End-to-End, Machine-Learning-Based Event Reconstruction and Detector Calibration in ICARUS

on behalf of the ICARUS collaboration

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SLAC
Oct 29, 2025

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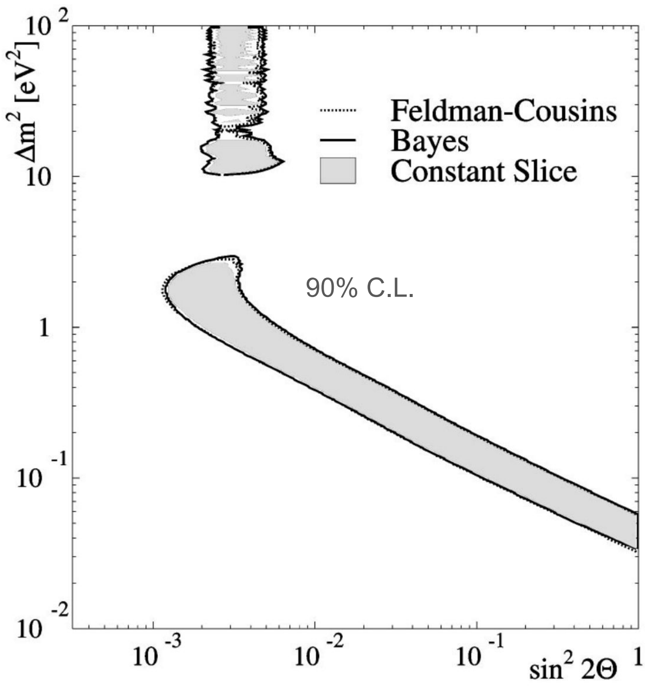
Imaging Cosmic And Rare Underground Signals

LSND, MiniBooNE, and MicroBooNE

PhysRevD.64.112007

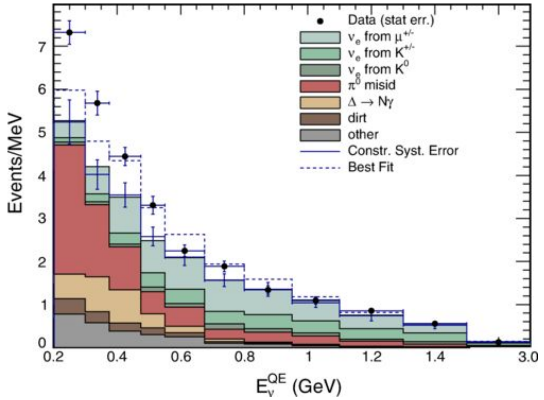


Liquid Scintillator Neutrino Detector (LSND) [1992-1998]

- 30 m from muon antineutrino beam target
- Observed electron antineutrinos 5-times greater than the expected beam intrinsic background
- Inspired a series of experiments to test the **non-standard neutrino oscillation**

LSND, **MiniBooNE, and MicroBooNE**

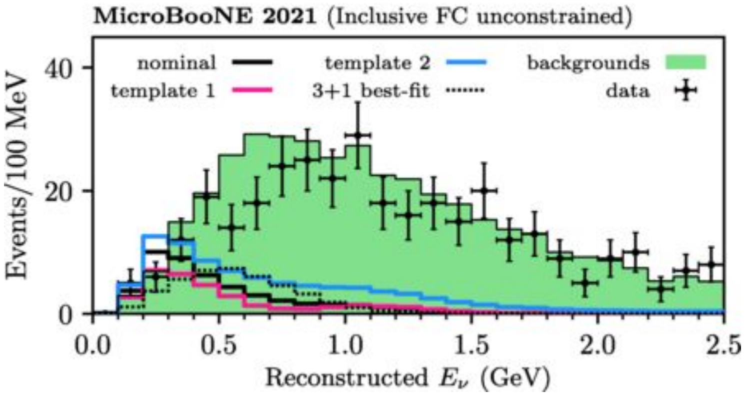
PhysRevD.103.052002



MiniBooNE [2002-2017]

- Mineral oil cherenkov detector placed in Fermilab Booster Neutrino Beam (BNB), 541 m from the beam target, searching for both $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ channels.
- Reported a 4.8σ excess of CCQE ν_e events across the energy range of 200-1250 MeV.
- One possible signal contamination is $\pi^0 \rightarrow \gamma\gamma$

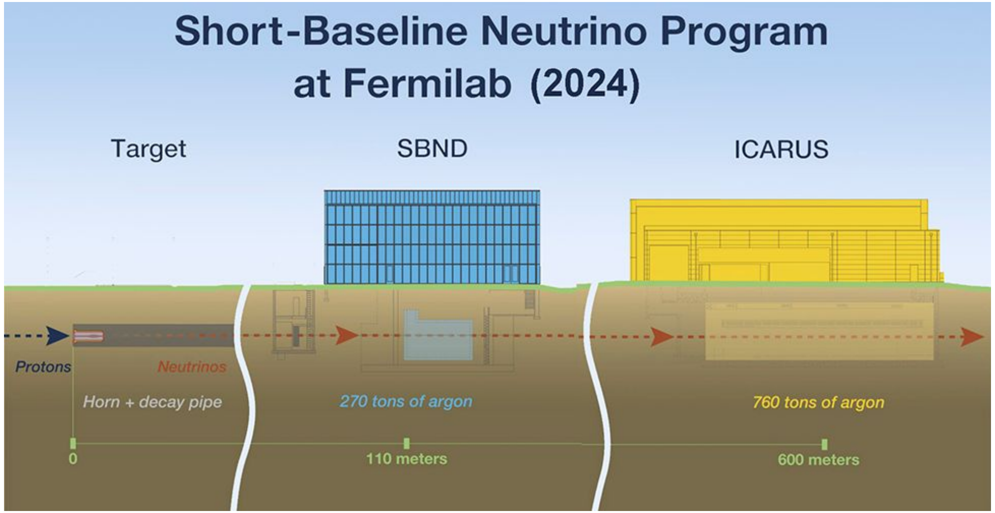
PhysRevLett.128.241802



MicroBooNE [2013-2023]

- Liquid Argon Time Projection Chamber (LArTPC) at BNB, 470 m from the beam target.
- Found no low energy CCQE ν_e excess, however the nature of MiniBooNE excess remained inconclusive.

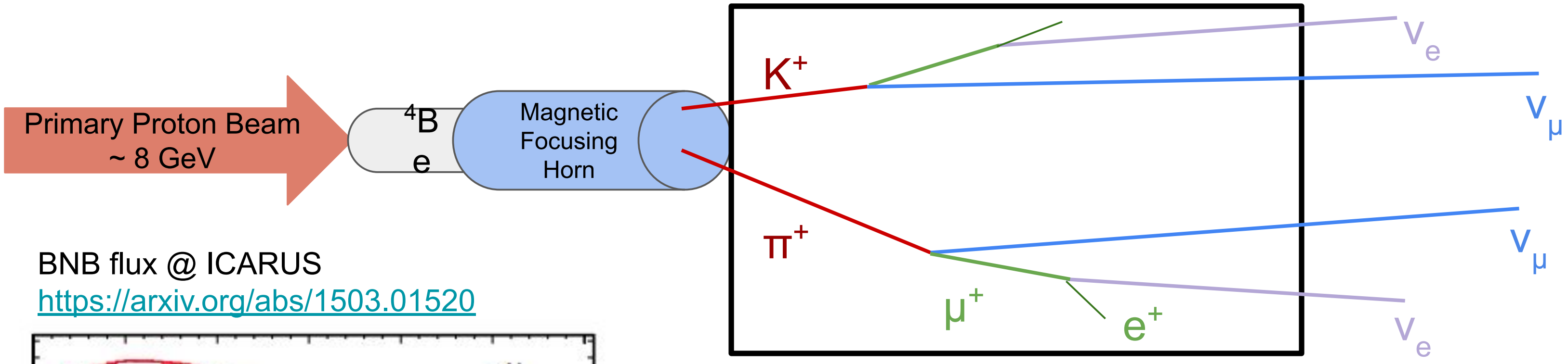
The Short Baseline Neutrino (SBN) Program



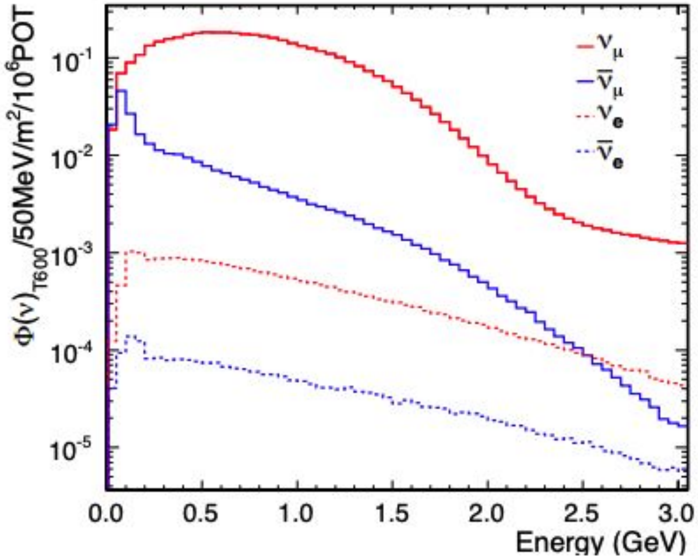
SBN [2021 ~]

- Situated in the BNB beamline, consists of the Short Baseline Near Detector (SBND) at 110 m and ICARUS detector at 600 m. Both detectors are LArTPC.
- Aims to address the LSND anomaly with the “near-far detectors” technique and simultaneous fit for appearance and disappearance channels.

