Prototyping the DUNE Far Detector Single Phase Design with the 35 ton Experiment: Experiment & Results

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for the 35 ton collaboration

IOP HEPP&APP Conference 2017, University of Sheffield
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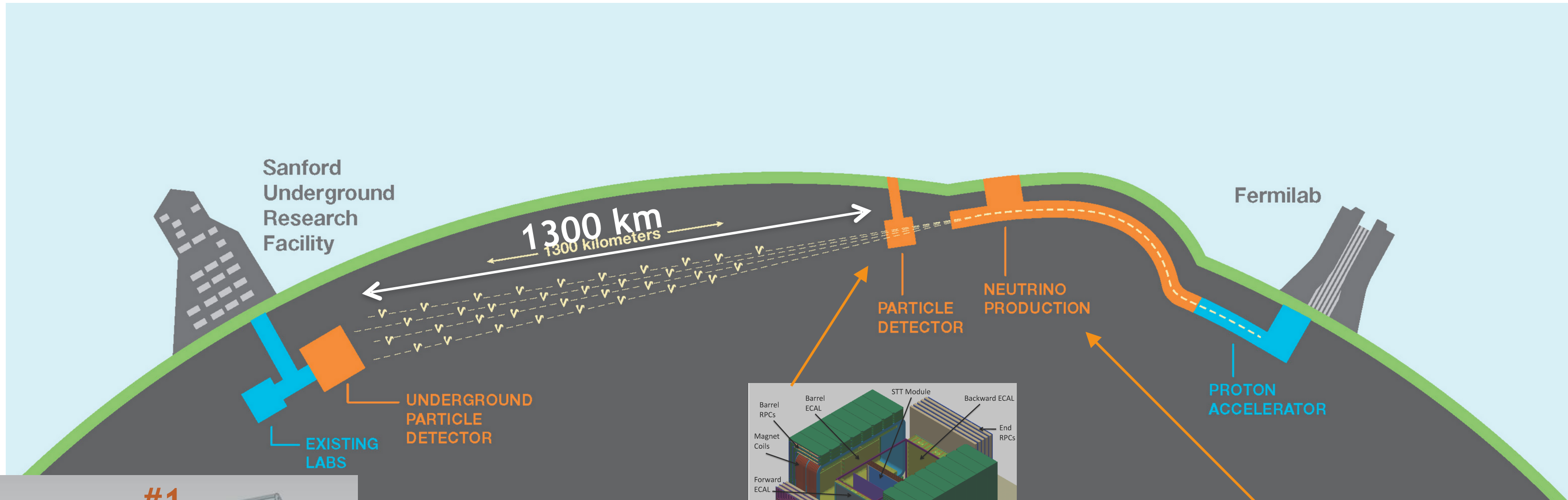
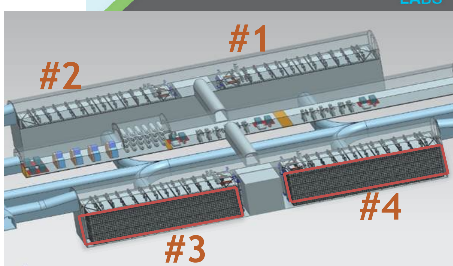
DUNE

The Deep Underground Neutrino Experiment (DUNE)





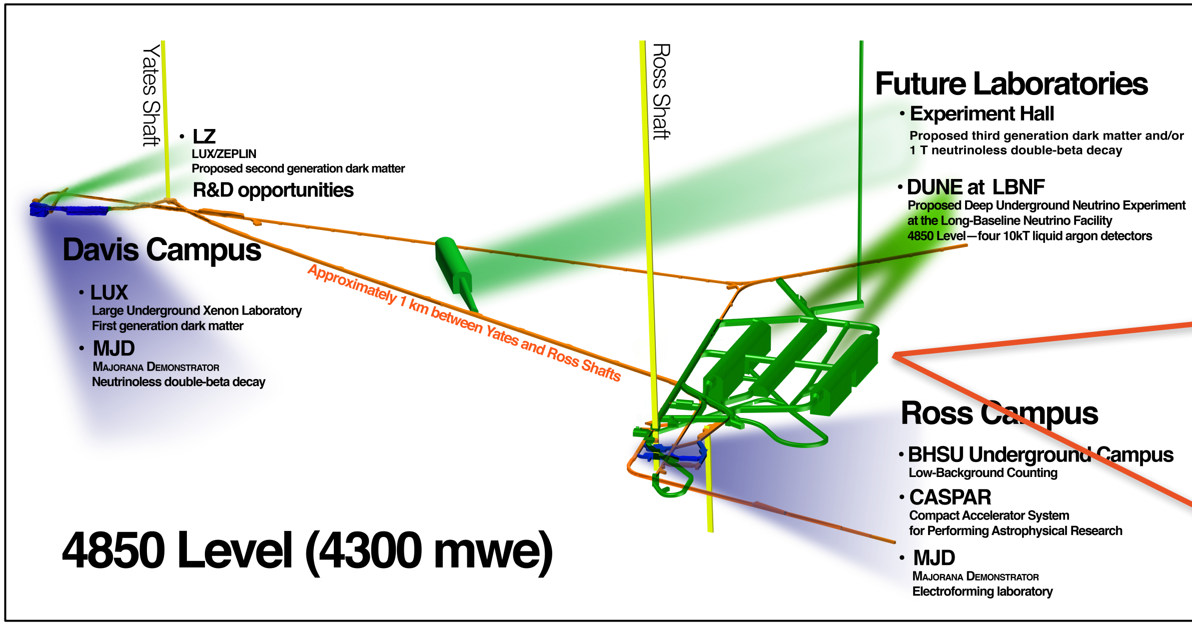
Four identical cryostats deep underground; staged approach to four independent 10kton LAr detector modules

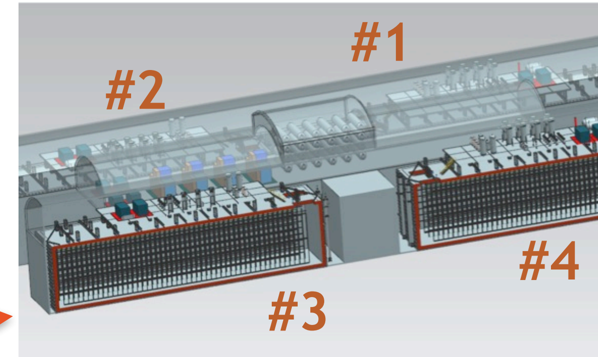
High precision near detector at 574 m

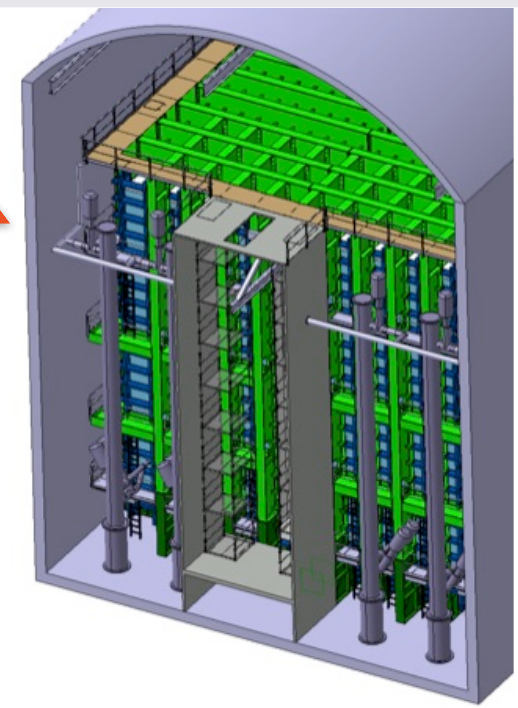
Wide band, high purity beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradable

- Future long-baseline neutrino oscillation experiment with a rich program in neutrino physics, 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 DUNE Far Detector

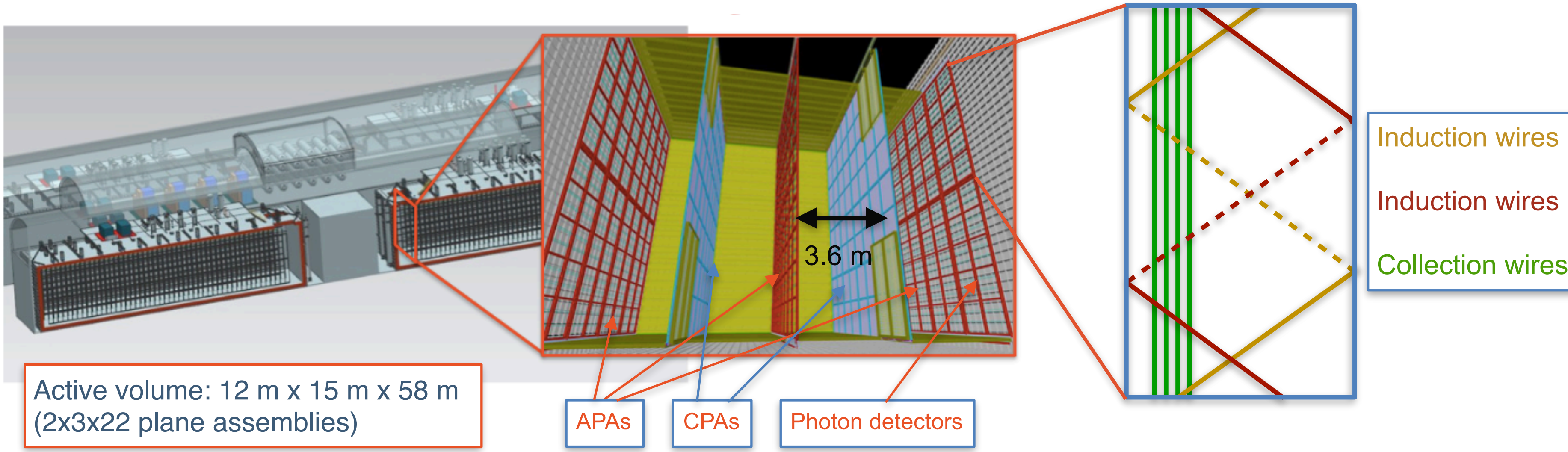






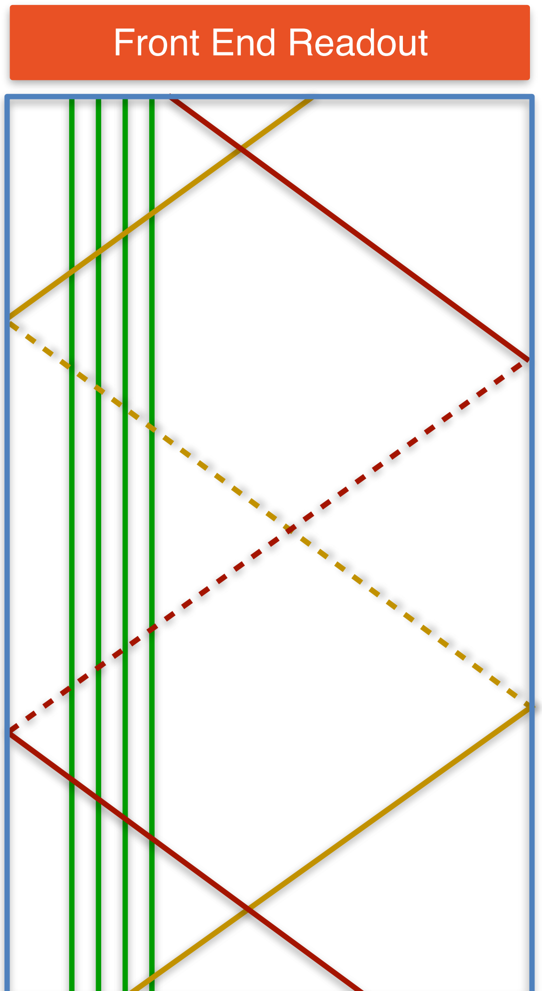
- LAr both the interaction target and the detector.
- 4 identical cryostats, each 17 kton total volume, can house either single phase (SP) or dual phase (DP) detector modules.
- First module, built by 2024, will be SP.
- Future modules may be either.

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).

