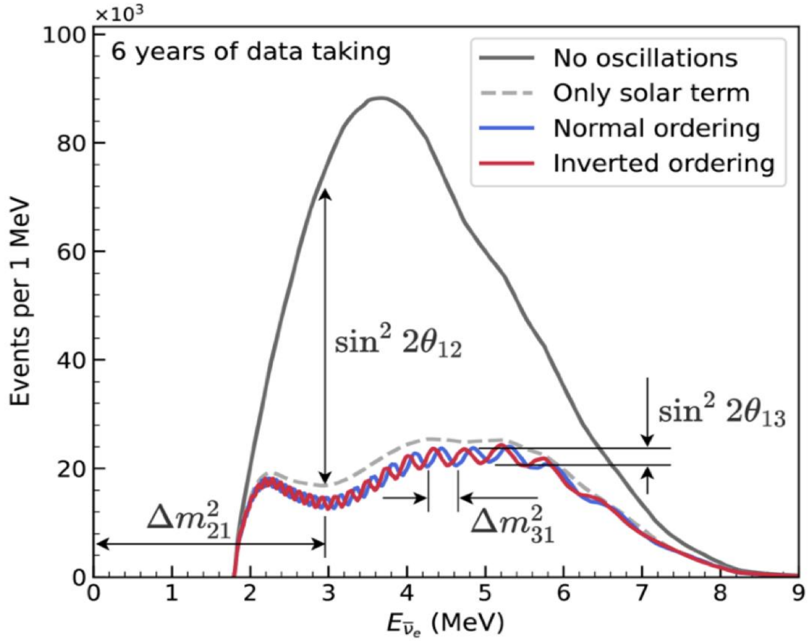
Overview of Machine Learning Applications in JUNO

Teng LI on behalf of JUNO
Shandong University
2024.6.25
NPML2024, ETH Zurich

The JUNO Experiment

- **J**iangmen **U**nderground **N**eutrino **O**bservatory
- Main physics goals
  - Determination of the mass ordering at the 3σ level in 6 years of data taking
  - Precise measurement of oscillation parameters, θ_{12}, Δm^2_{21} and Δm^2_{31}
- JUNO also serves as an observatory detecting neutrinos from Supernova, Sun, Atmosphere and Earth etc.

Experiment	Target Mass	E Resolution
KamLAND	1000t	6%@1MeV
D. Chooz	8+22t	
RENO	16t	8%@1MeV
Daya Bay	20t	
Borexino	300t	5%@1MeV
JUNO	**20000t**	**3%@1MeV**



Reactor neutrino energy spectrum expected to be observed

JUNO Site

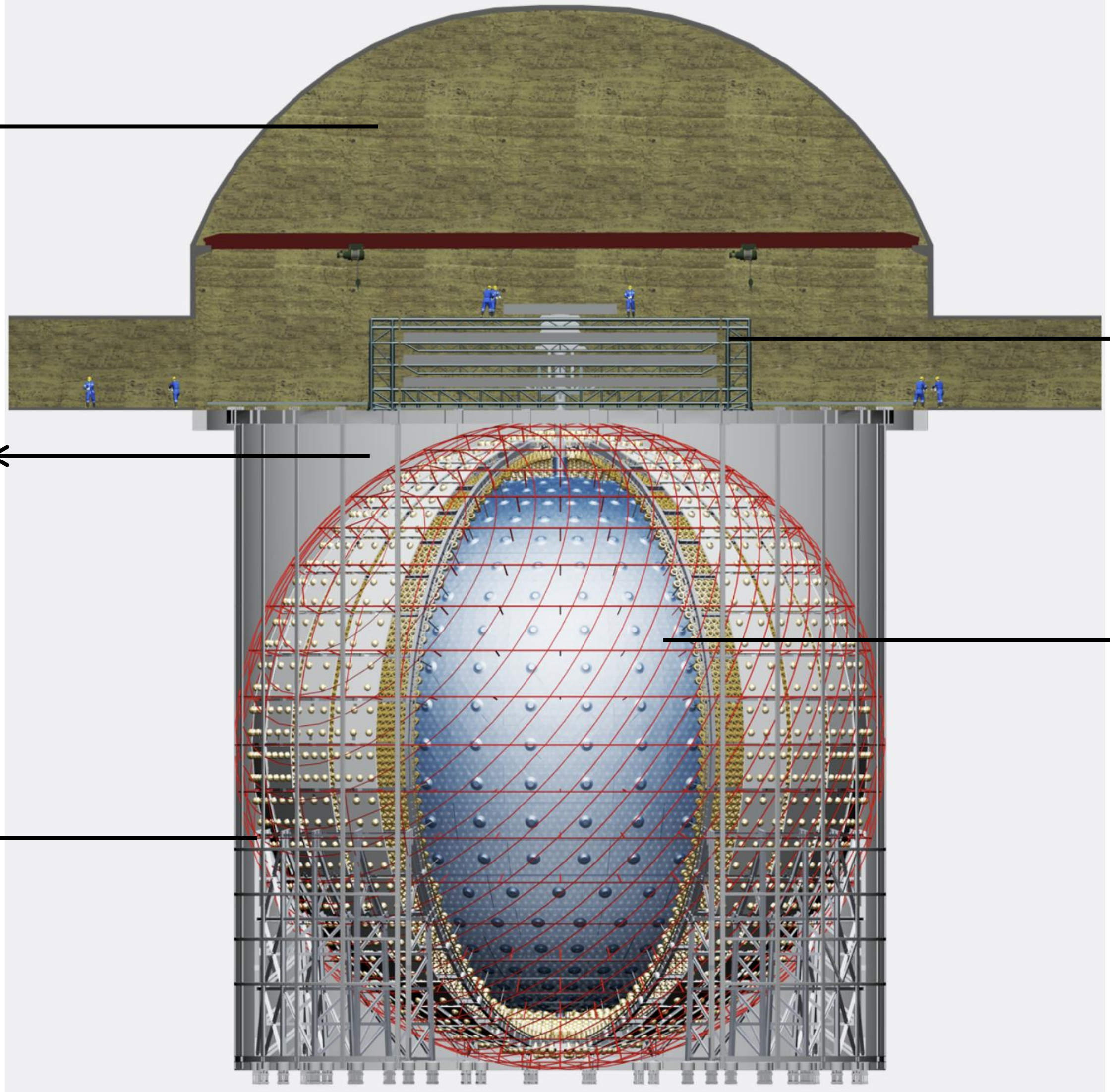
Surface buildings / campus
• Office / Dorm
• Surface Assembly Building
• LAB storage (5 kton)
• Water purification / Nitrogen
• Computing
• Power station
• Cable train
564 m
Vertical Tunnel
~ 650 m
1266 m Slope tunnel
Experiment
Hall

The JUNO Detector

~650m overburden
(1800 m.w.e)

<u>Water Cherenkov Detector</u>
35 kton of ultrapure water as passive shield and cherenkov detector

Stainless steel truss

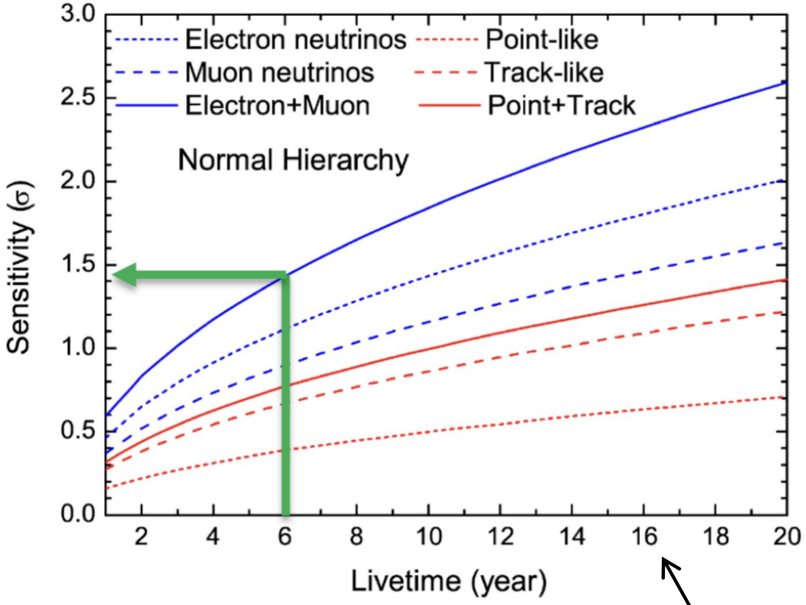


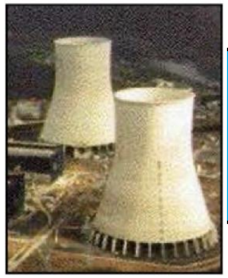
<u>Top Tracker</u>
Three layers plastic scintillator to veto muons

<u>Central Detector</u>
World-largest acrylic vessel (Φ 35.4 m, 124 ± 4 mm thickness)
20 kton LS
17,612 20” PMTs
and 25,600 3” PMTs

~78% PMT coverage
3%@1MeV energy resolution

JUNO Reconstruction Road-map (for NMO)



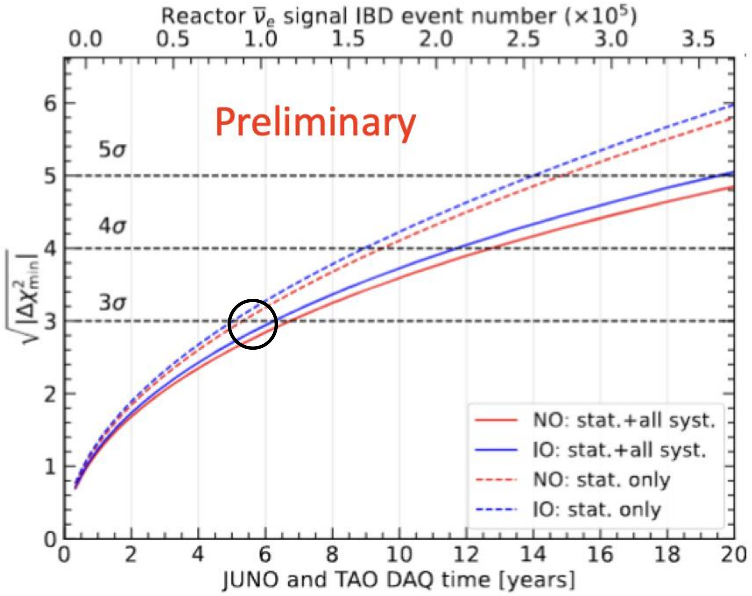


MeV

Reactor Neutrino

Vertex Rec.

