Atmospheric neutrinos in JUNO

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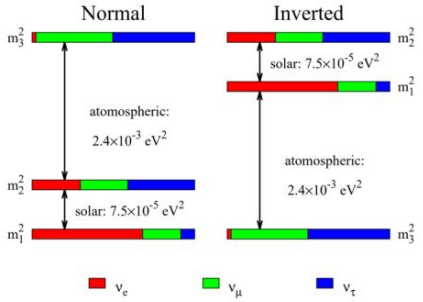
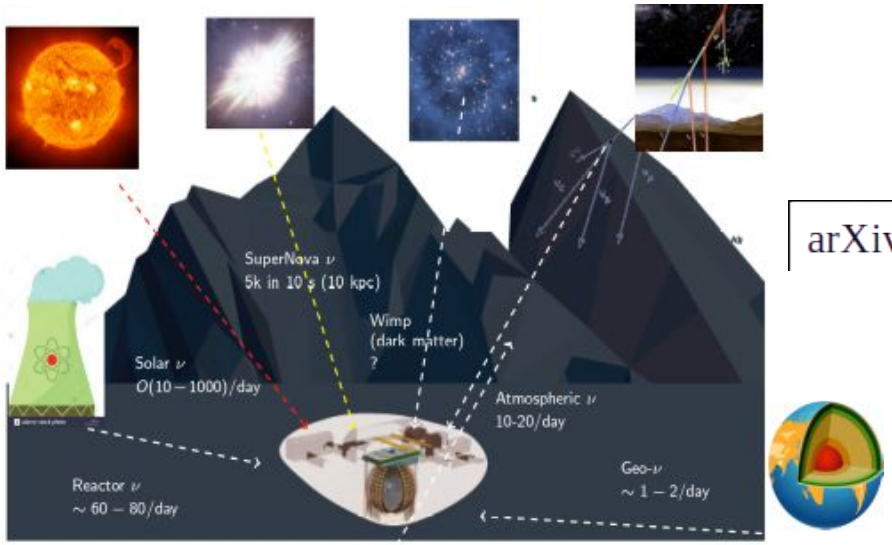
On behalf of the JUNO Collaboration

WIN 2025, 9-13 June, University of Sussex

Physics at Jiangmen Underground Neutrino Observatory

- **Neutrino Mass Ordering (NMO)measurement**
  - -Reactor: JUNO will determine NMO with 3σ significance in 6 years exposure
  - -Atmospheric neutrino: Combined analysis with reactor further improve the NMO sensitivity
- **Precision measurement of oscillation parameters**
  - for $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, world-leading precision in 100 days, and precision <0.5% in 6 years
- **Many other physics programs**
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova burst neutrinos
  - Supernova relic neutrinos
  - Exotic neutrinos
  - Nucleon decay
  - ...

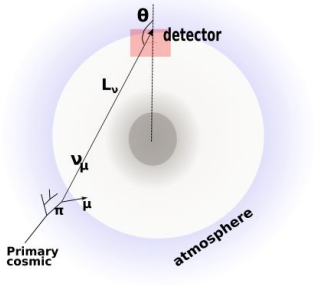


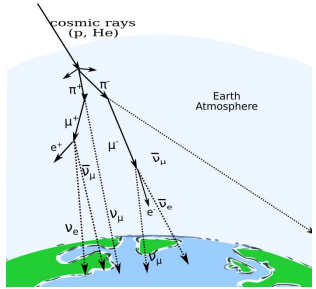


arXiv:2405.18008 (2024)

Atmospheric neutrino oscillation

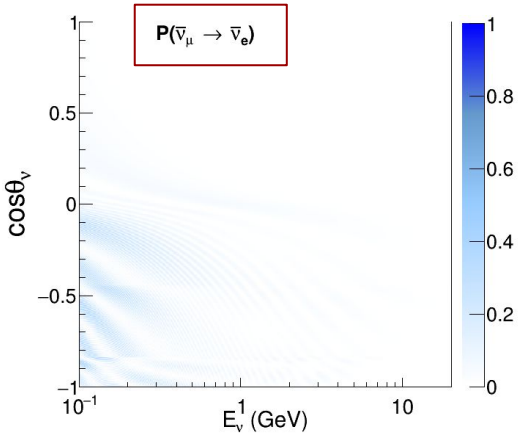
- Neutrino oscillation probabilities are function of neutrino energy, path length traversed, flavor identity and density of the medium
- Multi-GeV neutrinos go through matter effect (MSW effect) while passing Earth's matter if NMO is NO
- Antineutrinos have the matter effect if NMO is Inverted ordering
- Atmospheric multi-GeV neutrino and antineutrino passing through Earth offer complementary channel to measure NMO

