Results from the 35-ton LAr Prototype and Lessons Learned

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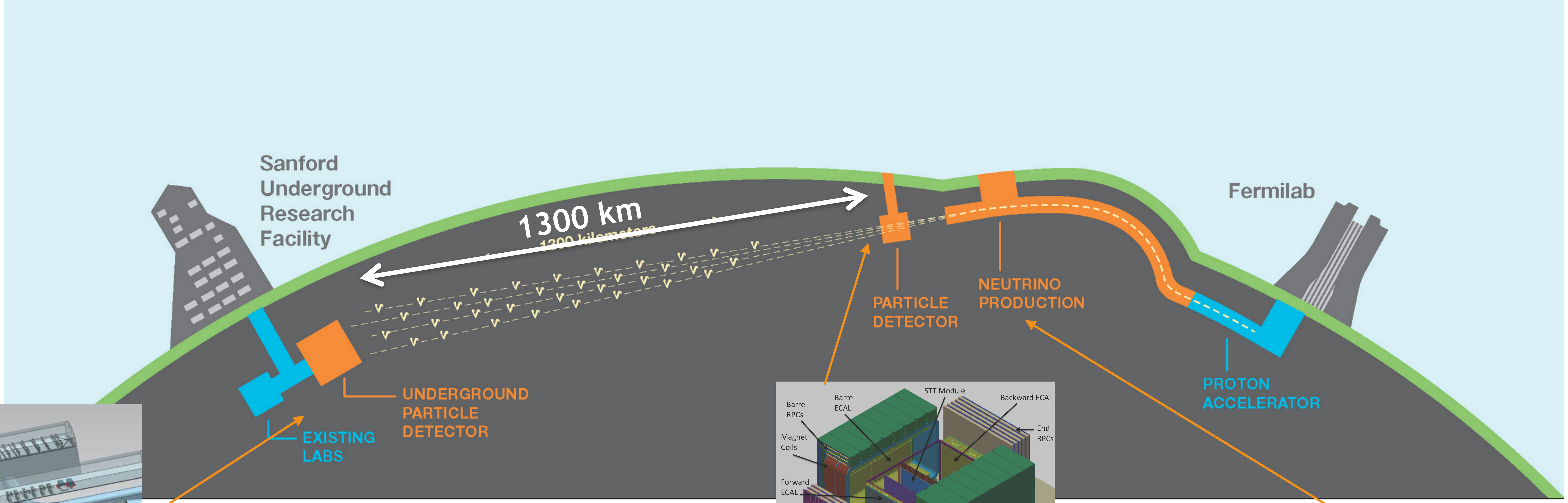
for the 35-ton and DUNE collaborations

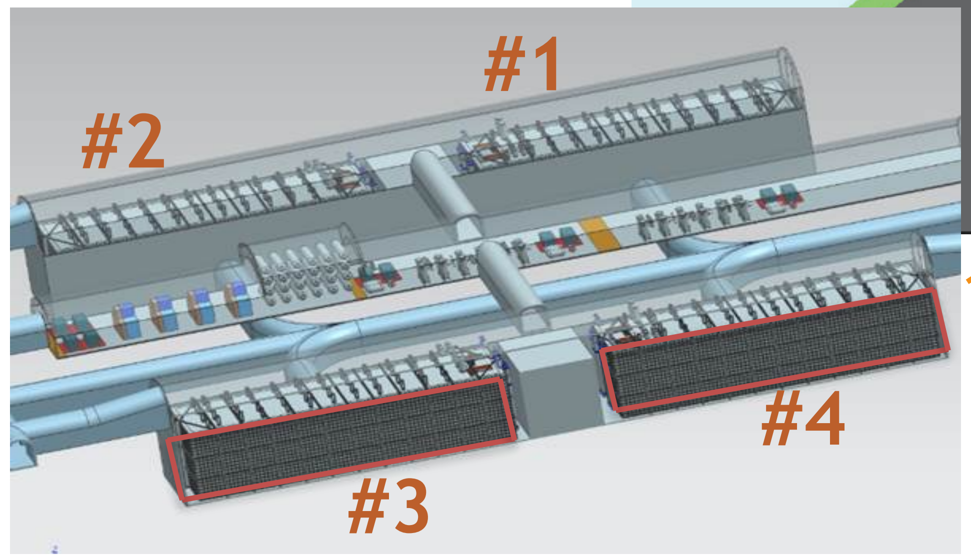
EPS-HEP Conference 2017, Venice, Italy
Saturday 8th July 2017

The University Of Sheffield.

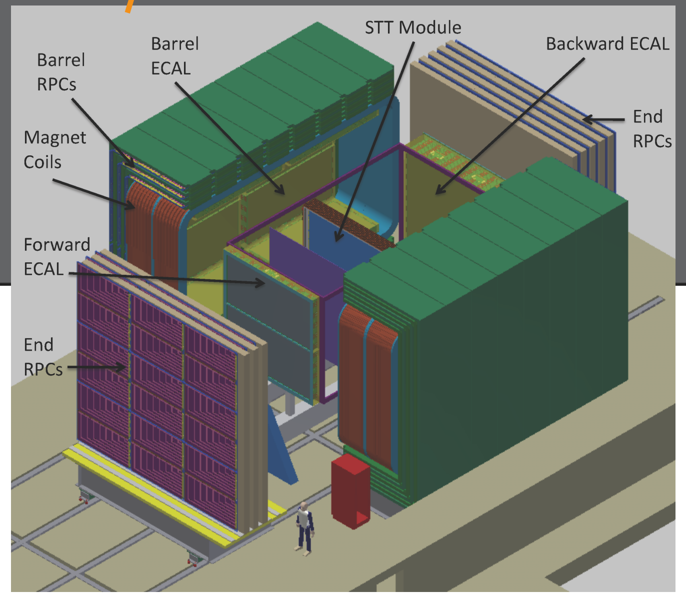
DUNE

The Deep Underground Neutrino Experiment (DUNE)





Four identical cryostats deep underground; staged approach to four independent 10kton LAr detector modules.

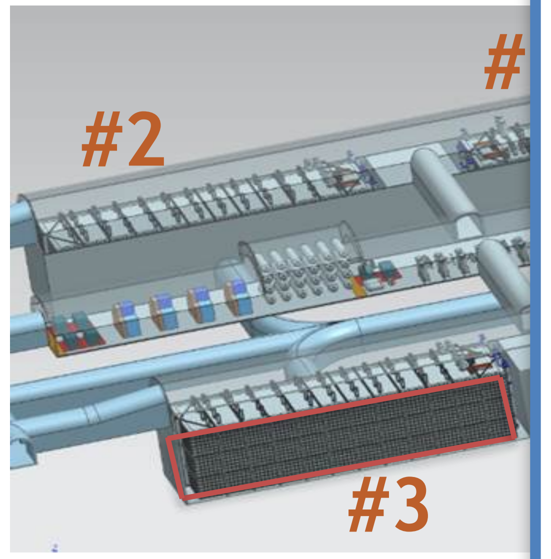


High precision near detector at 574 m

Wide band, high purity beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradable

- Future long-baseline neutrino oscillation experiment with a rich program in neutrinos, nucleon decay and astroparticle physics.
- Also precision measurements of neutrino interactions in the near detector.
- Utilises LArTPC technology to make highly sensitive physics measurements.

The Deep Underground Neutrino Experiment (DUNE)



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- Also precis…
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DUNE at EPS-HEP 2017

6 talks, 3 posters!

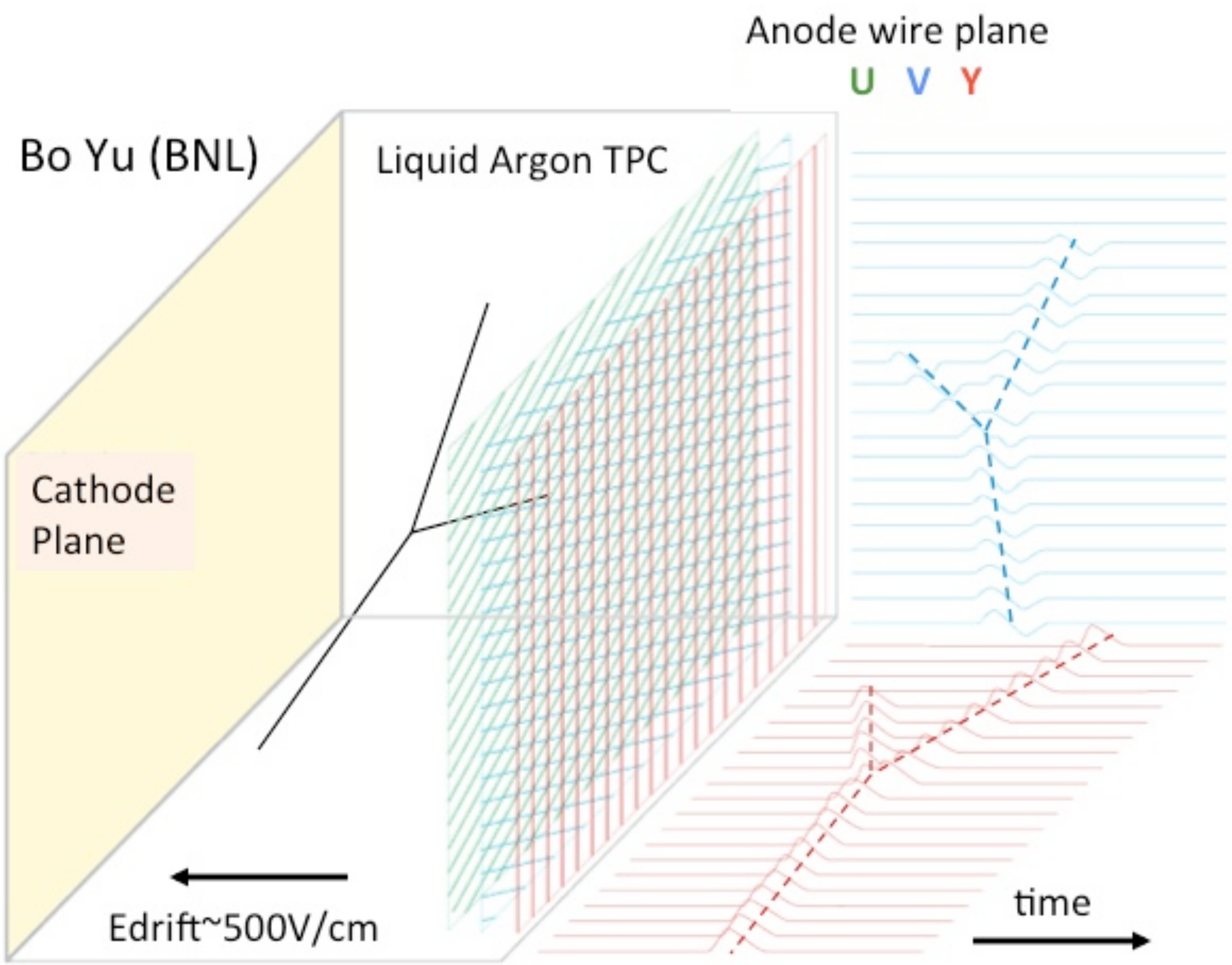
Talks

- Sensitivity of the DUNE Experiment to CP Violation and to Physics Beyond the SM (Justo Martin-Albo)
- Studying Neutrino Oscillations and Searches for BSM Physics with Atmospheric Neutrinos in DUNE/ Nucleon Decay Searches (Aaron Higuera)
- Results from the 35-ton Liquid-argon Prototype using Cosmic Rays and Lessons Learned (Mike Wallbank)
- Supernova Neutrinos at the DUNE Experiment and Nucleon Decay Searches with DUNE (Ines Gil Botella)
- ProtoDUNE-SP and 35-ton (Maxim Potekhin)
- DUNE Far and Near Detector, Photon Detector, Reconstruction (Nicola McConkey)

Posters

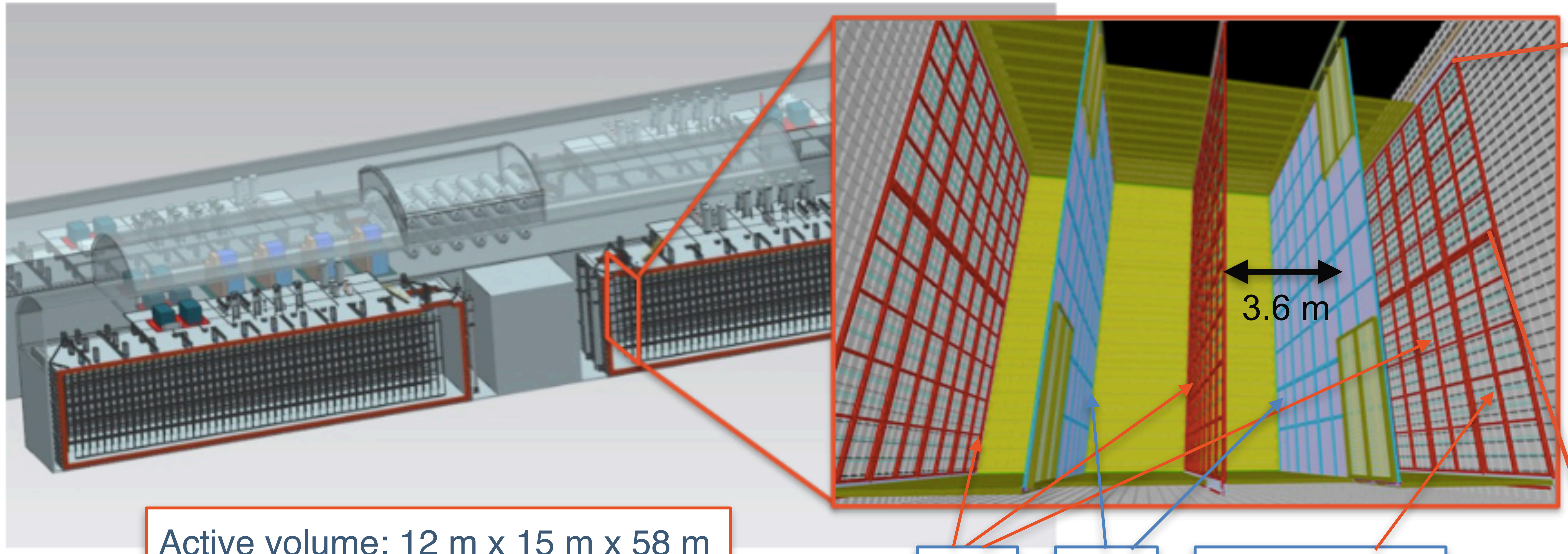
- Performance and physics measurements at protoDUNE-SP (Stefania Bordoni, Leigh Whitehead)
- The DUNE Far Detector (Diego Garcia Gamez)
- Automated Reconstruction, Signal Processing and Particle Identification in DUNE (Mike Wallbank)

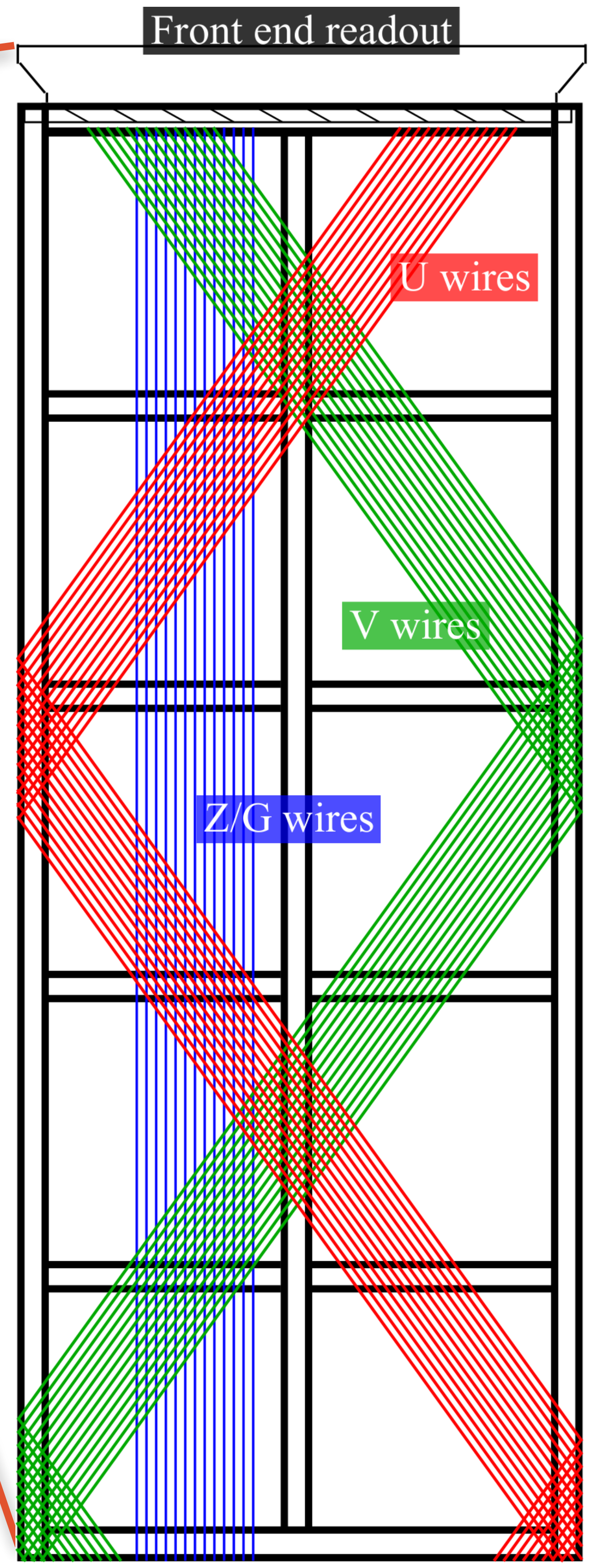
Liquid Argon Time Projection Chamber



- HV on cathode to provide electric field to drift ionisation electrons.
- Three wire planes to record electron signals. Wire spacing 5 mm.
- Photon detectors to record scintillation light — useful for assigning an absolute event time.

DUNE Single-Phase Detector Design



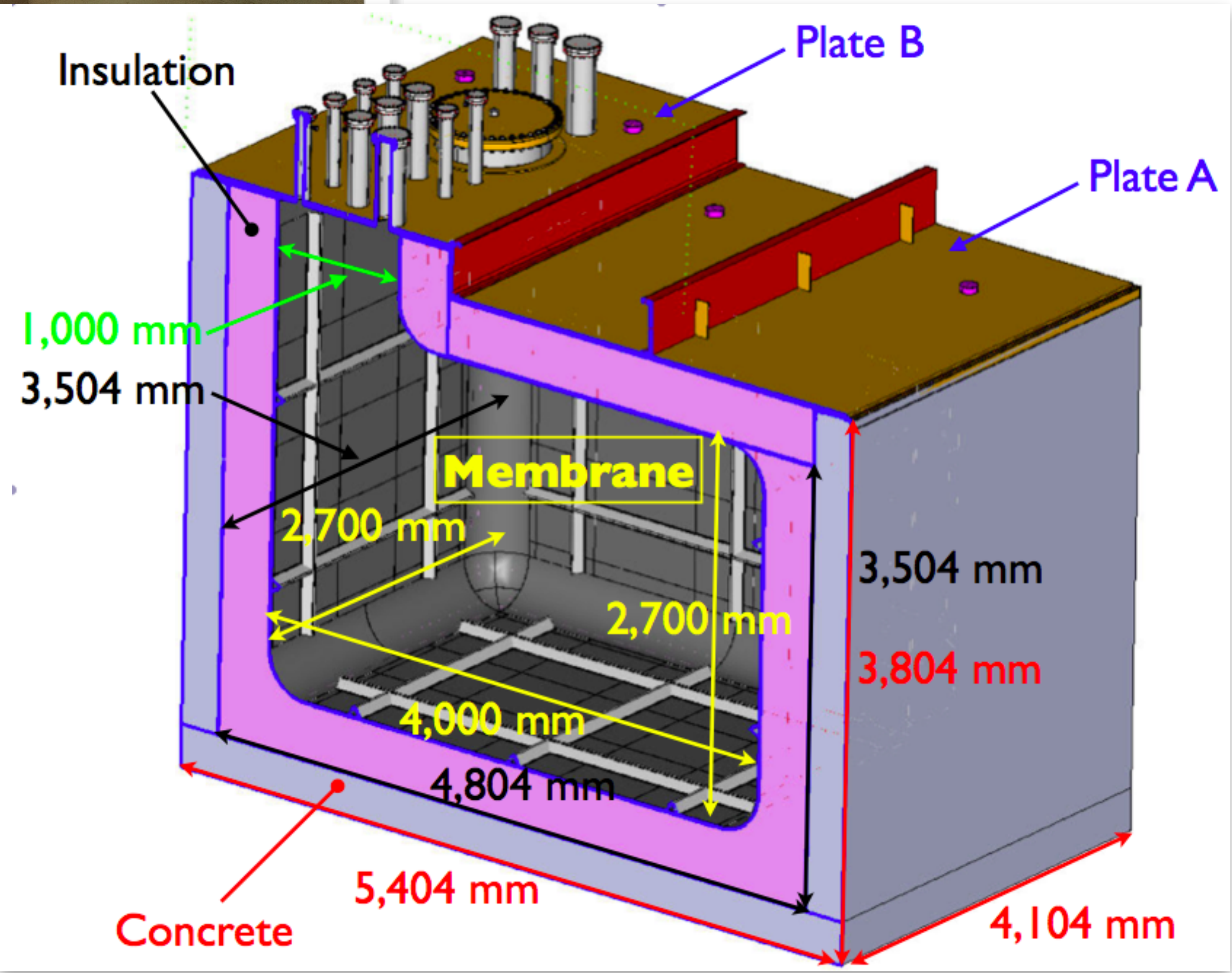


- Suspended Anode Plane Assemblies (APAs) and Cathode Plane Assemblies (CPAs).
- APAs have three active readout planes on each side (two induction, one collection) to read out ionisation charge.
- CPAs (180 kV) to provide drift field of 500 V/cm.
- Photon Detection System (PDS) inside the APAs to detect scintillation light.
- Cold electronics (pre-amplifiers and digitisers).

- Wrapped induction wires ~36° to vertical read out charge from both sides of the APAs.
  - Reduce number of channels.
- Collection wires are vertical and not wrapped.
- Readout at the top of the upper APAs and at bottom of the lower APAs.
  - Enable tiling and reduce dead region.
- Grounded meshes in centre of APAs.
- Outer grid plane to shield charge from active wires.

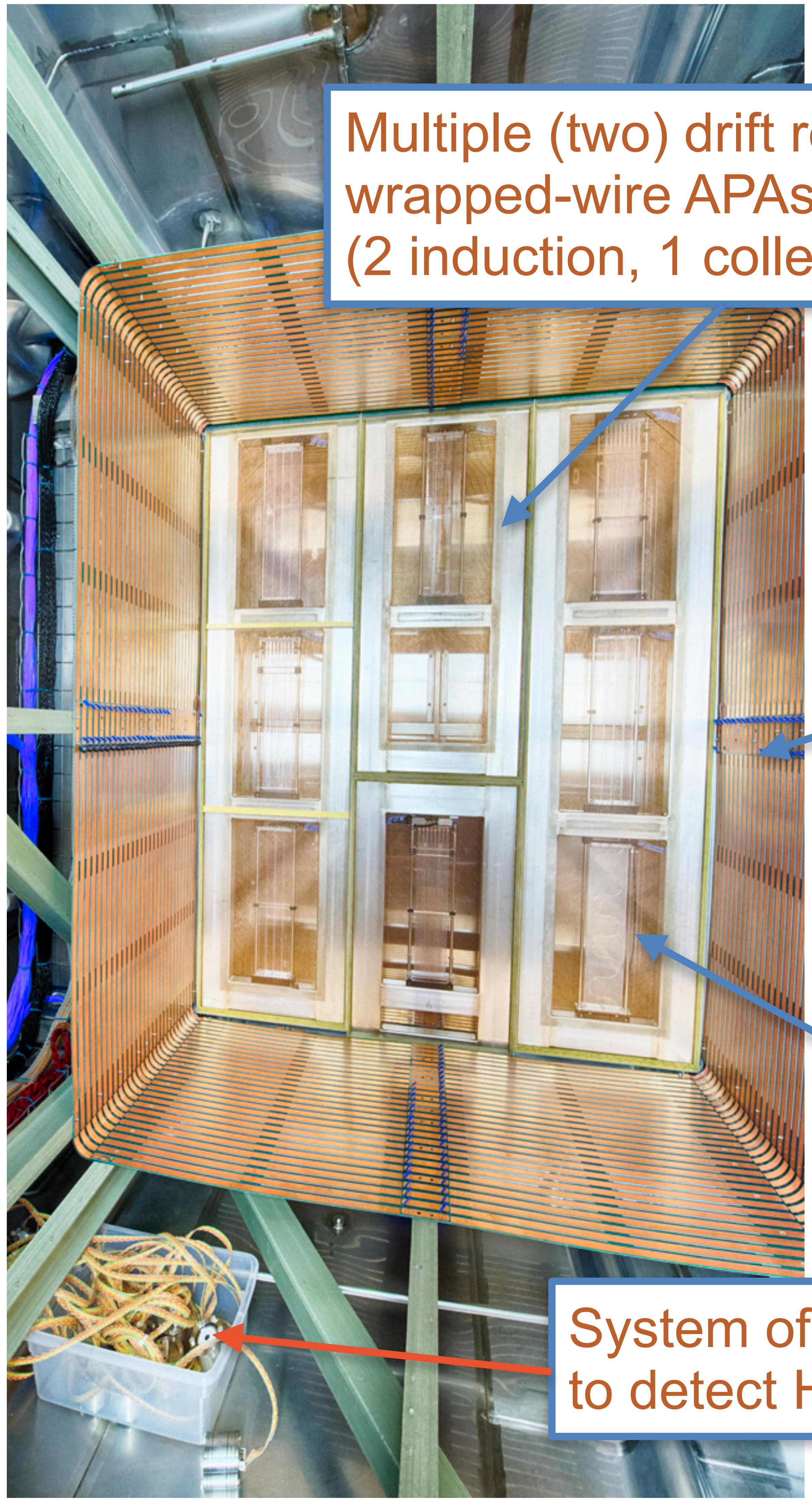
The 35-ton Prototype

- First use of membrane cryostat for scientific application.
- Test many design features of the DUNE far detector.
- Phase I (December 2013—February 2014):
    - Test cryostat concept and purification system, no detector.
    - Achieved and held electron lifetime of 3 ms.
- Phase 2 (January — March 2016):
    - Data run with detector (TPC, photon detectors, external muon counters).
    - Achieved and held 3 ms lifetime — validated integrated system.
    - Data analyses nearing completion.

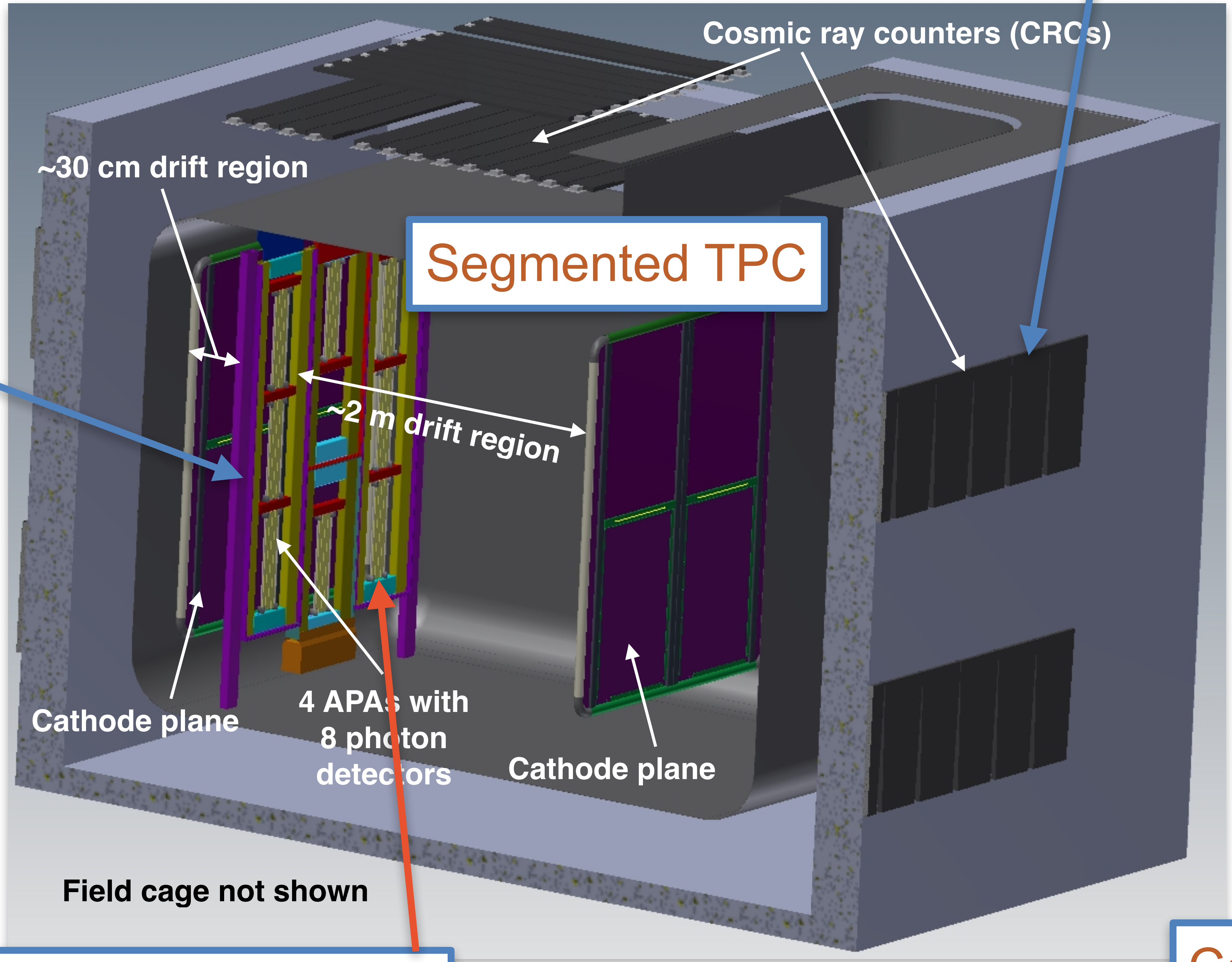


The 35-ton Detector

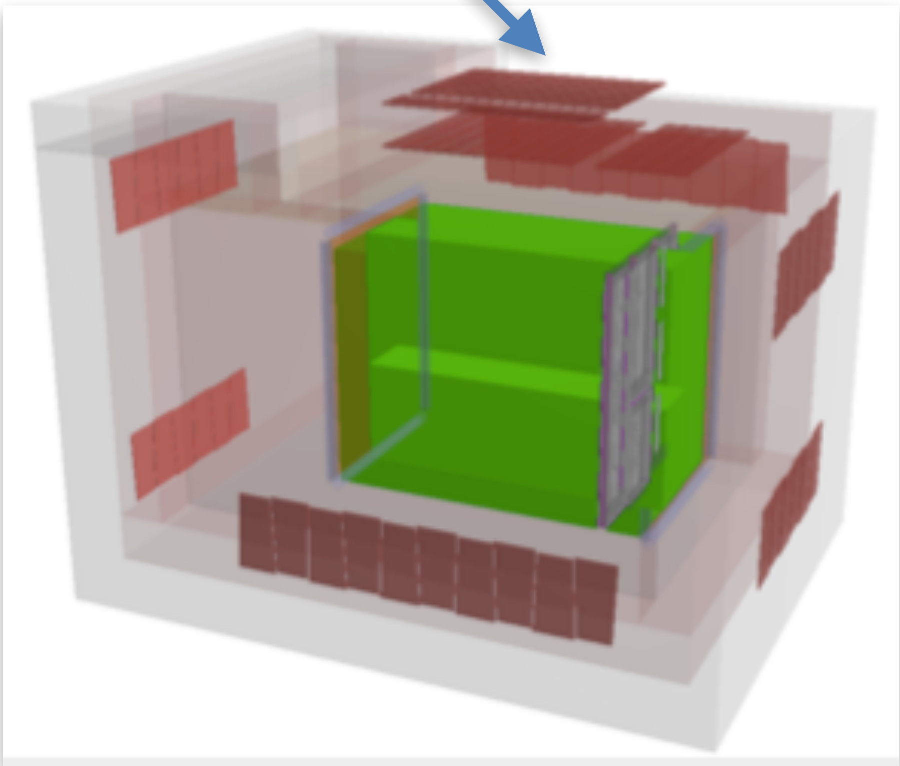
~100 scintillation paddles on the outer cryostat walls to provide cosmic triggers



Multiple (two) drift regions read out by four wrapped-wire APAs — three readout planes (2 induction, 1 collection), 2048 channels



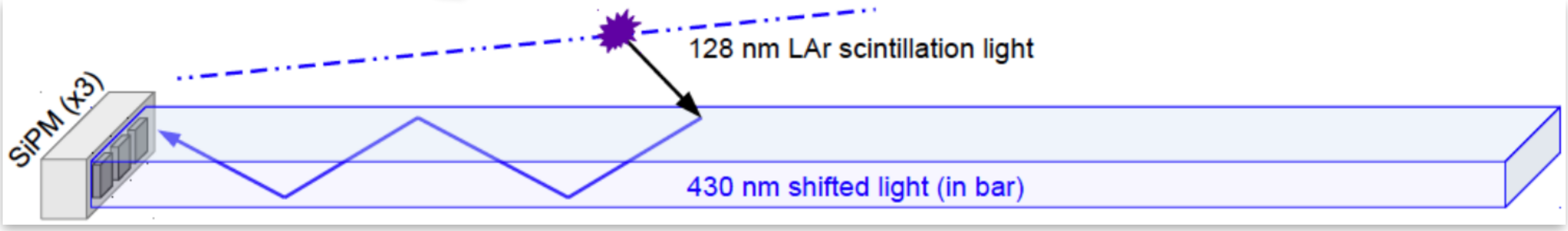
Segmented TPC



FR4 printed circuit board field cage (LBNE design)

APAs contain integrated photon detectors: wavelength shifting (from 128 nm) lightguides with SiPM readout

Cold analog and digital electronics

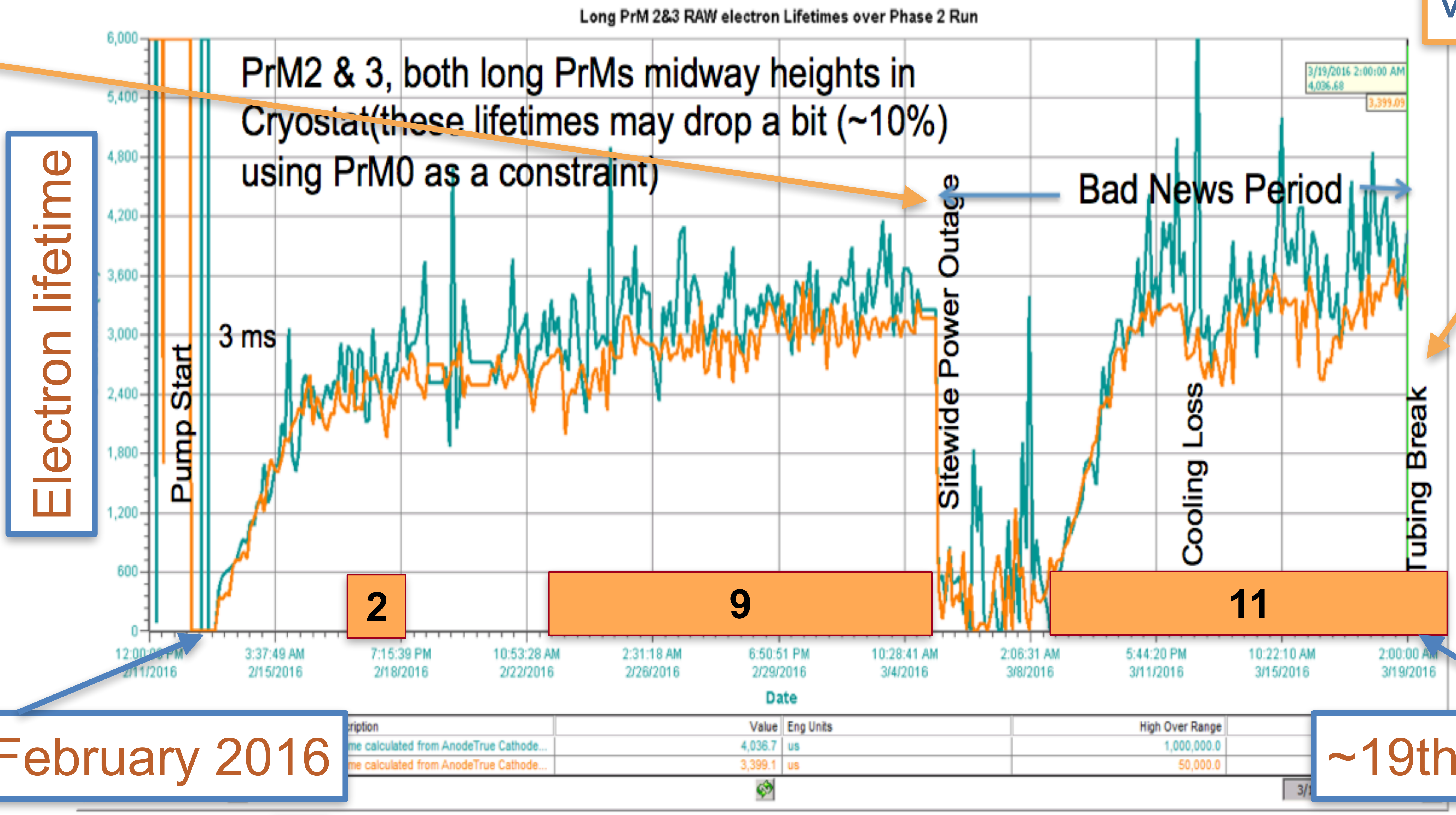


System of 8 optical cameras to detect HV breakdowns

35-ton Data Taking

Recovering from issues such as power outages needs improvement!

