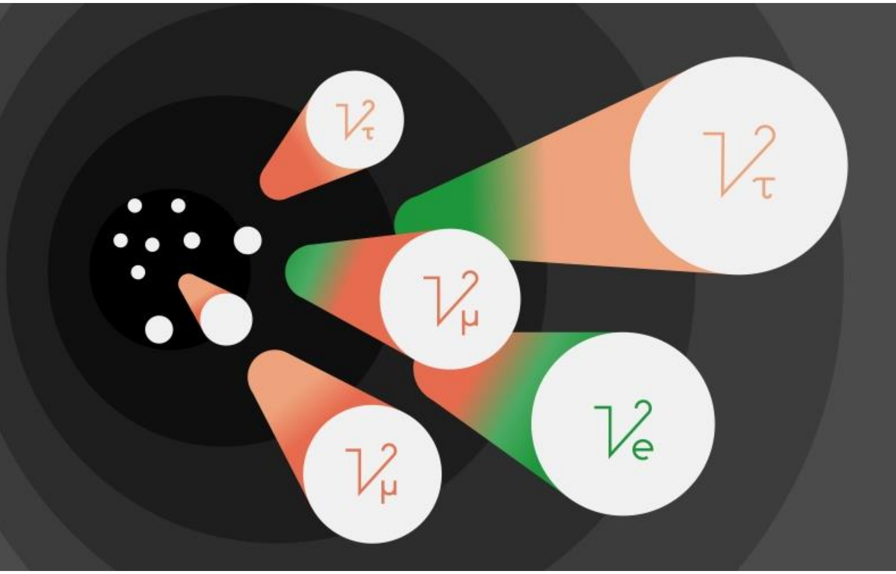
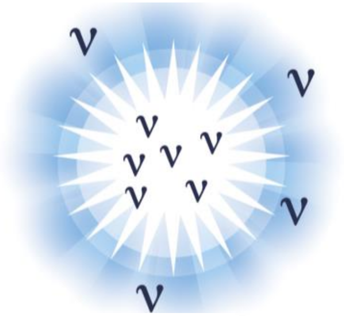
FIRST PHYSICS STUDIES WITH DUNE NEAR DETECTOR PROTOTYPE



MUHAMMAD BILAL AZAM
Ph.D. Physics Student *(under the supervision of* ***Prof. Dr. Zelimir Djurcic****)*
Illinois Institute of Technology
Chicago

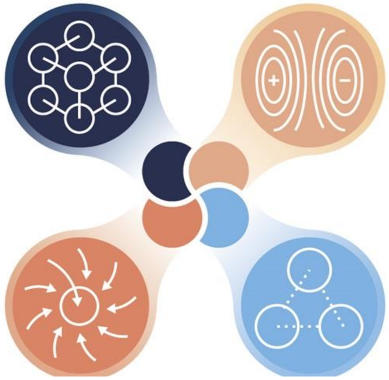
December 5, 2023
Young Scientist Symposium Series (YSSS), Argonne

SCIENCE GOALS OF DUNE



- **Constrain flavor and mass models**
  - Measurement of precise neutrino oscillation parameters
  - CP violation
  - Mass hierarchy

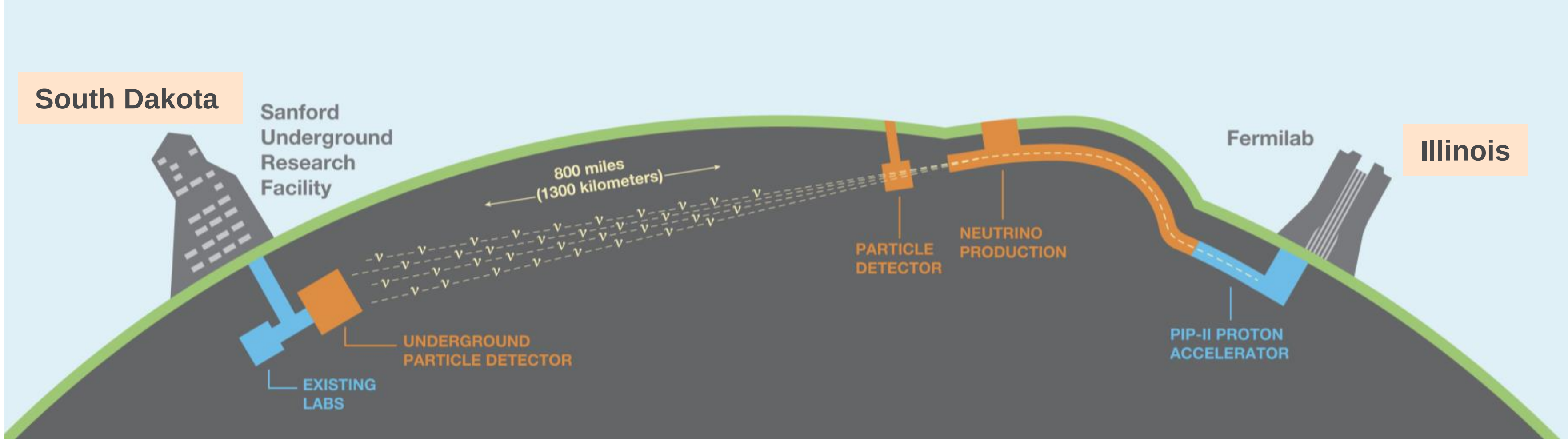
- **Learn more about supernovae and black holes**
  - DUNE alone would detect $> 3x$ as many neutrinos as all active detectors did for SN1987A



- **GUT and beyond SM**
  - Proton decay
  - Baryon number violation
  - Sterile neutrinos
  - Non-standard interactions and more

DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

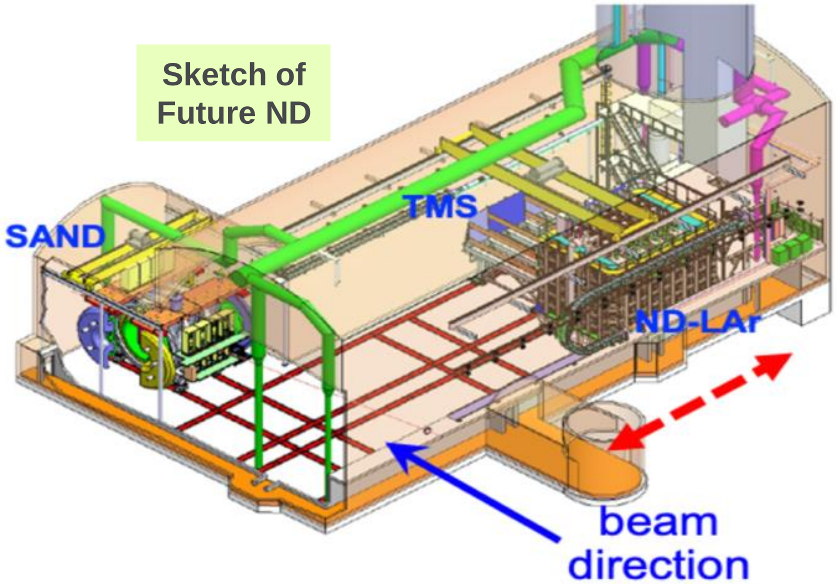
- Long baseline experiment: $1300\ \mathrm{km}$ from Fermilab to SURF
- Intense neutrino beam: $1.2\ \mathrm{MW}$ (upgradable to $2.4\ \mathrm{MW}$)
- Two detectors
  - Near Detector: To measure un-oscillated neutrino flux
  - Far Detector: A $70-\mathrm{kiloton}$ detector to measure oscillated neutrino flux
- DUNE detector prototypes
  - 2×2 at Fermilab for ND
  - ProtoDUNE at CERN for FD



FULL NEAR DETECTOR AND ITS PROTOTYPE

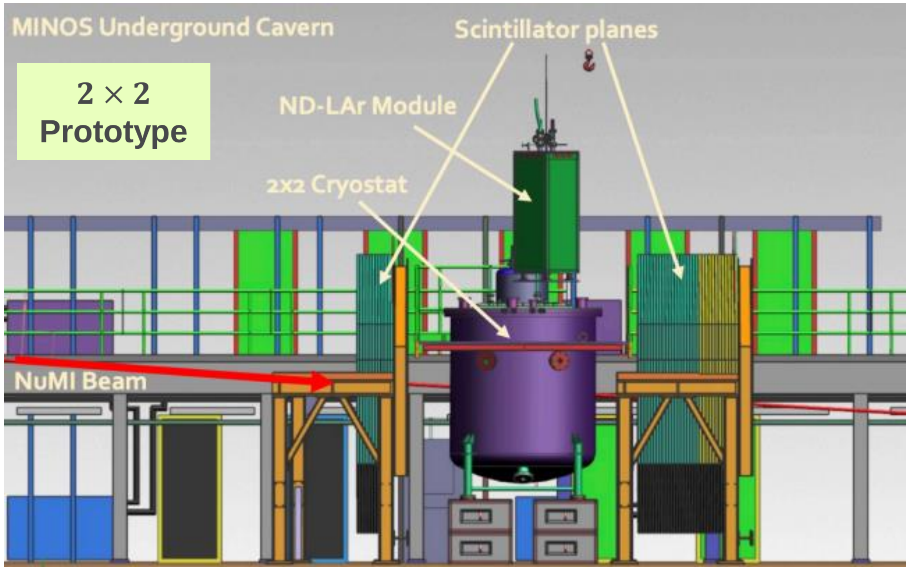
- Full Near Detector have:
  - Near Detector Liquid Argon
  - The Muon Spectrometer
  - System for On-Axis Neutrino Detection

- Under construction



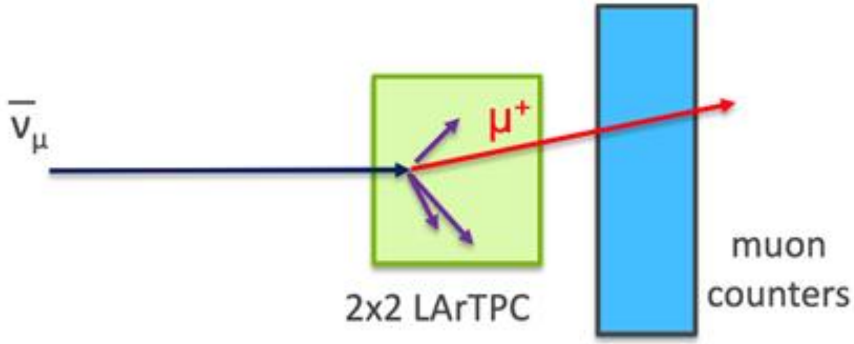
- Our current effort is with ND-LAr prototype (also known as 2×2)

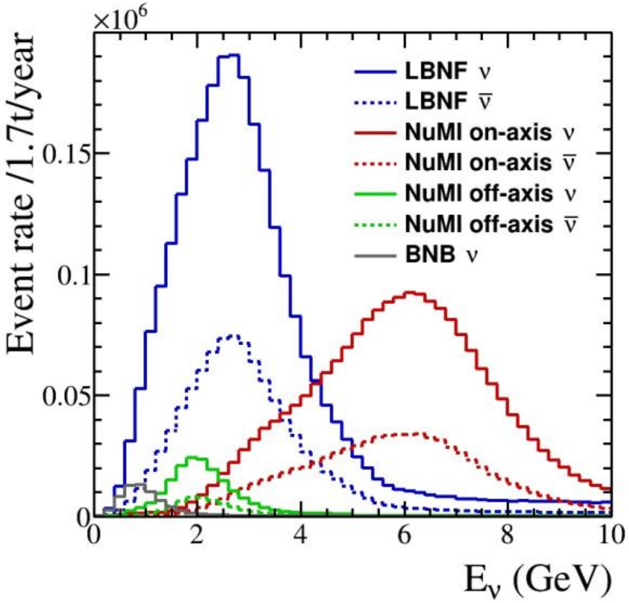
- Will start taking data in Spring 2024



OUR PLANS AND WHY THESE ARE IMPORTANT?

