Reconstruction of Atmospheric Neutrino's Directionality and Energy in JUNO

Zekun Yang,[1] Jiaxi Liu,[2] Hongyue Duyang,[1] Teng Li,[1] Zhen Liu,[2] Wuming Luo,[2] Xiaohan Tan[1]

[1] Shandong University

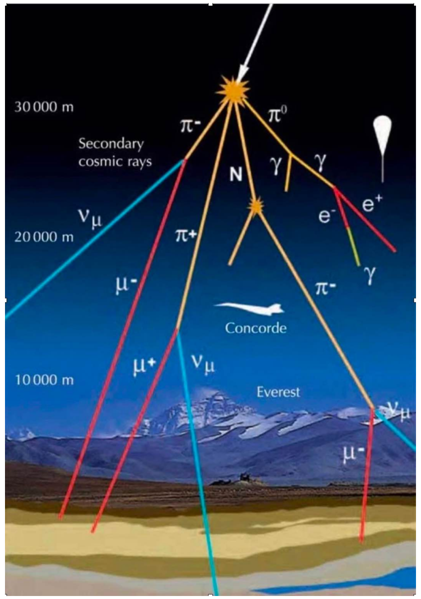
[2] Institute of High Energy

26 Oct. 2023

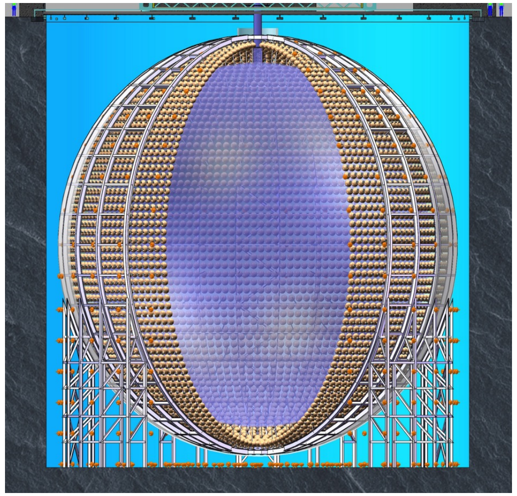
Motivation

- The measure of atmospheric neutrino oscillations has great potential to enhance JUNO's neutrino mass ordering (NMO) sensitivity.
- Atmospheric neutrino oscillations analysis ($P = f\left(\frac{L}{E}\right)$) requires reconstructions of:
  - Zenith angle θ_ν ➢ L;
  - Neutrino energy;

  This talk
  - Flavor (PID). See Rosmarie's talk



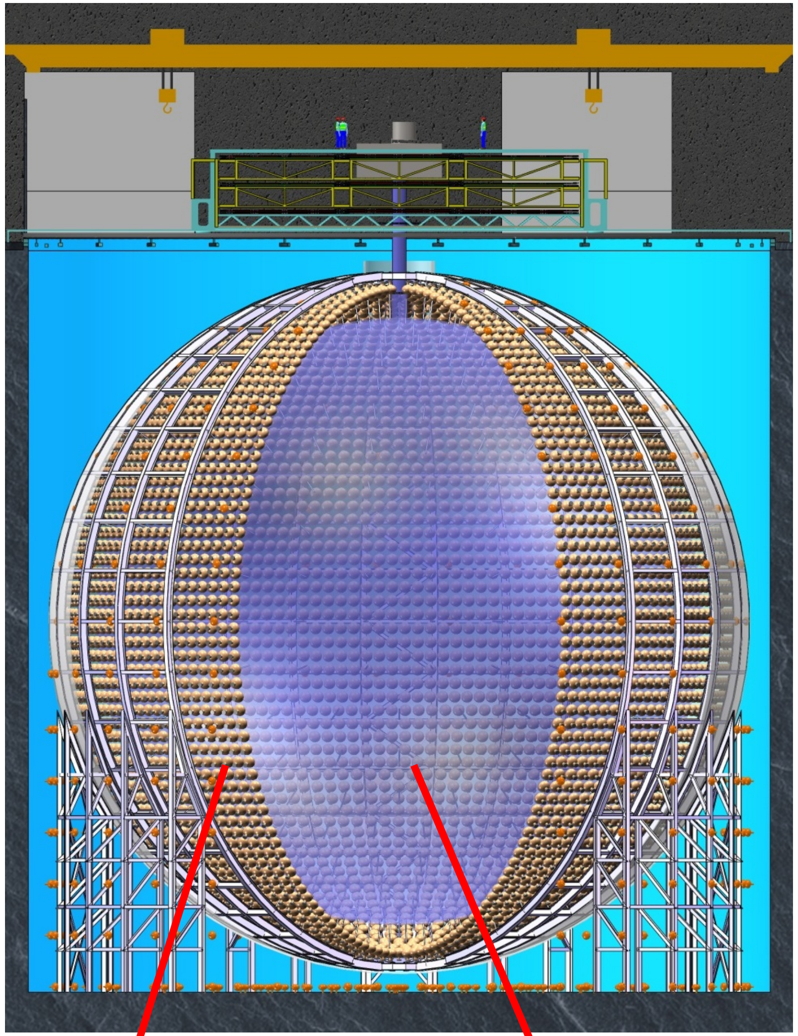
Reactor neutrinos:
Sensitivity to NMO via
oscillation in vacuum



