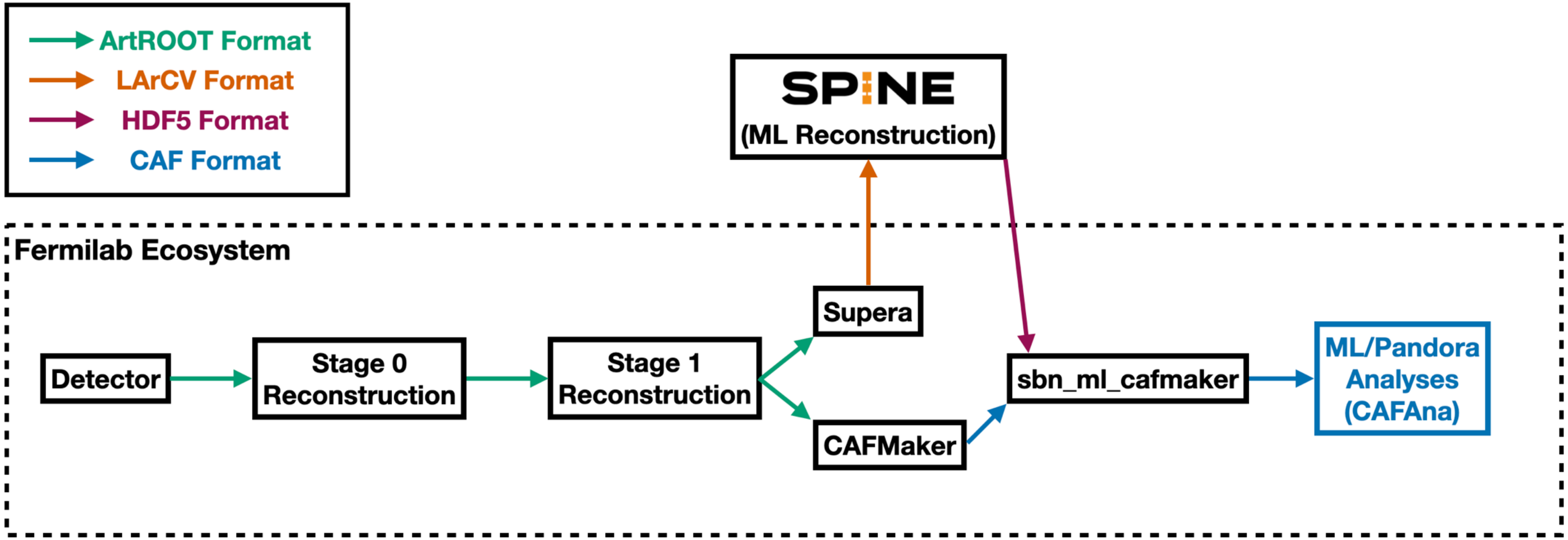
ν_e Selections with SPINE for BNB and NuMI

Dan Carber, October 16th, 2024

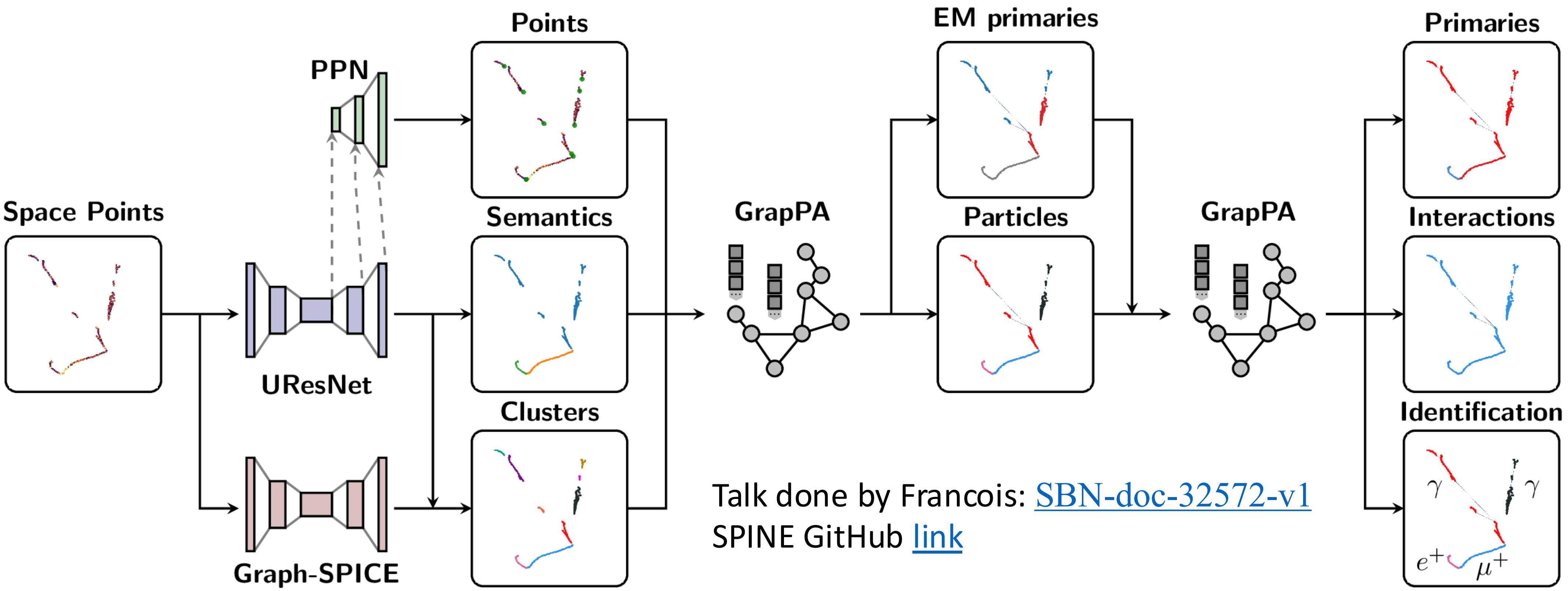
Colorado State University

Overview of Workflow



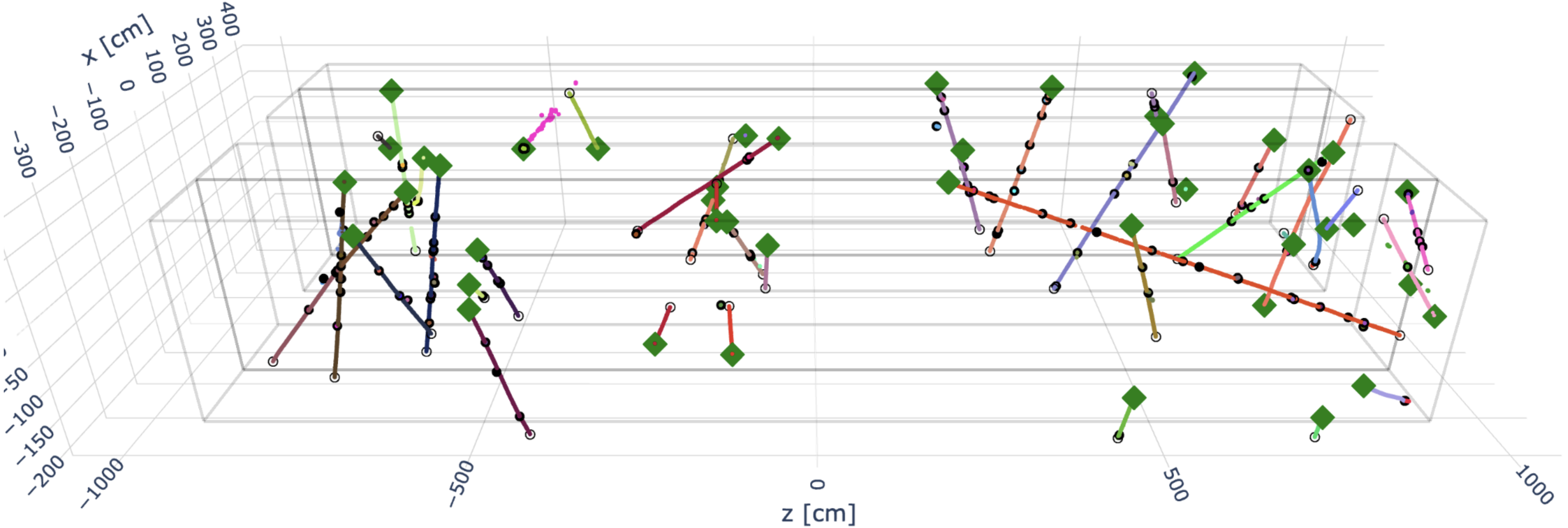
- Generator: prodcorsika_genie_protononly_icarus_numi{_nue}.fcl, prodcorsika_bnb{_nue}_genie_protononly_icarus.fcl
- Filter: filter_genie_active_icarus.fcl (Only on BNB)
- G4: larg4_icarus_cosmics_sce_2d_drift.fcl
- Detsim: detsim_2d_icarus_fitFR_refactored.fcl
- Stage 0: stage0_run2_icarus_mc_refactored.fcl
- Stage 1: stage1_run2_1d_larcv_icarus_MC.fcl
- Cafmaker: cafmakerjob_icarus_detsim2d.fcl

Scalable Particle Imaging with Neural Embeddings (SPINE)

