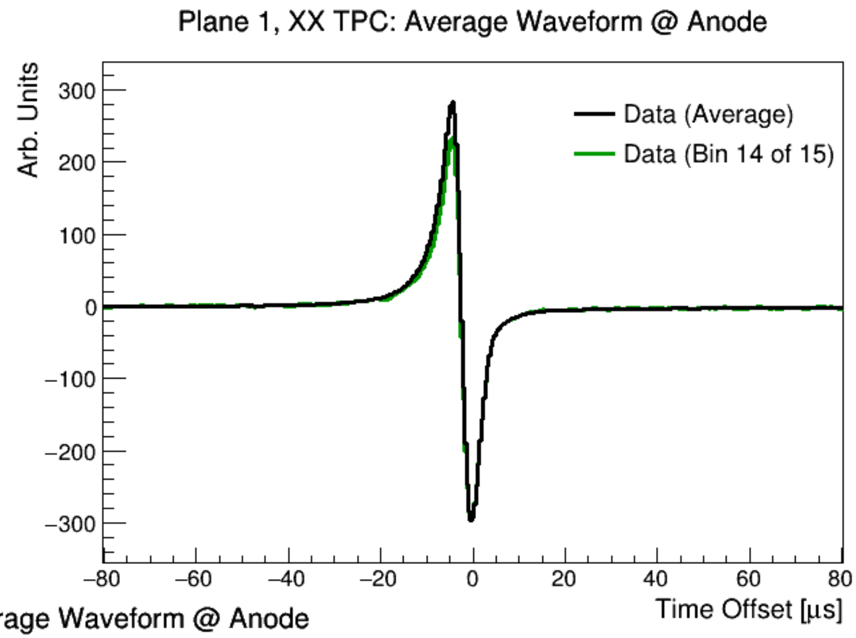


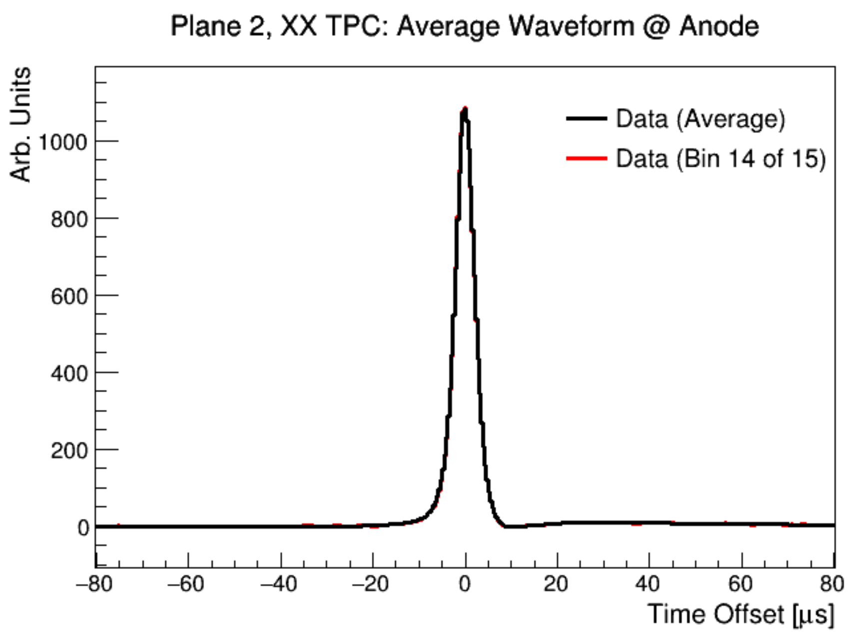




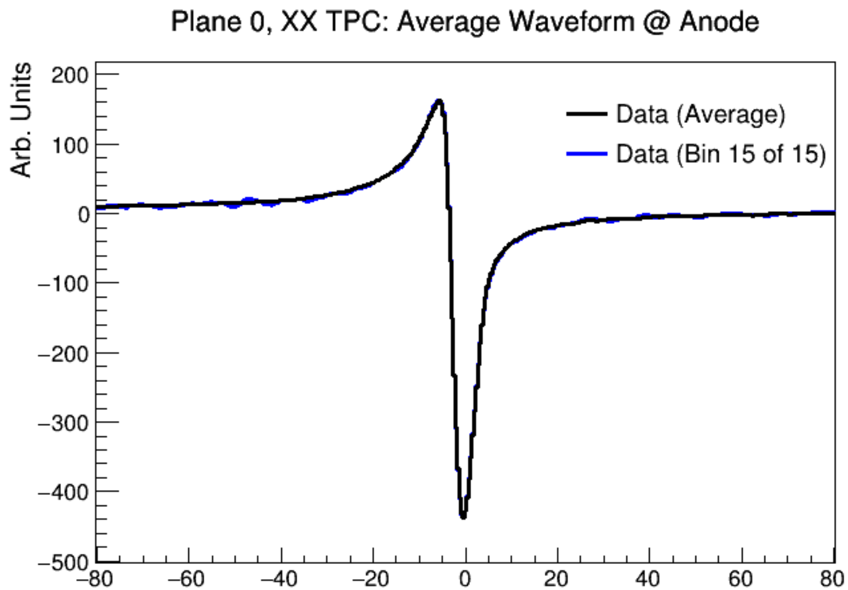
Spatial Study Results – Bin 14

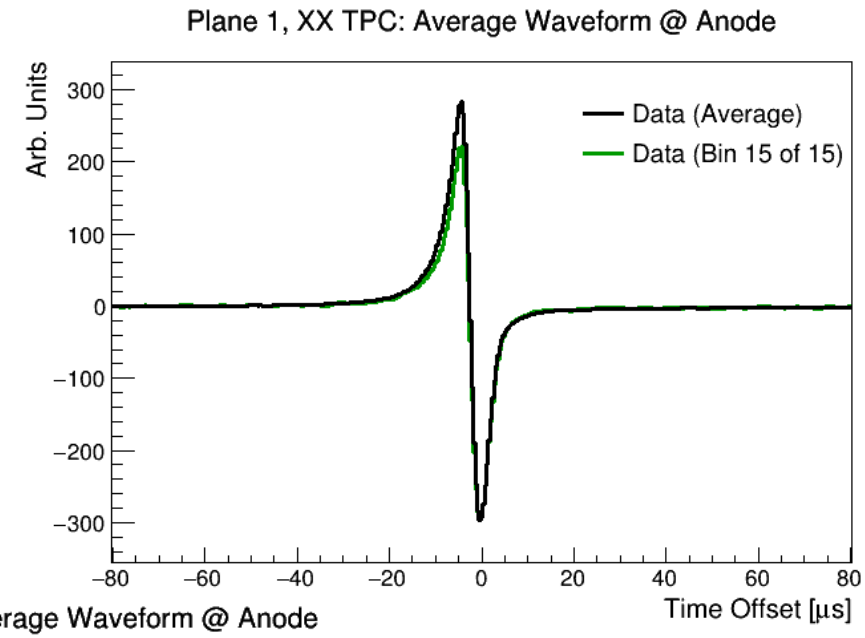


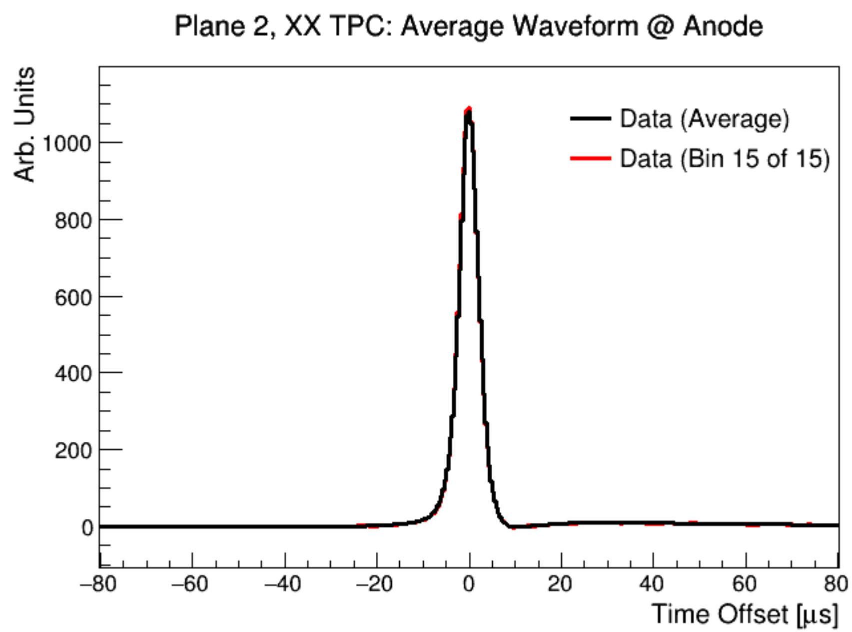




Spatial Study Results – Bin 15





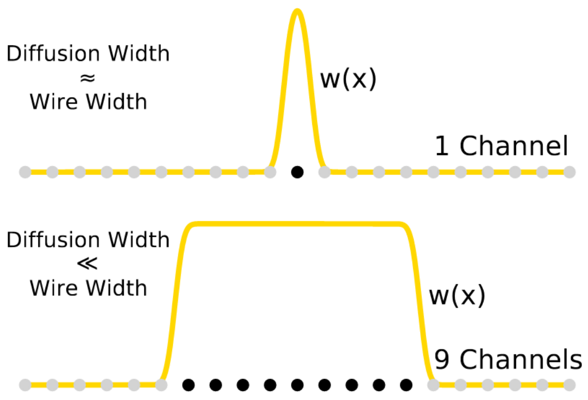


Plan for Response Variations

- Main conclusions from study of response spatial variations:
  - No change in signal shape for Induction 1, Collection planes
  - Systematic variation of signal shape for Induction 2 that seems to be parameterizable via single variable: ratio of positive lobe amplitude to negative lobe amplitude
- Normalization is such that Induction 1 and Induction 2 signal shapes are forced to agree at extremum of negative lobe (integral forced to agree for Collection plane), obscuring true effect: negative lobe gets smaller for lower transparency
- Plan moving forward:
  - London Cooper-Troendle working on extracting signal shape variations from data via same fitting procedure as before (see **here**)