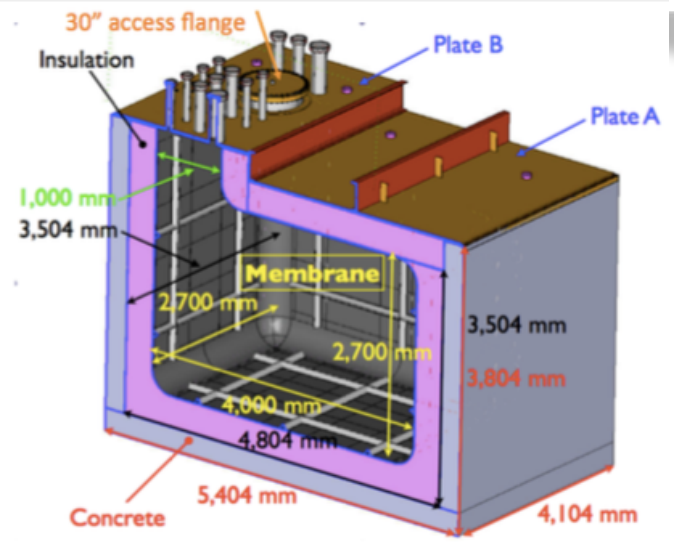
DUNE Single-Phase APA Design



- Wrapped wires read out charge from both sides of the APAs to reduce number of channels.
- Readout at the top of the upper APAs and at bottom of the lower APAs.
  - Allows APAs to be placed next to each other thus helps reduce dead region.
- Induction channels at angle of ~36° to vertical; collection channels vertical.
- Collection wires are not wrapped.
- Grounded mesh at centre of APAs.

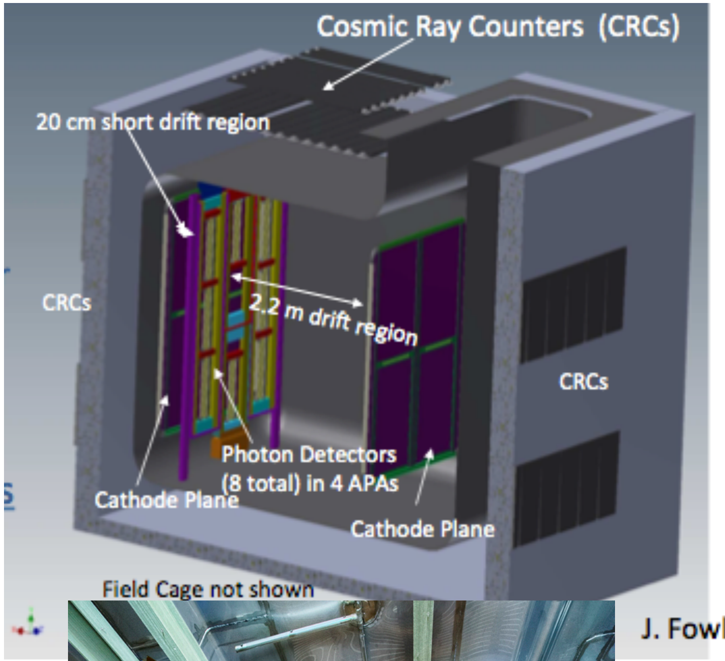
The 35 ton Experiment

- First use of membrane cryostat in for scientific application.
- Test many of the 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 analysis ongoing…



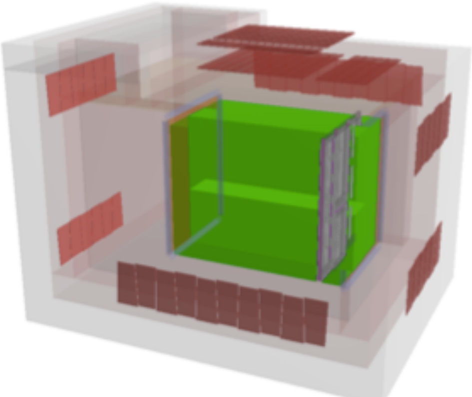
35 ton Detector

- Segmented TPC.
- Multiple (two) drift regions read out by 4 wrapped-wire APAs (with integrated PDS).
- Cold analog and digital electronics.
- FR4 printed circuit board field cage (LBNE design).
- Three readout planes (two induction, one collection) and a grid plane.
- ~100 scintillation paddles on the outer cryostat walls to provide cosmic triggers.

