Muon Neutrino Charged-Current Neutral Pion Analysis at ICARUS

Lane Kashur
ICARUS Collaboration Meeting
16 October 2024

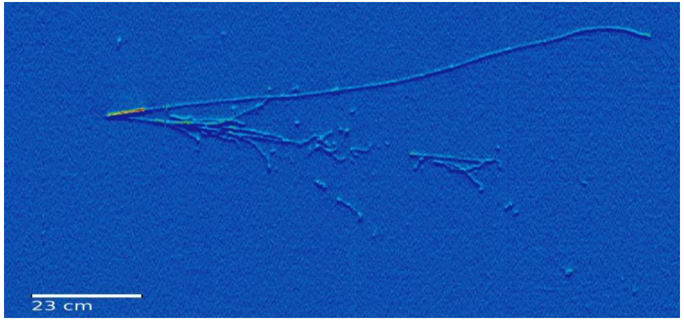
Colorado State University

Neutral Pions at ICARUS

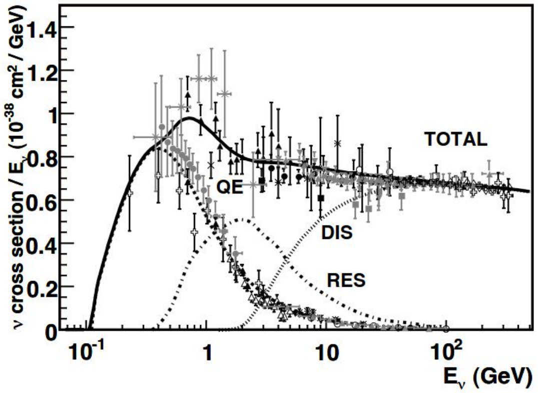
Motivation

There are many reasons to study neutral pions at ICARUS

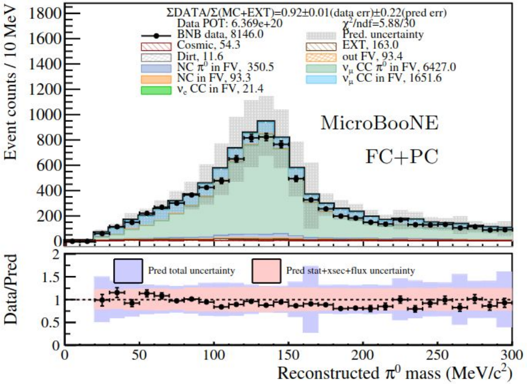
- π^0 production creates background for $\nu_\mu \to \nu_e$ oscillation search
- Cross section analysis / improving neutrino-nucleus interaction modeling
- Calibrations: Invariant mass provides standard candle for shower energy scale



Ambiguous event in ICARUS data, but likely $1\mu1\pi^0$
Credit: Christian Farnese



Neutrino cross sections as a function of energy
https://doi.org/10.1103/RevModPhys.84.1307



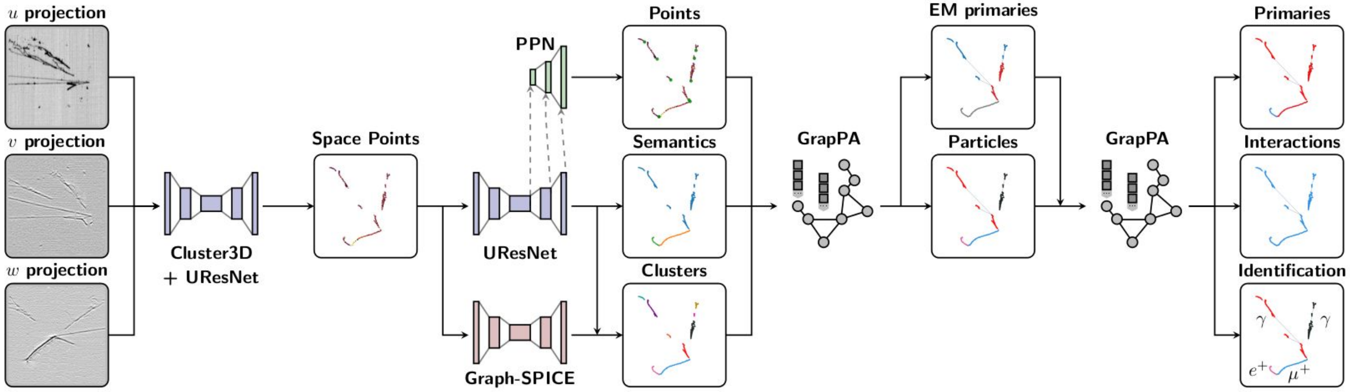
Example π^0 mass peak from MicroBooNE
https://doi.org/10.1103/PhysRevD.105.112005

Machine Learning Reconstruction

Selection and reconstruction of muon neutrino charged-current interactions containing neutral pions has been carried out with **SPINE** (Scalable Particle Imaging with Neural Embeddings)

After combining 2D projections from each wire plane, SPINE algorithms...

1. Separate topologically distinguishable types of activity
2. Identify points of interest (start/end points)
3. Cluster individual particles (tracks and showers)
4. Group individual particles into interactions



SPINE reconstruction chain (arXiv:2102.01033)

Signal Definition and Selection

Signal Definition: $1\mu 1\pi^0$

Topology

- Exactly one primary muon with length > 50 cm (for consistency across analyses)
- Exactly one primary neutral pion with decay photons having energy > 25 MeV
- Inclusive to all other particles

Fiducial Volume: Require interaction vertex to be at least 25 cm from X,Y detector boundaries and 30 [50] cm from upstream [downstream] Z detector boundaries

