Machine-Learning-Based Data Reconstruction Chain for the Short Baseline Near Detector

B. Carlson

SBND

July 1, 2025

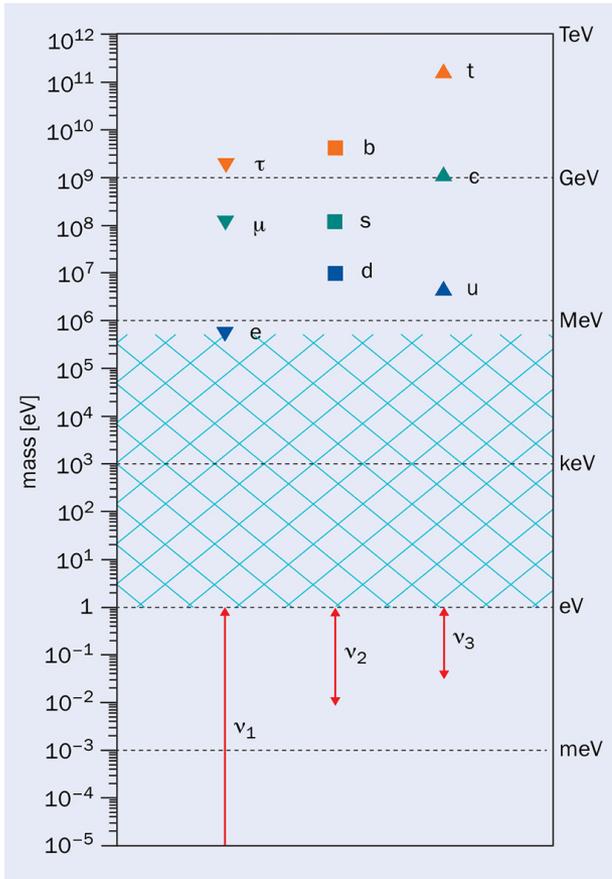- Neutrinos are electrically neutral, nearly massless leptons with three flavor generations

Neutrinos

- Neutrino interact in flavor states (*interaction basis*) via weak force bosons

    - Charged current (CC) interact via $W^{\pm}$ bosons

    - Neutral current (NC) interact via Z^0 boson
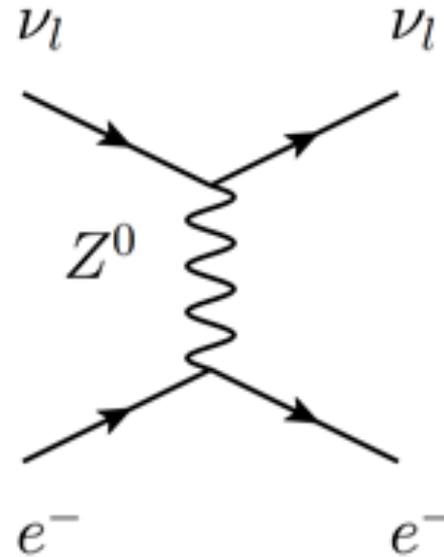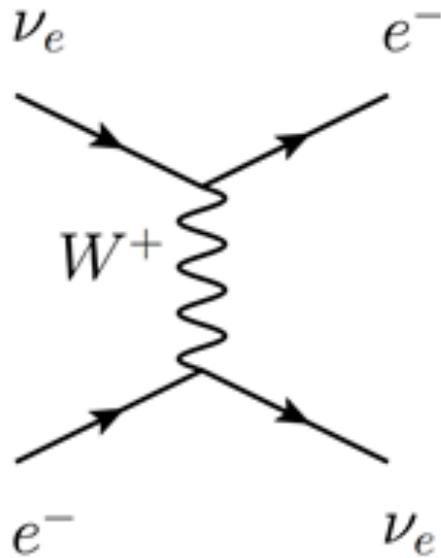
Neutrinos

- Neutrino flavor states (*interaction basis*) are mixed between mass states (*mass basis*)
  - This gives rise to **neutrino oscillations**

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^* |\nu_i\rangle$$
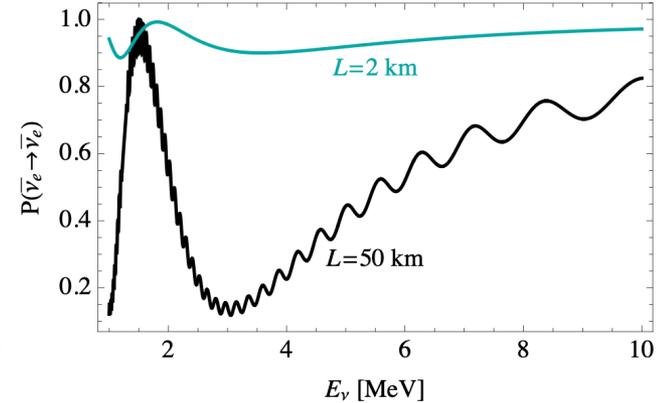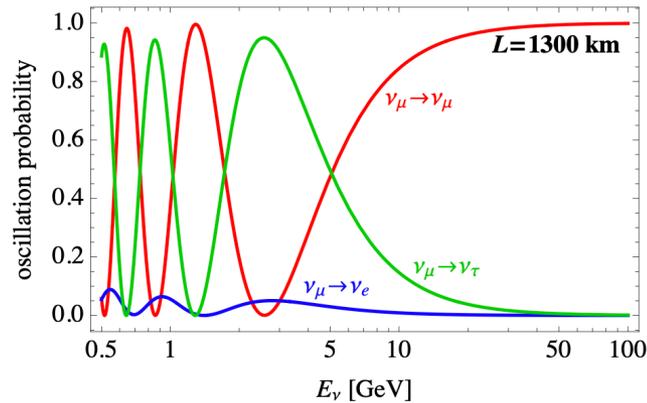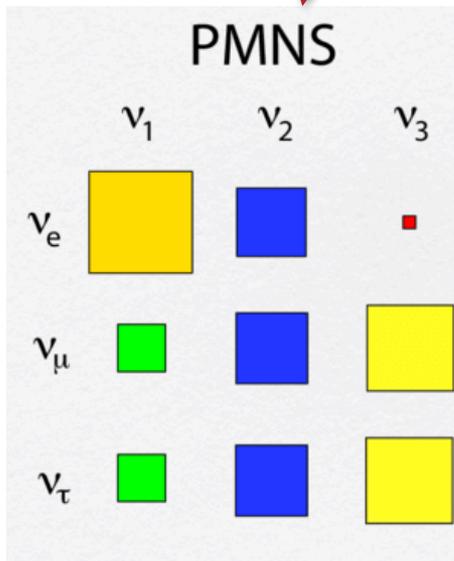
$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 = \left| \sum_j U_{\alpha j}^* U_{\beta j} e^{-im_j^2 L/(2E)} \right|^2$$

Neutrinos
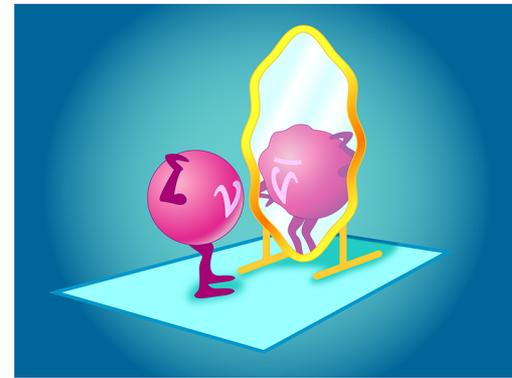
What are the neutrino masses?

Beta decay experiments e.g. KATRIN

Cosmology e.g. Planck (CMB + BAO)

Are neutrinos their own antiparticles (Majorana vs. Dirac)?

Neutrinoless double beta decay e.g. LEGEND, CUORE, NEXT, nEXO, KamLAND-Zen

Is there CP violation in the neutrino sector?

Long baseline experiments e.g. T2K, NOvA, DUNE, Hyper K etc.

Are there more than three neutrinos?

Short baseline experiments e.g. LSND, MiniBooNE, SBN

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Neutrinos

- 3 active neutrinos from measuring the Z^0 boson branching ratio
- Leaves the possibility of one or more *sterile neutrinos,* which do not interact with the weak nuclear force
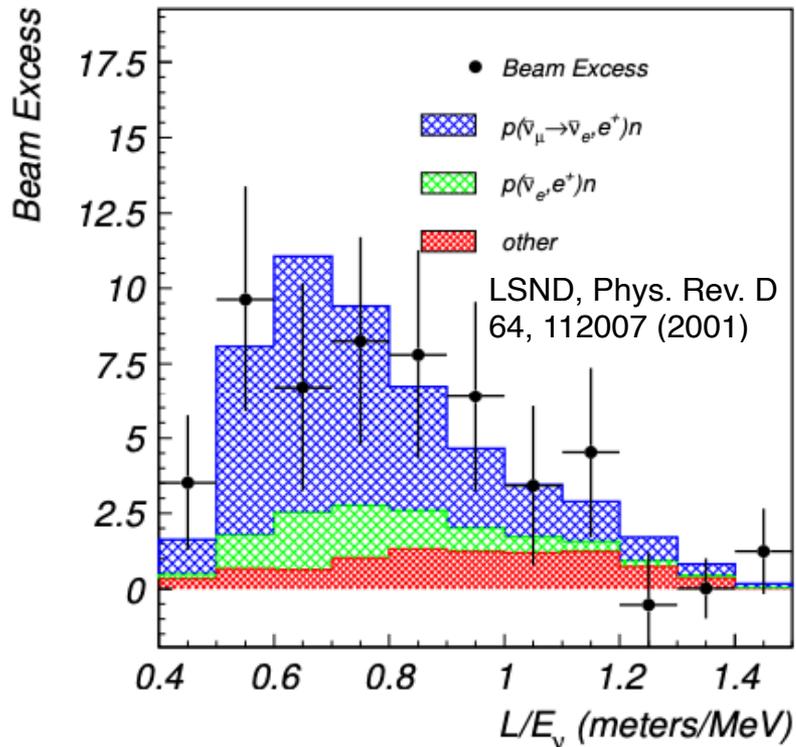
LSND ν_e excess at low energy
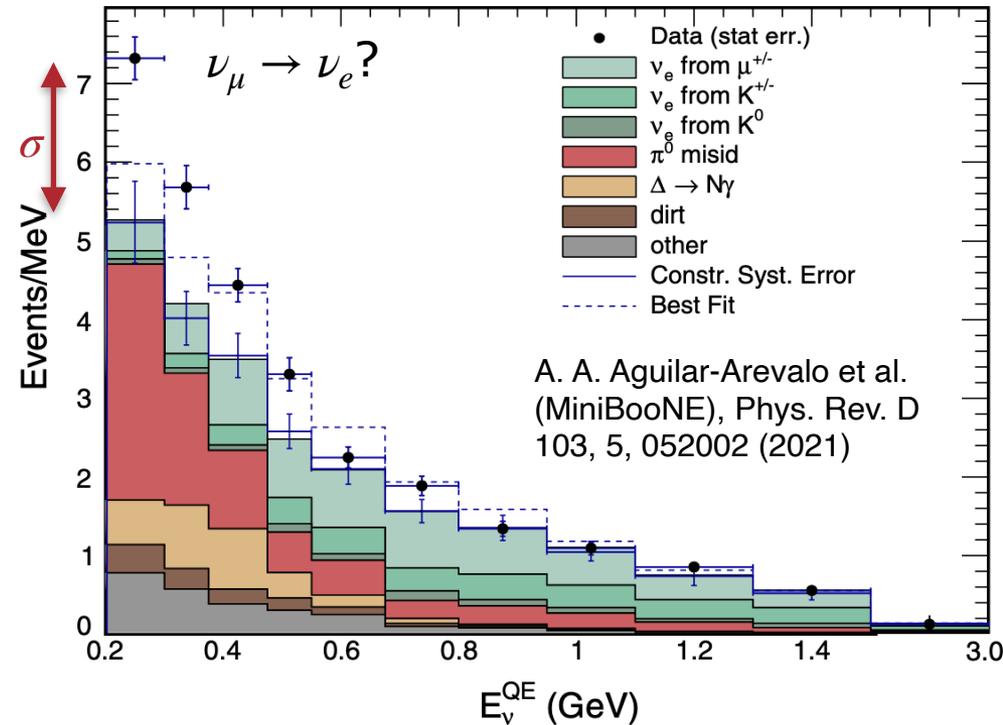
MiniBooNE ν_e excess at low energy

Short-Baseline Neutrino (SBN) Program

Short-Baseline Neutrino Program at Fermilab (2024)

P. Machado, O. Palamara, D. Schmitz
Ann.Rev.Nucl.Part.Sci. 69 (2019) 363-387
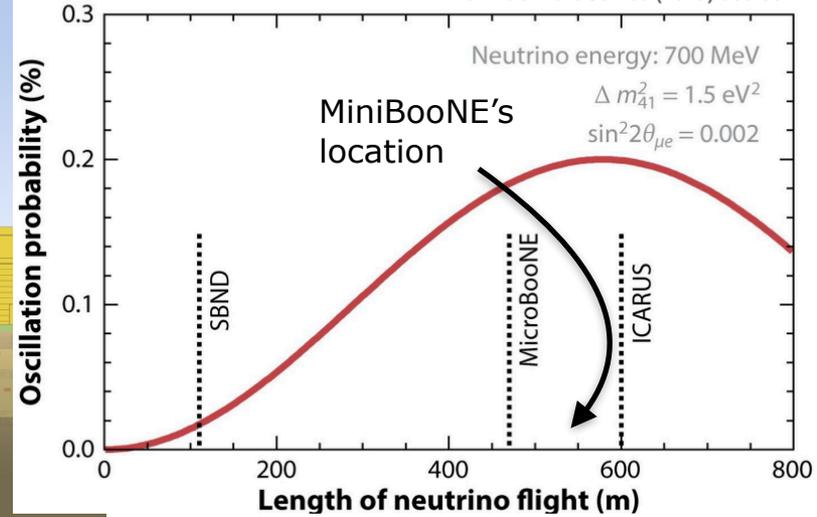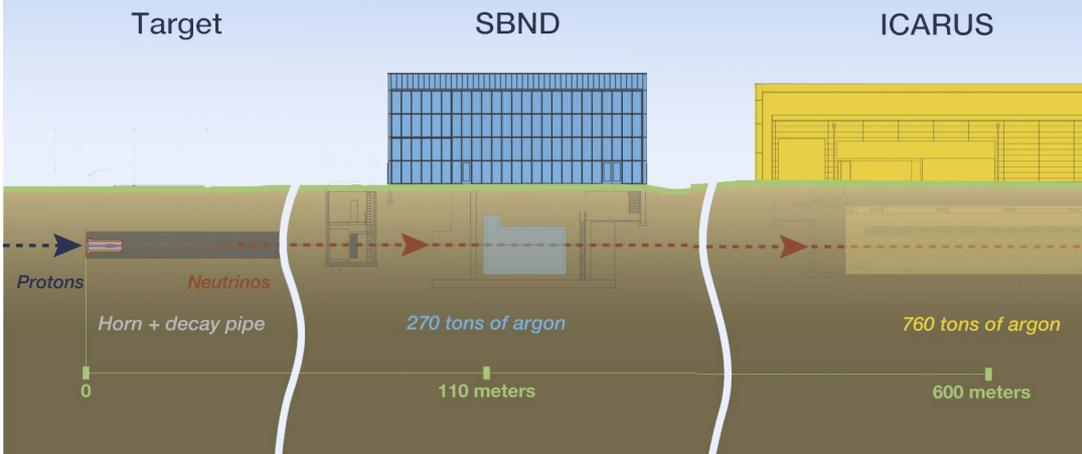
SBN program and detectors

$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{\mu e})\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\mu e}) \equiv 4\,|U_{e4}U_{\mu 4}|^2$$

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Short-Baseline Neutrino (SBN) Program

- Compute expected number of events as a function of E_ν

- O(10-15%) uncertainty on neutrino xsec and flux and E_ν resolution

$$N(E_\nu) = B + \int P_{\nu_\mu \to \nu_e}(E_\nu) \times \Phi(E_\nu) \times \sigma(E_\nu) \times n_t \times \epsilon(E_\nu) \times D(E_{\mathrm{reco}}, E_\nu) dE_\nu$$
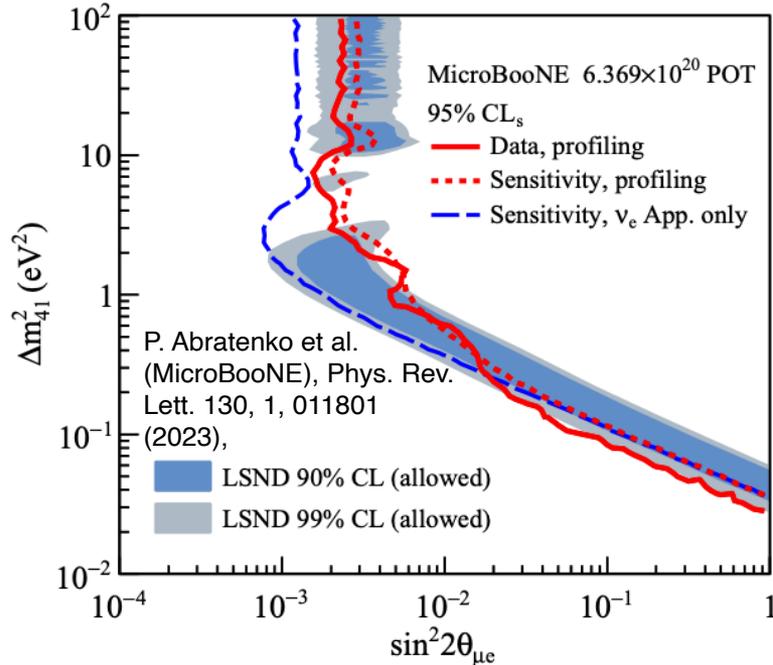
MicroBooNE only result
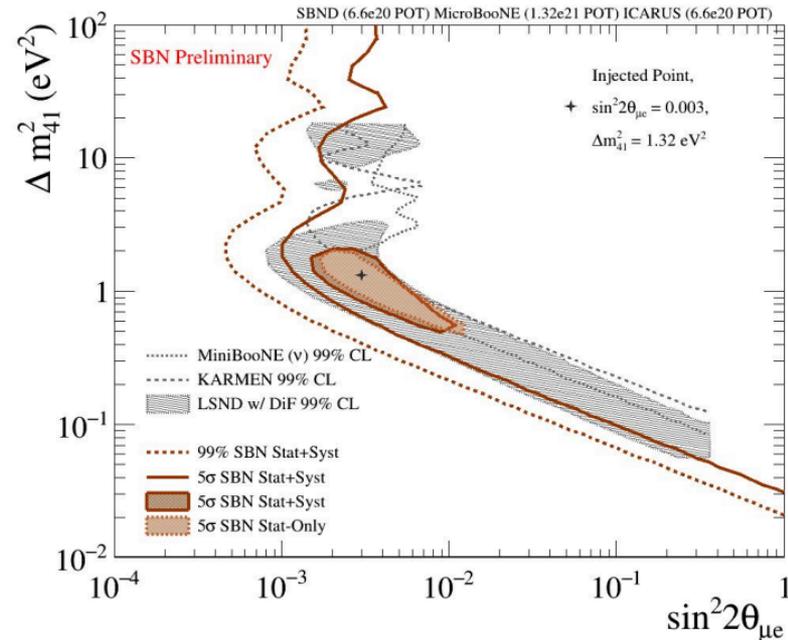
Projected full SBN sensitivity assuming oscillations

Short-Baseline Neutrino (SBN) Program
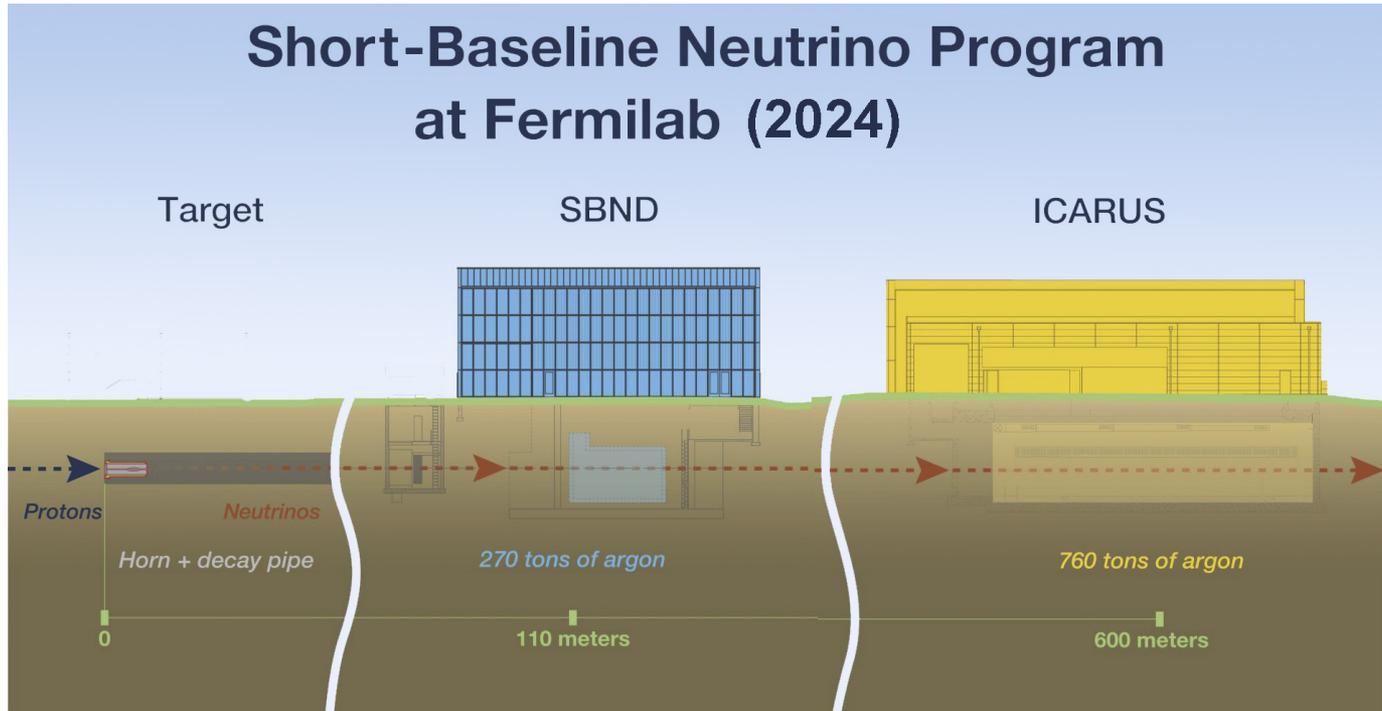
- Short Baseline Near Detector (SBND) - Constrain flux and cross section systematics
- ICARUS - Measure neutrino oscillations by taking ratio of events at near and far detectors
- Both detectors are **L**iquid **Ar**gon **T**ime **P**rojection **C**hambers (LArTPC)

Liquid Argon Time Projection Chamber (LArTPC)
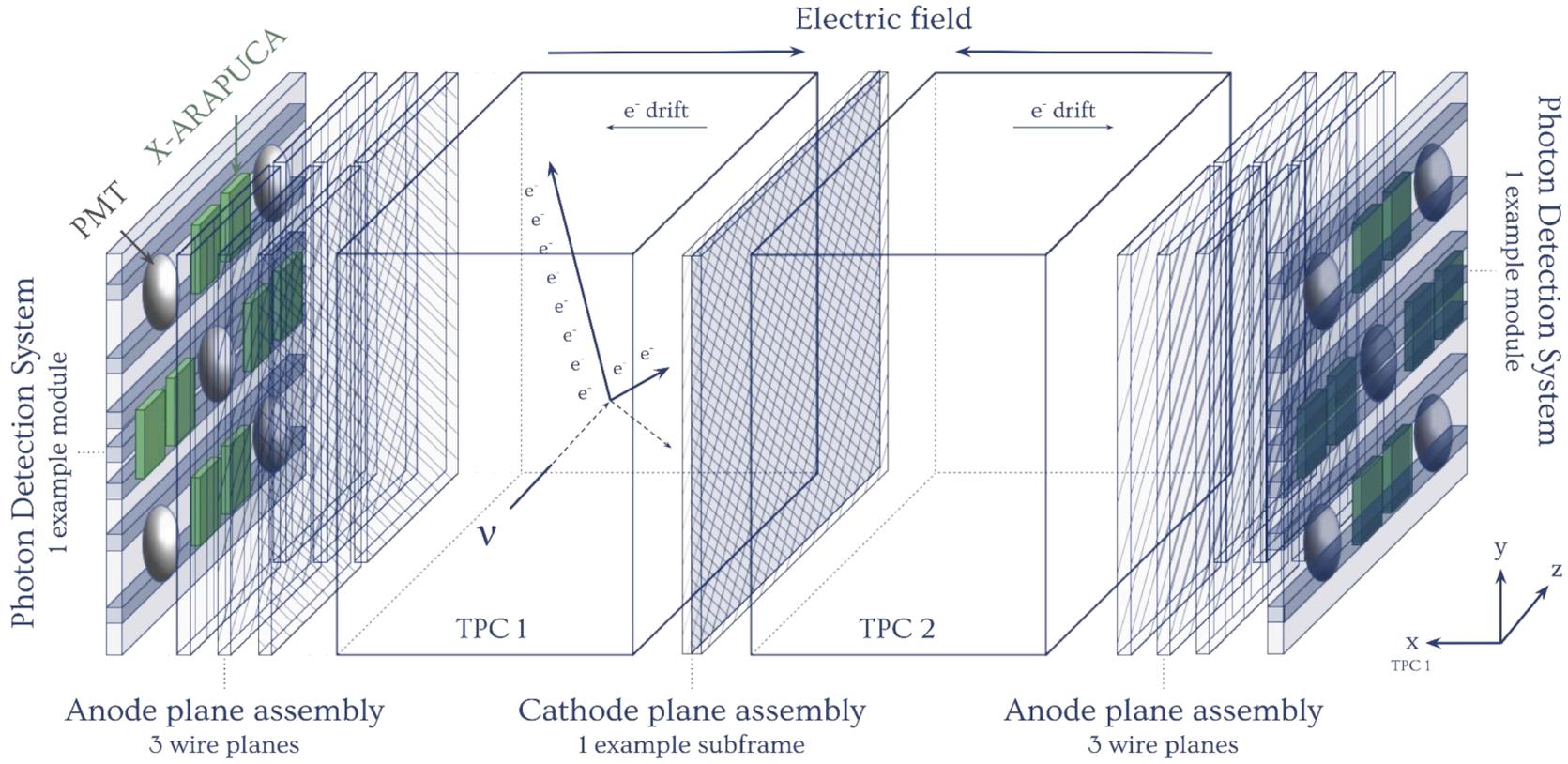
SBND Technical Design