Energy Rec.



Neutrino Mass Ordering

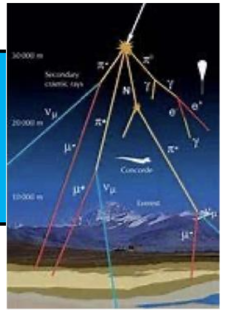
Flavor Identification

Directionality

Energy

Atmospheric Neutrino

GeV



Cosmic Muon (Veto)

GeV

Muon Classification

Track Reconstruction

Shower/Vertex Rec. (dE/dx)

Work shown in this talk is non-exhaustive

Ref. W. Luo's talk @ NuFact23

Outline

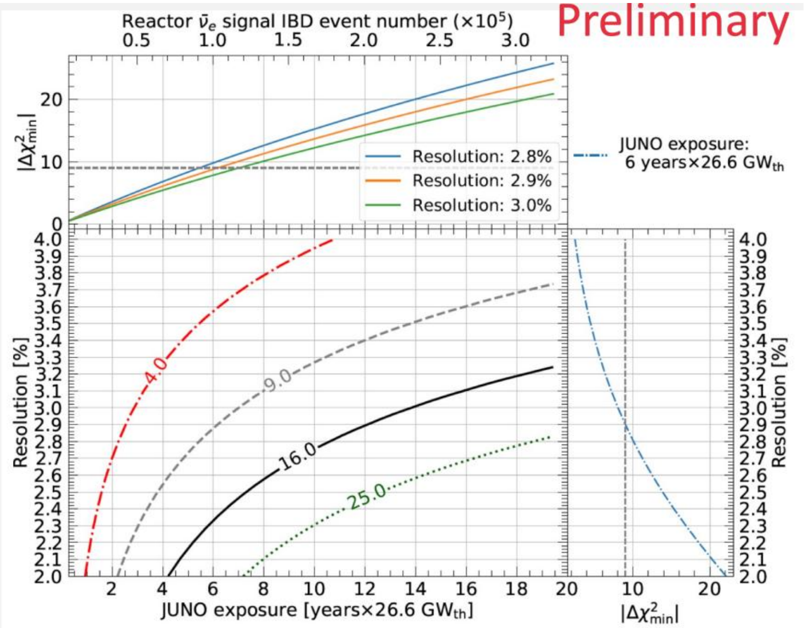
- **PMT waveform reconstruction**
  - Photon counting and calibration data based reconstruction
- **Particle reconstruction in MeV region**
  - Reactor neutrino vertex and energy recostruction
- **Particle reconstruction in GeV region**
  - Atmospheric neutrino directionality, PID and energy reconstruction
  - Muon track reconstruction

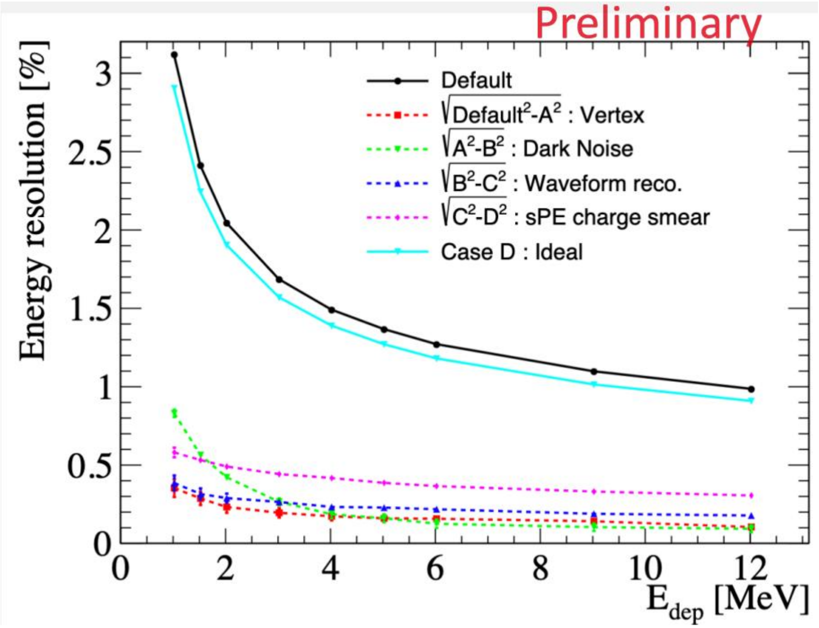
PMT waveform reconstruction

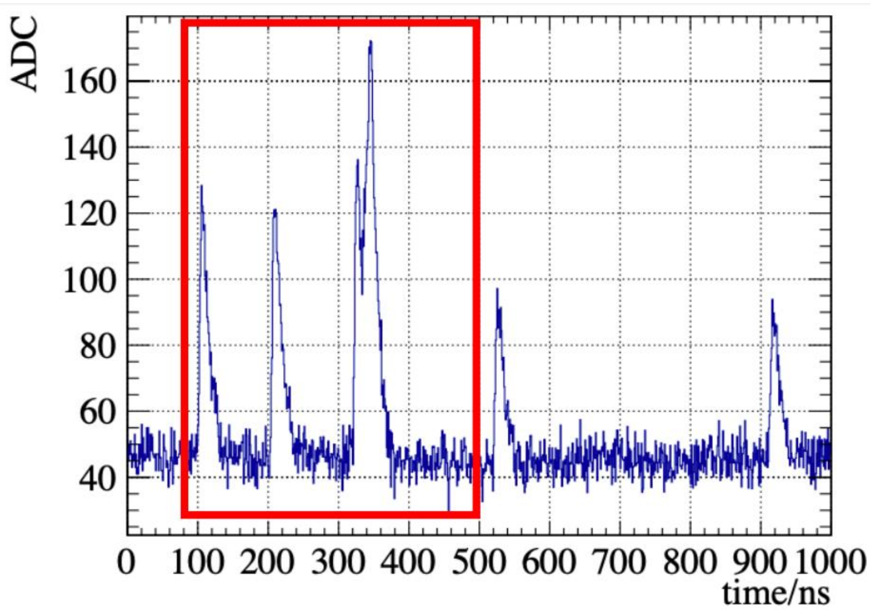
Photon counting and calibration data based reconstruction

ML Based Photon Counting

- Energy resolution is crucial for NMO sensitivity in JUNO, where PMT charge smearing is one of the dominant factors







- Can we use ML to predict the number of received photons of each PMT?
  - Perform 1-D convolution on the raw waveform
  - Use a classification model to “count the photons”

Details in Guihong’s talk

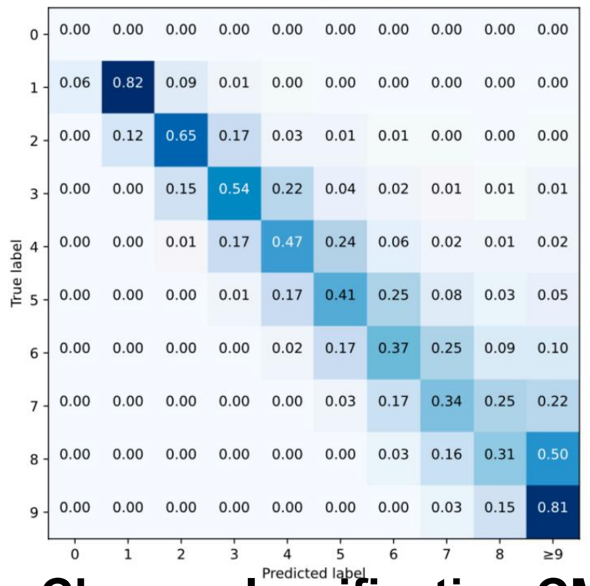
ML Based Photon Counting

Model: Customized RawNet

Table 2: Modified RawNet architecture. For convolutional layers, numbers inside parentheses refer to filter length, stride size, and number of filters. For gated recurrent unit (GRU) and fully-connected layers, numbers inside the parentheses indicate the number of nodes.

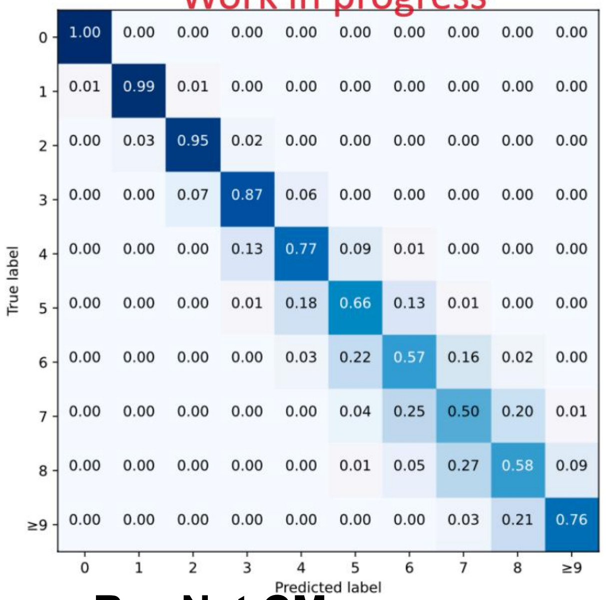
Layer	Input	Output shape
Strided -conv	Conv(3,3,128) BN LeakyReLU	(128, 140)
Res block	{ Conv(3,1,128) BN LeakyReLU Conv(3,1,128) BN LeakyReLU MaxPool(3) } ×2	(128, 46)
Res block	{ Conv(3,1,256) BN LeakyReLU Conv(3,1,256) BN LeakyReLU MaxPool(3) } ×2	(256, 1)
GRU	GRU(1024)	(1024,)
Speaker embedding	FC(128)	(128,)
Output	FC(10)	(10,)