Premature end of run caused by pipe break, LAr volume poisoned with air



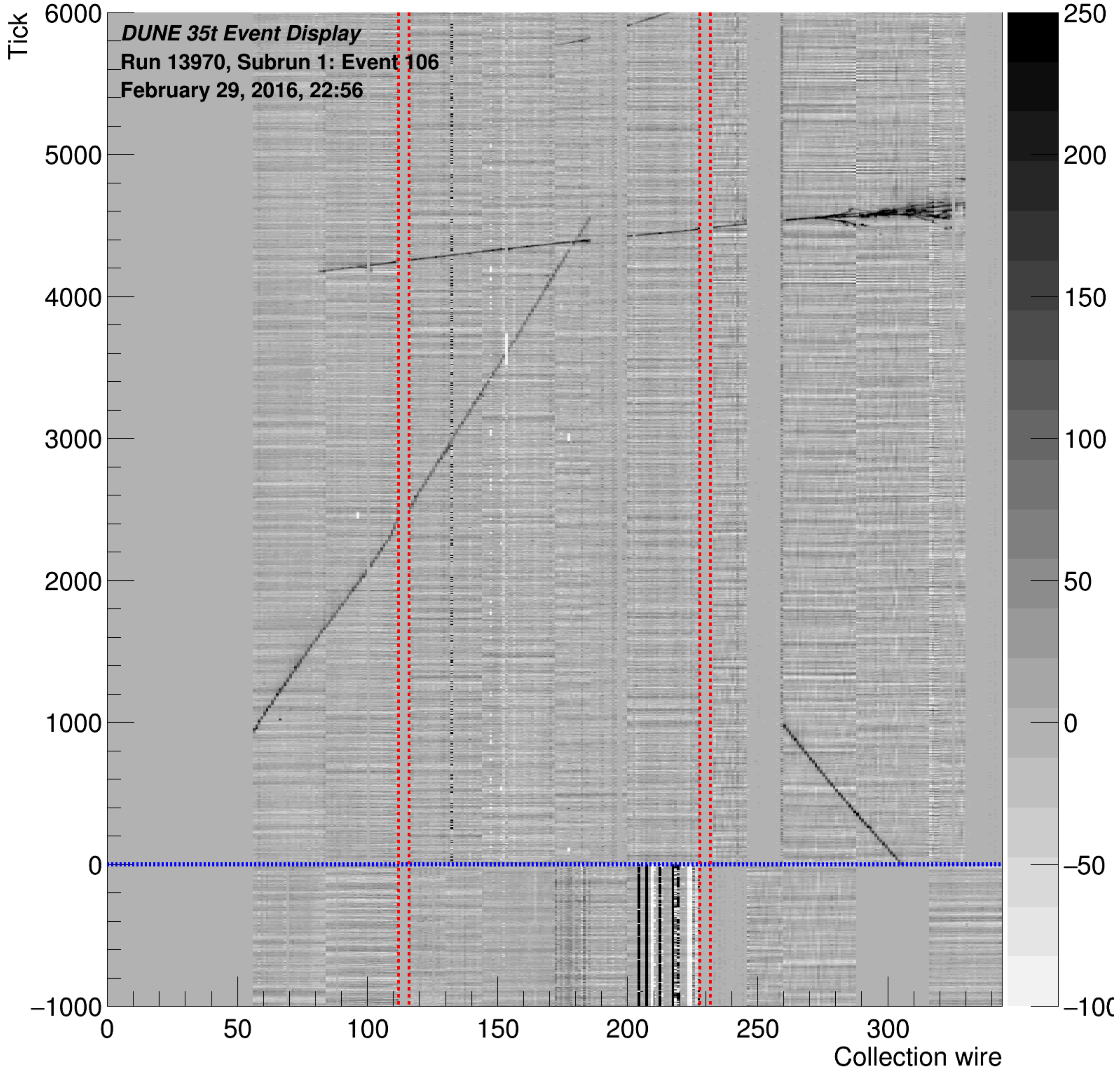
~13th February 2016

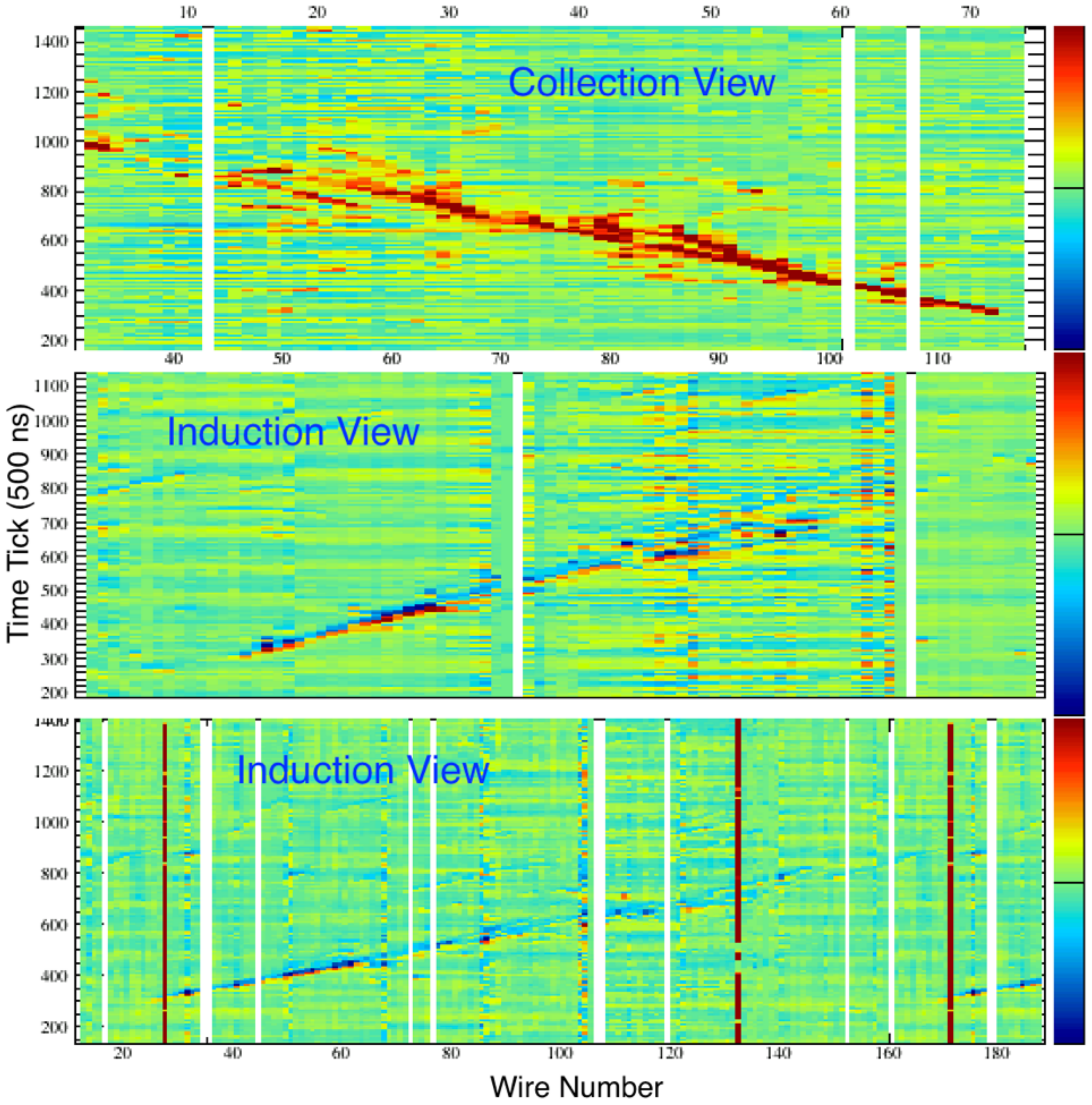
~19th March 2016

N - Drift field on at 250 V/cm for N days

- 22 days of ‘analysable’ (good purity, high voltage) data.
- Triggered on counter coincidences by through-going particles.

35-ton Data





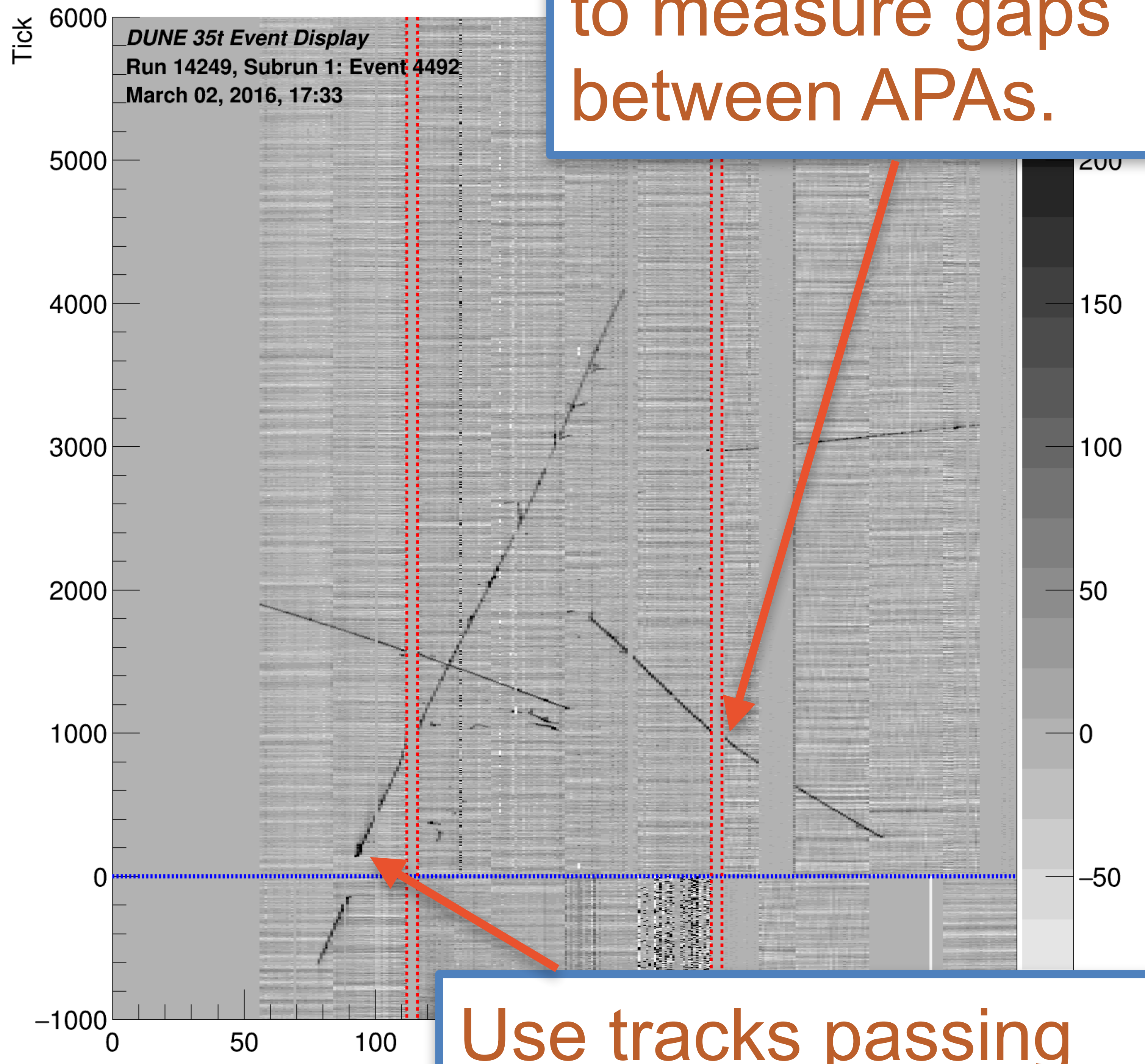
Tracks and showers observed in the online event display

Electron shower seen in three views in 35-ton

35-ton Data Outcomes

- Automated reconstruction shown to work on real data.
- Validated modular TPC design.
- High voltage was a success but premature end of run resulted in no data being collected at design drift field.
- Continuous data taking with the DAQ was demonstrated but zero suppression was untested due to the noise and time limitations.
- Vertical stratification of purity and temperature in the cryostat during the run noticed.
- Unexpected issues with TPC data resulted in fewer physics-based and more detector-focussed analyses.
- Focussing on analyses of unique 35-ton datasets:
  - Measurements of the modular TPC design;
  - Making use of the external counters for positioning and timing;
  - Understanding the performance of the photon detectors in integrated system.
- Results preliminary — may change before publication.

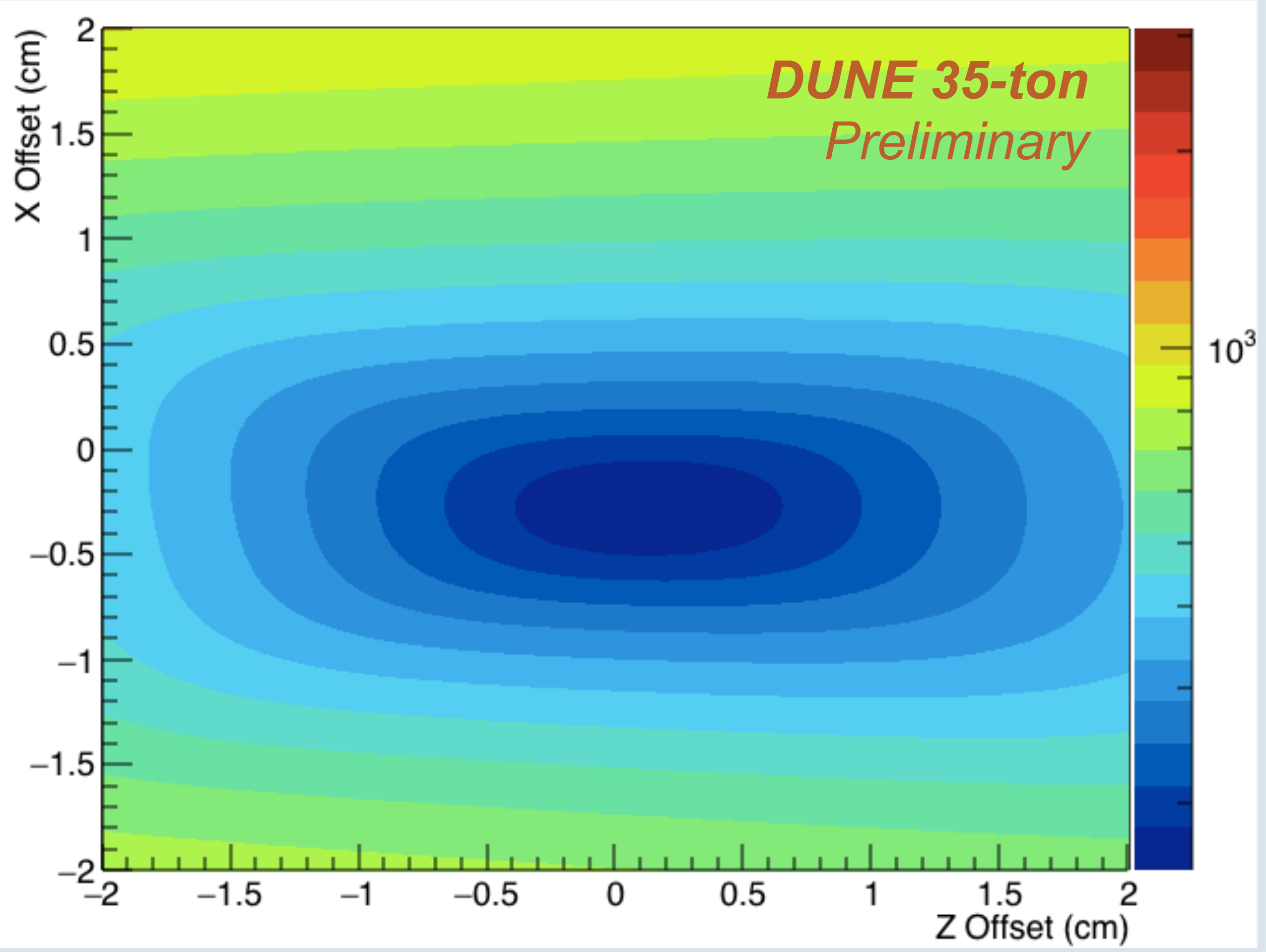
Detector-Crossing Muons

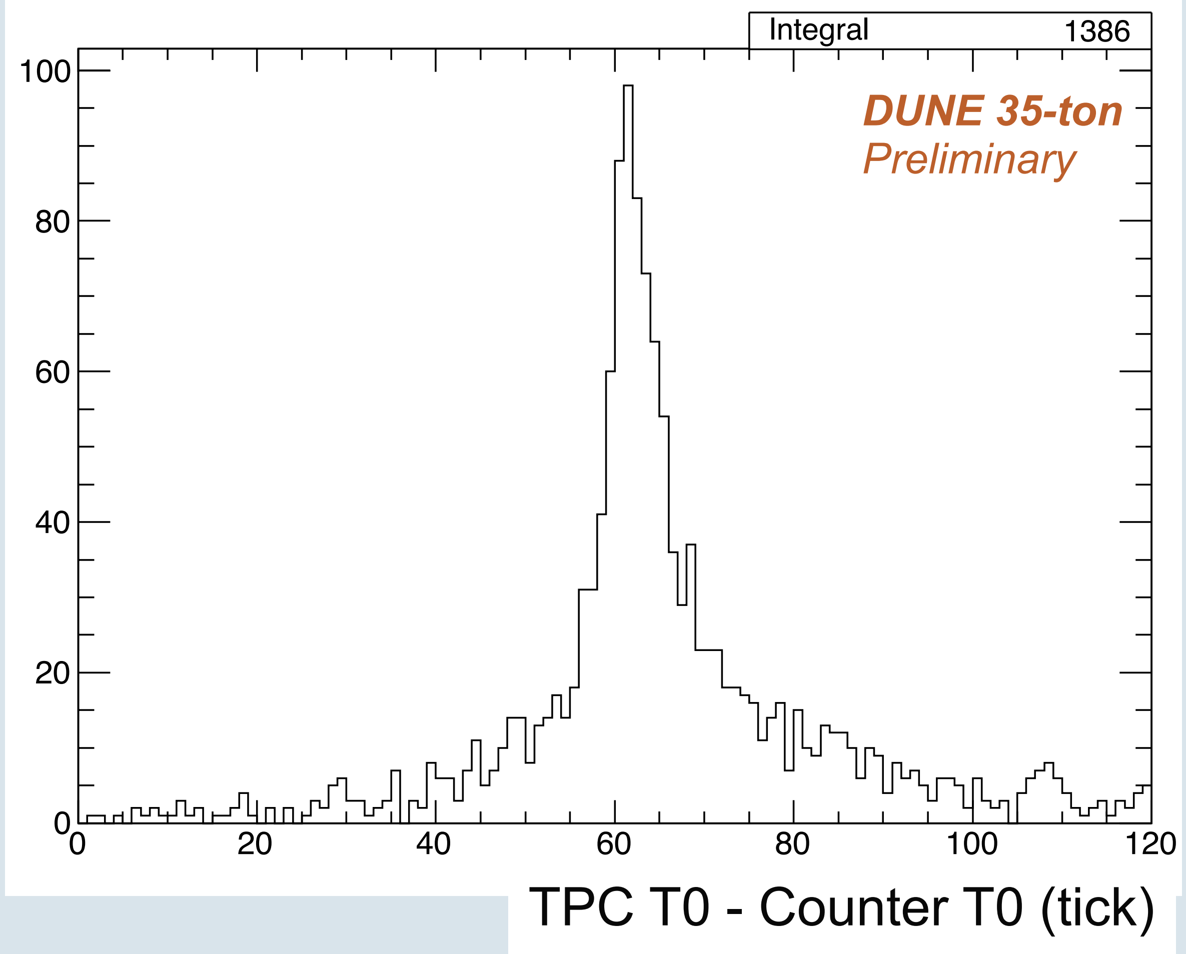


Use tracks crossing different drift regions to measure gaps between APAs.

Use tracks passing through the APAs to measure the interaction time, T0

- When measuring APA gap offsets in *z*, also found evidence for offsets in *x*, the drift direction.
- Can measure both simultaneously.
- Vital for DUNE far detector — each module will contain 150 APAs —> lots of offsets to understand!

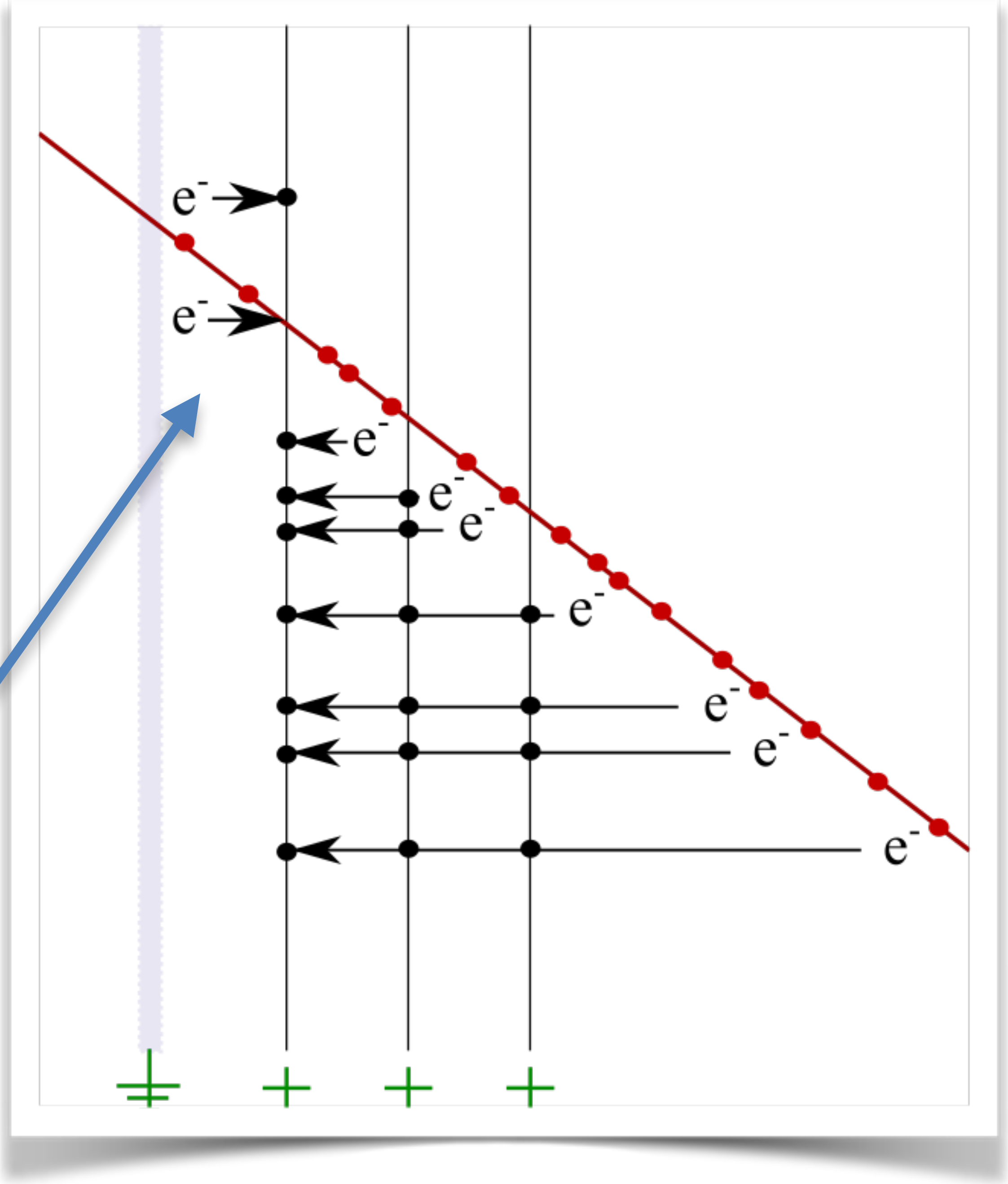




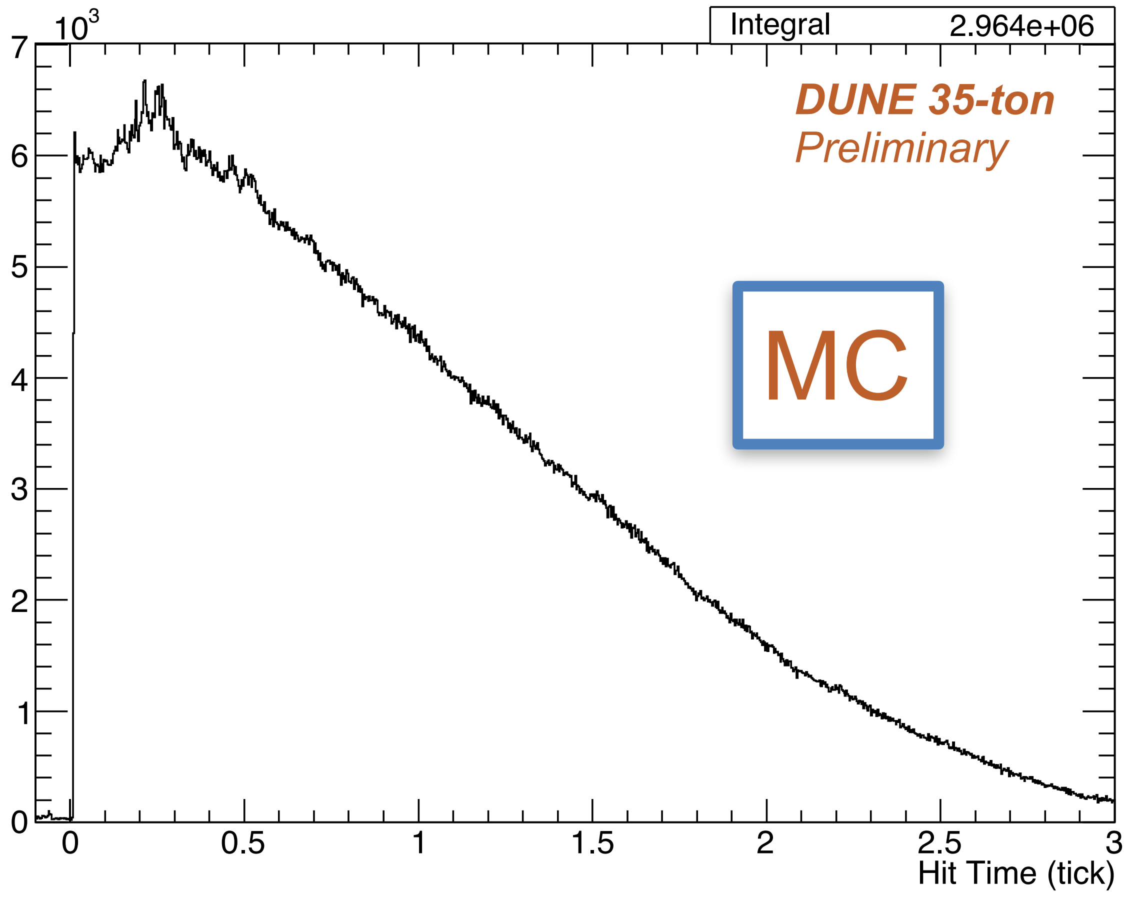
- Found evidence of timing offset between external counters and TPC when measuring T0.
  - ~31 μs (62 TPC ticks).
- Highly useful calibration tool, important for DUNE far detector.

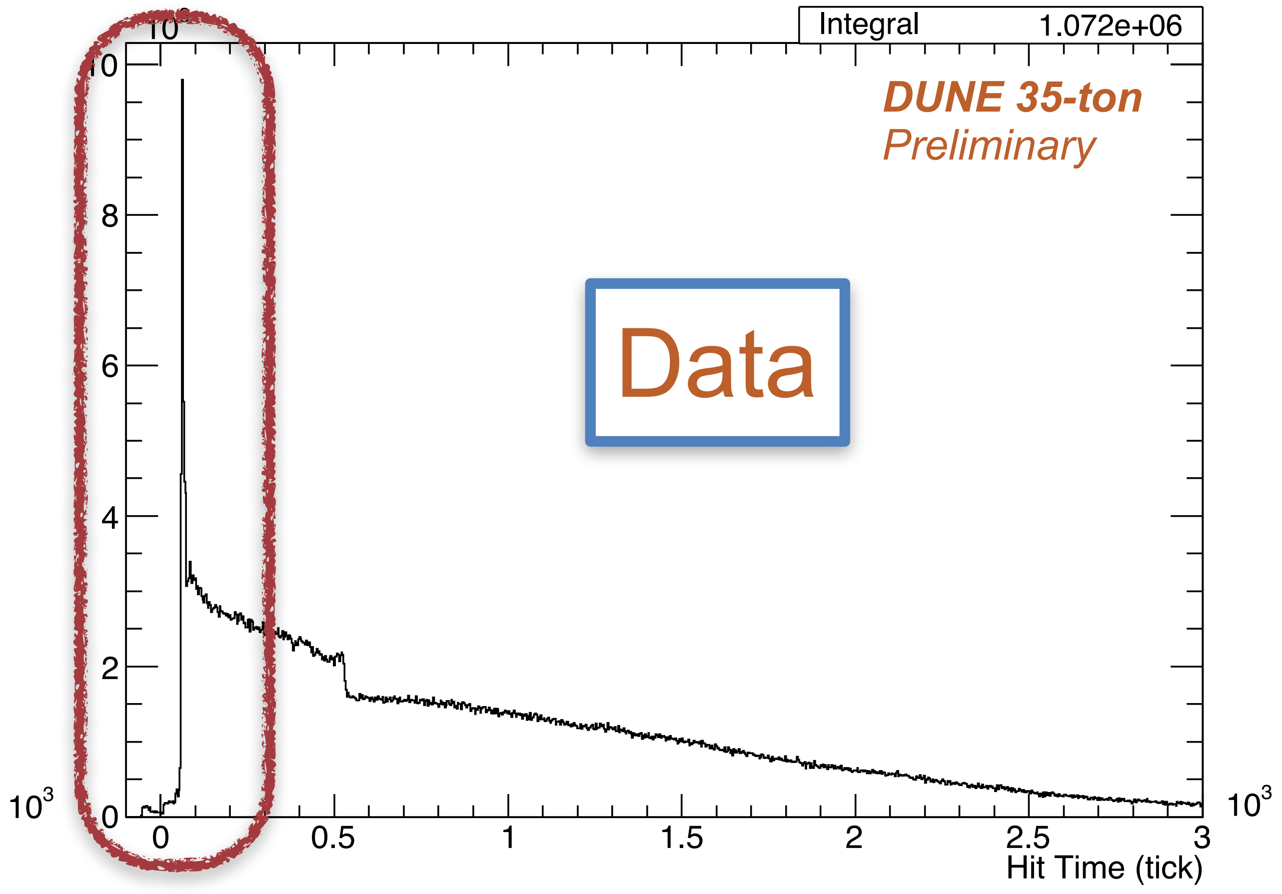
Charge Deposition in TPC

- All the field lines originate on the collection plane and terminate on either the cathode plane, or the grounded mesh behind the collection planes.
- Because of the electric fields on both sides of the collection plane, interesting effects have been observed when an ionising track passes through the APAs.
- Not currently simulating this — will eventually need to!