  - Joseph Zennamo working with Sergey Martynenko to enable the simulation of spatial variations in signal shape within Wire-Cell
  - Goal is to implement this in MC simulation by **end of summer**

Impact of Diffusion on dE/dx

G. Putnam, D. Schmitz

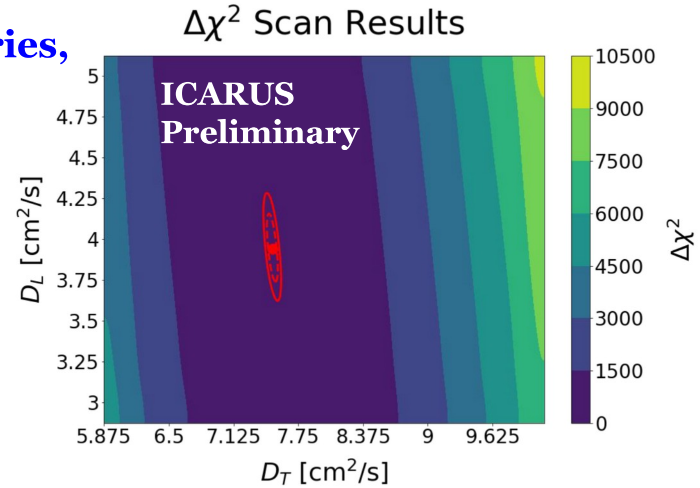


Detector	Wire Pitch [mm]	Drift Time [ms]	Diffusion Const. D_T [cm^2/s]	MPV dE/dx, No Diffusion [MeV/cm]	MPV dE/dx at Cathode (Full Diff.) [MeV/cm]	Difference [%]
MicroBooNE [4]	3.00	2.33	5.85	1.69	1.79	5.9
ArgoNeuT [3]	4.00	0.295	12.0 (9.30)	1.72 (1.72)	1.76 (1.75)	2.3 (1.7)
ICARUS [5]	3.00	0.960	12.0 (9.30)	1.69 (1.69)	1.78 (1.77)	5.3 (4.7)
SBND [5]	3.00	1.28	12.0 (9.30)	1.69 (1.69)	1.79 (1.78)	5.9 (5.3)
DUNE-FD (SP) [7]	4.71	2.2	12.0 (9.30)	1.74 (1.74)	1.82 (1.81)	4.6 (4.0)

- Two JINST articles from **SBN** collaborators on impact of diffusion on dE/dx measurements – see **here** and **here**
- Work shows that D_T in particular can bias dE/dx MPV
- Proposed solution: average many neighboring channels together when estimating track dE/dx (~10)
- Problem: **no measurement of D_T in LAr exists** at E field anywhere near ICARUS drift E field of 500 V/cm!

