Directionality Reconstruction for Atmospheric Neutrinos with Machine Learning Methods in JUNO

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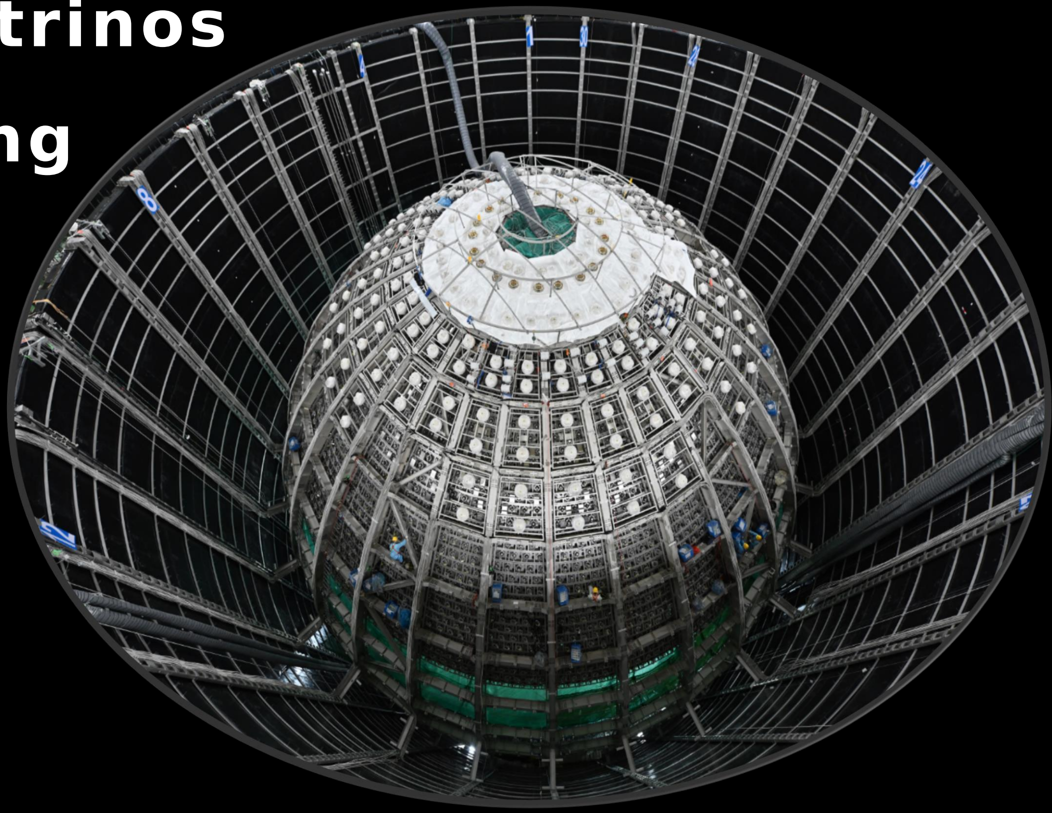
25-06-2024

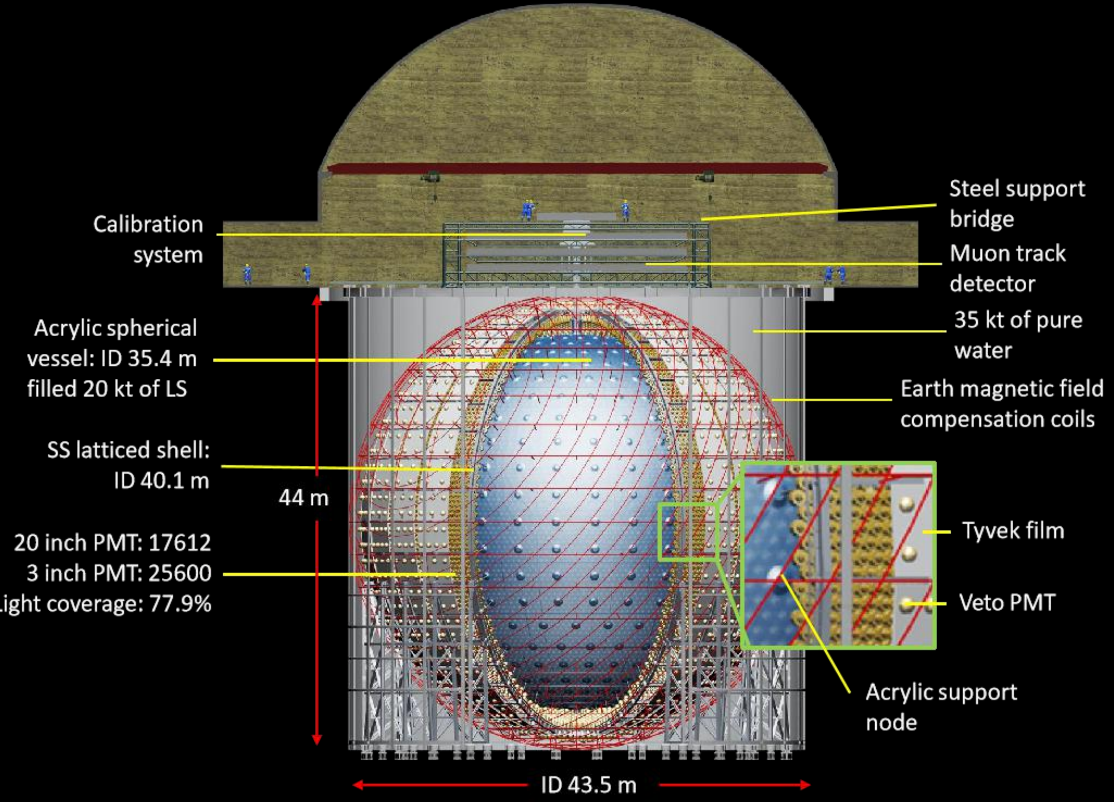
NPML2024, ETH Zurich



Jiangmen Underground Neutrino Observation (JUNO)

- JUNO is a medium baseline (53 km) reactor neutrino experiment, with 20 kton liquid scintillator(LS) in a spherical vessel surrounded by ~17k 20'' + ~25k 3'' PMTs
- Located in Guangdong Province, South of China. It is located 650 m underground.