BNB Beam Flux @ ICARUS

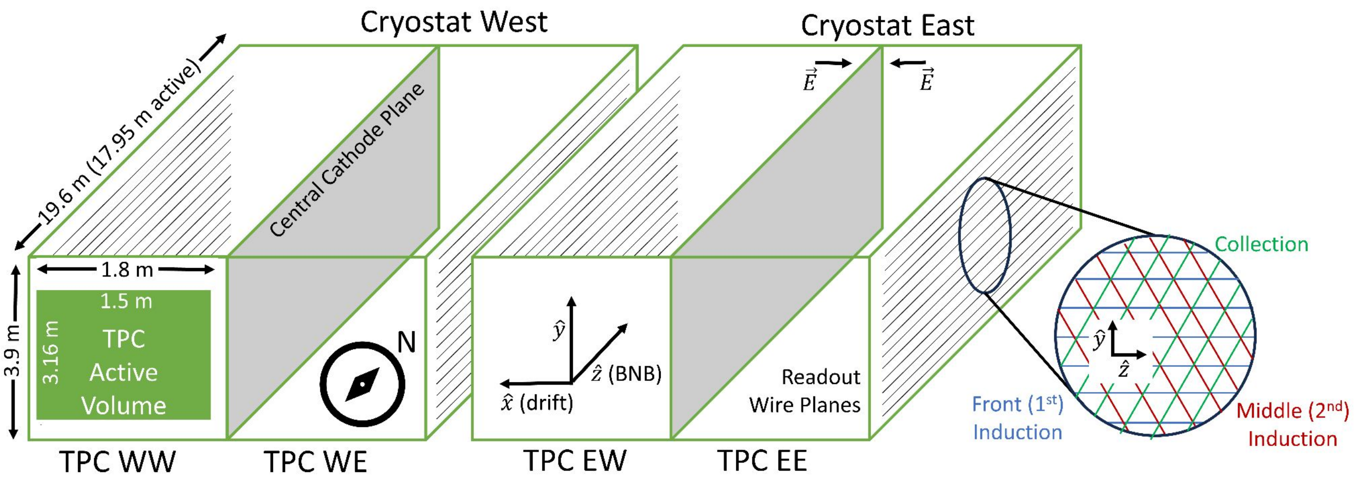


BNB flux @ ICARUS
https://arxiv.org/abs/1503.01520



- Intrinsic electron (anti)neutrino background exists in the beam
- Efficient and accurate ν_e signal selection is critical for SBN oscillation analysis - see more on the selection in D. Carber and D. Totani's talks

The ICARUS Detector and Data Taking

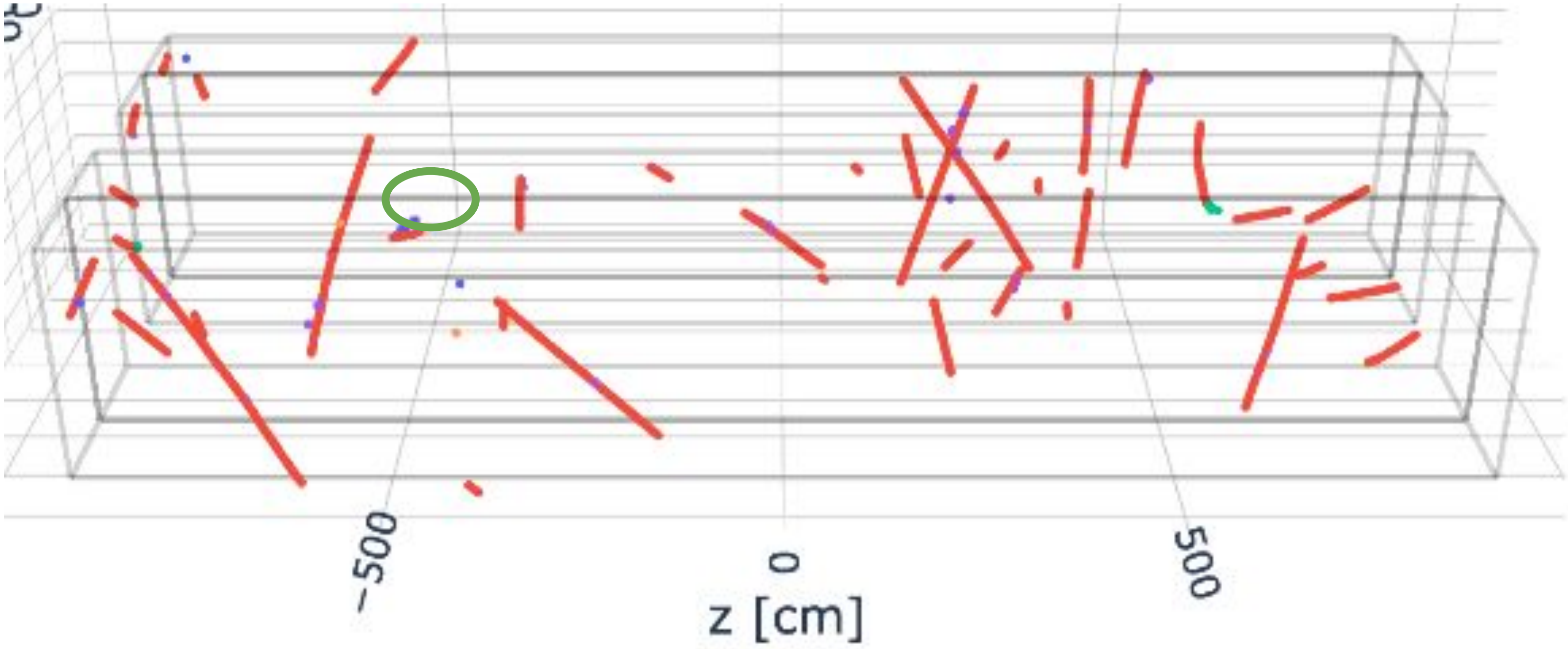


- Wire LArTPC at surface-level, 500 tons fiducial mass.

- Max drift time is **1 ms** at the nominal field (500 V/cm)
  - BNB beam: **~0.03 Hz** neutrinos
  - In-time cosmic activity: **~0.25 Hz**

ICARUS Event display - Can you find the neutrino interaction?

ICARUS MC



Optical Readout in ICARUS

LAr has a large scintillation light yield at O(10k) per MeV

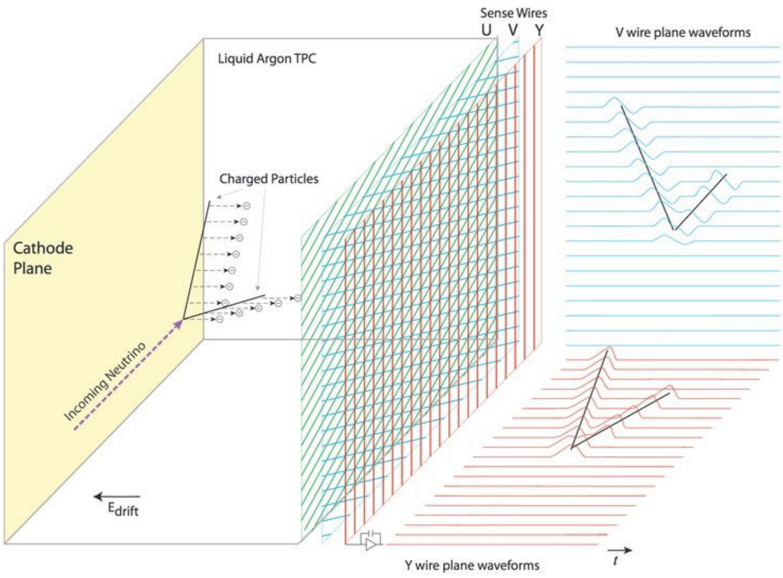
- LAr is transparent to its scintillation photons
- Fast component 4~8 ns
- Slow component 1.5~1.6 μs

360 PMTs behind the wire plane register optical information called “flash”

Require a **coincidence within 1.6 μs for the charge and optical readouts** to select neutrino interactions inside the detector.

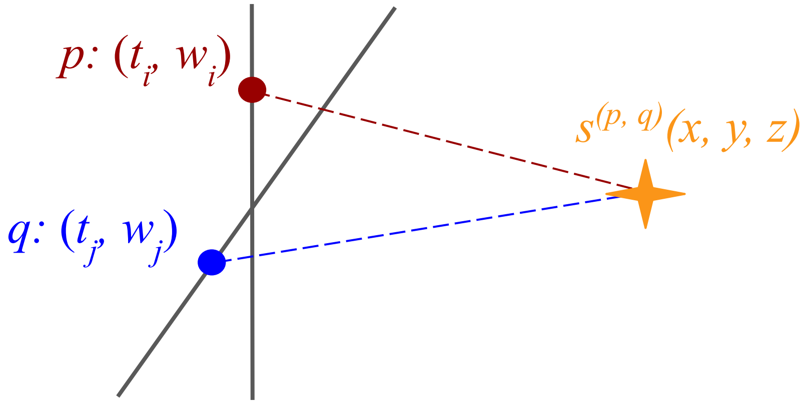
Charge Readout in ICARUS - How Does A Wire LArTPC Work?

arxiv.org/abs/1704.02927



- 3 wire planes oriented at different angles register the drifting charges at anode.
  - First two planes have negative voltage applied and register the inductive charge signals
  - The third plane collects charges
  - Each pair of 2 planes forms a projection view of the 3D particle trajectories
- 3 mm wire pitches in ICARUS helps achieving O(1) mm spatial resolution

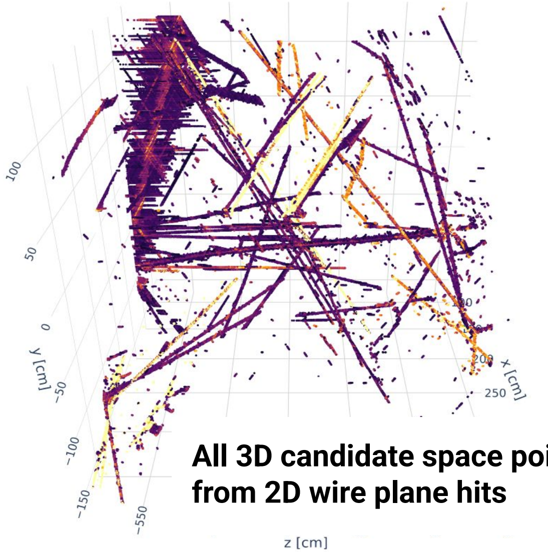
Charge Readout in ICARUS - Forming 3D Spacepoints