Work in progress



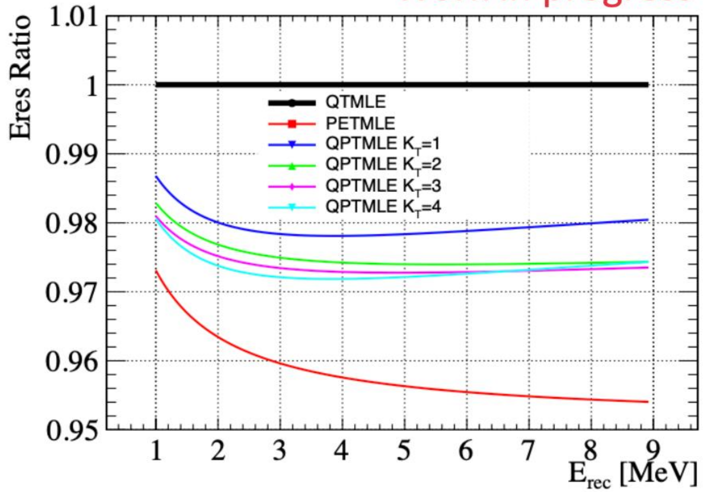
Charge classification CM

Work in progress



RawNet CM

Work in progress



2% to 2.8% relative improvement on the energy resolution can be achieved

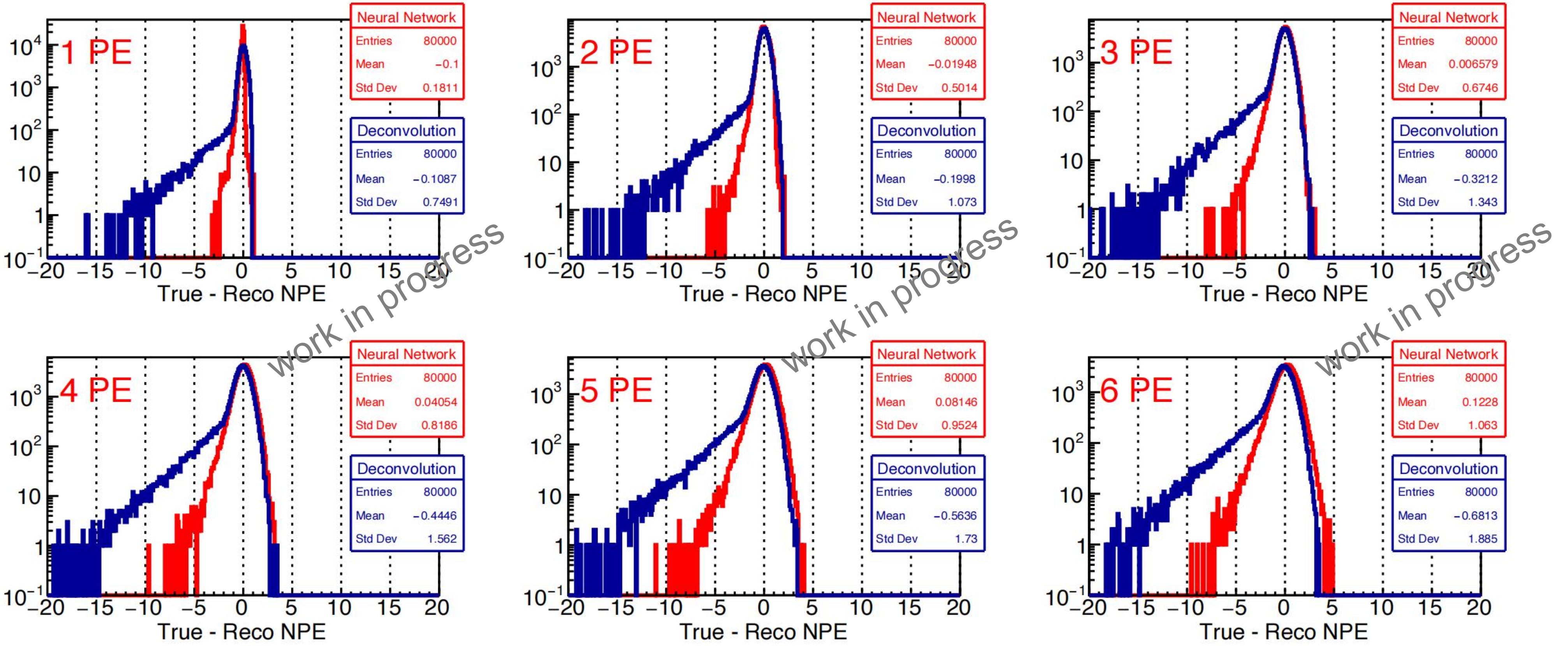
Details in Guihong's talk

Calibration-based Waveform Reconstruction

- Assemble "fake" waveform using calibration data, then train ML model (MLP) to learn from calibration data, and reconstruct number of PEs
  - Immune from the MC-data discrepancy problem
  - "Long tail" problem of the deconvolution-based waveform reconstruction algorithm is mitigated

- Input:
  "Fake" waveform
- Model:
  32*64 MLP network
- Output:
  Number of PEs

Ref. Junting's poster @Neutrino2024

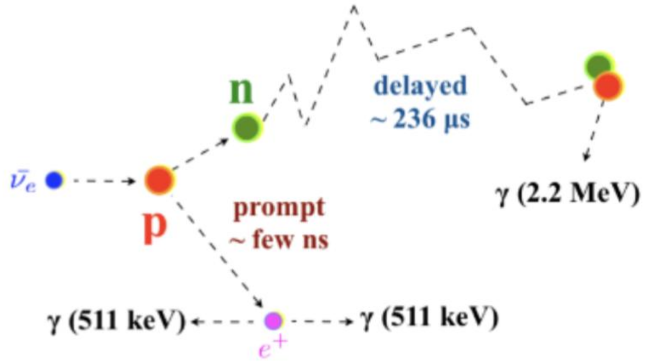


Particle reconstruction in MeV region

Reactor ν vertex and energy

Reactor Neutrino Reconstruction: Principle

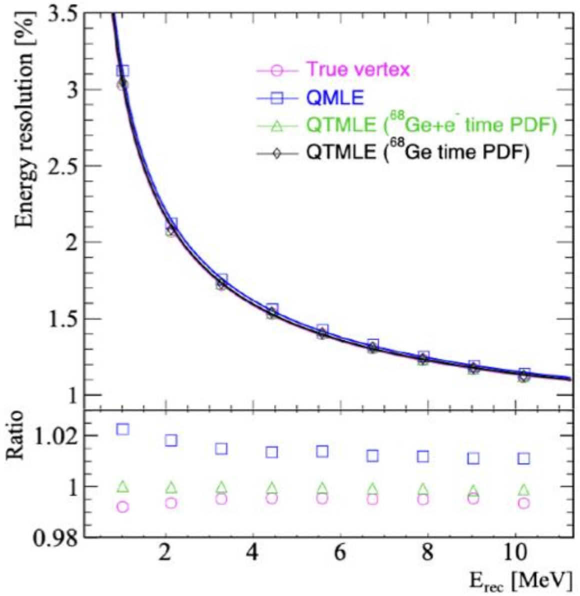
- Reactor neutrinos ($\bar{\nu}_e$) are detected via the inverse beta decay reaction in the CD
  - The e^+ generates a prompt signal in the CD
  - The neutron generates a delayed signal in the CD, with a 2.2 MeV gamma from the neutron capture process
  - Seek the coincidence between the detection of a positron and a neutron signal, with ~200 μs
- Classical methods are based on likelihood algorithms, taking
  - Charge, first hit time, position of each fired PMT

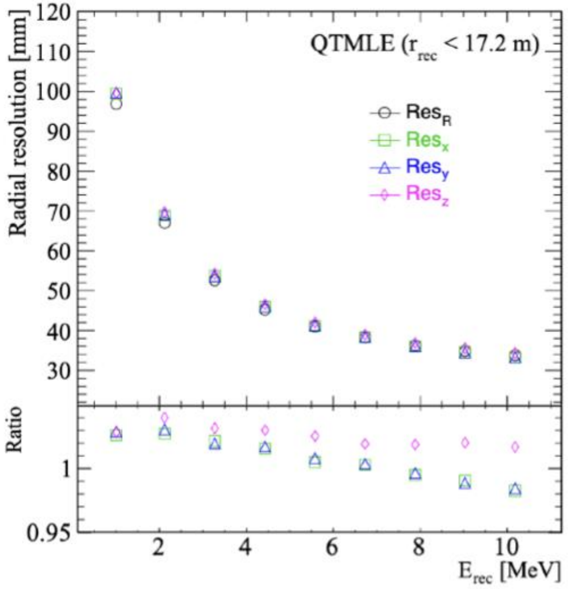


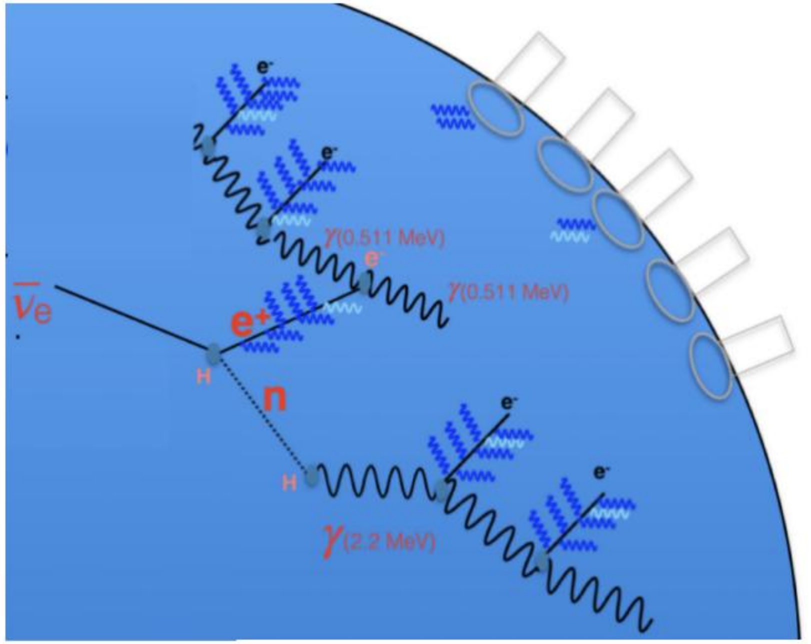
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Energy and radial resolution of QTMLE

Can this be further improved using ML?