Containment: Require muon to be at least 5 cm from detector boundaries

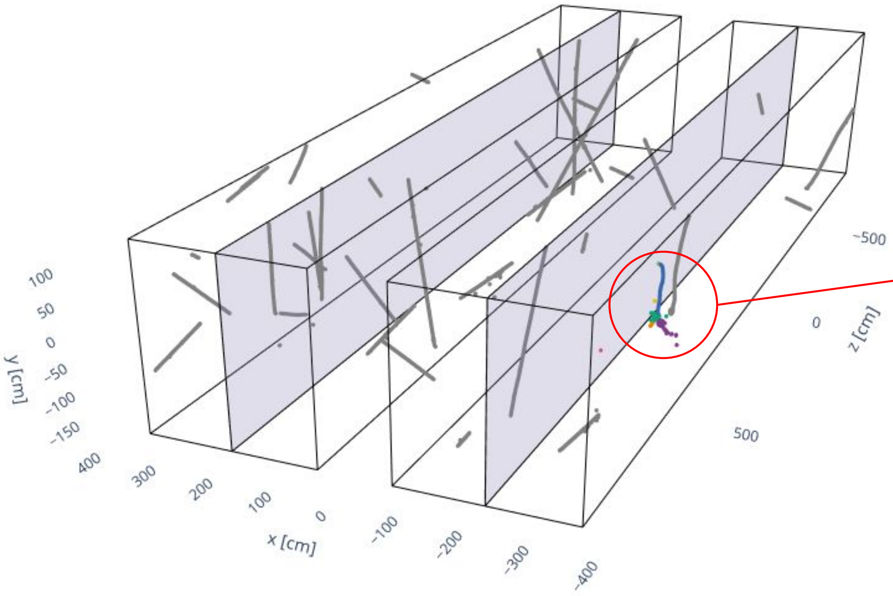
Selection

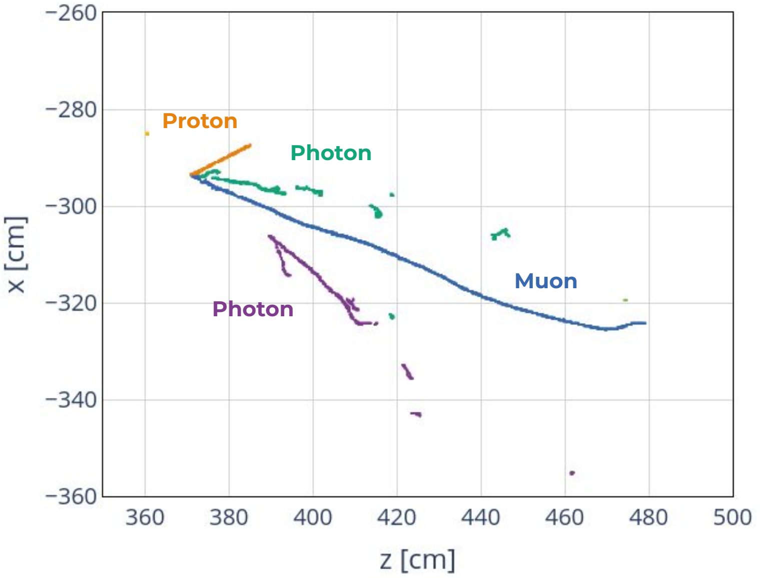
Require interaction to contain exactly 1 muon and at exactly two photons (satisfying thresholding, fiducialization, and containment cuts from signal definition)*

In-time: Require interaction to be matched to an in-time optical flash

Signal Definition and Selection

Example of a reconstructed $1\mu 1\pi^0$ interaction in ICARUS Monte Carlo





Selection Performance

Selection performance is measured using Monte Carlo simulation

- BNB ν + cosmics (icaruscode v09_84_00_01)
- NuMI ν + cosmics (icaruscode v09_89_00_01)

Purity: What fraction of selected interactions are matched to true signal interaction?

Efficiency: What fraction of true signal interactions are matched to selected interactions?

Cut	BNB Purity	BNB Efficiency	NuMI Purity	NuMI Efficiency
Flash Time	2.09%	96.8%	0.92%	96.14%
Fiducial Volume	3.21%	96.06%	1.98%	95.5%
Topology	46.66%	56.99%	22.44%	56.47%
Containment	87.47%	54.68%	73.35%	49.84%

Shower Energy Reconstruction

To select $1\mu1\pi^0$ interactions, it is necessary to measure the energy of π^0 decay photons

The following expression is used for reconstructed shower energy (photons and electrons):

$$E_{shower} = W_i[\frac{MeV}{e^-}] \cdot C_{cal}[\frac{e^-}{ADC}] \cdot C_{adj} \cdot \frac{1}{R} \cdot \sum_{dep} e^{\frac{t_{drift}}{\tau}} \cdot dep[ADC]$$

Ar Work Function

Calorimetric Constant (TPC Gain)

Adjustment Factor

Recombination Correction

Electron Lifetime Correction

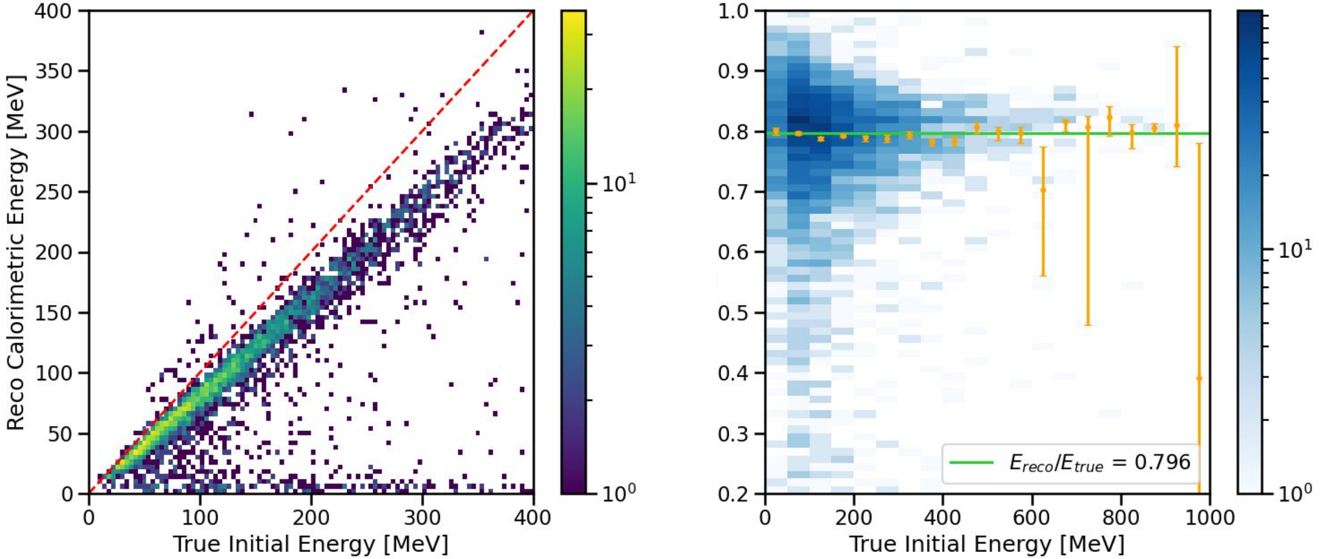
Deposited Charge

Shower Energy Reconstruction

Shower Adjustment Factor

Corrects for energy missing due to thresholding and clustering effects in reconstruction

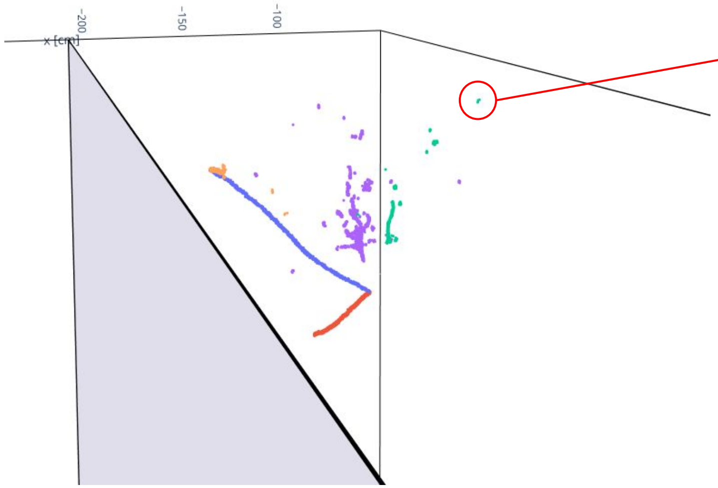
→ Derived by comparing reconstructed shower energy to true shower energy for contained, simulated photons



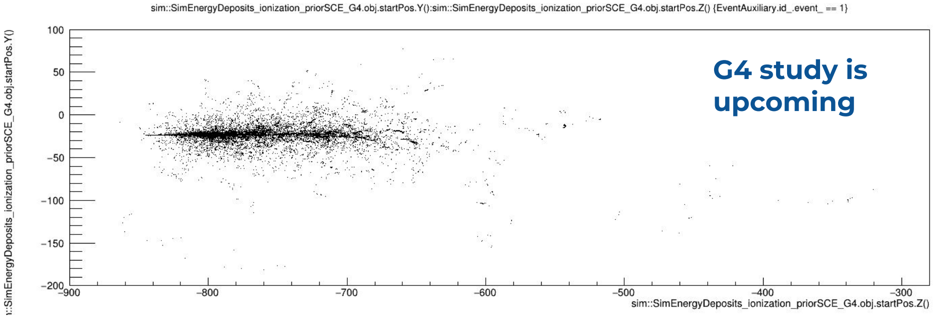
Shower Energy Reconstruction

To Do: Shower Containment Factor

Corrects for energy missing due to lack of shower containment cut
→ Plan to derive with dedicated G4 study

