Cosmogenic simulations for the DUNE far detector and particle identification in the 35 ton prototype

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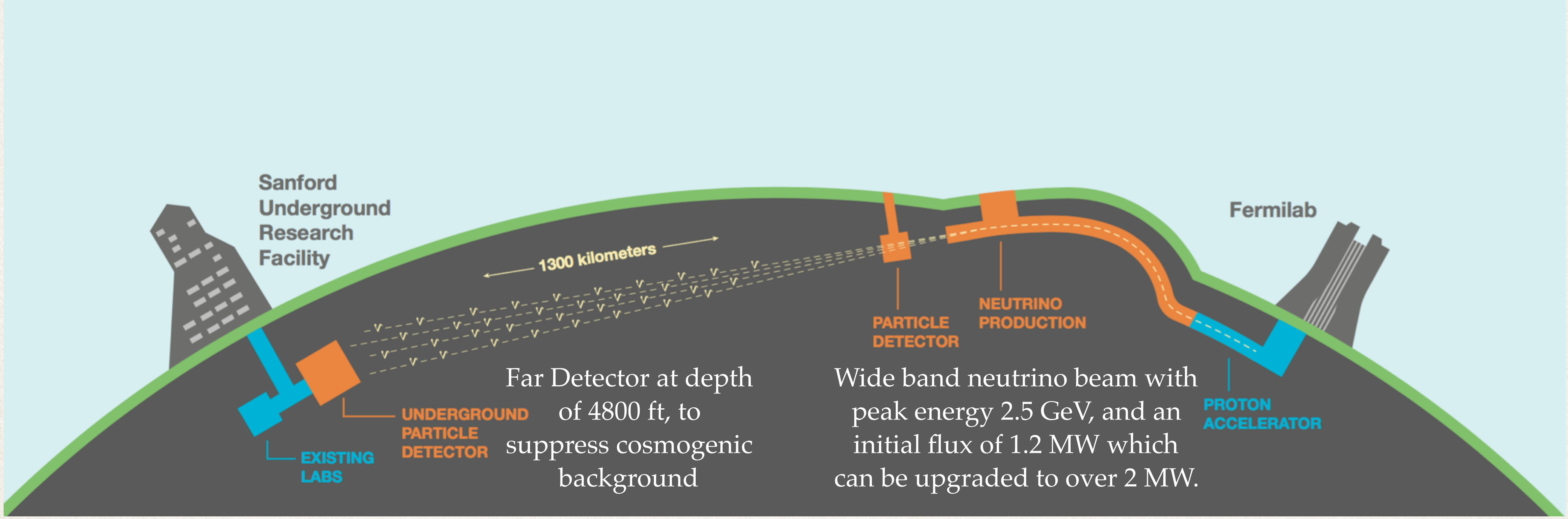
Overview

- Deep Underground Neutrino Experiment (DUNE) overview
- Reconstruction in Liquid Argon Time Projection Chambers (LArTPCs)
- Cosmogenic background at the DUNE far detector
- The 35 ton prototype at Fermilab
- Particle Identification in the 35 ton prototype
- Summary

Deep Underground Neutrino Experiment (DUNE)



- The flagship experiment of America's Neutrino program, due to start taking physics data in 2026 with 10 kton active LAr, full completion of four modules by early 2030's.

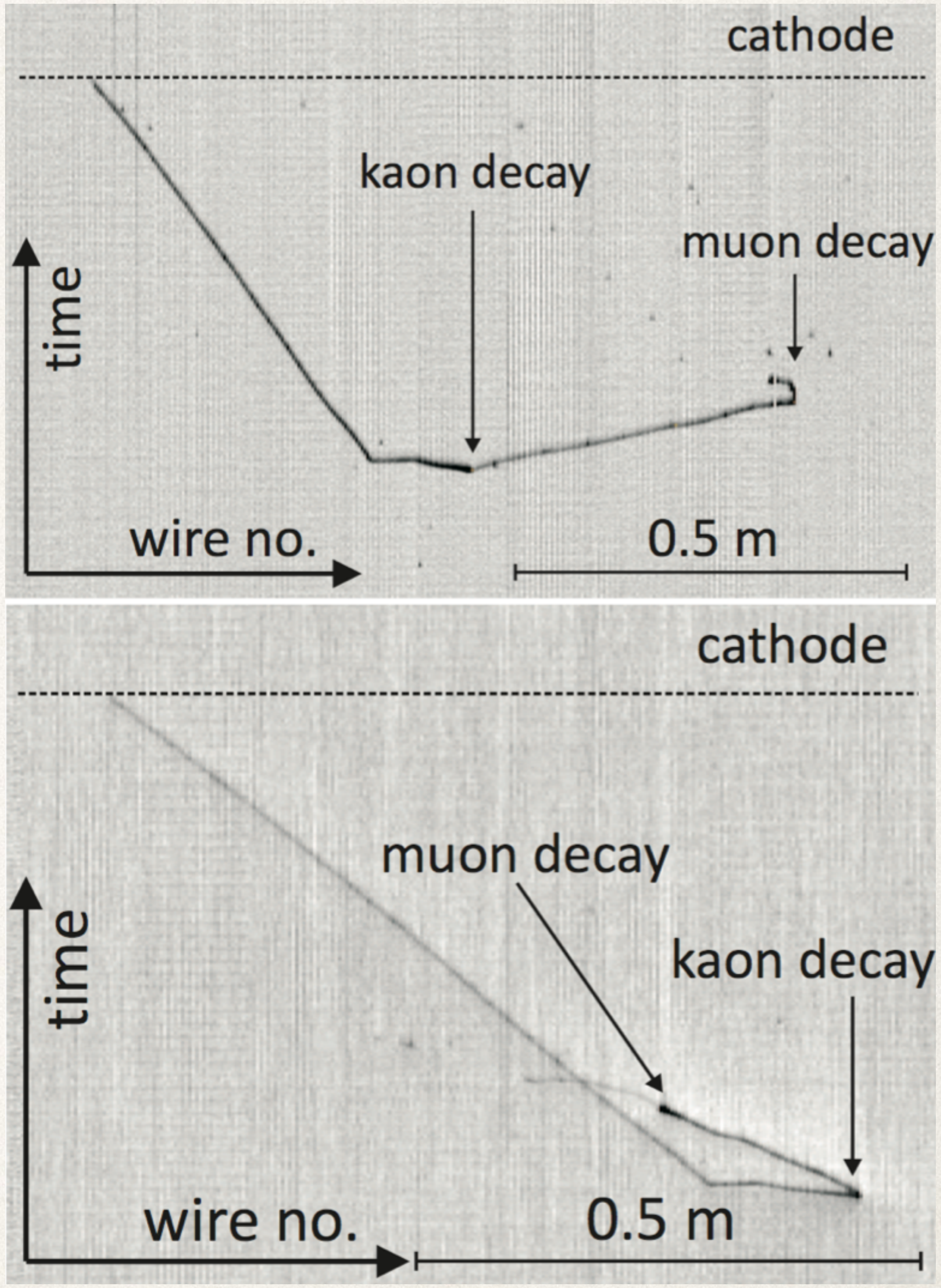
- Staged construction of 4 x 10 kton fiducial LAr detectors, the first of which will be a single phase LArTPC.

- Will have a high precision near detector, technology still to be decided.

- Designed to have a very rich neutrino oscillation programme, plus searches for nucleon decay and neutrinos from supernova bursts.

Reconstruction in LArTPCs

- LArTPCs are often compared to bubble chambers due to the high resolution of reconstructed tracks due to dense fully active detector medium.
- Collection and induction wire planes see pulses from ionisation electrons.
- Pulses are interpreted as hits on wires by reconstruction algorithms.
- Hits are combined into 2D clusters and then into 3D objects such as tracks.
- This requires;
    - A high electric field (500 V cm^{-1})
    - High LAr purity
    - High signal to noise on wire planes
    - Sophisticated reconstruction algorithms.



A reconstructed event from a cosmic induced decay in Icarus.
Antonello et al., Adv. High Energy Phys., vol. 2013, p. 260820.

Observing proton decay in DUNE

- High quality reconstruction means that with sufficient background rejection a single event would be enough to signal an observation.