A wire hit on the wire plane p is defined by the hit time and wire ID

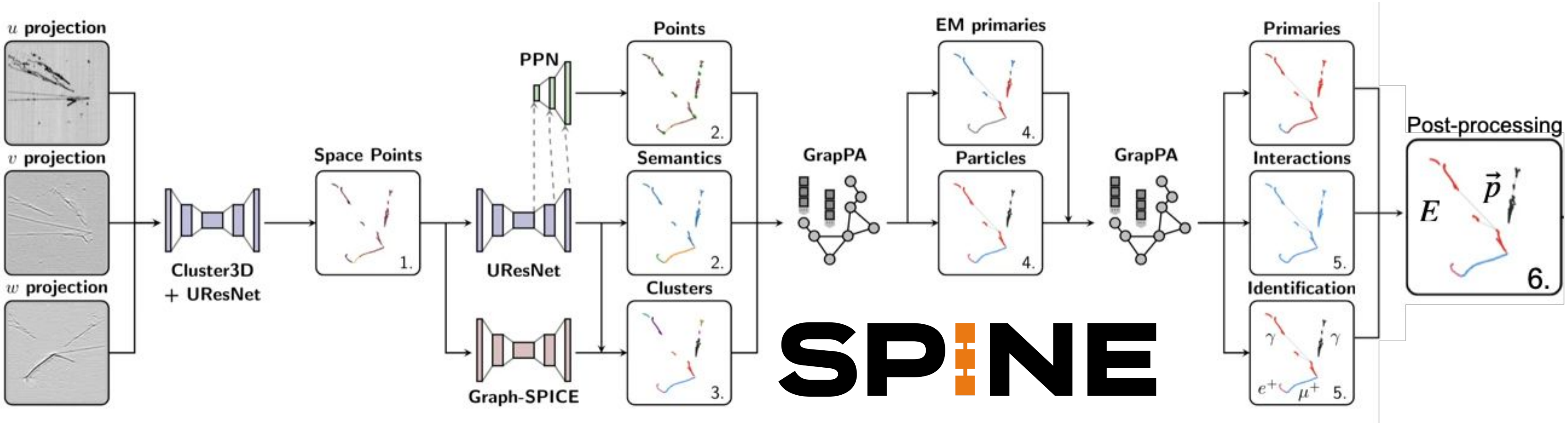
The 2 hits from different wire planes (p&q) that have a hit time coincidence are used to reconstruct a 3D spacepoint.

Since this is the very first step in event reconstruction, the algorithm (*Cluster3D*) is prioritized to maximize the efficiency while leave the spurious spacepoints “ghosts” to be removed in the downstream process.



All 3D candidate space points from 2D wire plane hits

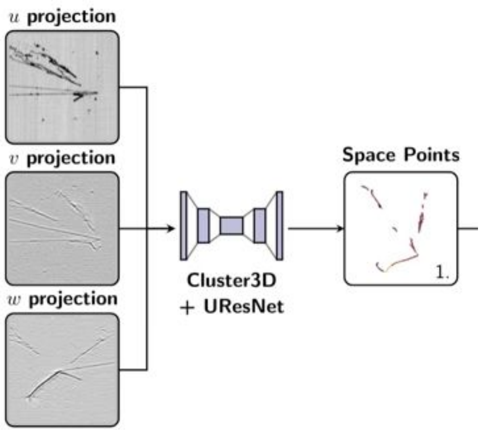
Scalable Particle Imaging with Neural Embeddings (SPINE)

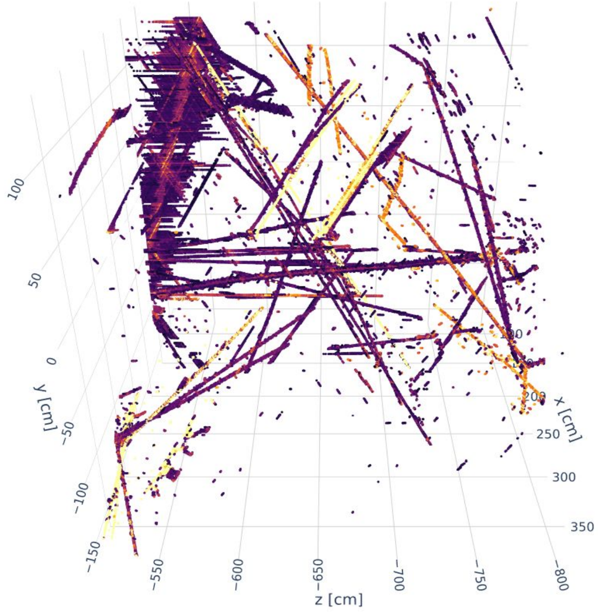


Paper: https://arxiv.org/abs/2102.01033
Github: https://github.com/DeepLearnPhysics/spine

More details in
F. Drielsma's talk

Deghosting with SPINE





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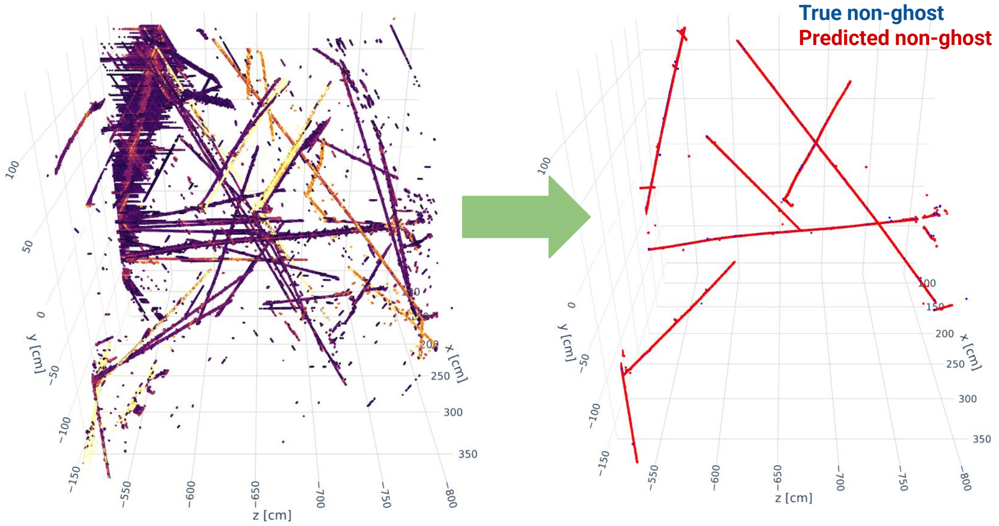
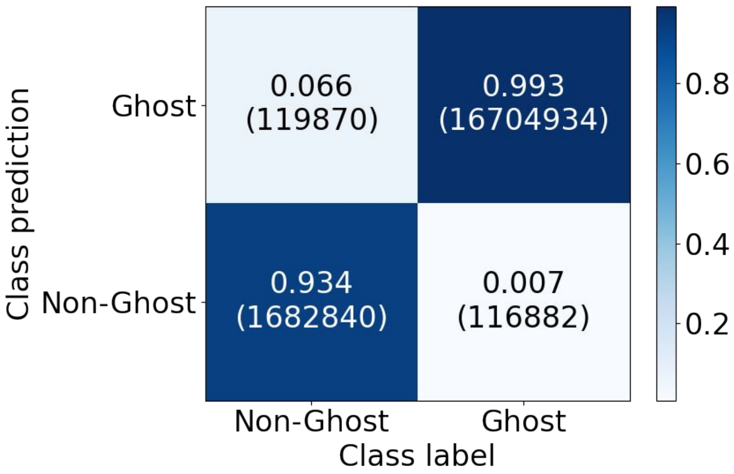
Deghosting with SPINE

F.Drielsma @ SPINE workshop 2025



BNB ν_μ only

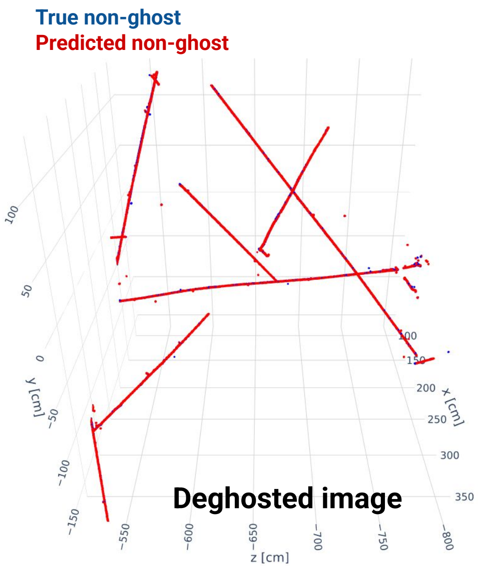


Using UResNet + Sparse Convolution on voxelized particle trajectories to extract the features and classify “non-ghost” vs. “ghost”

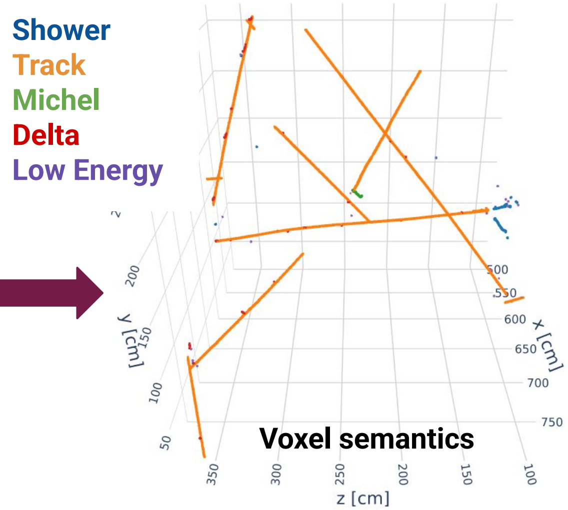
Re-distribute the charge based on the number of times each wire hit is used in the deghosted voxels.

