Event reconstruction of atmospheric neutrinos using Machine Learning–based method in JUNO

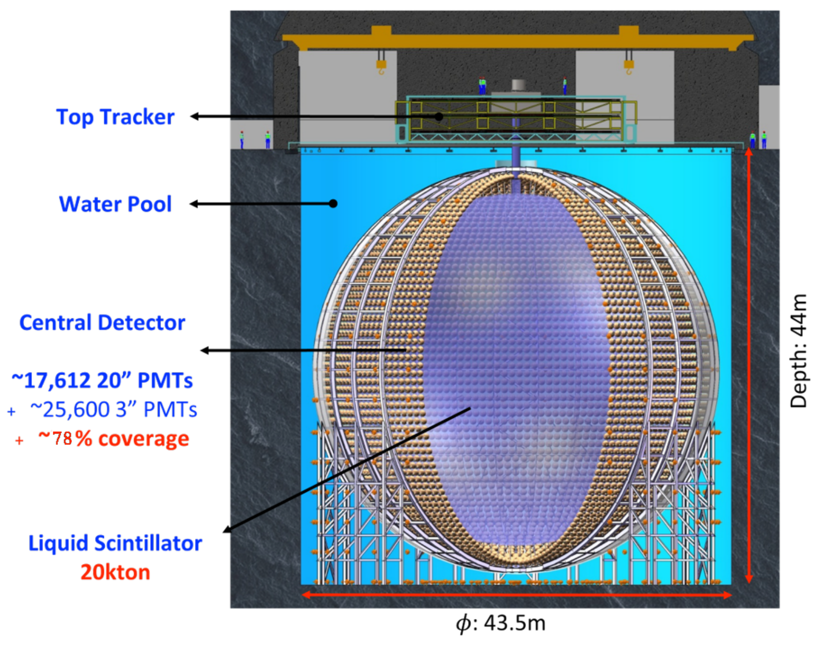
Wing Yan Ma[a], Fanrui Zeng[a], Jiaxi Liu[b], Xinhai He[b], Zhen Liu[b], Wuming Luo[b], Hongye Duyang[a], Teng Li[a], YongPeng Zhang[b]

[a] Shandong University [b] Institute of High Energy Physics, CAS

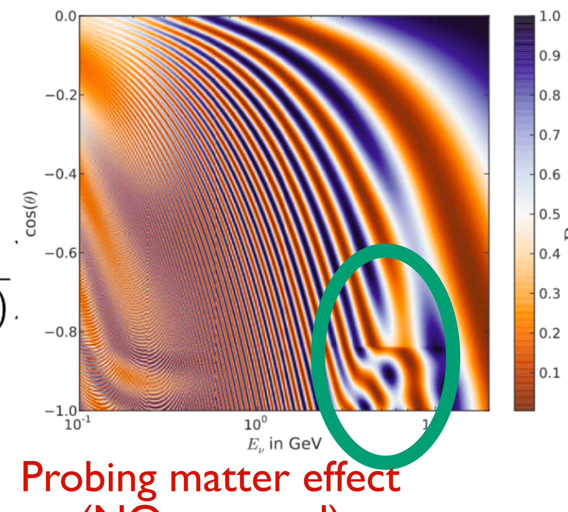
wingyanma@sdu.edu.cn

1. Overview

- The Jiangmen Underground Neutrino Observatory (**JUNO**) is designed to determine Neutrino Mass Ordering (**NMO**) with a large homogeneous liquid scintillator (LS) detector by measuring reactor electron antineutrino ($\bar{\nu}_e$) oscillations
- NMO sensitivity can be enhanced by a **combined analysis on reactor and atmospheric neutrino oscillations**
- Typical LS detectors are designed for low-energy neutrinos - ν_{atm} oscillations measurements using LS detectors has never been performed prior to this study
- Precise **energy, direction, particle identification (PID)** for atmospheric neutrinos