JUNO experiment



Detector of JUNO

- A 20 kton liquid scintillator (LS) detector
- PMT coverage: 78%
- Energy resolution @ 1 MeV: 3%
- Currently under construction. Physics run to start in 2025

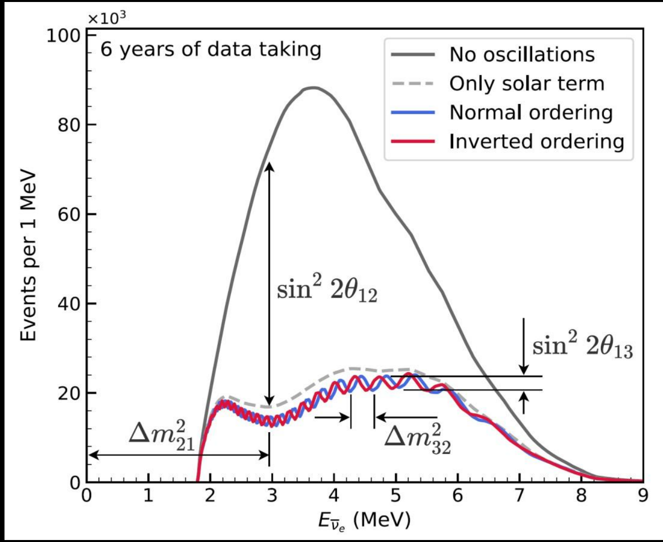
JUNO Physics

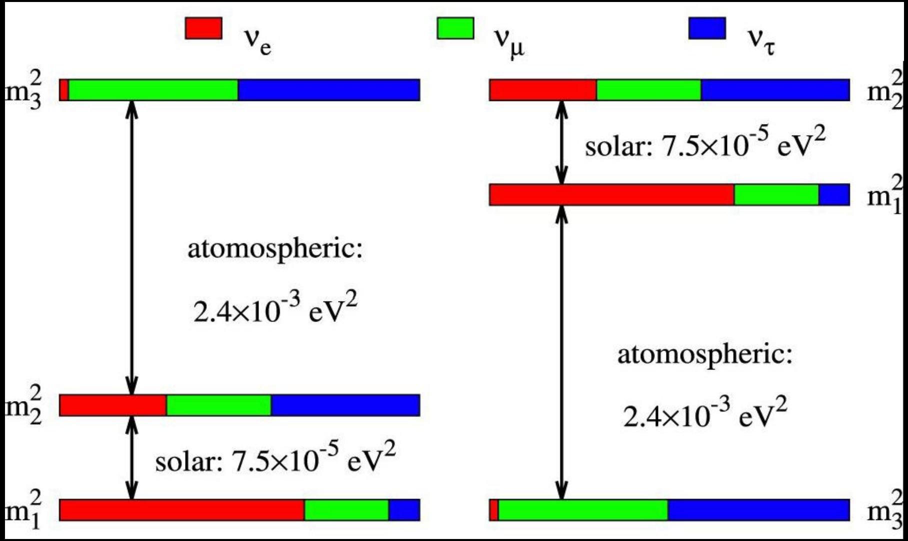
The primary goal: determination of neutrino mass ordering(NMO).

- Pure source of electron anti-neutrino of ~1-10 MeV from reactor

Measure neutrino oscillation parameters to sub-percent level

Wide range of measurable neutrino energies + sources!SuperNova, Solar, Geo., Atm., etc.





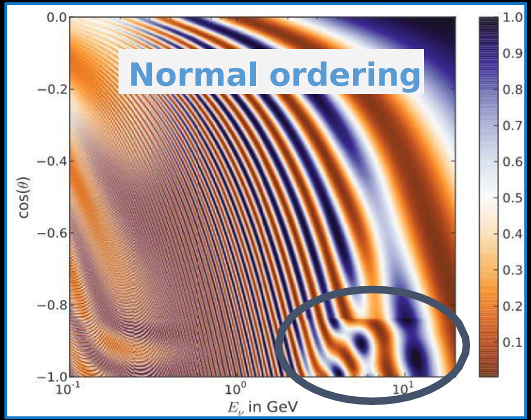
$$P_{\overline{\nu_e}\to\overline{\nu_e}} = 1 - \sin^2 2\theta_{13}\,(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

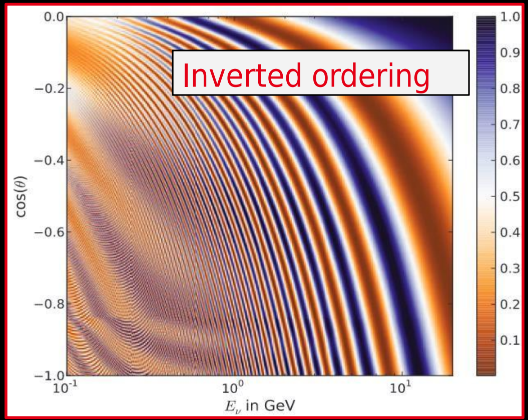
Why Atmospheric Neutrinos in JUNO?

Atmospheric neutrinos provide independent sensitivity to NMO via matter effects.

Combing reactor and atmospheric neutrino oscillations has the potential to maximize JUNO's total sensitivity

- reactor anti-neutrinos at low energies
- atmospheric neutrinos at high energies(GeV level)





Challenge: LS detector for ν_{atmo}

For Atmospheric neutrinos study:

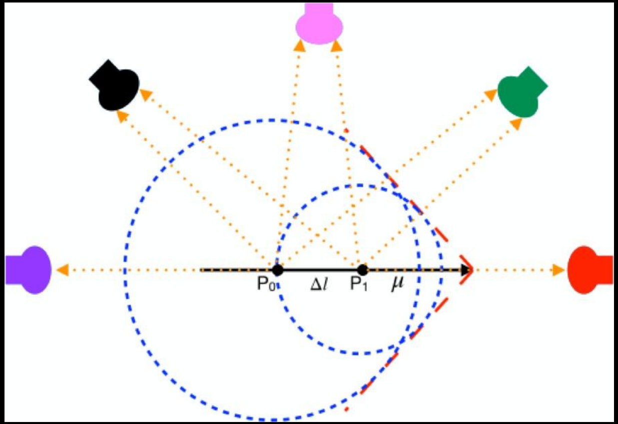
- Matter effects on oscillations are dependent on zenith angle since it is directly related to the oscillation baseline length.
- Neutrino directionality (cosθ) is mandatory to the atmospheric neutrino.

