Muon Neutrino Reconstruction and Neutral Pion Calibration with Machine Learning Techniques at the ICARUS Detector

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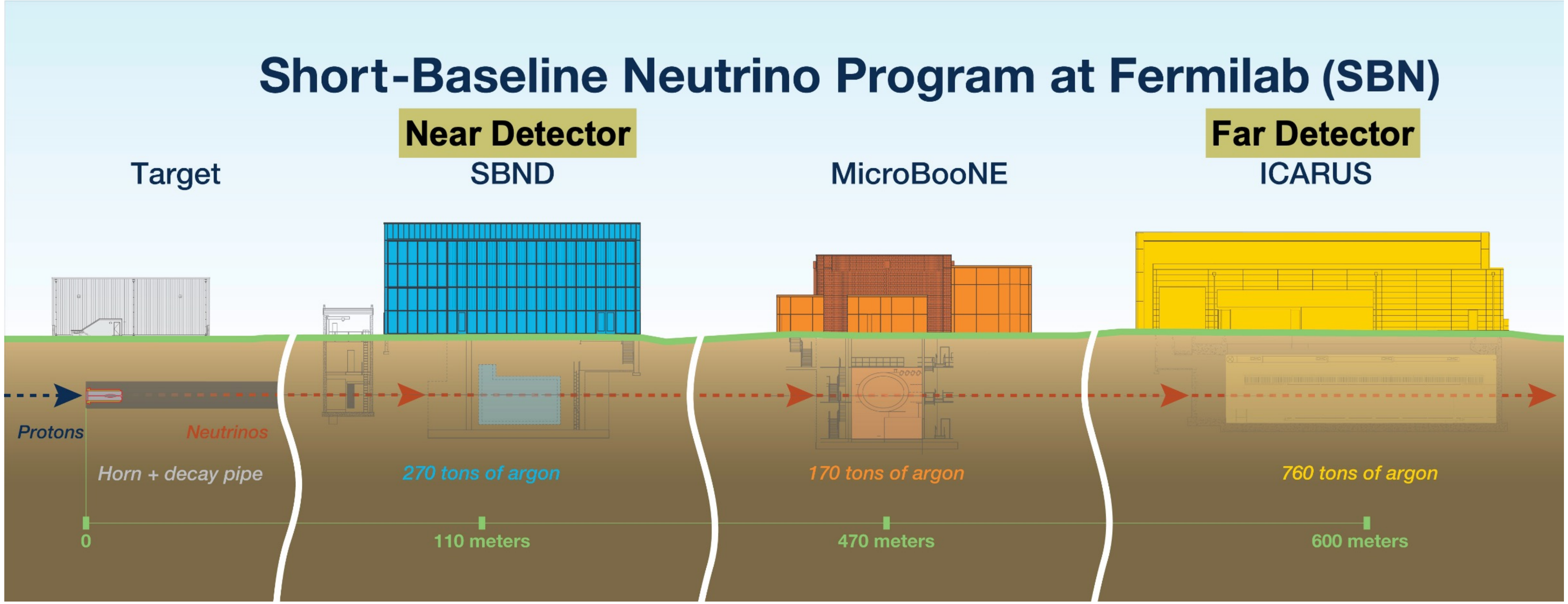
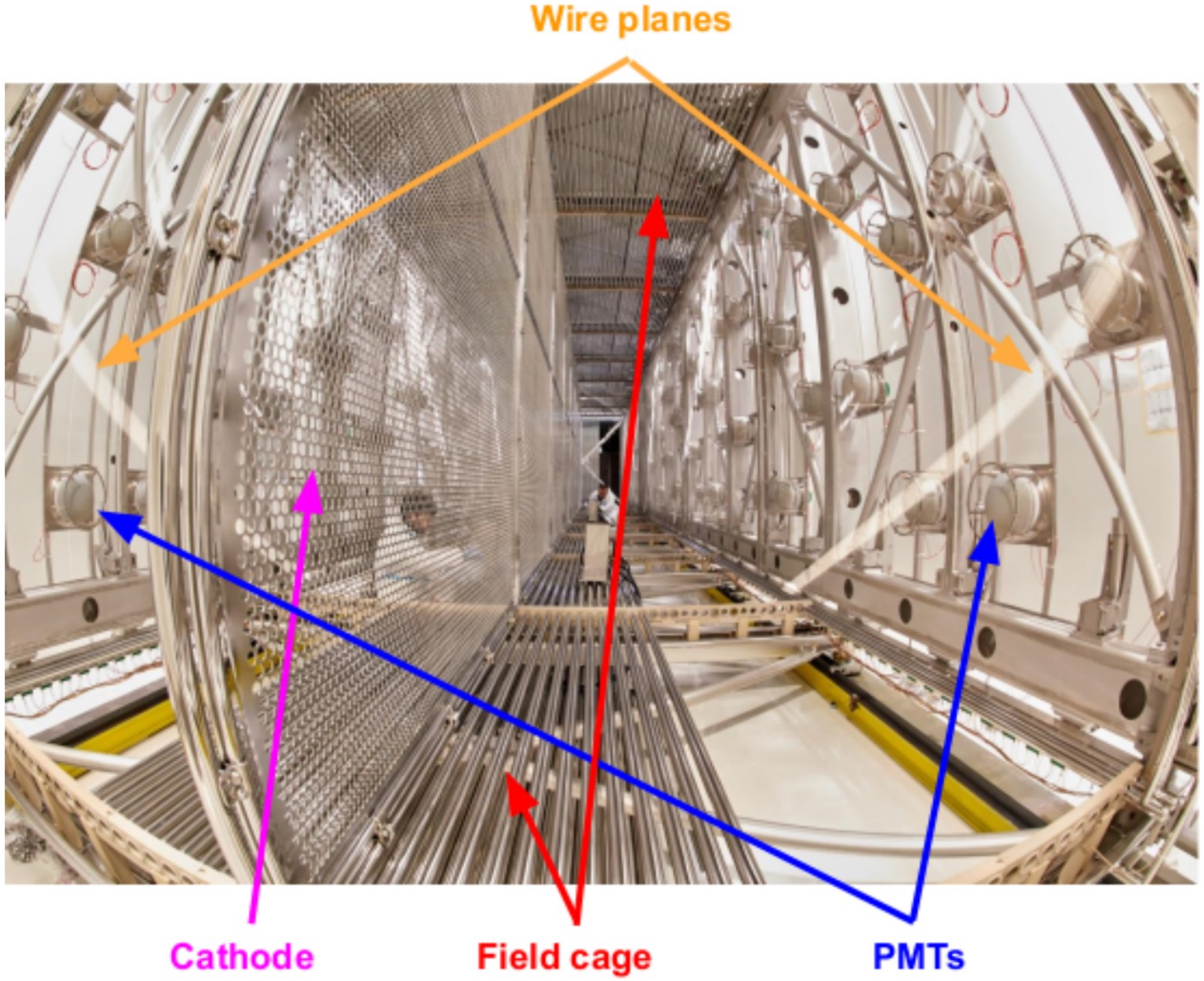
Short Baseline Neutrino Program at Fermilab (SBN)



https://vms.fnal.gov/asset/detail?recid=1962973

- SBN consists of multiple detectors utilizing the liquid argon time-projection chamber (LArTPC) technology to sample neutrinos from the Booster Neutrino Beam (BNB) at different baselines
- Capable of ***both*** muon neutrino disappearance and electron neutrino appearance searches
- Goal: discovery or exclusion of the LSND/MiniBooNE sterile neutrino hypothesis

ICARUS Detector and Subsystems



https://doi.org/10.1140/epjc/s10052-023-11610-y

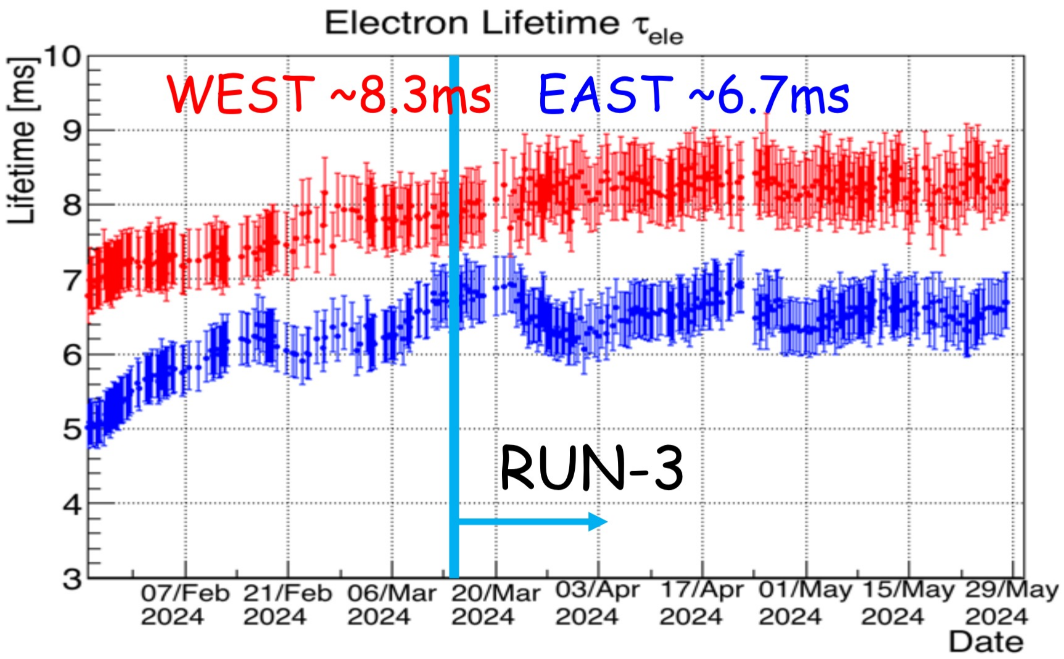
ICARUS is comprised of **four** LArTPCs in **two** identical volumes

