Brookhaven National Laboratory

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

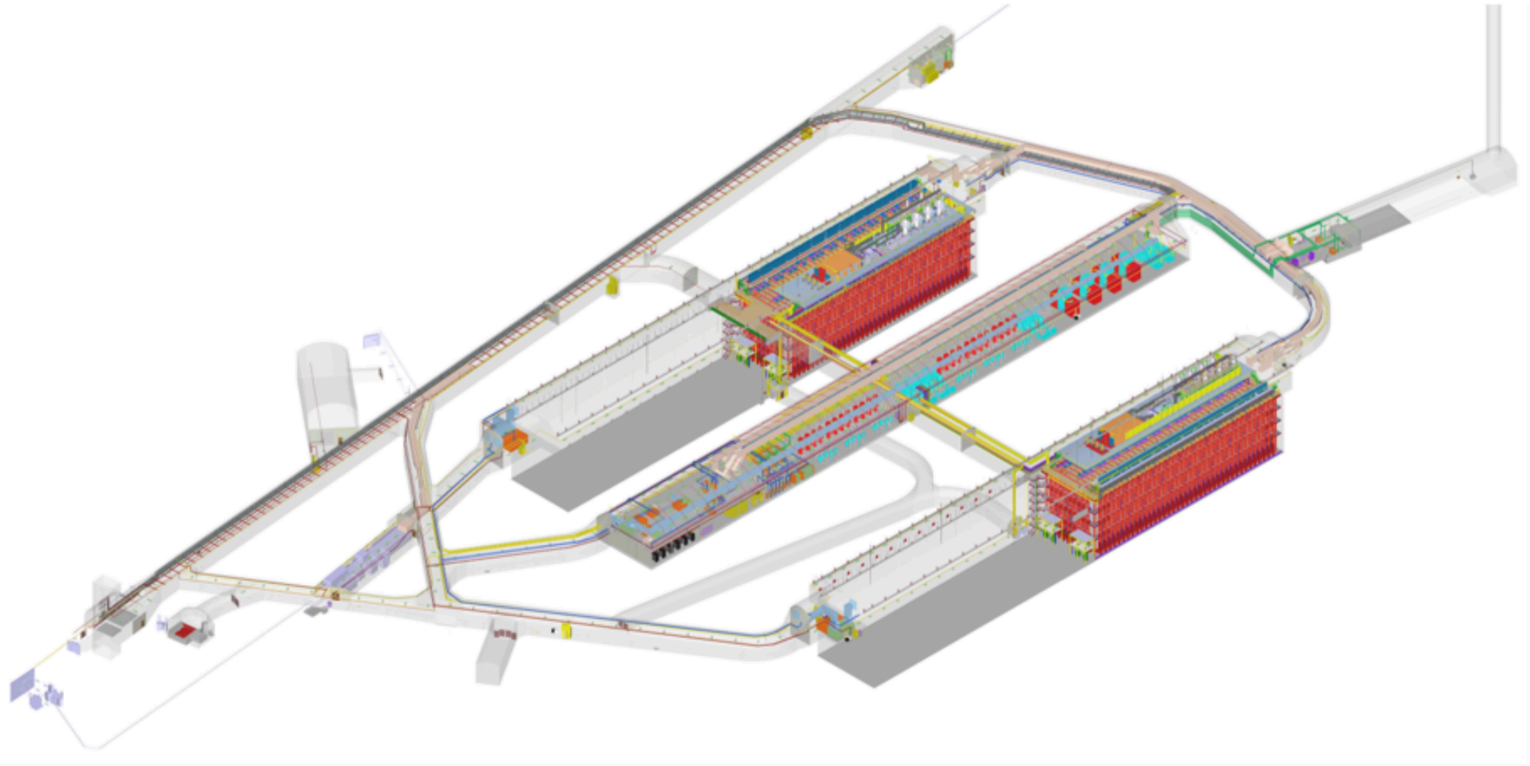
Status and Progress towards the second DUNE Far Detector Module

ICHEP-2022

Nitish Nayak (BNL)
for the DUNE collaboration

7th July, 2022

DUNE Outline

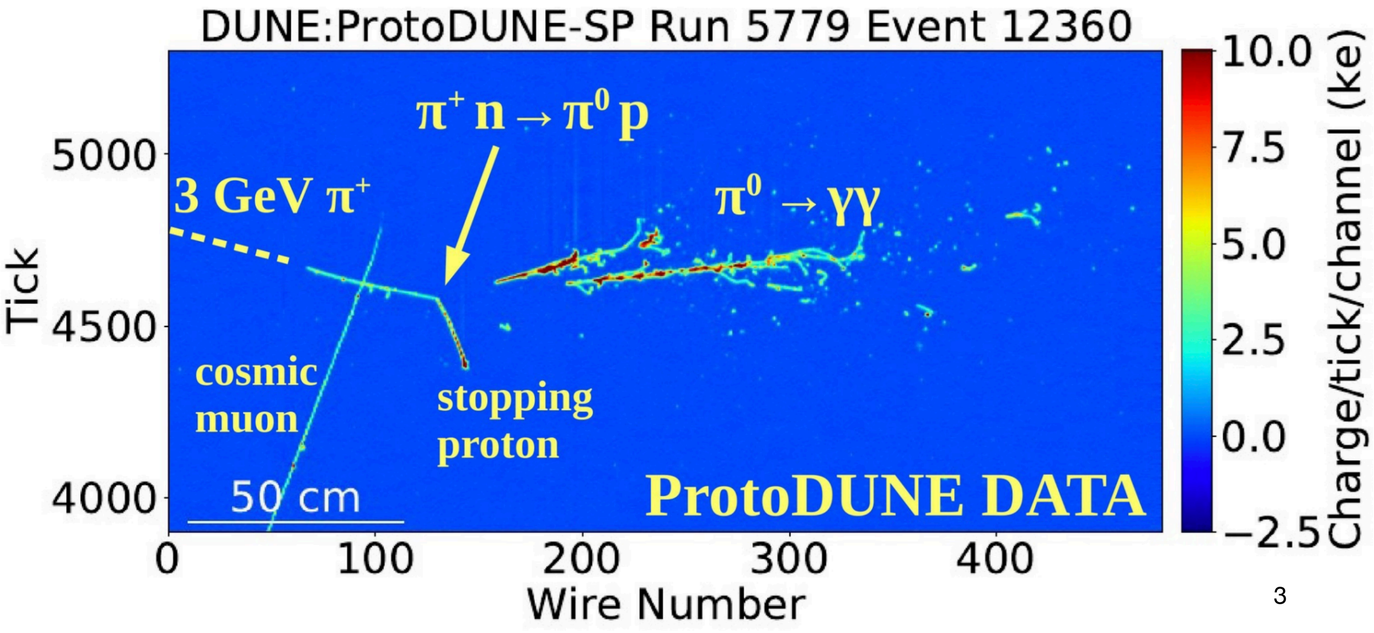


- Sensitivity to discovery of CP-violation
- Unambiguous discovery of neutrino mass hierarchy, octant of θ_{23}
- High-precision measurements of Δm^2_{32} , δ_{CP} and θ_{23}
- Sensitivity to neutrinos from galactic supernovae
- Sensitivity to proton-decay and other physics beyond the Standard Model

- 1300 km baseline with a high power 1.2 - 2.4 MW neutrino beam
- Far Detector (located 1.5km underground) to house upto four modules of 17.5 kT each utilizing LArTPC technology

Liquid Argon (LAr) TPCs — Horizontal Drift

- Drift e^- in pure LAr medium induces charge at 2 of 3 anode wire-planes and is collected at the 3rd
- Enables ~mm spatial resolution in 3D along with calorimetry to explore interactions in unprecedented detail
- PMTs collect prompt scintillation light for T0 identification



