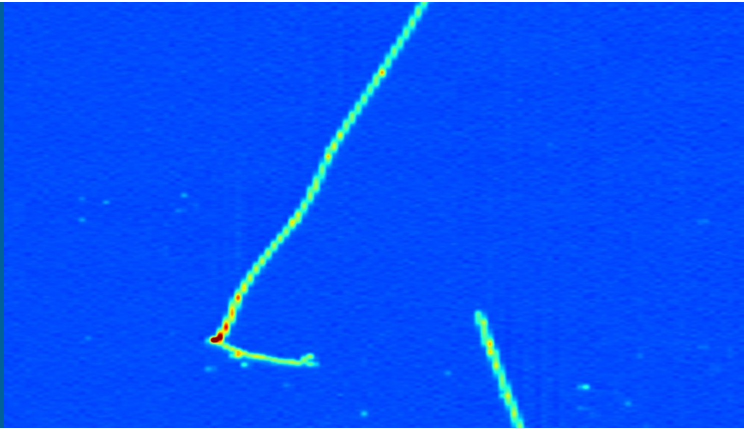
IDENTIFICATION AND RECONSTRUCTION OF LOW-ENERGY ELECTRONS IN THE PROTODUNE-SP DETECTOR



ALEENA RAFIQUE (for the DUNE collaboration)
Assistant Physicist
High Energy Physics Division
Argonne National Laboratory
Lemont, IL 60439

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

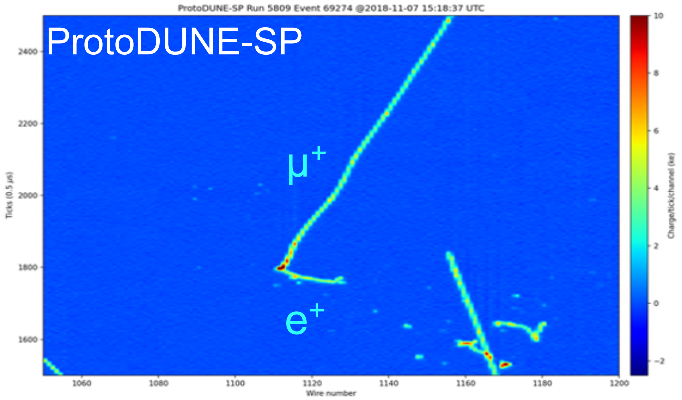
04/28/2022

OUTLINE

- Introduction to low-energy electrons (Michel electrons)
- DUNE and ProtoDUNE
- Michel electron analysis
  - Event selection
  - Energy reconstruction
  - Missing energy studies
  - Energy resolution studies
  - Analysis current status
- Conclusion

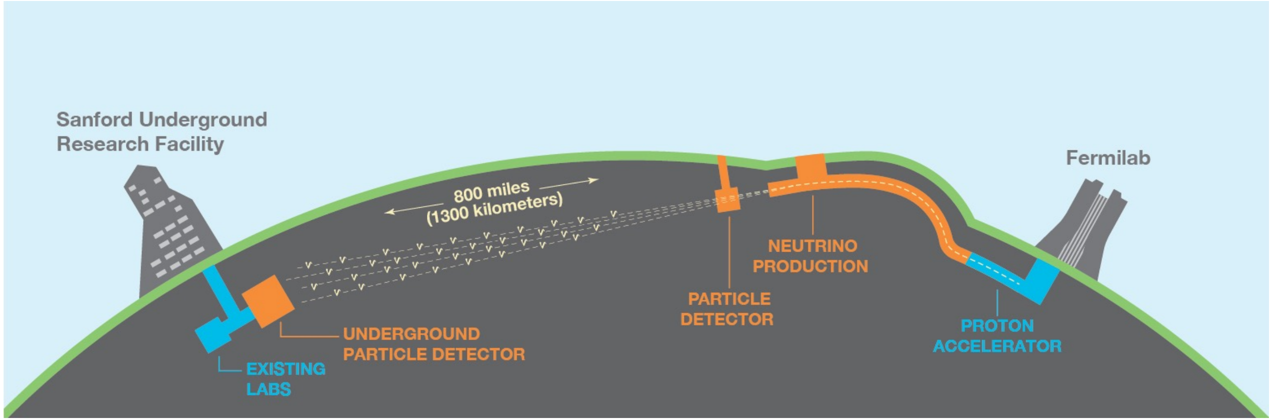
LOW-ENERGY ELECTRONS STUDIES

- DUNE goal is to measure CP-violation via ν_e appearance ($\nu_\mu \rightarrow \nu_e$)
  – To measure ν_e appearance we need to select electron showers in LAr TPC, and reconstruct their energy
- Important to show that the detector can use the topological / calorimetric information provided by the TPC to identify a specific topology [Michel electrons]
- Reconstruct the low-energy electrons and produce their visible energy spectrum
- Ideal to study detector's response to electrons in the tens of MeV energy range
  – Useful for the search of low energy events e.g supernova
- The goal is to deliver Michel analysis algorithm to use on DUNE-FD Day 1



INTRODUCTION TO DUNE

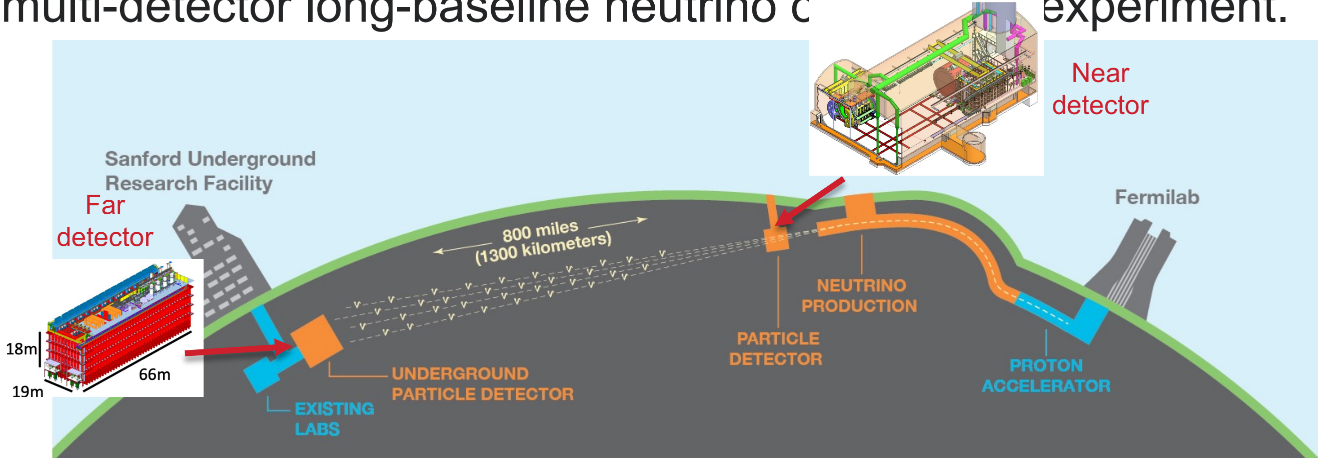
- The Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillations experiment.



- Major DUNE goals:
  – Neutrino Oscillation Physics
  – Nucleon Decay
  – Supernova burst physics & astrophysics

INTRODUCTION TO DUNE

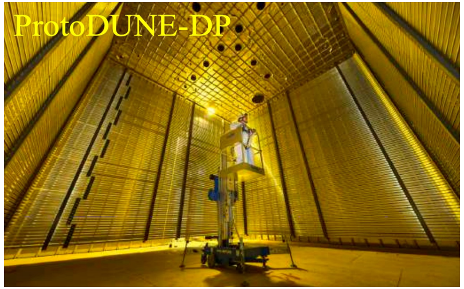
- The Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillations experiment.

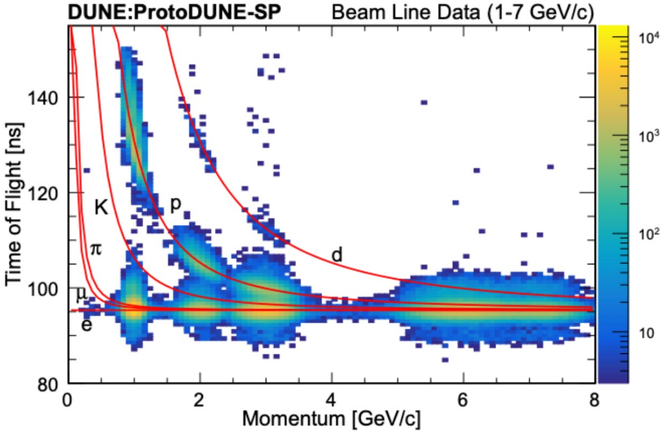


- New neutrino beam at Fermilab,1300 km baseline
- Multiple technologies for the **Near Detector (ND)** at Fermilab
- 70 kton Liquid Argon Time Projection Chamber (LArTPC) **Far Detector (FD)** at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Excavation started in 2017, begin taking data in late 2020s- early 2030s

PROTODUNE SP AND DP AT CERN

- Single-phase (SP) and dual-phase (DP) DUNE prototype LArTPCs at CERN
- 770 t LAr mass each
- Exposed to H2 (DP) and H4 (SP) test beams at CERN, momentum dependent beam composition contains *e*, $K^{\pm}$, $\mu^{\pm}$, *p*, $\pi^{\pm}$
- Also collected cosmic ray data
- ProtoDUNE-II is currently being commissioned

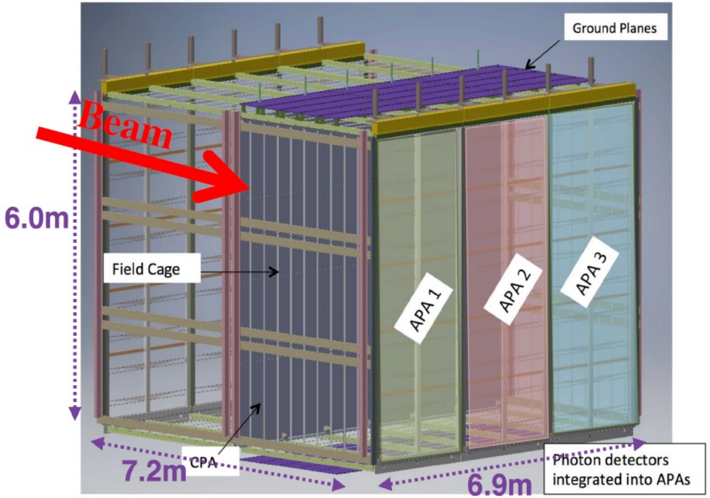




PROTODUNE-SP

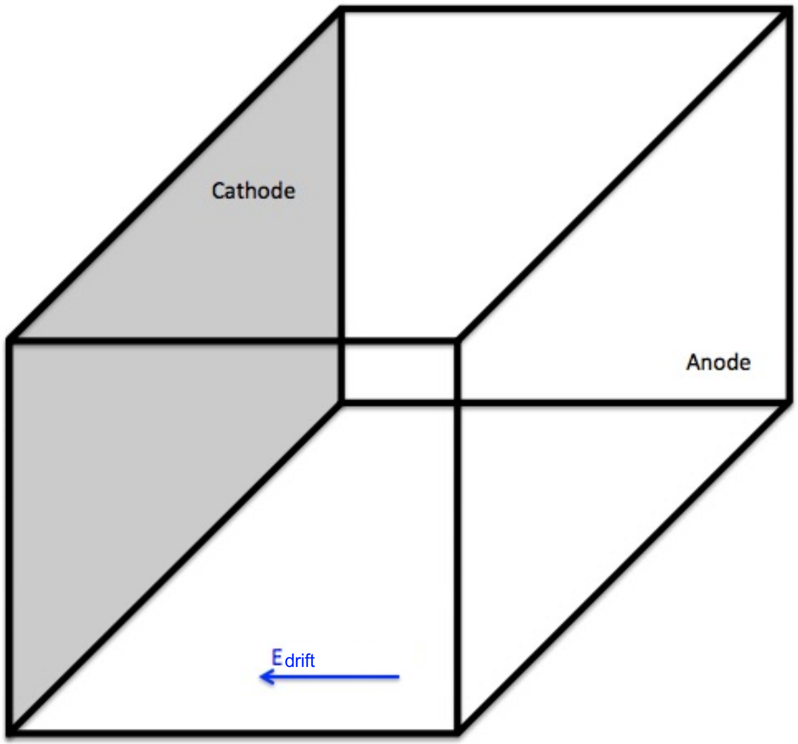
- Active Volume: 6m (H) x 7m (L) x 2 x 3.6m (W)
- Central Cathode Plane Assembly (CPA) :
  - 3.6 m drift distance @180 kV
  - 500 V/cm field in drift volume
- Anode Plane Assembly (APA):
  - 3 APAs on each side
  - Each APA module: 6m high, 2.3m wide
  - Two induction planes and one collection plane