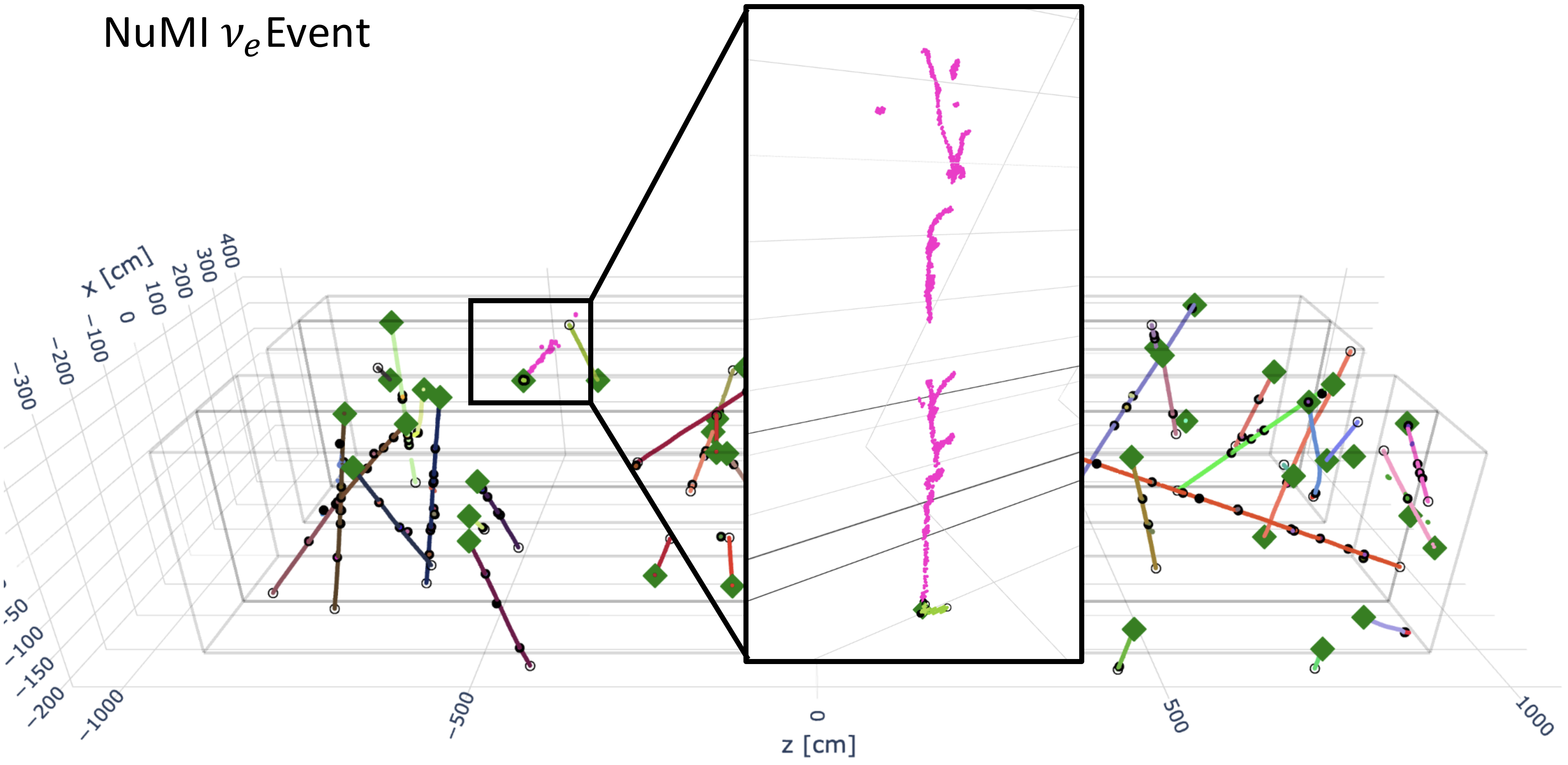


Talk done by Francois: SBN-doc-32572-v1
SPINE GitHub link

NuMI ν_e Event



NuMI ν_e Event



BNB ν_e Selection

Dae Heun Koh

Sample and Data Processing

MC samples

- BNB ν + out of time cosmics (~300,000 events)
  - Icaruscode version v09_84_00_01
- BNB ν_e + out of time cosmics (~100,000 events)
  - (Icaruscode version v09_89_01_01)
- Actively making MC samples to study systematics

Run 2 Data (Icaruscode version v09_84_00_01)

- BNB Offbeam Majority
  - LArCV files have been transferred to SLAC
  - Processed for Justin Mueller’s Analysis
- BNB Onbeam Majority (~1.92E20 POT)
  - LArCV files have been transferred to SLAC
  - Processed for Justin Mueller’s Analysis

BNB ν_e Selection

- Containment
  - Require depositions to be within the TPC that it was collected only for **tracks**
    - 5 cm margin on TPC borders
    - -5 cm margin on the cathode
- Fiducial volume: 25 cm from X and Y detector boundaries, 30 cm from beam-side and 50 cm from downstream edge in Z (same as used in Pandora-based selections)
- Signal Definition:
  - 1 primary electron with energy greater than 100 MeV
  - N > 0 primary protons with energy greater than 40 MeV
  - Any other primary particle must be greater than 25 MeV
- Flash Matching:
  - Utilizing OpT0Finder to constrain flash match to be withing BNB beam window

BNB ν_e Heuristic Selections

- Shower Conversion Distance: An electron primary shower must be within 2 cm from the vertex
- Multi-Shower Check:
    - All electron primary showers must not have two distinct shower fragments that are separated more than 41 degrees (threshold not fine-tuned)
- Track-Shower Merger:
    - Merge a track to a leading shower in a given interaction if it satisfies all of the following conditions:
        - Track is less than 50cm
        - (Reco) Track direction and (Reco) shower direction angular separation less than 10 degrees
        - Track start $\frac{dE}{dx}$ is less than 15 MeV / cm (to avoid merging colinear protons)
        - Track is within 1cm from leading shower
- Primary-Track Vertex Adjacency:
    - All track primaries must be within 3cm from vertex (if not, we override the primary labels and classify them as non-primaries)

BNB ν_e Selection

Cuts	Efficiency (%)	# Efficiency	Purity (%)	# Purity
True ν_e	100.00	487 / 487	0.0045	555 / 12234234
Containment (Tracks)	96.3	469 / 487	0.052	537 / 1025739
Fiducial	94.9	462 / 487	0.100	512 / 514064
Flash Time	92.4	450 / 487	0.374	452 / 120799
Final State	70.8	345 / 487	30.5	345 / 1131
Visible Final State	71.5	348 / 487	50.4	348 / 690
PID-Semantic Agreement	71.0	346 / 487	50.4	346 / 686
PID Score Thresholding	60.4	294 / 487	51.2	294 / 574
Shower Conversion Distance	52.4	255 / 487	63.4	255 / 402
Multi-Shower Check	49.7	242 / 487	75.4	242 / 321
Track-Shower Merger	53.8	262 / 487	75.9	262 / 345
Primary Track-Vertex Adjacency	55.2	269 / 487	73.7	269 / 365

TABLE 1. Effects of cuts for BNB ν + COSIKA sample ($\approx$300k).

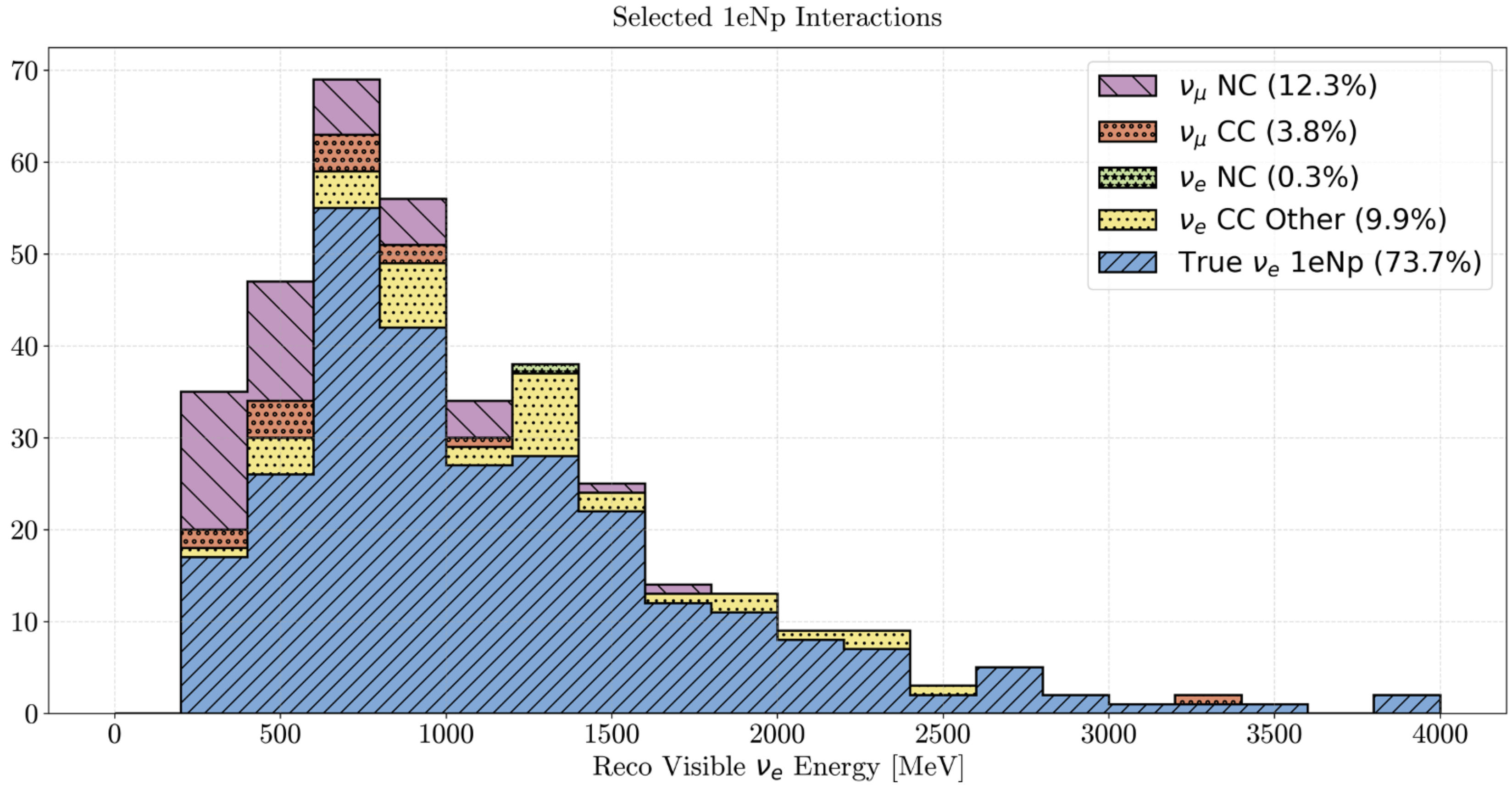
BNB ν_e Selection

- **Efficiency = 55.24% (269 / 497), Purity = 73.70% (269 / 365)**

Reconstructed \ Truth	Cosmics	ν_e 1eNp	ν_e CC	ν_e NC	ν_μ CC	ν_μ NC
Background	97.10% (11878968)	0.00% (286)	0.01% (1240)	0.01% (633)	2.19% (267733)	0.69% (85009)
Signal	0.00% (0)	73.70% (269)	9.86% (36)	0.27% (1)	3.84% (14)	12.33% (45)