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^4(\theta_{13})\sin^2(2\theta_{23})\sin^2\left(1.267\Delta m^2_{32}(\text{eV}^2)\frac{L(\text{km})}{E(\text{GeV})}\right)$$

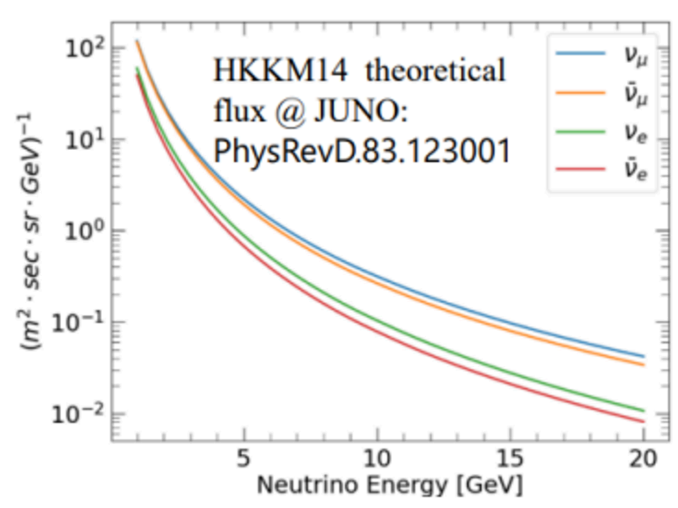


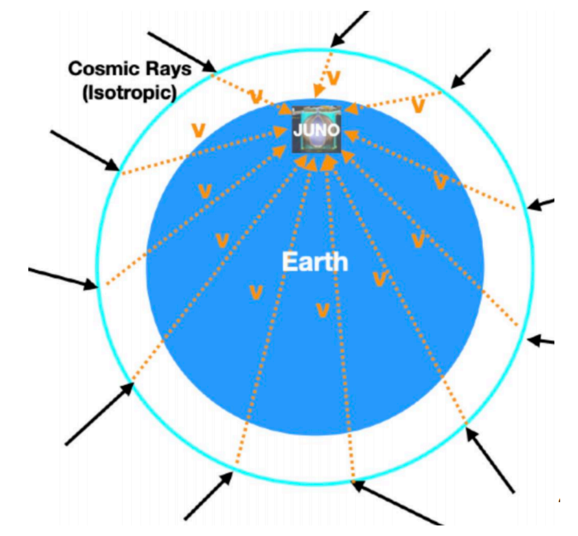
Probing matter effect (NO assumed)

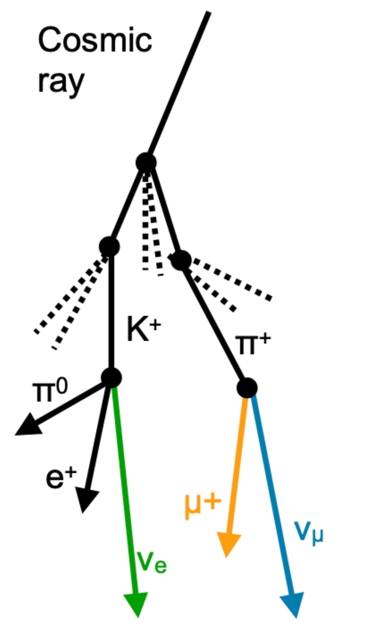
- **Demonstrate our ML approach in performing event reconstruction for atmospheric neutrinos**

2. Atmospheric Neutrinos

- Large flux of atmospheric neutrinos (ν_{atm}) produced by cosmic ray interactions
- Isotropic with different baseline (L) and energy (E)
- Rich source of muon and electron neutrinos in GeV region