Reconstruction with SPINE

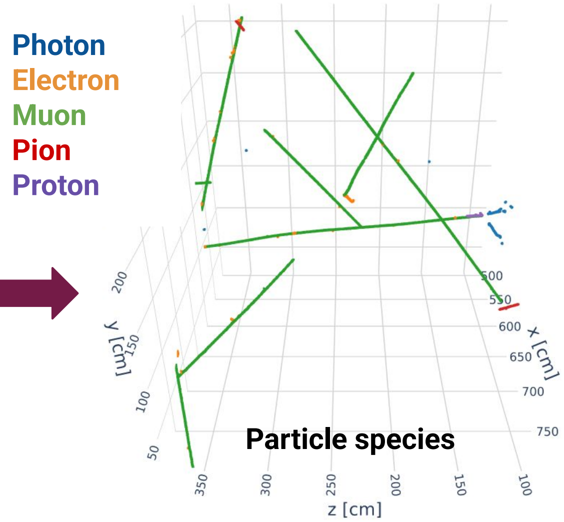
F.Drielsma @ SPINE workshop 2025



Semantic segmentation at voxel level with UResNet



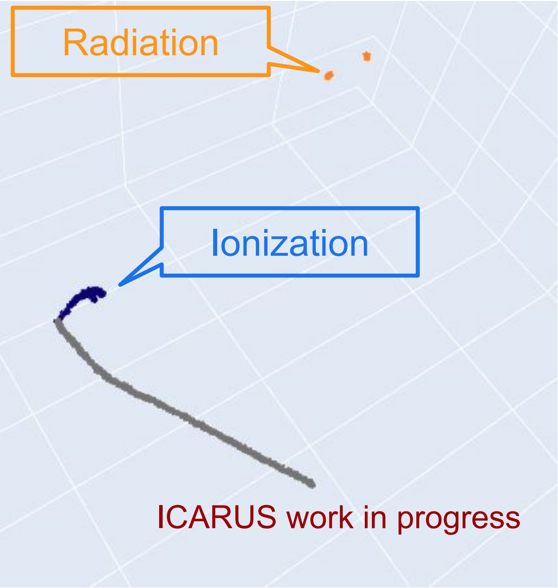
Fragment clustering and interaction aggregation with GNN



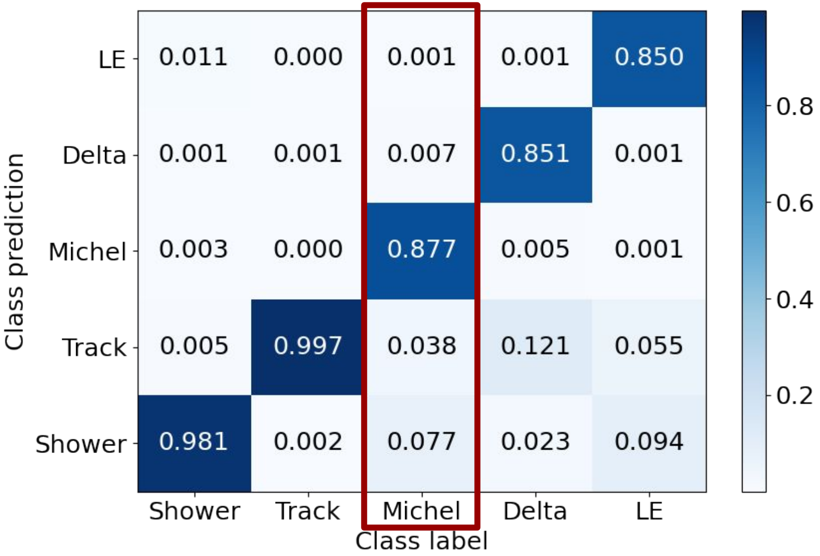
More details in
F. Drielsma's talk

Particle trajectories are voxelized in 3D space with O(1) mm^3 resolution

Michel electrons in LArTPC



BNB ν_μ semantic segmentation



A michel electron can deposit energy in LArTPC via ionization (primary michel) and bremsstrahlung radiation (secondary michel)

Selecting Michel electrons with SPINE

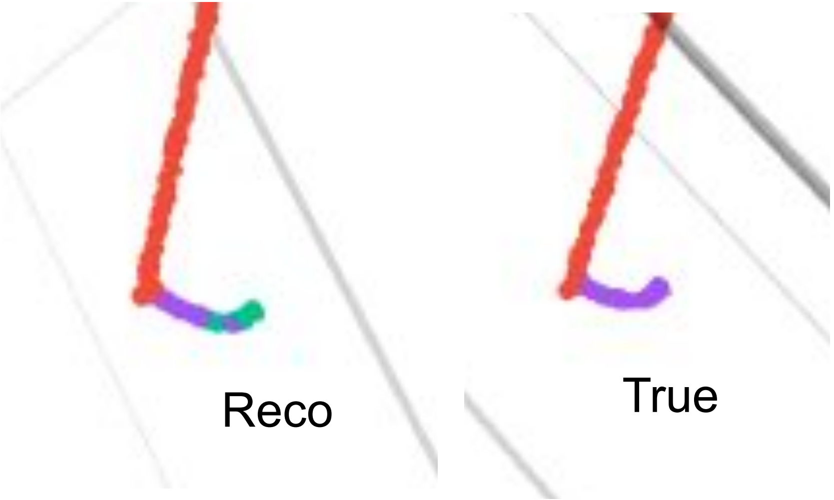
J. Xia

ICARUS work in progress

In MC, a Michel electron is considered successfully reconstructed if the **Intersection over Union (IoU)** between the **matched truth and reconstructed** particle voxels' semantic type is **greater than 50%**.

$$\mathrm{IoU} = \frac{|x \cap y|}{|x \cup y|}$$

In addition, we require the parent **muon track** to have at least **20 voxels** of reconstructed visible energy deposition.



Matched for delta, unmatched for Michel.

Red: track, green: michel, purple: delta

Selecting Michel electron with SPINE

J. Xia

To improve the selection purity, we apply two more selection criteria:

- The reconstructed **Michel electron** has at least **20 voxels** of reconstructed visible energy deposition
- The reconstructed primary **Michel electron** is at most **3 cm** away **from the parent muon track end**

ICARUS work in progress

~140k Michel electrons	Efficiency	Purity
Matched & Muon n voxel > 20	82.2%	89.8%
Michel n voxel > 20	80.0%	92.8%
Attached at muon end	78.8%	94.0%

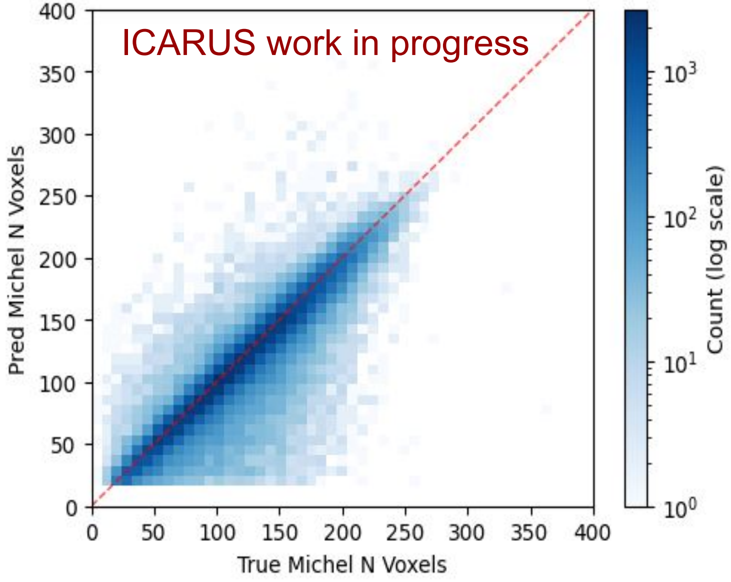
**Efficiency = n_reco_truth / n_truth*
Purity = n_reco_truth / n_reco

ProtoDUNE-SP (PhysRevD.107.092012): ~15% efficiency and 95% purity

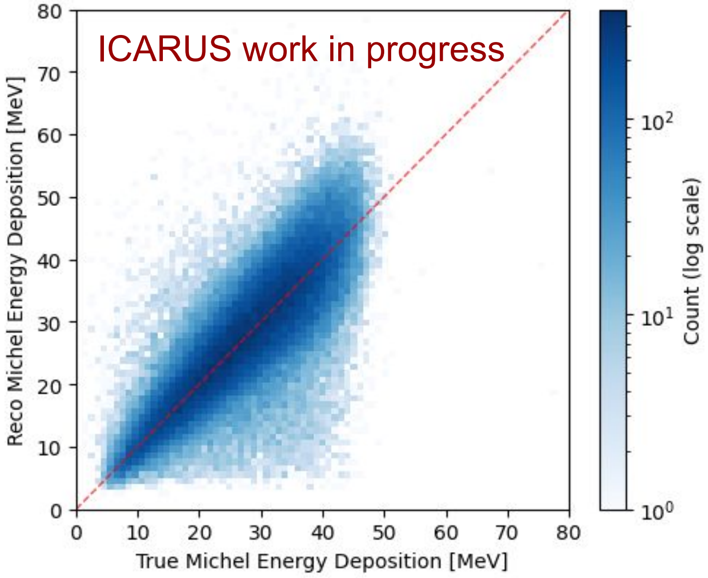
Reconstructing Michel electron with SPINE

J. Xia

Number of voxels



Energy deposition

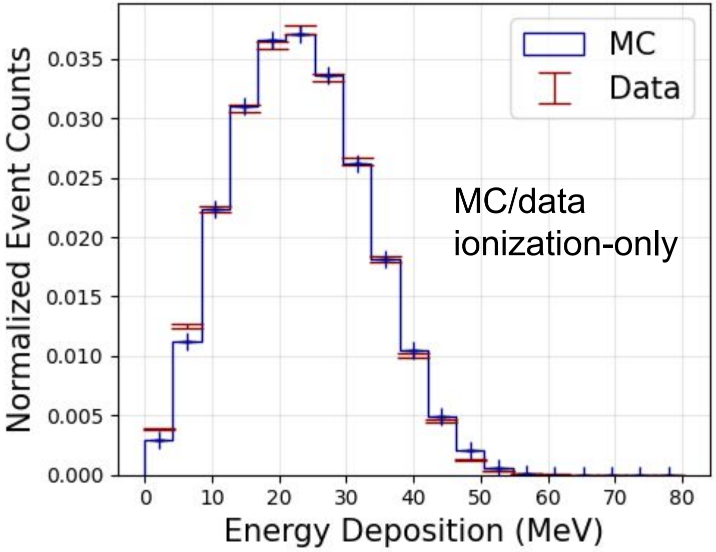


Reconstruction and MC truth show a strong correlation, with smearing from various systematic uncertainties, e.g. deghosting, calorimetry, etc.