- Perform a first measurement of multiplicity of the charged-particle tracks generated by ν (or $\bar{\nu}$) interactions



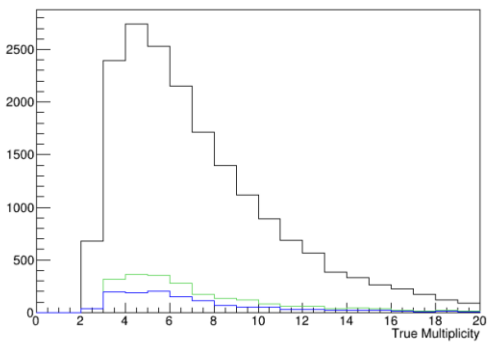


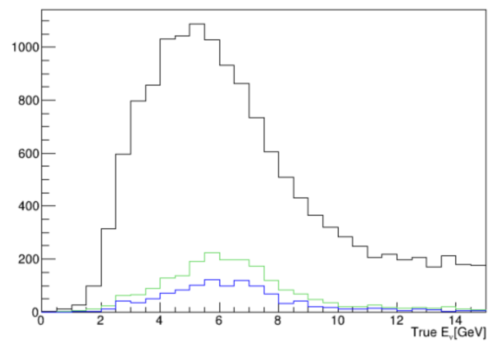
- Help in demonstrating DUNE ND-LAr capabilities early at the prototype stage
  - Validate event simulation and reconstruction

- Will help benchmark and define the base neutrino interaction generator model for first round of DUNE analysis
  - Compare measurements to various neutrino generator models (GENIE etc.)
  - Identify areas where new systematic uncertainties will need to be implemented in the analysis, before the ND data becomes available ($\sim 2031+$)

TRUTH STUDIES

- Looking at MiniRun4 Simulated data: plots of true multiplicity, neutrino energy, and ν-interaction vertex
  - **Black:** all simulated ν's; **Green:** ν interactions in LAr; **Blue:** ν interactions in LAr FV.
- Helps visualize/understand analysis flow.
- Used a fraction of MiniRun4 files
  - No "nominal" cuts applied (CC requirement, minimum track length and/or energy cuts).

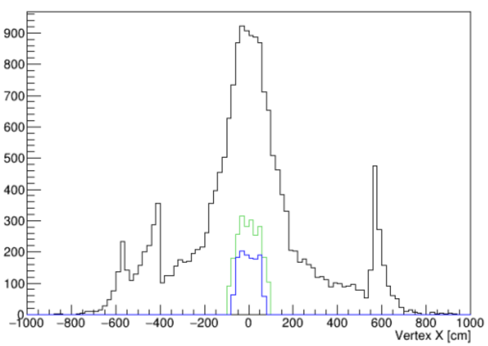


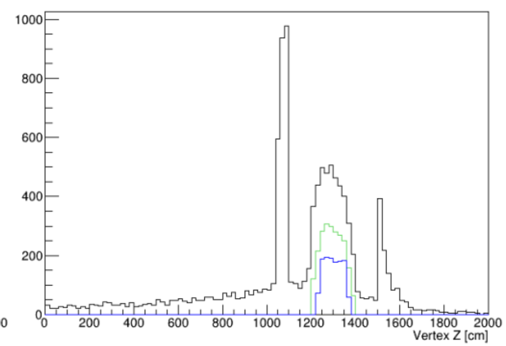


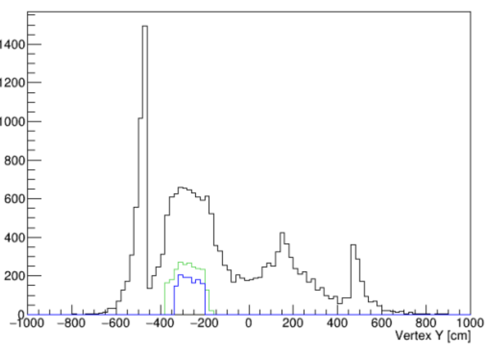
The center of the 2×2 is at $(0, -268, 1300)$ cm. Here the FV cuts [cm] are:

$$-67 < x < 60$$
$$-335 < y < -201$$
$$1233 < z < 1367$$

Many thanks to the simulation group!



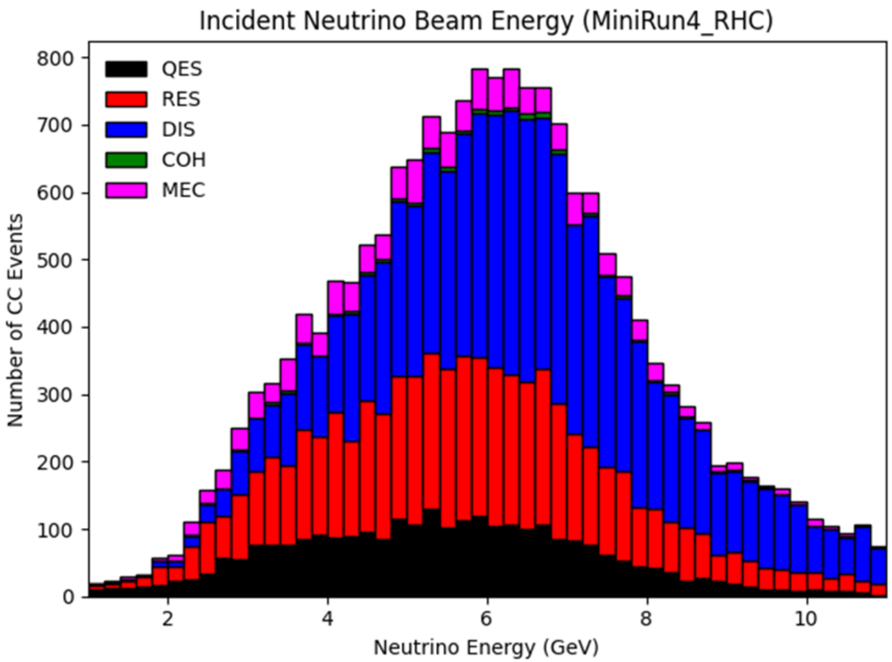


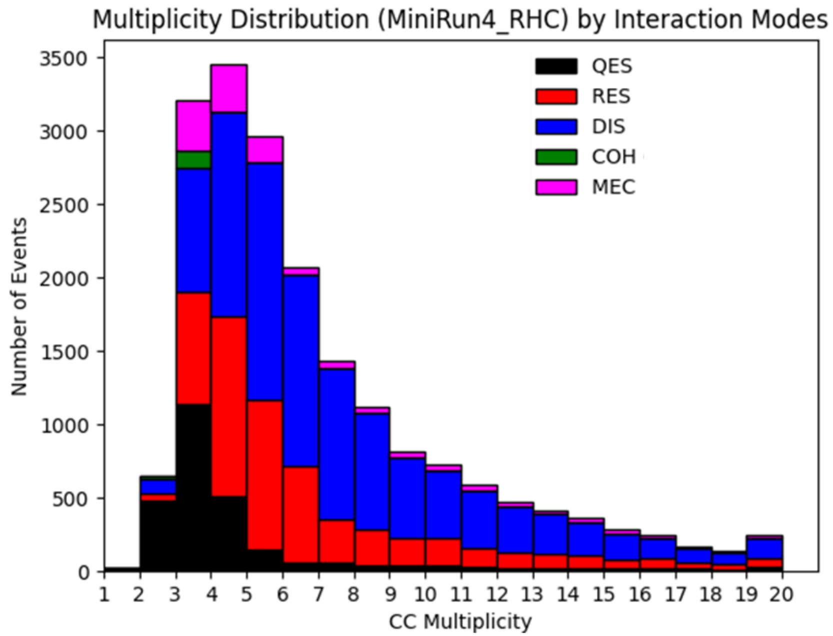


Argonne NATIONAL LABORATORY

TRUTH PARTICLE STUDIES

- Performed truth studies in MiniRun4 files (for anti-neutrinos)
  - For example, energy distribution for CC neutrinos interacting with LAr in FV and corresponding final state particles are shown.





- Now, we are doing reconstructed event studies
  - *Reconstruction is based on Machine Learning*

HOW DATA LOOKS LIKE?

- Data in expected in Spring 2024
- The Hierarchical Data Format (HDF5) is used to store terabytes of data
- Two forms of data
  - **Truth data:** Simulated events
  - **Reconstructed data:** Experimental measurements with detector effects and uncertainties.

Dataset: /mc_truth/***interactions***/data

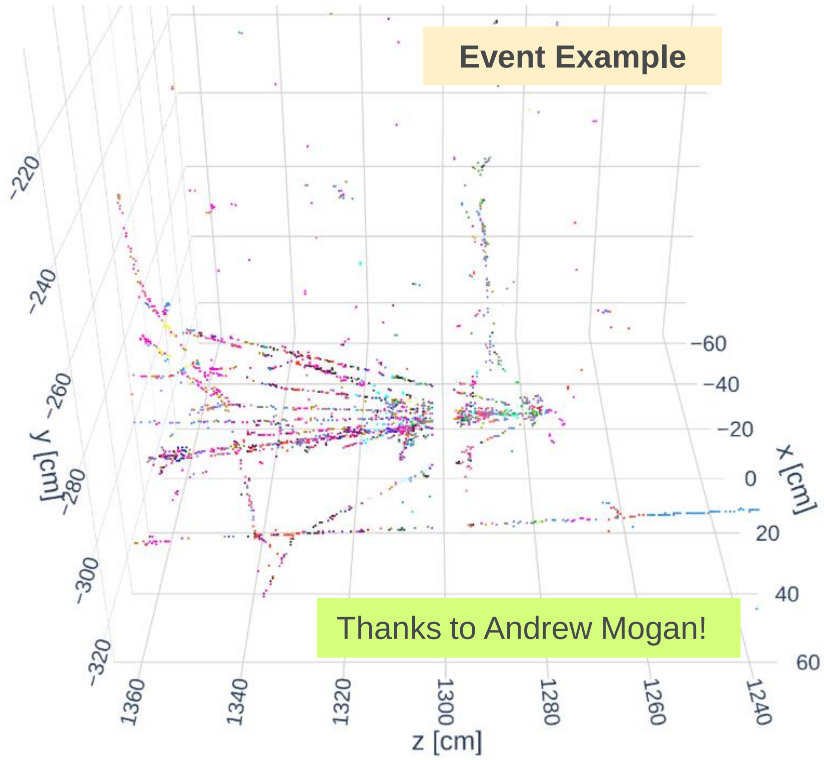
Names	Formats	Offsets
event_id	uint32	0
vertex_id	uint64	8
vertex	('<f8', (4,))	16
target	uint32	48
reaction	int32	52
isCC	bool	56
isQES	bool	57
isMEC	bool	58
isRES	bool	59
isDIS	bool	60
isCOH	bool	61
Enu	float32	64
nu_4mom	('<f4', (4,))	68
nu_pdg	int32	84
Elep	float32	88
lep_mom	float32	92

Dataset: /mc_truth/***trajectories***/data

Names	Formats	Offsets
event_id	uint32	0
vertex_id	uint64	8
traj_id	uint32	16
local_traj_id	uint32	20
parent_id	int32	24
E_start	float32	28
pxyz_start	('<f4', (3,))	32
xyz_start	('<f4', (3,))	44
t_start	float64	56
E_end	float32	64
pxyz_end	('<f4', (3,))	68
xyz_end	('<f4', (3,))	80
t_end	float64	96
pdg_id	int32	104

HOW WILL THE MULTIPLICITY ANALYSIS PROCEED?

- **Charged Multiplicity Analysis Steps**
  - Collect charge hits vs time
  - Reconstruct hit clusters → tracks/showers
  - Reconstruct neutrino slices within each event
  - Find an event vertex
  - Loop around vertex to find associated tracks
  - Use track length in the track selection
  - Count number of charged particle tracks
  - Compare data to MC distributions
  - Account for systematic uncertainties.