Atmospheric neutrinos:
Sensitivity to NMO via
oscillation with matter effect

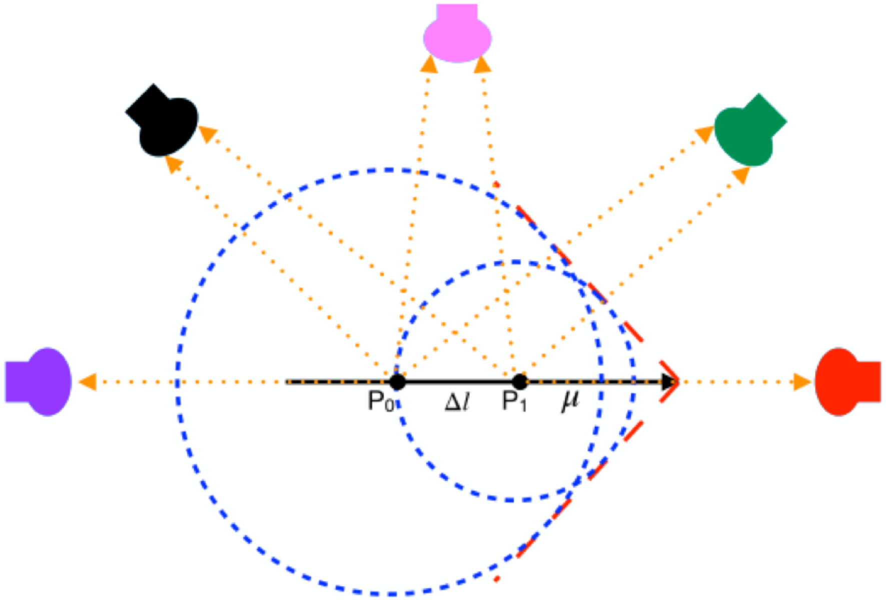
Challenge

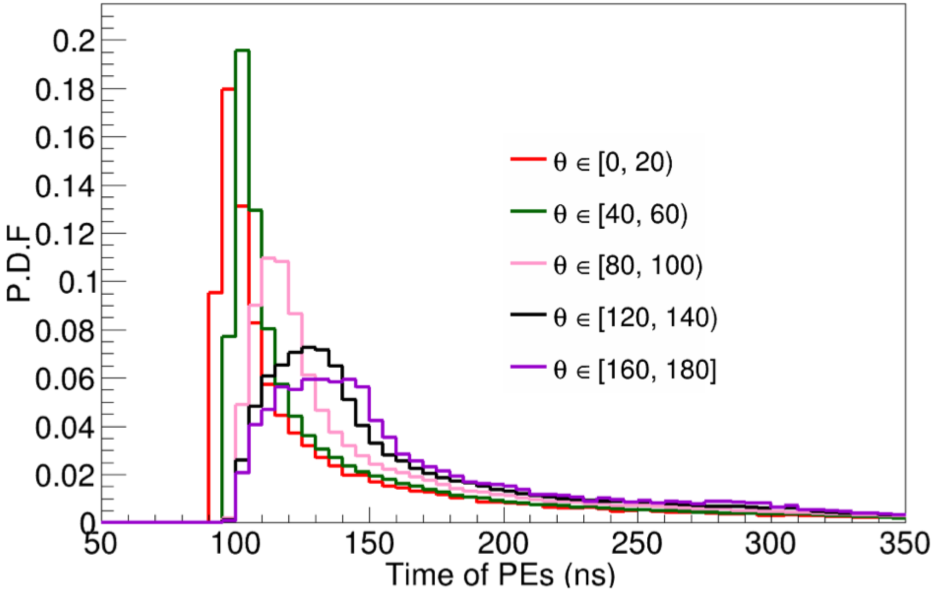
- Center detector of JUNO is not designed for atmospheric neutrino measurement at the beginning.
- Directionality measurement is very challenging:
  1. Liquid scintillator (LS) detectors do not offer direct track information.
  2. Cherenkov light ≪ Scintillation light in a typical LS detector.