- Each volume has a central cathode shared by two TPCs
- 54,000 channels spread out amongst **three** wire planes (0°, ±60° from horizontal)

Three distinct subsystems:

- TPC: precise imaging of particle ionization
- Photomultiplier Tubes (PMTs): detect scintillation light for timing and triggering
- Cosmic Ray Tagger (CRT): tags particles as they cross into/out of detector volume

ICARUS Operations and Data Runs



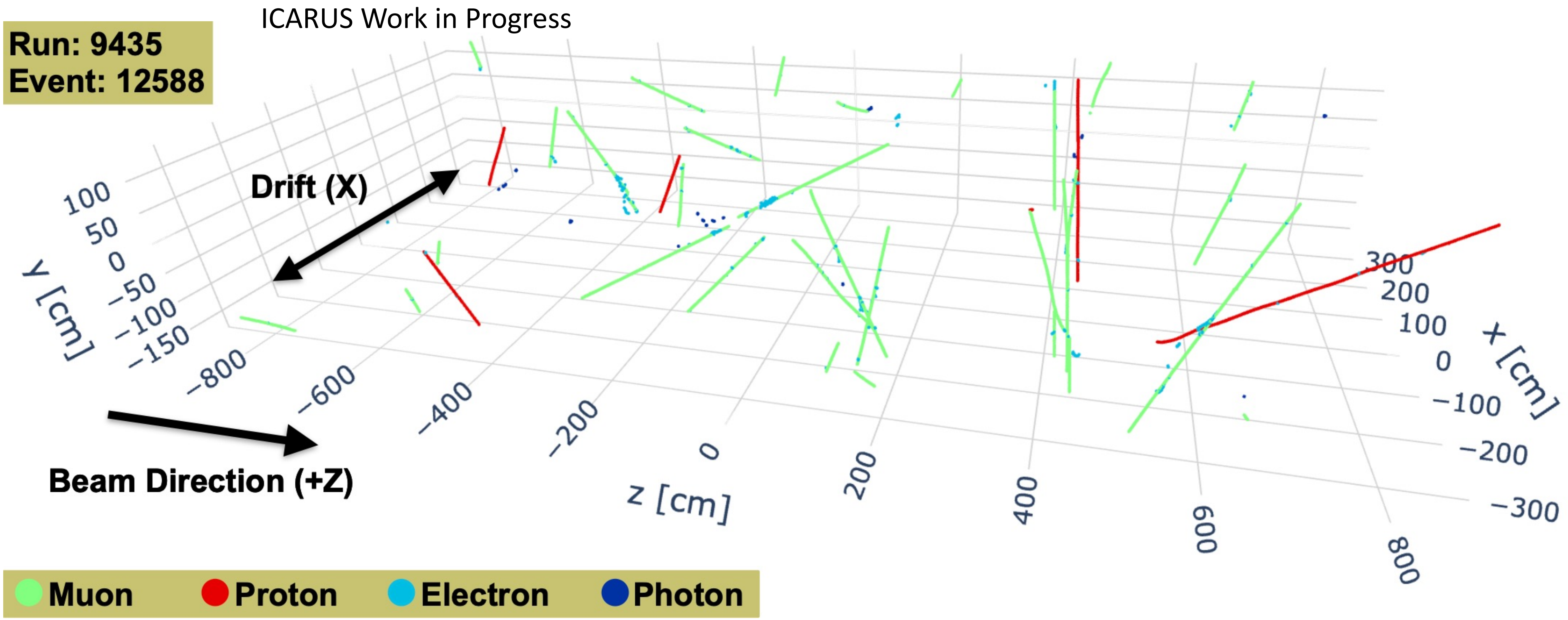
Collected Protons on Target (POT)	BNB Forward Horn Current	NuMI Forward Horn Current	NuMI Reverse Horn Current
Run 1 (Jun-Jul 22)	0.41E20	0.68E20	-
Run 2 (Dec-Jul 23)	2.05E20	2.74E20	-
Run 3 (Mar-Jun 24)	0.95E20	-	2.02E20
Total POT	3.41E20	3.42E20	2.02E20

ICARUS has been able to take high quality data runs for 3 years and continuing . We are analyzing the data runs now and putting out analyses studying neutrino and beyond standard model physics

ICARUS uses two reconstruction methods to analyze the data

- PANDORA (Traditional reconstruction)
- SPINE (Machine learning based reconstruction)

ICARUS Event Display of Neutrino Event



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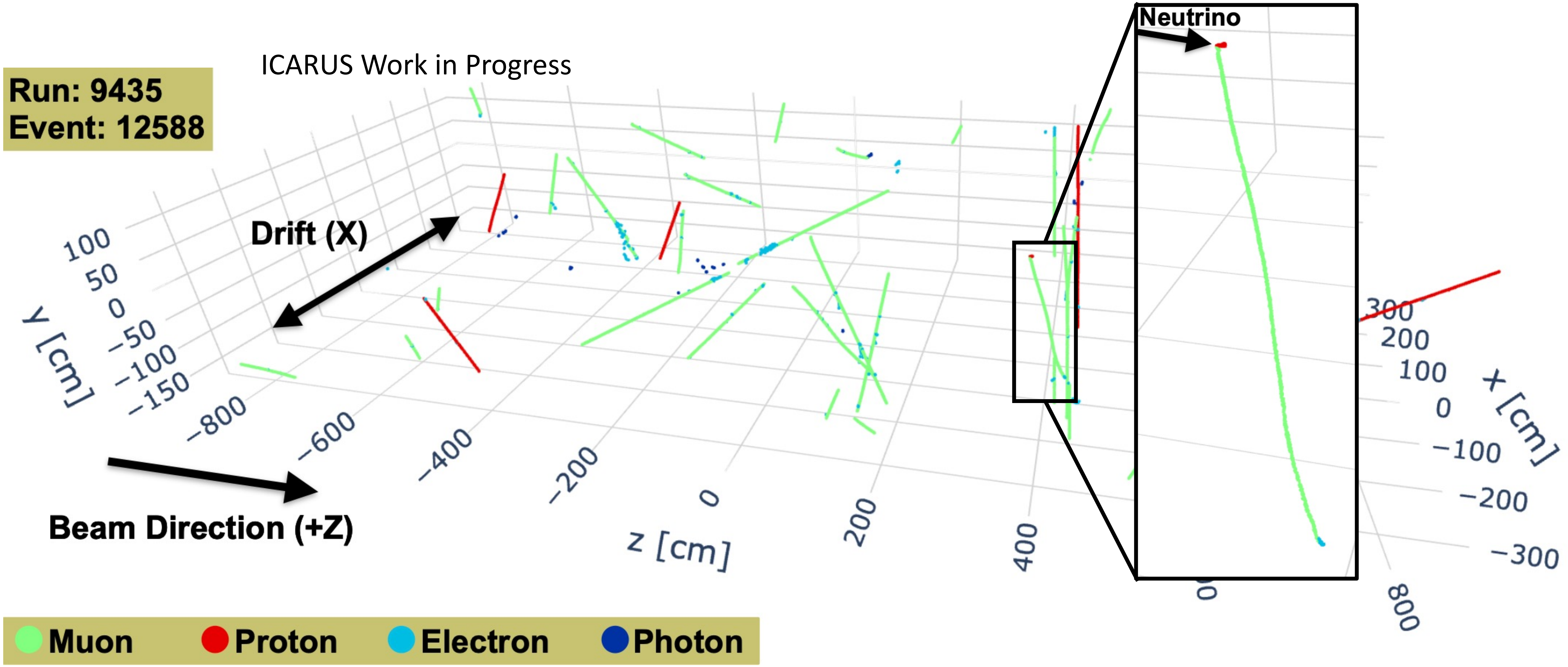
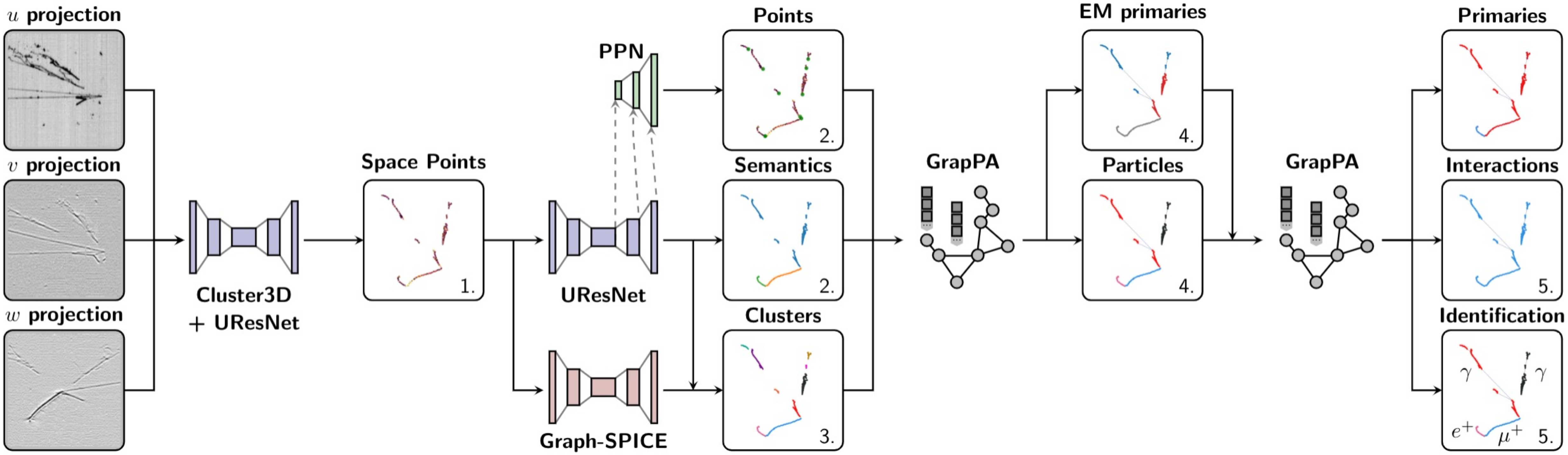
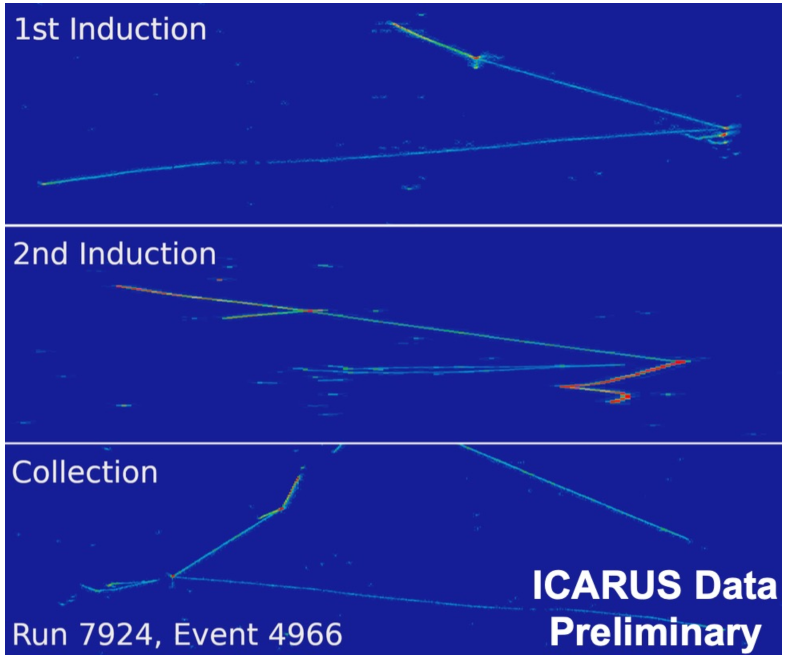