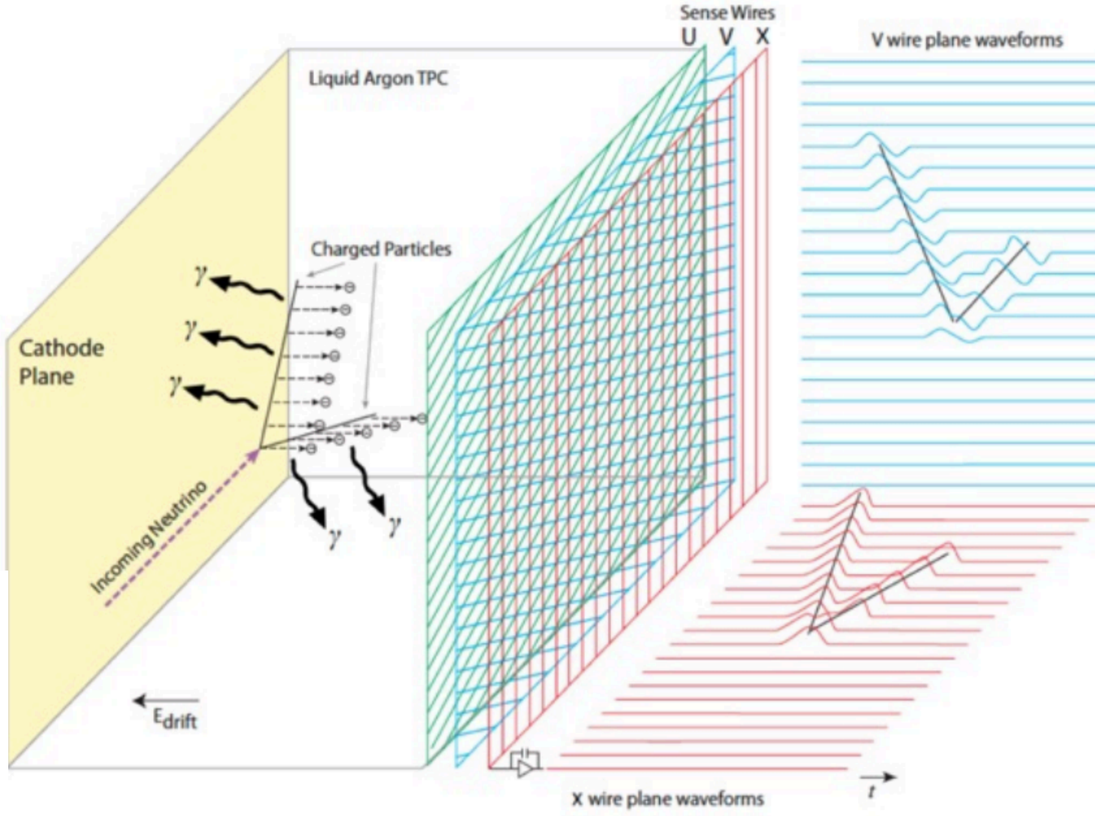
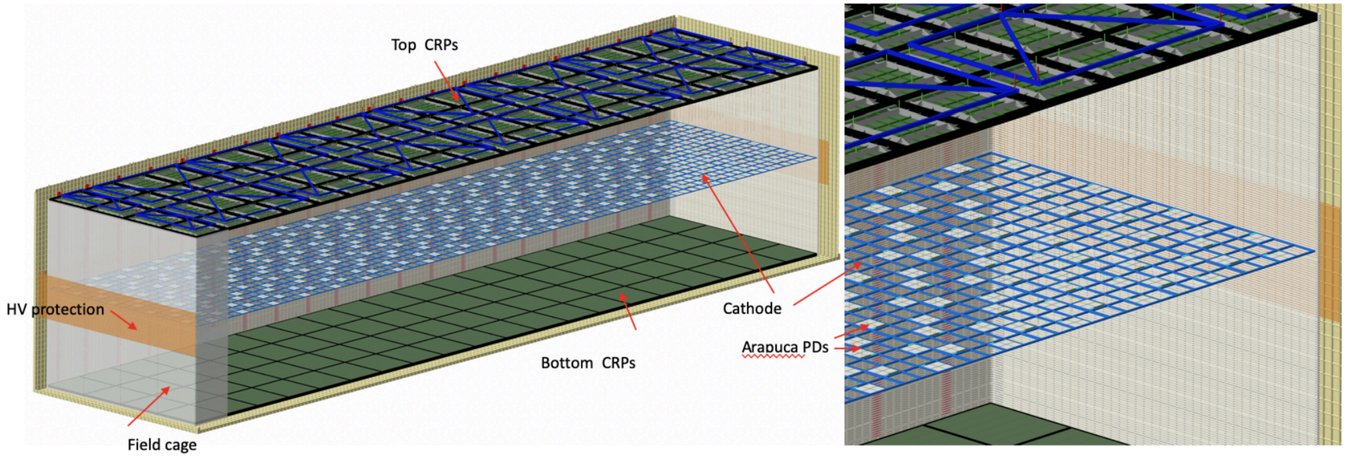


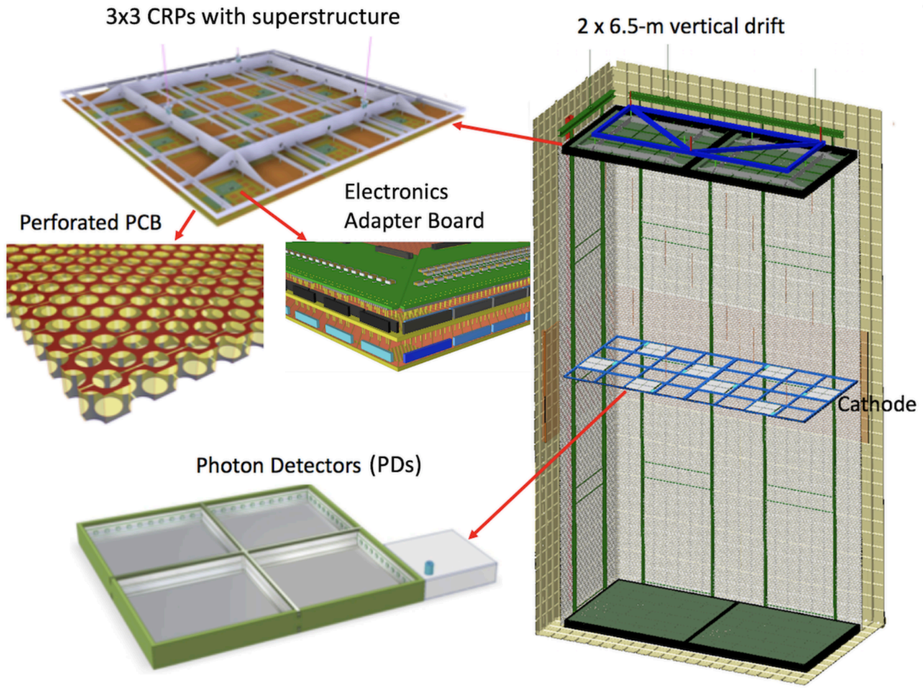
Illustration of LArTPC concept — Made by Bo Yu (BNL)

- Horizontal drift (HD) validated with test-beam at the CERN Neutrino Platform (ProtoDUNE-SP)
- Basis of 1st FD module as well as sensitivity studies for TDR