Methodology

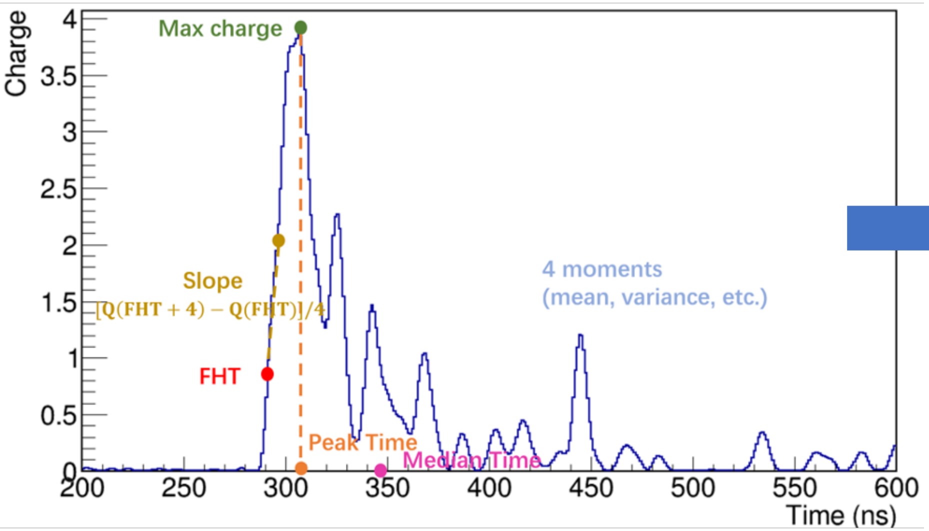
- The light received by a PMT is the superposition of light from many points on the particle track in the detector.
- The track depicts distinct shapes of nPE(t) for PMTs at different angles, which then reflected in the PMT waveforms.



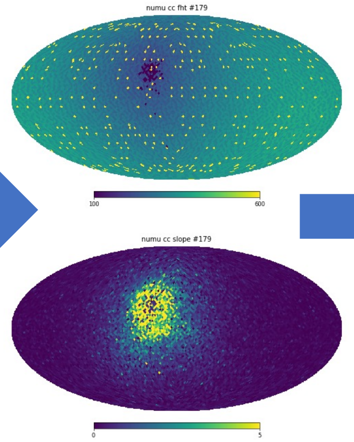


Methodology

- Features are extracted from waveforms to keep only the useful information relevant to reconstructions.
- Machine Learning (ML) models are trained to reconstruct directionality, energy, and flavors and other quantities from PMT features.

