Improving ProtoDUNE Pion cross-section measurements with NuGraph Michel-electron tagging

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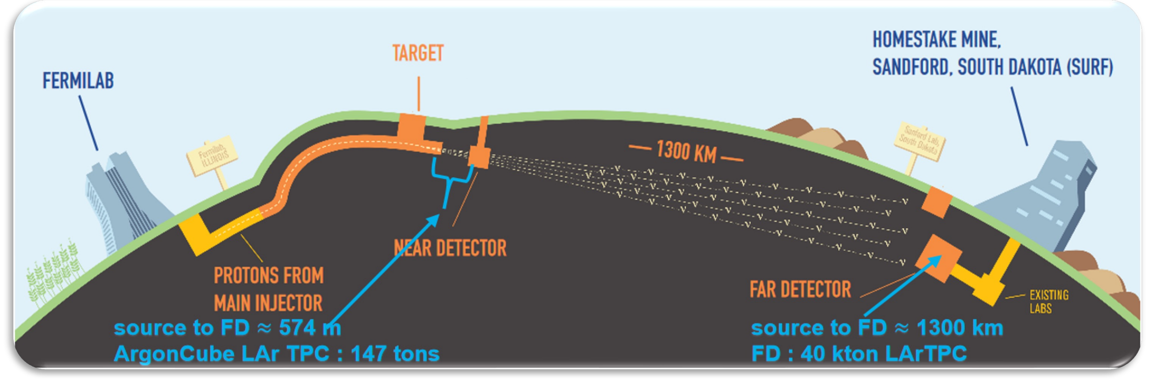
DEEP UNDERGROUND NEUTRINO EXPERIMENT

FERMILAB-POSTER-26-0082-LBNF

University of CINCINNATI

U.S. DEPARTMENT OF ENERGY | Office of Science

1 DUNE Experiment



- LBL experiment with a baseline of 1300 km (Fermilab to South Dakota)
- Uses a ν_μ beam provided by the LBNF Facility (with ~1% ν_e contamination).

DUNE PRIMARY PHYSICS GOALS :

- Measurements of the charge parity (CP) phase.
- Determination of the neutrino mass ordering(the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$)
- Measurement of the mixing angle θ_{23} and the determination of the octant in which it lies.
- Search for Physics Beyond the Standard Model.

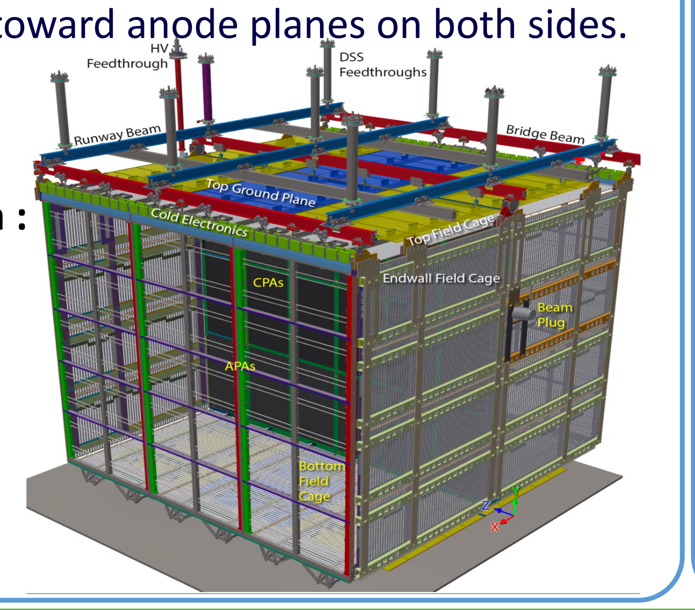
2 Detector Design

ProtoDUNE - SP

A large single-phase LArTPC prototype for DUNE at CERN, with a 7.2 m × 6.1 m × 7.0 m active volume and about 770 tons of liquid argon. Ionization electrons drift horizontally for 3.6 m from the central cathode toward anode planes on both sides.

