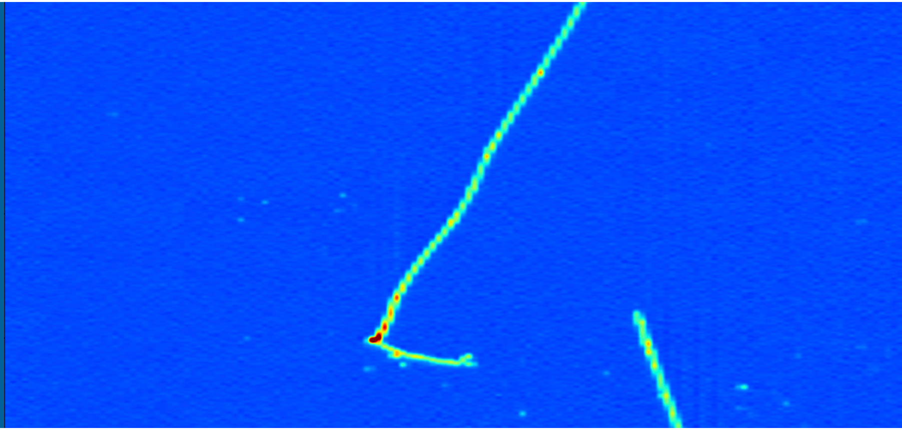
DEVELOPMENT OF LARTPC TECHNOLOGY FOR NEUTRINO OSCILLATION MEASUREMENTS



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02/23/2021

PHYSICS GOALS OF MY RESEARCH

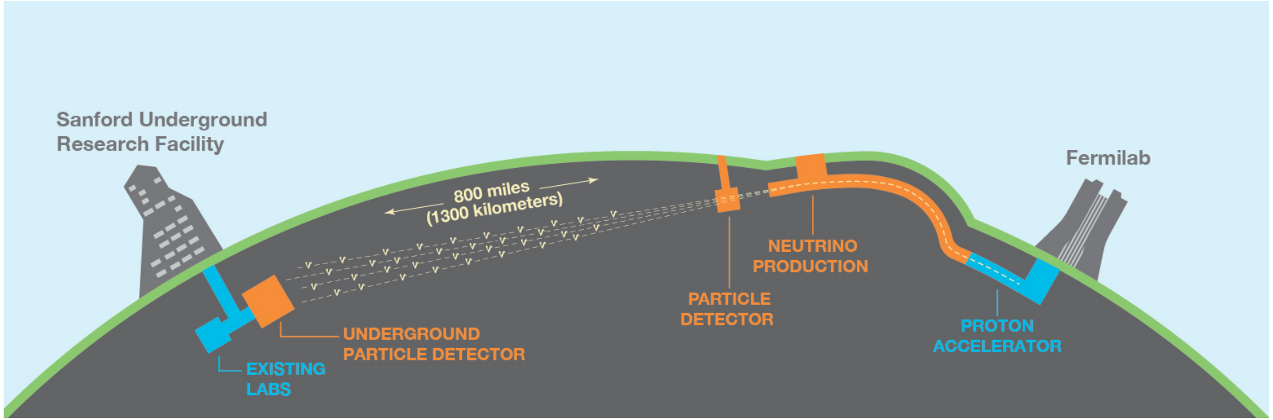
- My research goal is to carry out a comprehensive program of neutrino oscillation measurements using Long and Short baseline neutrino experiments
  1. Search for Charge-Parity symmetry violation in the leptonic sector
  2. Support 1. by reducing systematics in lepton and neutrino interaction measurements that are currently dominant systematics for the neutrino oscillation measurements

SEARCH FOR CP-VIOLATION IN NEUTRINOS

- CP-symmetry violation has already been found in quark oscillations
  - However, more CP-violation must be observed in order to explain the universe's matter dominance.
- CP symmetry violation in neutrinos is our best bet for explaining why matter is dominant in the universe
- What is the value of the Dirac CP-violating phase δ_{CP}?
  - If ≠ 0 (or 180^0), then CP-violation exists
- Deep Underground Neutrino Experient (DUNE) can discover CP-violation in the neutrino sector
  - Therefore I will be focusing on DUNE development

INTRODUCTION TO DUNE

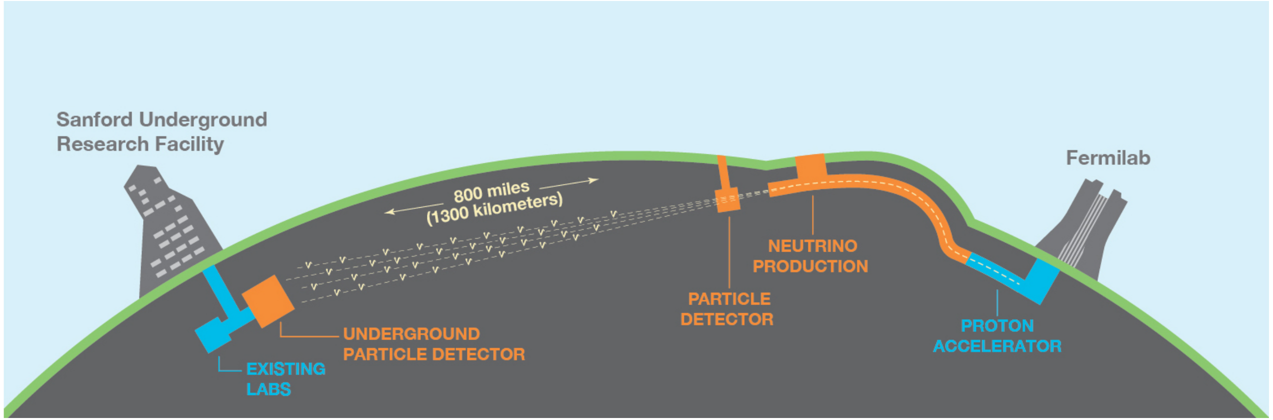
- The Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillations experiment.



- Major DUNE goals:
  - Neutrino Oscillation Physics (CPV, Mass hierarchy etc)
  - Nucleon Decay
  - Supernova burst physics & astrophysics

INTRODUCTION TO DUNE

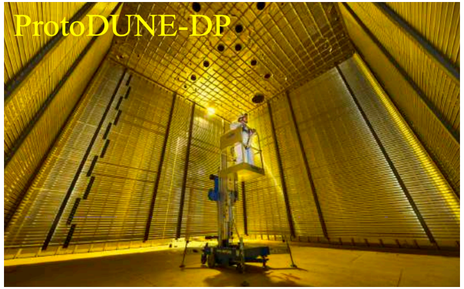
- The Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillations experiment.

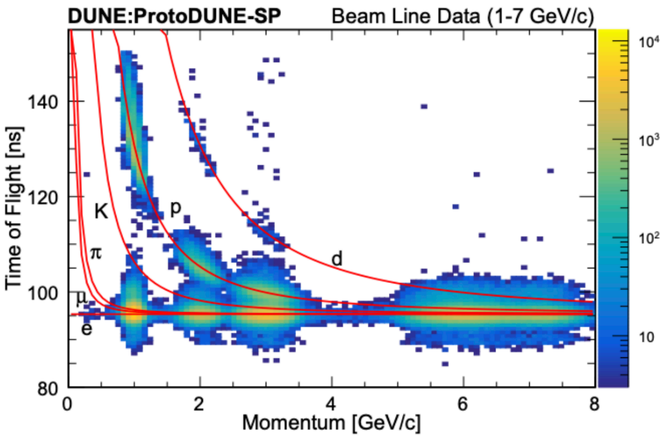


- New neutrino beam at Fermilab,1300 km baseline
- Multiple technologies for the Near Detector (ND) at Fermilab
- 70 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
  - Will begin taking data in late 2020s
  - Current effort is to demonstrate that technology works

PROTODUNE SP AND DP AT CERN

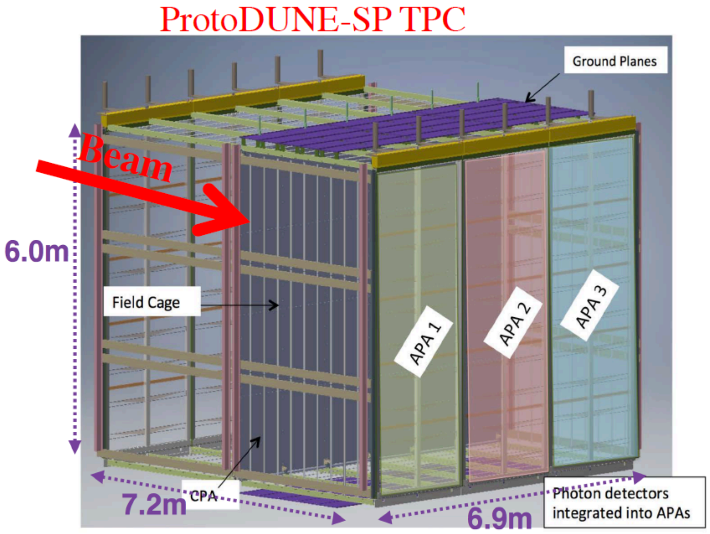
- Single-phase (SP) and dual-phase (DP) DUNE prototype LArTPCs at CERN
- 770 t LAr mass each
- Exposed to H2 (DP) and H4 (SP) test beams at CERN, momentum dependent beam composition contains *e*, $K^{\pm}$, $\mu^{\pm}$,*p* , $\pi^{\pm}$
- Also collect cosmic ray data





PROTODUNE-SP

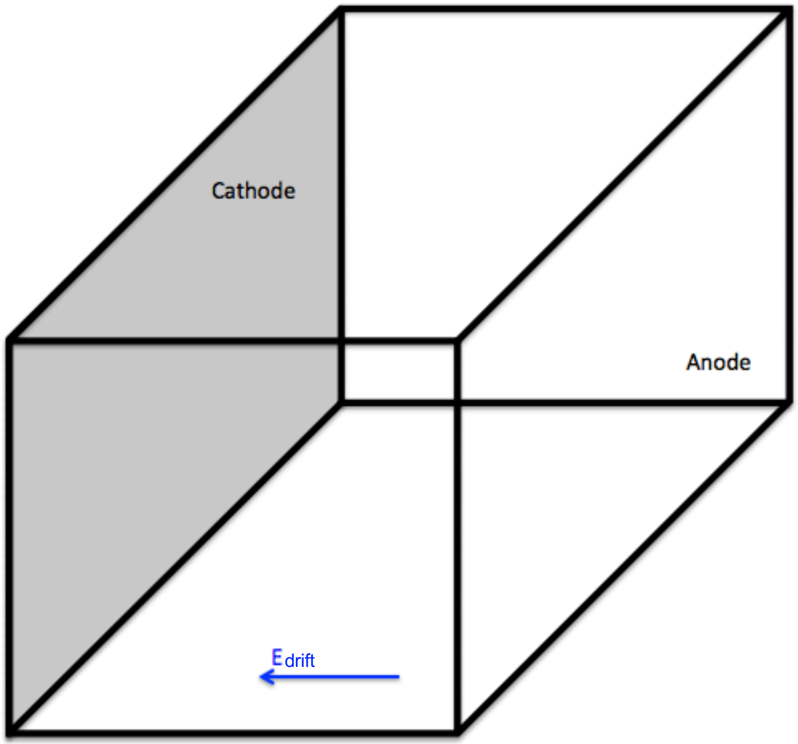
- Active Volume: 6m (H) x 7m (L) x 2 x 3.6m (W)
- Central Cathode Plane Assembly (CPA) :
  - 3.6 m drift distance @180 kV
  - 500 V/cm field in drift volume
- Anode Plane Assembly (APA):
  - 3 APAs on each side
  - Each APA module: 6m high, 2.3m wide



- 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 paper on ProtoDUNE-SP performance published: JINST 15 (2020) 12, P12004
- ProtoDUNE-SP Phase-I operated Sept. 2018 – July 2020, Phase-II data taking under preparation

A. Rafique

HOW LARTPC WORKS



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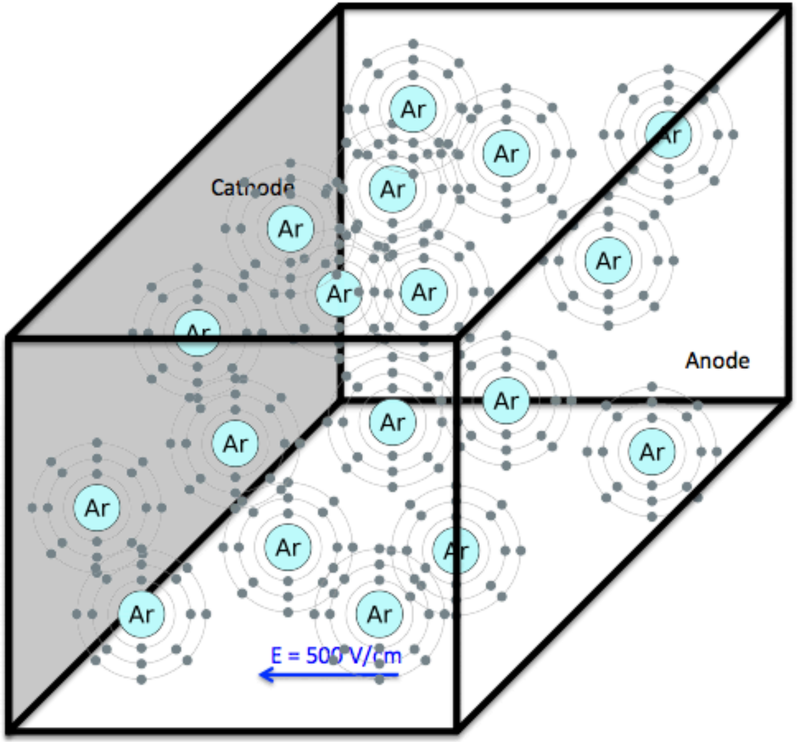
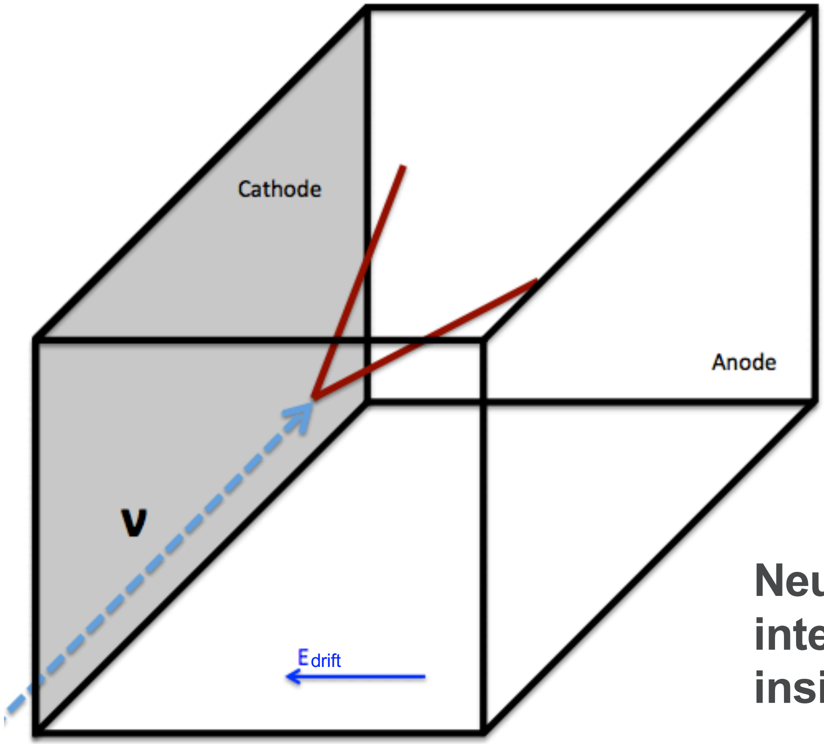
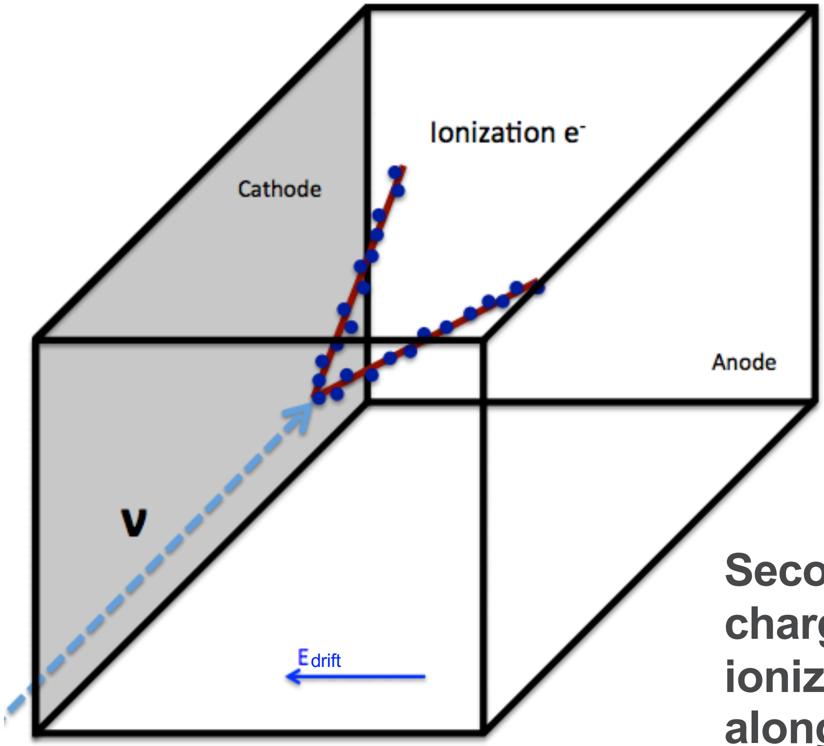


