Capabilities of the DUNE Far Detector

Thomas R. Junk
on behalf of the DUNE Collaboration

IceDUNE Workshop
June 16, 2021

https://en.wikipedia.org/wiki/Ice_dune

References

Far Detector Technical Design Report

- Volume 1: Introduction to DUNE, *JINST* 15 (2020) 08, T08008 e-Print: 2002.02967
- Volume 2: DUNE Physics, e-Print: 2002.03005 [hep-ex]
- Volume 3: DUNE Far Detector Technical Coordination, *JINST* 15 (2020) 08, T08009 e-Print: 2002.03008 [physics.ins-det]
- Volume 4: Far Detector Single-Phase Technology, *JINST* 15 (2020) 08, T08010 e-Print: 2002.03010 [physics.ins-det]

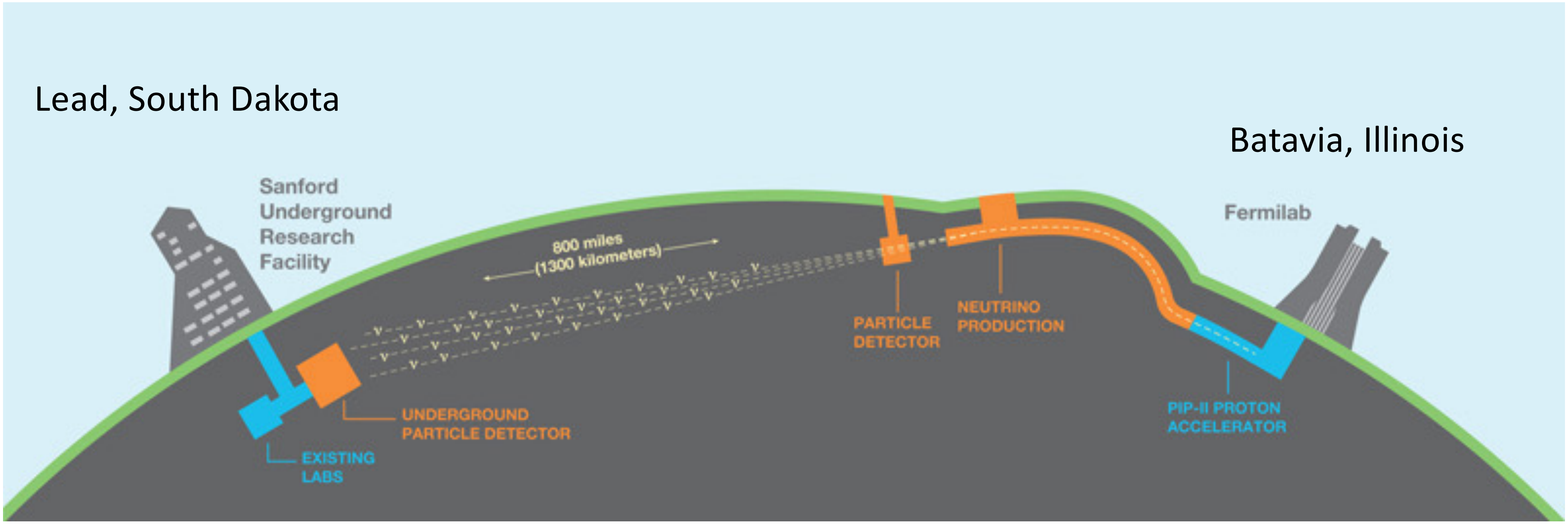
ProtoDUNE-SP

- Technical Design Report: e-Print: 1706.07081 [physics.ins-det]
- First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform: *JINST* 15 (2020) 12, P12004 e-Print: 2007.06722 [physics.ins-det]

Outline

- Overview of DUNE's Detectors
- DUNE's Physics Program
- Far Detector Modules
- not covered: Beam and Near Detectors

LBNF/DUNE Overview



Powerful neutrino beam from Fermilab. Initial PIP-II design: 1.2 MW Protons on Target. Upgradeable to 2.4 MW.

Dominantly ν_μ in forward horn current mode, $\bar{\nu}_\mu$ in reverse horn current mode

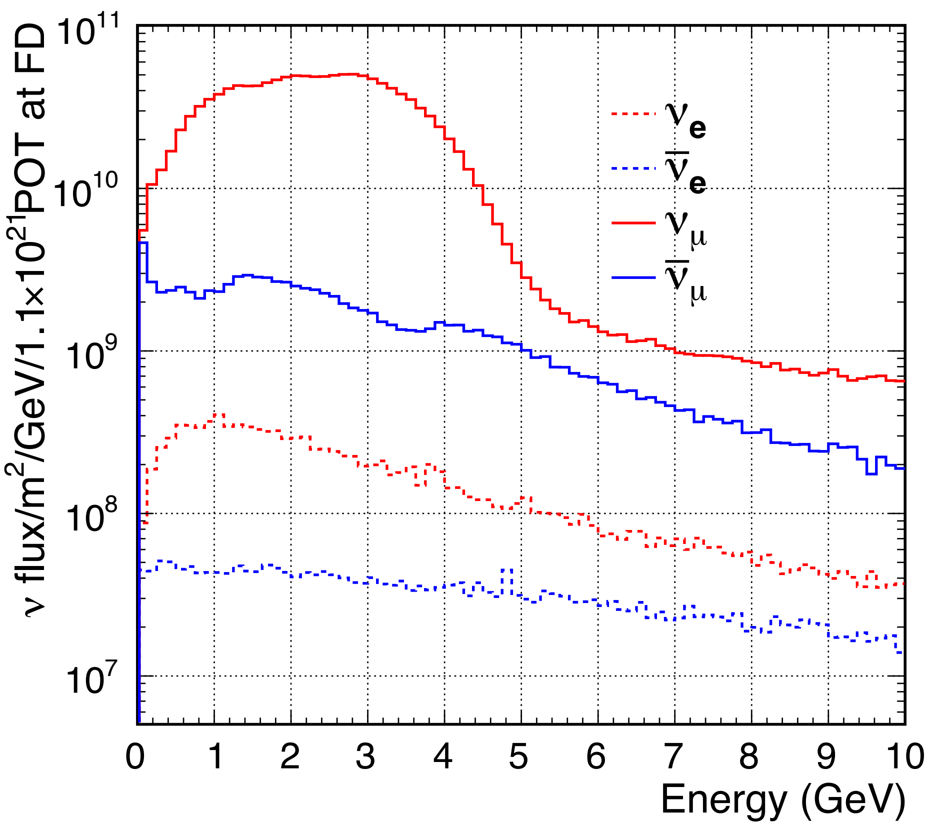
Broad-band energy spectrum peaking at ~2 GeV, near the first oscillation maximum

DUNE's Physics Goals

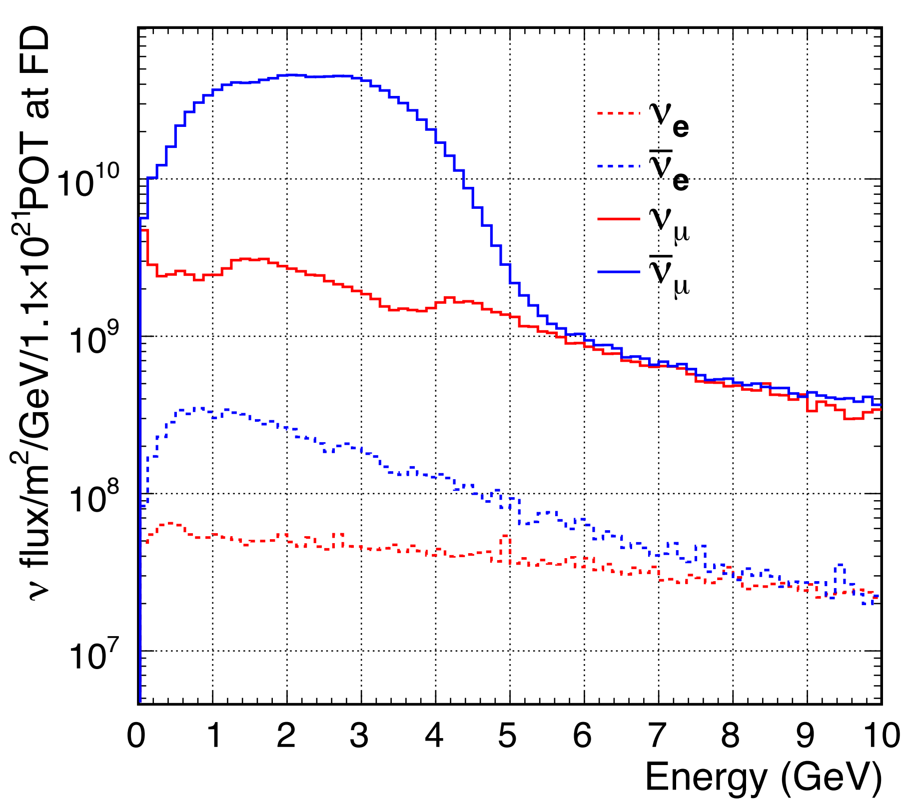
- Three primary goals. Detector design requirements flow from these:
  - Test whether CP is violated in the neutrino sector. Measure neutrino oscillation parameters with beam neutrinos: δ_{CP}. Determine mass ordering.
  - Observe neutrinos from supernova bursts within the galaxy and its satellites
  - Test for nucleon decay
- Many additional physics topics (just a few here, not an exhaustive list)
  - neutron-antineutron oscillations
  - Atmospheric neutrino contributions to oscillation measurements
  - Searches for BSM phenomena
  - Test the 3-flavor oscillation model – search for non-standard interactions
  - Solar neutrino physics
  - Tau neutrino appearance

Unoscillated Beam Spectra @ FD

Forward Horn Current



Reverse Horn Current



Oscillated, Reconstructed Expected Spectra

Energy range of interest for beam events:

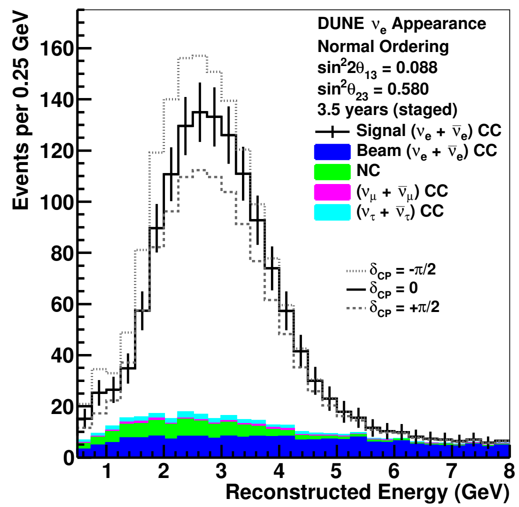
0.5 GeV to 8 GeV

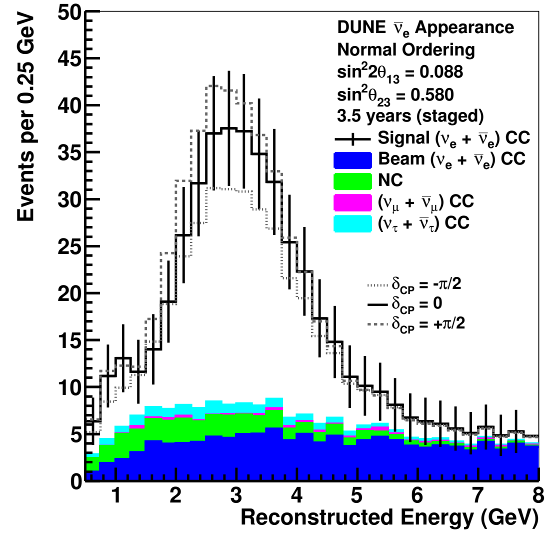
Detector is designed to do this physics well.

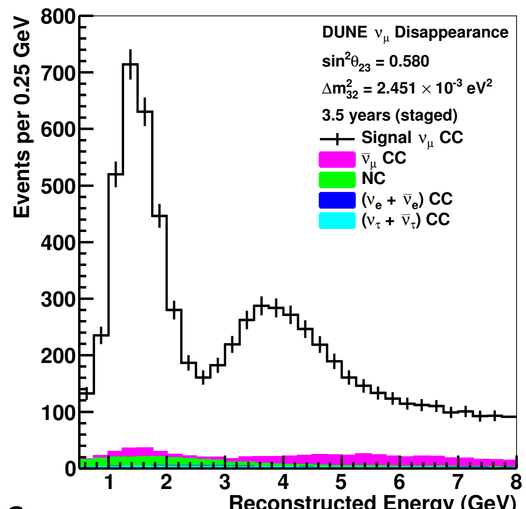
$\boldsymbol{\nu}_e$CC reco energy resolution: 13%

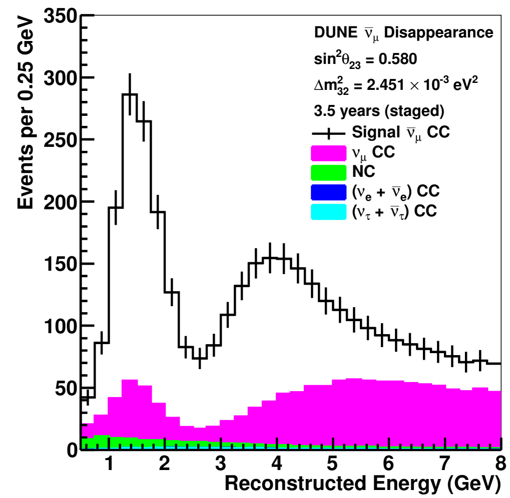
$\boldsymbol{\nu}_\mu$CC reco energy resolution: 18%