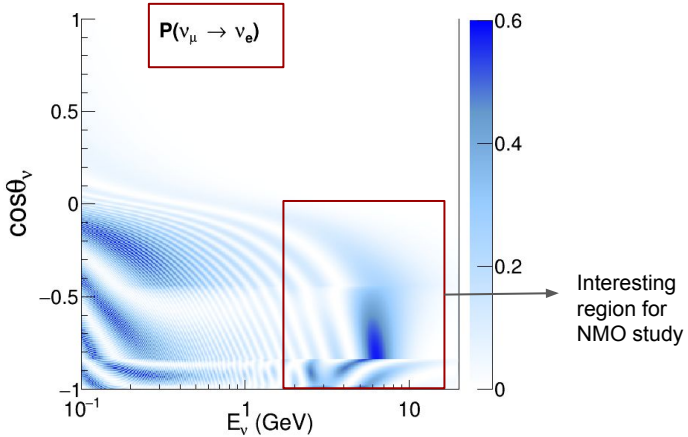




With normal ordering (NO): $m_3 > m_2 > m_1$

Good selection efficiency, energy, direction and particle ID reconstruction are crucial for oscillation studies

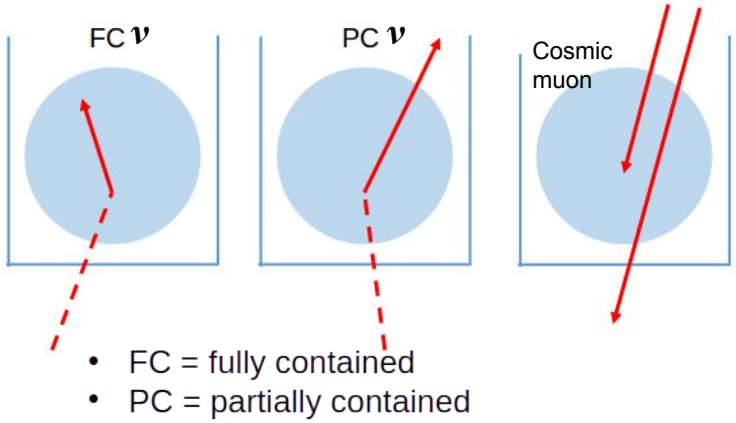




Cosmic muons vs. atmospheric neutrinos

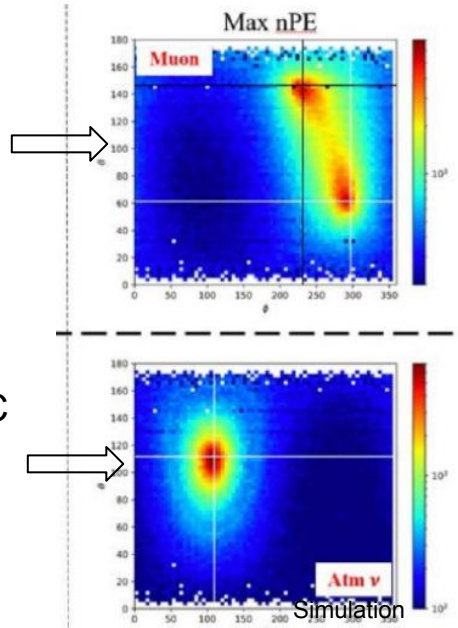
~650 m rock overburden suppress muon background
Expected muon rate ~ 5 Hz
Neutrino interactions in JUNO LS ~ 10/day

Correlation between CD and WP and TT is used to reject muons



Good purity can be achieved using PMT waveform features, max. charge distribution