HOW LARTPC WORKS



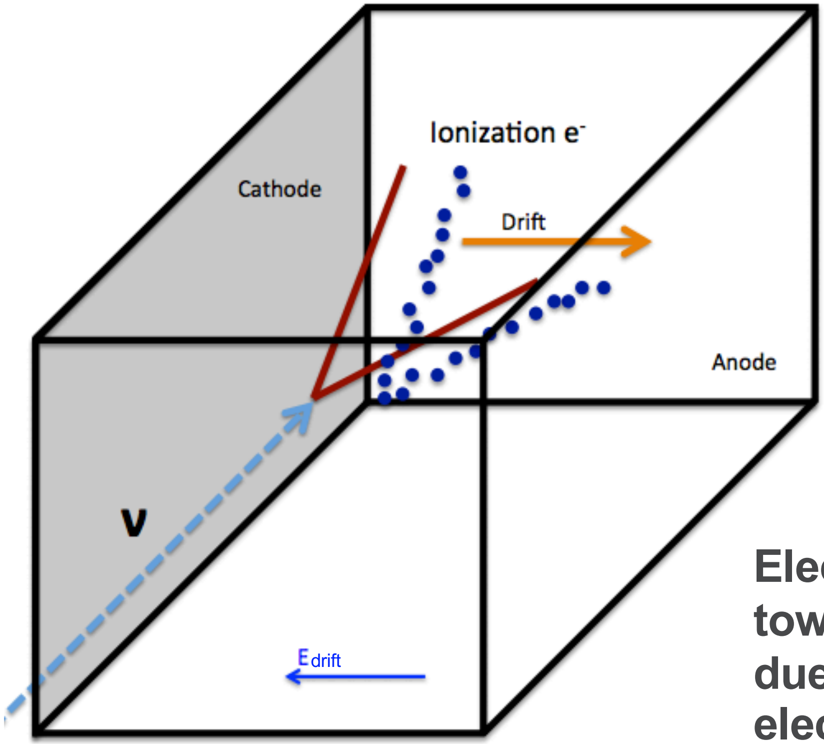
Neutrino interaction inside TPC

HOW LARTPC WORKS



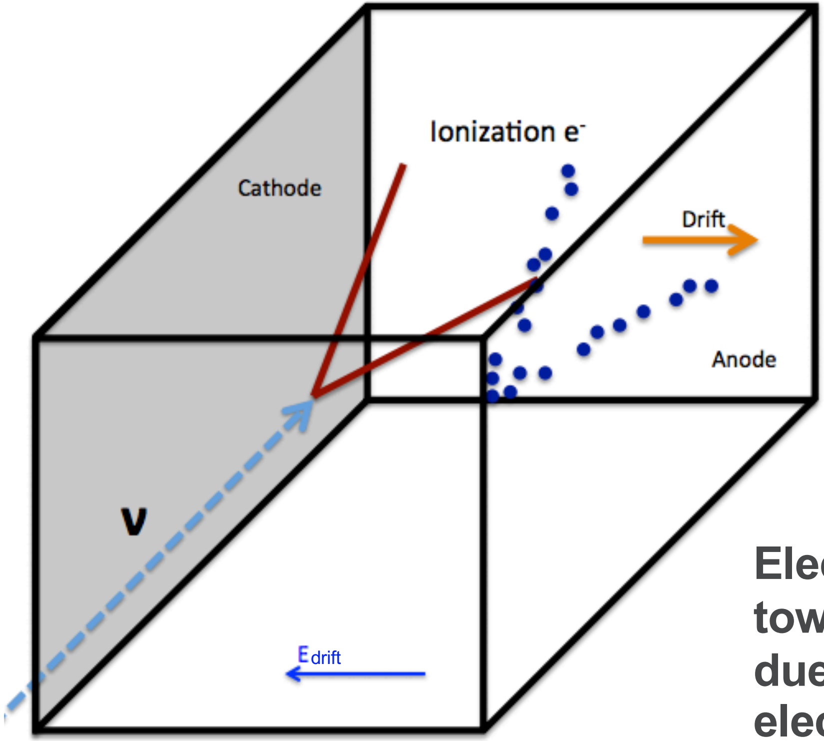
Secondary charged particles ionize atoms along their way

HOW LARTPC WORKS



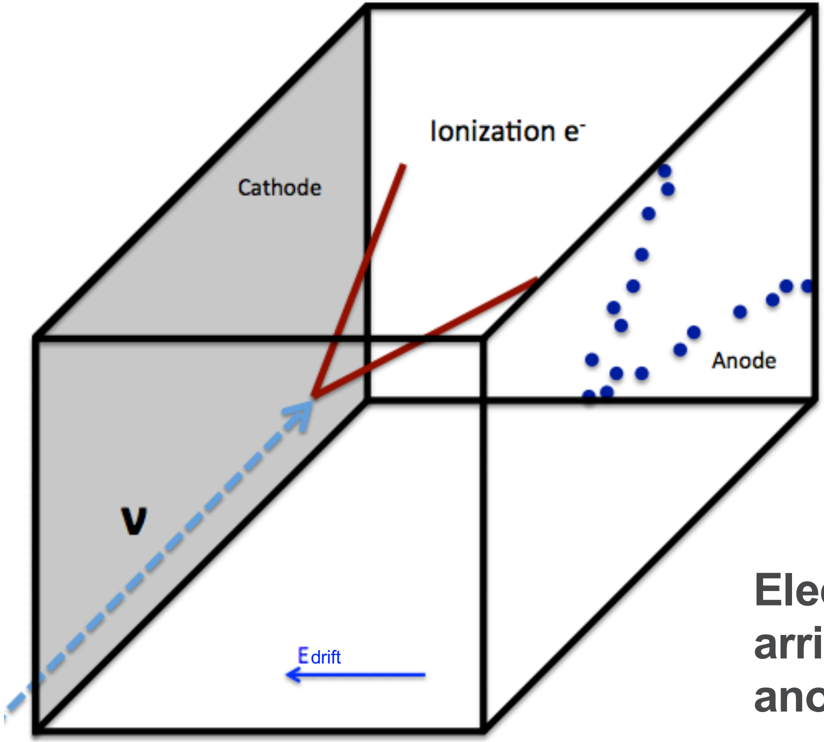
Electrons drift towards anode due to applied electric field

HOW LARTPC WORKS



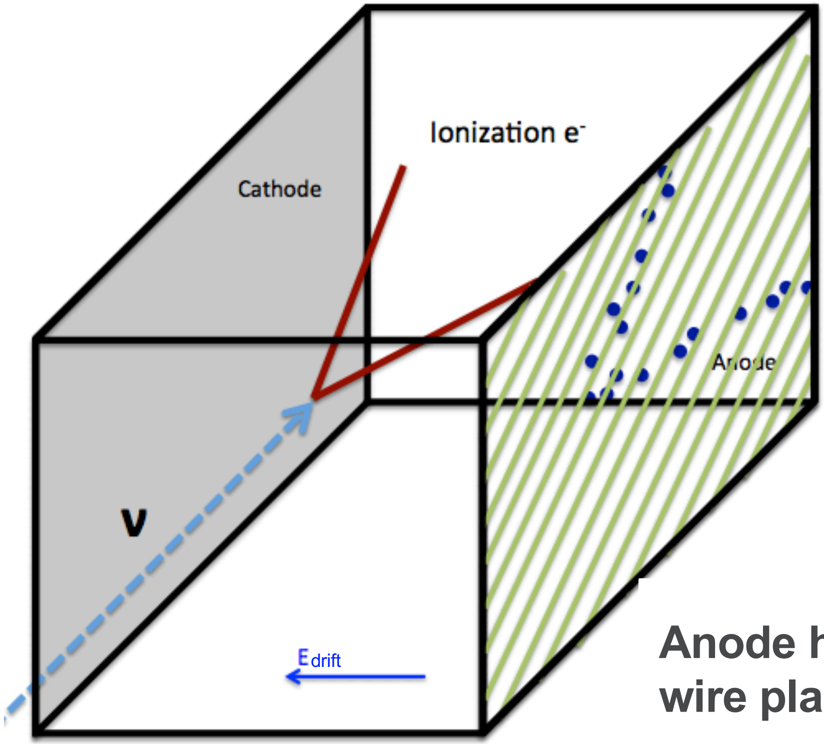
Electrons drift towards anode due to applied electric field

HOW LARTPC WORKS



Electrons arrive at anode

HOW LARTPC WORKS

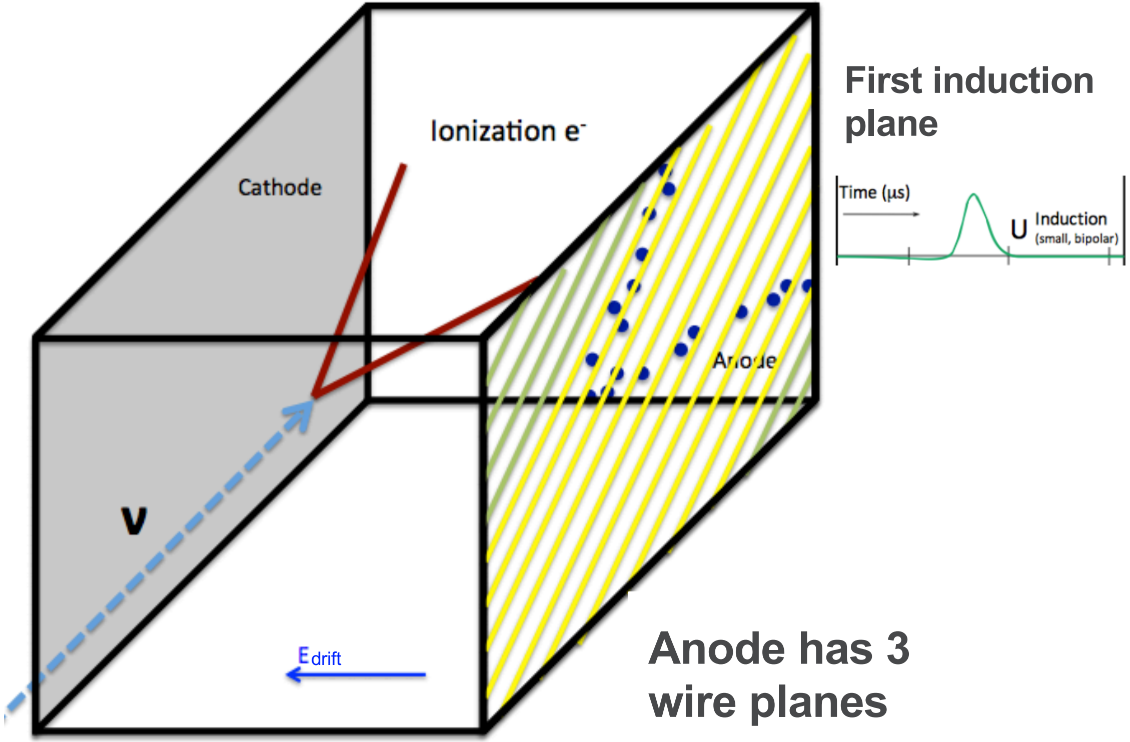


First induction plane

Anode has 3 wire planes

Anne Schukraft @ Users Meeting 2016, FNAL

HOW LARTPC WORKS



First induction plane

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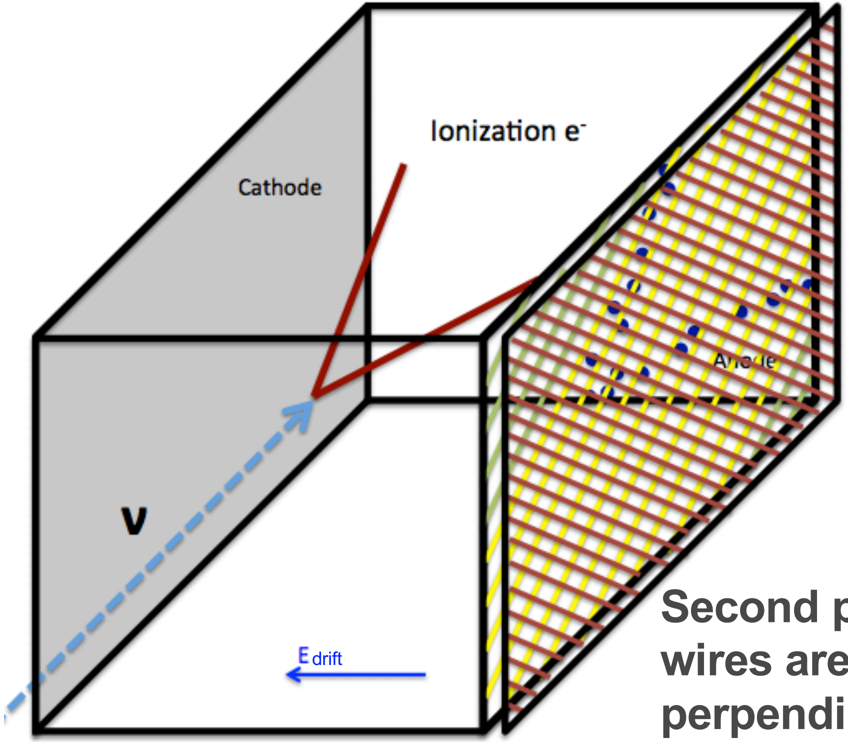
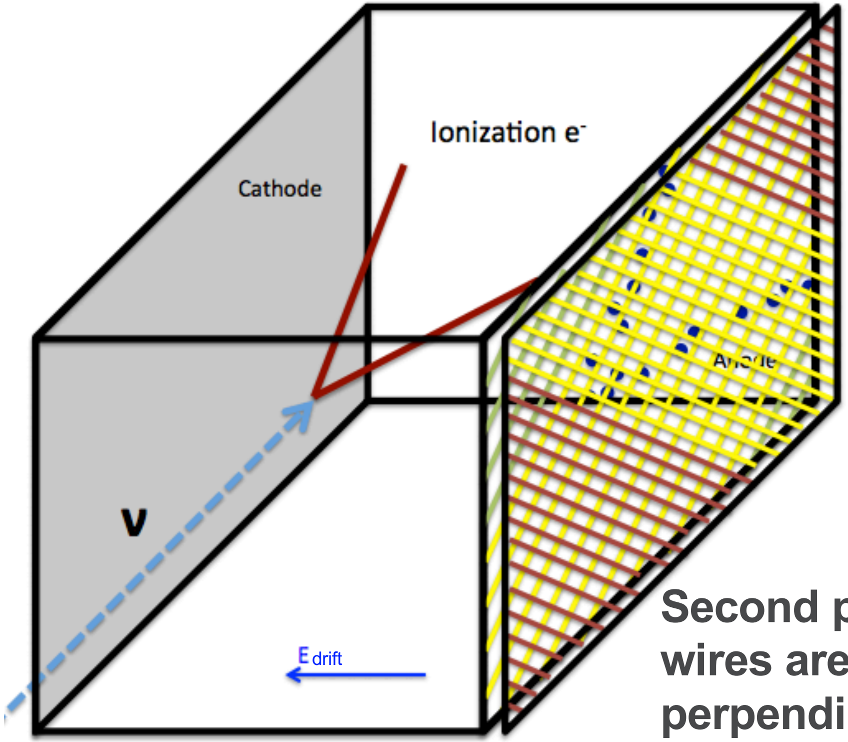