Liquid Argon Time Projection Chamber (LArTPC)

Induction

Collection

Electric field

Ar

Ionization

Ar⁺

e⁻

Ionized Electron

e⁻ drift

Photon Detection System
1 example module

Photon Detection
1 example mo

ν

TPC 1

TPC 2

y

z

x

TPC 1

Anode plane assembly
3 wire planes

Cathode plane assembly
1 example subframe

Anode plane assembly
3 wire planes
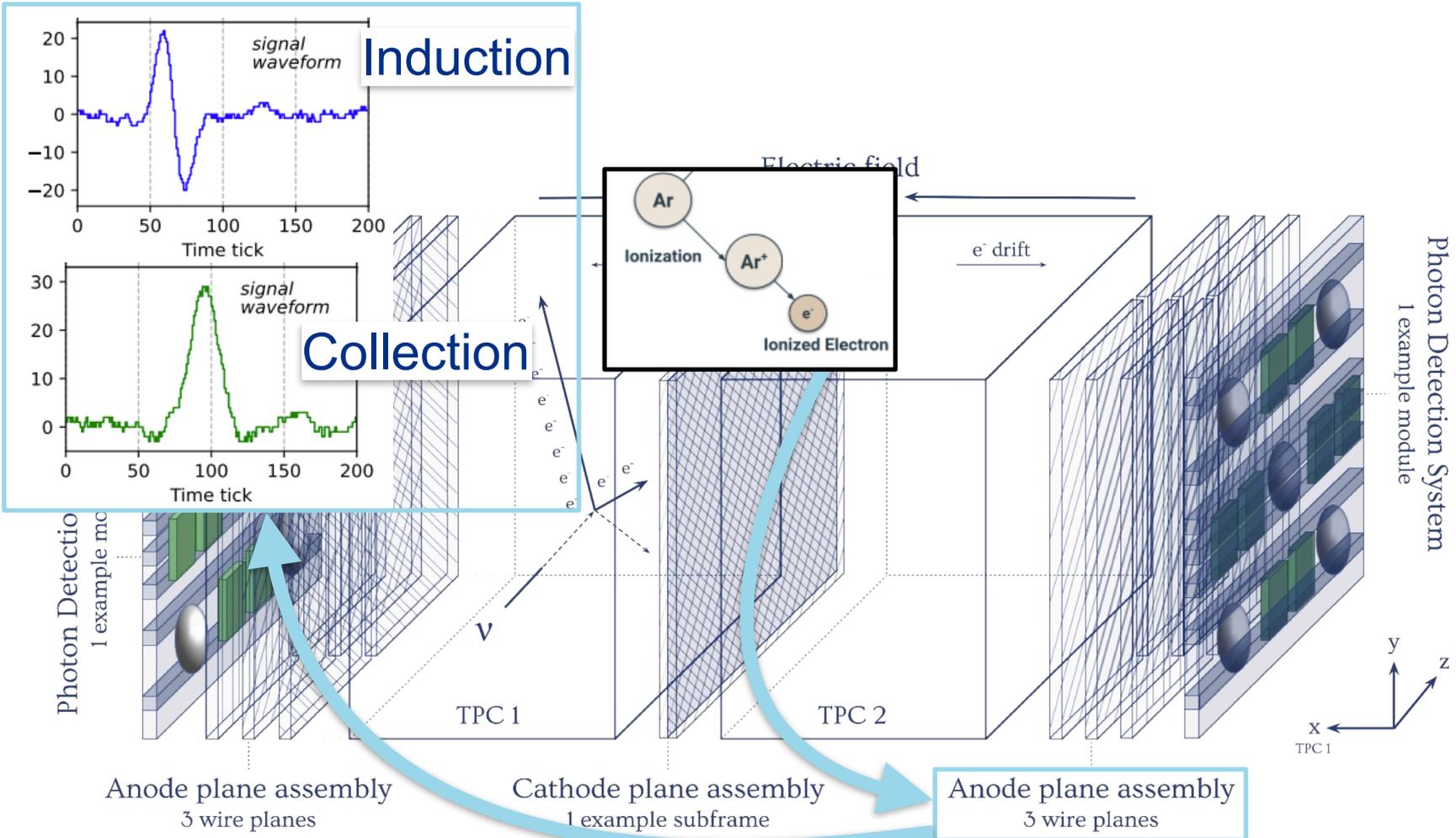
SBND Technical Design

Liquid Argon Time Projection Chamber (LArTPC)

SBND Technical Design

Liquid Argon Time Projection Chamber (LArTPC)

- Precise tracking
- Detailed calorimetry

- Cheap (O(1) $/kg)
- High A

- Dense (1.4 g/cm3)
- Scalable

SBND Technical Design

Short Baseline Near Detector (SBND)

- SBND is a monolithic LArTPC with 2 TPCs divided by a cathode plane assembly (CPA) [1]
- 3 wireplanes with 2 induction wireplanes at ±60 deg
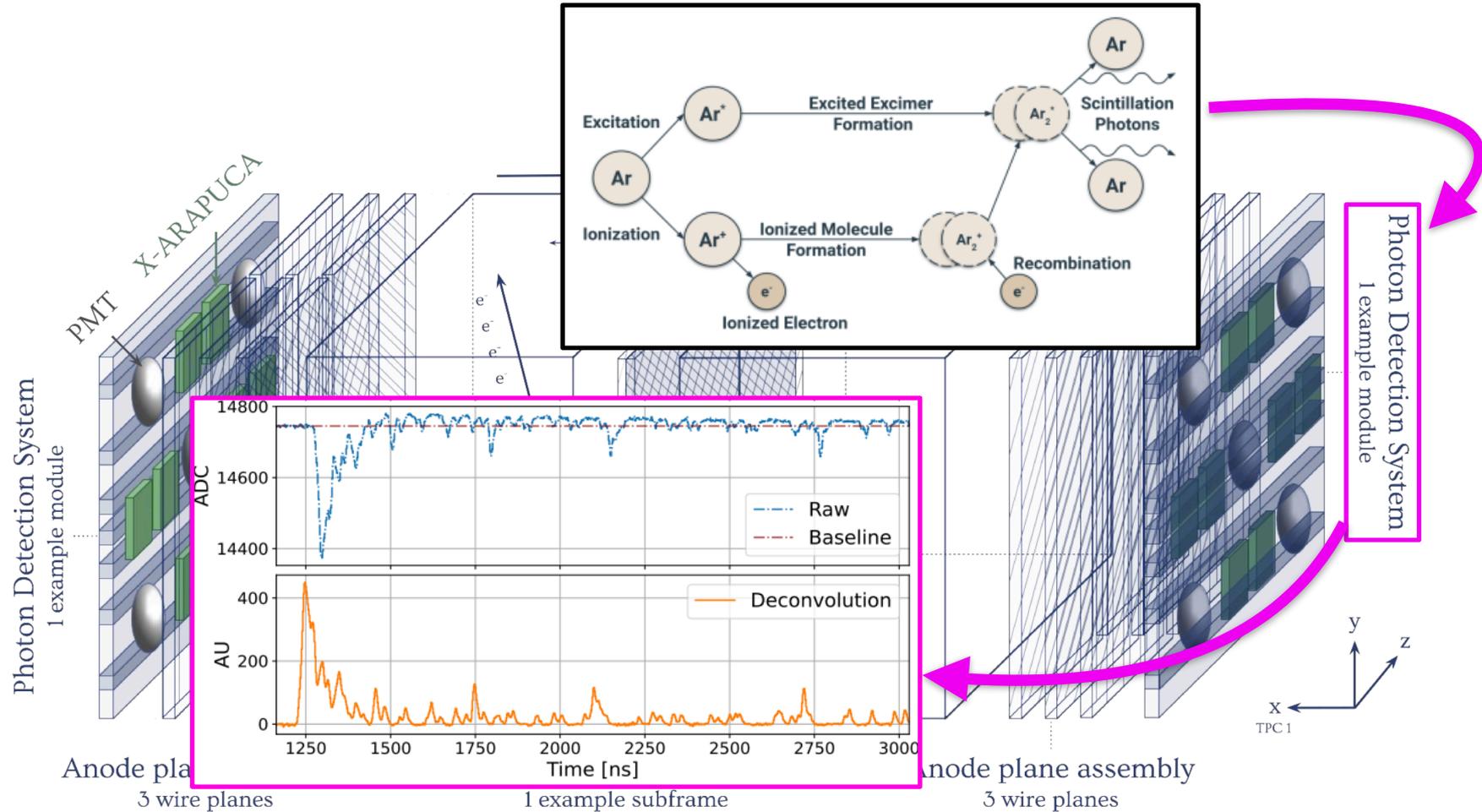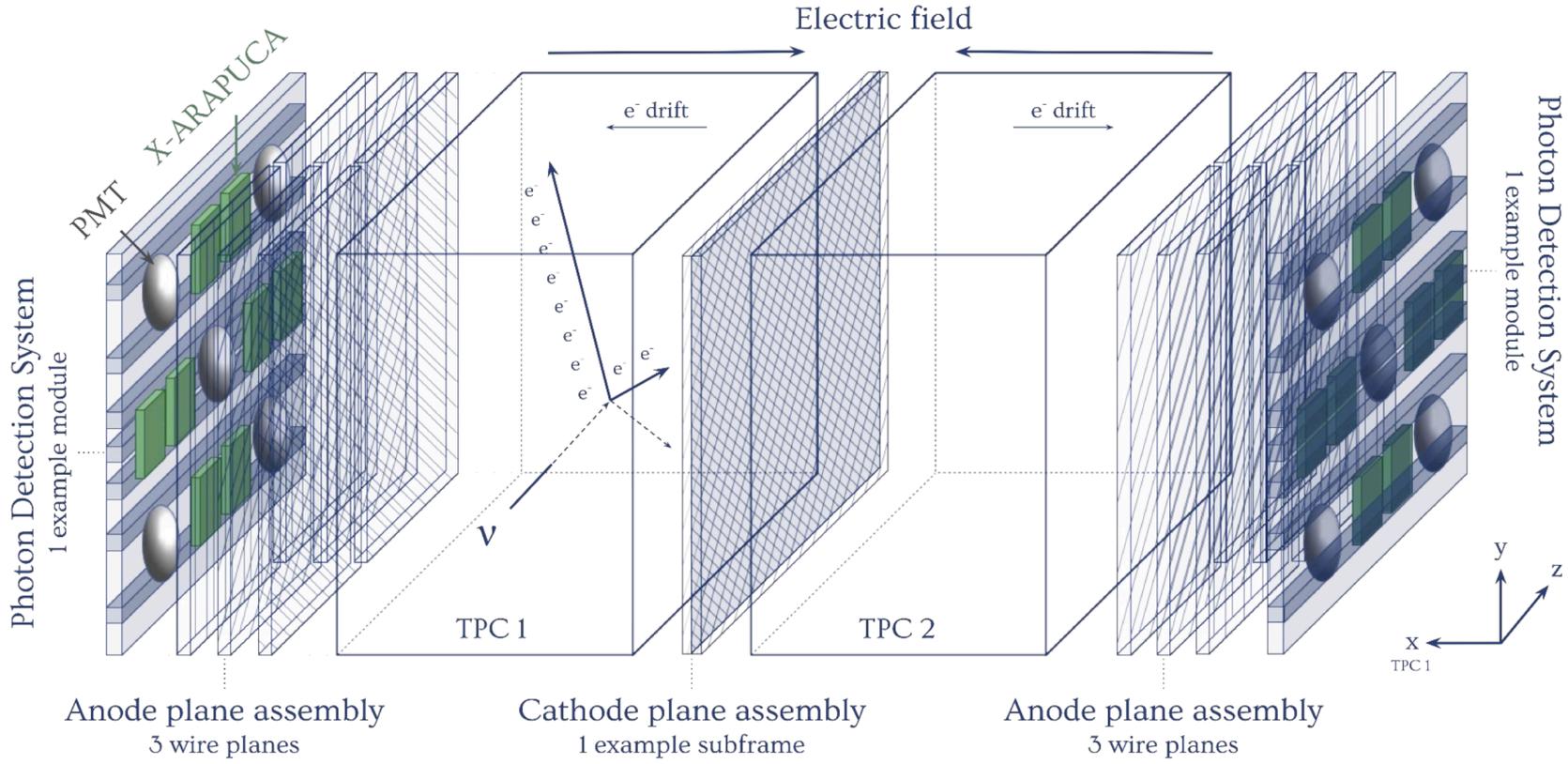 - **3 mm** wire and inter-plane spacing
  - 11,892 wires per anode plane assembly (APA)
- 120 photomultiplier tubes (PMTs) and 192 X-ARAPUCAs*[2]
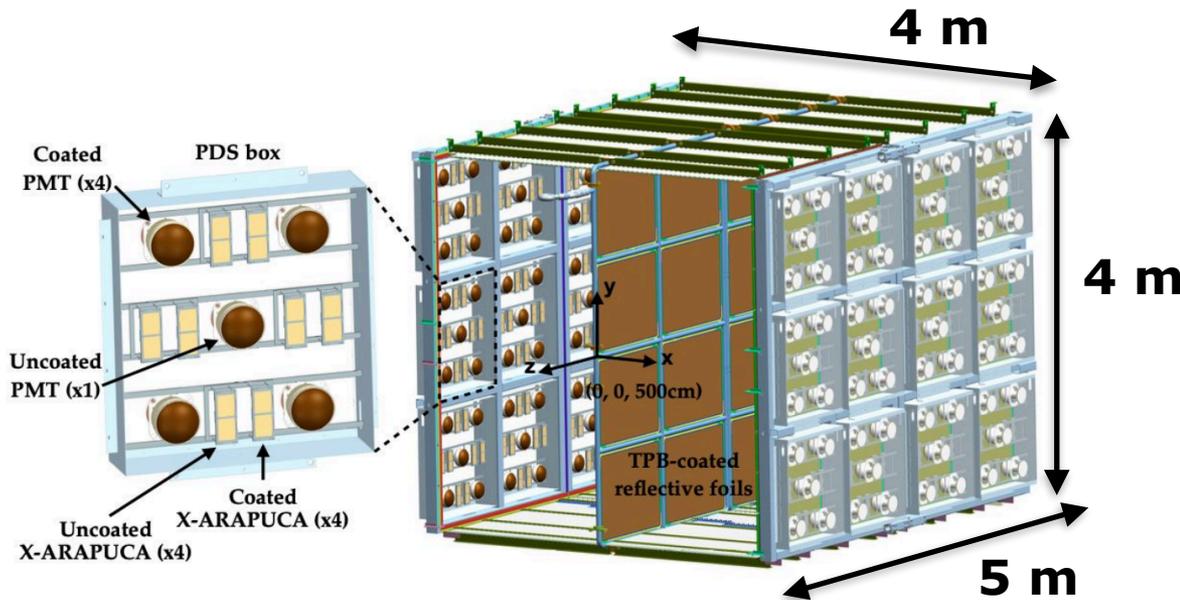
SBND with coordinate system

[1] Construction of precision wire readout planes for the Short-Baseline Near Detector (SBND) arXiv:2002.08424

[2] Scintillation Light in SBND: Simulation, Reconstruction, and Expected Performance of the Photon Detection System arXiv:2406.07514

*Silicon-based photomultiplier light trap

SBND circa. March 2023
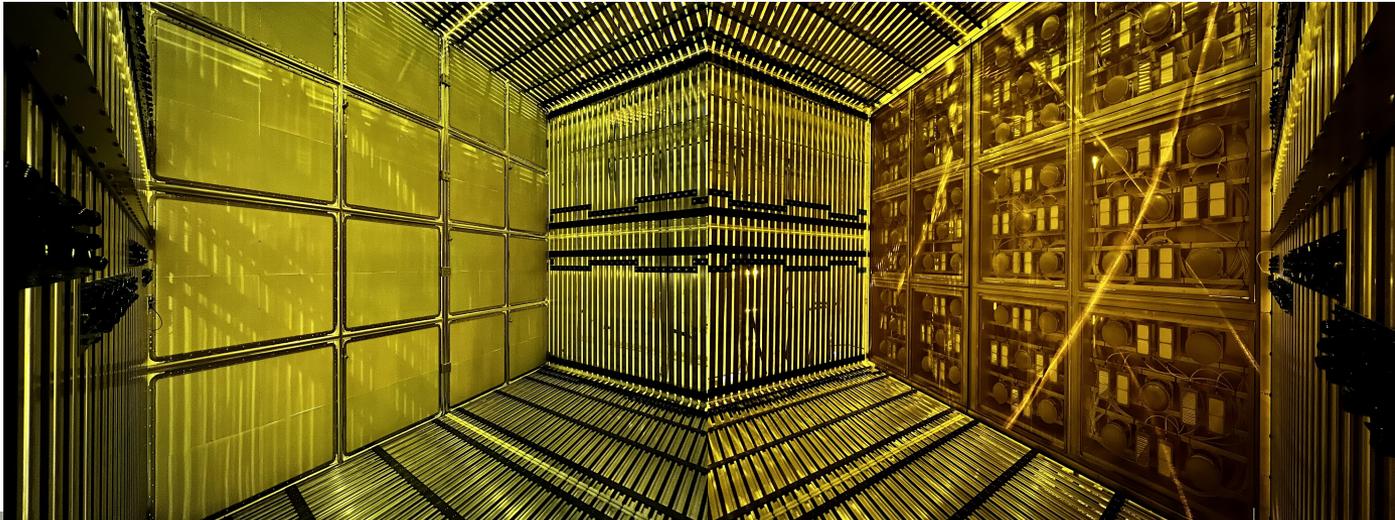
Short Baseline Near Detector (SBND)

First neutrinos recorded in July, 2024 - press release
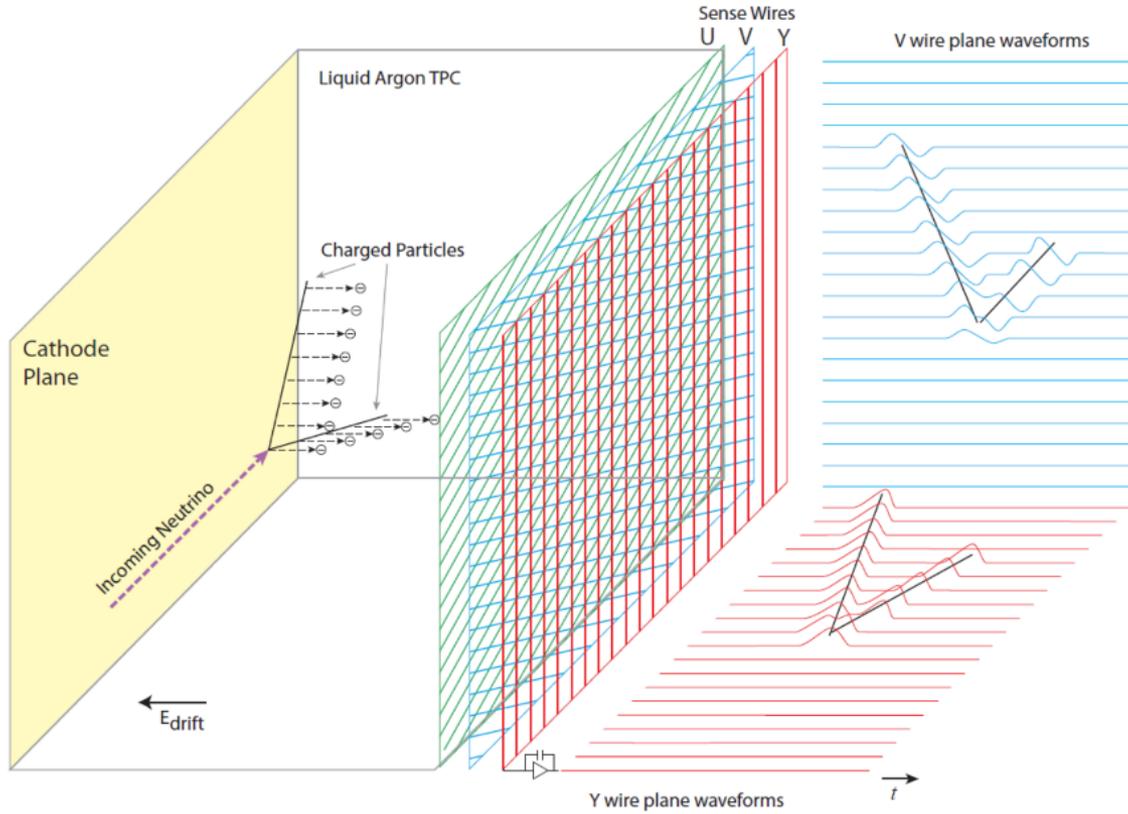
1/2 TPC event display
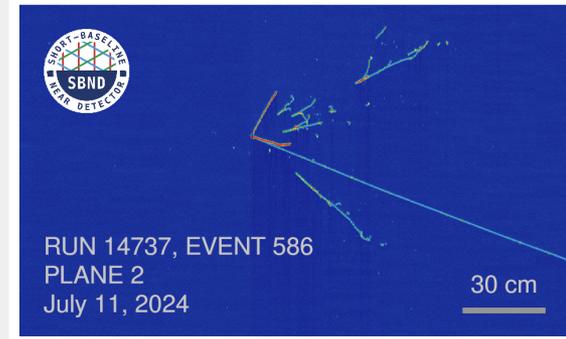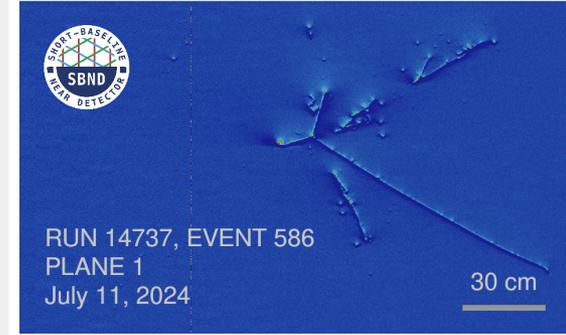
Short Baseline Near Detector (SBND)

$\nu_\mu - {}^{40}Ar$
2M ν_μ CC events in 1 year

$\nu_e - {}^{40}Ar$
15k ν_e CC events in 1 year
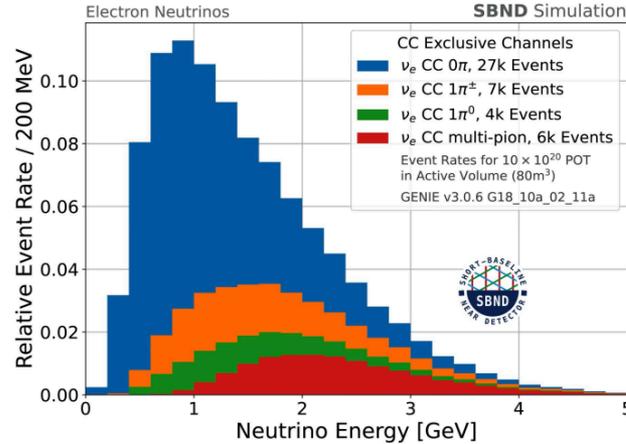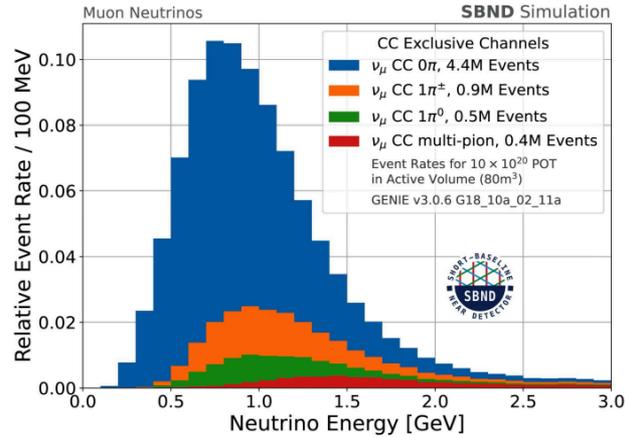
- Expect **millions neutrino interactions** for SBND's lifetime (10e20 POT)
- Collected neutrinos from >2.57e20 POT already

SBND Cumulative POT through May 20, 2025

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Liquid Argon Time Projection Chamber (LArTPC)

ν_μ

Q

RUN 14737, EVENT 586
PLANE 2
July 11, 2024

30 cm

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Liquid Argon Time Projection Chamber (LArTPC)

ν_μ

Highly Ionizing

Q

RUN 14737, EVENT 586
PLANE 2
July 11, 2024

30 cm

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Liquid Argon Time Projection Chamber (LArTPC)

Liquid Argon Time Projection Chamber (LArTPC)

Liquid Argon Time Projection Chamber (LArTPC)

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- For charged current (CC) interactions, E_ν is the sum of the visible components (E_ℓ, E_h) minus the binding energy of the nucleus E_{nuc}

$$E_\nu = E_\ell + E_h - E_{nuc}$$

Low momentum   High momentum
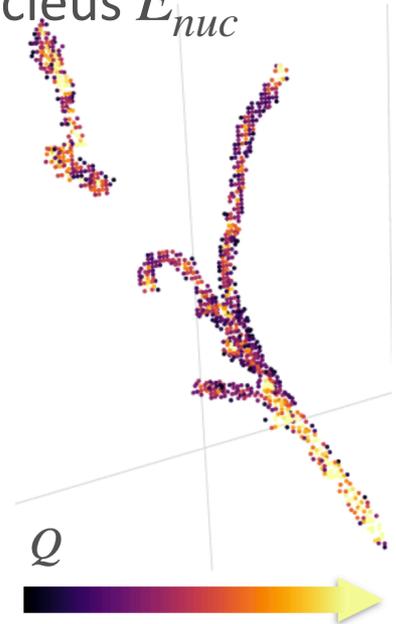
Muon   Kaon
Pion   Proton

LArIAT

$$\Delta x = \int_0^{E_0} \frac{1}{dE/dx} dE$$

$$\theta_0 = \frac{S_2}{p\beta c} z \sqrt{\frac{x}{X_0}} \left[1 + \epsilon \log\left(\frac{x}{X_0}\right) \right]$$

Q

$$E_{shower} = W_i \cdot C_{calo} \cdot C_{adj} \cdot \frac{1}{R} \cdot \sum_Q e^{\frac{t_{drift}}{\tau}} Q$$