ν_e Selection (with PID score thresholding)

- **Efficiency = 55.24% (269 / 497), Purity = 73.70% (269 / 365)**



NuMI ν_e Selection

Dan Carber

Sample and Data Processing

All samples are version v09_89_01_01p01

MC samples

- NuMI ν + out of time cosmics (~300k events)
  - Samweb def: icaruspro_production_v09_89_01_01p01_2024A_ICARUS_NuMI_MC_NuMI_MC_{caf,larcv}
- NuMI ν_e + out of time cosmics (~100k events)
  - Samweb def: icaruspro_production_v09_89_01_01p01_2024A_ICARUS_NuMI_nue_MC_NuMI_nue_MC_{caf,larcv}

Run 2 Data

- NuMI Offbeam Majority
  - LArCV files have been transferred to SLAC
- NuMI Onbeam Majority (~2.4E20 POT)
  - LArCV files have been transferred to SLAC

Selection of 1eNp (N > 0)

Containment:

Require depositions to be within the TPC that it was collected only for **tracks**

- 5 cm margin on TPC borders
- -5 cm margin on the cathode

Signal Definition:

Selecting primary particles associated to interaction

- Electrons must be greater than 70 MeV
- Protons must be greater than 40 MeV
- All other particles > 25 MeV

- 1eNp: 1 primary electron and N>0 primary protons

Flash Matching:

Utilizing OpT0Finder to constrain flash match to be withing NuMI beam window 0-9.6 µseconds

Conversion distance cut:

Requires closest point of primary shower to be < 2 cm from the vertex

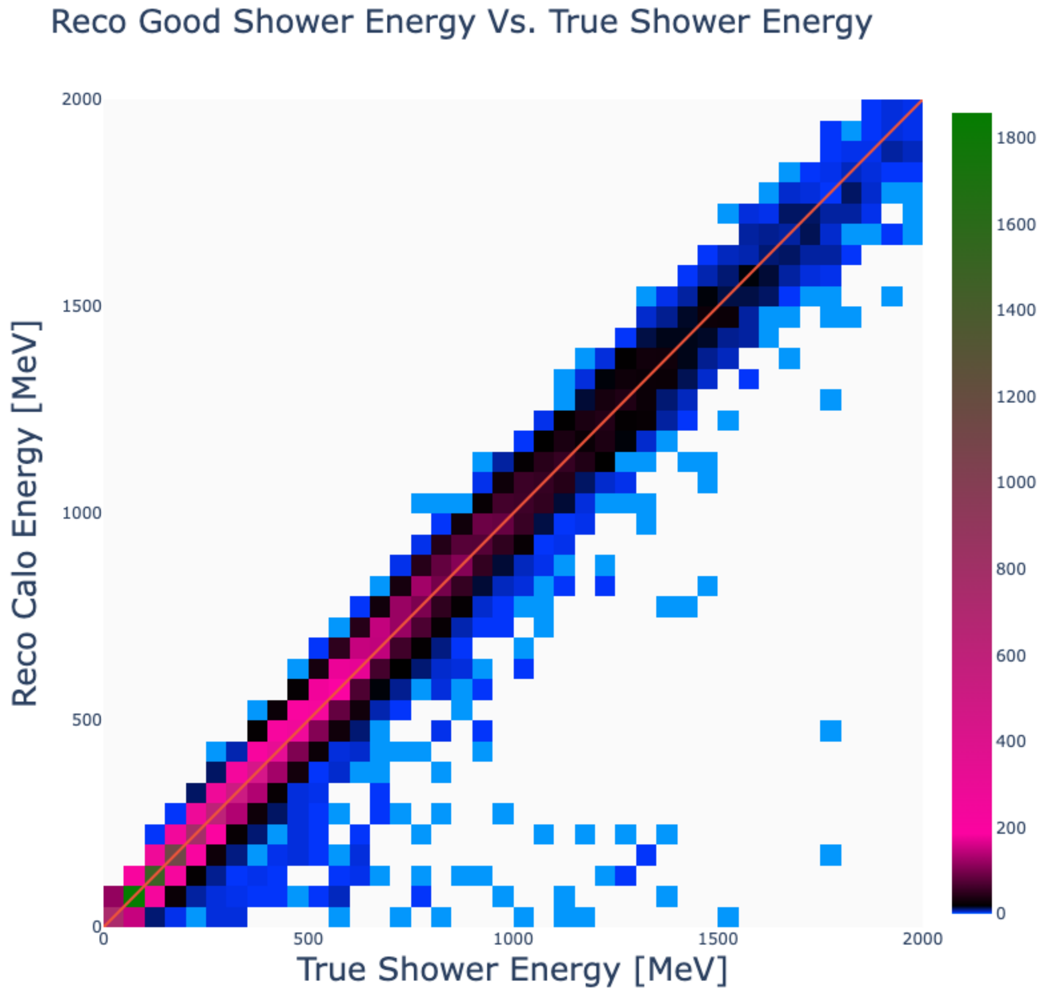
Selection of 1eNp (N > 0)

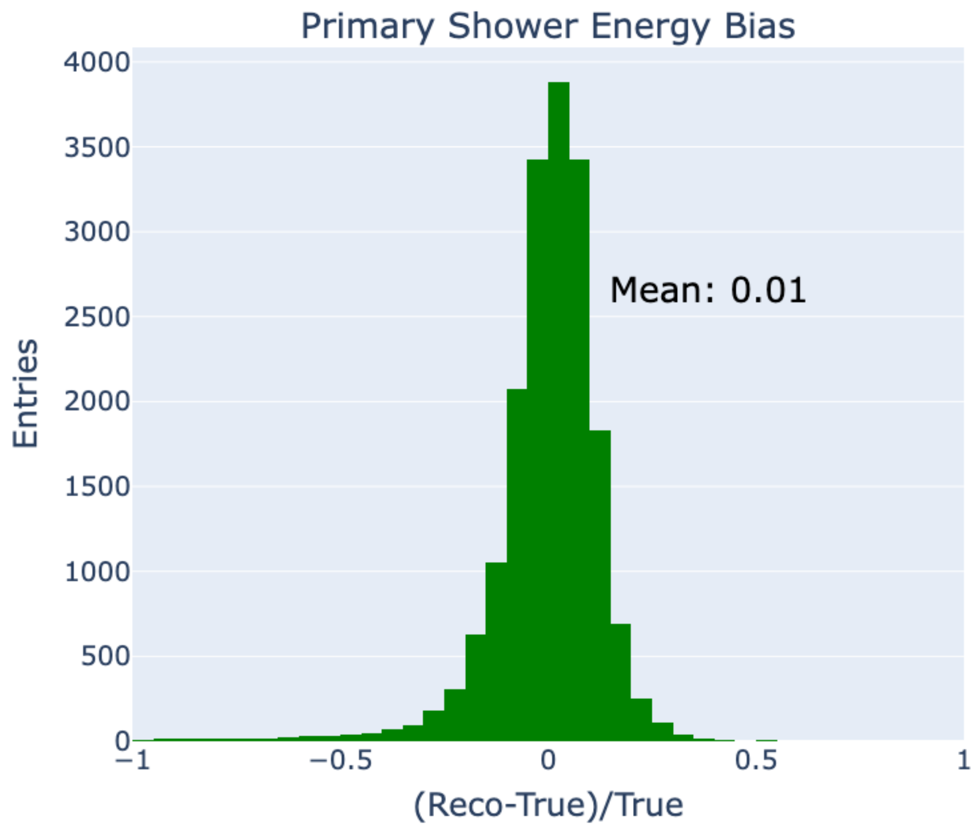
Signal: 1eNp (N > 0)

Cuts	Efficiency %	# Efficiency	Purity %	# Purity
Containment	94.4%	$\frac{12272}{12998}$	.028%	$\frac{2211}{793717}$
Flash Match	90.6%	$\frac{11779}{12998}$	.98%	$\frac{1938}{201677}$
Final State	60.3%	$\frac{7833}{12998}$	75.8%	$\frac{1224}{1614}$
Conversion Distance	51.5%	$\frac{6691}{12998}$	81.4%	$\frac{1040}{1278}$

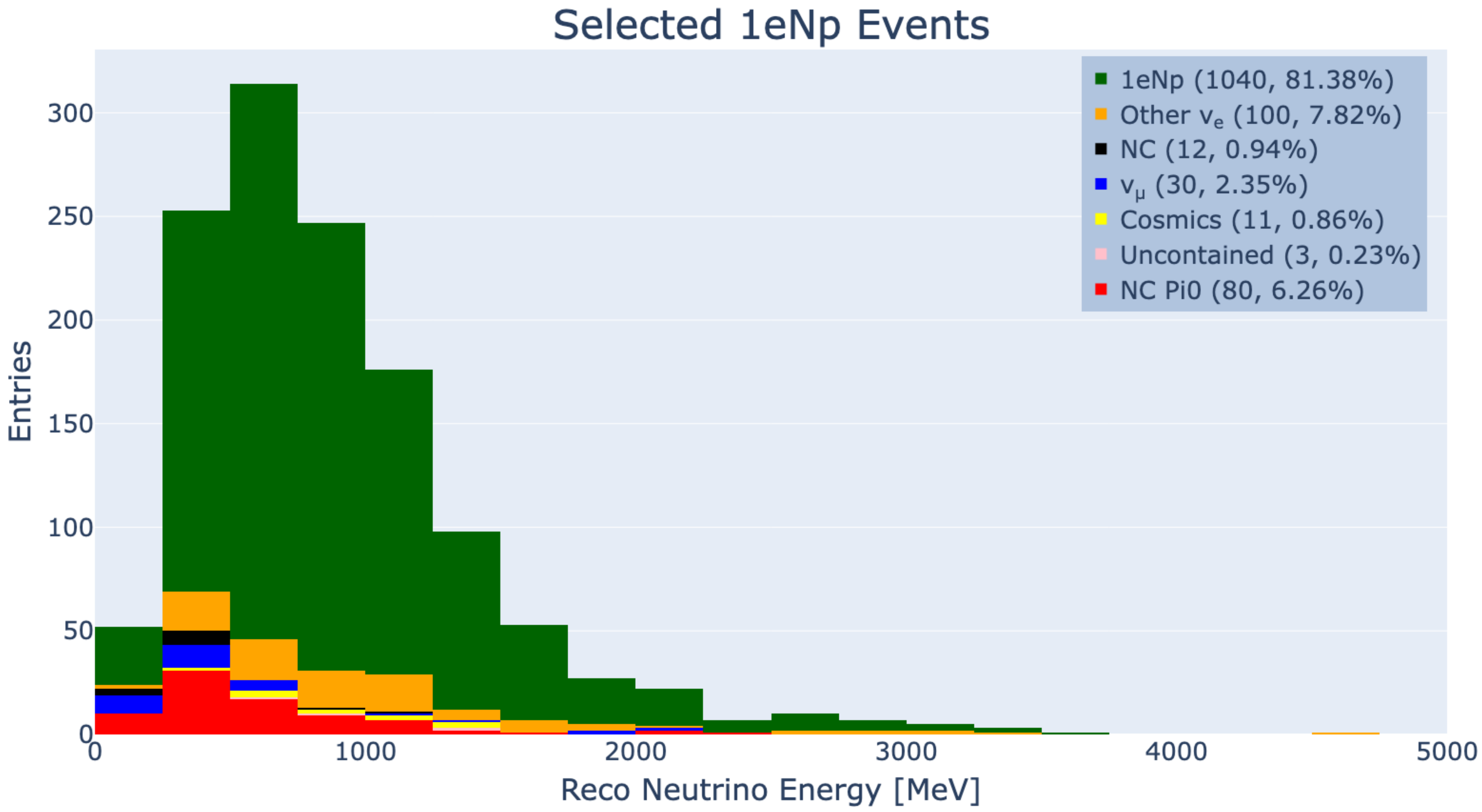
Purity is done with NuMI ν + cosmics (~300k events), Efficiency is done with NuMI ν_e + cosmics (~100k events)