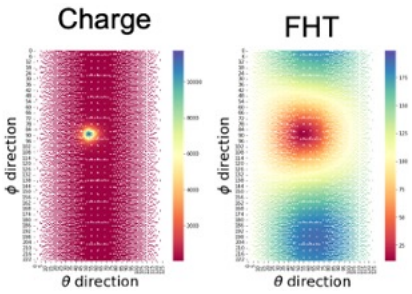


PMT Waveform

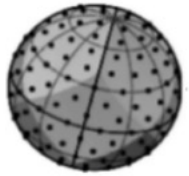


Pictures of features

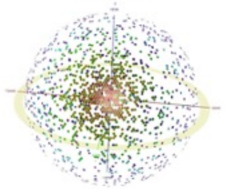
EfficientNet



DeepSphere



PointNet++



ML models

Direction

Energy

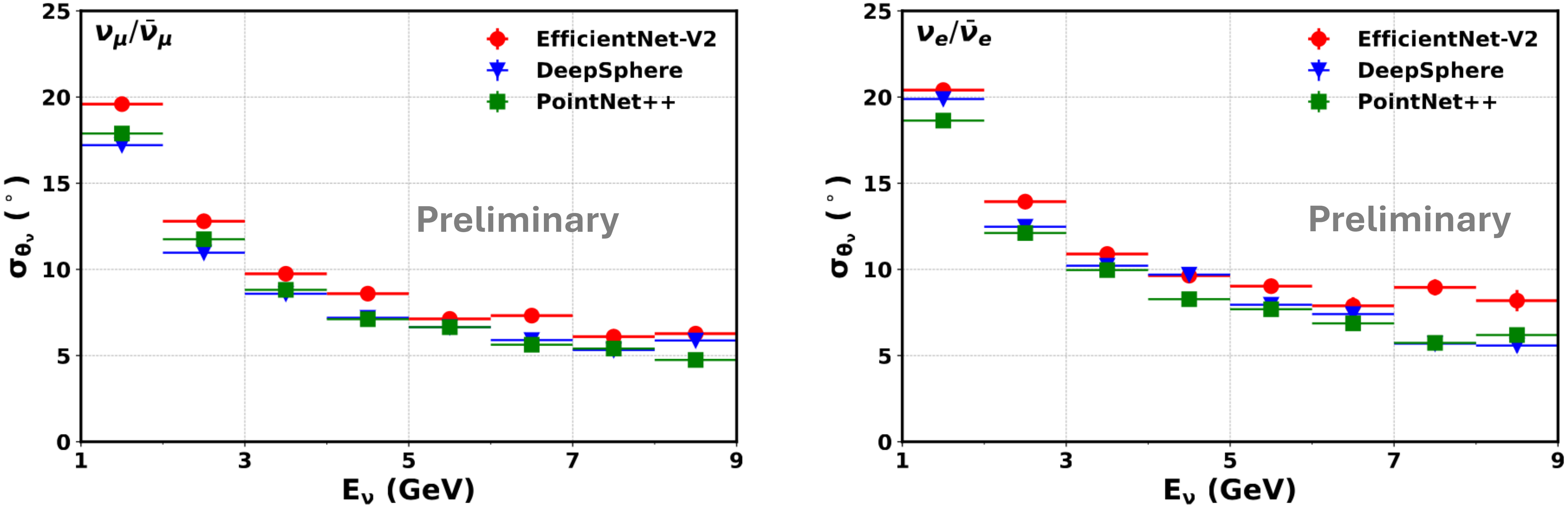
Flavor

Others...

Performance of directionality

arXiv:2310.06281

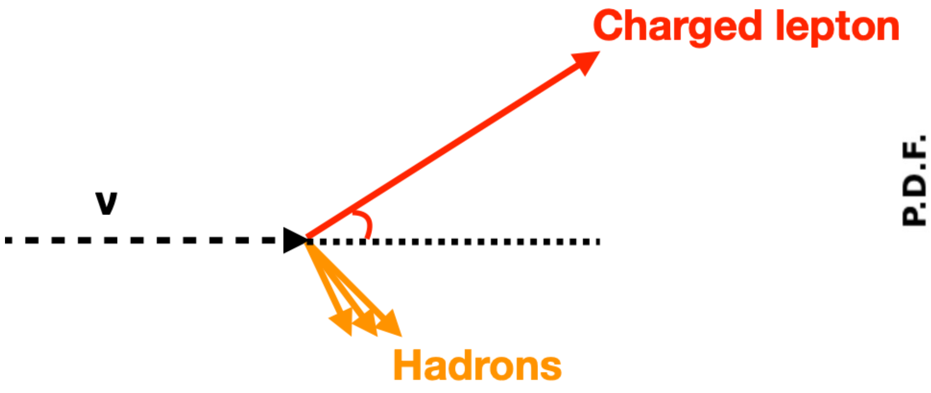
σ_{θ_ν}: The standard deviation of the Gaussian fit to the distribution of $\theta_{\nu,rec} - \theta_{\nu,\,true}$ in each energy bin.