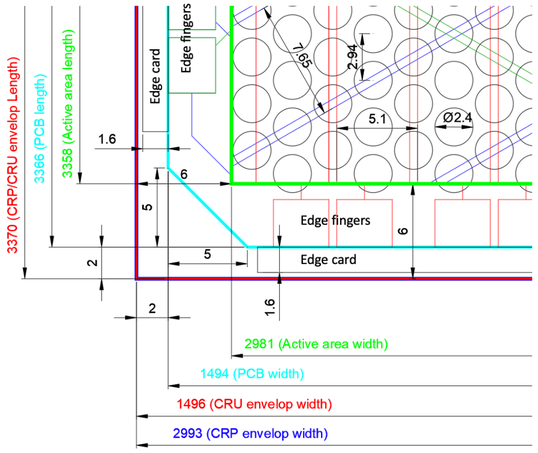
See talk by Oliver Lantwin (9/7 - Saturday, 2:45pm)

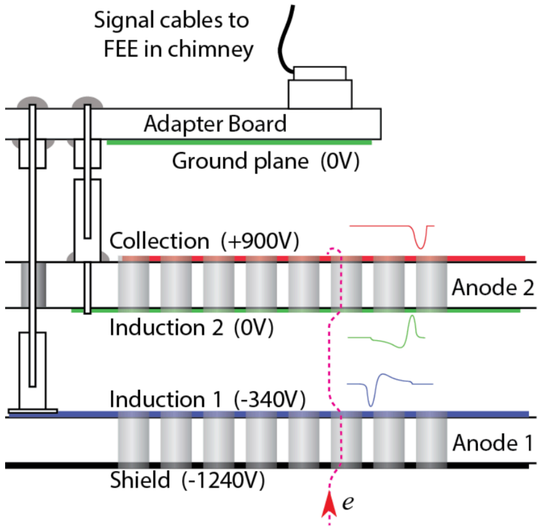
The Vertical Drift Concept





- For the 2nd FD module, has a vertical drift path in contrast to HD
- Anode plane consists of a stack of perforated PCBs with etched electrode strips for induced signals and charge collection
- Modular design allows easy assembly and production. Wires -> strips improves mechanical robustness
- Two drift volumes, readout by different electronics.
- Various design choices including strip orientations being evaluated

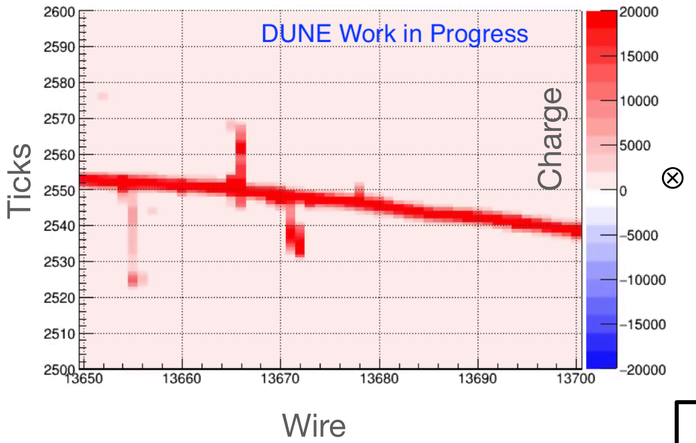




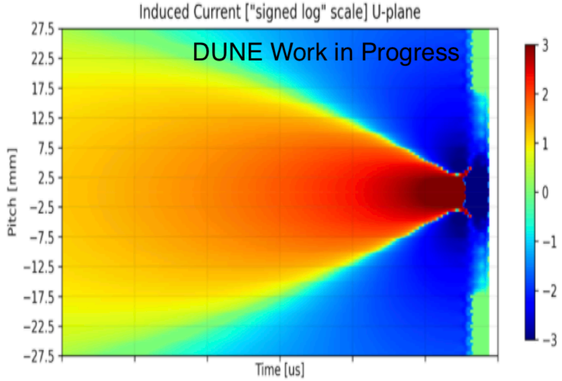
Simulation Efforts

$$M(t',x') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R(t,t',x,x')\cdot S(t,x)dtdx + N(t',x')$$

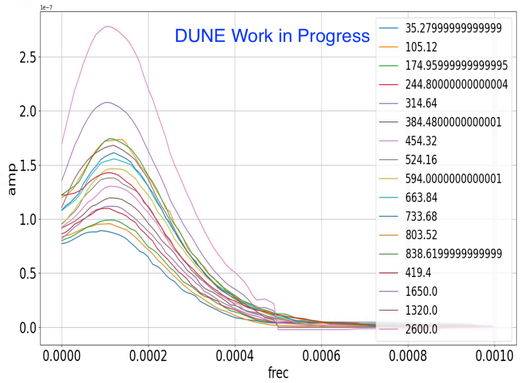
Energy depo + diffusion + rasterization (From G4)



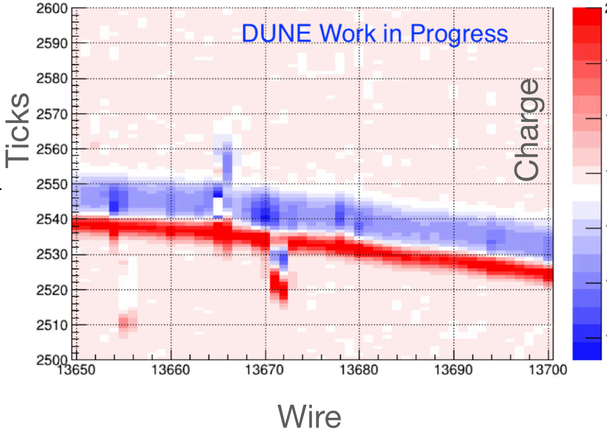
Position-dependent Field response



Wire/Strip-dependent noise simulation



Simulated charge signal (induced + collected)



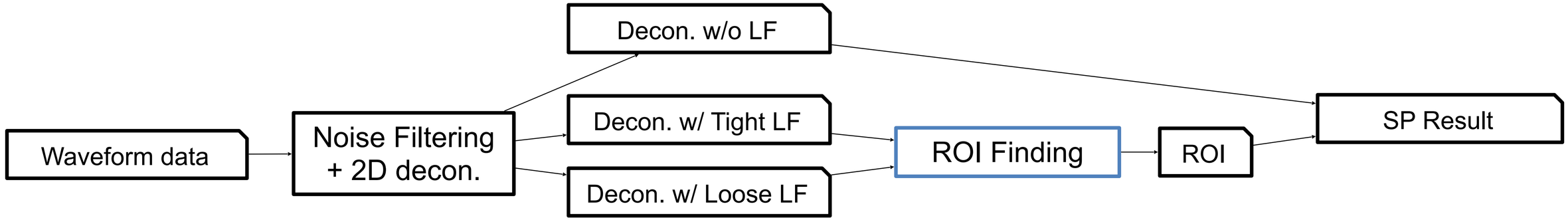
Ramo's theorem: $i = -q\,\vec{E}_w \cdot \vec{v}_q$

- We use the WireCell paradigm to simulate the charge response for the FD vertical drift geometry [JINST 13 P07006 (2018)]
- WireCell relies on a first-principles based algorithm using Geant4 inputs (“energy depositions”)
  - Convolves with simulated electric field response using Ramo’s theorem (geometry-dependent weighting field) as well as electronics response
  - Noise simulation based on data from ProtoDUNE-SP and MicroBooNE
  - Output is induction and collection plane waveforms
- 2D simulation : assumes approximate translational symmetry along wire/strip direction