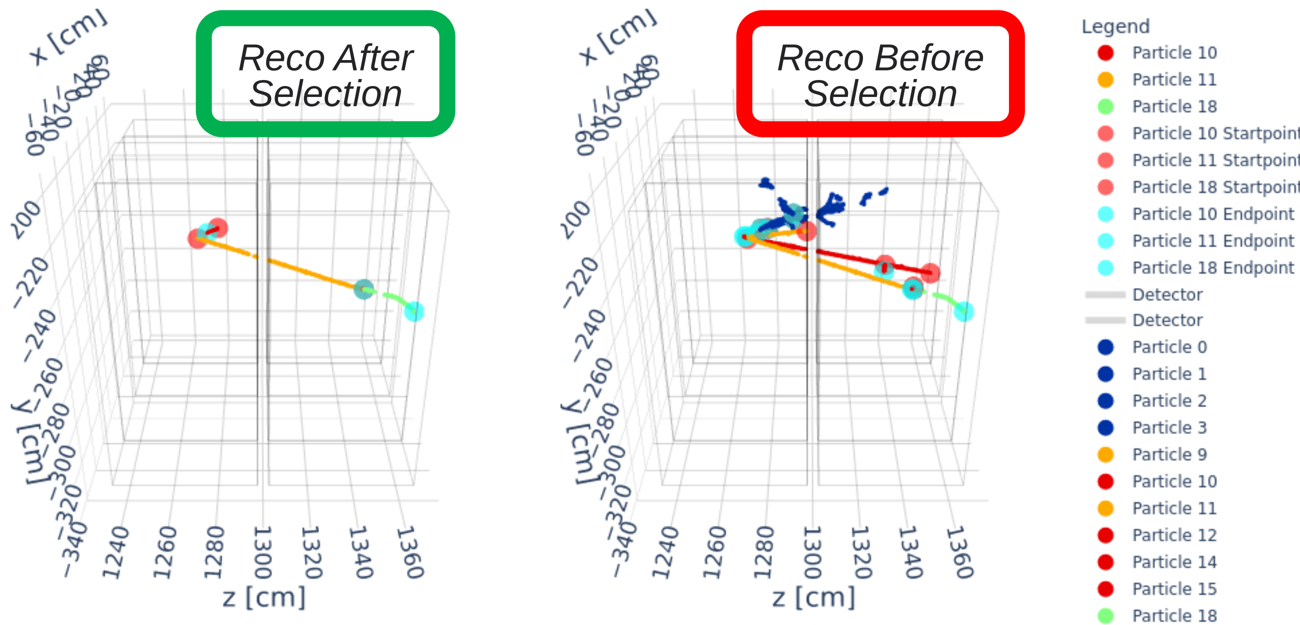


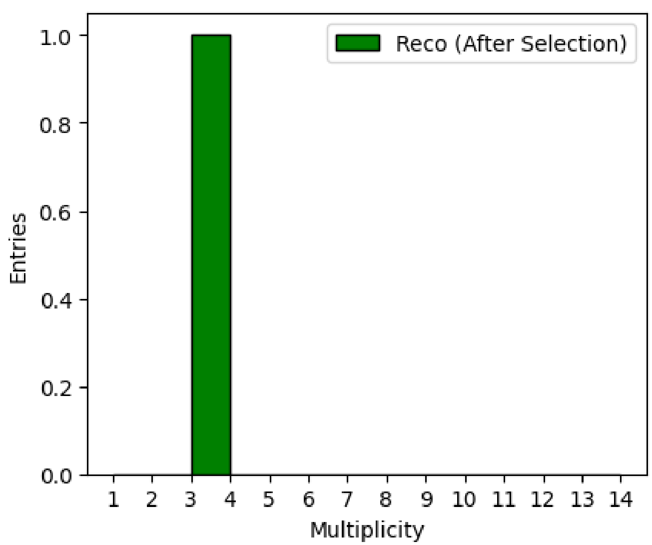
Argonne NATIONAL LABORATORY

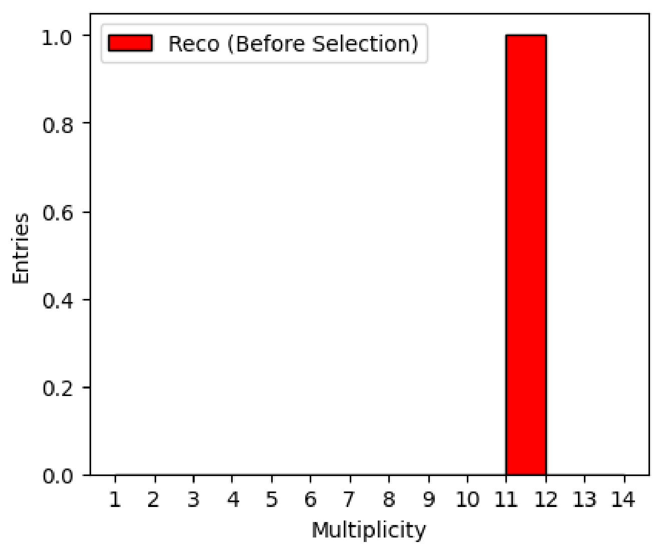
HOW EVENT LOOKS LIKE?

output_27023276_64-larcv_mlreco_ana.h5 (Event 30, Interaction 18)

- **Multiplicity**
  - **Before Selection:** 11
  - **After Selection:** 3





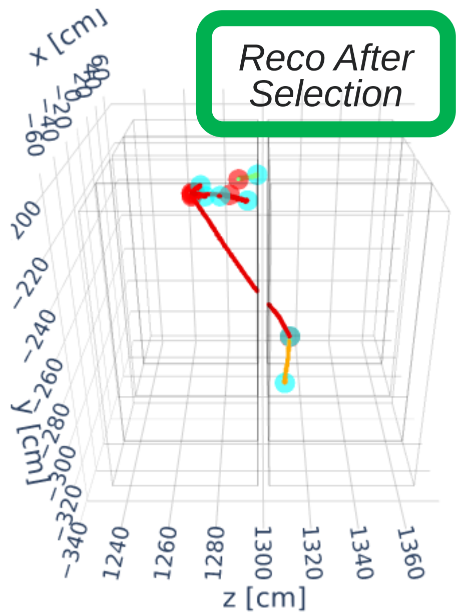


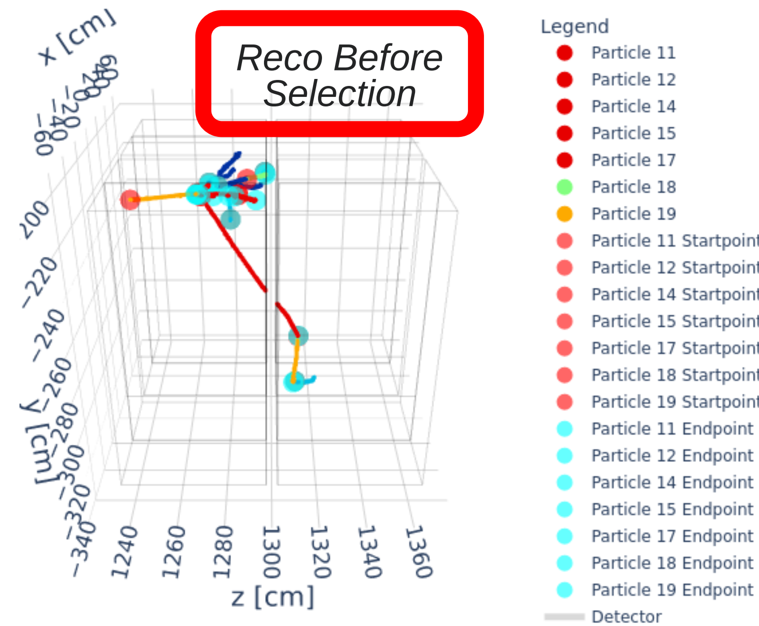
Argonne NATIONAL LABORATORY

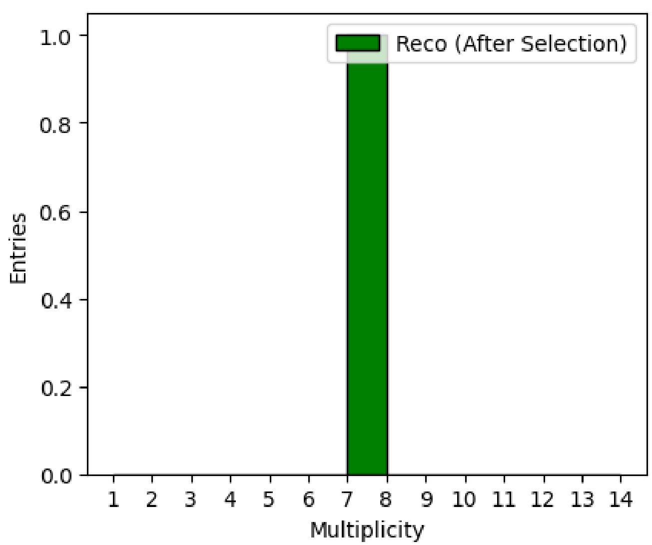
HOW EVENT LOOKS LIKE?

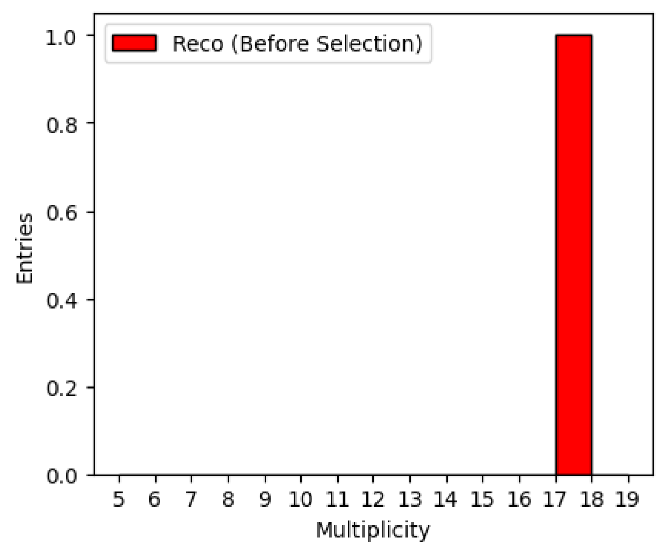
output_27023276_28-larcv_mlreco_ana.h5 (Event 81, Interaction 6)

- **Multiplicity**
  - **Before Selection:** 17
  - **After Selection:** 7



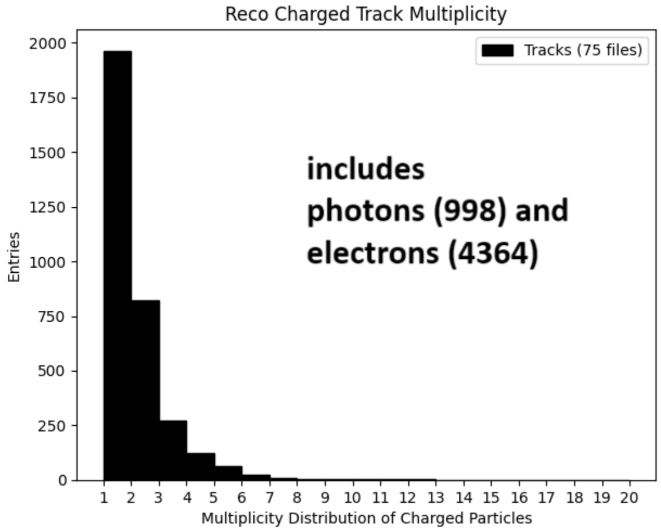


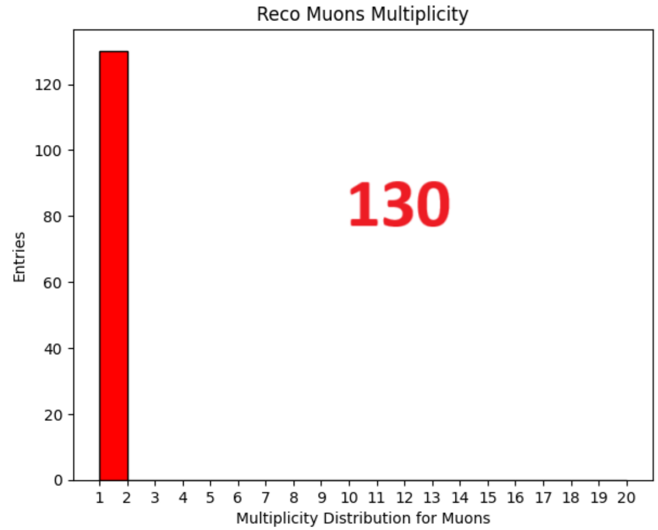


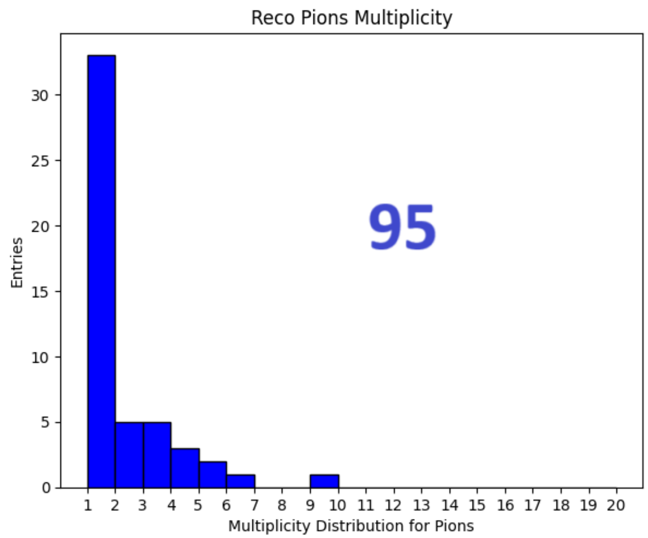


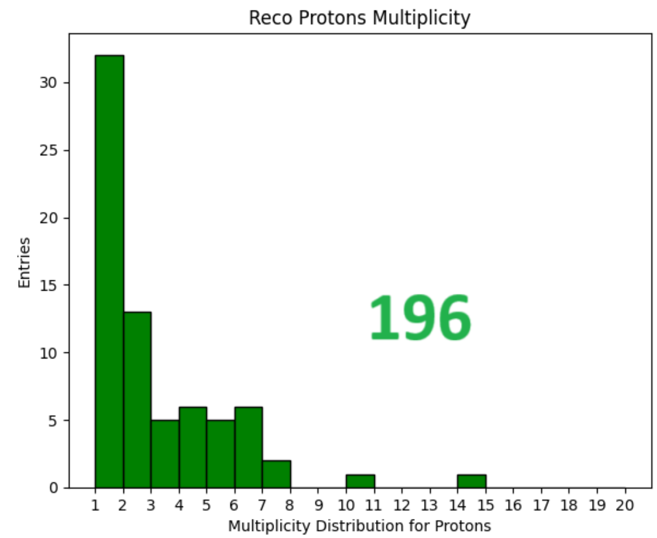
ANALYSIS WITH LARGER STATISTICS

1 muon plus other particles
Track > 0 cm; within FV; 10 cm from outer boundaries (along x, y, z) and inner boundaries (along x and z)