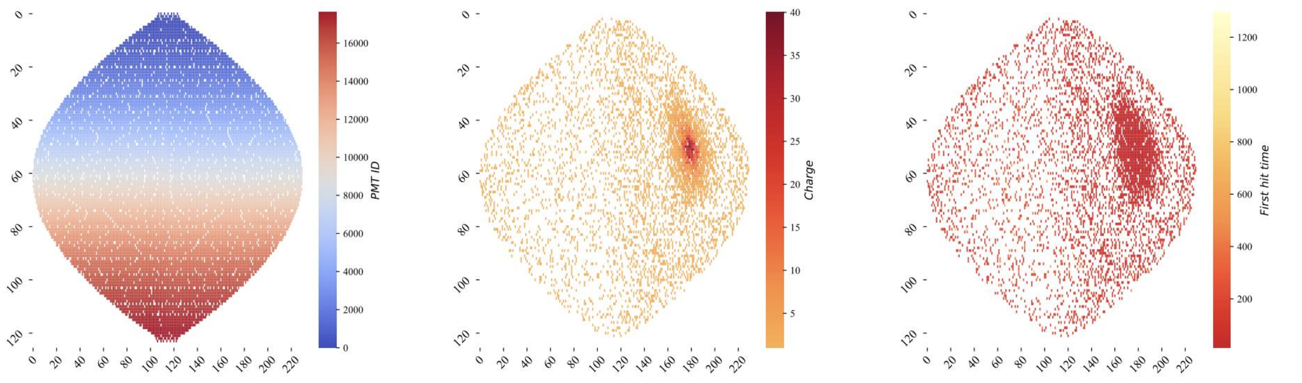






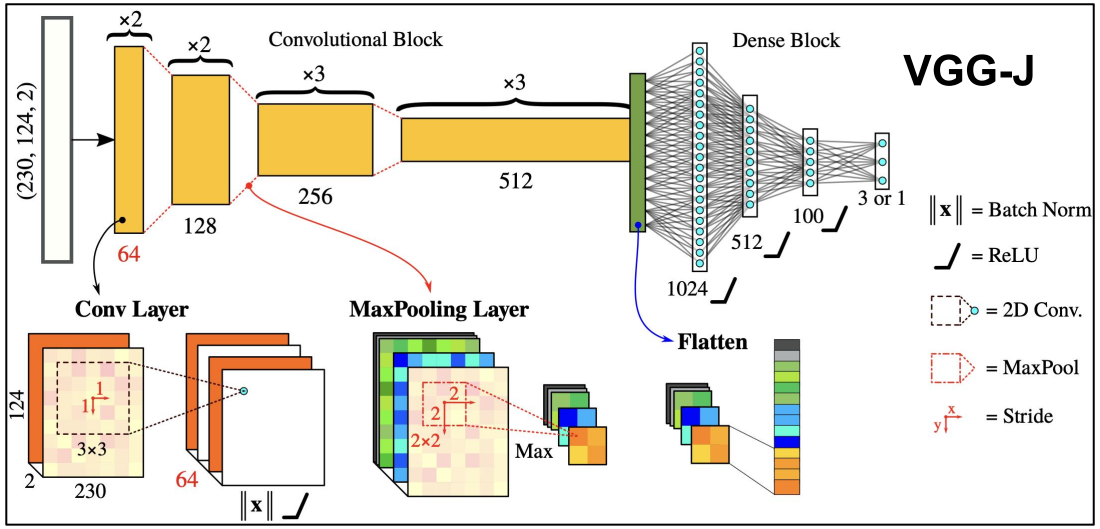
IBD Reconstruction: Planar CNN

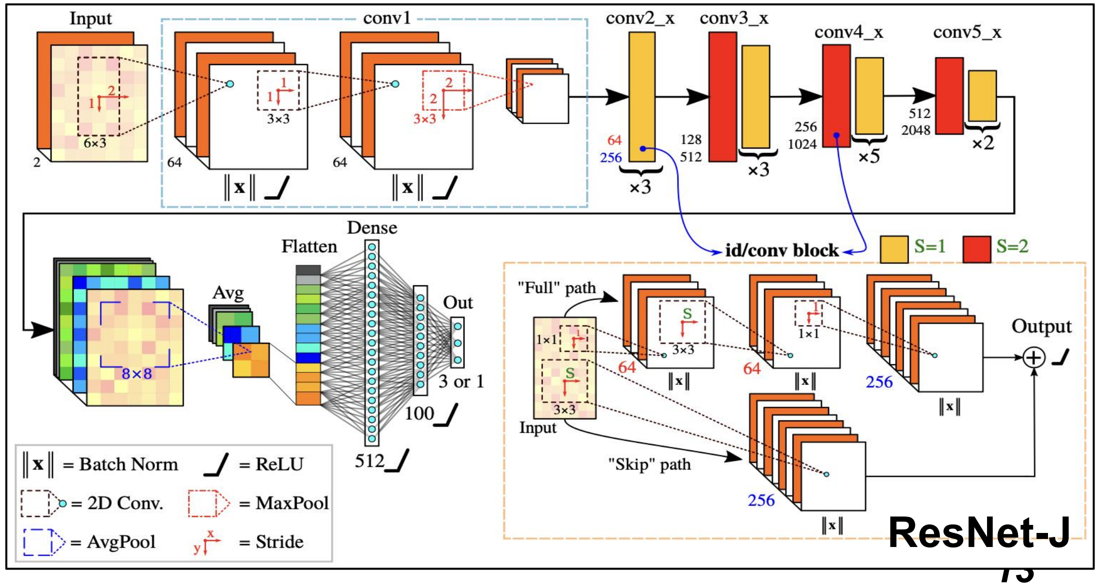
- Treating the JUNO detector as a camera and using the image recognition technique
  - The PMT data is projected onto the planar surface, and fed into CNN models
  - VGG and ResNet models are customized for JUNO



(a) Map of PMTs. (b) Charge channel. (c) First hit time channel.

- Distortion, i.e. breaking of the SO(3) symmetry is a potential problem
- Can we do better?





IBD Reconstruction: Spherical GNN

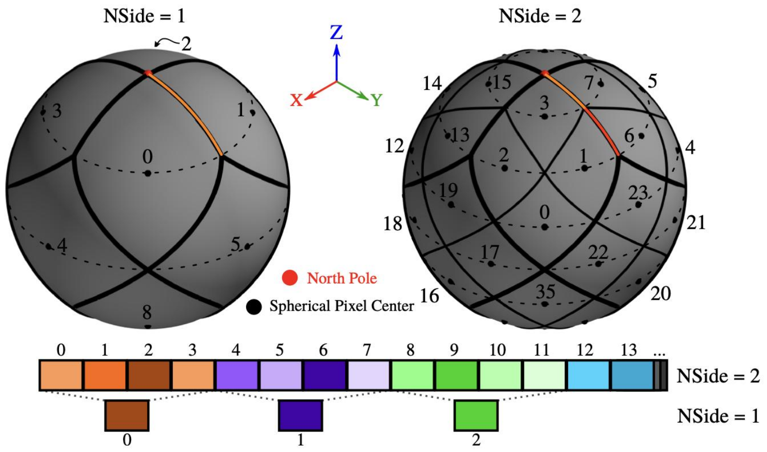
- The Spherical GNN method takes the SO(3) symmetry of JUNO detector into account
  - Convolution is performed on the graph using spectral graph method
  - Convergence becomes easier compared to planar CNN

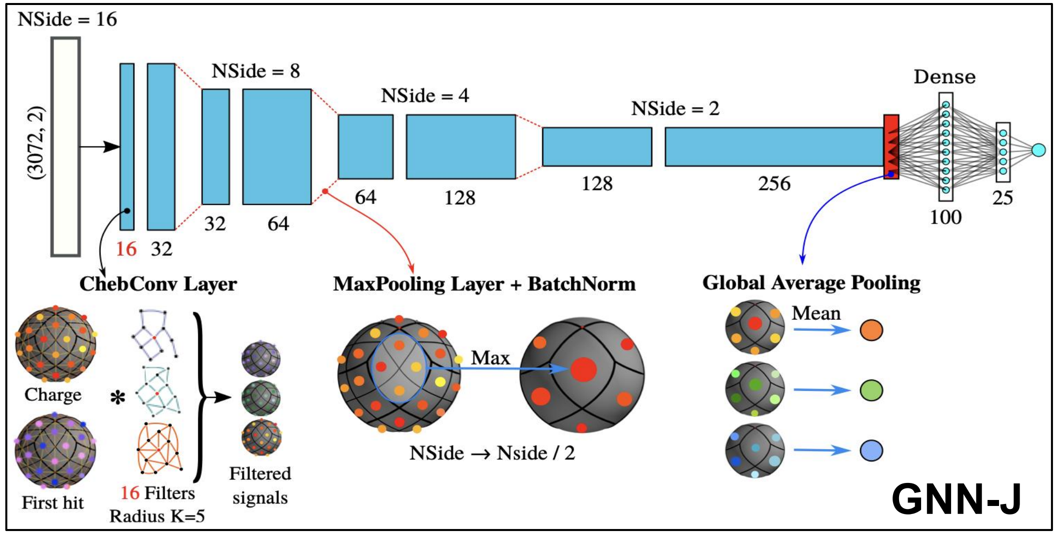
HEALPix Sampling Scheme to pixelise the detector

Then build Graph with adjacency matrix

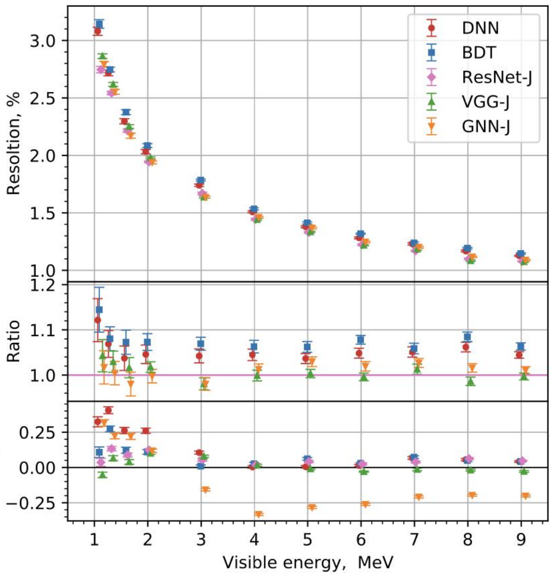
$$W_{ij} = \exp\left(-\frac{\|\boldsymbol{v_i} - \boldsymbol{v_j}\|_2^2}{2\overline{d^2}}\right)$$

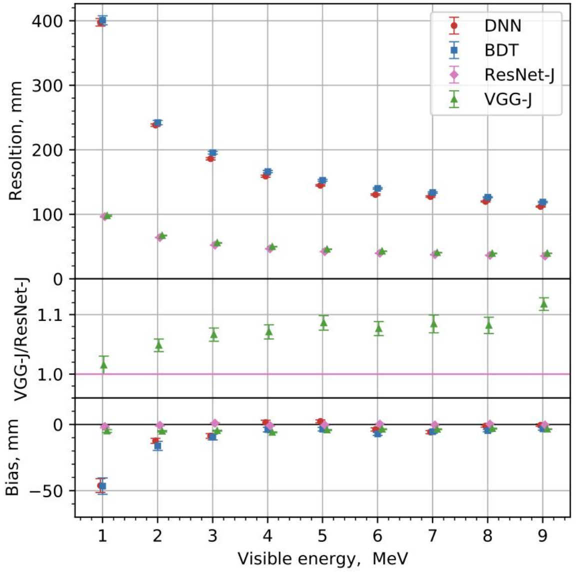
$$\overline{d^2} = \frac{1}{|\mathcal{E}|}\sum_{(\boldsymbol{v_i},\boldsymbol{v_j})\in\mathcal{E}} \|\boldsymbol{v_i} - \boldsymbol{v_j}\|_2^2$$