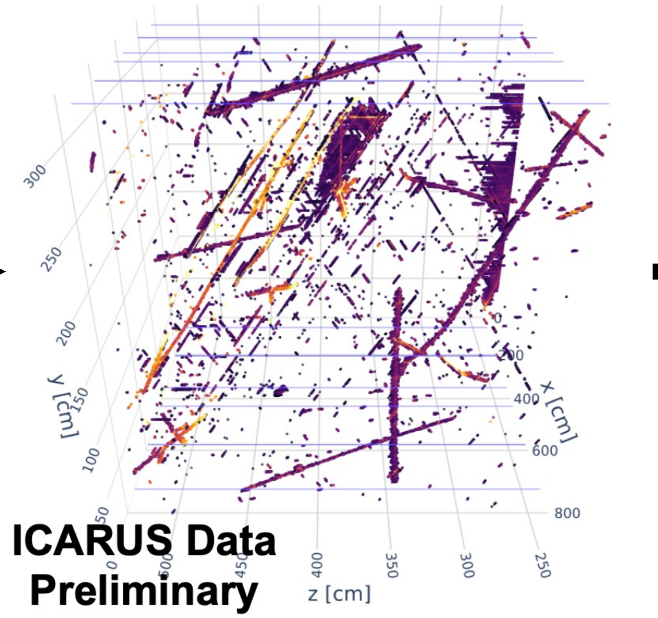
Reconstruction with Scalable Particle Imaging with Neural Embeddings (SPINE)

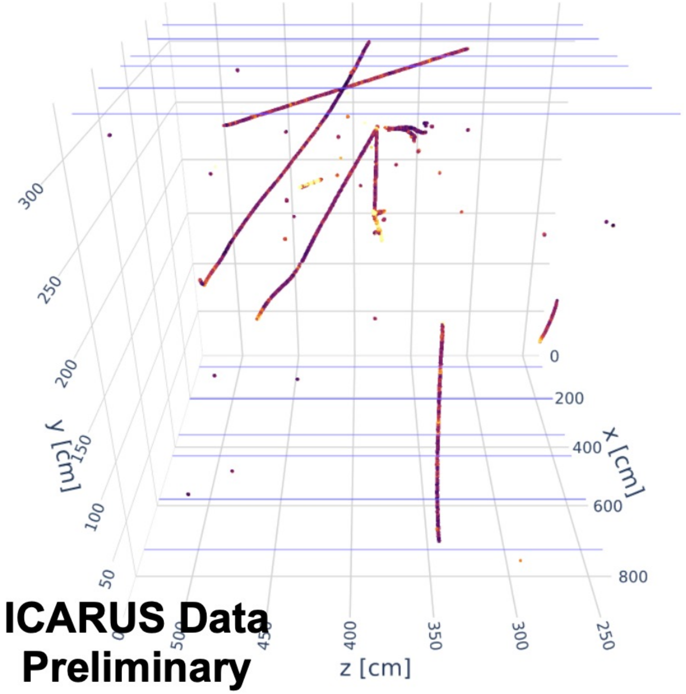


More details on SPINE by Francois Drielsma on Wednesday
GitHub link: https://github.com/DeepLearnPhysics/spine

Reconstruction with SPINE







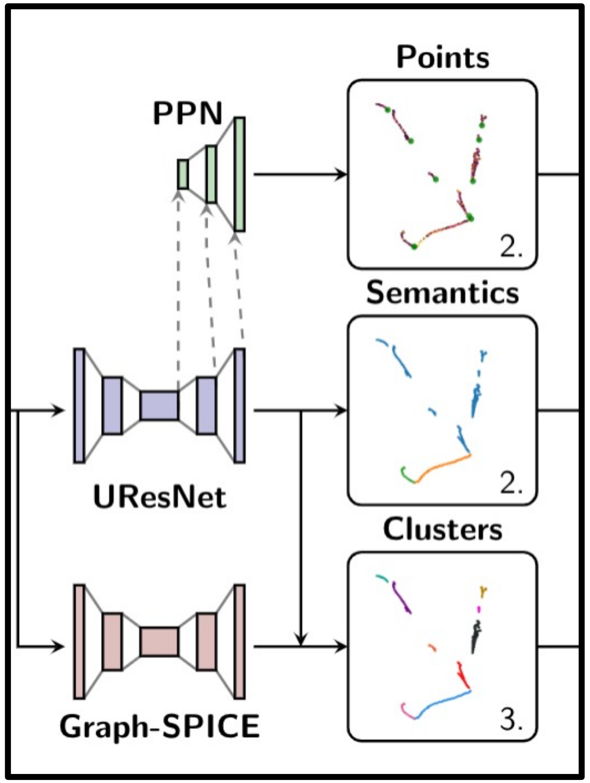
- Cluster3D: Find valid 3D combinations of hits across 2 or 3 planes
- Inherent artifacts ("ghost points") from ambiguities in matching — a hit may be consistent with many hits on the other plane(s)
- Artifact Removal: The artifacts from tomographic reconstruction are removed using a CNN

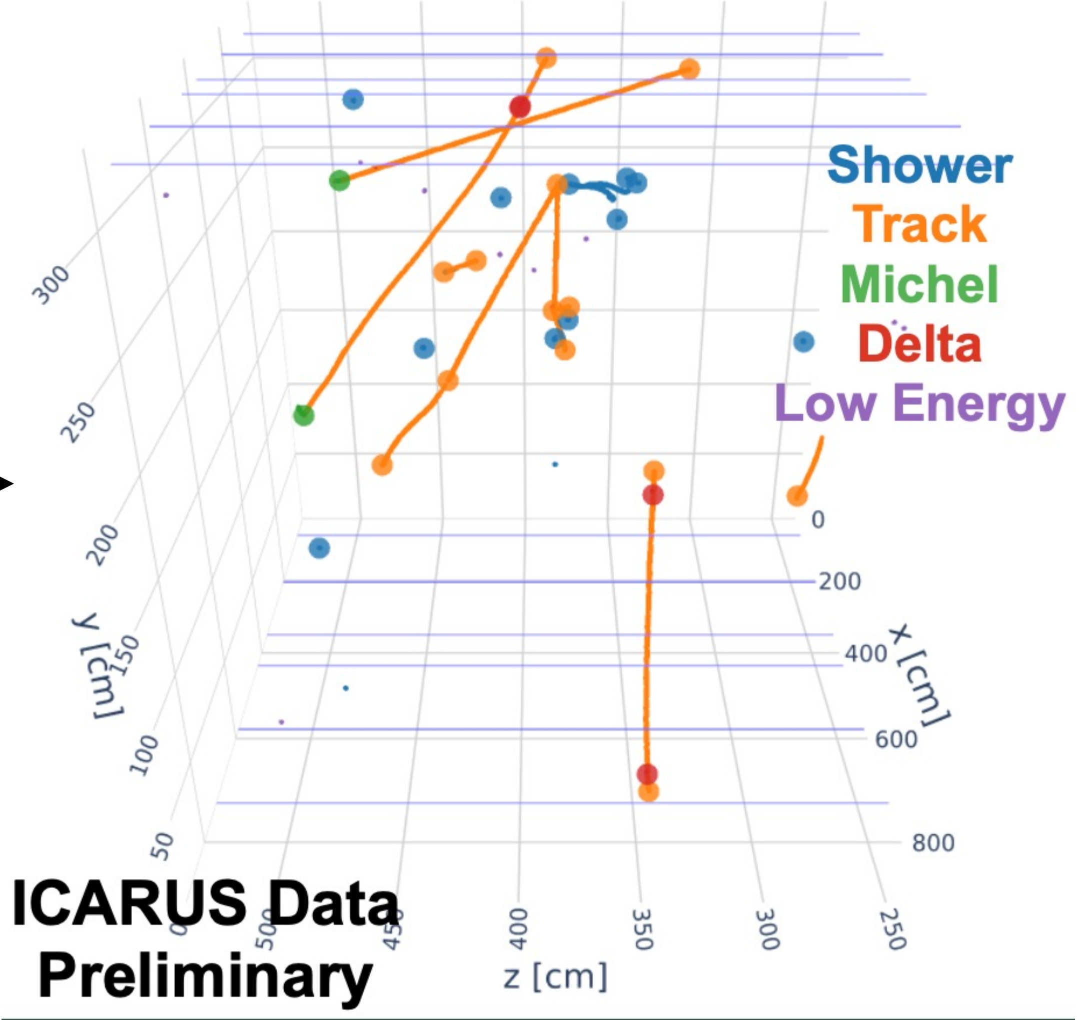
Reconstruction with SPINE

Points of Interest:
Predict start/end points of particles (Point Proposal Network — PPN)