Argonne NATIONAL LABORATORY

SUMMARY AND NEXT STEPS

- We did truth studies and now we are looking at reconstructed events.
- Working on to optimize event selection criteria

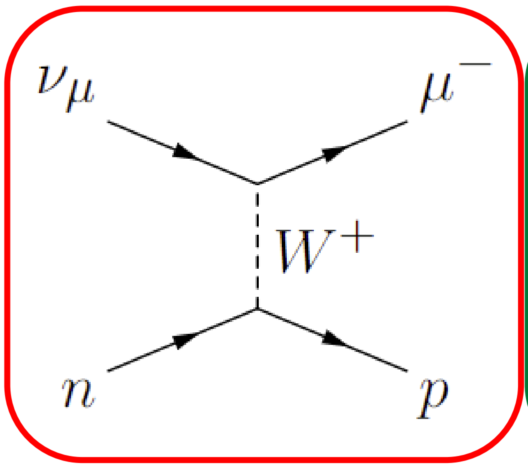
- Quantifying features such as multiplicity, energy and, angular distributions.
  - Looking at specific neutrino interactions such as CC events $(1\mu + \text{other})$
  - Continue developing the analysis

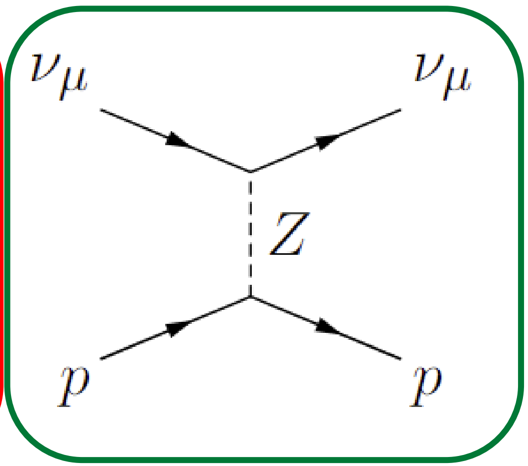
- Later, we will include systematics in the analysis
  - Re-Weightable Systematics
    - Flux systematics
    - GENIE/Cross-section and FSI systematics
    - GEANT4 re-interaction systematics
  - Detector systematics
    - Charge readout systematics: threshold, gain, time dependance
    - Space charge effect systematics
    - Recombination model systematics and diffusion systematics
    - Electron lifetime
  - Reconstruction systematics
    - PANDORA and/or ML-Reco uncertainties in track counting efficiency

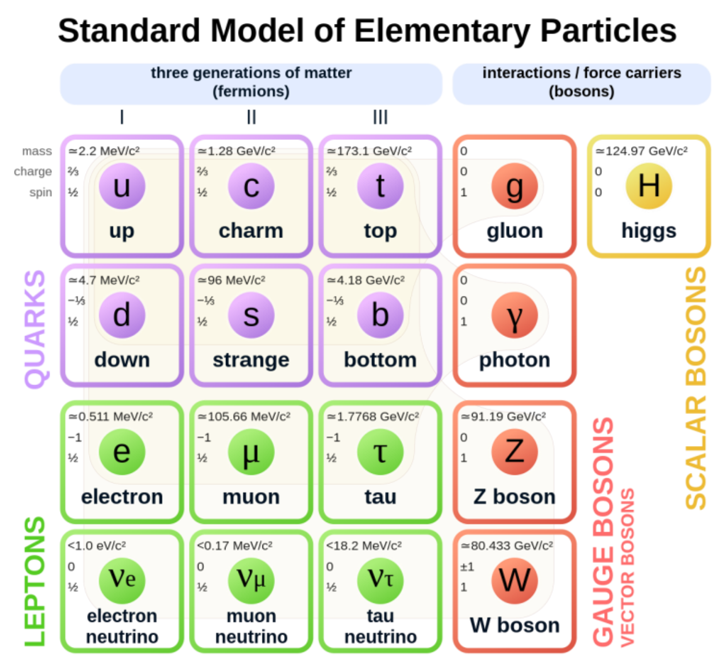
BACKUP SLIDES

NEUTRINOS

- Spin ½ fermions with very light masses
- 3 neutrino flavors: electron, muon, and tau
- Left-handed weak interactions (very small cross-section)
- Oscillate between mass and flavor eigenstates
- Interact via Charged Current (CC) and Neutral Current (NC)



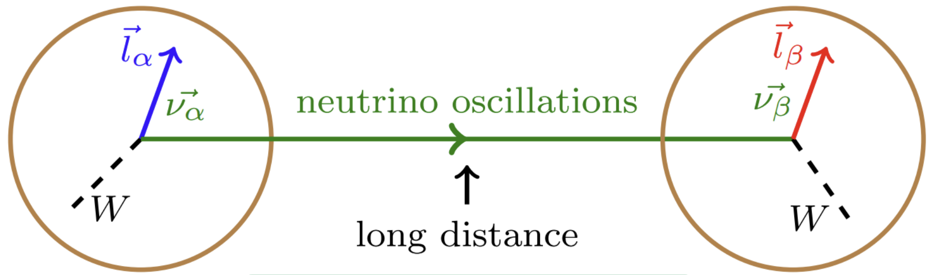




NEUTRINO OSCILLATIONS

- Change flavor when travels over a distance (neutrino oscillations)
- Flavor states $(\nu_e, \nu_\mu, \nu_\tau)$ are a **linear combination** of mass eigenstates (ν_1, ν_2, ν_3)

Production
$|\nu_\alpha\rangle$: Beam of only one neutrino specie



Detection
$$\langle \nu_\alpha | = \sum_k \langle \nu_j | U_{\alpha k}$$
Projection over flavor states

Propagation
$$\nu_k\text{: } \exp(-iE_k t)$$
Different propagation phases change ν_k composition

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Argonne NATIONAL LABORATORY

NEUTRINO MIXING

- 2-neutrino mixing depends on **1 angle** only.

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- 3-neutrino mixing is described by **3 angles** and **1 Dirac** CP violating phase.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

oscillation of atmospheric neutrinos

measured by reactor neutrino experiments

Dirac phase on which oscillations depend

oscillation of solar neutrinos

Argonne NATIONAL LABORATORY

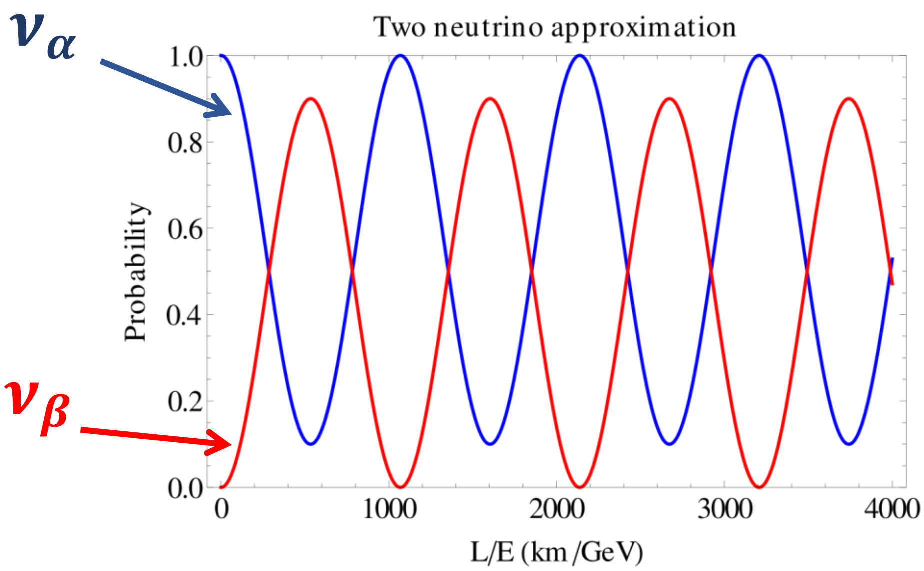
TWO NEUTRINO OSCILLATIONS

- Two-neutrino oscillation probability $(\alpha \neq \beta)$

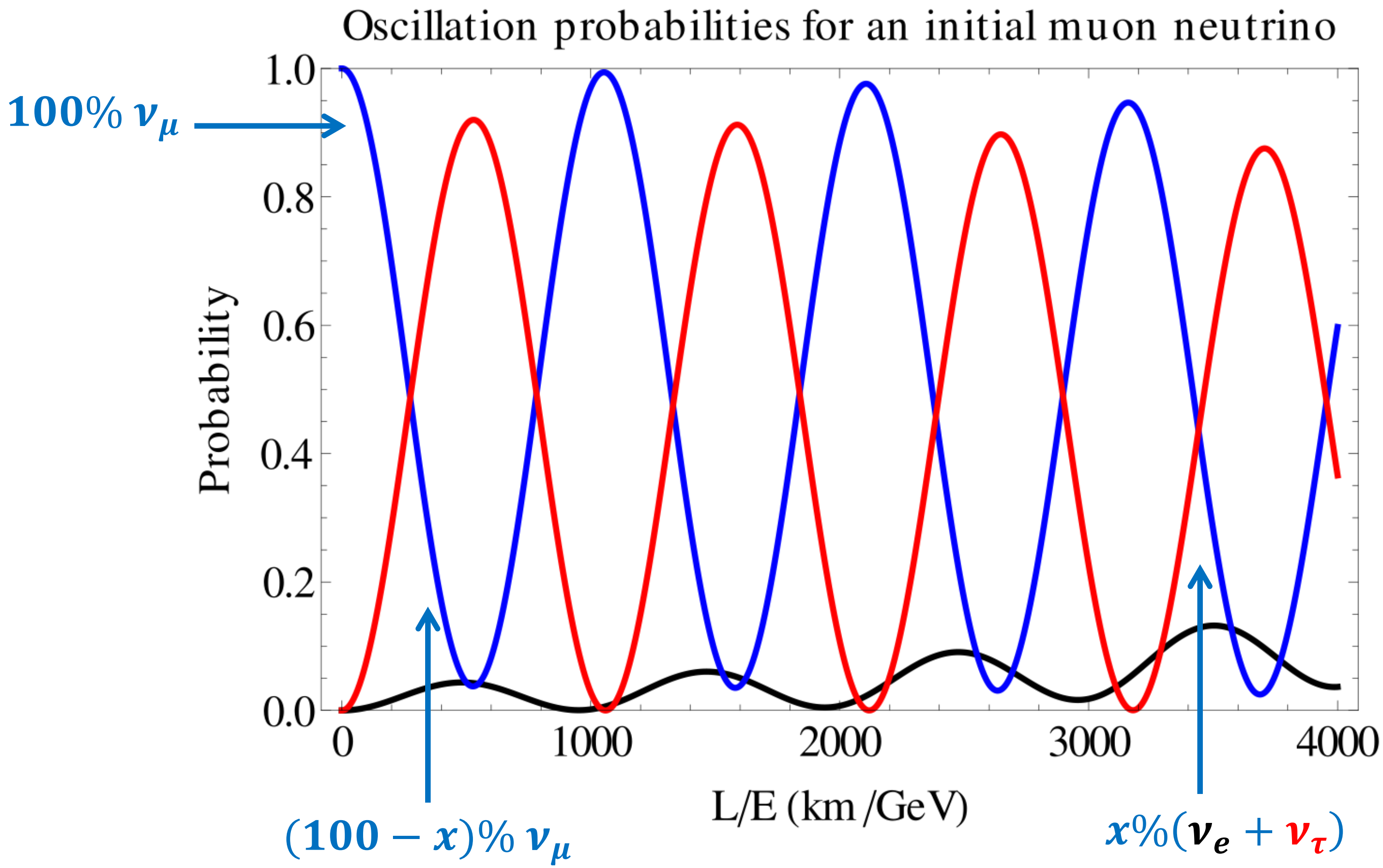
$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2(2\boldsymbol{\theta}) \sin^2(\phi)$$