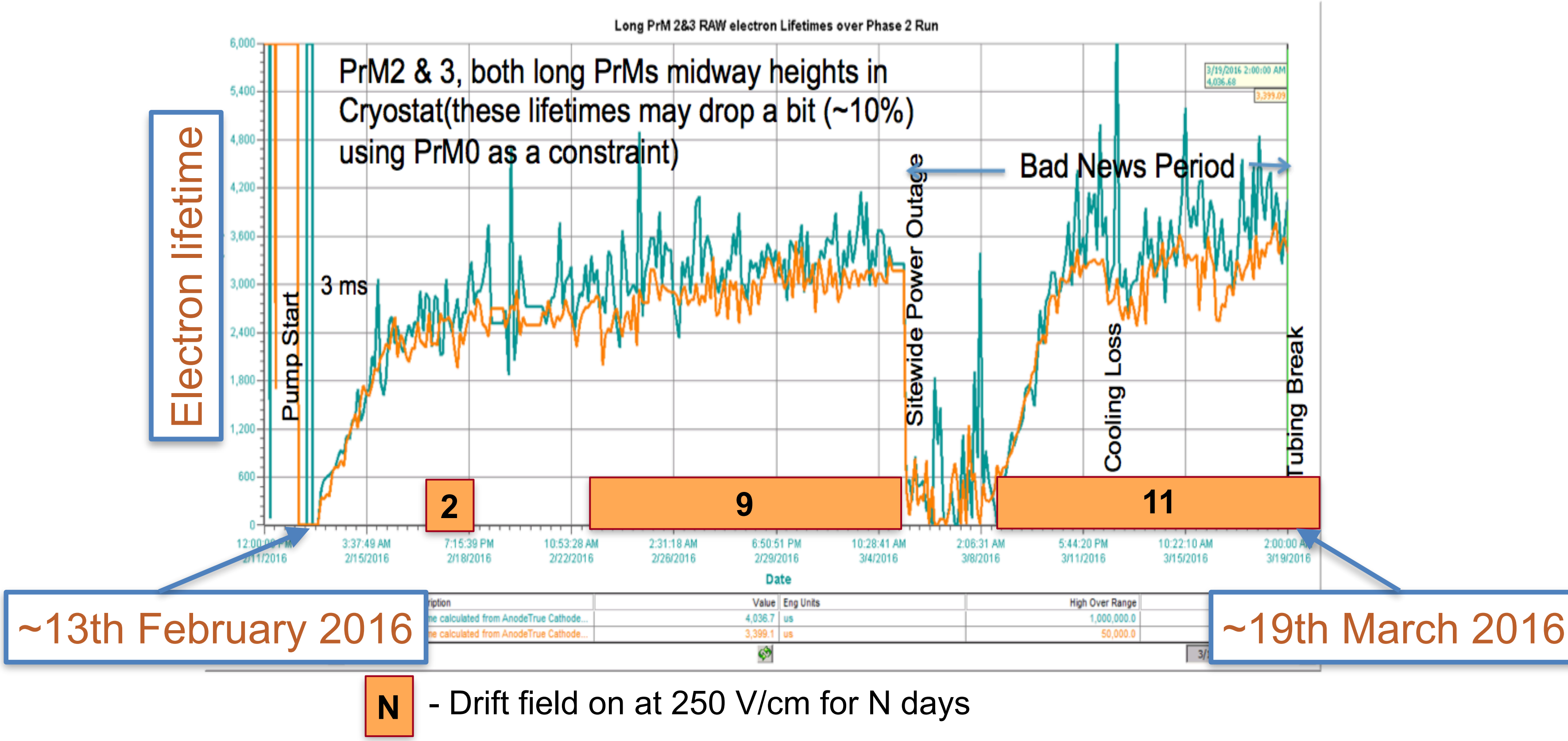


J. Fowler

Scintillation counters surround TPC

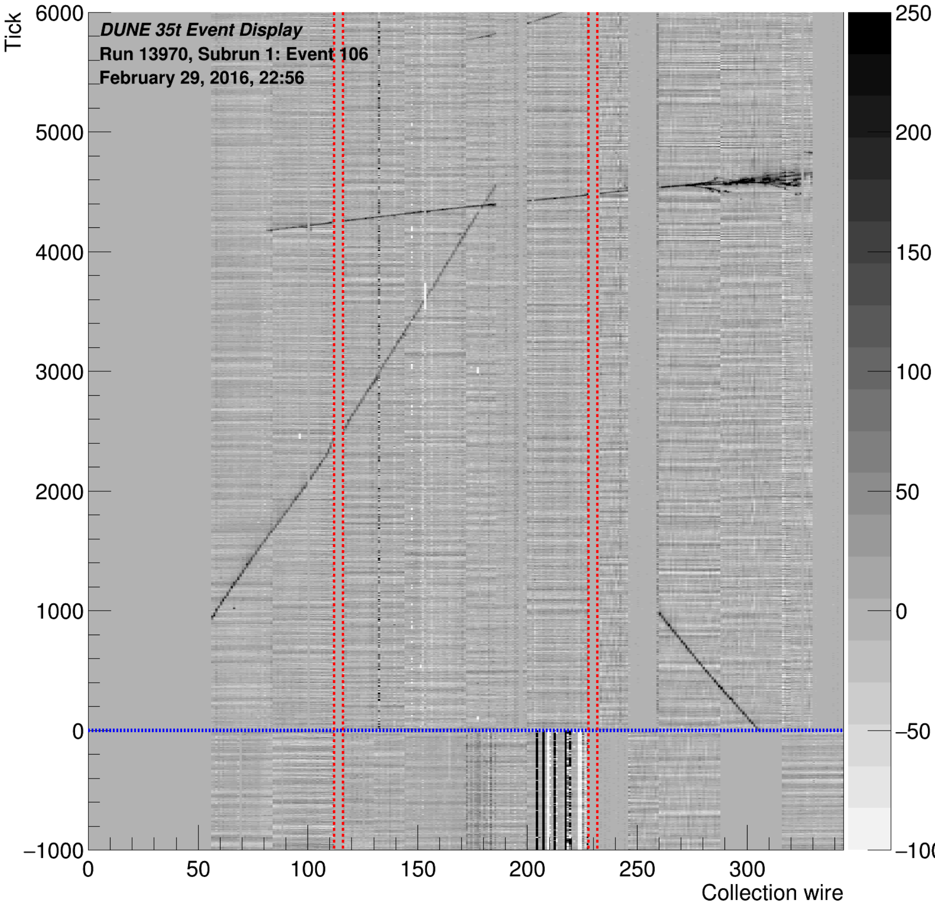


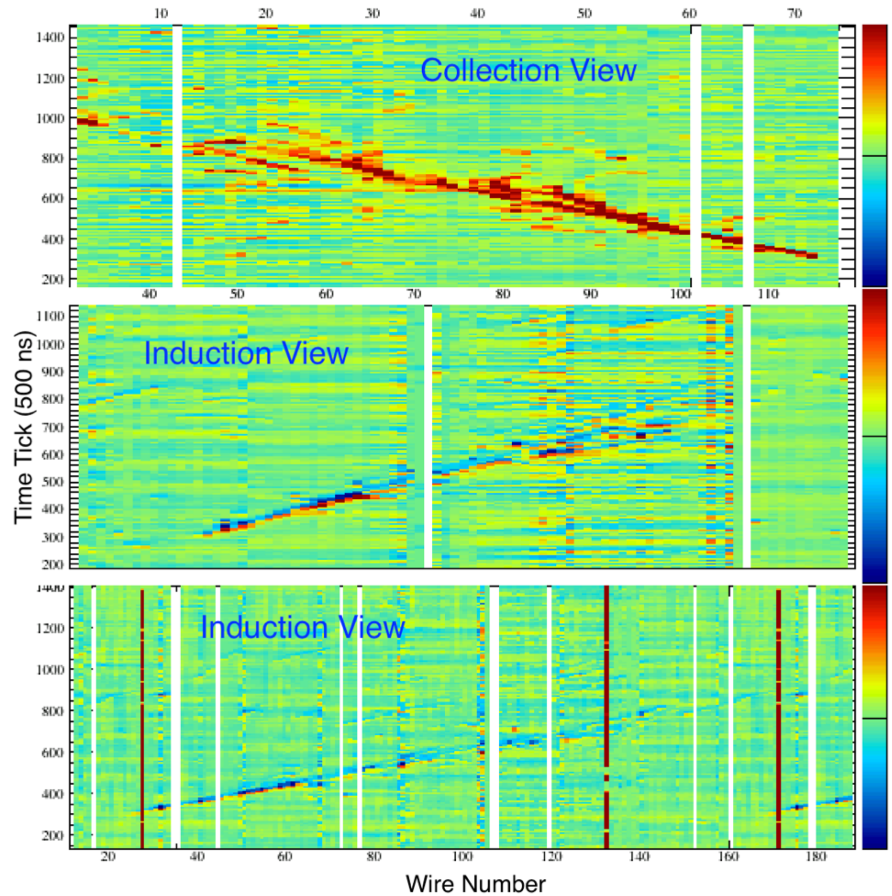
35 ton Data Sample



- 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

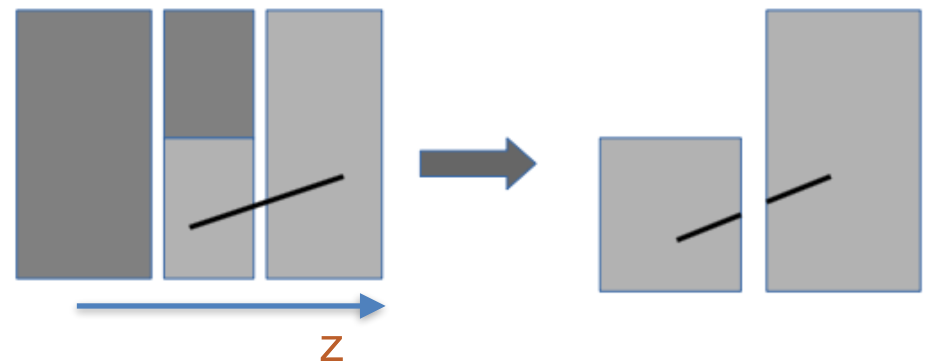
35 ton Data Outcomes

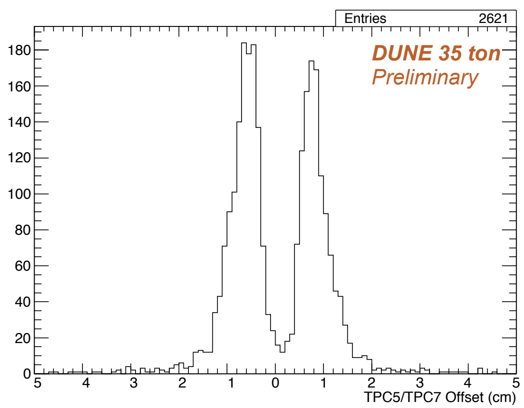
- Automated reconstruction shown to work on real data.
- Unexpected issues with data:
  - Higher electronic noise than expected, mainly in FE electronics (signal/noise ~10 (collection channels), ~2 (induction channels)).
  - Most noise problems have been identified and understood.
    - Successful prototype!
  - Premature end of the run — no chance to collect data at design drift field.
- Focussing on analyses of unique 35 ton datasets:
  - Measurements of the modular TPC design;
  - Making use of external counters for positioning and timing.
- Results preliminary — may change before publication.
- Look out for papers coming very very soon!

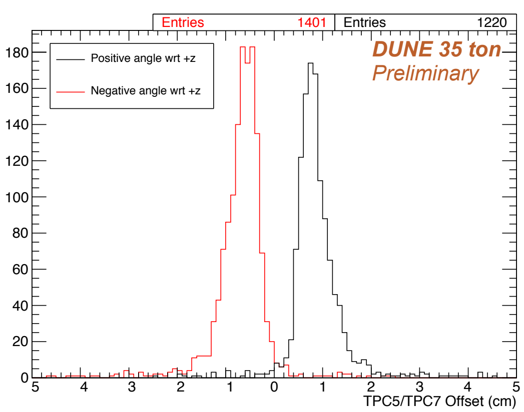
M Wallbank

APA Gap Crossing Muons

- Can use tracks which cross APAs to measure the gaps in between.
- Vary the gap, minimise residual of least square fit across all hits.





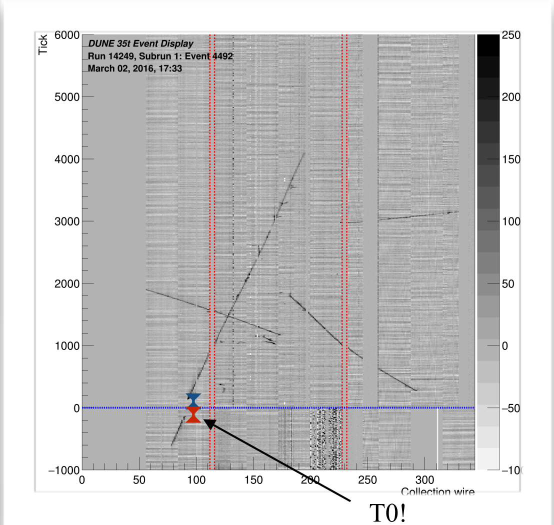


- When measuring the offset in *z*, noticed a strange 'double peak' effect — seemingly related to the angle the track makes to the APAs.
- Possibly an indication of further offsets — in *x*, the drift direction.
- Developed a method to measure both the *x* and *z* offsets from the same data set.
- Vital for DUNE far detector — each module will contain 150 APAs —> lots of offsets to understand!

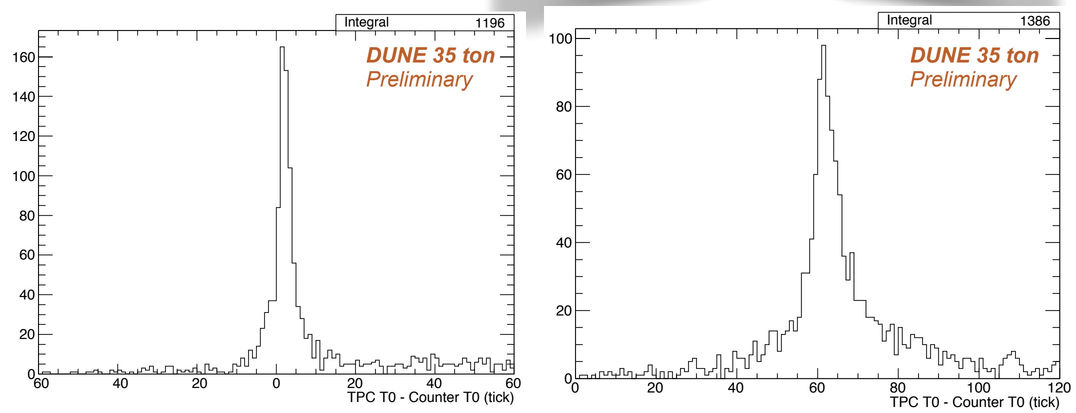
M Wallbank

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).

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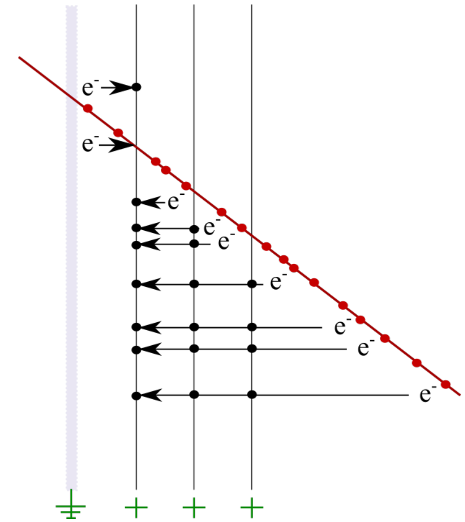
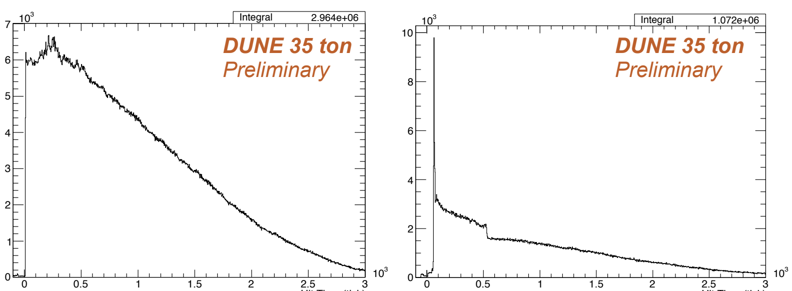
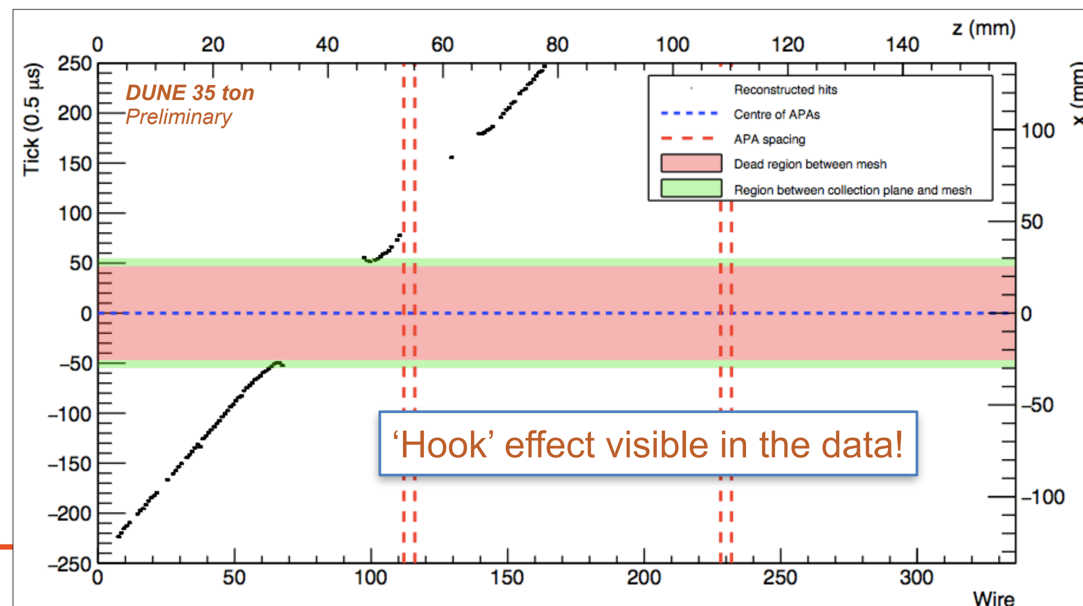
APA-Crossing Muons: Deposited Charge

- All the field lines originate on the collection plane and terminate on either the cathode plane, or the grounded mesh at the centre of the APA.
- An ionising track passing through deposits charge throughout.
- Because of the electric fields on both sides of the collection plane, interesting effects have been observed in the data.
- Not currently simulating this — will eventually need to!