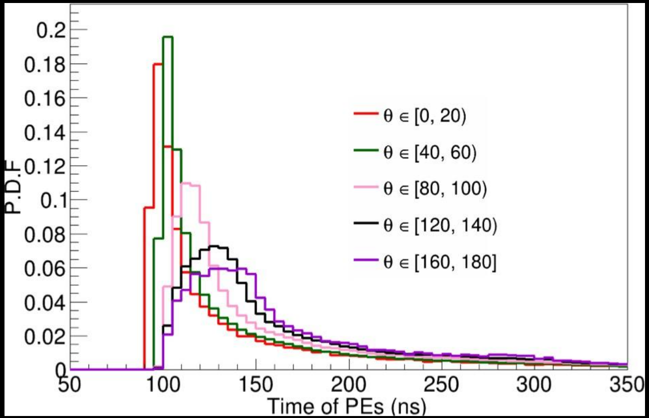
For LS detector

- Scintillation light is isotropic, Cherenkov light is only a few percent: no direct directional information.
- Atmospheric neutrino oscillation measurements in LS detectors have never been reported before

Methodology for the directionality reconstruction

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



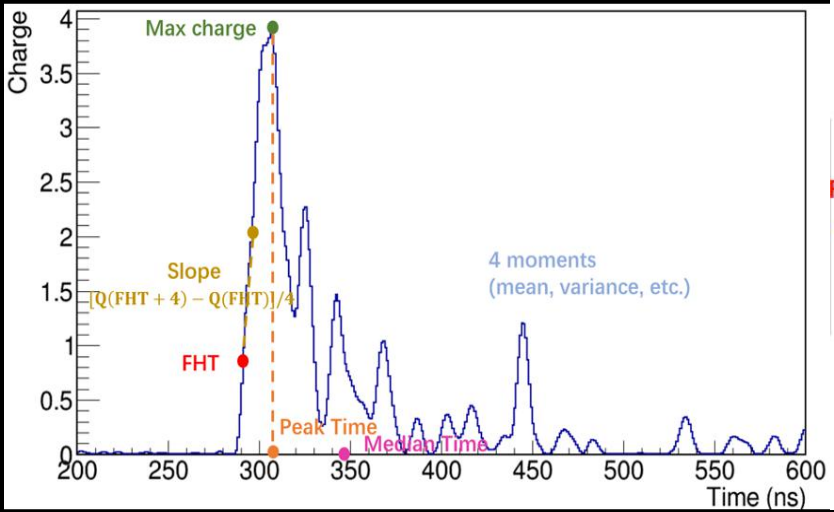


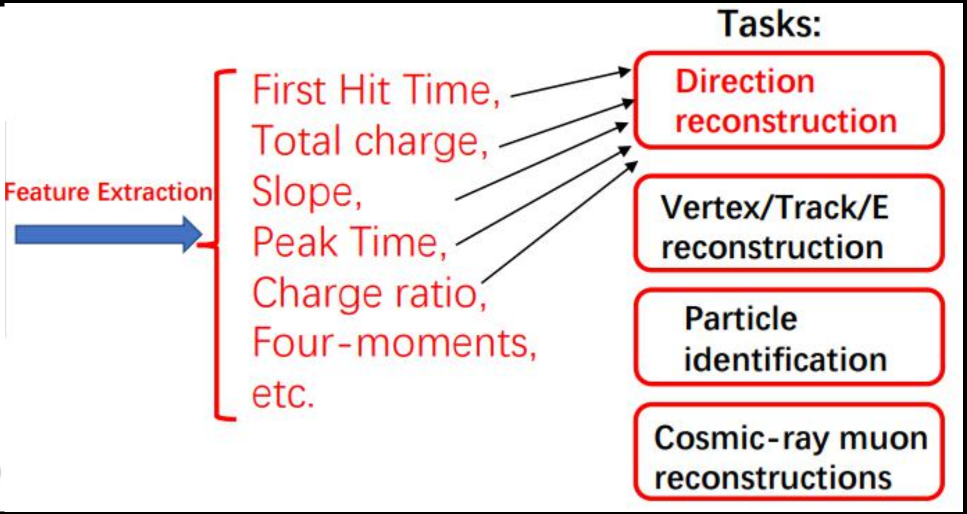
Methodology for the directionality reconstruction

Using waveform analysis and machine learning techniques.

- Features are extracted from waveforms to keep only the useful information relevant to reconstructions.