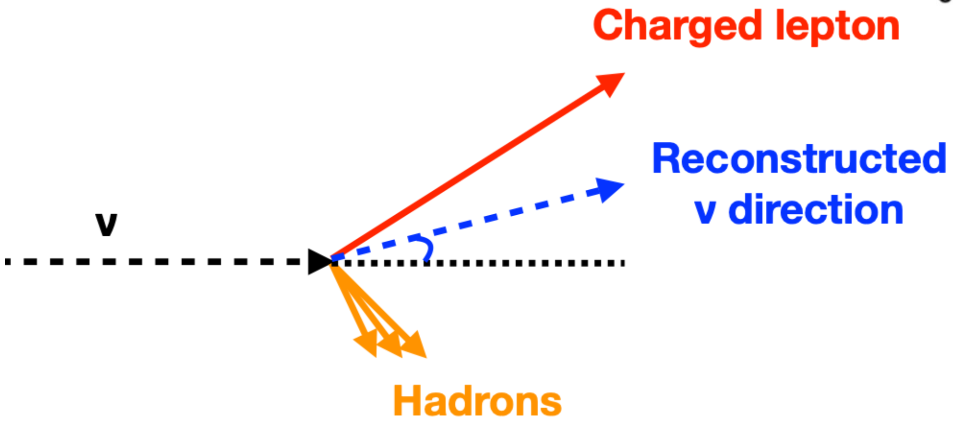


Cross-checked with different ML models, and validated with different generators (GENIE and NuWro).

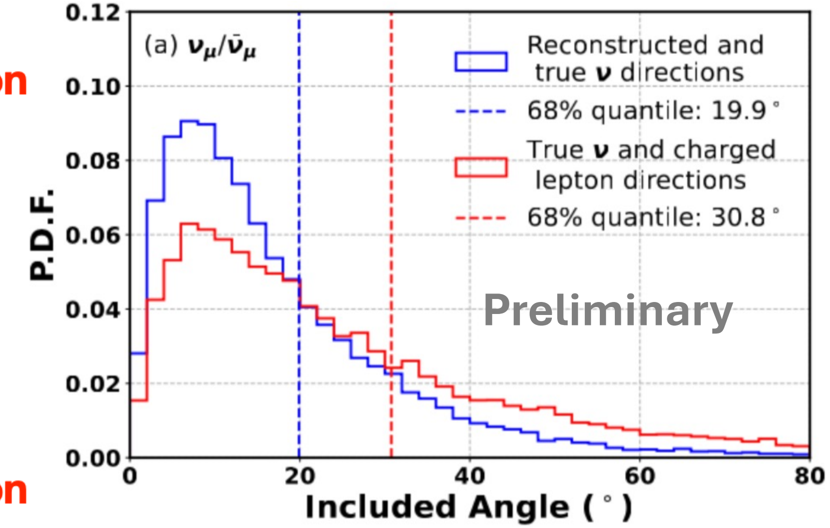
Better than 10° resolution for $E_\nu > 3\text{GeV}$ for both $\nu_\mu/\bar{\nu}_\mu$-CC and $\nu_e/\bar{\nu}_e$-CC events.