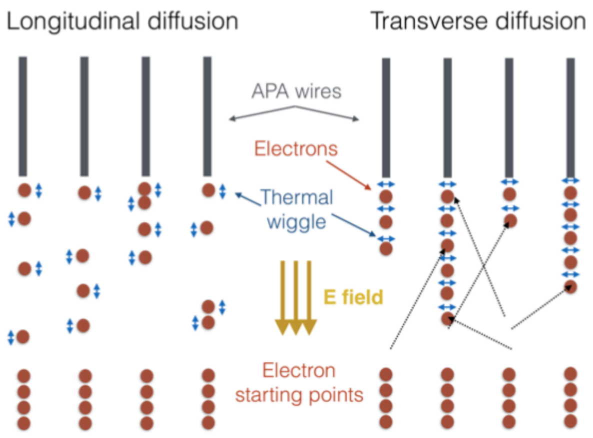
Hit time distributions for simulation (left) and data (right)

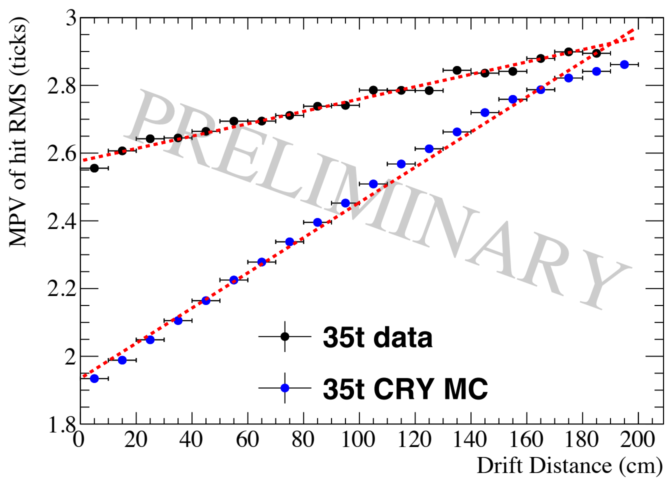


K Warburton

Measuring T0 from Diffusion

Image: D Brailsford





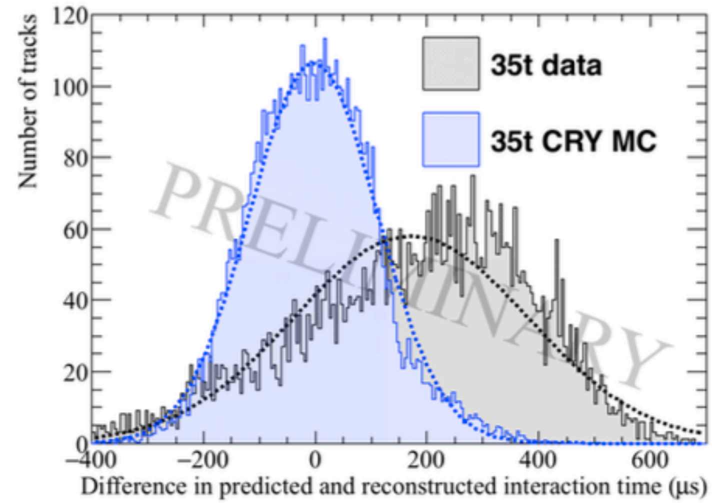
Transpose this plot to make look-up table

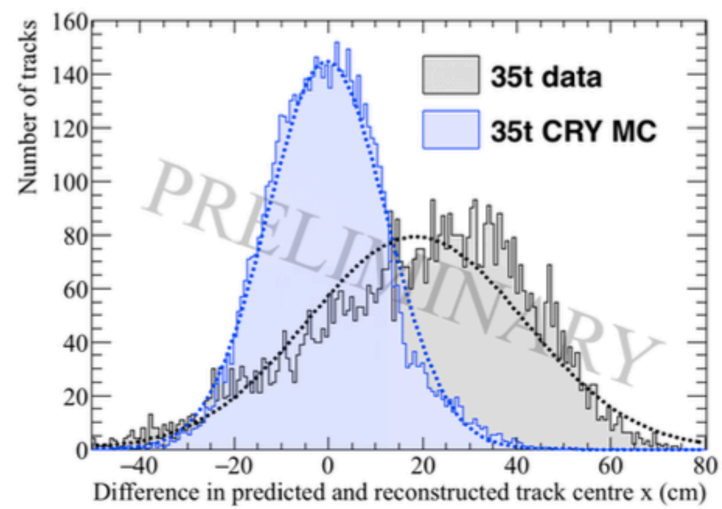
- Diffusion is spreading out of electrons as they travel from common source.
  - Longitudinal: spread in time.
  - Transverse: spread across wires.
- Hypothesis: any single track has enough information to determine an interaction time without the need for an external trigger system.
- Can use the change in hit width (in time) caused by diffusion along the track to backtrack its original location.
- The muon counters around the 35ton allow tracks to be selected with known track angles and interaction times.
- Longitudinal diffusion will cause the modal hit width (i.e. RMS width) to increase at further drift distances.

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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DUNE

M Thiesse

Measuring Purity from Tracks

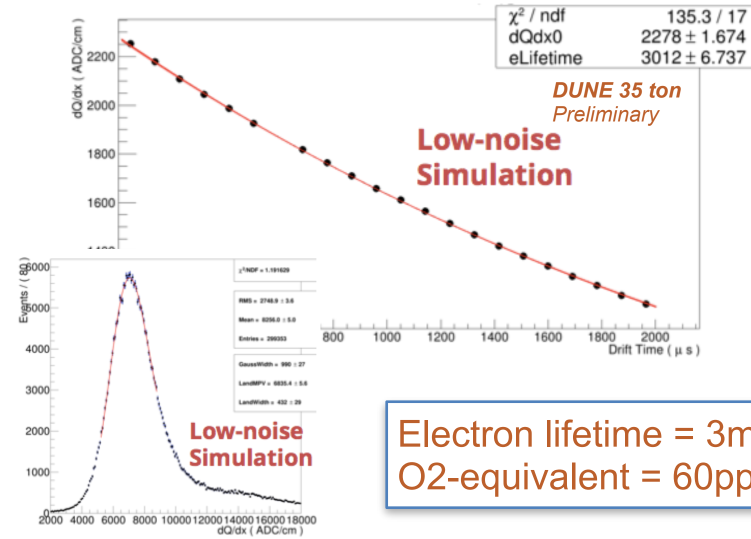
- Charge attenuation due to electronegative impurities (e.g. O2, H20).

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

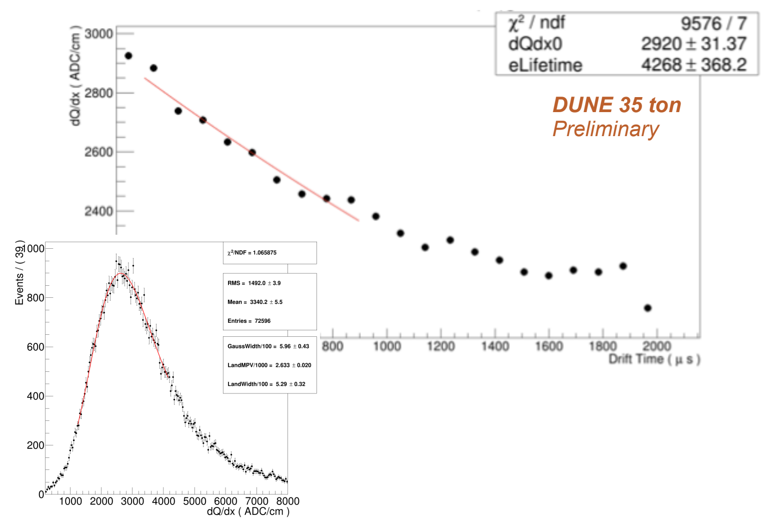
- Impurity concentration of *i* species is determined by electron lifetime:

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

- 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.



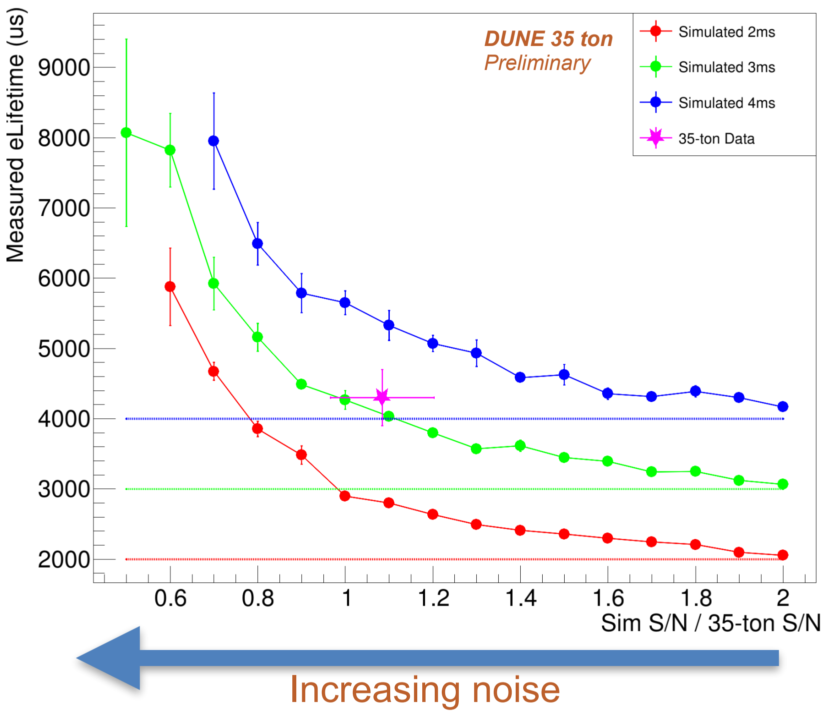
Electron lifetime = 3ms
O2-equivalent = 60ppt



M Thiesse

Measuring Purity from Tracks

- Because of noise, hit finding threshold is above low end of Landau — effect gets worse at longer drift distances.
- 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.
- Examine biases by applying 'data-driven' noise model to simulation:
    - Add waveforms from unbiased data runs to simulated waveforms.
- Measured lifetime is consistent with simulation if S/N is high enough.
- Real data electron lifetime implied —> ~ 3.2 ms.



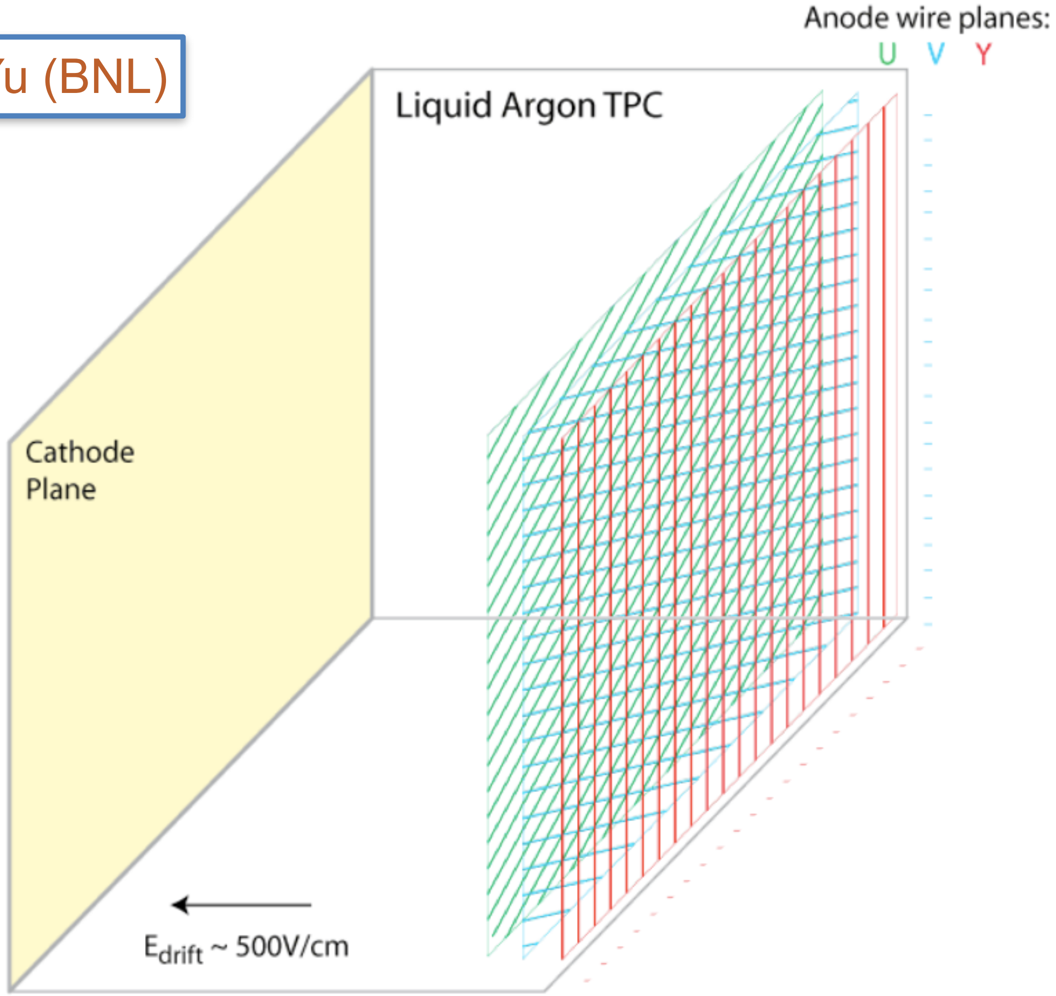
Summary

- The DUNE experiment has the capability to make world leading measurements and will drastically 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.
- The 35ton prototype is the first test of the DUNE detector design and a lot has been learnt from the experience.
- Lessons learned from the hardware, DAQ and detector systems is currently being taken forward into the next prototype, ProtoDUNE.
- Unique analyses were possible with the 35ton data and lots of new ideas developed which will be vital for the final DUNE far detector.
- Look out for publications in the coming weeks!