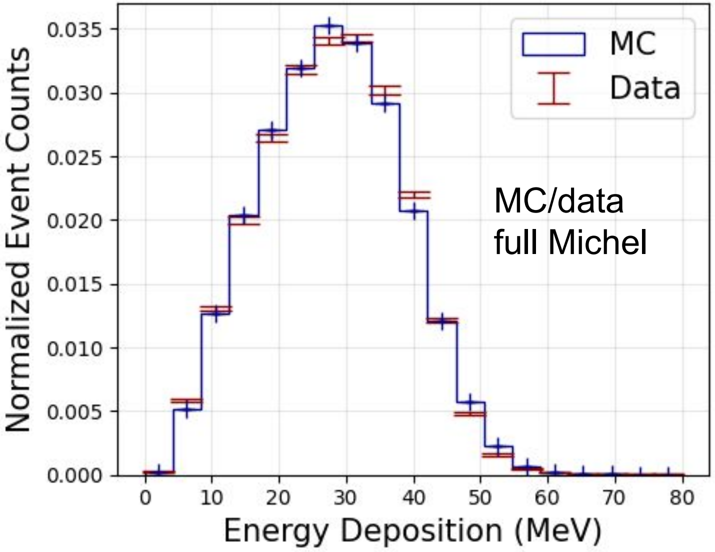
SPINE performance check: Data/MC shape comparisons

J. Xia

ICARUS work in progress



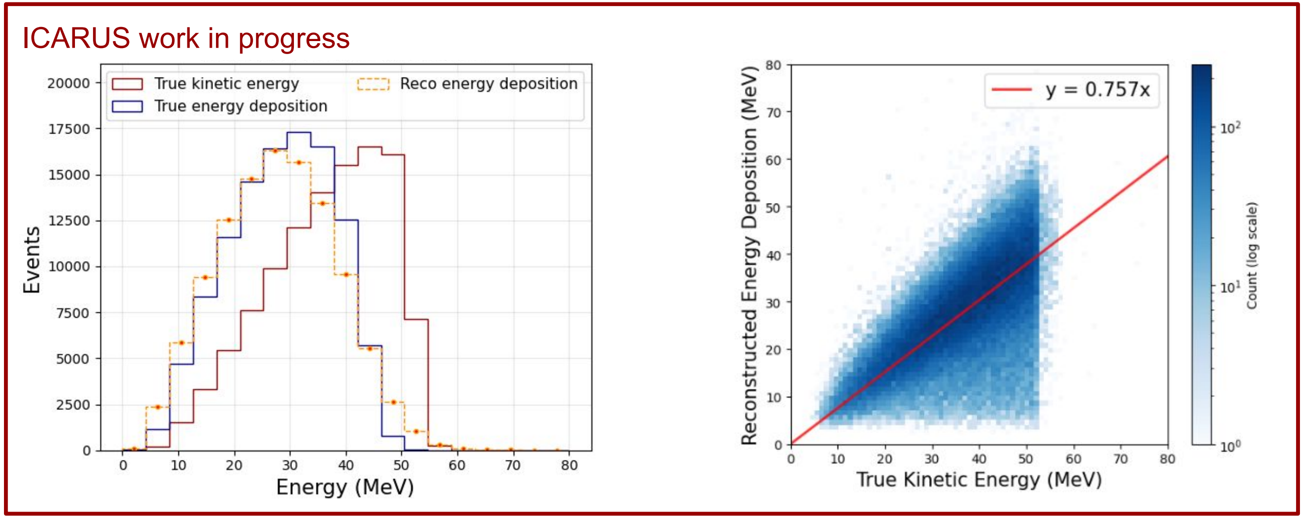
ICARUS work in progress



Achieved 92.45% “yield” over ~80k data samples with the current selection.

Correcting missing energy of Michel electron

J. Xia

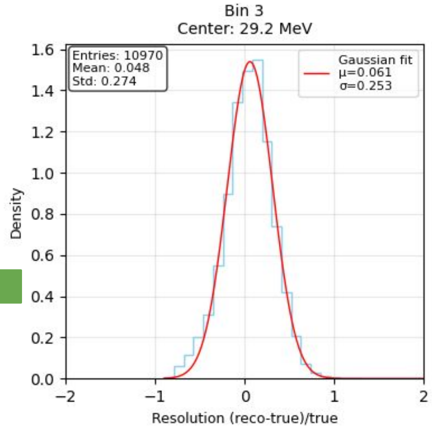


- Due to various detector effects, not all of particle's kinetic energy are deposited
- The reconstructed energy deposition is differed from the MC truth due to reconstruction errors
- We apply a constant multiplicative factor from a linear regression for reconstructed Michel electron kinetic energy

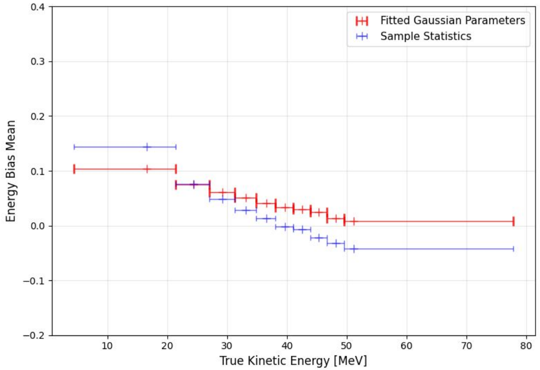
Energy scale calibration with Michel electron

J. Xia

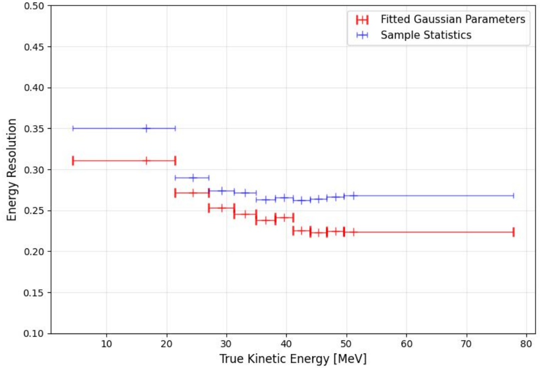
ICARUS work in progress



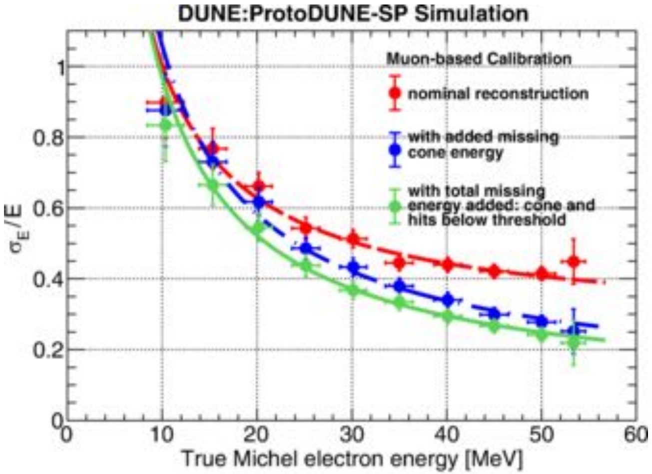
Energy Bias



Energy Resolution



PhysRevD.107.092012



Neutral pion events in ICARUS

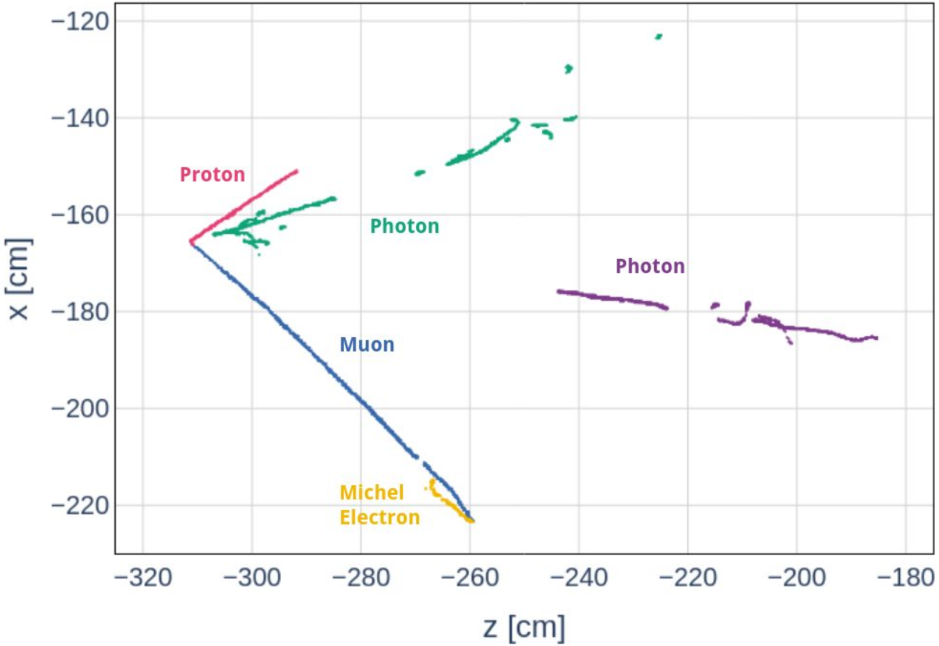
L. Kashur

Target topology: Charged-Current (CC) muon neutrino interaction on argon with a single π^0 in the final state:

$$\nu_\mu + \mathrm{Ar} \rightarrow 1\mu^- + 1\pi^0 + 0\pi^\pm + X$$

where X represents any final state particles other than muons or charged pions.