- The oscillation phase

$$\phi = \frac{\boldsymbol{\Delta m^2_{21}} L}{4E} = 1.27 \frac{\Delta m^2_{21}[\mathrm{eV}^2]\boldsymbol{L}[\mathrm{km}]}{\boldsymbol{E}[\mathrm{GeV}]}$$



THREE NEUTRINO OSCILLATION PROBABILITY AS A FUNCTION OF THE BASELINE



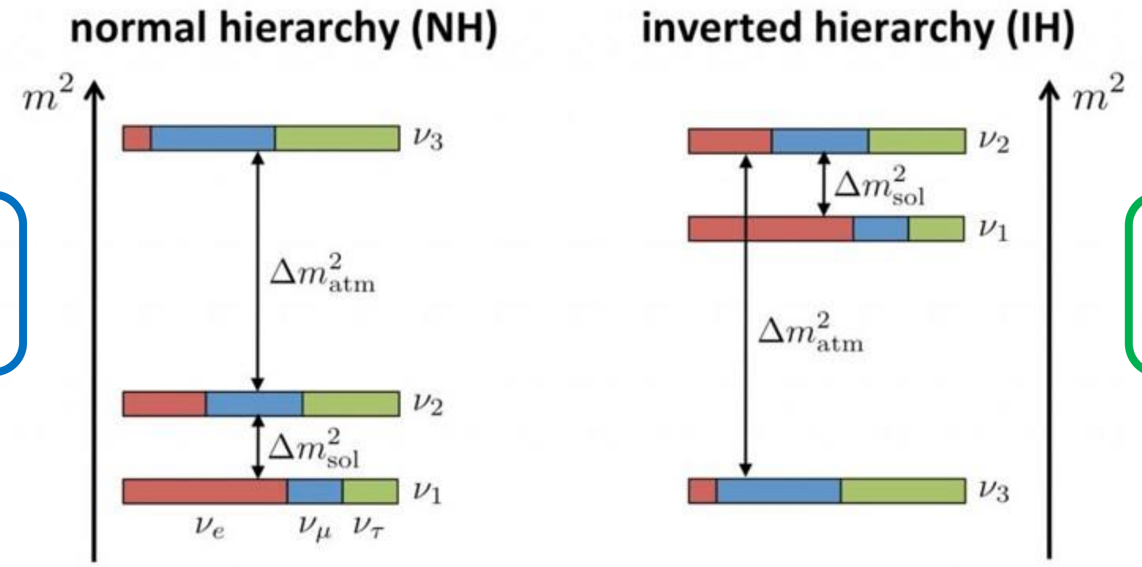
NEUTRINO MASS ORDERING

- We know the two mass-squared differences from neutrino oscillations

$$|\Delta m^2_{\text{atm}}| \sim 2.5 \times 10^{-3}\ \text{eV}^2$$
$$\Delta m^2_{\text{sol}} \sim 7.5 \times 10^{-3}\ \text{eV}^2$$

- Sign of Δm^2_{atm} is unknown.

$\nu_3 > \nu_2 > \nu_1$
ν_e is lighter.

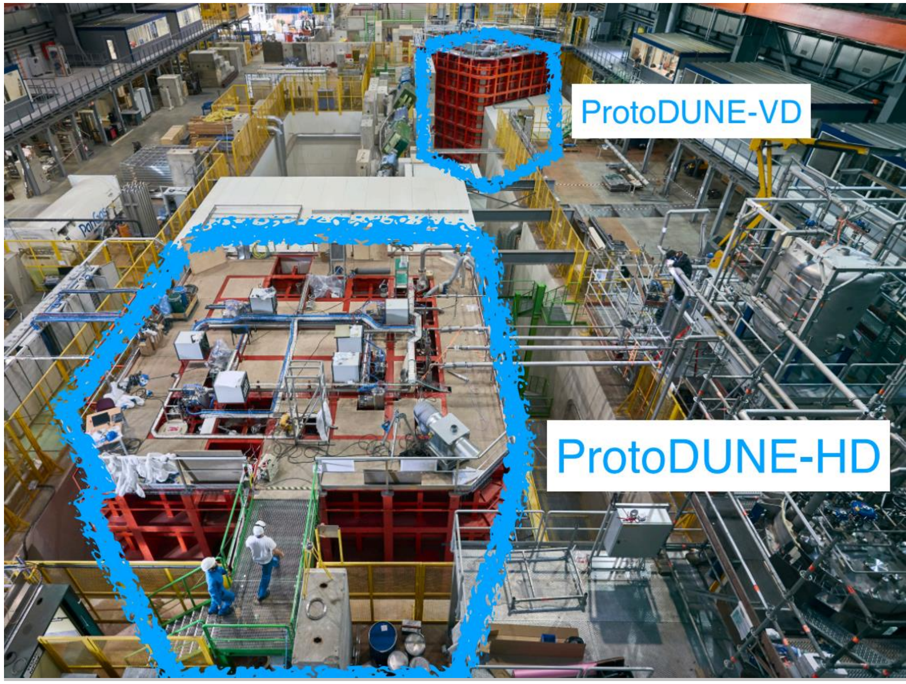


$\nu_2 > \nu_1 > \nu_3$
ν_e is heavier.

ProtoDUNE at CERN

- Two $750\ \text{ton}$ prototypes: $(7.2 \times 6.1 \times 7.0)\ \text{m}$
  – Single-Phase Horizontal Drift (HD)
  – Single-Phase Vertical Drift (HD)

- Advantages
  – Design validation of all components
  – Characterize detector performance on charged-particle beams
  – Train and develop reconstruction algorithms
  – Perform in-depth physics analysis
  – Provide feedback to AI/ML reconstruction and Monte-Carlo simulations



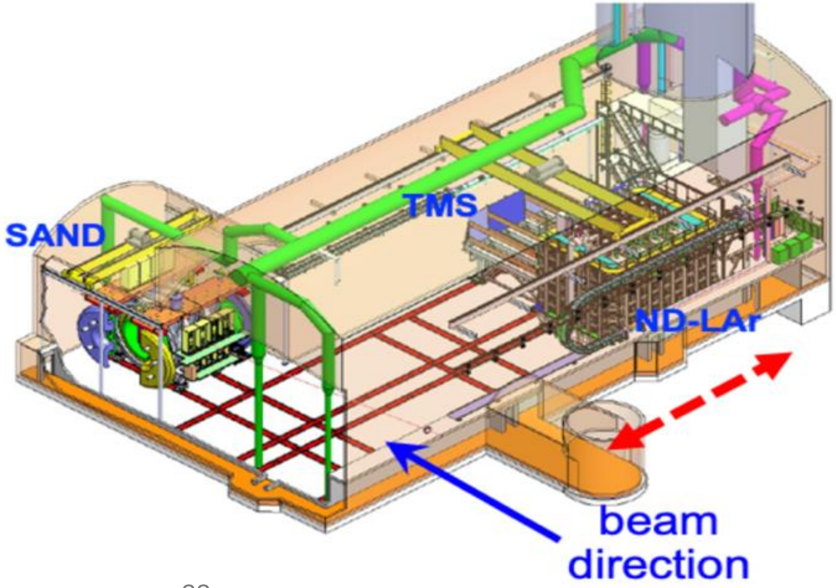
Each DUNE-FD module will be $\mathbf{20}$ *times larger than one ProtoDUNE detector.*

NEAR DETECTOR COMPLEX

- Near Detector Liquid Argon **(ND-LAr)**
  - A $67 - \text{ton}$ liquid argon time projection chamber (TPC)
  - Allows target for neutrino interactions with hadronic activity

- Temporary Muon Spectrometer **(TMS)**
  - Muon spectrometer for forward muons not contained in ND-LAr

- System for On-Axis Neutrino Detection **(SAND)**
  - Provides baseline monitoring with a detector and target that enables weekly beam-monitoring

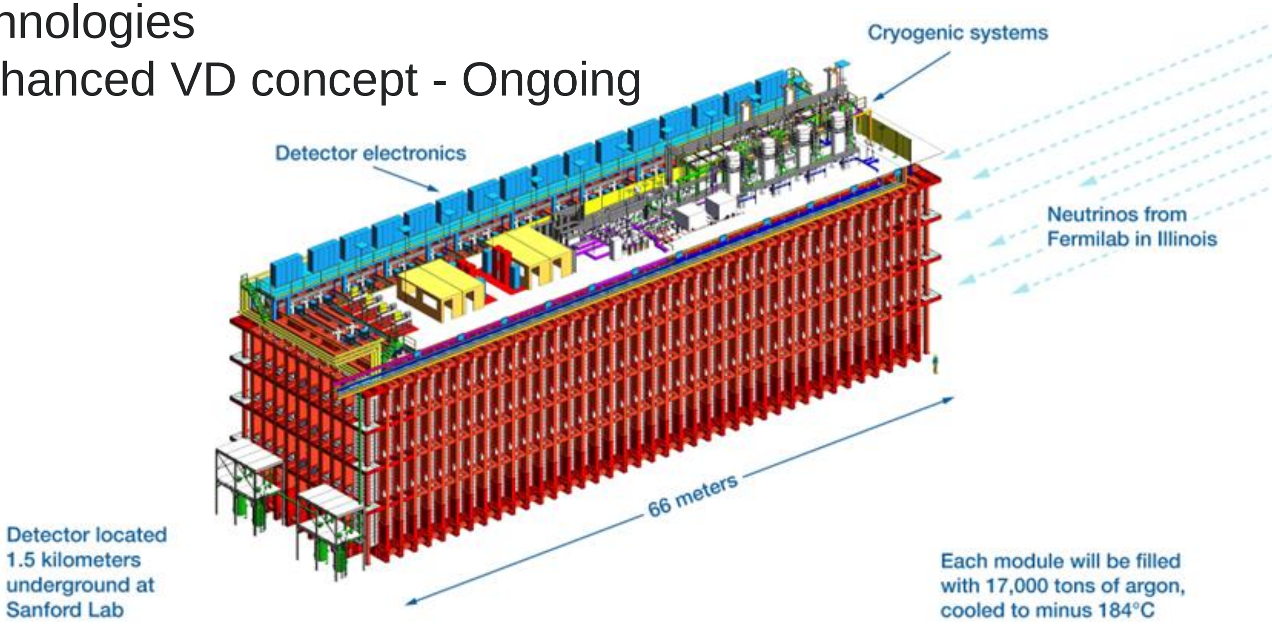


FAR DETECTOR COMPLEX

- 4 detector modules, 17 kt total mass each (~10 kt of FV each)
  - Construction in stages
  - 2 single-phase (SP) and 2 dual-phase (DP) LArTPCs

- Single-Phase LArTPC
  - FD #1: Horizontal Drift (HD) − Construction starts in mid 2020's
  - FD #2: Vertical Drift (VD)