Backups

LArTPC Concept

Bo Yu (BNL)



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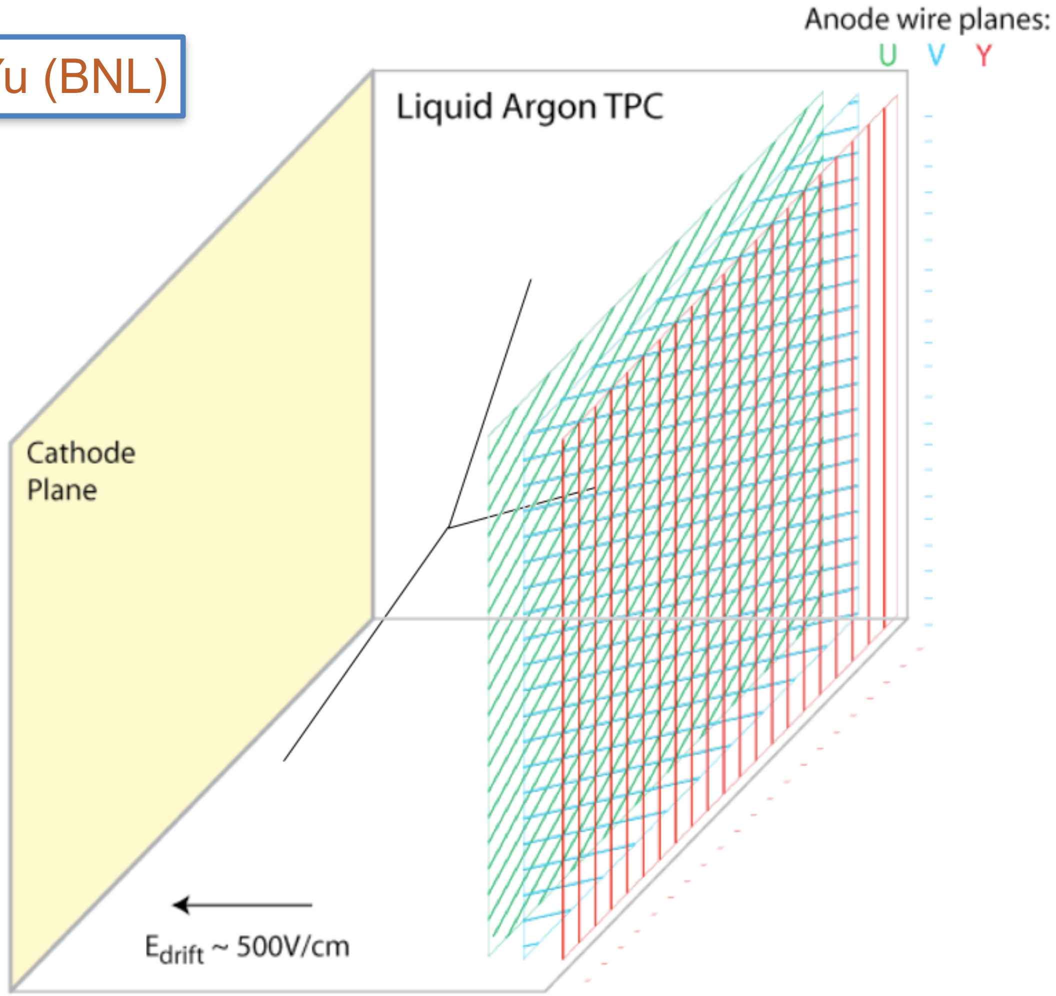

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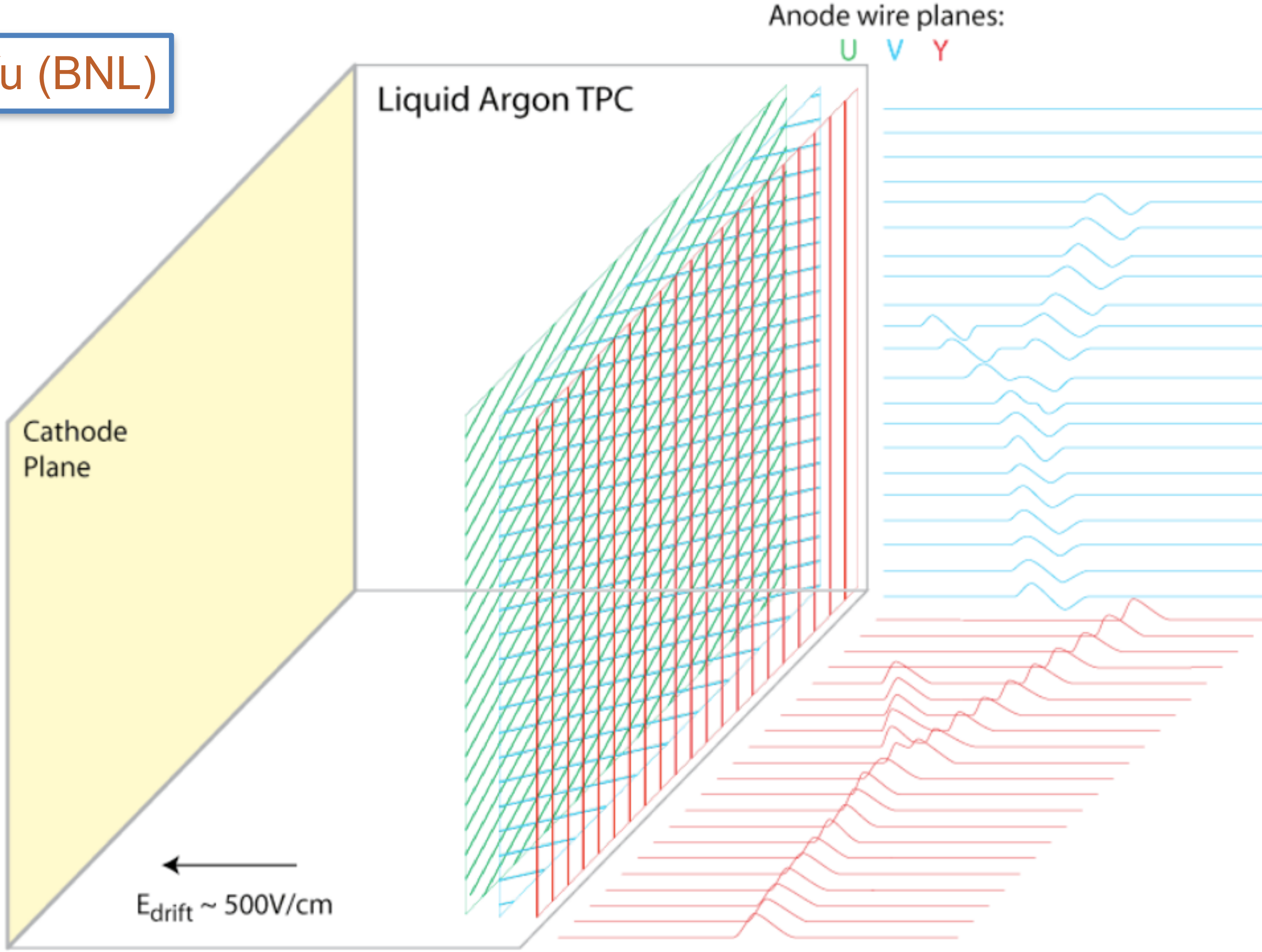

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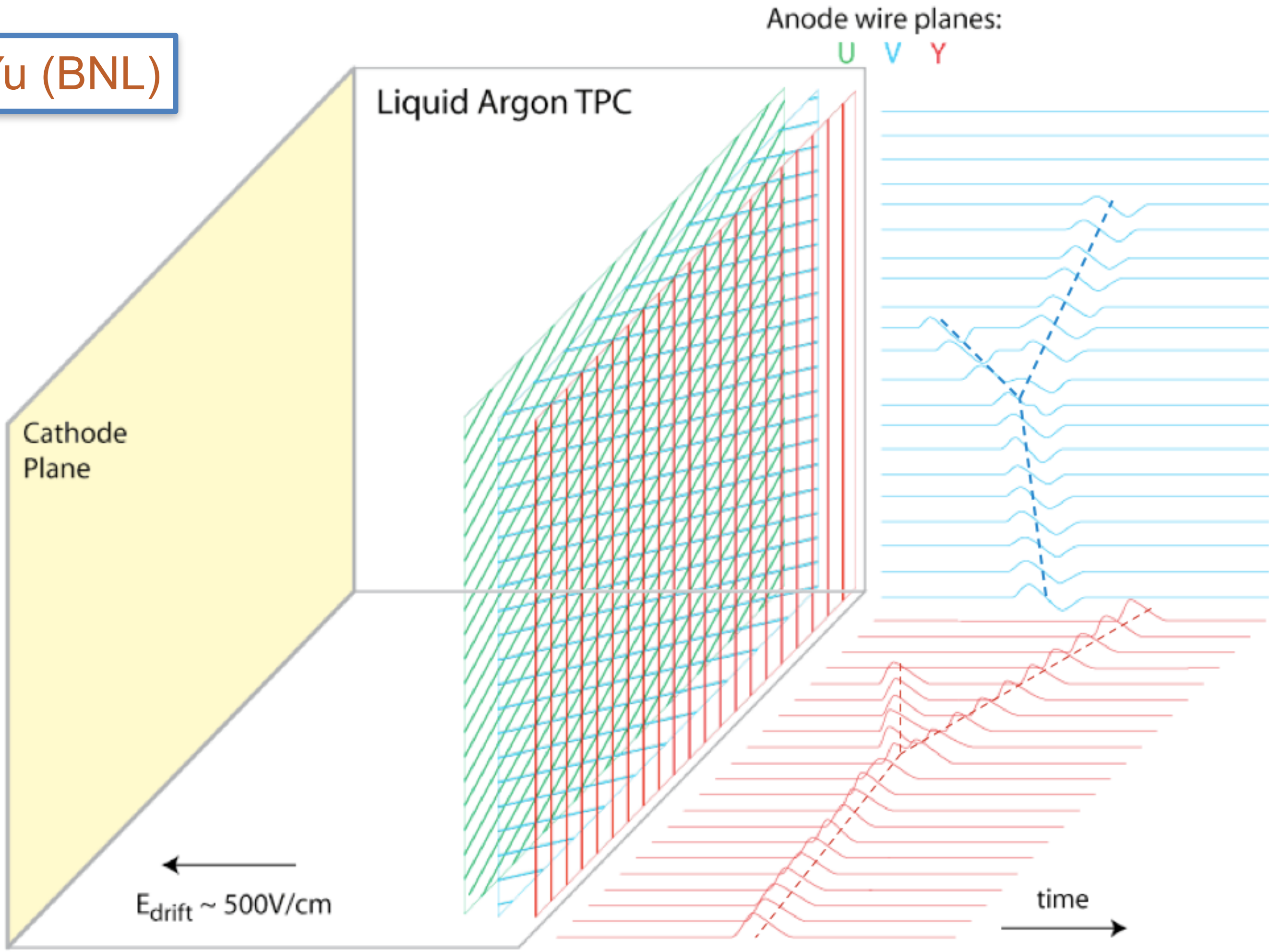
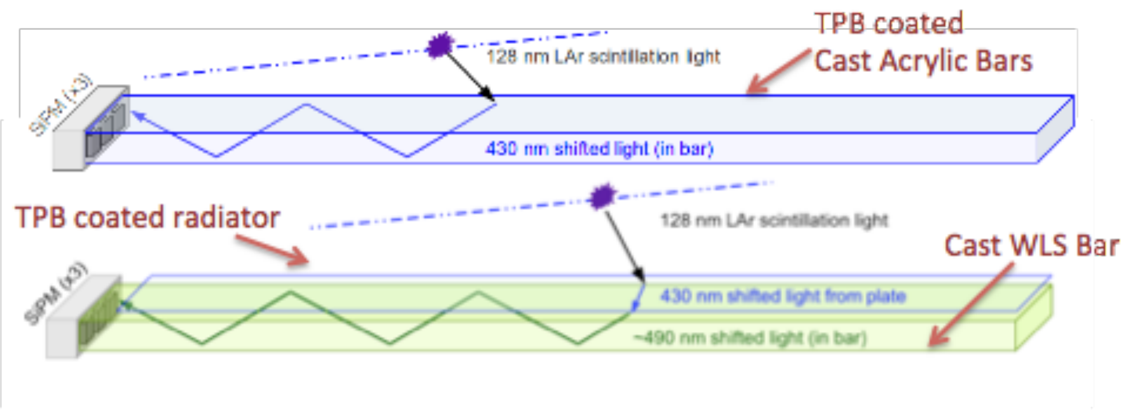