Resolutions are current in the TDR: expect improvements as time passes

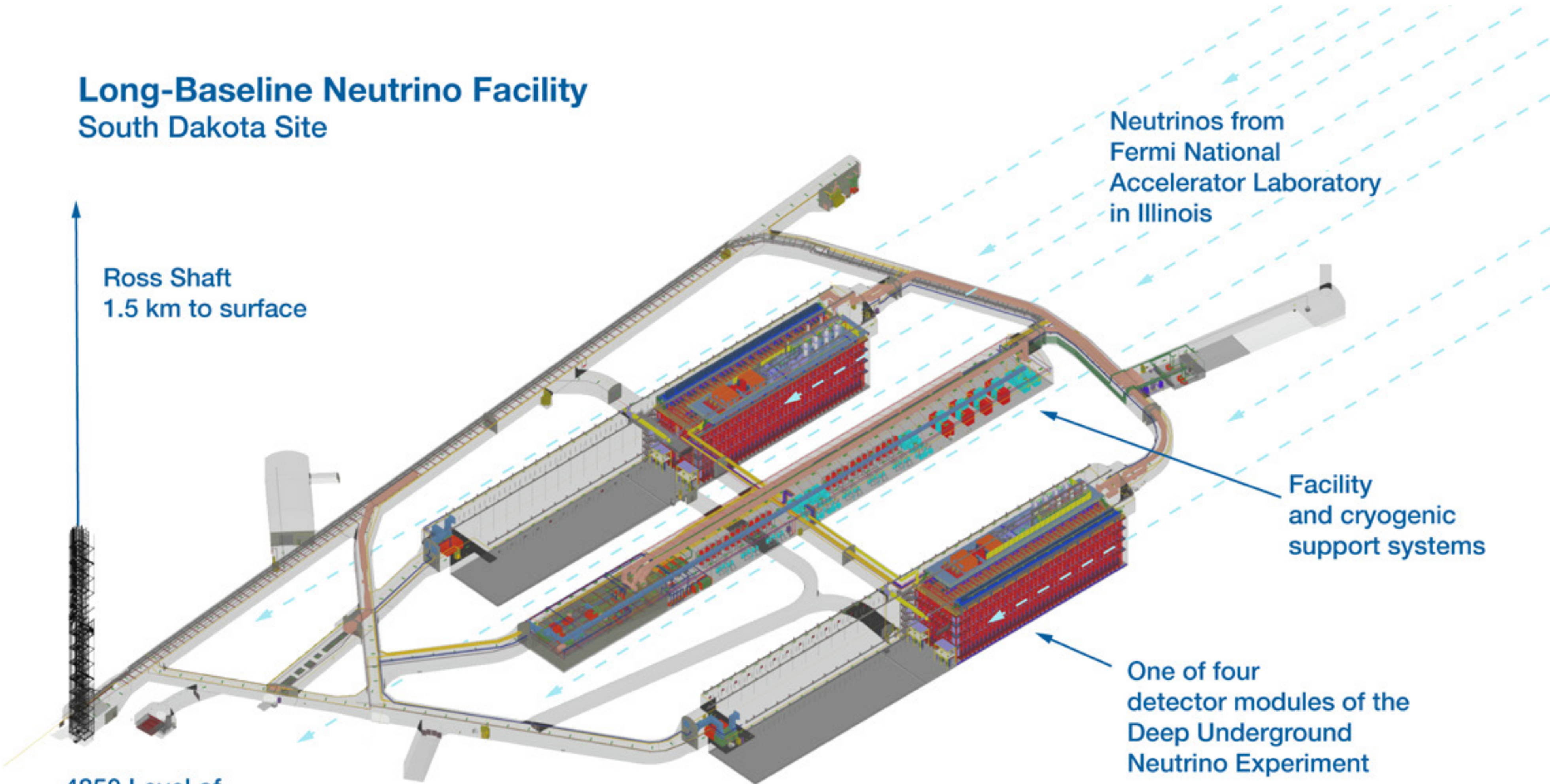






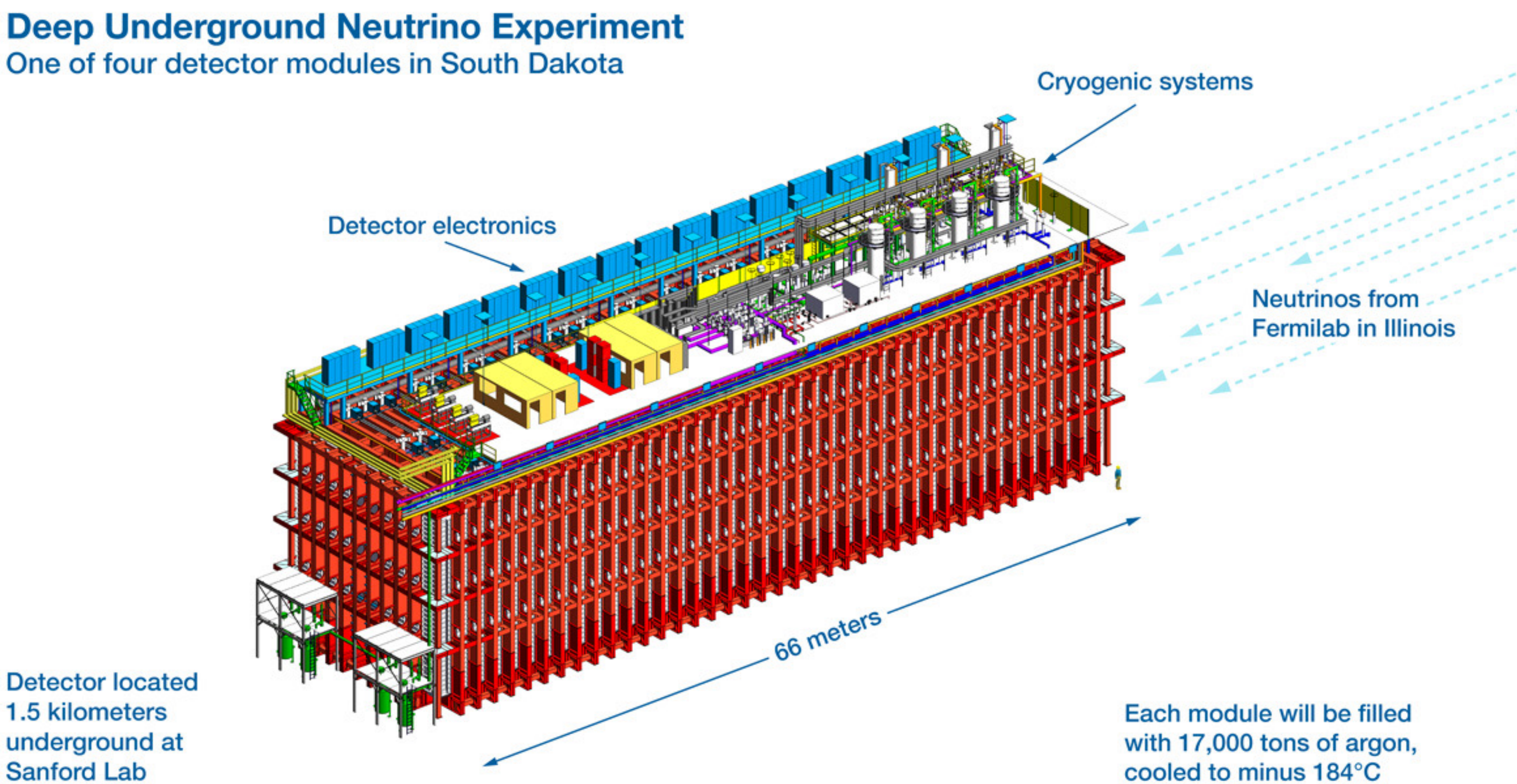


Underground Facilities at SURF



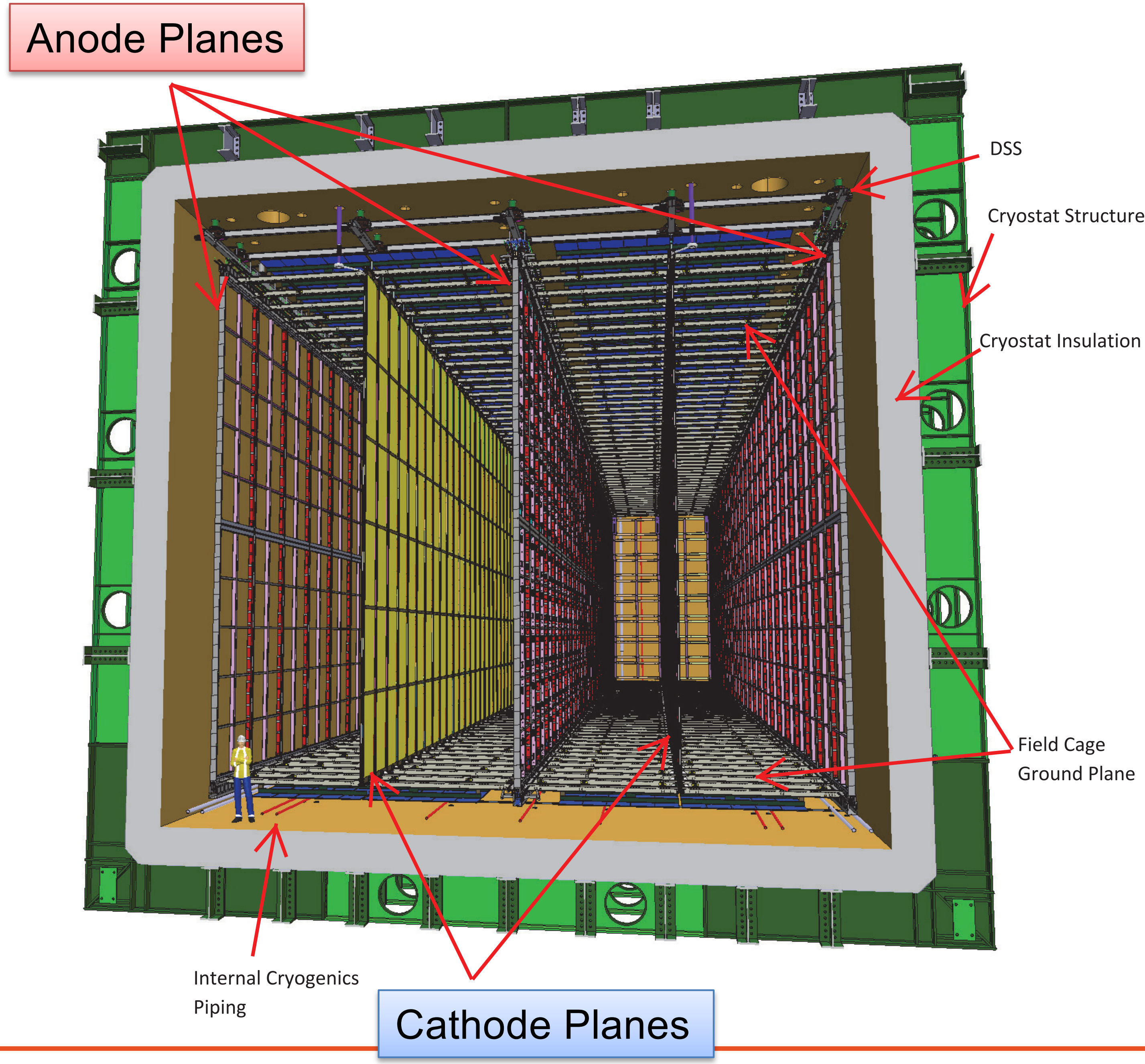
Depth = 4300 MWE

One of Four Far Detector Modules

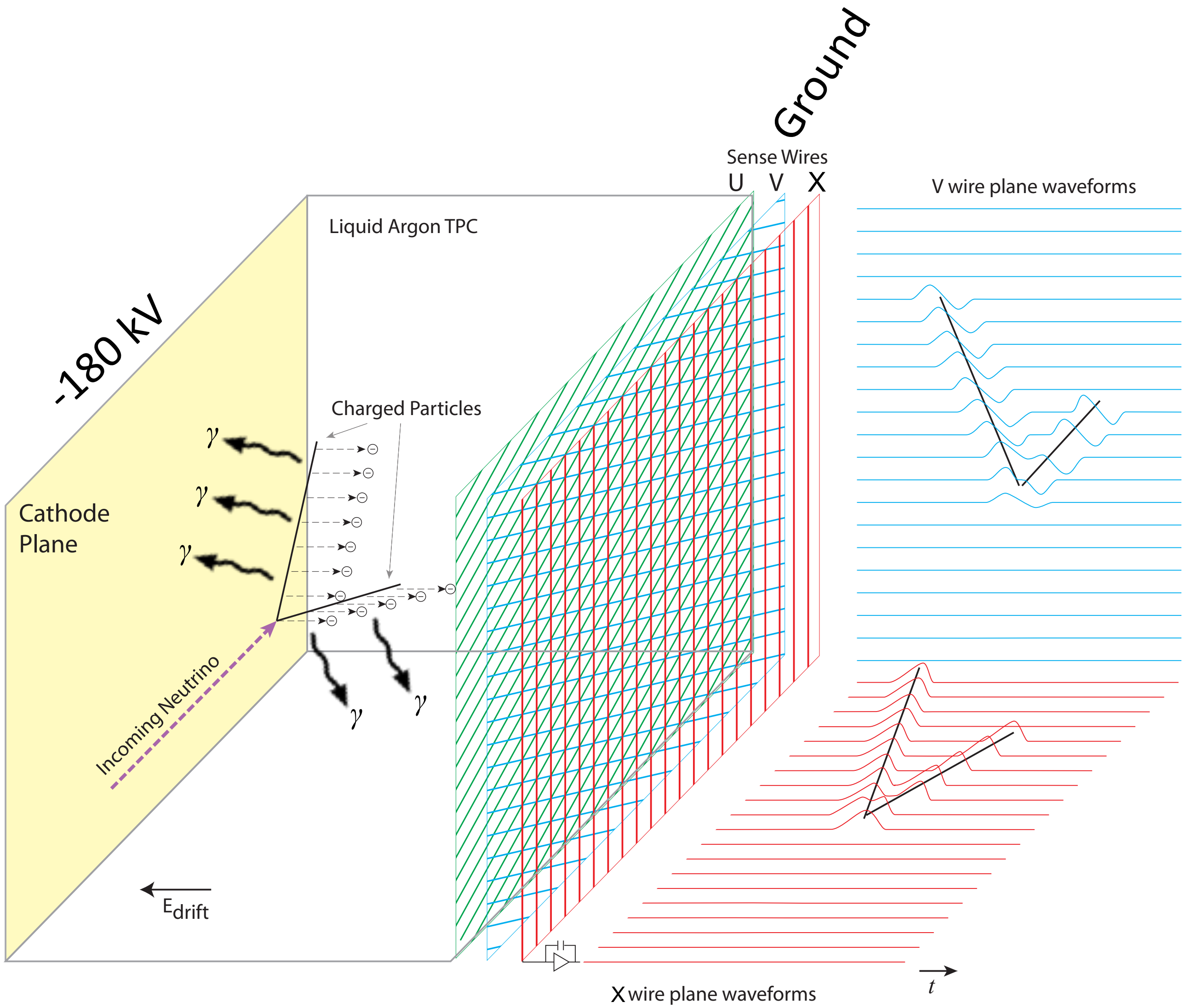


10 kt fiducial
vertex location
in beam events

Cross Section View of a Single-Phase FD Module

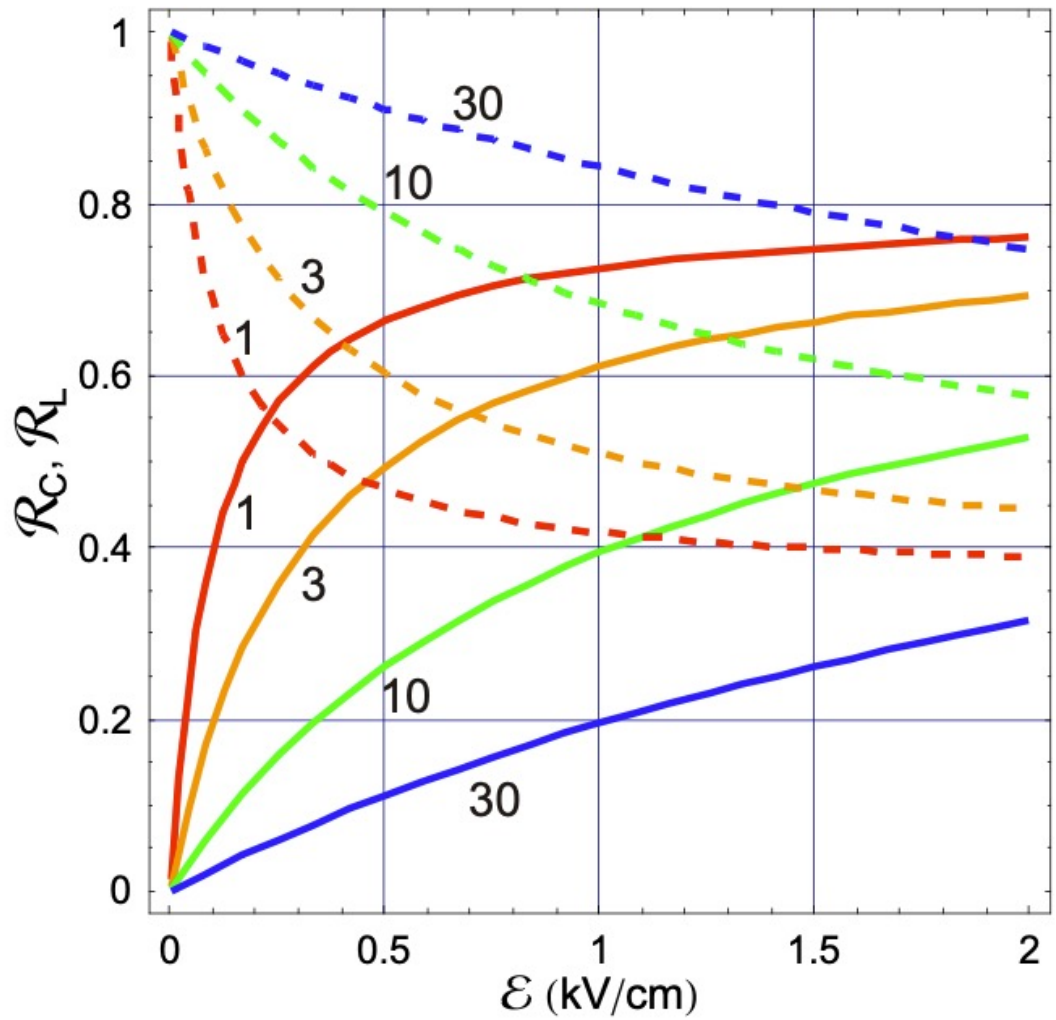


Production of Charge and Light in a LArTPC



Recombination in LAr

Nominal DUNE FD
electric field strength = 500 V/cm



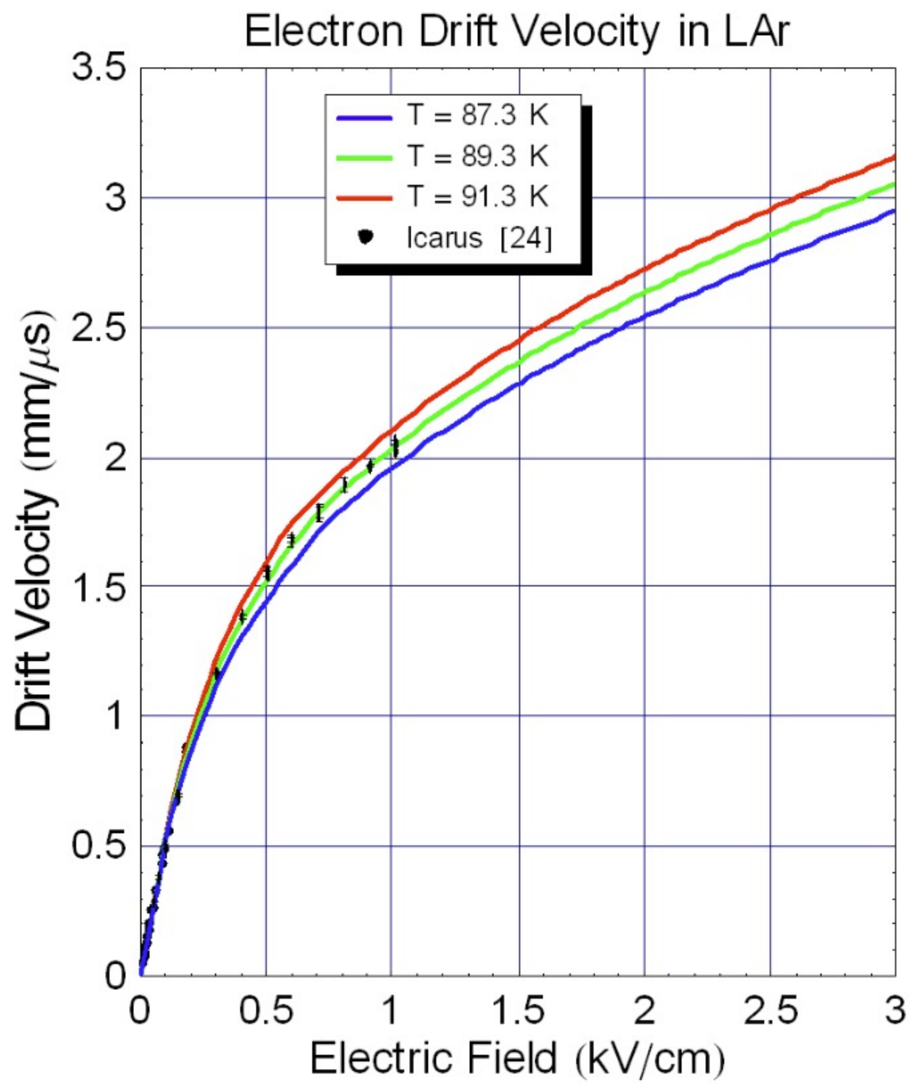
Solid lines are the recombination factor for charge (charge collected at finite field divided by charge collected at infinite field) [31, 32]. Dashed lines are the light recombination factor (light collected at field divided by light collected at zero field) [43]. The numbers labeling the curves are the specific energy loss (dE/dx) in units of mip.