Semantic Segmentation:
Classify each point into one of five Categories (Sparse-UResNet)

Clustering:
Groups 3D points into associated fragments (Graph-SPICE)

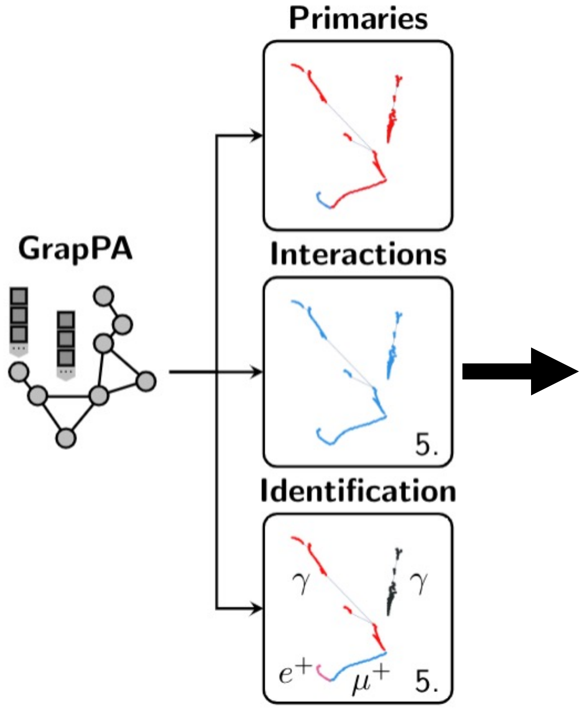


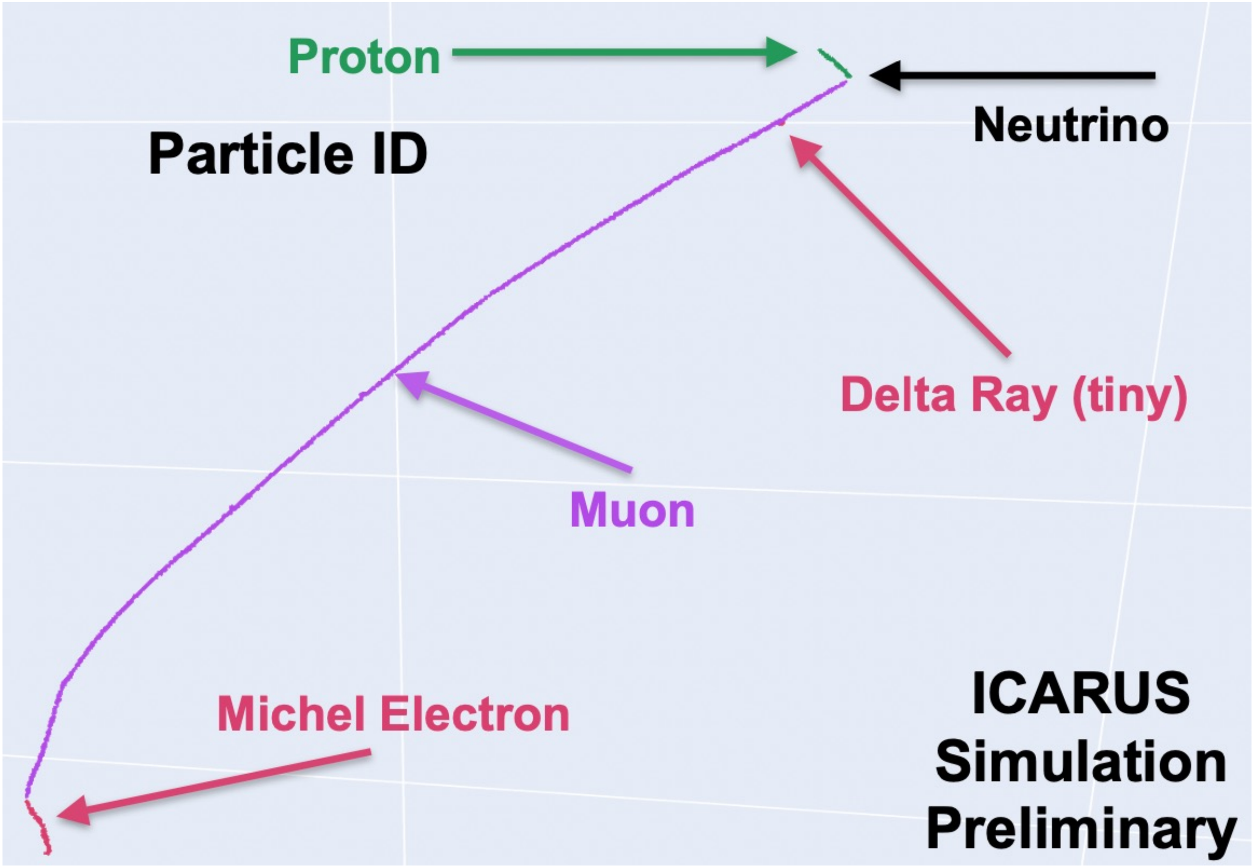


Output of Reconstruction

The reconstruction groups the 3D points at two different levels:

- **Particles**: hits that are predicted to belong to the same particle instance
- **Interactions**: hits that are predicted to belong to the same interaction group (set of particles)





Each particle object has a predicted particle type (photon, electron, muon, pion, or proton) and is classified as a primary/secondary particle

This information is used in downstream analyses to select specific final states

Selection of ν_μ

Final state (1μ1p and 1μNp)

- Exactly one primary muon (L > 50 cm)
- N ≥ 1 primary protons (> 50 MeV)
- No other primary particles > 25 MeV

Final state (ν_μ CC inclusive)

- Exactly one primary muon (L > 50 cm)
- Any number of primary particles > 25 MeV

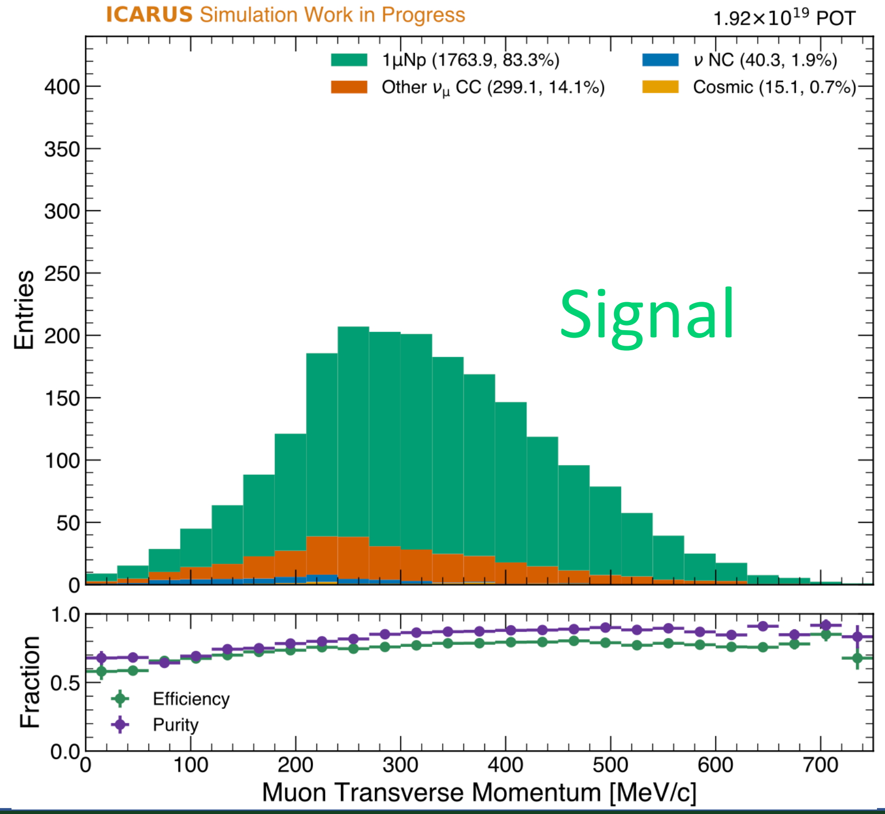
Two additional cleaning cuts have been applied for background rejection:

- PMT Flash Time: the interaction must be associated with a PMT flash that is in-time with the neutrino beam association done with a likelihood-based tool called OpT0Finder
- CRT-PMT Veto: no CRT hits within 100 ns of at least one PMT flash that is in-time with the neutrino beam

Selection Performance on Simulation

Selection Cut	$1\mu 1p$ Purity [%]	$1\mu 1p$ Efficiency [%]	$1\mu Np$ Purity [%]	$1\mu Np$ Efficiency [%]	ν_μ CC Purity [%]	ν_μ CC Efficiency [%]
No Cut	0.0	99.9	0.1	100.0	0.1	100.0
Fiducial Volume	0.1	98.8	0.1	98.8	0.3	98.2
Containment	1.1	94.9	1.5	95.0	3.5	94.1
Final State	66.2	73.9	71.2	77.9	9.5	86.3
Flash Time	80.1	72.4	83.0	76.4	87.8	84.5
CRT Veto	80.3	71.3	83.3	75.4	90.4	83.3