ProtoDUNE-SP 2GeV data :

Fall 2018

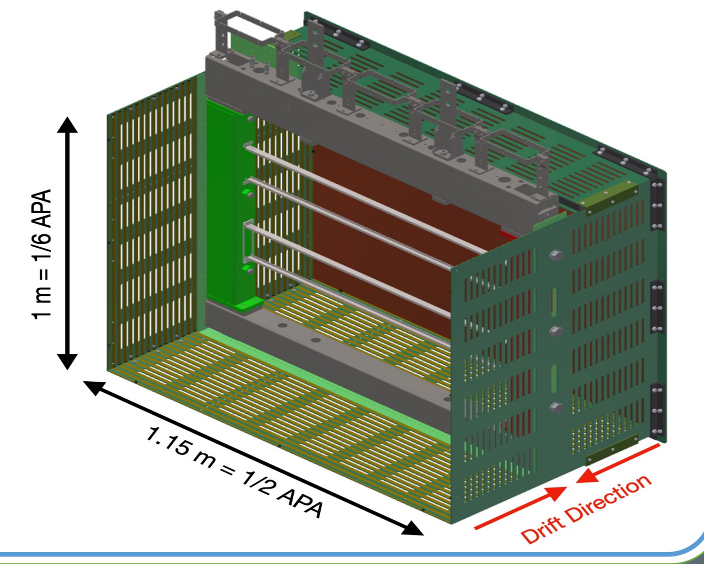


ICEBERG

A small LArTPC test stand at Fermilab used to test DUNE electronics, reconstruction, and calibration tools. In this analysis, ICEBERG Run 9 data are used to benchmark NuGraph3 particle identification before applying the method to ProtoDUNE-SP.

ICEBERG data Run 9 :

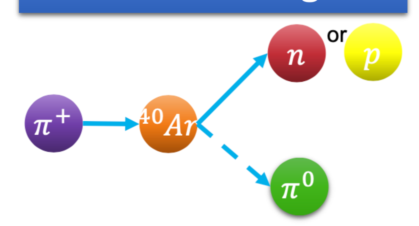
May 2024



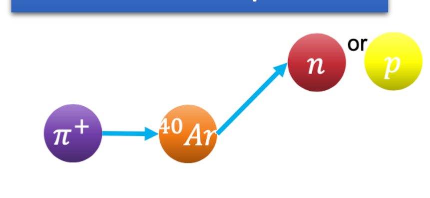
3 Objectives of the analysis

- Measure Pion absorption and charge-exchange differential cross sections for the 2 GeV/c ProtoDUNE-SP pion sample.
- **Evaluate NuGraph3 particle identification for ProtoDUNE-SP** with a focused study on **Michel-electron tagging**:
  - Provides an additional handle for distinguishing pion decay-like activity from hadronic interaction topologies.
  - Supports low-energy electromagnetic reconstruction and calibration studies in LArTPC detectors.