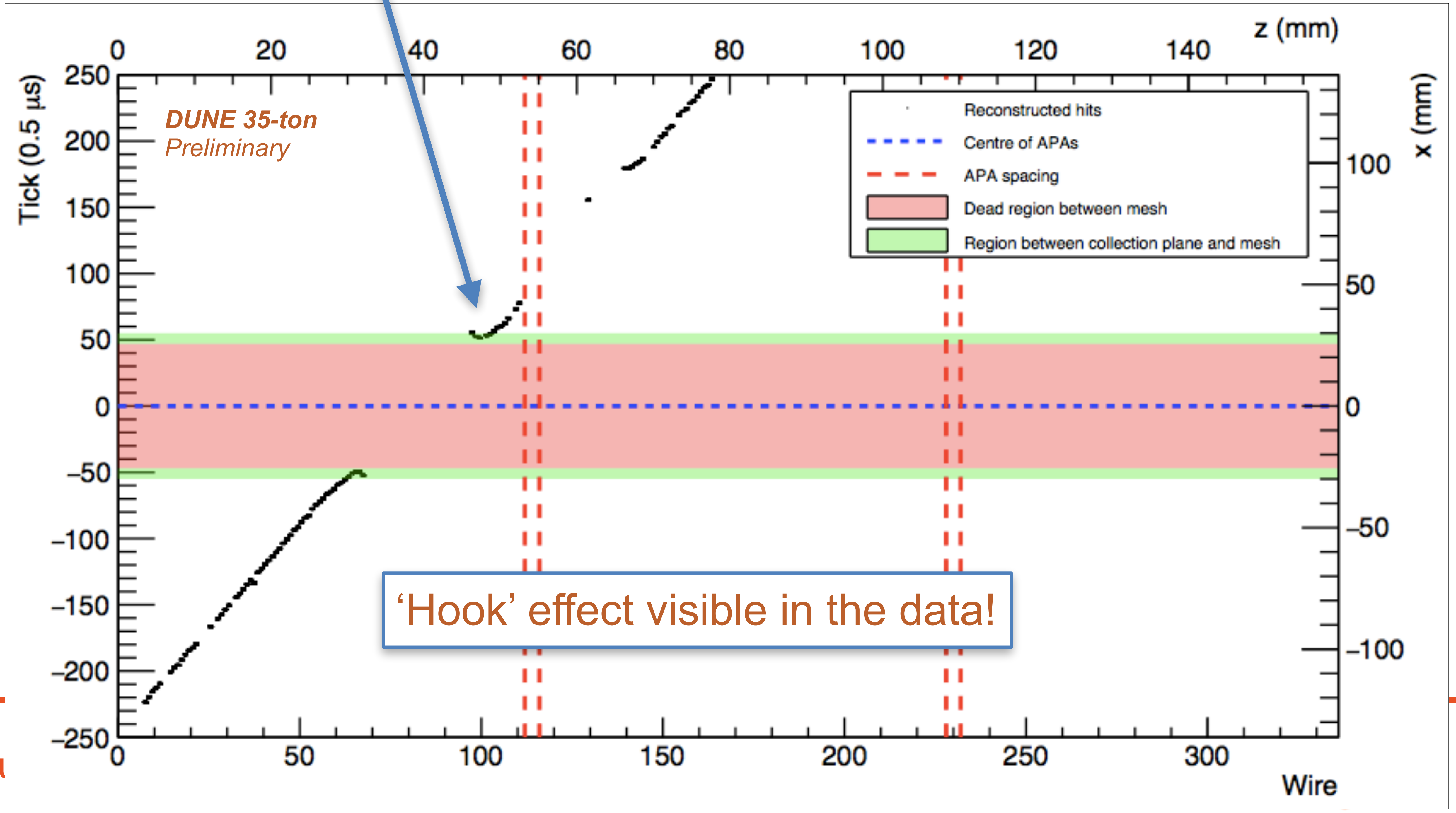


'Backward' drifting charge



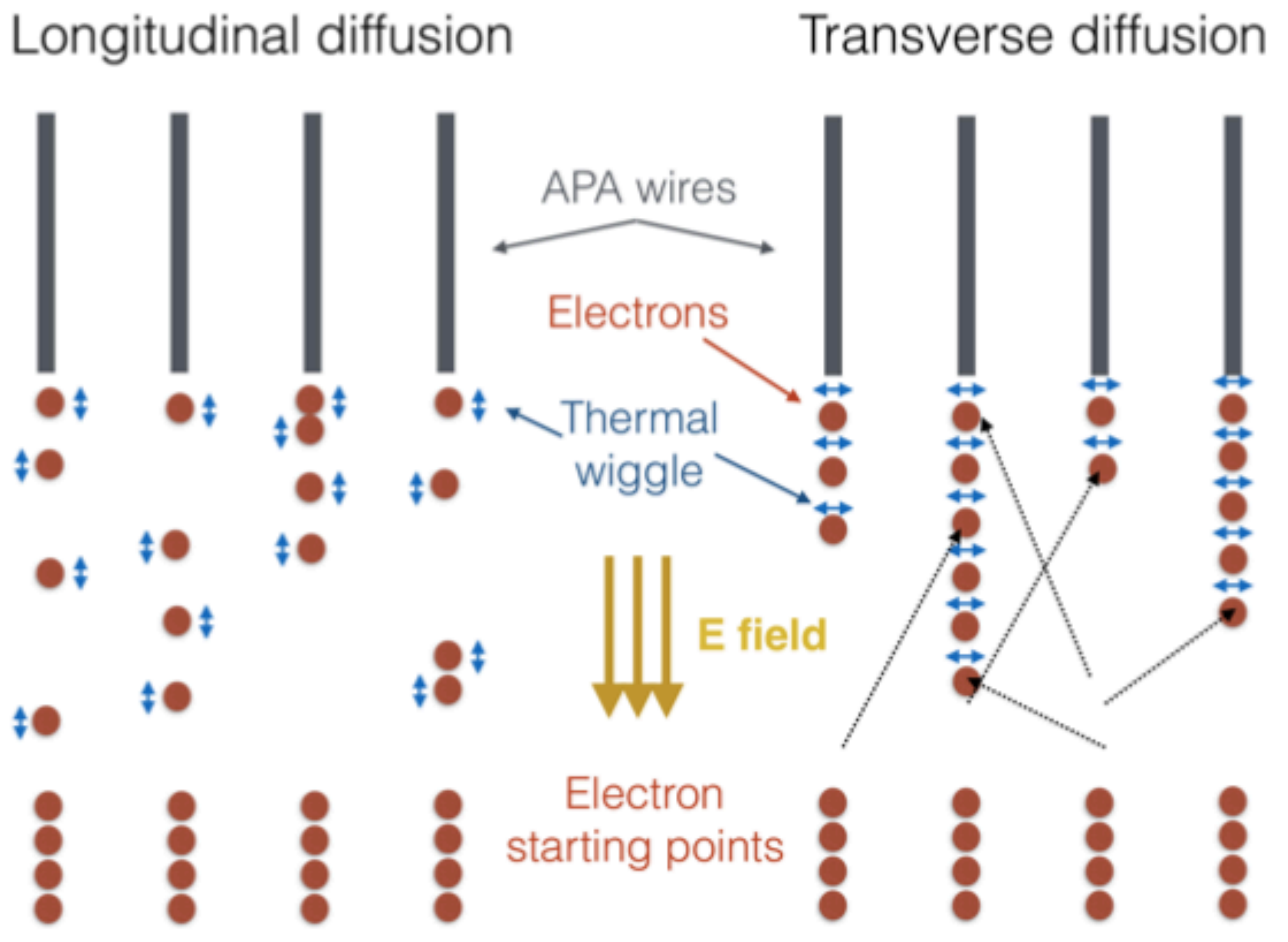


Hit time distributions
Excess of hits around the interaction time in data.



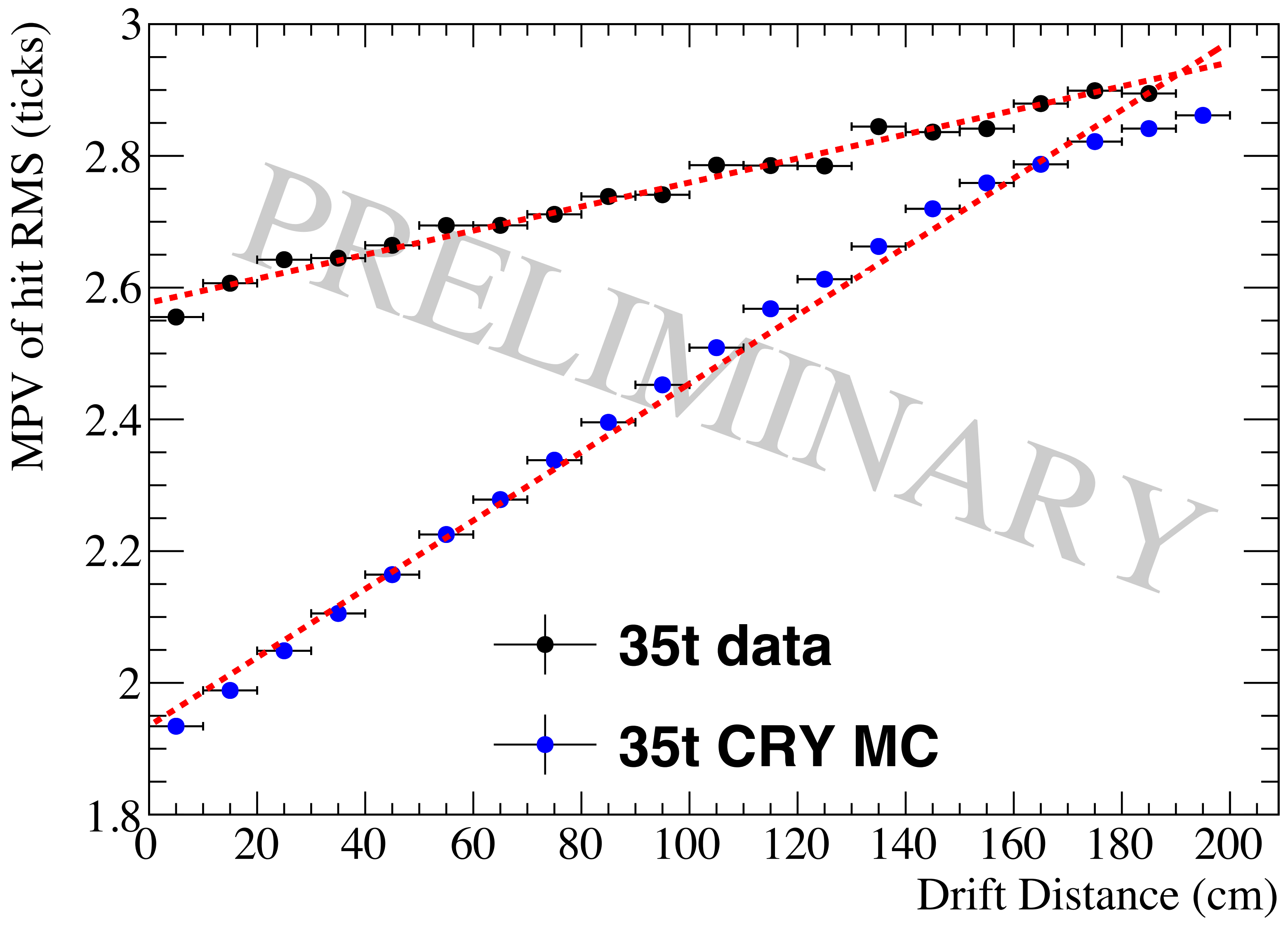
Measuring T0 from Diffusion

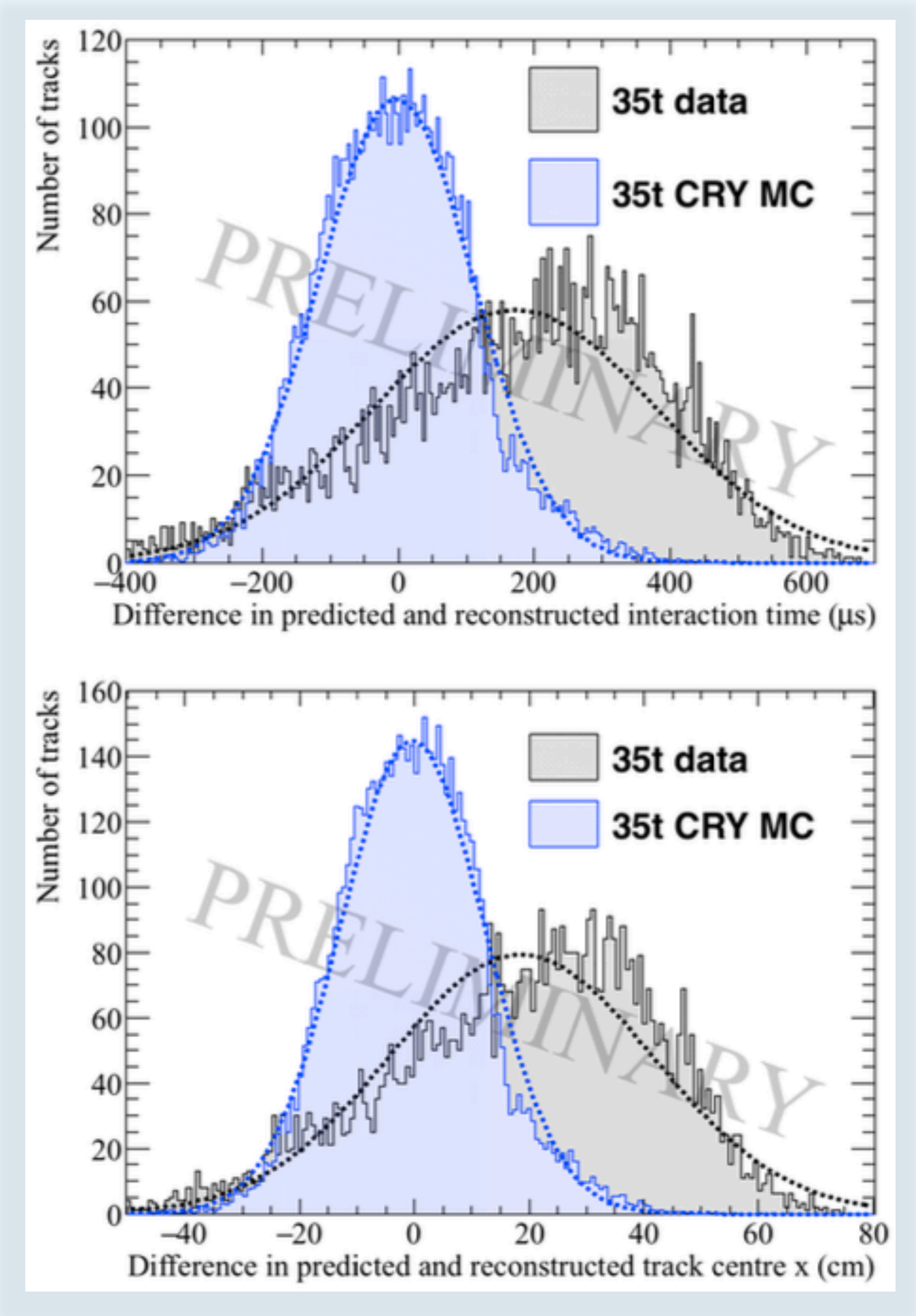
Image: D Brailsford



- Diffusion is the scattering of electrons as they travel from common source.
  - Longitudinal: spread in time.
  - Transverse: spread across wires.

- Hypothesis: any track has enough information to determine T0 without need for an external trigger system.
- Use the change in hit width (in time) caused by diffusion along the track to infer its original location.
- Can use counters to select tracks with known angles and interaction times.





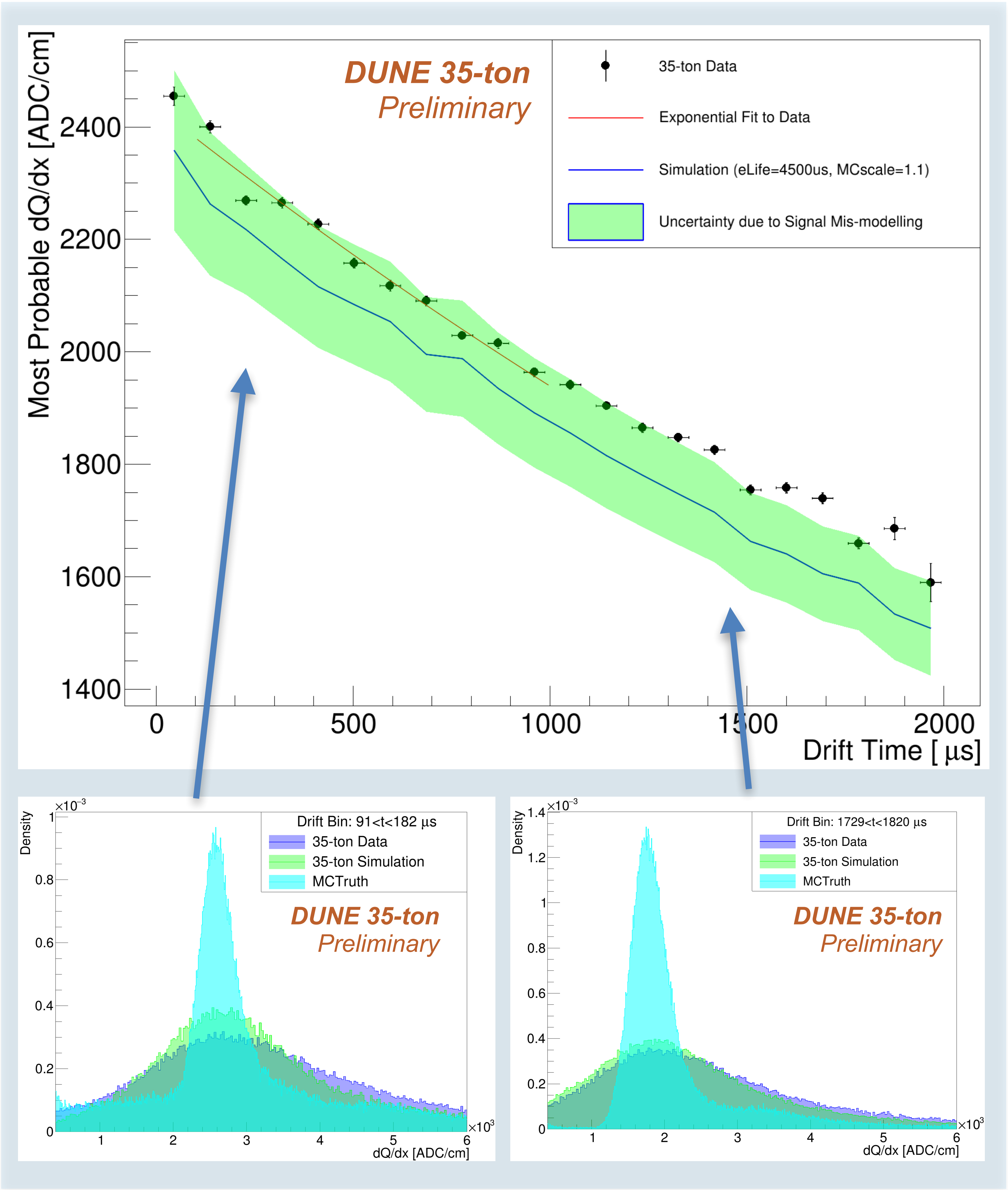
Measuring Purity from Tracks

- Charge attenuation due to electronegative impurities (e.g. O_2, H_20):

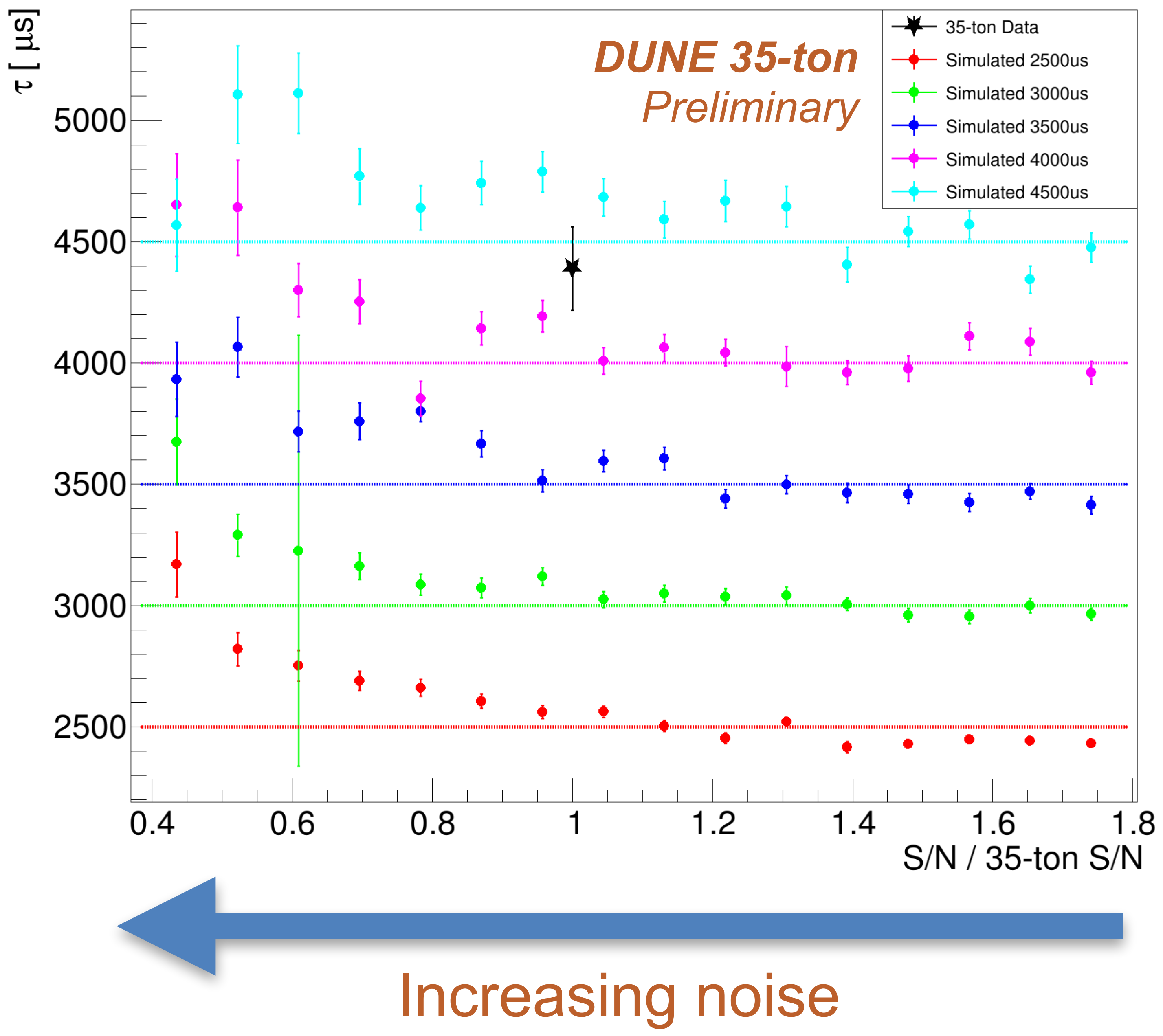
$$Q = Q_0 e^{-t/\tau},$$

where t is drift time and τ is electron lifetime.

- Use hits on a given track to measure deposited charge as a function of drift time.
- Measured average over full data run: 4.25 +/- 0.24 (stat.) +/- 0.28 (sys.) ms (PRELIMINARY).
  - ~ 41 ppt O_2 equivalent.



- Electronics noise biased the observed lifetime.
- The quoted value is found by fitting to measurements made from multiple simulations with differing true lifetimes.



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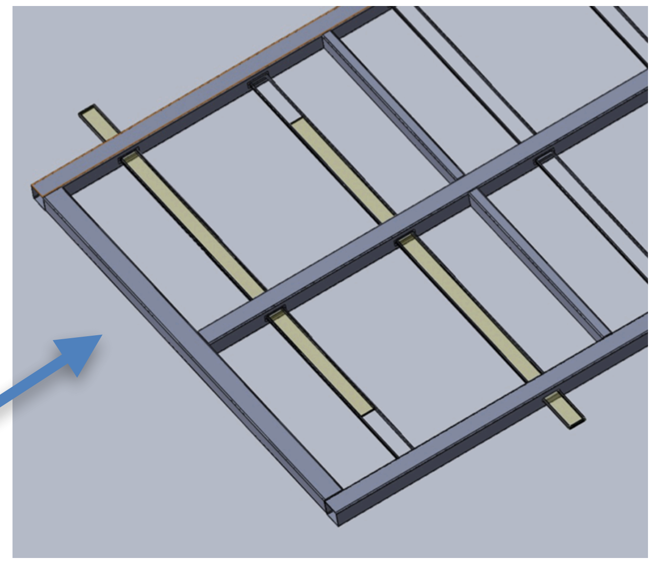
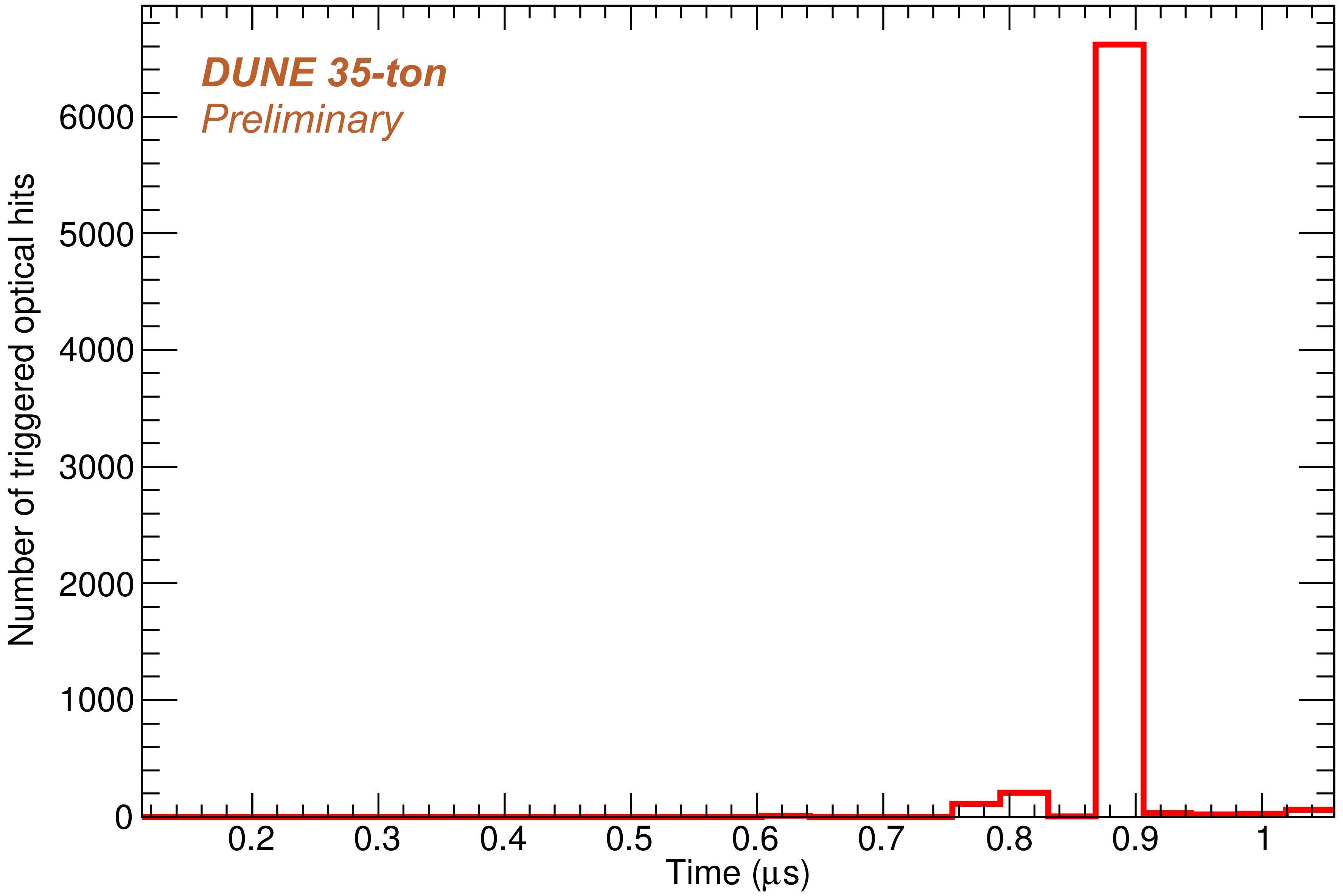
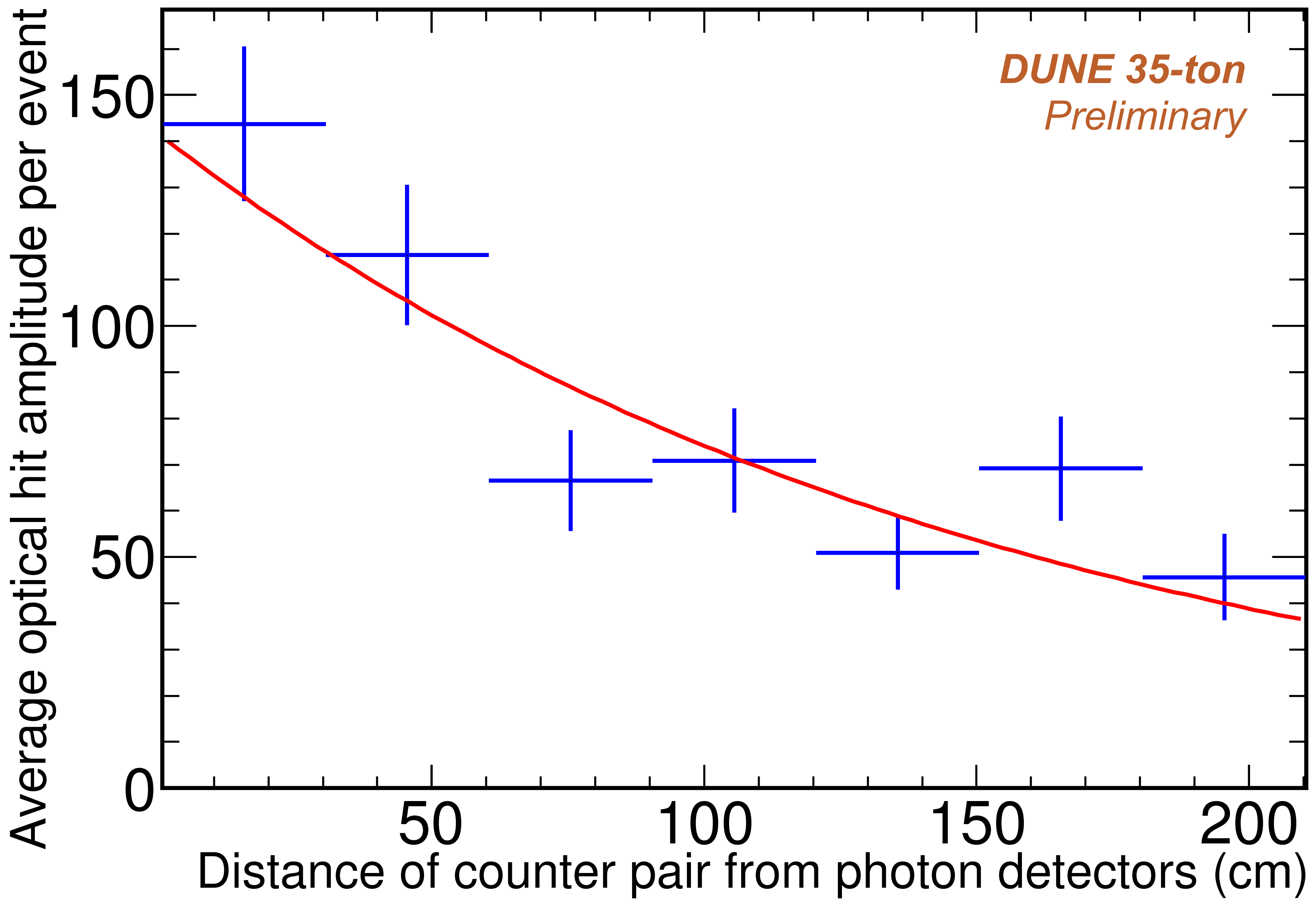
Photon Detectors

Dedicated photon detector paper:
'Photon Detection System Performance in the DUNE 35-ton prototype LAr-TPC detector'
In preparation

- Successful demonstration of APA-embedded photon detectors.
- Excellent timing resolution: < 100 ns wrt the external counters.
- Found an attenuation length for LAr of 155 +/- 28 cm.
- Lessons learned carried forward into the current DUNE designs — now inserted after wrapping.
- SSPs (SiPM Signal Processors) developed at ANL to process FE readout successfully deployed and will be used again in ProtoDUNE-SP.

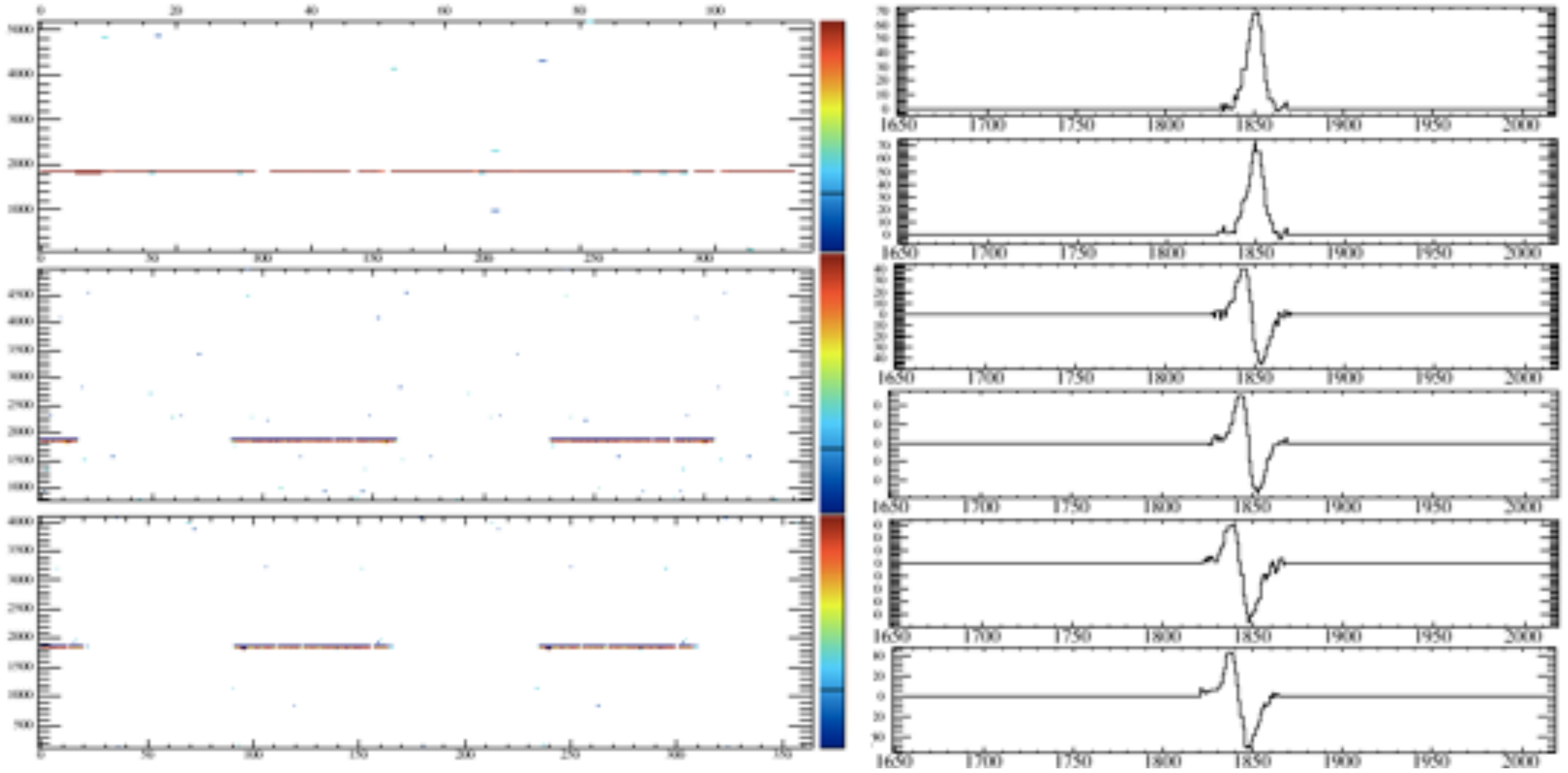




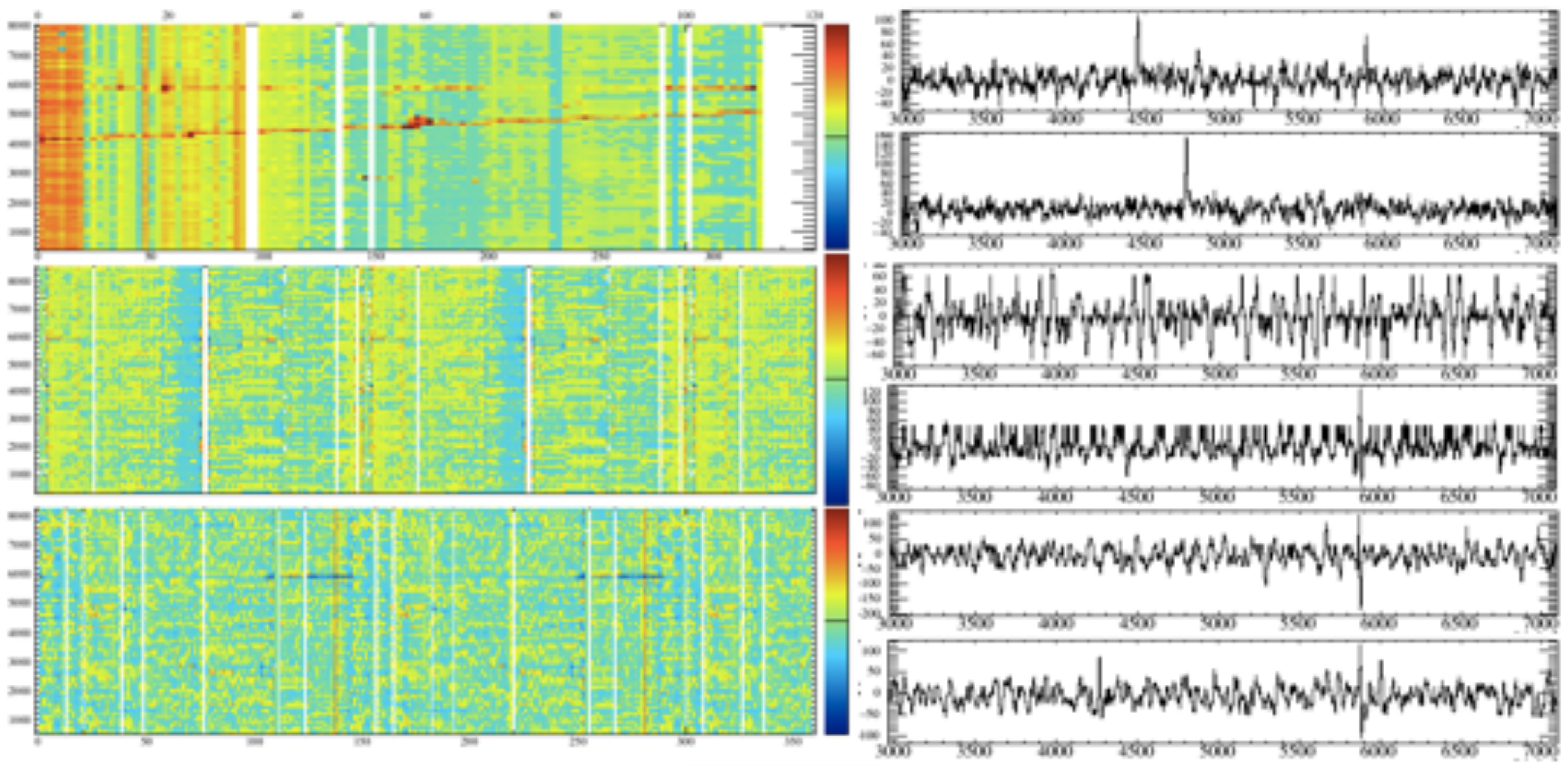


35-ton Noise Issues

- Higher electronics noise in TPC data than expected, mainly in FE electronics (signal/noise ~10 (collection channels), ~2 (induction channels)).
- ‘High noise state’, a couple oscillation of all detector components, regularly affected the data.
- Digitiser had problems with stuck bits, regularly erroneously reporting particular values.
- **Electronics development continuing using 35-ton experience, problems with noise have been identified and understood.**



Simulation



Data

Summary and Outlook

- The DUNE experiment has the capability to make world-leading measurements and will dramatically improve our understanding of neutrino physics and beyond.
- The novel design of DUNE must be tested and prototyped to ensure the successful running of the experiment.