Selected 1µNp Candidates



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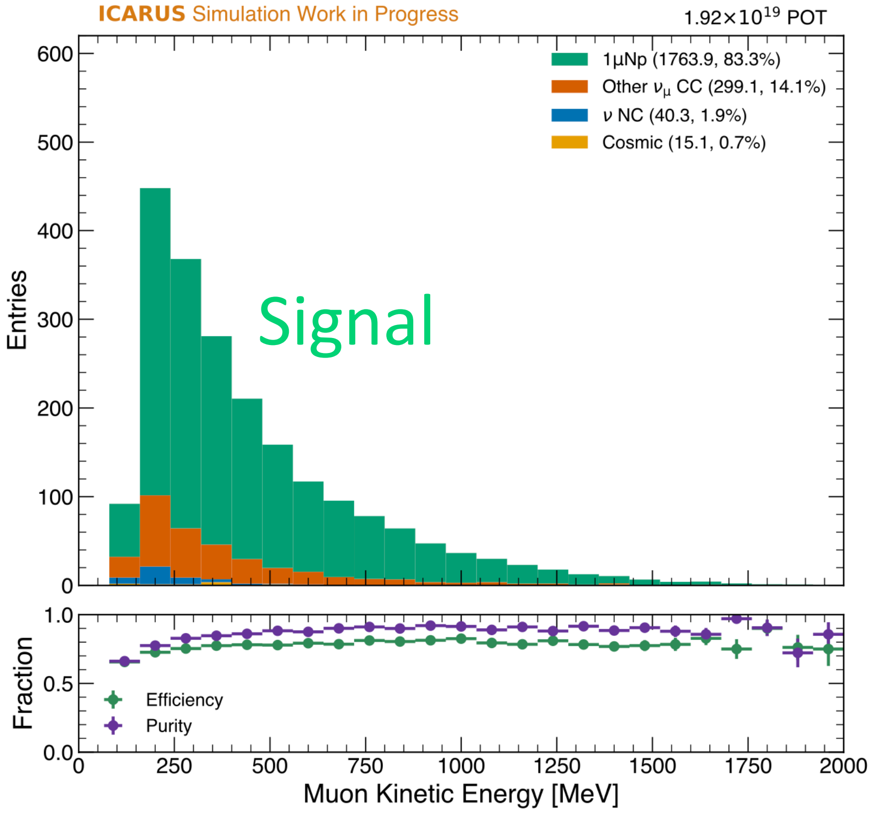


Systematic Uncertainties

The detector systematics are currently implemented using dedicated samples with the systematic shift implemented

Treating each systematic sample as a "1σ" variation, a bootstrapping method was used to estimate the covariance matrix

The bootstrapping method allows for a more robust determination of bin-to-bin correlations

For the rest of the systematic parameters, throw M "universes" and assign each interaction a weight reflecting the probability of the true parameter value living in that universe

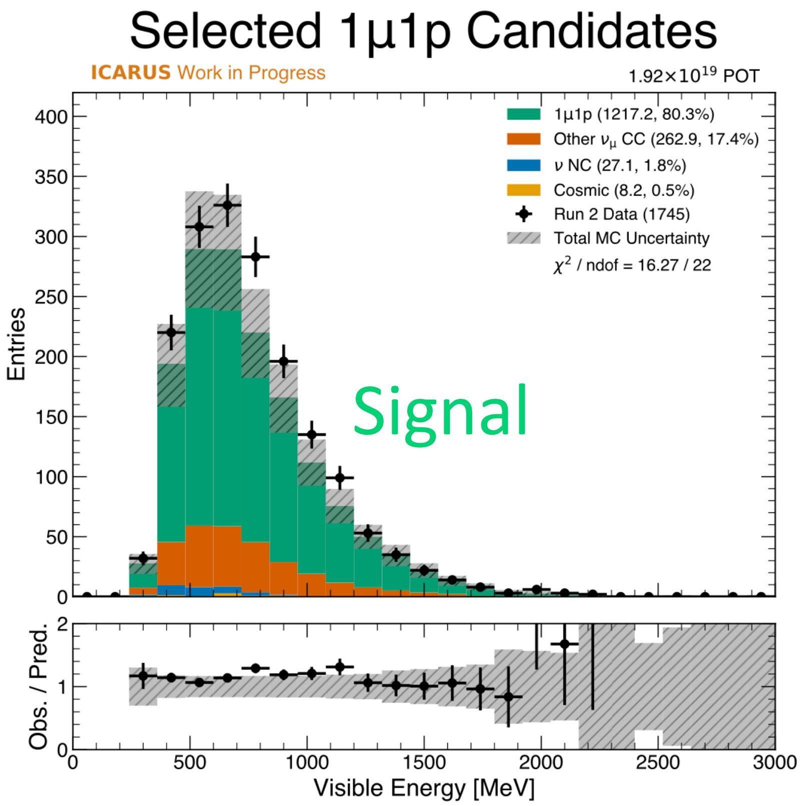
$$E_{ij}^{\alpha} = \frac{1}{M}\sum_{m}^{M}(N_{CV}^{i} - N_{\alpha,m}^{i})(N_{CV}^{j} - N_{\alpha,m}^{j})$$

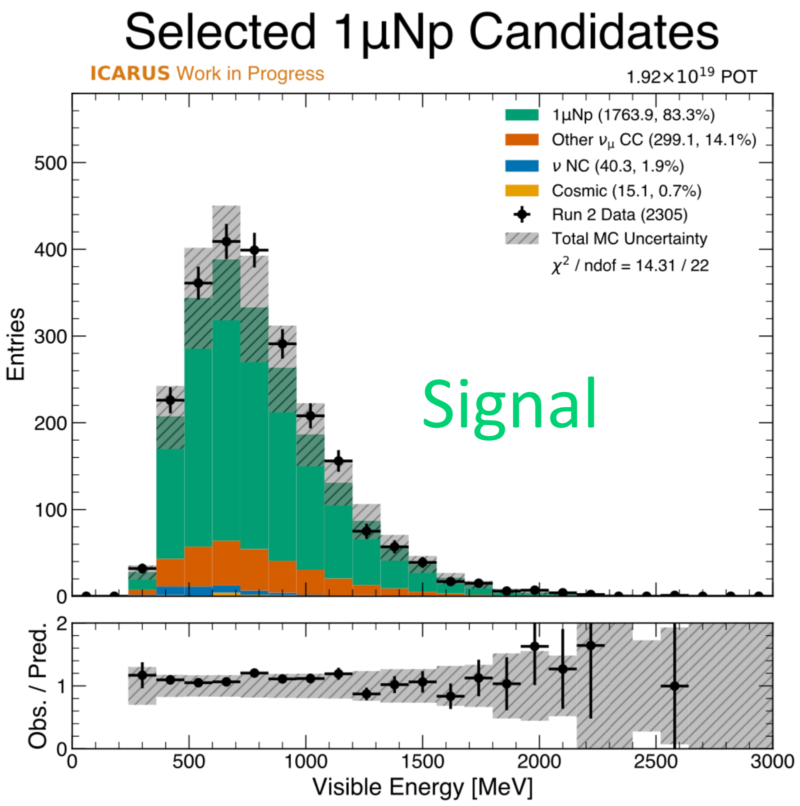
E_{ij}^{α} is the covariance matrix for systematic parameter is the α and bins (i, j)

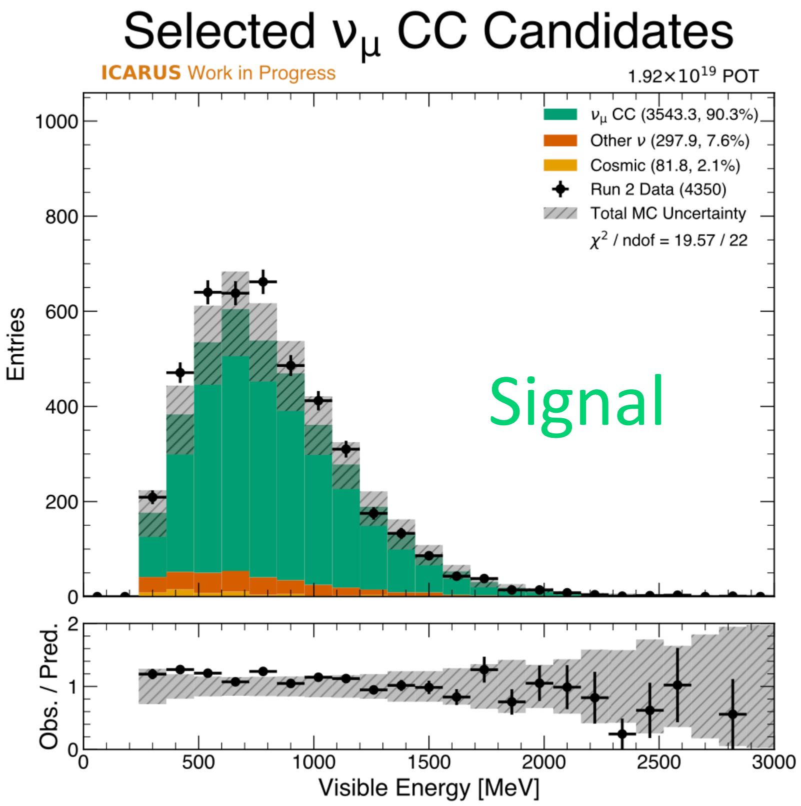
If the underlying parameters are not correlated, the total covariance matrix is the sum over all covariance matrices