Second induction plane

Second plane wires are perpendicular to first plane wires

HOW LARTPC WORKS



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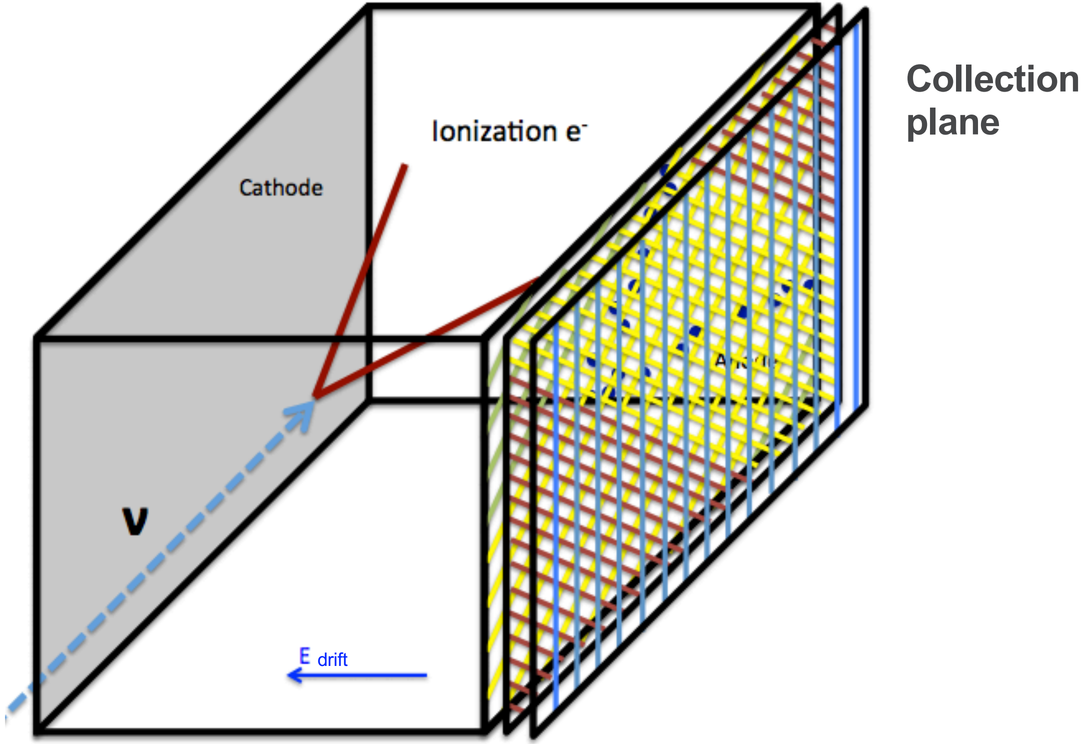
HOW LARTPC WORKS



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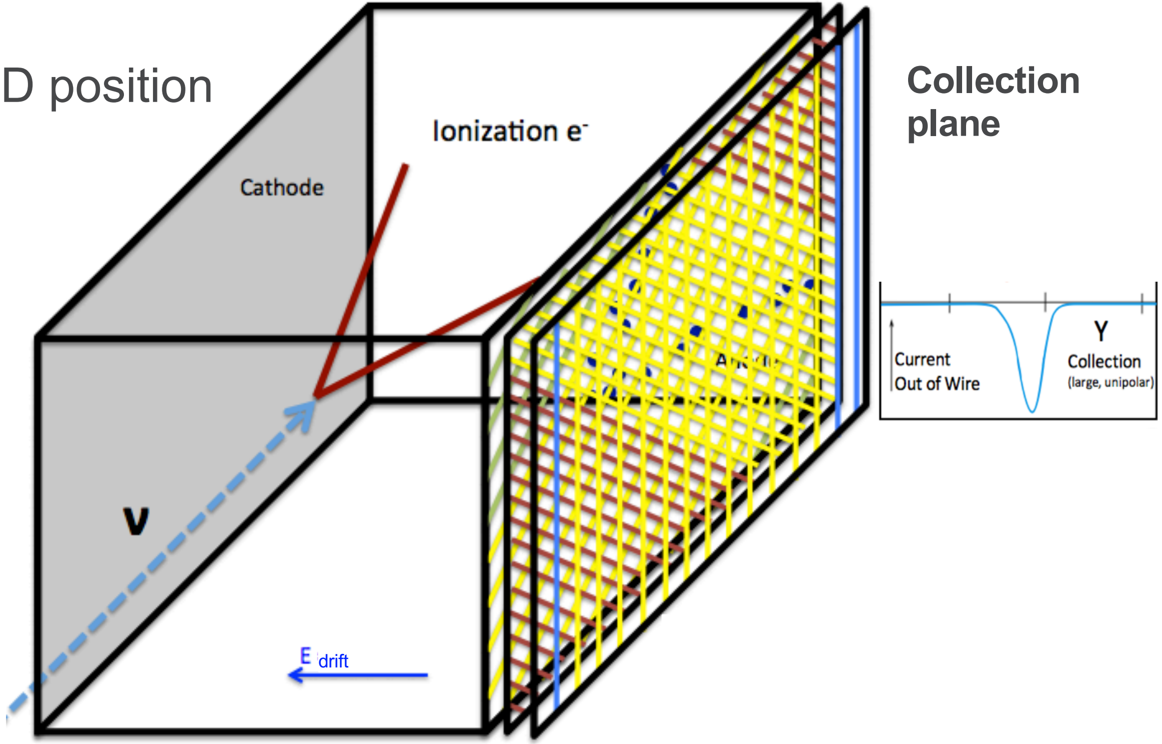
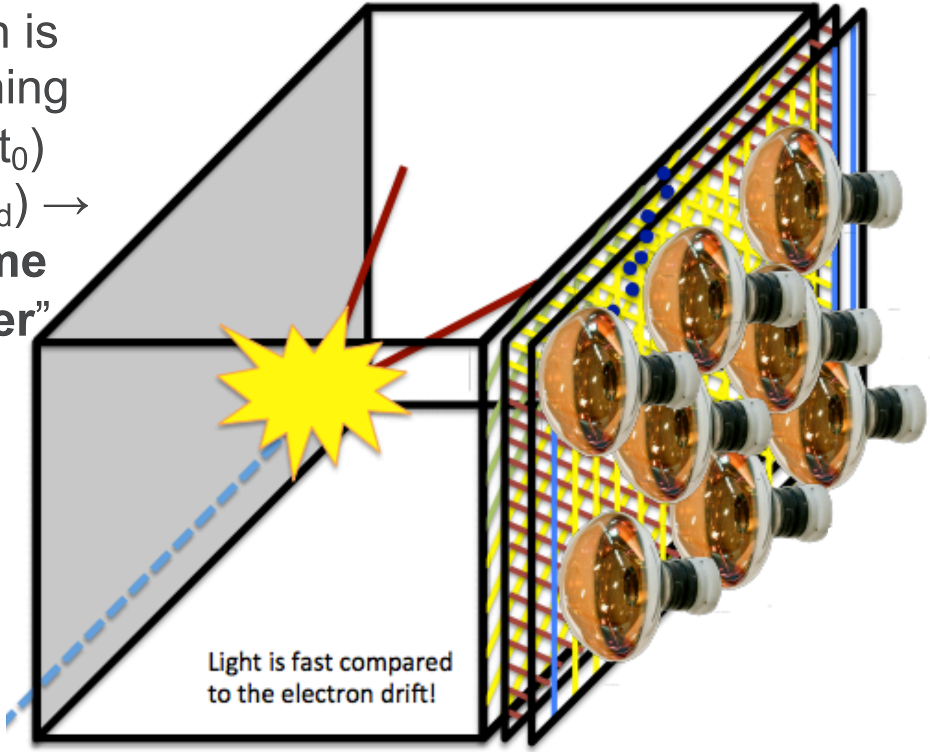
HOW LARTPC WORKS

- 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

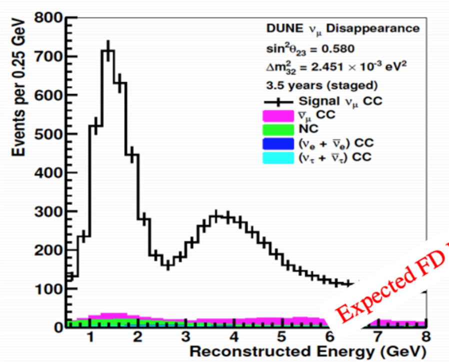
Anne Schukraft @ Users Meeting 2016, FNAL

DUNE SENSITIVITY AND MEASURING DELTA-CP

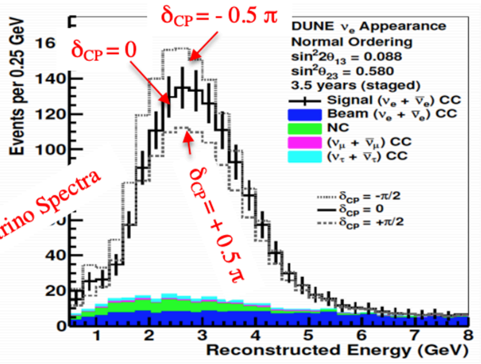
- CP violation measured as a difference of neutrino and anti-neutrino oscillation probabilities.

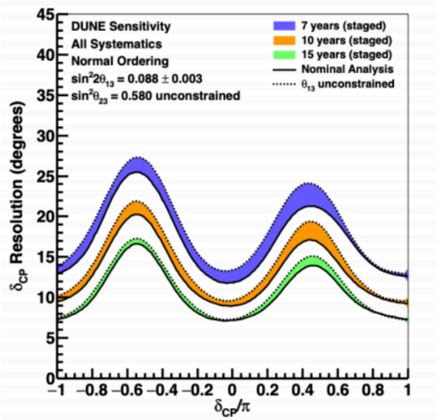
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- 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 id required for
  - Early DUNE physics milestone is to reduce δ_{CP} uncertainty below 20^0 (at $\delta_{CP} = -90^0$)



Expected FD Neutrino Spectra





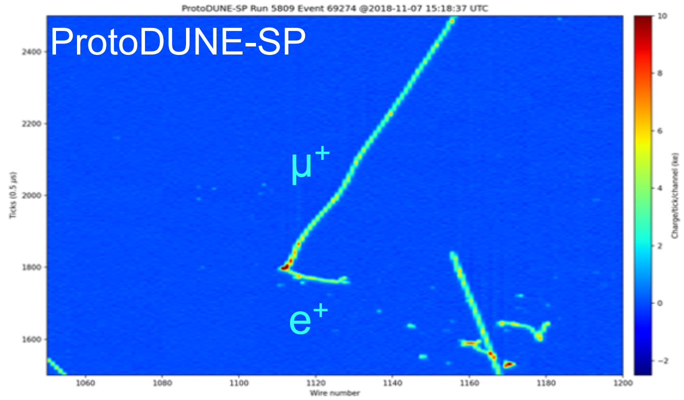
ACCURATE RECONSTRUCTION OF VISIBLE ENERGY

- Perform oscillation analysis
  - Reduce systematics in lepton and neutrino interaction measurements that are currently dominant systematics for the neutrino oscillation 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 oscillation measurements

LEPTONIC ENERGY MEASUREMENTS

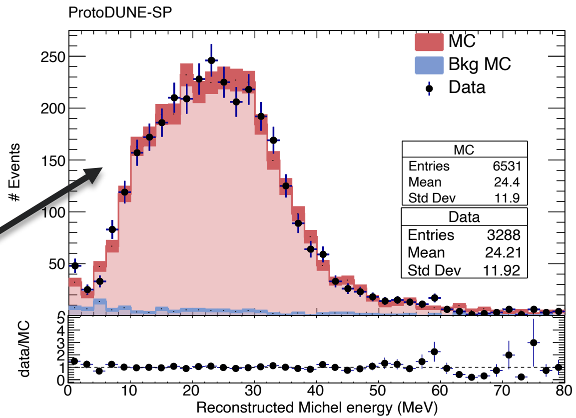
LOW-ENERGY ELECTRONS STUDIES

- 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

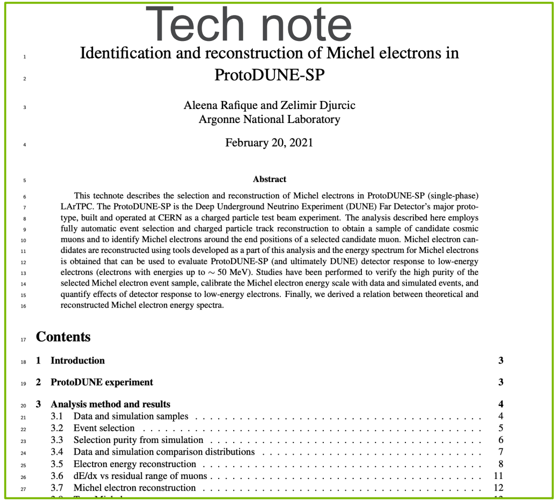


ACHIEVED RESULTS USING PROTODUNE-SP

- Deliver selection and reconstruction framework to isolate muons and its Michel electrons to calibrate electron energy scale at DUNE Far Detector
- Already developed selection, reconstruction, and energy calibration tools for ProtoDUNE-SP
  - Achieved 95% event purity
  - Variation in Michel electron energy energy is <2%
  - Using “charge” deposition inside TPC only
- Tech note is already out
- Paper draft is ready to be circulated to the collaboration
- Will deliver Michel analysis algorithm to use on DUNE-FD Day 1



Tech note



Identification and reconstruction of Michel electrons in ProtoDUNE-SP

Aleena Rafique and Zelimir Djurcic
Argonne National Laboratory

February 20, 2021

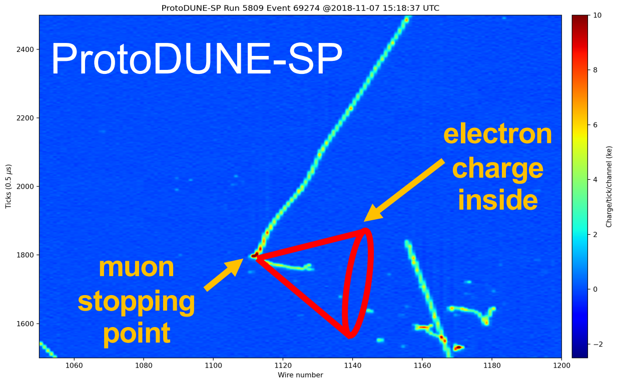
Abstract

This technote describes the selection and reconstruction of Michel electrons in ProtoDUNE-SP (single-phase) LArTPC. The ProtoDUNE-SP is the Deep Underground Neutrino Experiment (DUNE) Far Detector's major prototype, built and operated at CERN as a charged particle test beam experiment. The analysis described here employs fully automatic event selection and charged particle track reconstruction to obtain a sample of candidate cosmic muons and to identify Michel electrons around the end positions of a selected candidate muon. Michel electron candidates are reconstructed using tools developed as a part of this analysis and the energy spectrum for Michel electrons is obtained that can be used to evaluate ProtoDUNE-SP (and ultimately DUNE) detector response to low-energy electrons (electrons with energies up to ∼ 50 MeV). Studies have been performed to verify the high purity of the selected Michel electron event sample, calibrate the Michel electron energy scale with data and simulated events, and quantify effects of detector response to low-energy electrons. Finally, we derived a relation between theoretical and reconstructed Michel electron energy spectra.