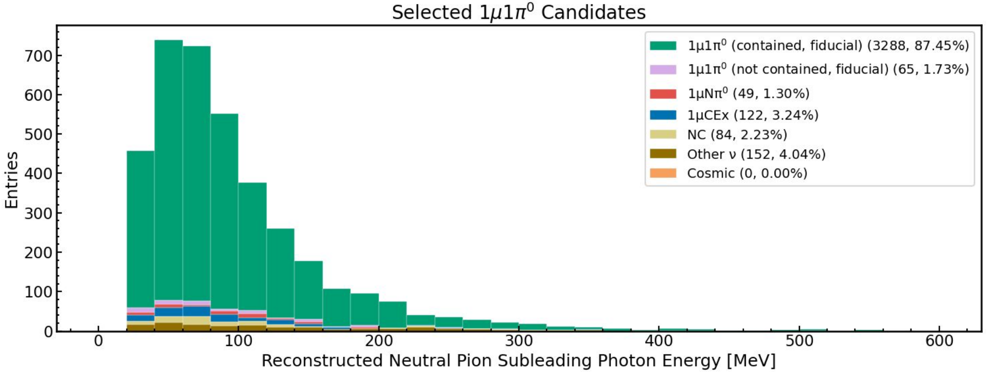


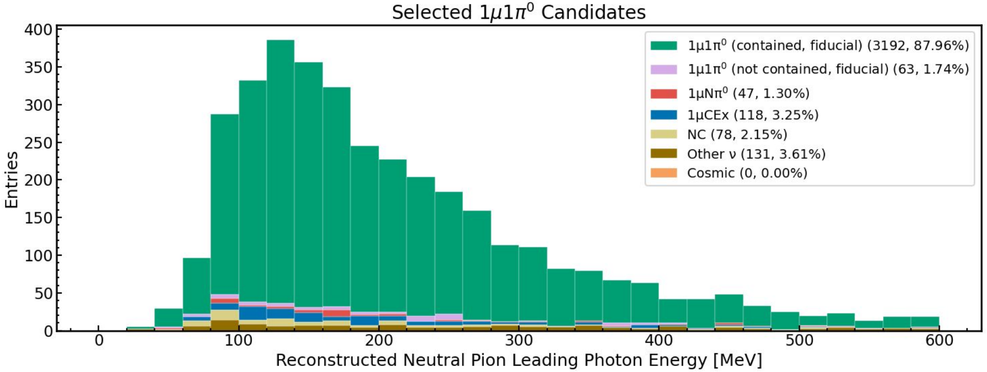
Example of interaction that would fail a traditional containment cut (e.g. 5 cm from detector boundary)

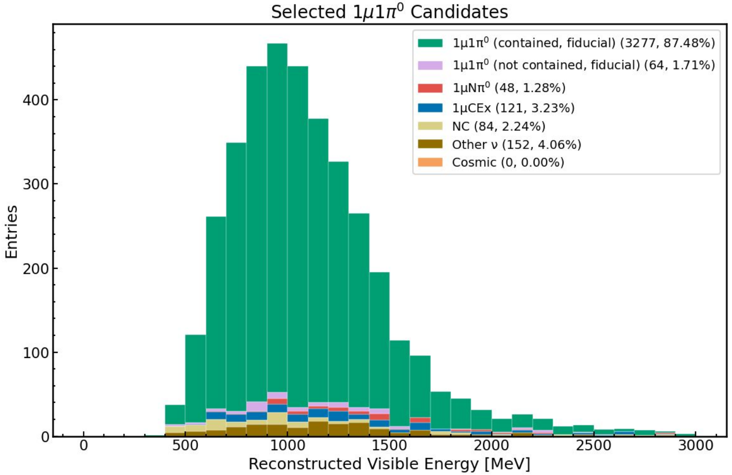


G4 study is upcoming

Reconstructed Variables (BNB)







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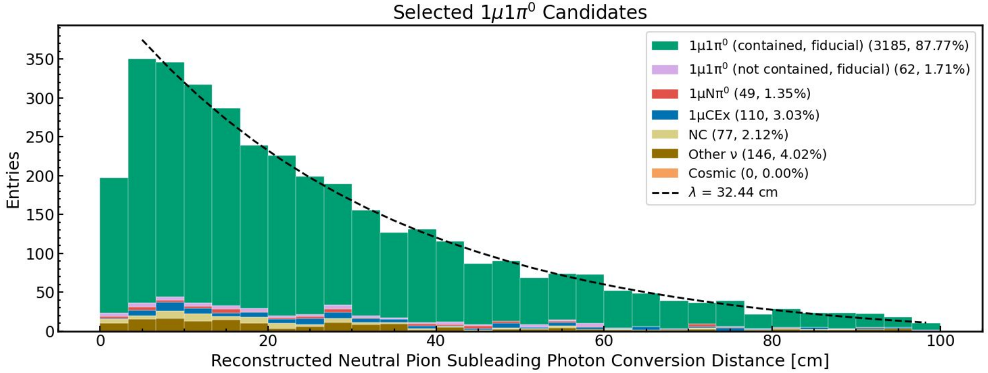