Uncertainty	Description	$1\mu 1p$ [%]	$1\mu Np$ [%]	ν_μ CC [%]
Detector	Uncertainties related to the modeling of the detector response	8.1	8.6	6.9
Flux	Uncertainties related to the modeling of the neutrino flux	6.7	6.9	7.3
Cross Section	Uncertainties related to neutrino interaction modeling	14.7	15.7	14.6
Statistical	Statistical uncertainties associated with the Monte Carlo simulation sample	2.4	2.0	1.6
Off-beam Statistical	Statistical uncertainties associated with the off-beam sample used to estimate cosmic backgrounds	0.3	0.4	0.5
Total		18.6	19.6	18.3

Comparison of Run 1/2 Data and Monte Carlo Simulation





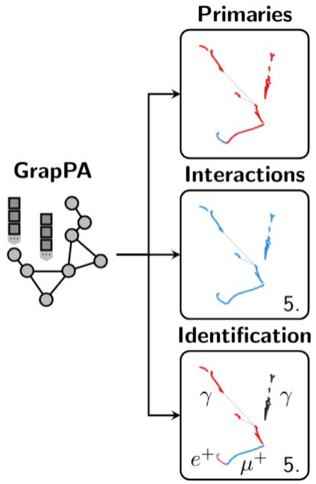


Neutral Pions at ICARUS

There are many reasons to study neutral pions in the SBN Program:

- π^0 production creates background for $\nu_\mu \rightarrow \nu_e$ oscillation search
- Cross section analysis / improving neutrino-nucleus interaction modeling
- Calibrations: Invariant mass provides standard candle for shower energy scale

Analysis Example: ICARUS ν_μ CC π^0



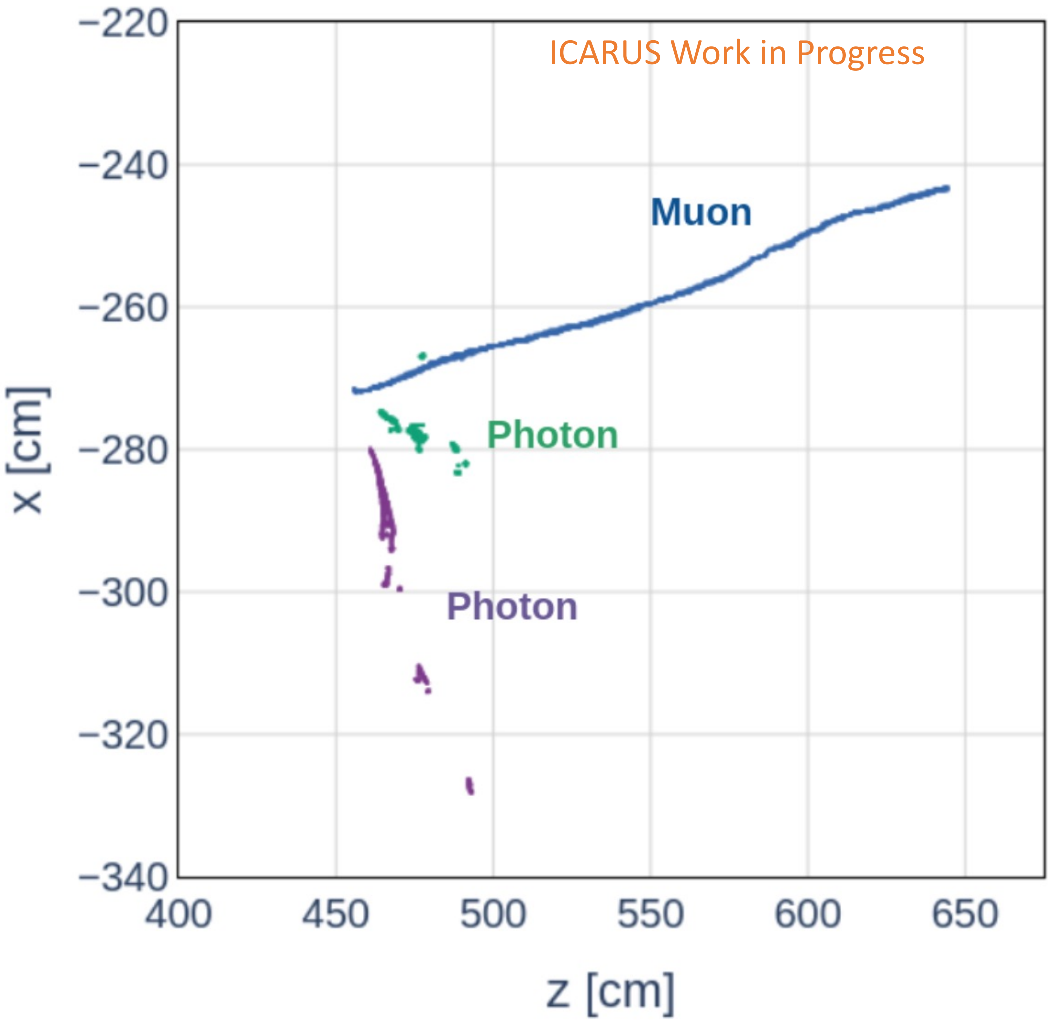
$1\mu1\pi^0$ Selection

Topology: One primary muon (> 50 cm), at least two primary photons (> 40 MeV)

Containment: Interaction contained within 5 cm of detector boundaries

Fiducial Volume: Interaction vertex within 25 cm from beam-transverse detector boundaries, 30 cm from beam-side, and 50 cm from downstream edge

Flash Cut: Interaction matched to flash within beam window



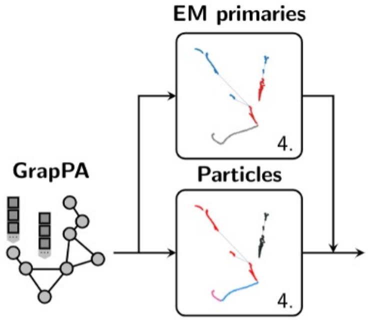
Analysis Example: ICARUS ν_μ CC π^0

In $\pi^0 \rightarrow \gamma\gamma$ decay, the invariant diphoton mass is

$$m_{\gamma\gamma} = \sqrt{2\underbrace{E_1 E_2}_{\text{Reconstructed Photon Energy}}(1 - \underbrace{\cos\theta}_{\text{Reconstructed Opening Angle}})}$$

Important note on calibration:
If θ is known precisely, then any data/MC comparisons of $m_{\gamma\gamma}$ inform us about EM shower energy scale bias

Analysis Example: ICARUS ν_μ CC π^0



Reconstructed Opening Angle

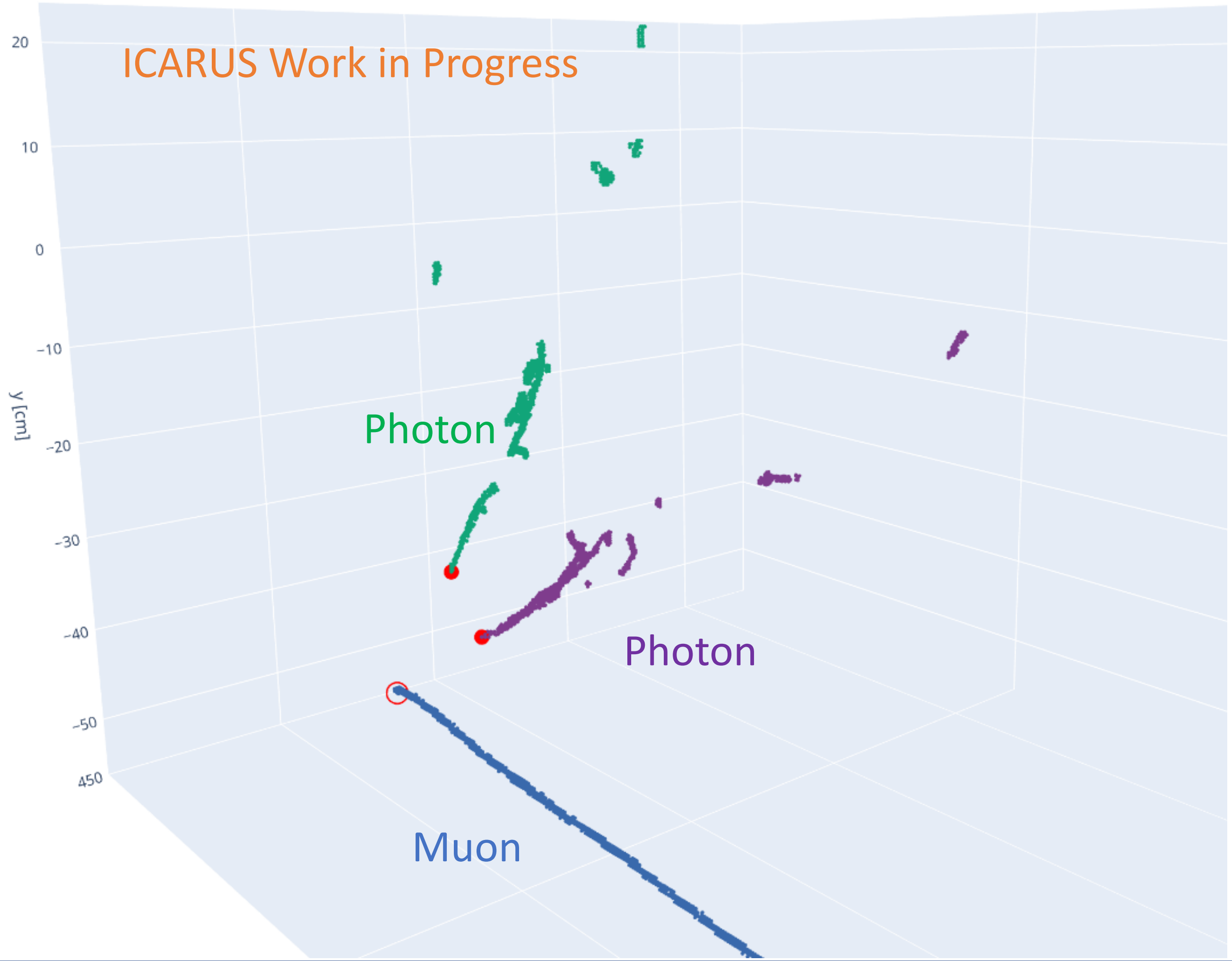
Two approaches to calculate directional vector for photons:

1.Clustering methods (NC or CC)

→ Rely on clustering of shower Space Points, often near the start of the shower (example: PCA direction)

2.Start point method (only CC)

→ Form vector between muon track start point (interaction vertex) and shower start point



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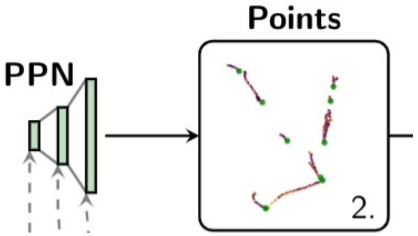

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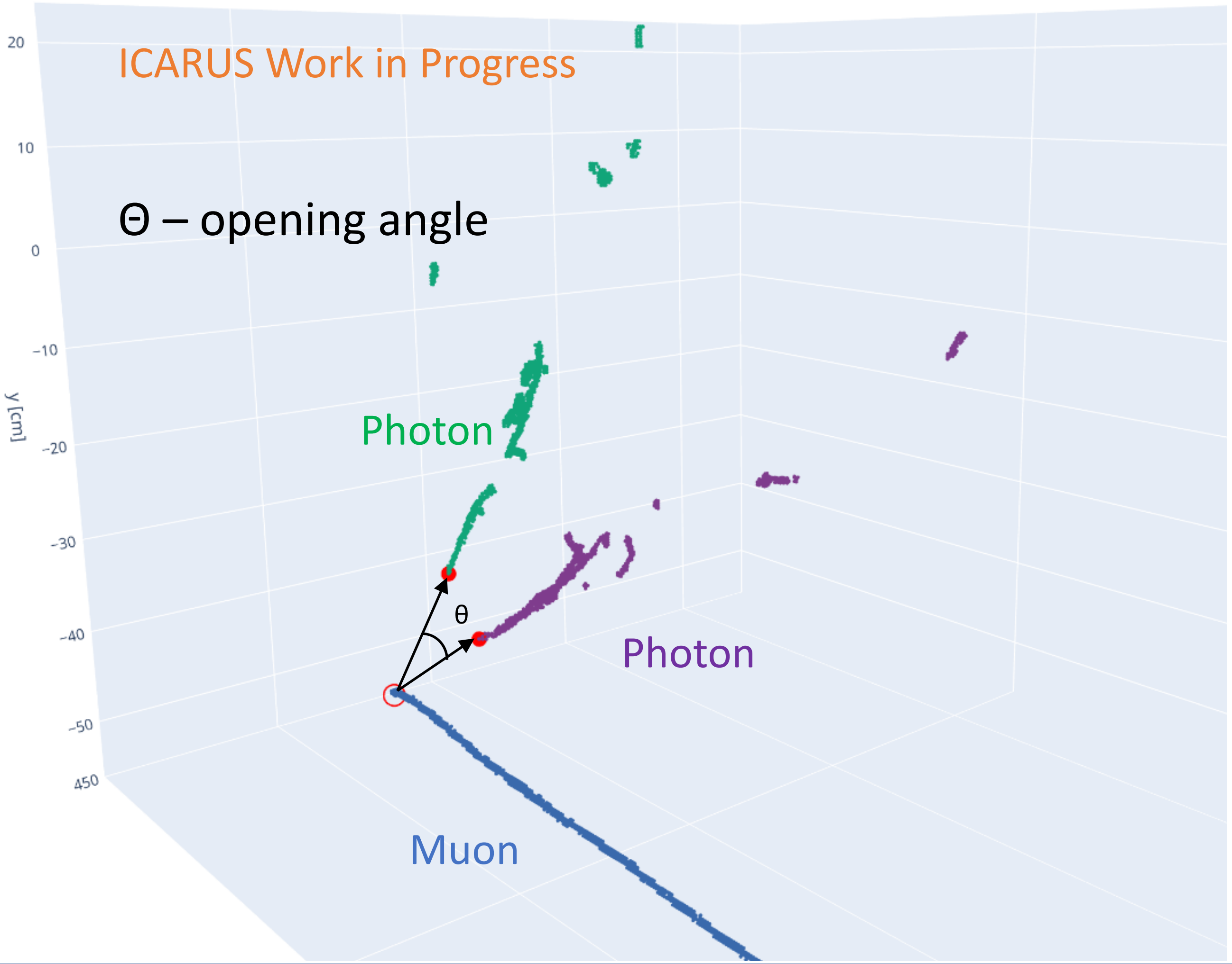

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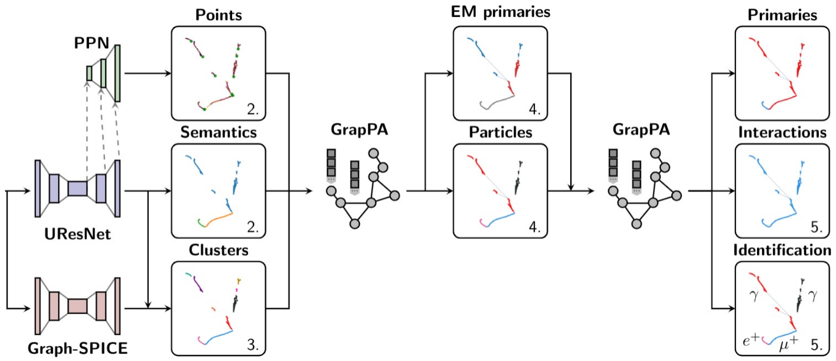


Reconstructed Shower Energy

For both photons and electrons, reconstructed energy generally takes the form of

$$E_{shower} = \underbrace{W_i\left[\frac{MeV}{e^-}\right]}_{\text{Ar Work Function}} \cdot \underbrace{C_{cal}\left[\frac{e^-}{ADC}\right]}_{\text{Calorimetric Constant (TPC Gain)}} \cdot \underbrace{C_{adj}}_{\text{Adjustment Factor Due to Minimum Threshold (Data Driven)}} \cdot \underbrace{\frac{1}{R}}_{\text{Recombination}} \cdot \sum_{dep} \underbrace{e^{\frac{t_{drift}}{\tau}}}_{\text{Electron Lifetime Correction}} \cdot \underbrace{dep[ADC]}_{\text{Deposited Charge}}$$

Analysis Example: ICARUS ν_μ CC π^0

Reconstructed Invariant Mass

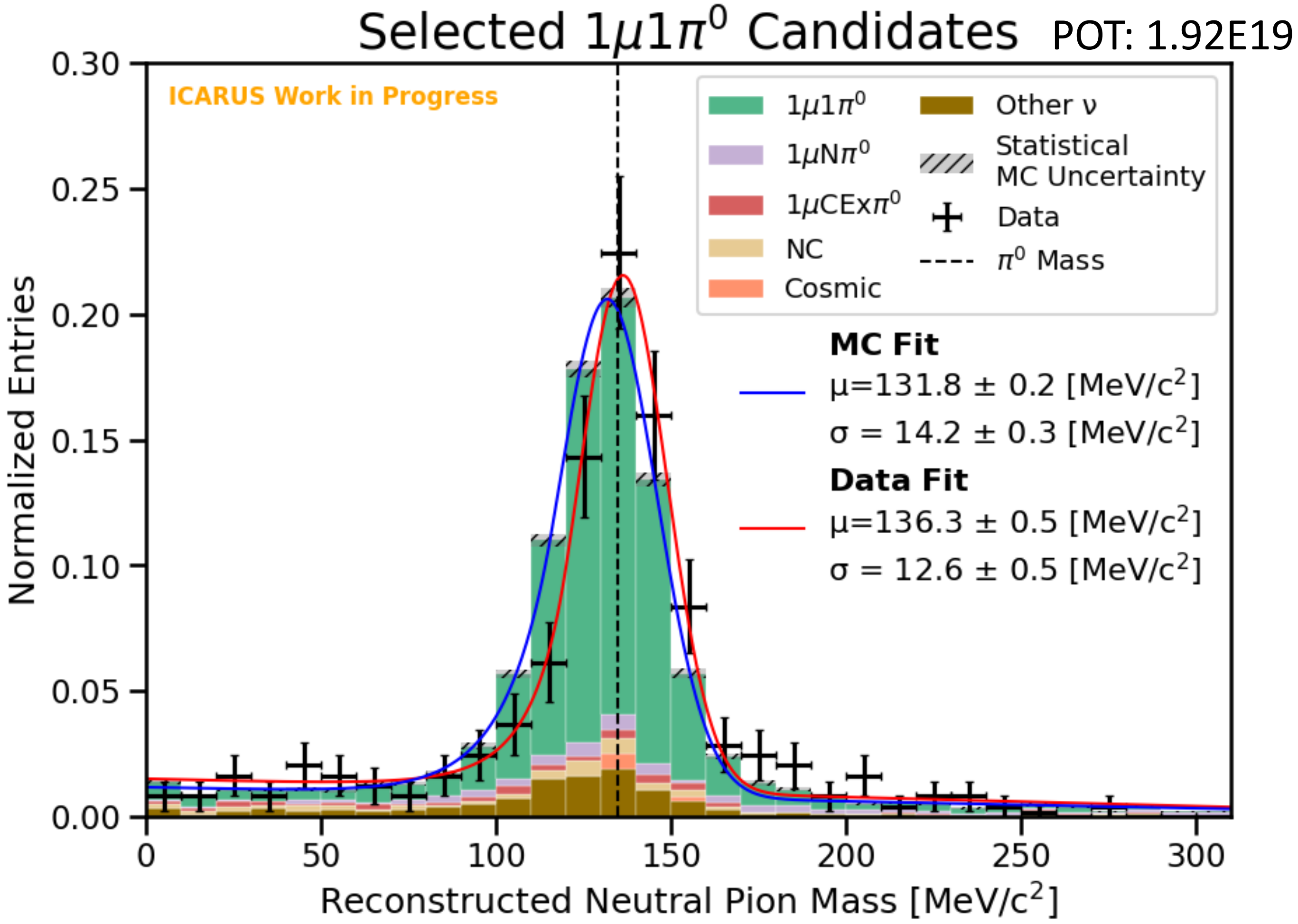
Using previously-defined expressions for reconstructed shower energy and opening angle, the invariant mass is reconstructed