DUNE Single-Phase Photon Detection

- 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

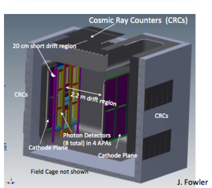
2017: Far detector construction begins

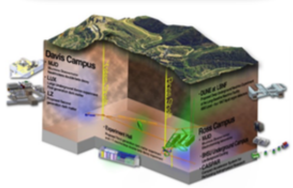
2018: ProtoDUNEs at CERN

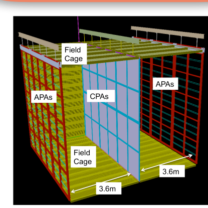
2021: Far detector installation begins

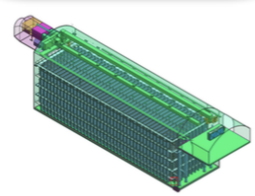
2024: Physics data begins

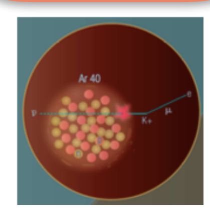
2026: Neutrino data taking

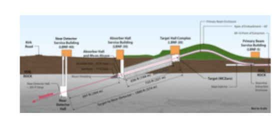








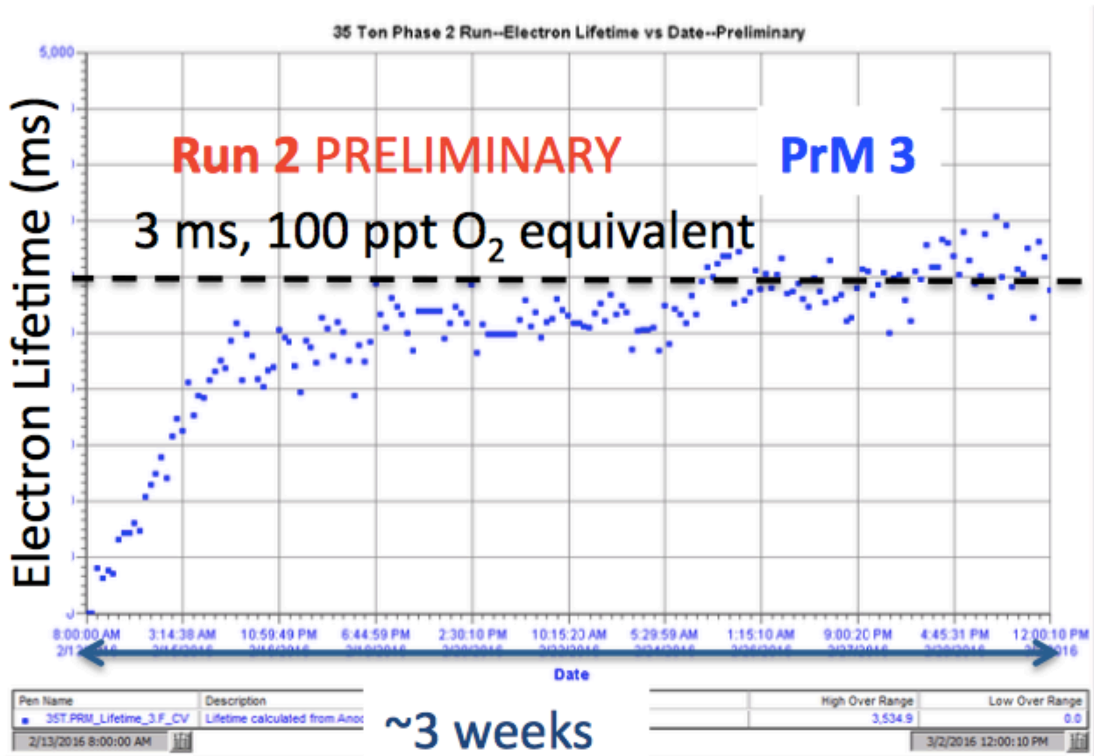




35-ton HV

- 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

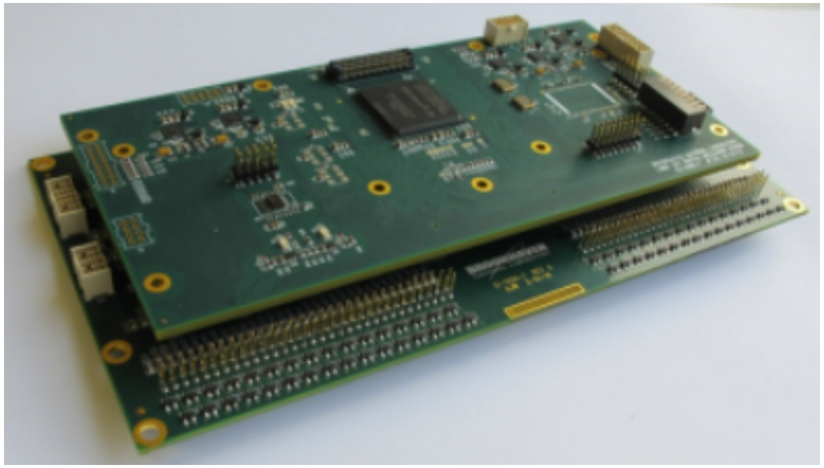


35-ton Field Cage

- Held 130 kV in contaminated argon

35-ton Cold Electronics

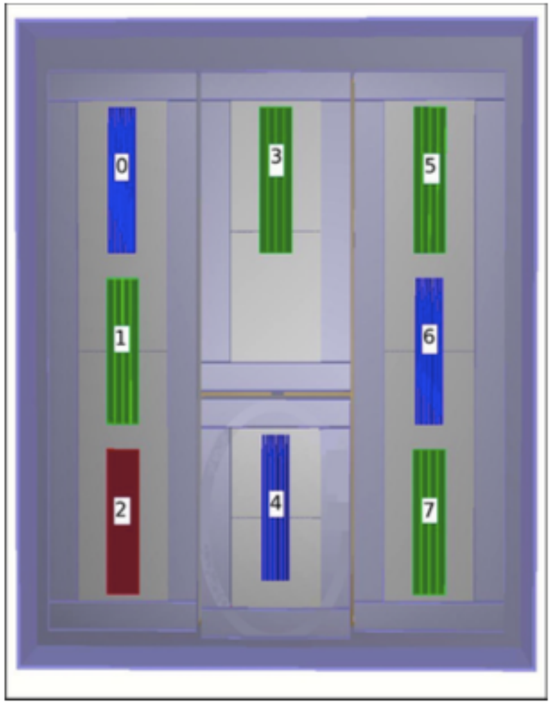
- First deployment of cold electronics (still under development).
- FE & ADC immersed in LAr.
- 128 channels per FEMB
  - High resonant noise, not all FEMB read out at same time.
- Noise tests have determined source of a lot of the noise (see next slide).
- Continuous testing during installation built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



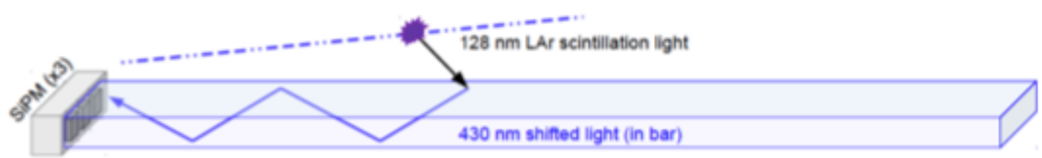
35-ton Noise Issues

- 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).

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

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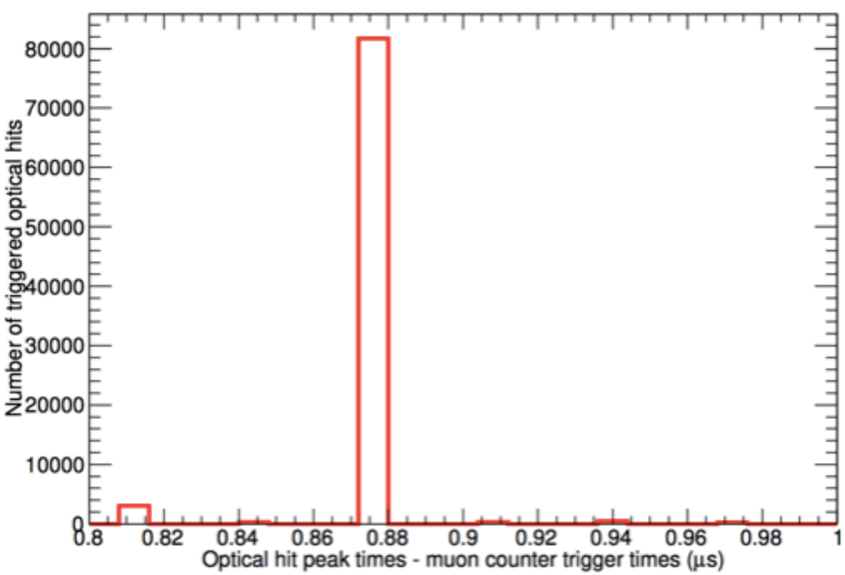
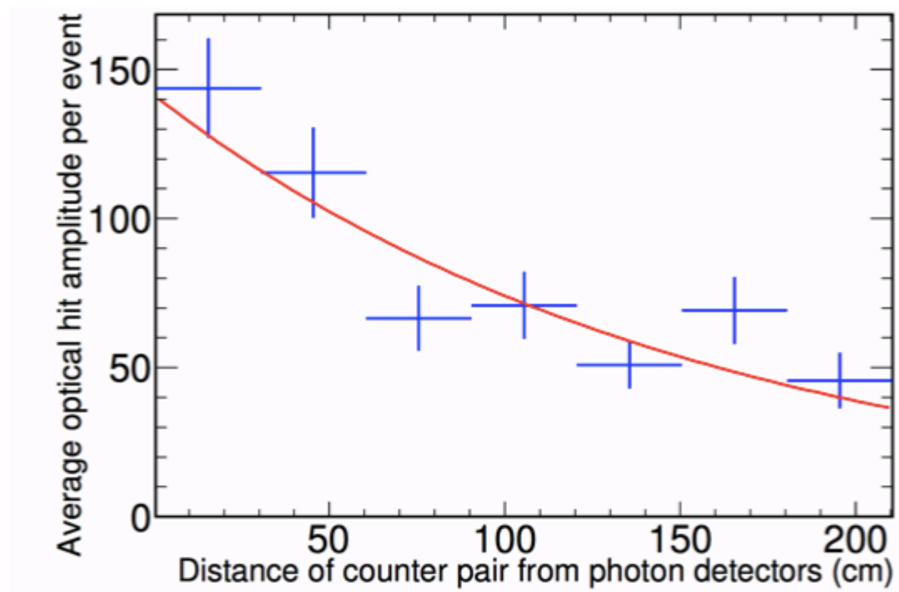
Photon Detectors

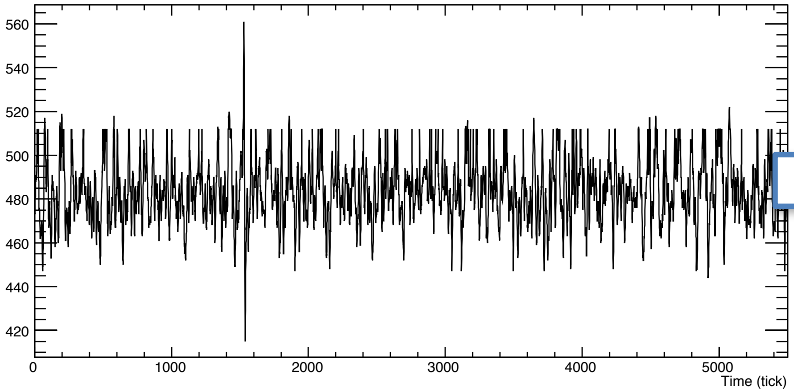
- Successful outcome of the 35 ton.
- Excellent timing resolution: < 100 ns wrt the external counters.
- Found an attenuation length for LAr of 155 +/- 28 cm.
- Lessons learned carried forward into the current DUNE designs.