New Diffusion Measurements

S. Ruterbories, A. Mogan

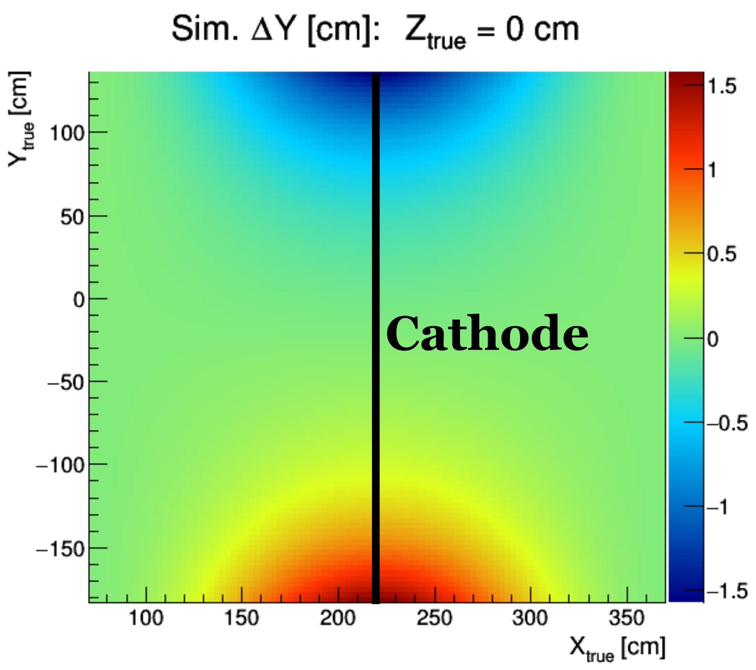


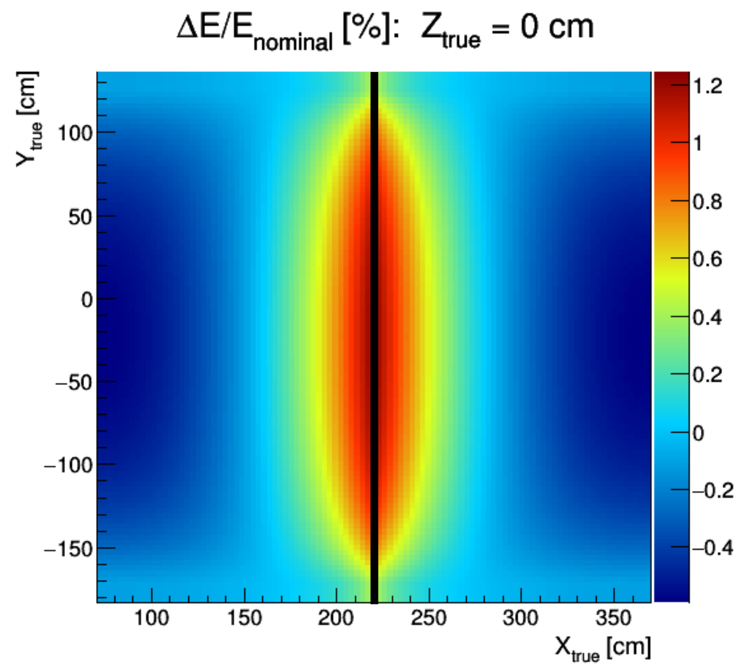
E. Hinkle

D_L (cm²/s)	D_T = 8.8 cm²/s	D_T = 0.0 cm²/s
5tr, different Y start positions	4.122 ± 0.004	4.057 ± 0.004
5tr, same Y start positions	4.103 ± 0.004	4.052 ± 0.003
5tr, different start energies	4.100 ± 0.004	4.058 ± 0.004
5tr, low drift time hits	3.976 ± 0.023	3.959 ± 0.027
5tr, mid drift time hits	4.138 ± 0.012	4.039 ± 0.012
5tr, high drift time hits	4.190 ± 0.017	4.153 ± 0.022
6tr, low/high drift time clusters	4.085 ± 0.003	4.049 ± 0.003

- New LAr diffusion measurements (D_L and D_T) being pursued at both ICARUS and ProtoDUNE-SP
  - ICARUS method uses (noise-filtered) raw waveforms for measurement of both D_L and D_T
  - ProtoDUNE-SP method uses deconvolved waveforms for D_L and potentially for D_T as well, though dE/dx also looked at; see **here**
- ICARUS work will converge this summer – update D_L and D_T in our MC simulation soon after

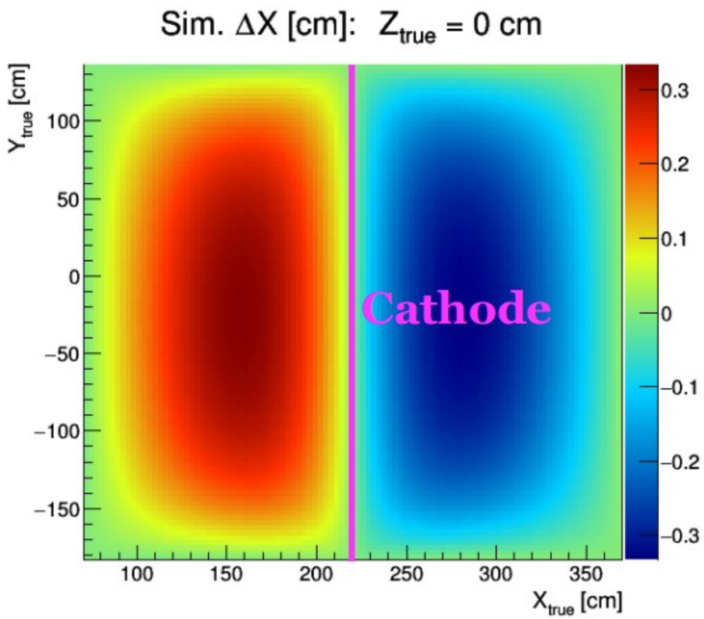
Space Charge Effects (SCE)

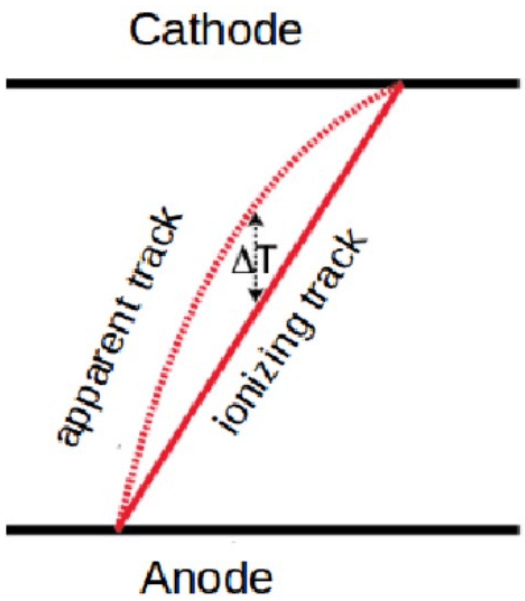




- Space charge effects (SCE) modeled in simulation
  - Above: spatial distortions (left), electric field distortions (right)
- Have begun to use 3D-reconstucted cosmic muon tracks to compare SCE in data and MC (see next slides)
  - Producing data-driven SCE map to be put into simulation

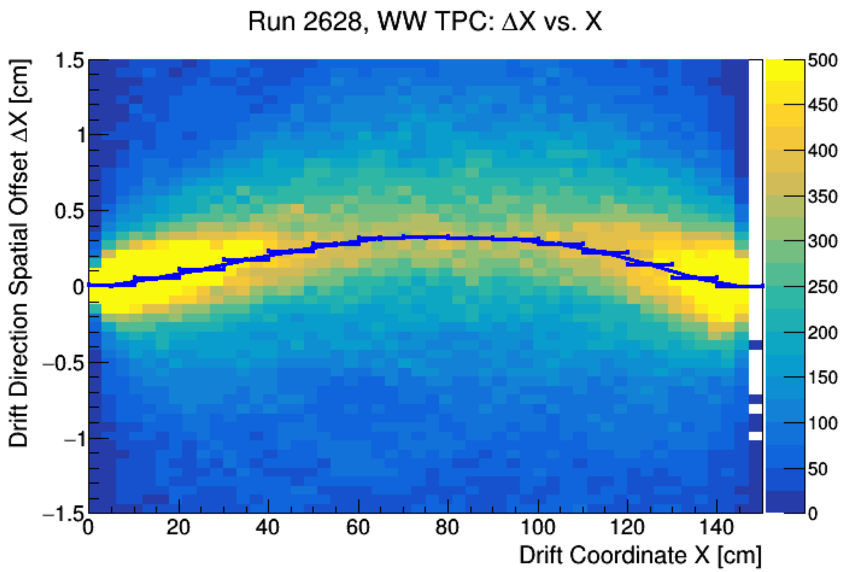
Measuring SCE

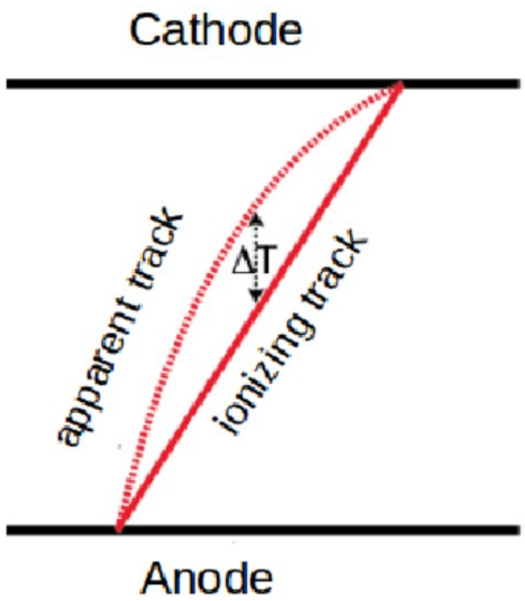




- Biggest effect of SCE is transverse displacement from top/bottom of TPC
  - From previous slide: ΔY ~ 1.5 cm for track entry/exit points at TPC top/bottom
- Simpler: estimate SCE in **drift direction** using reconstructed collection plane hit times from anode-cathode-crossing cosmic muon tracks
  - Effect small in drift direction (ΔX ~ 0.3 cm), but measurable
  - Methodology taken from previous ICARUS work: **arXiv:2001.08934**