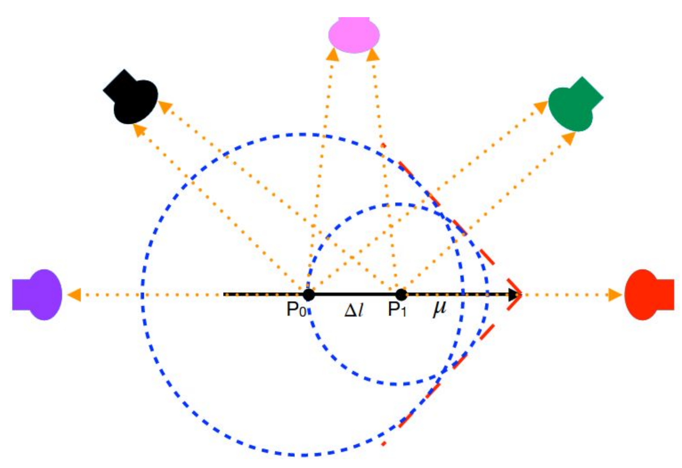


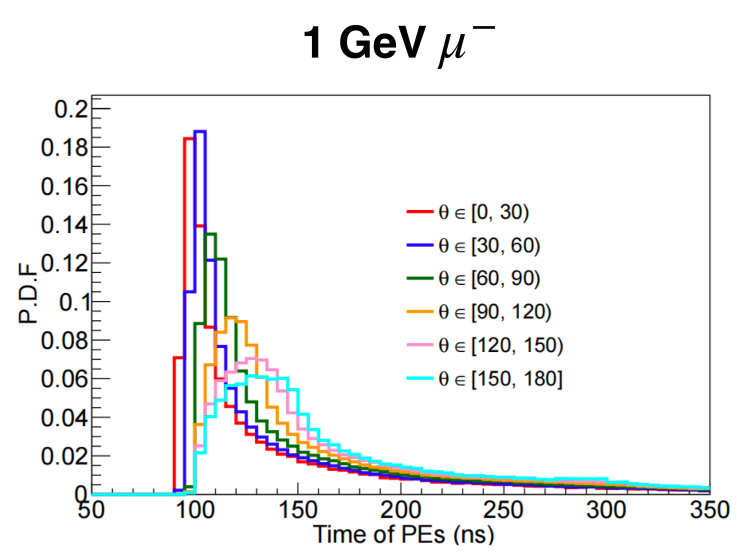




3. Methodology

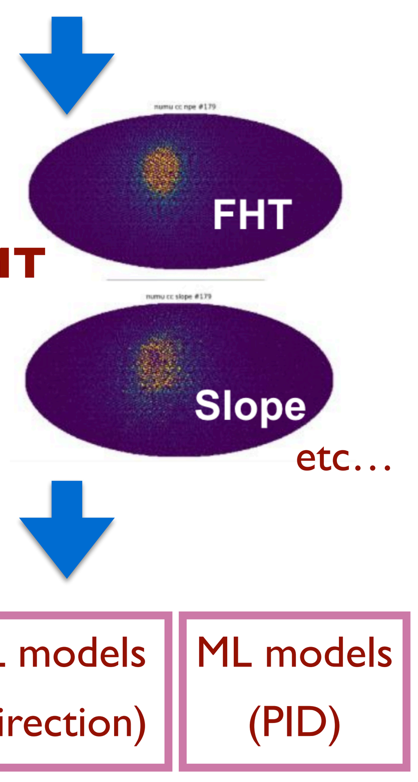
- Neutrino flavor can be determined by outgoing charged lepton from CC interactions
- Light seen by PMTs of an LS detector is a superposition of light generated from many points along the track
- Shape of light curve received by each PMT depends on angle w.r.t. track direction θ, track starting and stopping position, and particle type - different dE/dx
- Directly feeding full waveform from all PMTs are computationally expensive
  - Features are extracted to reduce data volume
  - **First fit time (FHT), total PE (nPE), peak charge, peak time**, and others such as median time and four moments of the waveform distributions (more details in Ref. [1])