ProtoDUNE-SP TPC

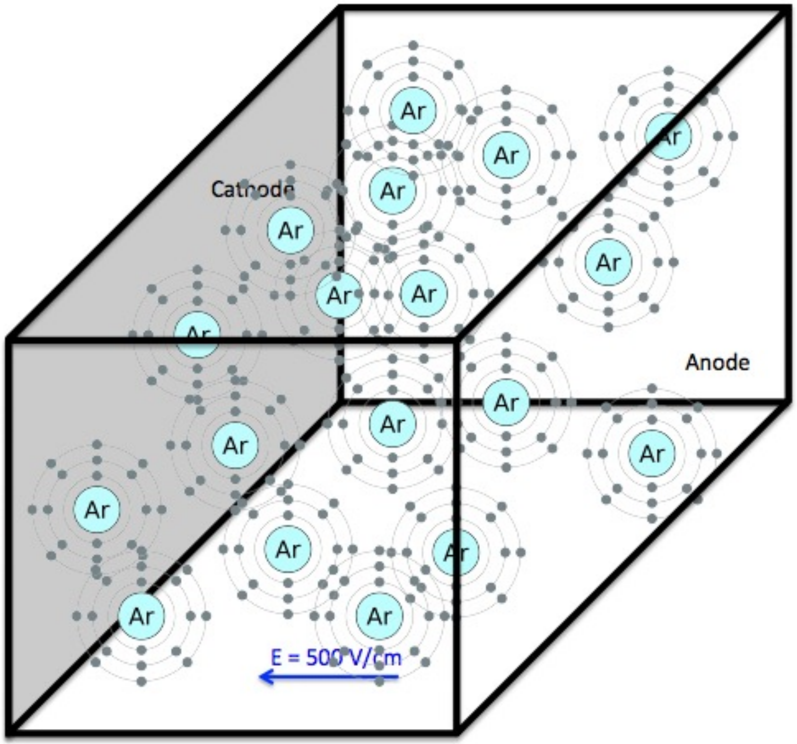


- Cold electronics: directly attached to the top of the APA (2560 wires/APA, 15360 total wires)
- Photon detectors (PDS): 3 designs integrated into APA frame bars
- Cryogenic Instrumentations outside of field cage: measure argon purity, temperature, liquid level and tag cosmic rays
- First papers from ProtoDUNE-SP are published e.g JINST 15 (2020) 12, P12004
- ProtoDUNE-SP Phase-I operated Sept. 2018 – July 2020, Phase-II data taking under preparation

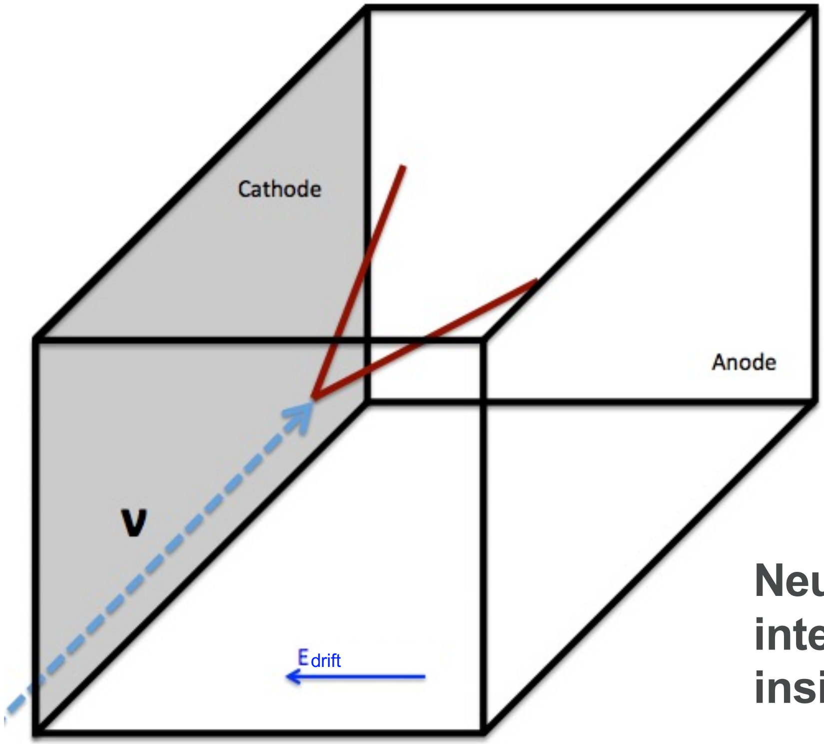
HOW LARTPC WORKS



HOW LARTPC WORKS

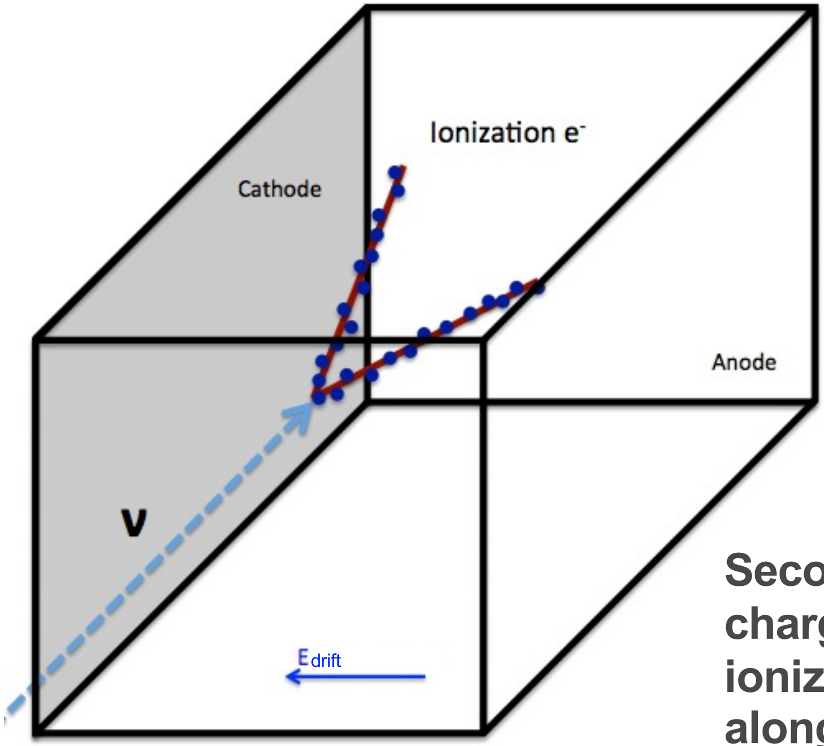


HOW LARTPC WORKS



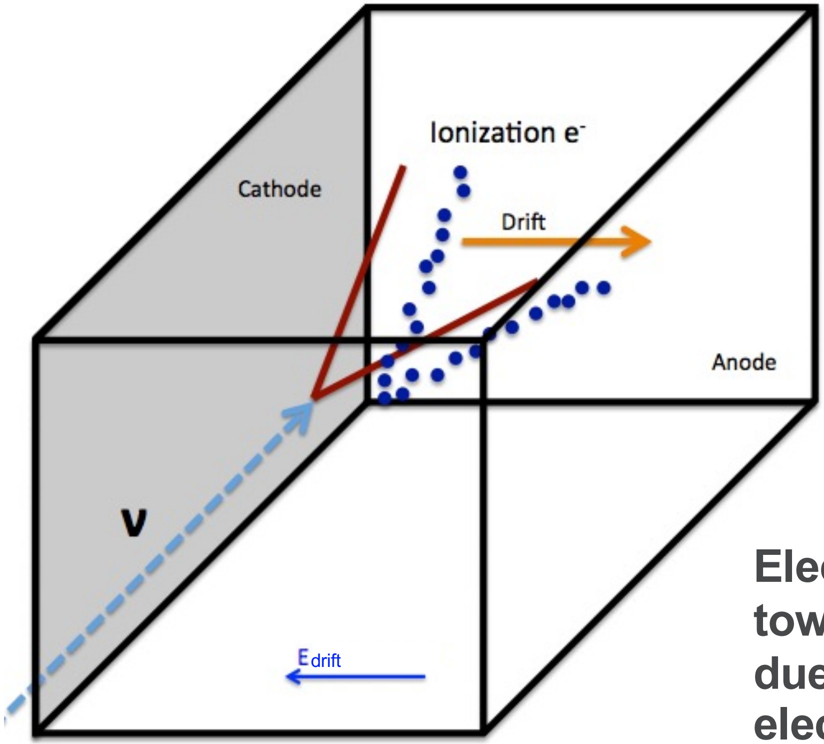
Neutrino interaction inside TPC

HOW LARTPC WORKS



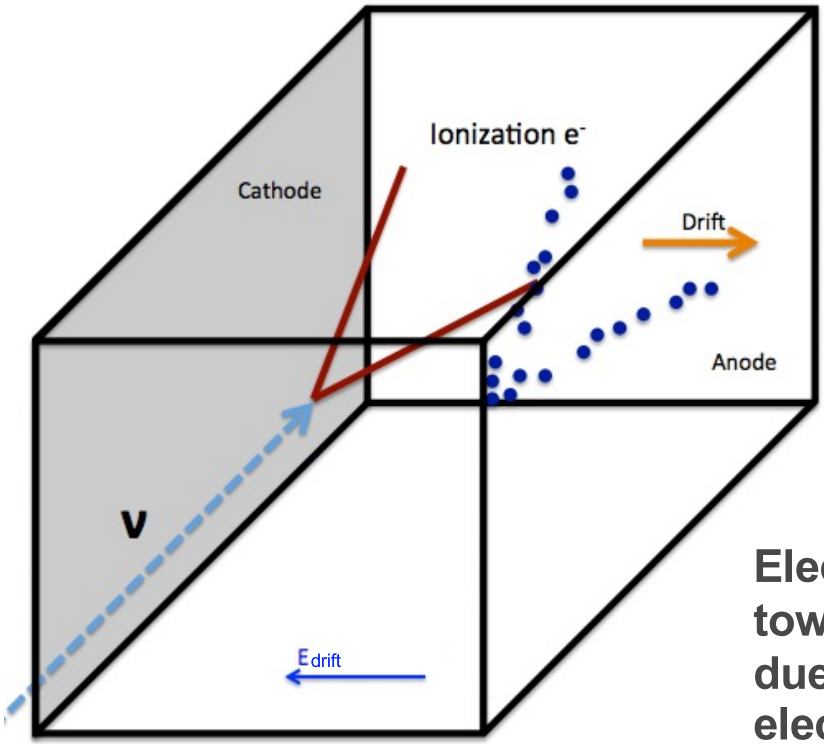
Secondary charged particles ionize atoms along their way

HOW LARTPC WORKS



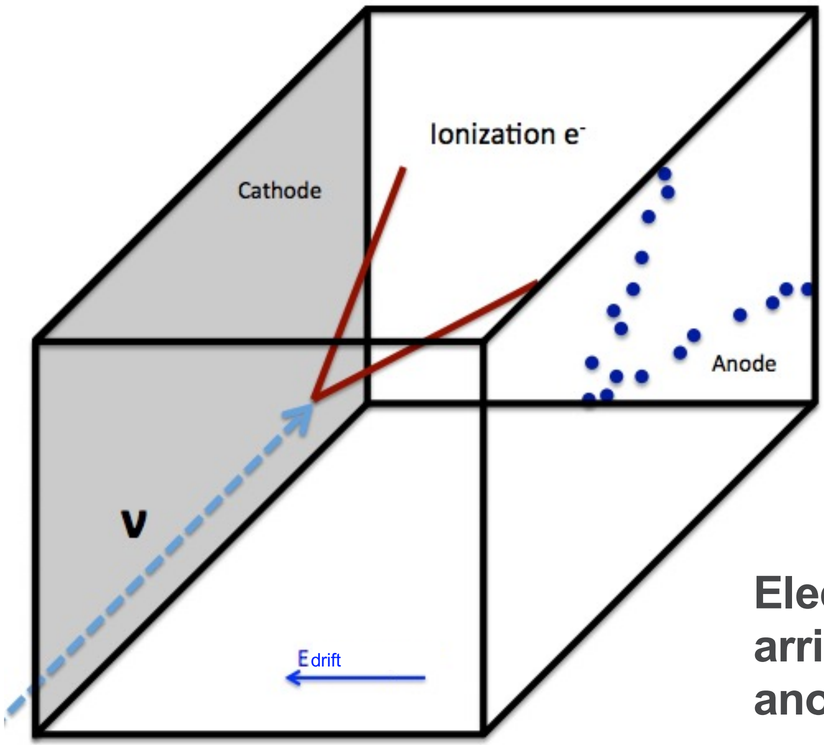
Electrons drift towards anode due to applied electric field