Two red patches correspond to an entry and an exit points of muon



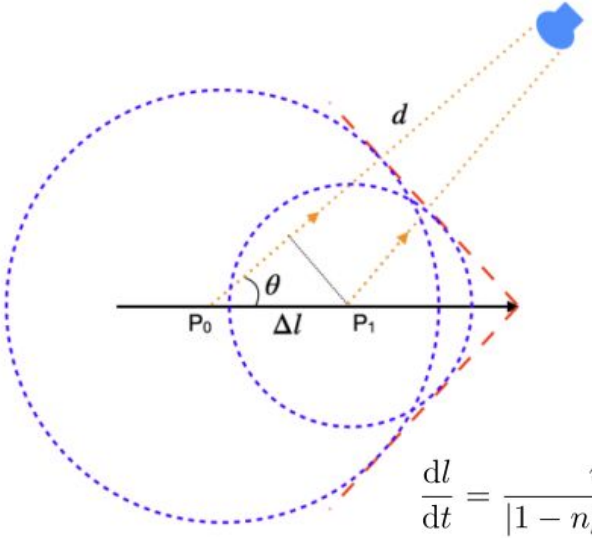
on the contrary, FC atm. ν has a single high nPE patch

Additional Veto PMTs on WP wall

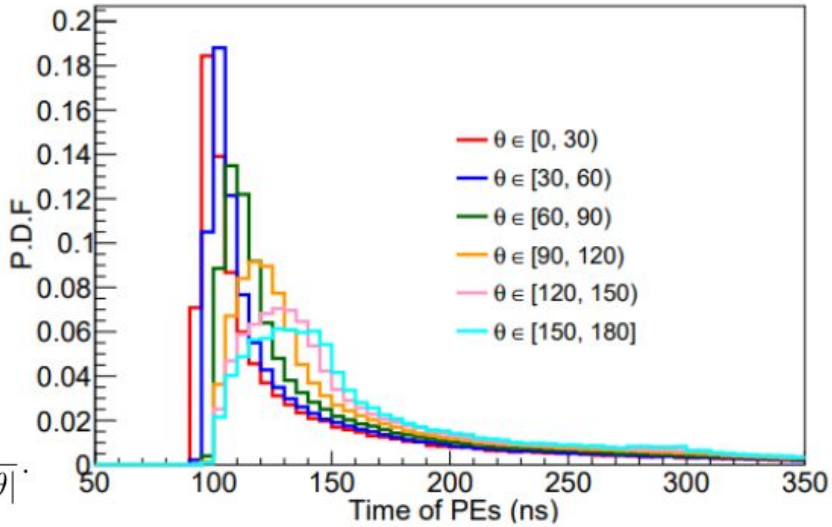
- 2 rings of 20” PMTs (348) and 2 rings of 8” PMTs (600) on the side of WP top wall
- Improve atmospheric neutrino reconstruction and muon selection
- More details of current status of JUNO : talk by **Marco Grassi @ 11:45 AM Thursday**

Direction reconstruction

- Scintillation light emission is isotropic, light emission from low energy particle is like point like
- High energy particles travelling with speed larger than light in the medium, scintillation light form cone light front structure, therefore, the first hit time in PMTs carry event directionality information



$$\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{v}{|1 - n\beta\cos\theta|}.$$