Contents

RECONSTRUCTION OF LOW-ENERGY ELECTRONS

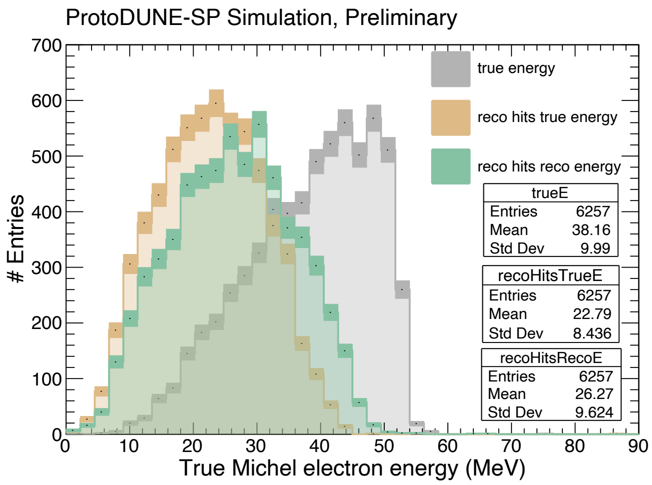
- Defined a cone at the end point of the parent muon
- All hits inside the cone are taken to be as candidate Michel hits based on simulation studies
- Selected, reconstructed and performed energy calibration for low energy electrons (Michels) in ProtoDUNE

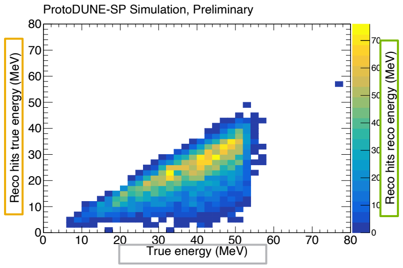


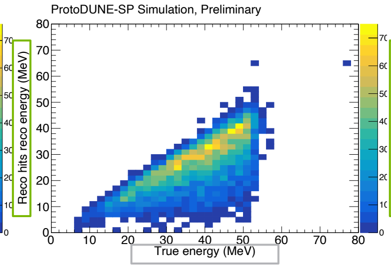
TRUE ENERGY SPECTRA

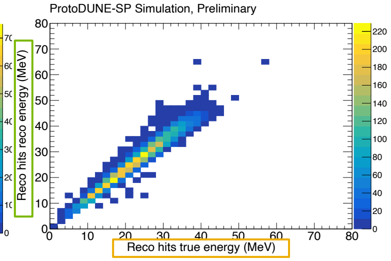
Calculated in three different ways

- True Michel true Energy: by extracting energy directly from GEANT for the true Michel
- True Michel reco hits true energy: by summing up the true energy of true Michel deposited on all reconstructed hits
- True Michel reco hits reco energy: by summing up the reconstructed energy of true Michel deposited on all reconstructed hits





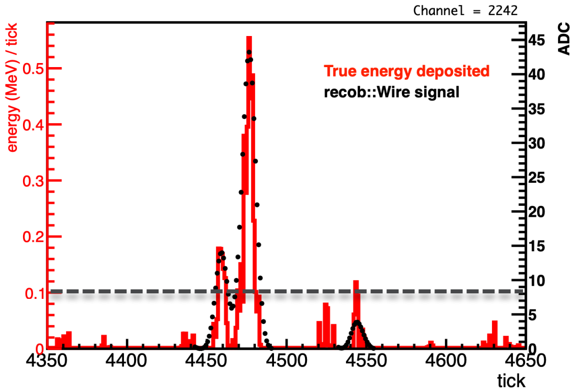




UNDERSTANDING THE MISSING ENERGY

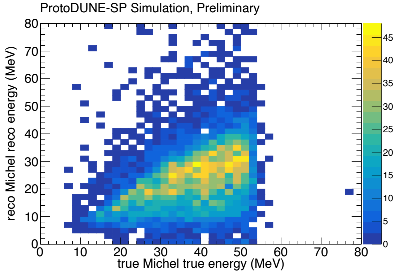
Hit reconstruction threshold ~ 100 keV/tick

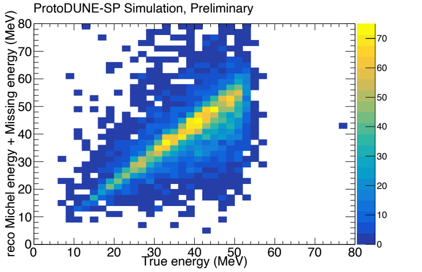
- Investigated the source of missing energy due to hit reconstruction threshold
  - We lose 11 MeV on average due to this threshold for Michel spectrum
- Compared energy resolution plots before and after the addition of the missing energy on event-by-event basis
- Energy resolution:
  - Before: $\delta(E)/E$ = 26% at 50 MeV
  - After: $\delta(E)/E$ = 18% at 50 MeV
- My plan is to work with BNL EDG to further investigate how the threshold could be optimized to improve sensitivity

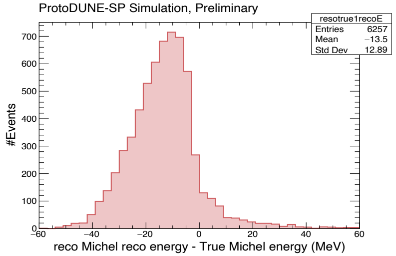


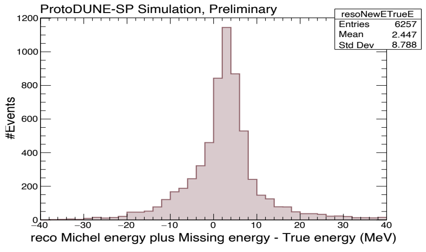
Before

After





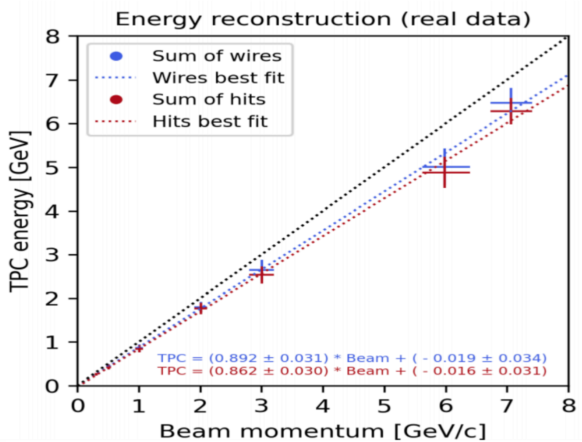


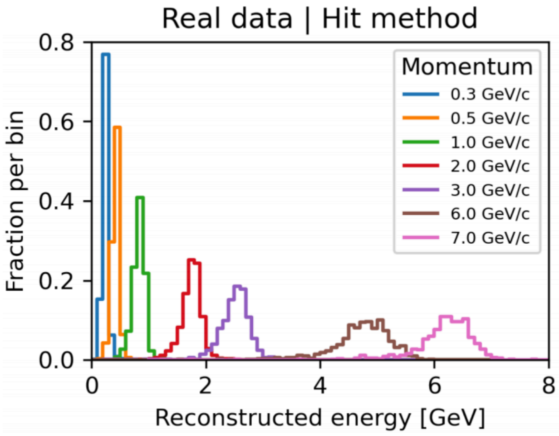


BEAM ELECTRON RESOLUTION STUDIES

Low → High energy electrons

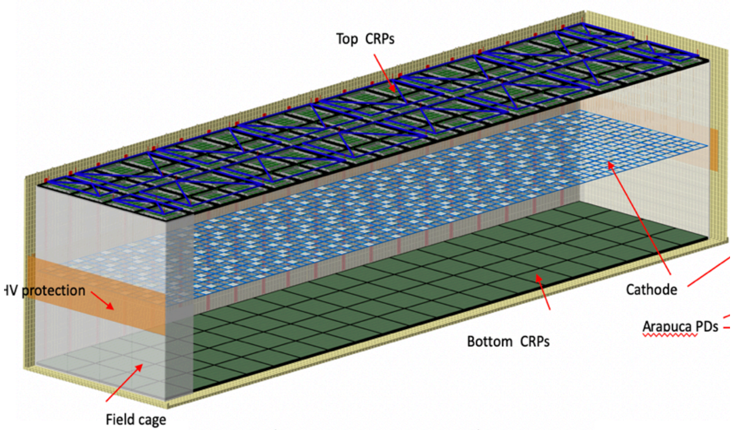
- Selected and reconstructed electron showers collected by ProtoDUNE-SP experiment from (0.3 – 7) GeV.
- Compared two different charge integration methods
  - Hit method: Utilized the hit information for charge collection
  - Wire method: One integrates the total charge in a reconstructed wire
- About ~15% of beam energy is missing
  - Hit reconstruction threshold effects could be the possible reason
  - Investigation is going on

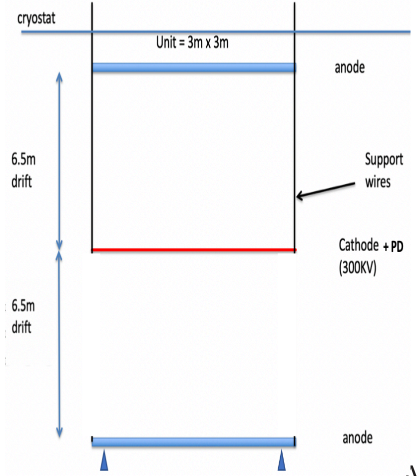




INVOLVEMENT IN DUNE VERTICAL DRIFT FD

- DUNE-US current project baseline: 2 Far detectors and Day 1 Near detector
  - Second DUNE Far Detector likely to be known as Vertical Drift FD
- Goal of vertical drift: Combine positive features of SP and DP designs
  - Excellent LAr purity and low noise electronics enable longer drift lengths with single-phase readout
  - DP vertical drift architecture, with 3 x 3 m horizontal readout planes, made detector assembly much simpler
- Plan to involve in the development of VD
  - Could get involved in 3X3 m module integration at CERN cold box and subsequent DUNE VD-FD

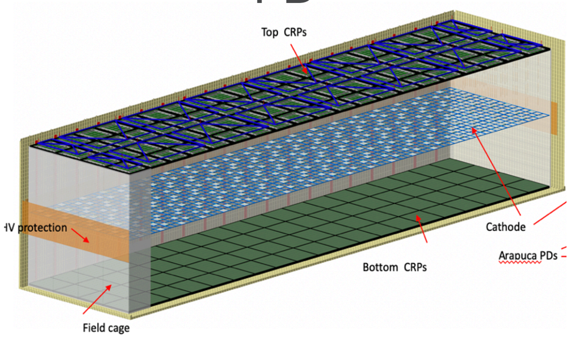




INVOLVEMENT IN DUNE VERTICAL DRIFT FD

- Plan to work with BNL EDG on cold electronics to:
  - Obtain the improved hit simulation and reconstruction thresholds
  - Plan to investigate the impacts of further lowering the threshold
  - Important to perform the accurate energy reconstruction to enable DUNE's oscillation physics program
- Experience with ProtoDUNE development and operations at CERN

DUNE Vertical Drift FD

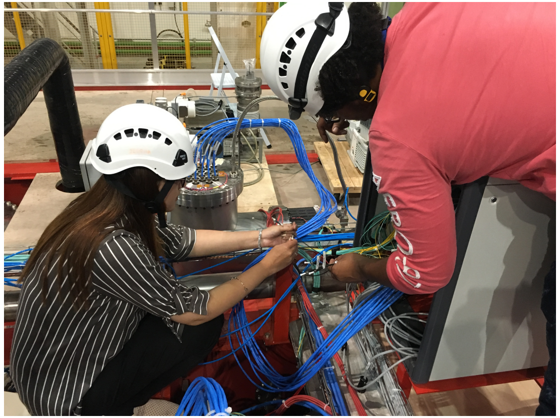


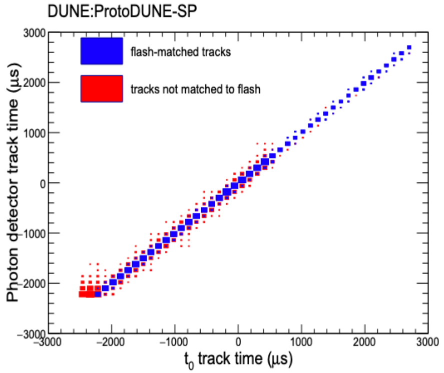
HARDWARE AND DETECTOR OPERATION EXPERIENCE AT PROTODUNE

Hardware piece of work

- Performed detector operation at CERN, Switzerland
  - Performed installation, operation and analysis of the data from ProtoDUNE photon detector readout and calibration systems
  - I served as photon detector lead at CERN
- Made significant contributions to timing studies for “First results from ProtoDUNE-SP” paper
  - Correlation of PDS and TPC timings
- In future, we are starting to combine light + charge

Photon calibration system installation on CERN neutrino platform

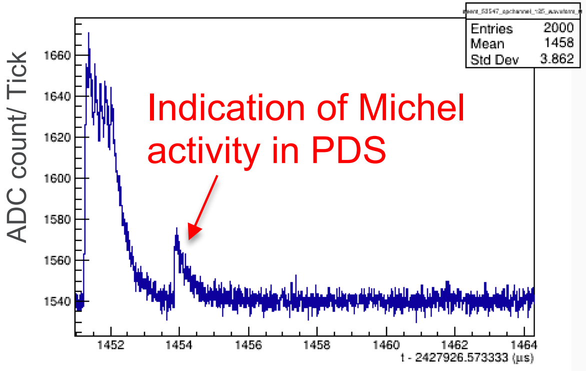




LIGHT + CHARGE COMBINATION STUDIES

- Goal is to achieve variation in visible energy to be <2% for DUNE sensitivity studies
  - Already proved that we can reconstruct and calibrate electrons using TPC information only
  - Now, I want to improve precision of lepton energy scale by using both TPC (charge) and PDS (light) measurements
- Took a first look at Michels in PDS by matching timing between TPC and PDS in ProtoDUNE
- My group started putting efforts for performing this study for beam electrons