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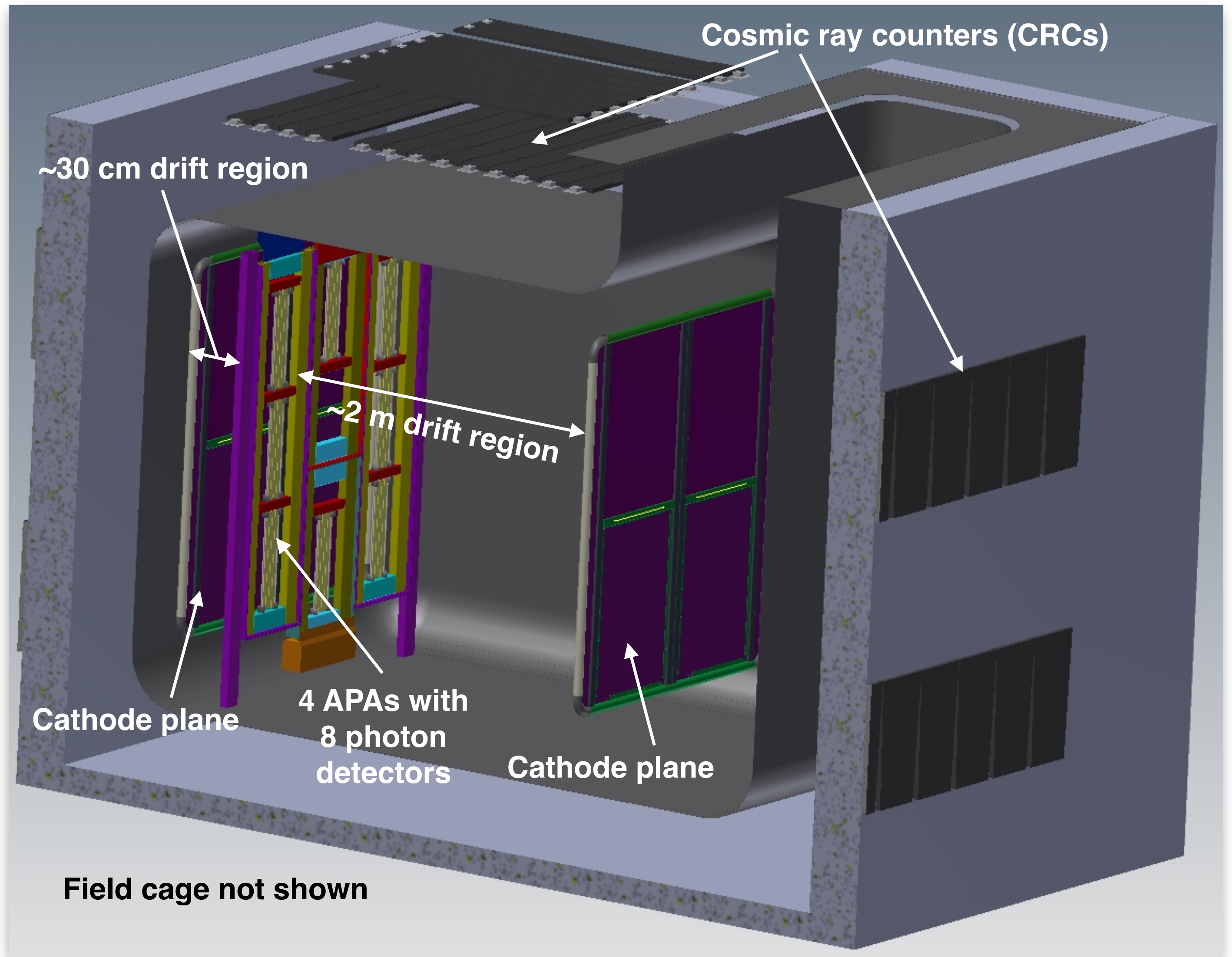
35-ton Summary

- The 35-ton prototype is the first test of the DUNE detector design and a lot has been learnt from the experience.
- Unique analyses were possible with the 35-ton data and lots of new ideas developed which will be vital for the final DUNE far detector.
- Look out for publications in the coming months!



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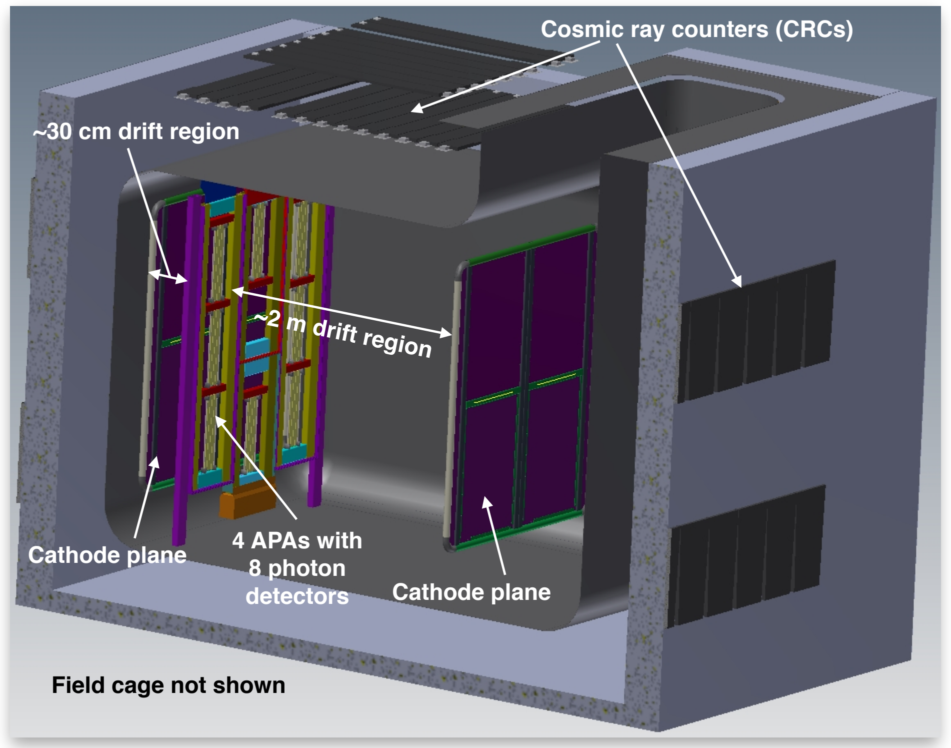
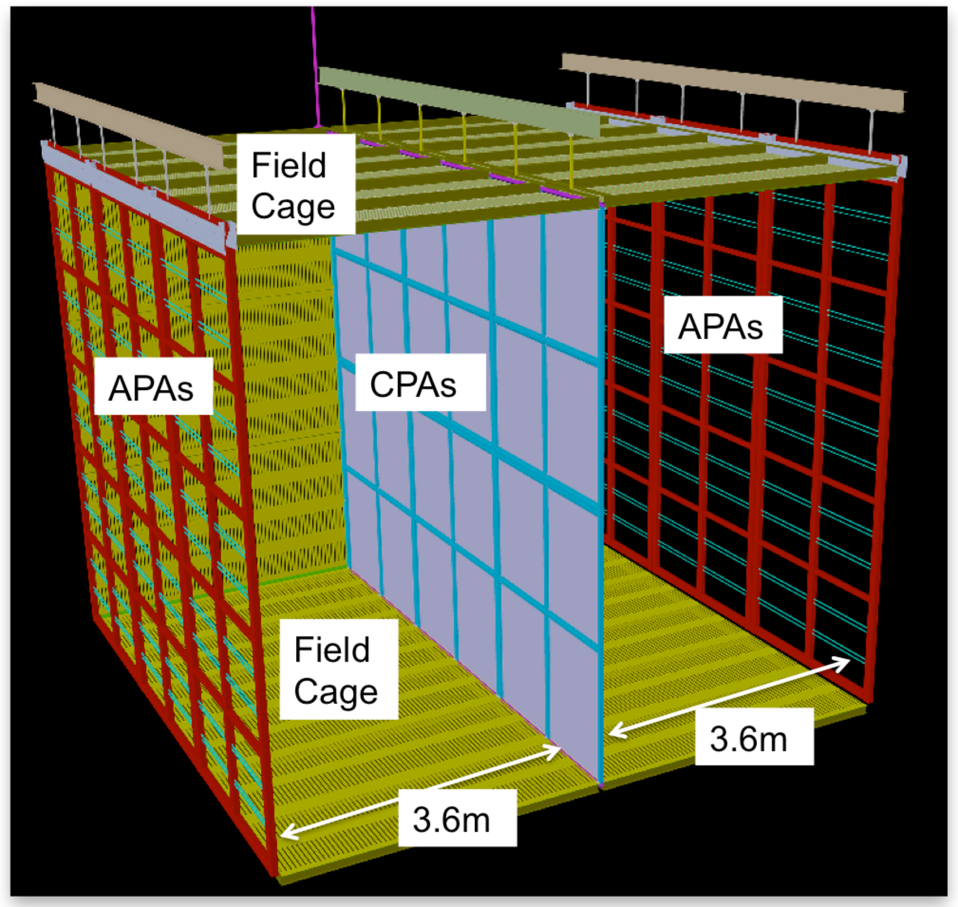
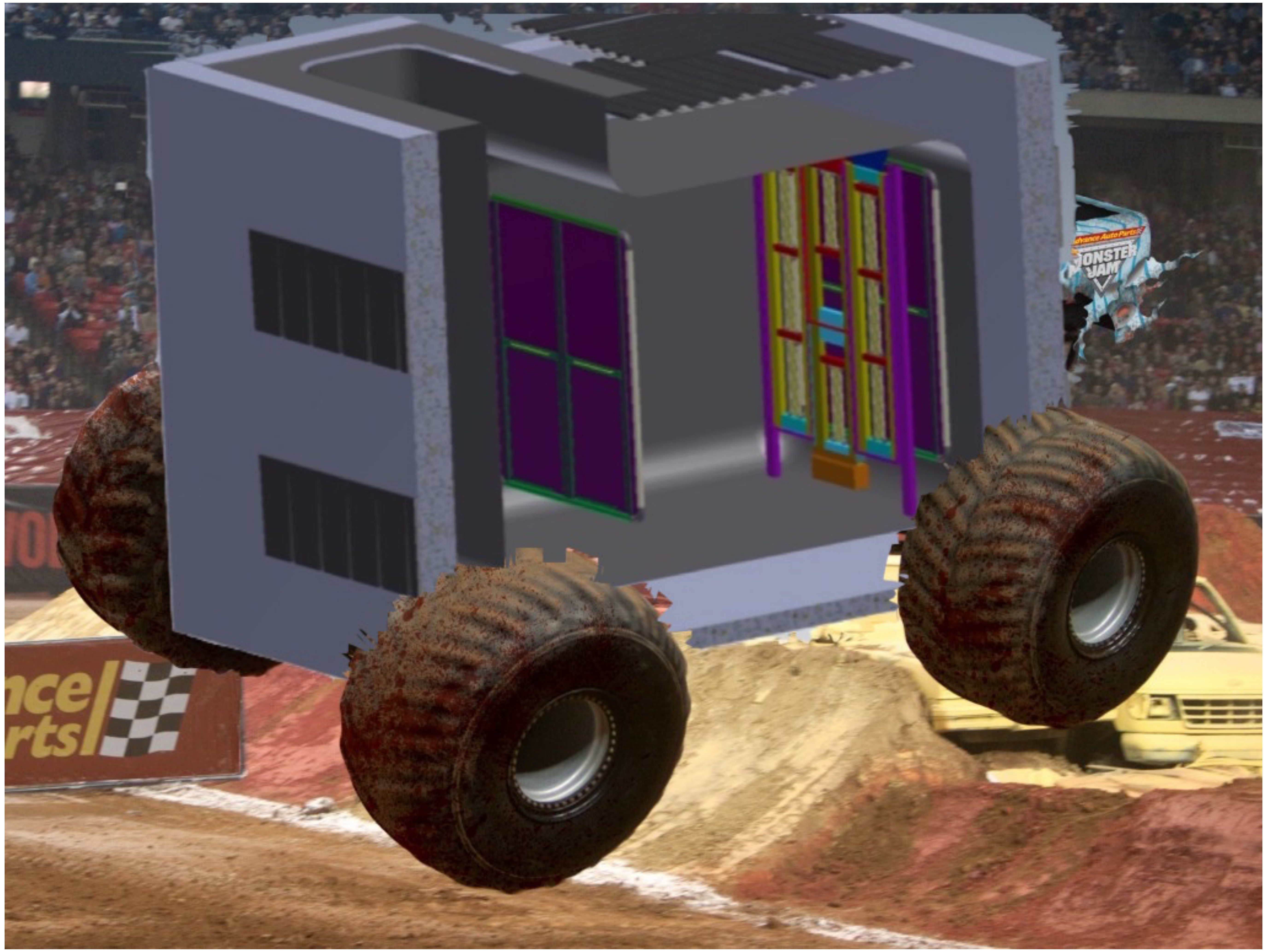




Outlook: ProtoDUNE-SP

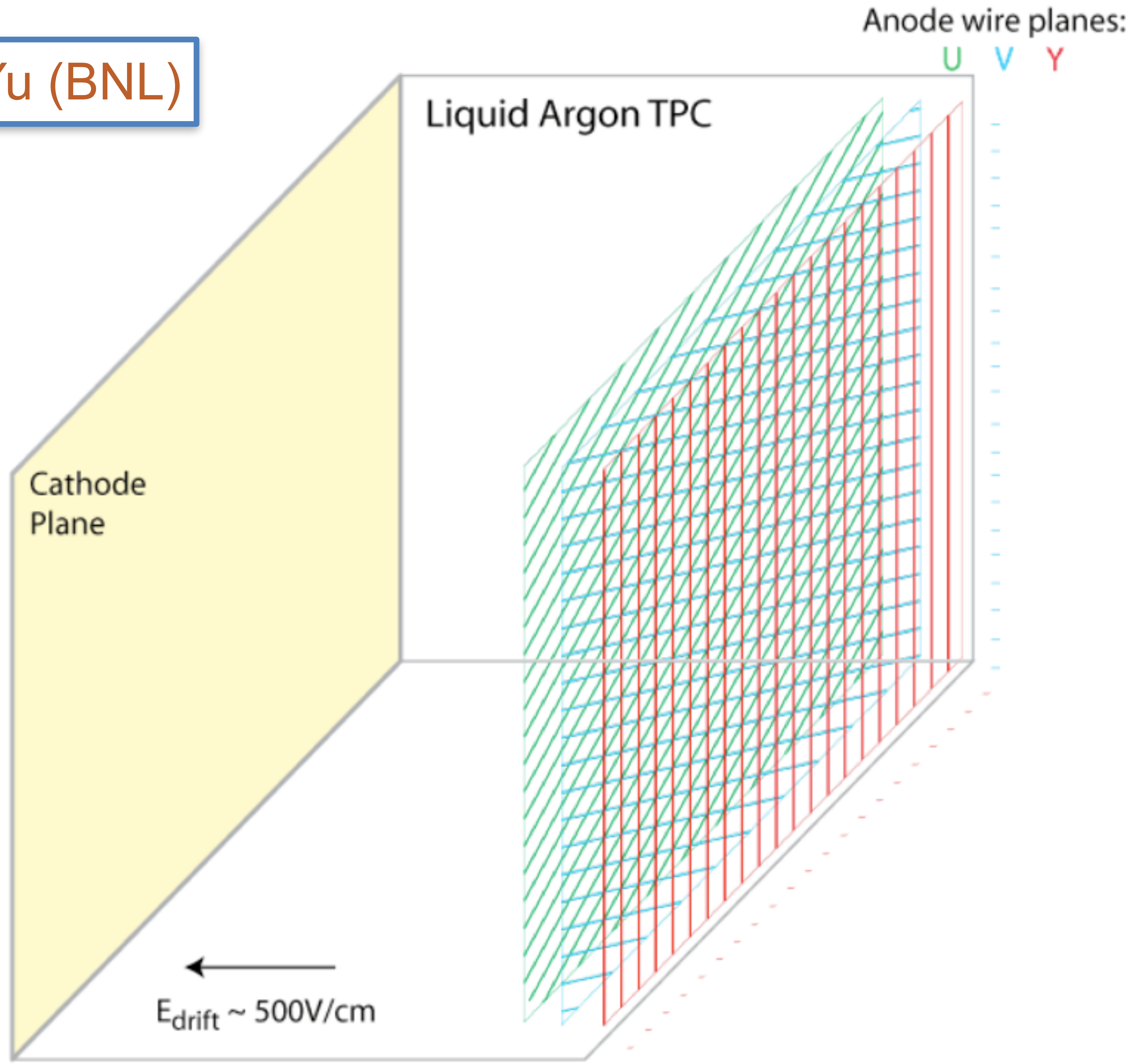
- Full-scale (APAs, CPAs and drift distance) engineering prototype in test beam at CERN neutrino platform, scheduled to take data in late 2018.
- Many of the 35-ton analyses are relevant for commissioning: CPA crossings, purity, counter-track matching, multiple drift region crossers.
- Experiences in detector installation, commissioning and running from 35-ton vital.

Backups



LArTPC Concept

Bo Yu (BNL)



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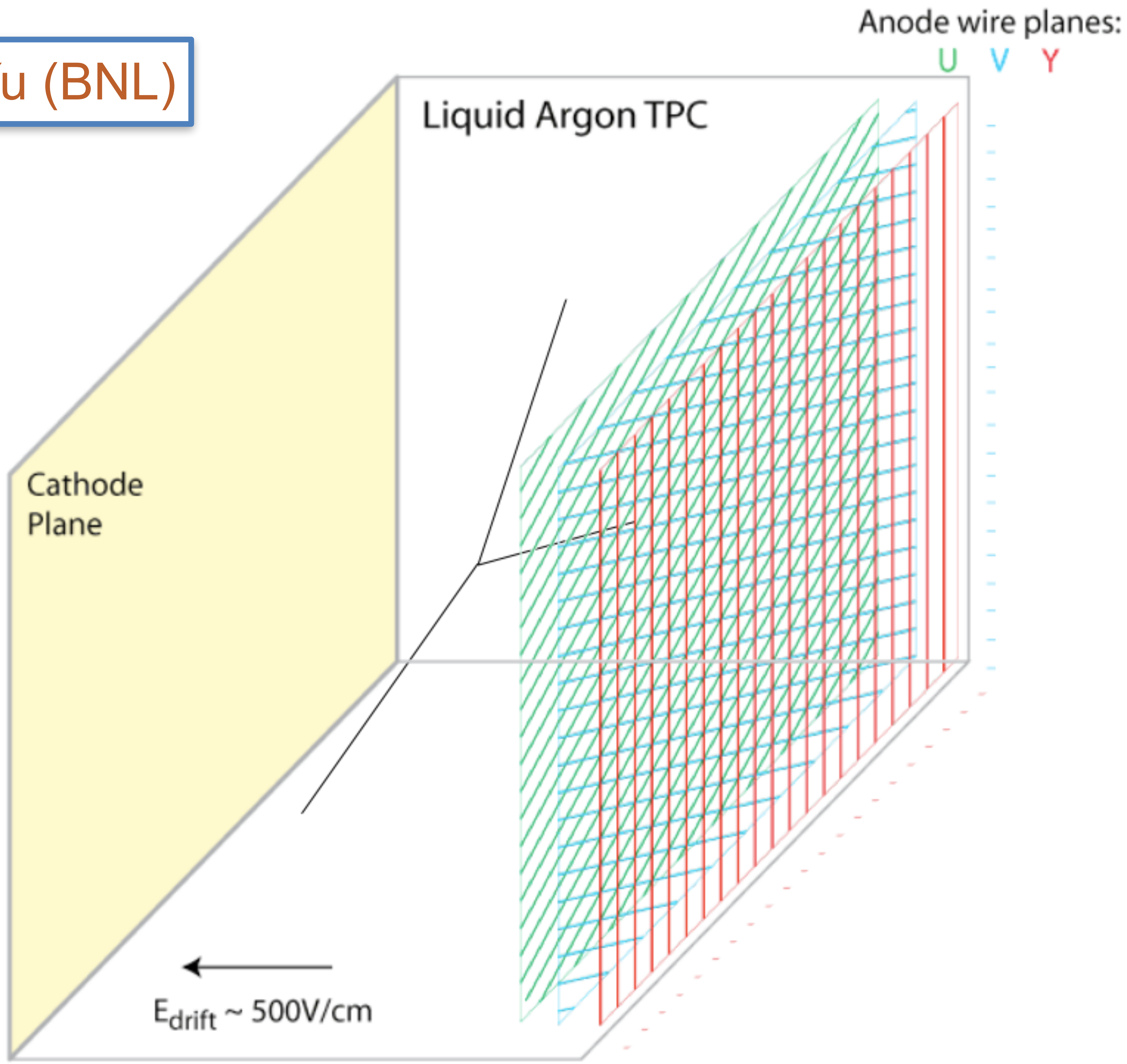

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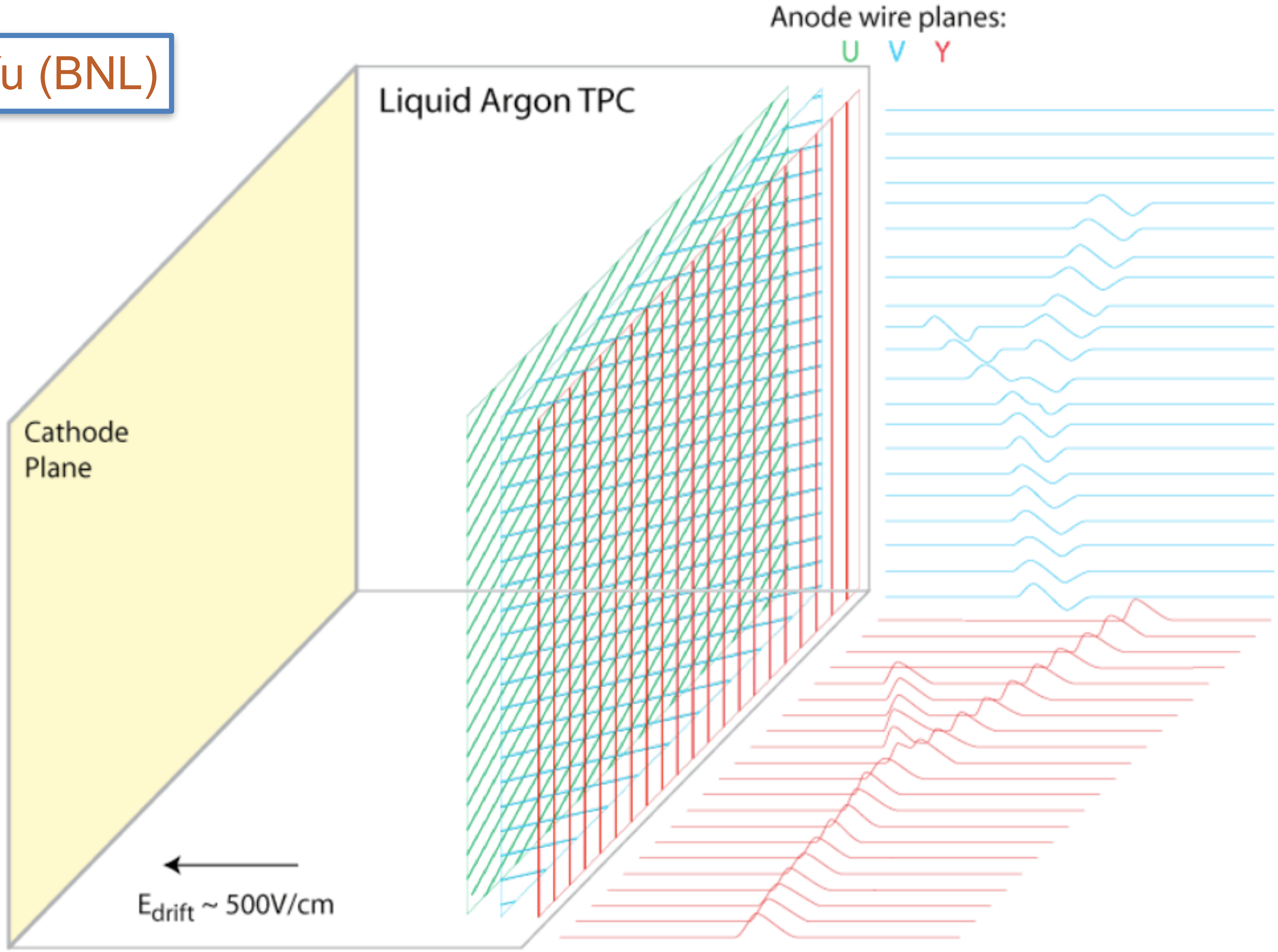

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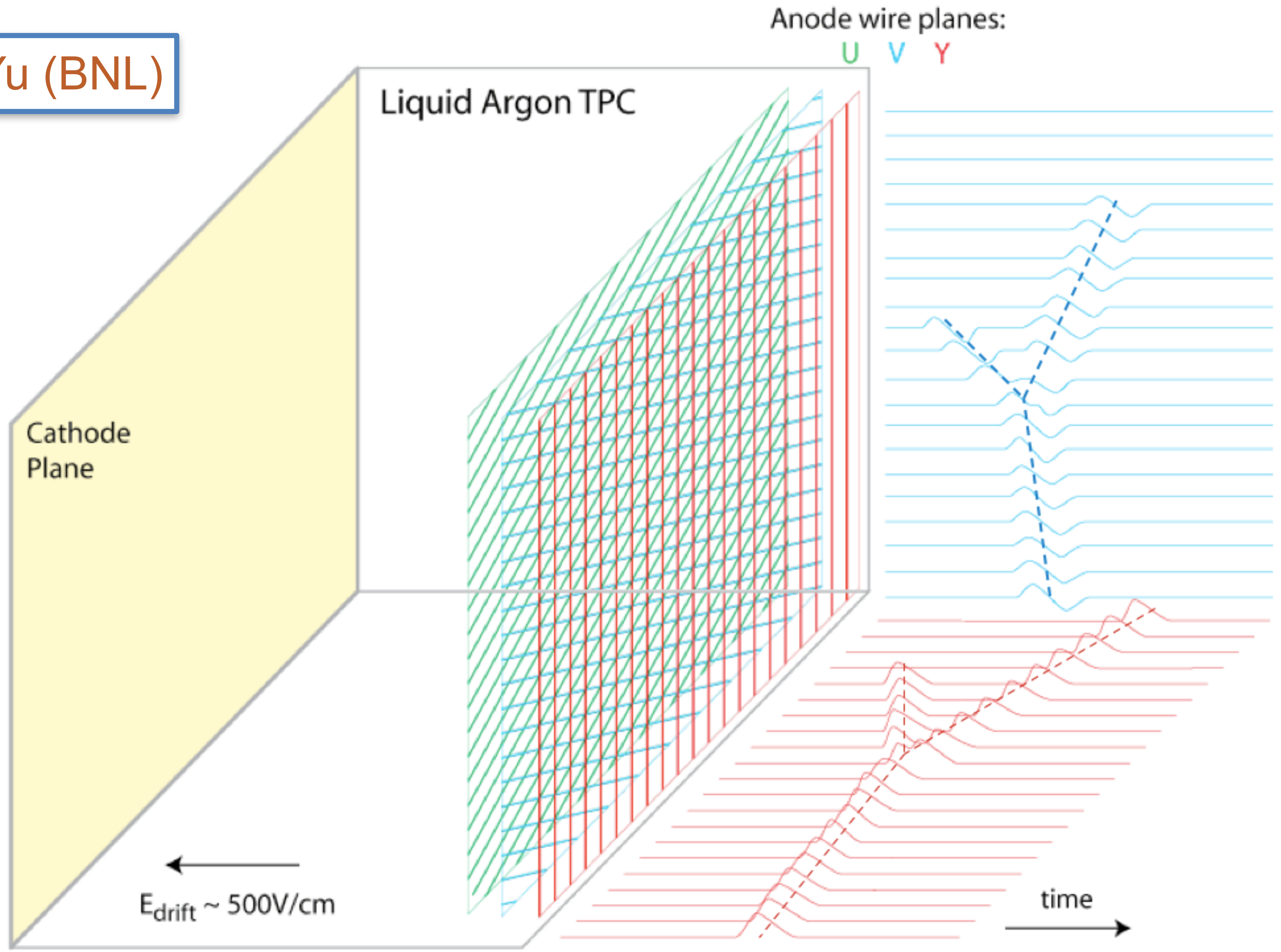
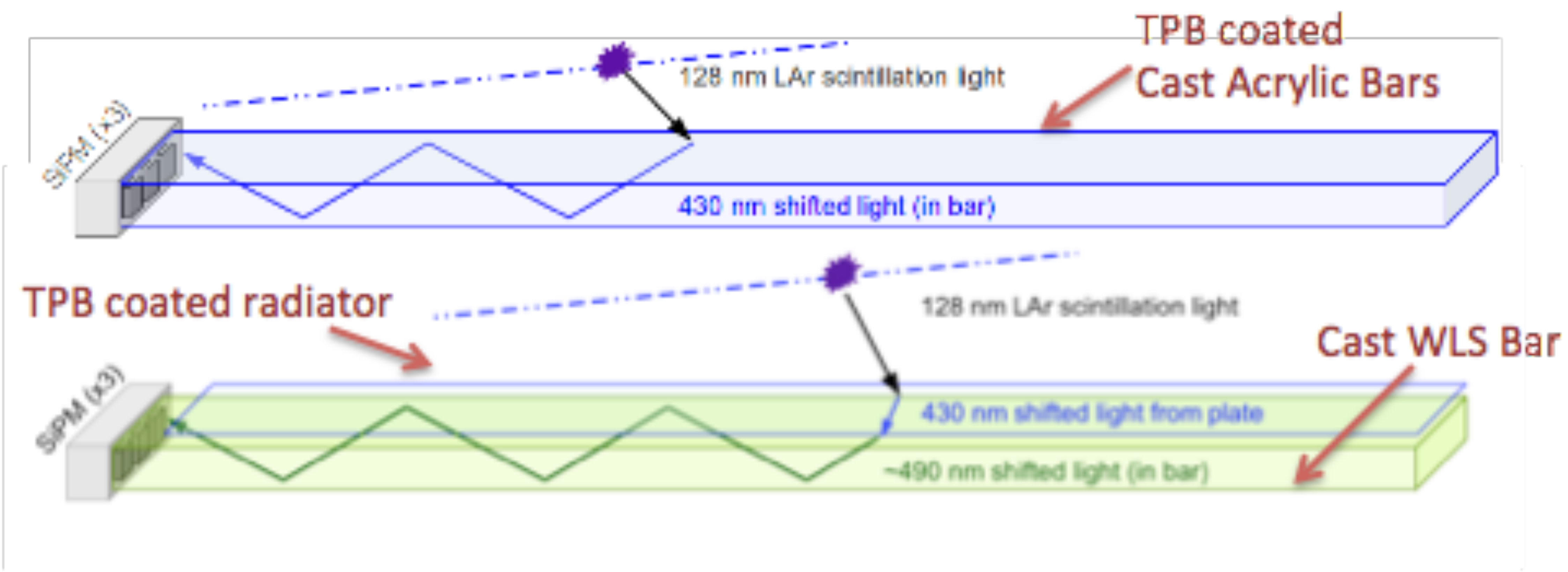


DUNE Single-Phase Photon Detection

- Scintillation light is detected instantaneously on the timescale of the TPC information
  - Sets an absolute time, and hence position, of an event.
- LAr is an excellent scintillator (24,000 ɣ/MeV) but the light is at 128 nm.
  - Wavelength shifting lightguides with SiPM readout will be embedded in APAs.
  - Multiple designs being considered.



Prototyping the DUNE SP Detector

- Mitigation of risks associated with benchmark design;
- Establishment of construction facilities required for full-scale production of detector components;
- Early detection of potential issues with construction and detector performance;
- Provide calibration of detector response to particle interactions;
- Develop and test fully automated reconstruction techniques required for final detector.