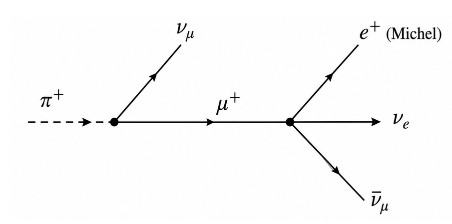
Pion Exchange



Pion Absorption

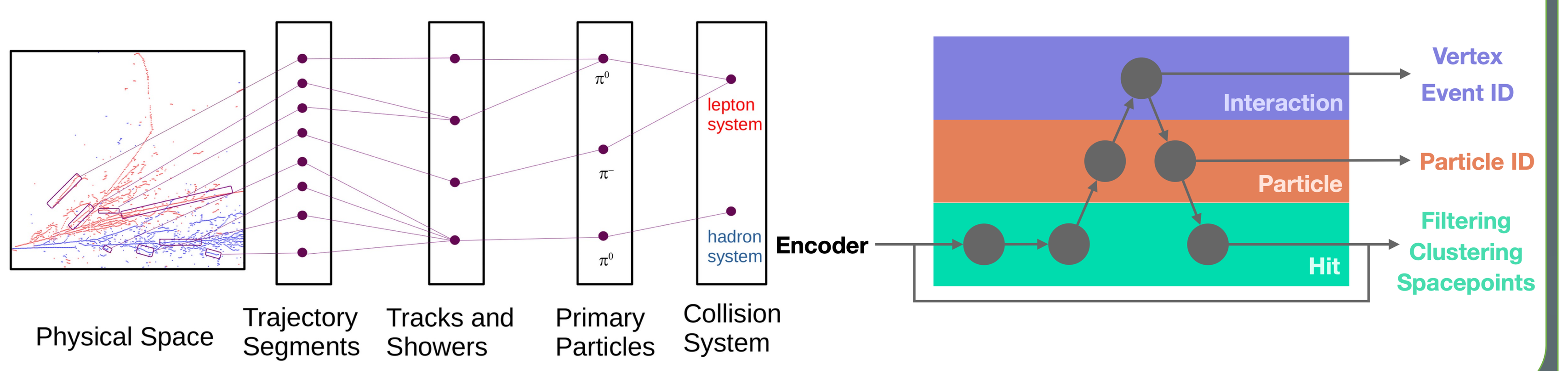


Pion decay background



4 NuGraph3 particle-flow reconstruction

- **NuGraph3:**
  - GNN-based particle-flow reconstruction framework for LArTPC events.
  - Represents detector hits as a graph, where nodes are connected using spatial and detector relationships.
  - Uses hierarchical message passing to combine local hit information with higher-level event context.
- In this analysis, NuGraph3 is used for particle identification in ProtoDUNE-SP, with a focus on Michel-electron tagging using a dedicated **Michel-electron filter decoder**.



5 Preliminary classification performance

ICEBERG – Training sample: stopping muons

(Efficiency) $\text{Recall} = \frac{\text{TT}}{\text{TT}+\text{TF}}$

True label \ Assigned label	pion	muon	kaon	hadron	shower	michel	diffuse
diffuse	0.0012	0.36	0	0.0046	0.22	0.022	0.39
michel	0.0036	0.14	0	0.0026	0.063	0.71	0.081
shower	0.0055	0.097	0	0.007	0.79	0.0088	0.091
hadron	0.075	0.23	0	0.58	0.073	0.019	0.023
kaon	0	0	0	0	0	0	0
muon	0.00087	0.94	0	0.0016	0.018	0.0037	0.036
pion	0.13	0.38	0	0.23	0.18	0.03	0.055

(Purity) $\text{Precision} = \frac{\text{TT}}{\text{TT}+\text{FT}}$

True label \ Assigned label	pion	muon	kaon	hadron	shower	michel	diffuse
diffuse	0.014	0.0075	0	0.021	0.06	0.024	0.15
michel	0.039	0.0028	0	0.011	0.016	0.74	0.03
shower	0.2	0.0064	0	0.1	0.68	0.03	0.11
hadron	0.14	0.00081	0	0.43	0.0033	0.0034	0.0015
kaon	0	0	0	0	0	0	0
muon	0.5	0.98	0	0.36	0.24	0.2	0.7
pion	0.11	0.00057	0	0.077	0.0035	0.0024	0.0015

ProtoDUNE – Training sample: ProtoDUNE-SP 2GeV samples

(Efficiency) $\text{Recall} = \frac{\text{TT}}{\text{TT}+\text{TF}}$

True label \ Assigned label	pion	muon	kaon	hadron	shower	michel	diffuse
diffuse	0.0013	0.12	0	0.0039	0.22	0.017	0.64
michel	0.0049	0.14	0	0.002	0.16	0.48	0.22
shower	0.0032	0.072	0	0.0017	0.72	0.015	0.19
hadron	0.084	0.22	0	0.64	0.03	0.0052	0.02
kaon	0.33	0.26	0	0.35	0.041	0.01	0.0063
muon	0.0049	0.94	0	0.0025	0.024	0.0057	0.022
pion	0.59	0.28	0	0.062	0.052	0.0096	0.012