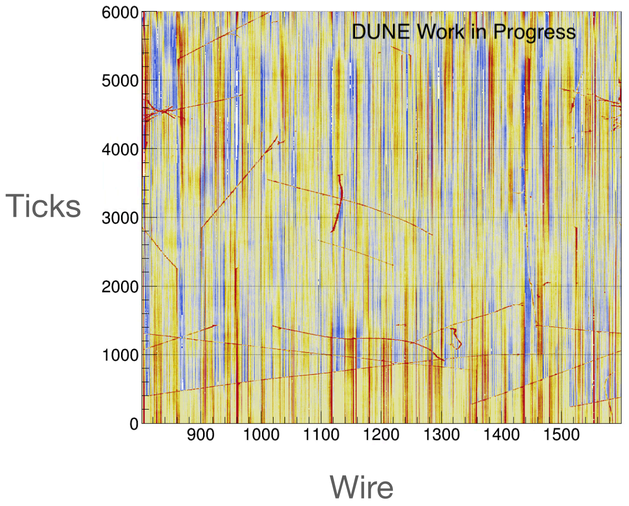
Signal Processing

$$S(\omega_t, \omega_x) \sim \frac{F(\omega_t, \omega_x) \cdot M(\omega_t, \omega_x)}{R(\omega_t, \omega_x)} \xrightarrow{IFT} S(t, x)$$

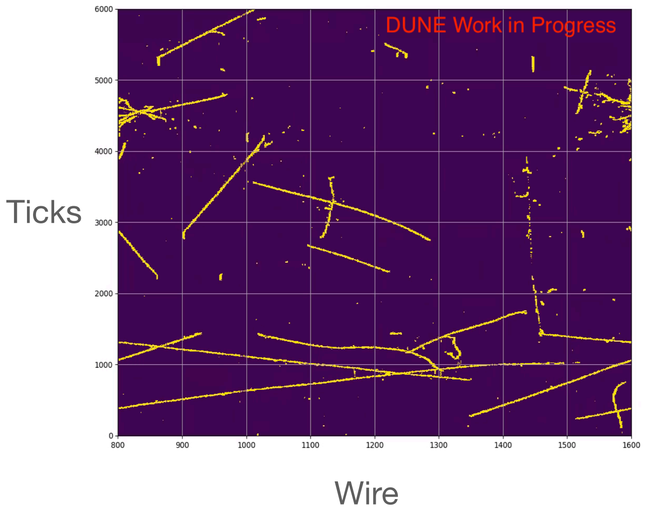
- Signal processing involves extracting signal from the original measurement
- Suite of noise filters acting in the Fourier domain along with “Region of Interest” (ROI) finding to isolate signal
- Input to downstream reconstruction, particle ID, pattern recognition etc
- Improvements incorporating deep-learning methods being studied : [H.W. Yu *et al* 2021 *JINST* **16** P01036]



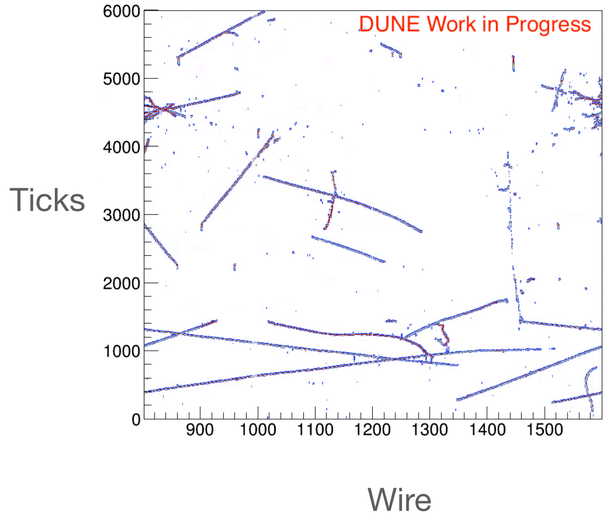
Decon. w/o LF filter
Waveform ⟶ charge, dense