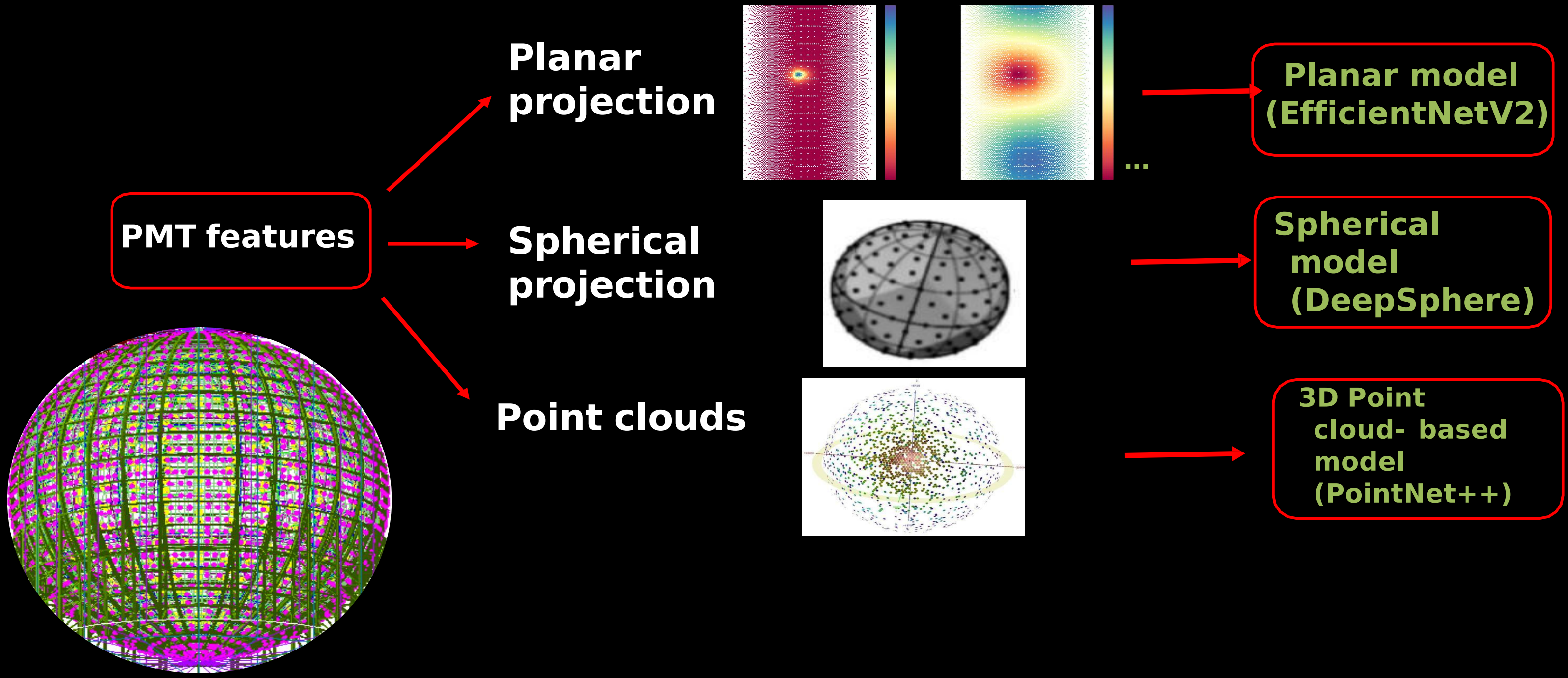
>>PMT feature also used for direction/energy/flavor/vertex etc. flavor talk see Wing’s talk.





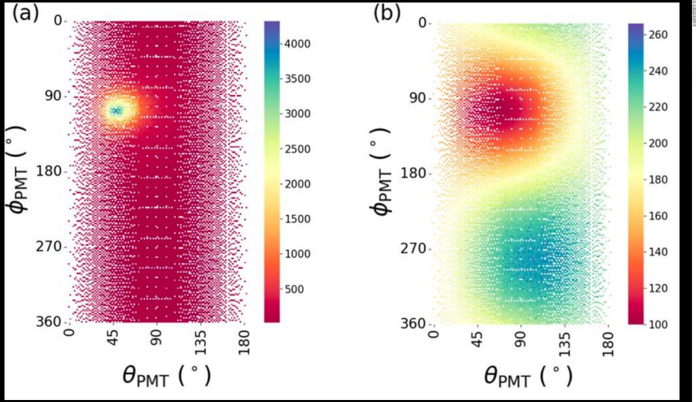
Machine Learning Models

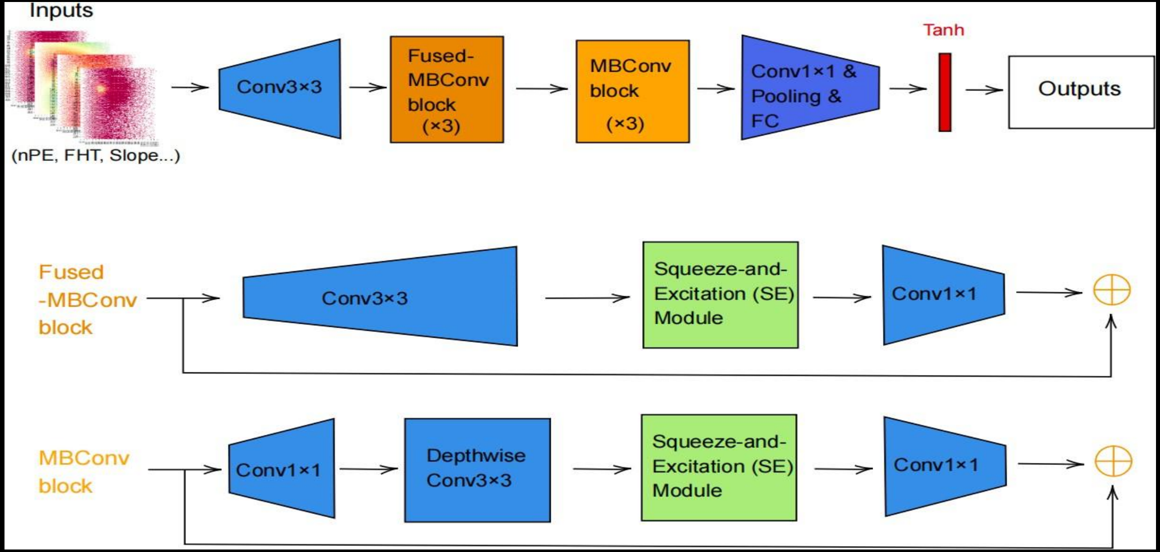
Three different approaches are developed to deal with the PMT features :



Planar Model: EfficientNetV2

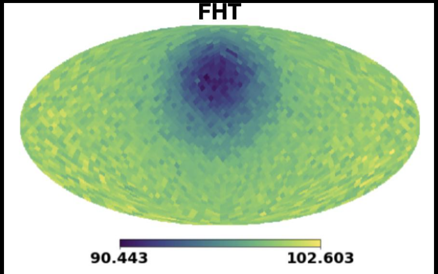
- EfficientNetV2: CNN model adapted for spherical data by projecting it onto a 2D grid.
- PMTs are seen as pixels, with each feature projected from the sphere to the planar surface
  E.g. projected total charge and FHT to $\theta_{PMT} - \phi_{PMT}$ plane
- Advantages: High performance, shorter training time.