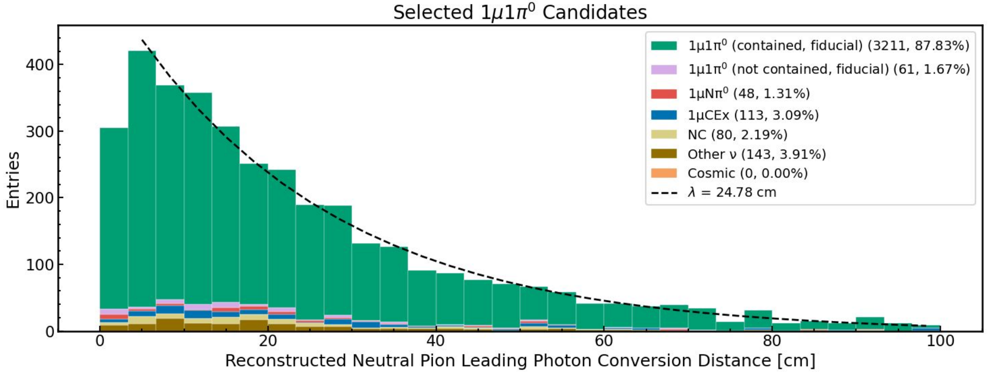

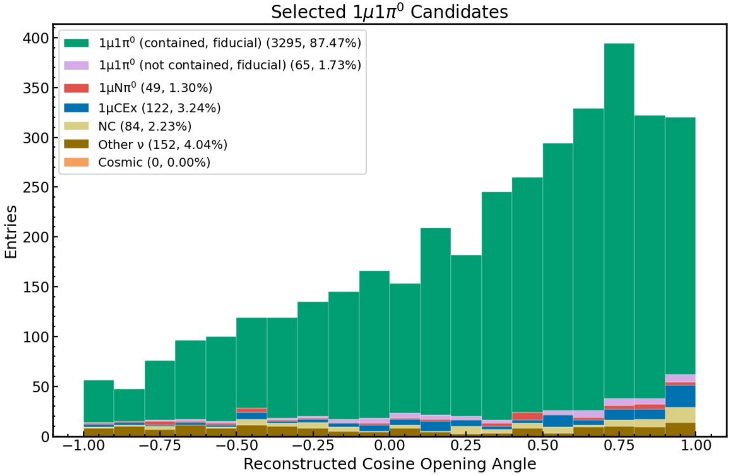

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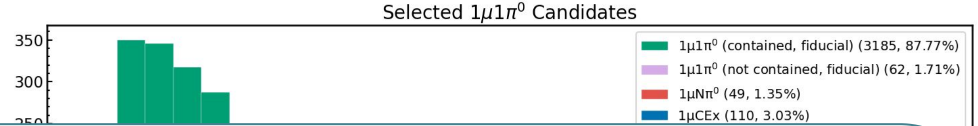
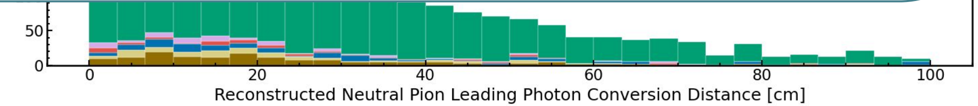
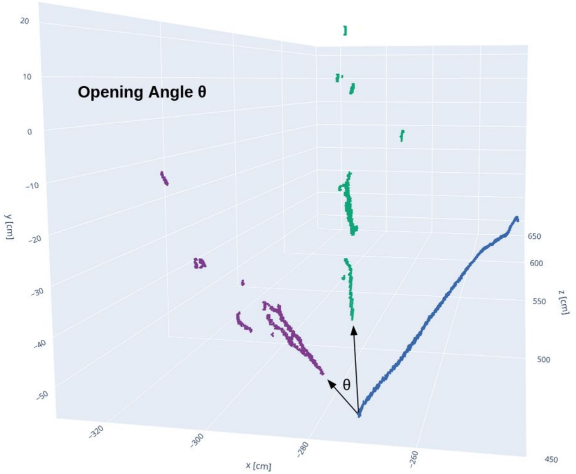


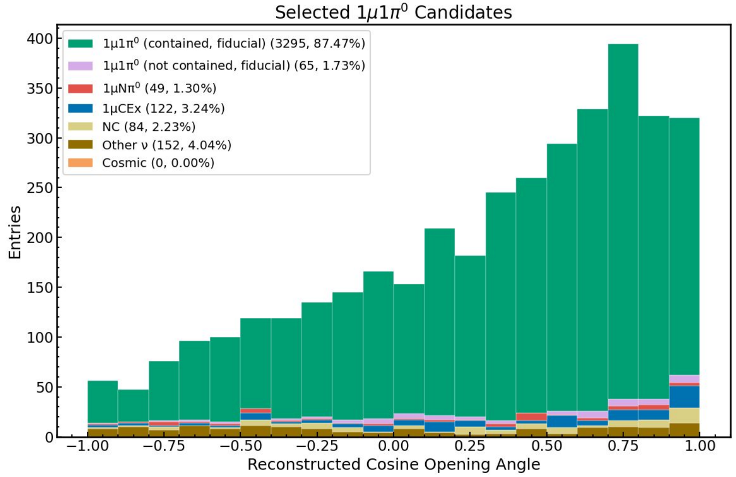




Reconstructed Opening Angle

Two approaches to calculate directional vector for photons:

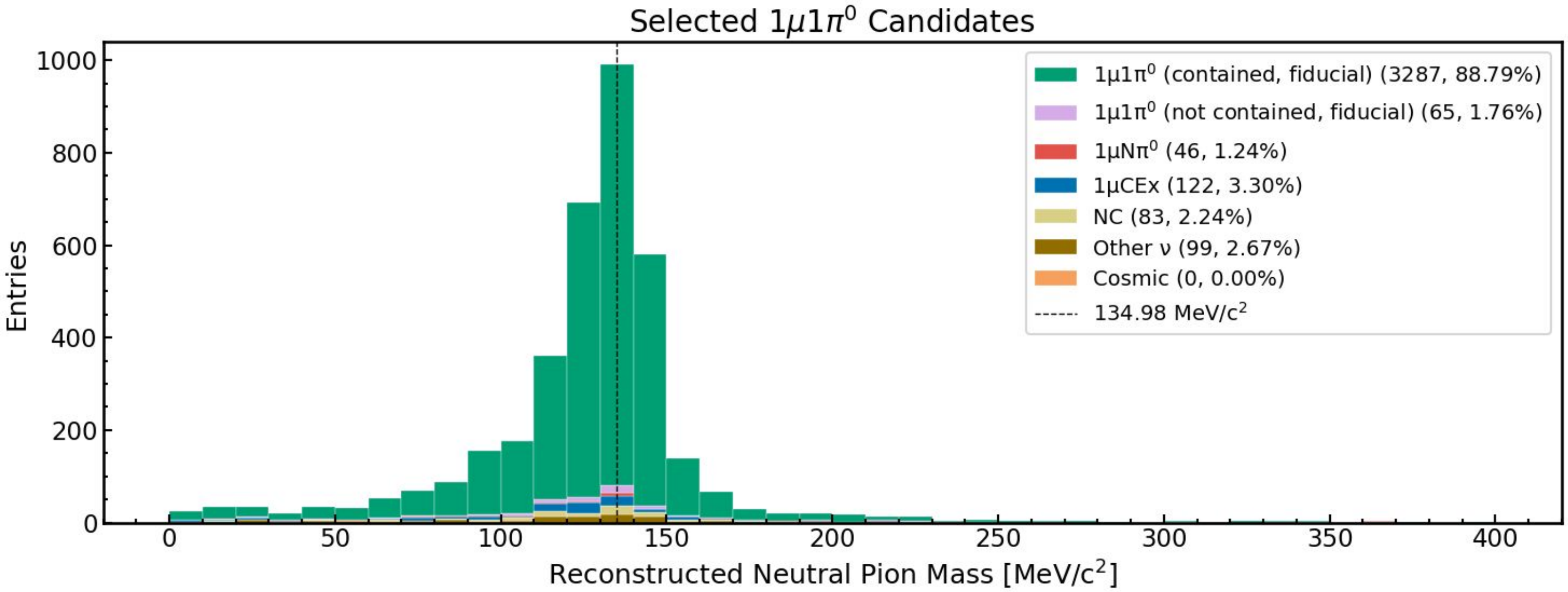
1. Clustering methods (e.g. PCA)
2. **Start point method**
   → Use interaction vertex and shower start points



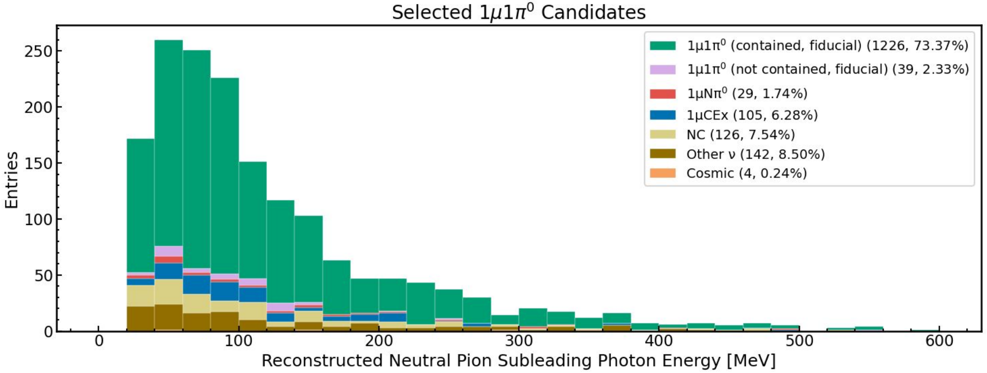
Reconstructed Variables (BNB)