Candidate Michel event in PDS

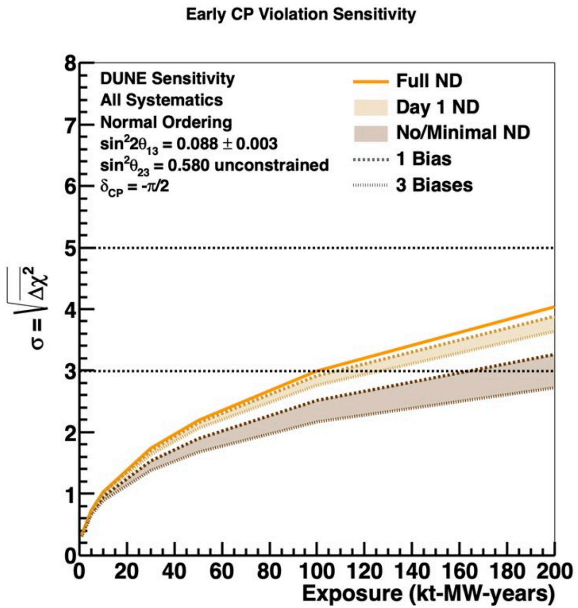


HADRONIC ENERGY MEASUREMENTS

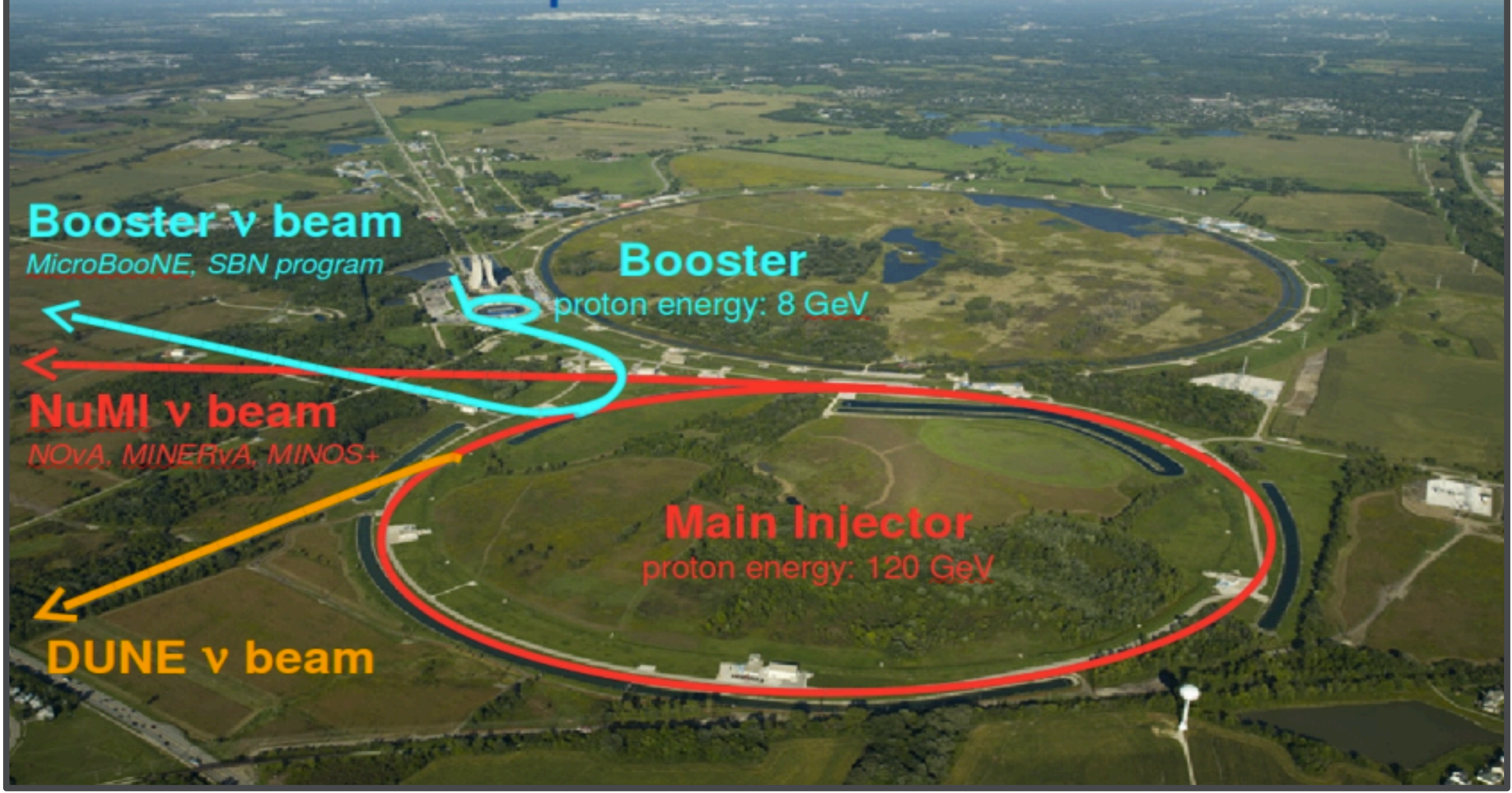
HADRONIC ENERGY MEASUREMENTS

- Both leptonic and hadronic measurements are needed to extract the accurate visible energy spectrum
- Hadronic measurements are important for the understanding of neutrino interaction measurements
  - Important to reduce neutrino model systematics that are currently dominant systematics for the neutrino oscillation studies
- Require to have an accurate estimate of the true neutrino energy scale in L Ar
- Expertise in neutrino-argon interaction measurements using MicroBooNE experiment
  - I will incorporate into the DUNE oscillation study

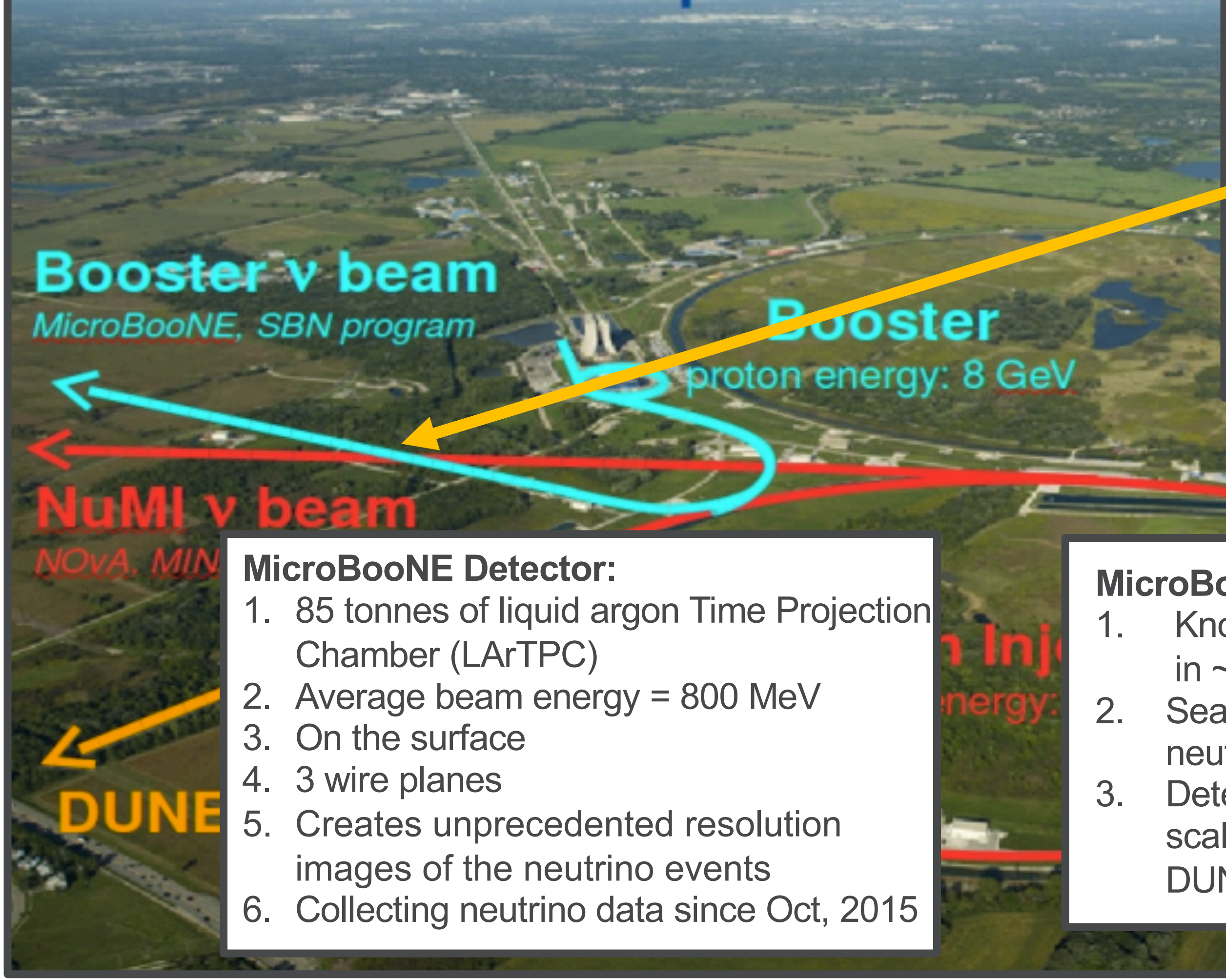
Early physics goal (~3 years) of 3σ sensitivity to maximal CPV can be reached with Day 1 ND

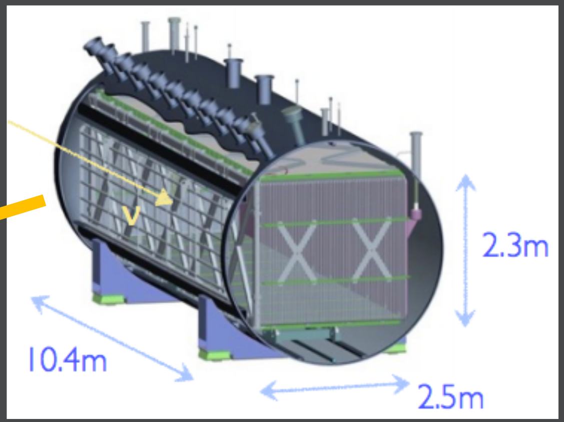


Fermilab Neutrino Experiments



Fermilab Neutrino Experiments





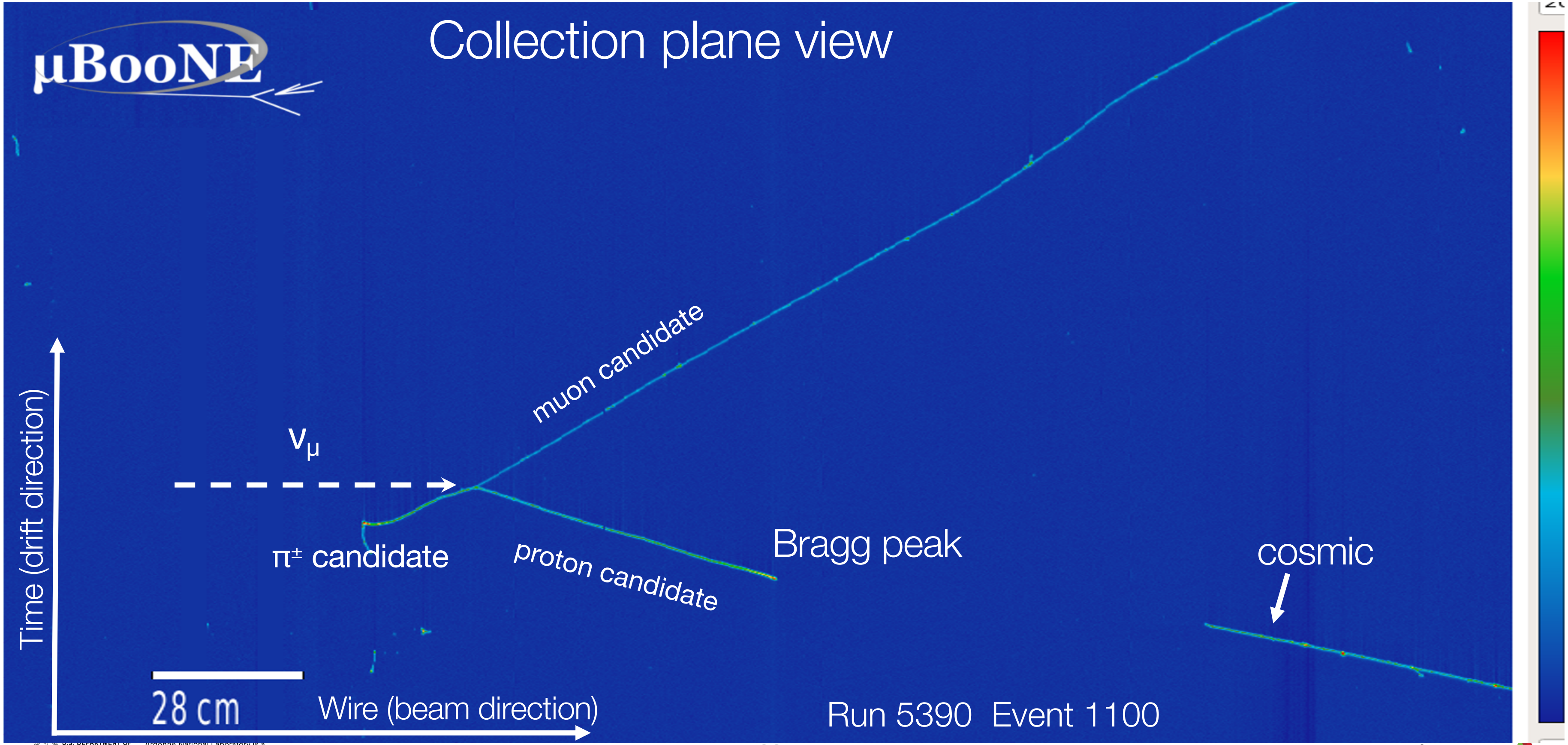
MicroBooNE Detector:

1. 85 tonnes of liquid argon Time Projection Chamber (LArTPC)
2. Average beam energy = 800 MeV
3. On the surface
4. 3 wire planes
5. Creates unprecedented resolution images of the neutrino events
6. Collecting neutrino data since Oct, 2015

MicroBooNE Physics Goals:

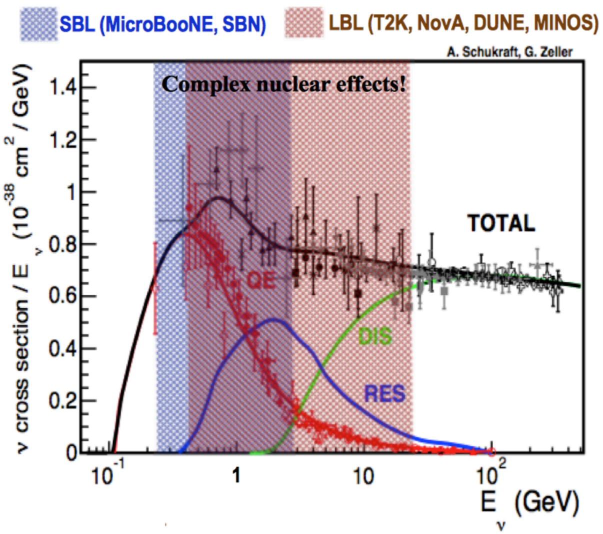
1. Knowledge of ν-Ar interactions in ~1 GeV range
2. Search for short baseline neutrino oscillations
3. Detector R&D for future large scale LArTPC detectors (e.g DUNE)

CANDIDATE NEUTRINO EVENT DISPLAY



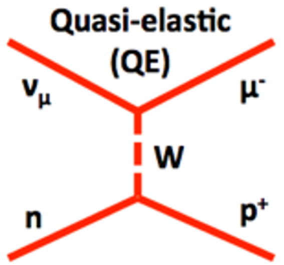
WHY STUDY NEUTRINO-ARGON INTERACTIONS

- Limited data is available on ν-Ar scattering
- Neutrino oscillation studies rely on correct modelling of the neutrino cross-section measurements
- Additional challenge is the understanding of the nuclear effects
- Great opportunity to use SBN measurements to inform DUNE oscillation studies



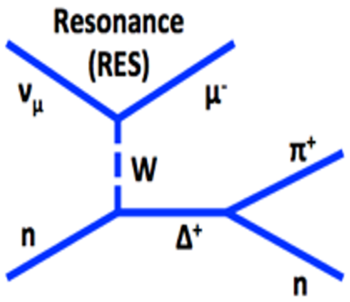
CHARGED CURRENT INTERACTIONS

Two charged particles



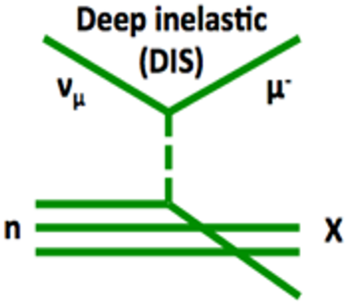
Scattering from Independent nucleon

Two/three charged particles



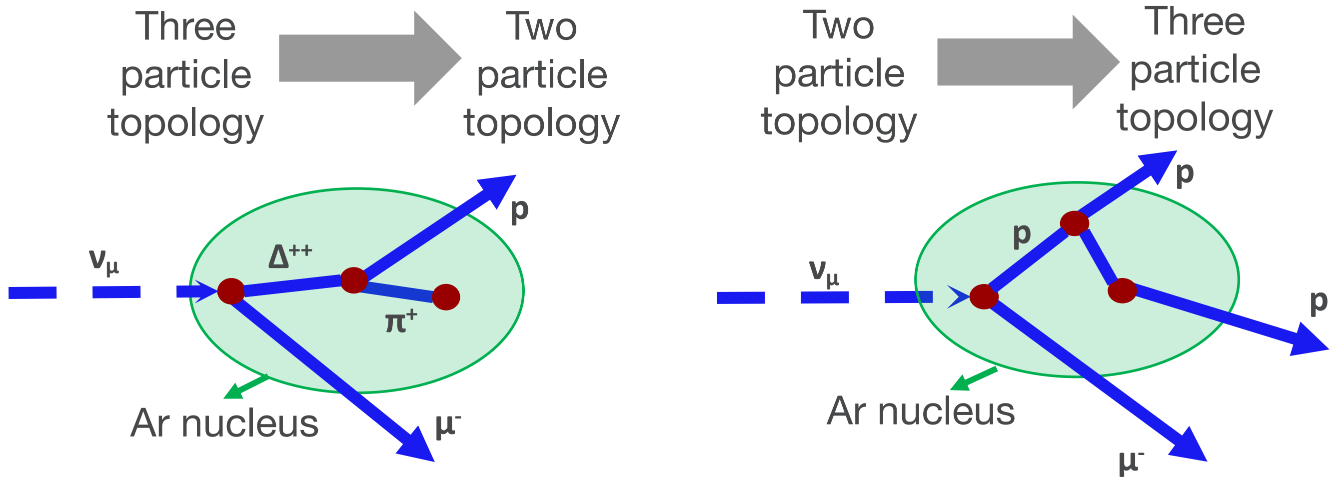
Inelastic scattering: Excites the nucleon