Nucl.Instrum.Meth.A 1010 (2021) 165527





- Both methods gives similar resolution as classical methods

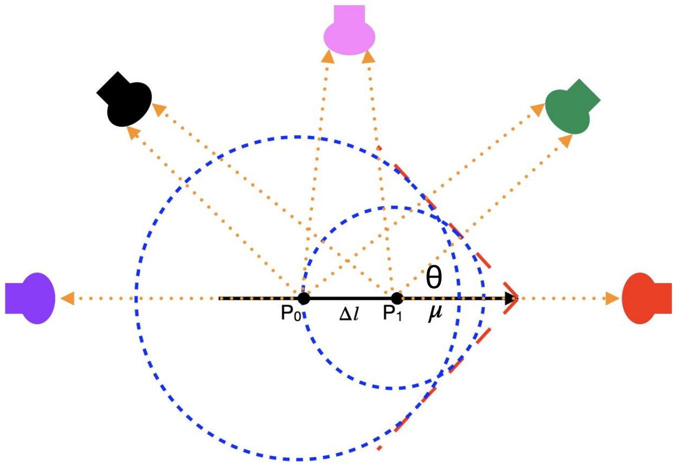
Particle reconstruction in GeV region

Atm. ν directionality, PID, energy and muon track

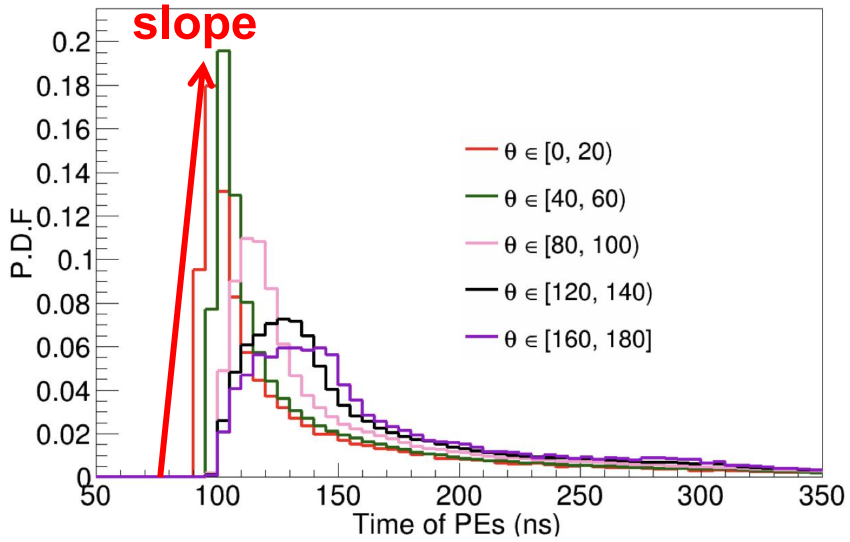
Methodology

- Light received by a PMT is the superposition of light from many points on tracks in the detector
- The number of photo-electrons (PEs) seen by a PMT as a function of time is determined by the event topology
- Features related to event topology can be extracted from deconvoluted PMT waveform to get:
  - Track direction
  - Track starting and stopping points
  - Track dE/dx

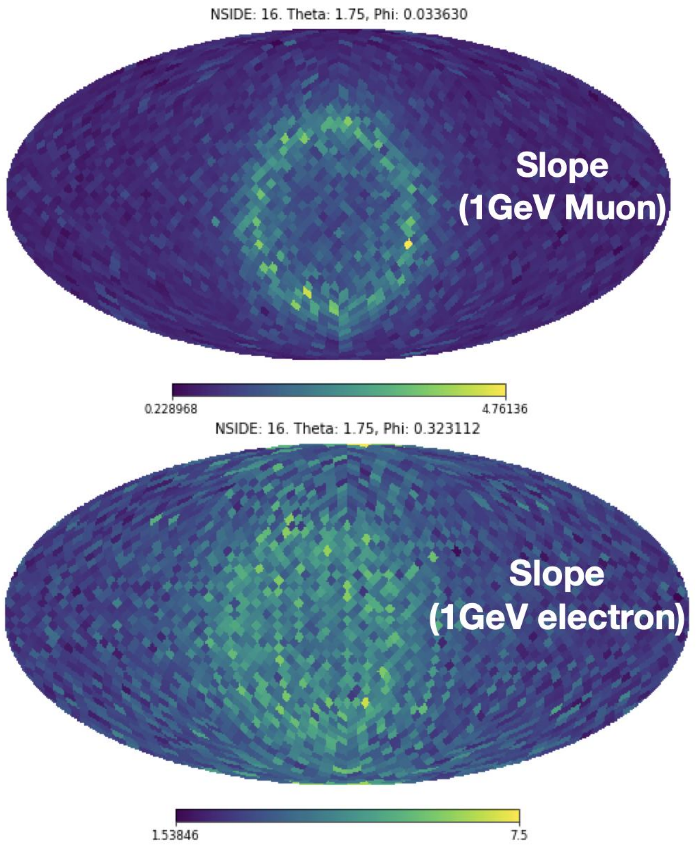
Directionality
Energy
PID



PMTs at different angles wrt the track see distinct shapes of nPE(t)