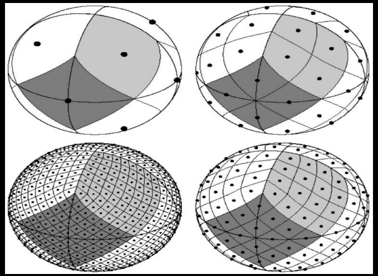


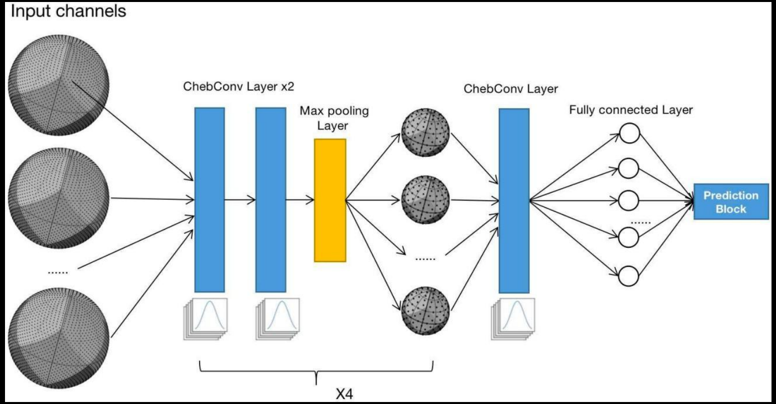


Spherical CNN: DeepSphere

- Graph-CNN: developed for processing spherical data originally developed for cosmology studies
- Advantages: Maintains rotation co-variance, avoid distortions caused by projection to a planar surface



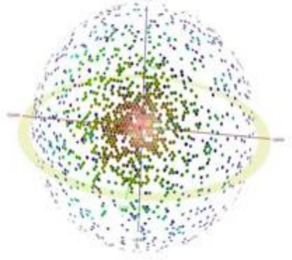


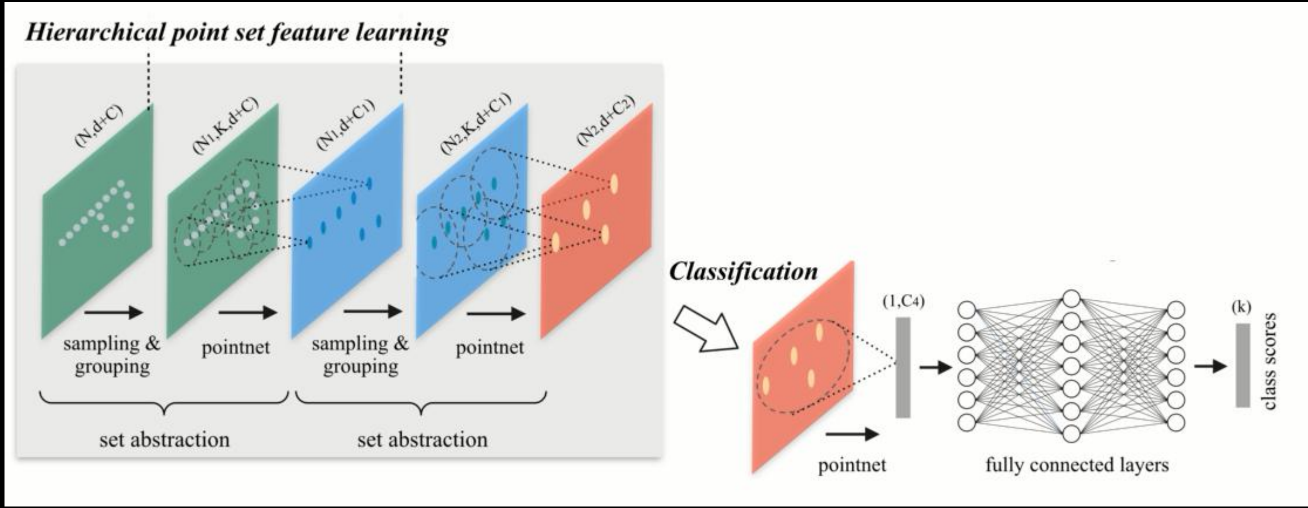


- Use Healpix sampling to define vertices
- Equally divide the sphere into 12 parts
- Further divide each part into Nside parts ($Nside = 2^n$)
- If more than one PMTs are in one pixel, info is merged

3D point-cloud: PointNet++

- Directly taking 3D point clouds (N(PMT) × [x, y, z, features...]) as inputs
- Advantages: Captures both global and local features.
- Detector signal more resemble point clouds
- Minimise information loss during projection





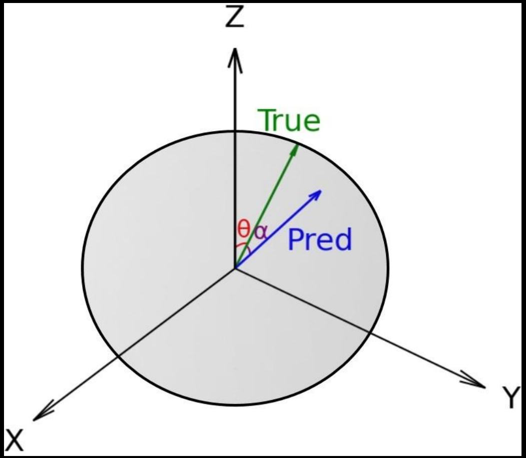
Performance of directionality

α: Angle between the true and reconstructed directional vector.

- The range of α is 0 to 180°, 68% quantile is used to quantify the performance of α