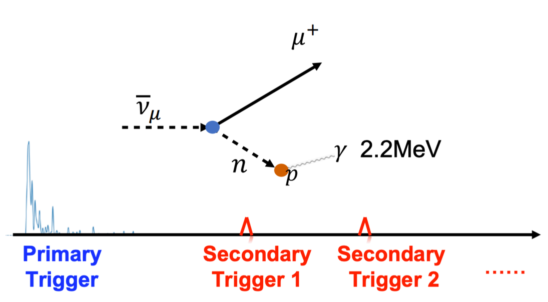


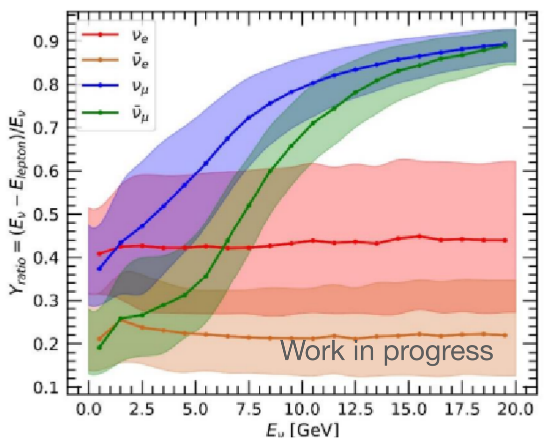


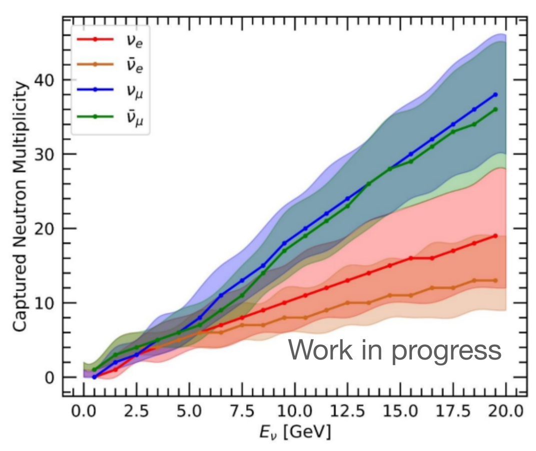
$\nu/\bar{\nu}$ Separation

- The difference between each CC interactions are also reflected by the final state hadrons from ν interactions
- Final state neutrons are captured by hydrogens in LS and emit a 2.2 MeV in ~ 200 μs, create delayed triggers after primary interactions
- Such events can be selected from delayed trigger with high efficiency
- The difference between $\nu/\bar{\nu}$ interactions can also be reflected by the hadronic energy fraction variable $Y_{ratio} = (E_\nu - E_{lepton})/E_\nu$, reflected by observables such as neutron multiplicity
- Expect to provide additional power especially for $\nu_e/\bar{\nu}_e$