HOW LARTPC WORKS



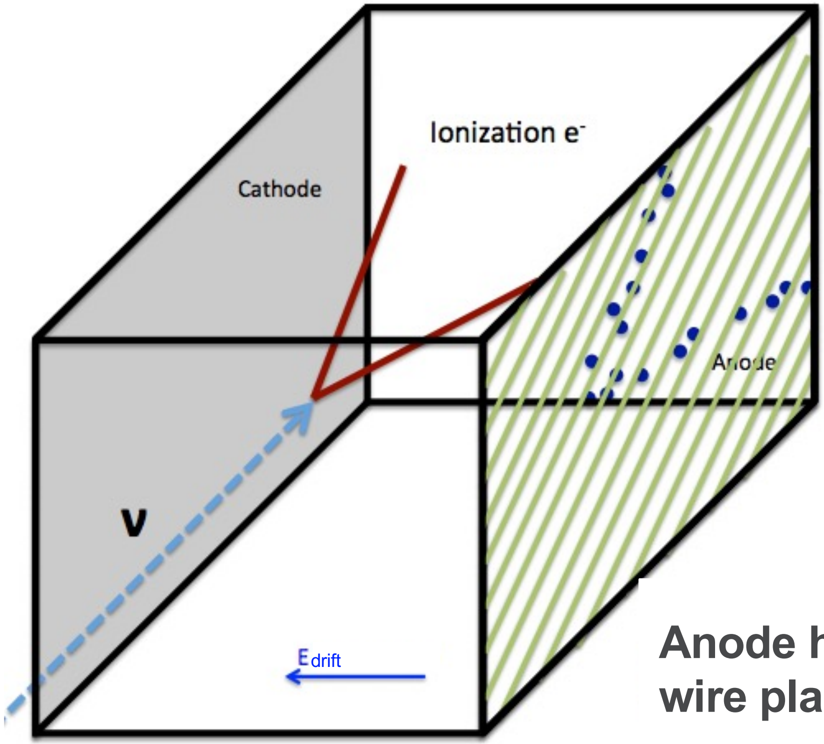
Electrons drift towards anode due to applied electric field