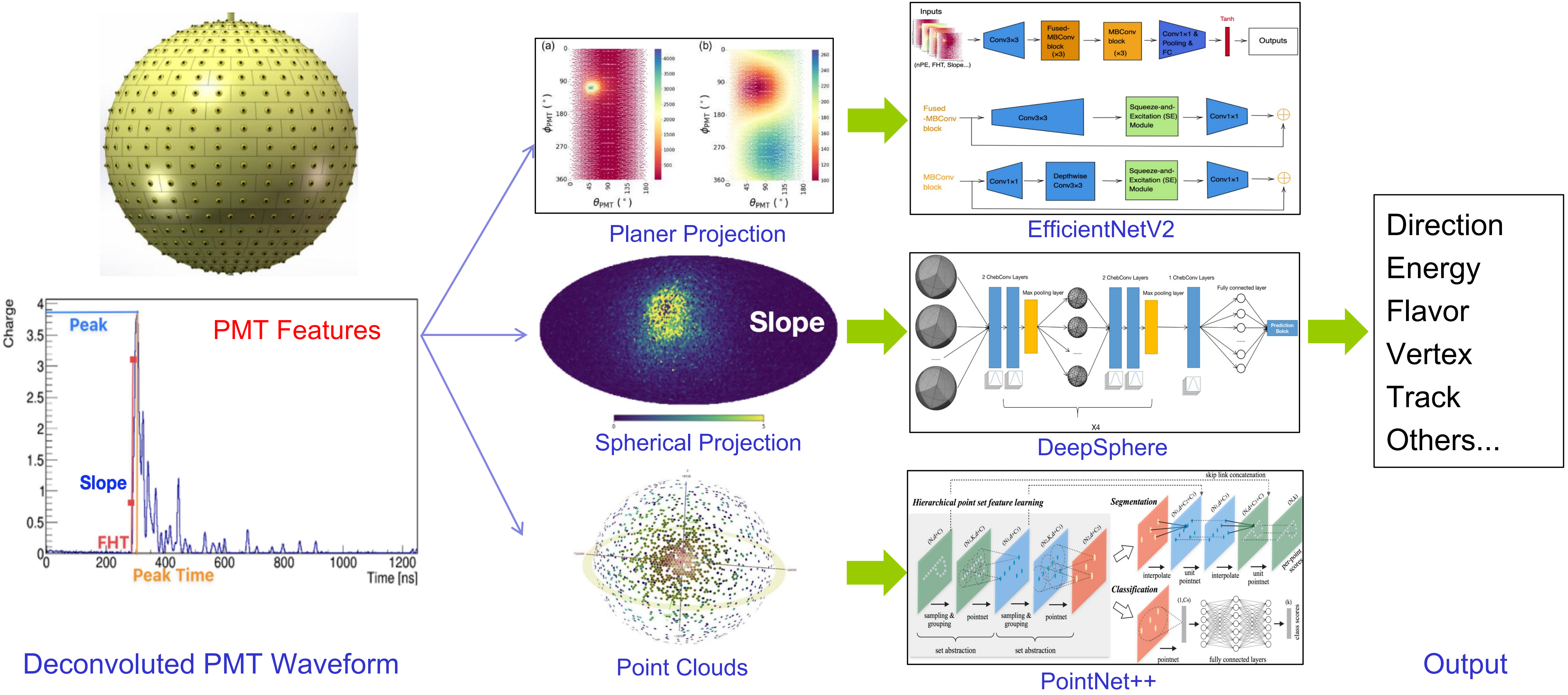


Ref. Duyang's talk @TIPP2023

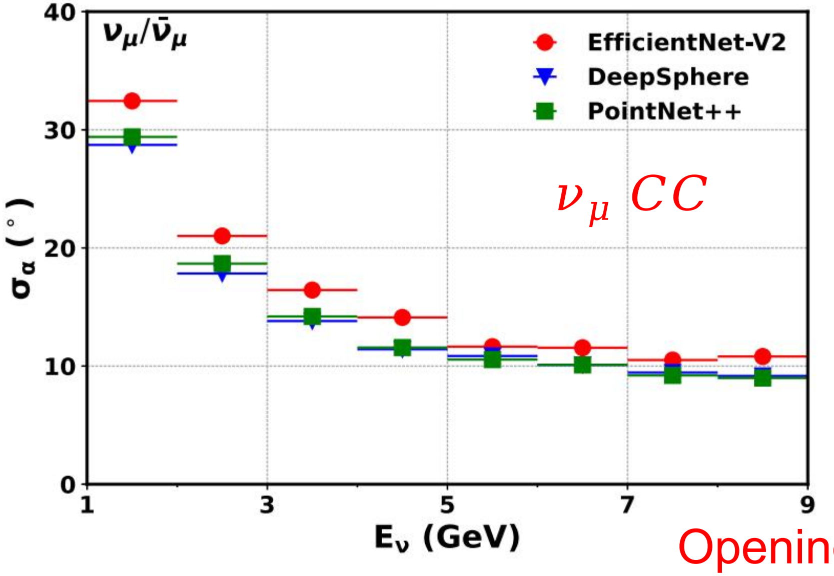


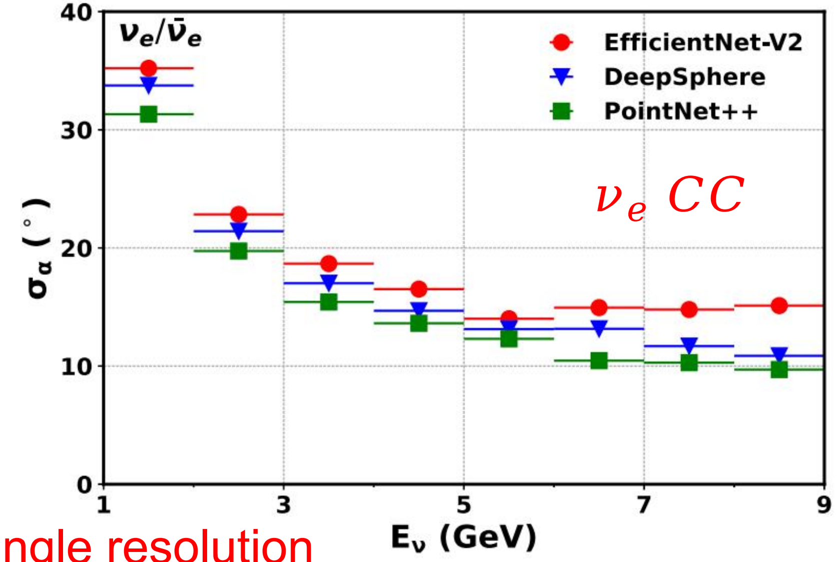
Methodology

❖ Event reconstruction with Deep-learning and Waveform INformation (EDWIN)



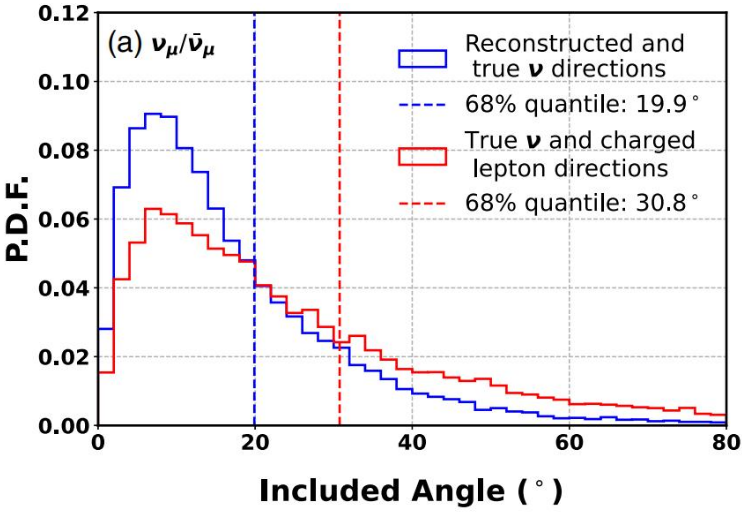
Atmospheric Neutrino Directionality Reconstruction

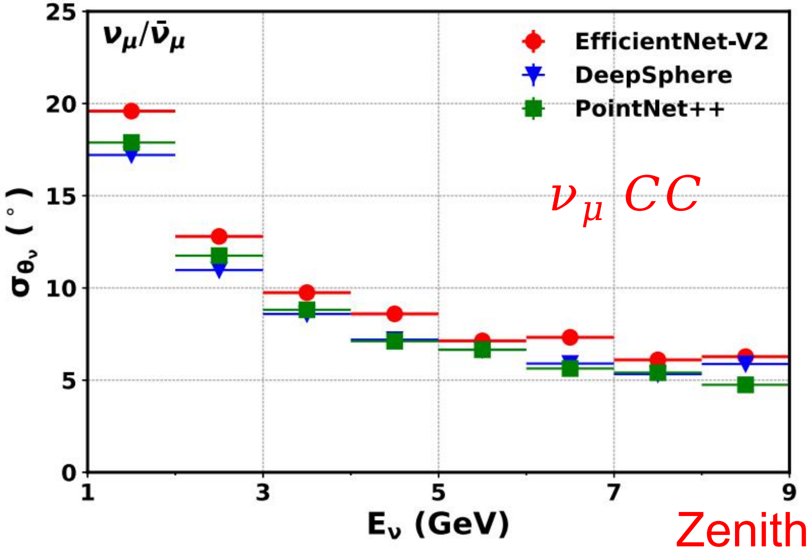


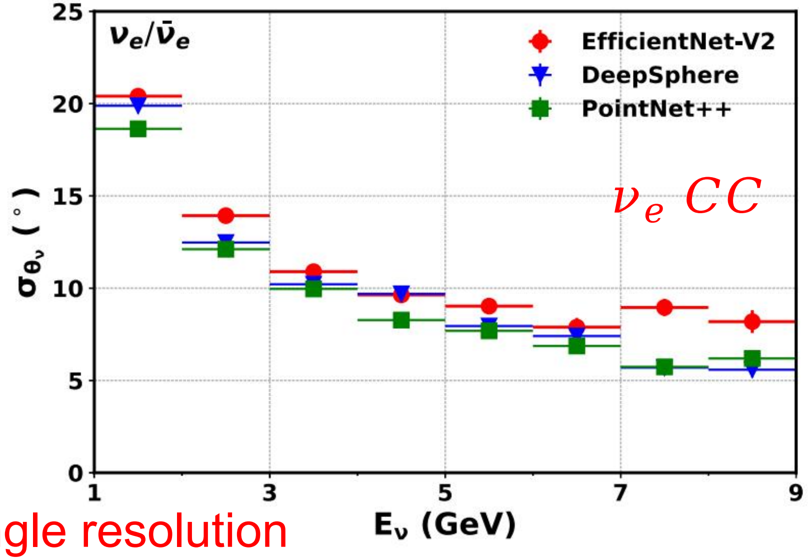


Opening angle resolution

Phys. Rev. D 109.052005







Zenith angle resolution

- Neutrino direction is directly reconstructed rather than the final-state charged lepton direction, with good angular resolution.
- World's first attempt to reconstruct atmospheric neutrinos' directionality in a large homogeneous LS detector.

Atmospheric Neutrino Flavor Identification

Strategy 1:

- Hybrid model: PointNet++ and DGCNN
- PMT features from primary trigger fed into PointNet++
- Scalar neutron capture features fed into DGCNN

Strategy 2:

- Spherical image-based model: DeepSphere
- Multiple neutron-candidate triggers are fed together with the primary trigger
- All features are at the PMT-level

Details in Jiaxi's and Wing's talks

3-label classification:

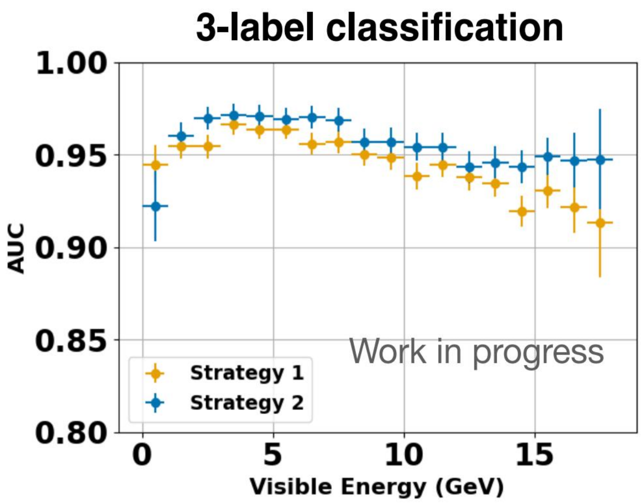
- Discriminate $\nu_e\ CC$, $\nu_\mu\ CC$ and NC

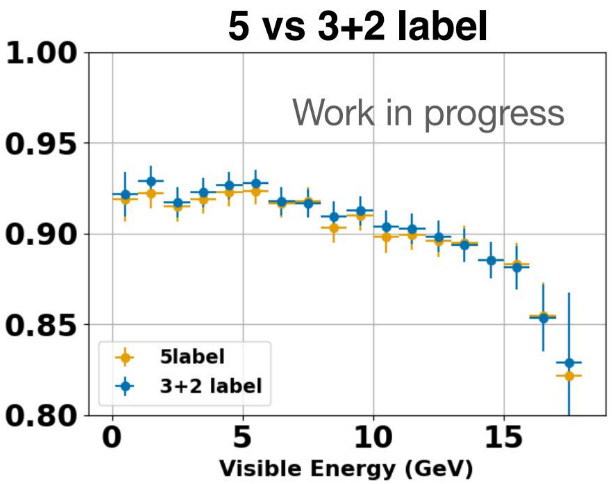
2-label classification:

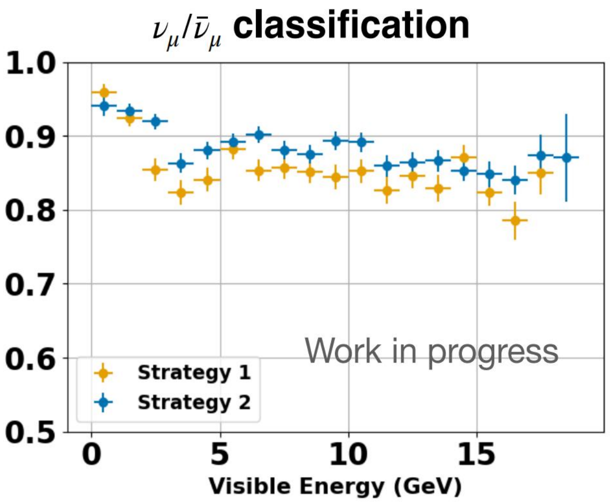
- Discriminate $\bar{\nu}/\nu$

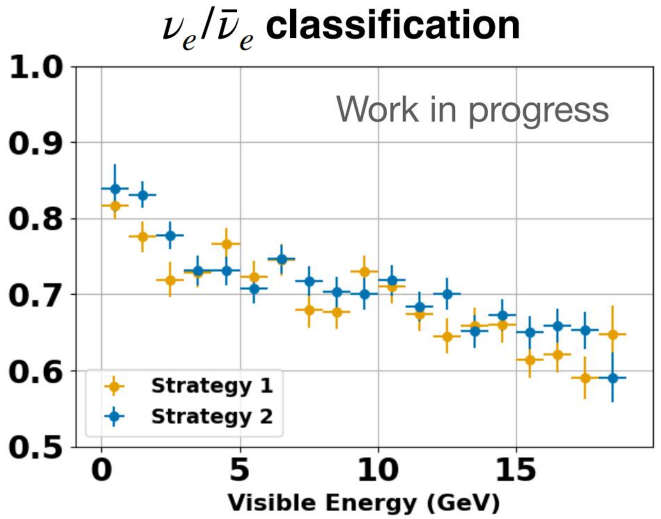
3+2 label classification:

- Combine the 3-label and 2-label models to achieve 5-label classification (roughly consistent)

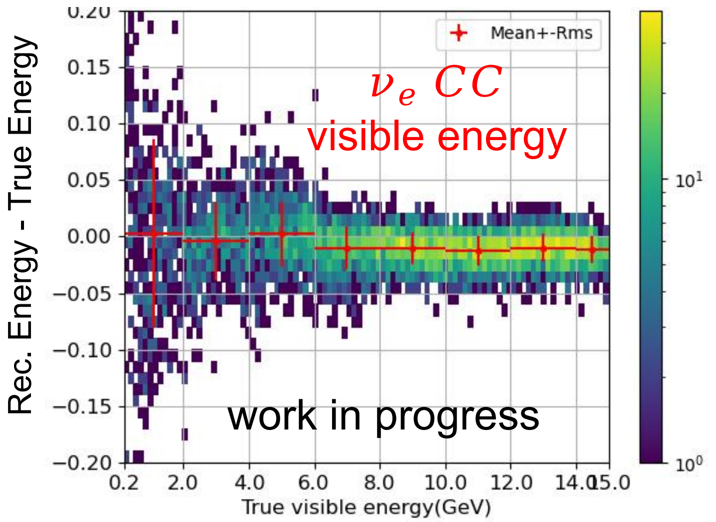


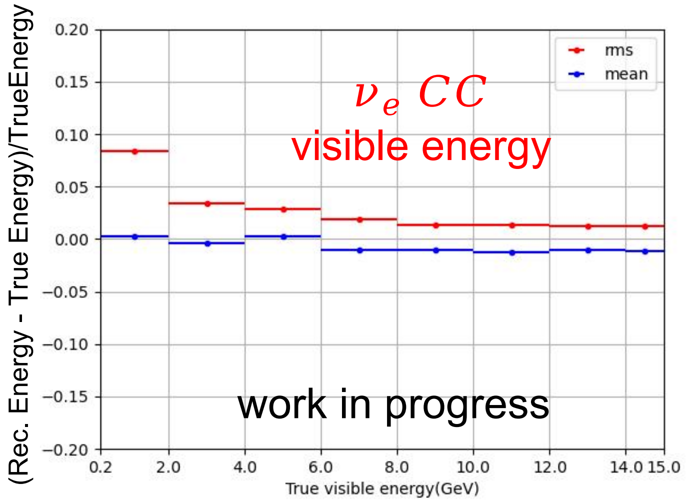




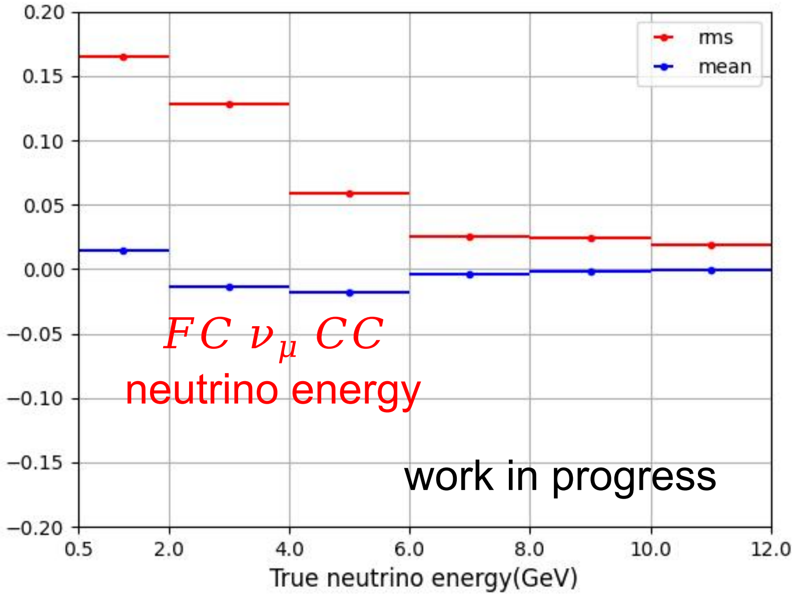


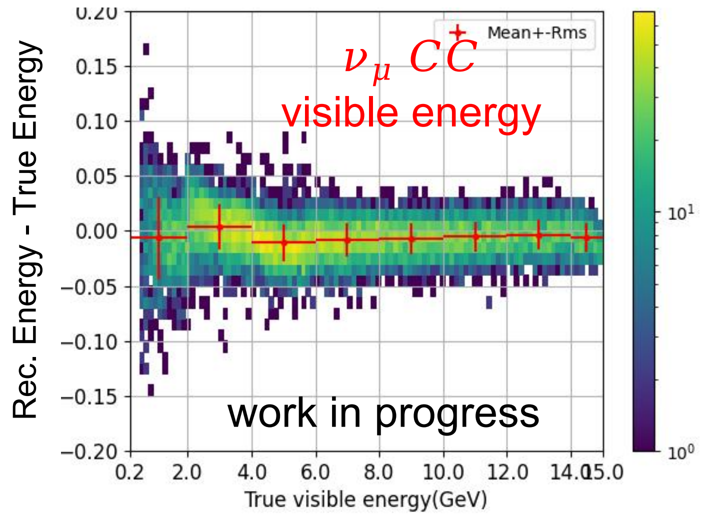
Atmospheric Neutrino Energy Reconstruction

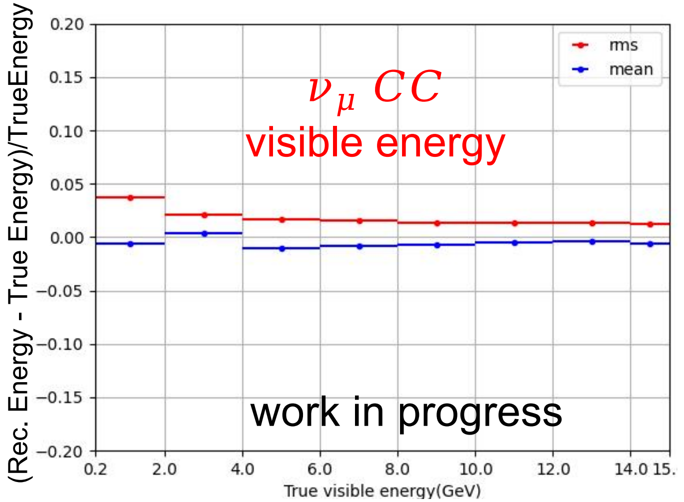




1% - 8% visible energy resolution for ν_e CC from 0.2-15GeV





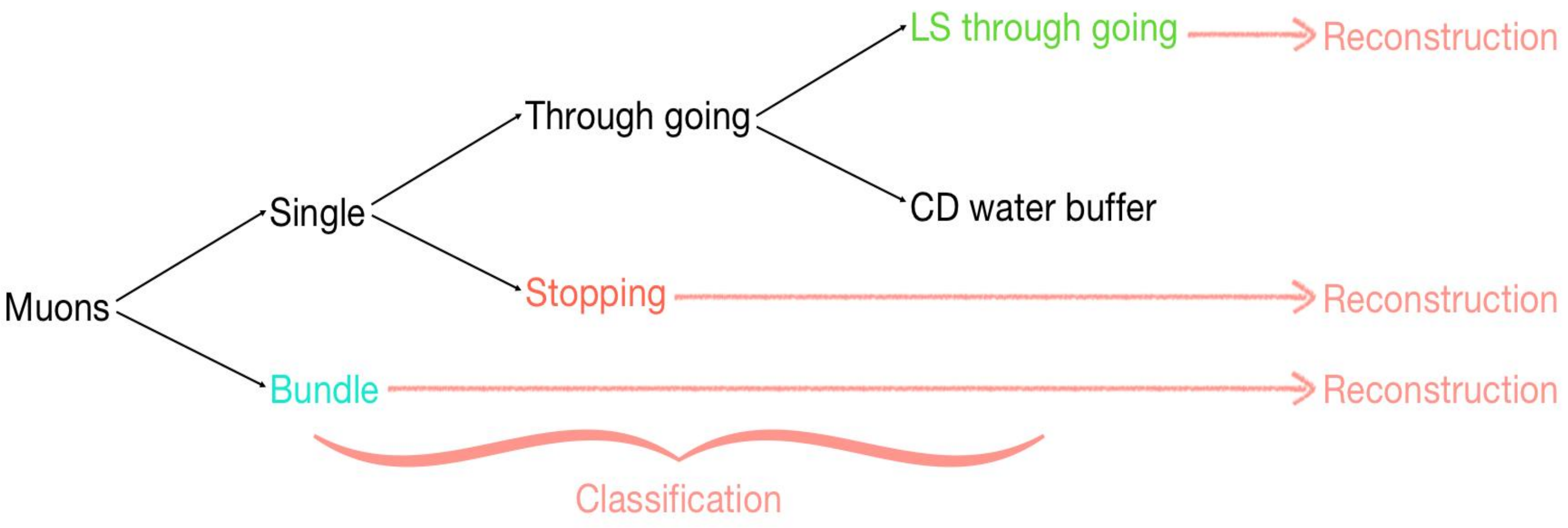


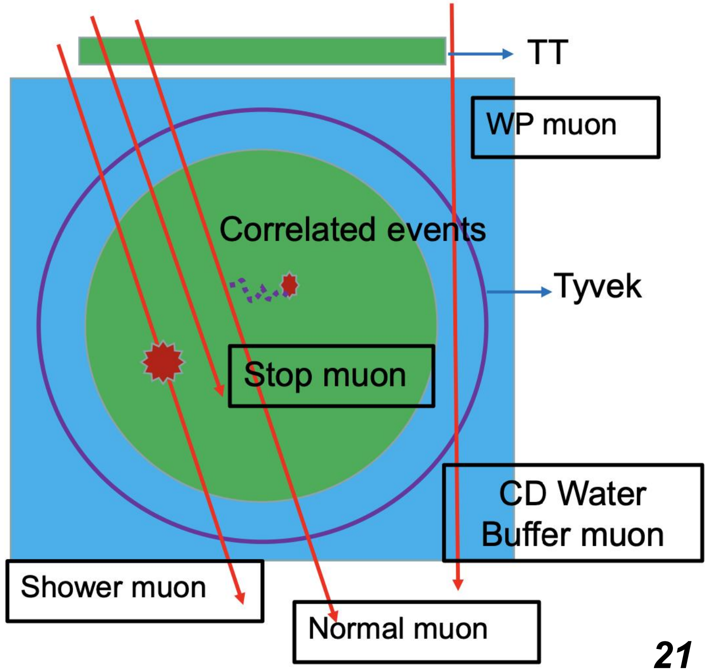
1% - 5% visible energy resolution for ν_μ CC from 0.2-15GeV