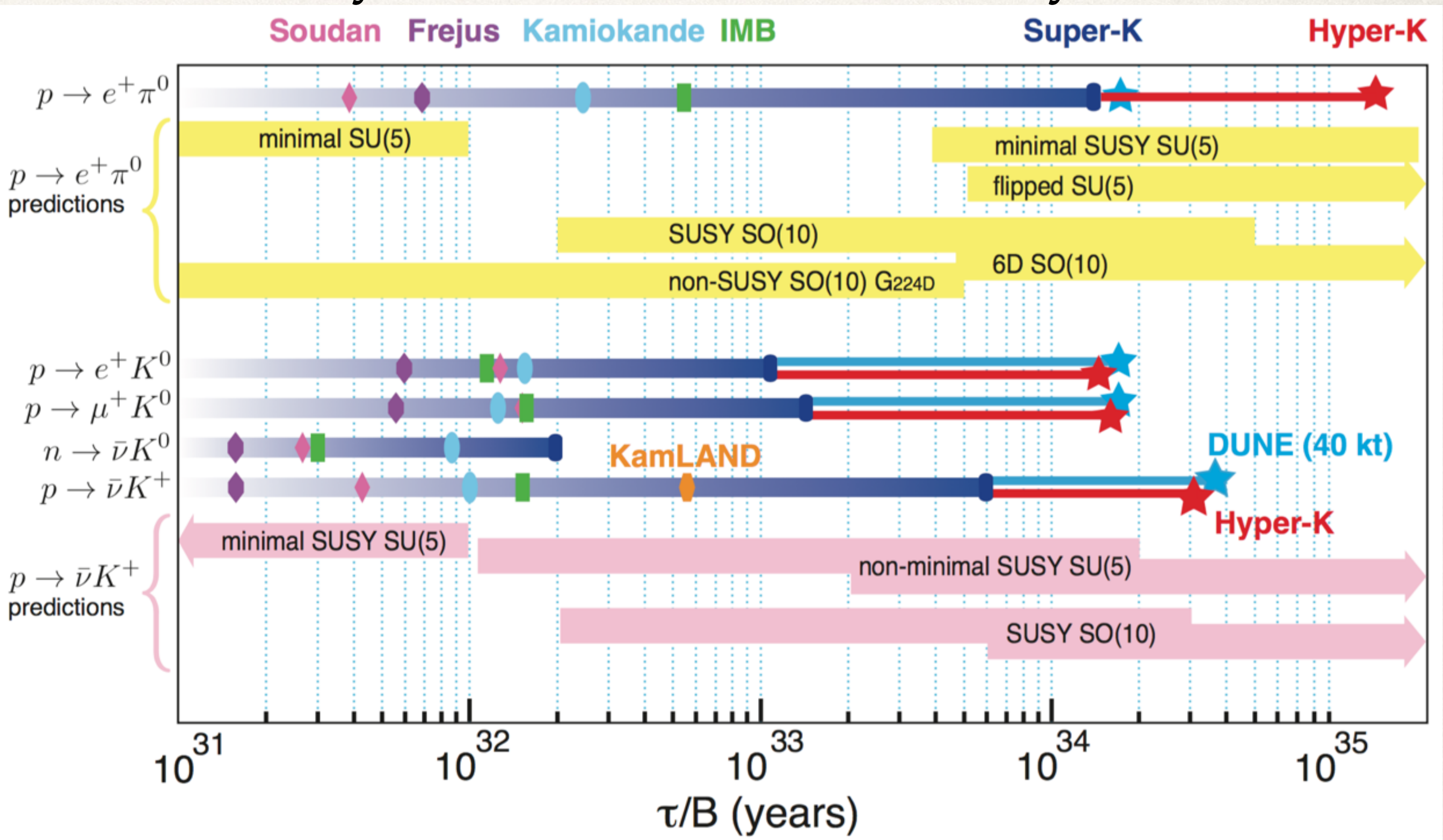
- Two of the most prominent signals searched for are:

$$p \rightarrow e^+\pi^0 \qquad\qquad p \rightarrow K^+\overline{\nu}$$

- DUNE will be highly sensitive to the K^+ decay mode, as the whole decay of the K^+ would be fully reconstructable.

- A decaying Kaon is identified by looking at its energy loss as a function of distance travelled.

- This is much more difficult in water Cherenkov detectors where the momentum is below threshold.