2016: 35-ton run

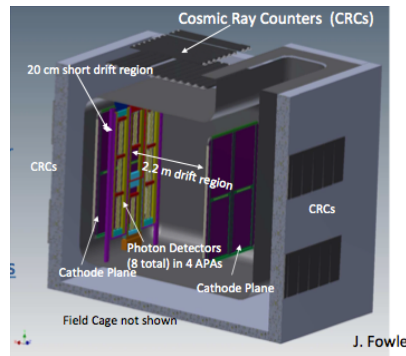
2017: Far detector construction begins

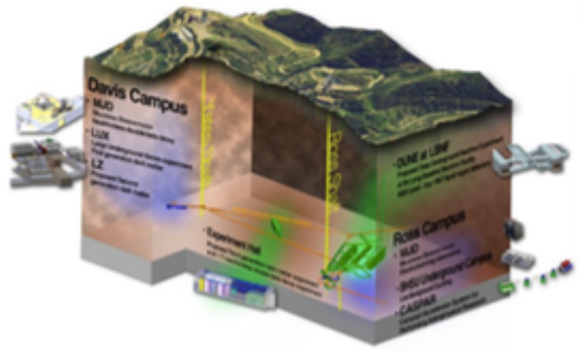
2018: ProtoDUNEs at CERN

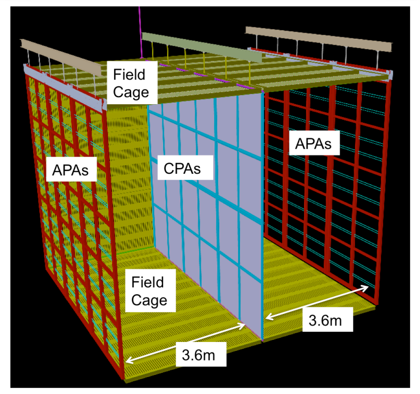
2021: Far detector installation begins

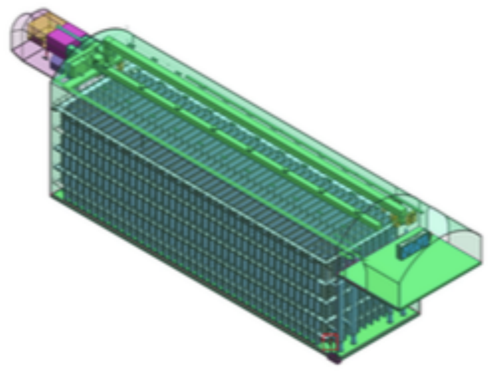
2024: Physics data begins

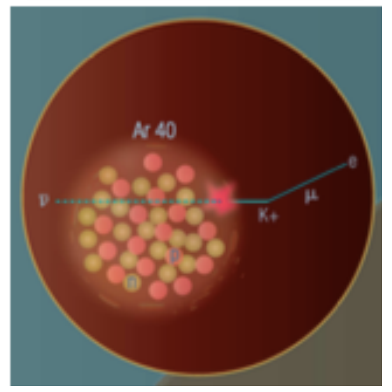
2026: Neutrino data taking

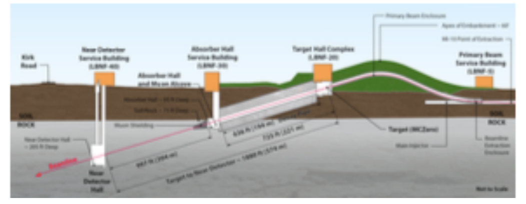








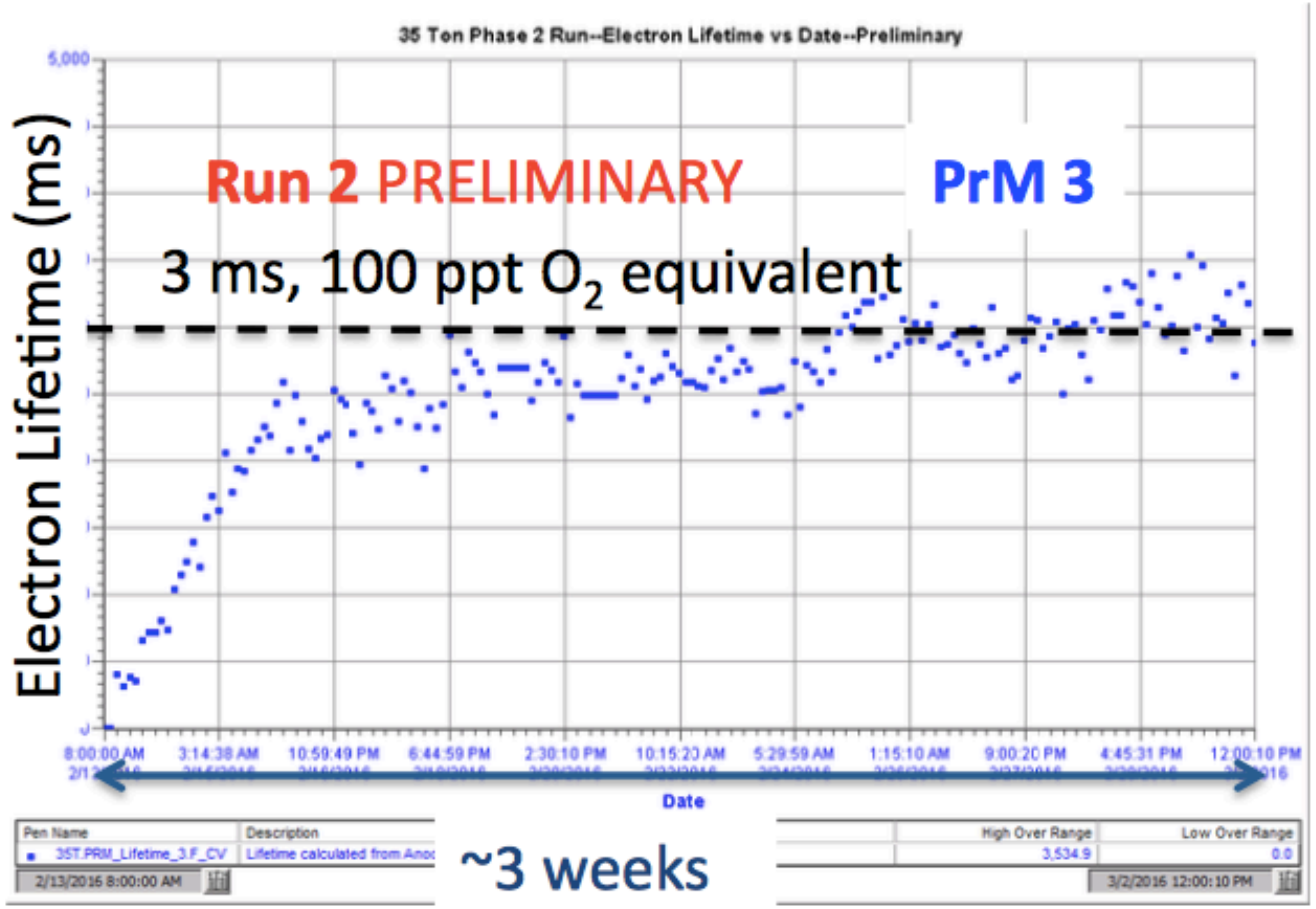




35-ton HV

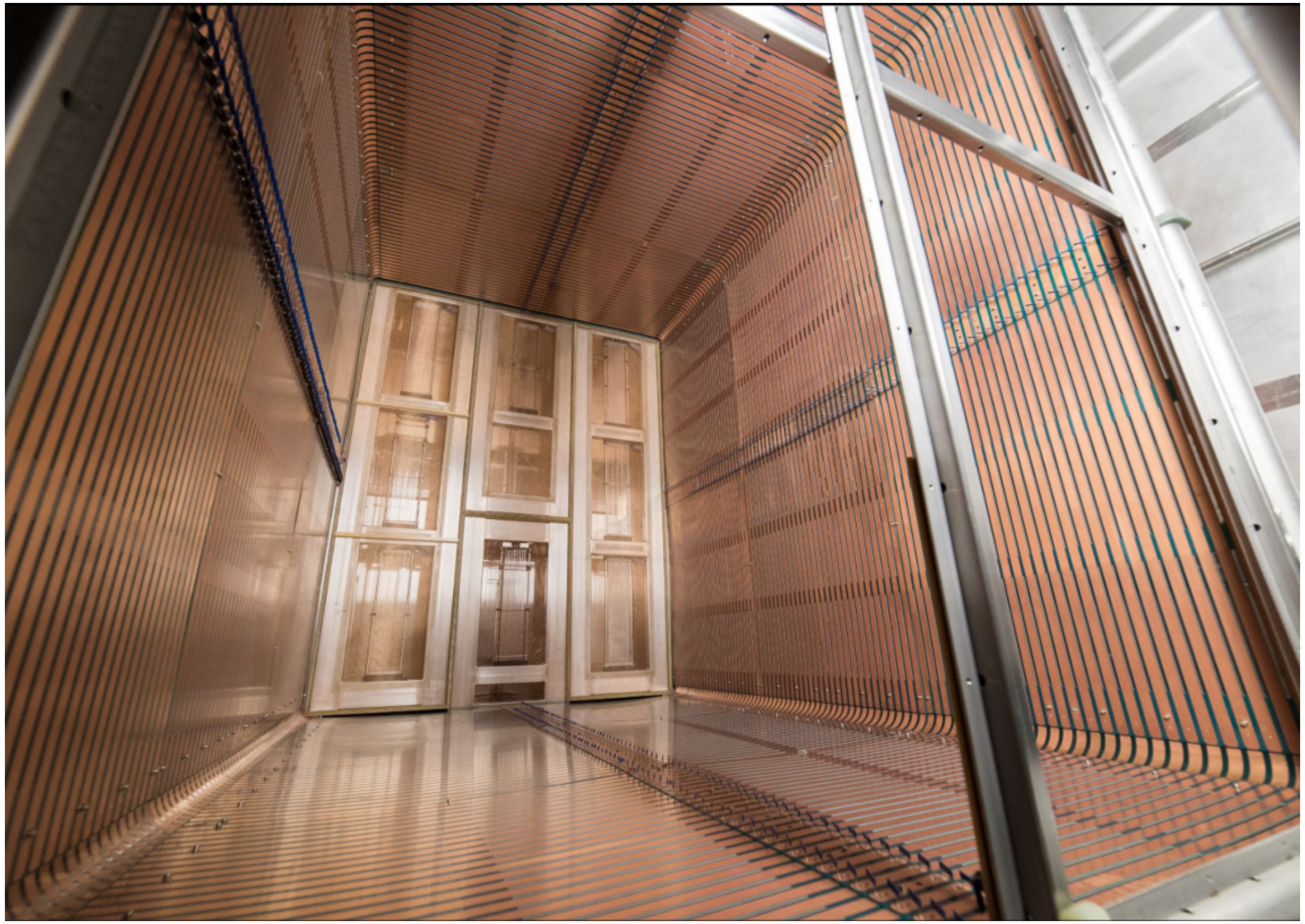
- HV distribution system (field cage, cathode, feedthrough) held 60 kV (half design stably over 6 weeks in pure liquid argon.
- No indications of field non-uniformities visible in TPC tracks.
- In contaminated argon, it was stable for several days at 90 kV and 120 kV (design).
  - Didn't get chance to raise the field before the argon contamination incident, 19th March 2016.

35-ton Purity/Lifetime



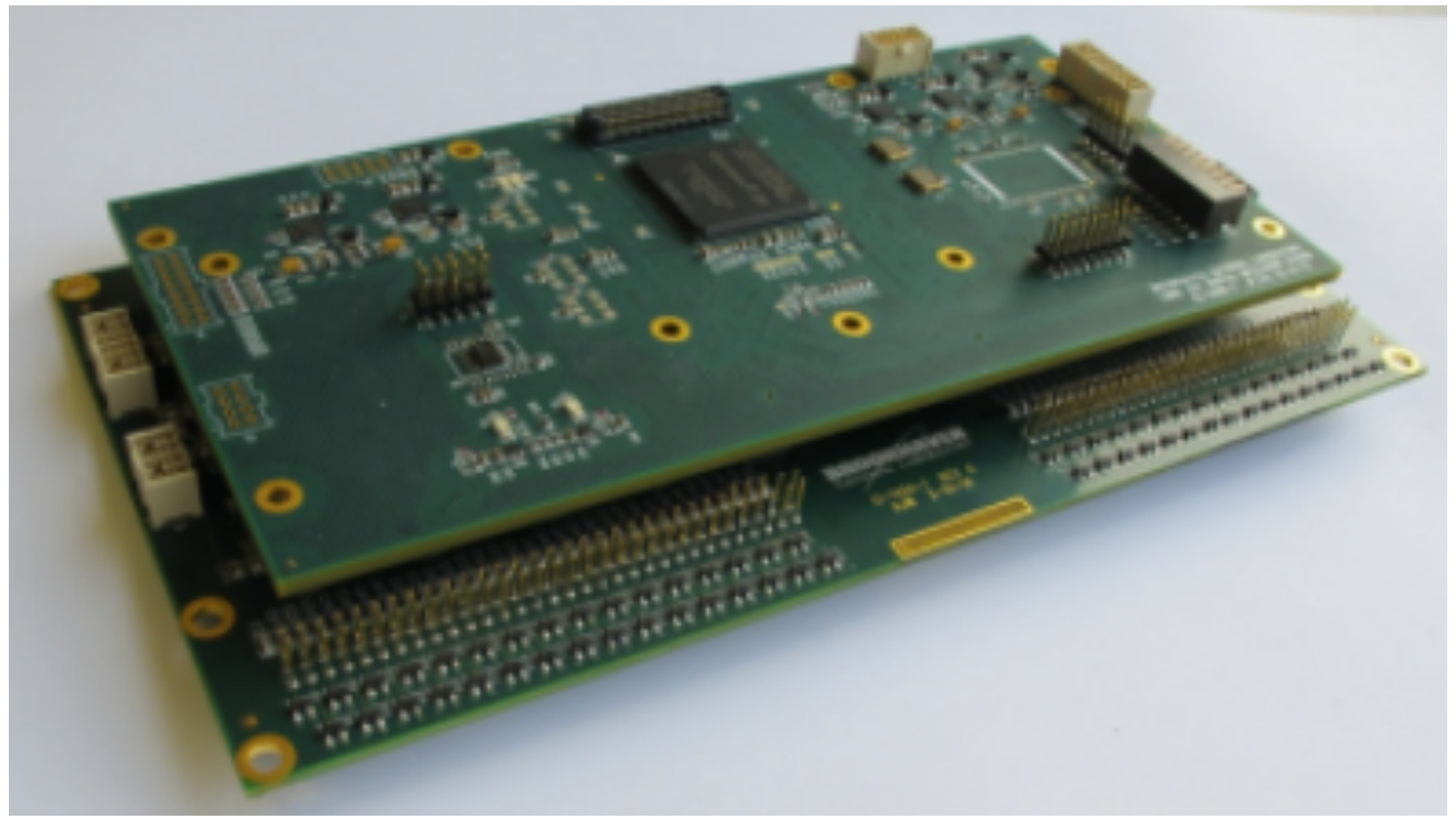
35-ton Field Cage

- Held 130 kV in contaminated argon



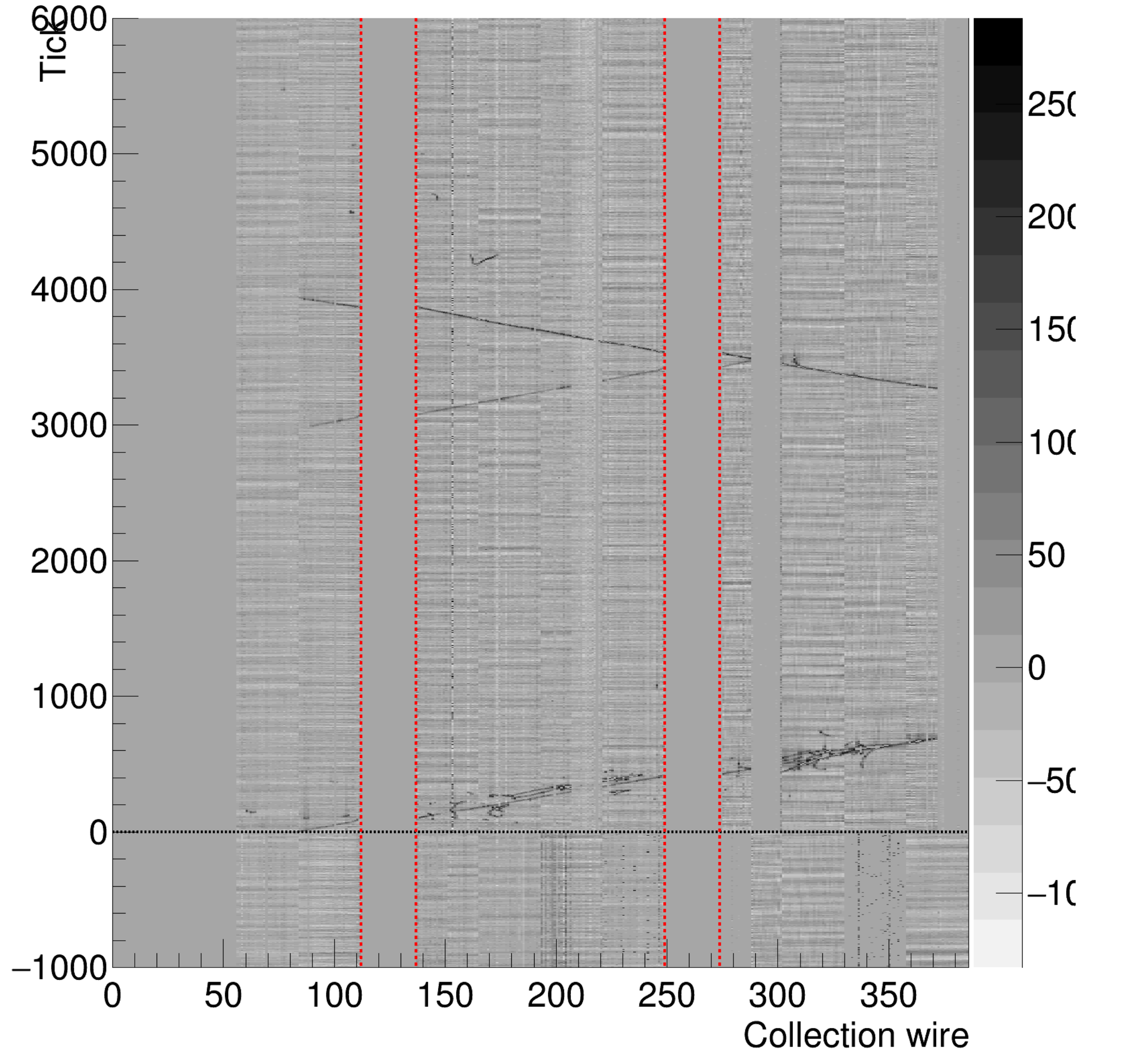
35-ton Cold Electronics

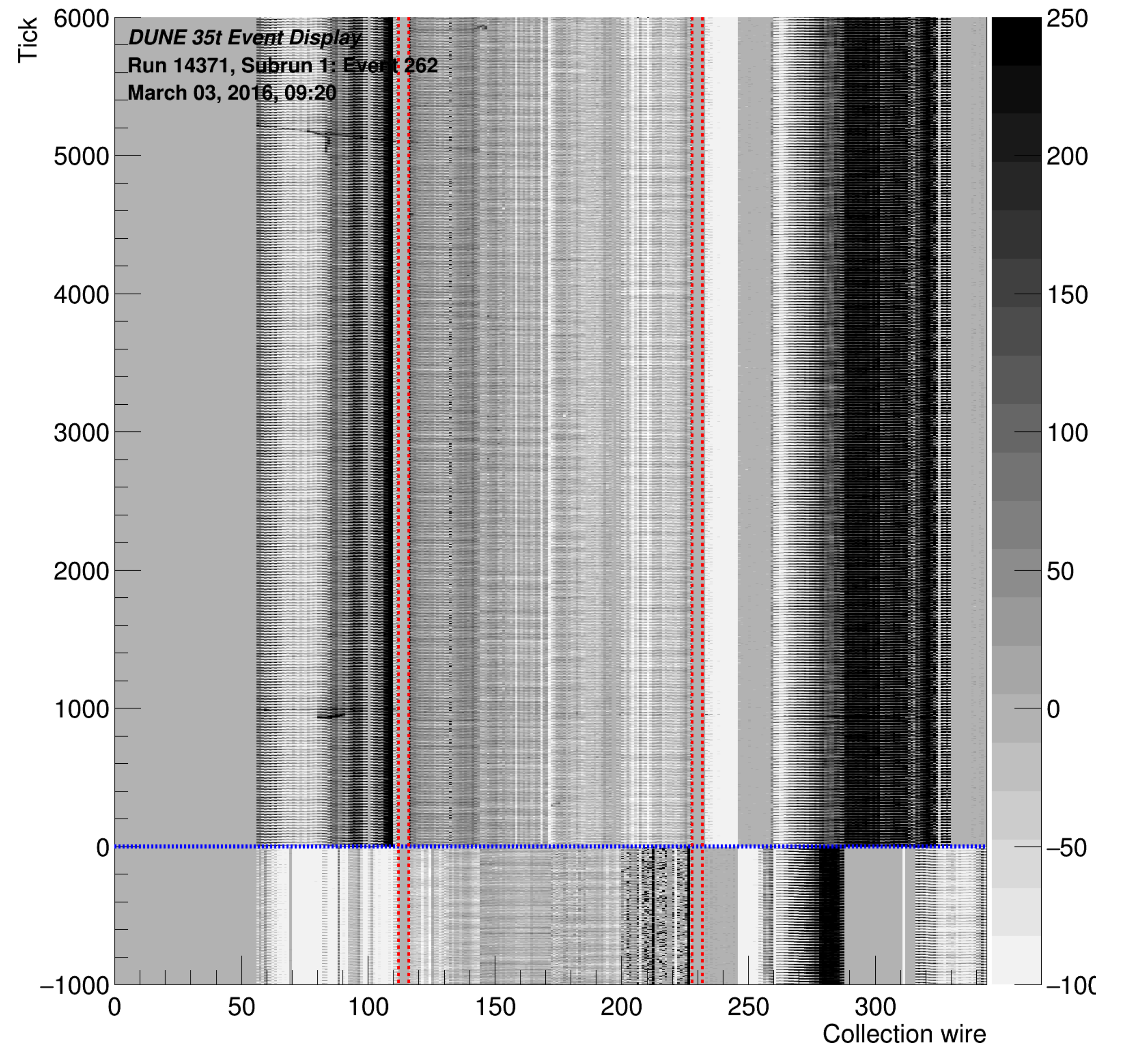
- First deployment of cold electronics (still under development).
- FE & ADC immersed in LAr.
- 128 channels per FEMB
  - High resonant noise, not all FEMB read out at same time.
- Noise tests have determined source of a lot of the noise (see next slide).
- Continuous testing during installation built into ProtoDUNE-SP installation process.



35-ton Noise Issues

- 11 kHz — appears to come form regulator chip (each regulate voltage on 4 FE ASIC chips (64 channels)). Resistor in series (low pass filter) removes this.
- 100 kHz — phase difference between each FEMB; each has its own low voltage supply. Short found on low voltage cabling between supply line for FE ASIC chips and chassis ground for supply.
- High noise state — origins unknown, only speculation (although well justified, not confirmed).
  - Likely problem: long cables carrying low voltage to the FEMBs may turn negative feedback in remote sense system into a positive feedback loop, causing circuit to search for correct voltage and oscillate.
  - Oscillating cable acts as resonator and couples to FE electronics of lower middle APA, then in turn to the grid plane, the cathode on the short drift side and then to all APAs.
  - Decreased capacitance of cable in air compared with LAr explains why this state could not be induced following the end of operations.

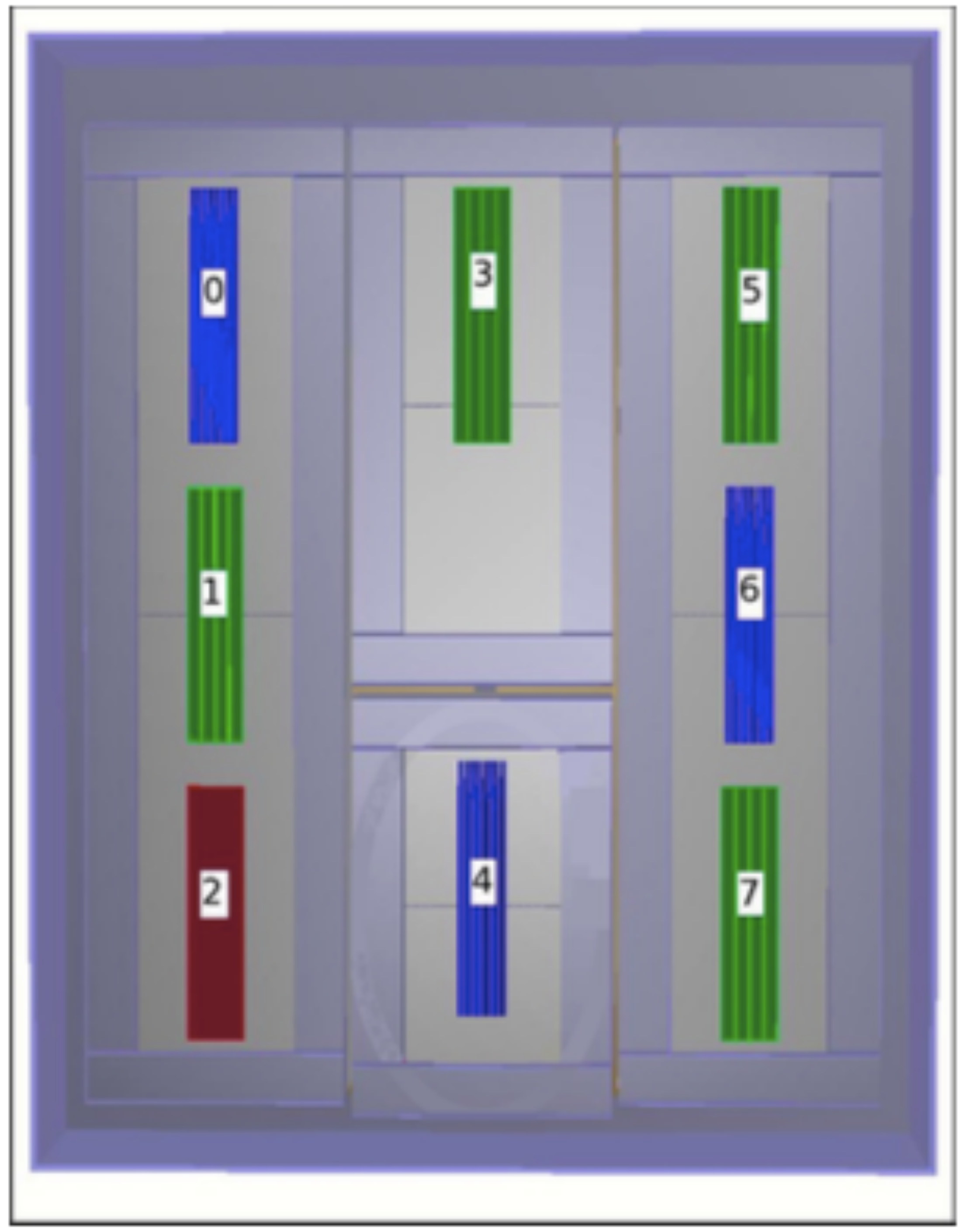


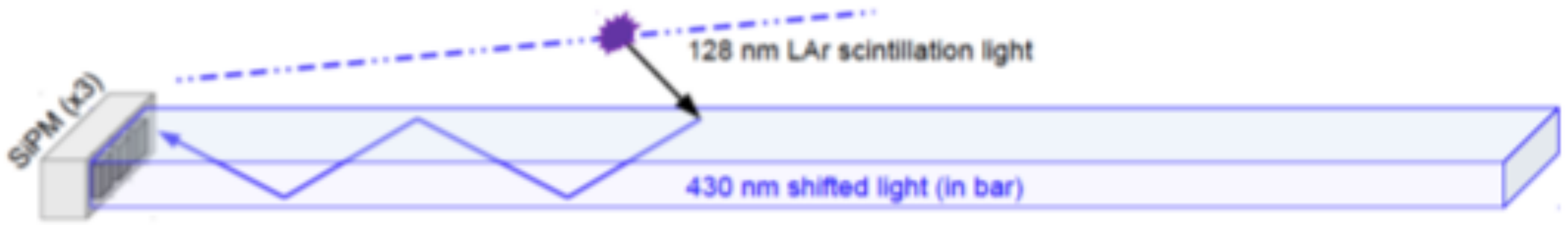


35-ton Photon Detection System

- Bars from IU and LBNL.
- Bundled fibres from CSU.
- Plate with an embedded WLS fibre from LSU.

- None currently being considered for the DUNE far detector.
  - Partly because of the assembly schedule for the 35-ton.
  - Lesson learnt: insert after wire wrapping!





IU or LBNL design

35-ton Camera System

N. McConkey, N. Spooner, M. Thiesse, M. Wallbank and T.K. Warburton, JINST **12**, P03014 (2017).

- 8 CMOS cameras designed to search for HV breakdowns in prone locations in the cryostat.
- Successfully operated in the cold for the entirety of the run and provided highly useful video of the inside of the cryostat upon sealing.

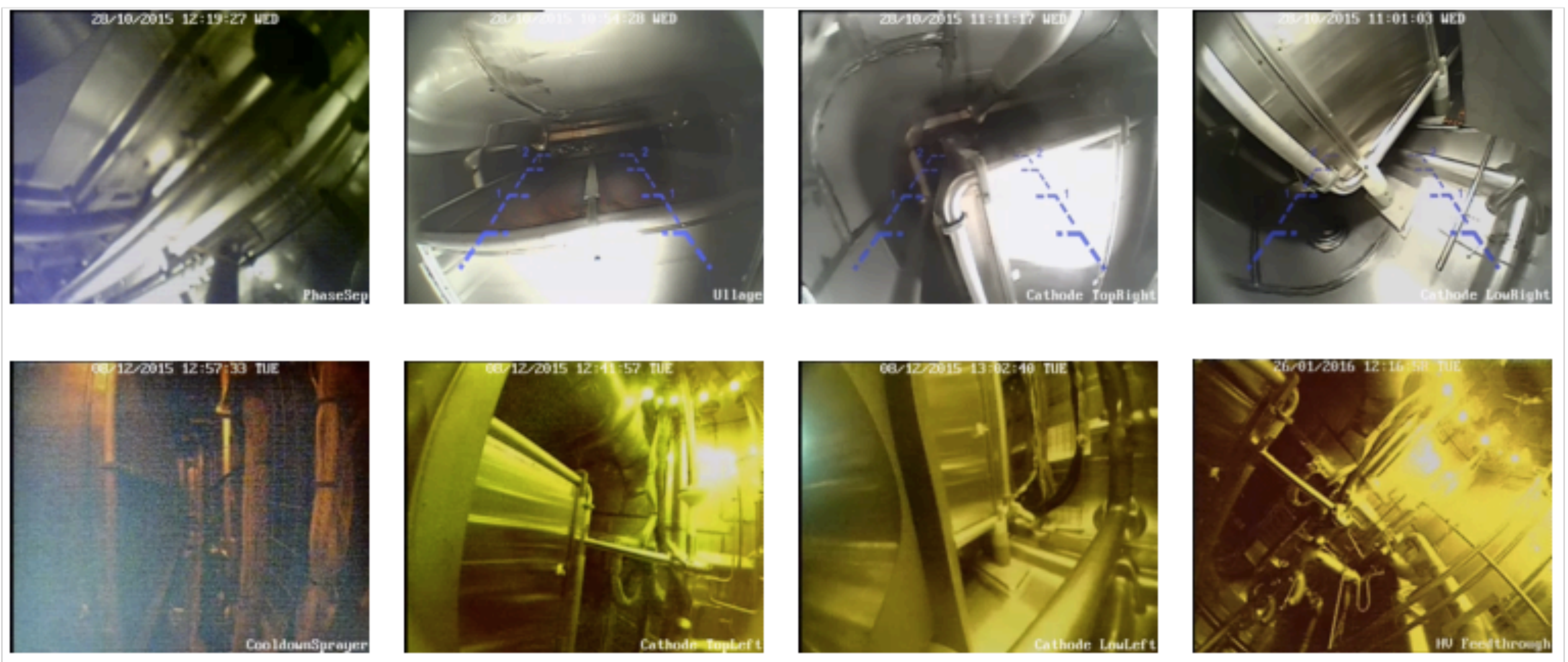
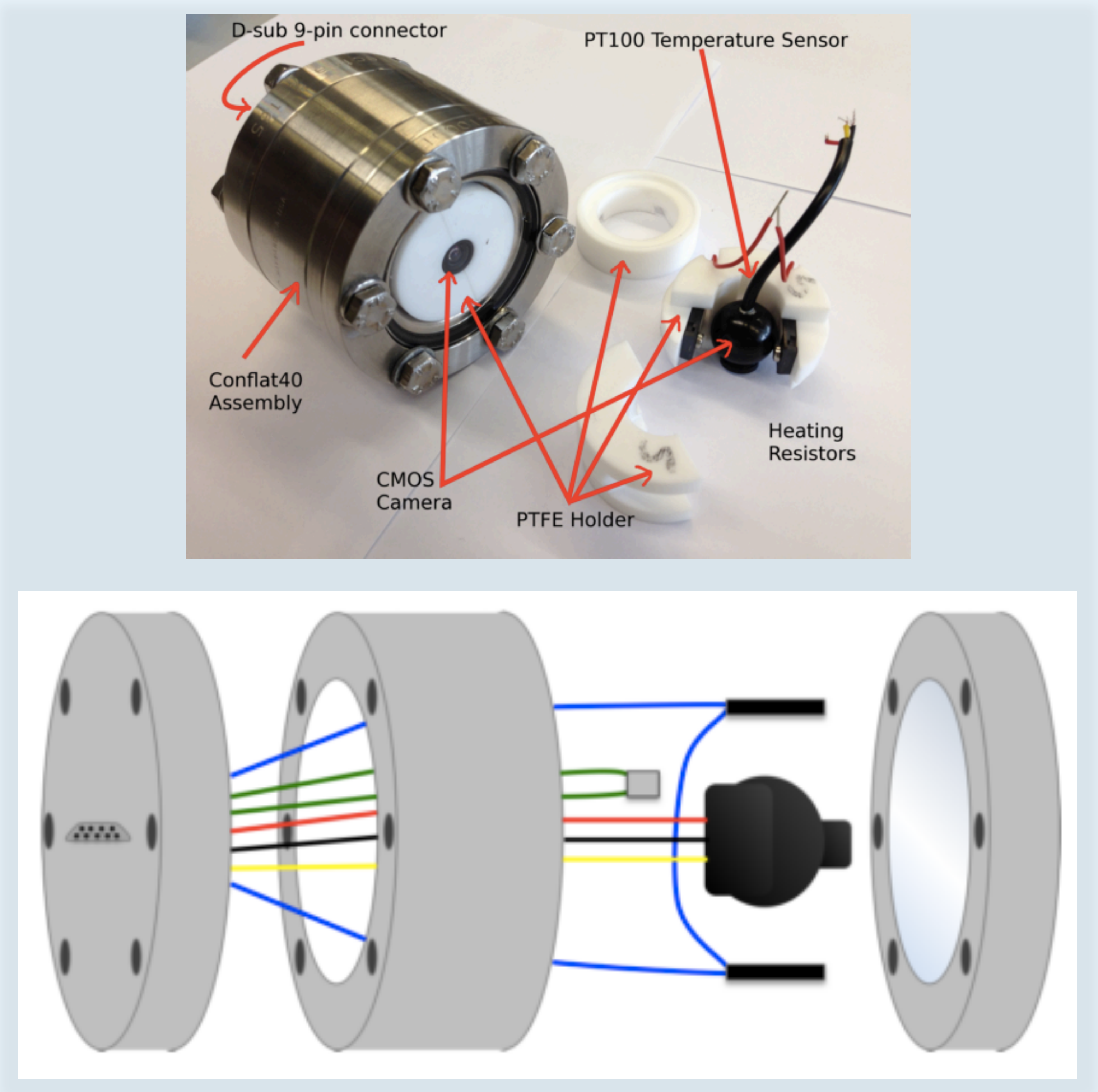
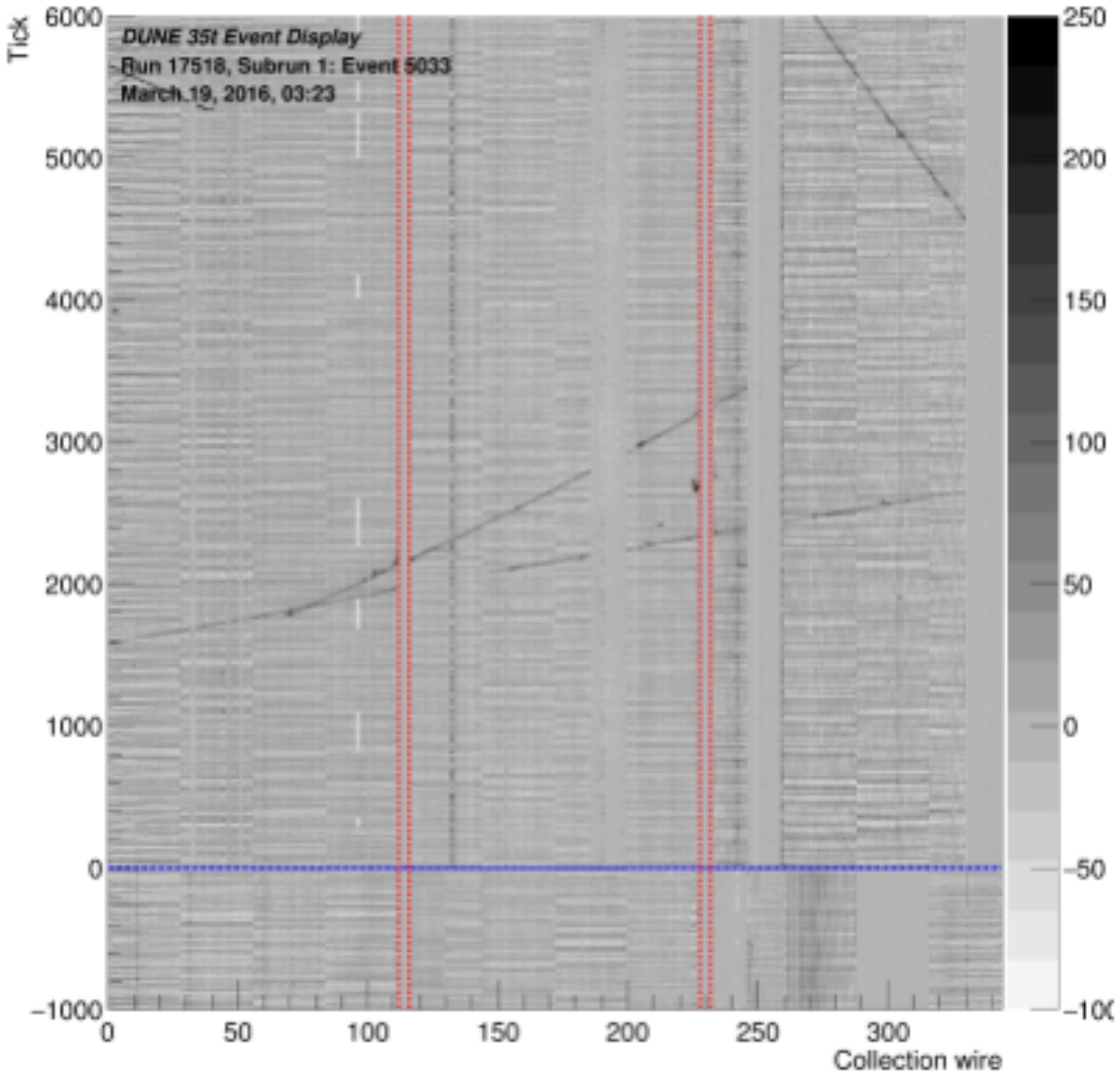


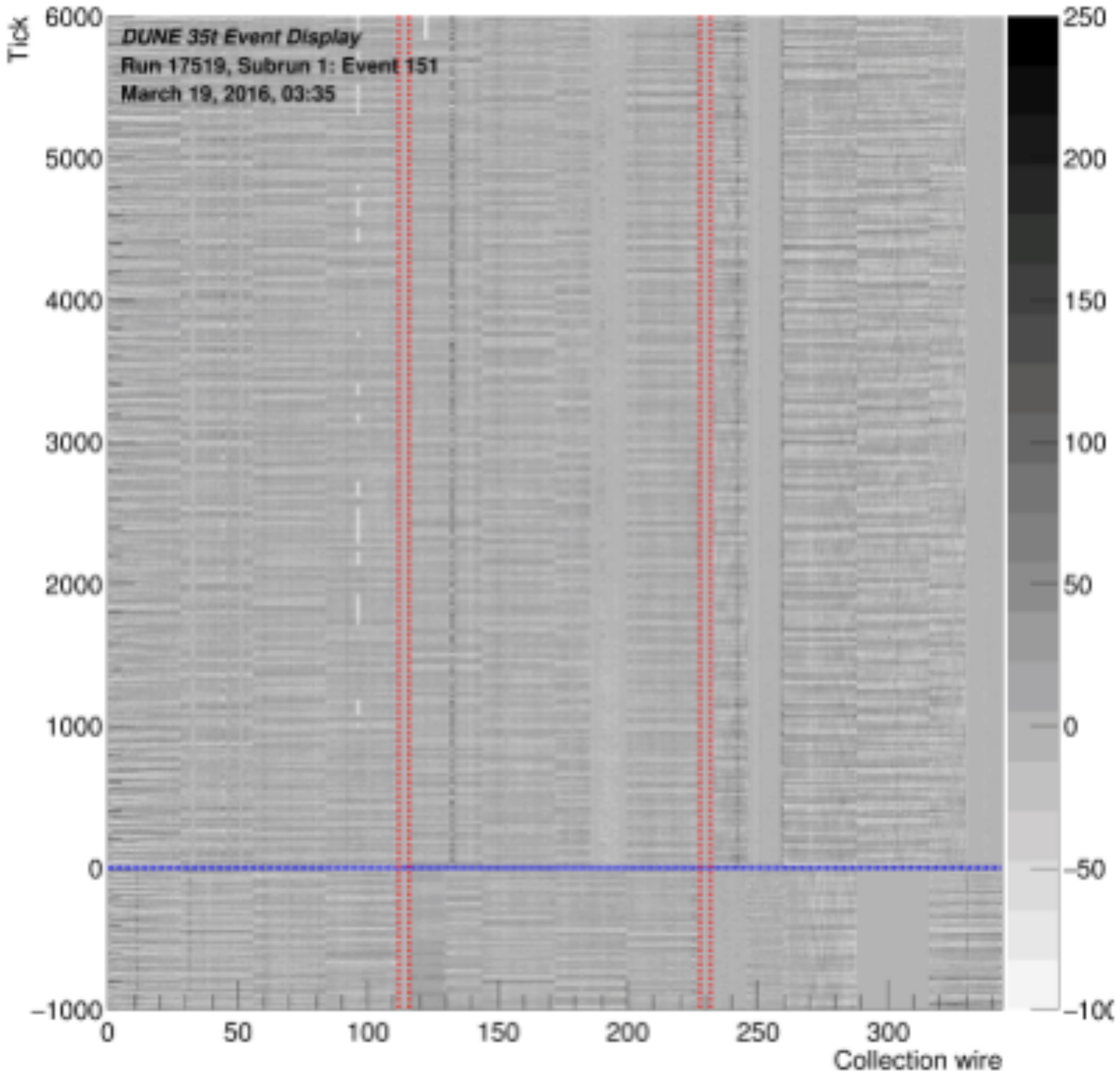
Figure 8. The calibration images for the 8 cameras in the system. Upper (left to right): phase separator, ullage, cathode top right, bottom right. Lower (left to right) cooldown sprayers, cathode top left, bottom left, and high voltage feedthrough. The upper images were taken with a halogen light illuminating the cryostat, prior to it being sealed up. The lower images were taken with the LED ring light on, with the cryostat sealed up. All images are left-right inverted due to software.