HOW LARTPC WORKS



Electrons arrive at anode

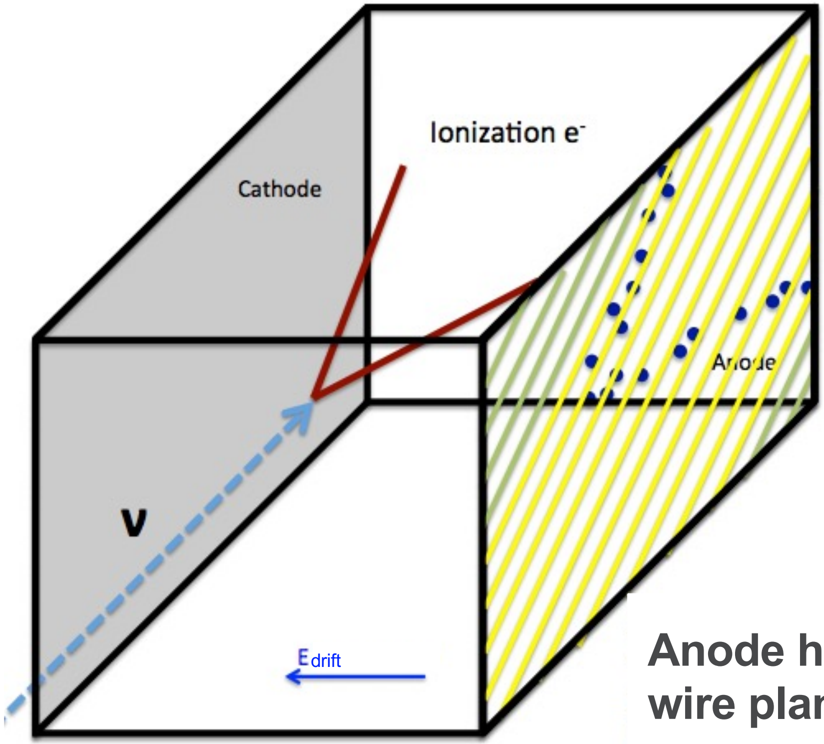
HOW LARTPC WORKS



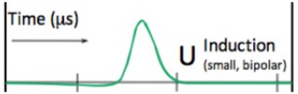
First induction plane

Anode has 3 wire planes

HOW LARTPC WORKS

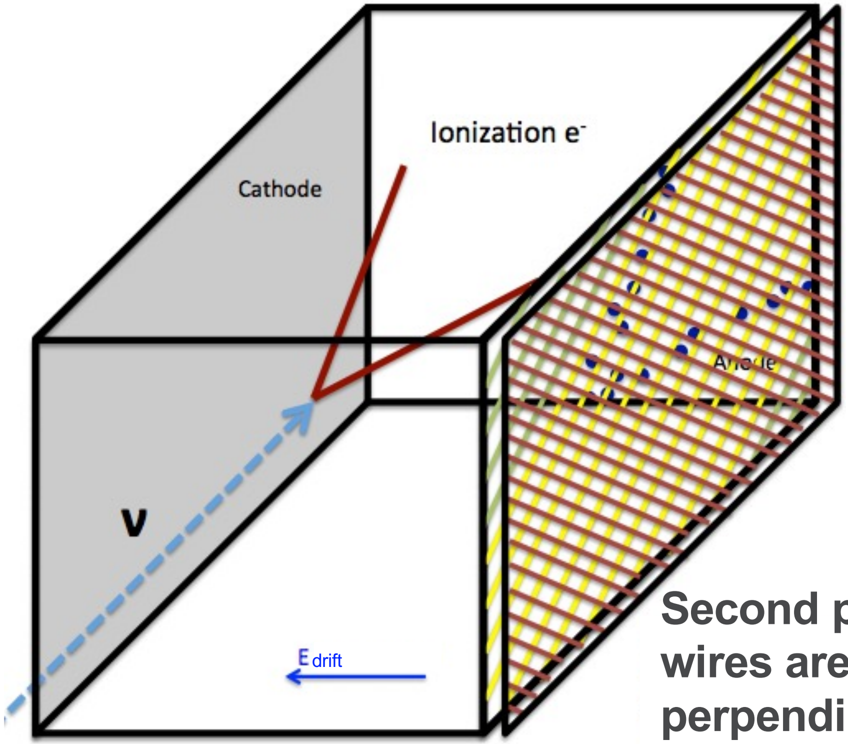


First induction plane



Anode has 3 wire planes

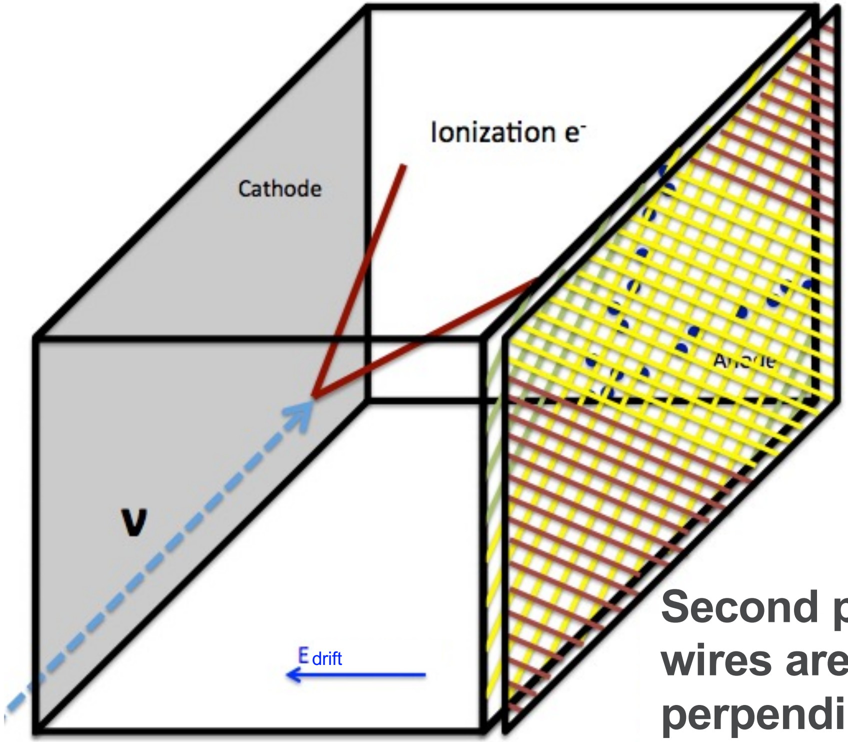
HOW LARTPC WORKS



Second induction plane

Second plane wires are perpendicular to first plane wires

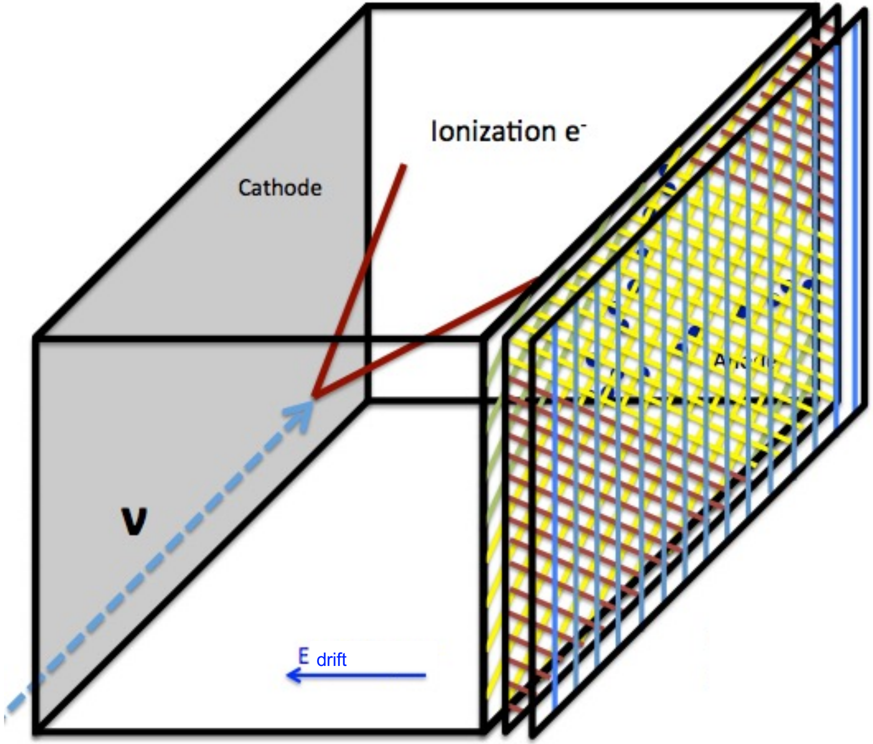
HOW LARTPC WORKS



Second induction plane

Second plane wires are perpendicular to first plane wires

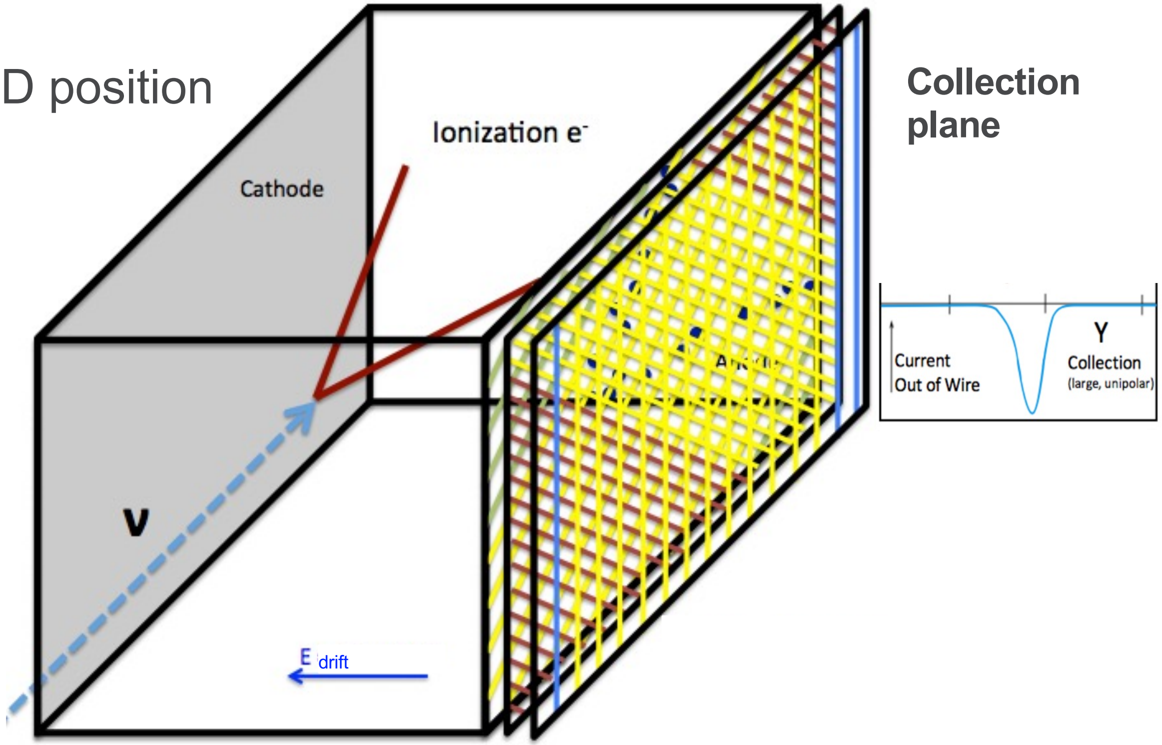
HOW LARTPC WORKS



Collection plane

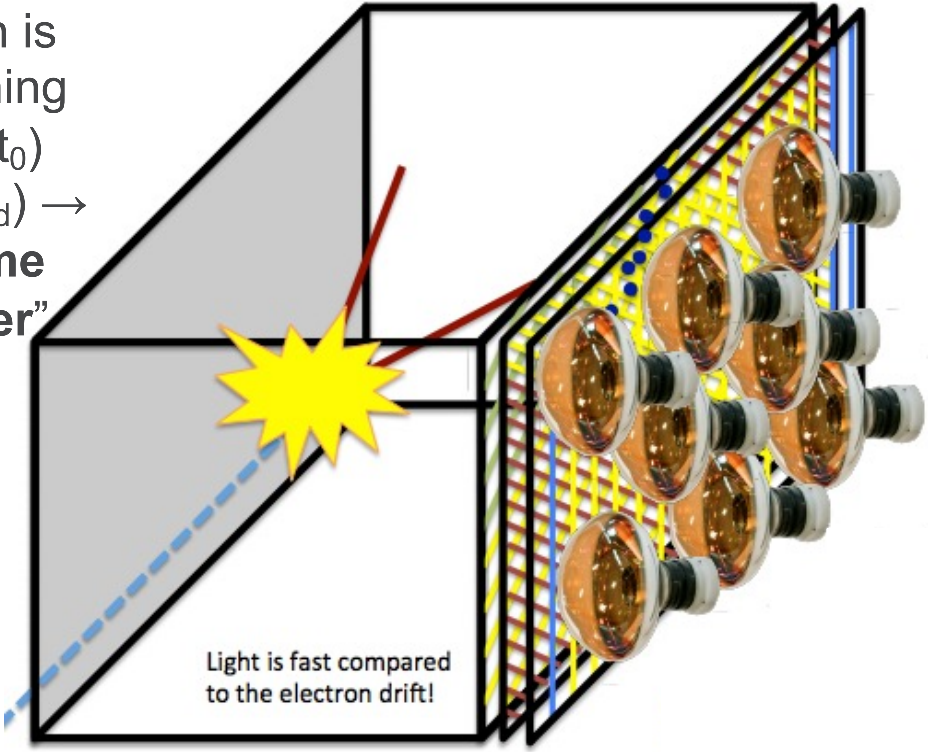
HOW LARTPC WORKS

- Wire planes give 2D position information



HOW LARTPC WORKS

- The third dimension is obtained by combining timing information (t_0) with drift velocity (v_d) → hence is called “**Time projection chamber**”



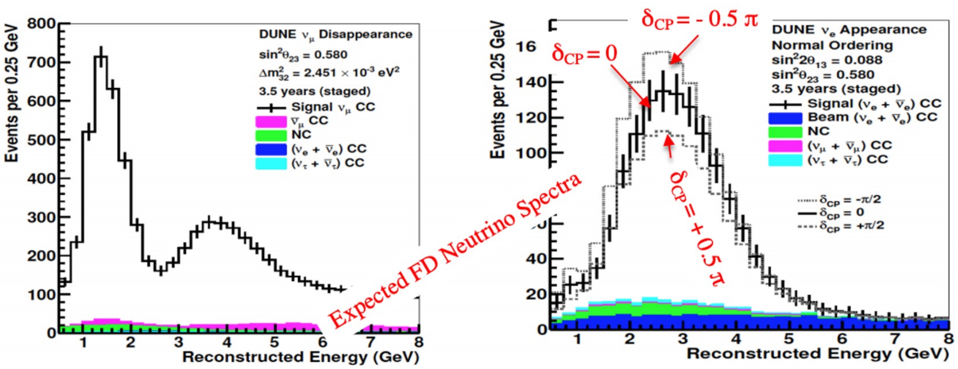
Scintillation light is collected by PMTs that give absolute time for the interaction

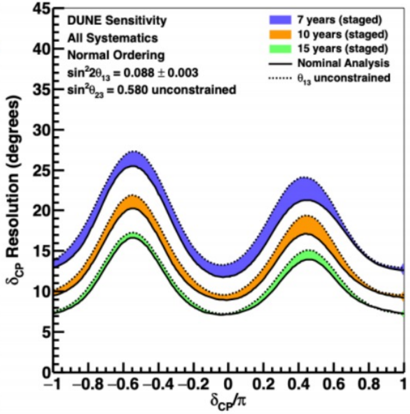
DUNE SENSITIVITY AND MEASURING DELTA-CP

- CP violation measured as a difference of neutrino and anti-neutrino oscillation probabilities.

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- Calibrate Far and Near detector visible energy to 2% to control systematics at the level needed to support neutrino oscillation measurements
- Precision of energy reconstruction is required for
  - Early DUNE physics milestone is to reduce δ_{CP} uncertainty below 20^0 (at δ_{CP} = -90^0)





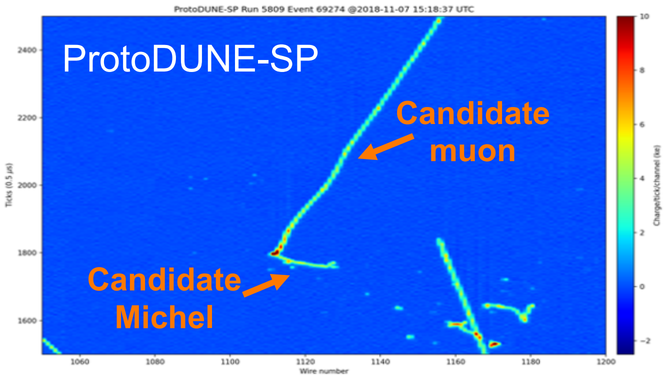
ACCURATE RECONSTRUCTION OF VISIBLE ENERGY

- Perform oscillation analysis
  - Reduce systematics in lepton and neutrino interaction measurements
- Visible energy is obtained by **leptonic + hadronic** energy components
  - Goal is to achieve variation in visible energy to be <2% for DUNE sensitivity studies
- Working on leptonic part of the energy by:
  - Serving as Electromagnetic Shower working group convener at ProtoDUNE
  - Working on low-energy electron shower reconstruction
  - Developing calibration schemes for high energy electrons
- Hadronic energy component can be understood by neutrino interaction measurements

MICHEL ELECTRON ANALYSIS

MICHEL ELECTRONS

- Michel electrons are electrons produced from the decay of muons (0-50 MeV)
- Common channels (in ProtoDUNE):
  - Muon decay: $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (80%)
  - Muon capture: $\mu^- \to e^- \nu_\mu \bar{\nu}_e n\gamma$ (20%)
- **Unique features of this analysis:**
  - data-driven determination of the recombination correction
  - evaluation of the missing Michel energy
  - comparison of the electron energy calibration based on muon derived calibration corrections with that based on the Michel electron true energy
  - characterization of the electron energy resolution



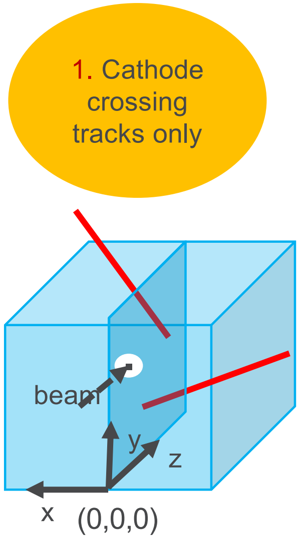
ANALYSIS FLOW

Full data / MC Sample → **Muon quality filter** → **Look for Michel activity** → **Final sample**

Looks for a long muon track that stops inside the detector fiducial volume

Look for charge deposition from candidate Michel hits around end position of the muon

EVENT SELECTION

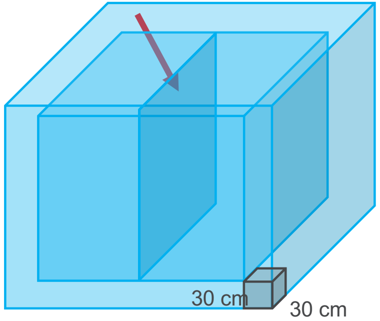


Position along the drift direction is only accurate for cathode crossers

EVENT SELECTION

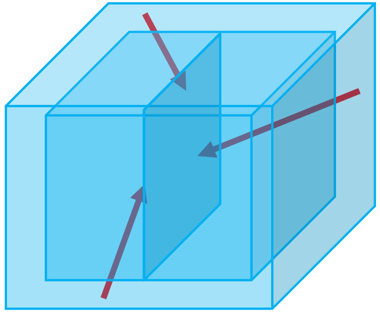
1. Cathode crossing tracks only

2. Tracks that start from the detector edges



EVENT SELECTION

1. Cathode crossing tracks only
2. Tracks that start from the detector edges
3. Tracks must stop within the FV



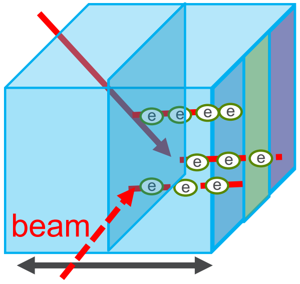
EVENT SELECTION

1. Cathode crossing tracks only

2. Tracks that start from the detector edges

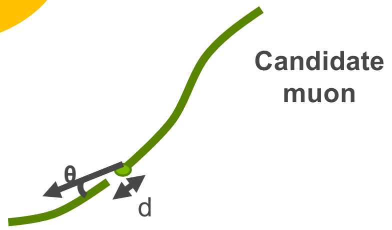
3. Tracks must stop within the FV

4. Tracks must not end around APA bounds



EVENT SELECTION

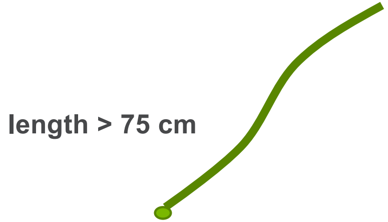
1. Cathode crossing tracks only
2. Tracks that start from the detector edges
3. Tracks must stop within the FV
4. Tracks must not end around APA bounds
5. Remove the broken tracks