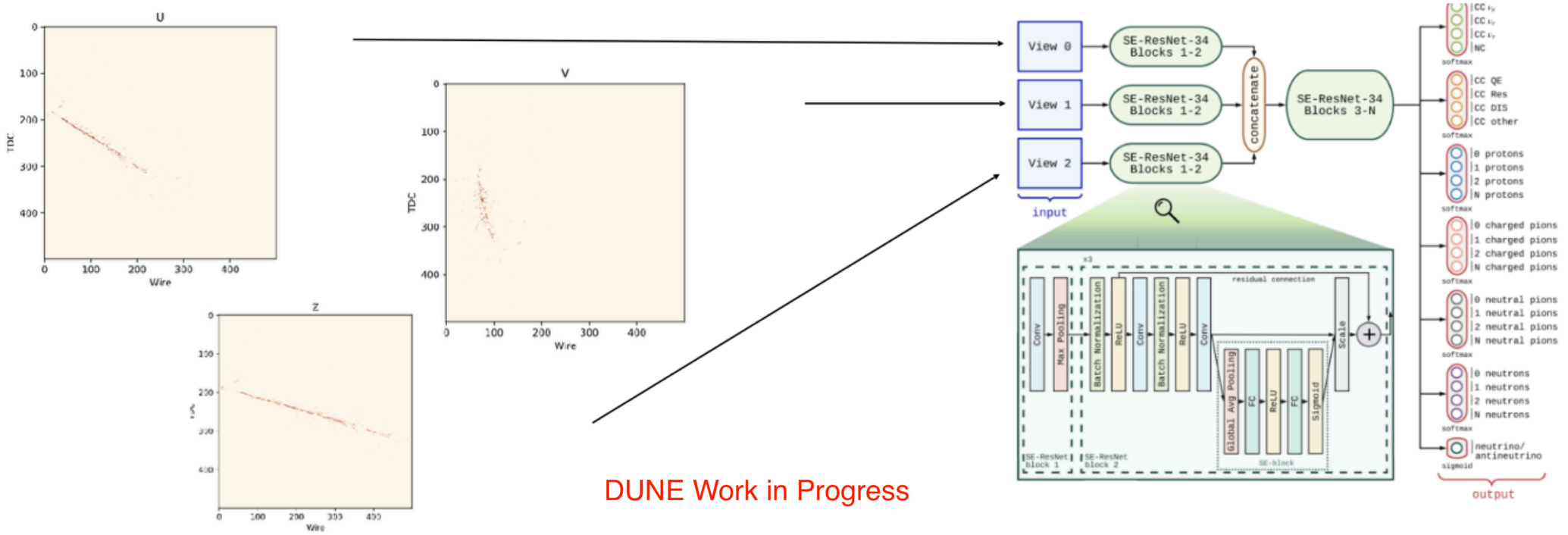
ROI:
Hit finding, sparsify



SP result:
Sparse, charge



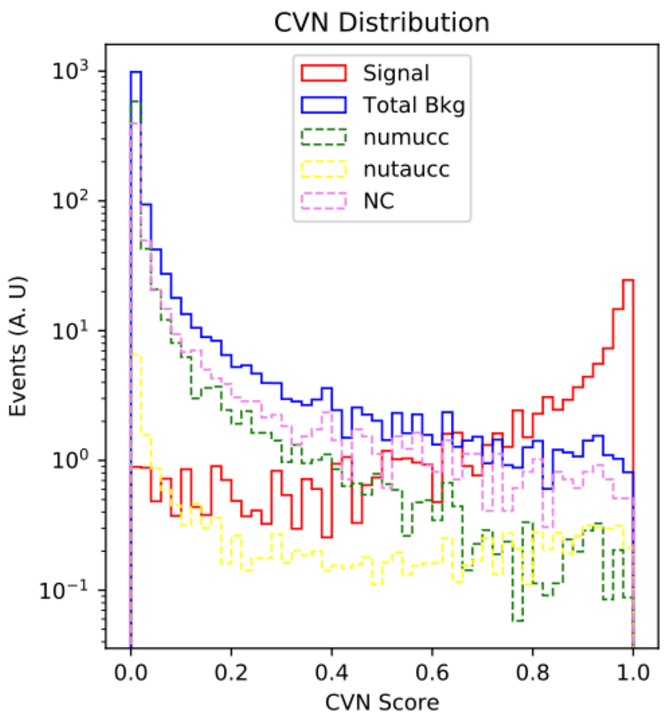
Particle Identification

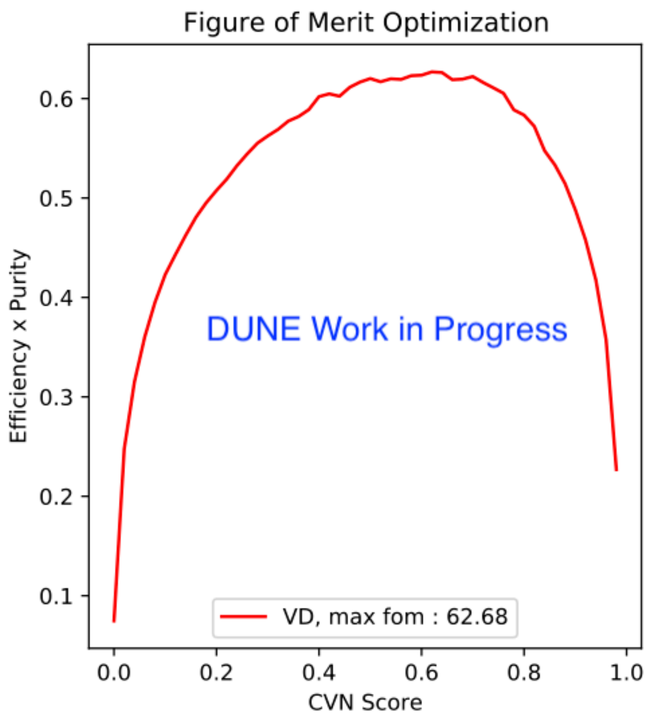


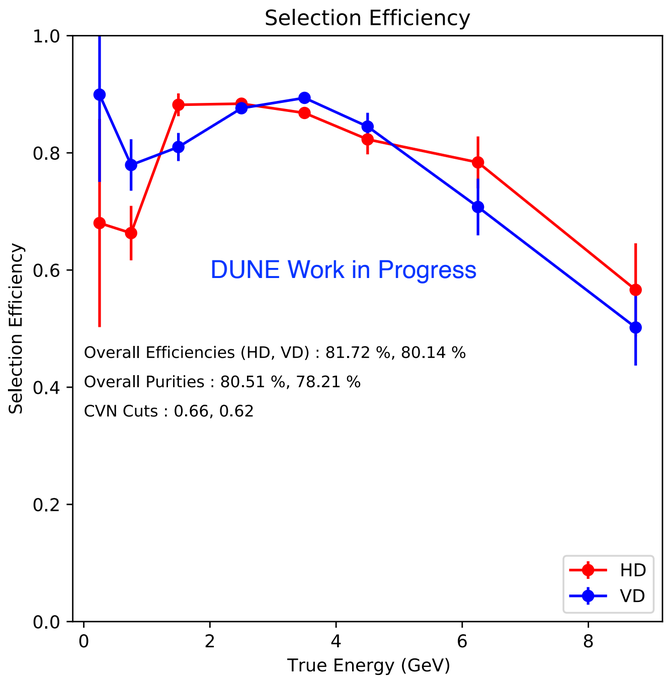
DUNE Work in Progress

- Convolutional Neural Network (CNN) -based classifier (“CVN”) to tag neutrino flavor, main PID for HD TDR analysis and basis for sensitivity projections [Phys. Rev. D 102, 092003, 2020]
- Uses 2D images of hit clusters (“pixel maps”), one for each wire-plane, directly as input to a Siamese tower-like CNN architecture
- CNN then merges information across the 3 planes and uses a fully connected layer at the end to predict neutrino flavor along with other potentially useful information about interaction topology
- Retrained for the VD simulation

CVN Performance

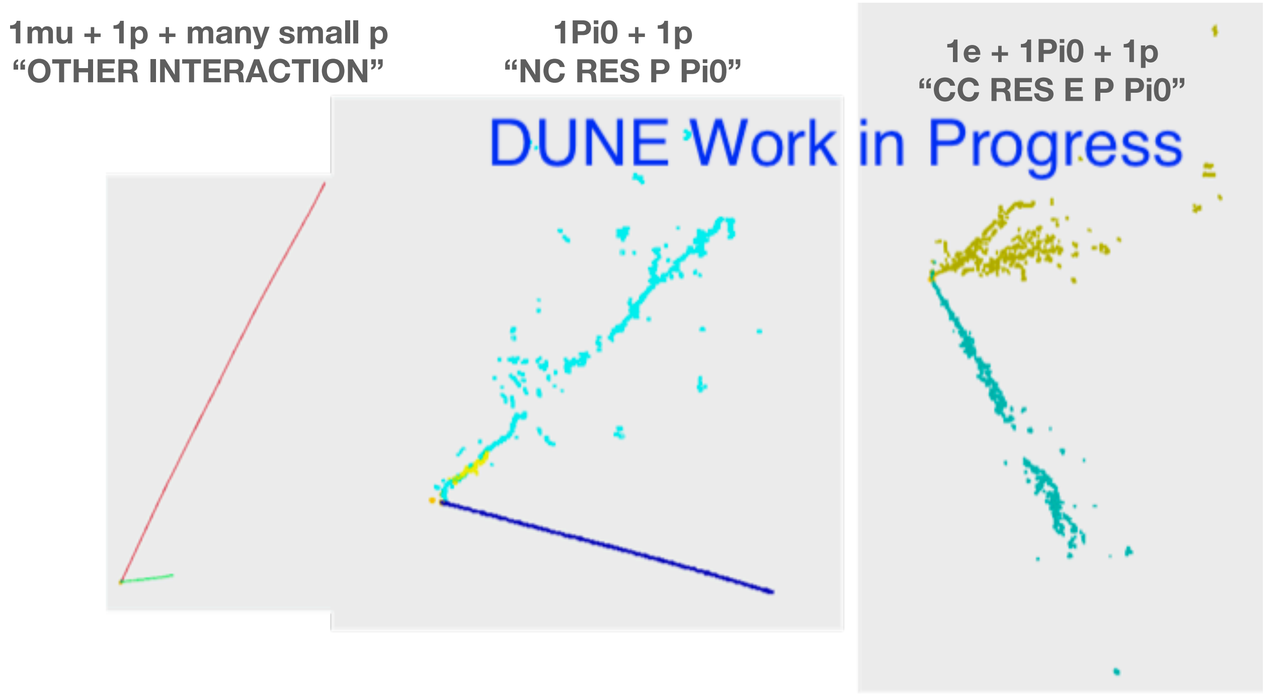


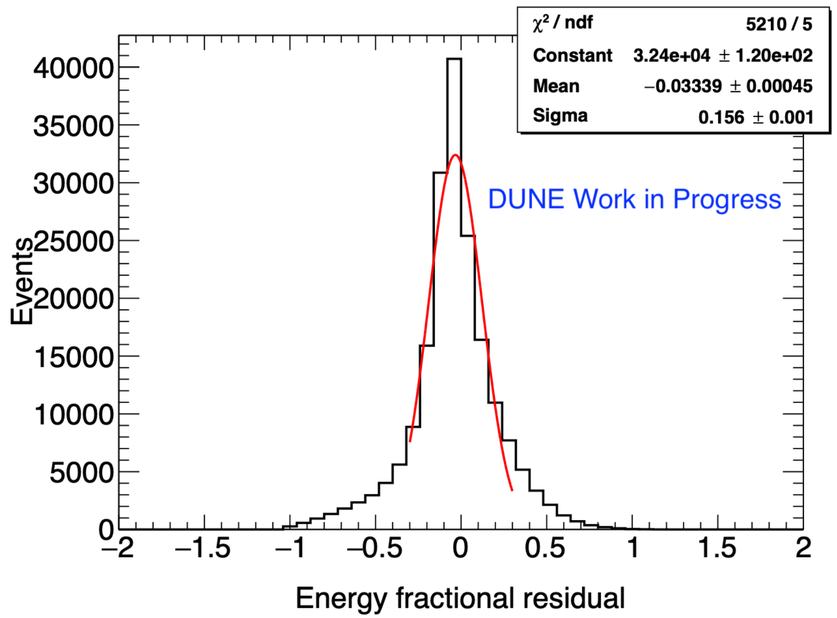




- Training on fraction of planned simulated sample shows very similar performance as for HD
- Efficiency to tag ν_e CC ~90% near peak DUNE flux (~2.5-3 GeV) with overall purity ~80%
- Further studies planned but this is already an important validation for the VD concept
- Will be used as input for new VD-based sensitivity studies (TDR analysis), expect similar results