Pipe Break

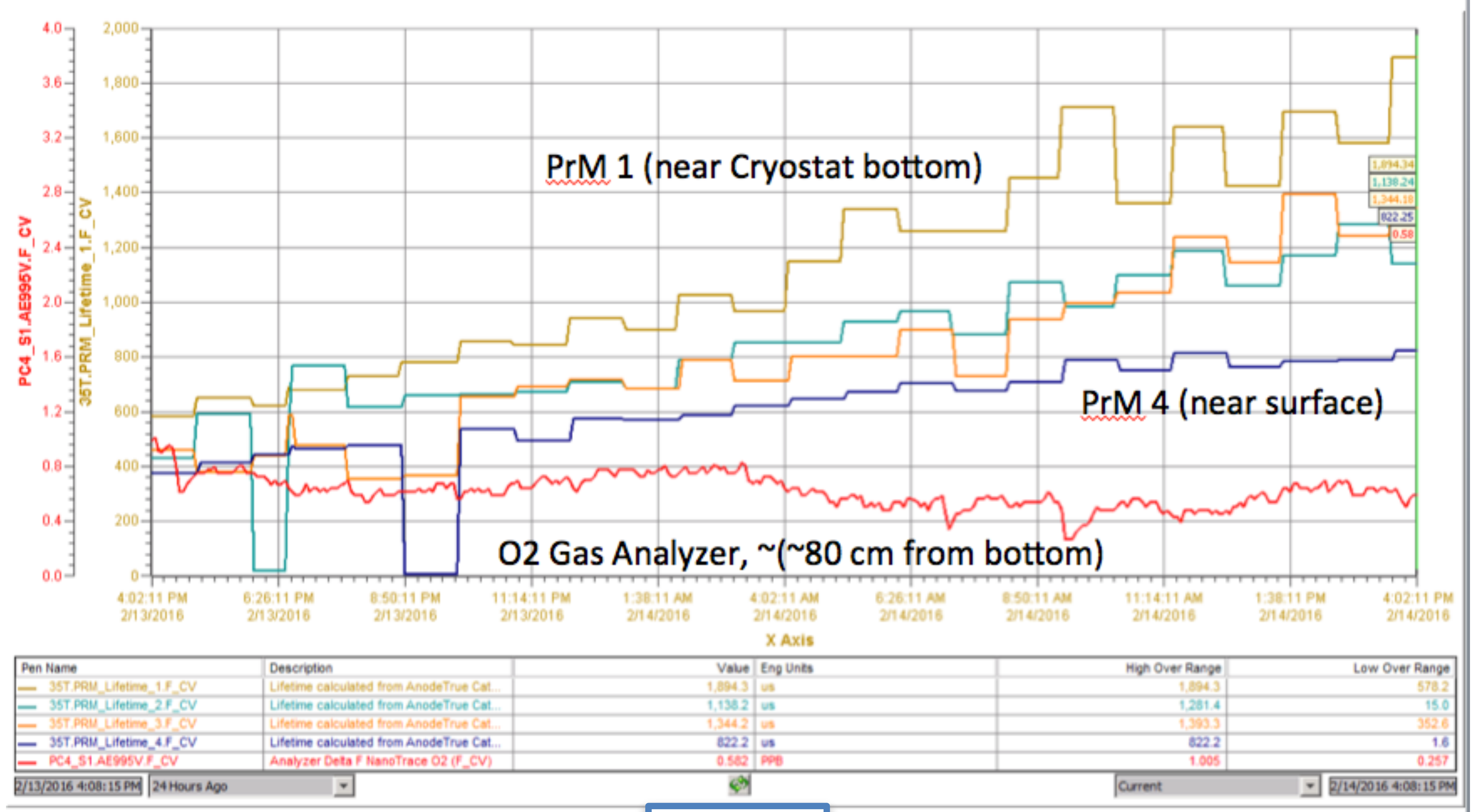


March 19, 3:23 AM

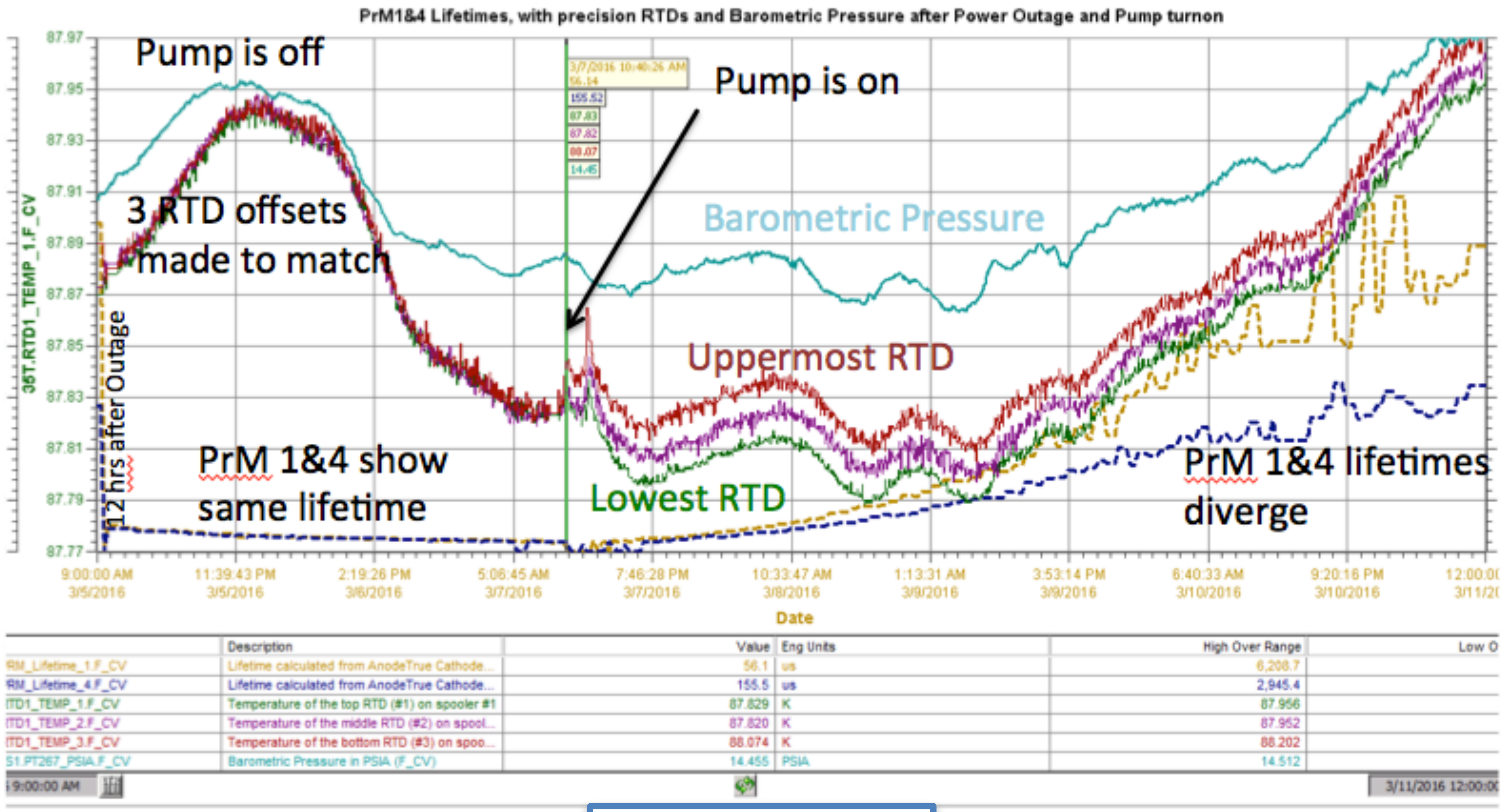


March 19, 3:35 AM

Temperature / Purity Stratification



Purity



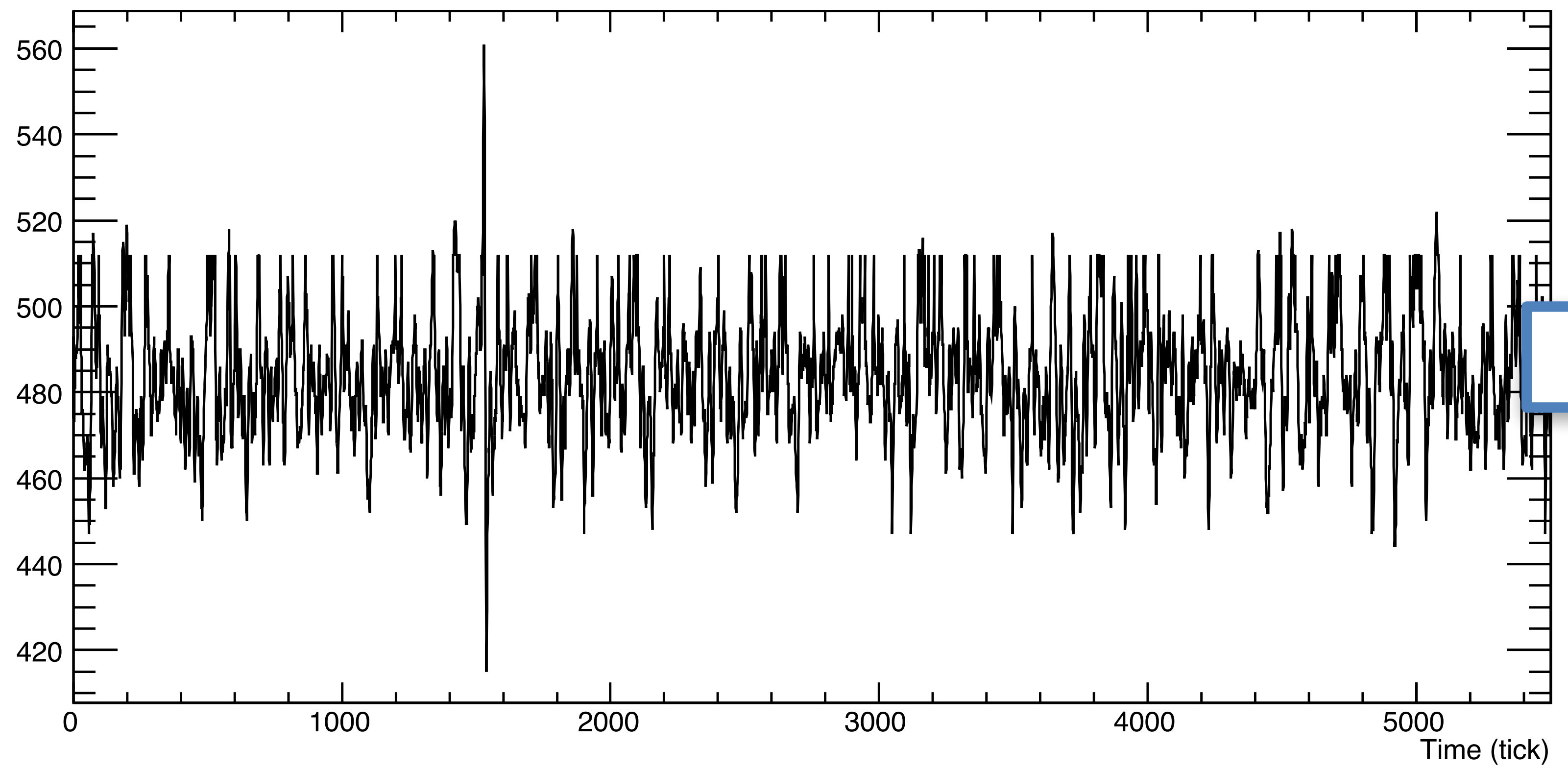
Temperature

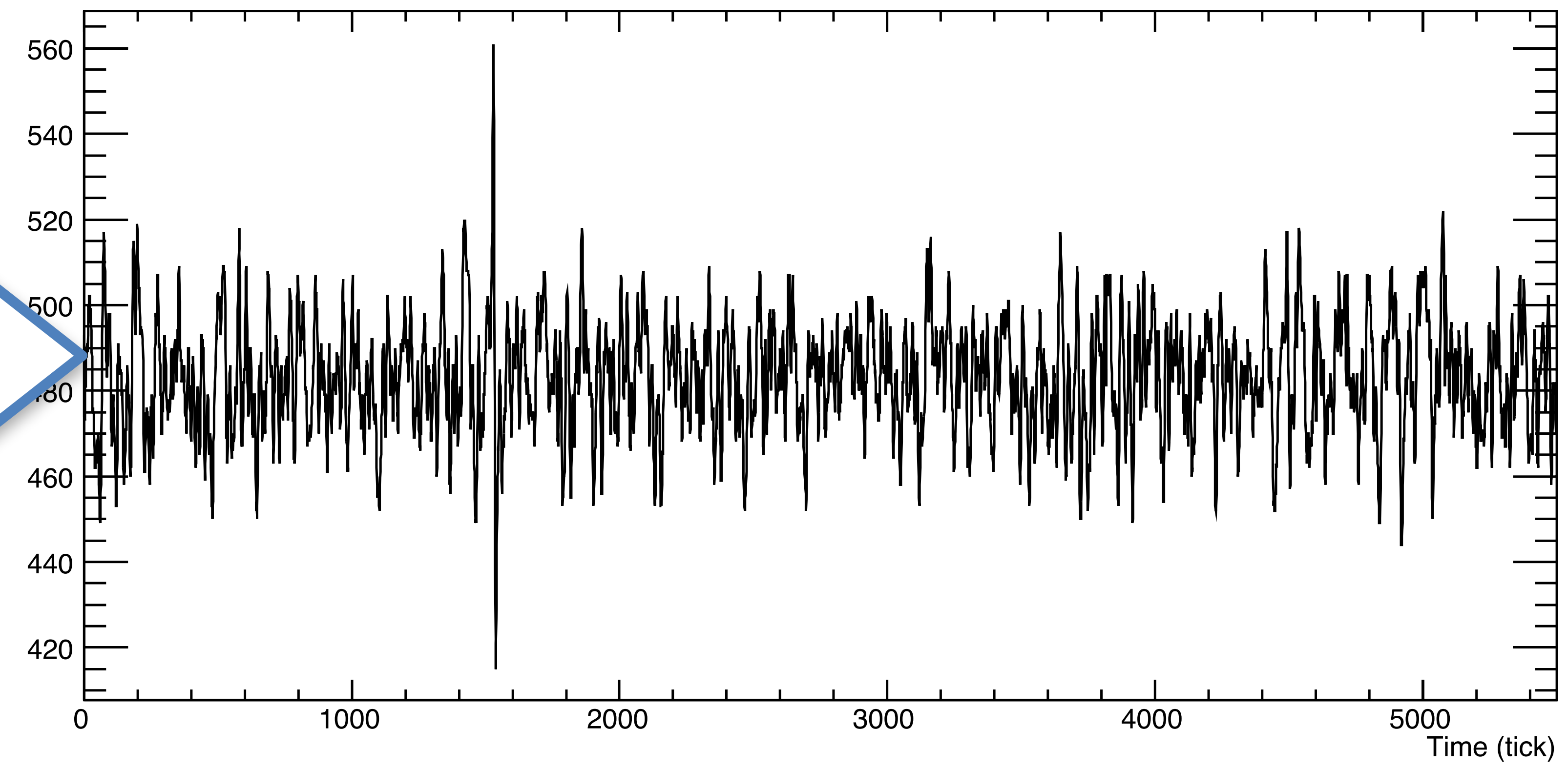
- The cause of this is likely due to returning LAr from the purification system being cooled below the 'bulk temperature' by the phase separator and reentering near the bottom of the cryostat, resulting in reduced convection and poor mixing.
- Resolutions, such as returning warmer LAr to the main volume, are being considered for future LArTPCs in an attempt to mitigate these effects and ensure a good, isotropic purity.

Preparing 35-ton Data

- Stuck code mitigation:

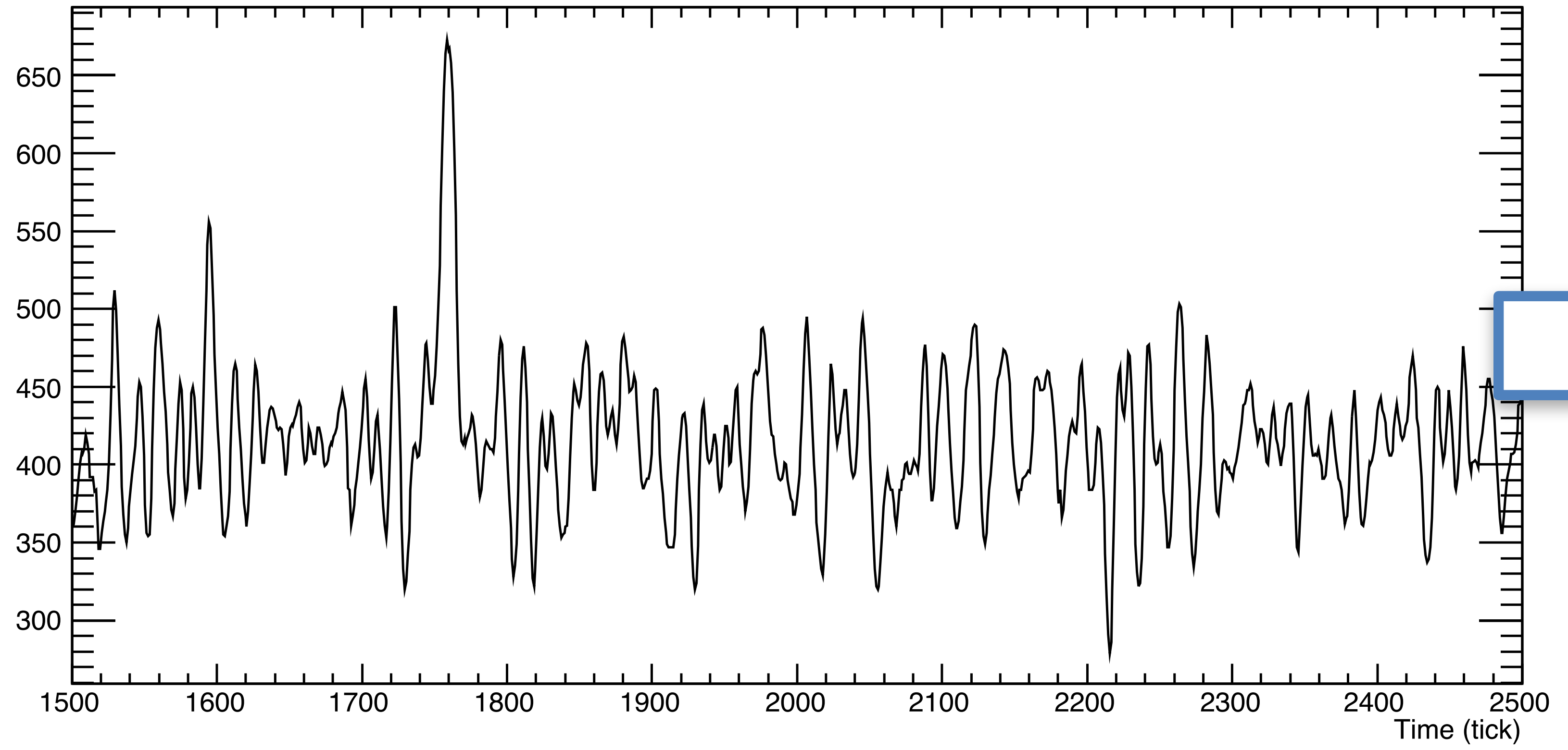
ADC would randomly ‘stick’ at nearest multiple of 64

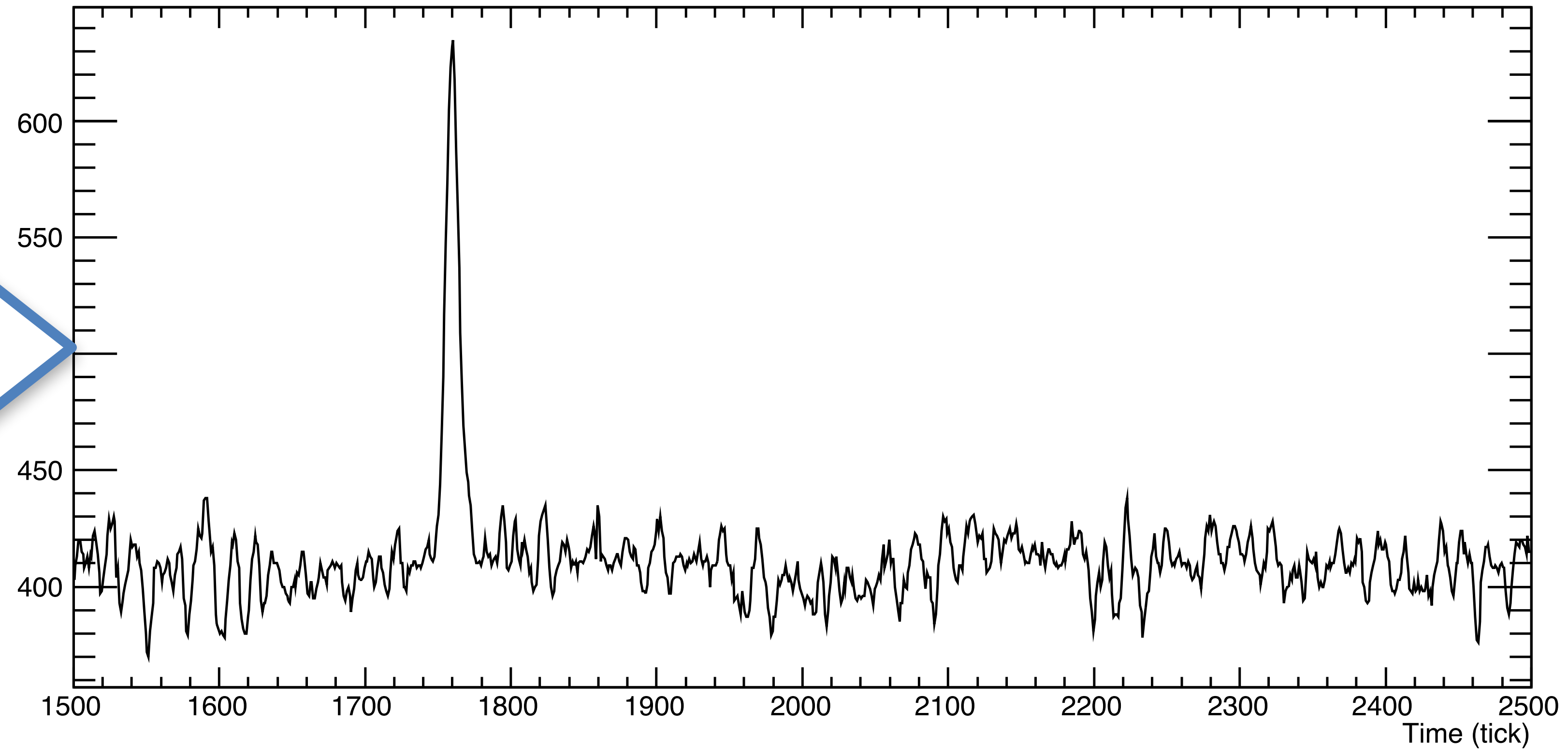




- Coherent noise removal:

Applied across channels sharing FE voltage regulator





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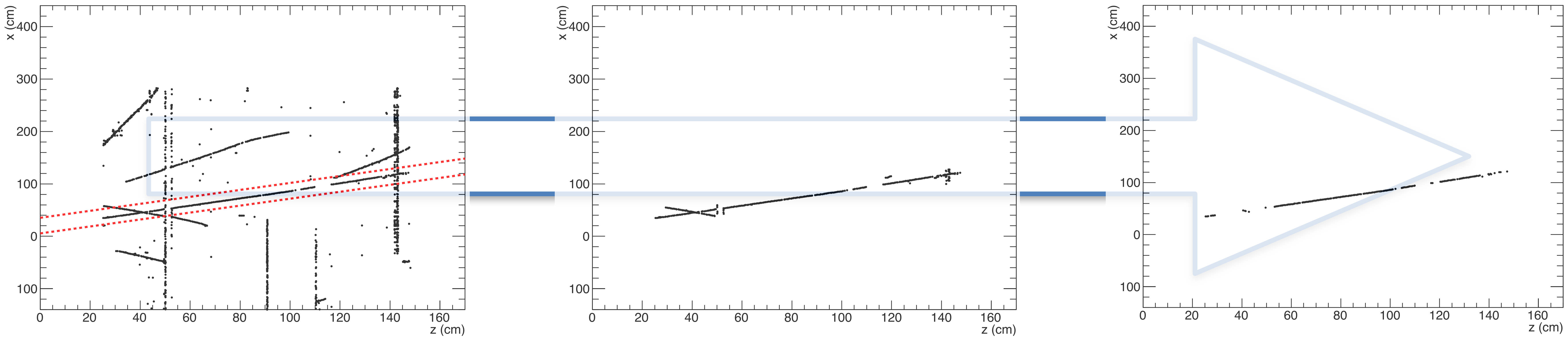
Reconstruction

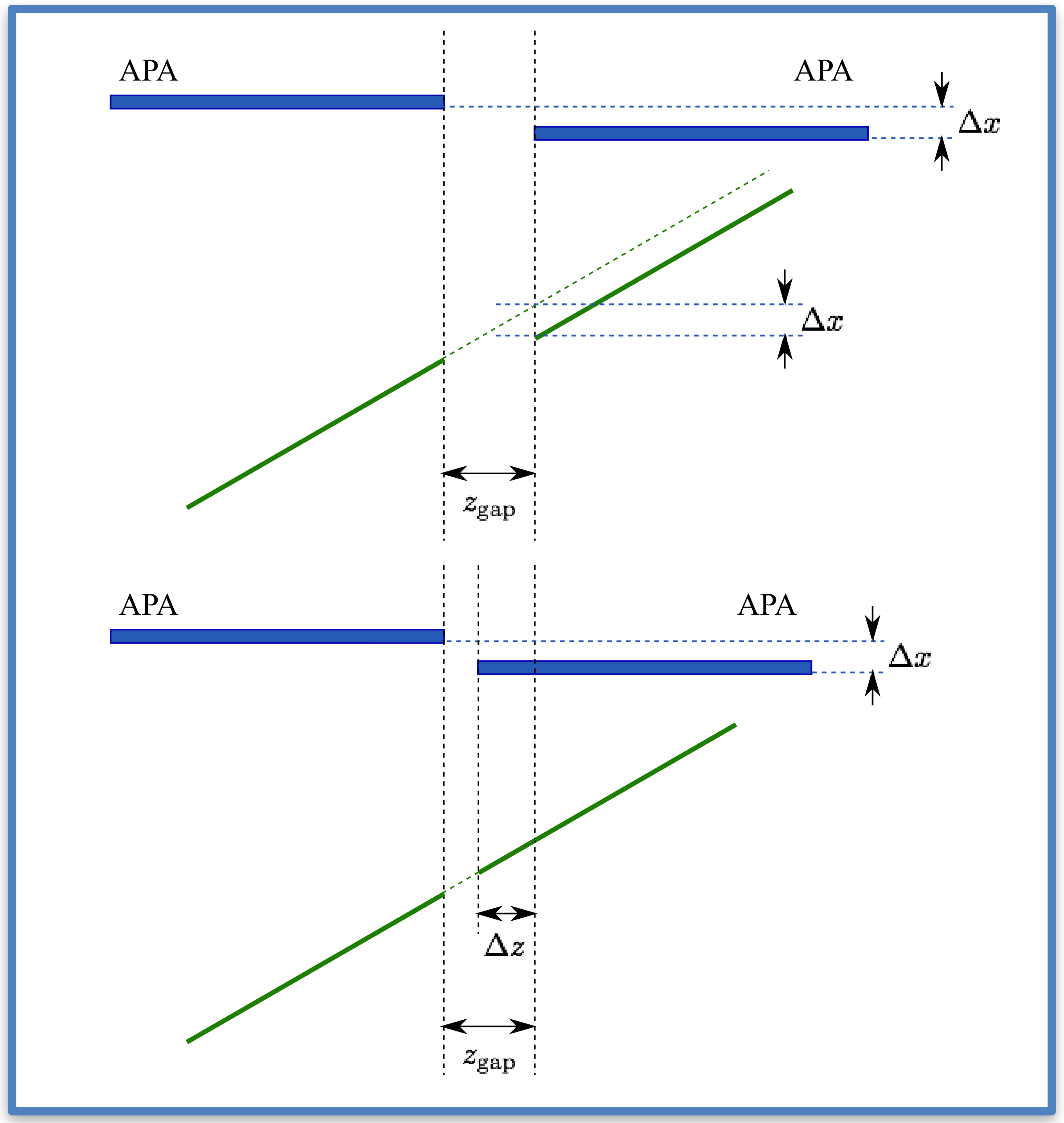
- Induction plane noise much larger than collection (longer wires —> larger capacitance).
- Most analyses use just collection hits — 2D reconstruction only.
  - Can get ‘quasi-3D’ reconstruction using the counter information from the triggering particle.

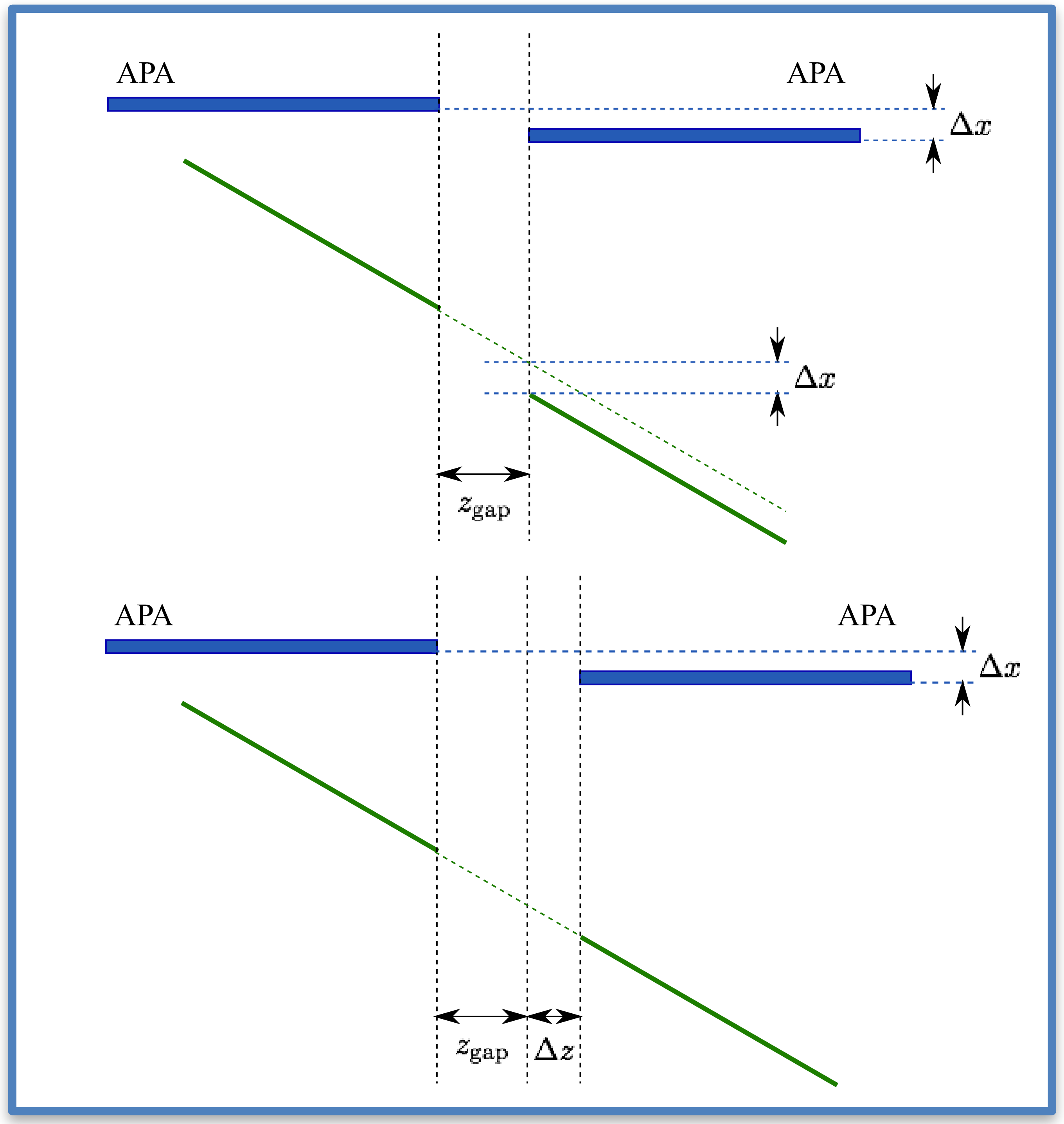


- Diffusion analysis uses track reconstruction.
- Purity analysis uses specially developed ‘robust hit finder’, designed to find hits efficiently given the noise issues. Thresholds for standard hit finding lead to hits being missed, or noise found, given the huge variations in noise across channels and between runs — uses variable thresholds based on event wire noise RMS.