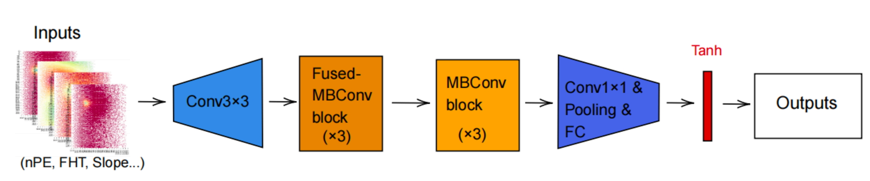






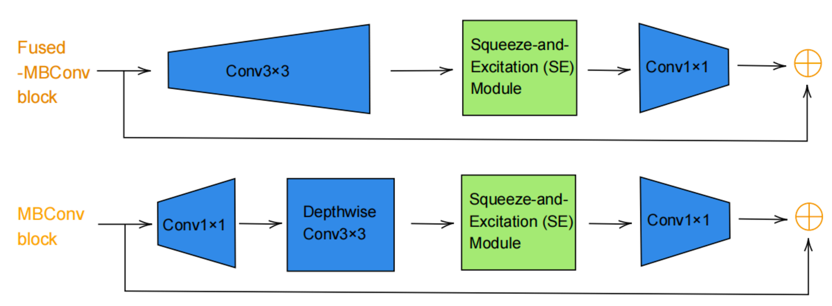


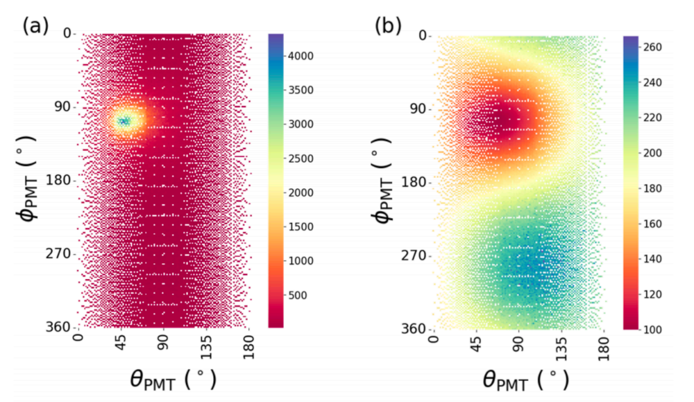
4. ML models



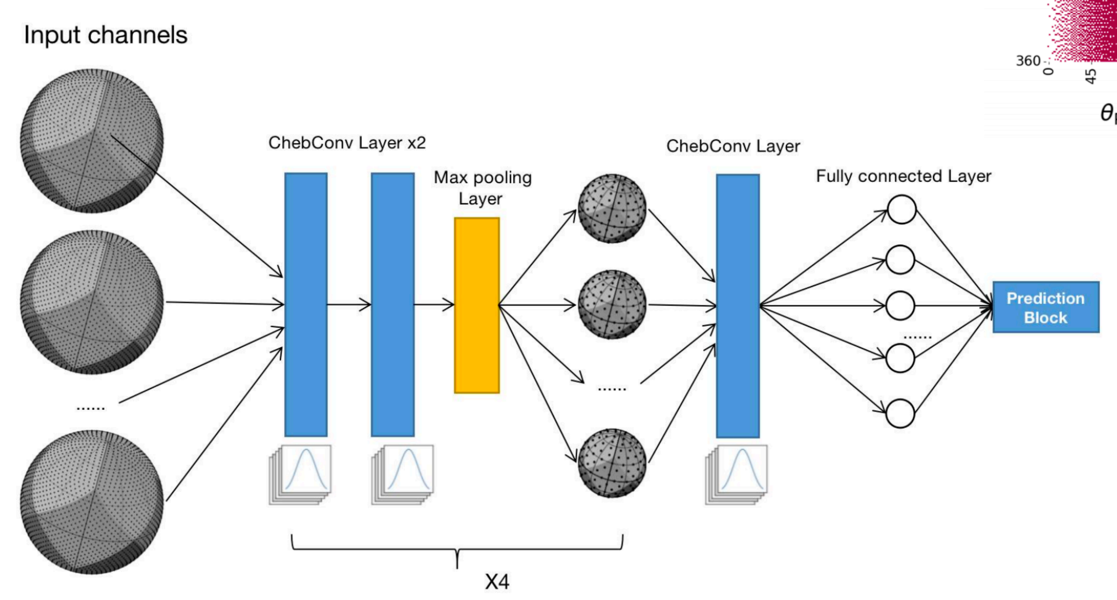
Planar Model: EfficientNetV2

- PMTs are seen as pixels, with each feature projected from the sphere to the planar surface
- EfficientNetV2: superior performance and shorter training time compared to other popular CNNs
- E.g. projected total charge and FHT to $\theta_{PMT} - \phi_{PMT}$ plane