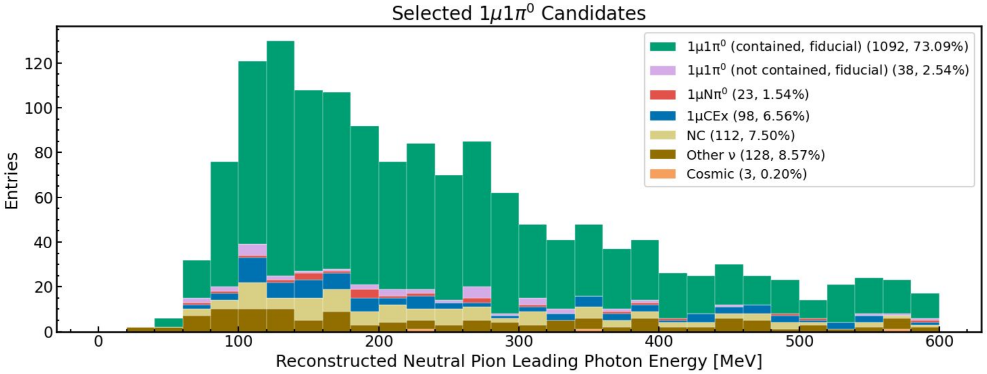
Invariant Mass

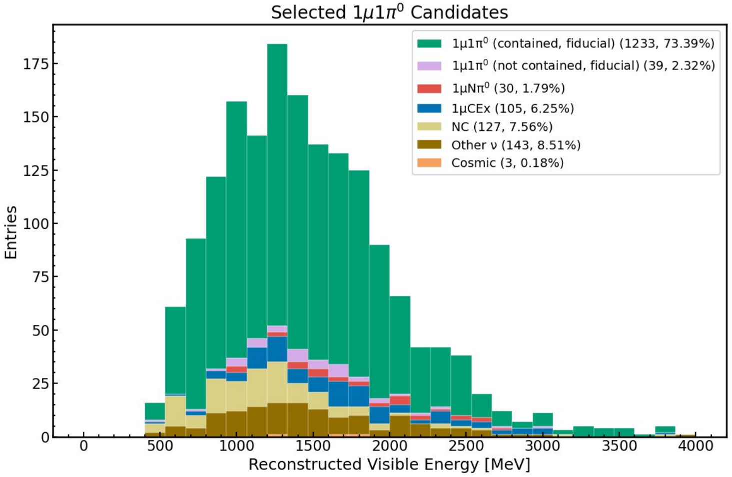
Use previously-defined shower energy and opening angle → $m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)}$



Reconstructed Variables (NuMI)







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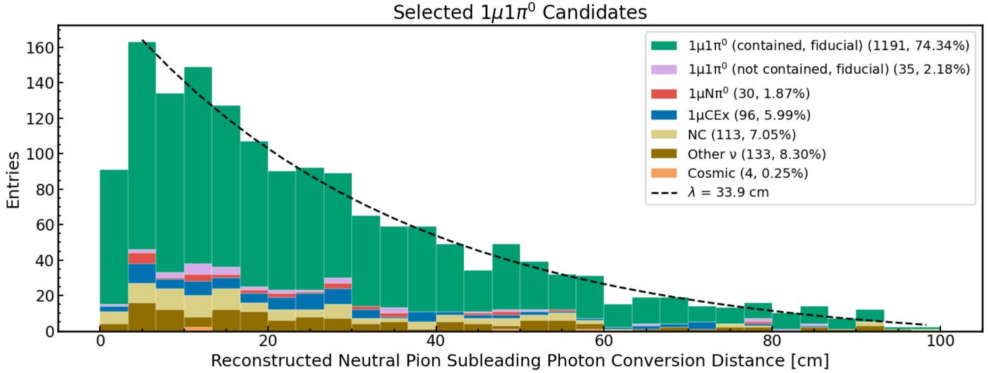