- Results based on the Spherical GNN
- Visible energy resolution is promising
- Neutrino energy resolution for fully contained neutrinos is sub-optimal, but still provides better sensitivity with preliminary NMO analysis

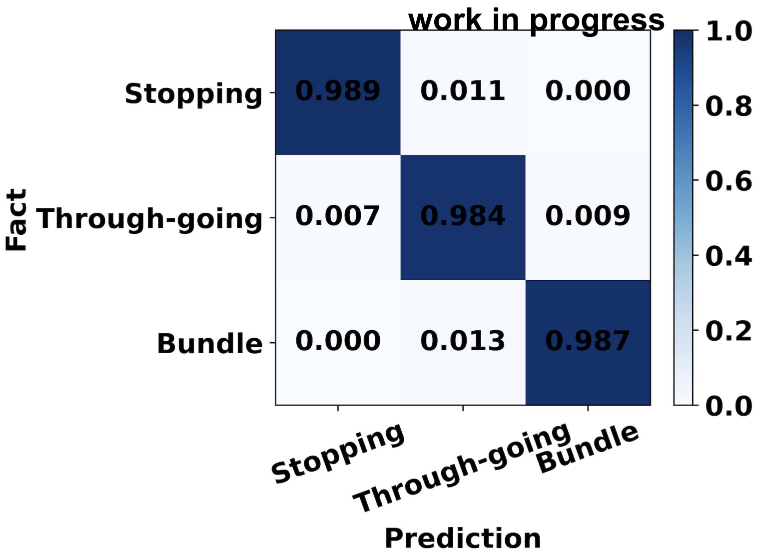
Muon Track Reconstruction: Methodology

- Isotopes produced by cosmic muons are the main backgroud of IBD signals
- Precise reconstruction of muon tracks is critical to veto major backgrounds
- Current ML-based reconstruction strategy for muons:
  - Classify through-going, stop and bundle muons
  - Reconstruct the entry point and exit point of LS through going, stop and bundle muons

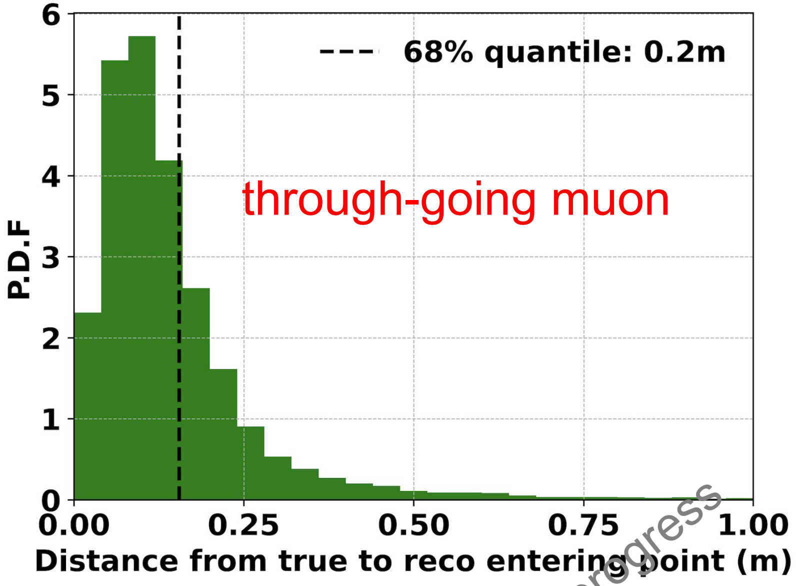


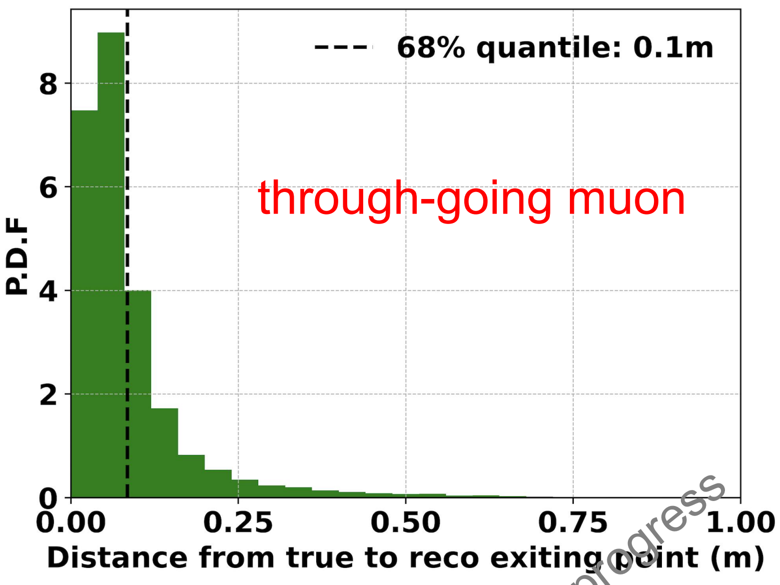


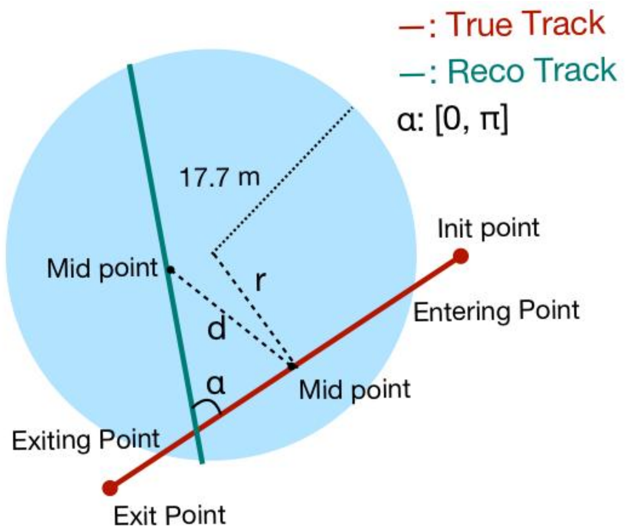
Muon Track Reconstruction: Performance

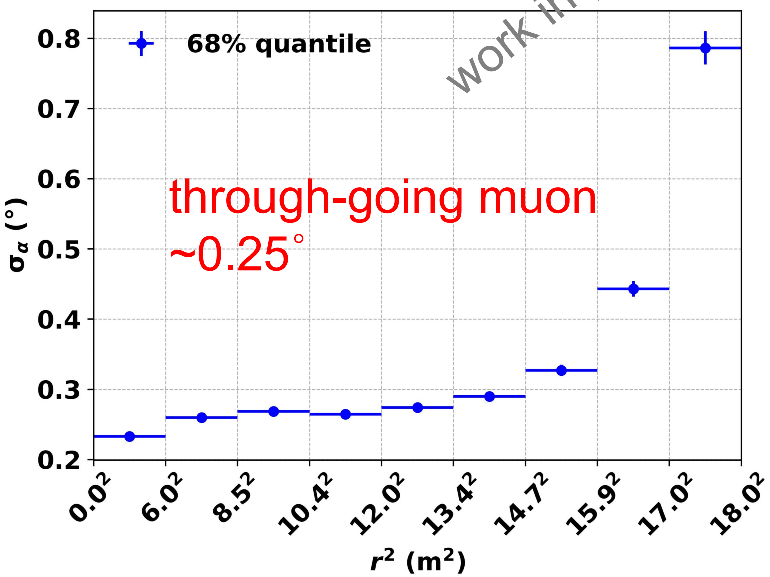


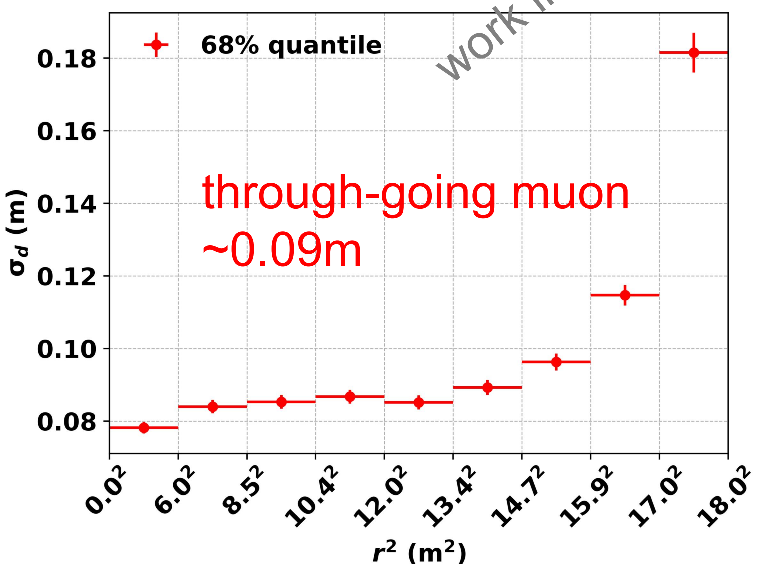
Muon Classification CM
Classification is precise











Summary

- Numerous ML models are (being) developed in JUNO (this talk shows only a sub-set)
- Even more exciting work is ongoing
- In general, comparable or superior performance can be achieved using ML, enhancing the NMO sensitivity
- Challenges ahead:
  - JUNO is a big detector, bringing challenges due to large quantities of data, sophisticated geometry and readout (training speed, GPU memory, ...)
  - MC-Data discrepancy is the major challenge damaging the reliability of ML models
  - Studies making use of calibration data have started

Thanks for your attention