Energy Reconstruction of Showers

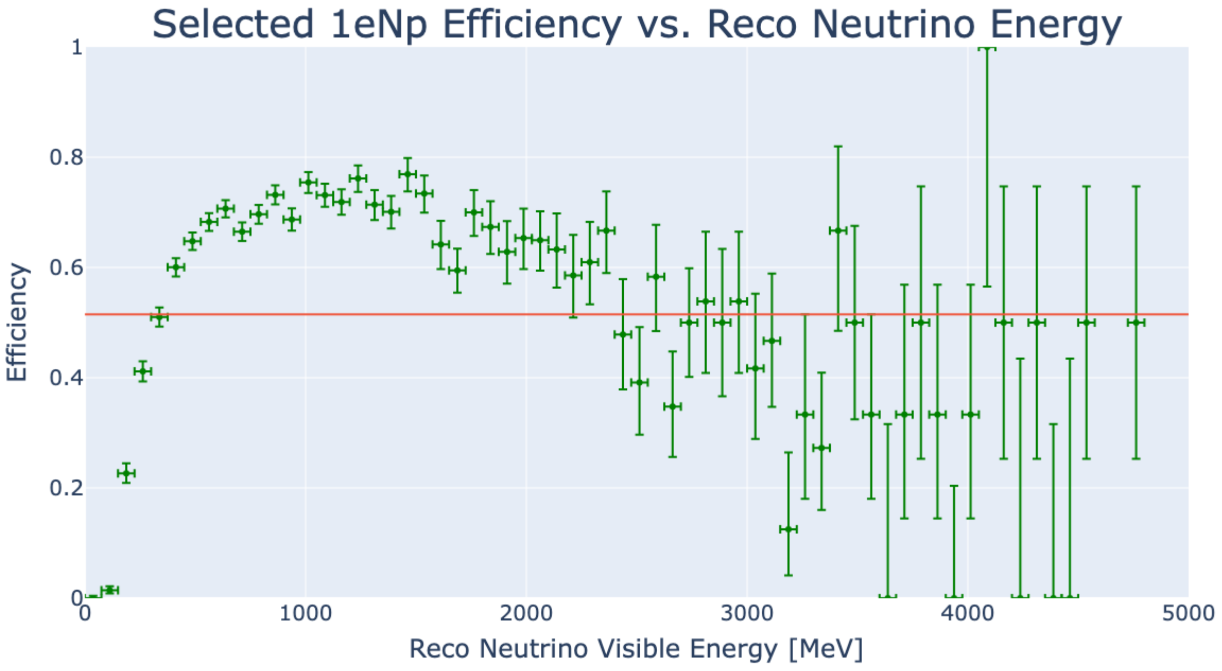


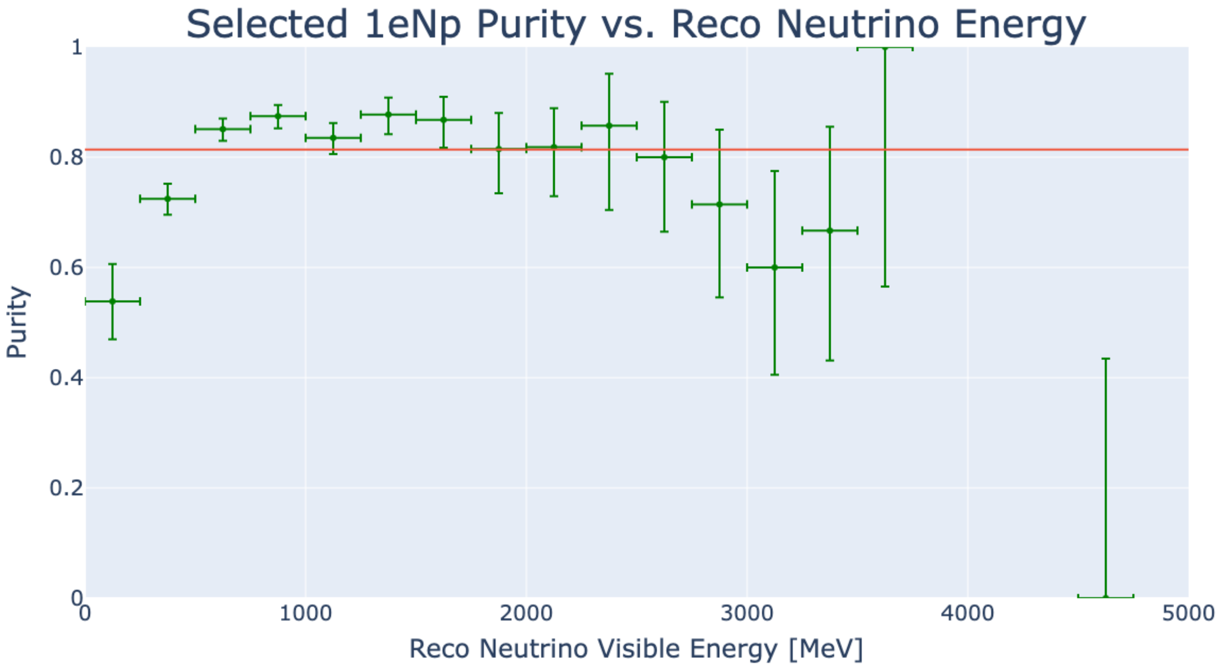


Energy Spectrum of 1eNp Selection



Efficiency, Purity Vs. Energy





Overall Efficiency: 51.5%

Overall Purity: 81.4%

Efficiency drop at higher energies are due to the training sample energy ranges

Conclusion and Next Steps

BNB ν_e

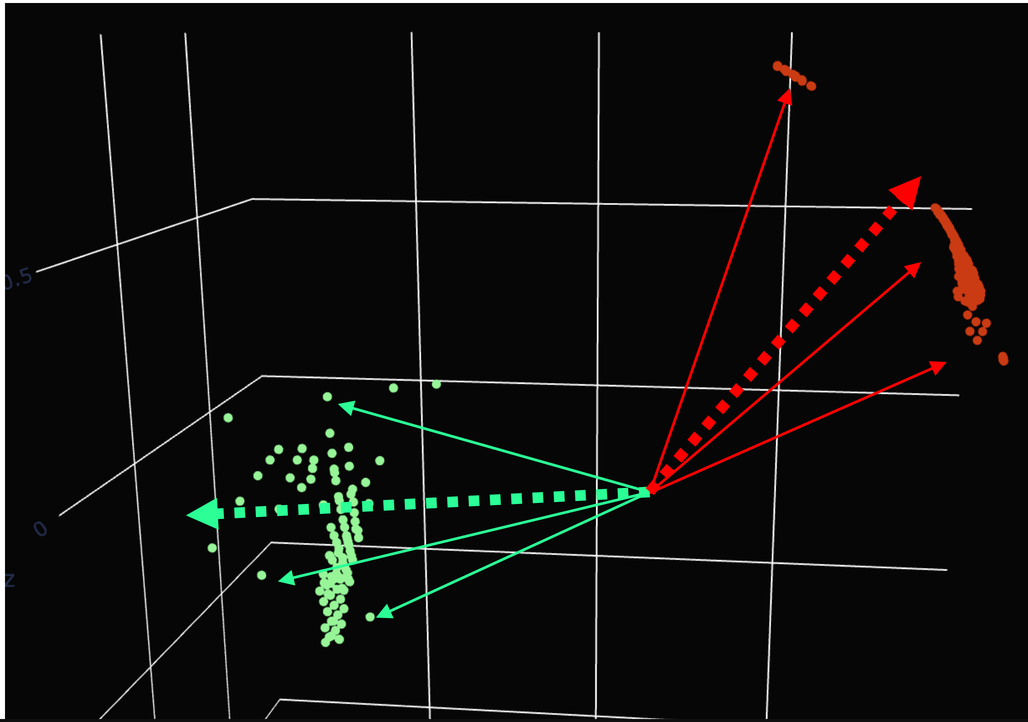
- Utilizing shower $\frac{dE}{dx}$ to remove ν_μ NC backgrounds
- Selections that have removed most background events
  - Most backgrounds are now due to signal definitions and events that resemble 1eNp events
- Planning for full description of MC systematics in the coming month
- BNB ν_e selection demonstration paper by end of the calendar year
- Thesis defense by sometime during March or before