ICARUS BNB Run 9435



Neutral pion selection with SPINE

L. Kashur

Selection Cuts	Efficiency	Purity
In-time flash	97.1%	0.5%
Fiducial Volume	96.6%	2.7%
Single Muon	90.8%	3.6%
No Charged Pions	83.3%	3.6%
2 Photons	70.2%	83.7%
$m_{\gamma\gamma} < 400$ MeV/c^2	**70.0%**	**85.5%**

**Efficiency = n_reco_truth / n_truth*
Purity = n_reco_truth / n_reco

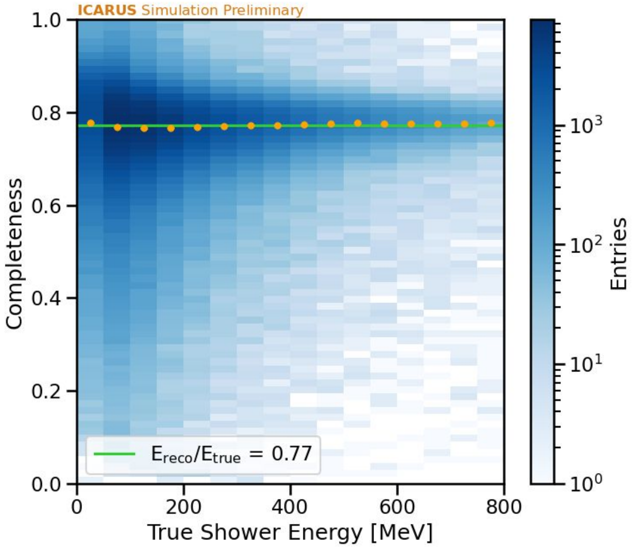
Trigger window by LArTPC optical readout “flash”

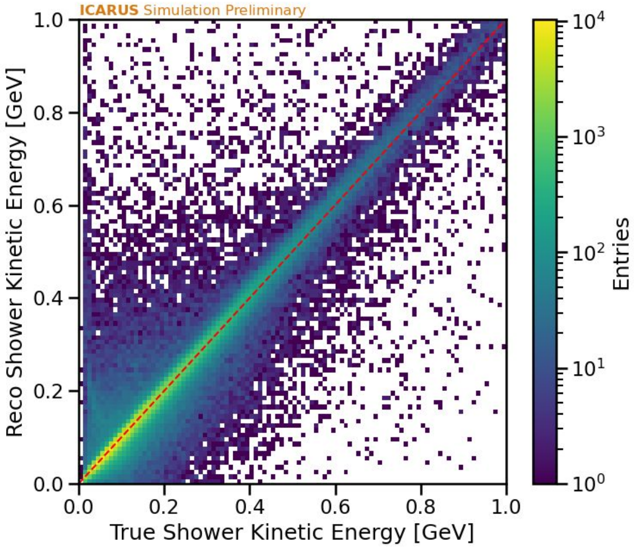
Confusion between electron and photon shower is the leading error source in the selection inefficiencies and impurities.

MicroBooNE (arxiv.org/pdf/2404.09949): 8.5% efficiency and 69% purity

Shower energy correction

L. Kashur



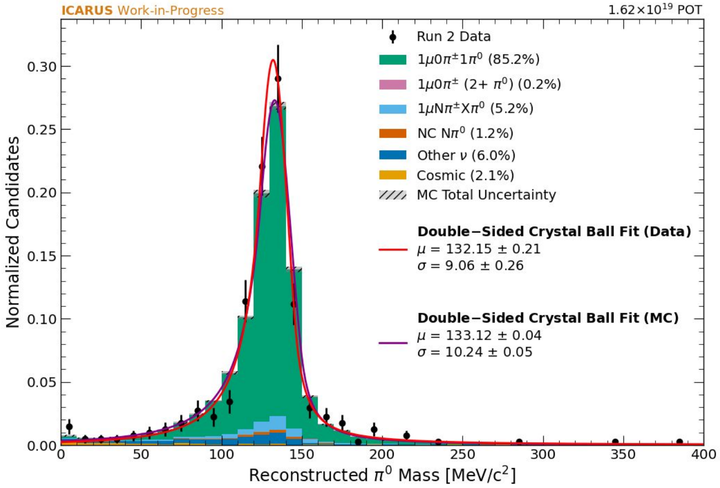


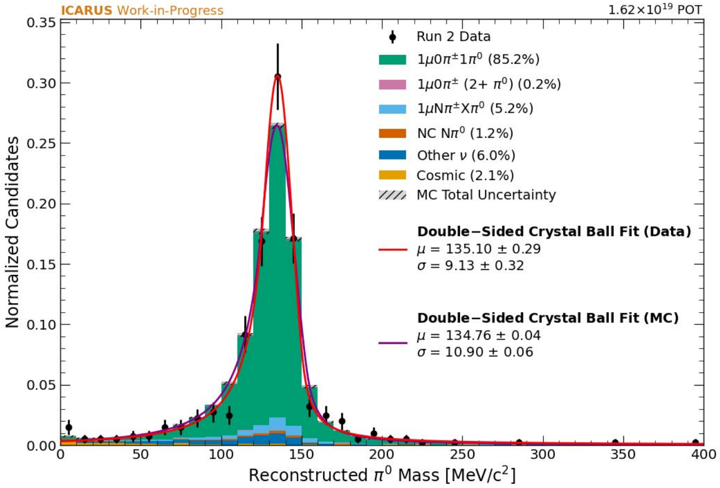
Shower energy is estimated calorimetrically by summing charge depositions

A constant factor can be applied to correct the missing shower energy

Neutral π^0 mass reconstruction

L. Kashur





- Study to account for the missing un-contained shower energy is ongoing
- Crystal Ball fit to derive a multiplicative correction factor
- The resulted π^0 mass reconstruction shows nice agreement between MC and data.

Conclusion and outlook

- SPINE achieved much better selection efficiency and purity compared to preceding work:
    - Michel electron: 78.8% efficiency, 94.0% purity.
    - ν_μ CC π^0: 70.0% efficiency, 85.5% purity

- Energy resolution with Michel electrons in ICARUS is better than preceding results, yet still limited by deghosting performance and semantic segmentation accuracy

- The unprecedented accuracy of π^0 mass reconstruction in LArTPC shows promising future of its application in SBN oscillation analysis

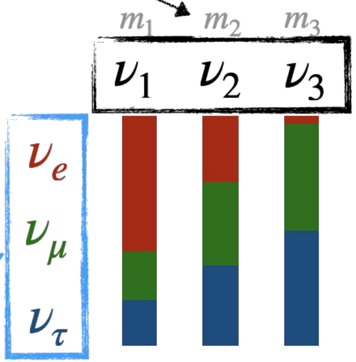
- How may SPINE and reconstruction/calibration be better?
    - Improvement of the UResNet segmentation accuracy?
    - *In-situ* shower energy correction instead of simple multiplicative factors?

Supplemental slides

The Standard Neutrino Oscillation

Hamiltonian basis

$\neq$ flavor basis



Oscillation probability:

$\Delta m^2_{ij}=m^2_i-m^2_j$ Traverse distance

$(i,j) \in (1,2,3)$

$$P(\nu_\alpha \to \nu_\beta) \sim \sum_{i>j} \mathcal{R}e\left(\boxed{U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}}\right)\sin^2\left[\frac{\boxed{\Delta m^2_{ij}}\boxed{L}}{4\boxed{E}}\right]+\ldots$$

$(\alpha,\beta) \in (e,\mu,\tau)$

Mixing matrix

neutrino energy

$s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$

Atmospheric | Reactor | Solar

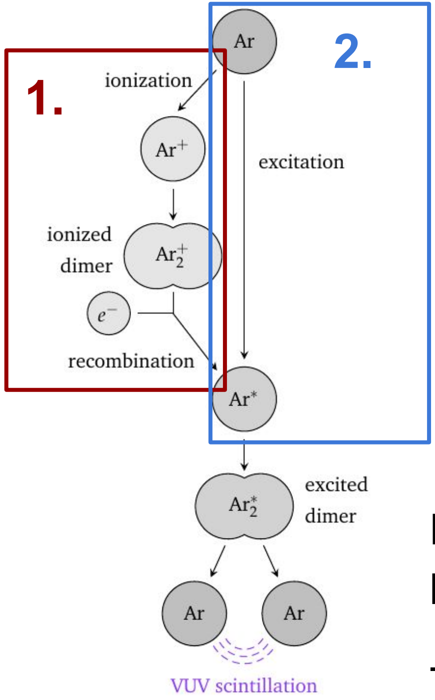
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

- The oscillation parameters are getting better constrained by reactor, atmospheric, and long baseline [O(100) km] neutrino oscillation experiments

- A few anomalies were seen in the short baseline oscillation experiments

Scintillation in LArTPC

Scintillation light:



Scintillation photons are produced from a dissociation of excited argon dimmers (Ar^*_2, also known as eximers).

1. When an electron is released from an argon atom, the Ar^+ can form an ionized dimer Ar^+_2 via

$$\mathrm{Ar}^+ + 2\mathrm{Ar} \rightarrow \mathrm{Ar}_2^+ + \mathrm{Ar}$$

which can recombine with the released electron and form an excimer.