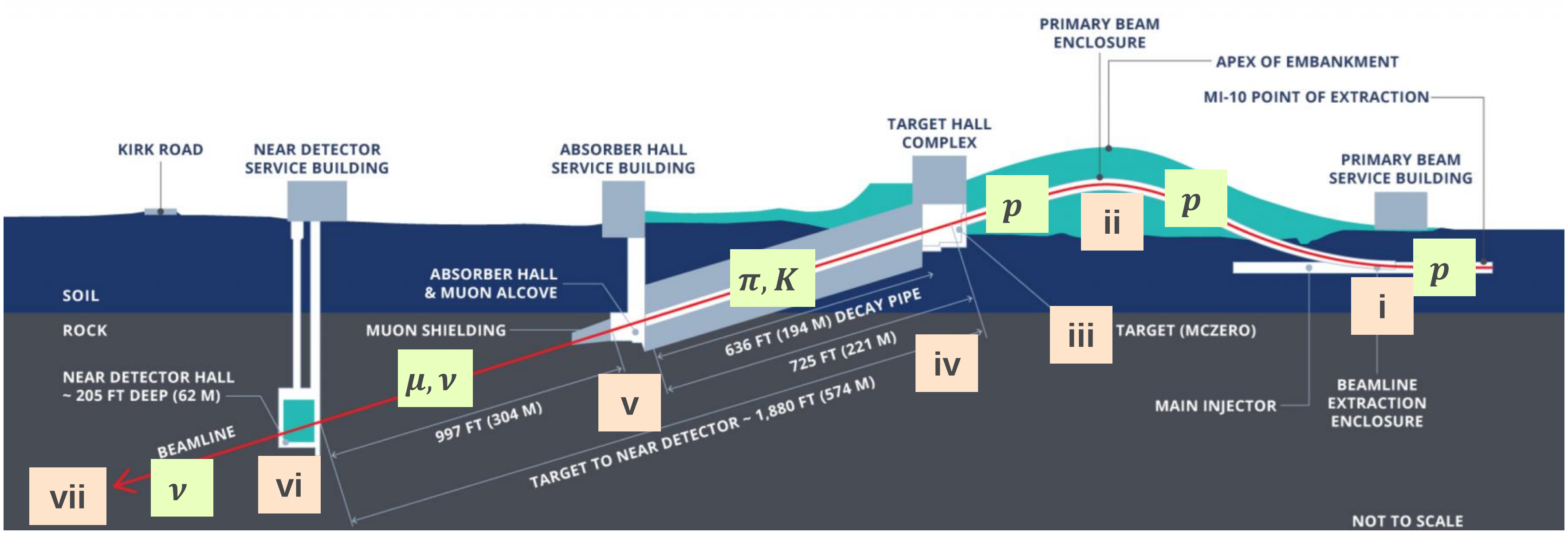
- Dual-Phase LArTPC Technologies
  - FD #3: SP LArTPC enhanced VD concept - Ongoing
  - FD #4: Ongoing R&D



LBNF NEUTRINO BEAM (WORKING)

i. Start with an intense (MW) proton beam
ii. Point towards South Dakota
iii. Smash high-energy (~80 GeV) protons into a target
iv. Focus positive pions/kaons
v. Allow them to decay
vi. Absorb remaining charged particles in rock (e.g., $\pi^+, \pi^-, K^+, K^-, K^0$)
vii. Left with a "collimated" ν_μ beam

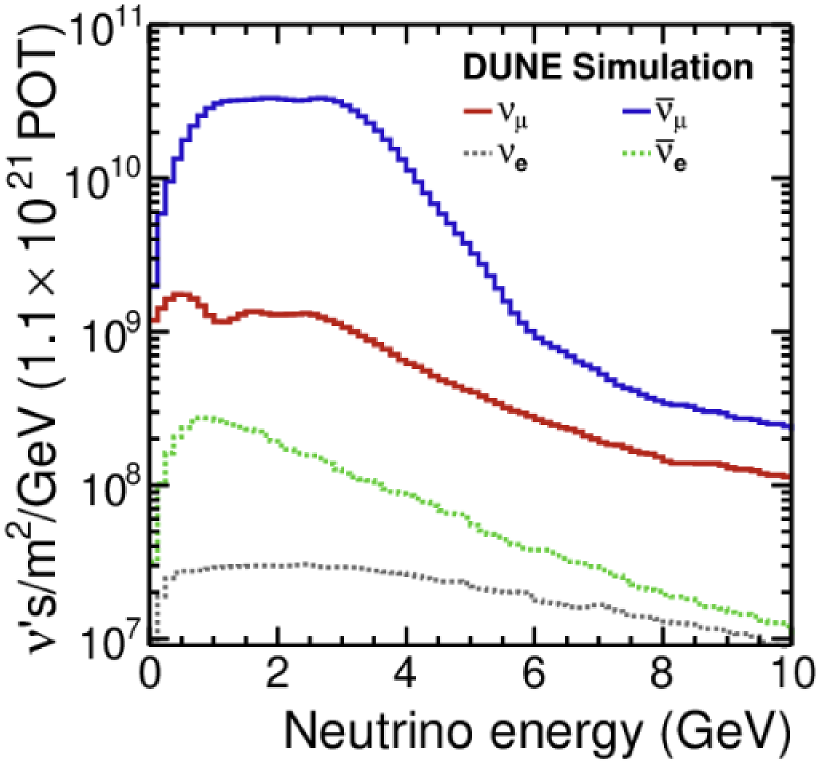
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \overline{\nu_\mu}$$
$$\mu^+ \to e^+ + \nu_e + \overline{\nu_\mu}$$
$$K^+ \to \mu^+ + \nu_\mu$$
$$k^+ \to \pi^0 + e^+ + \nu_e$$
$$K^- \to \mu^- + \overline{\nu_\mu}$$
$$K^- \to \pi^0 + e^- + \overline{\nu_e}$$



NEUTRINO BEAM FLUX

- Predicted fluxes at FD are shown.
- Generated using Geant4-based simulation of the LBNF neutrino beam
- Fluxes are available in both modes:
  - Forward Horn Current (FHC) mode (for neutrinos)
  - Reverse Horn Current (RHC) mode (for antineutrinos)
- DUNE oscillation
  - Around $3\ \mathrm{GeV}$
    - $\overline{\nu_\mu}$ is 3×10^{10}
    - $\overline{\nu_e}$ is 3×10^{8}

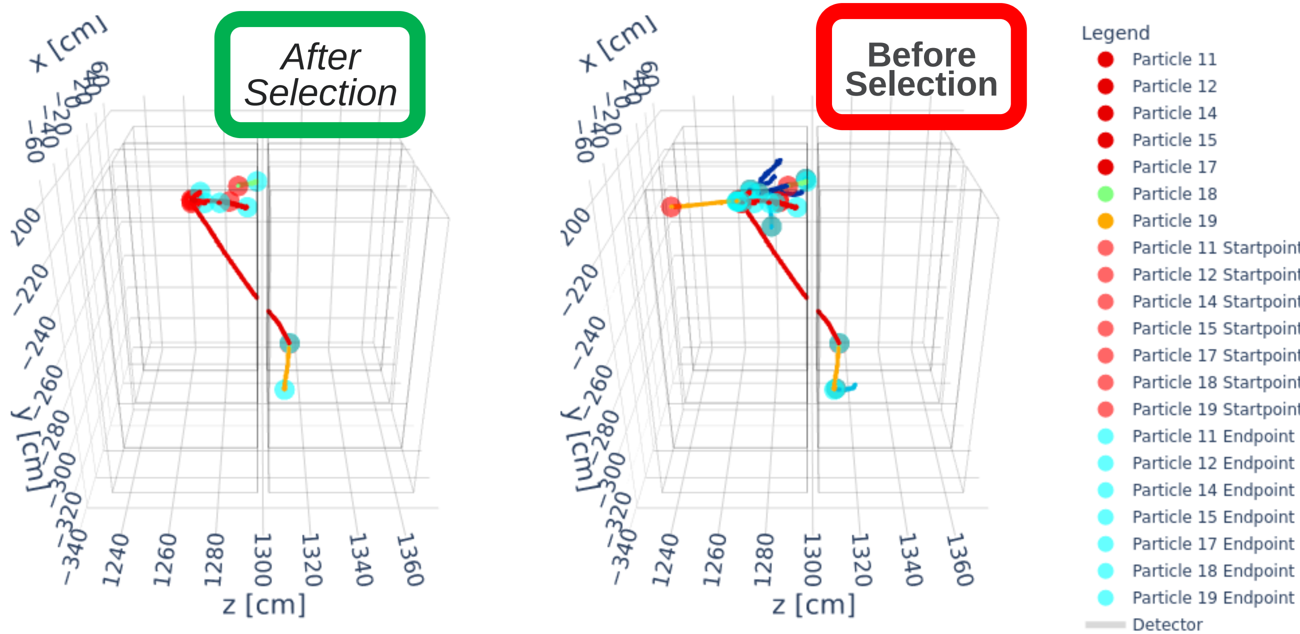
  1% of antineutrinos are electron-antineutrinos.

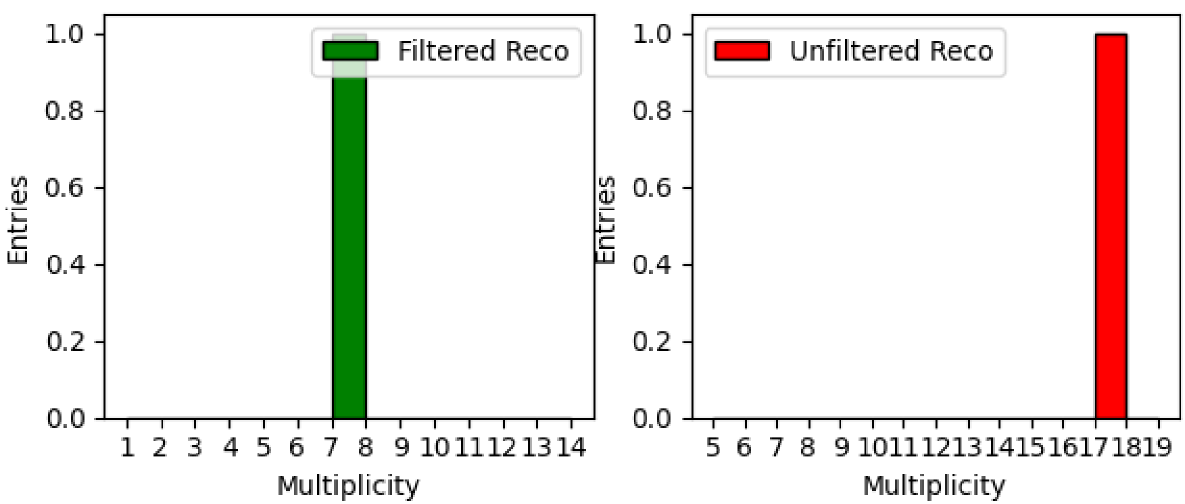


HOW EVENT LOOKS LIKE?

output_27023276_28-larcv_mlreco_ana.h5 (Event 81, Interaction 6)

	No Selection	After Selection
γ	2	0
e	3	0
μ	1	1
$\pi^{\pm}$	4	1
p	7	5
K	0	0



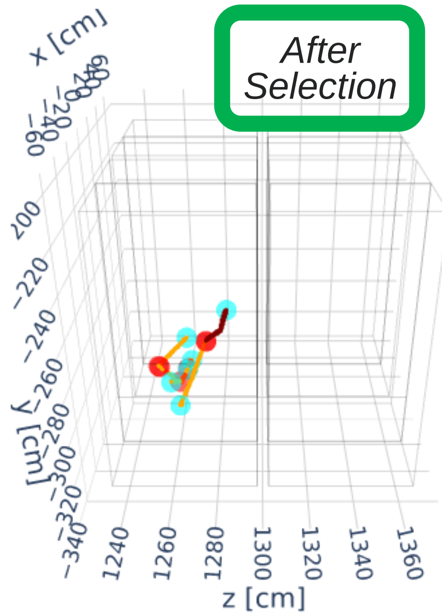


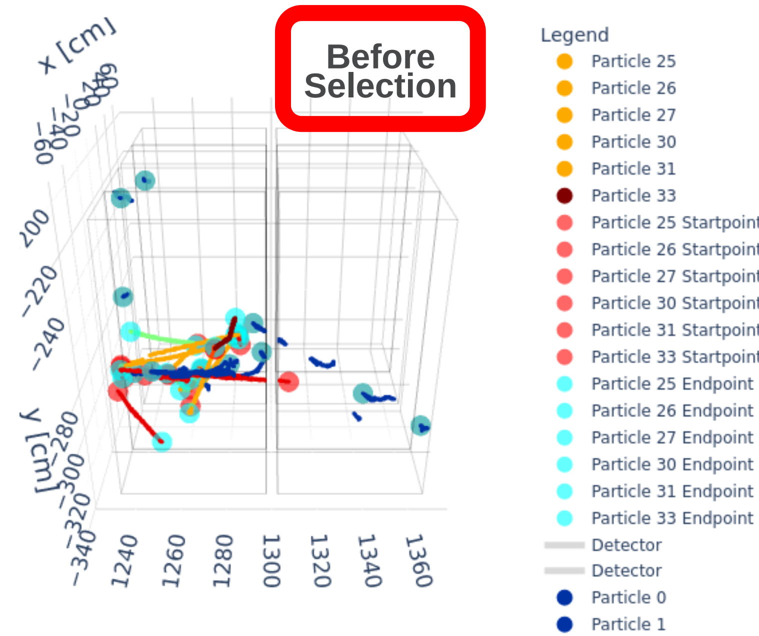
Argonne NATIONAL LABORATORY

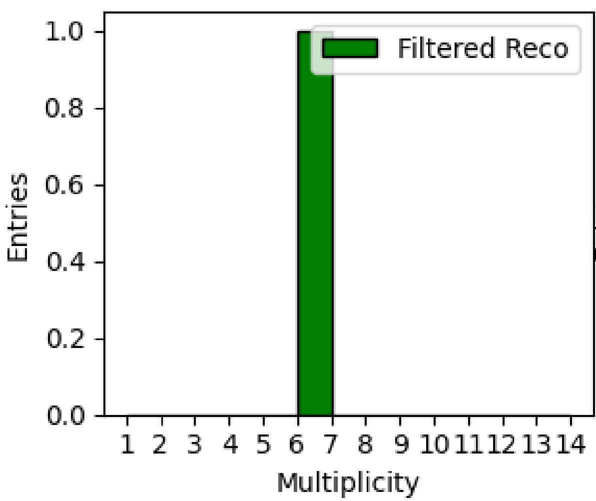
HOW EVENT LOOKS LIKE?