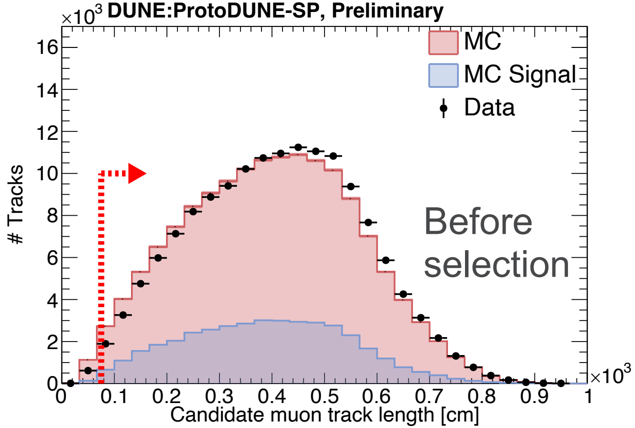


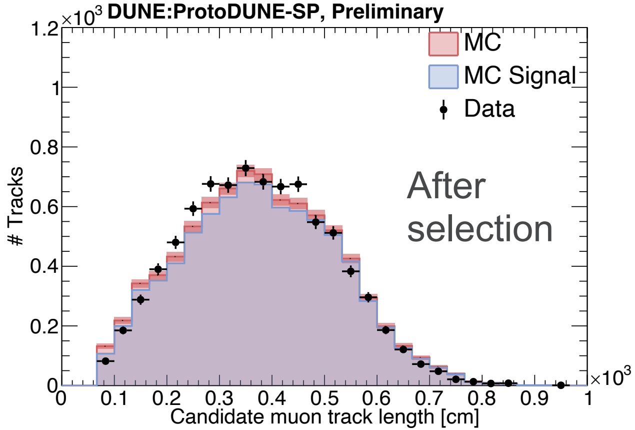
EVENT SELECTION

Muon selection

- Select candidate muon tracks with > 75 cm length





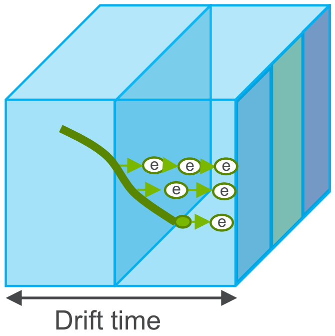


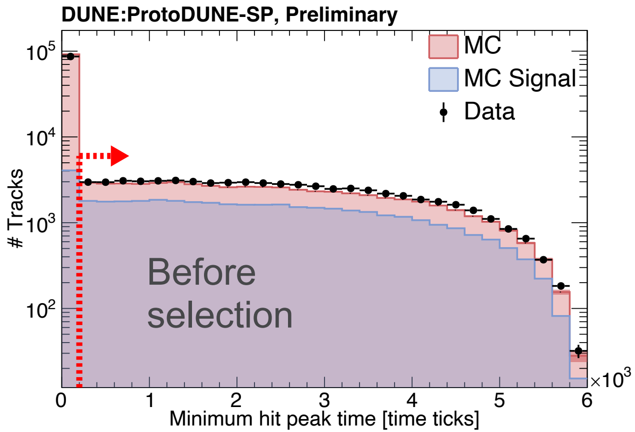
Sample purity = 27%

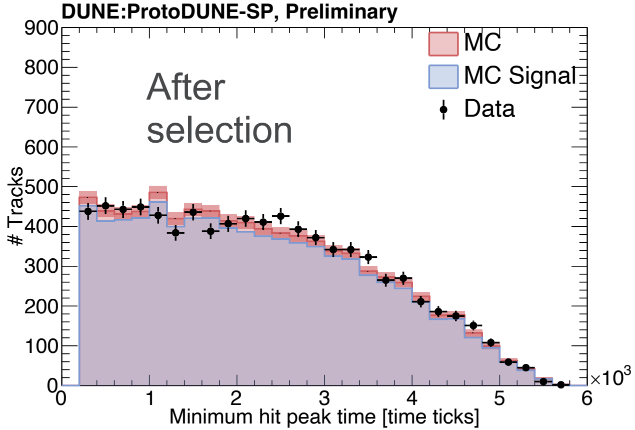
EVENT SELECTION

Muon selection

- Select candidate muon tracks with > 75 cm length
- Minimum hit time > 200 ticks
  - 1 time tick = 500 nsec





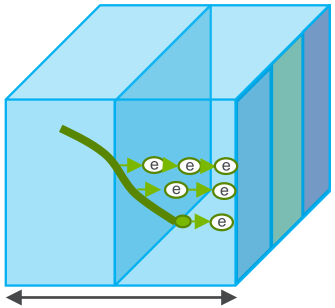


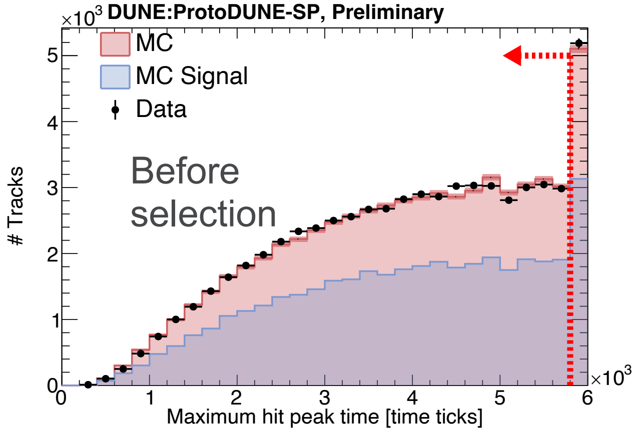
Sample purity = 62%

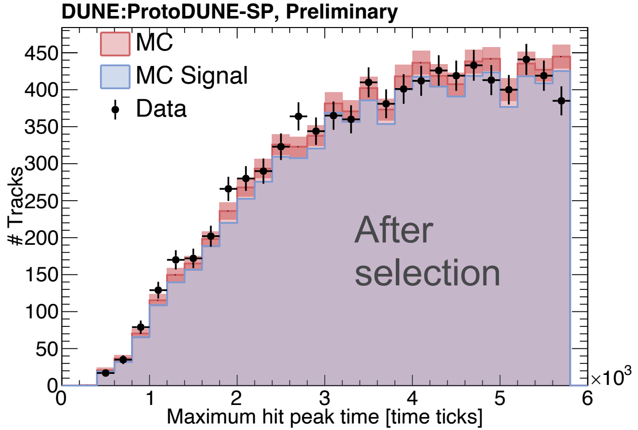
EVENT SELECTION

Muon selection

- Select candidate muon tracks with > 75 cm length
- Minimum hit time > 200 ticks
- Maximum hit time < 5800 ticks





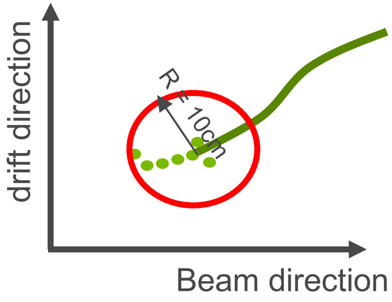


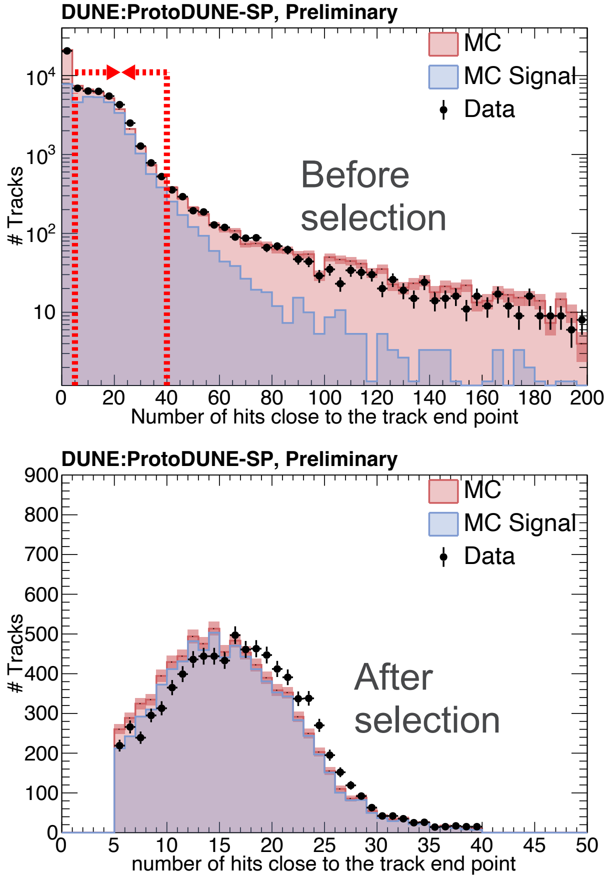
Sample purity = 63%

EVENT SELECTION

Michel selection

- Nearby hit count > 5 & < 40



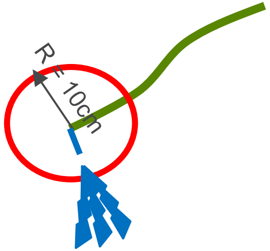


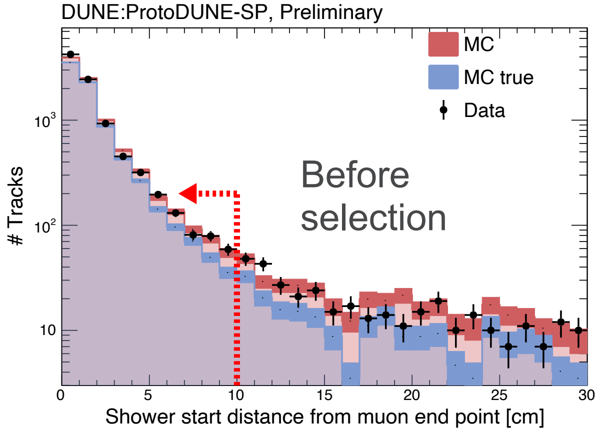
Sample purity = 82%

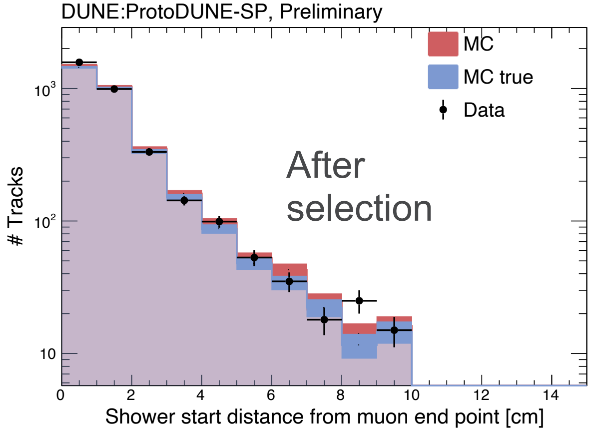
EVENT SELECTION

Michel selection

- Nearby hit count > 5 & < 40
- Closest reco shower distance < 10 cm





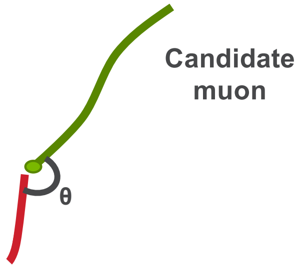


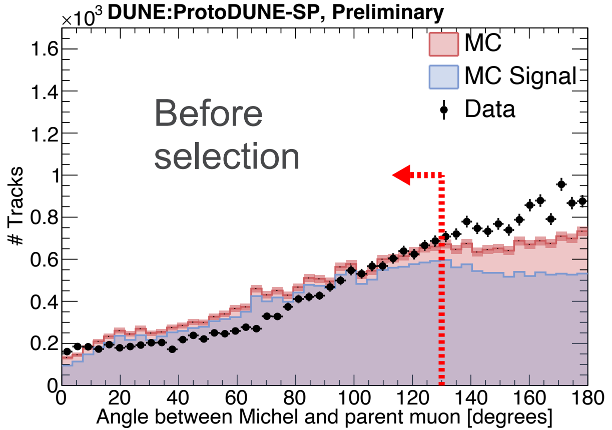
Sample purity = 87%

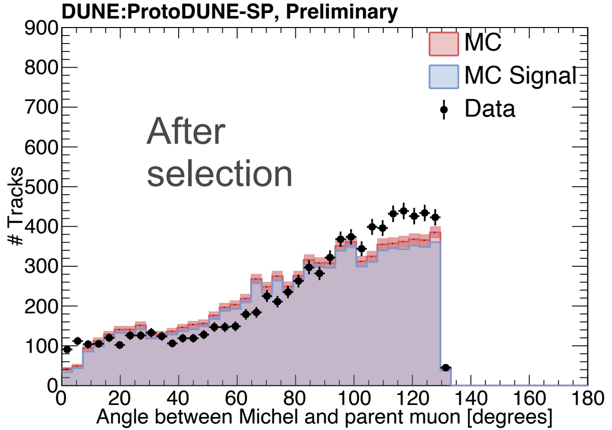
EVENT SELECTION

Michel selection

- Nearby hit count > 5 & < 40
- Closest reco shower distance < 10 cm
- Angle between muon and Michel < 130^0