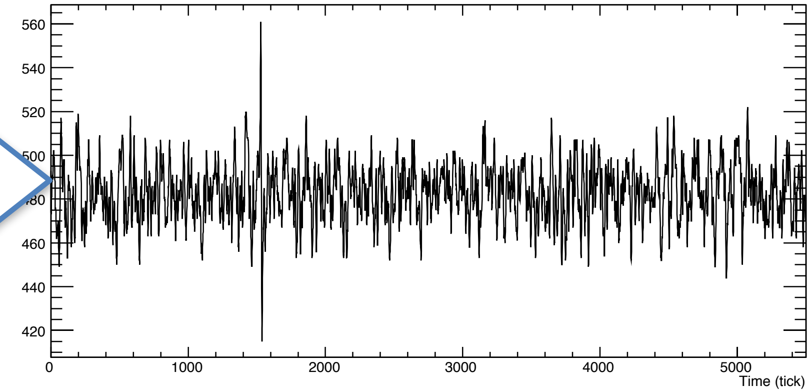




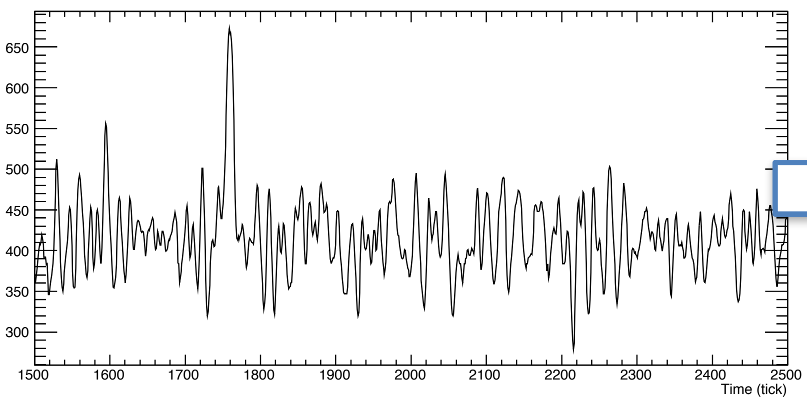
Preparing 35 ton Data

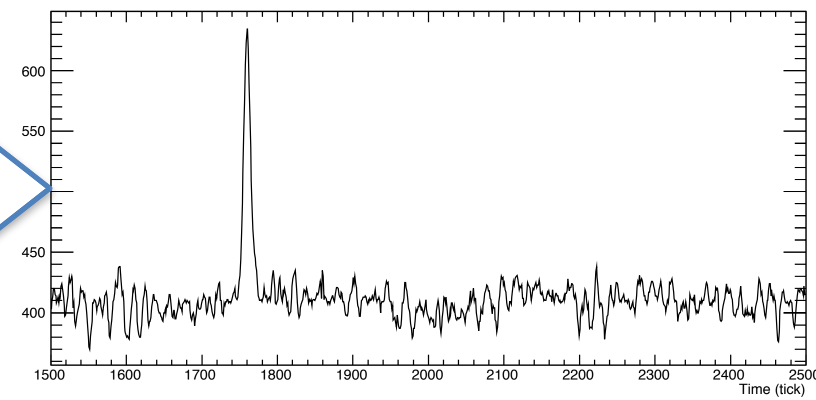
- Stuck code mitigation: ADC would randomly ‘stick’ at nearest multiple of 64





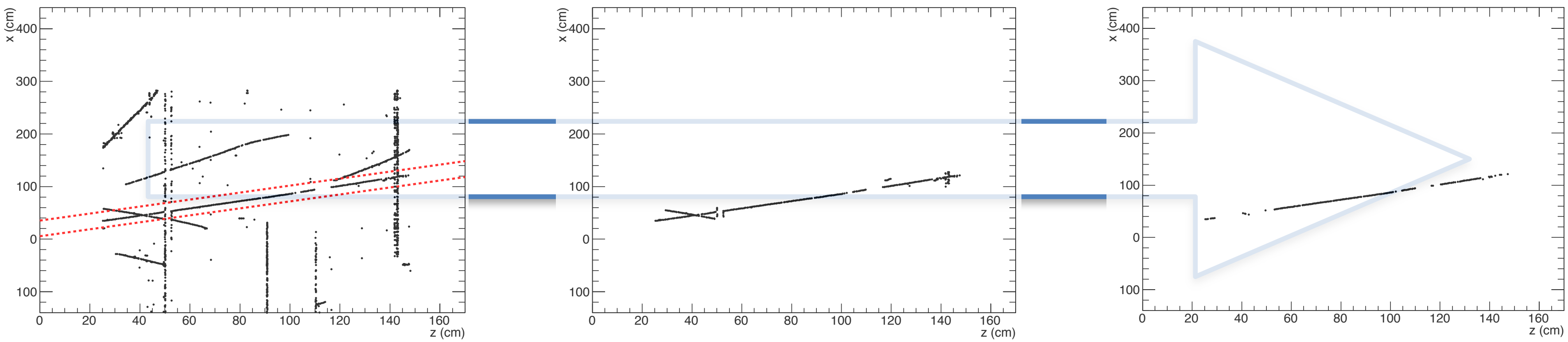
- Coherent noise removal: Applied across channels sharing FE voltage regulator





Reconstruction

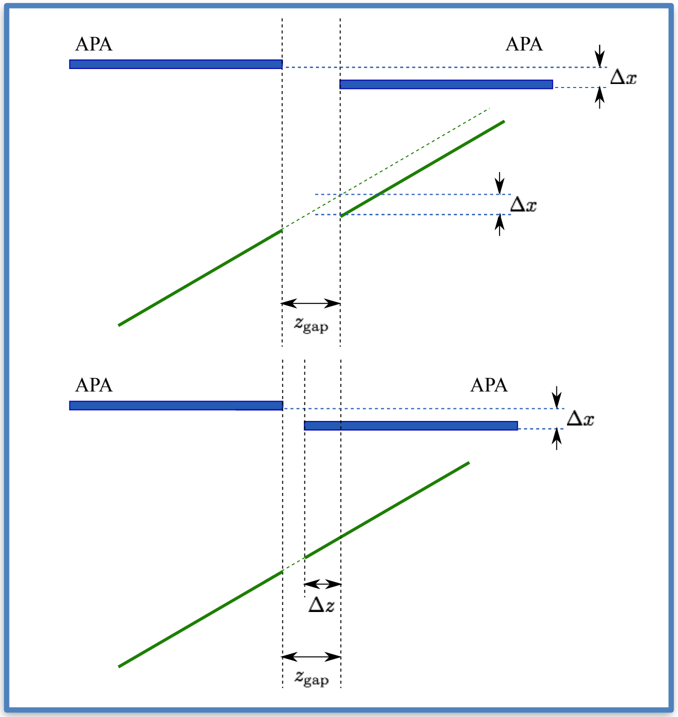
- Induction plane noise much larger than collection (longer wires —> larger capacitance).
- Most analyses use just collection hits — 2D reconstruction only.
  - Can get 'quasi-3D' reconstruction using the counter information from the triggering particle.

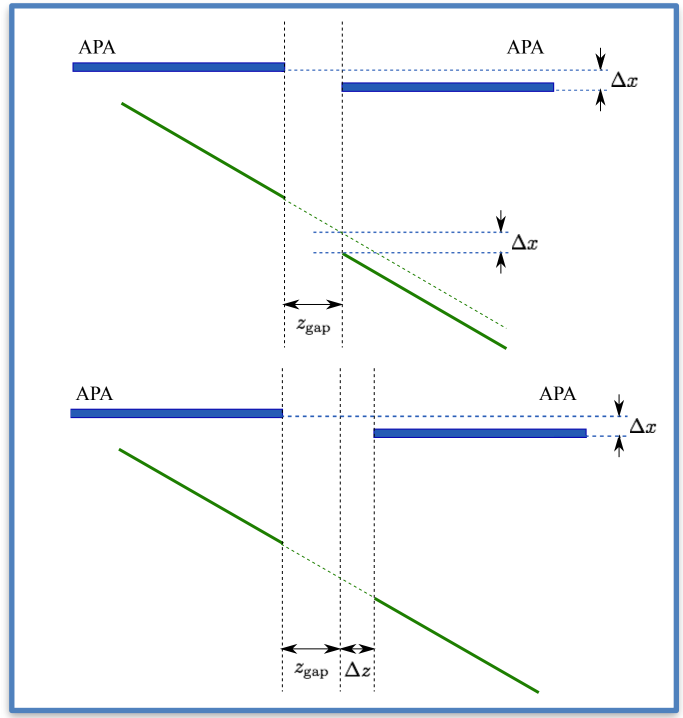


- Diffusion analysis uses track reconstruction.
- Purity analysis uses specially developed 'robust hit finder', designed to find hits efficiently given the noise issues. Thresholds for standard hit finding lead to hits being missed, or noise found, given the huge variations in noise across channels and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

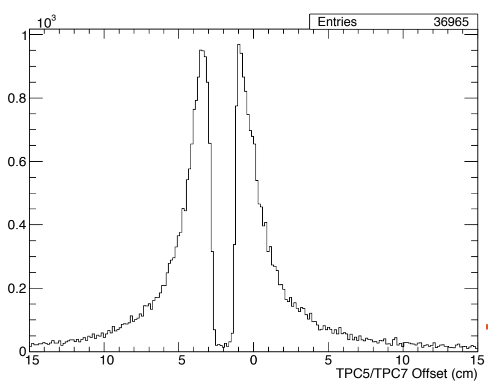
APA Gap Crossing Offsets

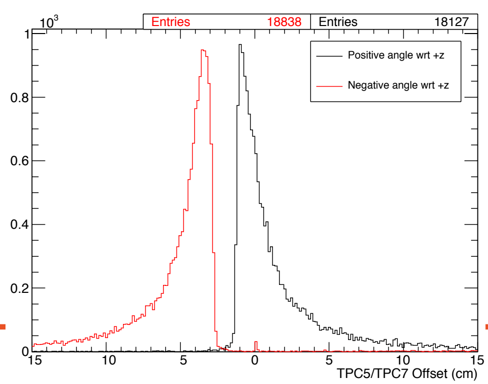
Positive track angle: measure negative *z*-offset





Negative track angle: measure positive *z*-offset

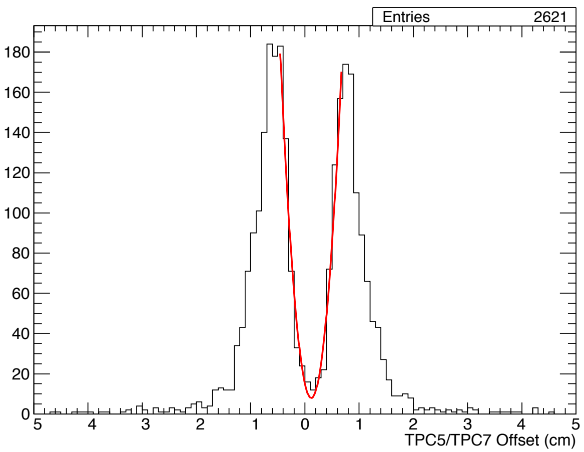


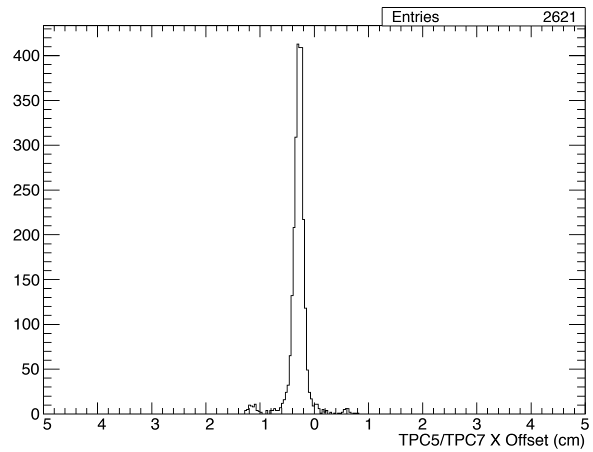


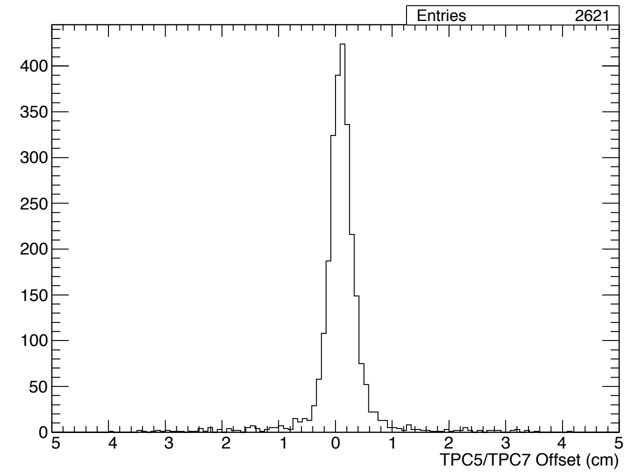
Tested in simulation — offsets of 2 cm in *z* and 0.5 cm in *x* artificially introduced. Same effect as seen in data!