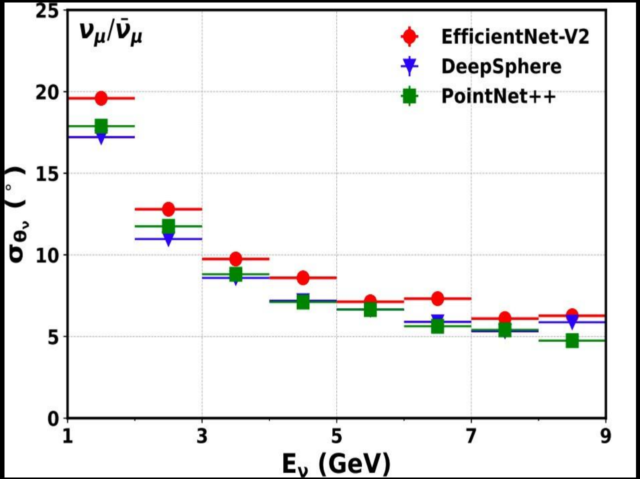
Reconstructed θ - True θ

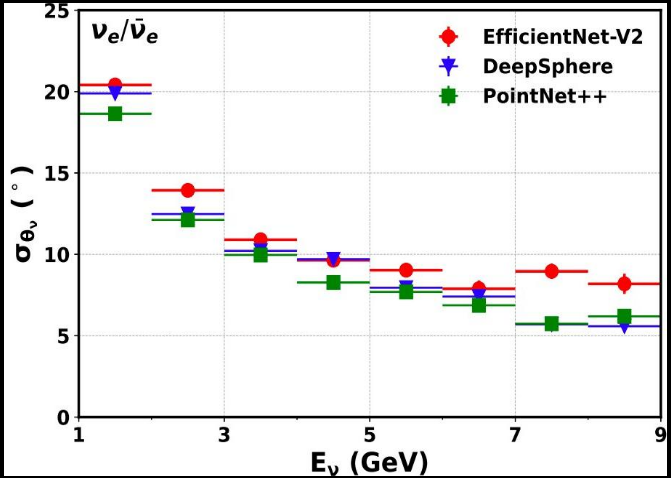
- Distribution in E_ν bins can be well described by Gaussian.
- σ_G from Gaussian fit is defined as the resolution.



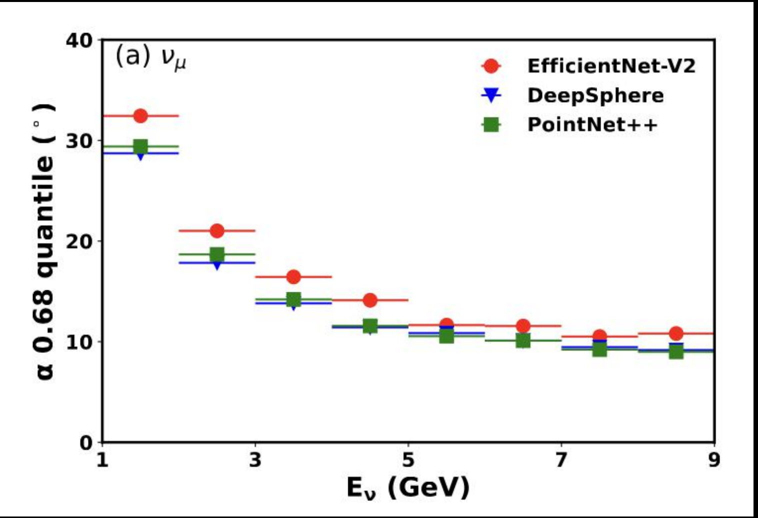
Performance of directionality

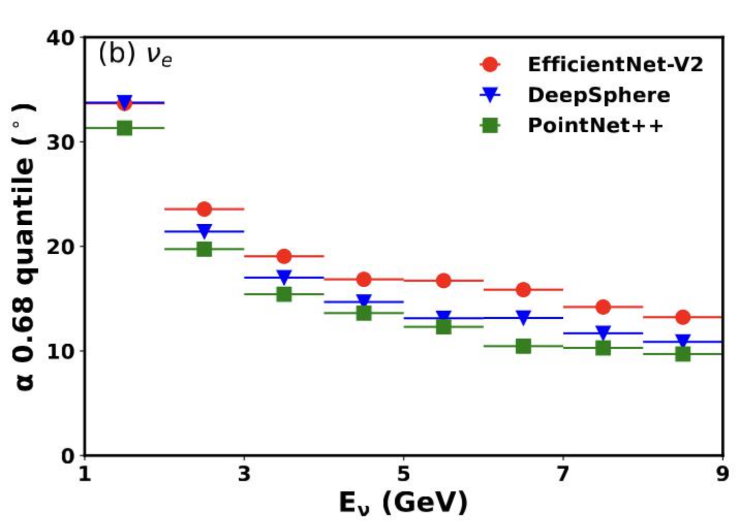
- Used JUNO Monte-Carlo sample: Data sample: 135k $\nu_\mu/\bar{\nu}_\mu$, 57k $\nu_e/\bar{\nu}_e$ Charged-Current events, 80% training
- First demonstration in reconstructing ν_{atm} direction in a LS detector with MC
- The performance gets better as the energy increases for both neutrino flavors
- A consistent trend is observed for the three different models



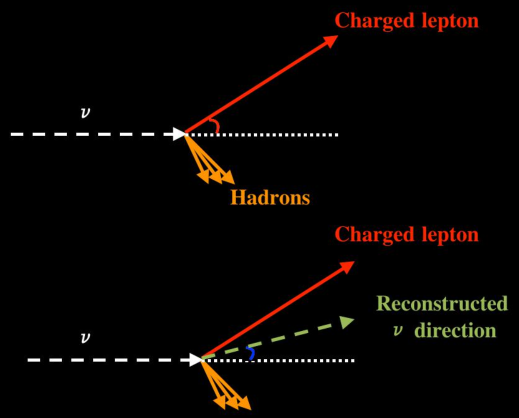


Performance of directionality: α

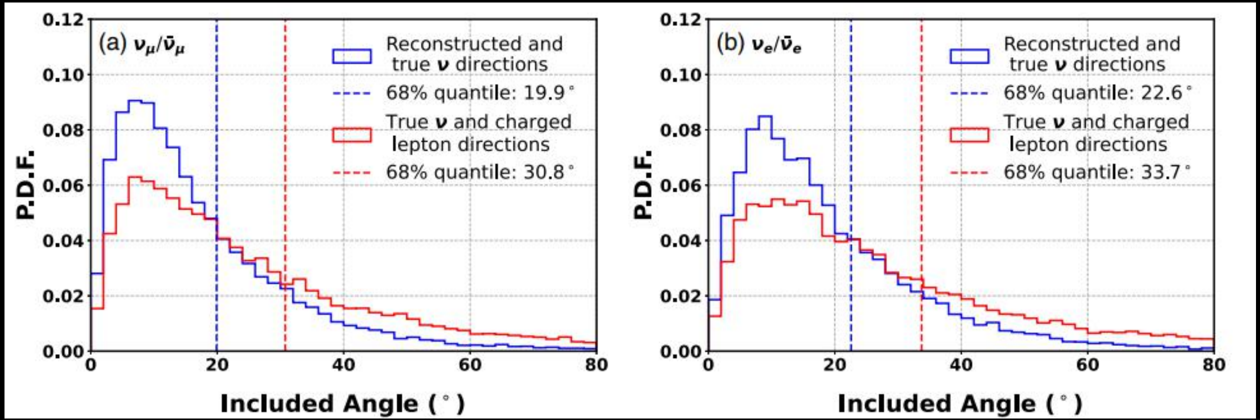




Performance of directionality



- LS detector see hadrons better than a WC detector thanks to its lower threshold.
- Both lepton and hadron informations are used in the directionality reconstruction.
- An advantage for an LS detector with this method for atmospheric neutrino oscillation measurements.