Work function for Ar — [MeV]
Shower adjustment factor
Electron lifetime correction
Calorimetric constant (TPC gain) — [MeV / e⁻]
Recombination factor — [e⁻ / ADC]
Deposited charge — [ADC]

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Energy

- For charged current (CC) interactions, E_ν is the sum of the visible components (E_ℓ, E_h) minus the binding energy of the nucleus E_{nuc}

$$E_\nu = E_\ell + E_h - E_{nuc}$$

Muon

BNB + Cosmics SBND Simulation
Work in Progress
Contained Reco

$\langle KE_{reco} - KE_{true} \rangle = 0.01$ GeV
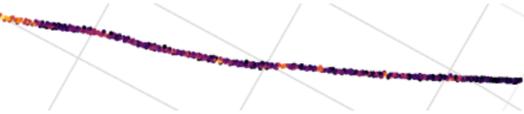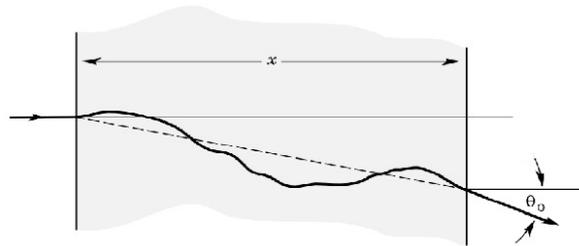$\sigma = 0.04$ GeV

KE_{reco} [GeV]

Bias

KE_{true} [GeV]

$$\Delta x = \int_0^{E_0} \frac{1}{dE/dx} dE$$

$$\theta_0 = \frac{S_2}{p\beta c} z \sqrt{\frac{x}{X_0}} \left[1 + \epsilon \log \left(\frac{x}{X_0} \right) \right]$$

Work function
for Ar

Shower adjustment
factor

Electron lifetime
correction

$$E_{\text{shower}} = W_i \cdot C_{\text{calo}} \cdot C_{\text{adj}} \cdot \frac{1}{R} \cdot \sum_Q e^{\frac{t_{\text{drift}}}{\tau}} Q$$

[MeV]   [MeV / e⁻]   [e⁻ / ADC]   [ADC]

Calorimetric
constant
(TPC gain)

Recombination
factor

Deposited
charge

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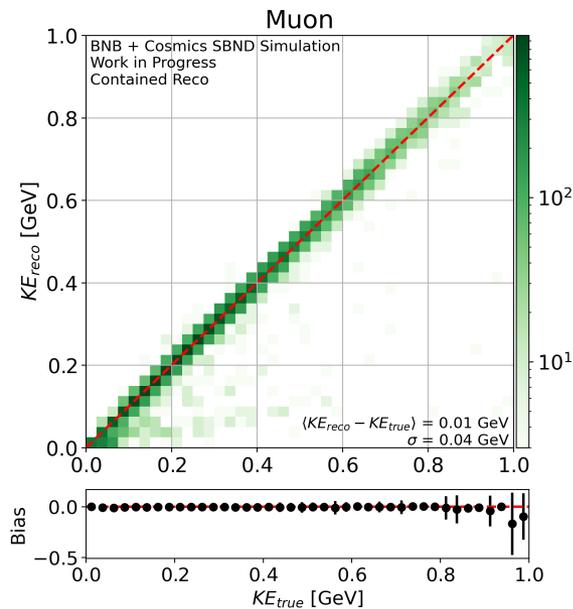
Limitations of LArTPC / SBND

- Slow drift time, about 1 m/ms due to dense medium
    - Cosmic ray in the readout window (SBND on surface) 5-10 / event
    - Use optical information to identify neutrino interaction
- High A target - 40 nucleons
    - Limitations due to unobservable nuclear effects obscure E_ν measurement
    - High particle multiplicity at vertex
    - Secondary hadronic interactions
- $\pi^\pm/\mu$ have similar energy loss profile
- Missing neutral particles

SBND Simulation
Work in progress

LArIAT

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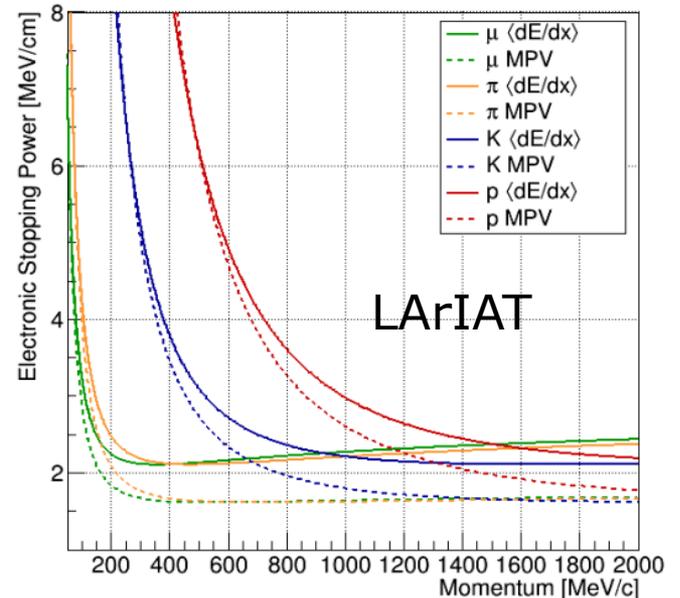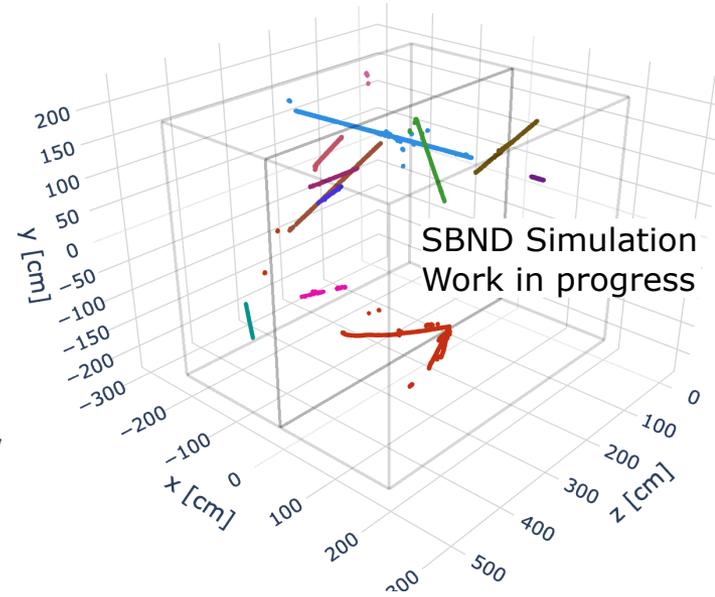
Hierarchical Neutrino Event Reconstruction

Relevant goals of pattern recognition in a detailed LArTPC image…

1. Separate topologically distinguishable **types of activity**

2. Identify **important points** (vertex, start points, end points)

3. Cluster individual **particles** (tracks and full showers)

4. Cluster **interactions**, identify **particle properties** in context
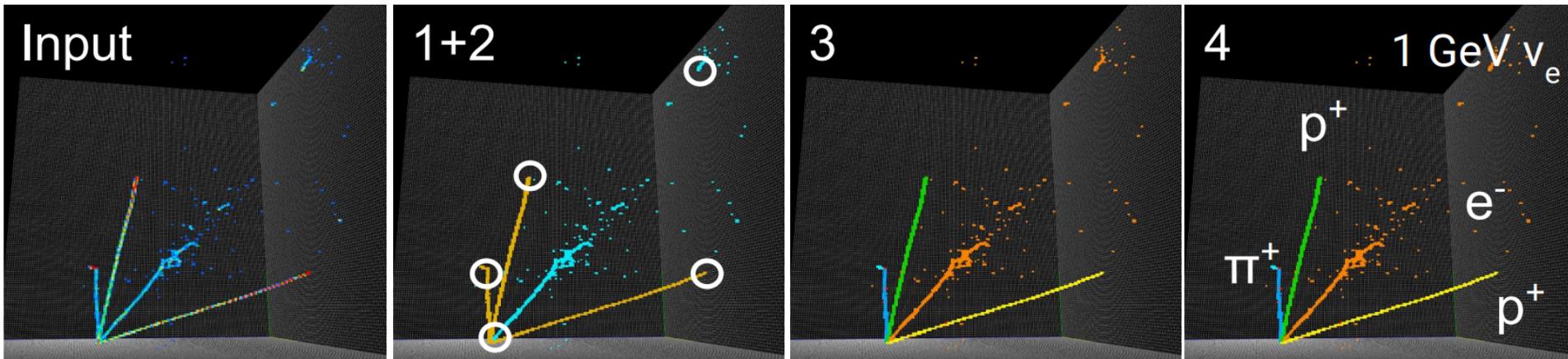
SPINE (**S**calable **P**article **I**maging with **N**eural **E**mbeddings) [4]

[4] F. Drielsma, K. Terao, L. Dominé, D.H. Koh https://arxiv.org/abs/2102.01033
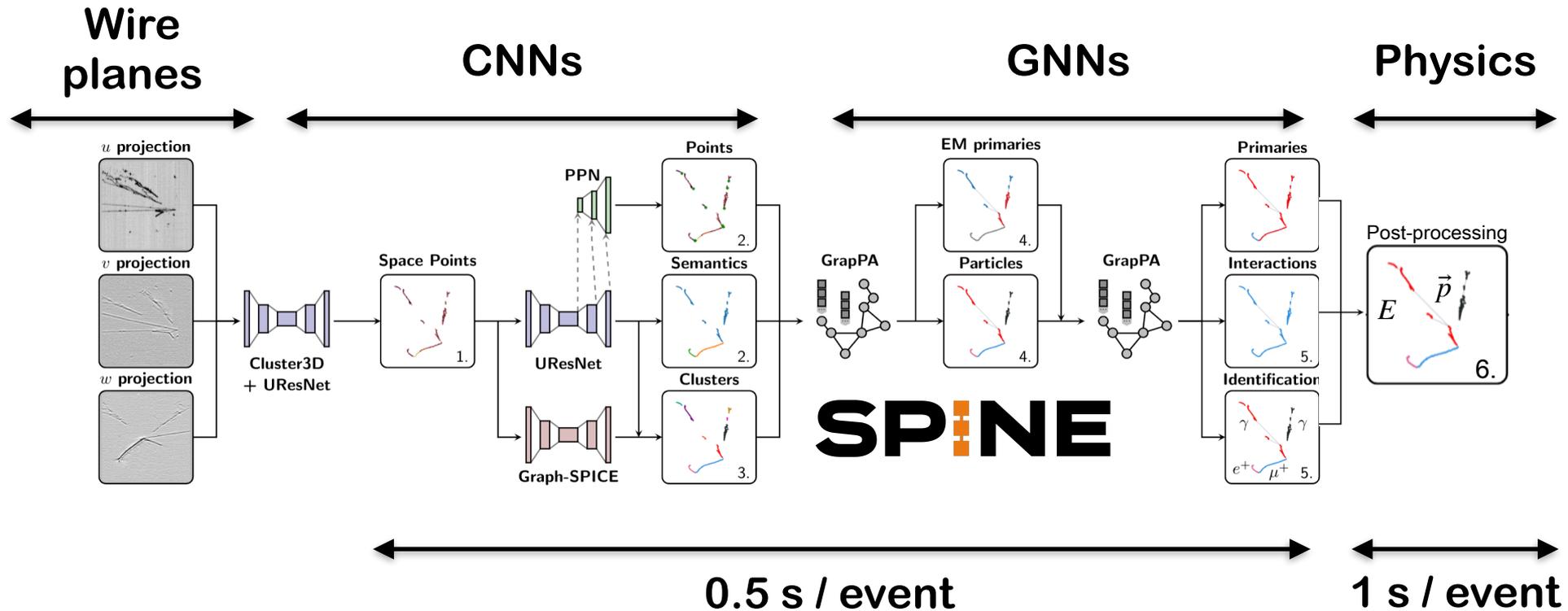
SPINE

SLAC: 2019
ICARUS: 2020
SBND: 2022
2x2/ND: 2023
DUNE FD: 2025
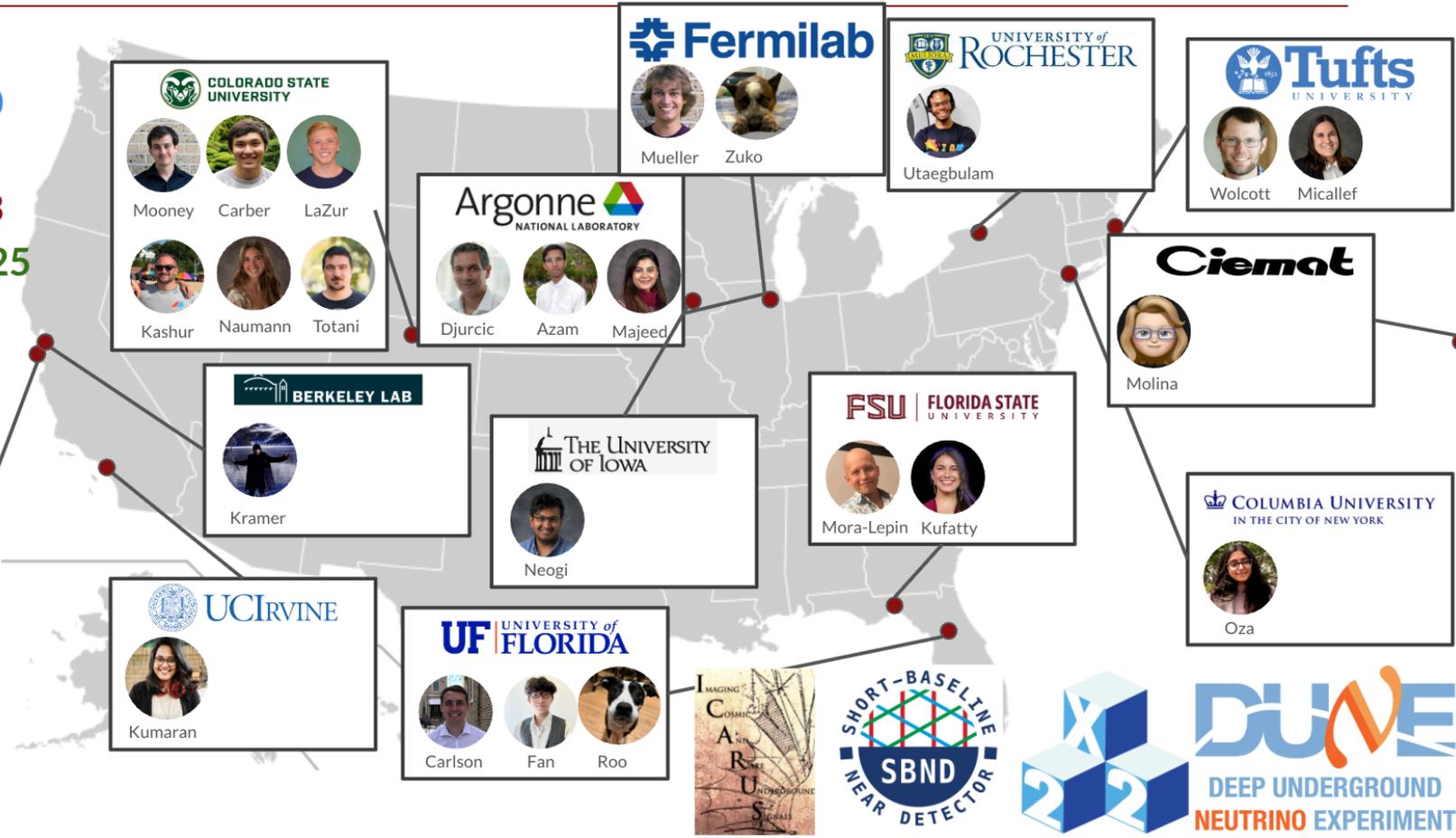
2D -> 3D Projection

Consume 2D hits in each of 3 projections to make space points
- Finds pairs of hits compatible within a time threshold
- Forms a **space point** from 3 wires where 2 hits are compatible in time to form candidate space point
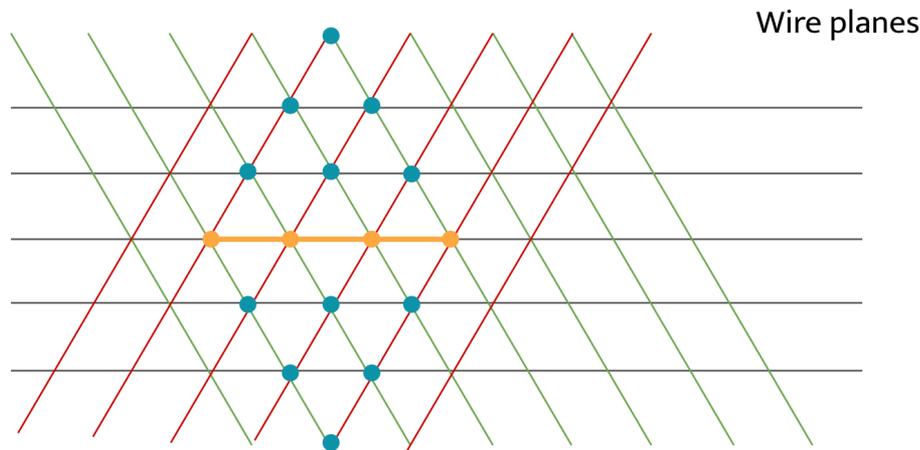
Wire planes

T. Usher

Position considered
By cluster3d from
combinatorial
analysis

2D Hit in wire
planes from track

- False hits create _ghost_ points, which are de-ghosted using a UResNet CNN

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Deghosting

- Label each point in simulation sample as ghost/non-ghost
- Learn ghost/non-ghost from reconstructed spacepoint information

SBND Simulation
Work in progress

SBND Simulation
Work in progress
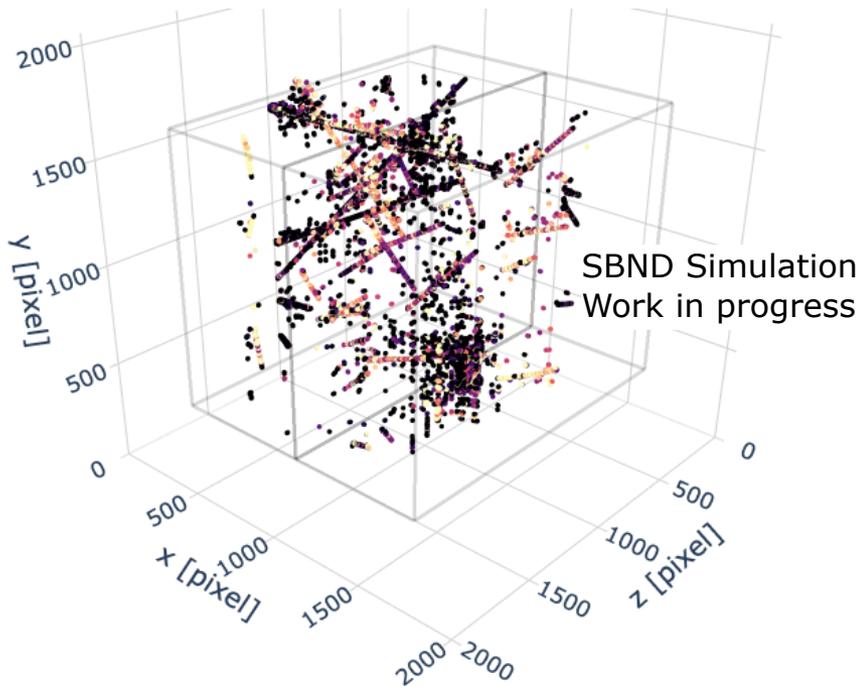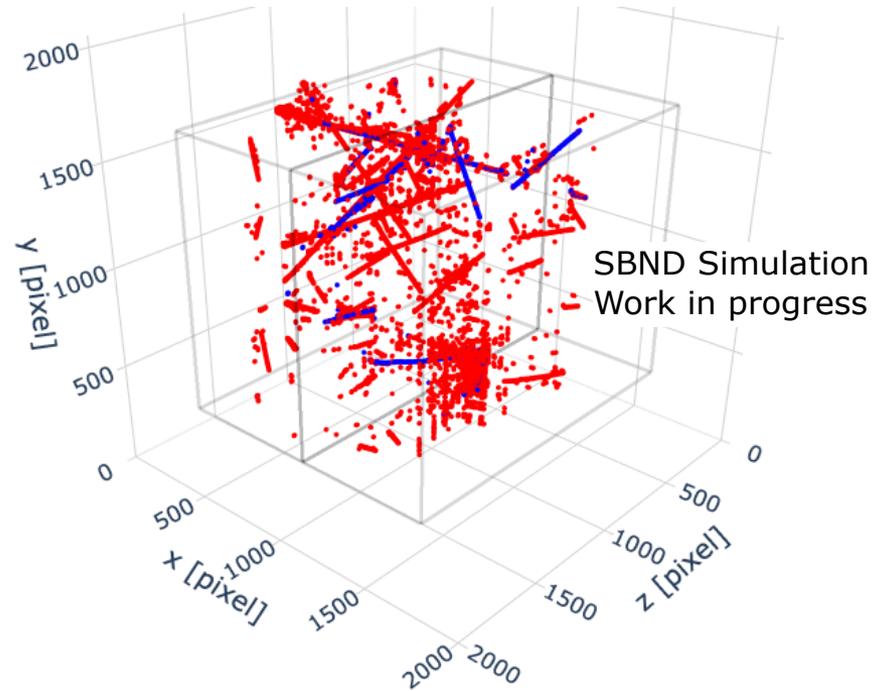
Raw Charge

Ghost vs Non-ghost label

UReSNet Sparse CNN

- Point-wise feature extraction uses Sparse Convolutional Neural Network (CNN)
- UReSNet architecture used as backbone feature extractor

Input

Output

Encoder   Decoder

input
conv
conv-s2-finc
tconv-s2-fdec
conv-fdec
softmax

→ Residual connections
- - → Concatenation

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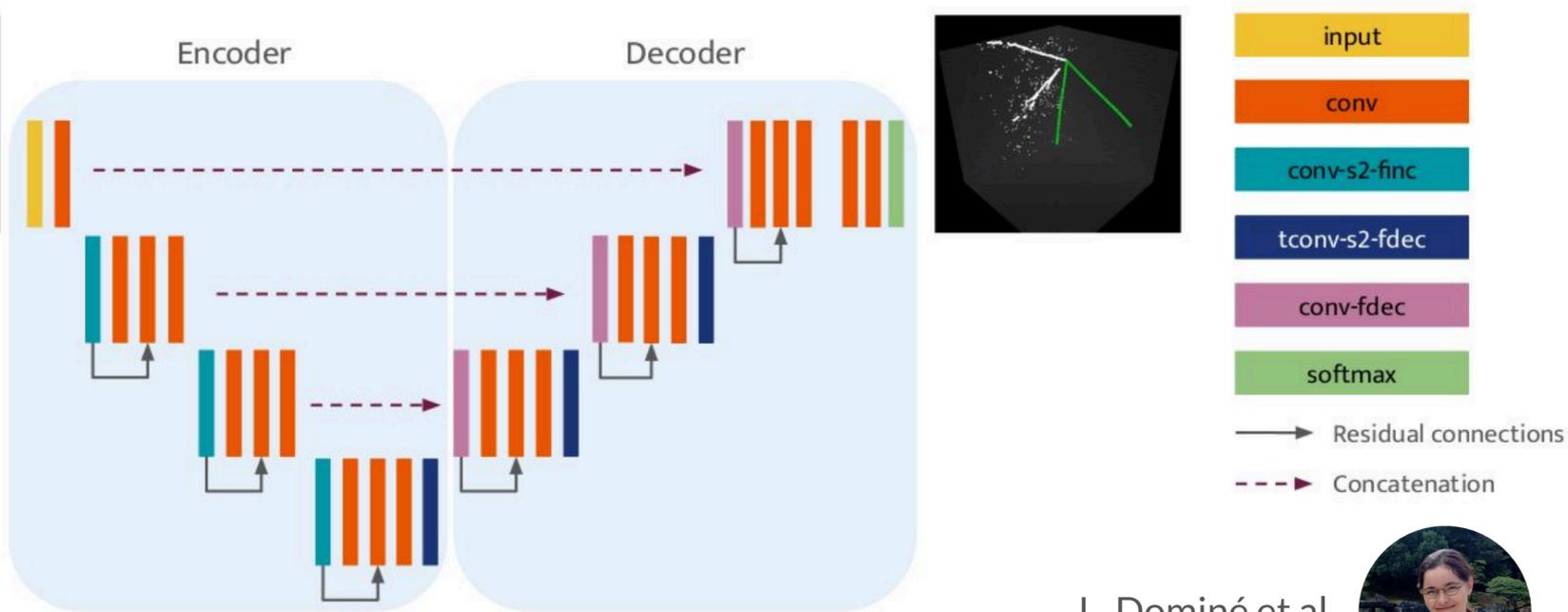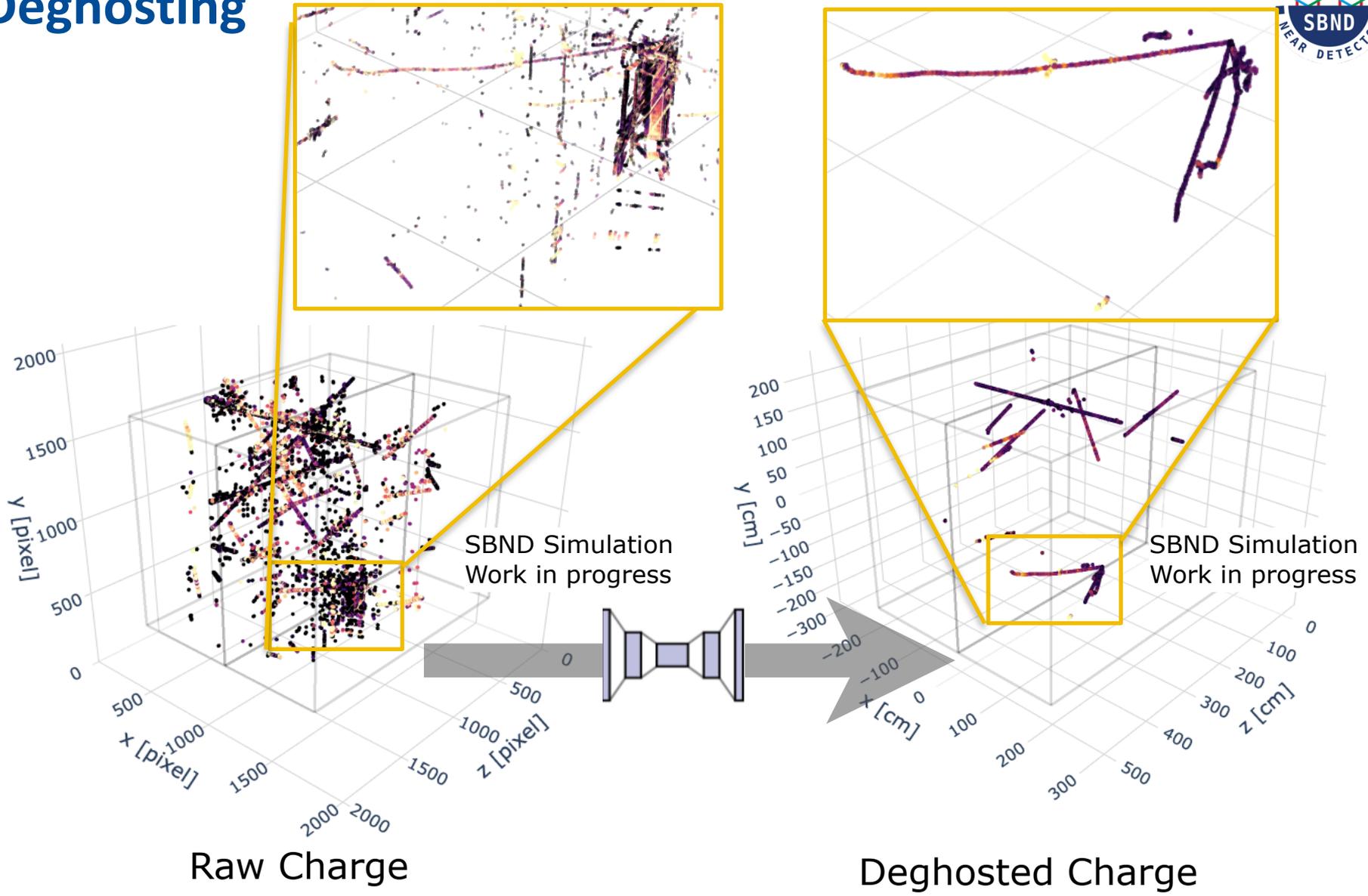
Deghosting