Performance of directionality

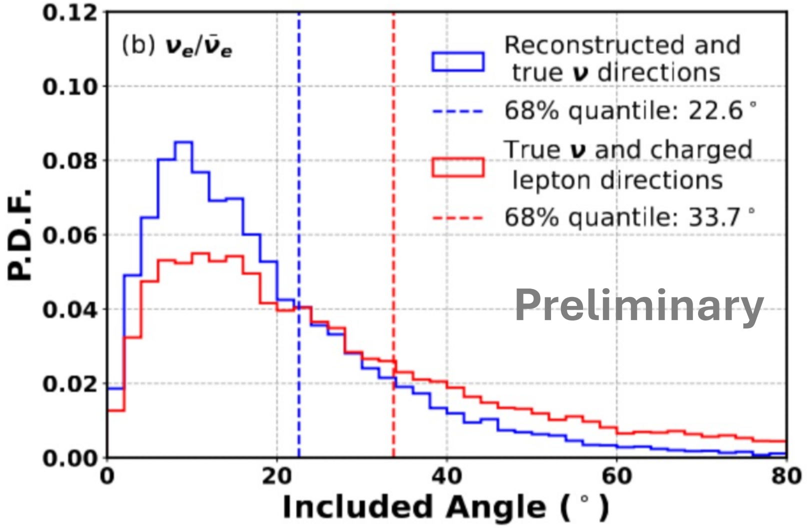




$\nu_\mu/\bar{\nu}_\mu$



$\nu_e/\bar{\nu}_e$



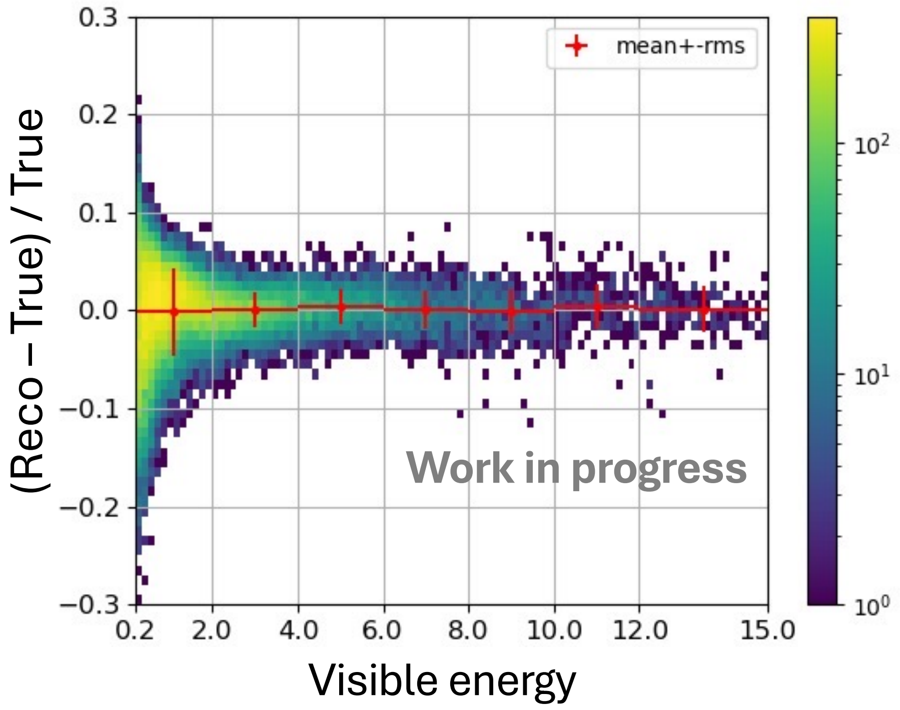
- Both lepton and hadron informations are used in the directionality reconstruction.
- The reconstructed neutrino direction is less smeared from the true neutrino direction compared with the charged lepton direction.

Performance of energy

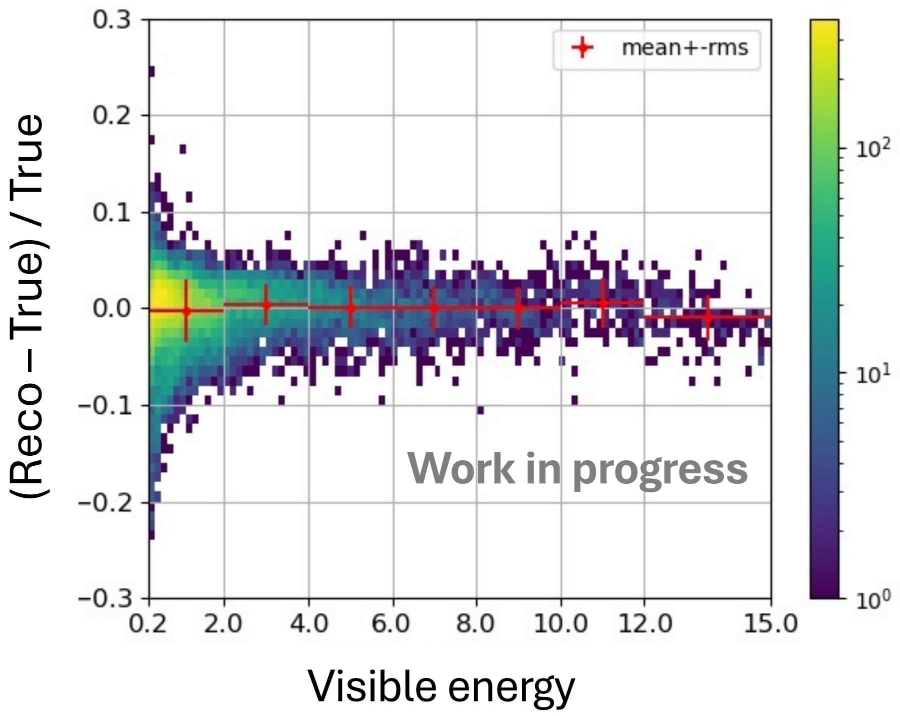
Same method with directionality reconstruction but change output to energy.