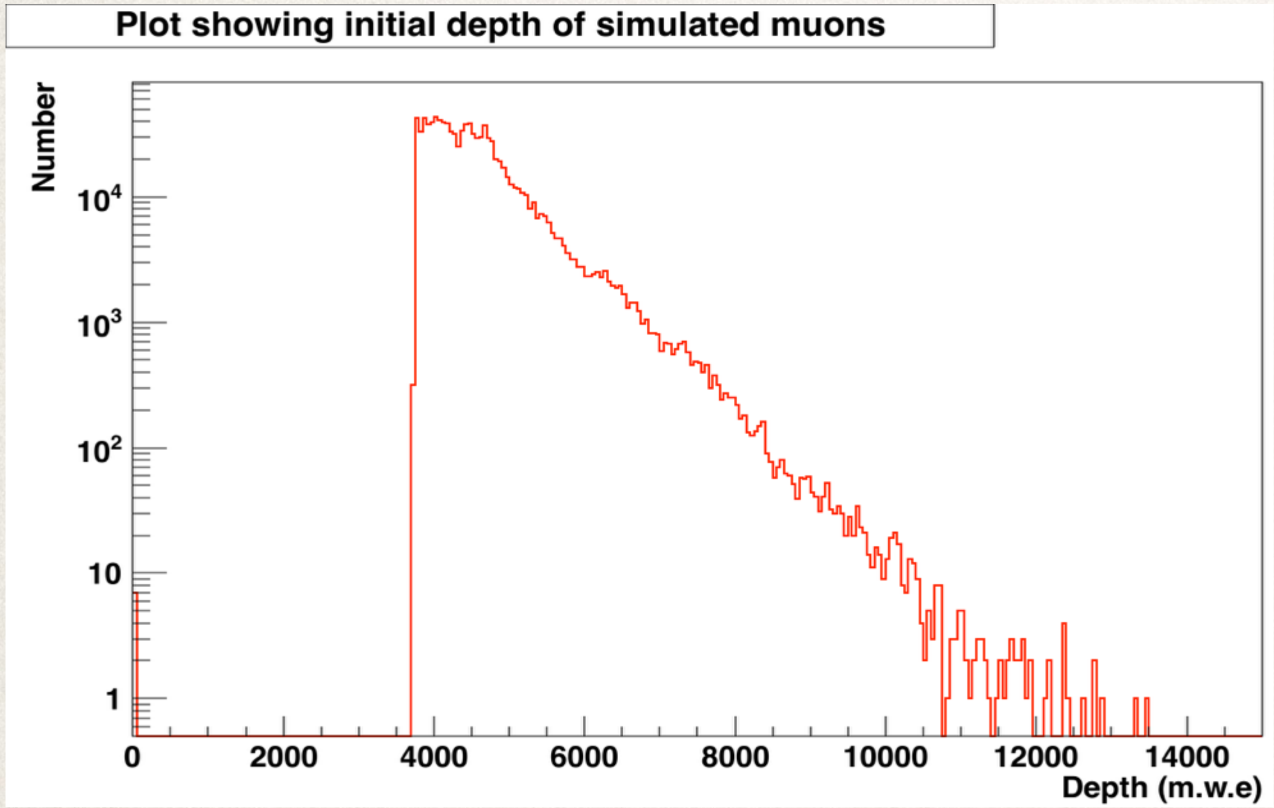


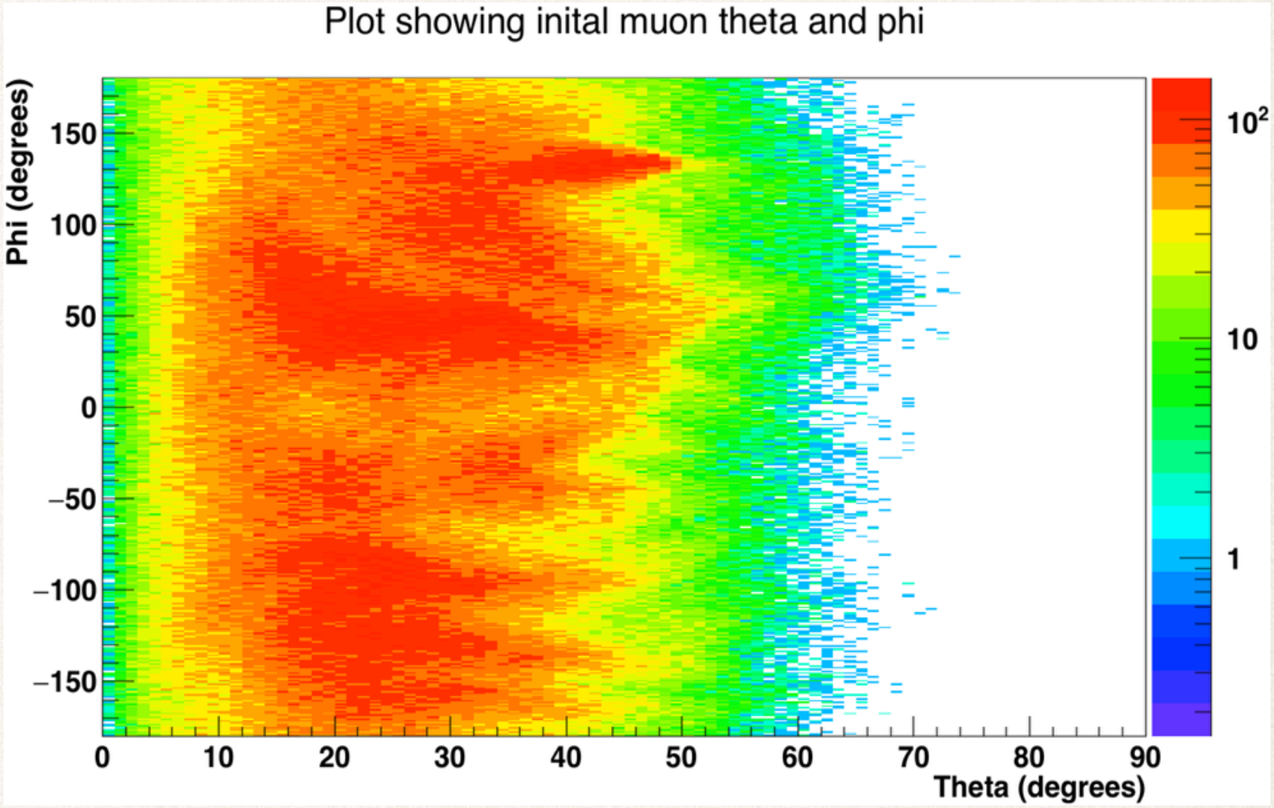
"DUNE CDR document" ArXiv:1512.06148

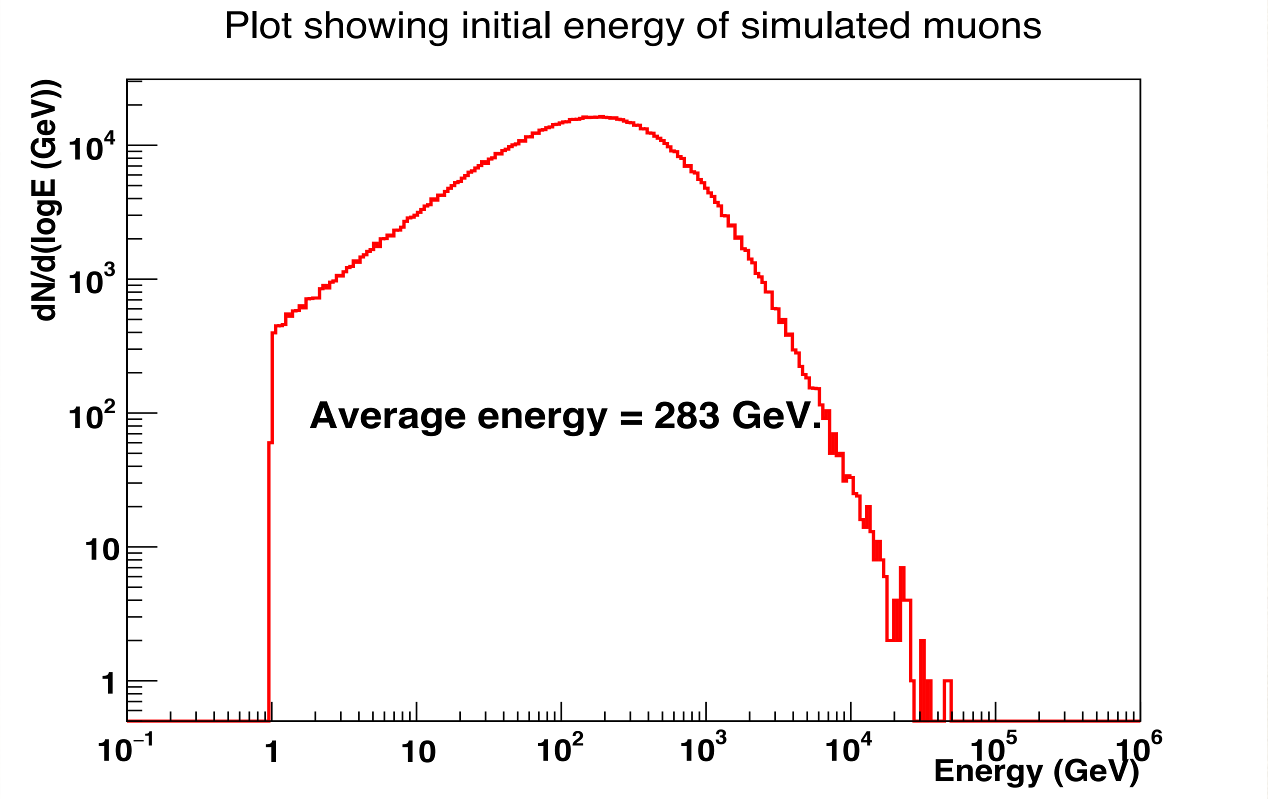
Simulating cosmogenic background

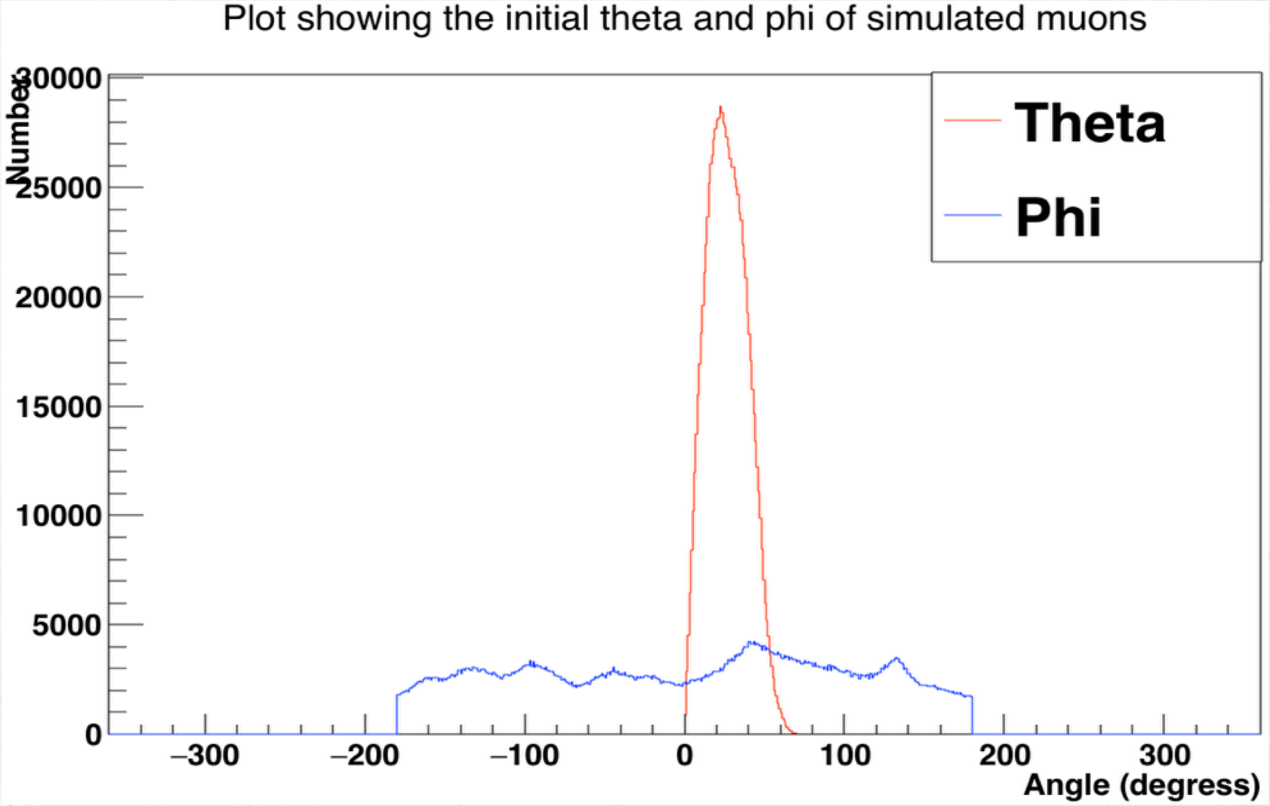
- All physics goals require detailed estimations of cosmogenically induced background.
- Siting the detector at 4850 ft level vastly reduces background.
- MUSUN (MUon Simulation Underground) which takes the output from MUSIC (MUon SImulation Code), V. Kudryavtsev ArXiv: 0810.4635, has been incorporated into the software used by DUNE,. Monte Carlo simulations are being performed using this software.
- Muons are generated on a cuboid in the rock surrounding the detector and propagated using GEANT4.
- A rock density of 2.7 g cm^{-3} is used, and the surface profile is considered.

Spectrum of simulated muons



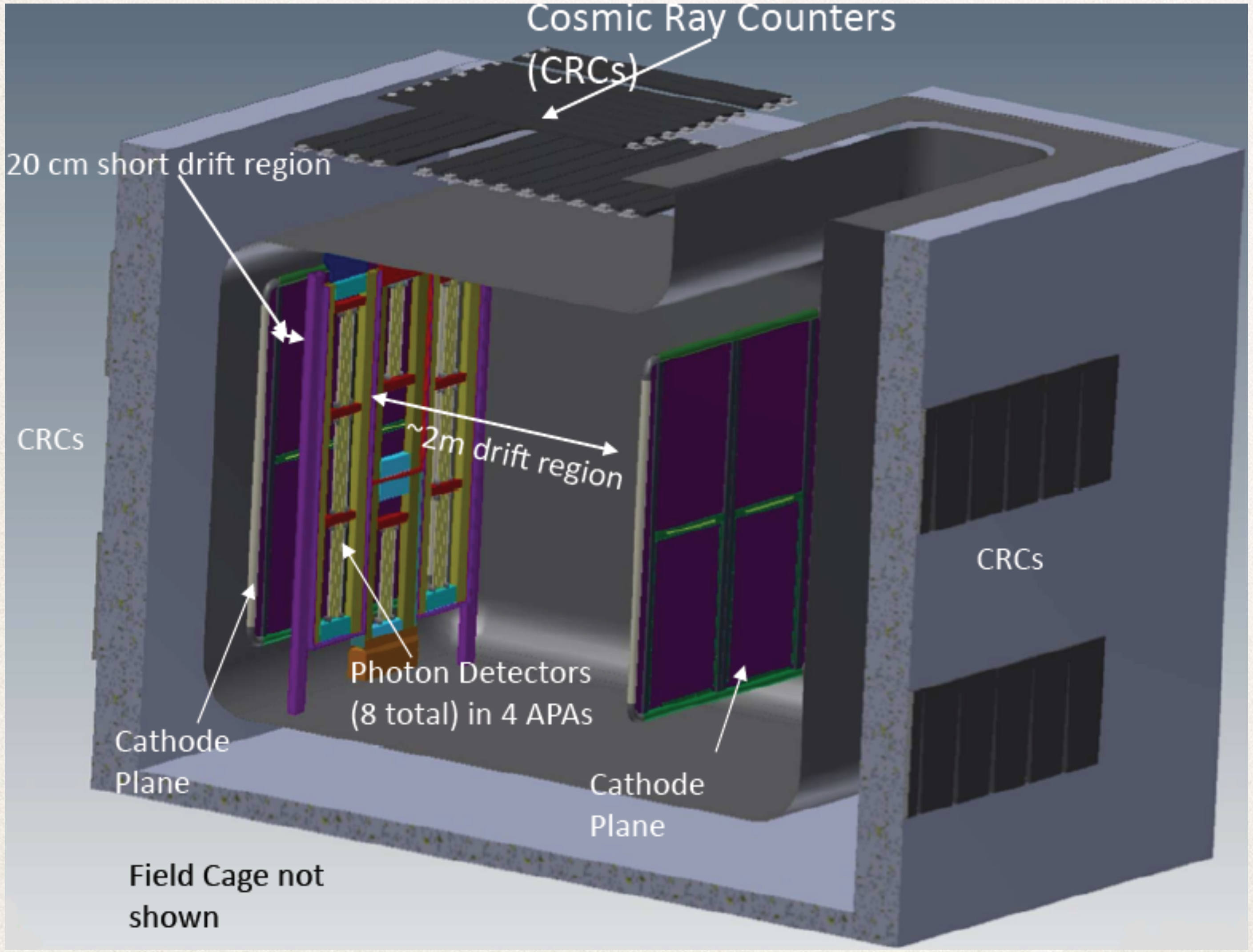






The 35 ton prototype

- A detector of the scale of DUNE requires significant prototyping as the design is different from other single phase LArTPCs.
- Also serves as verification of reconstruction algorithms and a test for PID.