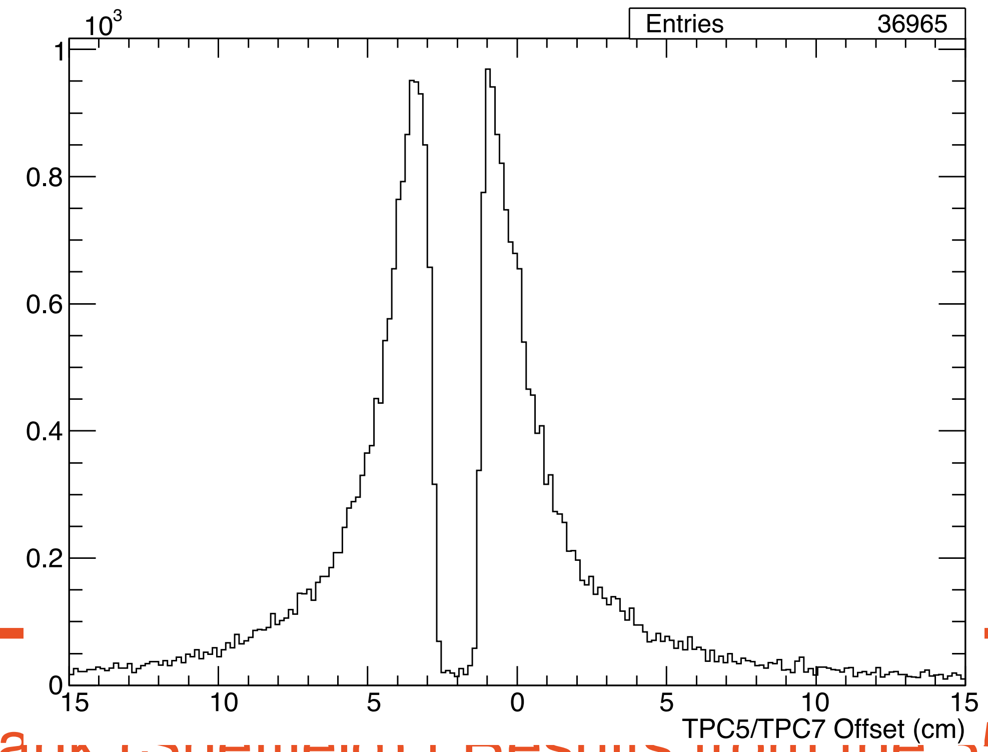
APA Gap Crossing Offsets

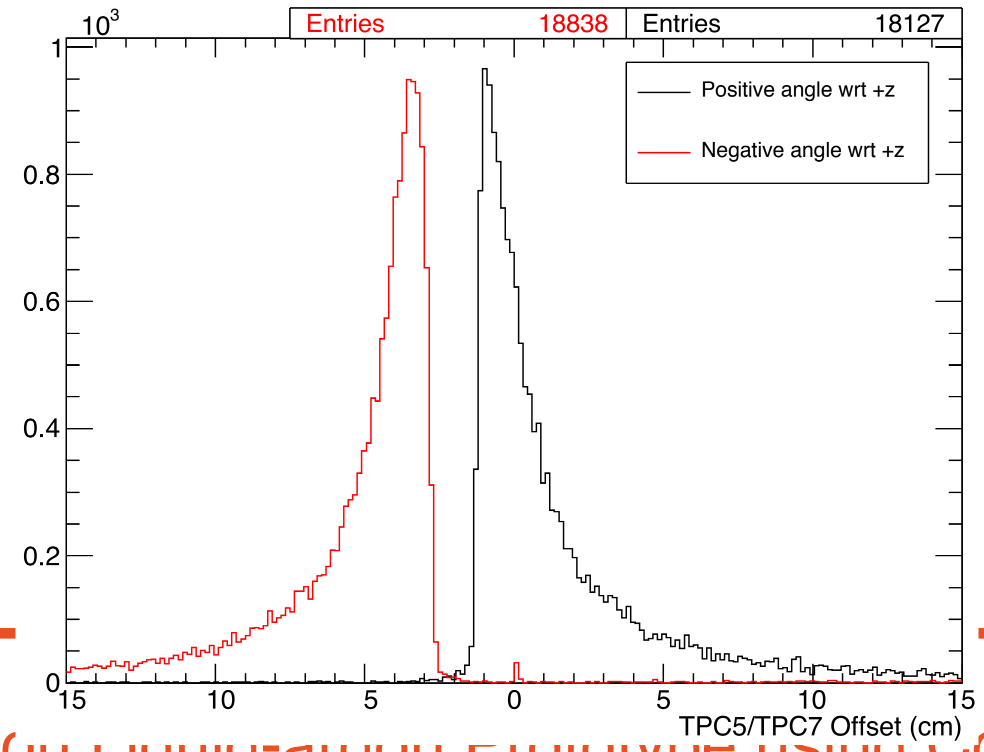
Positive track angle: measure negative *z*-offset





Negative track angle: measure positive *z*-offset

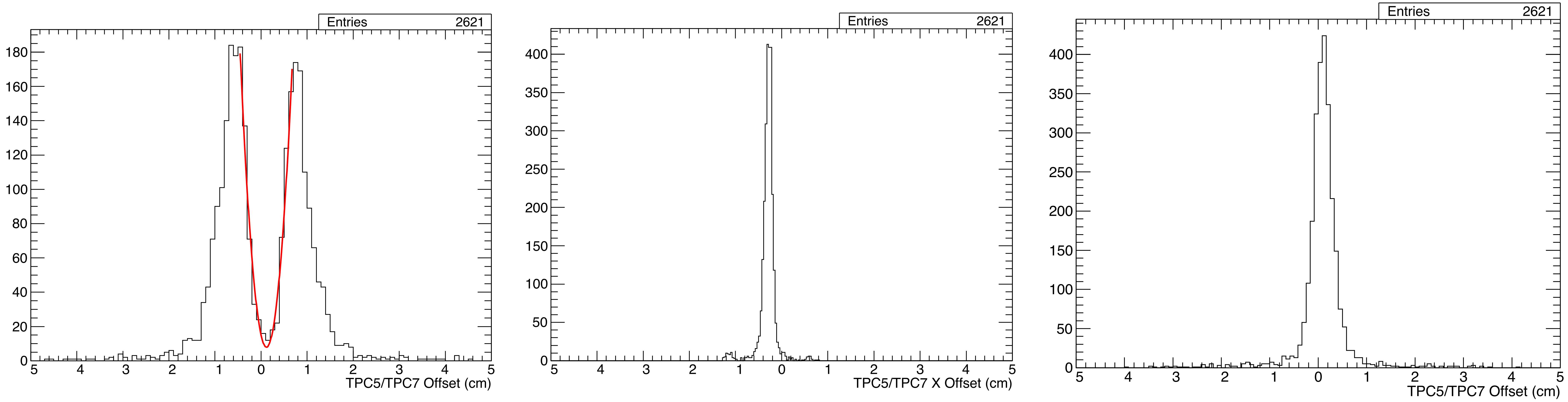




Tested in simulation — offsets of 2 cm in *z* and 0.5 cm in *x* artificially introduced. Same effect as seen in data!

APA Gap Crossing Muons

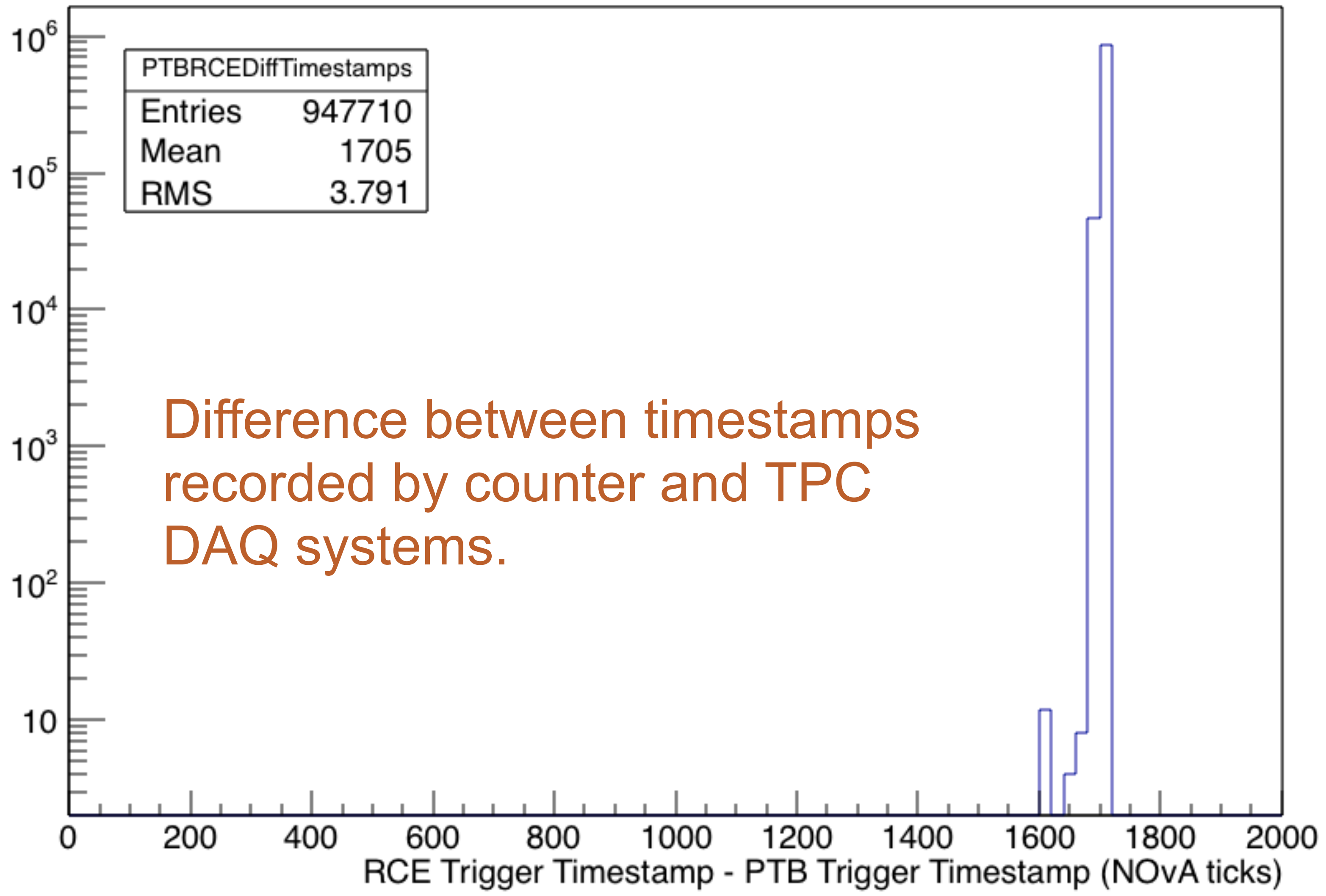
- Method to extract *x* and *z* offsets:

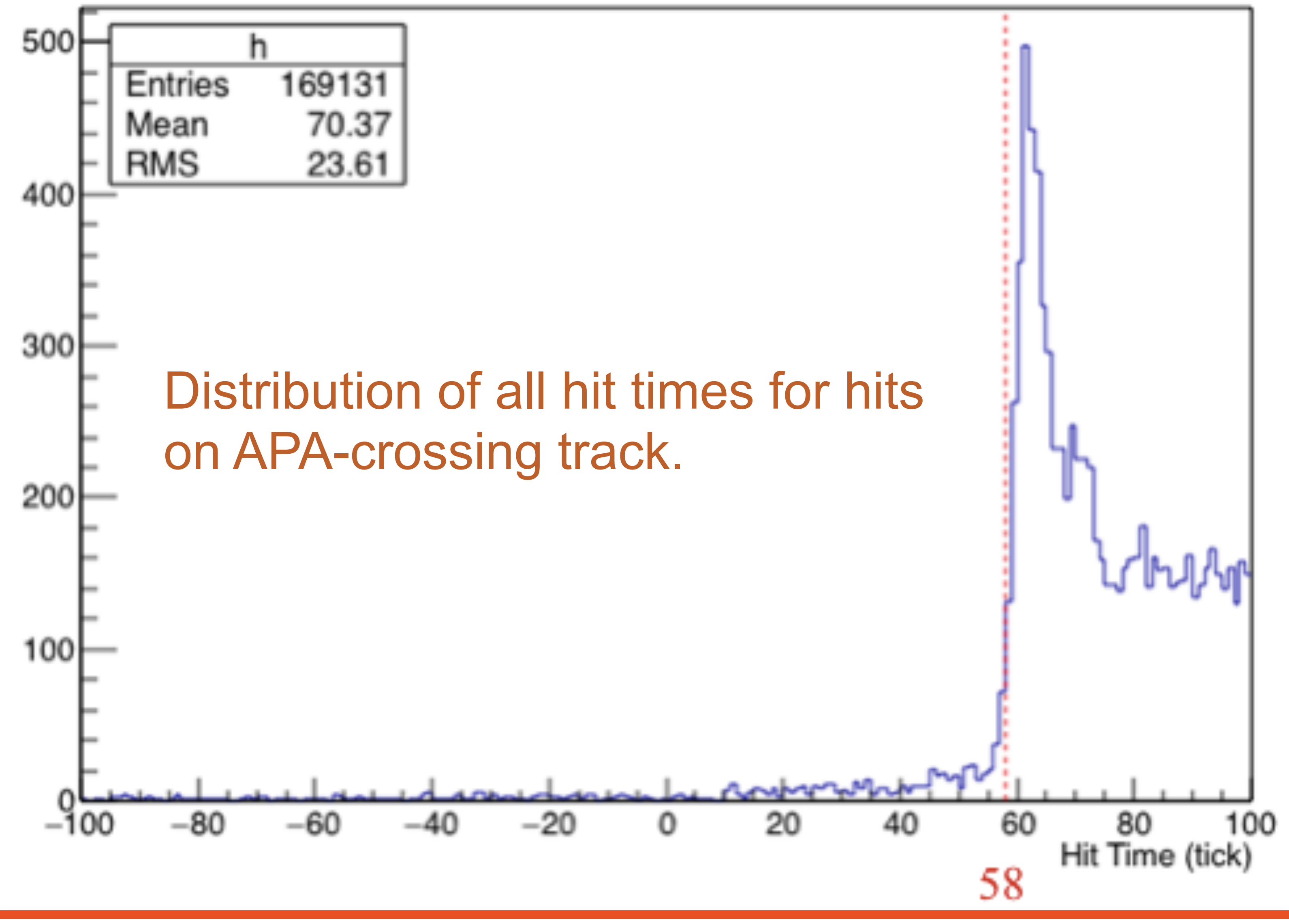


- Minimum of double peak distribution gives an estimate of the *z*-offset (from geometrical considerations).
- Can use that to measure the *x*-offset accurately.
- Then apply this *x*-offset to measure the *z*-offset again — this time with much greater accuracy.

APA-Crossing Muons: T0 Measurement

- Compare the timestamps of the trigger as recorded by the counters (PTB) and the TPC (RCE) (top plot):
  - 1705 NOvA ticks ~ 26.6 μs (~ 55 TPC ticks).
- Agrees reasonably with the leading edge of the distribution of all hit times on the APA-crossing track (bottom plot).
- Difference of ~ 6 μs between the two measurements:
  - Possible cause: geometry -> there are further offsets in the APA *z*-positions.
  - Would require ~2.5 mm offset between long and short regions —> very plausible!

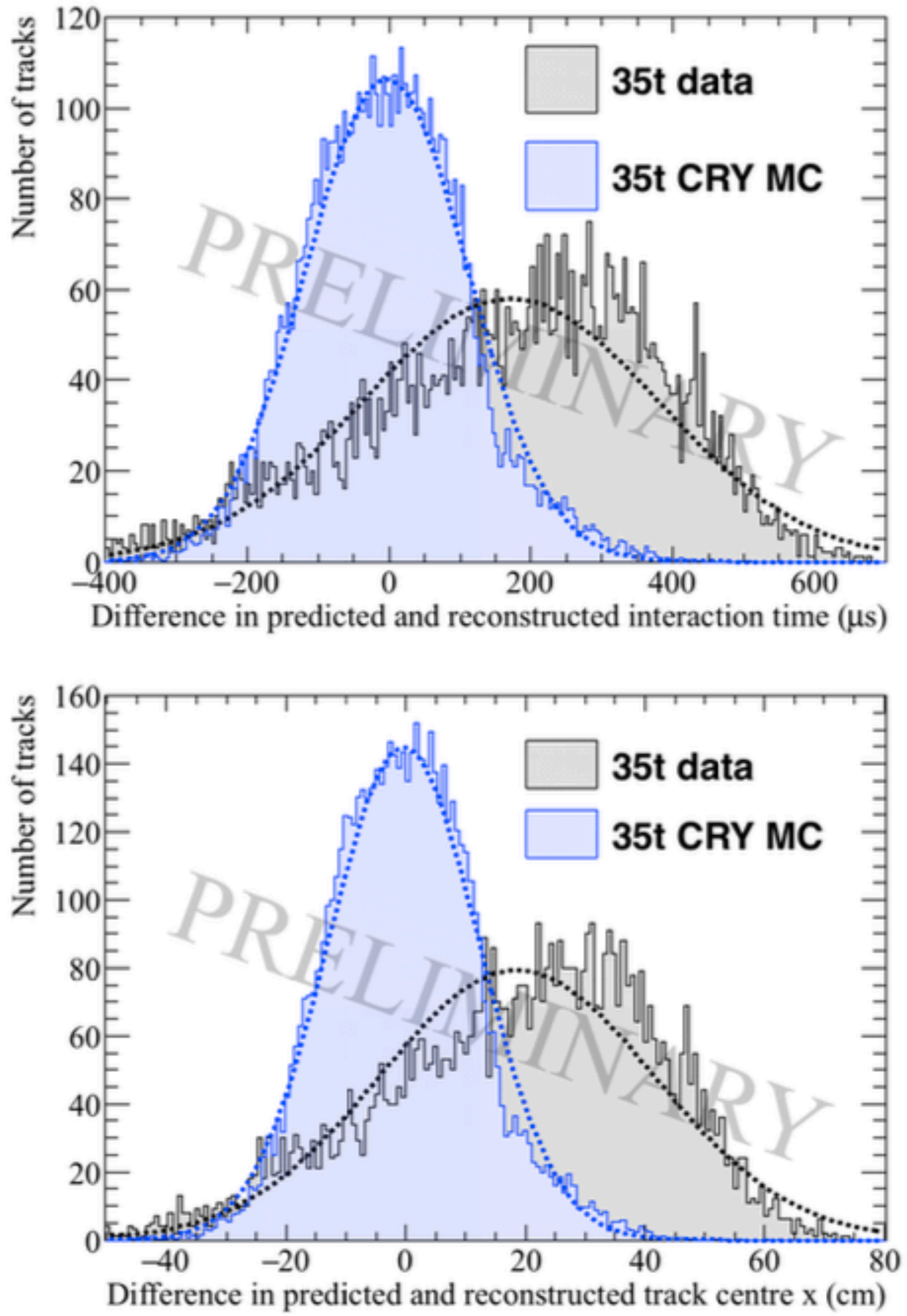




K Warburton

Measuring T0 from Diffusion

- Predict interaction time from tracks from the produced lookup tables. Difference between this and the counter T0:
- For 35-ton data:
  - The interaction time can be determined to within an accuracy of 171 μs (18.5 cm @ 250 V/cm) with FWHM of 210 μs (23 cm @ 250 V/cm).
  - Resolution not good enough to measure T0 precisely on its own but gives good handle.
- For simulated lower-noise detector:
  - Interaction time resolution: accuracy of ~-3 μs (-0.4 cm @ 250 V/cm) and FWHM of 114 μs (12.6 cm @ 250 V/cm).
- Diffusion also affected by electric field, electron lifetime and noise level (higher background noise leads to higher RMSs in data and the systematic T0 offset).



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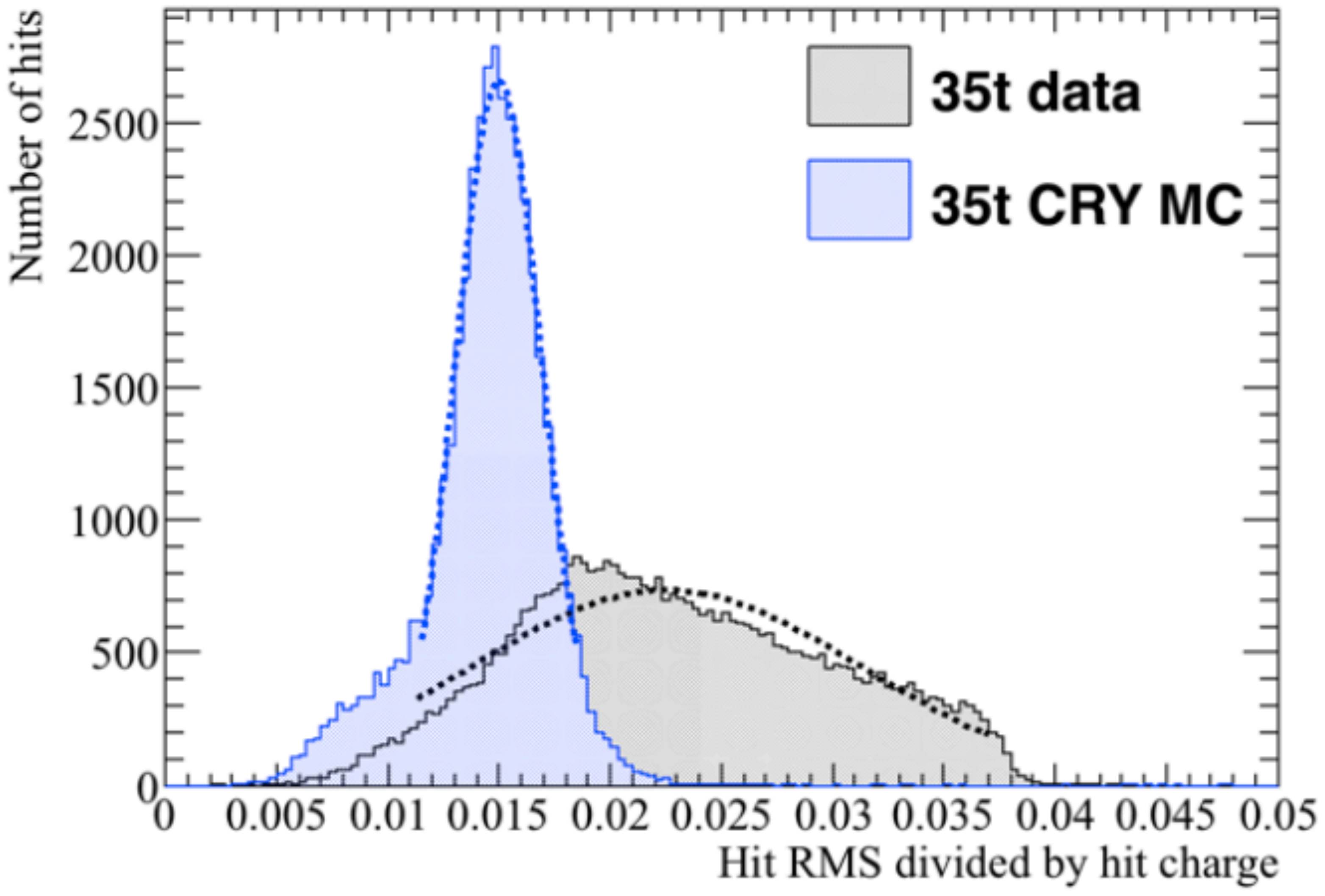
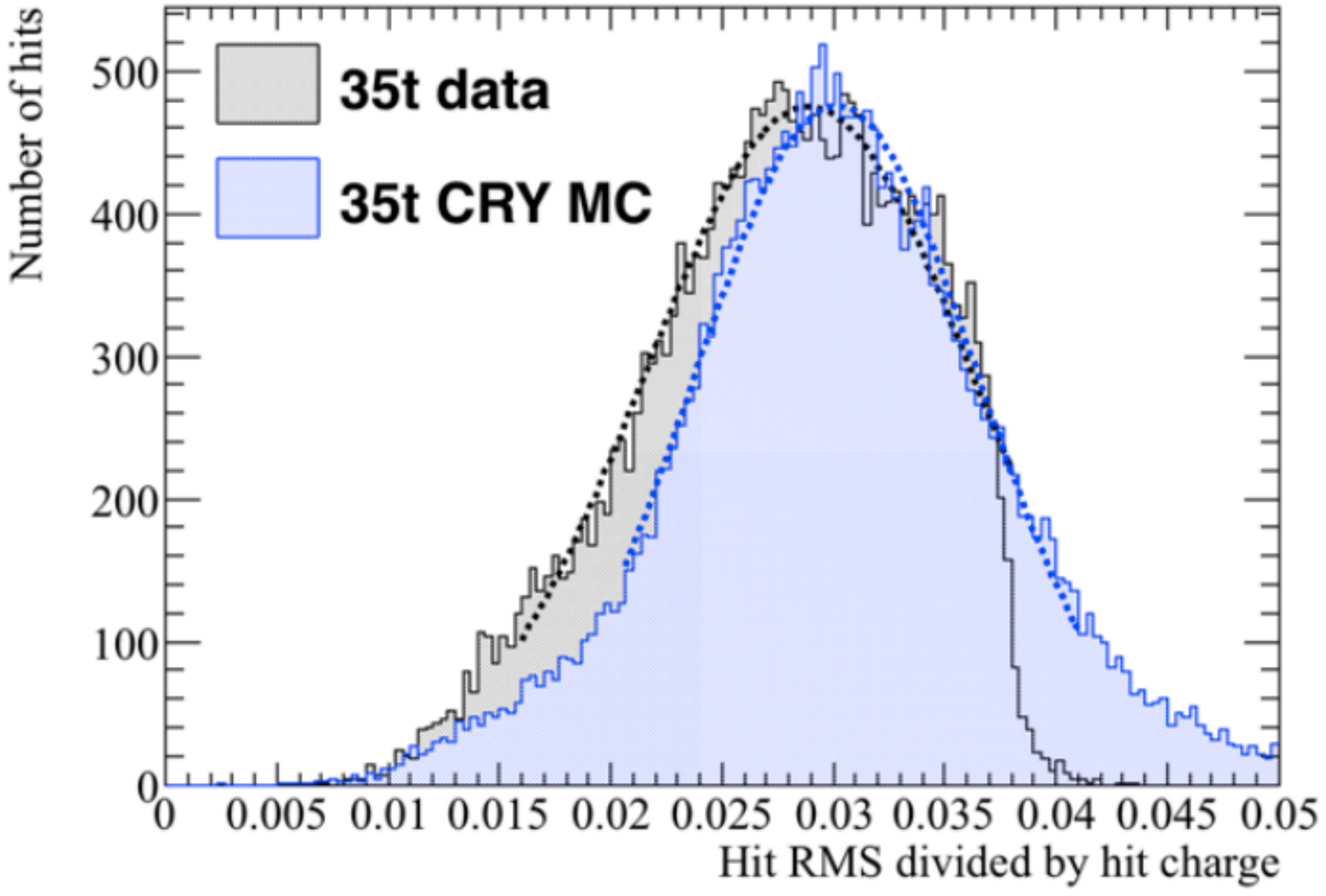
Measuring T0 from Diffusion

- Longitudinal diffusion will cause the modal hit width (i.e. RMS width) to increase at further drift distances.
  - Fit Gaussian, use mean as modal hit width and width as error.
- Use RMS/hit charge metric (as opposed to RMS) to minimise impact of track angle.