Raw Charge
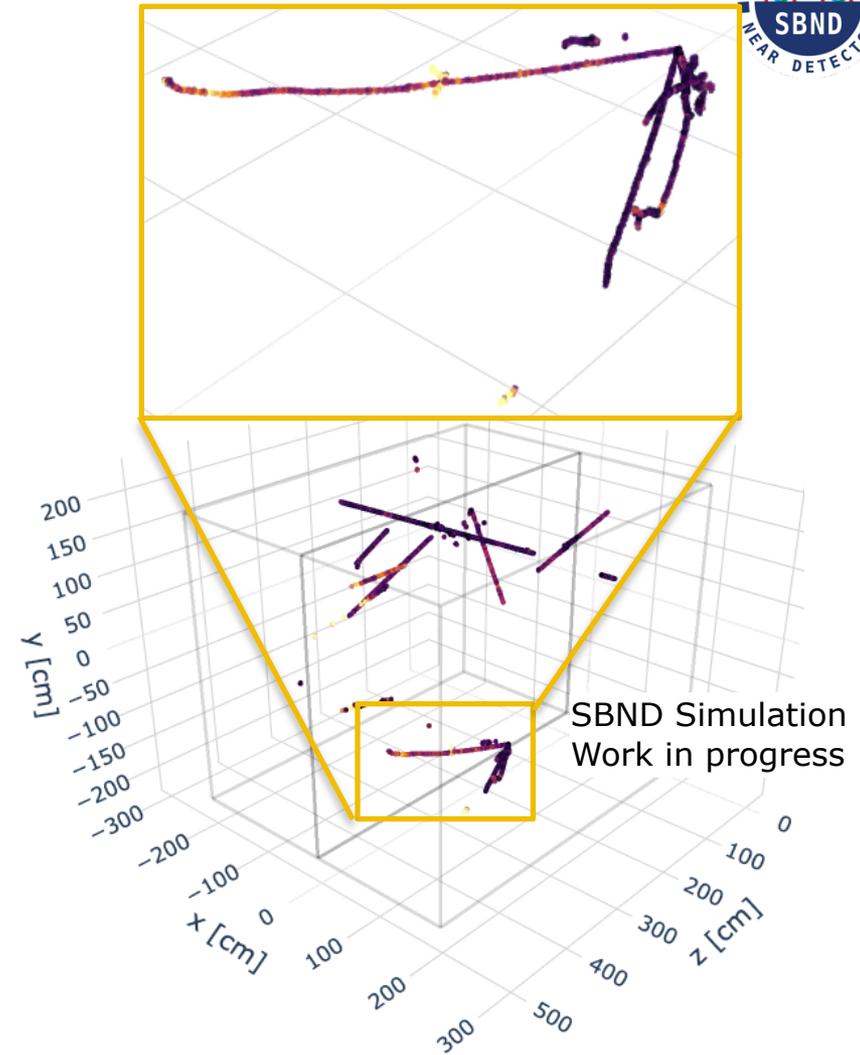
Deghosted Charge

SBND Simulation
Work in progress

SBND Simulation
Work in progress

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Deghosting

SBND MPVMPR Test Sample

SBND Simulation
Work in progress

Deghosted Charge

Semantic Segmentation
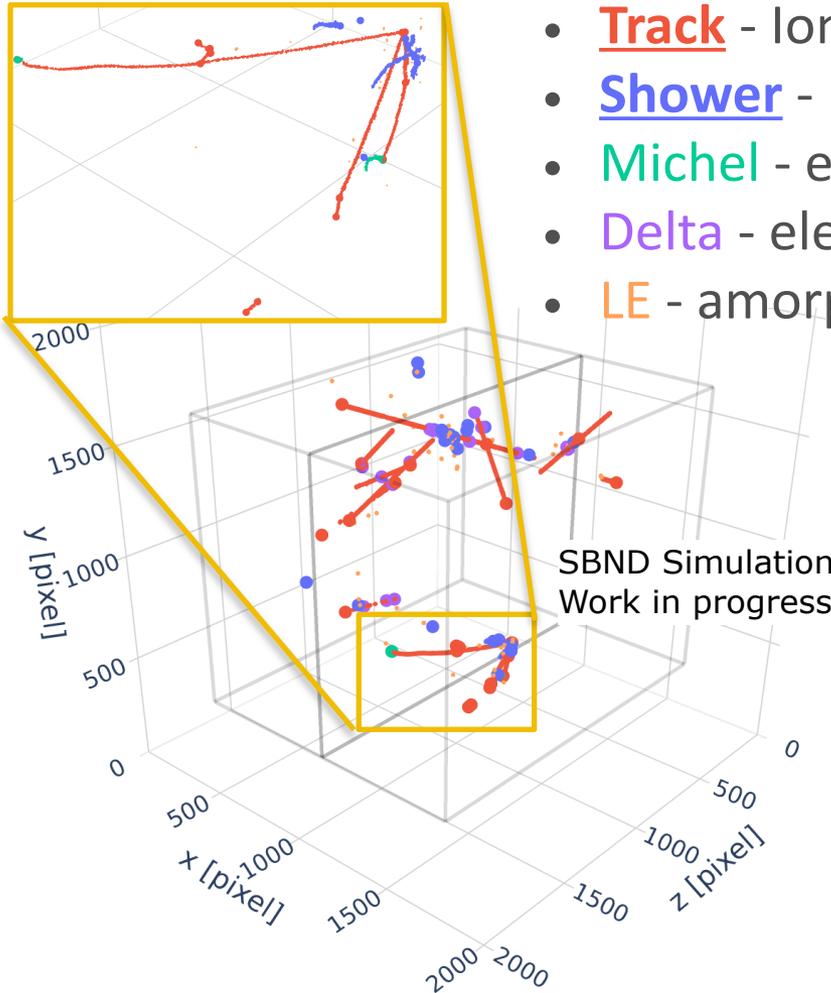
- **Track** - Ionizing, rectilinear
- **Shower** - EM shower
- Michel - electron from muon decay
- Delta - electron from track interaction
- LE - amorphous blips

Primaries

Secondaries

SBND Simulation
Work in progress

SBND Simulation
Work in progress

Neutrino + Cosmics

Deghosted Charge

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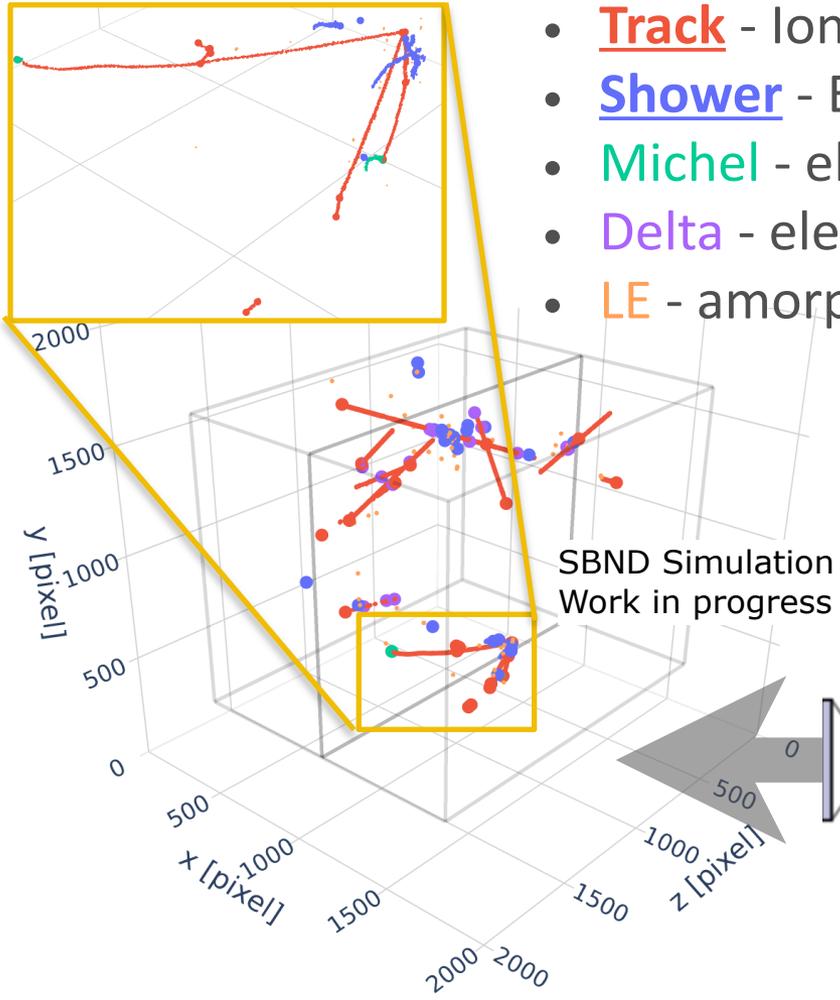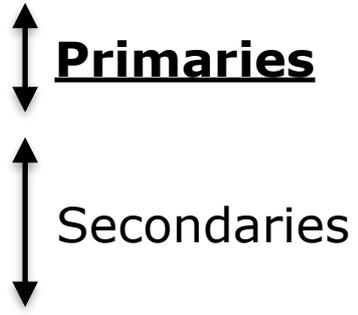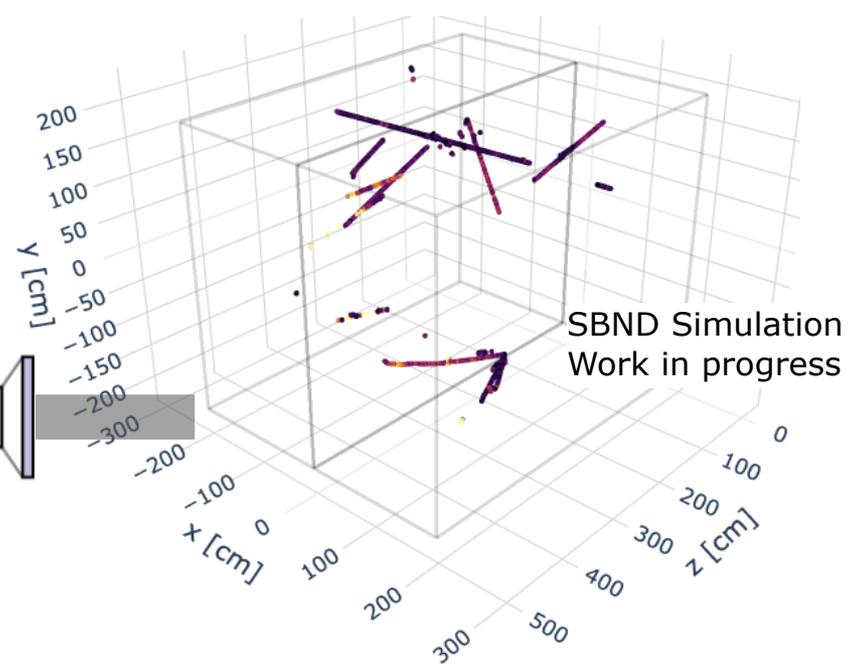# Semantic Segmentation

- **Track** - Ionizing, rectilinear
- **Shower** - EM shower
- Michel - electron from muon decay
- Delta - electron from track interaction
- LE - amorphous blips

Primaries

Secondaries

SBND Simulation
Work in progress

Neutrino + Cosmics

SBND MPVMPR Test Sample

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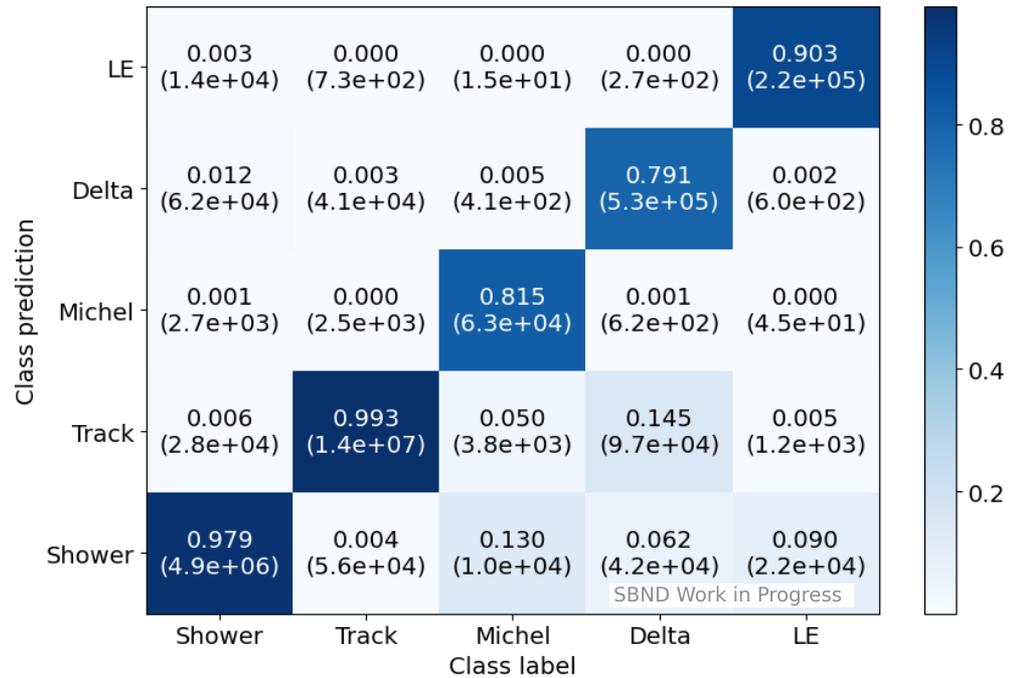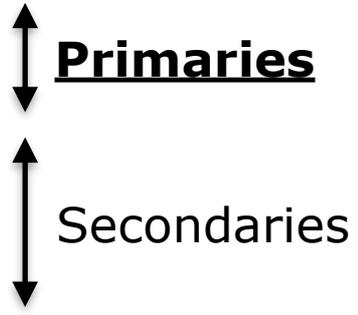
PPN

- Point proposal network (PPN) learns attention mask for points of interest
- L2 and CE losses used to learn point location to sub-voxel resolution
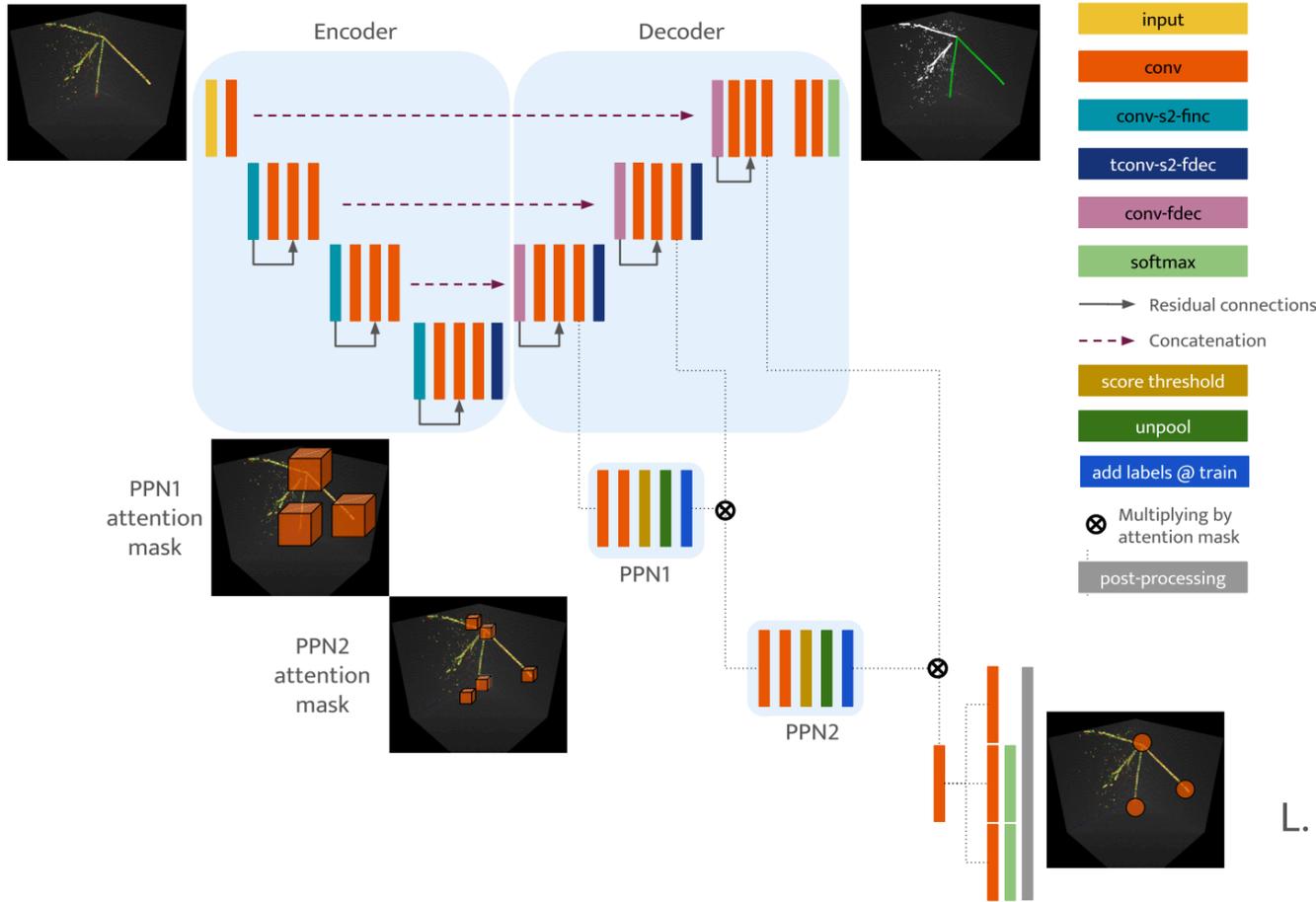
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PPN
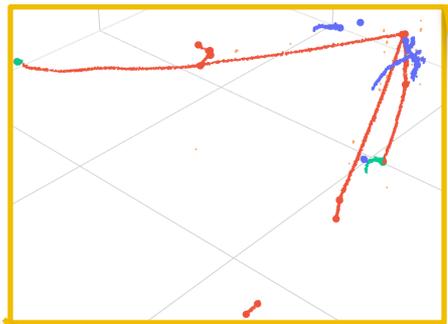
Missing point ->

Extra point ->

$E = 1; P = 1$

$E = 1/2; P = 1$

$E = 1; P = 2/3$

Track with start/end point

SBND Simulation
Work in progress

Neutrino + Cosmics

Sub-pixel resolution

Closest prediction
Efficiency: 0.950

Closest label
Purity: 0.841

SBND Work in Progress

SBND MPVMPR Test Sample

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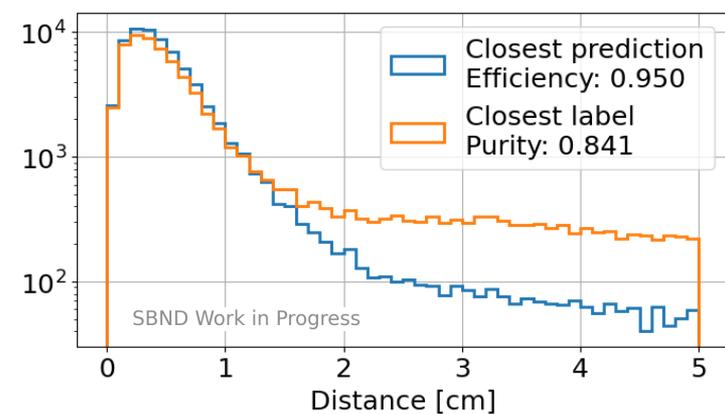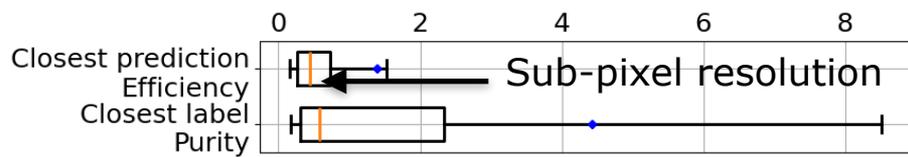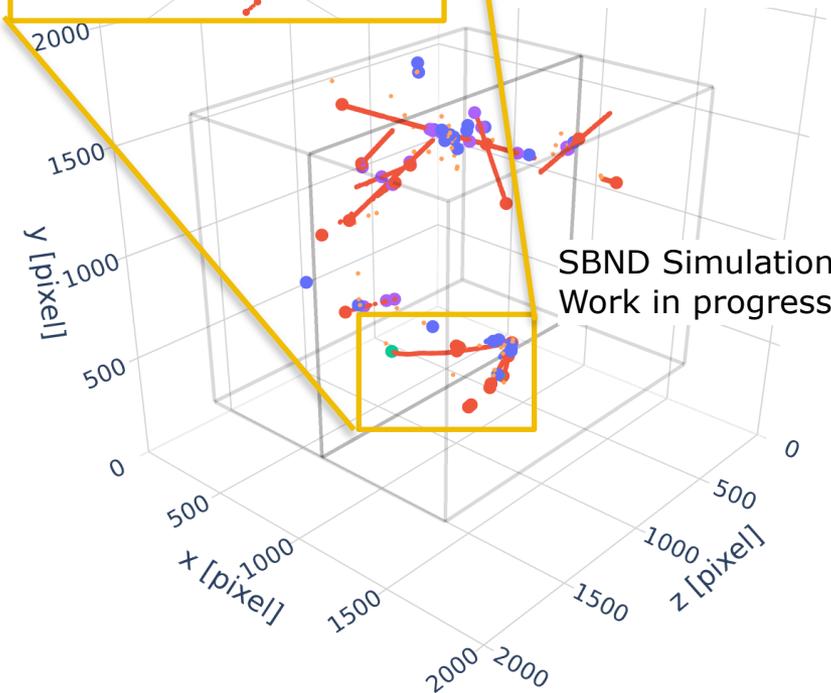
Fragment Clustering

- Construct intermediate representation of particles called **fragments**
  - Reduces complexity of downstream GNNs
- GraphSPICE is "smart" version of DBSCAN
  - Avoids clustering particles together at vertices

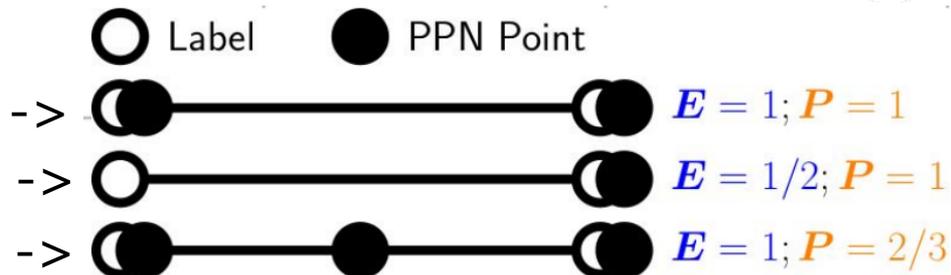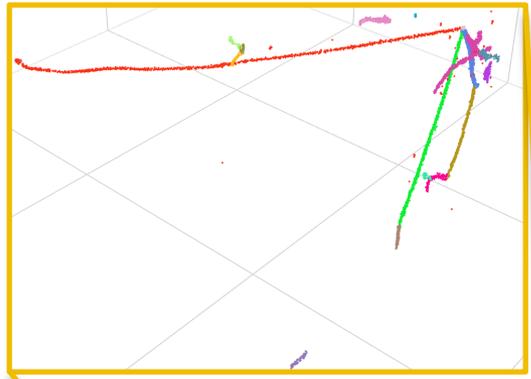Sparse UResNet → Point Features → Trainable Bilinear Kernel → Construct Nearest-Neighbor Graph → Drop Edges / Find Connected Components