Good results of visable energy:

$\nu_\mu/\bar{\nu}_\mu$



$\nu_e/\bar{\nu}_e$



Summary

1. In this talk, we present a multi-purpose machine learning approach for the reconstruction of atmospheric neutrino events in JUNO.
2. We demonstrated the feasibility of atmospheric neutrinos' directionality and energy reconstruction for the first time in a LS detector using this approach.
3. It provides the neccessary resolution for atmospheric neutrino oscillation analysis, and same method can be applied to other LS detector.

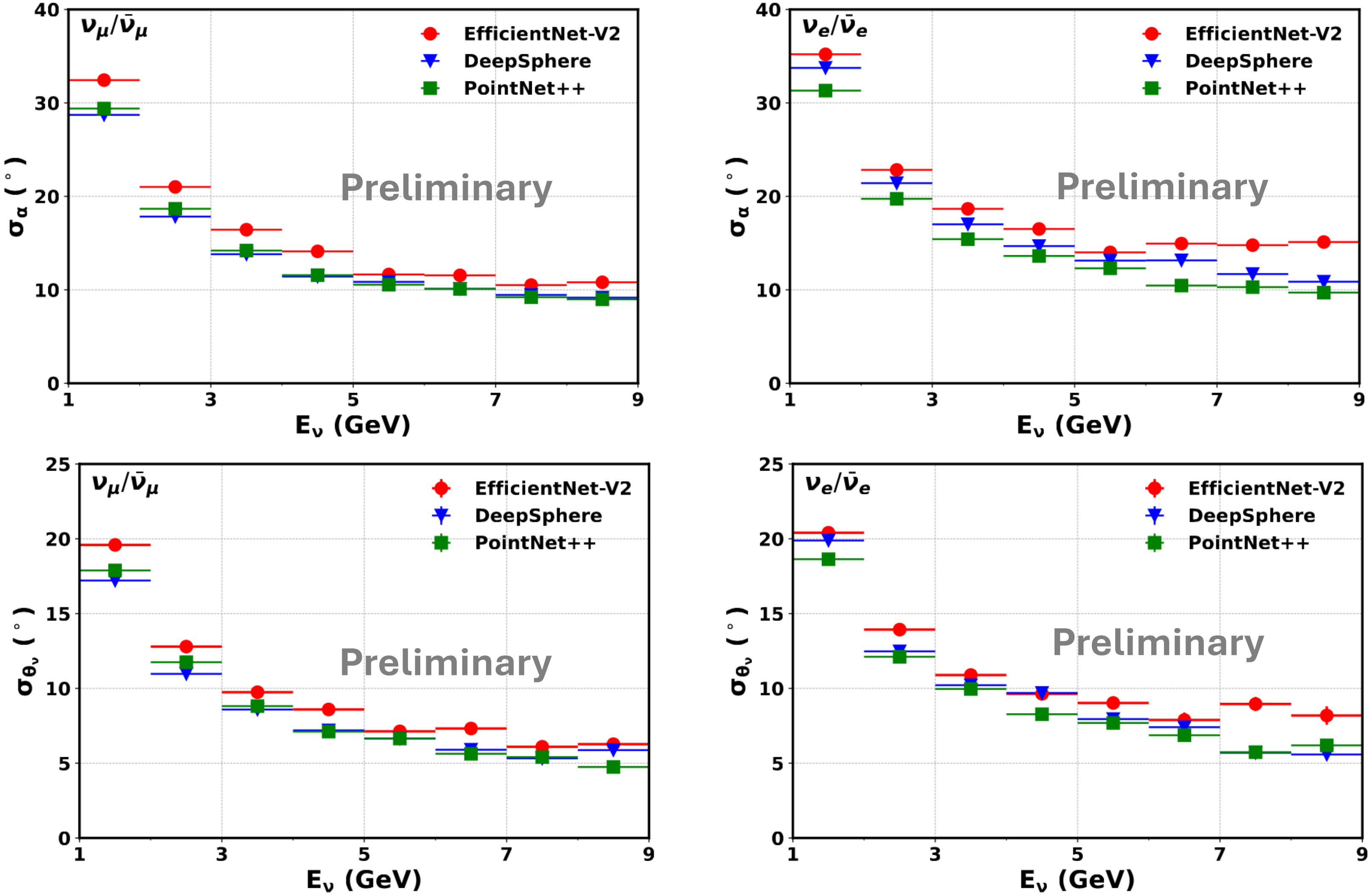
Thank you!