Measuring SCE





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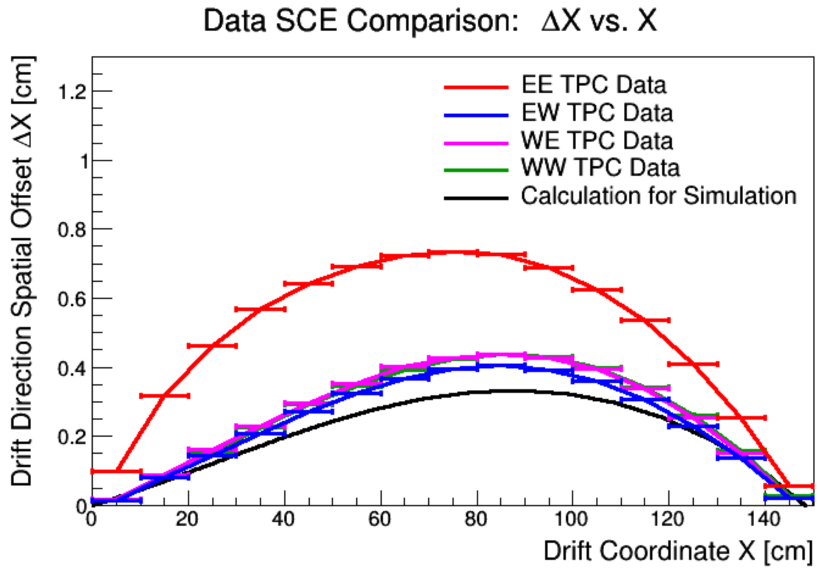
SCE in ICARUS Data



- Data used: “Run 0” dataset from 2021, May 31st through June 27th
- Slightly larger SCE in data than simulation for EW/WE/WW TPCs
- EE TPC shows larger discrepancy – related to field cage?
- Time dependence seems small (< 5%) but should study more data
- Lane Kashur working on measuring transverse offsets (in Y, Z) using end points of reconstructed tracks in 3D → consistency?

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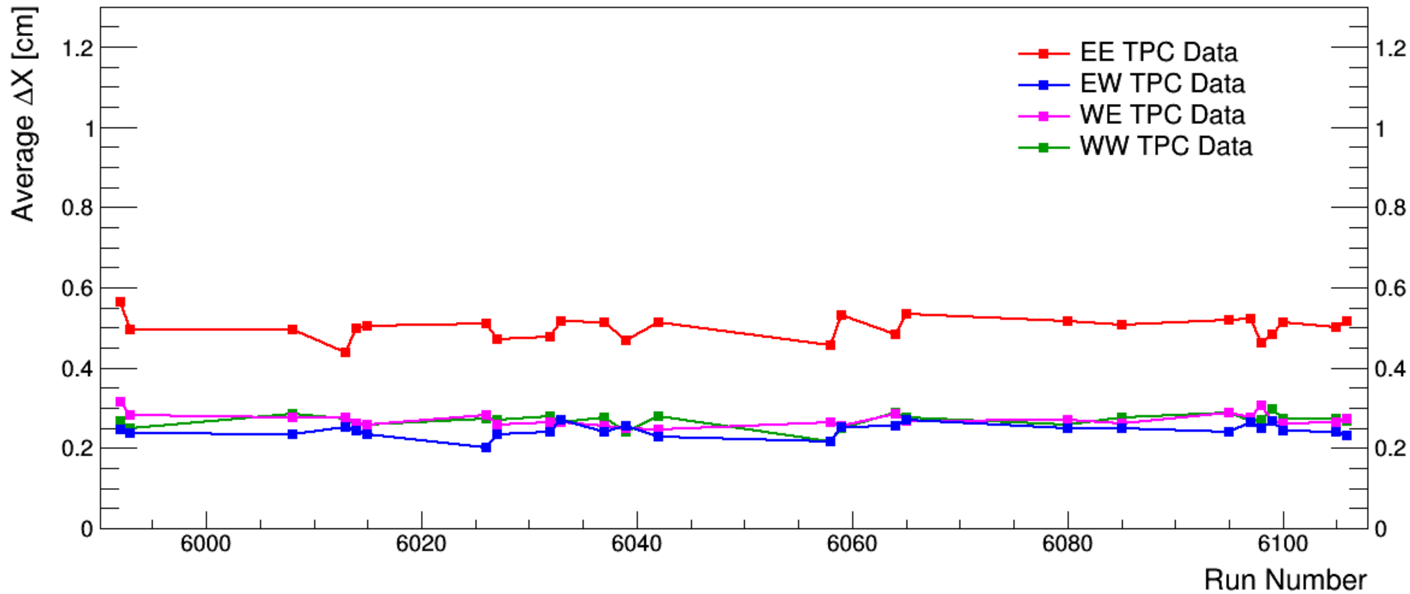