Many charged particles



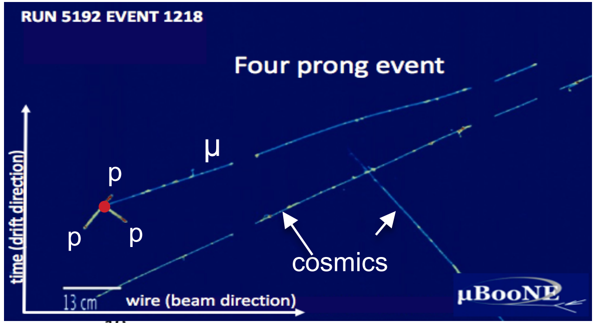
Scattering through quarks: Nucleon breaks up

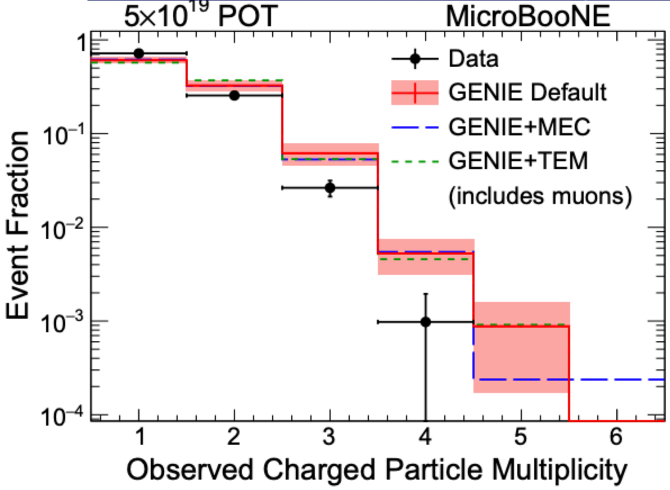
NUCLEAR EFFECTS



Argon is a complex nucleus in which final state interactions can change the final state topology of the interaction

CHARGED PARTICLE MULTIPLICITY MEASUREMENT





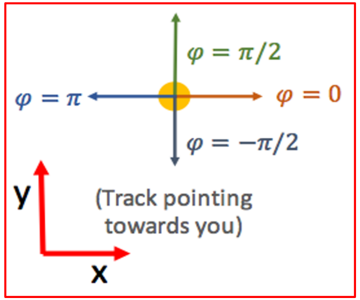
https://epjc.epj.org/articles/epjc/abs/2019/03/10052_2019_Article_6742/10052_2019_Article_6742.html

- **Analysis Goal:** Count the number of reconstructed charged particles exiting the target nuclei at the interaction point
  - Tagged $\mu^{\pm}$, $\pi^{\pm}$, and *p*
  - Kinetic energy thresholds: 69 MeV for *p* and 31 MeV for $\mu^{\pm}$/ $\pi^{\pm}$
- Selected candidate neutrino events
  - Used tools e.g sample generation, background rejection, event selection, reconstruction, and data analysis etc

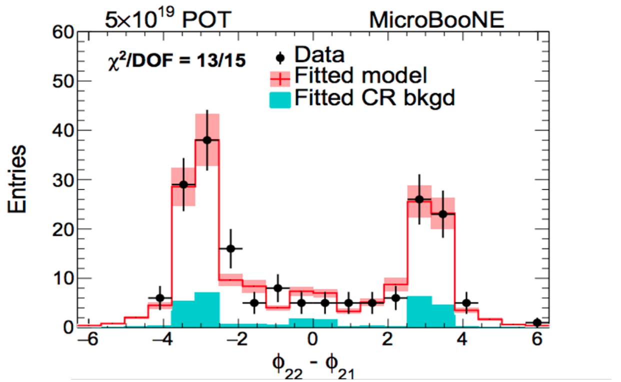
TESTS OF NEUTRINO INTERACTION MODELS USING MICROBOONE DETECTOR

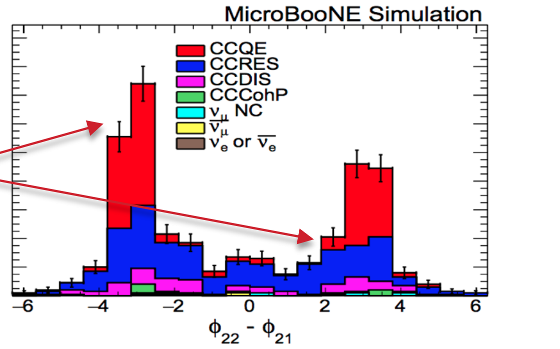
- Produced also a large set of kinematic plots
- Compared different neutrino models and plotted them against MicroBooNE data
- Produced the first neutrino beam-based result from MicroBooNE collaboration
  - https://news.fnal.gov/2018/05/microboone-measures-charged-particle-multiplicity-in-first-neutrino-beam-based-result/
- Need similar studies for DUNE systematics measurements

$\Phi_{short} - \Phi_{long}$ (multiplicity = 2)



Here an inclusive analysis gives a sense of exclusive final states

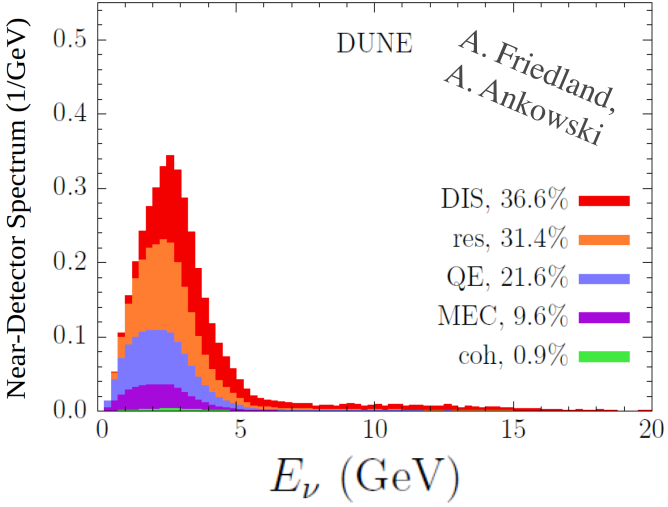




ACCURATE RECONSTRUCTION OF TRUE NEUTRINO ENERGY

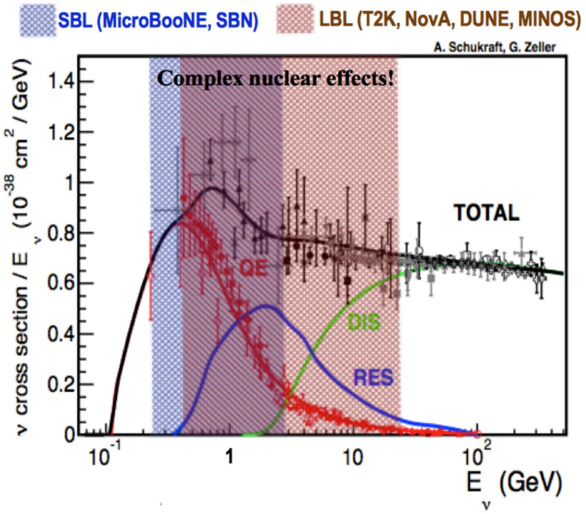
- DUNE goal is to achieve variation in both **true** and **visible** energies to be <2%
  - An accurate estimate of the true neutrino energy scale in L Ar relies on the measurement and modeling of neutrino interactions
  - Visible energy needs to be translated to the true energy using a cross-section model and Monte Carlo simulation.
- Plan to start working on SBN program and/or DUNE-ND
  - Can utilize NUMI beam in MicroBooNE and ICARUS to study and evaluate neutrino model systematics before DUNE starts

Relevant cross-section (based on current GENIE): ND Spectrum



MULTIPLICITY AND CROSS SECTION MEASUREMENTS USING DUNE-ND

- Plan is to measure charge particle multiplicity that can lead to the inclusive cross section measurement using SBN
  - My expertise from MicroBooNE will be utilized for event classification, simulation, and reconstruction
  - Test the cross-section models by comparing simulated data to neutrino interaction data from the SBN
  - Tune nuclear models to collected data with SBN
  - Incorporate the systematics into oscillation analysis
- Collaboration with BNL High Energy theory and Nuclear Theory groups will be valuable to pursue this study



SUMMARY

- I will focus on DUNE oscillation physics analysis
- Propose to work with BNL EDG group electronics readout and physics studies
- Interest and expertise in LArTPC operation, simulation, reconstruction and data analysis
- Extensive liquid argon software and hardware experience
  - Worked with all the LAr software tools for sample generation, reconstruction and analysis (MicroBooNE/ProtoDUNE/DUNE)
- Currently I am serving as EM shower working group convener in ProtoDUNE
  - Improving the leptonic energy scale for DUNE
- Focus on energy reconstruction with both leptons and hadrons
  - Both are required for the accurate neutrino energy reconstruction

THANK YOU FOR YOUR ATTENTION

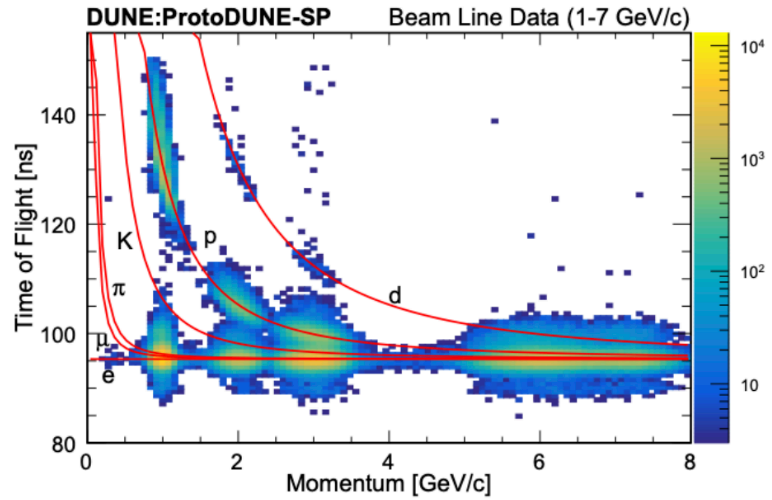
BACKUP SLIDES

GRANTS AND FUNDS

- Have experience on proposal writing and student mentoring from ANL
  - Presented at recent ANL DOE neutrino proposal review
  - Successfully recruited and mentored students
- Start-up package:
  - One postdoc
    - To perform the light and charge combination studies on ProtoDUNE
    - Photon calibration system studies for DUNE
    - To start on ND cross section analysis
    - Advance and complete DUNE-FD Michel analysis
  - M&S: travel, lab space, set-up calibration module test stand
- Plan to apply in Early career award (DOE), Career award (NSF?), Comparative review FOA, Project funds

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

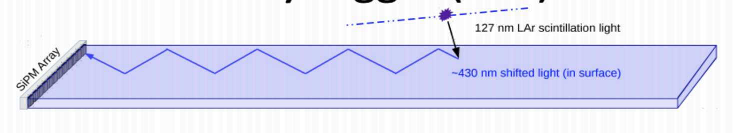


DUNE FD SP Prototype—Photon Detection System

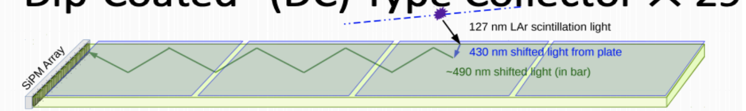
Testing new technologies!

ProtoDUNE-SP consists of:

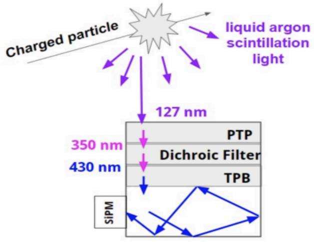
- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Photon Detection System (PDS)
- Cosmic-Ray Tagger (CRT)



”Dip-Coated” (DC) Type Collector × 29



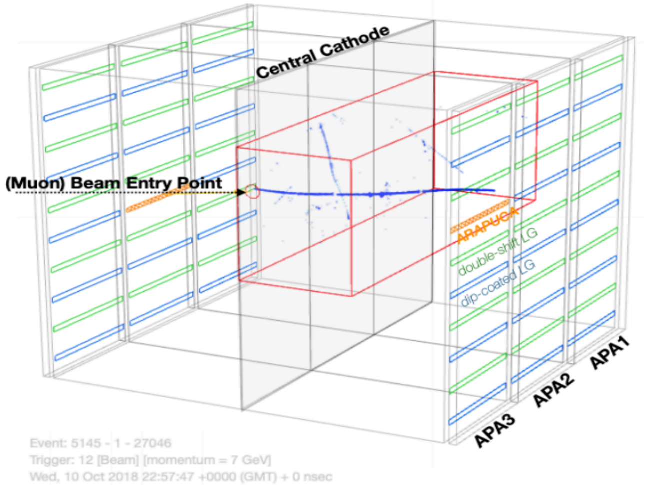
”Double-Shifted” (DS) Type Collector × 29



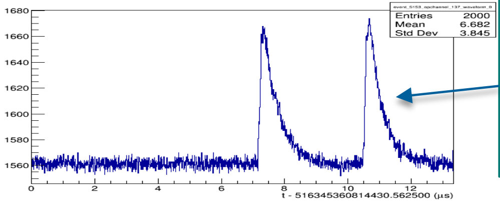
ARAPUCA Concept

Photon Detection System

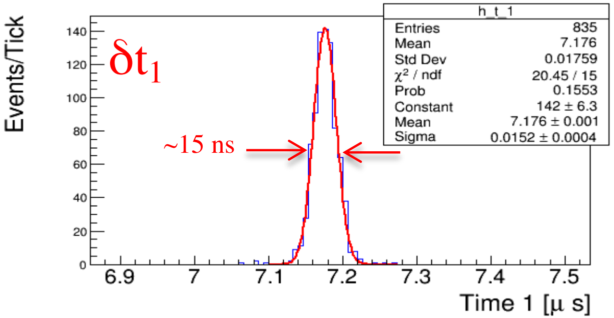
- Photon Detector Technology Demonstration
  - 60 Photon Detectors
  - 3 Photon Collector Technologies
    - 29 Dip Coated Light Guide Detectors
    - 29 Double Shift Light Guide Detectors
    - 2 S-ARAPUCAs
  - 2 Photon Sensors Manufactures
    - SensL & Hamamatsu

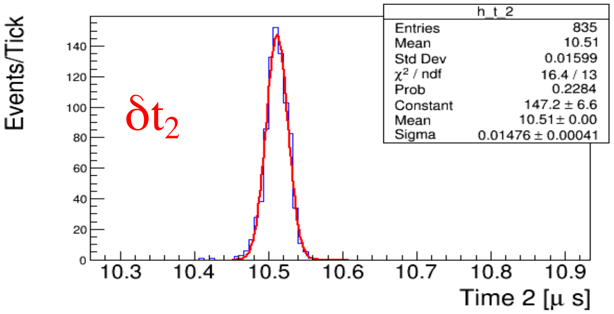


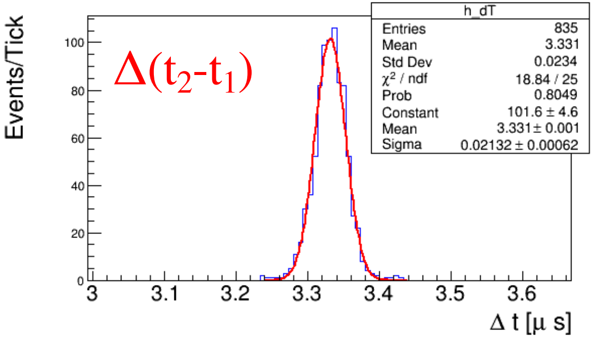
PHOTON DETECTOR CALIBRATION DATA ANALYSIS



Example of two waveforms (with double light pulses) recorded by photon readout system