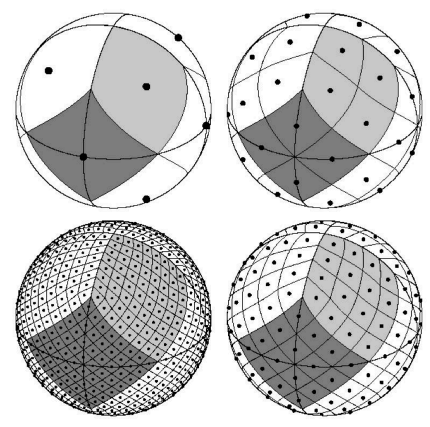




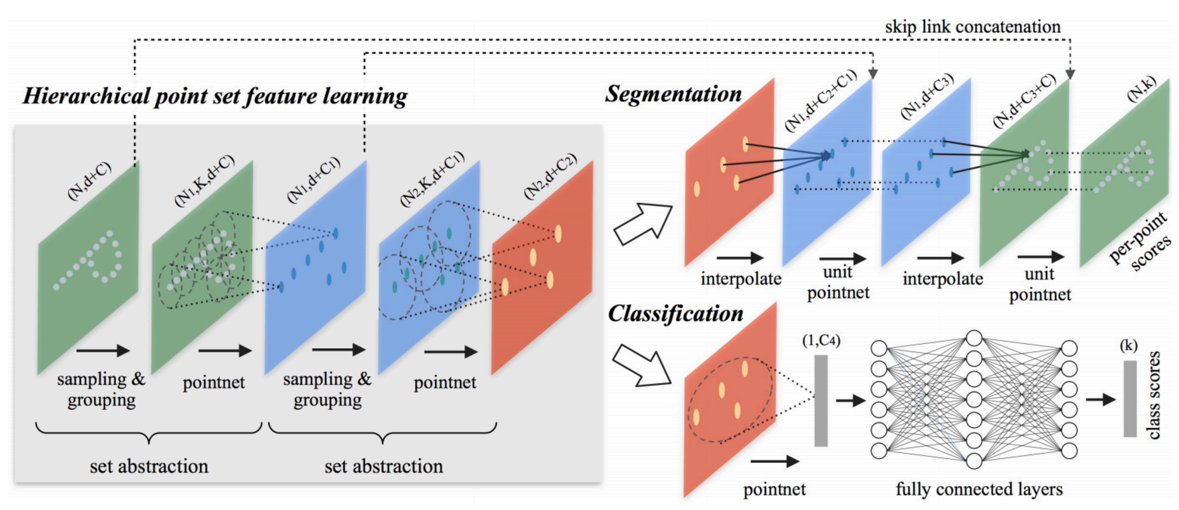
Spherical CNN: DeepSphere

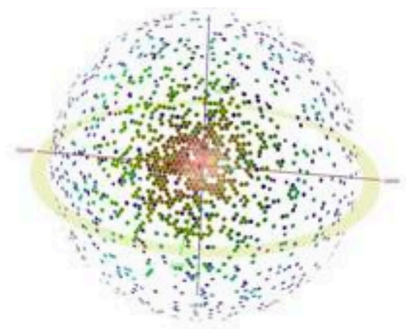


- Spherical image-based model: **DeepSphere**
- Designed to maintain rotational covariance
- Use Healpix sampling to define vertices: Total number of pixels is 12×2^n
- If more than one PMTs are in one pixel, info is merged