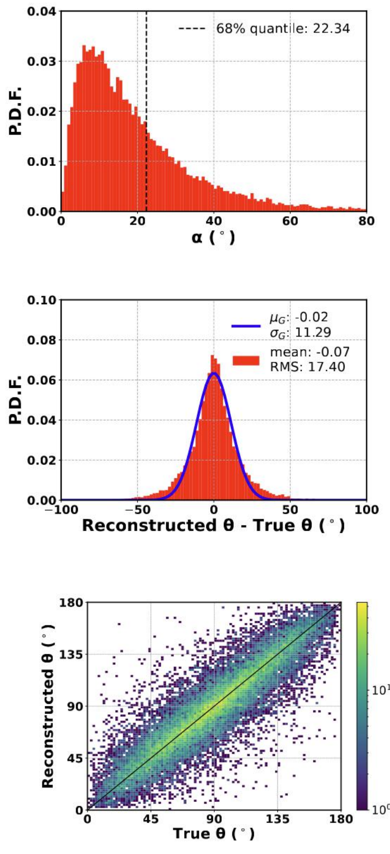
Summary

- In this talk, we presented waveform analysis and machine learning methods for the reconstruction of atmospheric neutrino’s directionality.
- The reliability of the results was tested by using different machine learning models.
- First successful directional reconstruction of atmospheric neutrino is done in a large-volume LS detector, greatly expanding the physics applications of such detectors
- Impact: Enhances JUNO’s capability in NMO measurements, providing critical data for future studies.

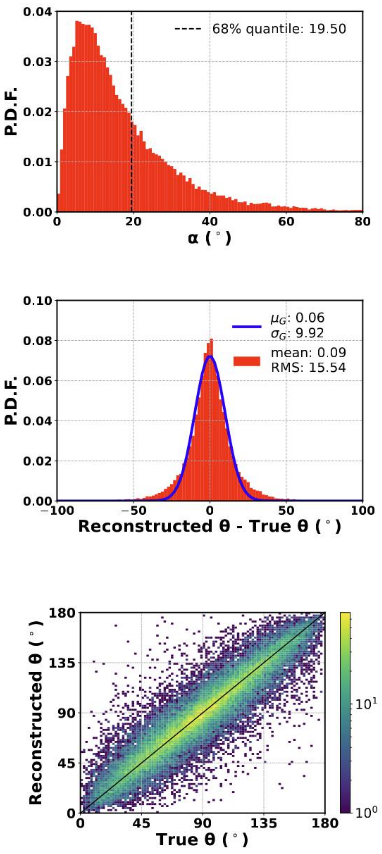
Thank you for your attention!

BACKUP

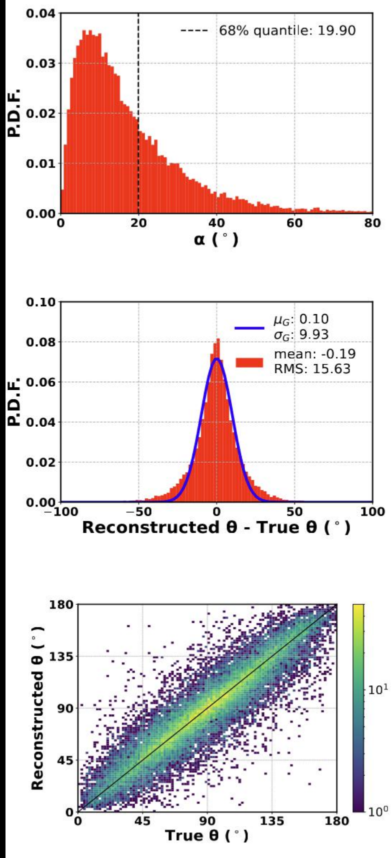
Performance of directionality： $\nu_\mu/\overline{\nu}_\mu$