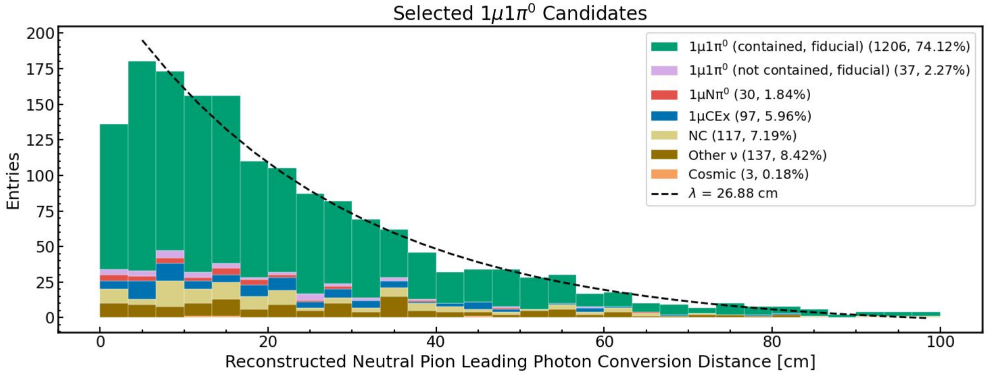

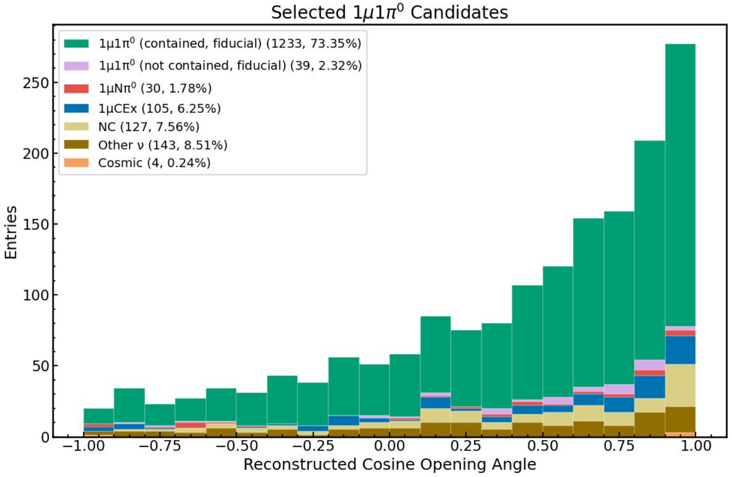

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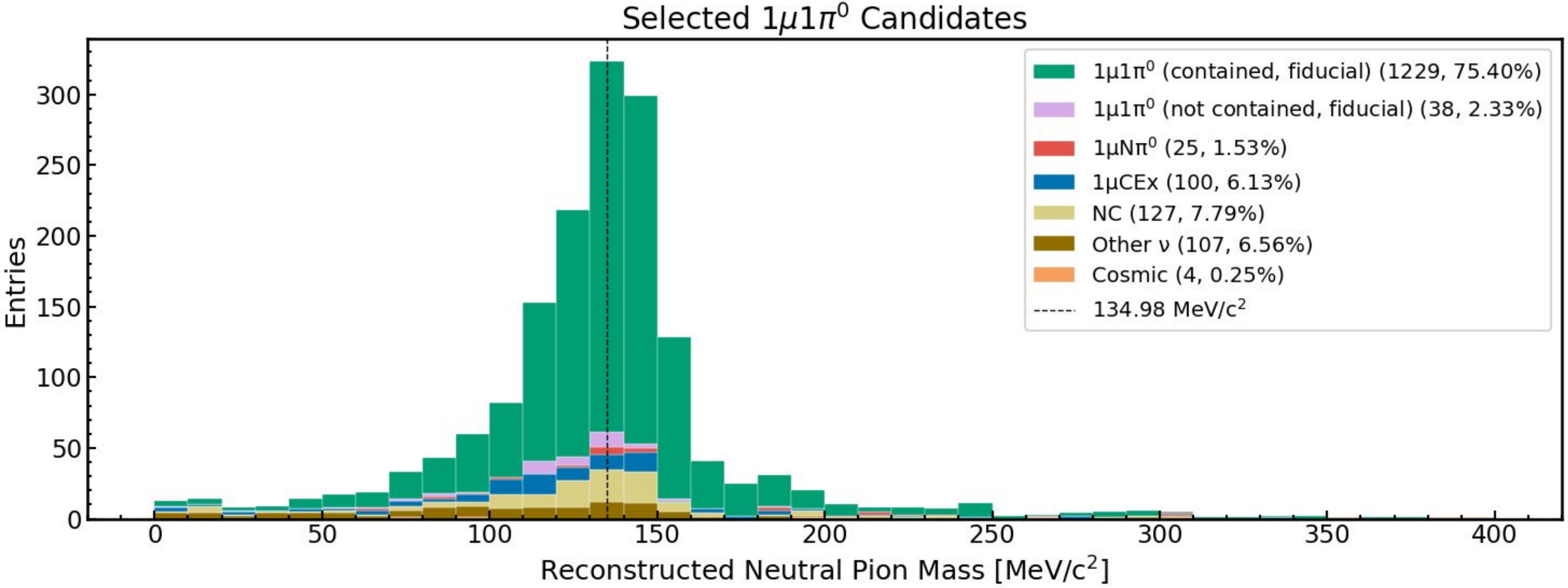
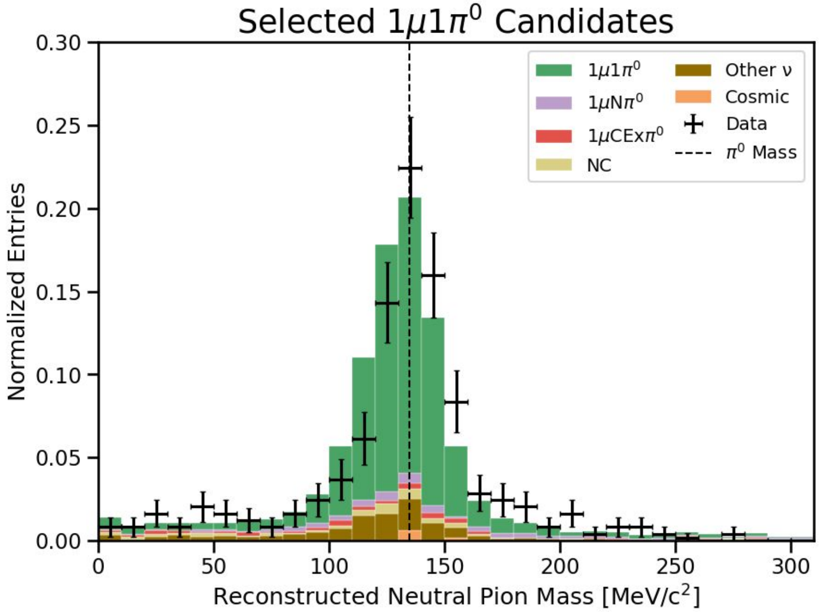


Revisiting Data/MC Comparisons

Data/MC comparisons were made previously for Summer 2024 conferences



Data

BNB Run 2 - 1.92 x 10^{19} POT
(10% unblinded)

Monte Carlo

BNB ν + cosmics simulation

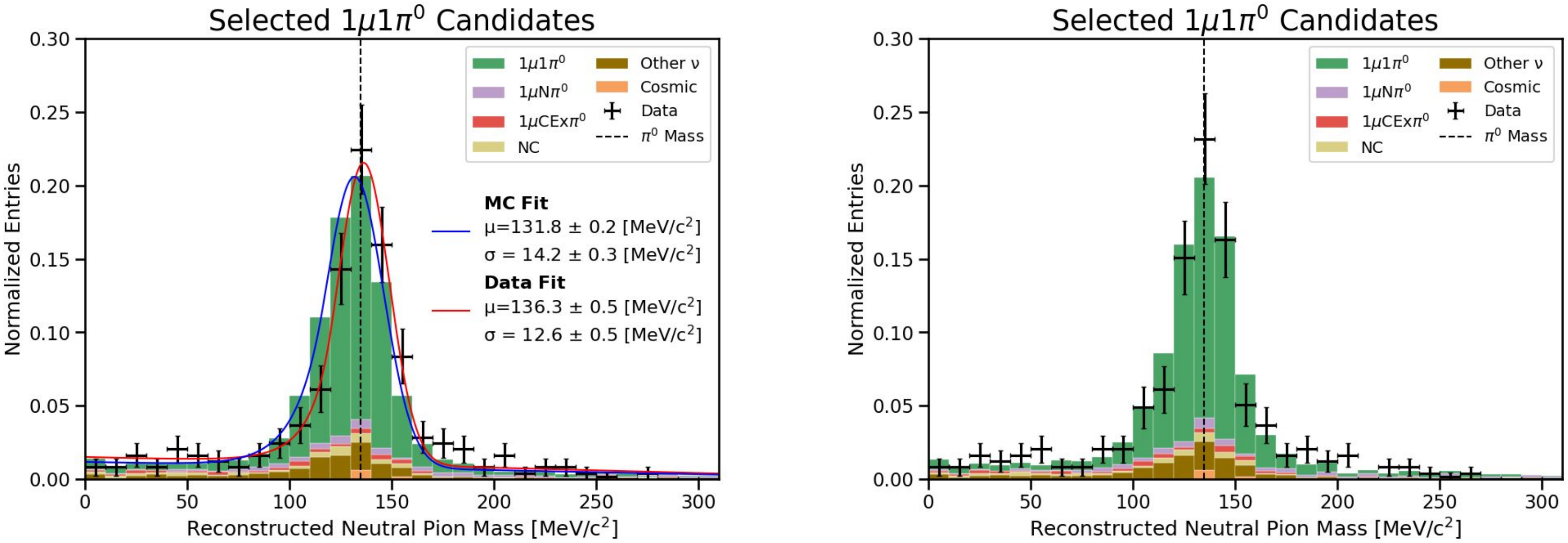
Data/MC comparisons make use of CAFs for unblinding, POT scaling

Important Note: Given a refactoring to SPINE, updates are needed to the ML CAF-making framework
→ Work is in-progress, but the data/MC comparisons presented here are made using legacy code

Revisiting Data/MC Comparisons

Invariant Mass Constraint

Crystal Ball fits to invariant mass distributions show small EM shower energy scale bias (~3%) and excellent EM shower energy resolution (~10%) → Allow for additional correction of shower energy

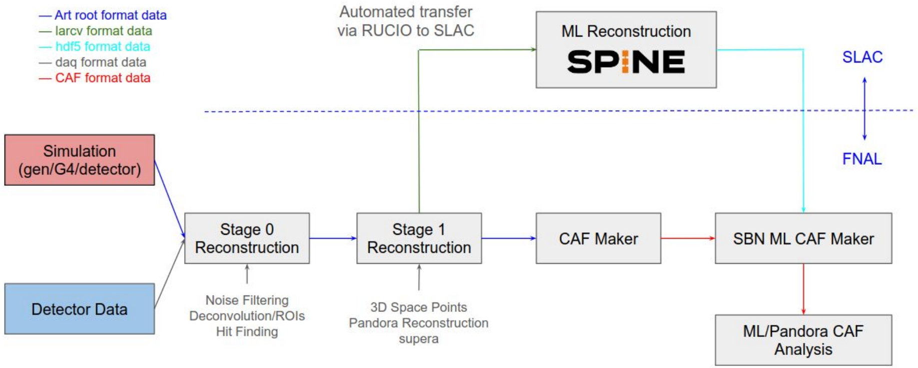


Summary and To-Dos

- Purity and efficiency of $1\mu 1\pi^0$ selection are in good shape
  → Efficiency losses still deserve an in-depth look (confusion matrices, event displays)

- Many outstanding tasks require ML outputs to be merged into CAFs
  - Data/MC comparisons, systematic assessment, etc.
  - Urgent to wrap up SBN ML CAF Maker updates ASAP

- Start work with the cross section group toward a Summer 2025 result!