APA Gap Crossing Muons

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



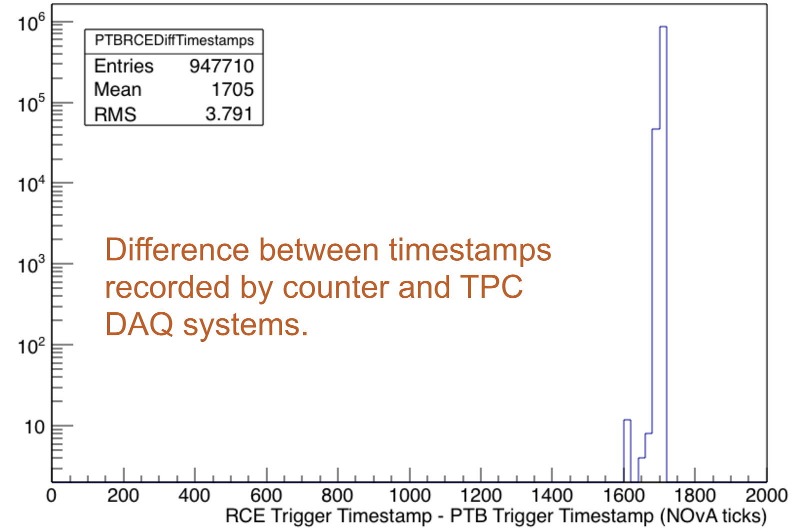


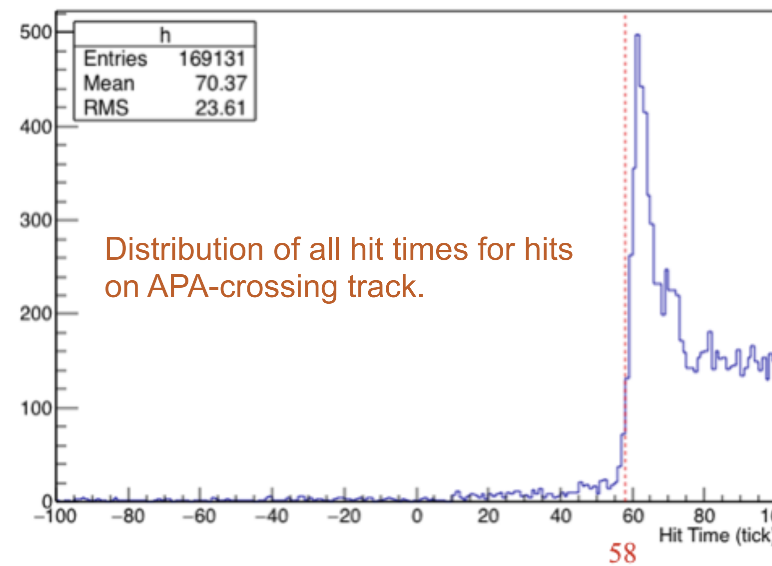


- Minimum of double peak distribution gives an estimate of the *z*-offset (from geometrical considerations).
- Can use that to measure the *x*-offset accurately.
- Then apply this *x*-offset to measure the *z*-offset again — this time with much greater accuracy.

APA-Crossing Muons: T0 Measurement

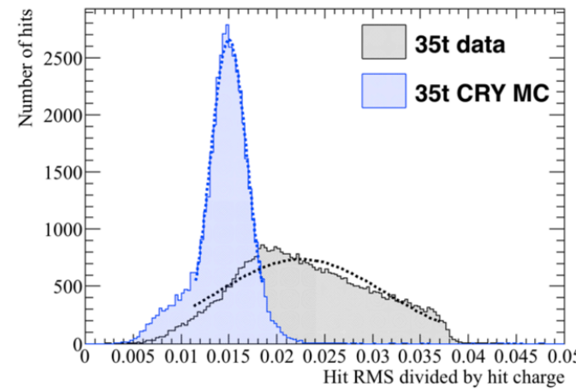
- Compare the timestamps of the trigger as recorded by the counters (PTB) and the TPC (RCE) (top plot):
  - 1705 NOvA ticks ~ 26.6 μs (~ 55 TPC ticks).
- Agrees reasonably with the leading edge of the distribution of all hit times on the APA-crossing track (bottom plot).
- Difference of ~ 6 μs between 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!



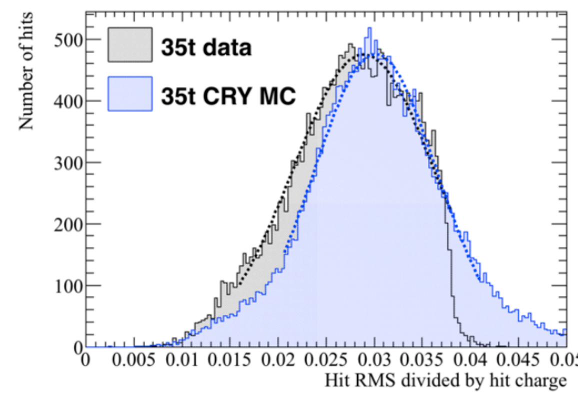


Measuring T0 from Diffusion

- 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.

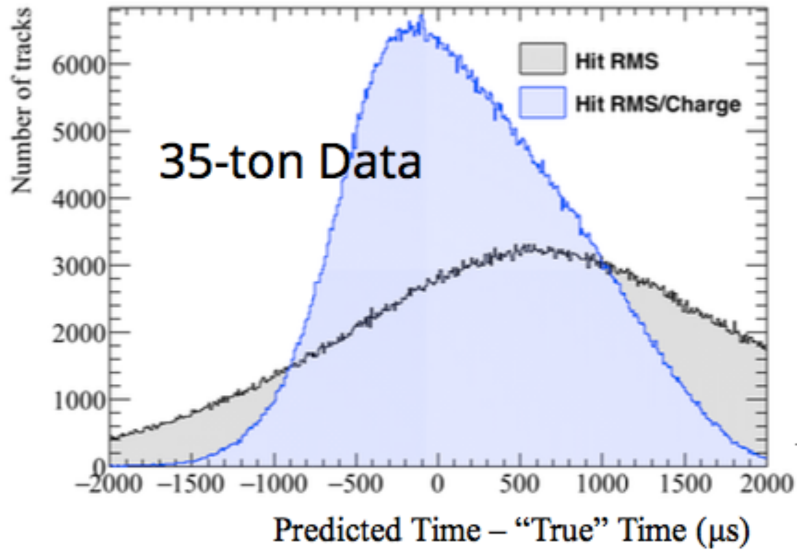


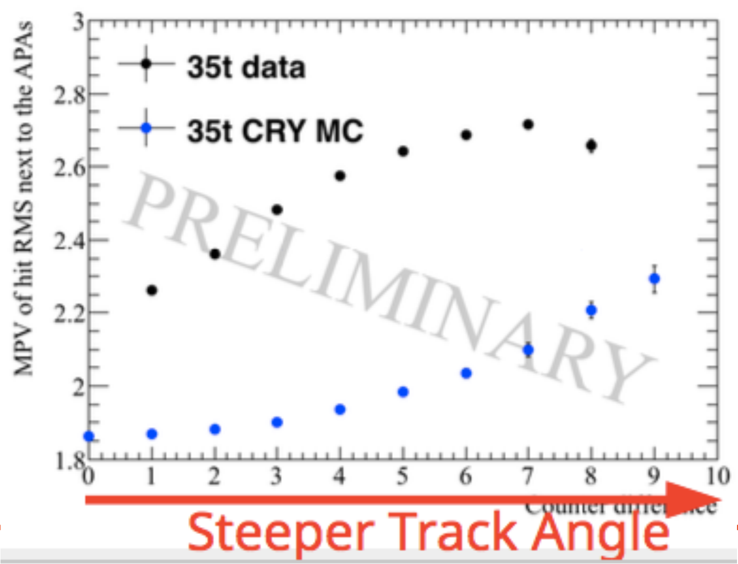
20 cm drift



140 cm drift

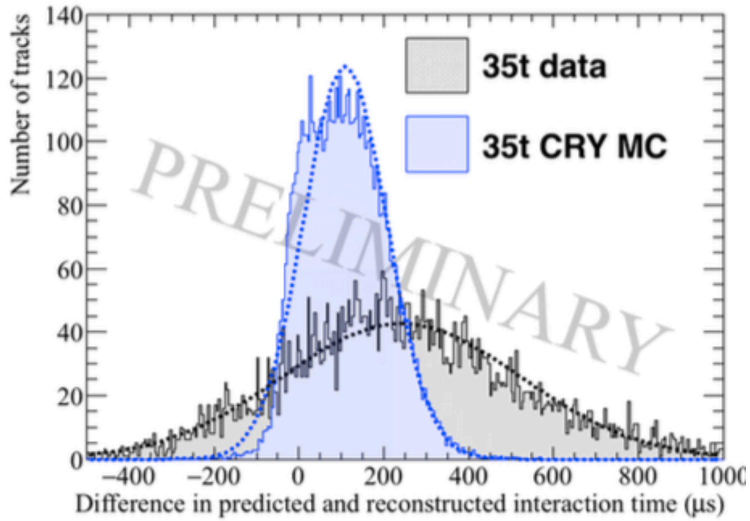
Diffusion RMS vs RMS/Charge Metric

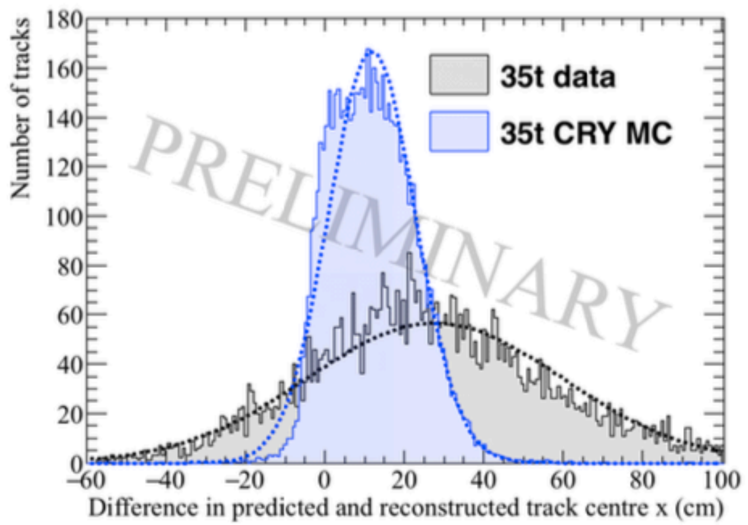




- RMS/Q better metric:
  - peaks closer to zero (more accurate);
  - Narrower (more precise).
- RMS shows strong dependence on track angle.
- RMS/Q removes this dependence.

Diffusion RMS vs RMS/Charge Metric





- Hit RMS metric

M Thiesse

Measuring Purity from Tracks

- 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.