(a) EfficientNet

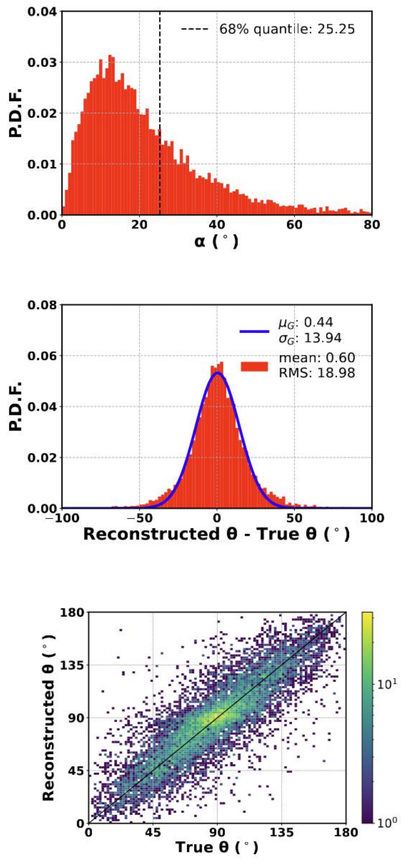


(b) DeepSphere

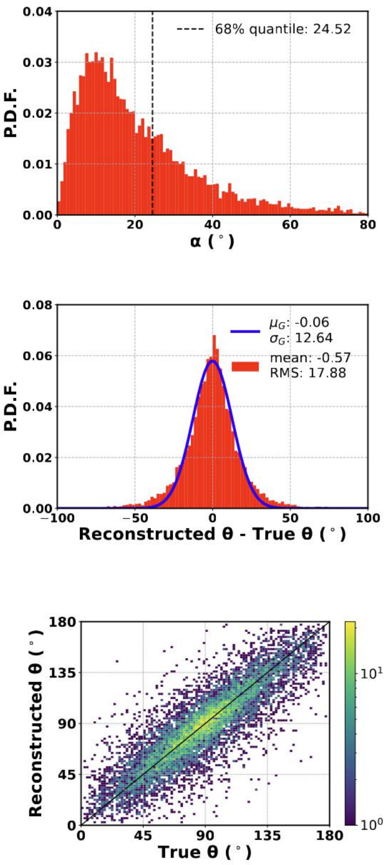


(c) PointNet++

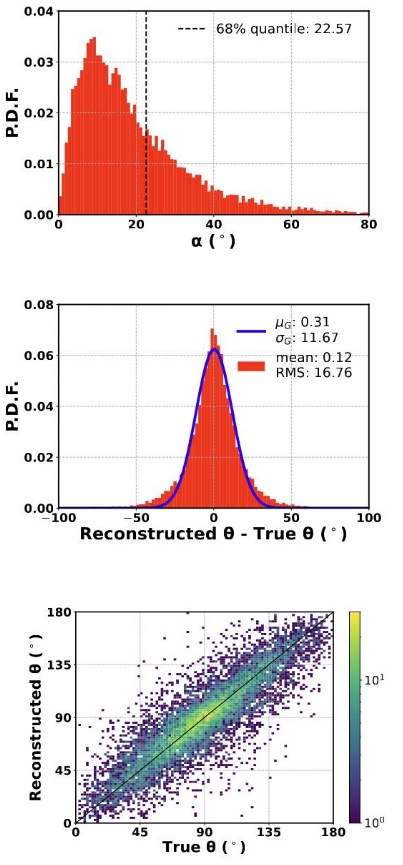
Performance of directionality： $\nu_e/\overline{\nu}_e$



(a) EfficientNet



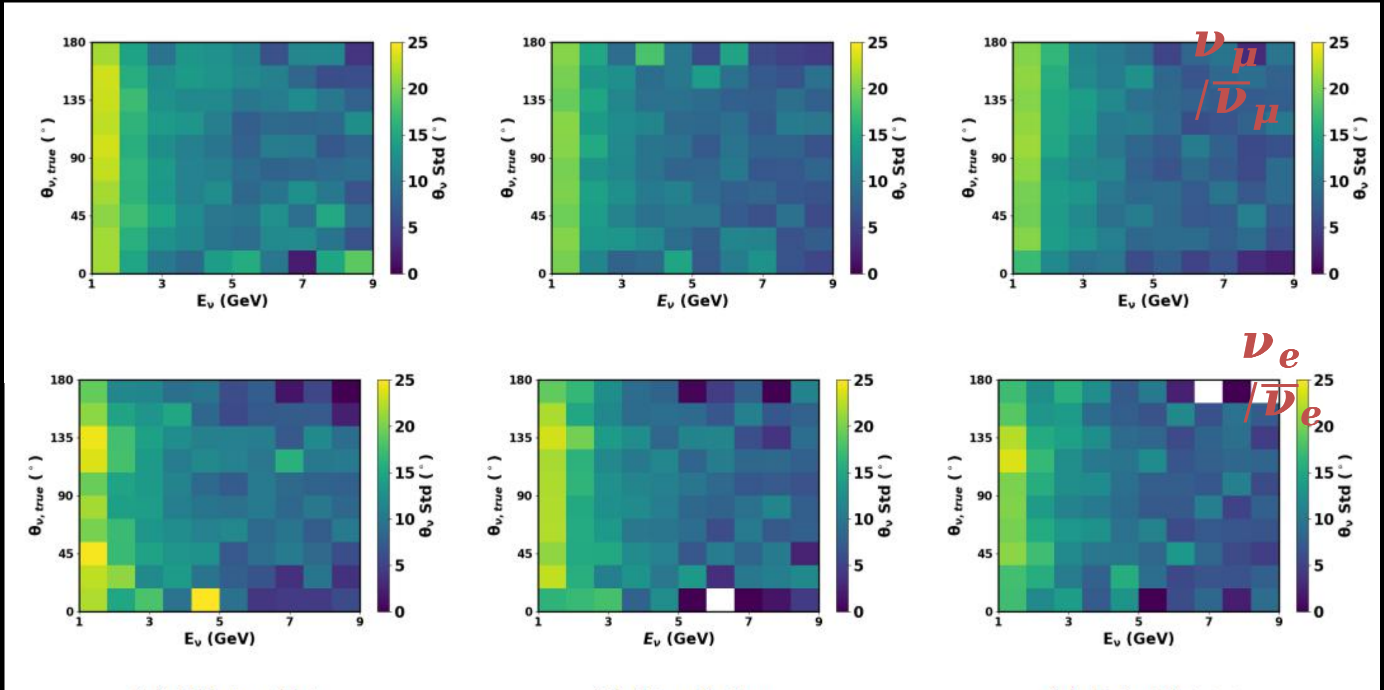
(b) DeepSphere



(c) PointNet++

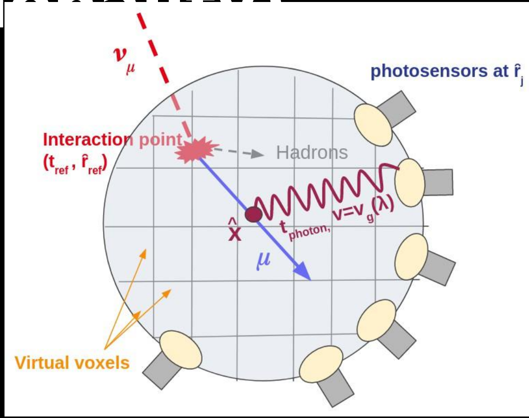
Performance of directionality: $\nu_e/\overline{\nu}_e$ $\nu_\mu/\overline{\nu}_\mu$

The two-dimensional distribution of directionality reconstruction performance



(a) EfficientNet (b) DeepSphere (c) PointNet++

Topological Reconstruction (directionality)



Idea: Reconstruct the photon emission probability distribution based on the detected hit charges and times

$$\hat{t}(x) = \underbrace{t_{ref}} \pm \underbrace{\frac{|\hat{x} - \hat{r}_{ref}|}{c_0}}_{t_{particle\ \mu/e}} + \underbrace{\frac{|\hat{r}_j - \hat{x}|}{v_g}}_{t_{photon}}$$

Includes: full simulation with electronics effects + waveform reconstruction

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ener ... ion neg ... e