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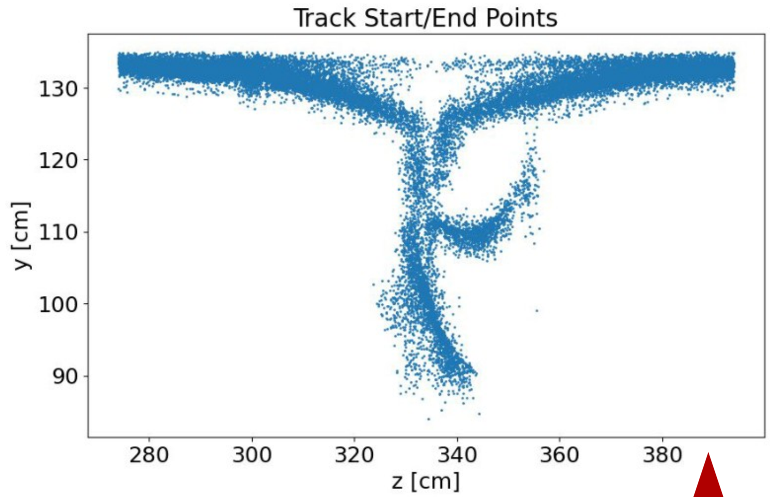
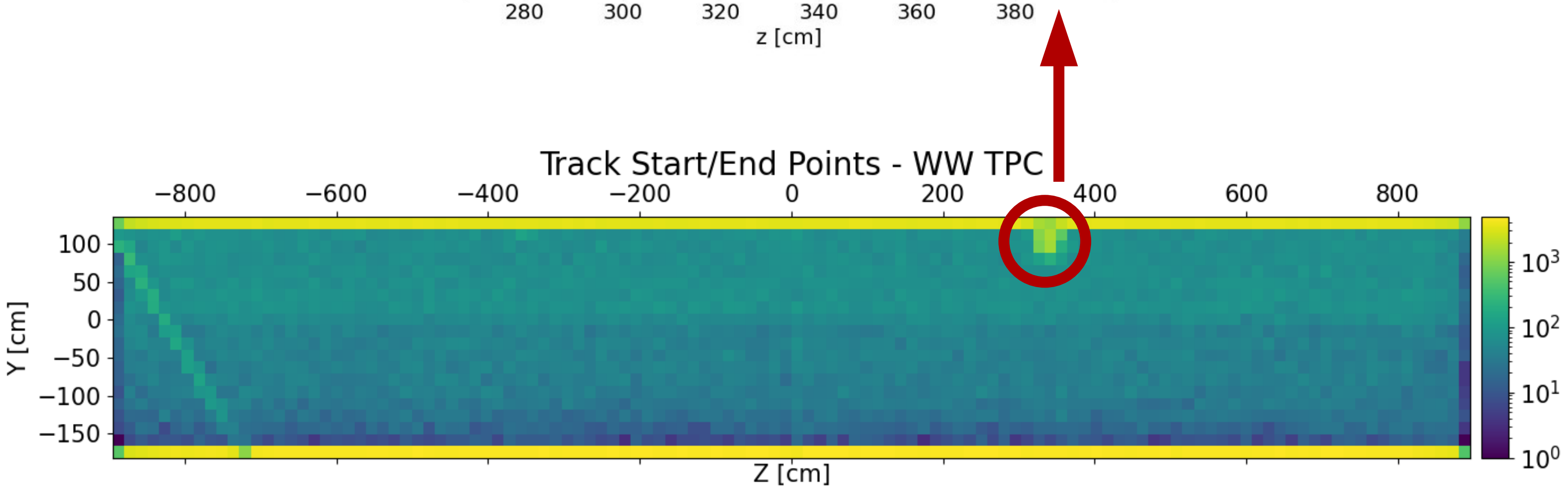
WW Cosmic Track Start/End Points

L. Kashur



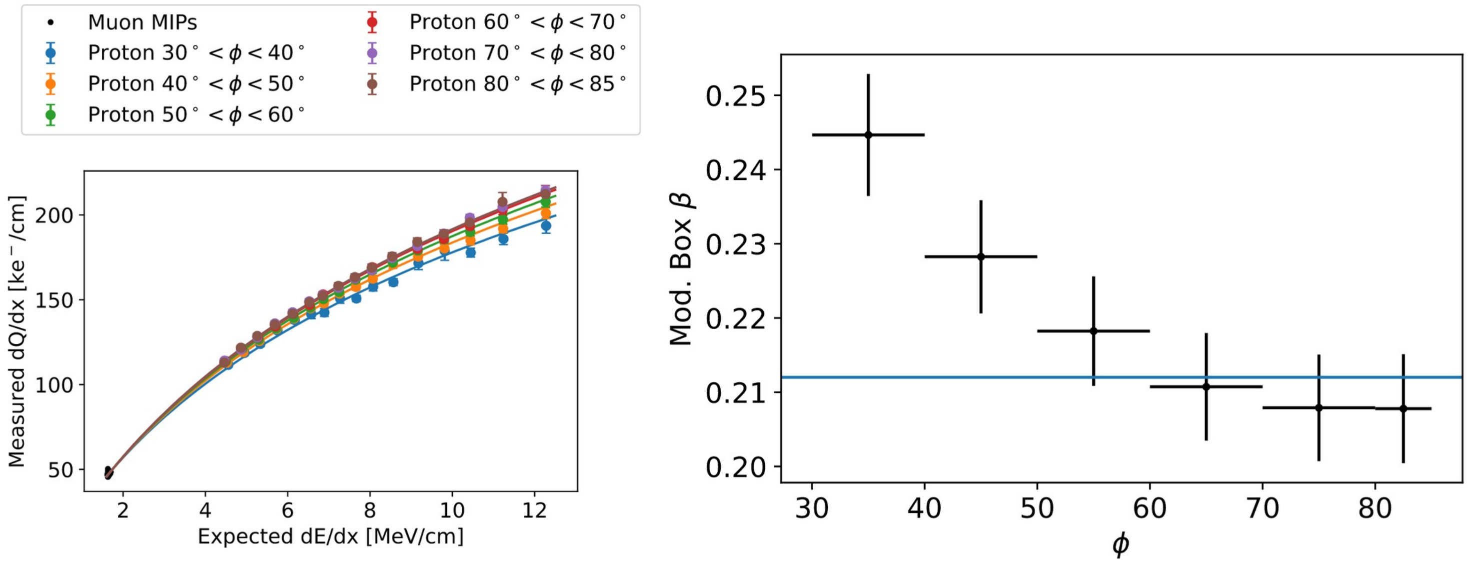
This will be hard to model in MC!

Instead, recommend to <u>veto</u> this region



Recombination

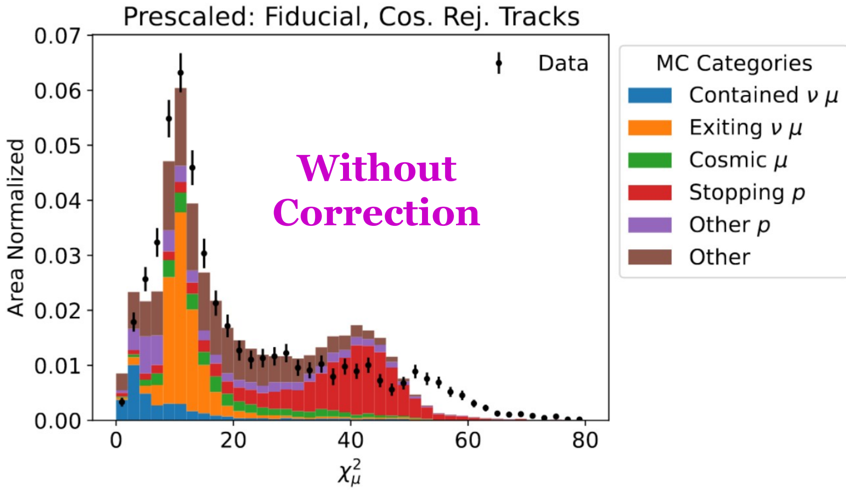
G. Putnam

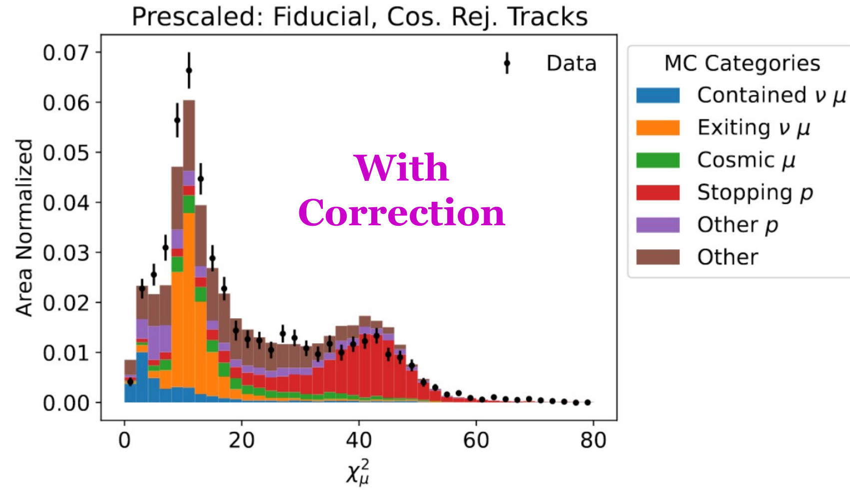


- ♦ Must correct for electron-ion recombination to nail energy scale for both MIPs (e.g. muons) and HIPs (e.g. protons)
- ♦ Nominally use Modified Box Model from ArgoNeuT
- ♦ Recently measured recombination at ICARUS, including angle dependence, and find consistent results with ArgoNeuT
  - Angle-dependent correction important to nail PID (see above)
  - Should also model this angular dependence in MC simulation