NuMI ν_e

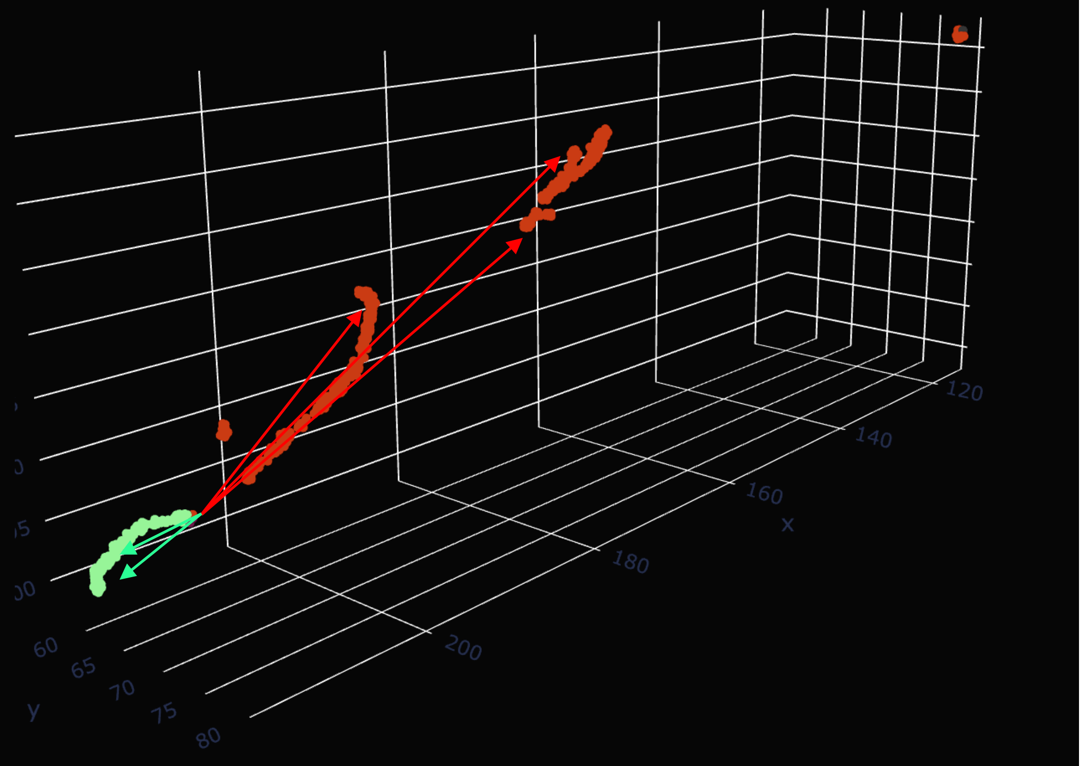
- Identify sources of efficiency loss and apply fixes
  - Fix vertex reconstruction
  - Apply new trainings from samples with larger energy ranges
- Look into reducing NC pi0 background
  - Utilizing reconstructed pi0 mass peak
  - This will help with CC ν_e Inclusive
- Data/Monte Carlo comparisons with 10% unblinded data from Run 2
- Plan for NuMI 1eNp cross-section result by summer of 2025

Back Up Slides

Multi-Shower Check

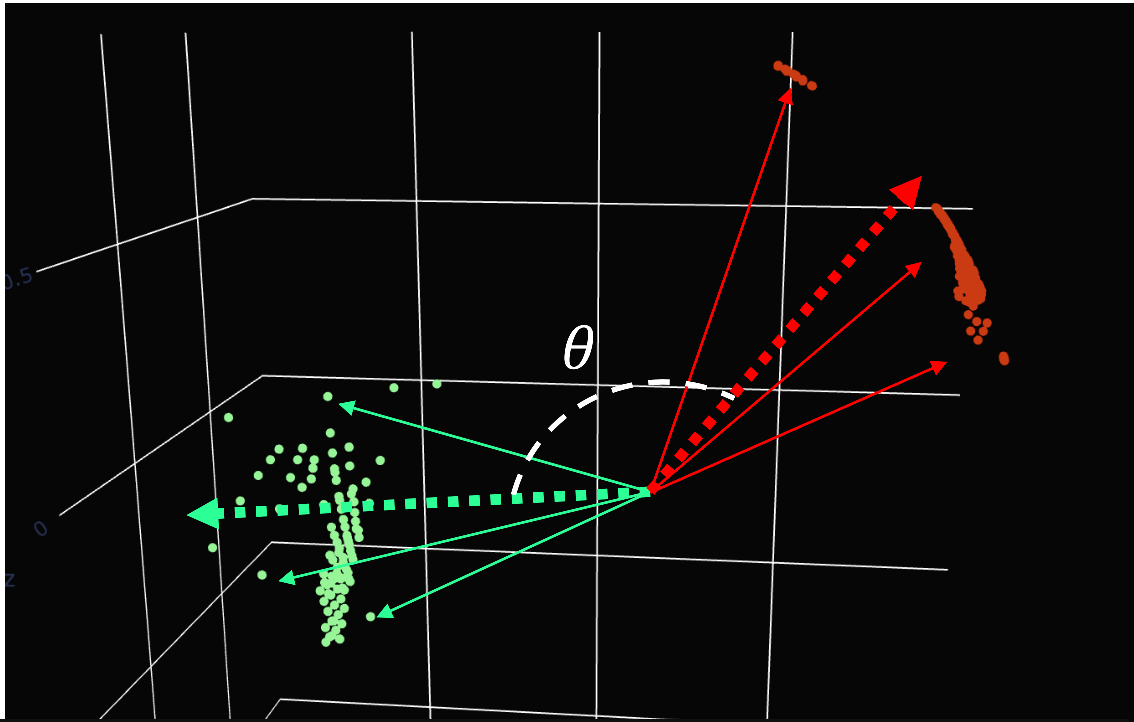


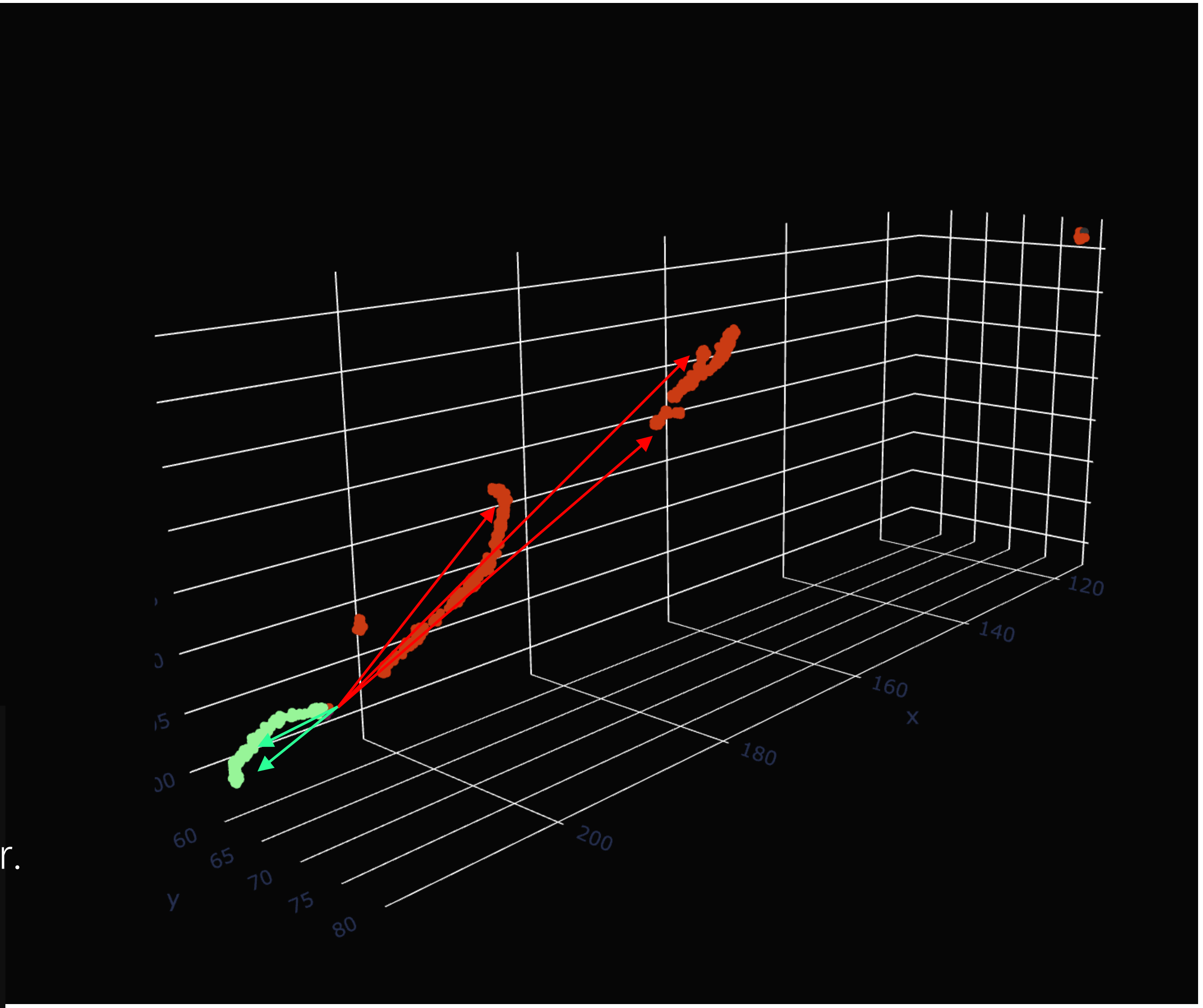
1. Compute displacement vectors from shower start to all points



2. Normalize and map to unit sphere
3. Cluster points on unit sphere using DBSCAN and cosine distance.
4. Measure mean direction vector for each clusters