Node i ● | K_{ij} | ● Node j → ●—● L_{edge}

Edge Feature

$P(e_{ij}) = 0.9$

D. Koh et al.

UNIVERSITY of FLORIDA

Fragment Clustering

Over-cluster->

Under-cluster->

$E = 1; P = 1$

$E = 1/2; P = 1$

$E = 1; P = 1/2$

SBND Simulation
Work in progress
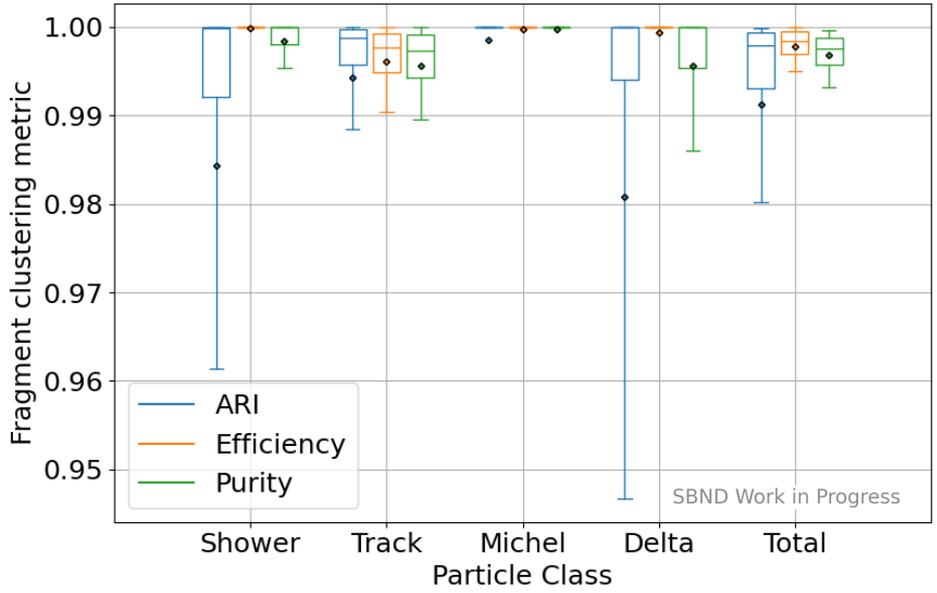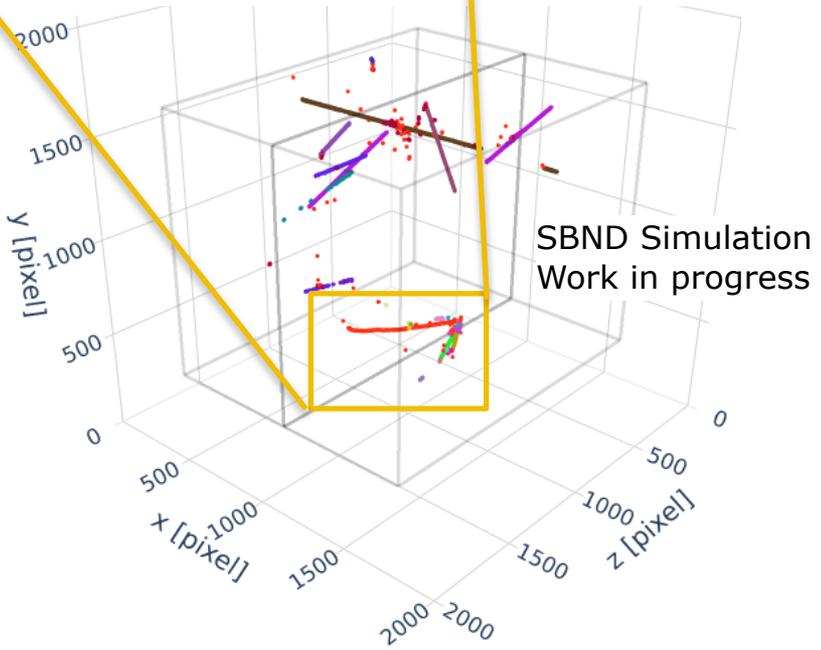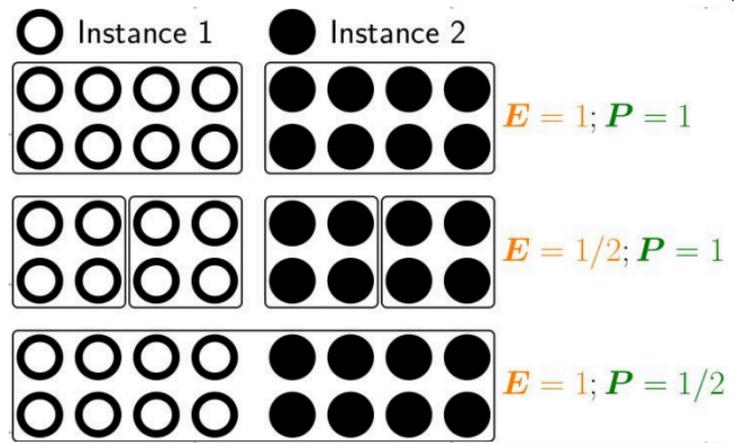
Neutrino + Cosmics

SBND MPVMPR Test Sample

Particle Clustering

- Aggregate fragments into **particles** using a Graph Neural Network (GNN)
- Edge representation is the correlation between fragments
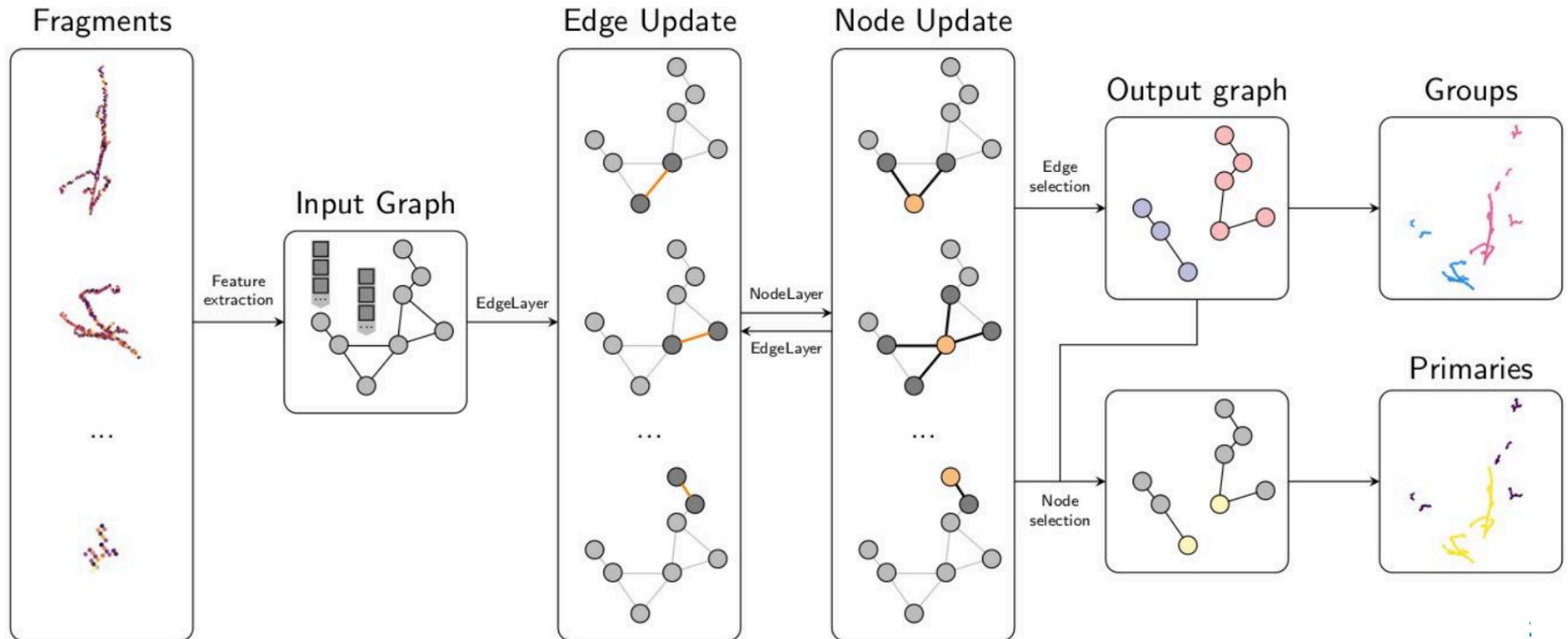
Particle Clustering

ARI = Adjusted Rand Index

Over-cluster->

Under-cluster->

$E = 1; P = 1$

$E = 1/2; P = 1$

$E = 1; P = 1/2$

SBND Simulation
Work in progress
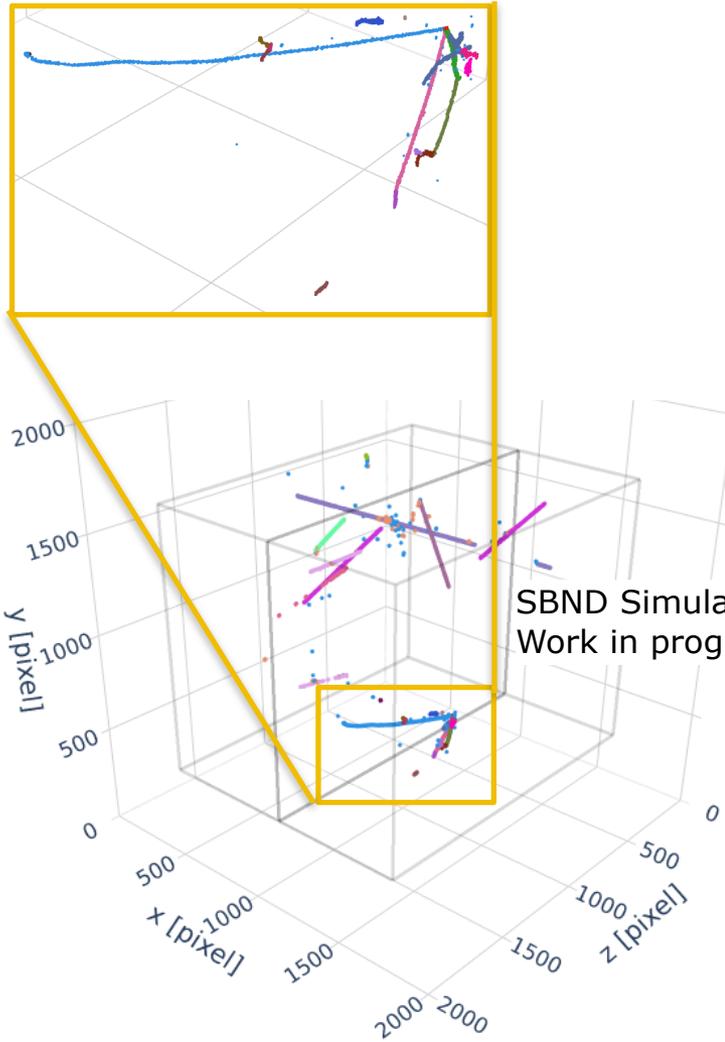
Neutrino + Cosmics

SBND Work in Progress
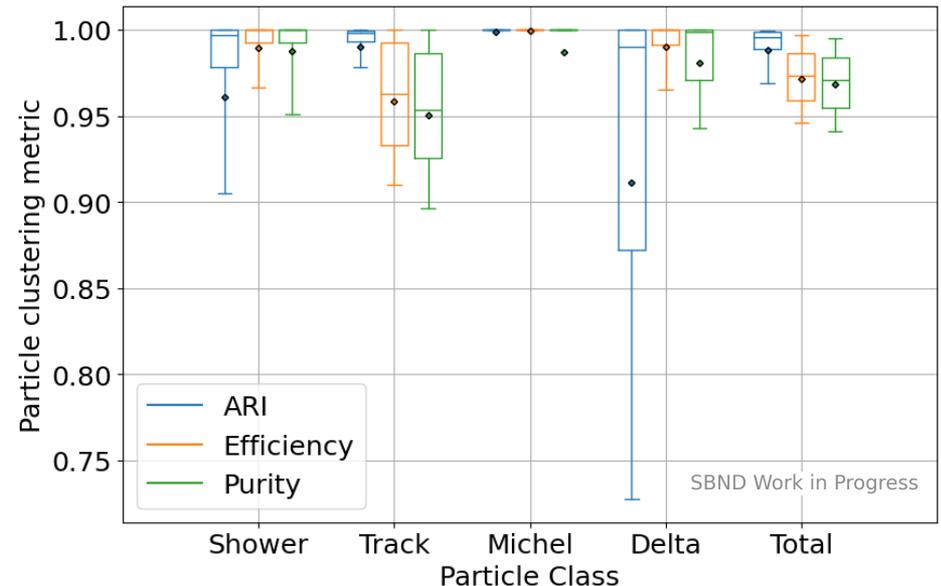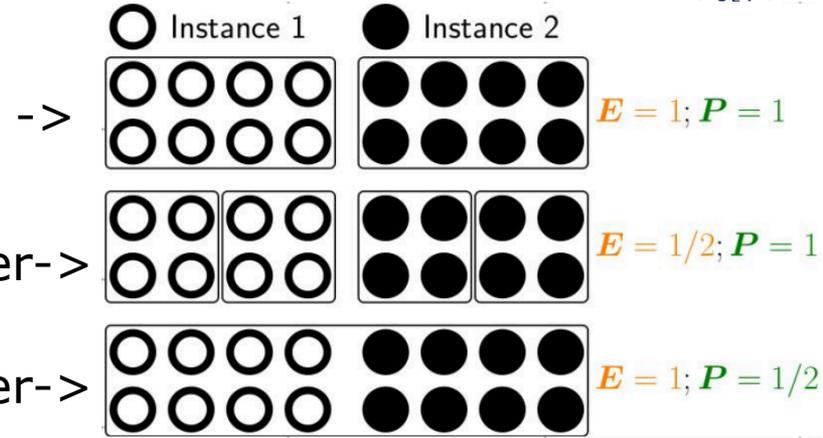
SBND MPVMPR Test Sample

Interaction Clustering

- Aggregate particles into **interactions** using a Graph Neural Network (GNN)
- Edge representation is the correlation between particles
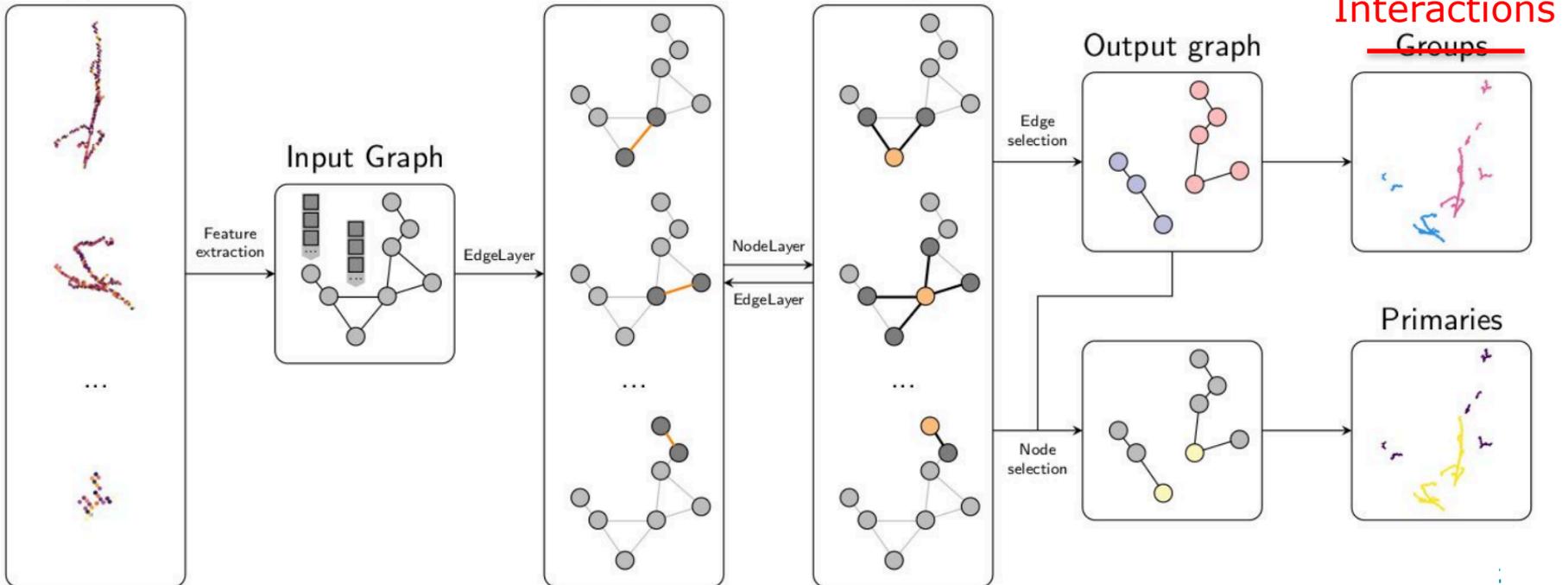
Interaction Clustering

ARI = Adjusted Rand Index

Over-cluster->

Under-cluster->

$E = 1; P = 1$

$E = 1/2; P = 1$

$E = 1; P = 1/2$

SBND Simulation
Work in progress

Neutrino + Cosmics

SBND MPVMPR Test Sample

B. Carlson / SBND

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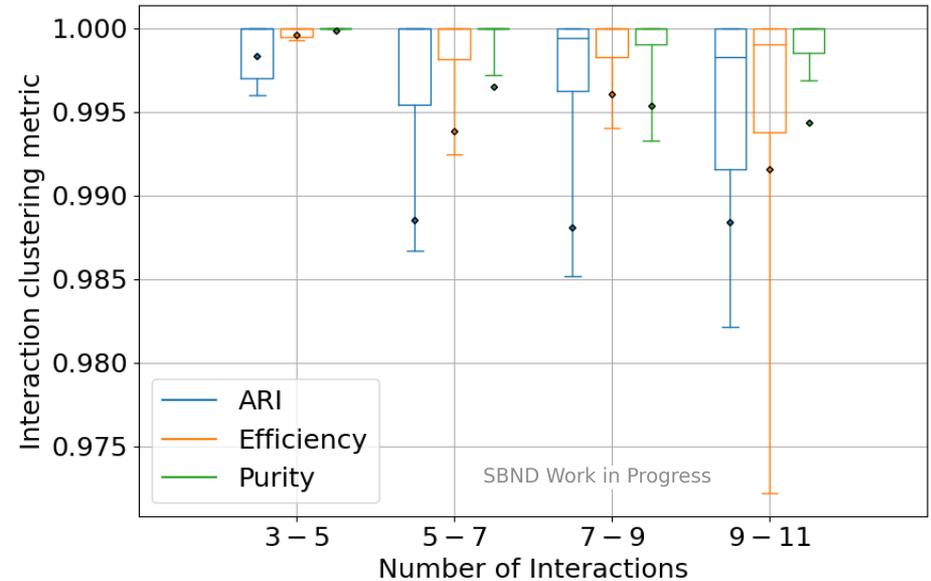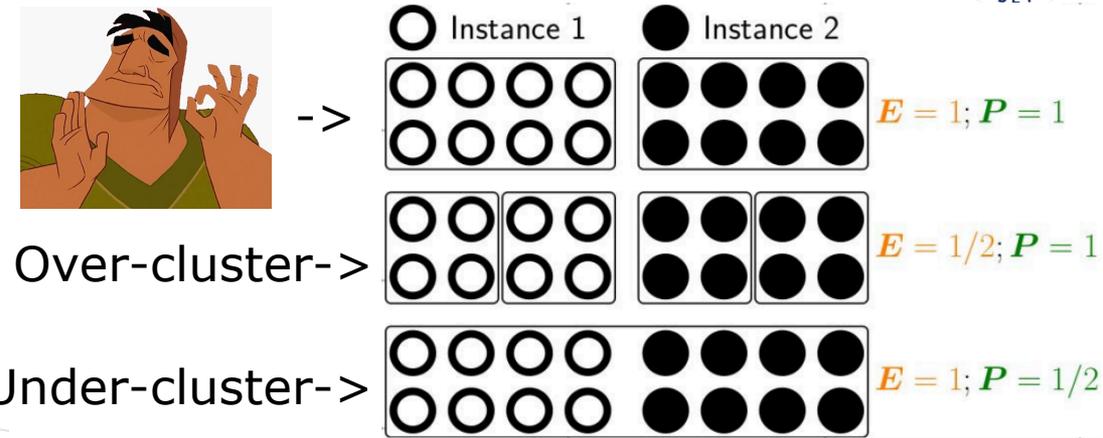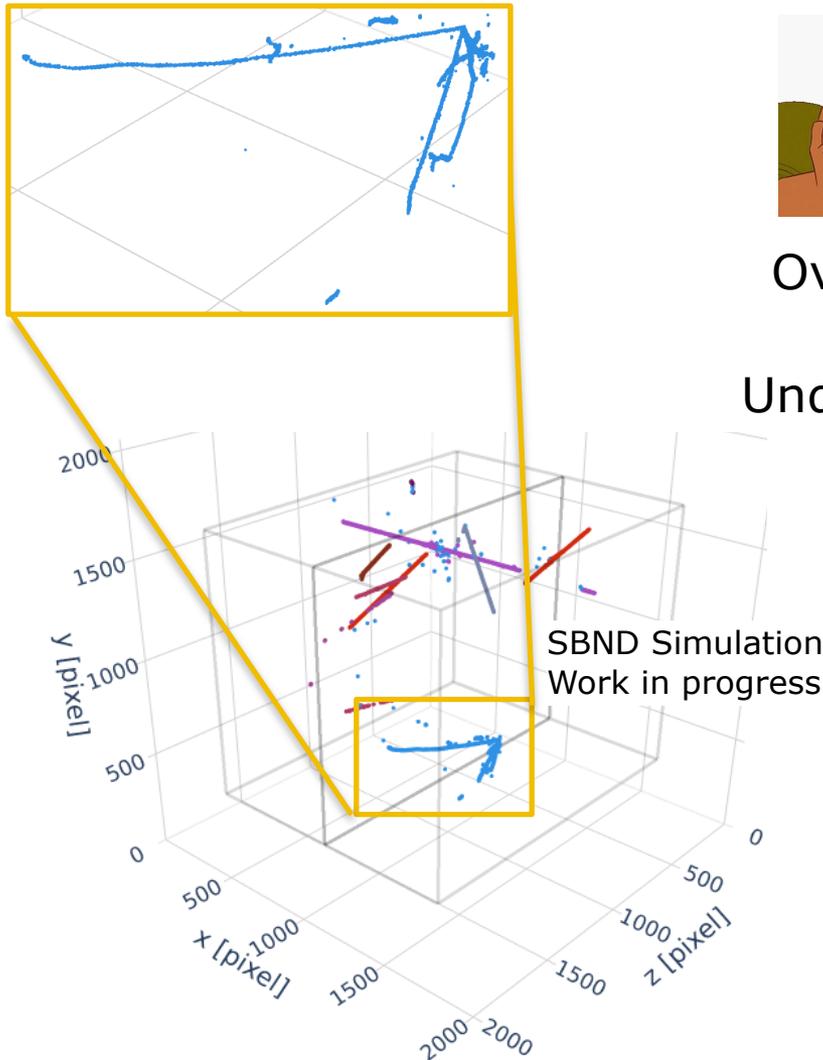
Particle ID

Photon
Electron
Muon
Pion
Proton

Reco
$\nu + \text{Ar} \rightarrow 2\gamma 1\mu 1\pi 1p$

Truth
$\nu + \text{Ar} \rightarrow 2\gamma 1\mu 1\pi 1p$

SBND Simulation
Work in progress

Neutrino + Cosmics

SBND MPVMPR Test Sample

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Particle ID

- Electron / photon separation is crucial for ν_e appearance oscillation searches
- Pi / mu separation achievable using GNN
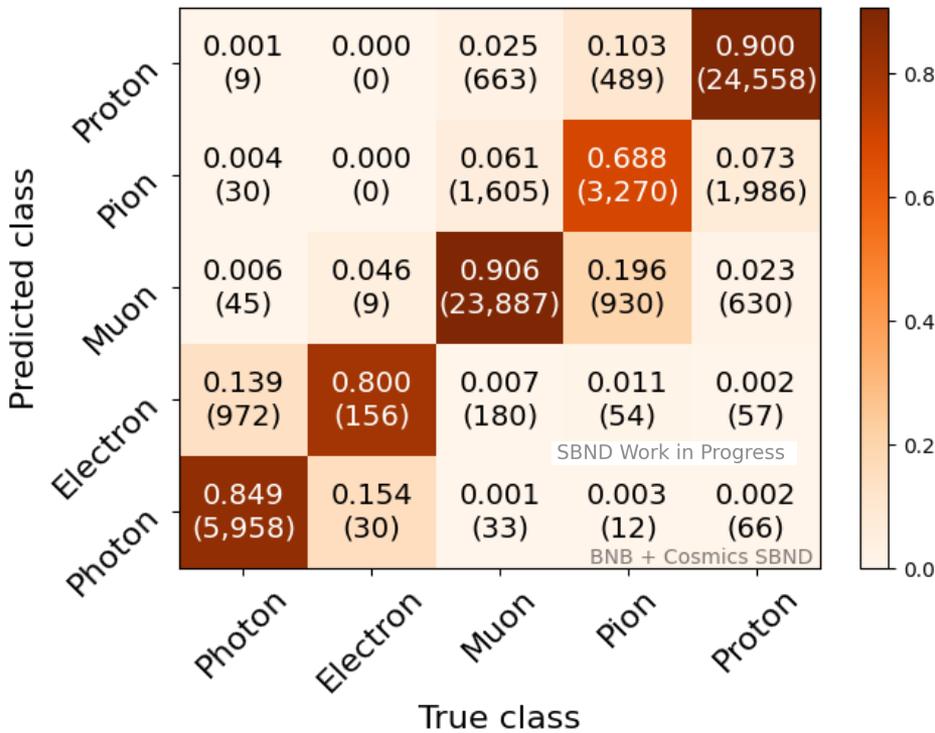
BNB Neutrino (ν_μ dominant)
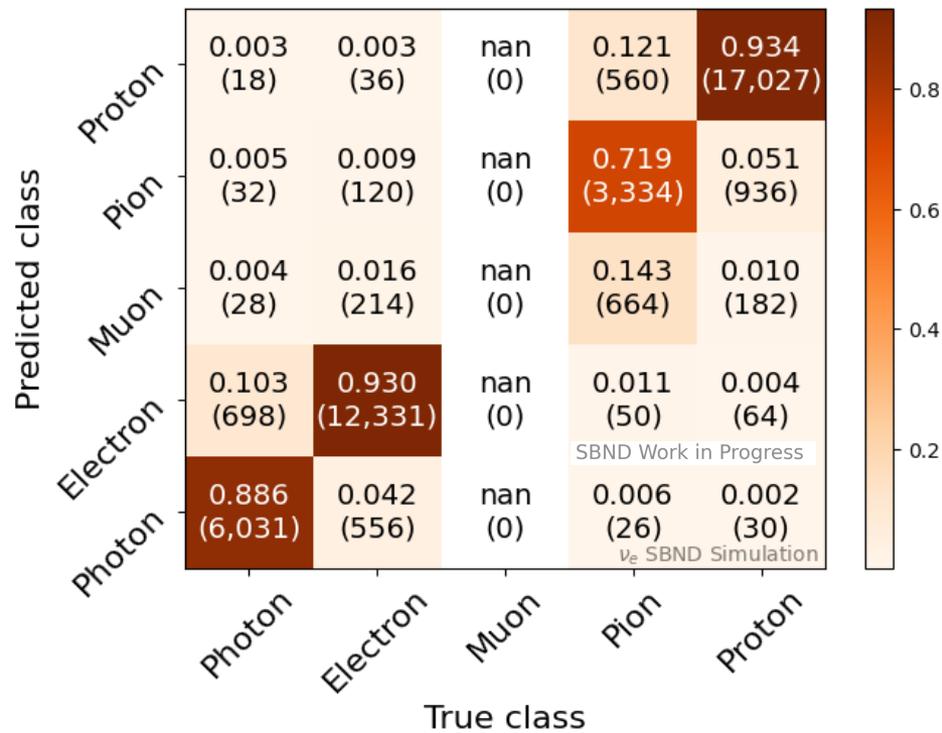
Intrinsic ν_e