Recombination

G. Putnam





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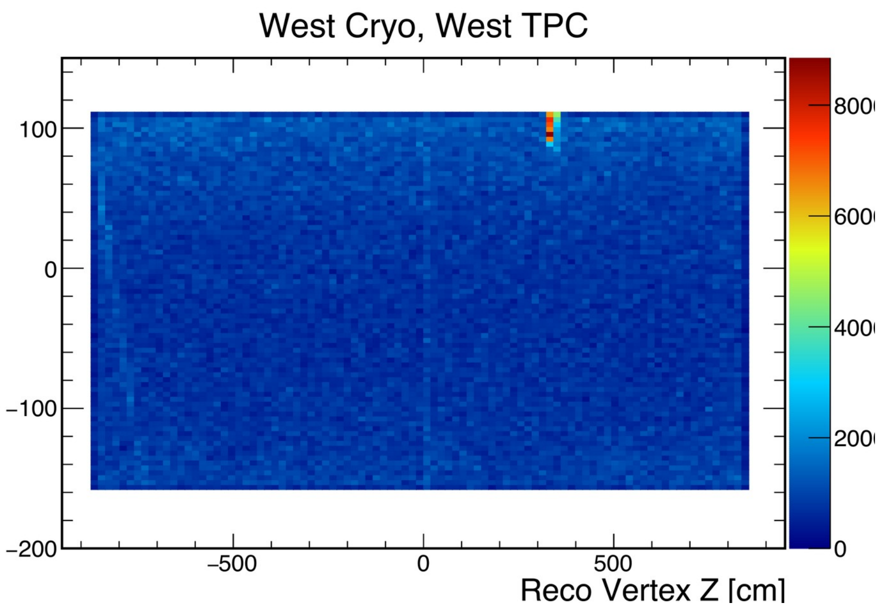
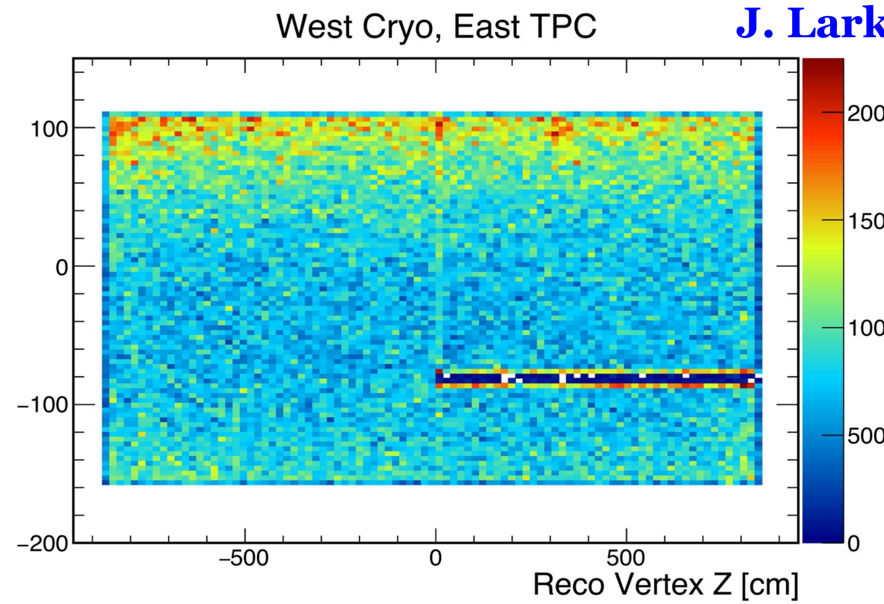
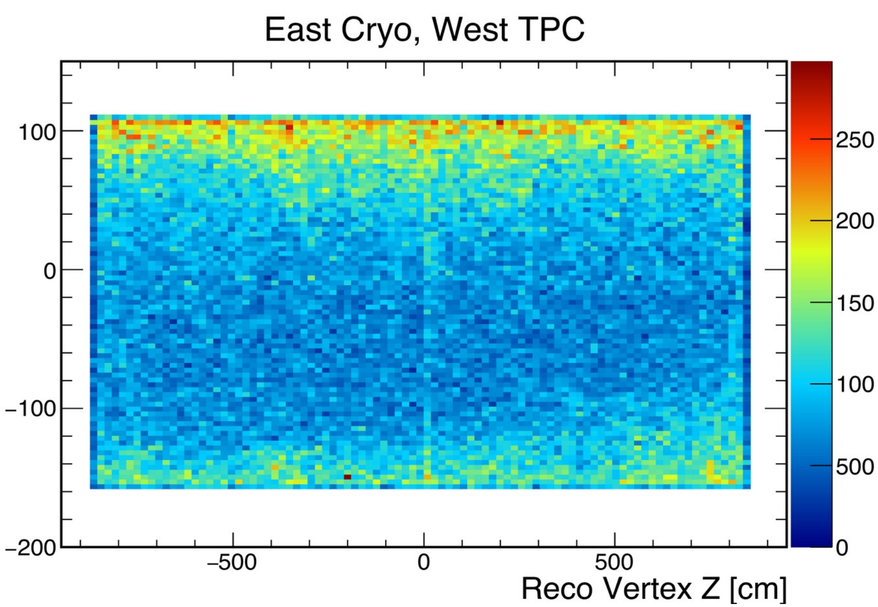
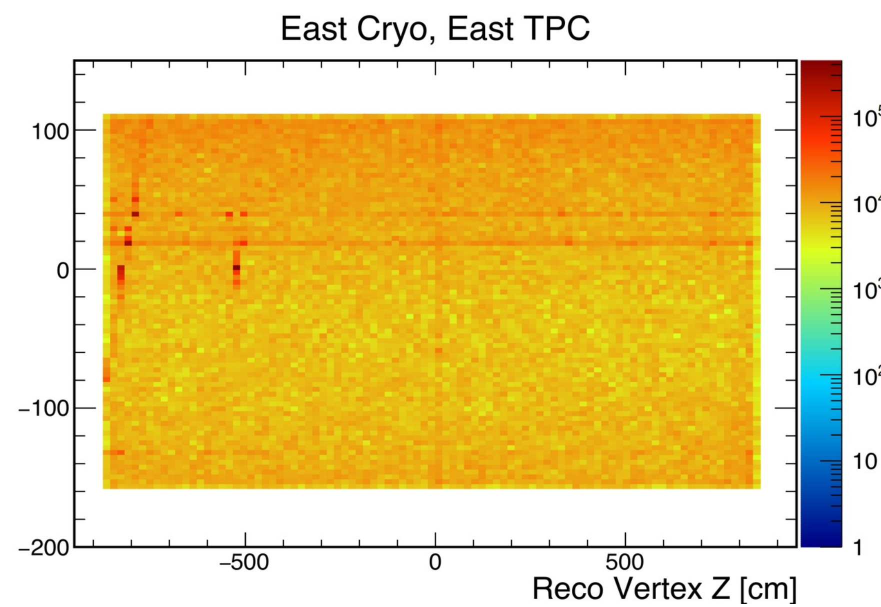
ν_μ 2D Vertex Dist. (Pandora)