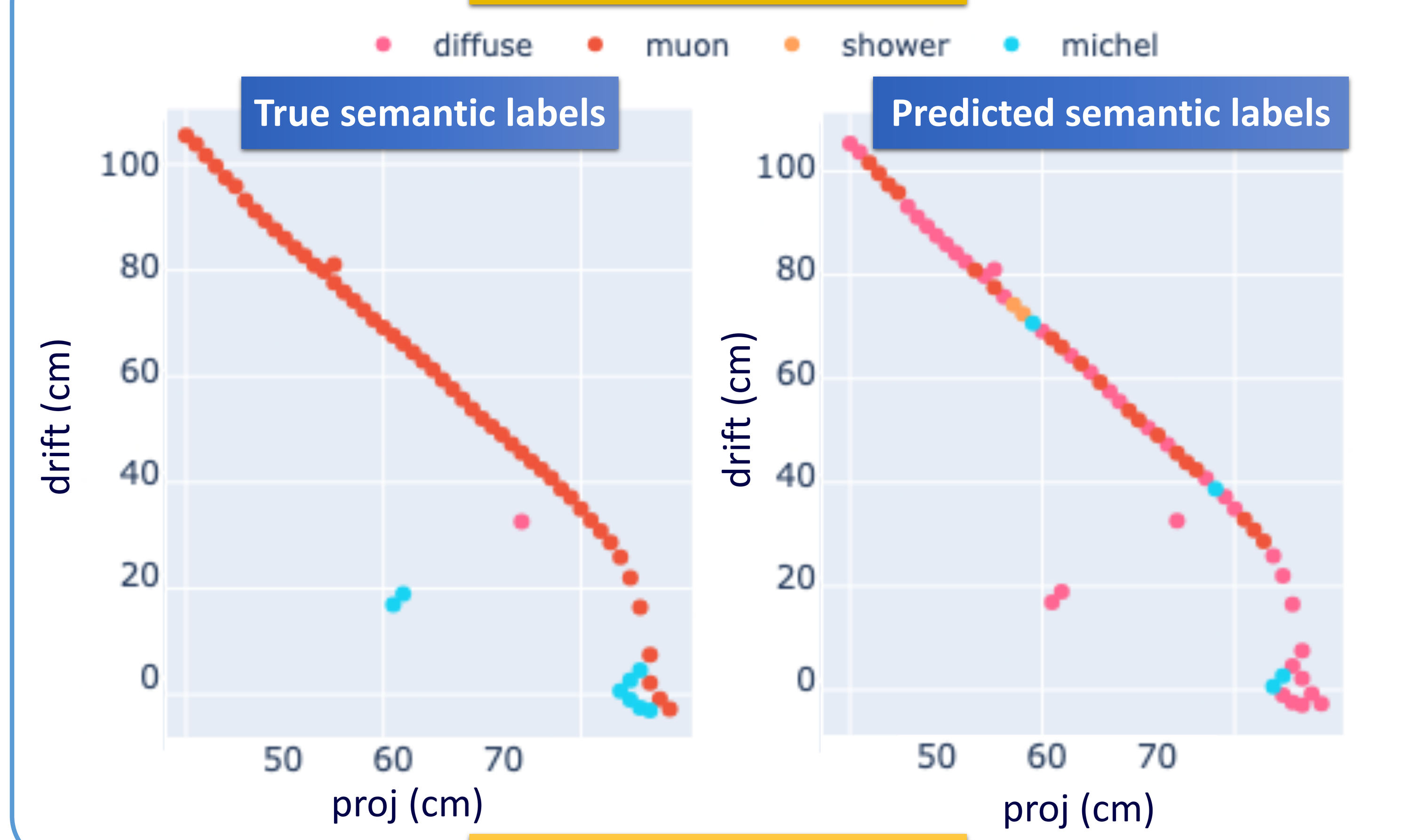
(Purity) $\text{Precision} = \frac{\text{TT}}{\text{TT}+\text{FT}}$

True label \ Assigned label	pion	muon	kaon	hadron	shower	michel	diffuse
diffuse	0.0072	0.0071	0	0.025	0.13	0.08	0.49
michel	0.0041	0.0013	0	0.002	0.014	0.34	0.026
shower	0.023	0.0058	0	0.015	0.59	0.096	0.19
hadron	0.066	0.0019	0	0.61	0.0026	0.0035	0.0022
kaon	0.0029	2.6e-05	0	0.0038	4.2e-05	7.8e-05	7.9e-06
muon	0.47	0.98	0	0.29	0.25	0.47	0.29
pion	0.43	0.0022	0	0.055	0.0042	0.0061	0.0013