J. Thomas and D.A. Imel, *Recombination of electron-ion pairs in liquid argon and liquid xenon*, Phys. Rev. **A36** (1987) 614.

S. Amoruso, *et al.*, *Study of electron recombination in liquid argon with the ICARUS TPC*, NIM **A523** (2004) 275.

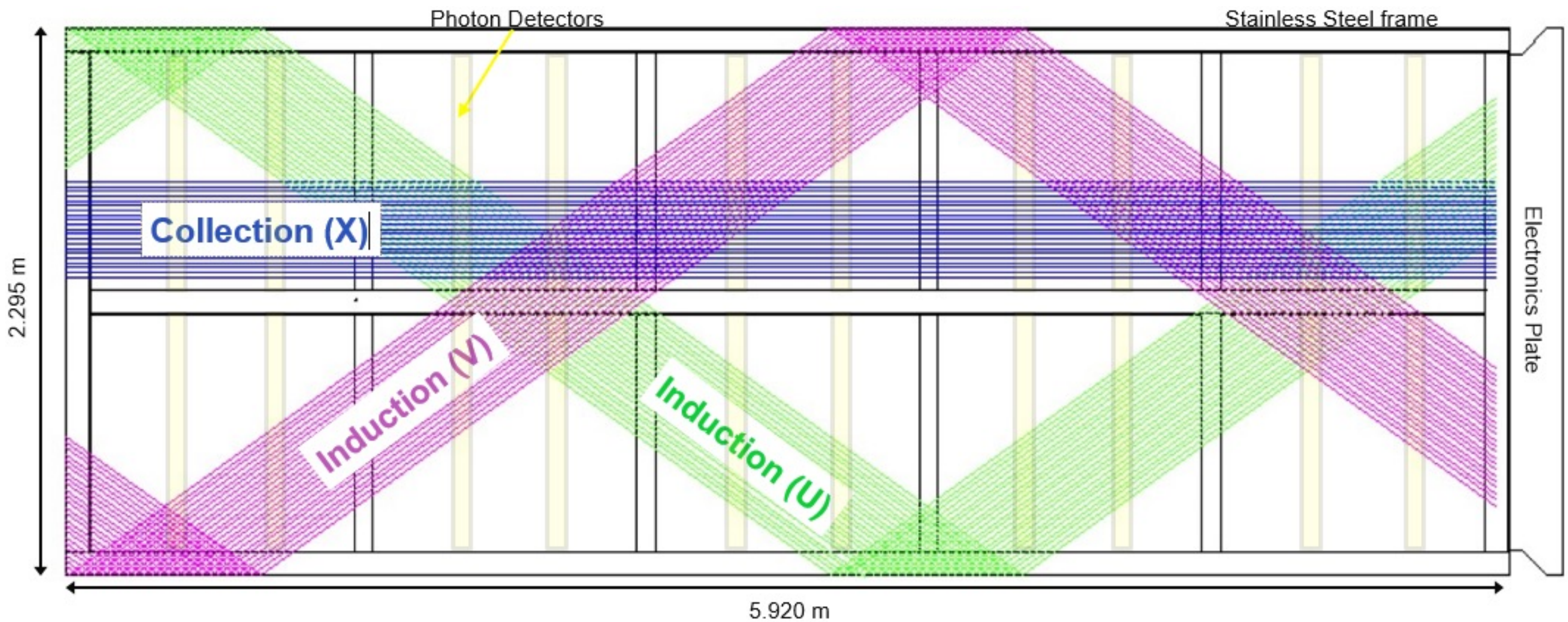
16 33. G. Bakale, U. Sowada, and W.F. Schmidt, *Effect of electric field on electron attachment to SF_6, N_2O, and O_2 in liquid argon and xenon*, J. Phys. Chem. **80** (1976) 2556.

Electron Drift Velocity in LAr



An Anode Plane Assembly (APA)

- Pairs of APAs are hung vertically
- Electronics on top of the top APA, on the bottom of the bottom APA
- Electronics are in the liquid argon – and are cold
- Four wire planes on each side – Grid (parallel to Collection) U, V, and Collection
- U and V plane wires wrap around front to back
- Grounded mesh behind the collection plane wires
- Photon detectors between the meshes



An APA on the Winding Machine

Anode-Plane Bias Voltages

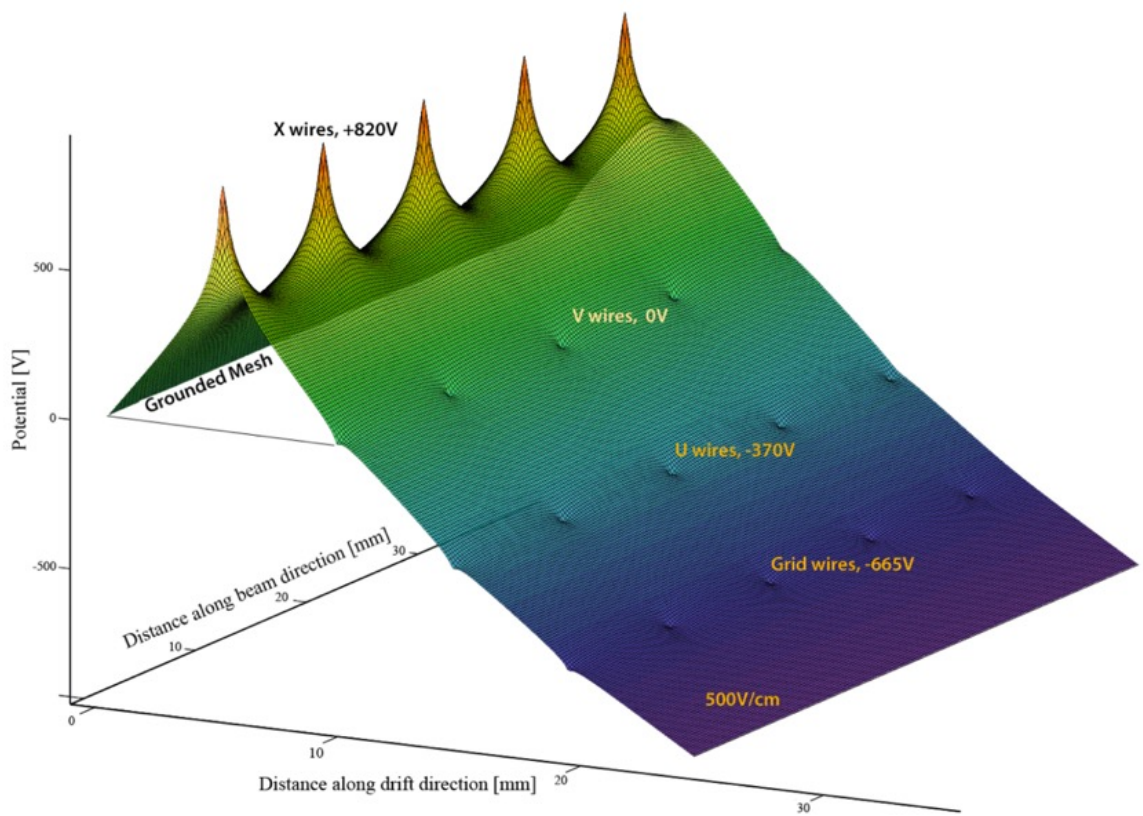
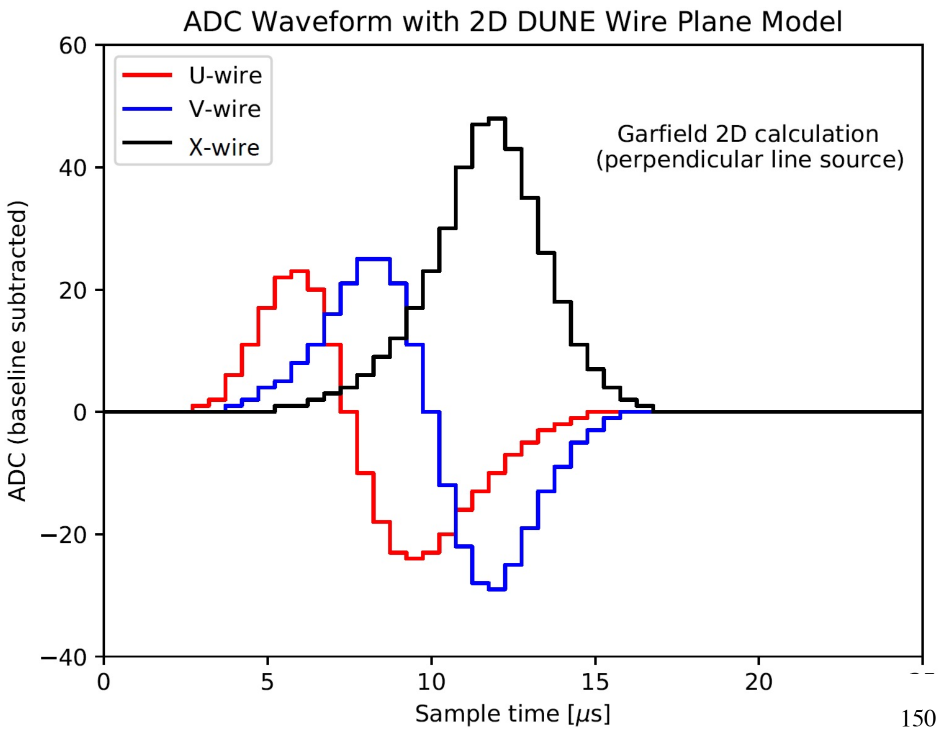


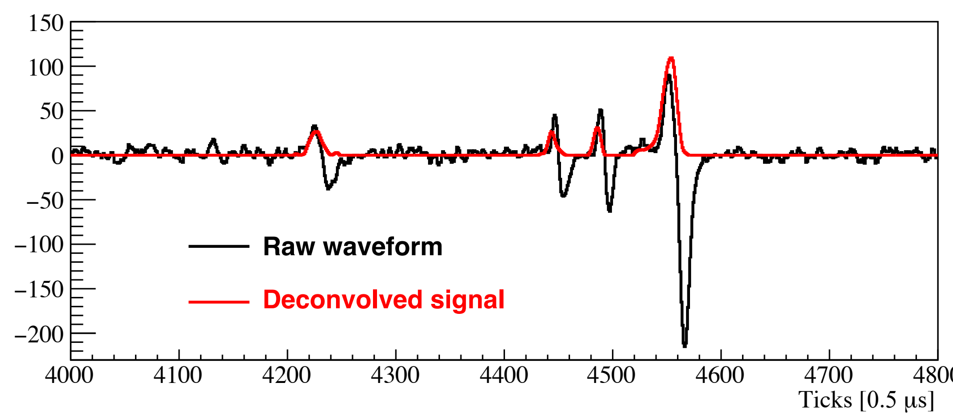
Figure 3–3: A surface plot of the electric potential distribution near the wire planes. The voltages on the wire planes are biased to provide complete electron transparency through the first three planes, and complete collection on the fourth plane.

Chosen to maintain transparency

Field between wire planes is adjustable – Stronger field --> faster drift, and higher-frequency signal shapes

Signal Shapes and Deconvolution





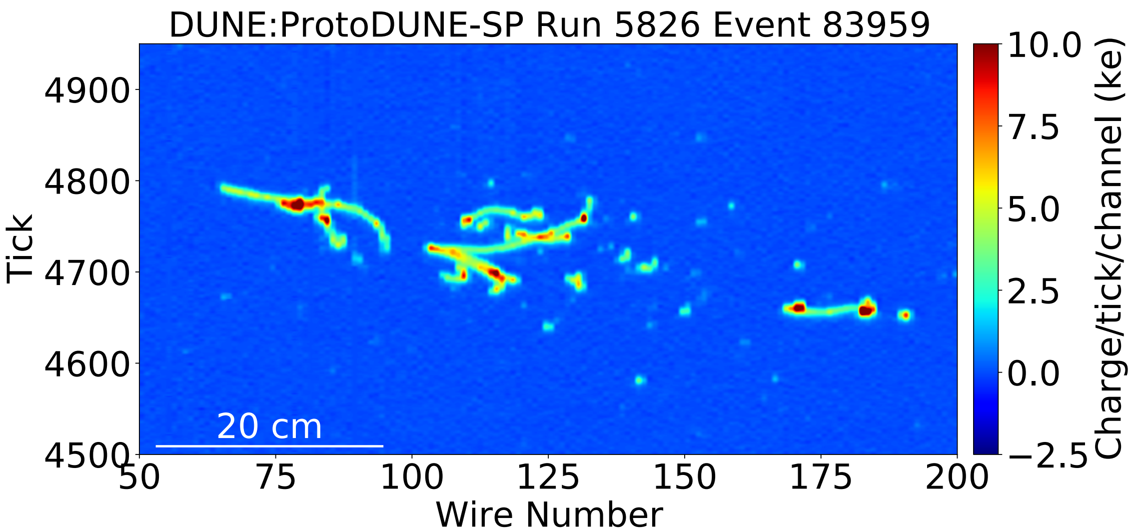
ProtoDUNEs at CERN

Two large-scale prototypes – ProtoDUNE-SP (NP04) and ProtoDUNE-DP (NP02)
Located in the EHN1 building at CERN on the Prévessin site
Low-energy beamline: 0.5 to 6 GeV momentum-selected mixture of electrons, pions, muons, protons, kaons

ProtoDUNE-SP uses full-scale FD components: APA, Cathode plane components, etc.

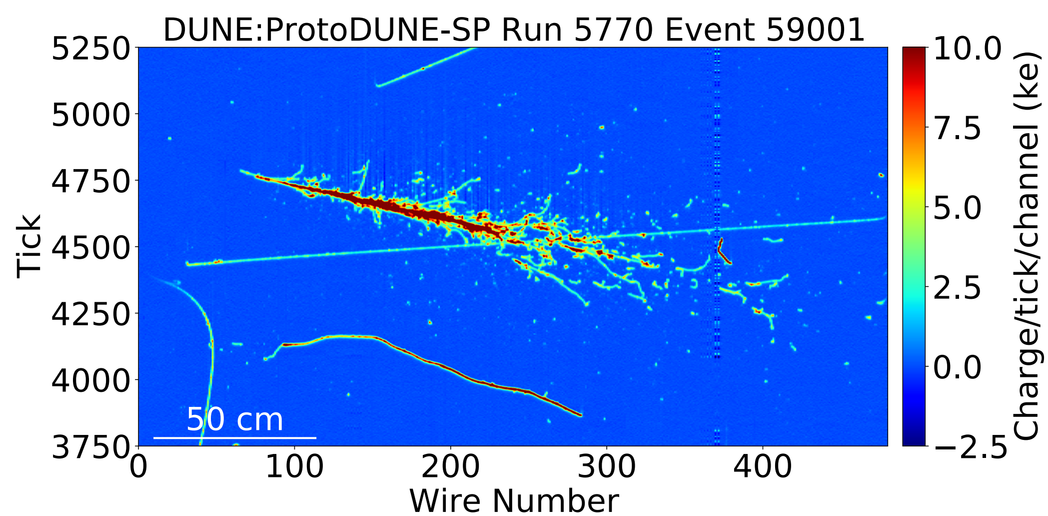
7.2 x 7.0 x 6.1 m^3 active volume of LAr in ProtoDUNE-SP