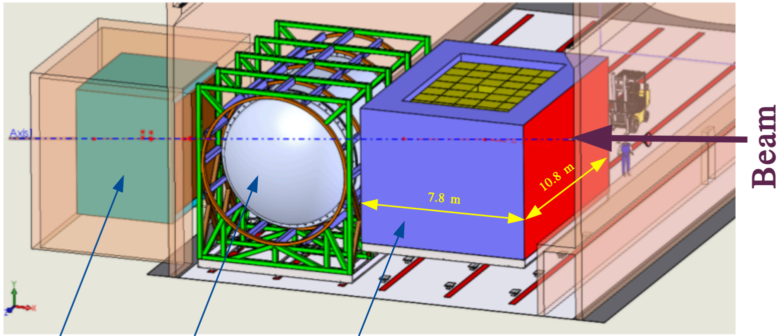






DUNE-ND DESIGN

DUNE-ND



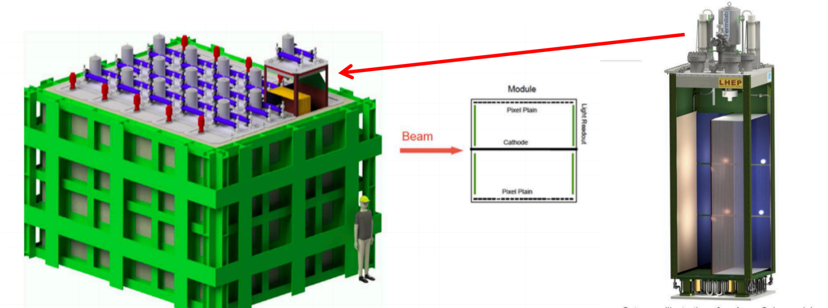
SAND Beam monitor

MPD

ArgonCUBE 5x7 modules

The LarTPC at the near side should be optically segmented, with a short drift space and 2-dimensional pixelated readout

- Modular structure (0.5m drift distance) to mitigate pile-up!
- ~30 tons of fiducial volume, complemented with muon chambers

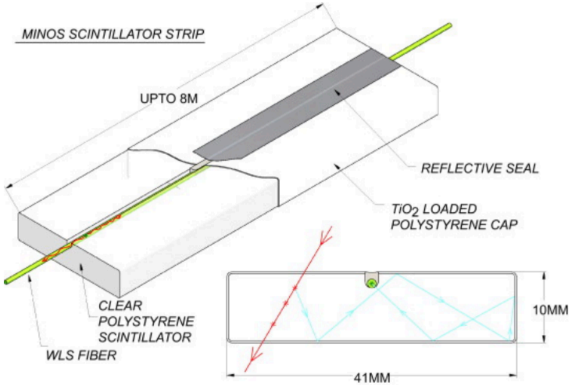


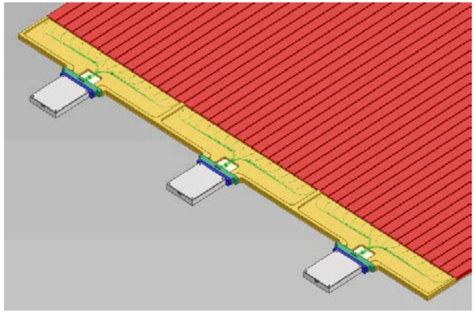
Cut-away illustration of an ArgonCube module

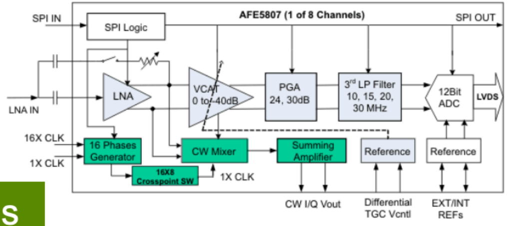
THOMAS J. LECOMPTE

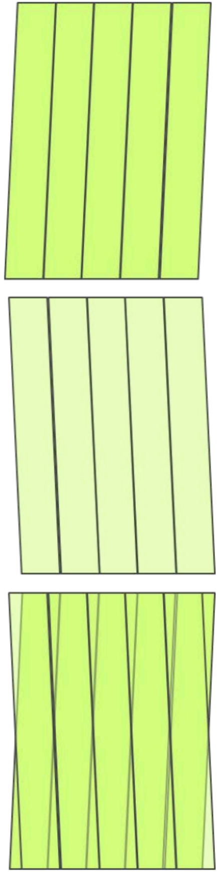
DETECTORS

- Design is MINOS/mu2e-like (co-extruded polystyrene)
- Each plane (of 100) has four panels (192 channels)
- Each panel is a self-contained box containing
  - 48 slats of scintillator 3.5 cm wide with Y11 wavelength-shifting fiber
  - SiPM, Front End-ADCs (based on Texas Instruments AFE5807 chip) and associated electronics
- Panels (which are rectangular) are tilted ±3° in alternating layers
  - Gets us ~45 cm resolution in y-direction
  - An inexpensive choice – but will be subject to pileup issues at 2.4 MW (Year 6).





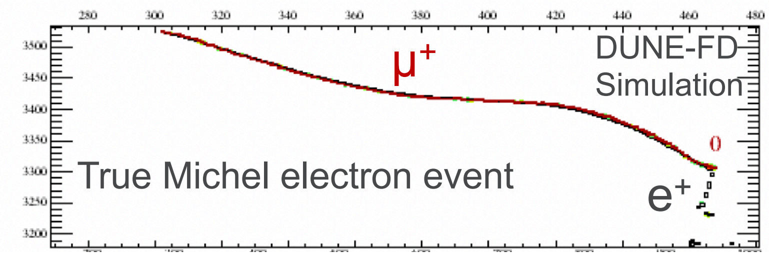


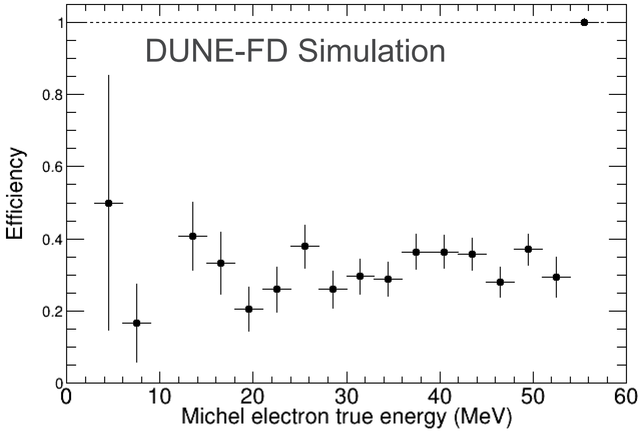


We could not do this without Argonne's EOF/SSS Divisions

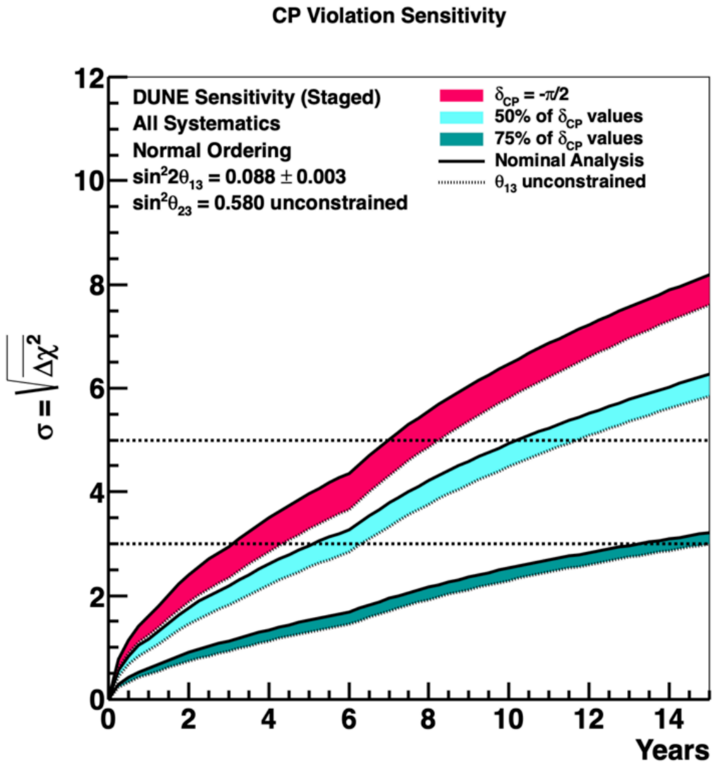
LOW-ENERGY ELECTRON STUDIES AT DUNE FAR DETECTOR

- 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





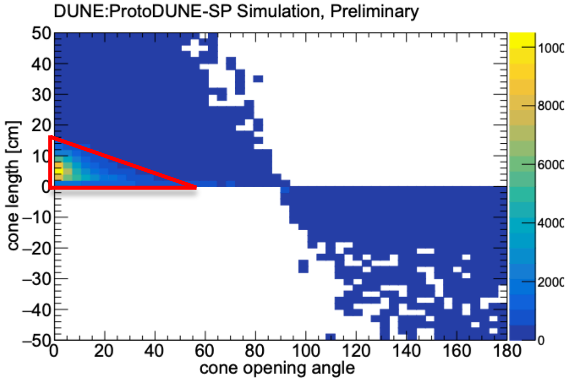
DUNE CP- VIOLATION SENSITIVITY



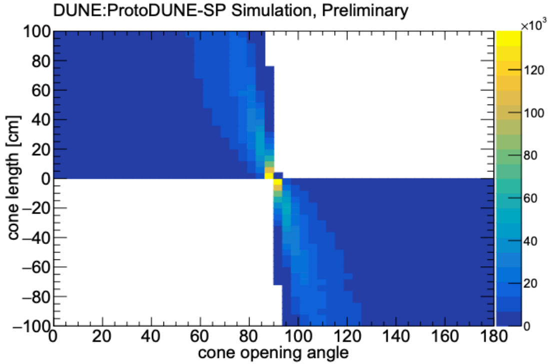
RECONSTRUCTION OF LOW-ENERGY ELECTRONS

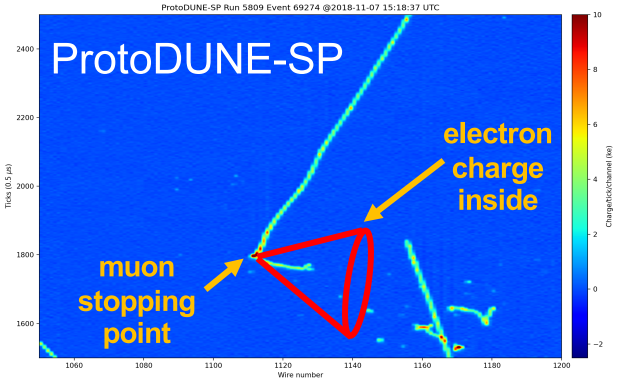
- Defined a cone at the end point of the parent muon
- All hits inside the cone are taken to be as candidate Michel hits based on simulation studies
- Selected, reconstructed and performed energy calibration for low energy electrons (Michels) in ProtoDUNE

True Michel reco hits



Other hits of the event

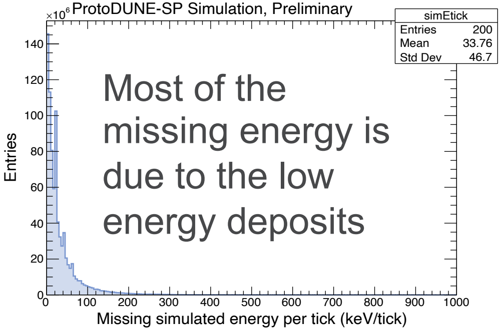


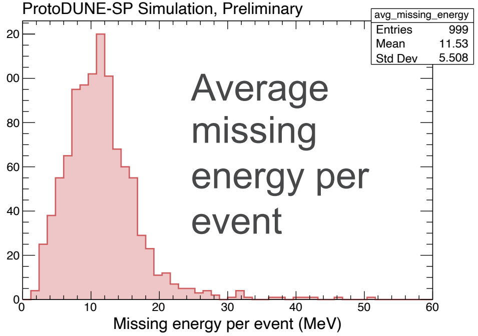


UNDERSTANDING THE ENERGY LOSS

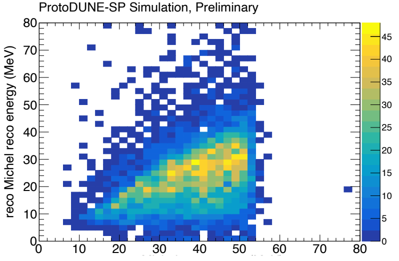
hit reconstruction threshold ~ 100 keV/tick

- Investigated the source of missing energy
  - Almost all missing energy is due to the hit reconstruction threshold.
- Compared energy resolution plots before and after the addition of the missing energy per event
- Energy resolution:
  - Before: δ(E)/E = 26% at 50 MeV
  - After: δ(E)/E = 18% at 50 MeV

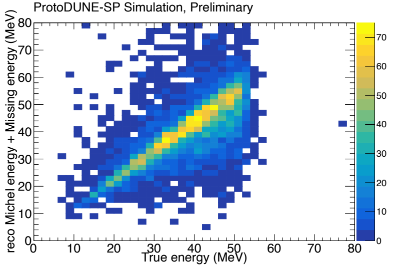


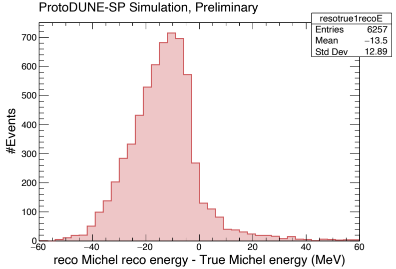


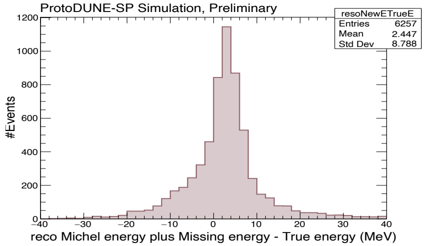
Before



After



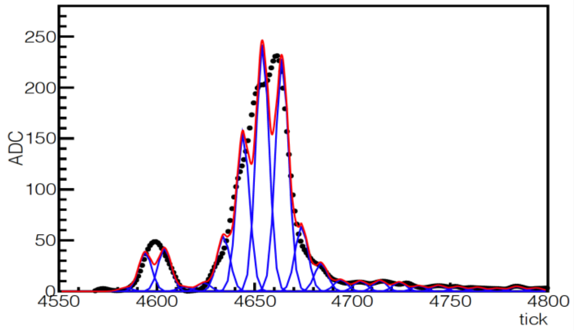




Calibration and Charge integration Procedure (cont.)

- Normalization and calibration constants for each data run.

Run	Normalisation	Calibration
5770	1.0962	$6.07 * 10^{-3}$
5771	1.0904	$6.00 * 10^{-3}$
5777	1.0695	$5.76 * 10^{-3}$
5786	1.0512	$5.58 * 10^{-3}$
5809	1.0384	$5.43 * 10^{-3}$
5815	1.0335	$5.37 * 10^{-3}$
5824	1.0272	$5.32 * 10^{-3}$
5826	1.0258	$5.30 * 10^{-3}$
5834	1.0235	$5.28 * 10^{-3}$



- Two methods of charge integration

➢ In the hit method Q_i is charge deposited in the i-th hit, with N being the total number of hits of the shower.

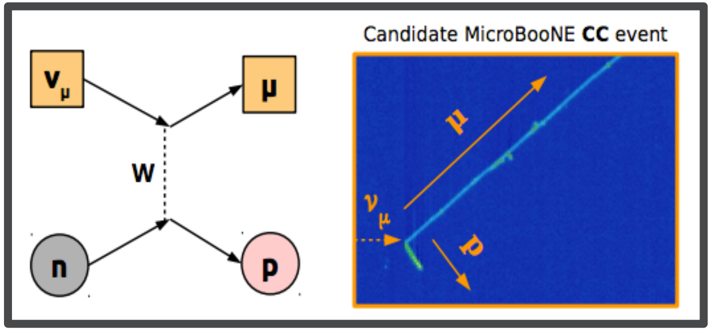
  -In the "hit" method a gaussian function fit is performed to integrate charge in so-called recob:hit object.

➢ In the wire integration method, dQ_i corresponds to the charge deposited in the i-th wire (integrated over potential multiple charge depositions), and N is the number of wires.

  -Rather than finding and summing up individual multiple hits one integrates a total charge in recob:wire object.