2. Ar can also be directly exited to Ar^* and combines with a nearby Ar via

$$\mathrm{Ar}^* + 2\mathrm{Ar} \rightarrow \mathrm{Ar}_2^* + \mathrm{Ar}$$

Depending on the recombined electron spin, the excimers formed by process 1 can exist in either a singlet (4~8 ns) or triplet (1.5~1.6 μs) state.

The characteristic wavelength of Ar^*_2 scintillation light is 128 nm.

MC and data samples

L. Kashur

For both analyses the ICARUS Monte Carlo simulation consisting of BNB neutrinos (GENIE-based) and cosmics (CORSIKA-based) is used.

The Michel electron analysis uses the ICARUS BNB off-beam data, which for the majority consists of cosmic muons.

The π^0 analysis uses $1.62\text{x}10^{19}$ POT of ICARUS BNB Run 2 (winter 2022 ~ spring 2023) on-beam data in addition to the off-beam.

Sample	Type	POT
BNB Run 2 On-Beam Majority Trigger	Data (On-Beam)	*1.62×10^{19}
BNB Run 2 Off-Beam Majority Trigger	Data (Off-Beam)	N/A
BNB ν + Cosmic	Simulation	1.68×10^{21}

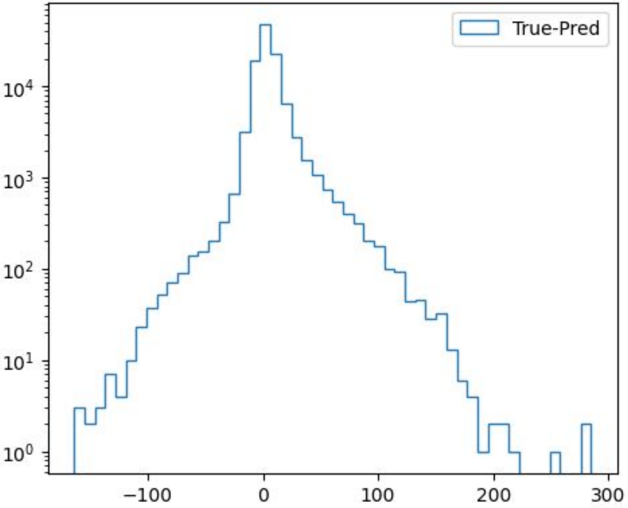
icaruscode v09_89_00_01

*after data/beam quality cuts

Impact of deghosting error

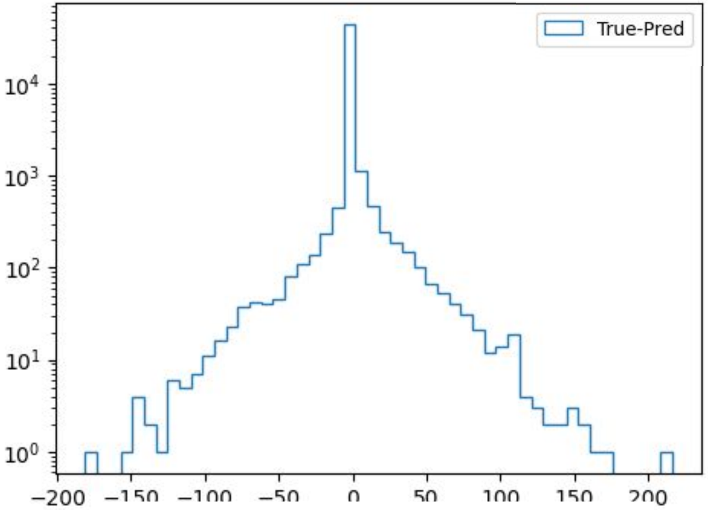
J. Xia

Default (with deghost)



Ionization N voxel bias

Adapted (“without” deghost)

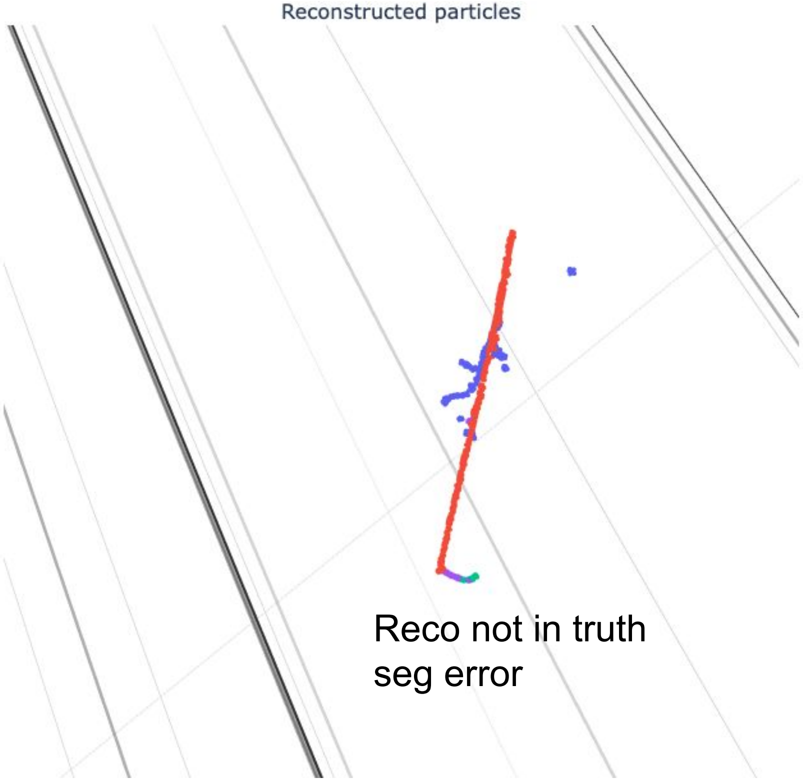


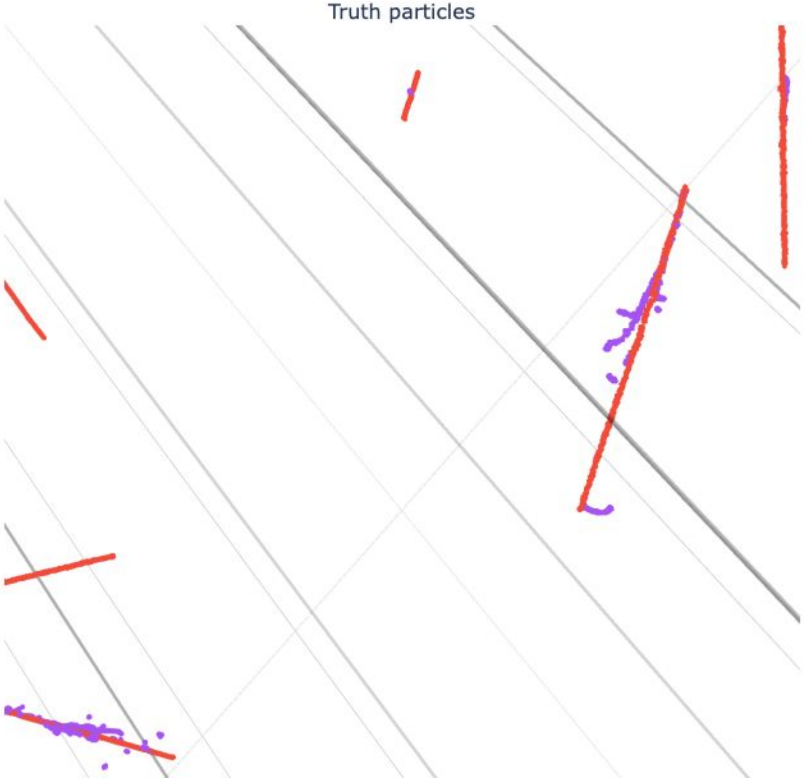
Ionization (no ghost) N voxel bias

90% quantile:

- with deghost: 24
- without deghost: 1

Unmatched reconstructed Michel electrons

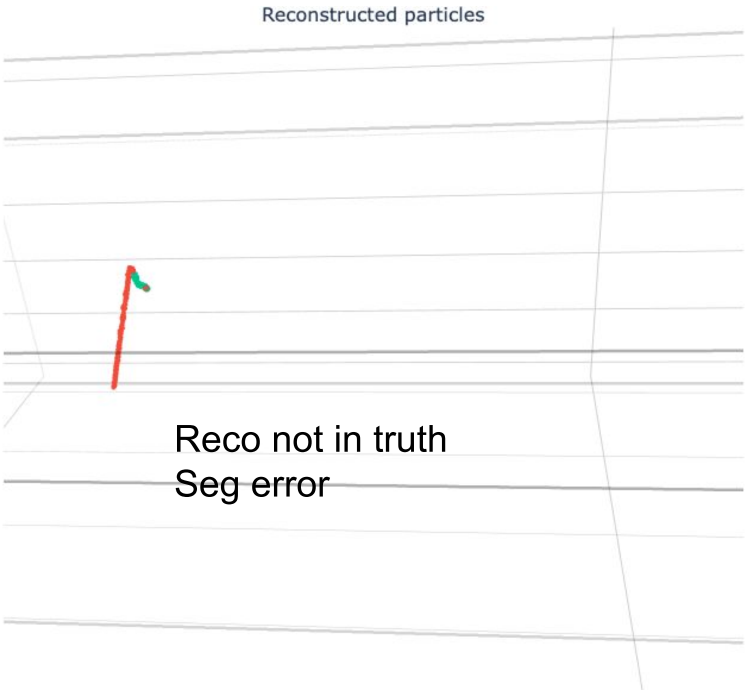


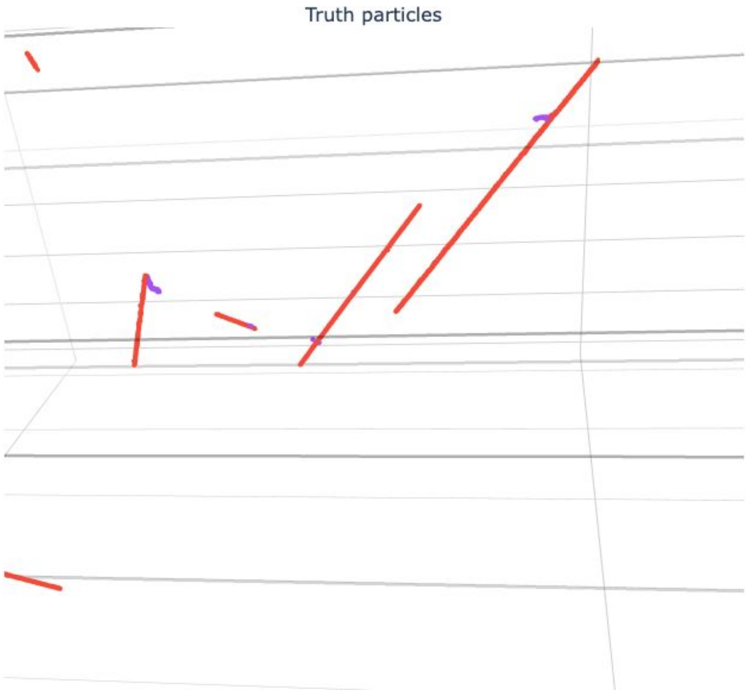


Reco not in truth
seg error

Blue: shower, Red: track, green: michel, purple: delta, orange: low E

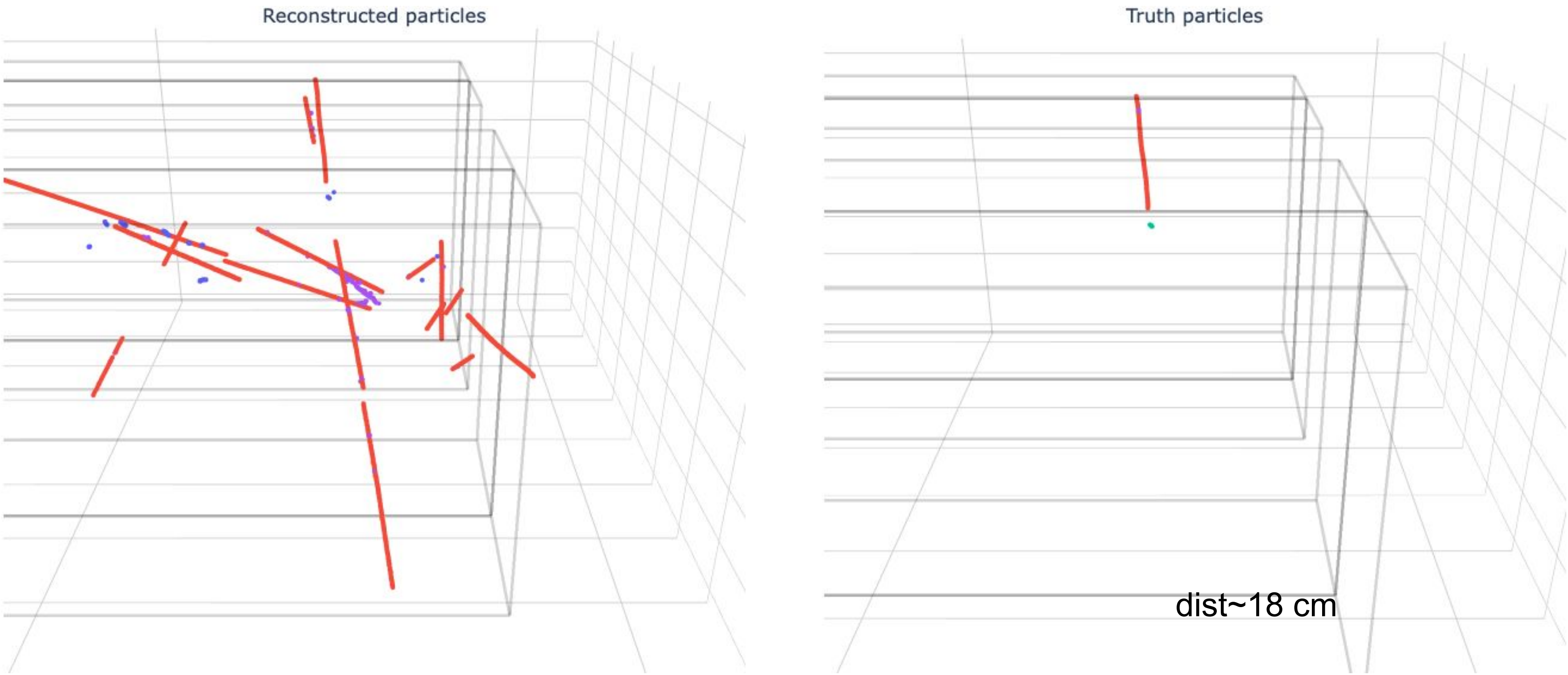
Unmatched reconstructed Michel electrons





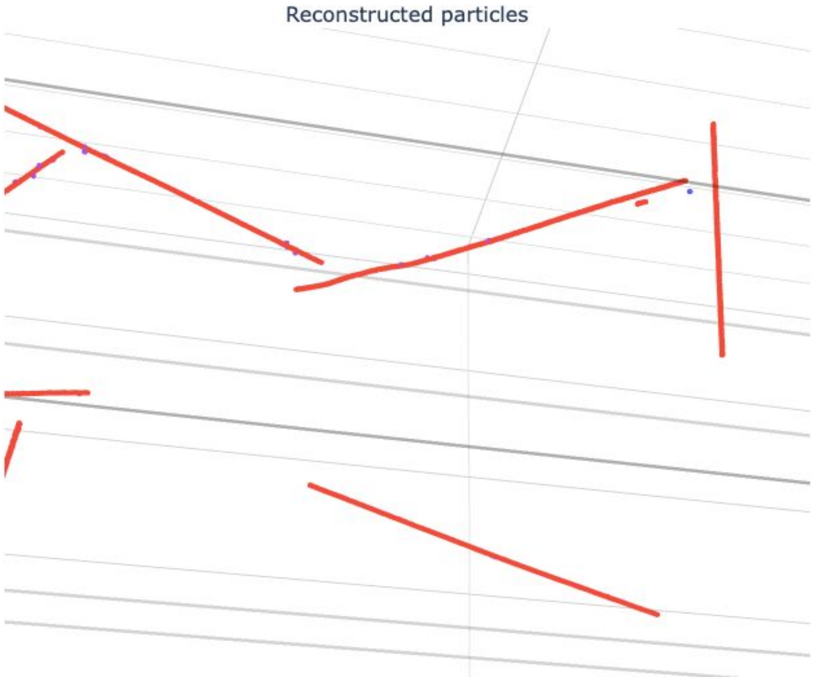
Blue: shower, Red: track, green: michel, purple: delta, orange: low E

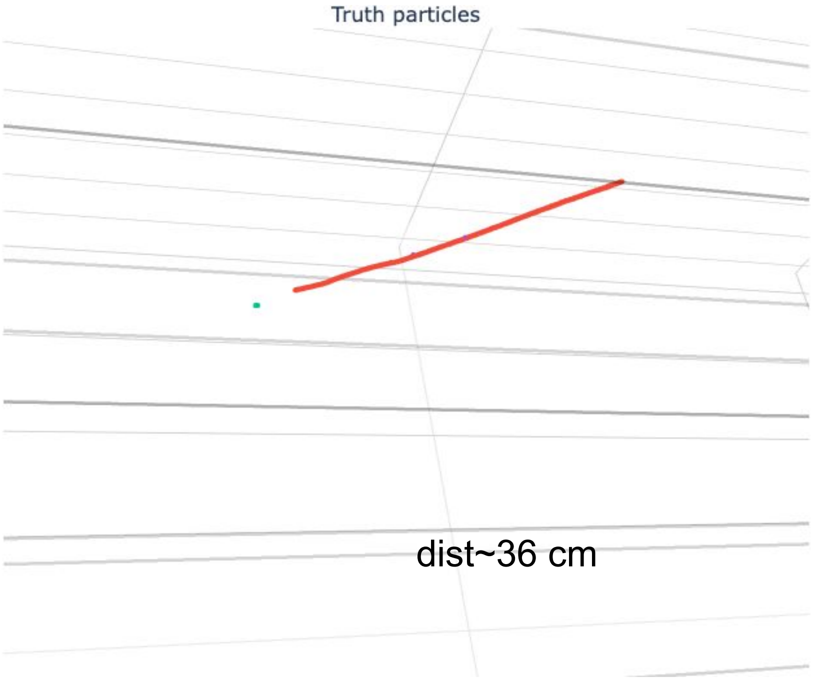
Michel is >3 cm from muon track (in truth space)



Blue: shower, Red: track, green: michel, purple: delta, orange: low E

Michel is >3 cm from muon track (in truth space)





Blue: shower, Red: track, green: michel, purple: delta, orange: low E

Michel electron reconstruction with SPINE

ICARUS work in progress

Bin Center [MeV]	Fitted Bias (%)	Stats. Bias (%)
16.56	10.39	14.35
24.36	7.44	7.59
29.19	6.12	4.83
33.10	5.13	2.86
36.52	4.06	1.36
39.61	3.34	-0.16
42.51	2.93	-0.70
45.31	2.49	-2.14
48.14	1.39	-3.18
51.19	0.83	-4.26

Biases of reconstructed kinetic energy

ICARUS work in progress

Bin Center [MeV]	Fitted Resolution (%)	Stats. Resolution (%)
16.56	31.10	35.04
24.36	27.11	28.97
29.19	25.34	27.42
33.10	24.57	27.13
36.52	23.82	26.35
39.61	24.15	26.58
42.51	22.53	26.22
45.31	22.32	26.41
48.14	22.47	26.63
51.19	22.41	26.78

Energy resolution