ProtoDUNE-SP Beam Events

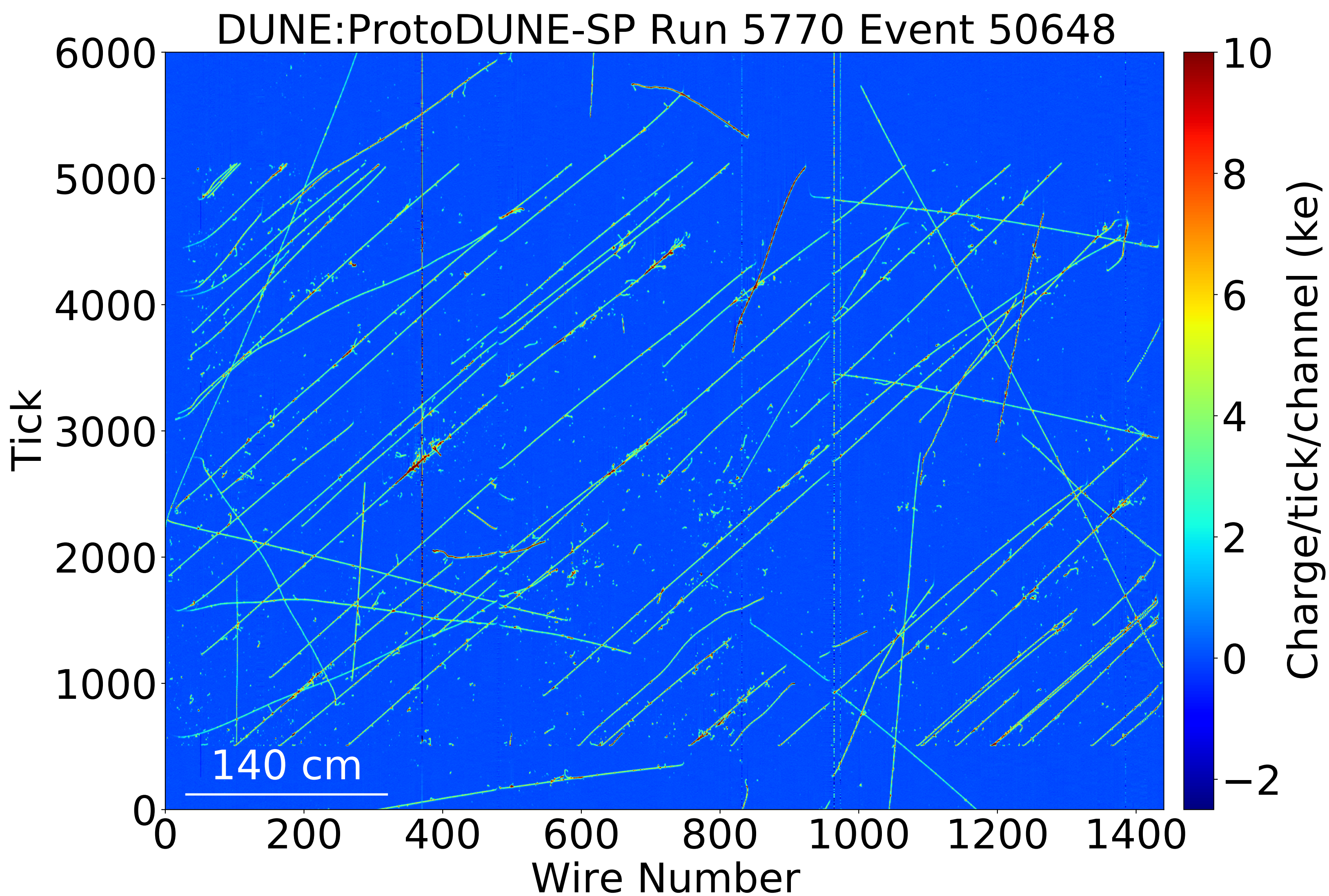


0.5 GeV Positron Candidate

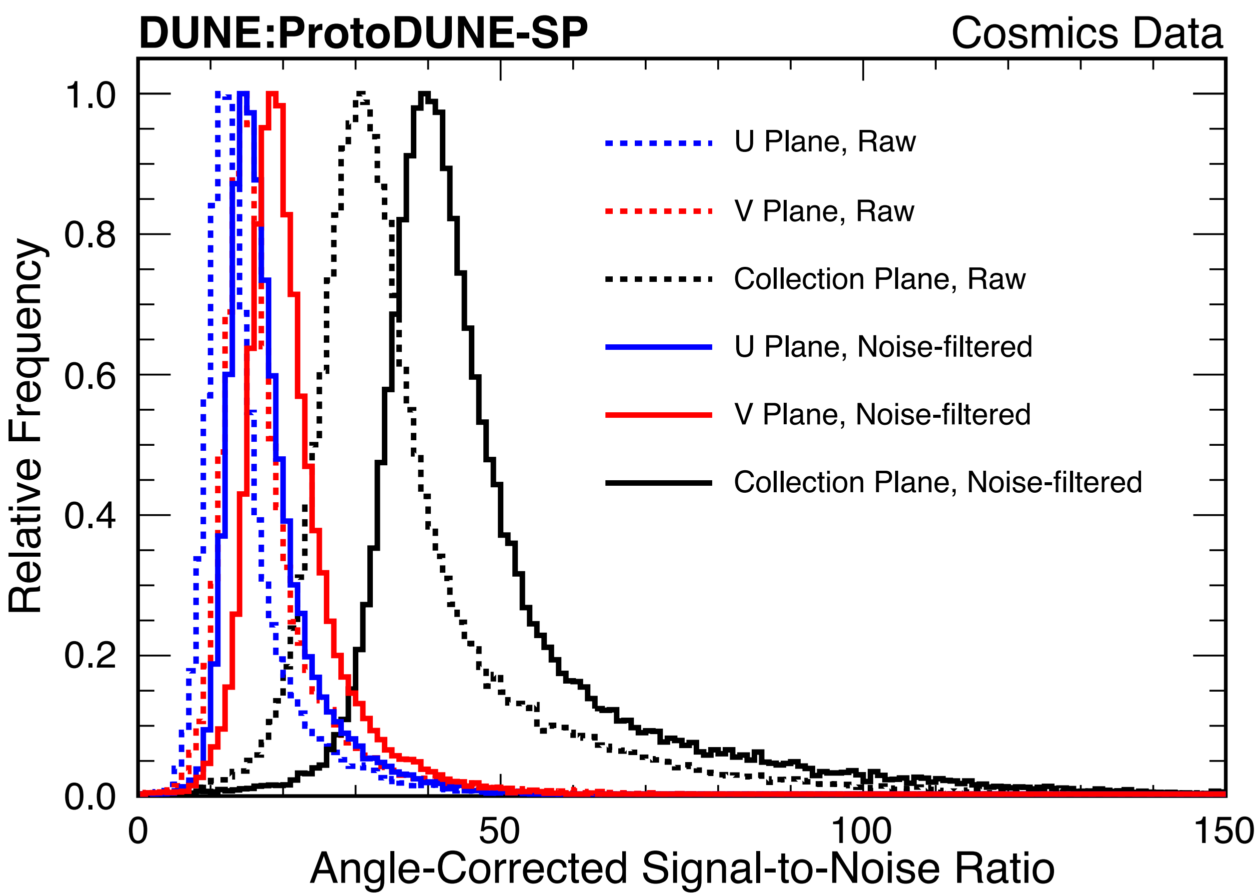
6 GeV Positron Candidate



A Cosmic-Ray Shower in ProtoDUNE-SP



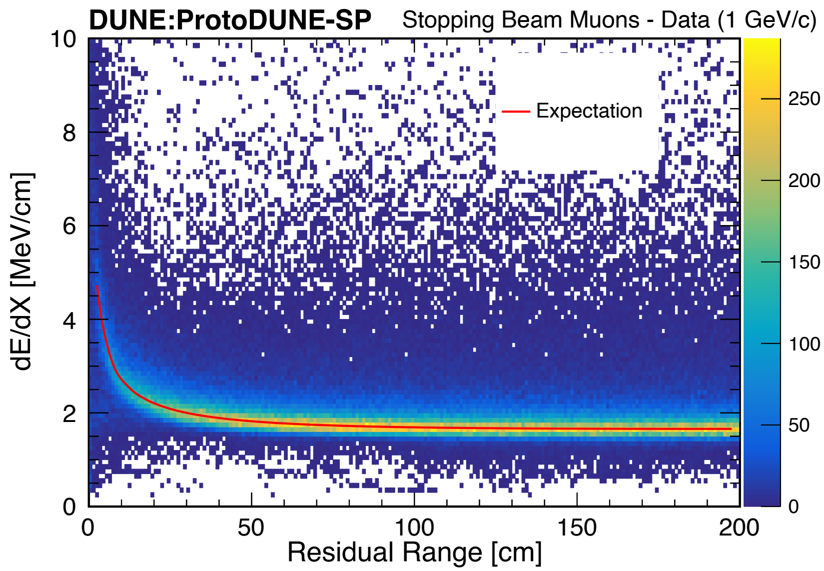
ProtoDUNE-SP Signal-to-Noise

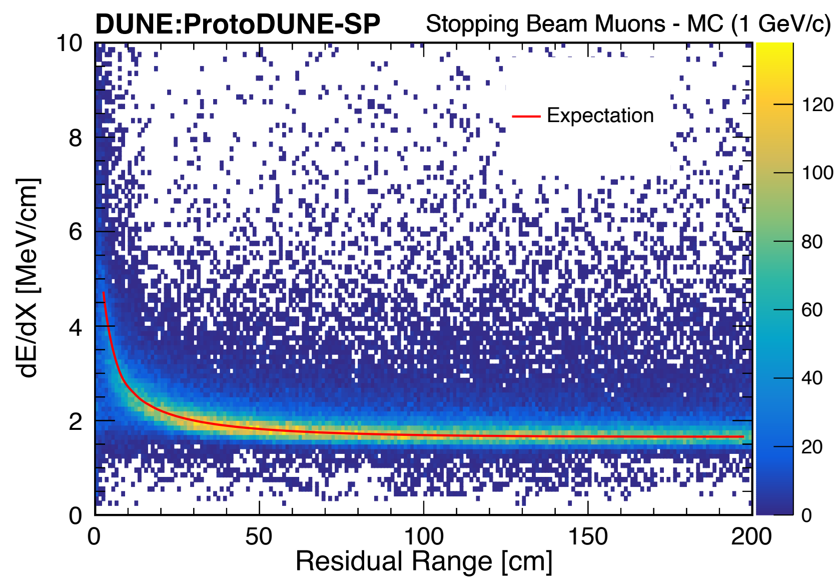


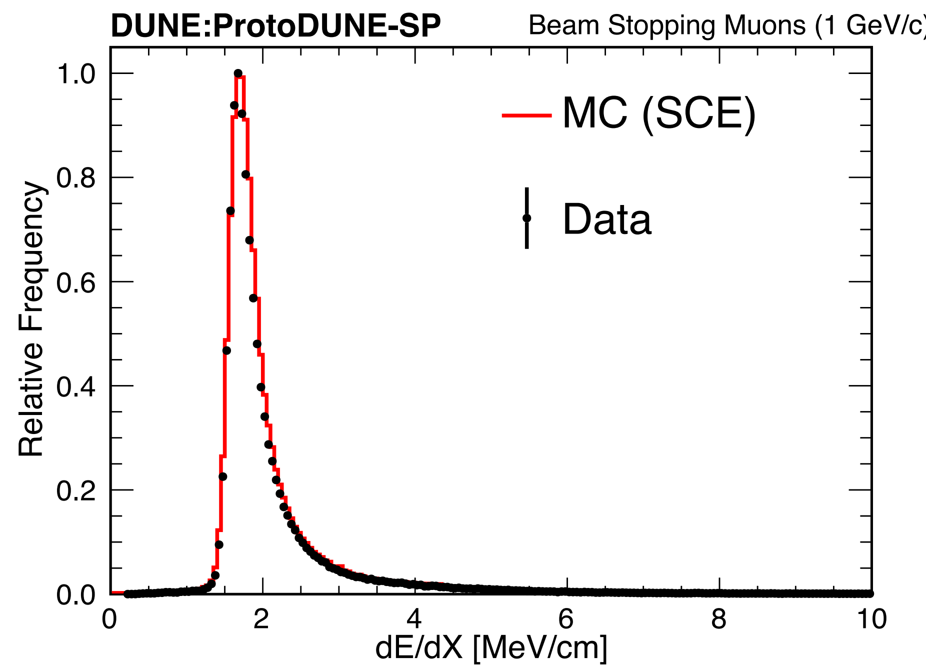
ProtoDUNE-SP performance paper

TPC+CE		
Noise	(C) 550 e, (I) 650 e ENC (raw)	< 1000 e ENC
Signal-to-noise ⟨SNR⟩	(C) 48.7, (I) 21.2 (w/CNR)	