3D Reconstruction and Calorimetry

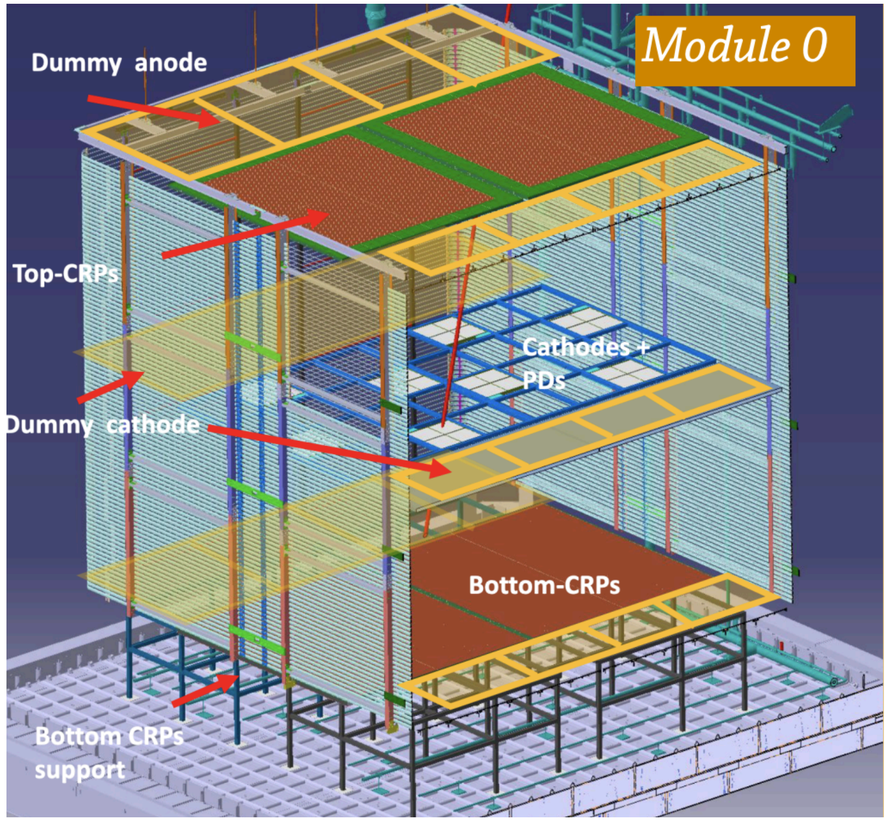


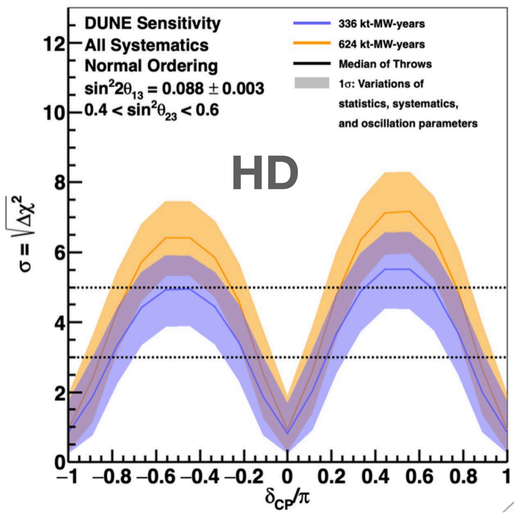


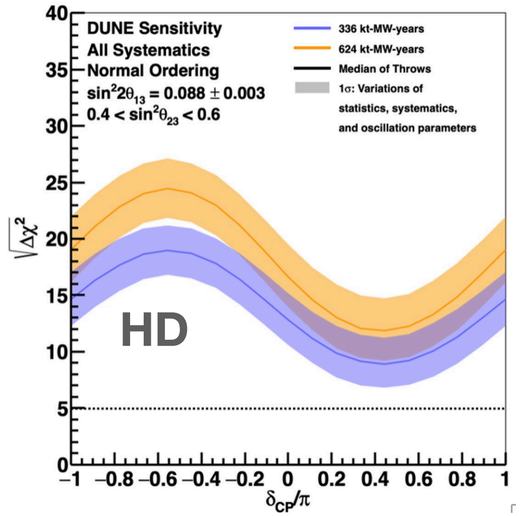
- Reconstruction of individual interaction products handled by the Pandora pattern-recognition software
- Suite of algorithms to handle different topologies and tag tracks/showers, vertex identification [Eur. Phys. J. C **78,** 82 (2018)]
- Successfully deployed at other LArTPC experiments like MicroBooNE, SBND etc
- Basis for calorimetric neutrino energy estimation combining separate estimates for lepton and hadronic portions.
- See energy resolution ~15-20%, similar to HD with more studies ongoing

Looking Ahead

- Prototyping efforts to test out various CRP designs and finally converge to Module-0 or ProtoDUNE-VD
  - Similar to ProtoDUNE-SP, will take beam as well as cosmic data
  - Characterize electronics performance, assess charge and light readout based on expected and observed particle propagation in LAr medium etc
- Simulation efforts
  - Geared towards assessing feasibility of various design considerations
  - TDR analysis to determine FD sensitivities and comparison with HD
  - Exploring various improvements to reconstruction and particle identification