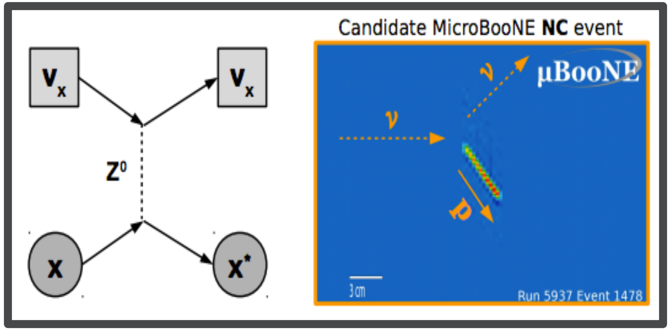
NEUTRINO INTERACTIONS

Charged Current Interactions

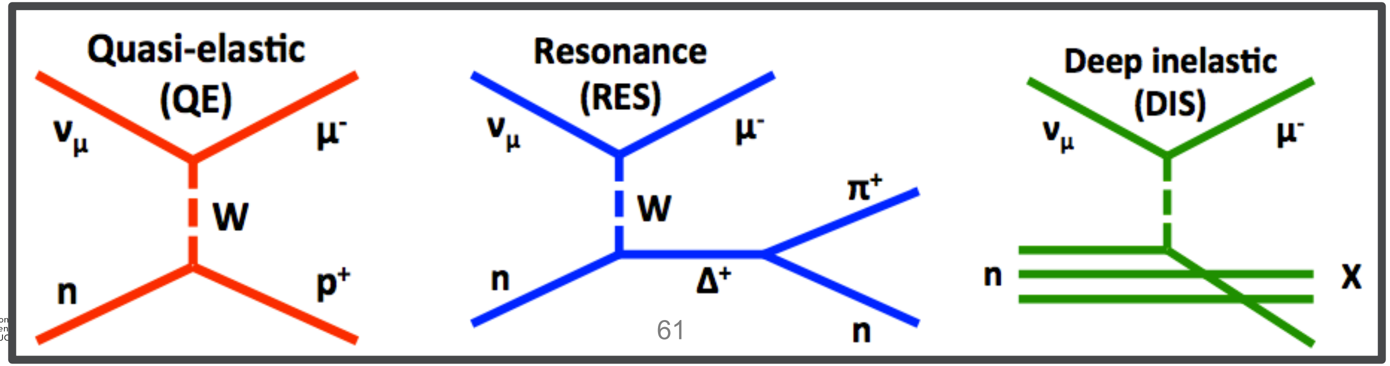


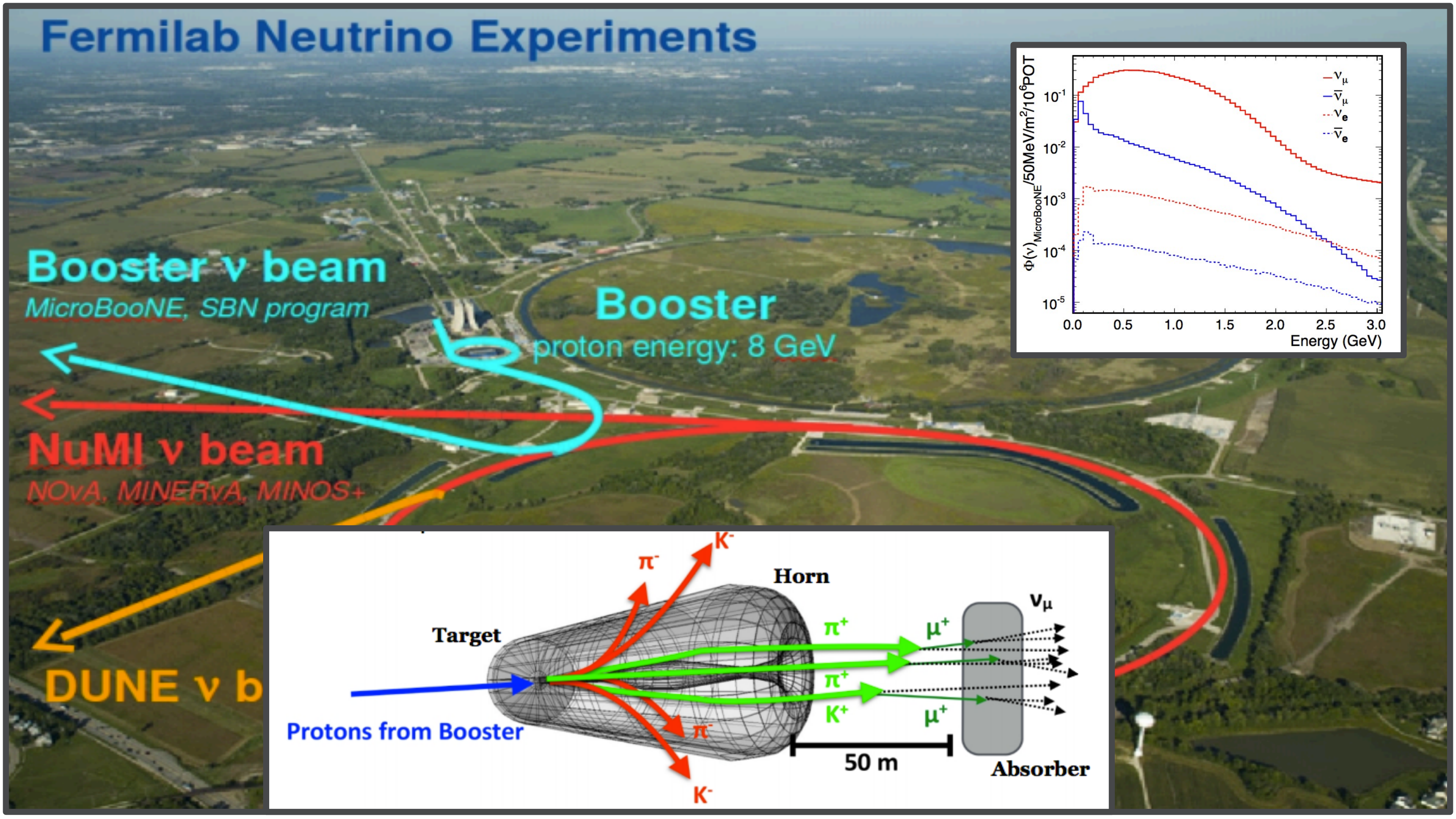
Gives information about neutrino flavor

Neutral Current Interactions



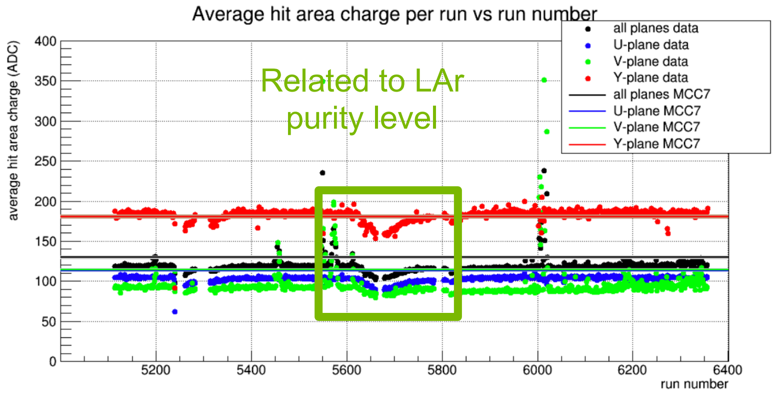
No information of neutrino flavor

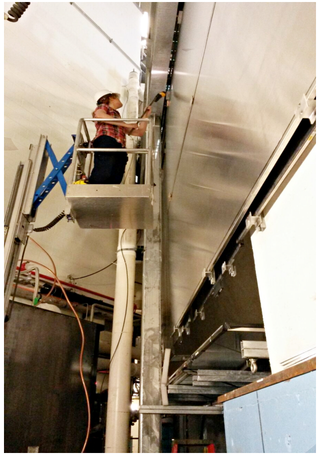



Fermilab Neutrino Experiments
Booster ν beam
MicroBooNE, SBN program
Booster
proton energy: 8 GeV
NuMI ν beam
NOvA, MINERvA, MINOS+
DUNE ν b
Φ(ν)_MicroBooNE/50MeV/m²/10⁶POT
Energy (GeV)
Horn
Target
Protons from Booster
50 m
Absorber

HARDWARE AND DETECTOR OPERATION EXPERIENCE AT MICROBOONE

- Event generation
- Event reconstruction performance
- Monte Carlo validation studies
- TPC noise studies
- Detector stability studies
  - My scripts are now a part of standard DQM tool in MicroBooNE
- Cosmic ray tagger (CRT) system installation studies

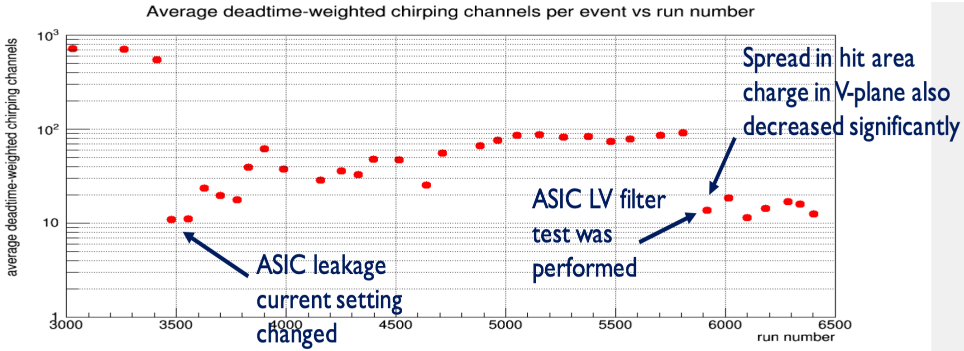


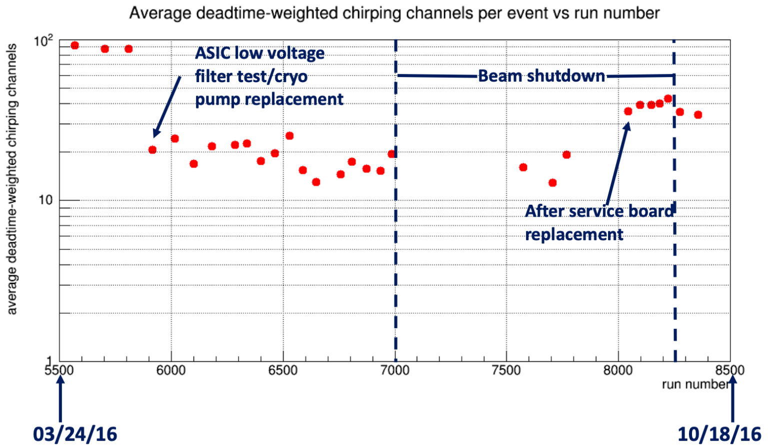


CRT system testing and installation

TPC NOISE STUDIES IN MICROBOONE

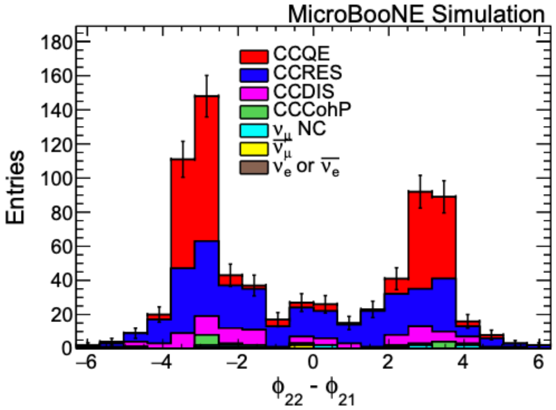
- Investigated the ASIC saturation rate
  - ASIC: application-specific integrated circuit
  - Plotted deadtime-weighted chirping channels per event by looking at the channels RMS
  - Found out the ASIC saturation rate changed when electronic work was performed.





PICKED OUT THE BEST NEUTRINO MODEL IN MICROBOONE

Found interesting features e.g a particular interaction behave in a certain way only (CCQE)



$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

		χ^2/DOF	
Distributions	**GENIE default**	**GENIE+MEC**	**GENIE+TEM**
L_{11}	19/14	22/14	13/14
L_{21}	4.0/9	4.6/9	7.3/9
L_{22}	10/7	8.4/7	16/7
L_{31}	4.5/6	3.4/6	5.5/6
L_{32}	5.8/5	3.9/6	6.5/6
L_{33}	0.1/3	0.7/3	0.5/3
$\cos\theta_{11}$	23/19	20/19	15/19
$\cos\theta_{21}$	14/14	24/14	22/14
$\cos\theta_{22}$	16/20	15/20	16/20
$\cos\theta_{31}$	6.0/7	4.2/7	9.2/7
$\cos\theta_{32}$	25/13	20/13	15/13
$\cos\theta_{33}$	15/11	13/11	17/11
$\sin\Theta_{11}$	24/20	21/20	25/20
$\sin\Theta_{21}$	6.4/7	3.6/7	6.3/7
$\sin\Theta_{22}$	2.4/7	3.4/7	2.4/6
$\sin\Theta_{31}$	4.3/5	6.0/5	9.1/5
$\sin\Theta_{32}$	2.1/4	2.5/4	1.6/4
$\sin\Theta_{33}$	8.5/6	7.0/5	9.5/6
$\phi_{22}-\phi_{21}$	13/15	12/15	14/15
$\phi_{32}-\phi_{31}$	10/13	9.2/13	10/14
$\phi_{33}-\phi_{31}$	15/12	13/12	8.7/11
$\phi_{32}-\phi_{33}$	11/14	11/14	11/14
$\cos\Omega_{221}$	19/20	13/20	13/20
$\cos\Omega_{321}$	14/13	13/13	17/13
$\cos\Omega_{331}$	21/14	16/14	12/14
$\cos\Omega_{323}$	12/15	18/15	19/15
Total χ^2/DOF	**228.1/216**	**216.9/216**	**229.6/216**

Cross Section Extraction

Event selection in data sample

Cosmic related background subtraction

Beam related MC background subtraction

Detection efficiency correction

events in beam-on data

events in beam-off data

beam related MC background

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_n} = \frac{N_n^{\mathrm{on}} - N_n^{\mathrm{off}} - B_n}{\epsilon_n \cdot \Phi_\nu \cdot N_{\mathrm{target}} \cdot \Delta_n^p}$$

Constants

effective detection efficiency

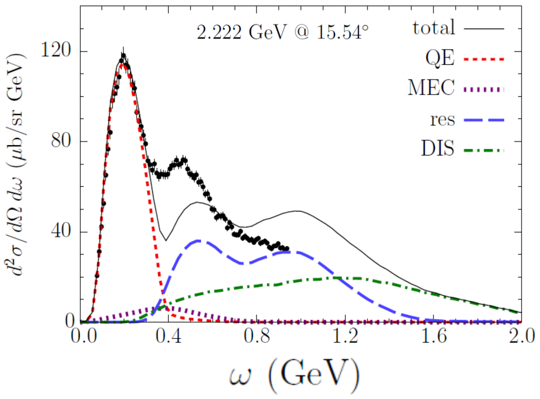
integrated neutrino flux

Number of targets

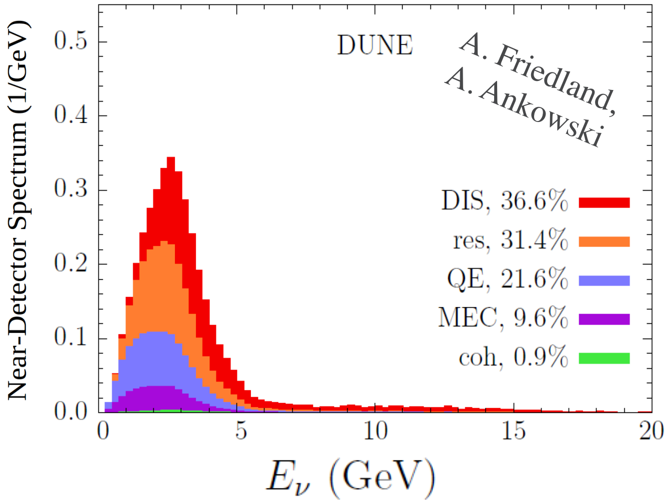
Bin width

CROSS SECTION MEASUREMENTS

GENIE "validated" with e-Ar scattering data: discrepancies of up to ~50%.



Relevant cross-section (based on current GENIE): ND Spectrum



WORK PLAN FOR CROSS SECTION MEASUREMNT

- Use ND to measure MEC contribution to the neutrino spectrum
  - Use BNL computing resources for simulation and AI/ML expertise could be used for neutrino event classification
  - Utilize expertise in event selection and energy reconstruction
- Use BNL HET and NT group to tune nuclear models to collected data with ND
  - Compare nuclear theory models to neutrino and electron-scattering data in similar kinematic regions
- The corrections to neutrino cross-sections will be applied to both Near and Far detector data to reconstruct neutrino energy scale