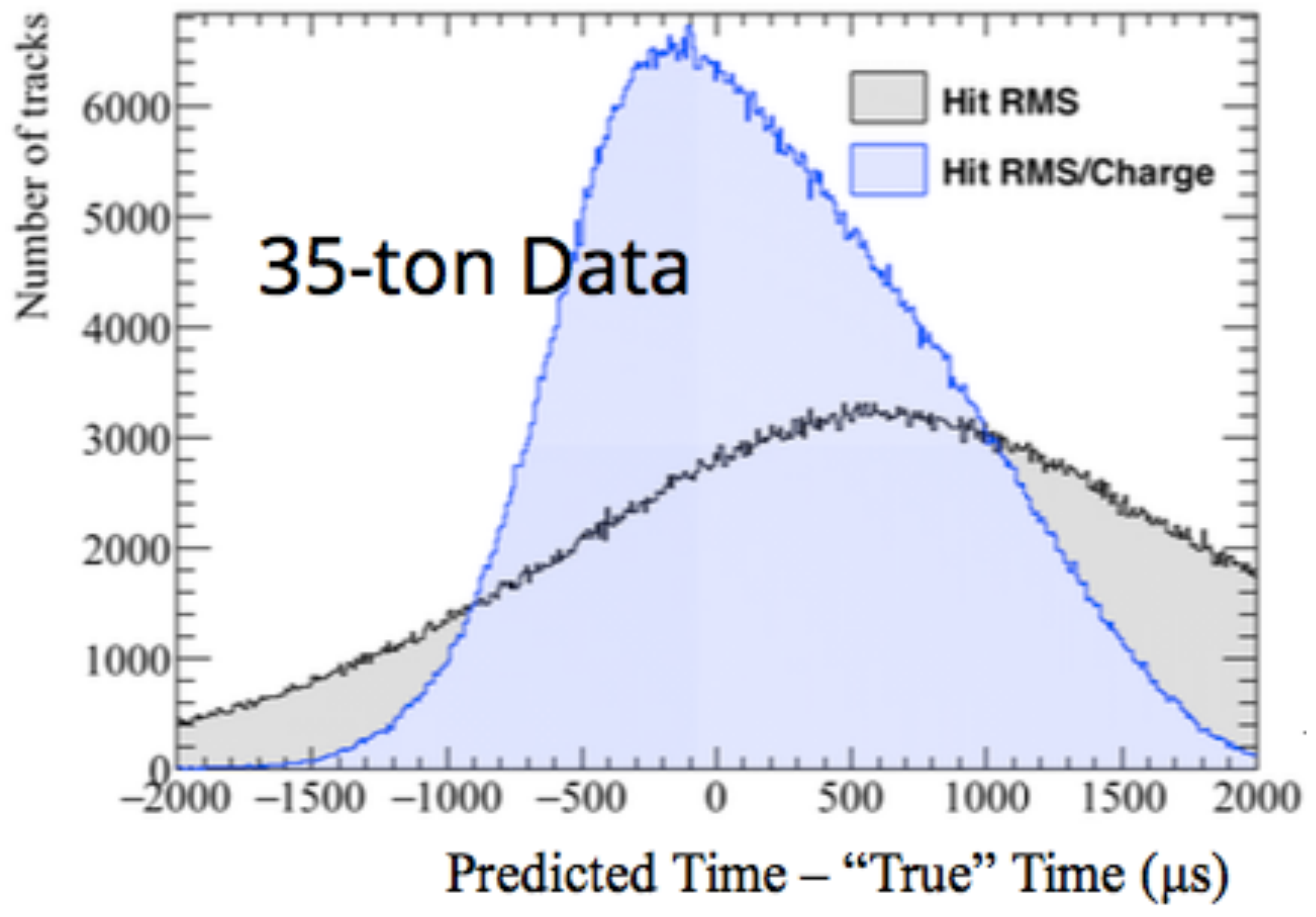
20 cm drift

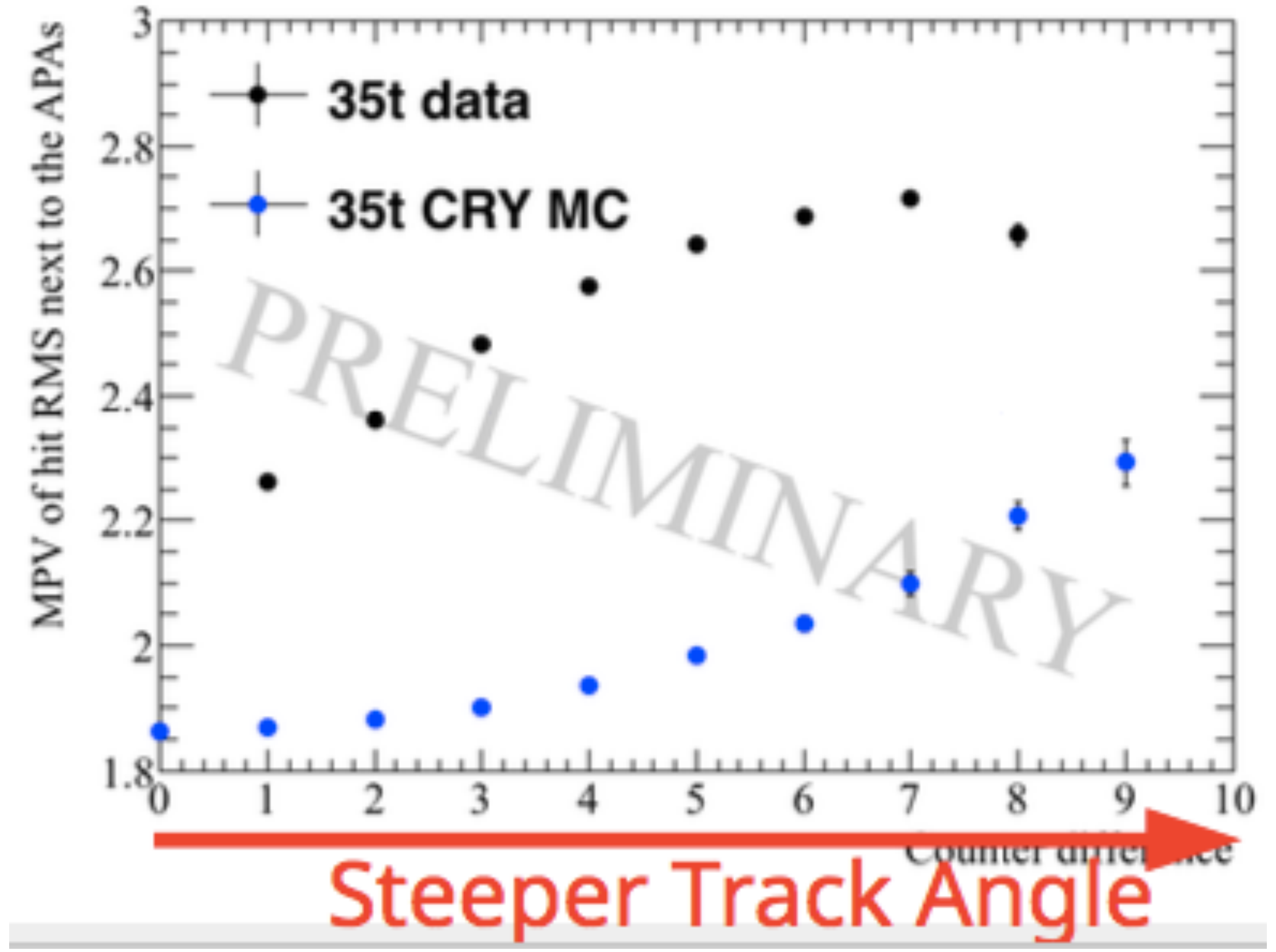


140 cm drift

K Warburton

Diffusion RMS vs RMS/Charge Metric

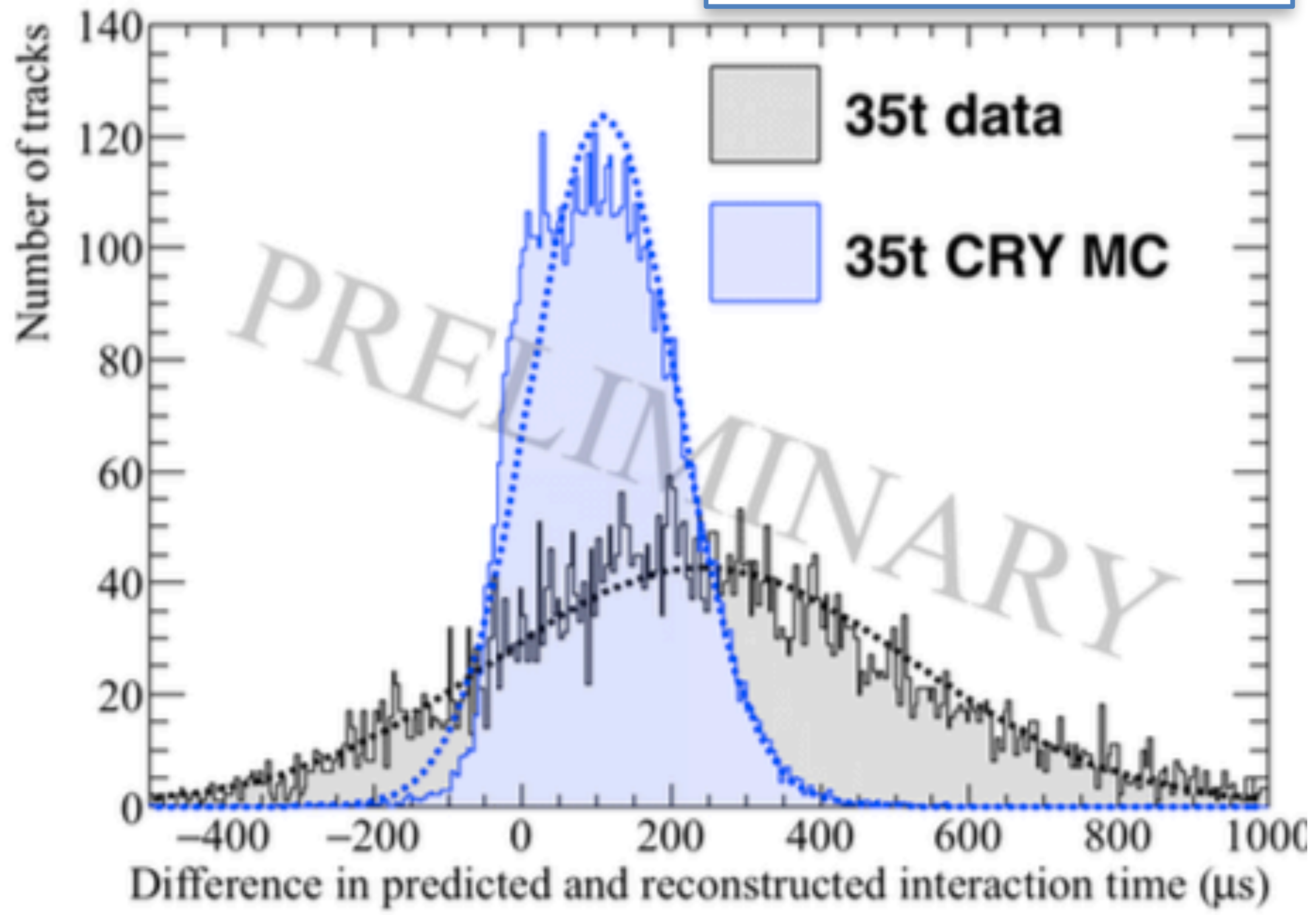


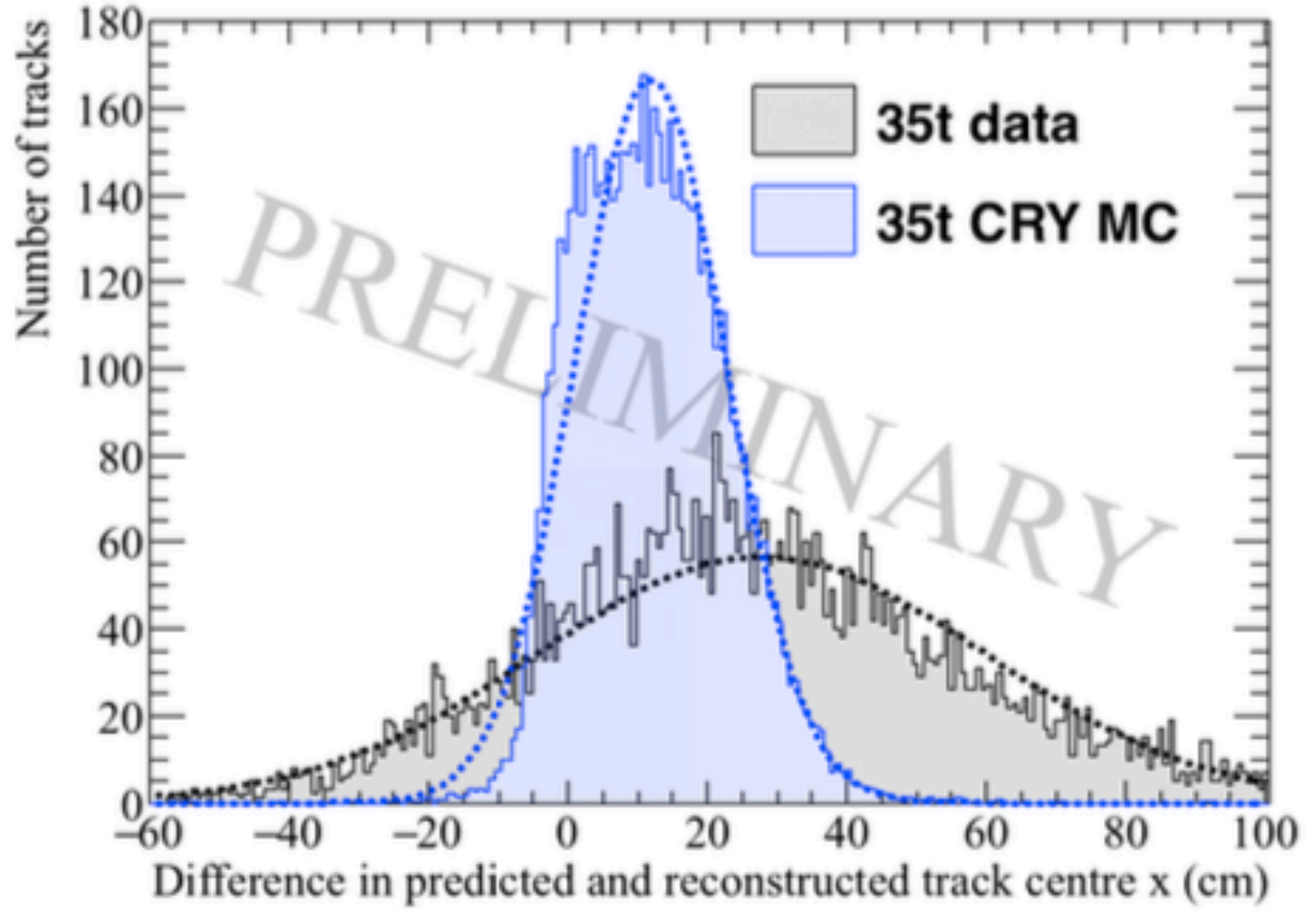


- RMS/Q better metric:
  - peaks closer to zero (more accurate);
  - Narrower (more precise).

- RMS shows strong dependence on track angle.
- RMS/Q removes this dependence.

Hit RMS metric





M Thiesse

Measuring Purity from Tracks — Details

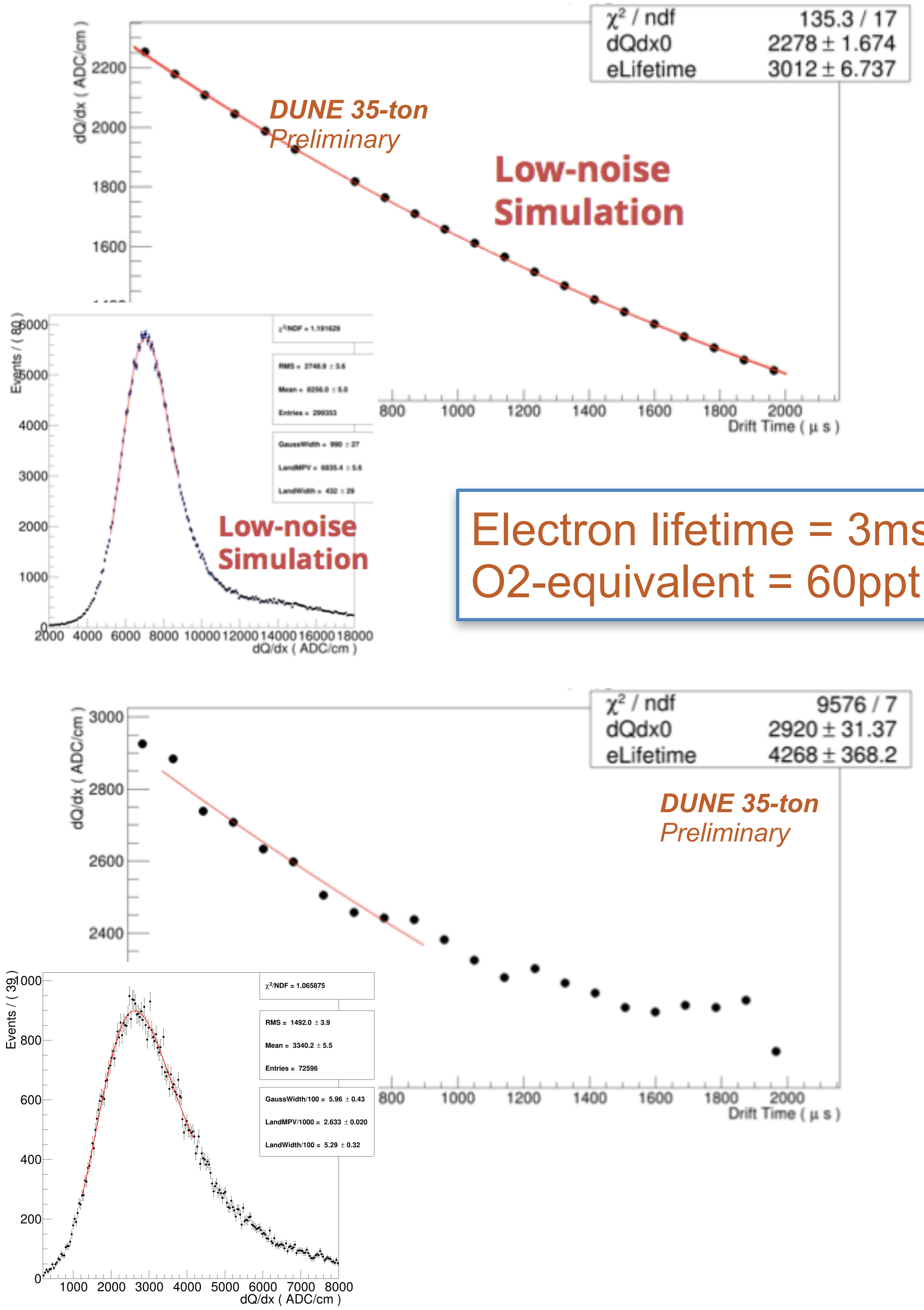
- Charge attenuation due to electronegative impurities (e.g. O2, H20).

$$Q_{\text{collected}} = (Q_{\text{ionised}} - Q_{\text{recombination}})e^{-t/\tau}$$

- Impurity concentration of *i* species is determined by electron lifetime:

$$\tau_{\text{lifetime}} = (\Sigma_i k_i n_i)^{-1}$$

- Hit charge follows Landau distribution (charge particle energy loss in medium).
- Landau(x)Gauss represents effects of detector response.
- dQ/dx — hit charge corrected for track angle.
- Measured average over full data run: 4.27 +/- 0.37 ms (stat.).
  - ~ 41 ppt O2 equivalent.
- c.f. dedicated purity monitors:
  - ~3.5 ms.

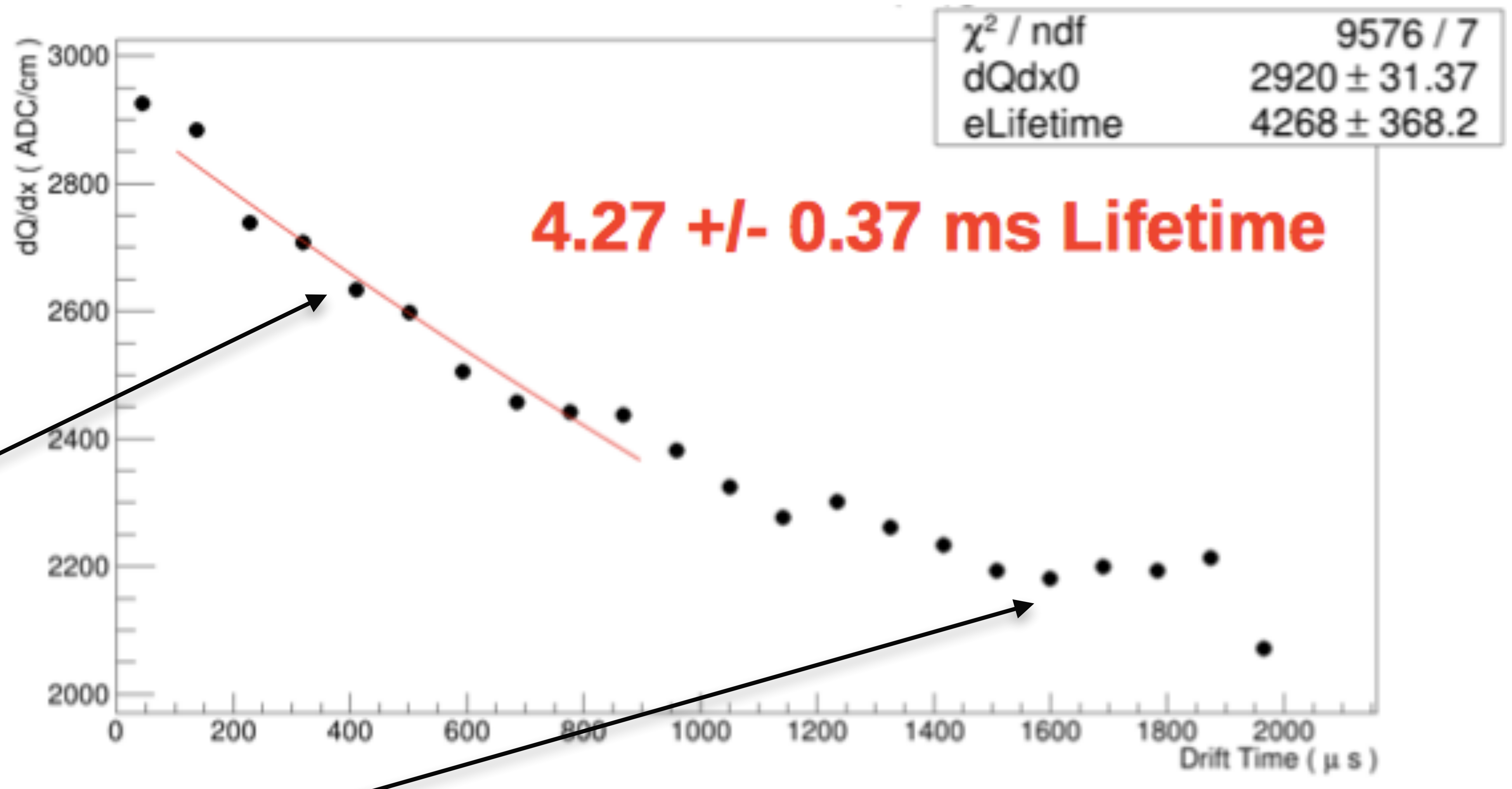


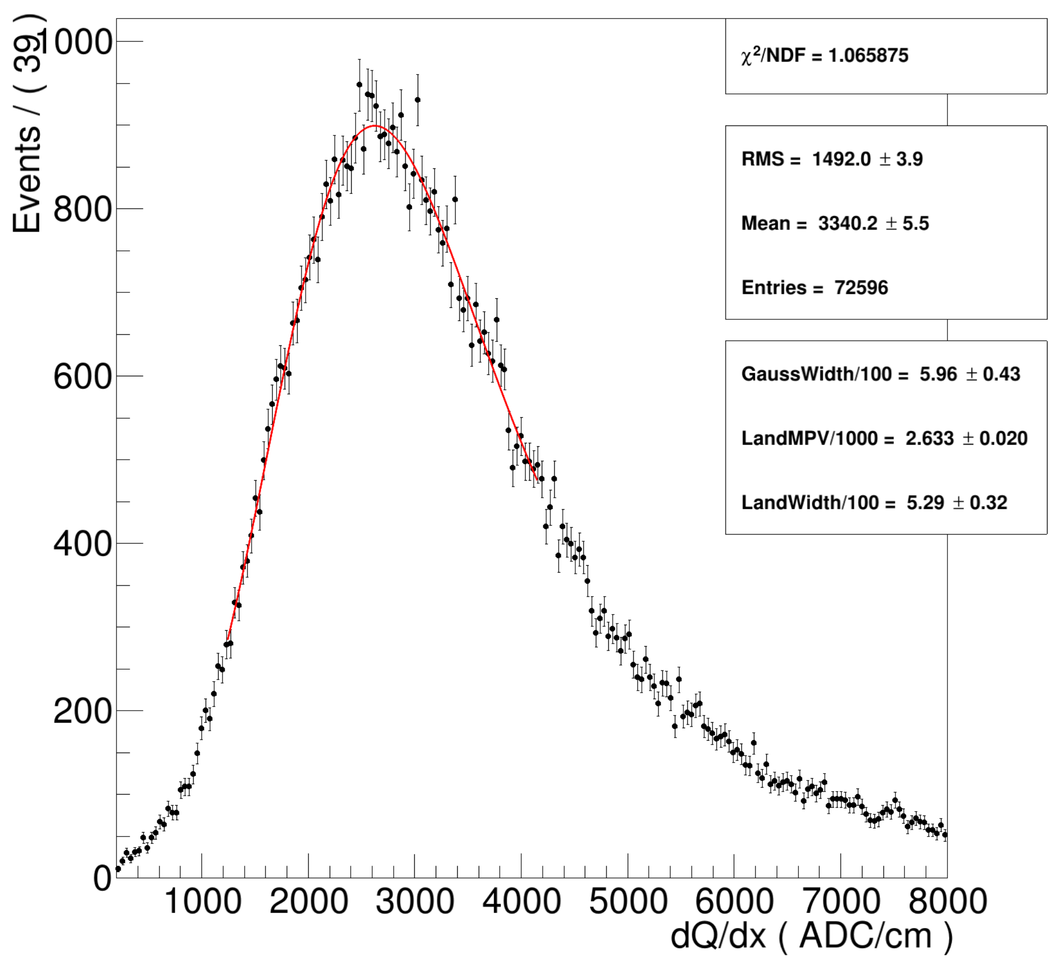
Electron lifetime = 3ms
O2-equivalent = 60ppt

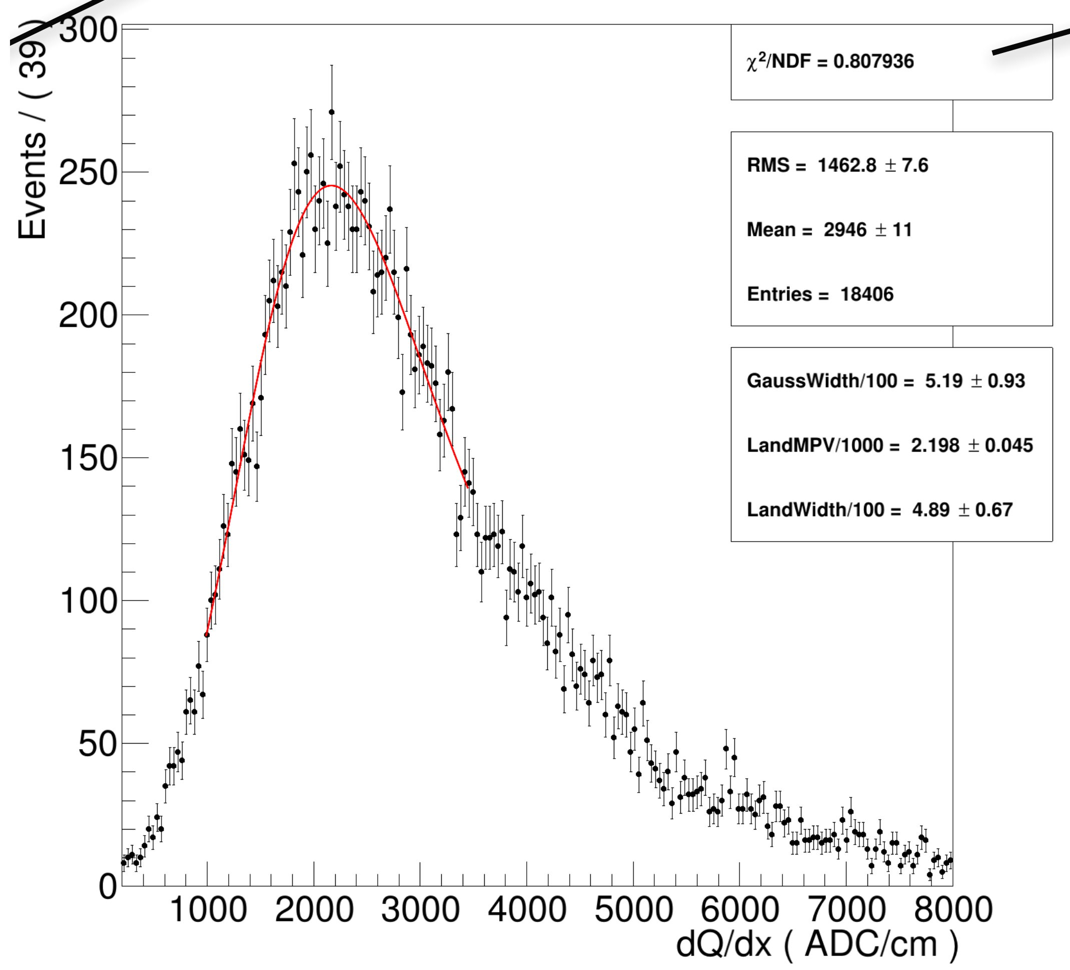
M Thiesse

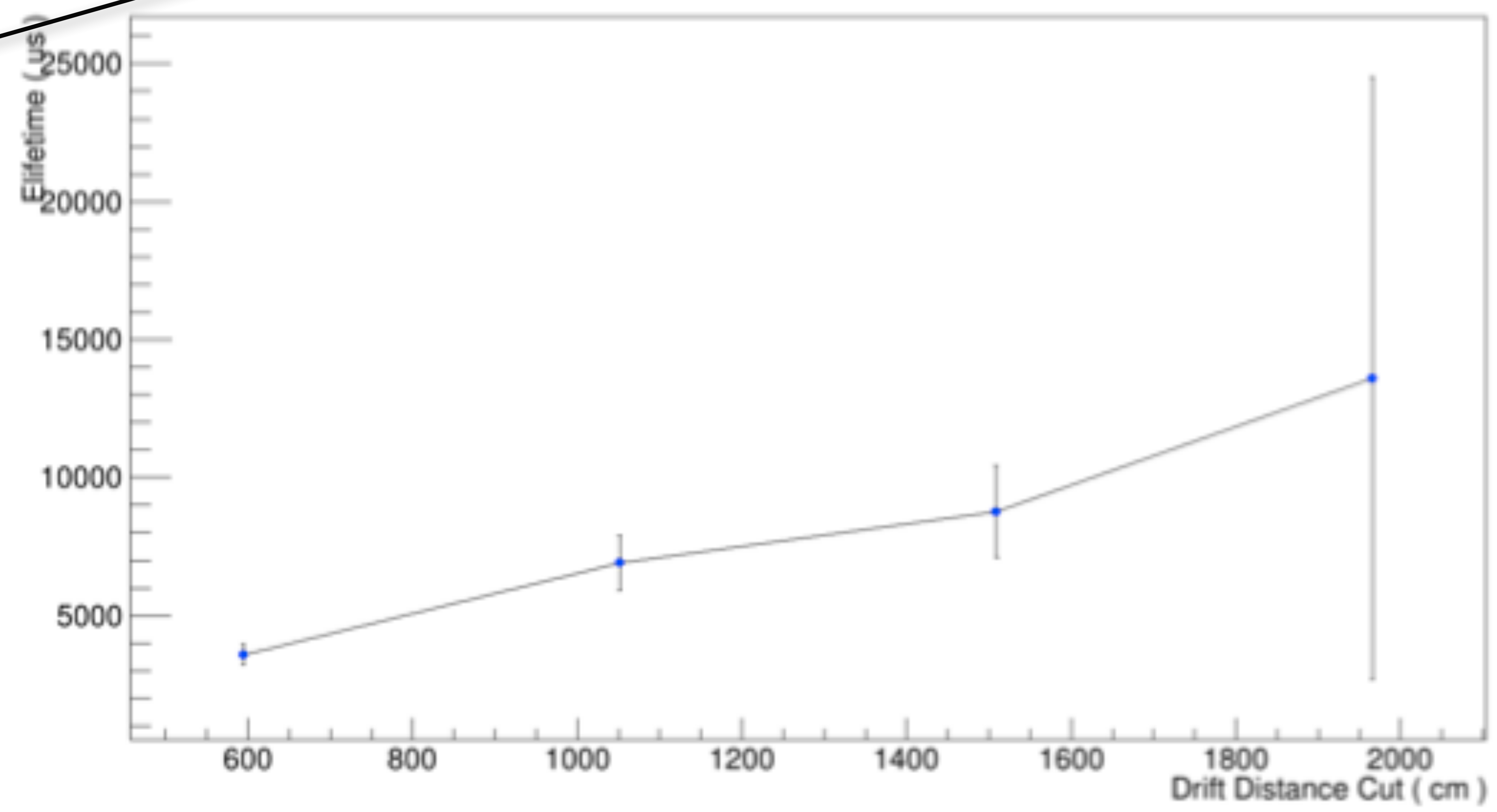
Measuring Purity from Tracks — Method

- Method:
  - Bin dQ/dx over drift distance;
  - Fit to Landau(x)Gauss and extract Landau MPV;
  - Lifetime is determine from decay of MPV over drift distance/time.
- Assumed fiducial volume cut at half of full drift length — justified from MC studies of biases and efficiencies of reconstruction.





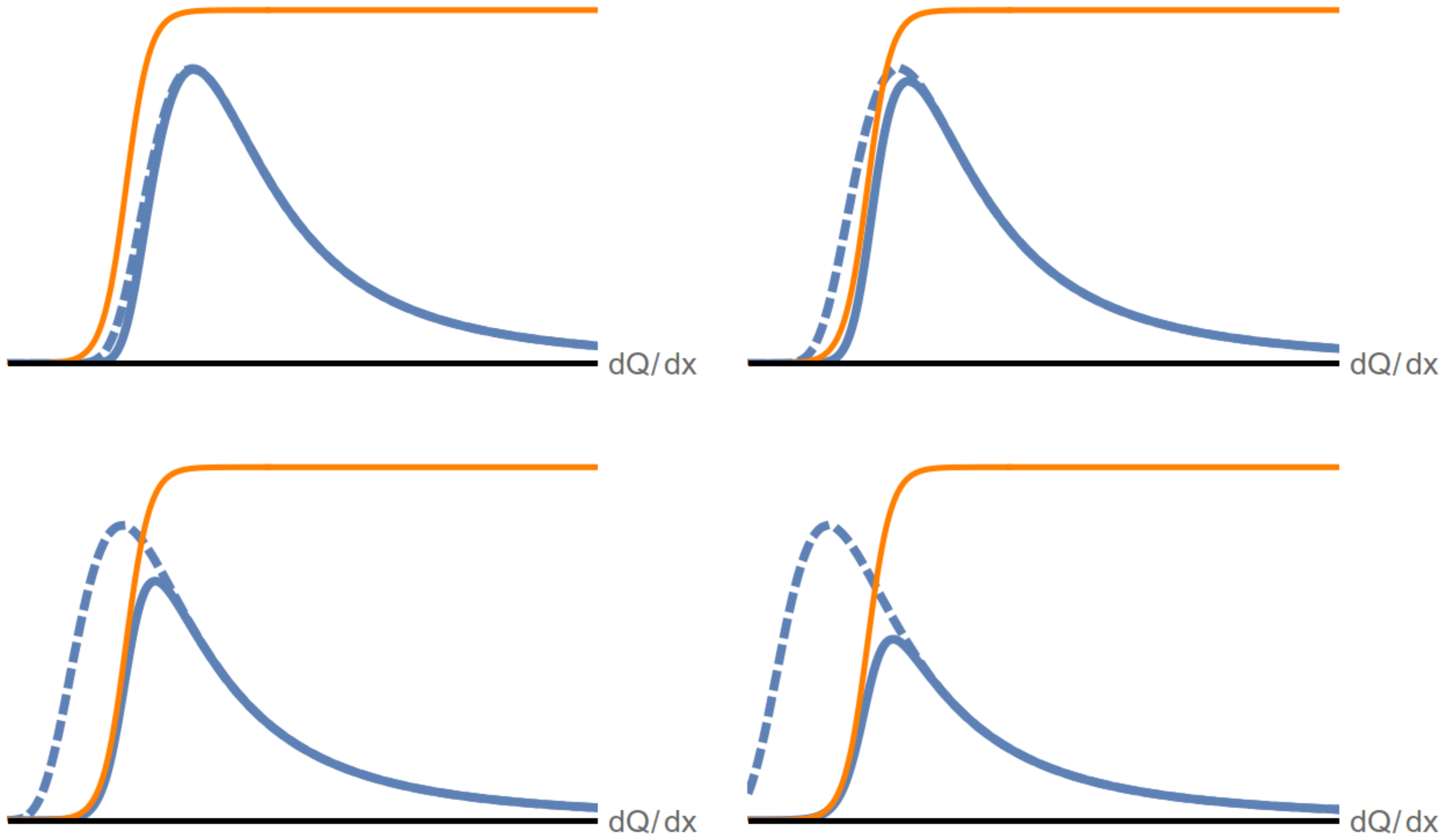




M Thiesse

Measuring Purity with Tracks — Biases

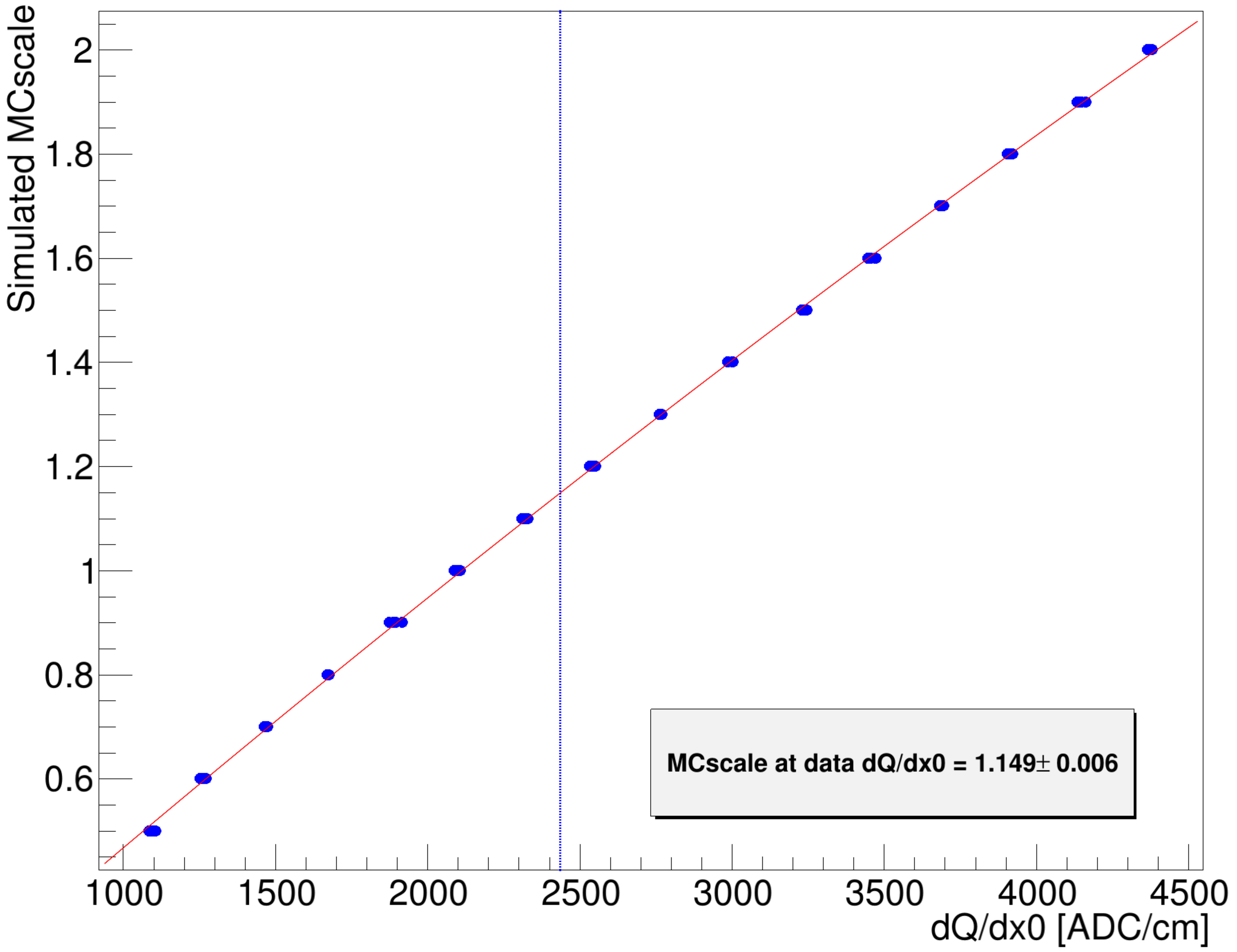
- Low charge hits get lost in noise
  - can’t lower threshold without sacrificing purity of hit reconstruction
  - —> dQ/dx skewed to large value because of loss of hits
  - —> MPV of Landau(x)Gauss skewed to higher values
  - —> measure larger lifetimes.



M Thiesse

Measuring Purity from Tracks — MC Scaling

- The intercept of charge vs time in data disagrees with the simulation.
- The extent is determined from running many simulations and scaling the MC to agree with the 'true' value (that measured from the data).



Measuring Purity from Tracks — Comparison

- Measured average over full data run: 4.25 +/- 0.24 (stat.) +/- 0.28 (sys.) ms.
    - ~ 41 ppt O_2 equivalent.
- c.f. dedicated purity monitors: ~3.0 +/- 0.2 (stat.) +/- 0.5 (sys.) ms.
- Difference between the values, combination of:
    - effects of space charge distortions in the electric field,
    - uneven distribution of impurities within the cryostat and TPC field cage,
    - limitations in purity monitor sensitivity,
    - additional unidentified systematics in the purity analysis.