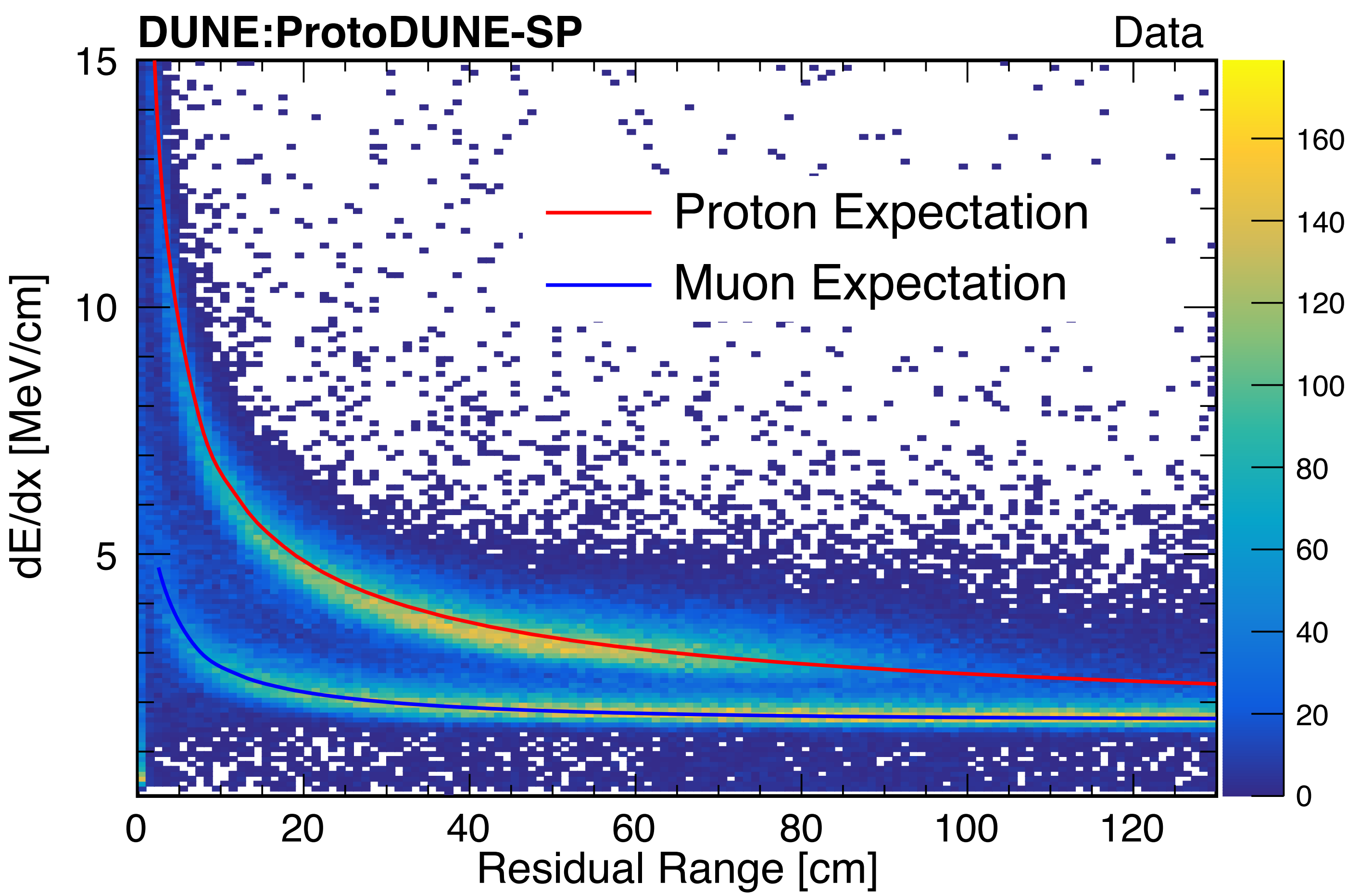
ProtoDUNE Stopping Beam Muons dE/dx





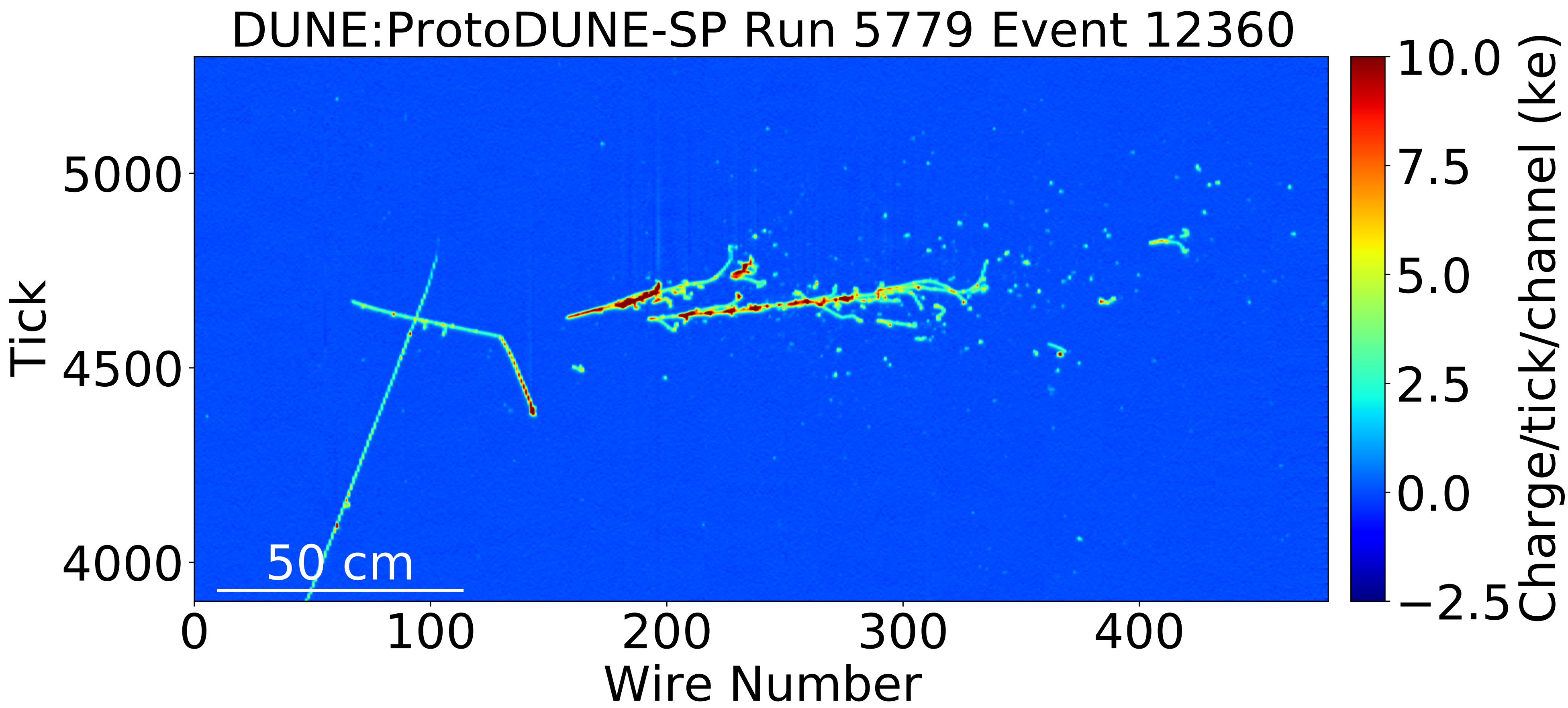


ProtoDUNE dE/dx Protons vs. Muons



Isolated Blips in ProtoDUNE-SP

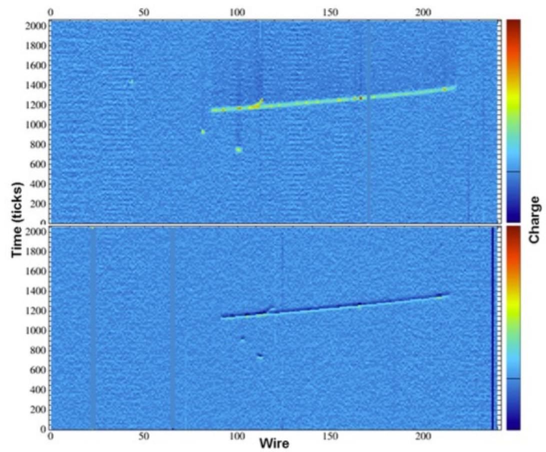
A π^0 candidate



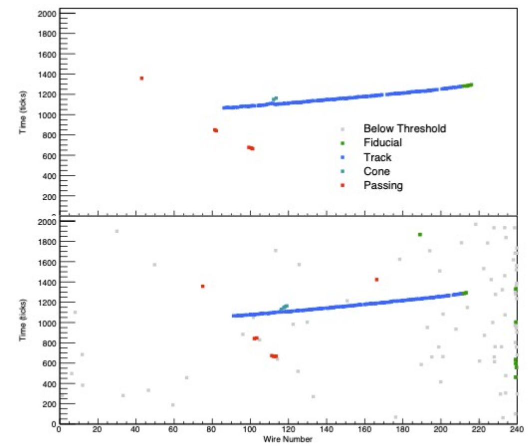
LAr Excels in Low-Energy Particles

- Delta rays
- 39Ar
- Nuclear de-excitation photons

Raw



Reconstructed



ArgoNeuT Collab.,
Phys. Rev. D 99, 012002 (2019)

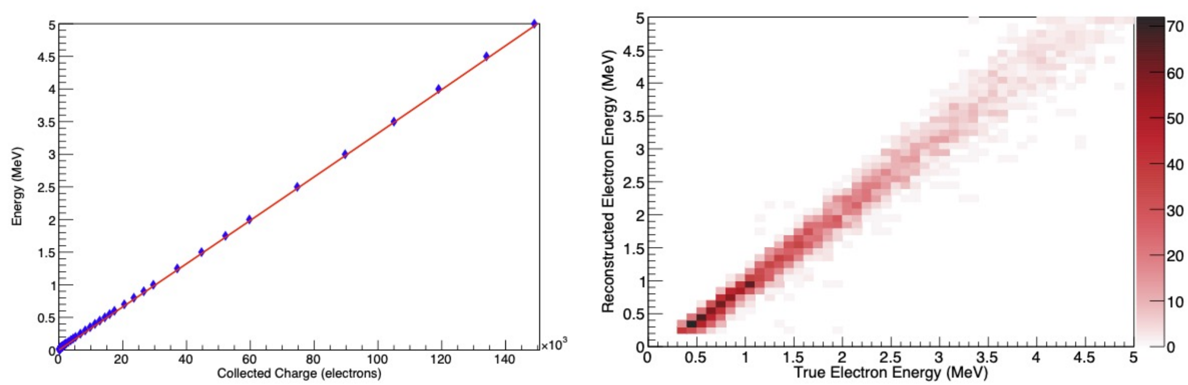
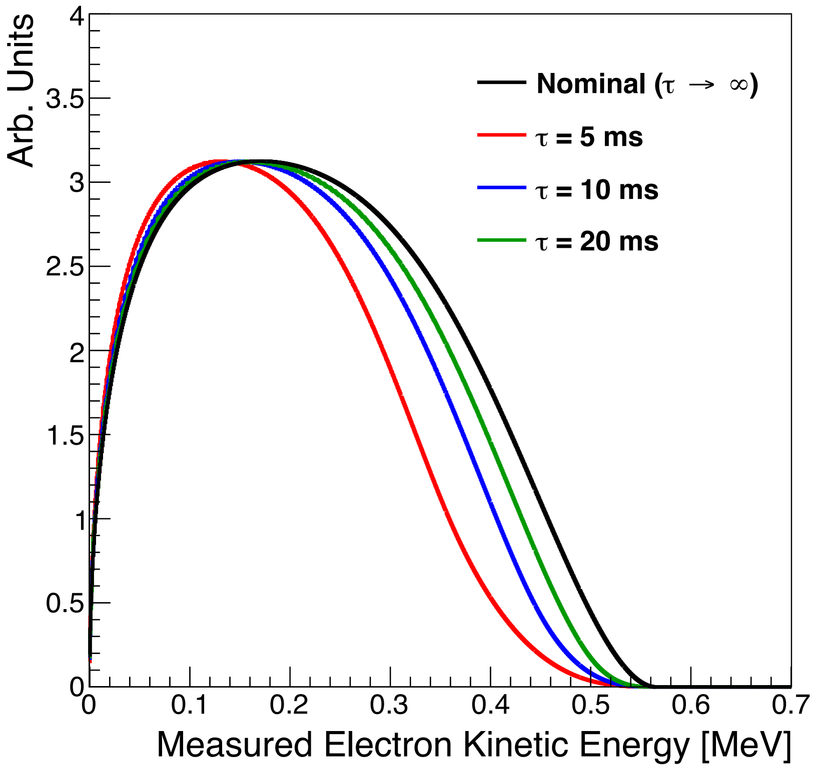
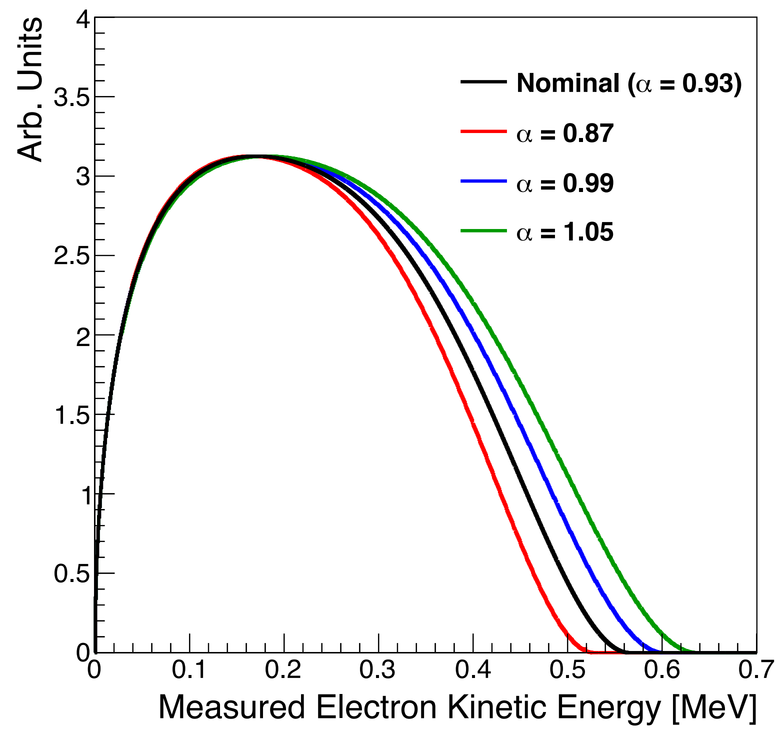


FIG. 5. Left: Energy deposited vs collected charge. Red curve indicates fit used to perform energy calculations from collected charge. Right: Reconstructed energy vs true electron energy using the charge method for a sample of simulated electrons with energies between 0 and 5 MeV. Events where the electron was not detectable are excluded.

Using ^{39}Ar to Calibrate Electron Attachment Rate



Electron spectrum vs. lifetime

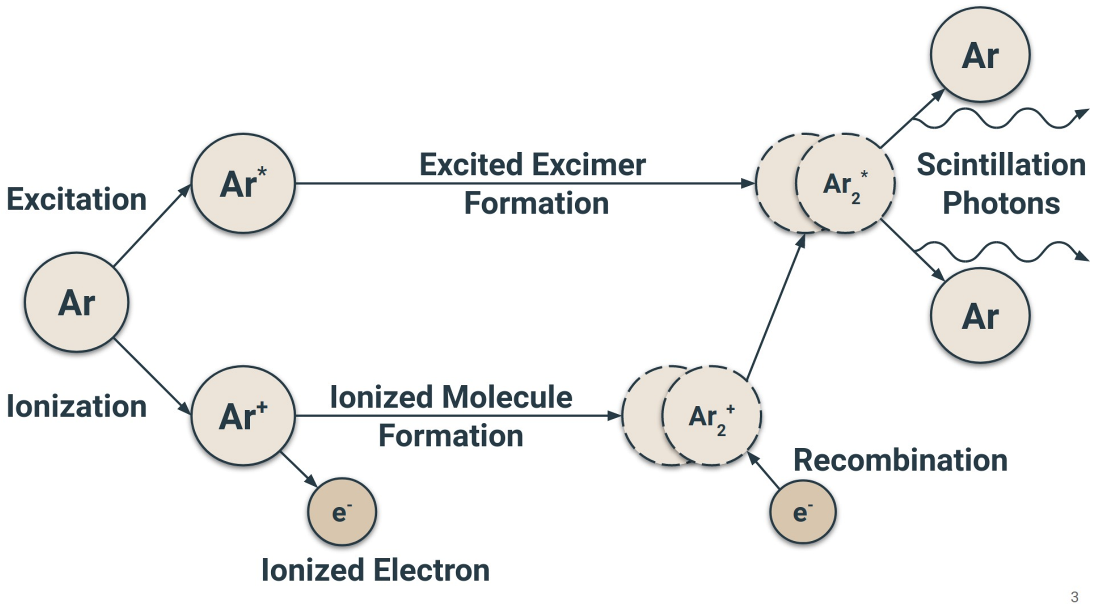


Modified Box model recombination parameter variation:

$R = \ln(\alpha + \xi)\,/\xi$, where $\xi = \beta\,\frac{dE}{dx}/\rho E_{\mathrm{drift}}$ and $\beta = 0.212$

Scintillation in Liquid Argon

- LAr scintillates very brightly – at 127 nm (vacuum ultraviolet)
- Also significant scintillation in the IR
- About 24,000 photons per MeV of energy deposited in LAr
- 1/3 of the light is prompt light (τ=6 ns) and 2/3 is late light (τ=1.5 μs)

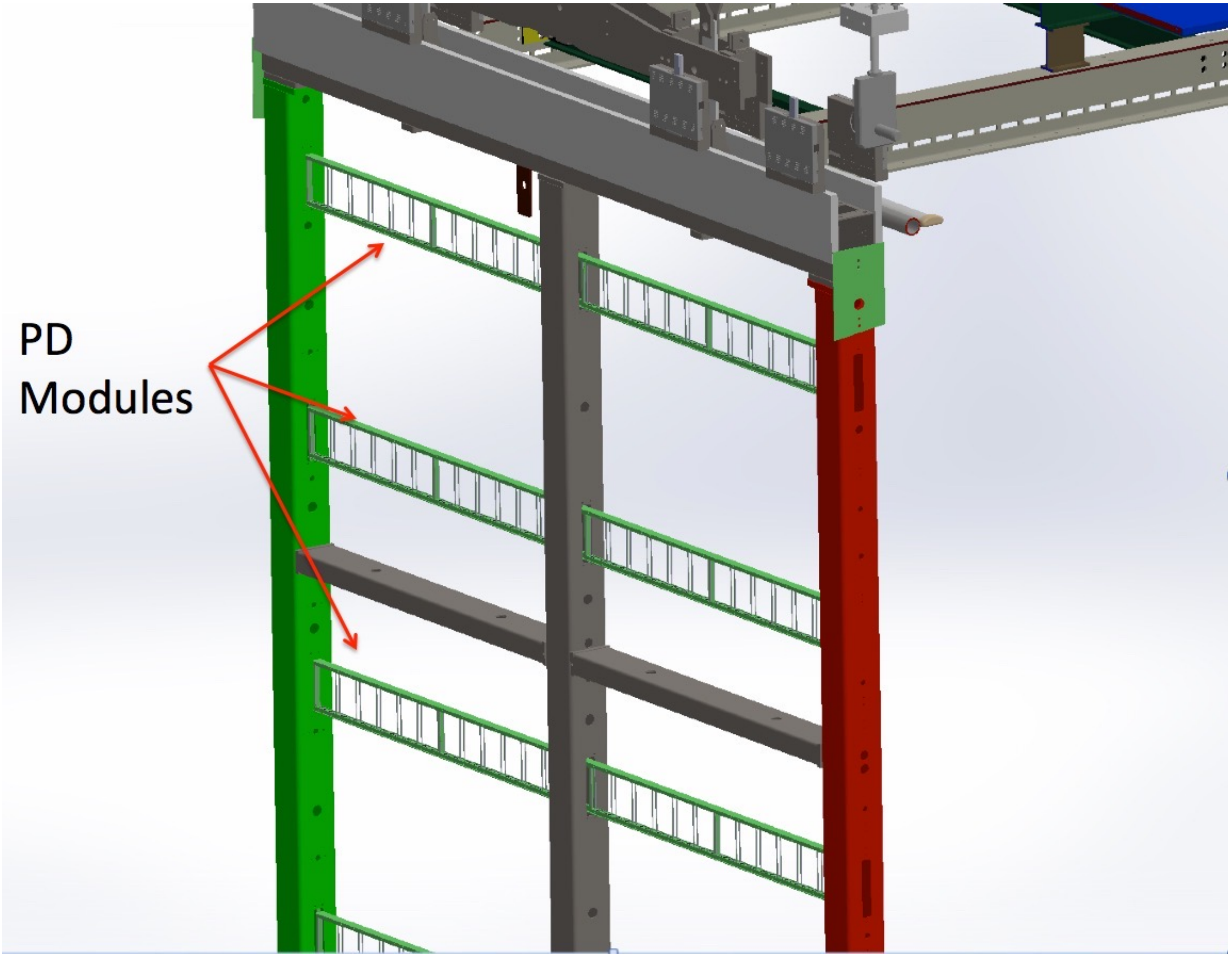


Prompt light from singlet-state excimer,
Late light from triplet state.