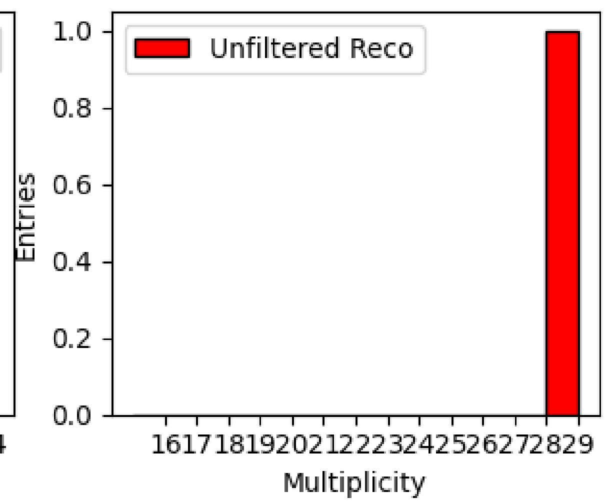
output_27023276_88-larcv_mlreco_ana.h5 (Event 99, Interaction 6)

	No Selection	After Selection
γ	10	0
e	1	0
μ	1	5
$\pi^{\pm}$	9	0
p	7	1
K	1	0





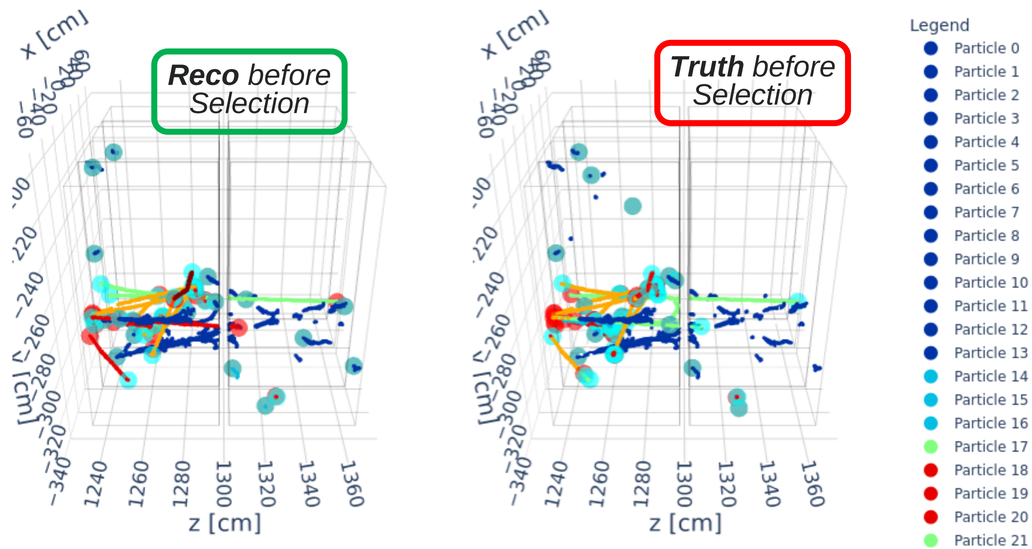


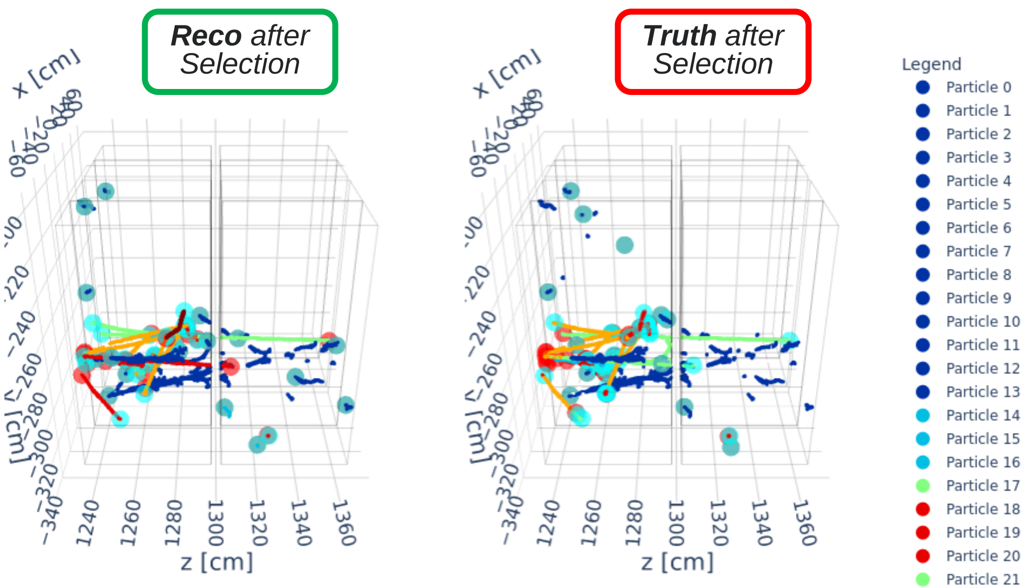


Argonne NATIONAL LABORATORY

HOW EVENT LOOKS LIKE?

output_27023276_88-larcv_mlreco_ana.h5 (Event 99)





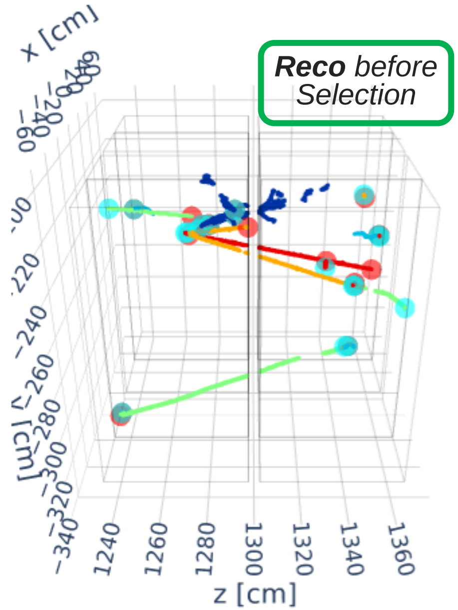
- Interaction IDs ***before*** Selection
  - **Truth:** 0, 1, 2, 3, 5
  - **Reco:** 3, 6, 15, 16, 17, 32, 37
- Interaction IDs ***after*** Selection
  - **Truth:** 3
  - **Reco:** 6

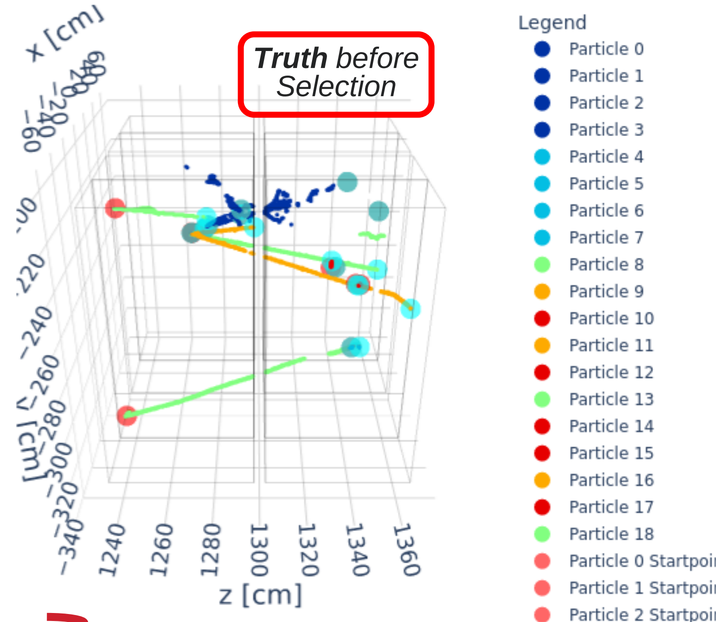
Argonne NATIONAL LABORATORY

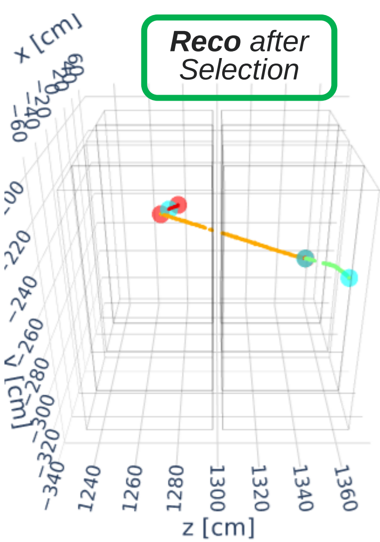
HOW EVENT LOOKS LIKE?

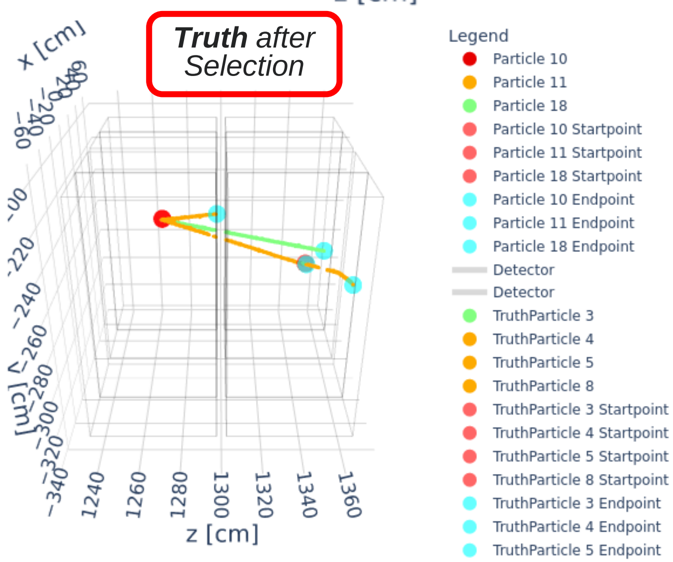
output_27023276_64-larcv_mlreco_ana.h5 (Event 30)

	Truth	Reco
γ	4	4
e	1	4
μ	3	3
$\pi^{\pm}$	3	3
p	6	5







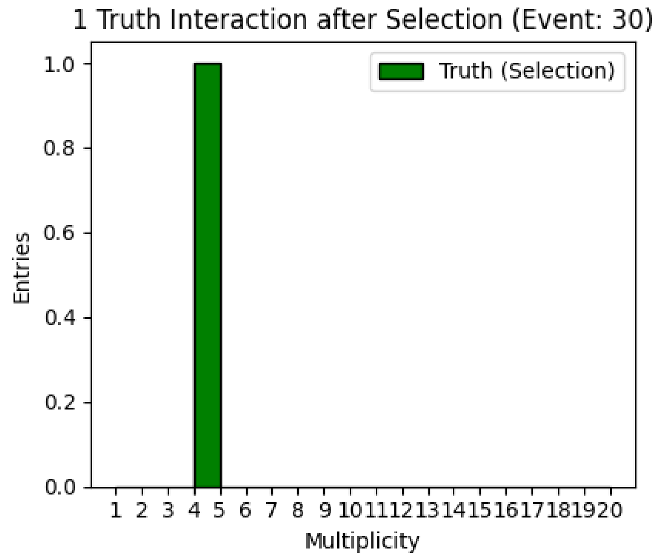


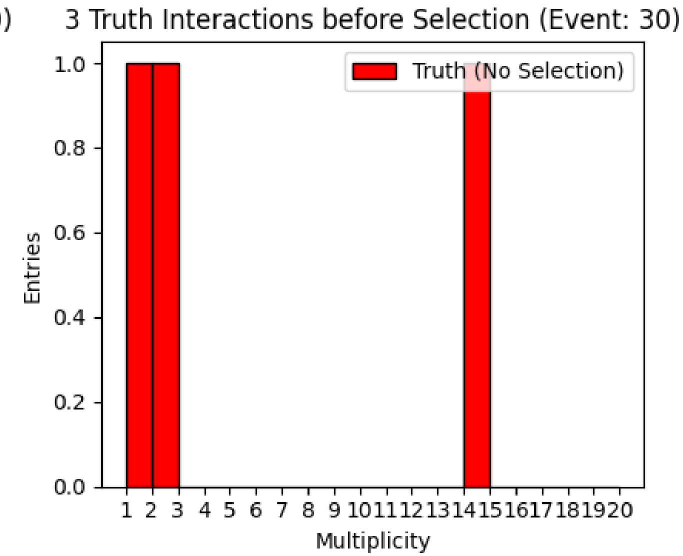
	Truth	Reco
γ	0	0
e	0	0
μ	1	1
$\pi^{\pm}$	3	1
p	0	0