Crystal Ball fits are performed for both data and MC

→ Small EM shower energy scale bias (~3%)

→ Excellent EM shower energy resolution (~10%)

→ Fit to true π^0 mass can be used to tweak shower energy calibration (see right)



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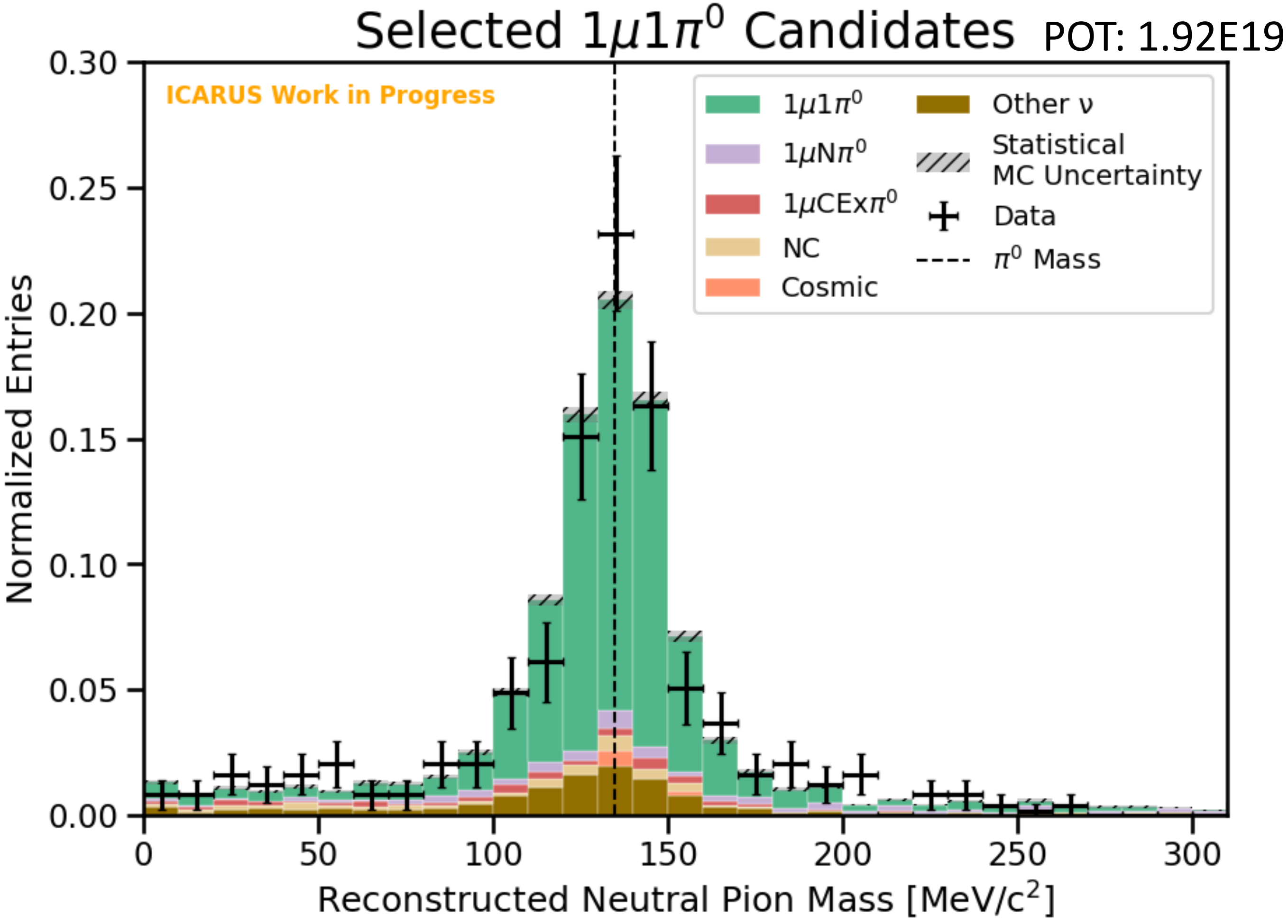
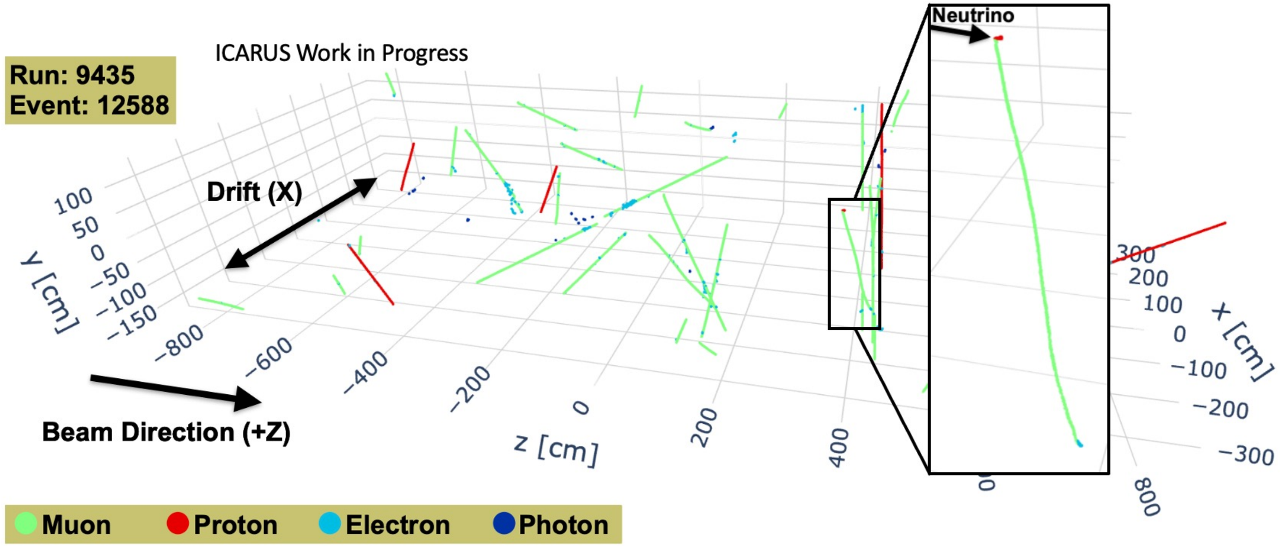


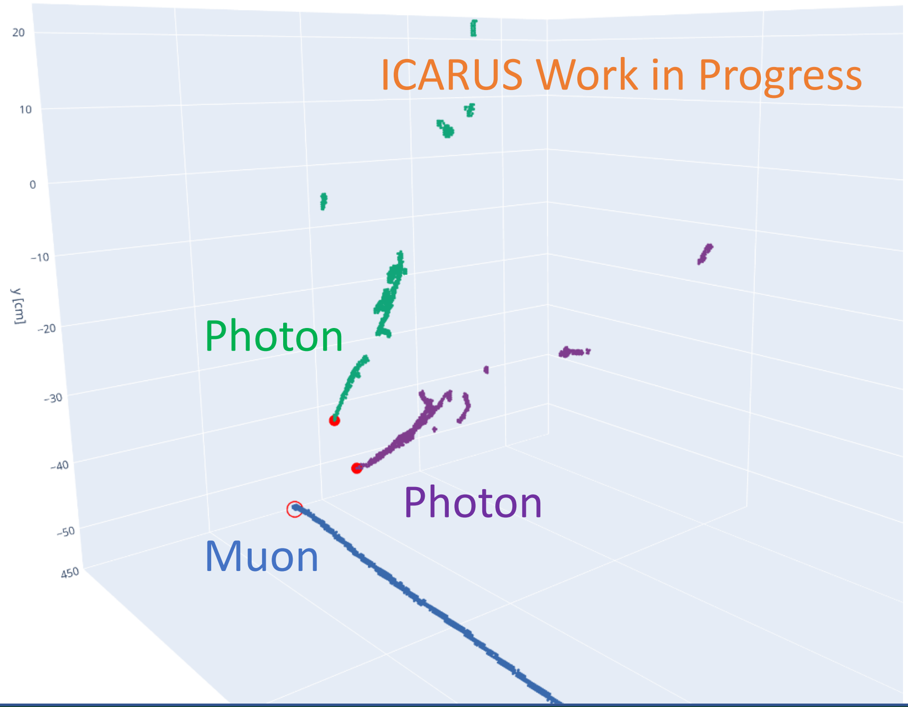
Conclusions

We have shown at ICARUS we can reconstruct muon neutrino events with SPINE, and create a selection with three distinct topologies (1μ1p, 1μNp, and ν_μ CC inclusive) with good purity and efficiency



- With these three selections we see no major differences between Monte Carlo simulations and data

We can create a selection on neutral pion showers from ν_μ CC events, and reconstruct the showers to create a mass peak that aligns well with data



- Small shift in shower energy calibration to match data, 3% energy systematic applicable strictly to showers