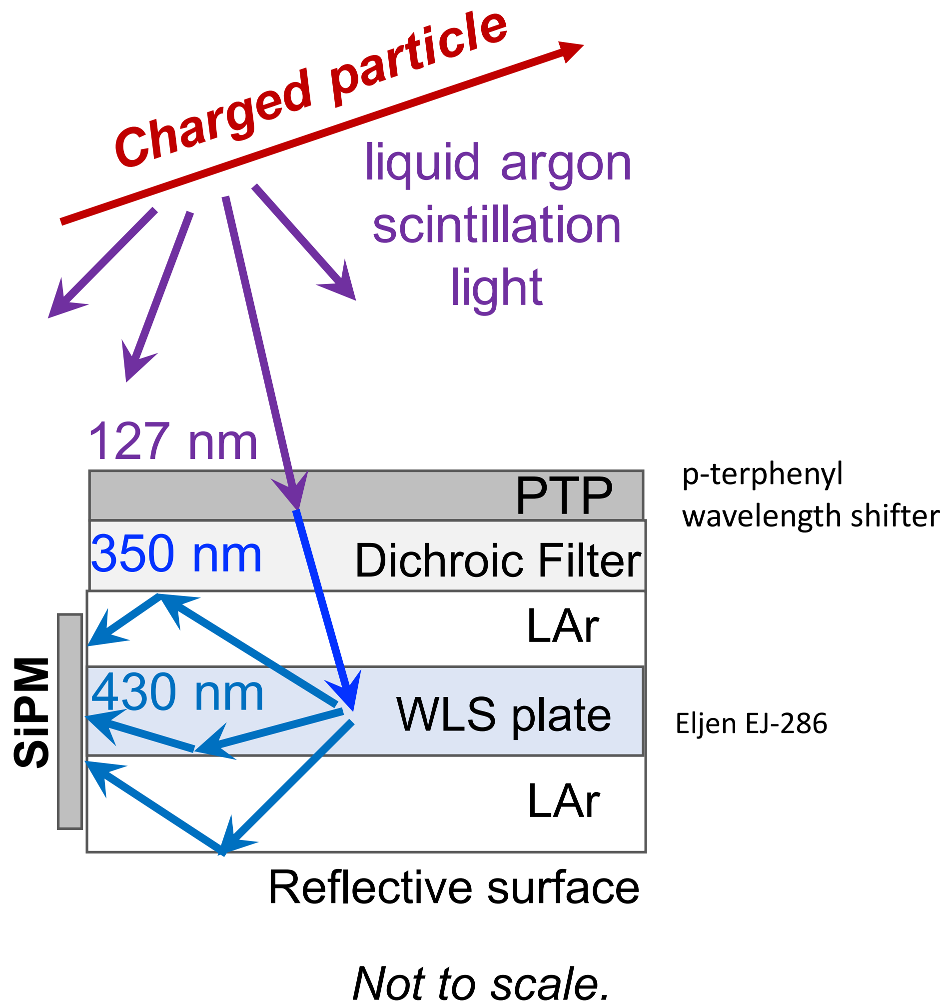
Scintillation Light Transport in LAr

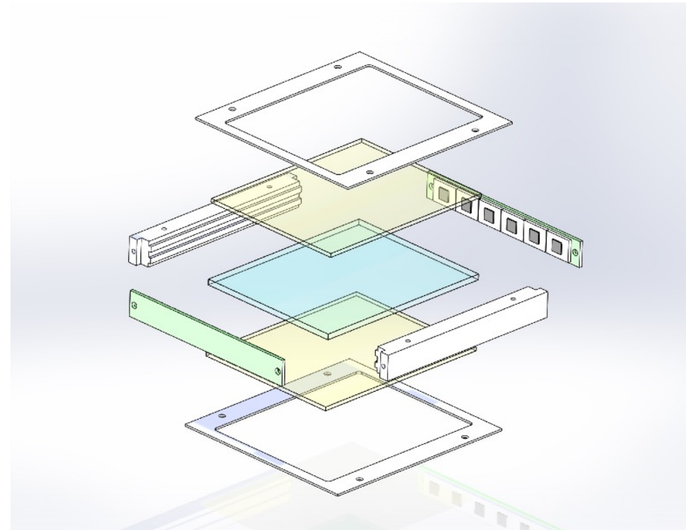
- LAr is transparent to its own scintillation light, but impurities (e.g. N_2) absorb it
- Rayleigh scattering length ~60 cm

Photon Detectors

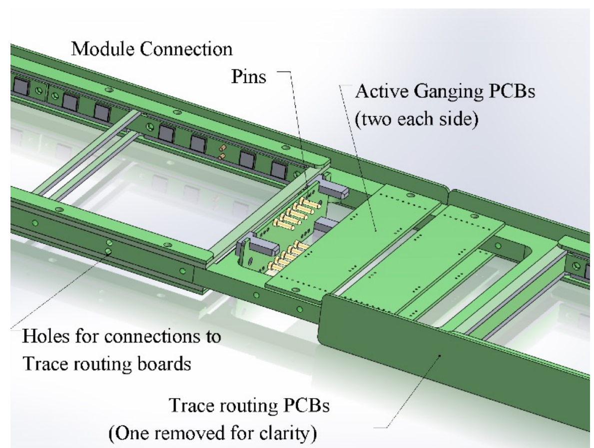


X-ARAPUCA Photon Detectors



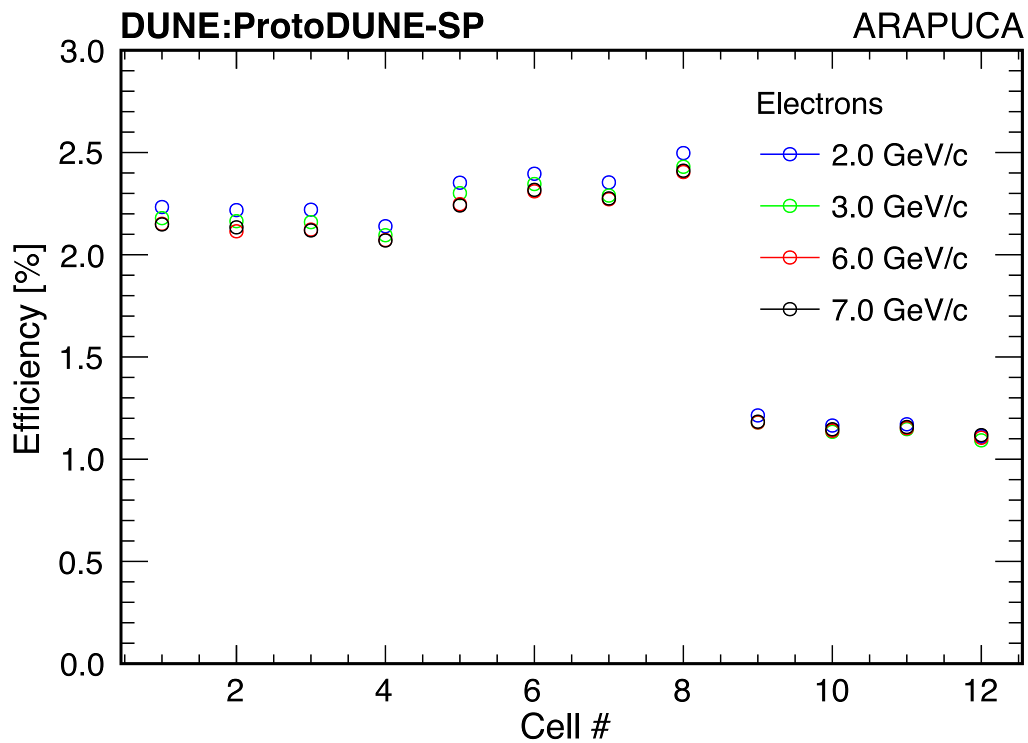


Sensitive to light coming from either side



An Arapuca

ProtoDUNE-SP S-ARAPUCA Efficiency



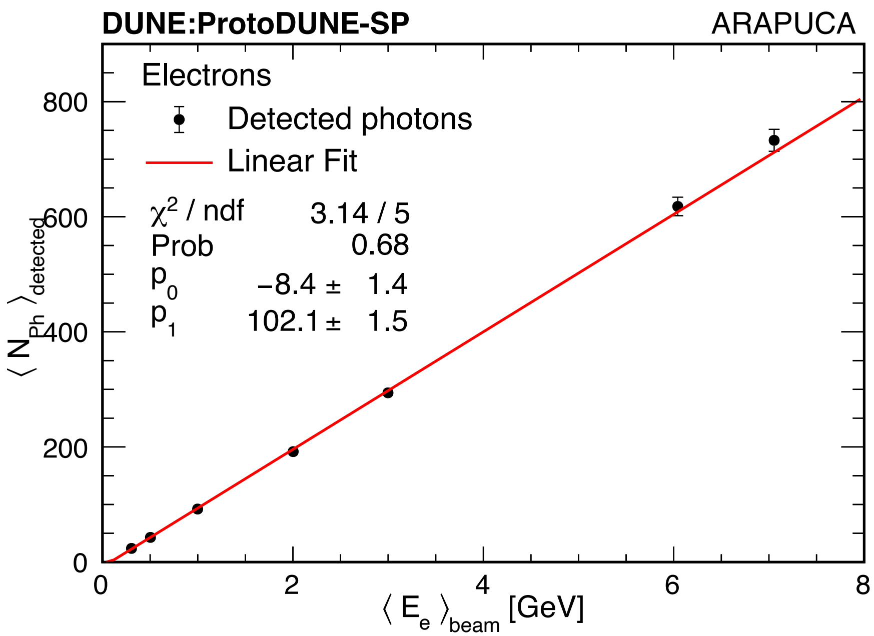
- Much higher efficiency than the dip-coated light guides used elsewhere in ProtoDUNE-SP
- ProtoDUNE-SP has an earlier version of ARAPUCA – instead of WLS plate, there was a coating of WLS material on the inner surfaces.
- X-ARAPUCA expected to have higher efficiency than S-ARAPUCA. Prototypes have 3.5% efficiency.

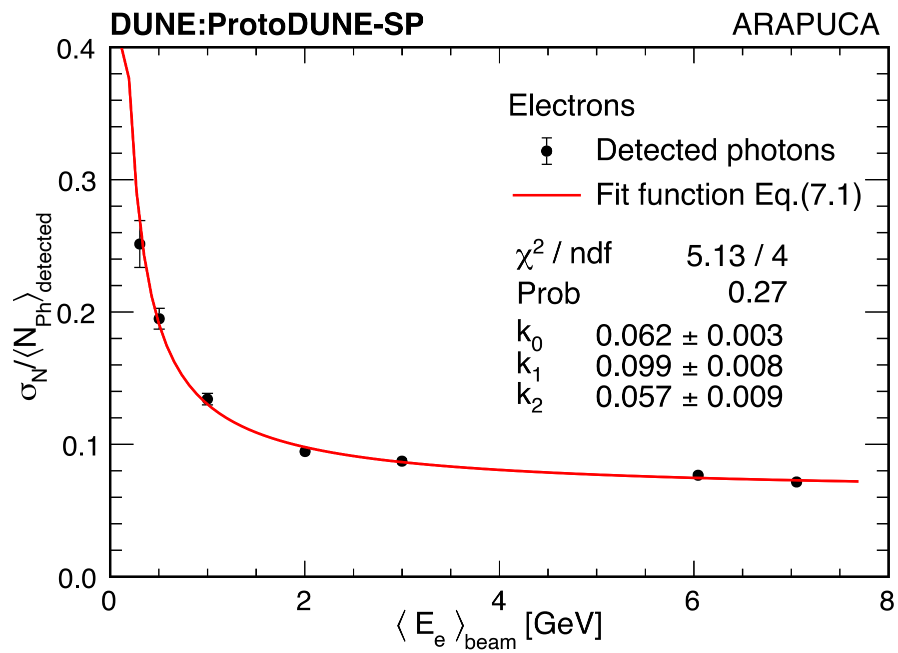
Timing Resolution and Physics

- Resolution requirement: better than 1 μs. Easily satisfied. About 10 ns resolution from double-pulse flasher response, dominated by digitization discreteness (6.67 ns sampling time). (double-pulse timing width is 14 ns)
- $\pm 1\mu$s timing gives mm precision on relationship between charge arrival time and distance
- Important for supernova burst events
  - No accelerator beam time
  - Calorimetry affected by electron attachment during drift – can correct for this if drift time is known
- Important for nucleon decay:
  - vertex fiducialization
- May contribute to event calorimetry

S-ARAPUCA Performance in ProtoDUNE-SP

- This is only a small sample – only two bars out of 60 were ARAPUCAs. The others were WLS+light guides.



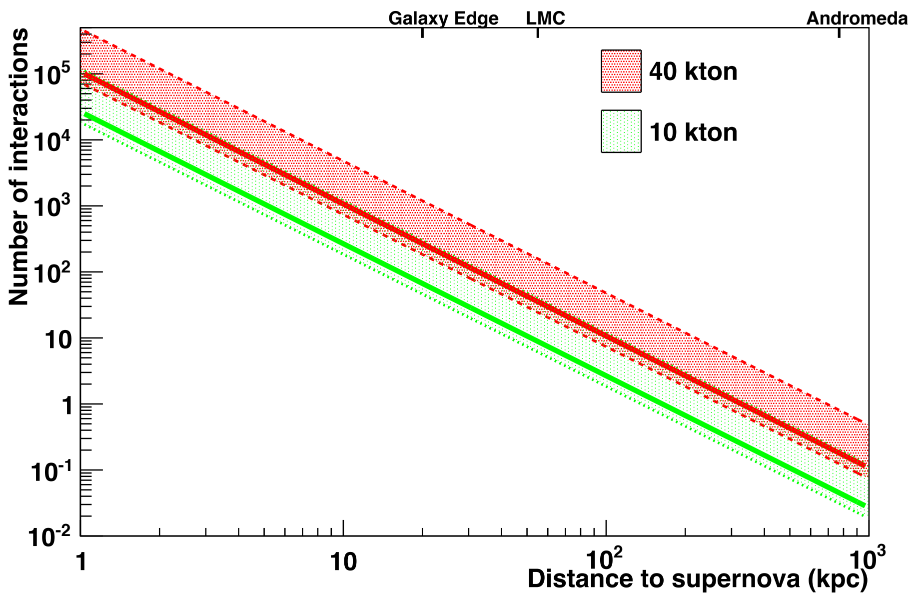


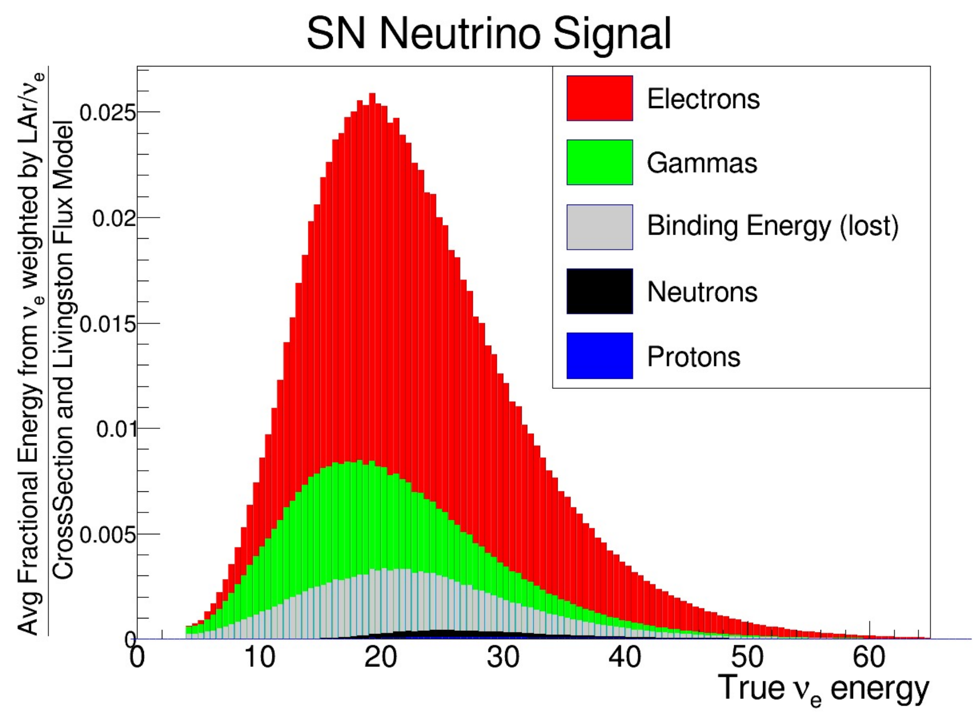
Estimated FD yield if all photon detectors are ARAPUCA-S: 1.9 Photons/MeV for scintillation at the cathode. Almost 4x the requirement.

$$\frac{\sigma_E}{E} = k_0 \oplus \frac{k_1}{\sqrt{E}} \oplus \frac{k_2}{E}$$

Supernova Bursts

- Expect of order 1000 ν_eCC interaction on ^{40}Ar in DUNE
- Arrival times up to 100 seconds from onset.   Most come early, but it's model dependent





- SNB data are very rare and precious. Need to go as low in threshold as possible.
- Full waveform readout for ~100s on SNB trigger (60 interaction threshold)

Fermilab DUNE

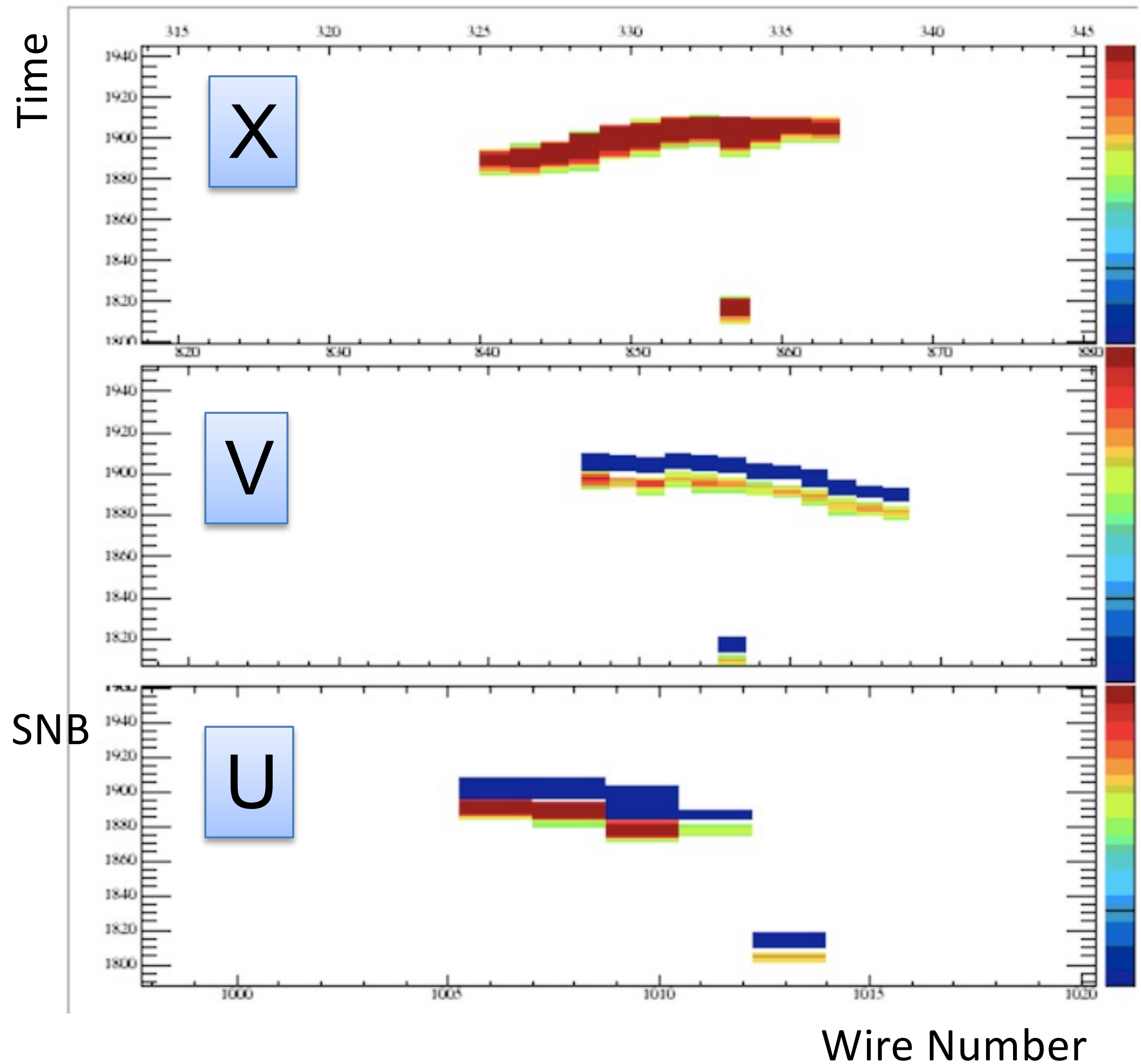
A Typical SNB Neutrino Interaction

ν_eCC interaction on ^{40}Ar

10.25 MeV Electron
Deposits charge on 12 collection-plane wires

Isolated blip from nuclear de-excitation photons

These blips can help distinguish SNB interactions from backgrounds
- radiologicals
- neutron interactions