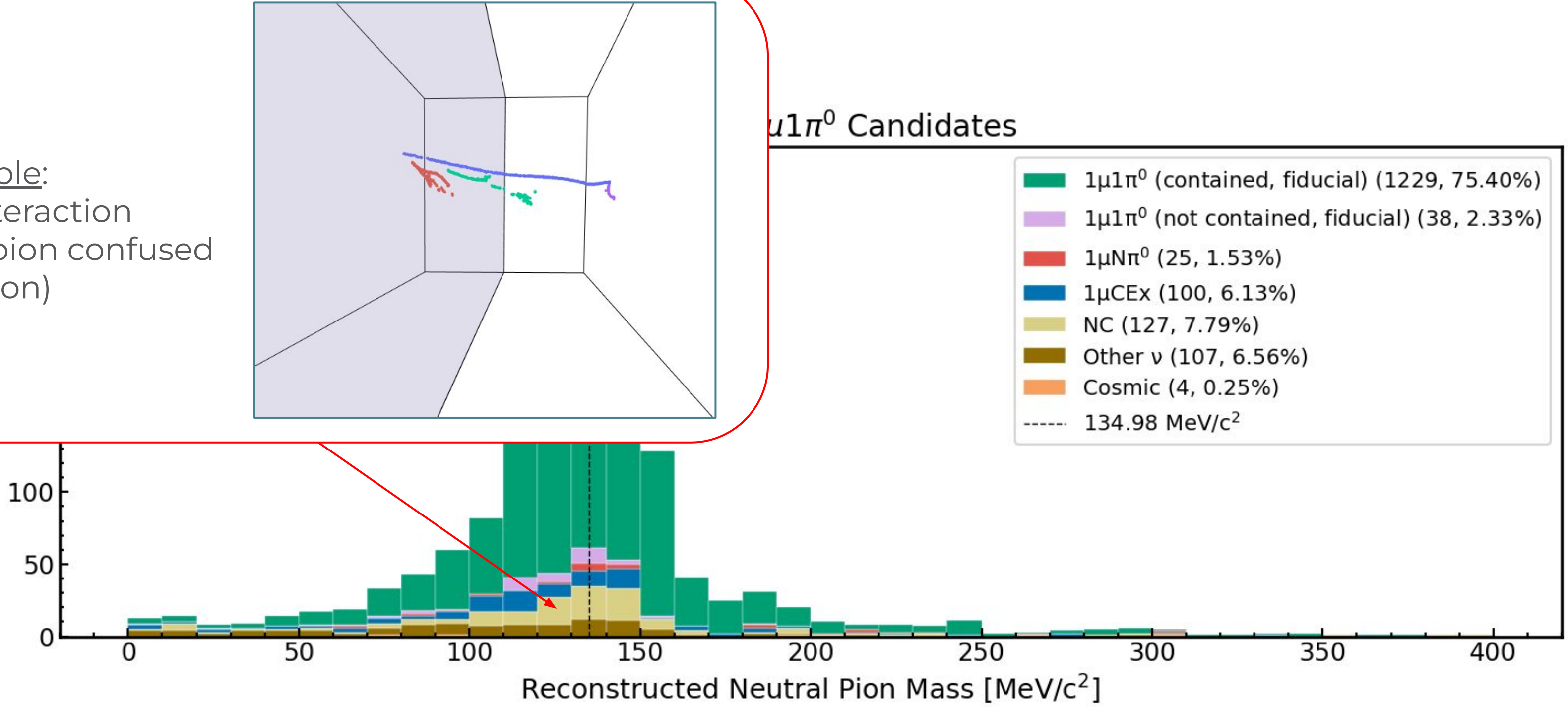


Credit: Justin Mueller

Backup

NuMI Selection Impurities

Example:
NC Interaction
(true pion confused as muon)