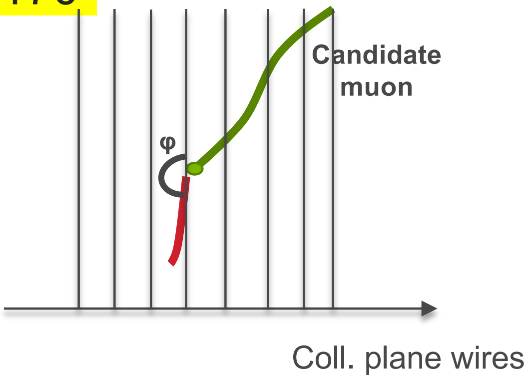


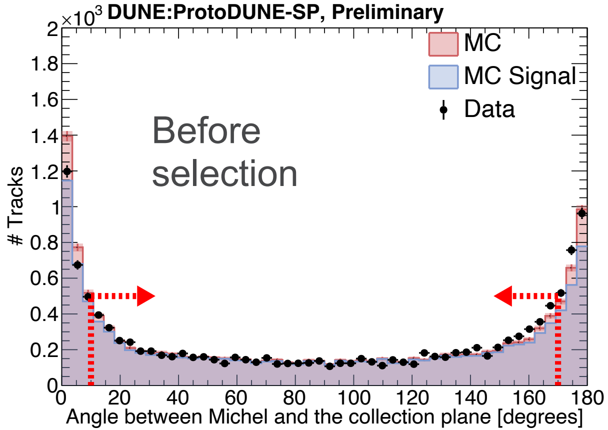
Sample purity = 91%

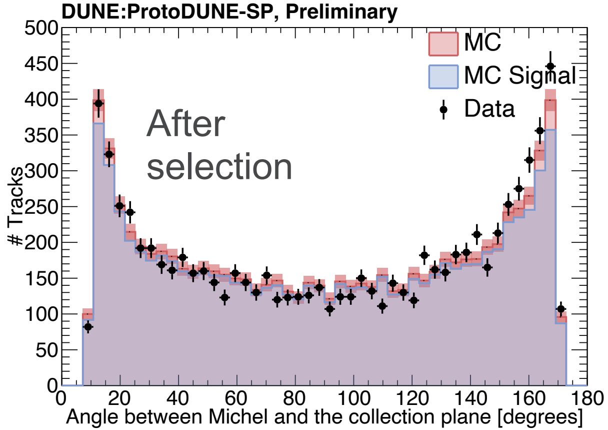
EVENT SELECTION

Michel selection

- Nearby hit count > 5 & < 40
- Closest reco shower distance < 10 cm
- Angle between muon and Michel < 130^0
- Angle between Michel and collection plane wires > 10^0 and < 170^0

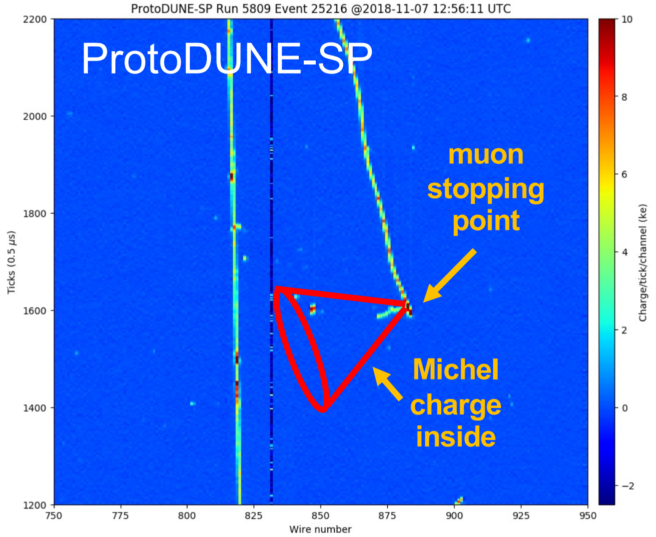






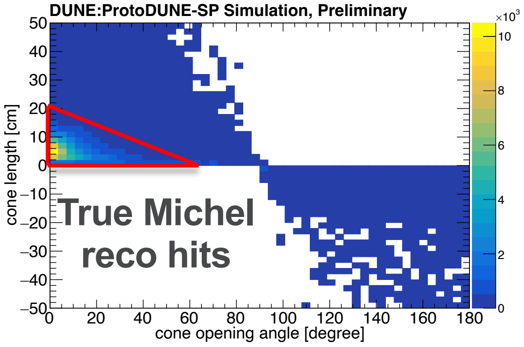
Sample purity = 95%

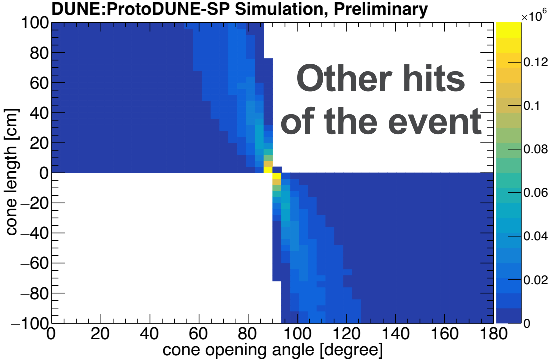
MICHEL HITS OPTIMIZATION

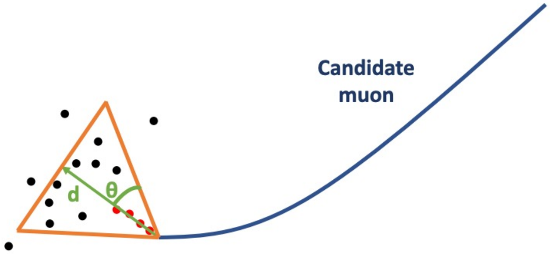


- Form a cone that contains candidate Michel electron hits
- Look for the nearby charge deposition around the muon end position
- Optimize the parameters cone length (d) and angle (θ) to maximize Michel hit purity and hit completeness matrices

'Hit purity' = fraction of hits that belong to the true Michel
'hit completeness' = fraction of true Michel hits inside the cone







U.S. DEPAR ENE

Argonne NATIONAL LABORATORY

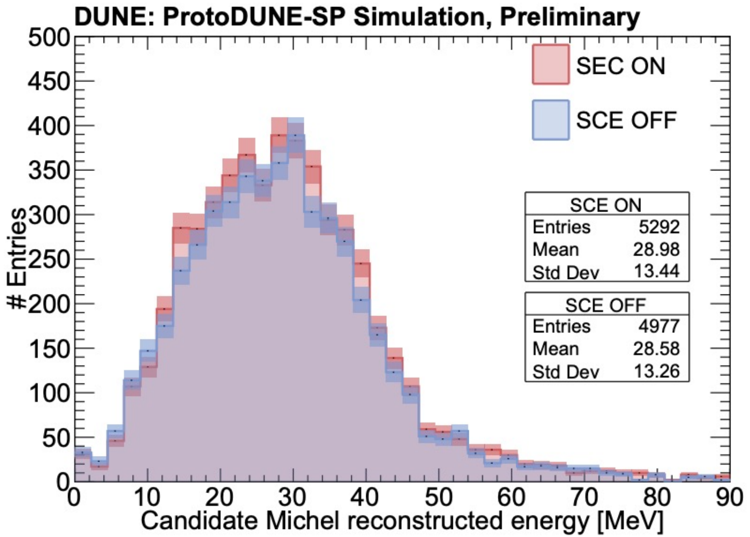
SYSTEMATIC UNCERTAINTY STUDIES

- Evaluated the impact of various systematics on the Michel energy spectrum
- The uncertainties are expressed with respect to the mean energy of the reconstructed Michel electron energy spectrum
- Some of the significant uncertainties are listed in the table

Uncertainty sources	Uncertainty estimates
Hit reconstruction efficiency systematic uncertainty	6.7%
Space charge effect systematic uncertainty	1.4%
Recombination factor systematic uncertainty	2.0%
Michel electron versus positron systematic uncertainty	1.7%
Total systematic uncertainties added in quadrature	**7.3%**

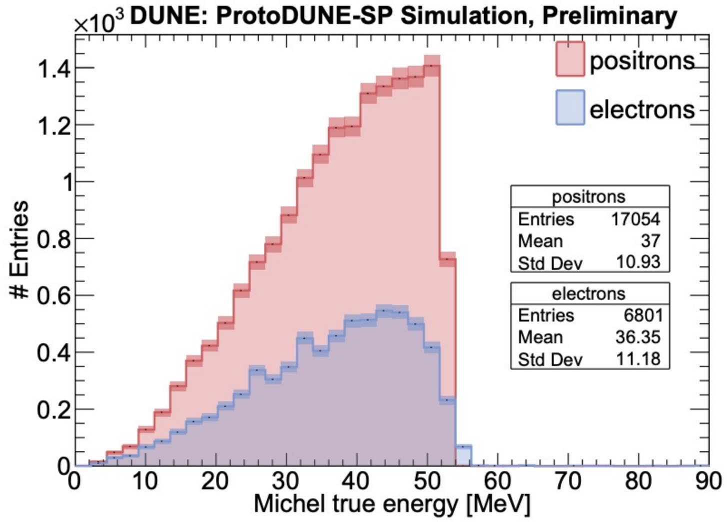
SPACE CHARGE SYSTEMATICS

- Reperformed the analysis from the MC sample generated with SCE OFF
- Compared Michel energy spectra with and without space charge
- The percentage difference in the mean of the distributions are taken to be the systematic uncertainty due to space charge



POSITRON VERSUS ELECTRON SYSTEMATICS

- Idea is to see whether Michel electrons behave differently than positron
- Plotted the true energy spectrums of positrons and electrons
- The difference in the mean of the distributions are taken to be the systematic uncertainty due to electron vs positron systematic

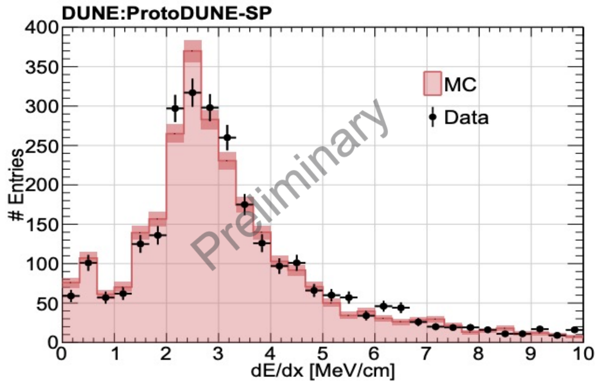


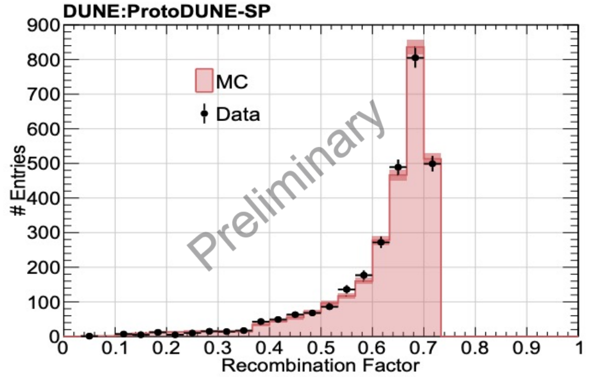
RECOMBINATION FACTOR SYSTEMATICS

- Evaluated the effective Michel recombination factor from MC sample using the modified box model

$$R = \frac{\ln\left(\frac{dE}{dx} \times \beta'/\rho E + \alpha\right)}{\frac{dE}{dx} \times \beta'/\rho E},$$

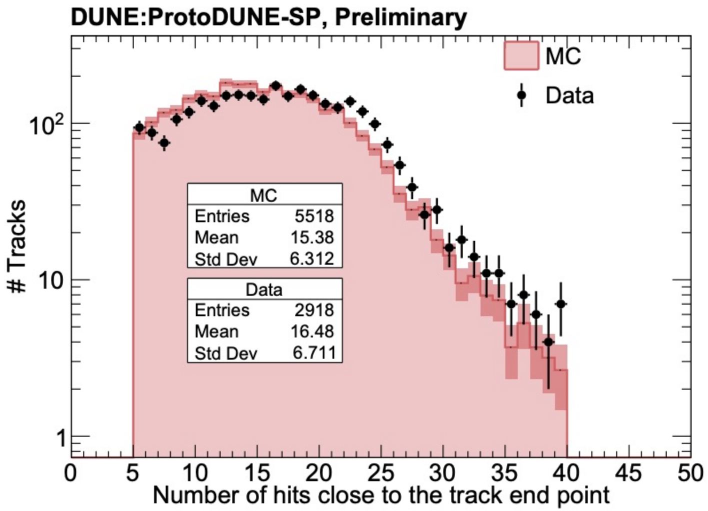
- This agrees to the recombination factor value used in the simulation within 2%
- The value is taken to be the systematic on recombination factor