3D point-cloud: PointNet++

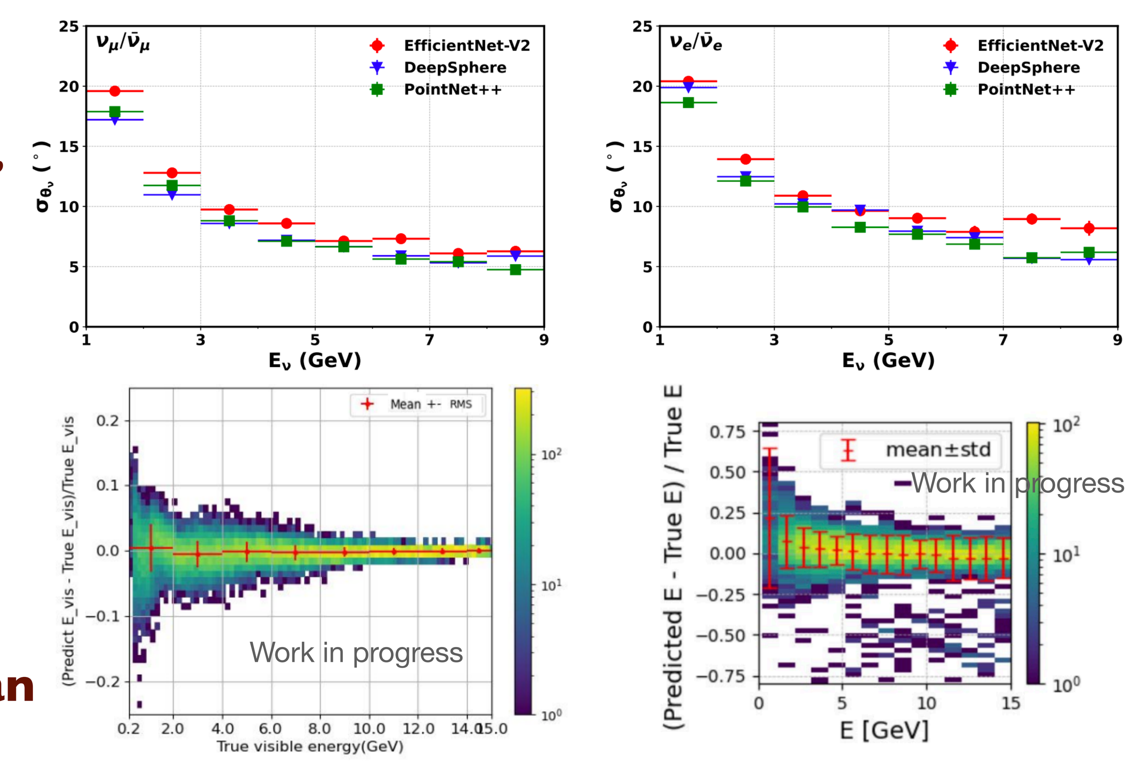




- Directly taking 3D point clouds ($N(PMT) \times$ [x, y, z, features...]) as inputs
- Detector signal more resemble point clouds
- Minimise information loss during projection

5. Performances

- Training and testing using JUNO Monte-Carlo events, optimised to avoid training biases, supervised learning with labelled data being energy/direction, or one of the 5 categories (ν_μ-CC, $\bar{\nu}_\mu$-CC, ν_e-CC, $\bar{\nu}_e$-CC, NC) considered
- Energy/direction reconstruction are done separately for ν_e-CC and ν_μ-CC events
- Systematic effects from ν interaction models and electronic effects are studied
- Can reconstruct both E_{vis}/E_ν with good resolution



Work in progress

Confusion matrix (Efficiency)

True label \ Predicted label	ν_e-CC	$\bar{\nu}_e$-CC	ν_μ-CC	$\bar{\nu}_\mu$-CC	NC
ν_e-CC	0.67	0.21	0.08	0.00	0.04
$\bar{\nu}_e$-CC	0.39	0.55	0.02	0.00	0.03
ν_μ-CC	0.12	0.01	0.66	0.15	0.07
$\bar{\nu}_\mu$-CC	0.01	0.00	0.15	0.69	0.15
NC	0.06	0.04	0.03	0.06	0.81

Results show promising potential for the ML-based reconstruction

The final performance of atmospheric neutrino (efficiency & purity) can be tuned to obtain the best NMO sensitivity in JUNO

References

[1] Zekun Yang et al. "First attempt of directionality reconstruction for atmospheric neutrinos in a large homogeneous liquid scintillator detector". Phys. Rev. D 109.5 (2024)