Flash Matching

- Goal - Find interactions compatible with PMT flashes during beam
- Do this by matching hypothesis flash with PMT flash

SBND Preliminary

Light Trigger
PMT flashes
XARAPUCA flashes
CRT Upstream + Downstream Walls

SBND Data
Run 18255
3.6×10^{18} POT

Beam spill

Area Normalized (arb. units)

Timestamp difference to TDC RWM (μs)

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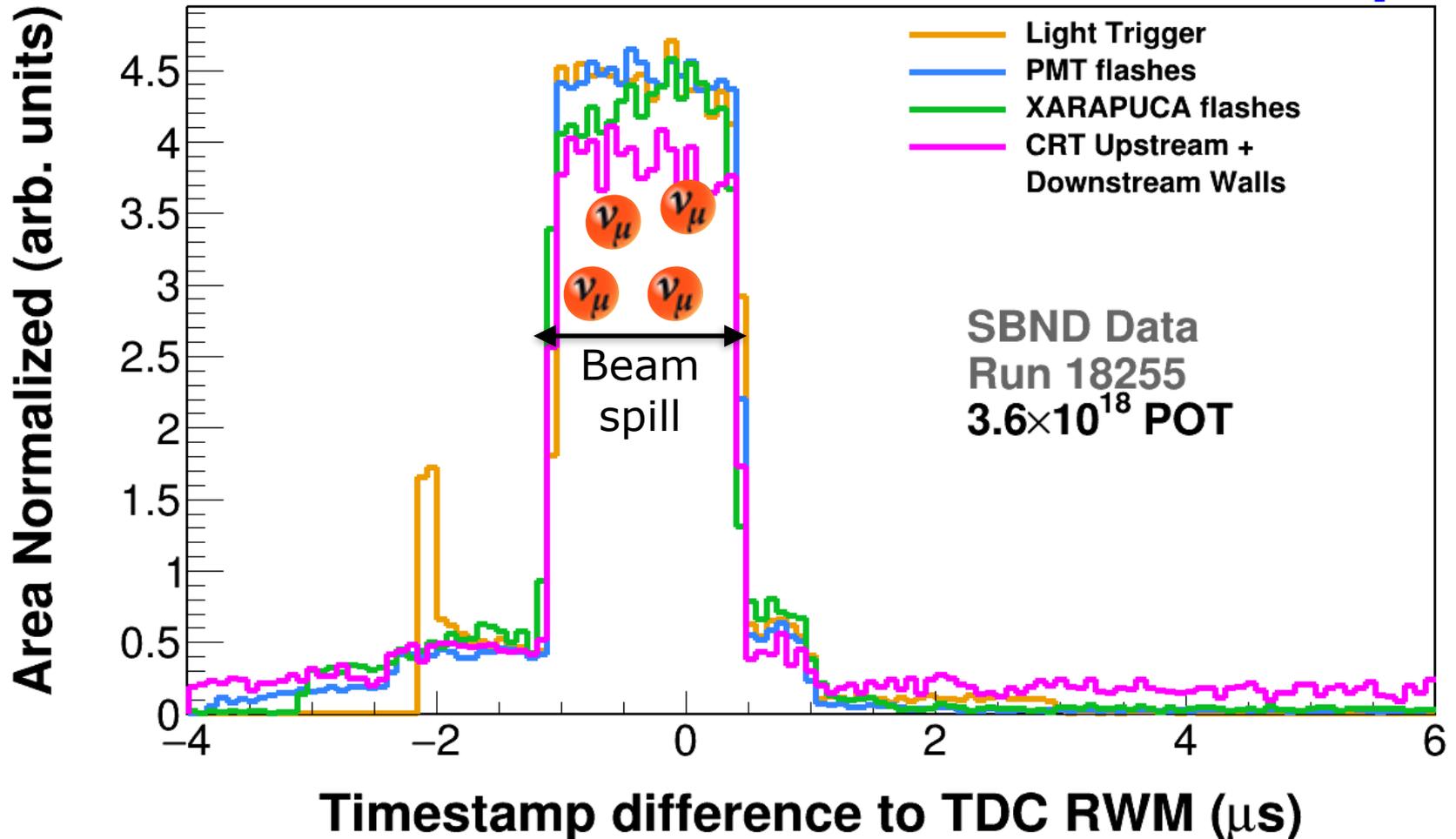
Flash Matching

[3] D. Garcia-Gamez, P. Green, A.M. Szelc Eur. Phys. J. C 81, 349 (2021)

- Compute hypothesis using semi-analytical model [3]

- Flash score calculated using χ^2

$$\chi^2 = \frac{1}{N_{PDS}} \sum_i \frac{(R_i - H_i)^2}{R_i}$$

- Purity = neutrinos selected / total selected

- Efficiency = true neutrinos selected / true neutrinos
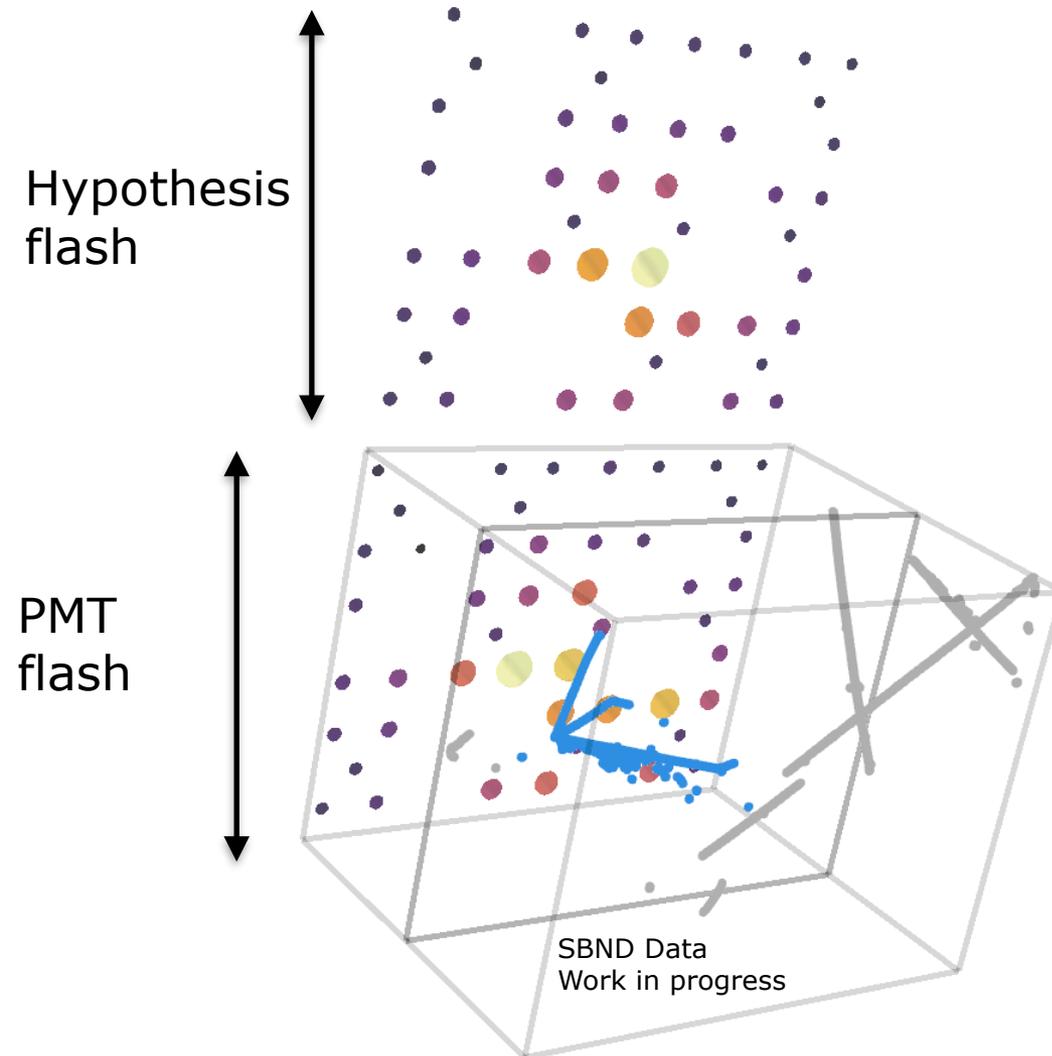
Hypothesis flash

PMT flash

SBND Data
Work in progress

Purity = 85%
Efficiency = 87%

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SPINE

SPINE (Scalable Particle Imaging with Neural Embeddings) [4]

Wire planes — CNNs — GNNs — Physics

0.5 s / event   1 s / event
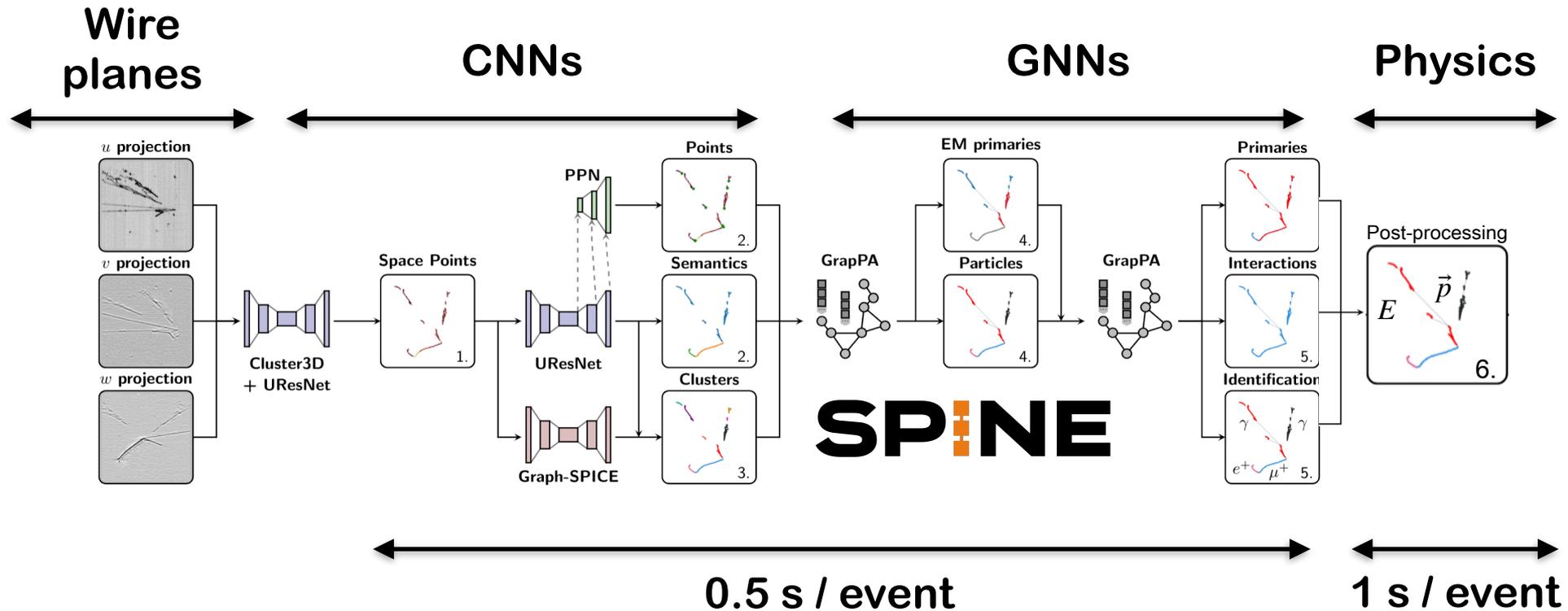
[4] F. Drielsma, K. Terao, L. Dominé, D.H. Koh https://arxiv.org/abs/2102.01033

Analyses

- SBND ν_μ CC selections will be used for flux and cross section constraints

Run 18255 Subrun 1 Event 142421
(Cosmics filtered out)

SBND Data
Work in progress

$$\nu + Ar \rightarrow 2\gamma 1\mu 1\pi 1p$$

Reco interaction vertex

SBND Data
Work in progress

$$\nu + Ar \rightarrow 2\gamma 1\mu 1\pi 1p$$
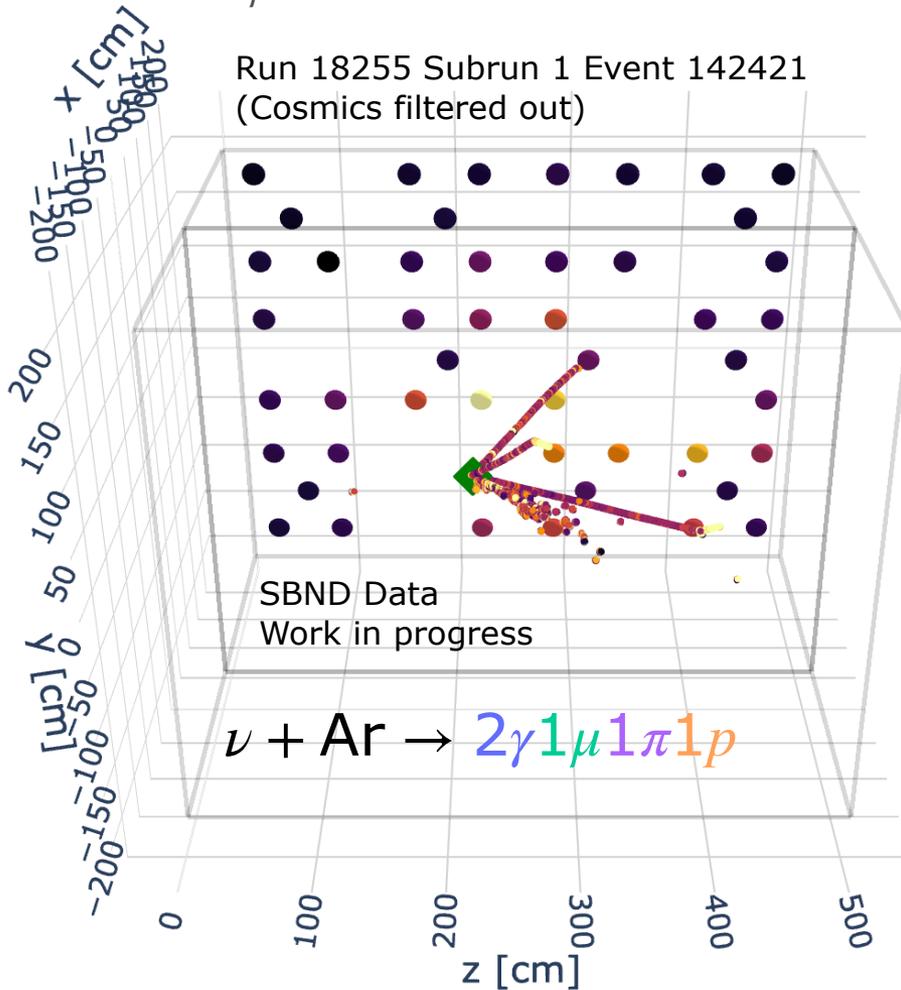
Energy depositions

PID
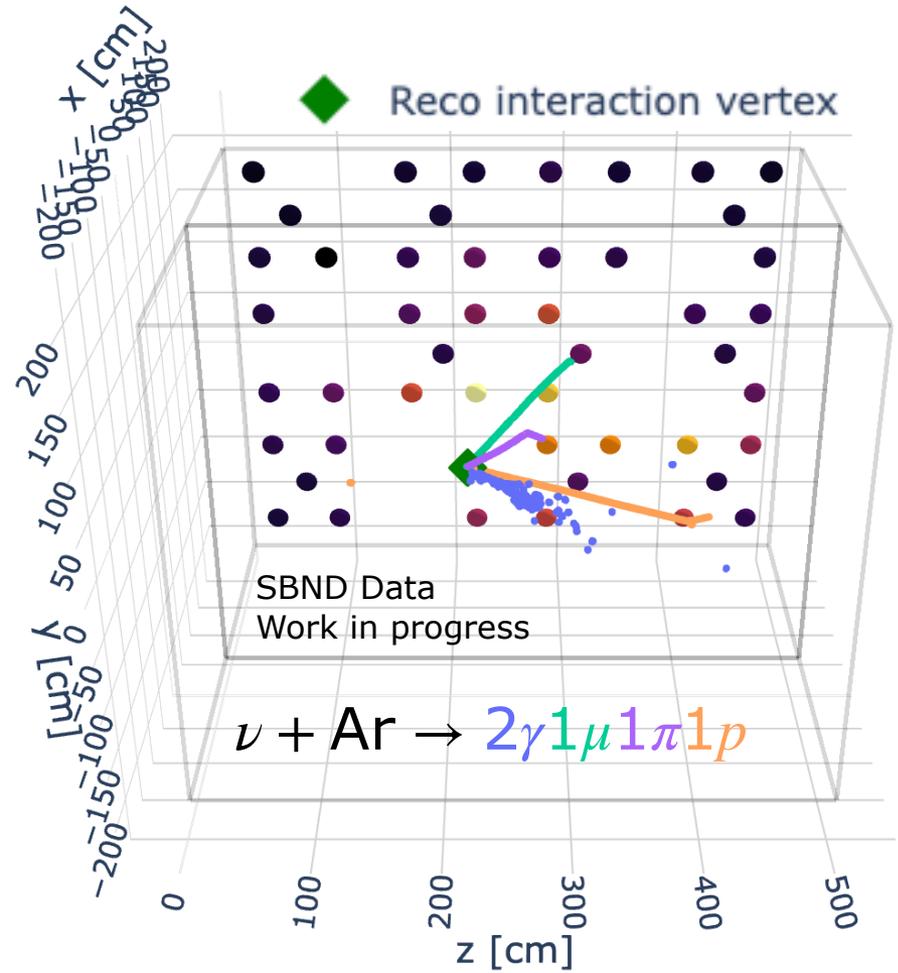
ν_μ CC Selections

- SBND ν_μ CC selections will be used for flux and cross section constraints
- Similar MicroBooNE Np selection had 49% efficiency and 95% purity [5]
- ICARUS performance shown, SBND has similar results in progress

Purity = true signal events selected / selected events

Efficiency = true signal events selected / true signal events

Neutrino 2024 ICARUS
Talk (Daniele Gibin)

Purity = 83%
Efficiency = 75%
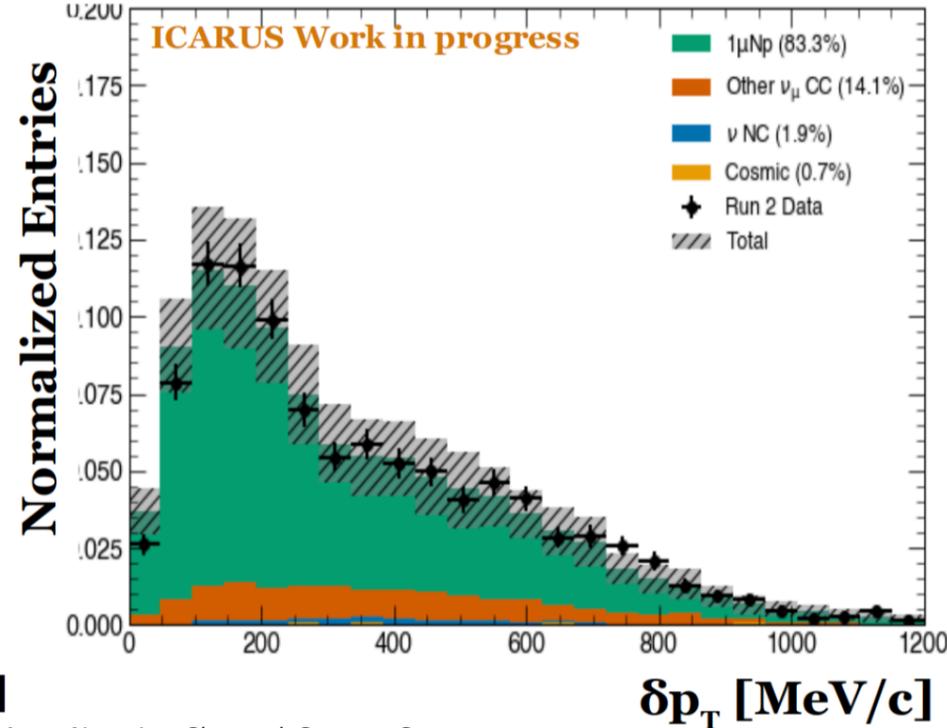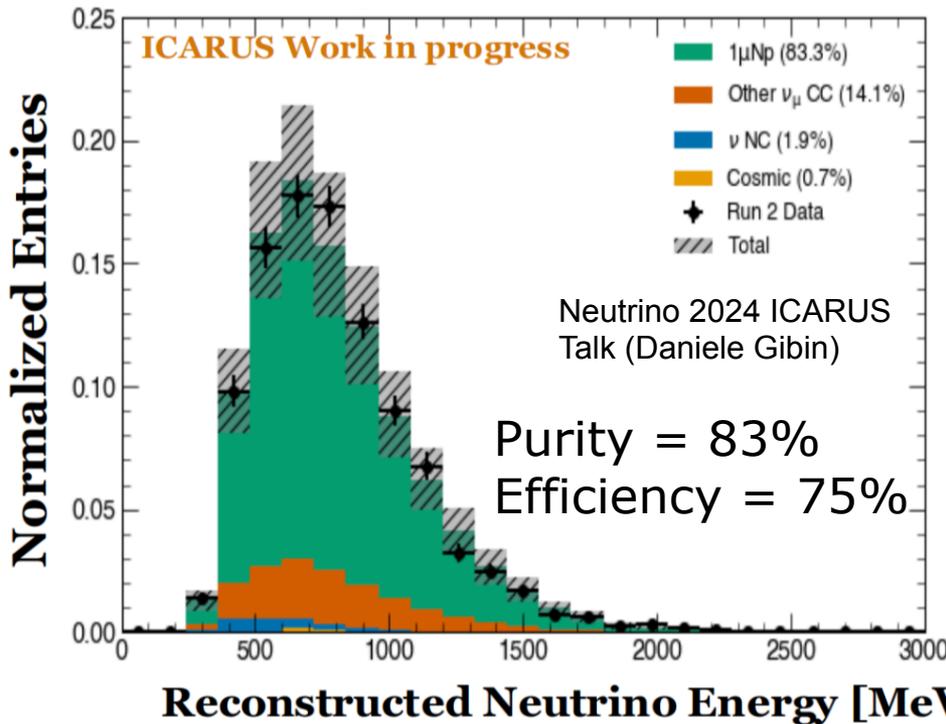
[5] MicroBooNE, First Simultaneous Measurement of Differential Muon-Neutrino Charged-Current Cross Sections on Argon for Final States with and without Protons Using MicroBooNE Data arxiv:2402.19281

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π^0 Selections

- NC/CC π^0 selections are crucial for shower energy calibration

L. Kasher

SBND Data
Work in progress

$$m_{\pi^0} = m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos\theta)}$$

Photon

E_2

Photon

E_1 θ

π^0

Muon

Proton

SBND Data
Work in progress

π^0 Selections

- NC/CC π^0 selections are crucial for shower energy calibration
- Similar MicroBooNE NC π^0 had 9% efficiency and 53% purity [6]

[6] MicroBooNE, Measurement of neutral current single π0 production on argon with the MicroBooNE detector, arXiv:2205.07943

Purity = true signal events selected / selected events
Efficiency = true signal events selected / true signal events