HIT RECONSTRUCTION SYSTEMATICS

- Considered the number of hits closer to the muon end position
- Calculated the difference between data and MC distribution
- The value is taken to be the systematic on the hit reconstruction



CHARGE TO ENERGY CALIBRATION

- Performed energy calibrations to extract Michel electron energy spectrum using modified box model*

$$E = \frac{C_{norm} * W_{ion}}{R * C_{calib}} * \sum_{i=1}^{N} \left[\varepsilon(X_i) * \varepsilon(Y_i, Z_i) * dQ_i \right]$$

- dQ_i is the reconstructed measured charge deposited on a hit
- W_{ion} is the work function for ionizing an argon atom
- C_{calib} represents the calibration constant that converts ADC to MeV
- C_{norm} normalizes the dQ/dx values to the dQ/dx at the anode plane
- $\varepsilon(X_i)$, $\varepsilon(Y_i, Z_i)$ are correction factors that are meant to remove the residual nonuniformities in the readout after correcting for all known effects (space charge, electron lifetime, etc).
- R = 0.6441 is recombination factor that accounts for recombination effects in the detector

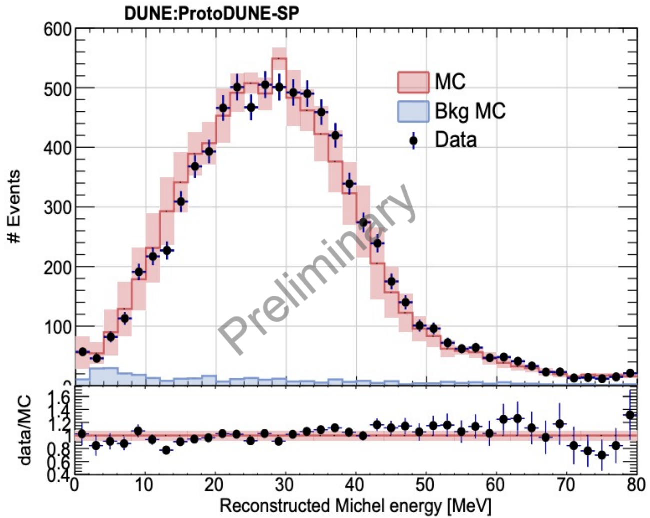
- Calculation follows the same calibration procedure developed using the cosmic muons and applied to the beam data
  – "ProtoDUNE performance paper": https://iopscience.iop.org/article/10.1088/1748-0221/15/12/P12004

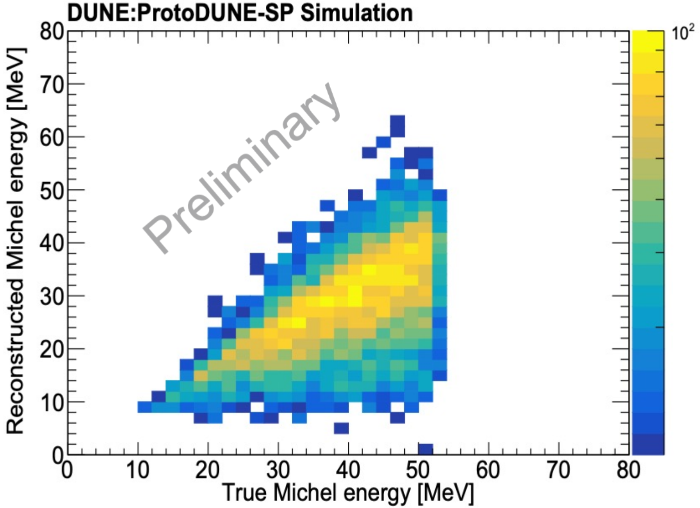
[*] JINST 8, P08005 (2013)

MICHEL ELECTRON RECONSTRUCTION

Muon-based method

- Simulation agrees very well with the data
  - Relative energy scales of data and Monte Carlo events agree to within 2%
- True versus reconstructed Michel energy plot shows a linear agreement

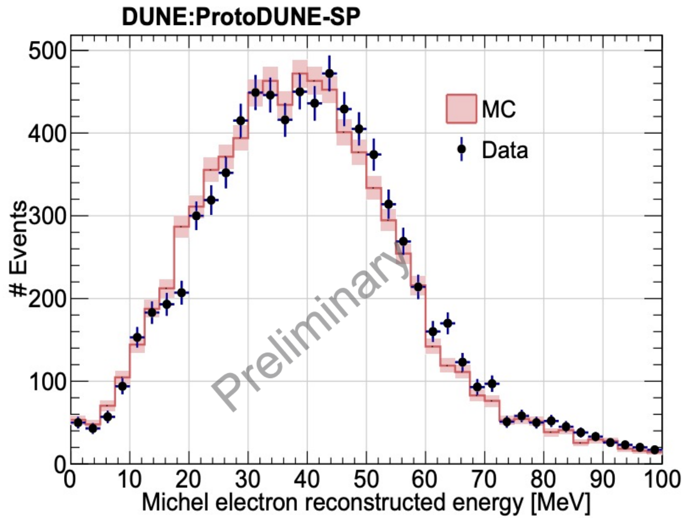


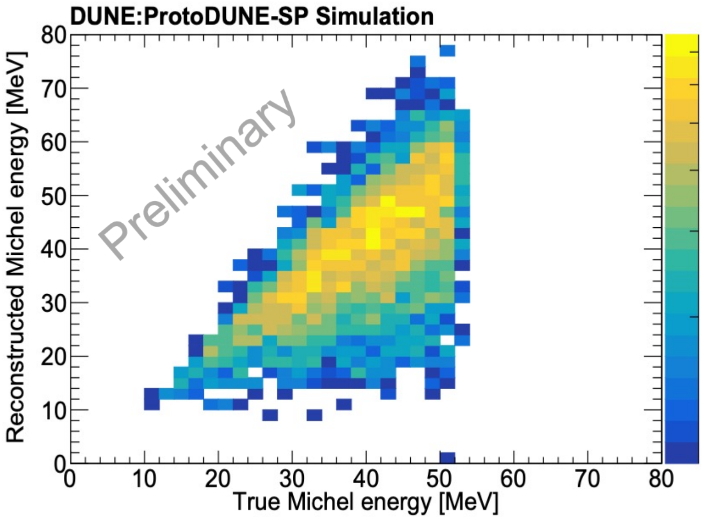


MICHEL ELECTRON RECONSTRUCTION

True-Michel based method

- Here, we match the shape of the reconstructed Michel charge directly with the true Michel energy smeared with a gaussian function
  - Optimize the gaussian uncertainty and charge to energy scale factor to find the best value of χ^2/ndf between both distributions
- Simulation agrees very well with the scaled data
  - Relative energy scales of data and Monte Carlo events agree to within 3%
- True versus reconstructed Michel energy plot shows a linear agreement

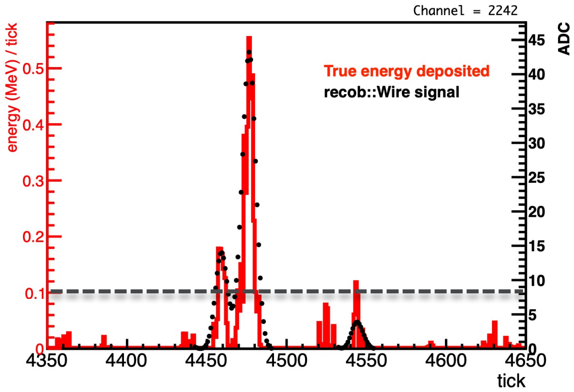


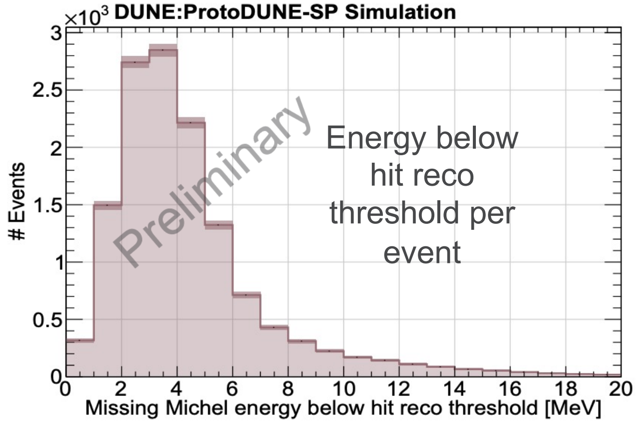


MISSING ENERGY STUDIES

Hit reconstruction threshold

- Investigated the source of missing energy due to hit reconstruction threshold
  - Applied at the signal processing level
- Since Michel electrons are already low in energy, losing a few hits significantly impact the final energy spectrum
- We lose 11% energy due to hit reconstruction threshold.

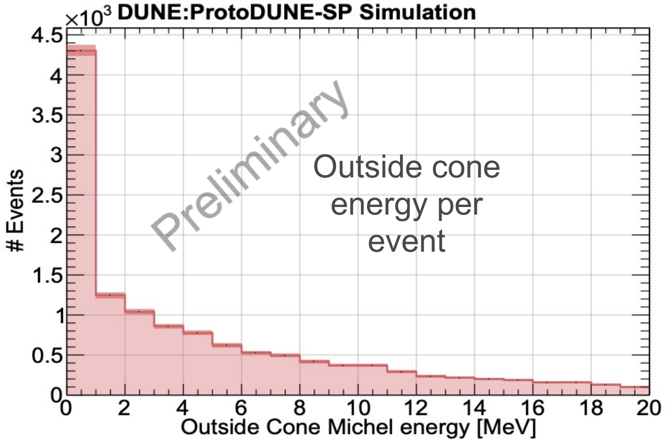




MISSING ENERGY STUDIES

Hit incompleteness

- The other major source of missing energy are the hits outside the cone
- We introduce a lot of unwanted hits if we elongate the cone
- We lose 13% energy due to this effect



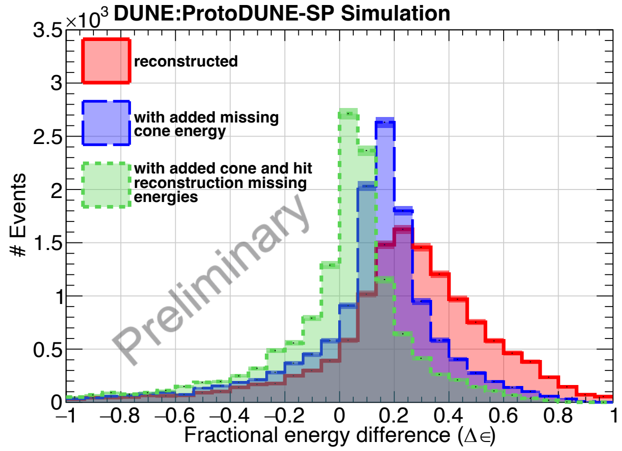
Energy	Percentage
Cone-only	76%
Off-cone	13%
Below hit reconstruction threshold	11%
Total	**100%**

FRACTIONAL ENERGY DIFFERENCE

- Fractional energy difference is defined as

$$\Delta\varepsilon = \frac{(E_{true} - E_{reco})}{E_{true}}$$

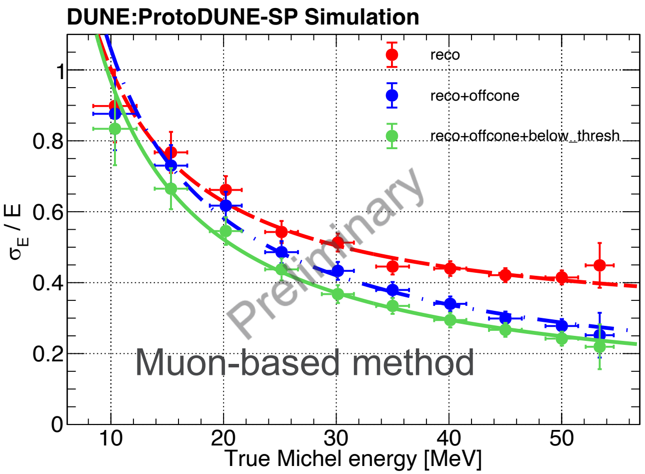
- The Δε per event peaks at zero when we add both missing energy contributions to the simulation as expected