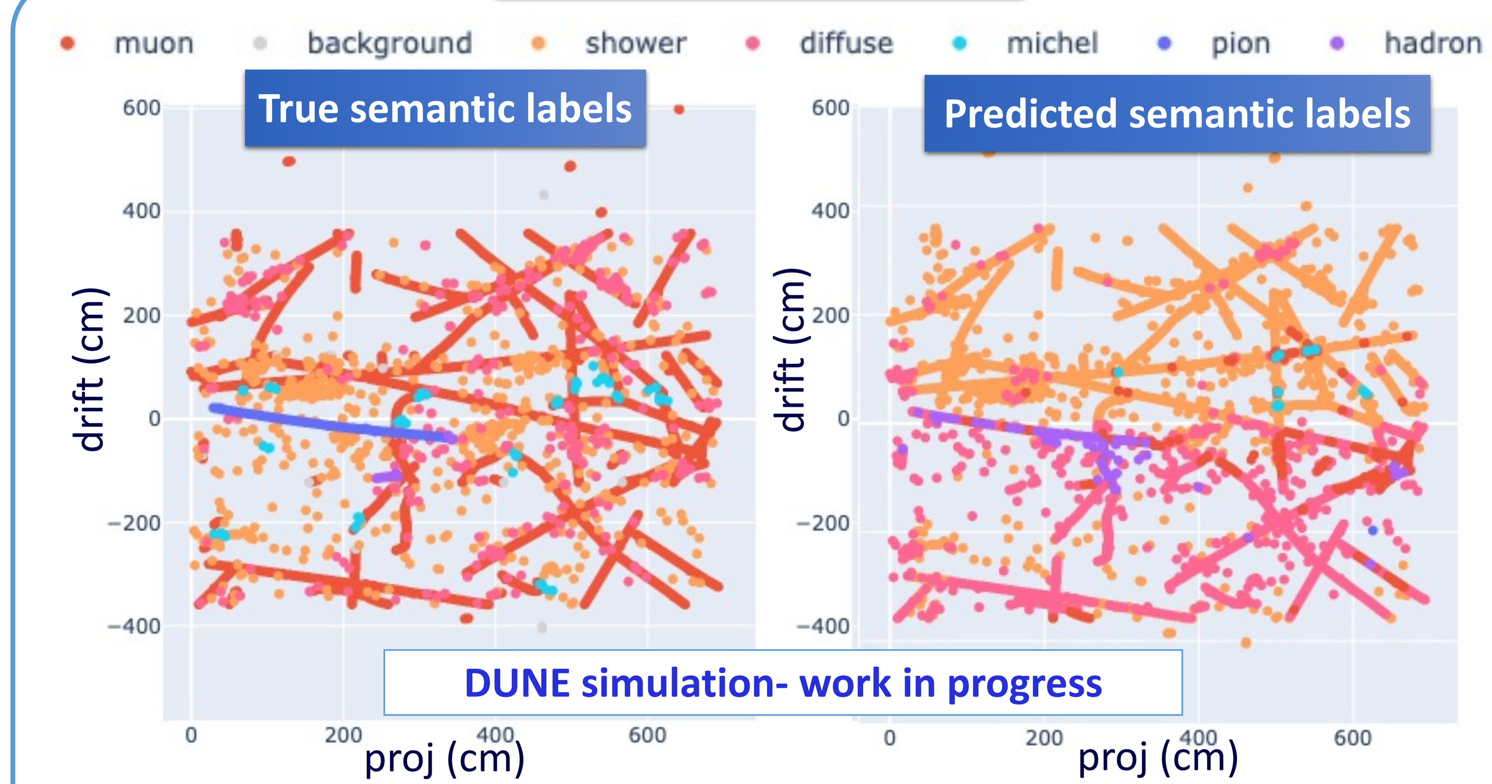
➢ ICEBERG shows clearer Michel tagging, while ProtoDUNE-SP exhibits stronger class confusion due to complex event activity and limited Michel-electron statistics.

6 Event displays

ICEBERG



ProtoDUNE-SP



$\text{proj} = z \sin\theta_z - y\cos\theta_z$

- x, y, z = coordinates of the wire center
- θ_z = wire angle in the yz-plane

$\text{drift} = x - s_{\text{drift}} L_{\text{drift}}$

- $s_{\text{drift}} = \pm 1$ is the TPC drift sign
- L_{drift} = drift distance

7 Conclusion

- NuGraph3 shows promising Michel-electron tagging performance in the ICEBERG stopping-muon sample, where the event topology is relatively clean, especially with the use of a dedicated Michel-electron filter decoder.
- Applying the same strategy to ProtoDUNE-SP is more challenging due to complex hit activity, overlapping low-energy deposits, and class imbalance from the small number of true Michel-electron examples in the sample.
- Further optimization is currently being explored to improve NuGraph3 Michel-electron classification for ProtoDUNE and address the class-imbalance effects.

Acknowledgements

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