L. Kasher

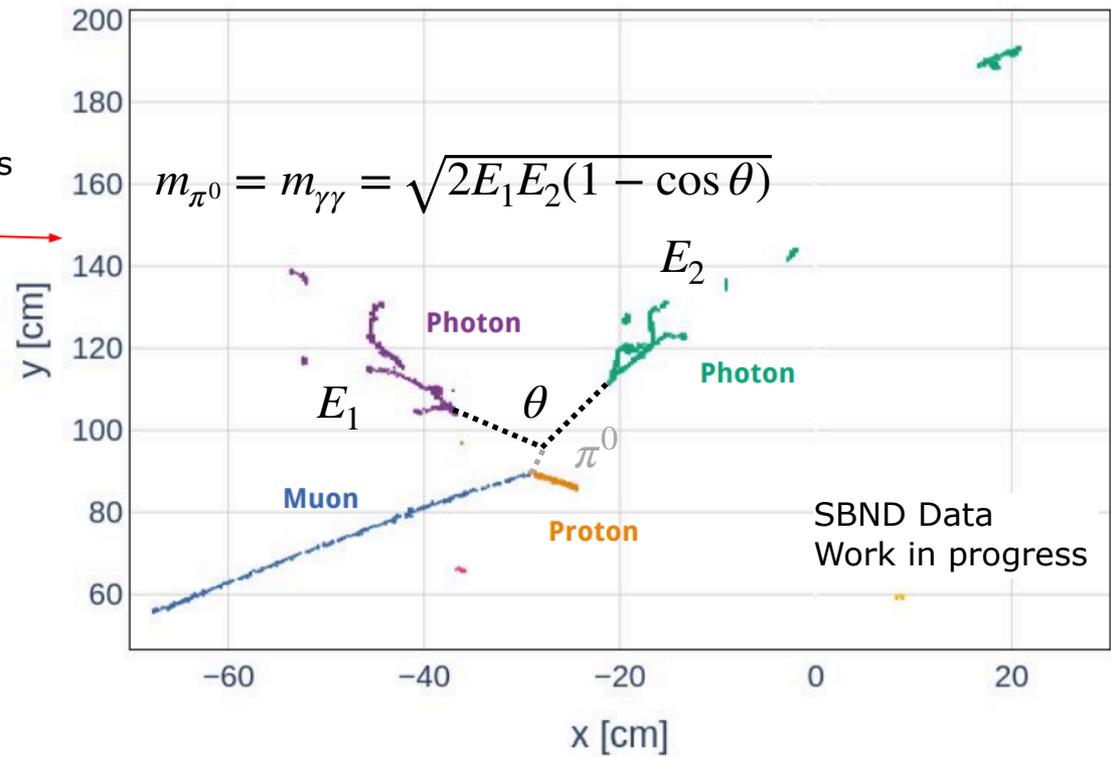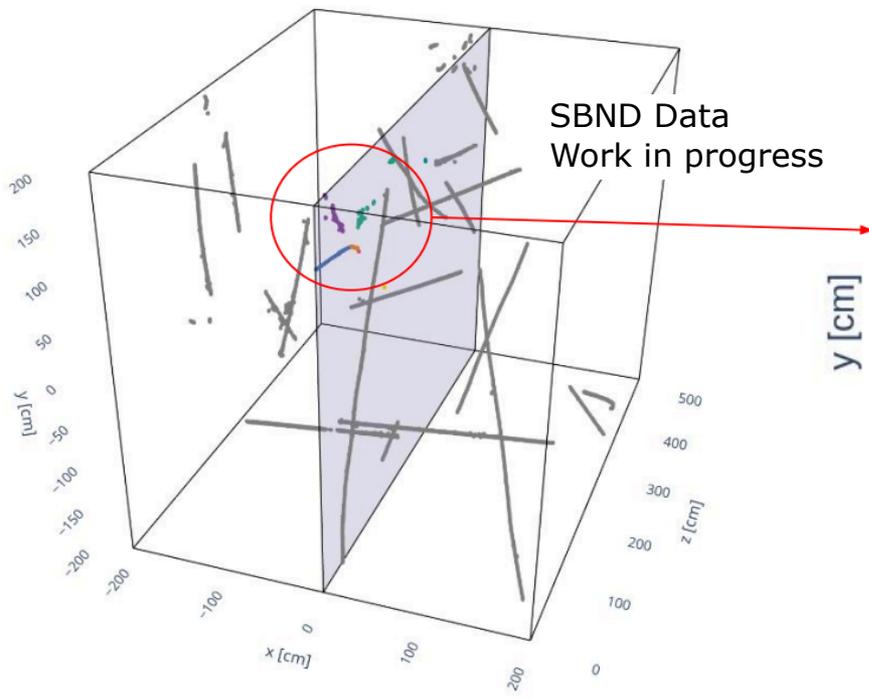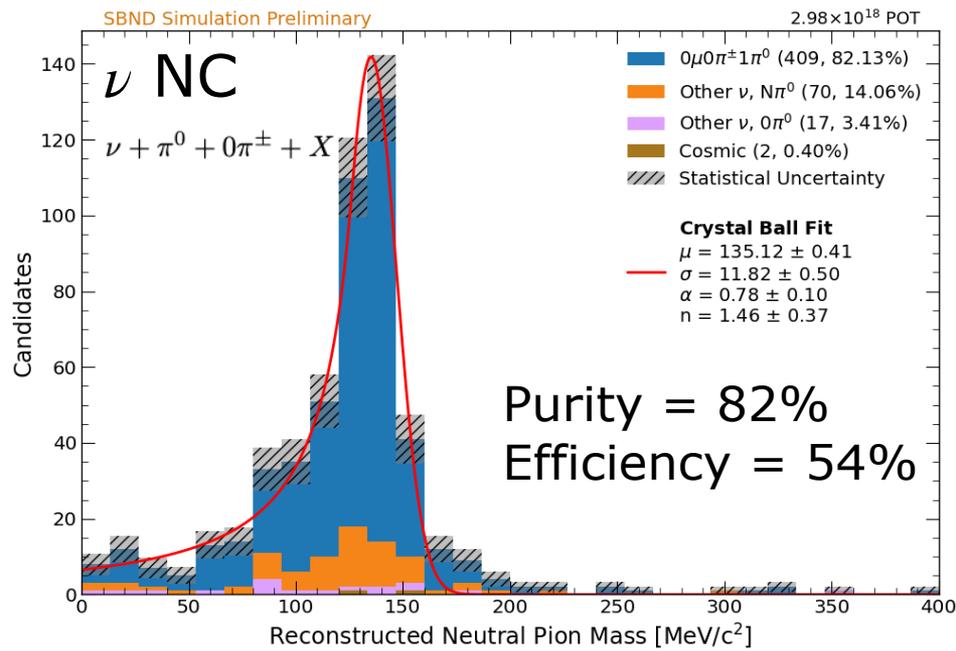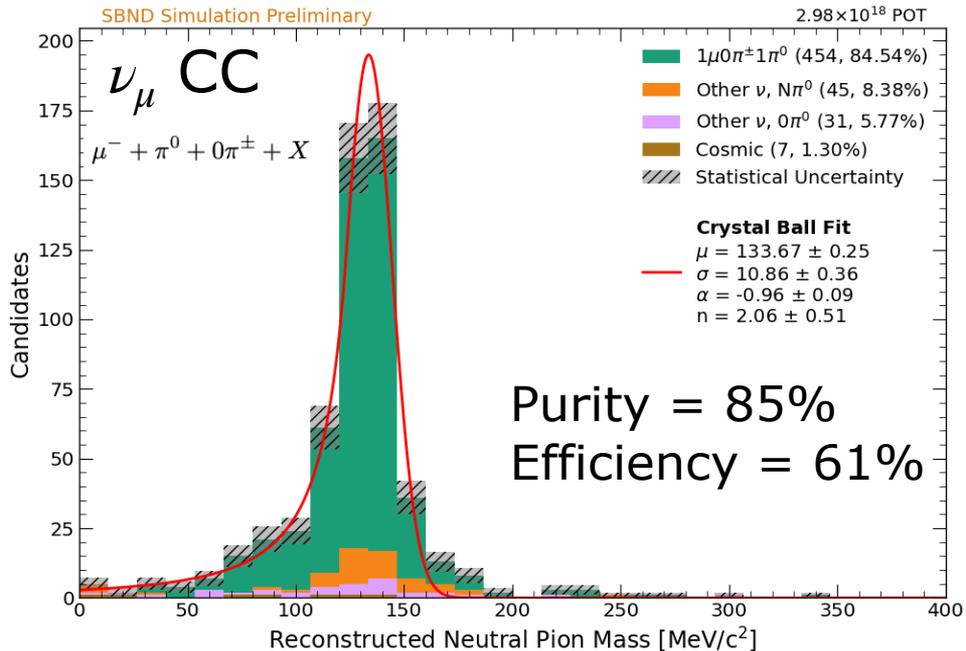$$m_{\pi^0} = 134.98 \text{ MeV}/c^2$$

SBND Simulation Preliminary — 2.98×10^{18} POT

ν_μ CC

$\mu^- + \pi^0 + 0\pi^\pm + X$

- 1μ0π±1π⁰ (454, 84.54%)
- Other ν, Nπ⁰ (45, 8.38%)
- Other ν, 0π⁰ (31, 5.77%)
- Cosmic (7, 1.30%)
- Statistical Uncertainty

Crystal Ball Fit
$\mu = 133.67 \pm 0.25$
$\sigma = 10.86 \pm 0.36$
$\alpha = -0.96 \pm 0.09$
$n = 2.06 \pm 0.51$

Purity = 85%
Efficiency = 61%

SBND Simulation Preliminary — 2.98×10^{18} POT

ν NC

$\nu + \pi^0 + 0\pi^\pm + X$

- 0μ0π±1π⁰ (409, 82.13%)
- Other ν, Nπ⁰ (70, 14.06%)
- Other ν, 0π⁰ (17, 3.41%)
- Cosmic (2, 0.40%)
- Statistical Uncertainty

Crystal Ball Fit
$\mu = 135.12 \pm 0.41$
$\sigma = 11.82 \pm 0.50$
$\alpha = 0.78 \pm 0.10$
$n = 1.46 \pm 0.37$

Purity = 82%
Efficiency = 54%

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Conclusion

- Evidence for $\Delta m^2 \sim 1\text{eV}^2$ neutrino oscillation is being explored by SBN
- LArTPC detector output can naturally be reconstructed using computer vision (CV)
- SPINE is a hierarchical feature extractor for LArTPC using CV
  - CNNs reconstruct point-wise attributes
  - GNNs cluster space points into super structures
  - Post processors are used to do physics (e.g. energy reconstruction, flash matching)
- **Reconstruction is essential** to **reducing uncertainties** and **measuring oscillations**
- Early simulation selections show promising performance (Michel electron selection in backups)
- SBND SPINE can reconstruct data reliably
  - Results with data to be shown at upcoming conferences…

B. Carlson / SBND

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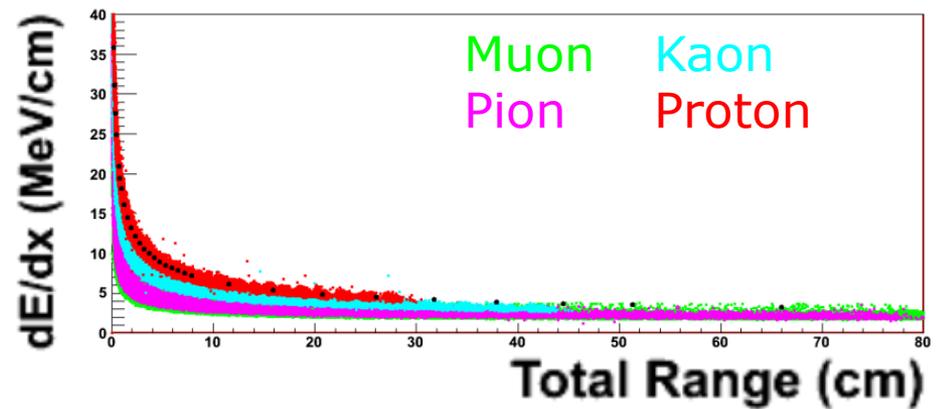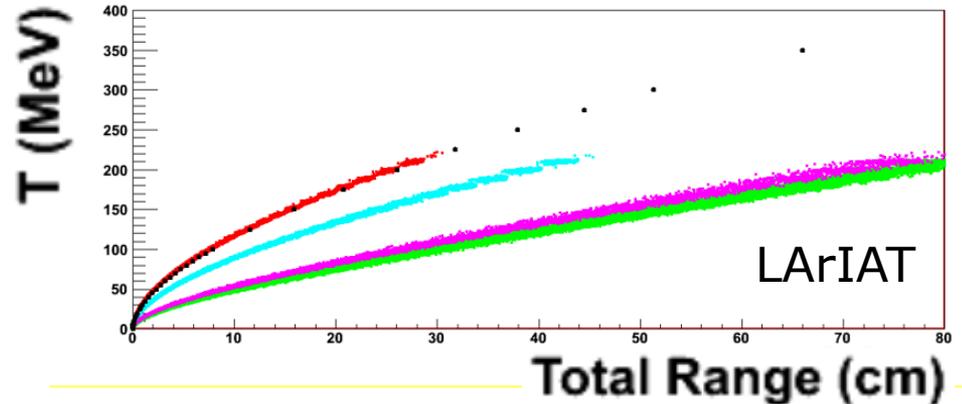
Thanks!

B. Carlson / SBND

Energy

- Can calculate energy of **stopped/contained tracks** in TPC using range based methods

$$\Delta x = \int_0^{E_0} \frac{1}{dE/dx} dE$$

- Match distance Δx to lookup table for E_0

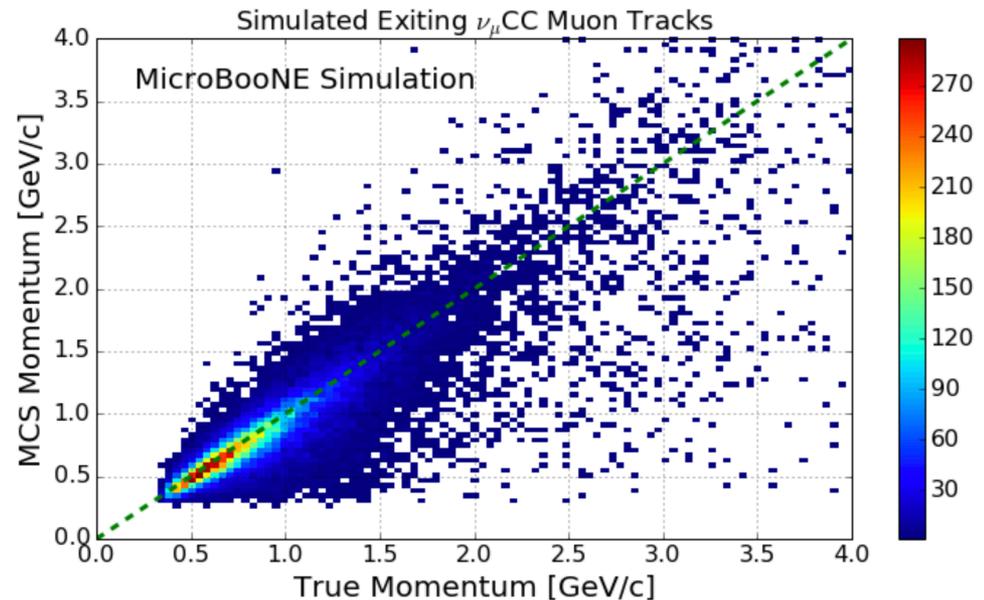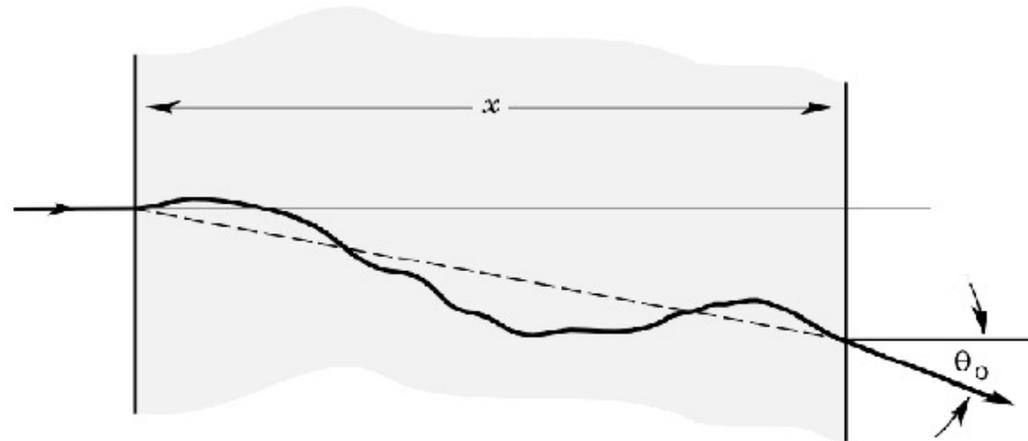Low momentum → High momentum

LArIAT

Muon   Kaon
Pion   Proton

Energy

- Can calculate energy of **exiting/uncontained tracks** using multiple coulomb scattering (MCS)

$$\theta_0 = \frac{S_2}{p\beta c}z\sqrt{\frac{x}{X_0}}\left[1 + \epsilon \log\left(\frac{x}{X_0}\right)\right]$$

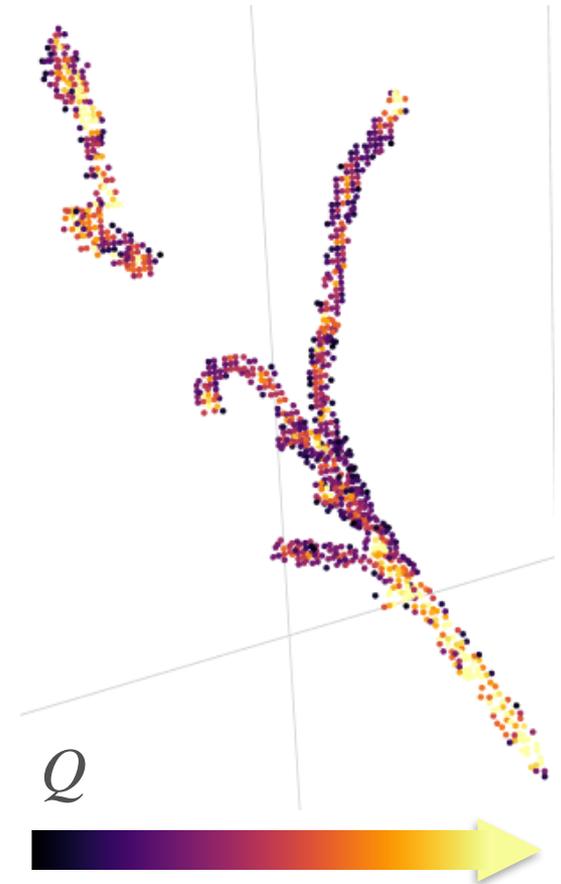- Fit deflection θ_0 to momentum p

Simulated Exiting ν_μCC Muon Tracks

MicroBooNE Simulation

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- Can calculate energy of **showers** by summing up all energy depositions
- Derive calibration constants from data

Work function for Ar

Shower adjustment factor

Electron lifetime correction

$$E_{\text{shower}} = W_i \cdot C_{\text{calo}} \cdot C_{\text{adj}} \cdot \frac{1}{R} \cdot \sum_Q e^{\frac{t_{\text{drift}}}{\tau}} Q$$

[MeV]   [MeV / e⁻]   [e⁻ / ADC]   [ADC]

Calorimetric constant (TPC gain)

Recombination factor

Deposited charge

Q

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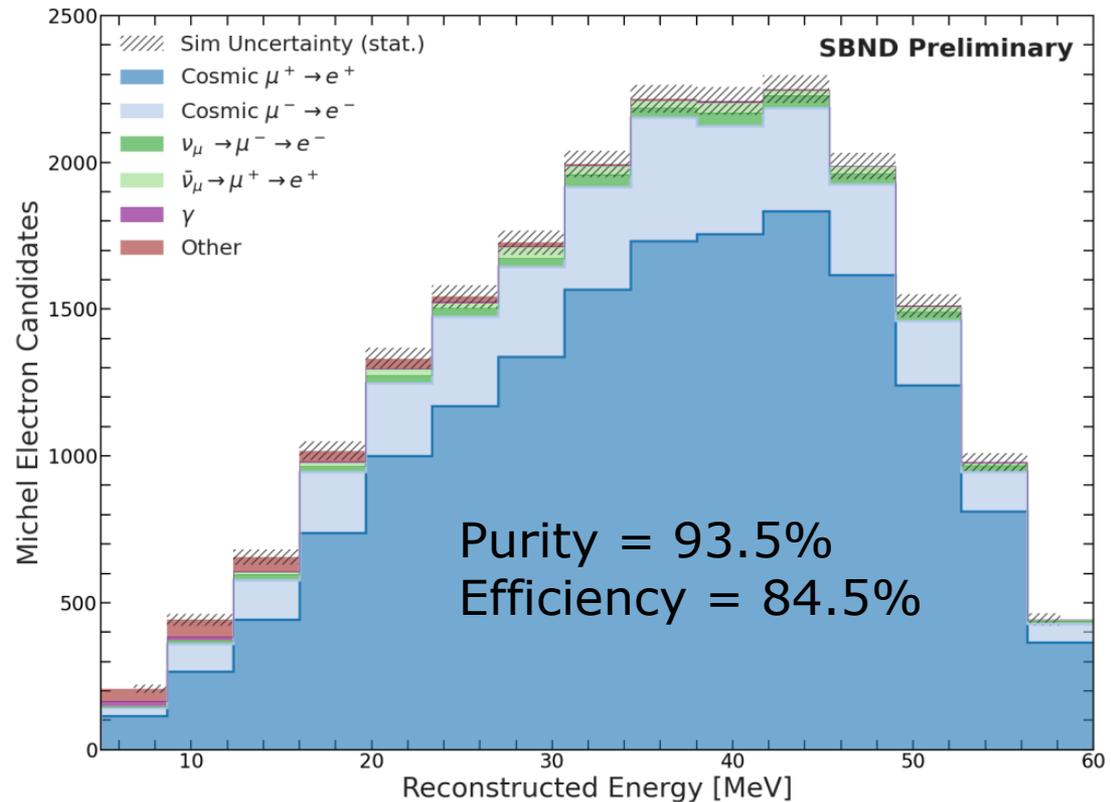
Michel e- Selection

- Michel electrons from decaying electrons from muons
- Useful for low energy calibrations
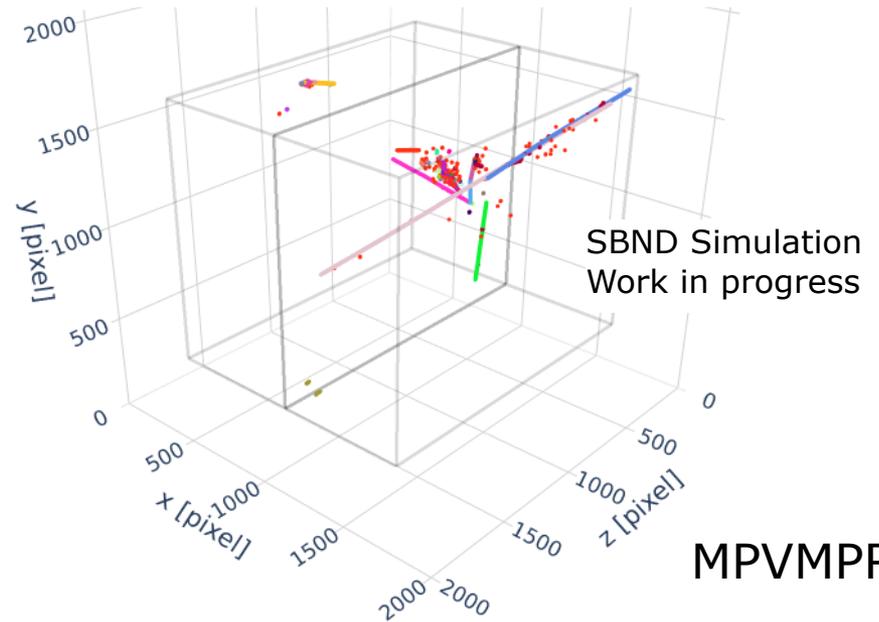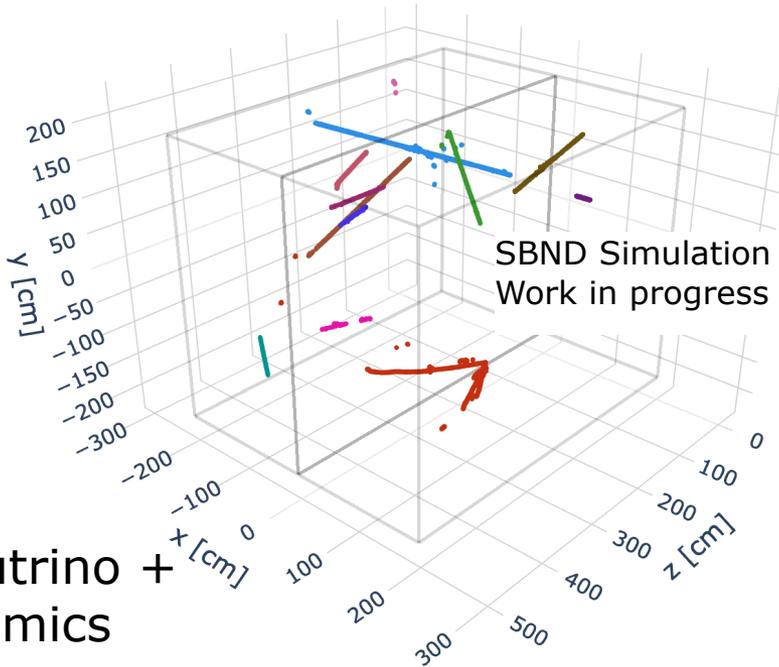- Similar MicroBooNE Michel had 2% efficiency and ~90% purity [6]

N. Oza

SBND Simulation
Work in progress

[6] MicroBooNE, Michel Electron Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC arxiv:1704.02927

Purity = 93.5%
Efficiency = 84.5%

Training Sample

- Multi-particle vertex multi-particle rain (MPVMPR) sample - 2 generators
  - Rain (MPR) <—> **cosmic activity**
  - Vertex (MPV) <—> **neutrino activity**
- Use this over neutrino + cosmics event generators to...
  - Sample particle abundances and energies from uniform distribution
  - Avoid biases from particular neutrino generator

SBND Simulation
Work in progress

Neutrino +
Cosmics

SBND Simulation
Work in progress

MPVMPR

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UReSNet Sparse CNN
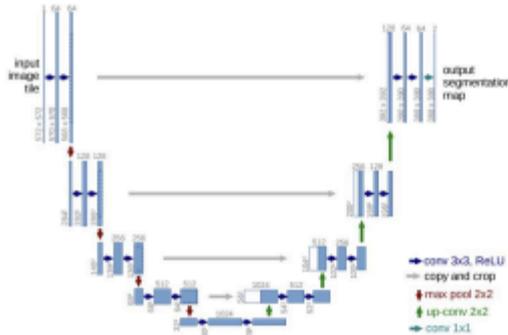
Semantic Segmentation

Backbone (L. Dominé)

UReSNet (UNet + ResNet + Sparse Conv.) as the **backbone feature extractor**

UNet
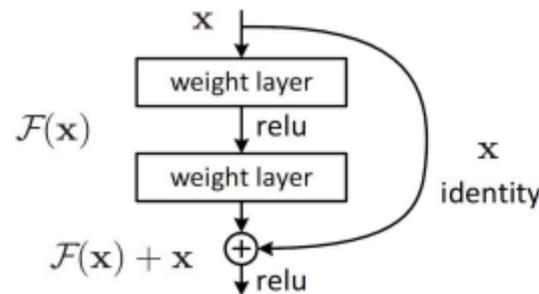- Downsizing -> expand receptive field
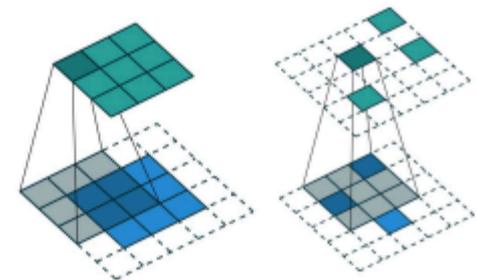- Skip connections -> preserve resolution