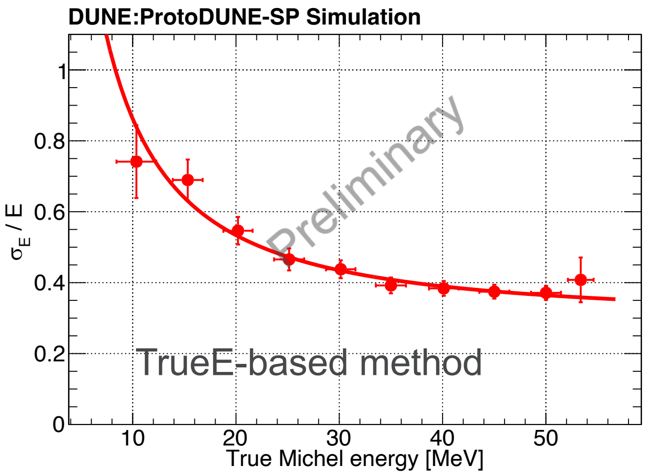


MICHEL ENERGY RESOLUTION

- Michel resolution parametrization:

$$\frac{\sigma(E)}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$





Energy reconstruction	Mean energy (MeV)		Energy resolution terms		
	Data	MC	Constant (p_0)	Stochastic (p_1)	Noise (p_2)
Cosmic muon-based nominal E-reconstruction	29.4±0.1	28.7±0.1	0.26 ± 0.12	1.91 ± 0.93	7.54 ± 3.05
Nominal with recovered missing energy (MC only)	–	39.3±0.1	0.00 ± 0.15	1.24 ± 0.22	8.86 ± 0.94
True energy-based E-reconstruction	39.3±0.2	38.0±0.1	0.29 ± 0.10	1.22 ± 1.28	7.16 ± 2.80

MICHEL ELECTRON PAPER STATUS

- We have drafted a technical note on this analysis
- The paper draft has been prepared that has completed its editorial board review
- Will soon be sent out to the entire DUNE collaboration for another round of review

Paper draft

Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector

(The DUNE Collaboration)

This article describes the selection and reconstruction of low energy electrons in the ProtoDUNE-SP detector. ProtoDUNE-SP is one of the prototypes for the Deep Underground Neutrino Experiment (DUNE) far detector, built and operated at CERN as a charged particle test beam experiment. The experiment collected data from August 2018 to July 2020. The analysis described here employs a fully automatic event selection and charged particle track reconstruction to obtain a sample of candidate cosmic muons, and to identify low-energy electrons around the end positions of selected candidate muons. Low-energy electron candidates are reconstructed using tools developed as a part of this analysis. Studies have been performed to verify the high purity (~95%) of selected low-energy electron event candidates and to calibrate the low-energy electron energy scale with both the cosmic-muon dE/dx method and the use of the theoretical low-energy electron energy spectrum. In addition, the effects of detector response to low-energy electrons including readout electronics threshold effects are quantified. Finally, the relation between the theoretical and reconstructed low-energy electron energy spectrum is derived and the energy resolution is characterized. Low-energy electron selection presented here accounts for about 75% of the total electron deposited energy. After the addition of missing energy the energy resolution improves from about 40% to 25% at 50 MeV.

I. INTRODUCTION

Discoveries over the past half-century have positioned neutrinos, one of the most abundant matter particles in the universe, at the fundamental physics center stage. Neutrinos are now being studied to answer open questions about the nature of matter and the evolution of the universe. In particular, the measurement of CP violation in the lepton sector [1, 2] may help probe the possibility that early-universe CP violation involving leptons might have led to the present dominance of matter over antimatter. Current long-baseline (LBL) neutrino oscillation experiments are beginning to provide initial constraints on the CP-violating phase δ_{CP} [3, 4], and definitive measurements are planned to be performed by the dedicated LBL accelerator neutrino experiments DUNE [5] and Hyper-Kamiokande [6]. The DUNE experiment [7] is a next-generation LBL accelerator neutrino experiment, designed to be sensitive to neutrino $\nu_\mu \rightarrow \nu_e$ oscillations. The DUNE experiment will consist of a far detector [8] to be located about 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, USA, at a distance of 1300 km from Fermilab, and a near detector [9] to be located at Fermilab. The far detector will be a large modular liquid argon time-projection chamber (LArTPC) with a total LAr mass of nearly 70 kt. With LAr technology it is possible to reconstruct neutrino interactions with image-like pre-

low-energy electrons and positrons. Neutrino detectors at the far site of DUNE are planned to be built inside four cryostats, each of which will contain 17.5 kt of liquid argon. The first detector to be constructed is planned to be a single-phase TPC [14].

The ProtoDUNE apparatus (ProtoDUNE-SP) [15] assembled and tested at the CERN Neutrino Platform [16], is a prototype of the first DUNE far detector module, and it incorporates full-size components as designed for that module. The ProtoDUNE-SP detector is a single-phase LArTPC with an active volume of $7.2 \times 6.1 \times 7.0\ m^3$. Major components of the ProtoDUNE-SP detector include the mechanical structure with a liquid argon membrane cryostat, the time-projection chamber, the photon detector system, electronics readout systems, and the computer data storage. ProtoDUNE-SP was operated from 2018 to 2020 and its collection of large samples of high-quality beam data were used to demonstrate the effectiveness of the single-phase far detector design. Results on the performance of the ProtoDUNE-SP liquid argon TPC in the test beam can be found in reference [17] including noise and gain measurements, dE/dx calibration for muons, protons, pions and electrons, drift electron lifetime measurements, and photon detector noise, signal sensitivity and time resolution measurements. The measured values meet or exceed the specifications for the DUNE far detector.

To achieve the planned DUNE physics program, it is critically important to accurately reconstruct and mea-

SUMMARY

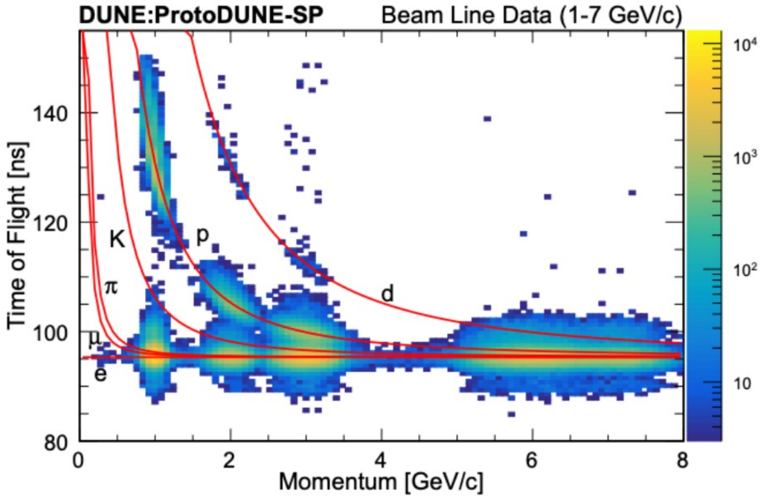
- Developed Michel electron selection, reconstruction, and energy calibration tools for ProtoDUNE-SP
  - Achieved 95% event selection purity
- Identified the major source of missing energy in the spectrum
  - Hit reconstruction threshold
  - Energy outside Michel reconstructed cone
- Presented Michel electron energy spectrum with two consistent methods
- Presented the Michel electron resolution
- A paper draft is under review within the collaboration
  - Stay tuned!

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

PROTODUNE-SP—TERTIARY CERN SPS BEAM

- Tertiary CERN SPS Beam
  - Beam coming from Super Proton Synchrotron
- CERN SPS Beam:
  - Protons from 400 GeV CERN SPS
  - Incident on Beryllium Target
  - Secondary Beam is 80 GeV
  - Incident on secondary target
  - 0.3-7 GeV H4-VLE Beam

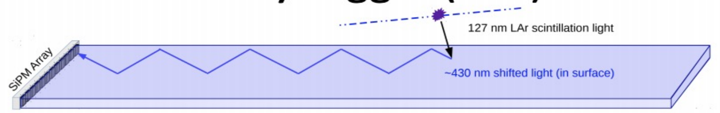


DUNE FD SP Prototype—Photon Detection System

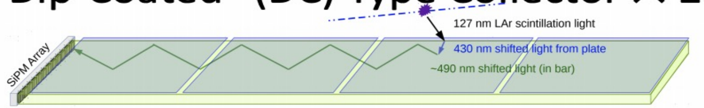
Testing new technologies!

ProtoDUNE-SP consists of:

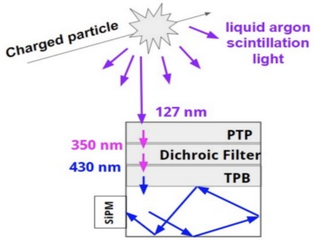
- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Photon Detection System (PDS)
- Cosmic-Ray Tagger (CRT)



”Dip-Coated” (DC) Type Collector × 29



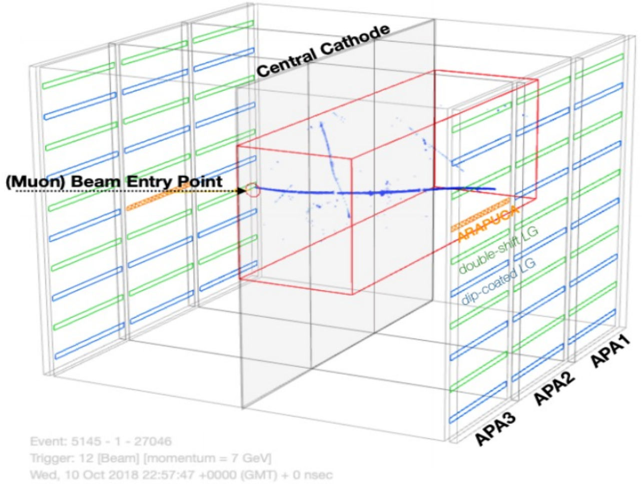
”Double-Shifted” (DS) Type Collector × 29



ARAPUCA Concept

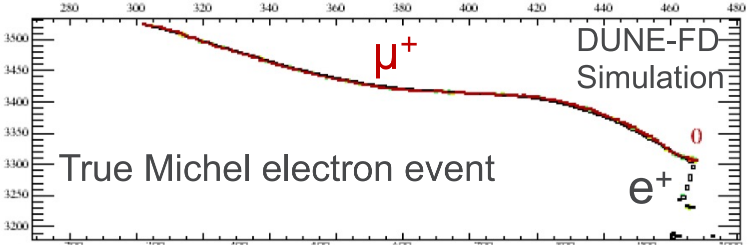
Photon Detection System

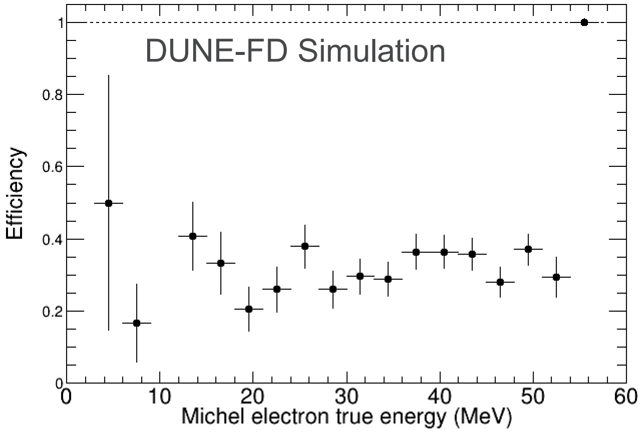
- Photon Detector Technology Demonstration
  - 60 Photon Detectors
  - 3 Photon Collector Technologies
    - 29 Dip Coated Light Guide Detectors
    - 29 Double Shift Light Guide Detectors
    - 2 S-ARAPUCAs
  - 2 Photon Sensors Manufactures
    - SensL & Hamamatsu



LOW-ENERGY ELECTRON STUDIES AT DUNE FAR DETECTOR

- Developing selection and reconstruction framework to isolate muons and its Michel electrons to calibrate electron energy scale at Far Detector (10 kt module).
  - Achieved 80% event purity
  - True Michel efficiency is 31%
  - My plan is to deliver Michel analysis algorithm for use in Far Detector on day one





PASSING RATE AS A FUNCTION OF TRUE MICHEL ENERGY