NuMI Selection Impurities

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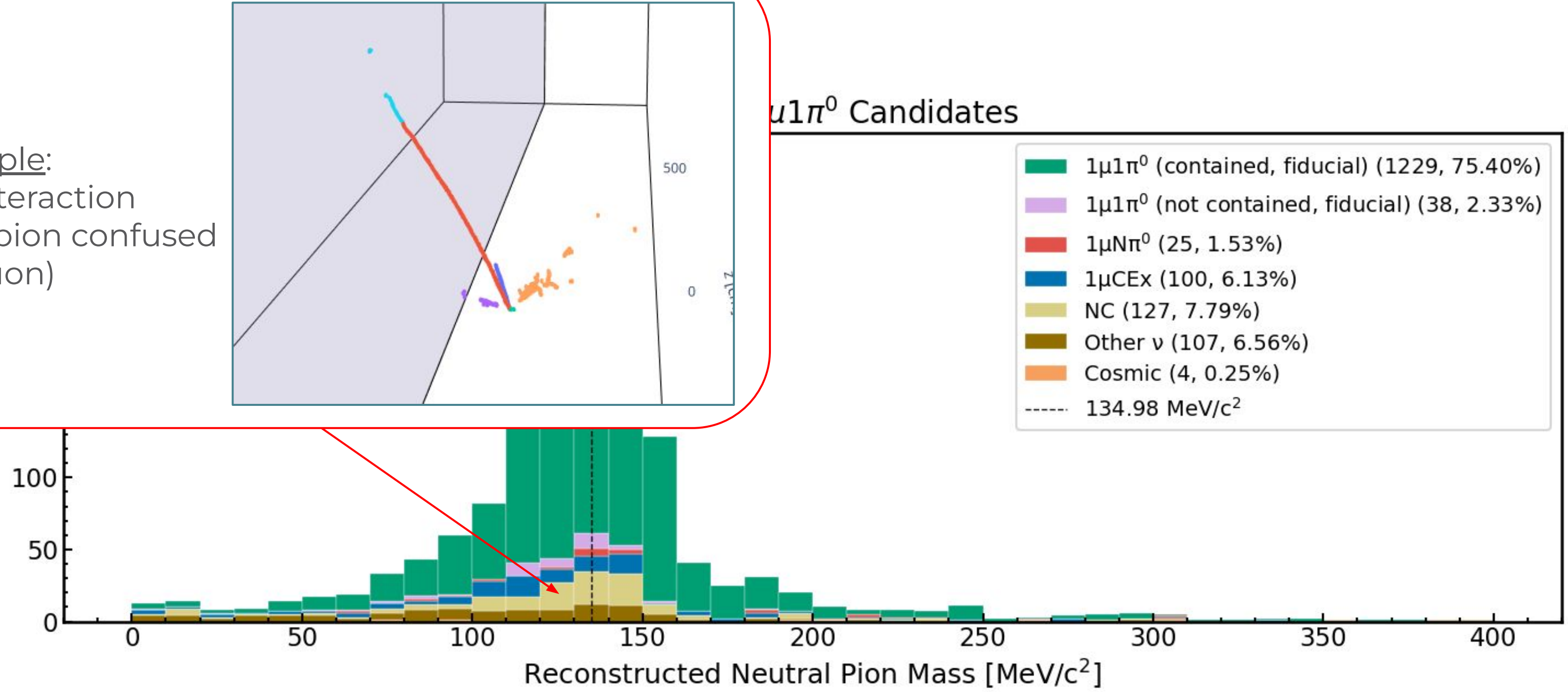
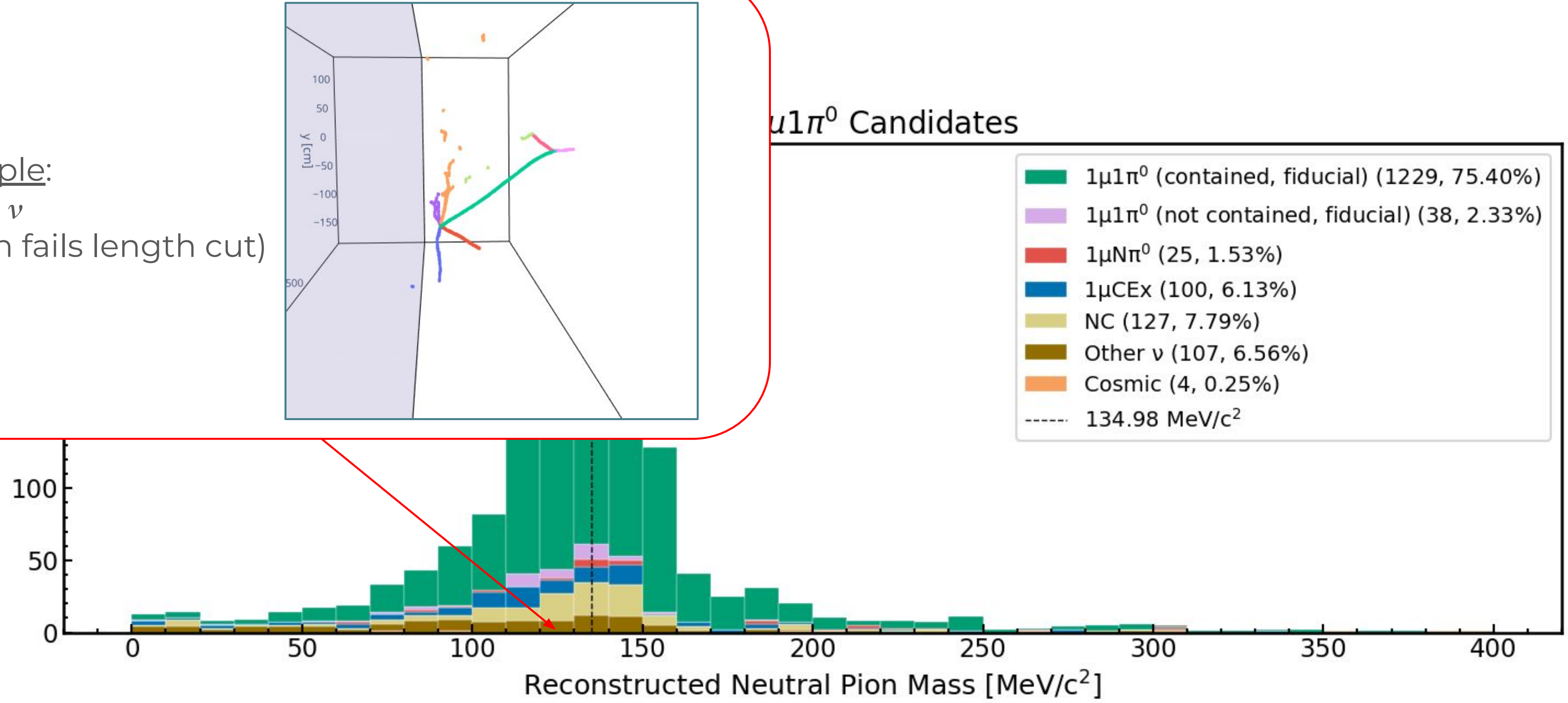


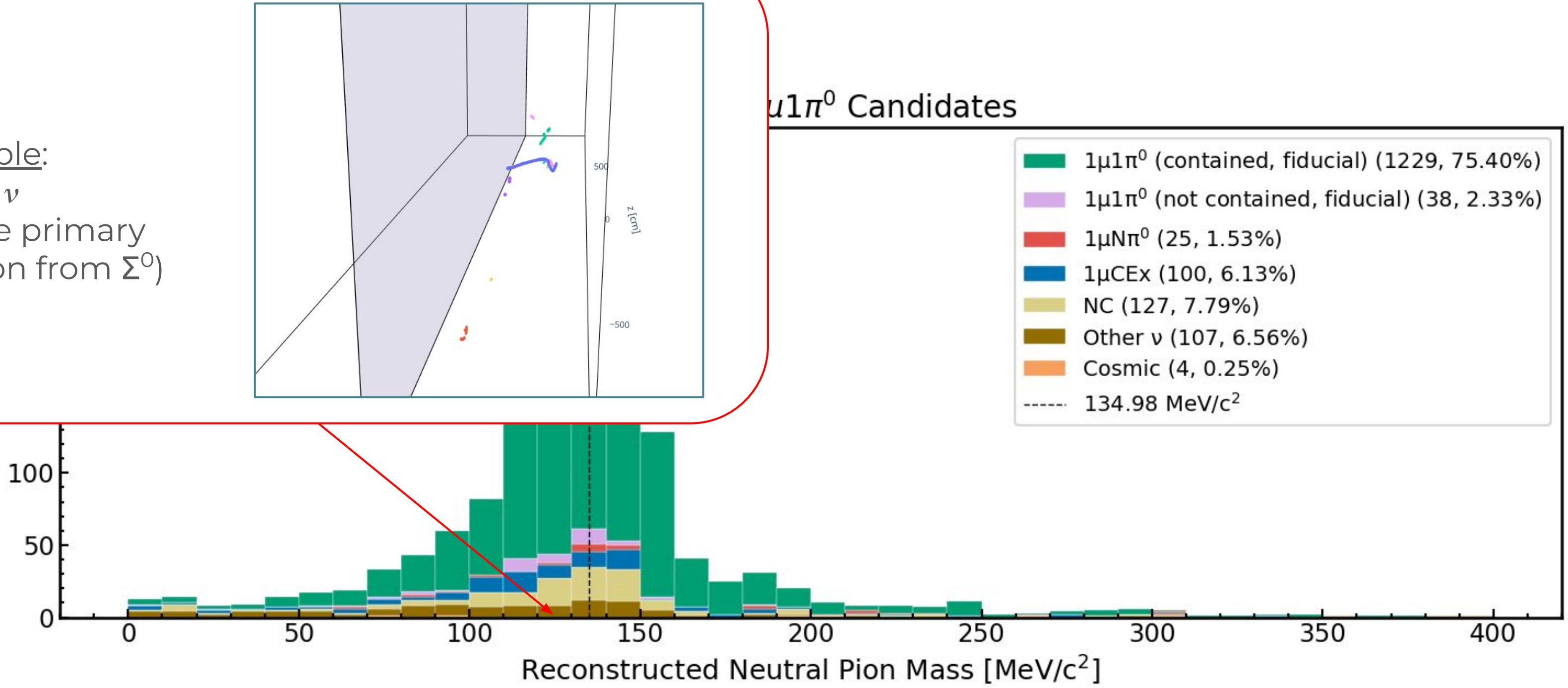
NuMI Selection Impurities

Example:
Other ν
(muon fails length cut)



NuMI Selection Impurities

Example:
Other ν
(Single primary
photon from Σ^0)



NuMI Selection Impurities

Example:
1μCEx
(Primary +
non-primary π^0)