ResNet
- Identity bypass + convolution -> learns residual transform
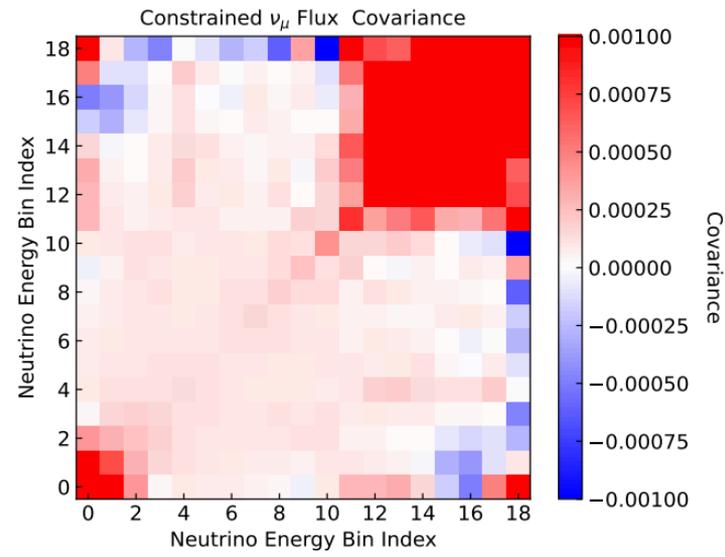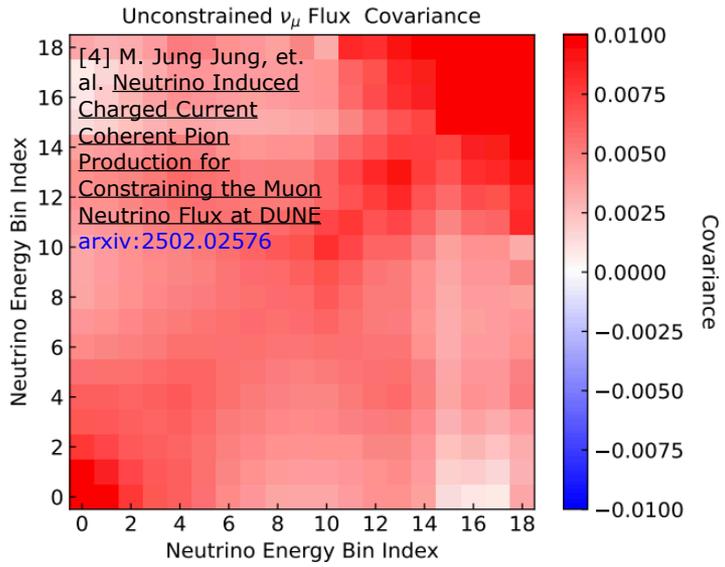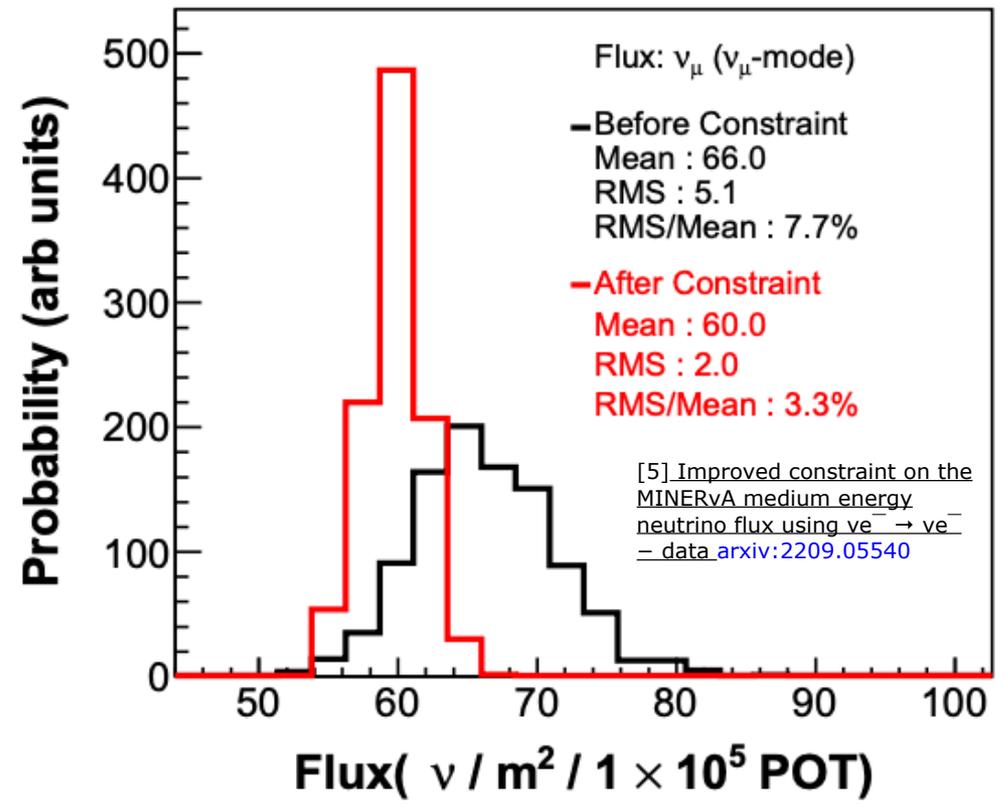- Speeds up learning, enables deeper networks

Sparse Convolutions
- Only applies convolutions on active pixels
- Saves memory, execution speed (dramatically)

ML-based Reconstruction for LArTPCs, F. Drielsma (SLAC)   15

Flux

Unconstrained ν_μ Flux Covariance

[4] M. Jung Jung, et. al. Neutrino Induced Charged Current Coherent Pion Production for Constraining the Muon Neutrino Flux at DUNE arxiv:2502.02576

Constrained ν_μ Flux Covariance

- Constrain flux uncertainties by measuring interactions with well known cross section [4,5]

Flux: ν_μ (ν_μ-mode)

— Before Constraint
Mean : 66.0
RMS : 5.1
RMS/Mean : 7.7%

— After Constraint
Mean : 60.0
RMS : 2.0
RMS/Mean : 3.3%

[5] Improved constraint on the MINERvA medium energy neutrino flux using $\nu e^- \rightarrow \nu e^-$ data arxiv:2209.05540

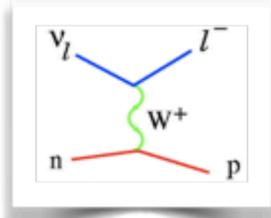B. Carlson / SBND SPINE

UNIVERSITY of FLORIDA
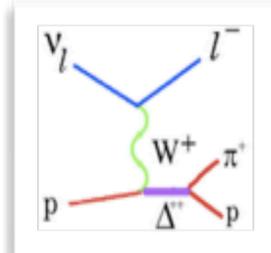
Cross Section

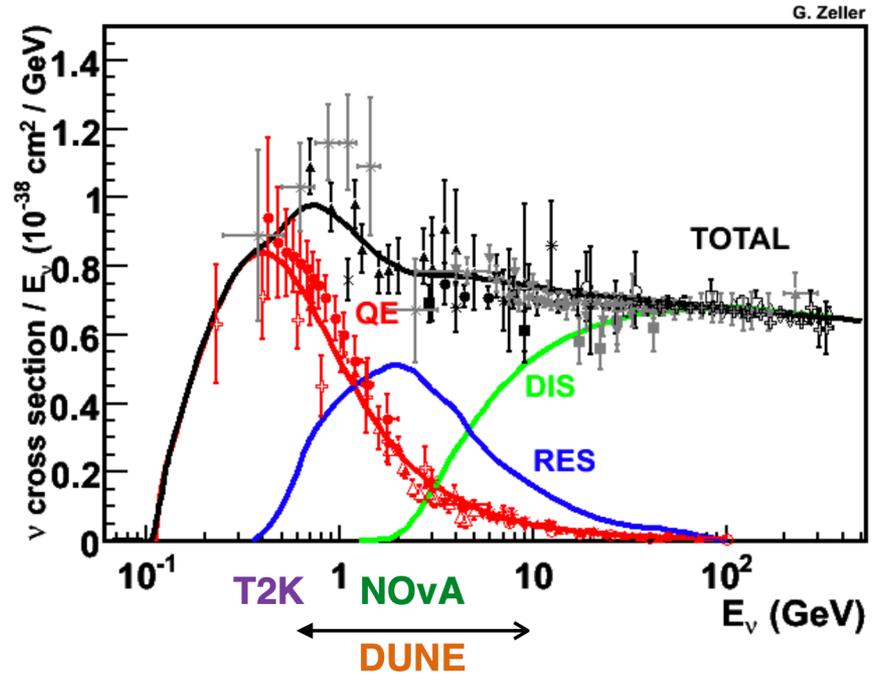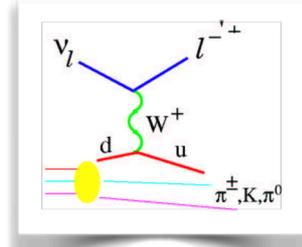- Measure cross sections of various neutrino interaction processes
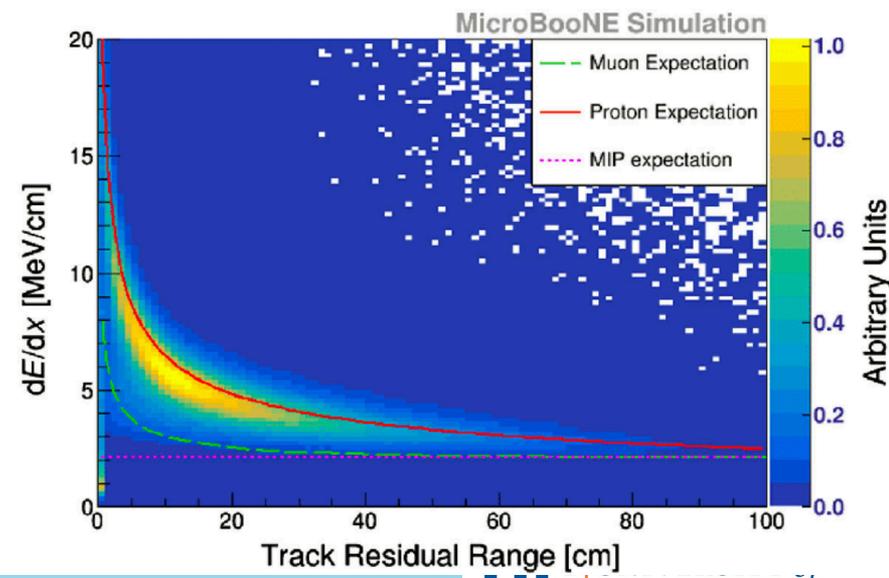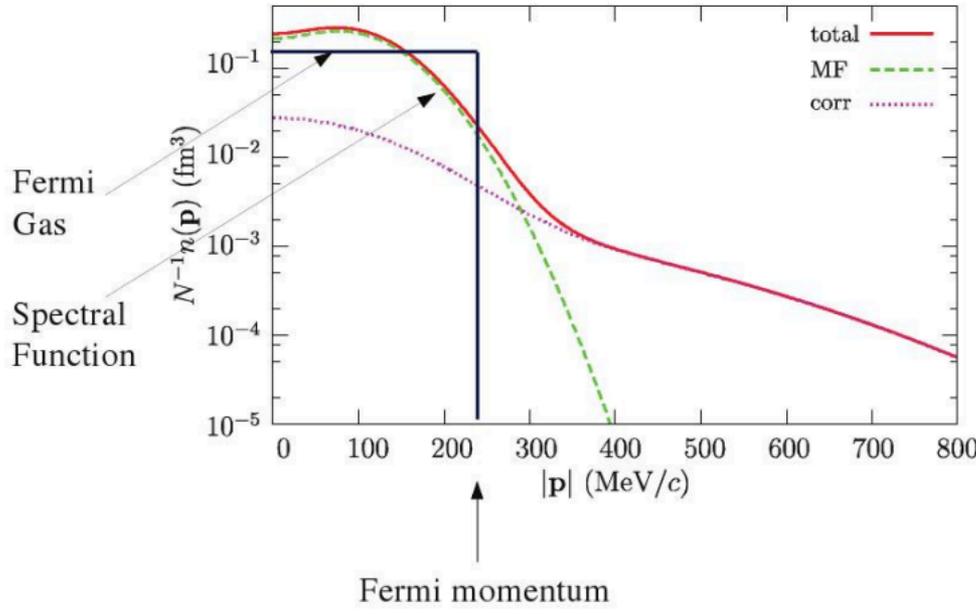

Differing observable final states
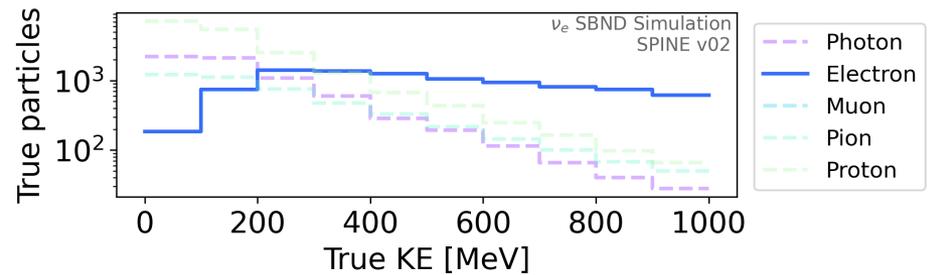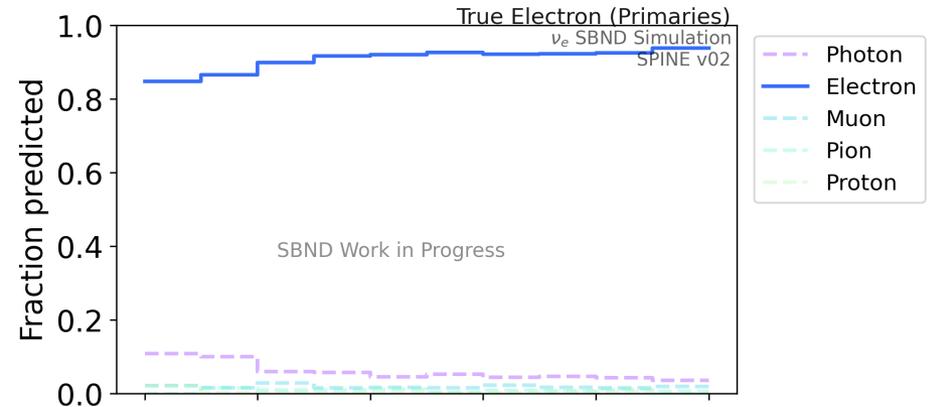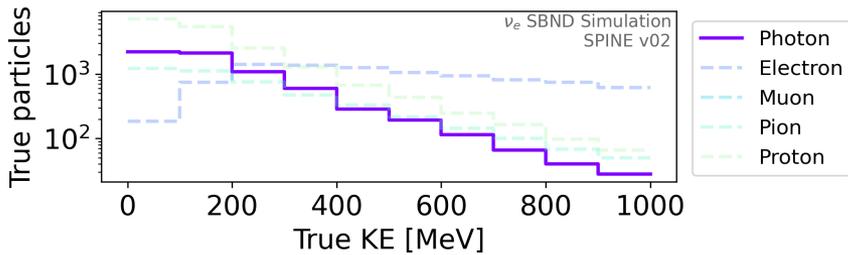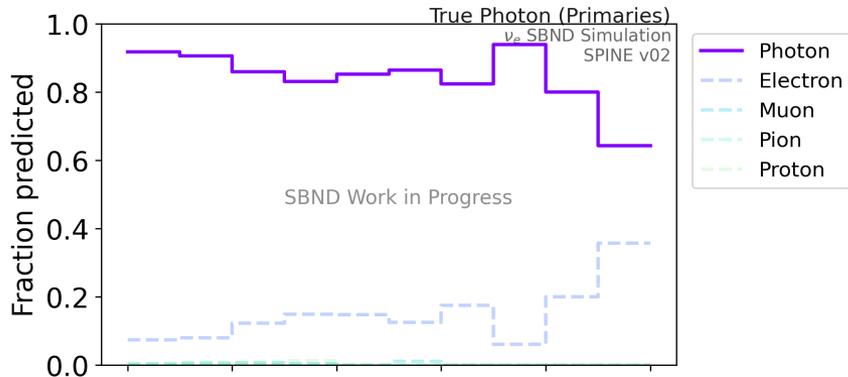
Quasi-elastic scattering (QE)

Resonance production (RES)

Deep Inelastic scattering (DIS)

J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

14

Fermi Gas

Spectral Function

Fermi momentum

B. Carlson / SBND SPINE

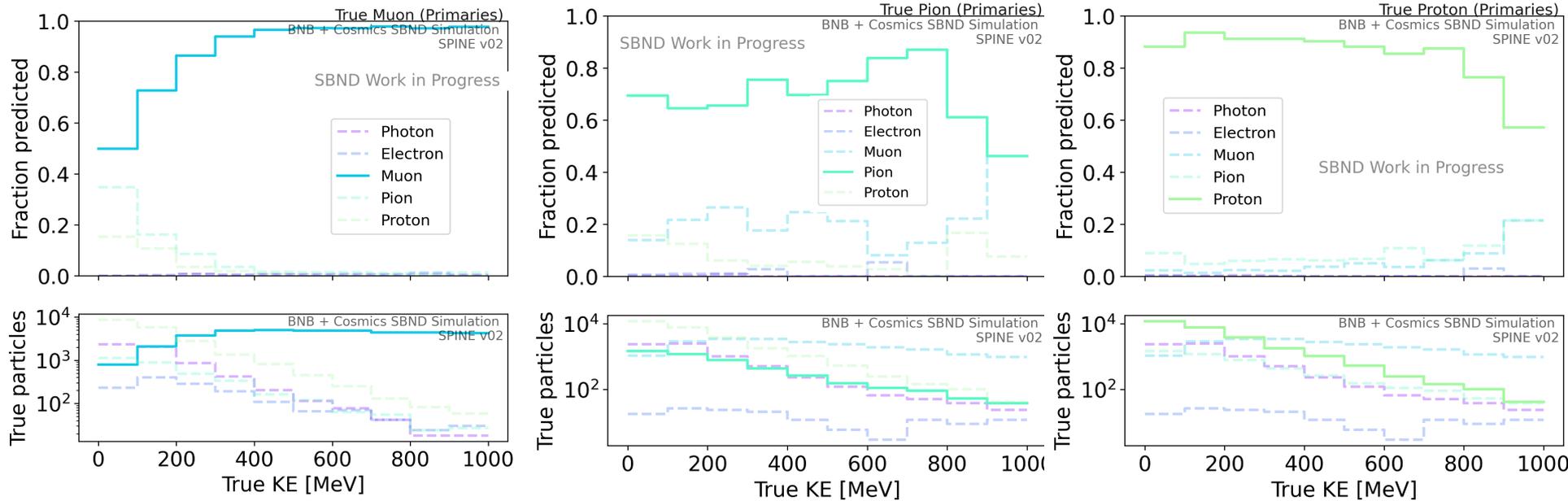UF FLORIDA

PID Confusion vs KE

Nue v02

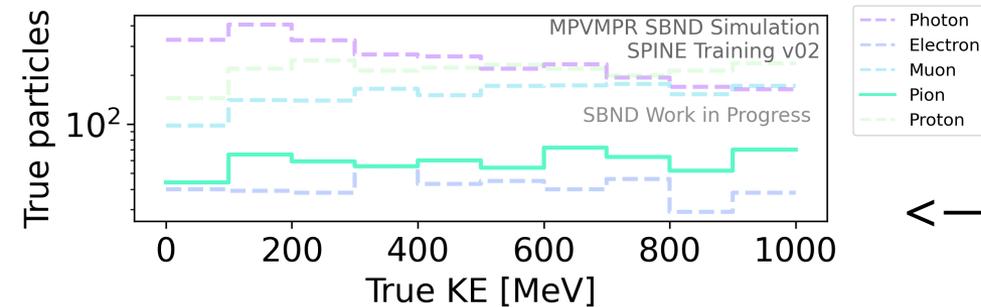# PID Confusion vs KE

- Low energy particles commonly identified as protons

BNB Cosmics Rockbox v02

<— Particle abundance
MPVMPR Test v02

B. Carlson / SBND SPINE

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PID Confusion vs Overlap

- This is where electron -> mu confusion comes from - misclustered track fragments. Probably classified as track in semantic seg stage
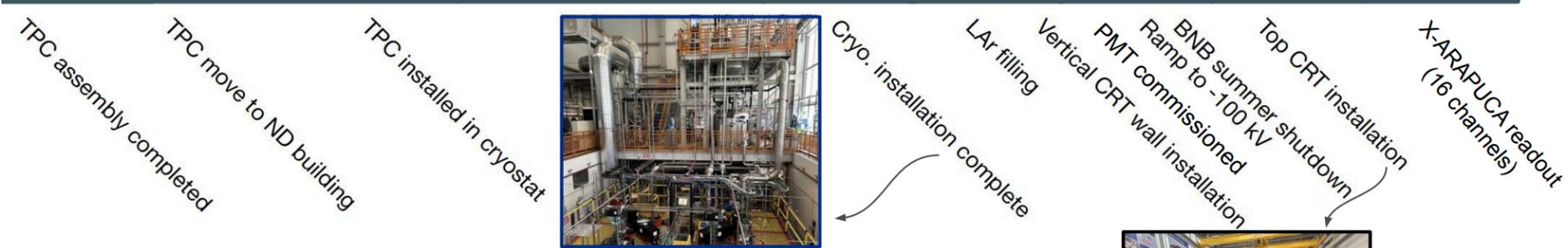- Showers are usually clustered only up to 85% level
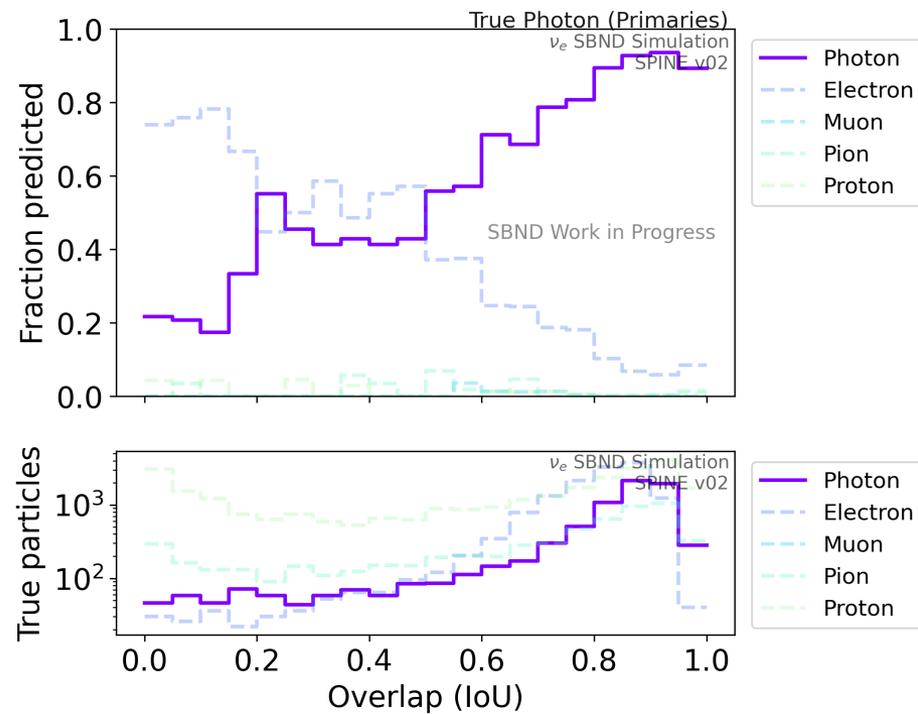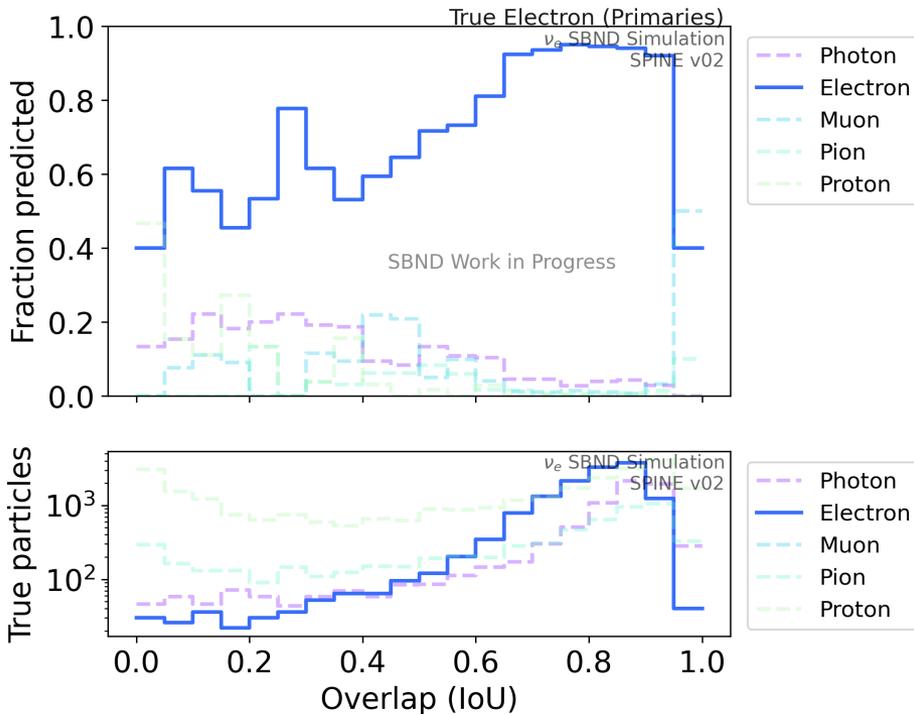
Nue v02

Short Baseline Near Detector (SBND)

- First neutrinos recorded on July 3, 2024 - [press release]

July 3rd, 2024

September 2022 -	December 2022 -	March 2023 -	June 2023 -	September 2023 -	December 2023 -	March 2024 -	June 2024 -	September 2023 -	December 2024 -

TPC assembly completed

TPC move to ND building

TPC installed in cryostat

Cryo. installation complete

LAr filling

Vertical CRT wall installation

PMT commissioned

Ramp to -100 kV

BNB summer shutdown

Top CRT installation

X-ARAPUCA readout (16 channels)

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Flash Matching

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