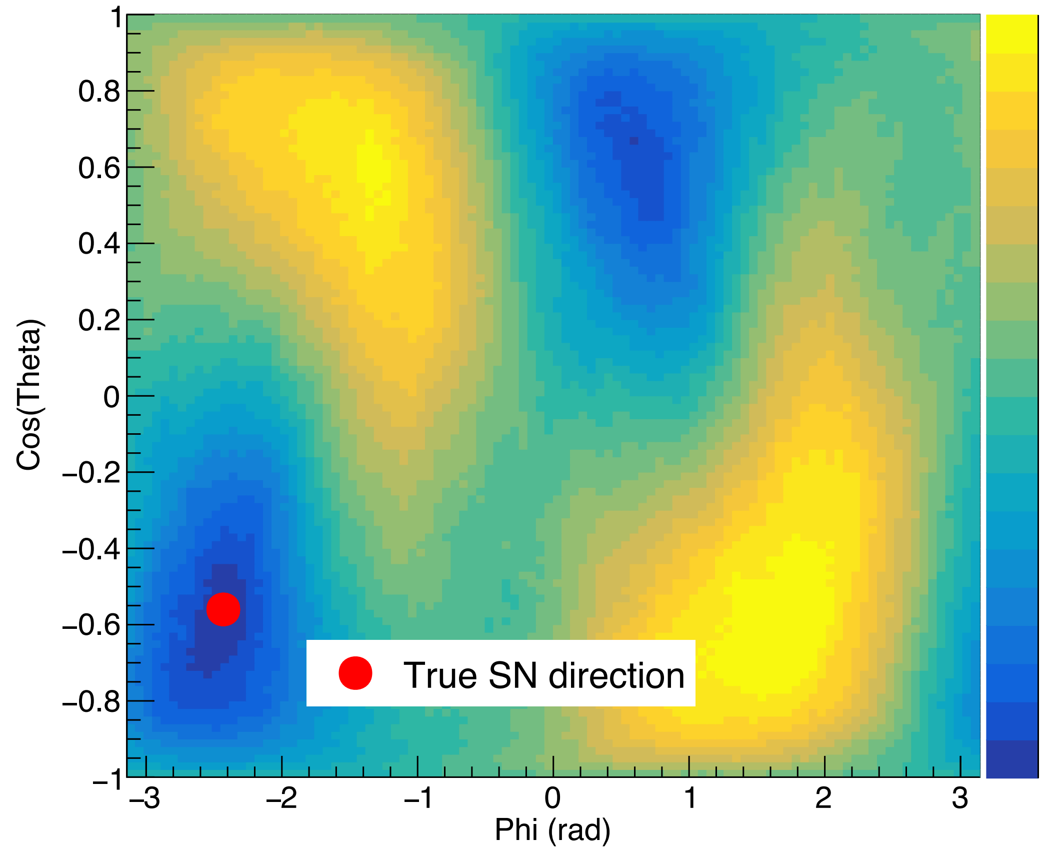


Supernova Burst Neutrino Pointing

Large dispersion in electron direction with respect to incoming neutrino

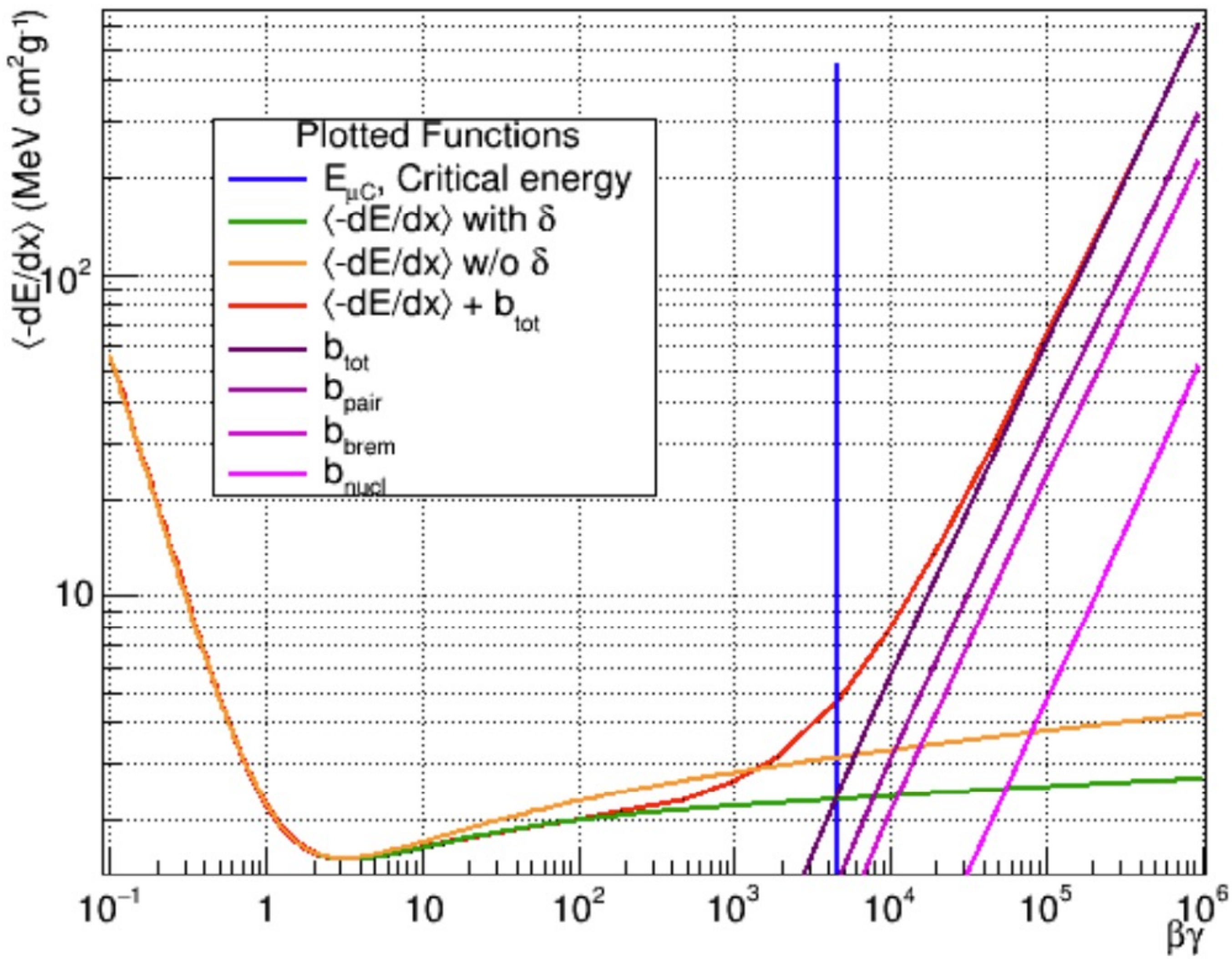
Reconstruction resolution and front-back ambiguity broken by looking for Compton-scatter blips.

Overall pointing resolution is about 4.5 degrees



Fermilab DUNE

Muon Stopping Power in LAr



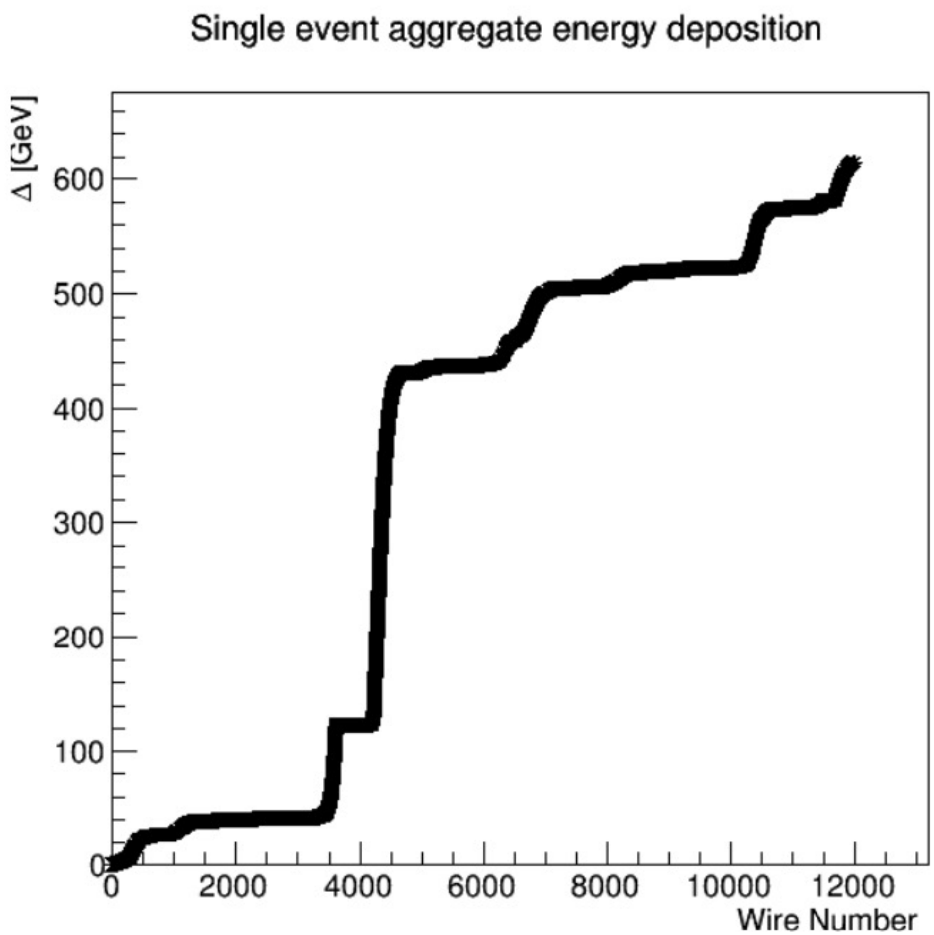
K. Ingles

Cumulative Energy Deposition From a 20 TeV Muon

Muon travels the length
of a FD module in this simuation.

Energy loss is very spiky!
- Bremsstrahlung processes dominate

Muon is MIP-like between showers. ("Fermi Plateau")

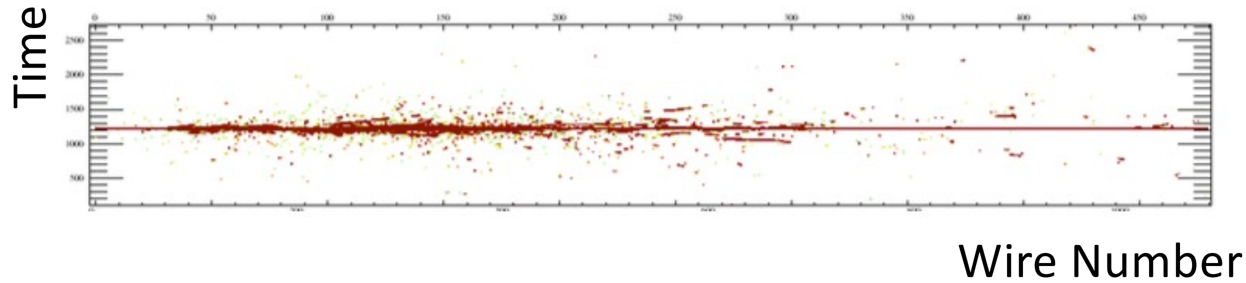


60 Meters

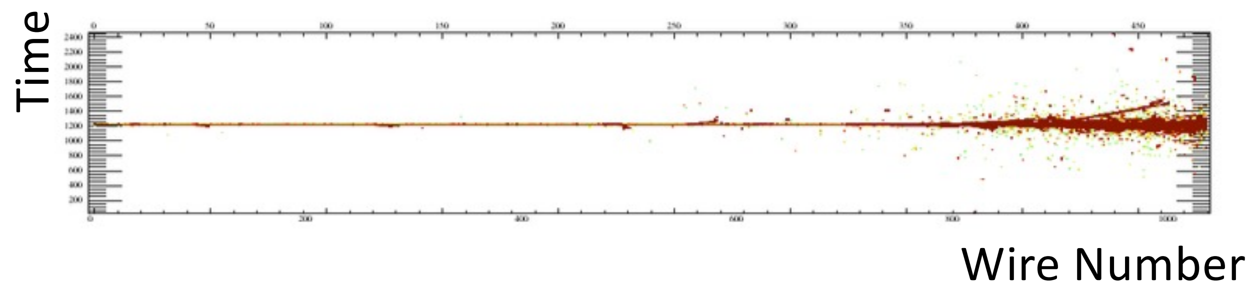
K. Ingles's thesis

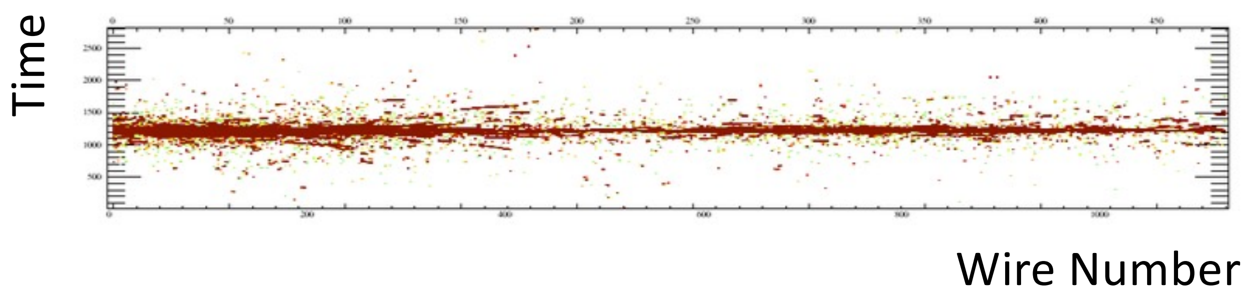
A 10 TeV Showering Muon in a LArTPC

GEANT4 energy deposits, no reco



From Kevin Ingles's Thesis



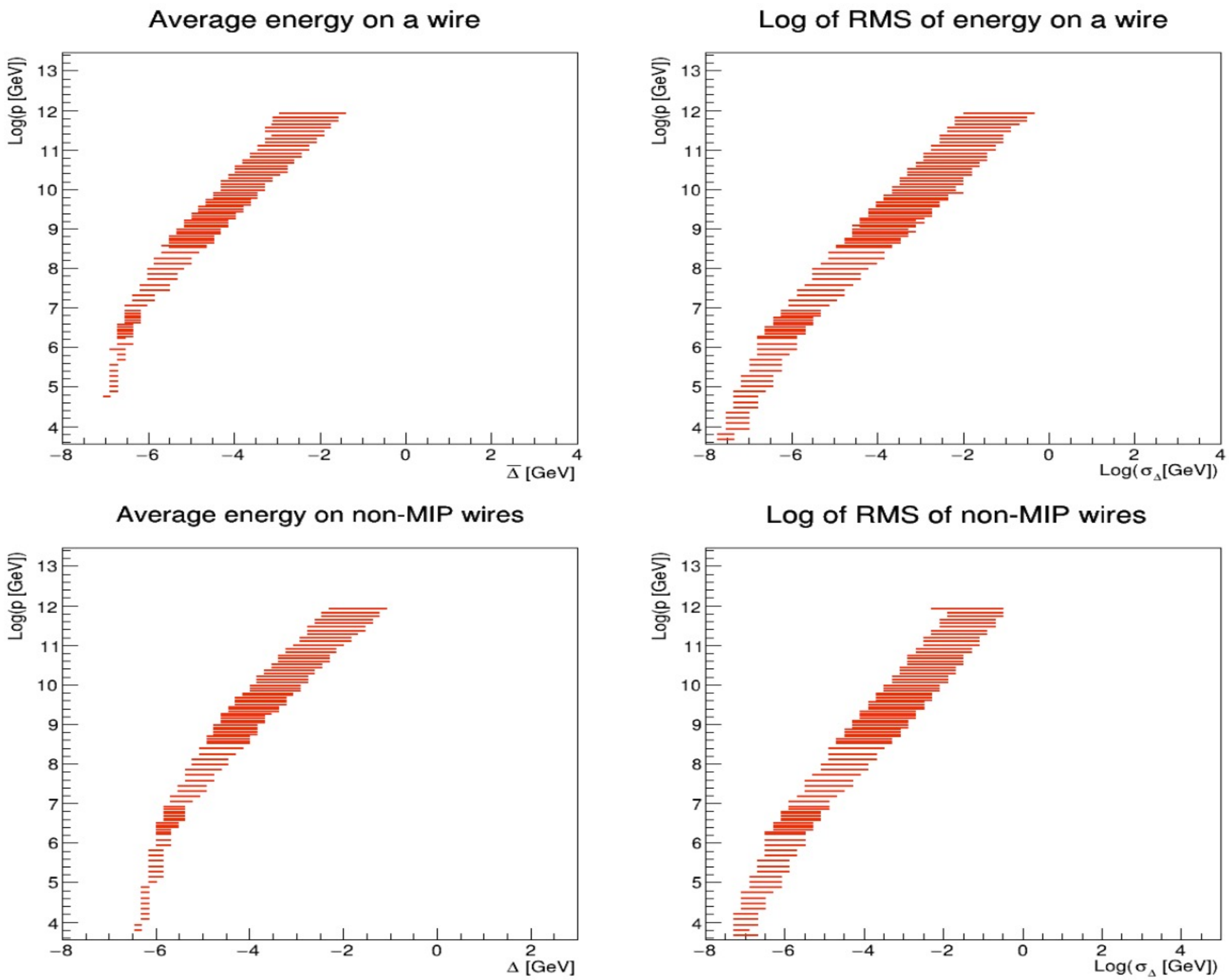


High-Energy Muon Energy Measurement

Best-case scenario: muons traverse a DUNE FD module horizontally (L~ 60 meters).