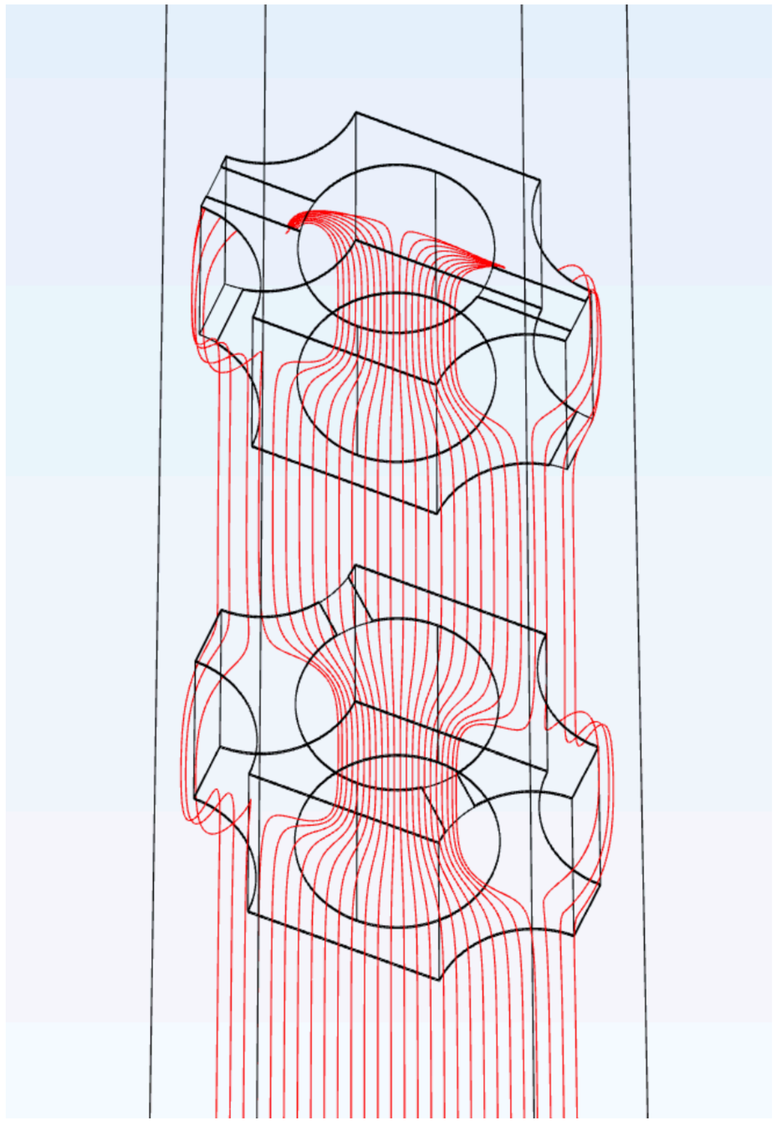
Summary

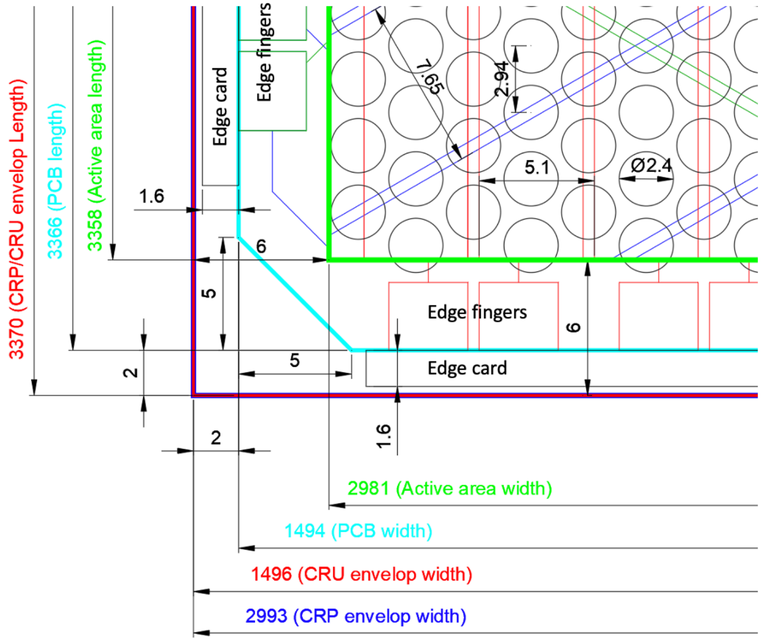
- The second DUNE Far Detector module will utilize a vertical drift concept
  - Uses a PCB-based modular anode design with two induction planes and one collection plane with strips etched on the PCBs rather than wires
- Significant effort underway for both prototyping as well as simulating this new design
  - Simulation used to train CNN-based PID as well as develop pattern recognition and calorimetric energy estimation
  - Performance is also very similar here to horizontal drift simulation studies and will be the basis for a new TDR analysis
- Stay tuned for more updates!

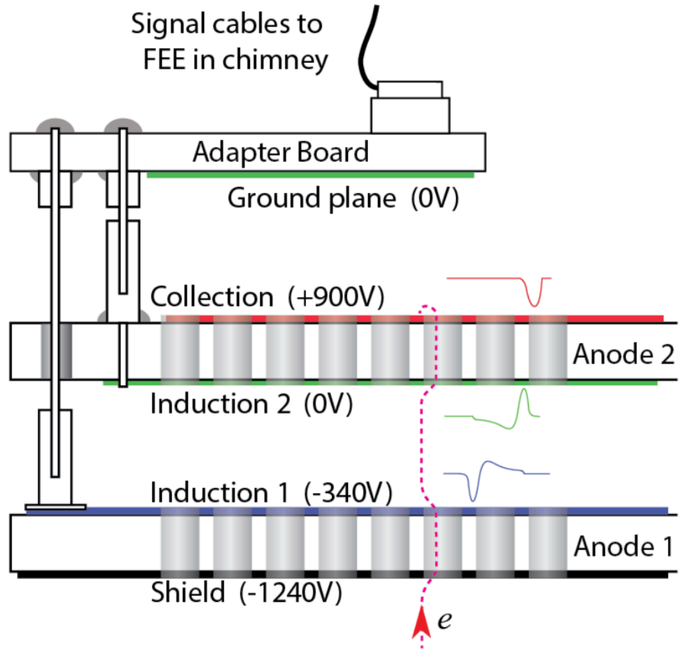
Thank you!