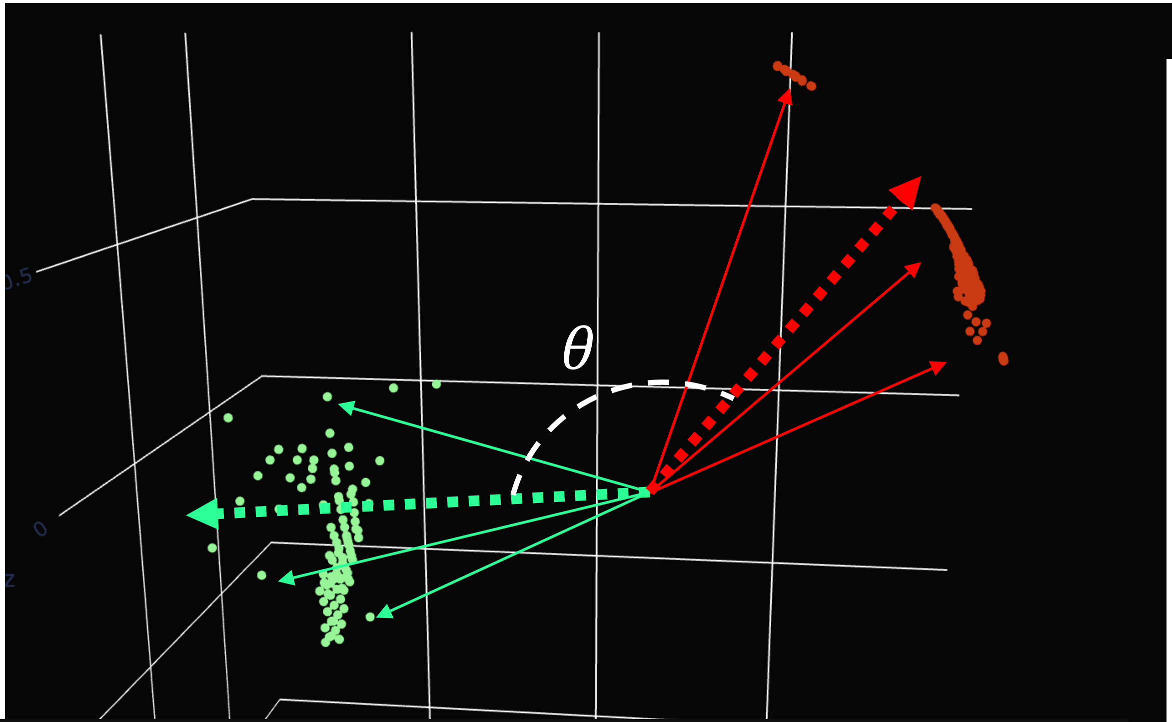
Multi-Shower Check

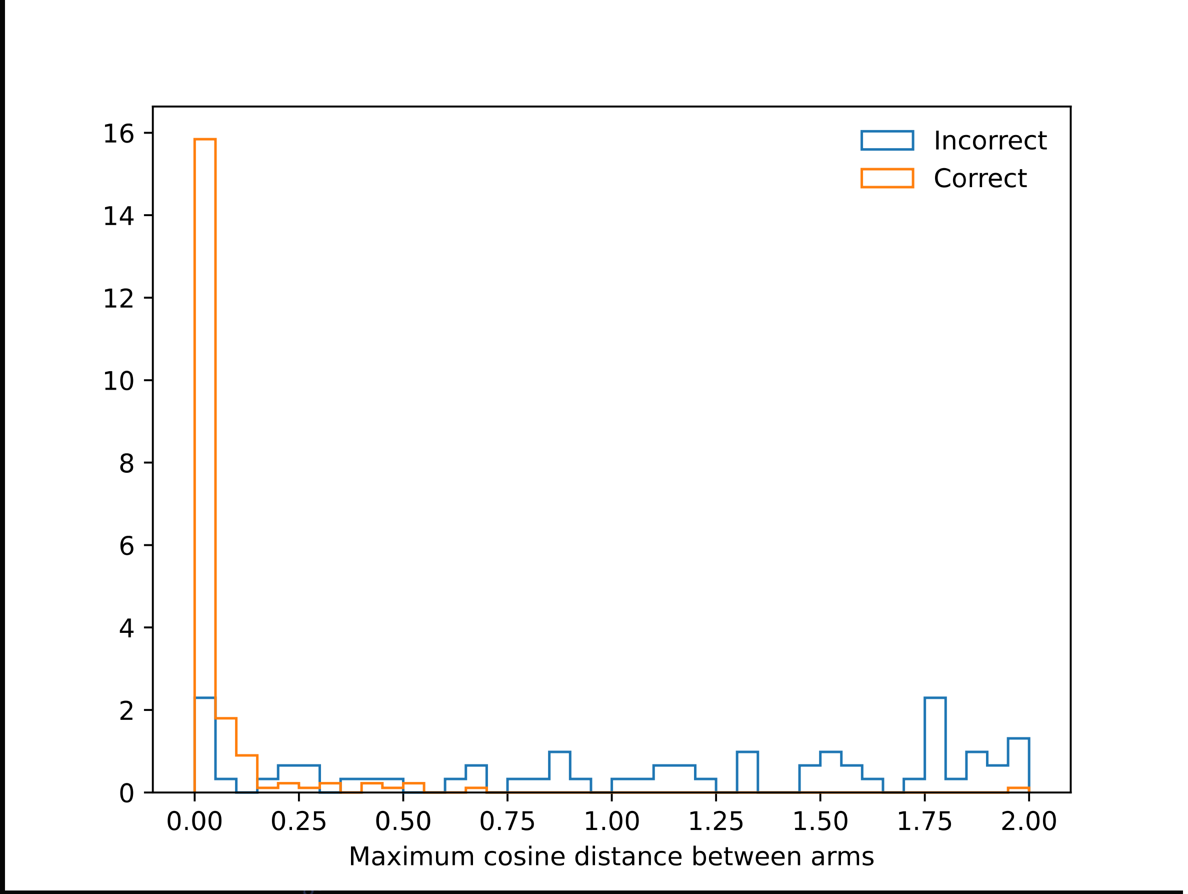




5. Compute separation angle between mean vectors
6. If $\theta \geq \theta_{threshold}$, reject shower as candidate electron shower.

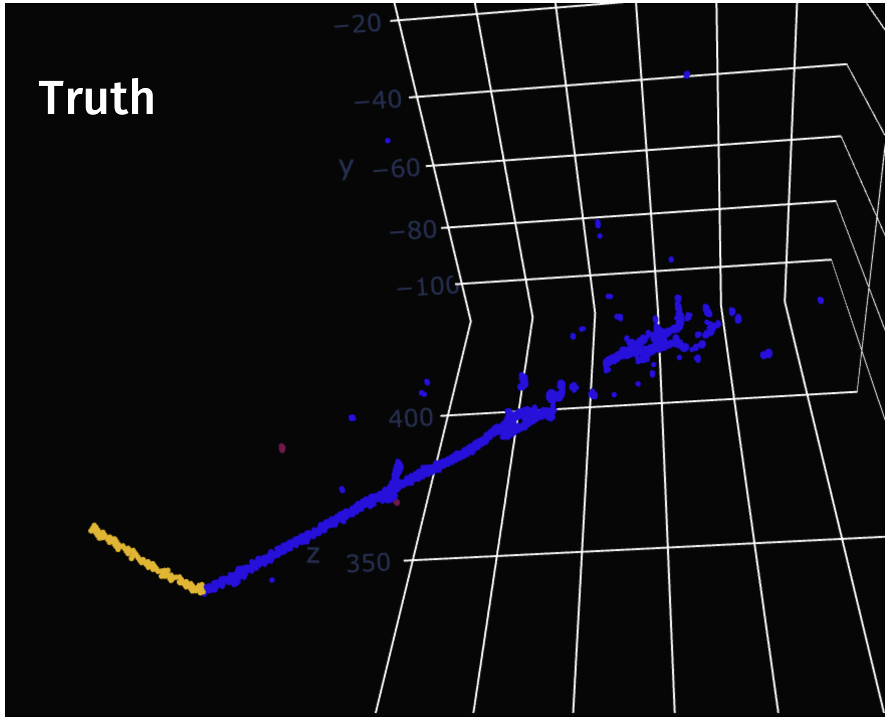
Multi-Shower Check

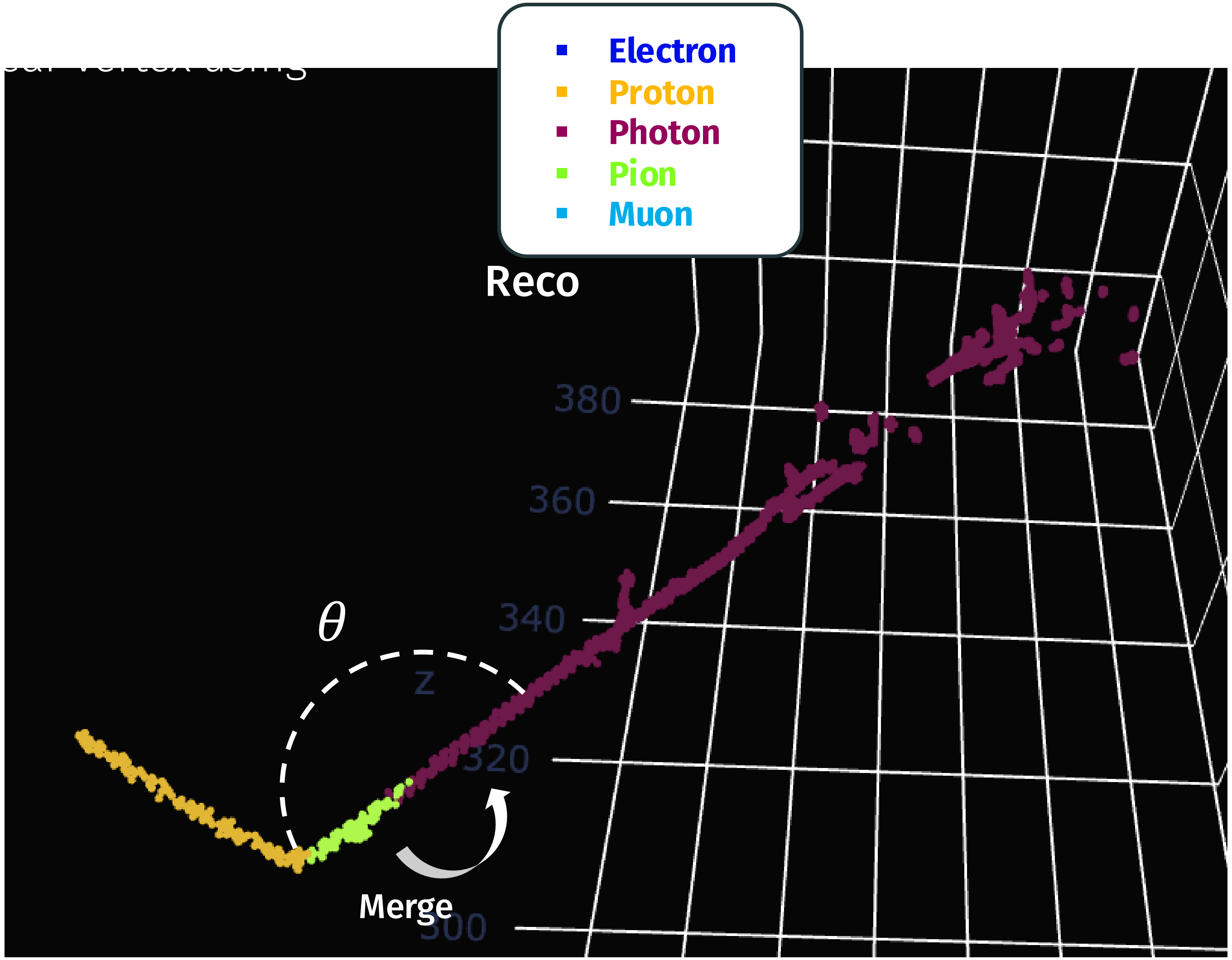




5. Compute separation angle between mean vectors
6. If $\theta \geq \theta_{threshold}$, reject shower as candidate electron shower.