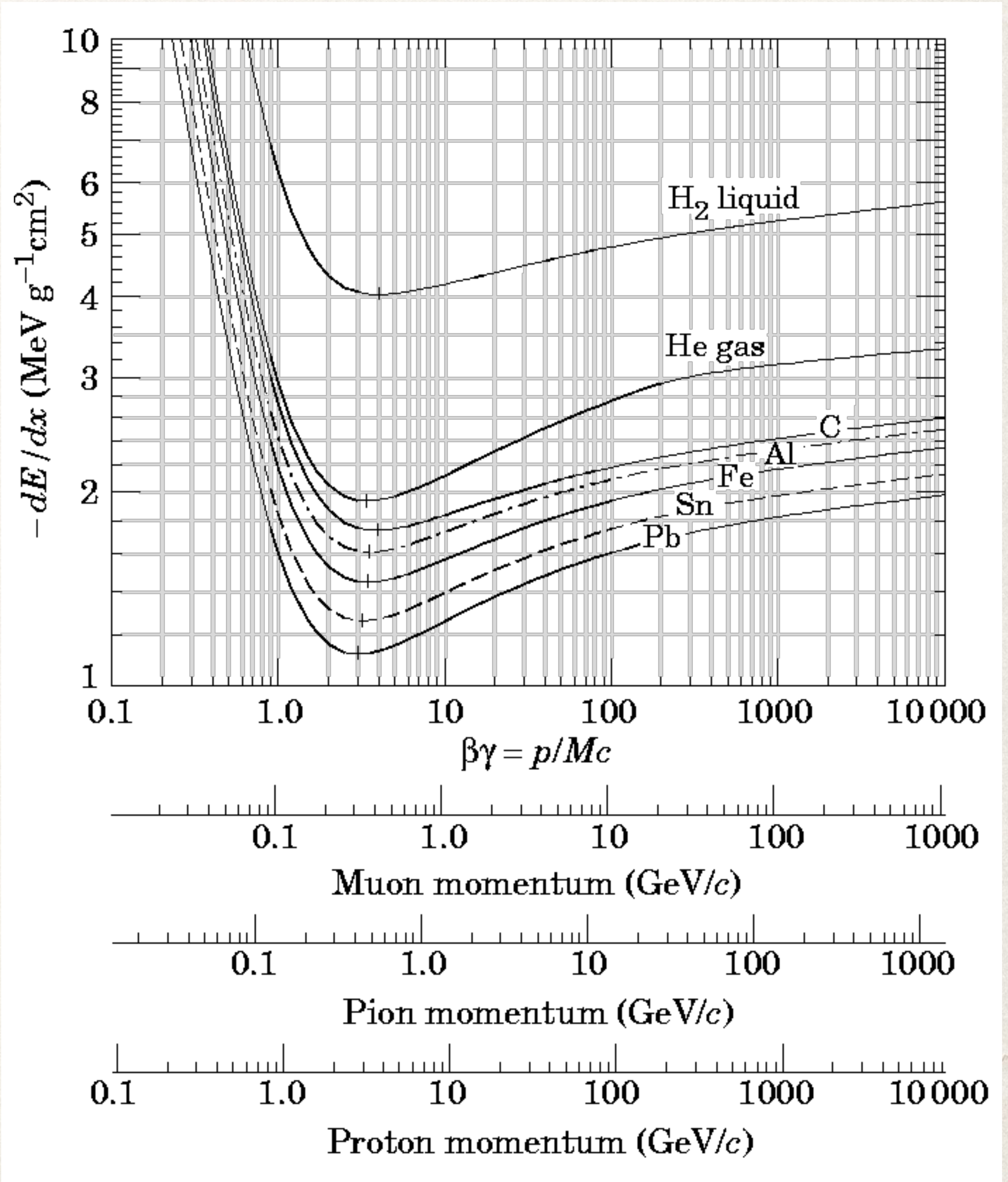
Above: Picture inside the 35 ton.
Left: Schematic of the 35 ton.

The 35 ton prototype

- Run 1 (Jan - Mar 2014), was the first LAr vessel built using a membrane cryostat. Achieved an electron lifetime of 3 ms.
- Run 2 (Jan 2016 - now), installed a detector to be tested with cosmic rays into the cryostat. It has many novel features:
  - FR4 printed circuit board field cage
  - Wrapped wire planes
  - Multiple drift volumes
  - Cold electronics - ASICs are in the cold
  - Triggerless DAQ operation
  - This is the first time that many of these systems have been used in an integrated detector.

Particle Identification in the 35 ton

- Bethe-Bloch equation describes energy loss per unit length as a function of energy in different materials.
- It is particle dependant, as shown by the particle dependant scales.
- LAr (1.4 g cm^{-3}) is slightly less dense than Carbon (1.8 g cm $^{-3}$)
- There is a large difference in the functions for muons and protons, so should be able to distinguish between them in the 35 ton.



A particle identification metric - PIDA

- Bethe-Bloch equation has power law dependence near stopping point.
- Table shows weak dependence on b, so set b = 0.42, and model dE/dx calculation by:

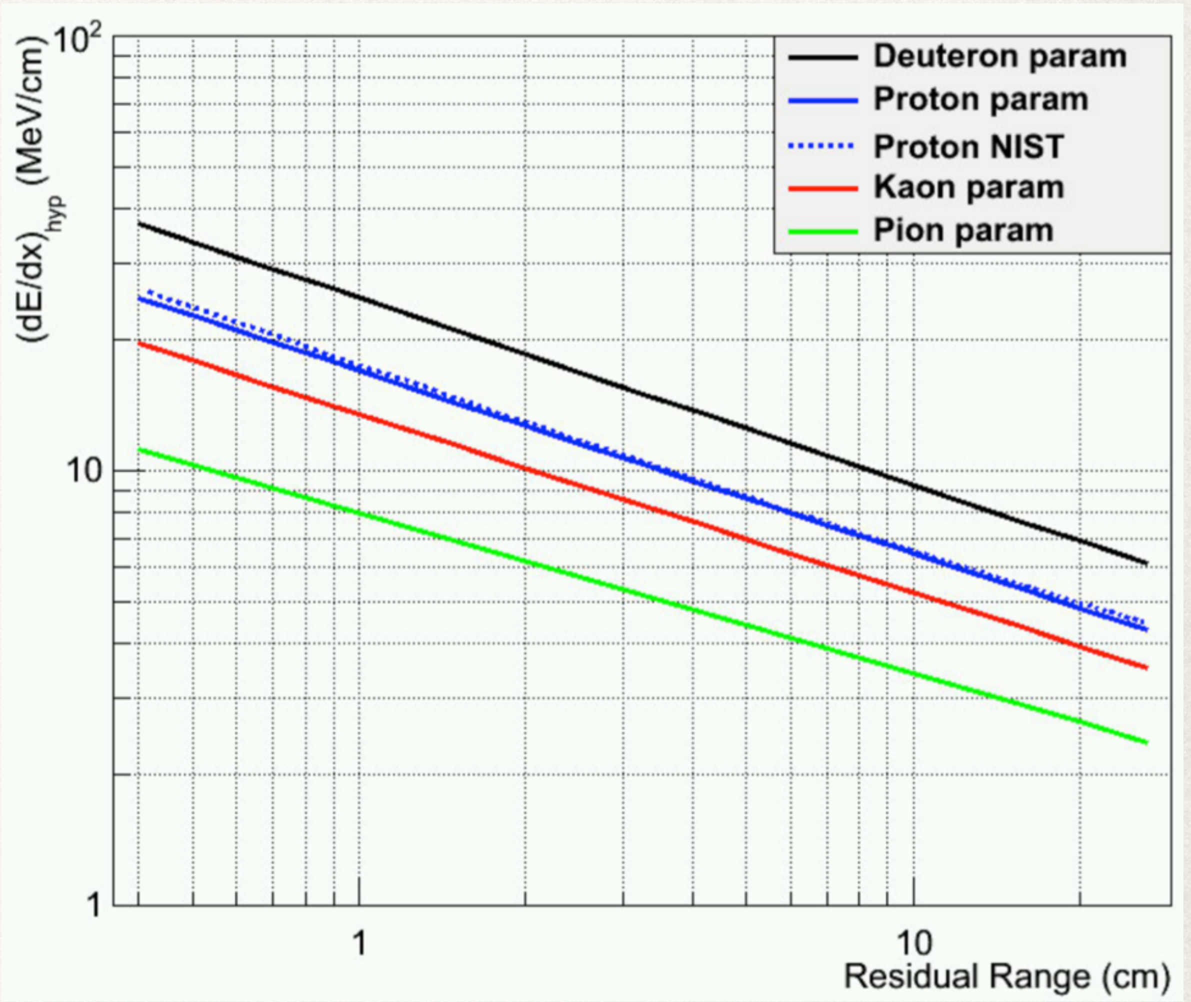
$$(dE/dx)_{hyp} = A\,R^{b}$$

- Calculate a value for PIDA by:

For each space point i, calculate

$$A_i = (dE/dx)_{calo} \times R^{0.42}$$

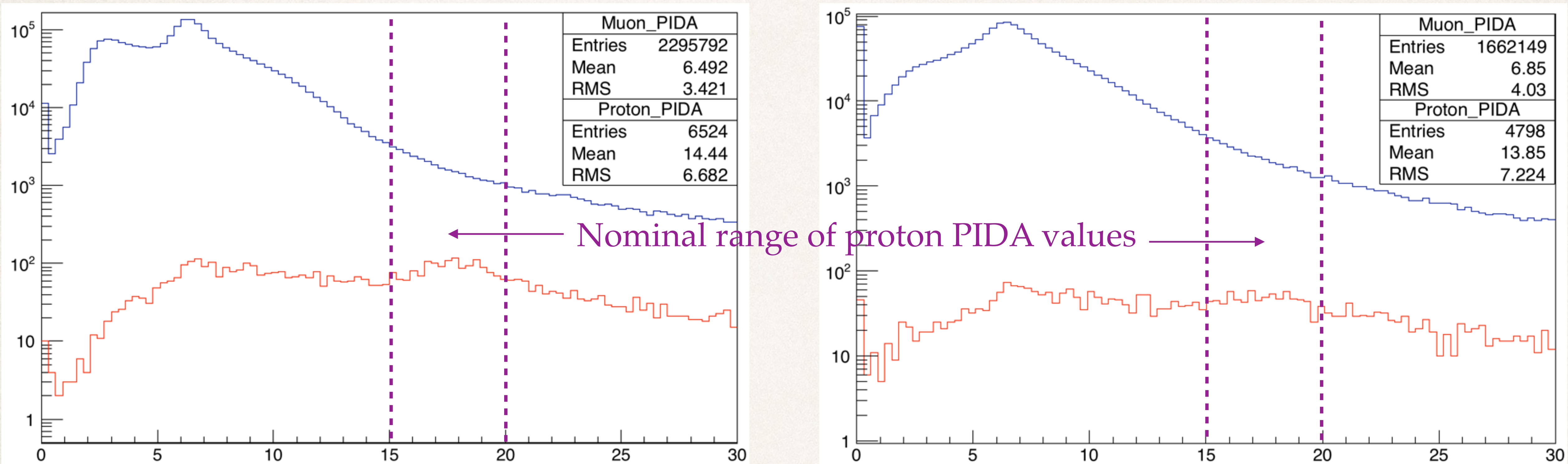
Define PIDA as the average value for the track.



Particle	A MeV/cm^{1-b}	b
pion	8	-0.37
kaon	14	-0.41
proton	17	-0.42
deuteron	25	-0.43

R. Acciarri et al., arXiv:1306.1712

Calculated PIDA for a CRY sample



Calculated PIDA values using PMTrack reconstruction

Calculated PIDA values using Pandora reconstruction

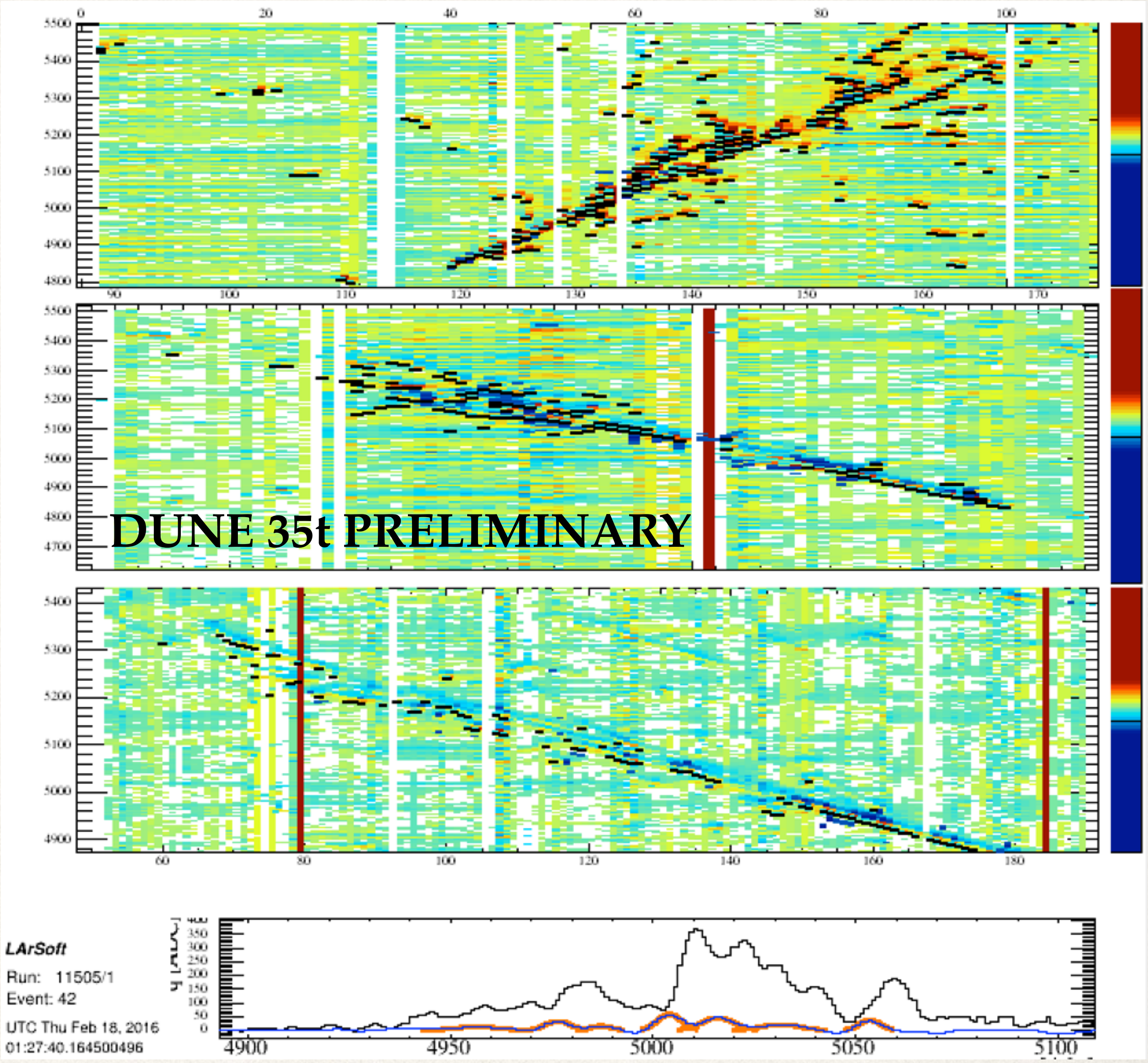
- There are two tracking algorithms used by the 35 ton:
    - PMTrack, Antonello et al, ArXiv:1210.5089.
    - Pandora, Marshall & Thompson, arXiv:1506.05348.
- Plots show a continuous detector live time of 40 minutes.
- Both reconstruct tracks with lengths greater than 10 cm excellently, but struggle with the shortest tracks, where they both correctly reconstruct around 25% of tracks.

Considerations from PIDA plots

- The peak at 6 MeV cm^{-1} for protons is due to Minimally Ionising Particles (MIPs). Some of these are broken tracks, as start and end positions are correlated to TPC boundaries.
    - Fixing broken tracks may increase resolution of calculated PIDA.
    - Imposing a minimum number of unique hits would also increase the resolution of the calculated PIDA values, as tracks with few hits are likely to be inaccurate.
    - An exact calculation of track end point, could increase resolution.
- Calculation of PIDA requires the track to stop in the detector, introducing a fiducial cut on the track end position would ensure that particles stop.
- Identifying a proton sample requires separating them from the much more numerous muons. This could be achieved by:
    - A fiducial cut on starting position will also remove externally produced particles, which are more likely to be muons.
    - Proton tracks are inherently short, especially if one discounts any externally produced particles. A cut on track length would remove muons.
    - Remove lightly ionising particles by comparing reconstructed track energy with an estimated proton energy for a track of that length.

Features of the 35 ton data not yet simulated

- Signal/noise was lower than expected, simulation is yet to take this into account.
    - Mitigation is being worked on, including a new method of reconstructing hits which appears to reduce effect of noise on induction planes significantly.
- Data has largely been triggered off horizontal cosmic ray counters, but simulation includes vertical muons and has a larger payload size.
    - The online to offline data reformatter has been set up to run on Monte Carlo. Use of the reformatter on Monte Carlo allows a smaller payload to be extracted from the initial data.
- Detector is not yet operating at design field strength. This reduces the strength of measured signals.
    - Plans to increase the field this week.