J. Larkin

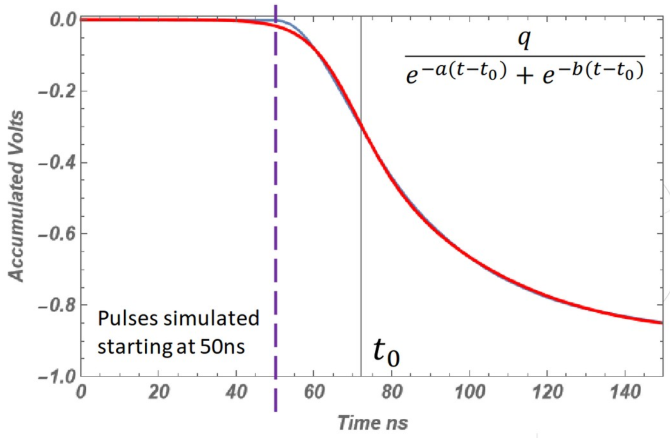


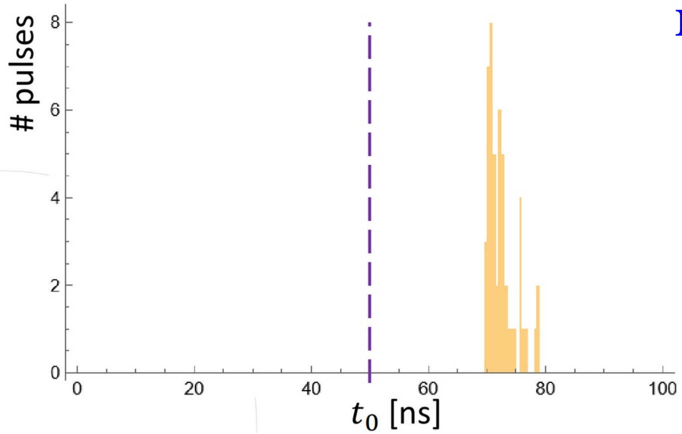






PMT Timing Calibration





M. Vicenzi

- Also need final PMT timing calibration in place **by this summer** – needs to be applied to OpWaveforms/OpHits in stage-0 reco (where OpFlash data product is created)
- Requires precise reconstruction of light timing information; potential change to OpHit time determination for calibration?
  - Move from mode signal time estimation to earliest signal time estimation in nominal OpHit reconstruction algorithm – baseline
  - Should we instead move to algorithm proposed by Milind/Matteo, using fit to OpWaveform (see **here** for more info)? Which is best?

BNB Beam Spill Structure

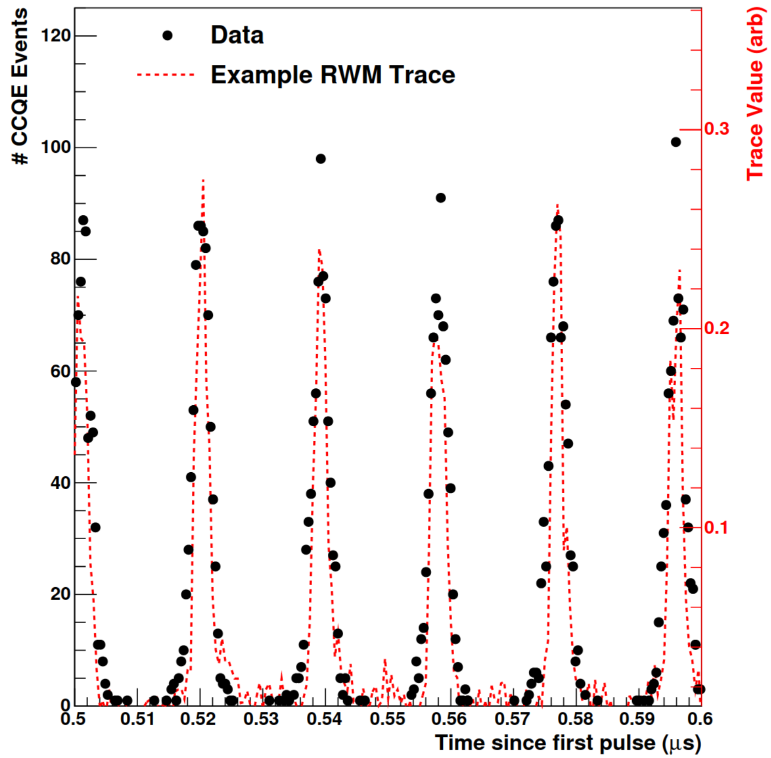


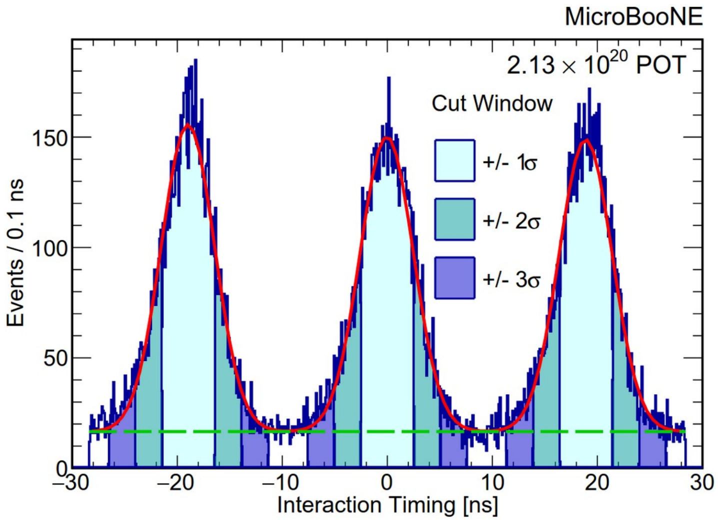
FIG. 4. Zoomed-in example of the BNB pulse microstructure as measured by the RWM. The data points come from neutrino-mode ν_μ charged-current interactions in the MiniBooNE detector during 2015–2016. The example RWM trace is plotted by the readout value of the trace.

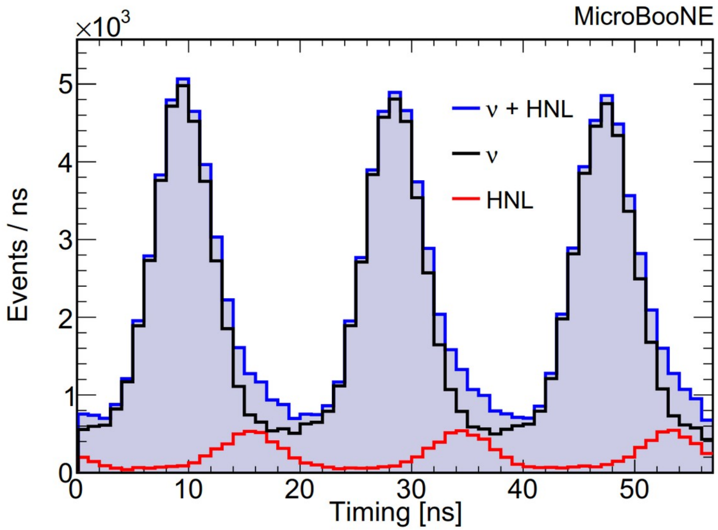
From MiniBooNE DM Paper (arXiv link)

This shows BNB beam spill structure.

Need O(ns) level PMT timing resolution!