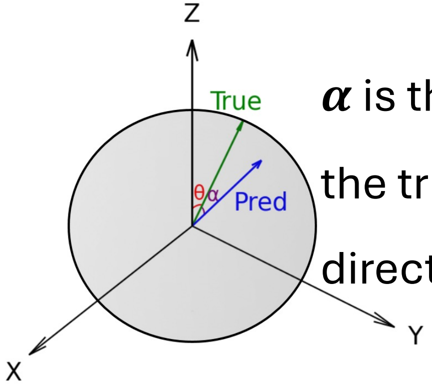
Backup

Backup

θ_ν

α





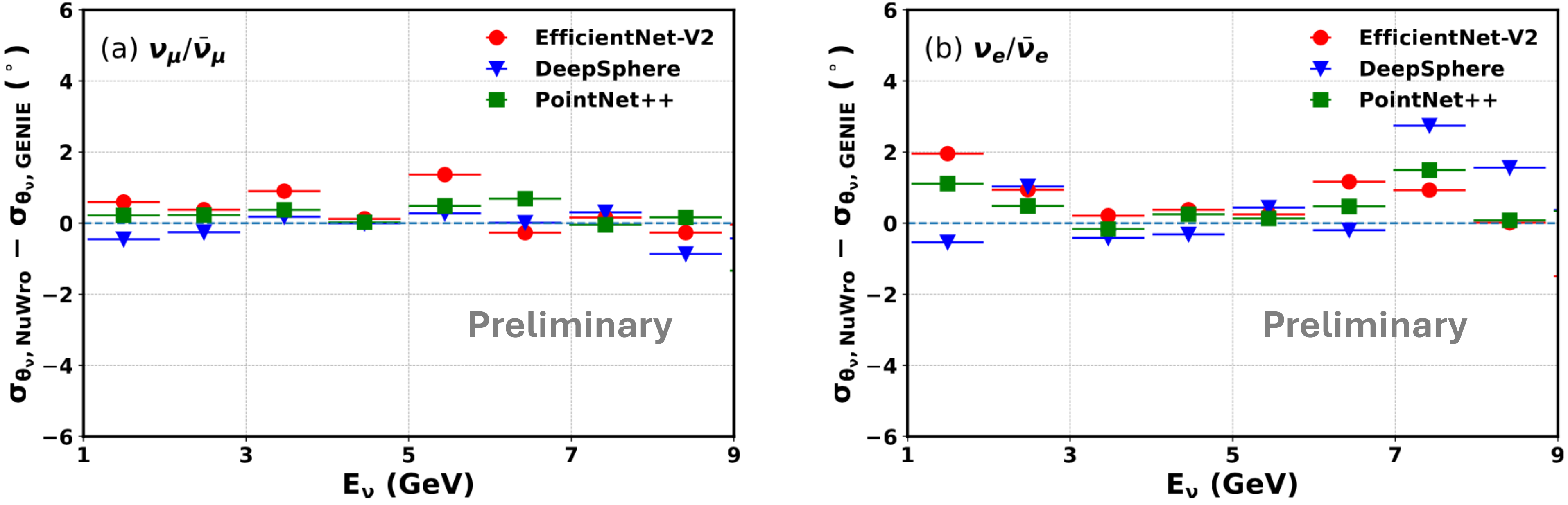
α is the angle between the true and reco directional vector;

The resolution on α (σ_α) is defined as the 68% quantile of the α distribution, given that α is always larger than 0.

For θ_ν, the resolution in each energy bin (σ_{θ_ν}) is defined as the standard deviation of the Gaussian fit to the distribution of $\theta_{\nu,rec} - \theta_{\nu,\,true}$, since these distributions are found to be approximately Gaussian.

Backup

To check models' robustness and estimate systematic uncertainties, a different generator, NuWro, is used for validation:



The result of GENIE and NuWro are consistent.