Backup

Vertical Drift Charge Readout

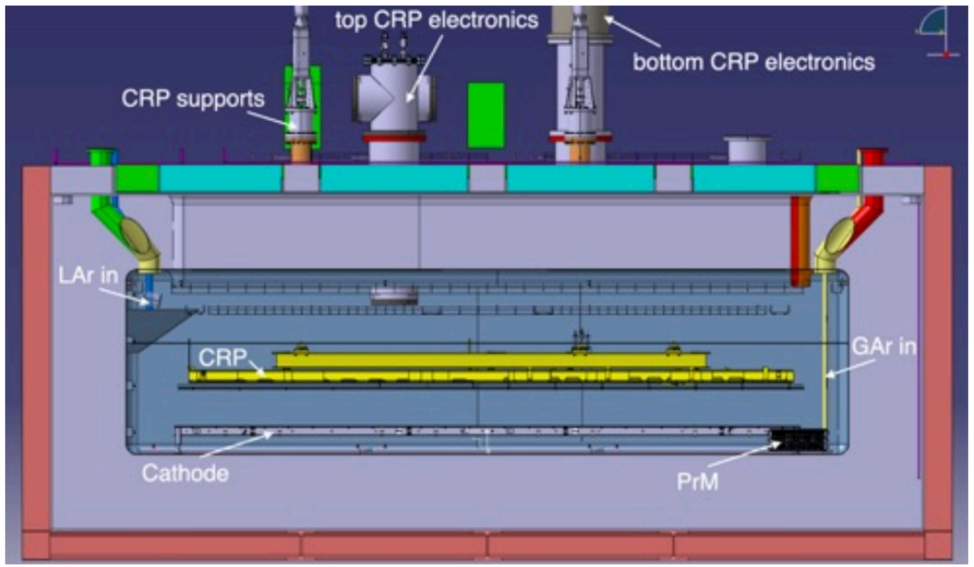


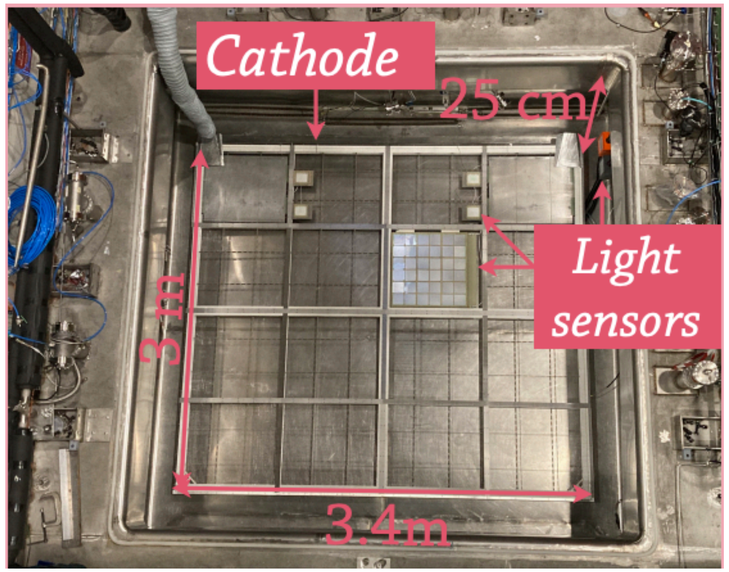


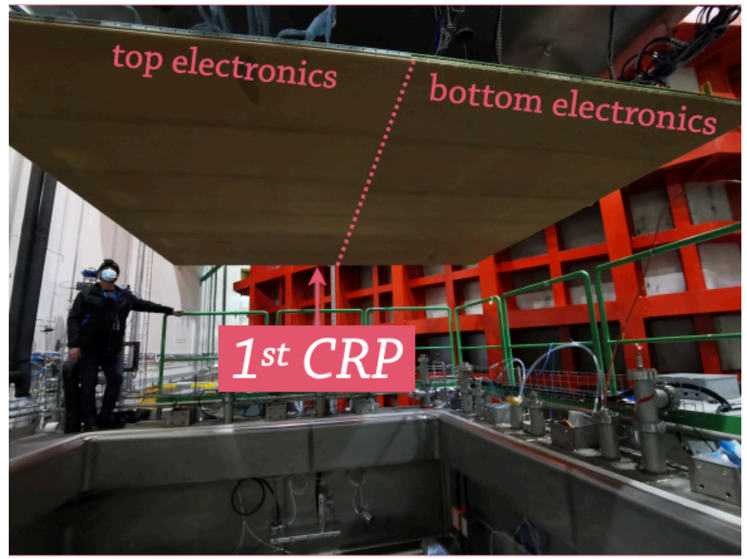


- Shield plane for protection of readout electronics against cathode discharge
- Bipolar signals induced at two planes on the double PCB stack as ionization e^- pass through the holes and finally collected at the 3rd plane
- Various anode strip configurations with different orientations currently being studied. Strip pitches ~8mm for induction planes, ~5mm for collection plane

Prototyping Efforts



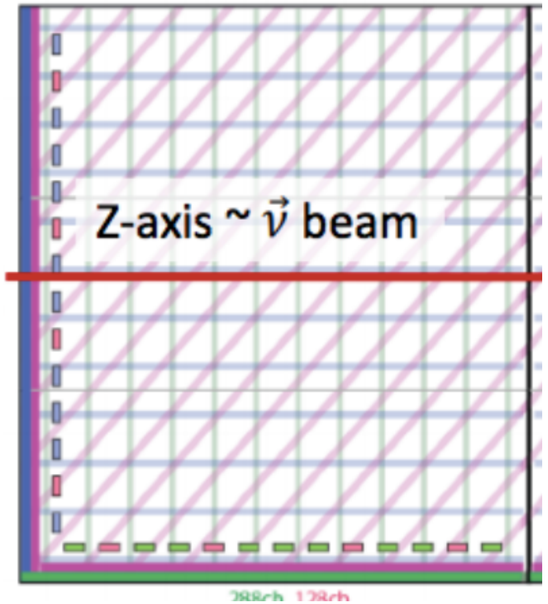


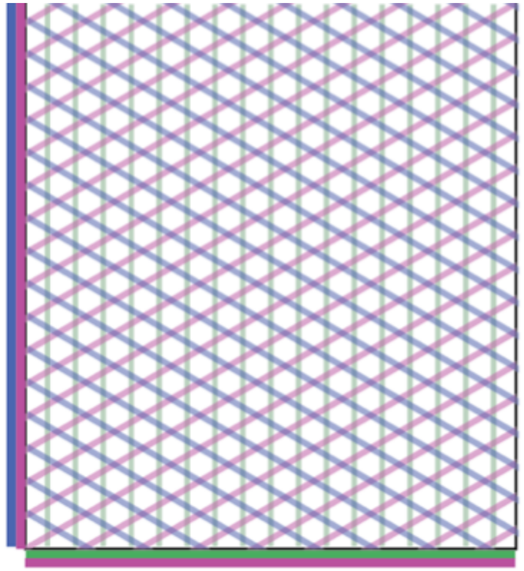


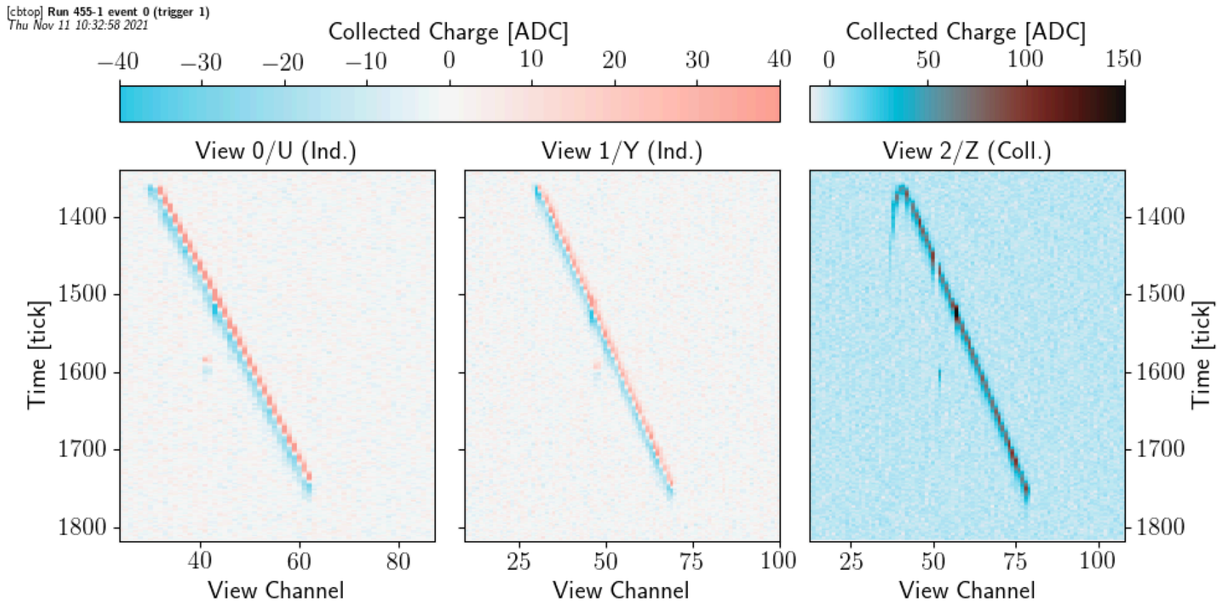
- Current tests involve cold-box demonstrators at the CERN Neutrino Platform, near NP04
- ~25cm drift length. Tests with a full-scale 3.4m x 3m Charge Readout Plane (CRP), each half instrumented by different electronic designs to be used for the FD module
- Proof of concept demonstrator using cosmic rays to characterize performance of anode plane, readout electronics etc in terms of CRP design, electronics signal-to-noise
- 1st test completed in Nov, Dec’ 21. Further tests ongoing and planned for FY’22 and FY’23

Coldbox Performance

- Observe clear cosmic tracks







- First test used base CRP design with strips oriented as ($0°$, $48°$, $90°$)
- Further tests planned this calendar year for more symmetric strip orientations ($\pm 30°$, $90°$)
- Results also show good S/N ratio w/ performance similar to ProtoDUNE-SP
- Further improvements planned for support frame and shielding/grounding