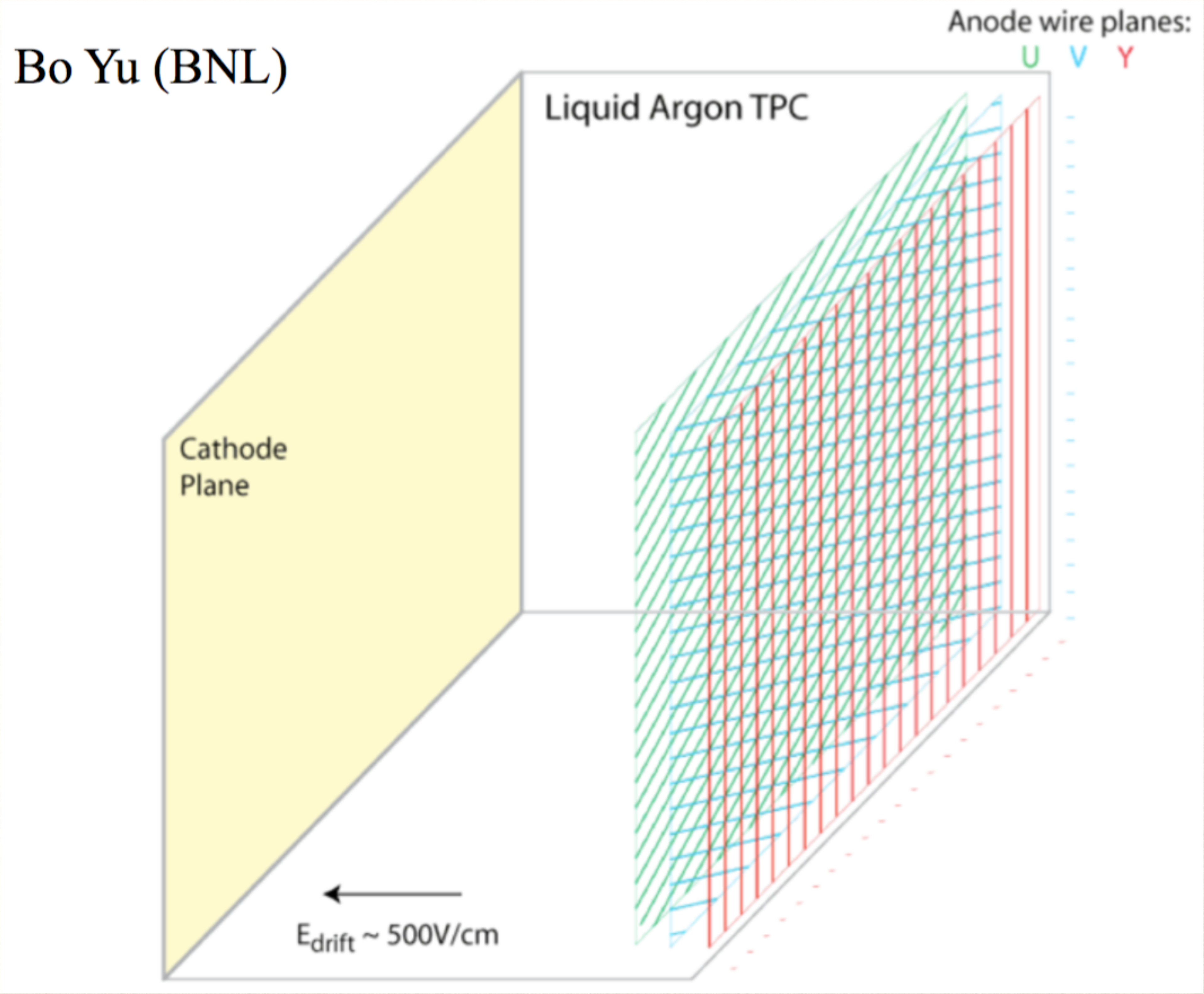
A deconvoluted hit from 35 ton data after the initial noise mitigation has been applied

Summary

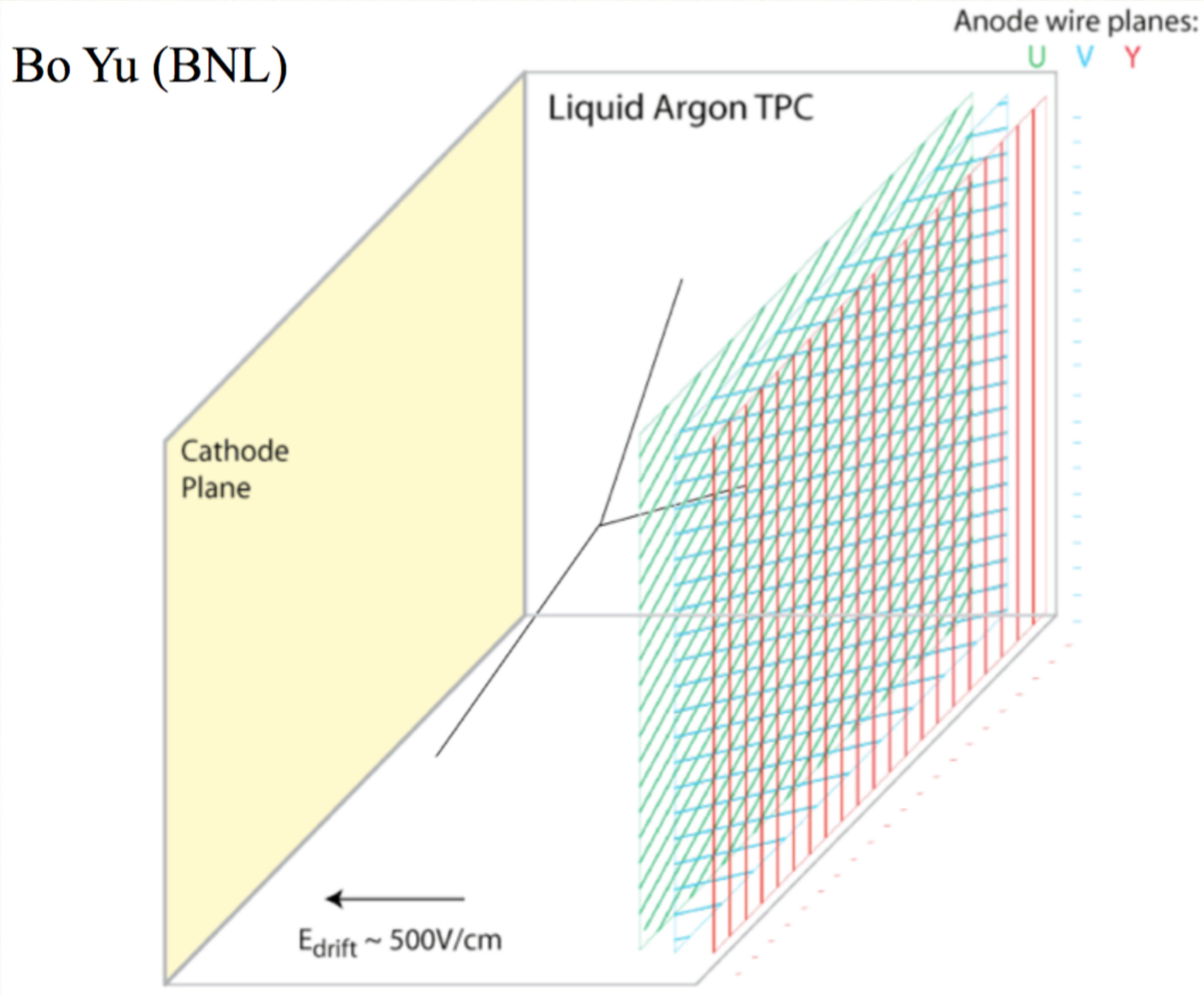
- LArTPCs are capable of excellent reconstruction even at low energies.
- DUNE will use a LArTPC to look for neutrino physics and nucleon decay.
  - Detailed simulation of cosmogenic background is vital for both of these.
  - A widely used package (MUSUN) has been incorporated into LArSoft for use by DUNE.
    - Simulations for the first 10 kton single phase LArTPC are underway.
- A prototype has been built at Fermilab and is taking cosmogenic data.
  - A study will be performed once the run has finished attempting to perform particle identification.