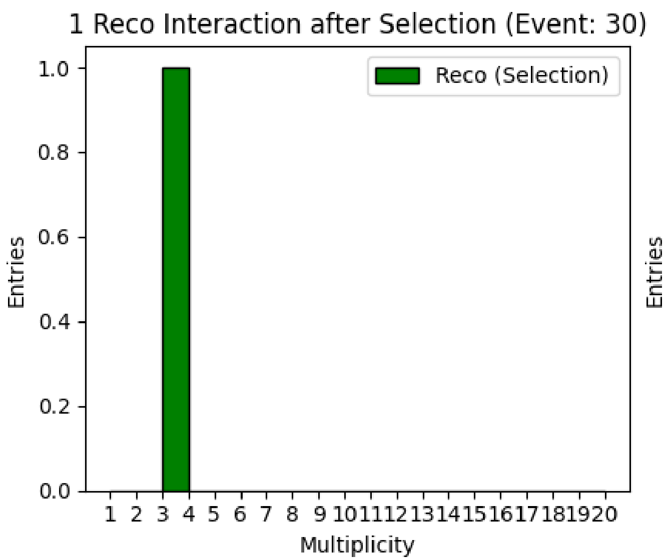
Argonne NATIONAL LABORATORY

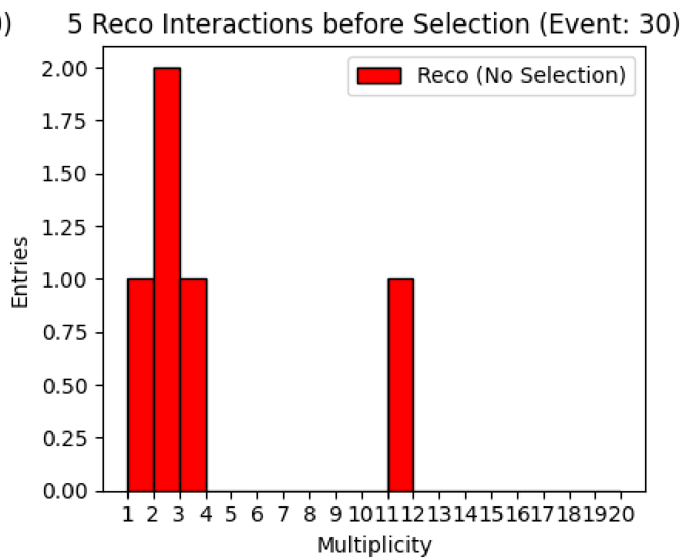
HOW EVENT LOOKS LIKE?

output_27023276_64-larcv_mlreco_ana.h5 (Event 30)



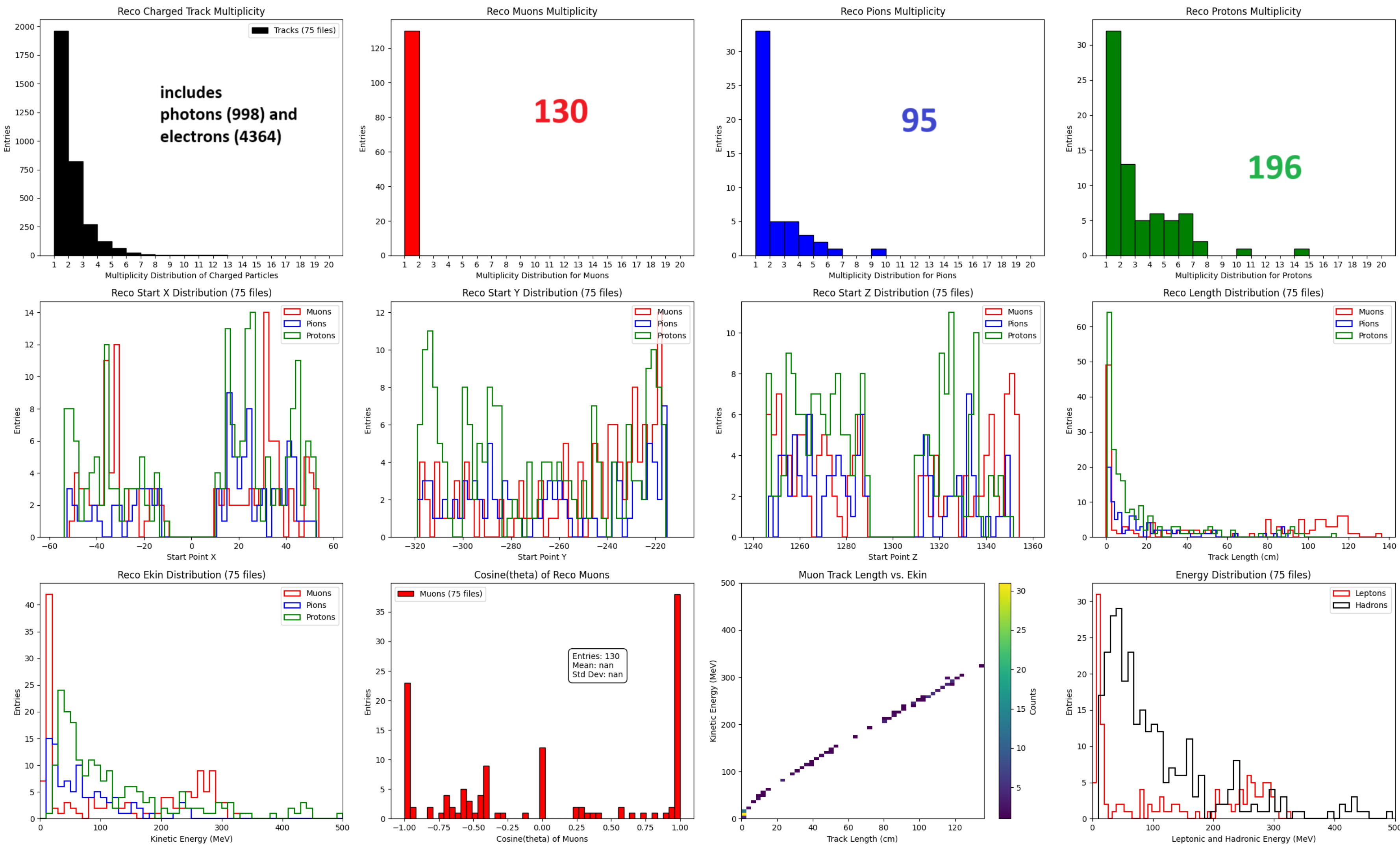






MORE ANALYSIS TO COME…

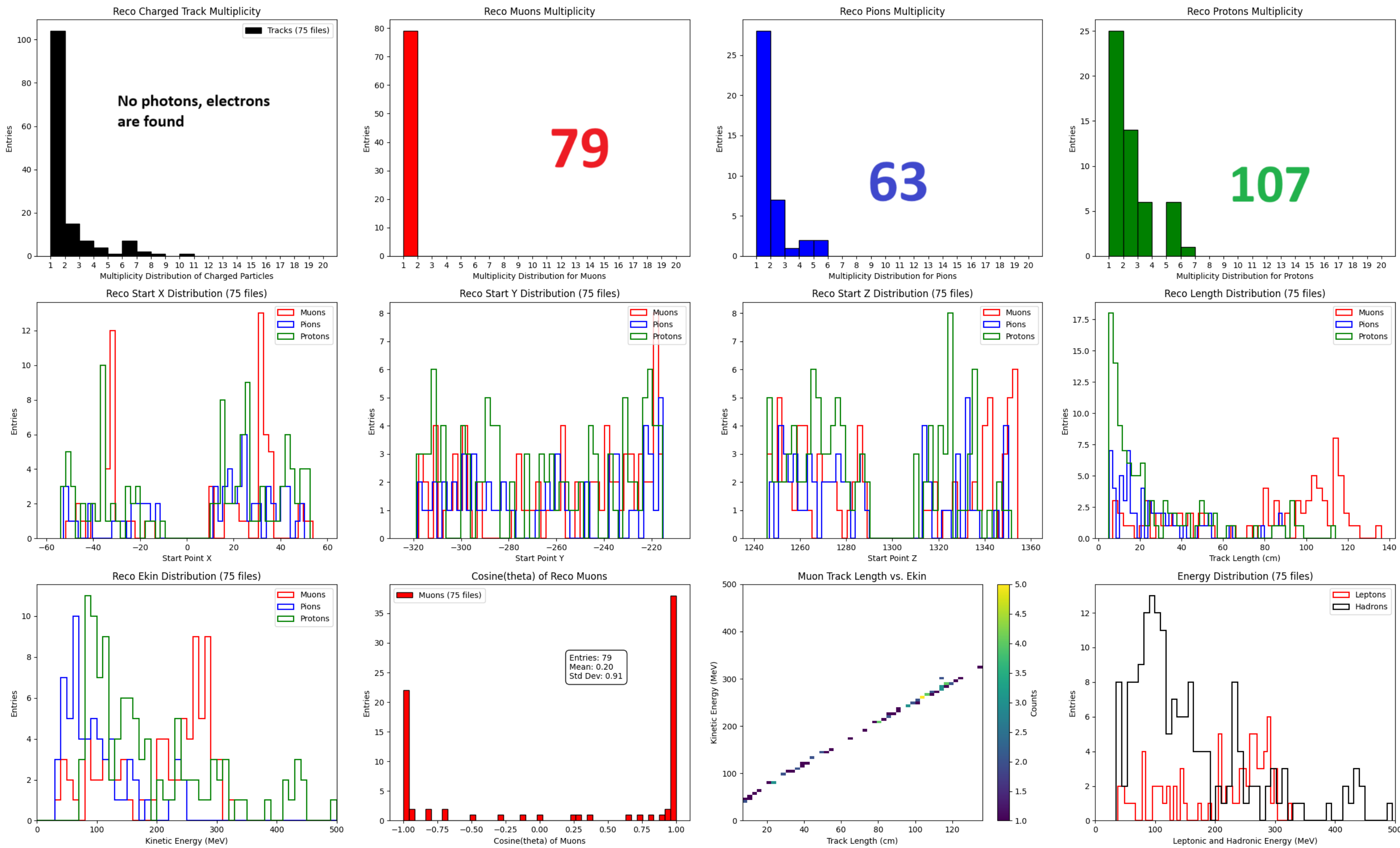
1 muon plus other particles
Track > 5 cm; within FV; 10 cm from outer and inner boundaries



Argonne NATIONAL LABORATORY

MORE ANALYSIS TO COME…

1 muon plus other particles
Track > 5 cm; within FV; 10 cm from outer and inner boundaries



Argonne NATIONAL LABORATORY

List of Statistical and Systematic Uncertainties Relevant for charged track multiplicity analysis

➢ **Statistical Uncertainties**

- Data sample statistical uncertainty: collected data set statistics with expected NuMI POT exposure
- Intrinsic Monte-Carlo Statistical Uncertainty: to be considered with a finite size simulated data set.

➢ **Systematic Uncertainties**

- Re-Weightable Systematics* :

  -Flux Systematics
  -GENIE/Cross-Section and FSI Systematics
  -Geant4 Re-Interaction Systematics.

Please also see Richie's talk on truth studies.

- Detector Systematics

  -Charge Readout Systematics: threshold, gain, time dependence
  -Space Charge Effect Systematics
  -Recombination Model Systematics and Diffusion Systematics
  -Electron lifetime.

- Reconstruction Systematics

  -PANDORA and/or ML-reco uncertainties in track counting efficiency: a function of particle type and deposited energy (short vs long-track).

Please see Aleena's talk on Pandora validation.

Argonne NATIONAL LABORATORY