PDS Timing @ MicroBooNE





- MicroBooNE has been able to achieve O(ns) timing resolution with PMT system – see **here**
  - MicroBooNE uses 60 ns shaping time, 64 MHz sampling
  - ICARUS has no additional shaping, 1 GHz sampling → even easier
- Basically we should just repeat MicroBooNE's procedure
  - Matteo Vicenzi revitalizing Andrea Scarpelli's older work on this
  - Must also finalize gain calibration, **begin** tuning of optical (photon) library – **still need people to take this to finish line**

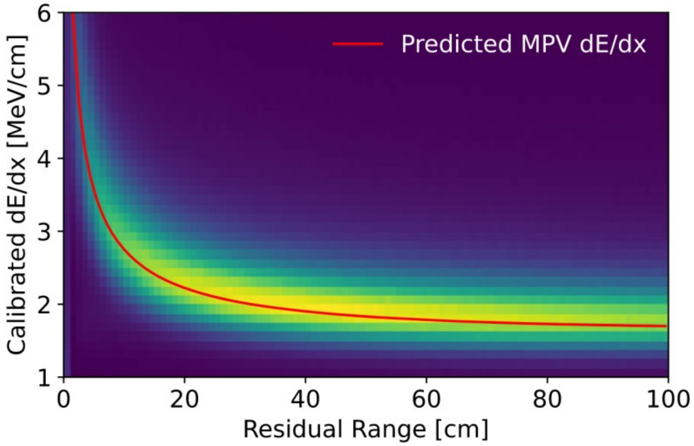
Discussion

- Discussed A LOT of items, but this isn't even everything
  - CRT gain/timing calibration for instance (not finished)
- Some immediate comments:
  - Only minor residual data/MC bias on Ind2/Col TPC planes
  - Major data/MC bias on Ind1 plane **now understood**
  - Loose cables in WW TPC → hard to model in MC, should veto region
  - High rates of vertex reconstruction in EE TPC – **not understood**
  - PDS timing needs to make further improvements if we want to use the beam spill structure for vetoing cosmics! Perhaps most important for BSM physics (veto neutrinos)
  - PDS light yield variations ("optical library") need study, will impact trigger efficiency calculations – very important **missing item**!
- Important for this workshop: should ML team repeat any of this work, and where do calibrations get applied for ML?

Calibrations for ML Approach

- Detector calibrations, if done properly, should be applicable to all reconstruction approaches
  - That is, biases specific to reconstruction approach should be accounted for in extracting calibration constants
  - Despite majority of calibrations done using tracks reconstructed using Pandora, *this is being done already*: force agreement between data and MC in one approach (e.g. Pandora) → unlikely to see significant bias between data and MC for another approach (e.g. ML)
- However, it is wise to perform **cross-checks** using each reconstruction approach independently (Pandora, ML, other)
  - Should expect no major data/MC bias – if do see such bias, revisit experiment-wide calibrations used for all reconstruction approaches
  - Additional benefit: may provide correction factors (e.g. for energy) specific to reconstruction approach to apply to **both data and MC**
  - We should do this for ML approach – which cross-checks though?

ML Calibration Cross-Checks



Produce distribution for both data and MC using ML as well

- <u>Suggestion</u>: carry out cross-checks at per-particle level, including as many particle types and topologies as possible
  - Stopping muon dE/dx vs. residual range – likely need additional ML-specific energy correction factor from this step (again, not to address data/MC bias, but get "correct" values for both data and MC)
  - Neutrino-induced proton dE/dx vs. residual range
  - Michel electron energy distribution
  - Neutral pion mass distribution
- We need data/MC comparisons w/ ML for all of these ASAP!

ML Calibration Infrastructure

- Where Pandora applies calibrations:
  - Corrections of TPC electronics gain, electron lifetime, recombination applied at CAF-making stage for both data and MC
  - Corrections of non-uniformities in TPC charge scale (i.e. corrections for transparency) applied at CAF-making stage for data only
  - SCE corrections not yet applied, but handles for them in Pandora
  - Nothing currently done for PMT/CRT calibrations outside of stage-0
  - All other detector effects (e.g. spatial variations in signal response, noise, diffusion) folded into MC – same for all reconstruction approaches
- For ML, we have decisions to make:
  - Apply calibrations when we make CAFs? Share code w/ Pandora reconstruction team, but forced to do selections on CAF files
  - Apply further upstream in ML chain? Must develop code, but allows more flexibility and may need it for ML training / applying weights
  - <u>Note</u>: just need 3D hits with charge to apply all TPC calibrations *except* angle-dependent recombination correction

BACKUP SLIDES

Possibly Relevant for EE Issue

Joseph Zennamo 12:49 PM

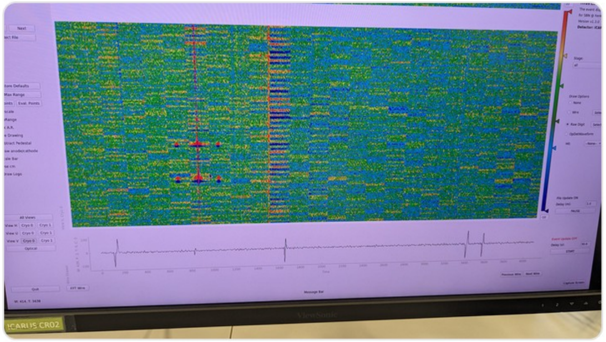
Bruce says EE

"south part"

so it could be that hot spot

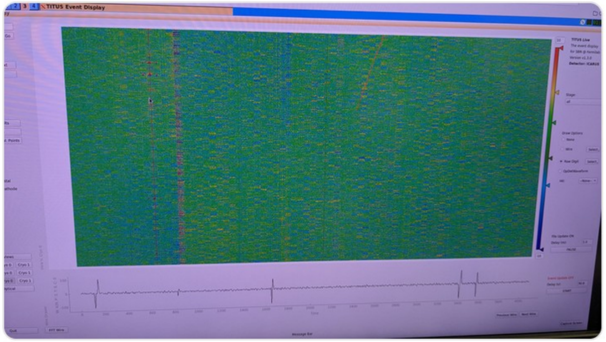
someone left the pulser on maybe?

image.png ▾



the waveforms are awesome

image.png ▾

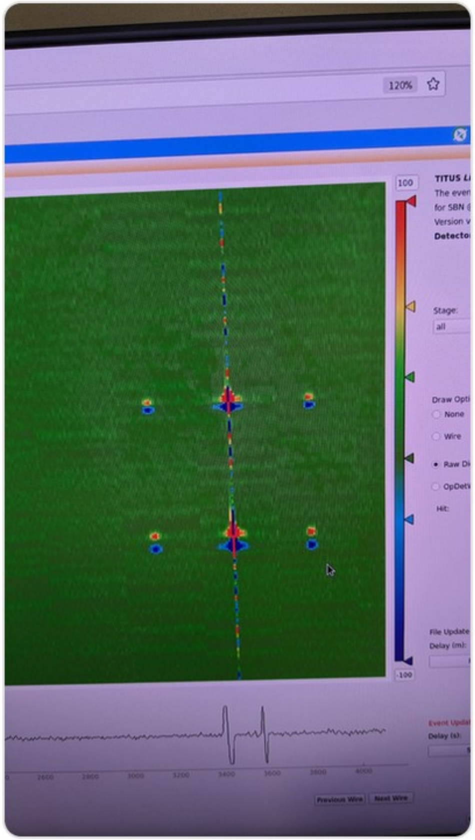


OMG!

even the dead channel sees it!

Joseph Zennamo 1:00 PM

image.png ▾



it's pretty

I found it, I get to name it