Track-Shower Merger





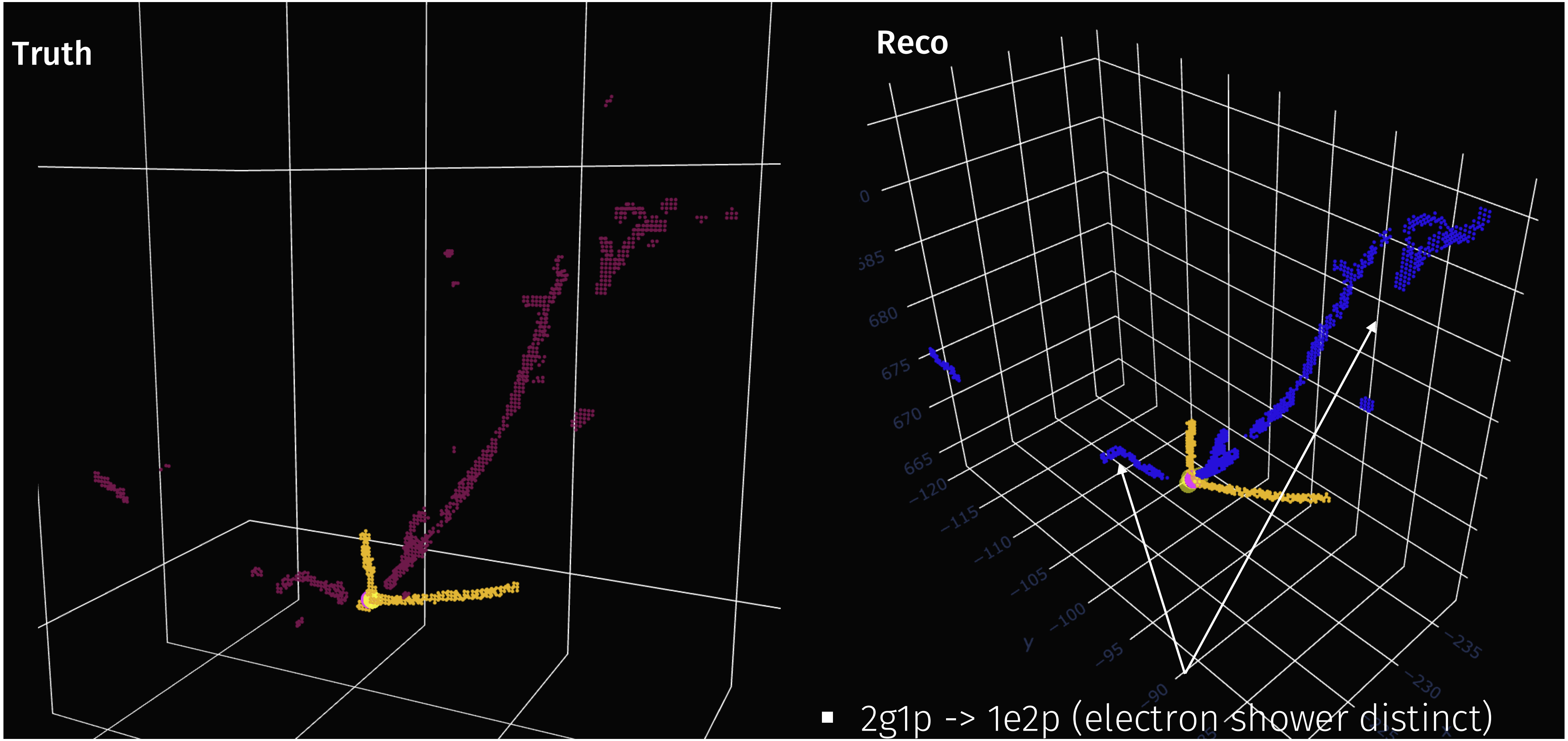
Nue Selection

- $\nu_\mu\ NC$: 12% (45 events)
  - 48% (22/45) due to 1gNp-like events (g is attached to vertex)
    - γ from π^0 decay either escaping detector volume entirely, or second shower barely visible
  - 31% (14/45) due to 2gNp-like events (one g attached, usually merged)
    - Mostly due to two-arm cut failures
  - 4/45 are (visually) detached 1gNp events, but passed shower-vertex adjacency due to small pixels near vertex
  - 4/45 Dalitz decay
  - 5/45 pid mistakes (p -> pi, and other)

Nue Selection (before shower containment removal + truth primary label fix)

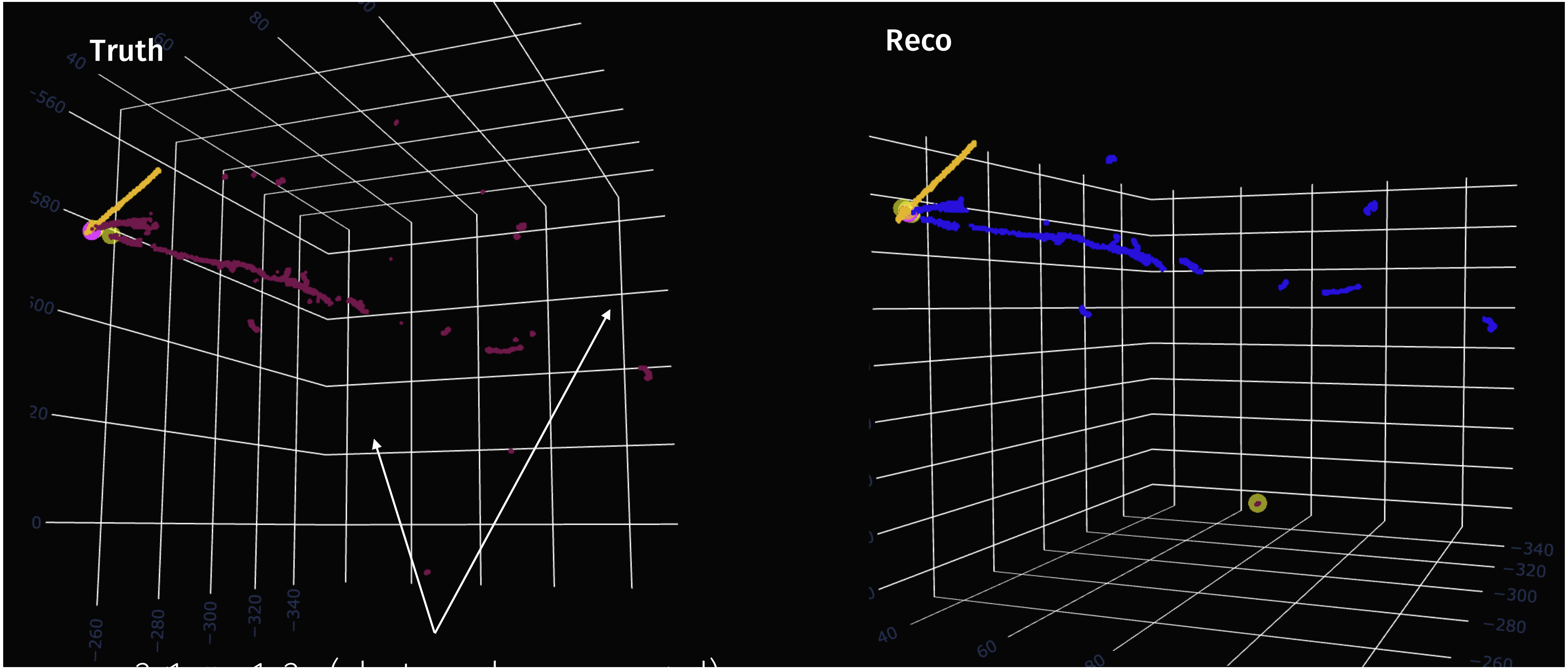
- $\nu_e\ CC$ (non-signal): 10% (36 events)
  - 33% (12/36) due to low energy protons (1e -> 1e1p)
  - 42% (15/36) due to p -> pi pid mistakes
  - 5 / 36 true nonfiducial / true uncontained, but reconstructed as valid 1eNp
  - 3 / 36 proton inelastic GENIE non-primaries having particle startpoint just outside 0.5cm true vertex – true particle startpoint threshold.