Backups

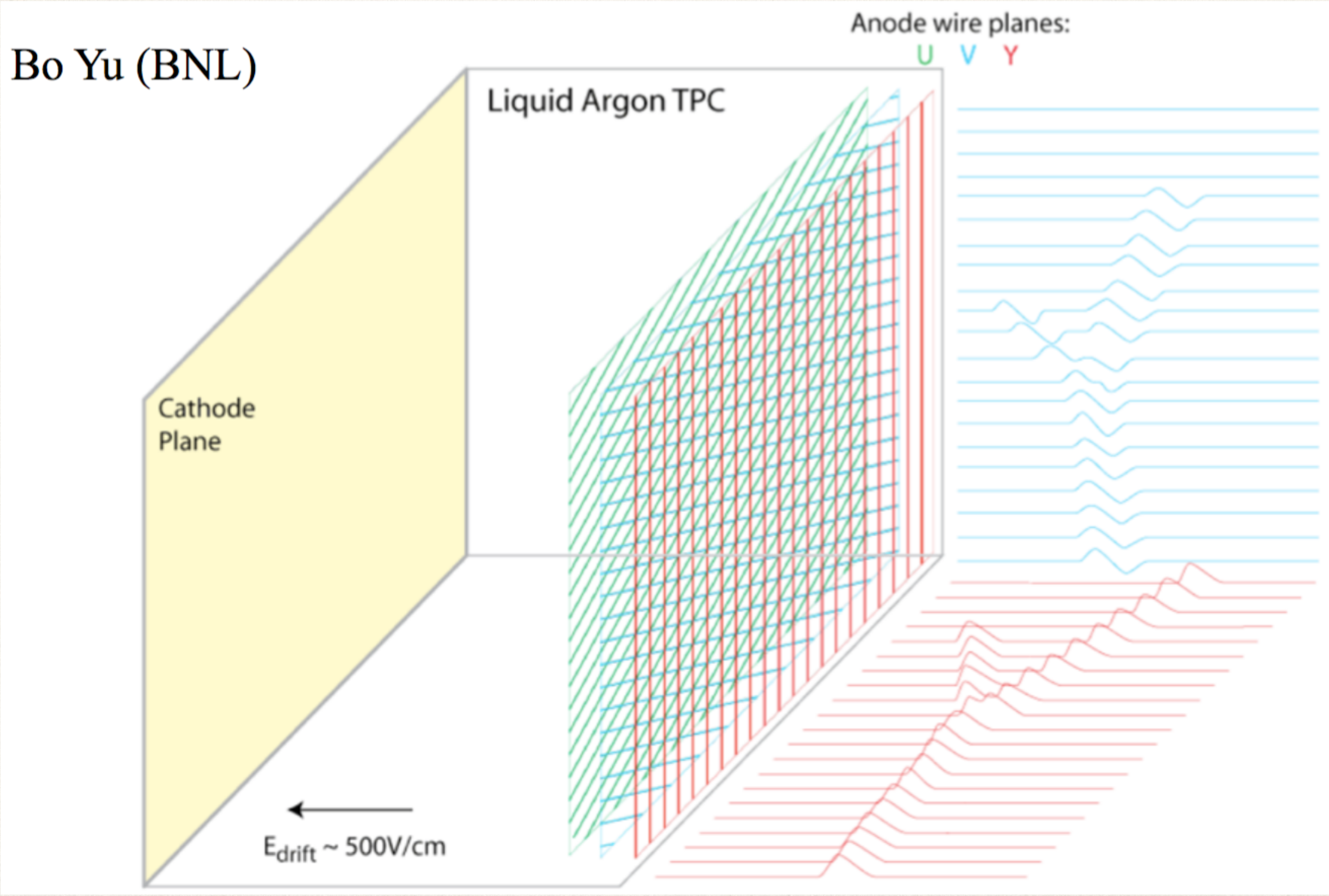
LArTPC concept



LArTPC concept

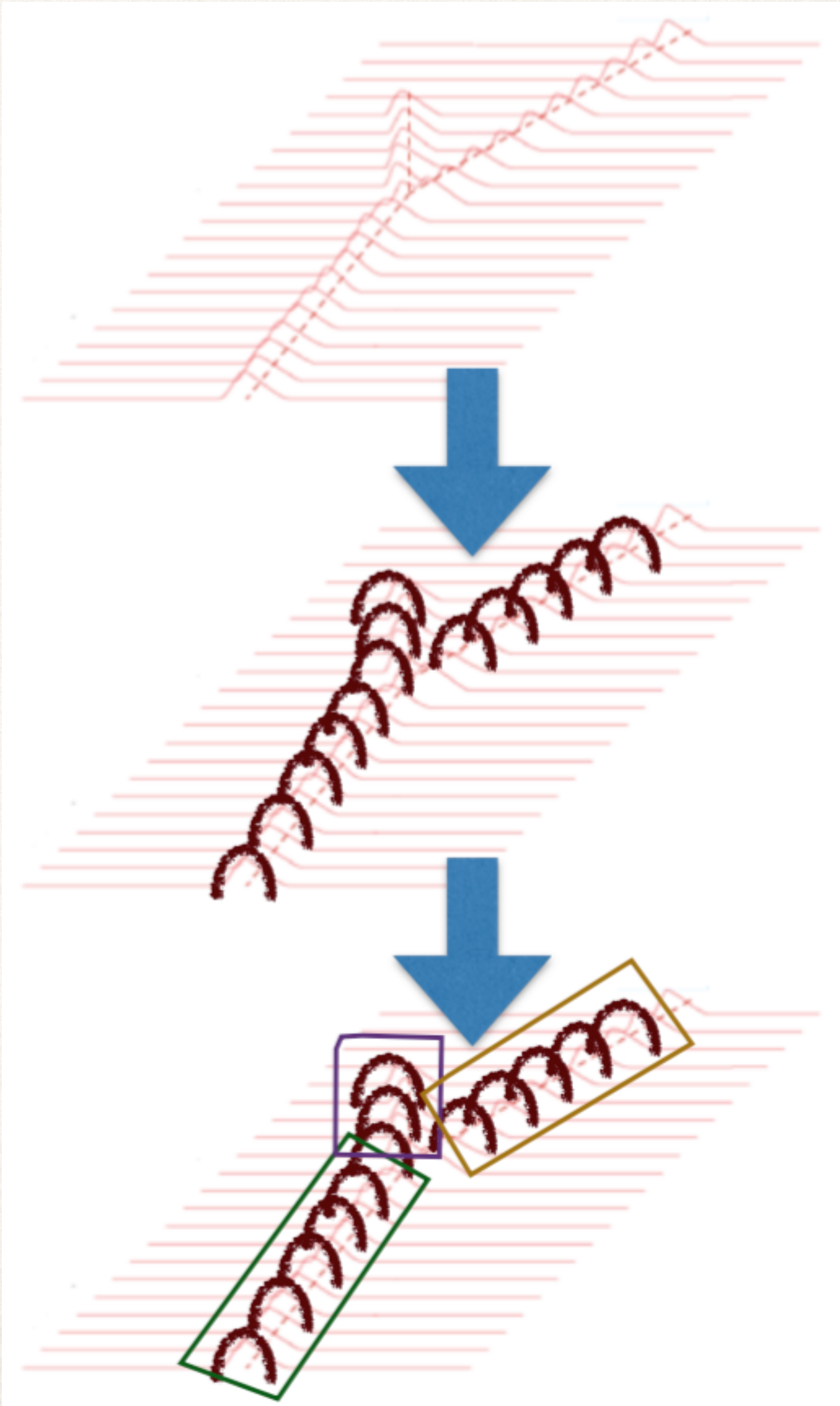


LArTPC concept



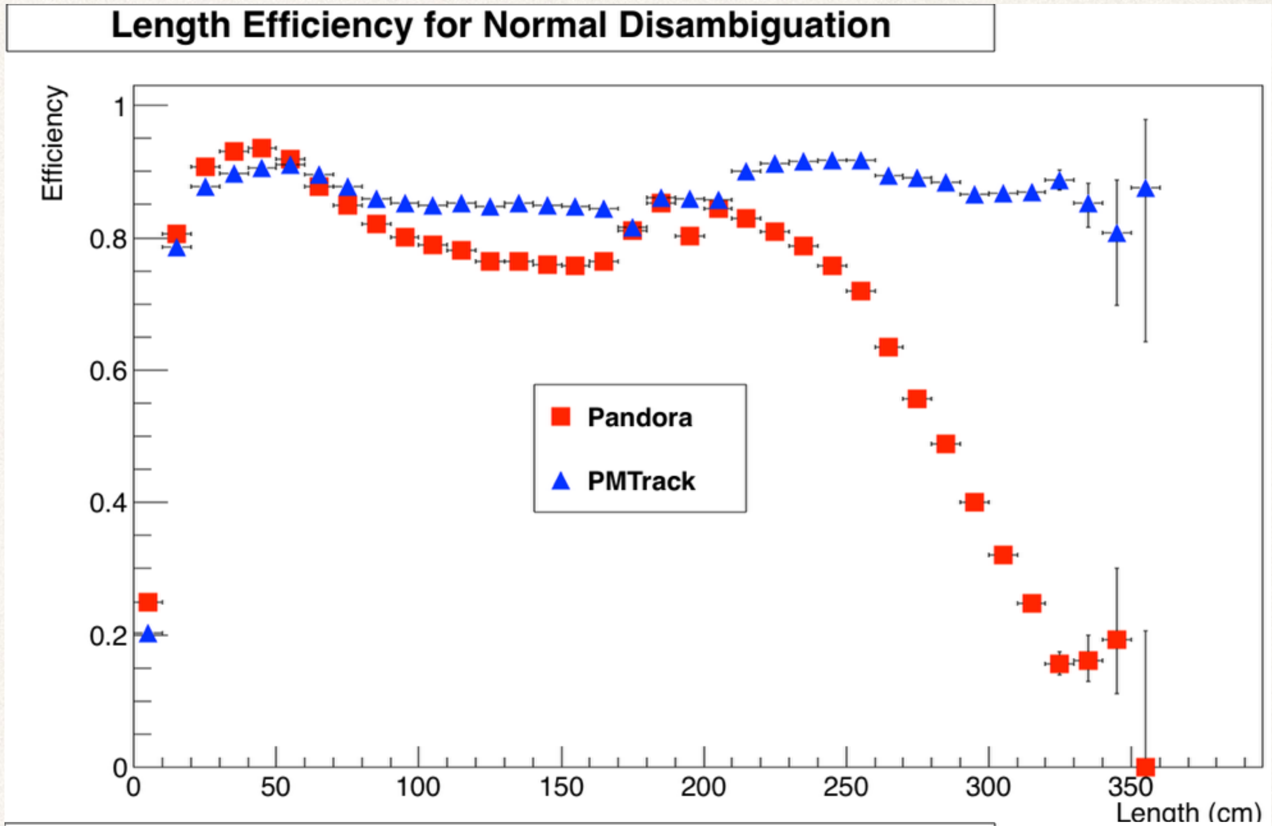
LArTPC concept

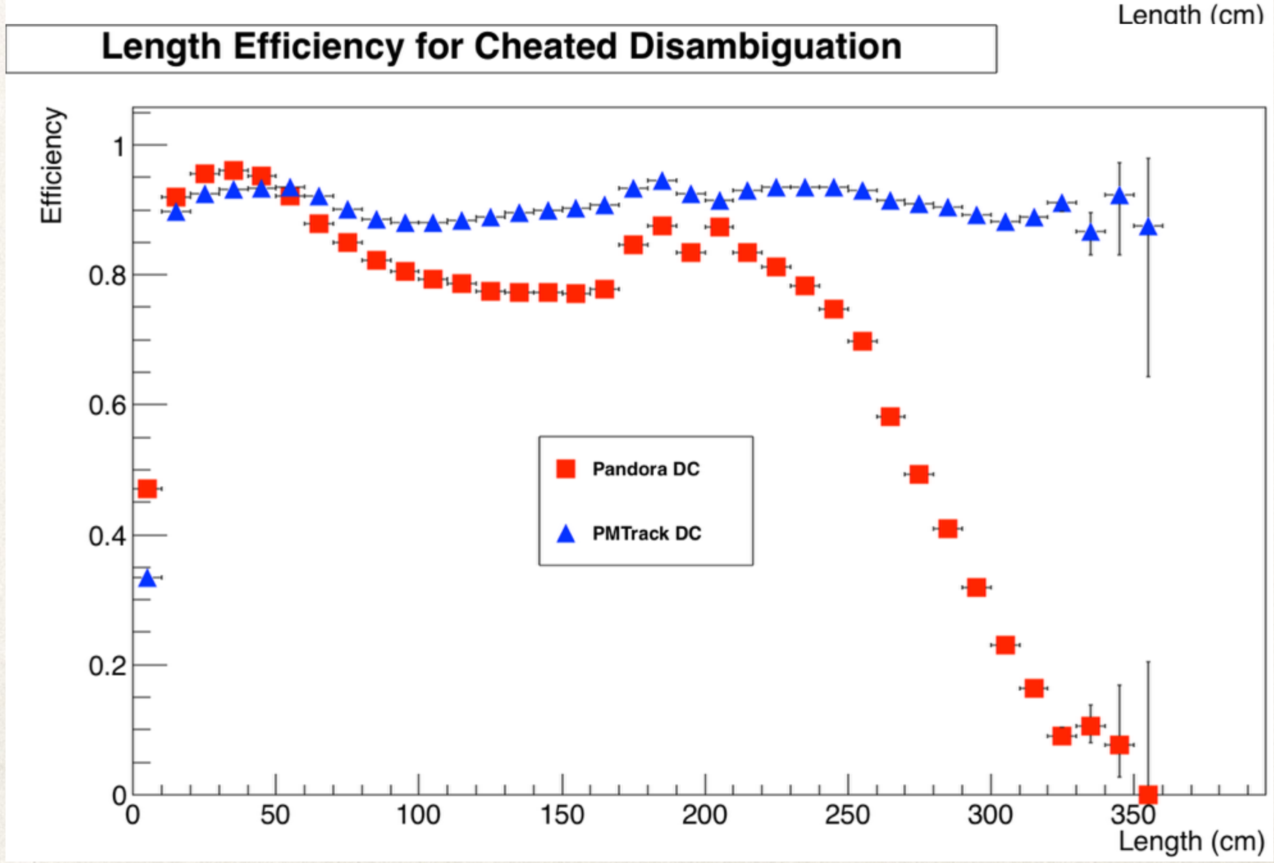
- A step-by-step guide as to how hits are combined into tracks.
  - First image shows raw signals
  - Second image the signals being reconstructed into hits
  - Third image shows clusters being combined into tracks.
- The 35 ton has and DUNE will have, a step between images 2 and 3 where due to the wrapped wires, hits have to be disambiguated as to which part of a wire the hit was on.