Resolution: about a factor of 2.5. Shorter tracks sample less radiation and thus have worse resolution

J. Singh,
New Perspectives, 2020
Exploring variables studied by K. Ingles



Multiple FD Module Designs

- DUNE TDR describes a dual-phase design
  - Vertical drift to a liquid-gas interface.
  - Same cryostat as single-phase, so max drift = 12 meters
  - Large charge gain in gas GEM-like layer (LEM)
  - Photon detectors at the bottom
  - Prototyped at CERN: ProtoDUNE-DP (NP02)
  - Design will not be used
- Vertical-drift single-phase design
  - Charge readout planes on top and bottom. Max drift=6 meters
  - strips on perforated printed-circuit boards for charge readout
  - Photon detectors around field cage and cathode. Much larger coverage than horizontal drift.
  - Very promising – design under review

Multiple FD Module Designs

- Fourth module – "Module of Opportunity"
  - Horizontal or vertical drift single-phase LArTPC
  - OR Pixel readout with integrated photon collection
  - OR Water Cherenkov?
  - OR Liquid Scintillator?
  - OR

DUNE Module of Opportunity Workshop, November 2019

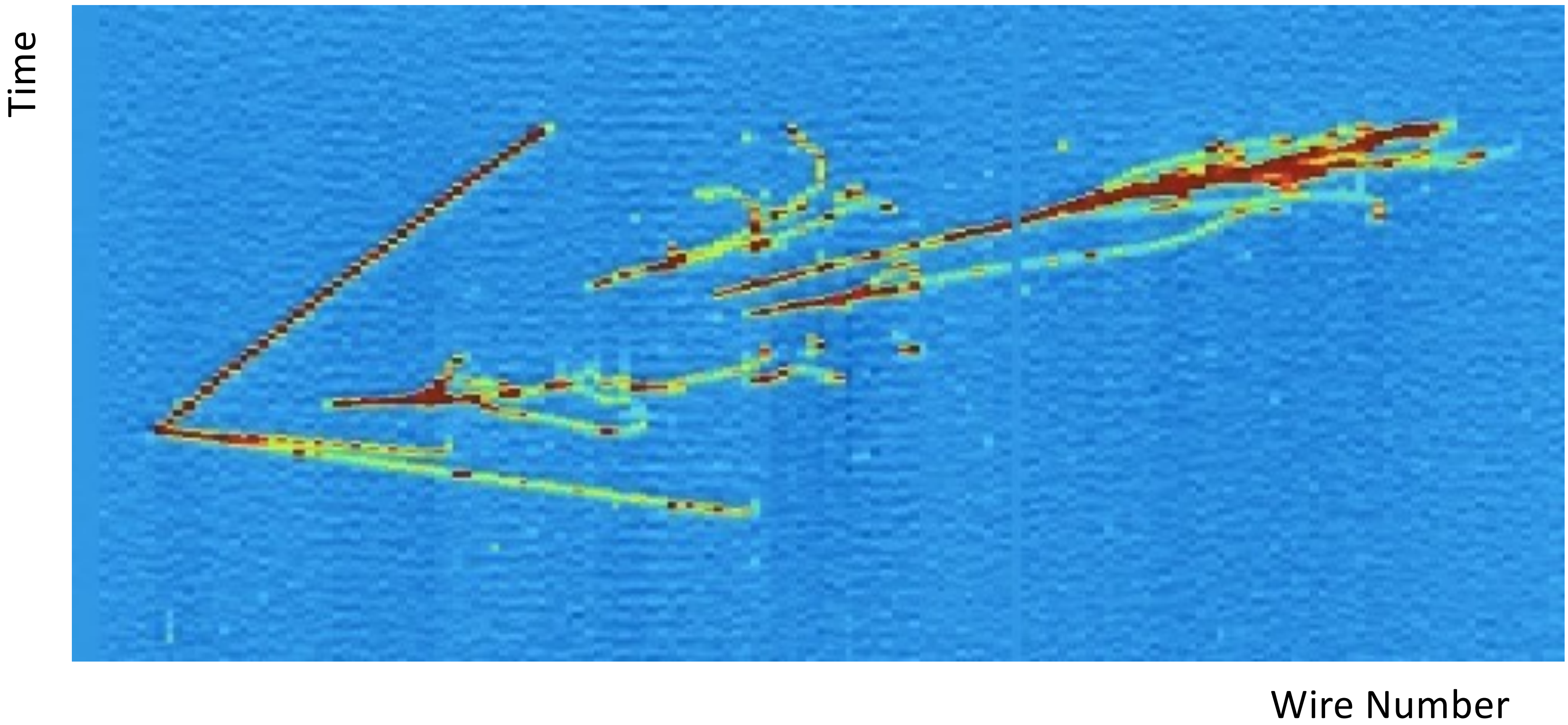
https://indico.fnal.gov/event/21535/timetable/?view=standard

Summary

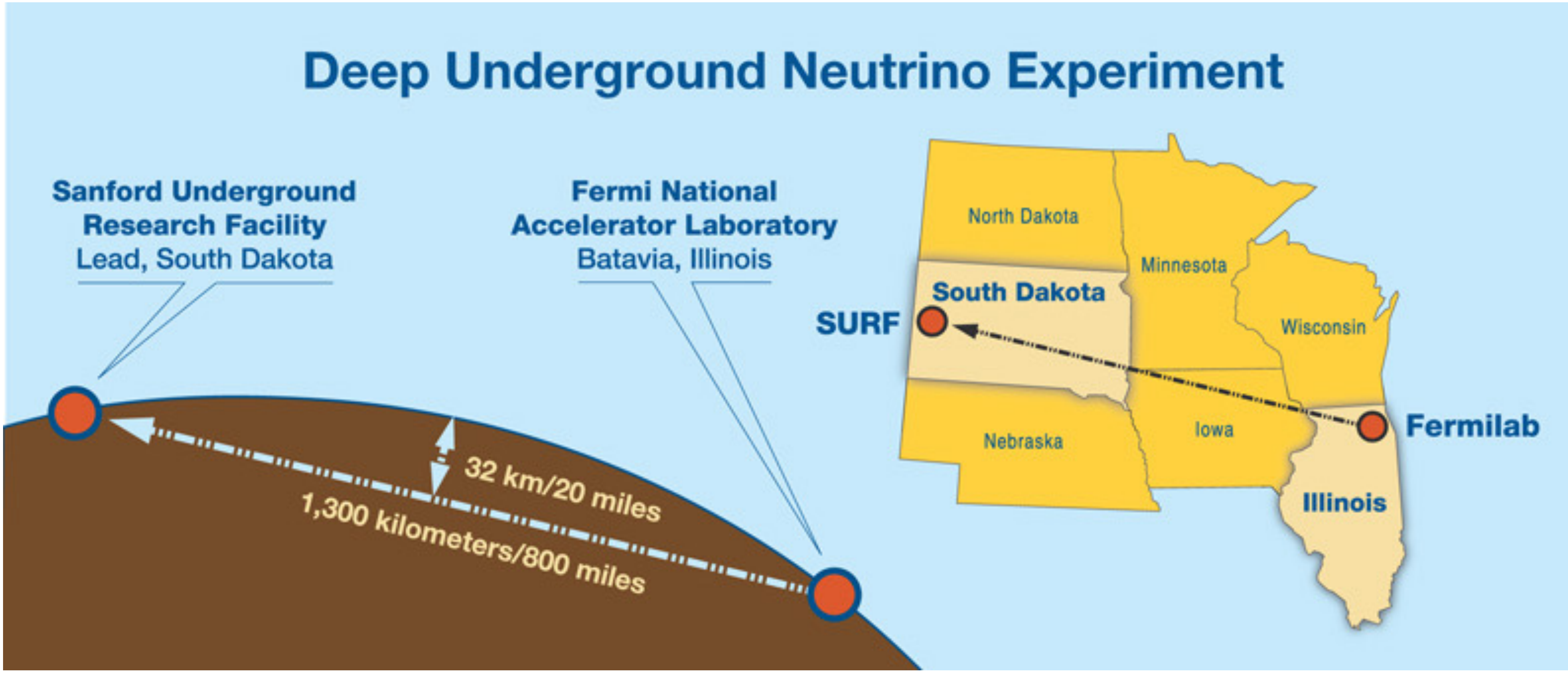
- LArTPC technology is maturing
- The DUNE Far Detector provides fine-grained spatial and energy measurements over a large volume
- The DUNE Far Detector is not nearly as big or as massive as IceCube
- DUNE's focus is on beam neutrino physics, SNB and nucleon decay
- DUNE has many unique capabilities and a broad physics program
- Let's make it broader!

Extras

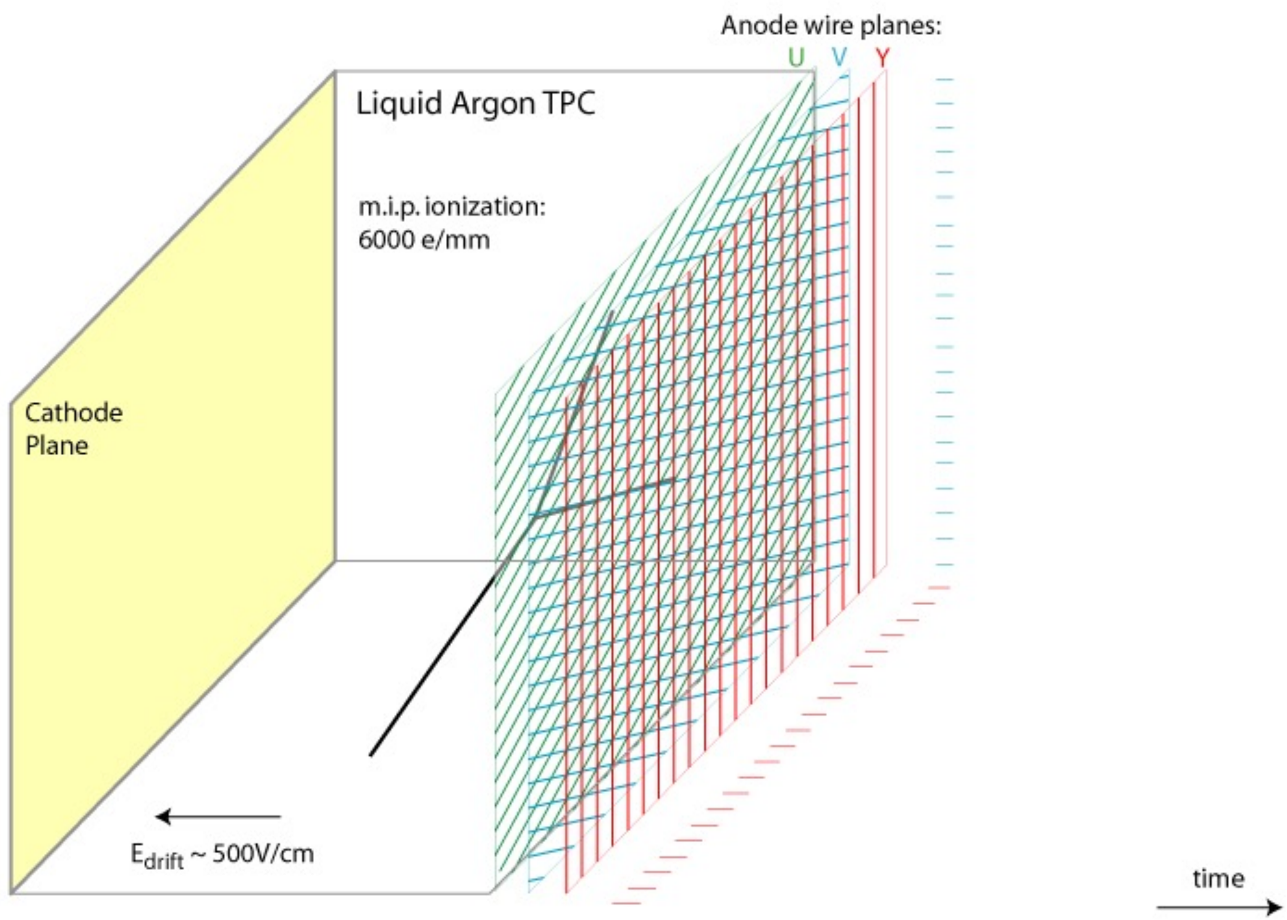
A Neutrino Scatter in ArgoNeuT



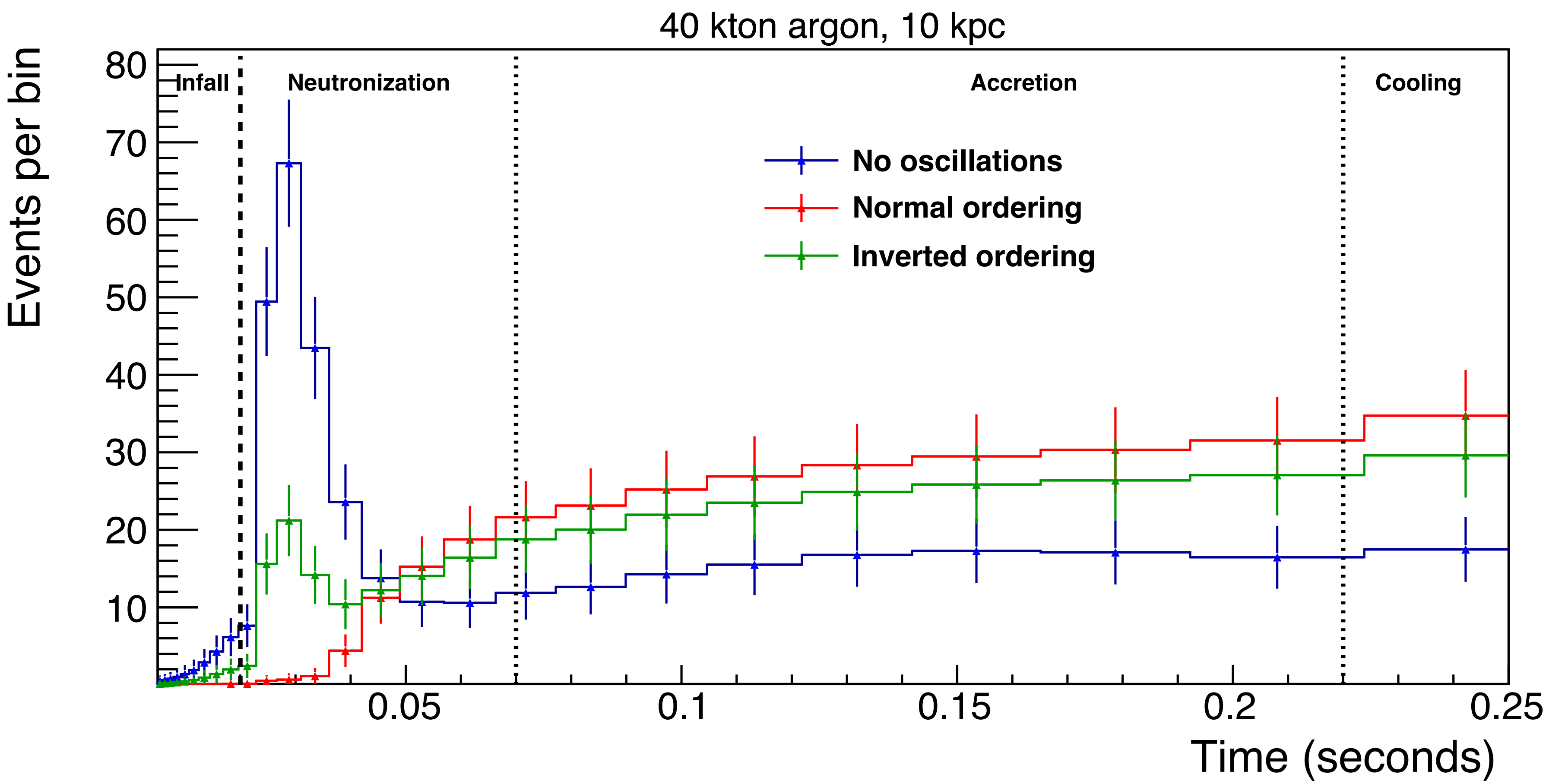
DUNE Overview



LArTPC Charge Measurement



SNB neutrino arrival times



Fermilab DUNE

Cross Section View of a Single-Phase FD Module