Nue Selection

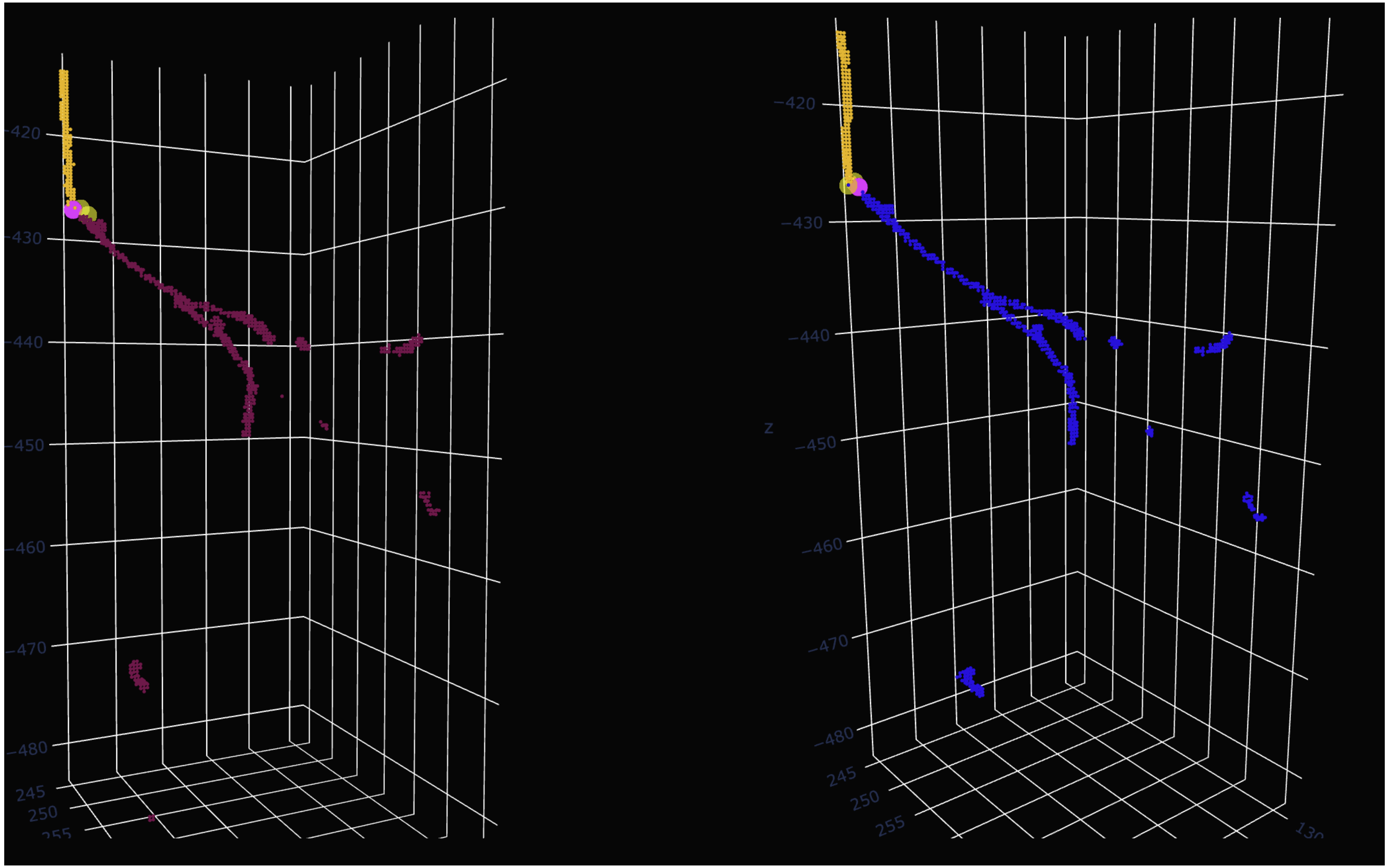


- 2g1p -> 1e2p (electron shower distinct)

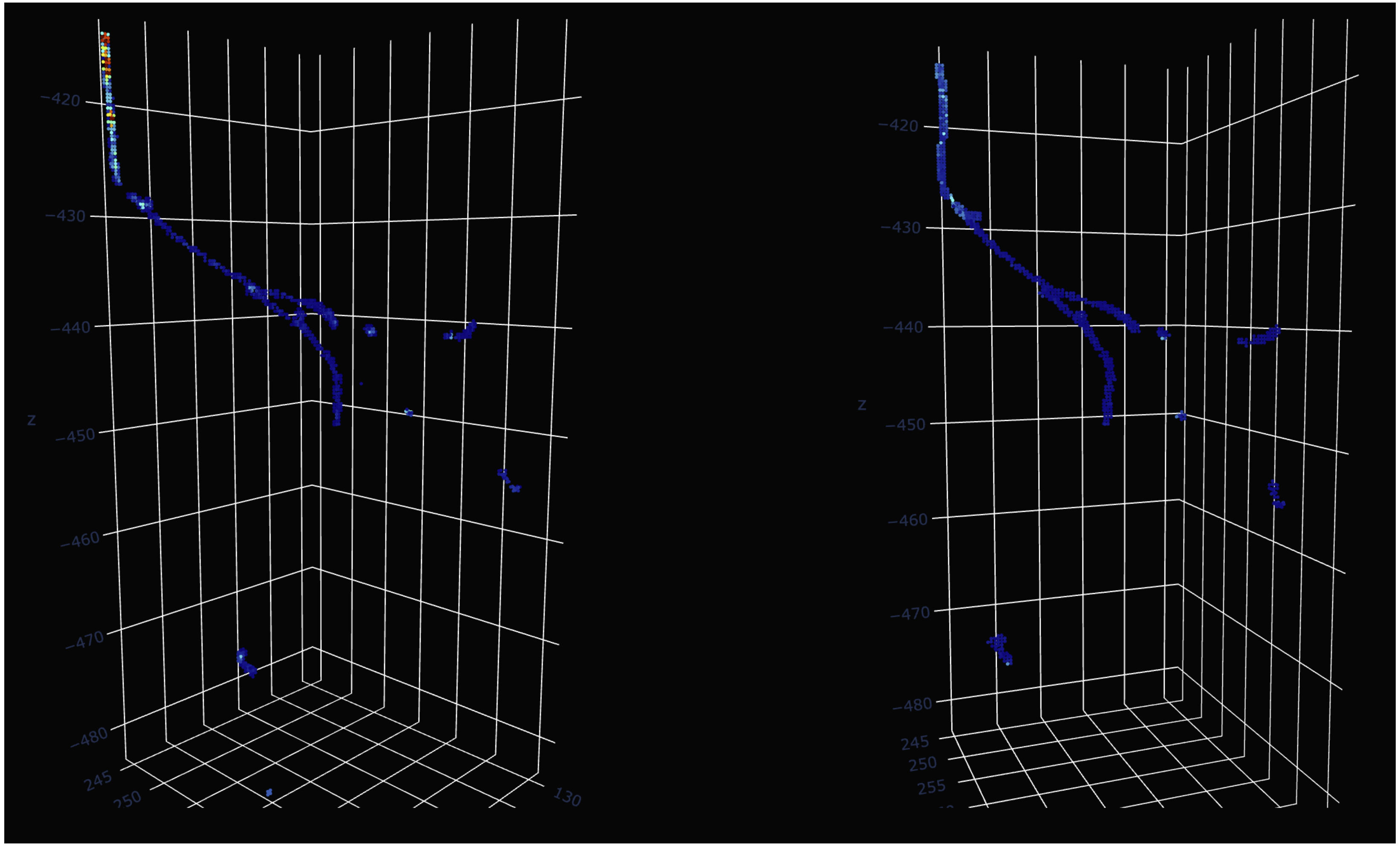
Nue Selection



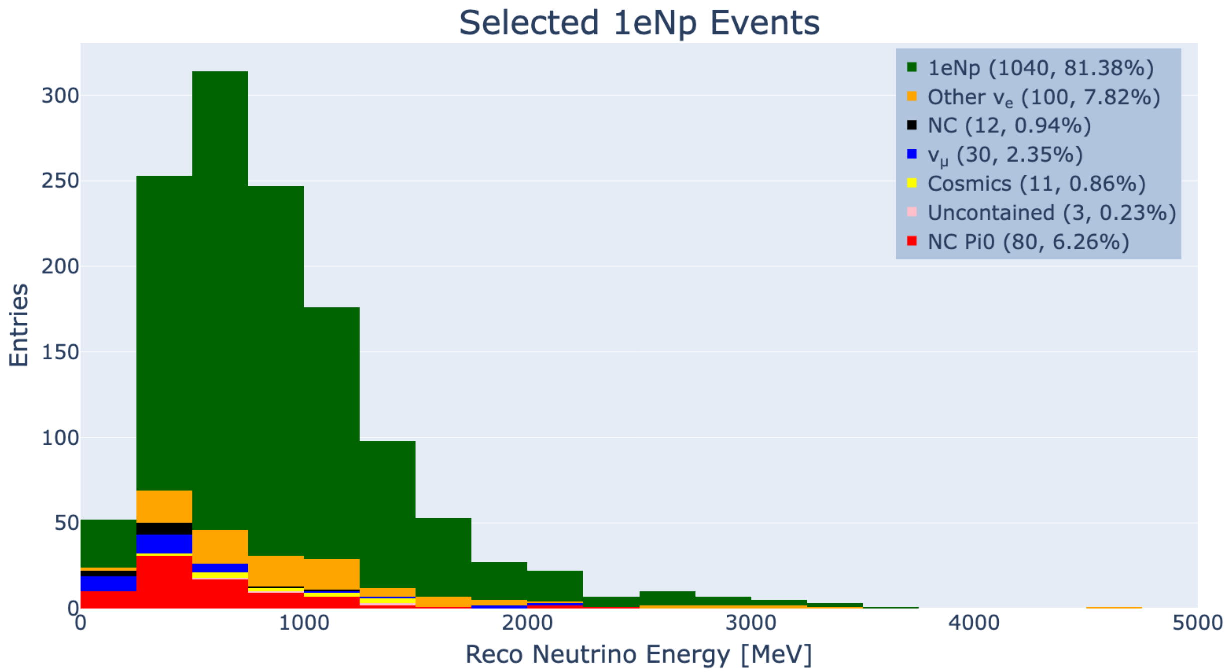
Nue Selection (1g1p -> 1e1p)



Nue Selection (1g1p -> 1e1p)



1eNp Selection Background breakdown



Other ν_e

- 55/100 – 1e1piNp
- 19/100 – 1e1pi
- 18/100 – 1e
- 3/100 – 1e2piNp
- 1/100 – 1g1e
- 1/100 – 1e2pi
- 1/100 – 1g1e2p
- 1/100 – 2g1e1pi
- 1/100 – 2g1e3p

ν_μ

- 14/30 – 1muNp
- 7/30 – 2g1muNp
- 4/30 – 1mu1piNp
- 1/30 – 1mu
- 2/30 – 1g1m1piNp
- 1/30 – 2g1m1pi
- 1/30 – 1e1m7p

Efficiency and Failure Mode Breakdown