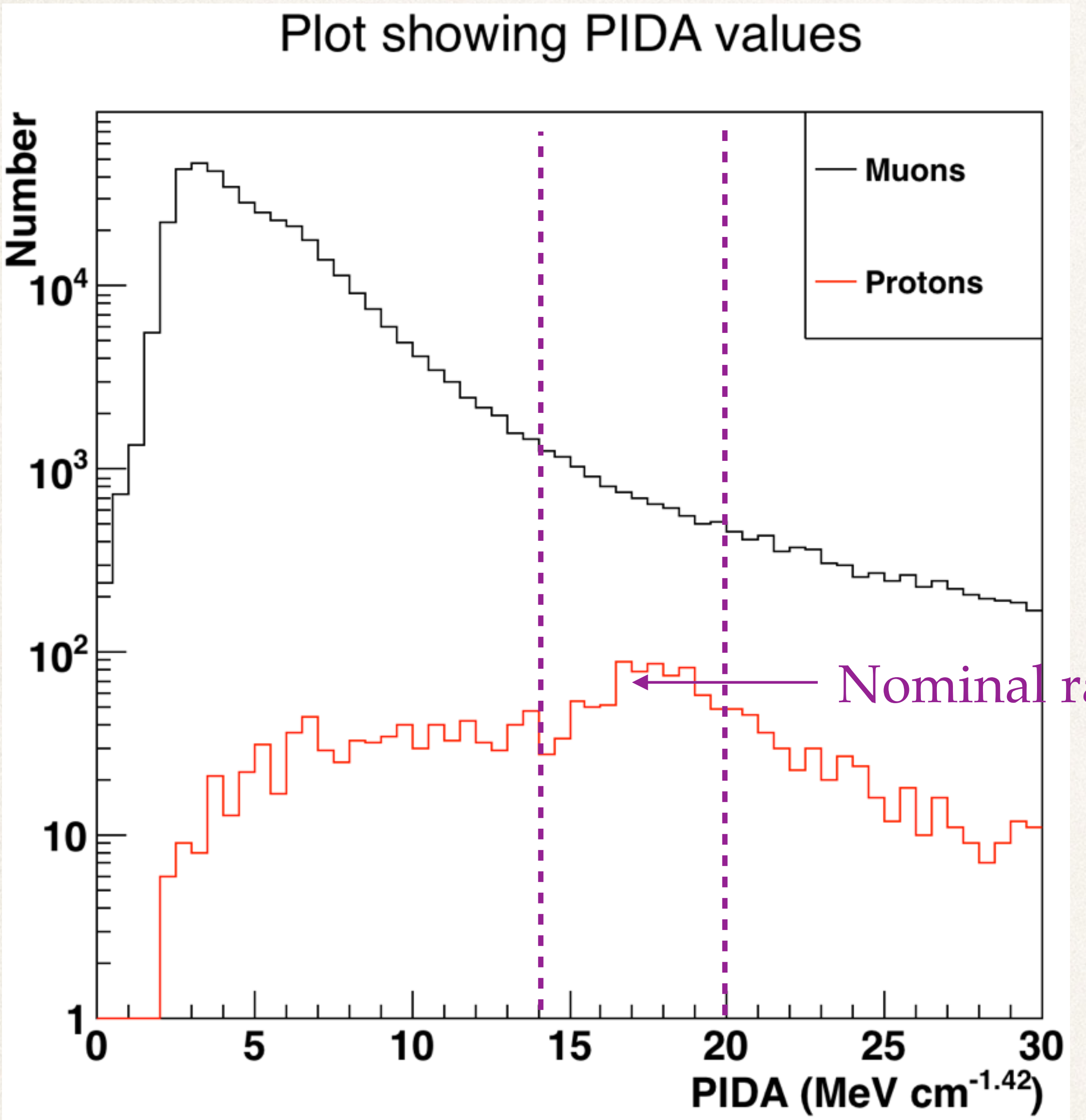
Reconstruction efficiencies

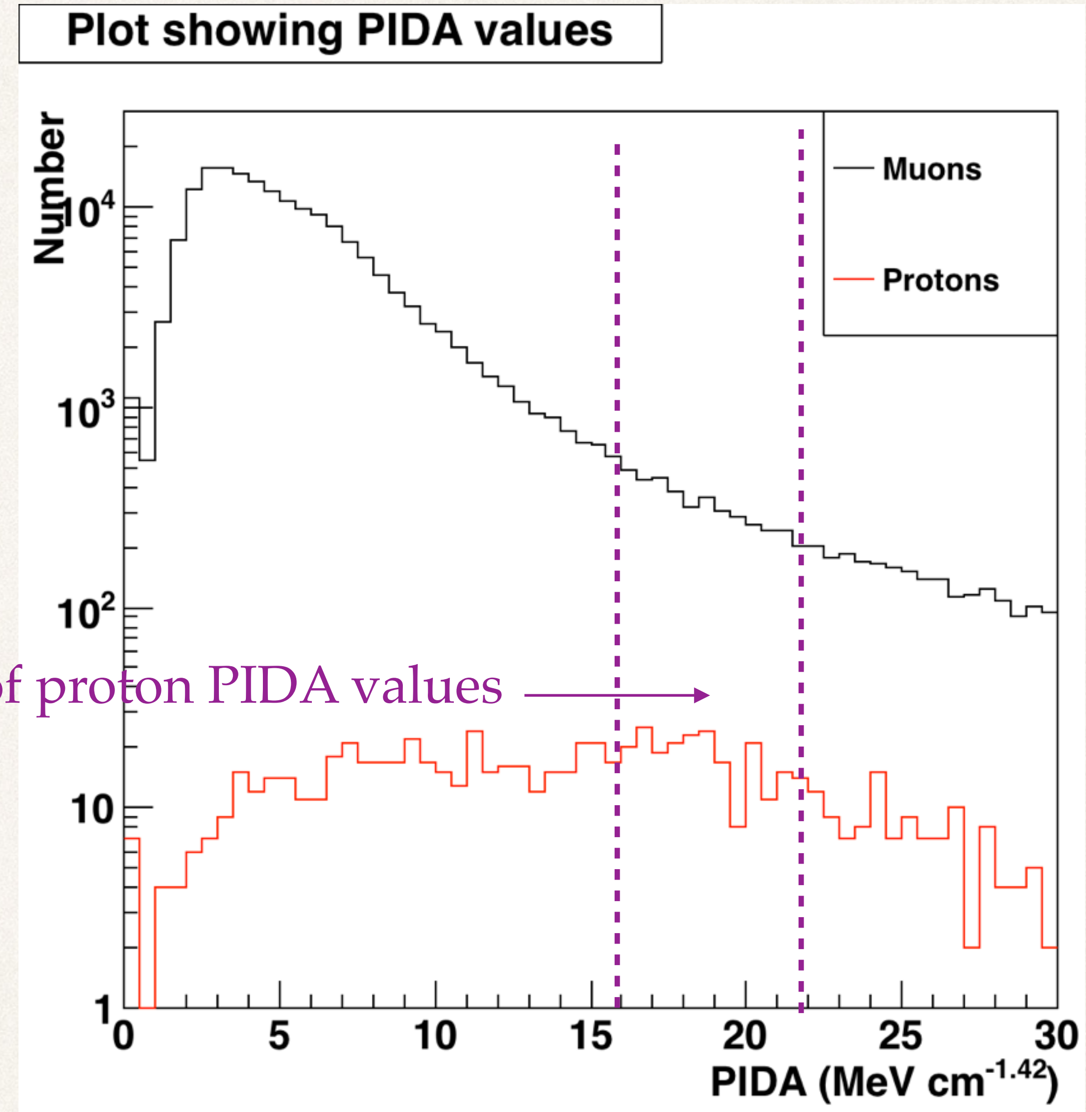
- The reconstruction efficiency for all particles in the cryostat.
- No more than 1 track is included for each particle, so if one particle is reconstructed as two tracks only the largest is considered.
- Criteria for being considered a well reconstructed track;
    - MC / Reco length 0.75 - 1.25
    - No prior track assigned to that MCParticle.
- Pandora has low efficiency at large lengths as is not stitching tracks which cross the APAs at large times.





Some simple cuts on PIDA





- Simple cuts applied to the raw PIDA calculations. PMTrack is shown on the left, pandora on the right.
- A 5 cm fiducial cut on detector edges, a minimum of 10 track hits and a track length of less than 300 cm.