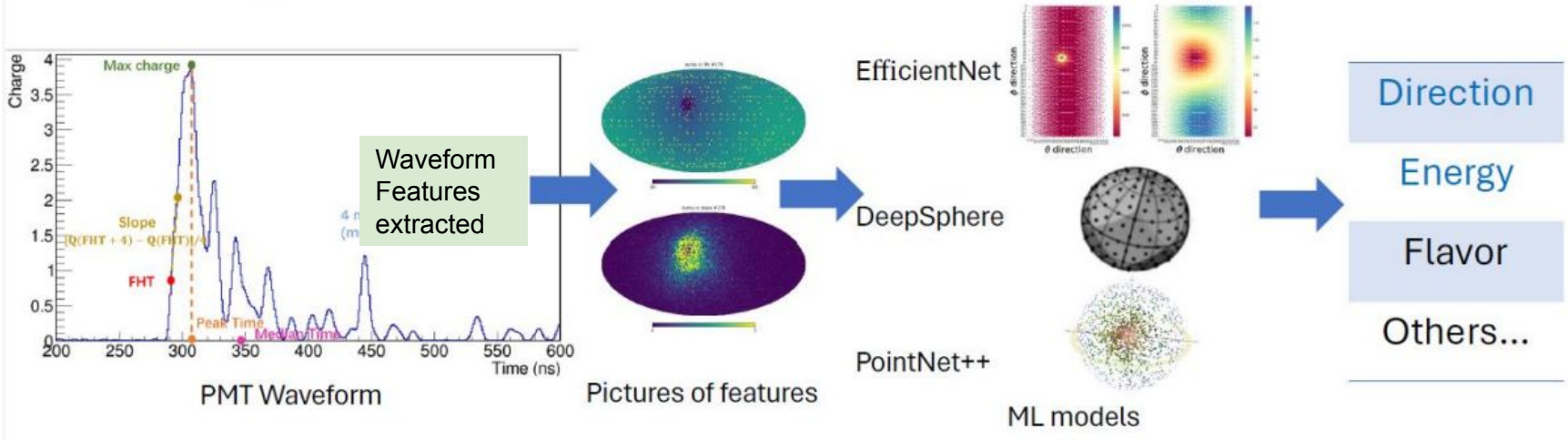


Particle directionality information is encoded within the PMT waveform

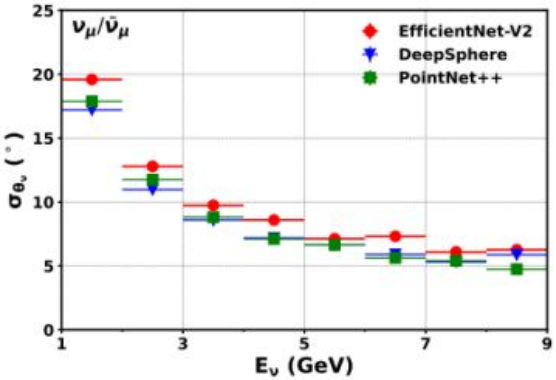
Multipurpose reconstruction method

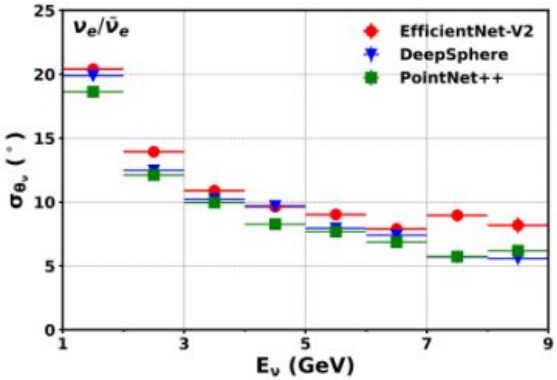
Two steps method

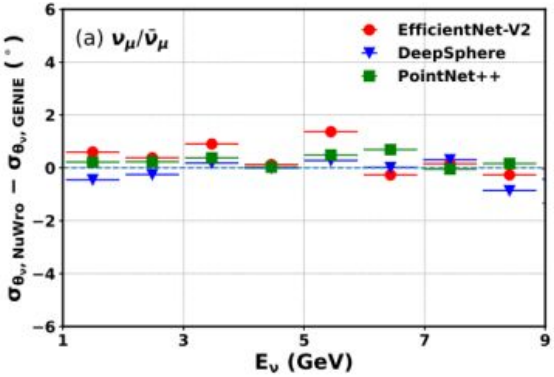
- Waveform features like first hit time, NPE, npe rising slope ets are extracted
- Feed these information to Machine learning training and reconstruct
  - Energy, direction and particle identity of neutrino

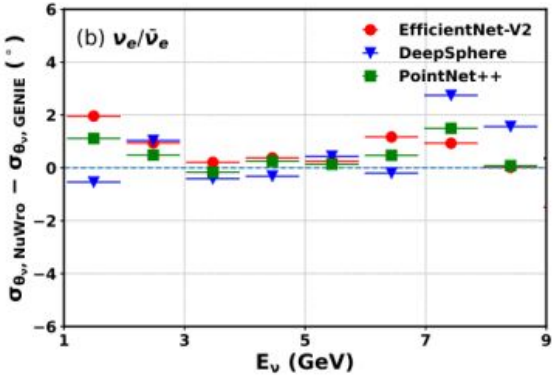


Angular resolution of neutrinos









Phys.Rev.D 109 (2024) 5, 052005

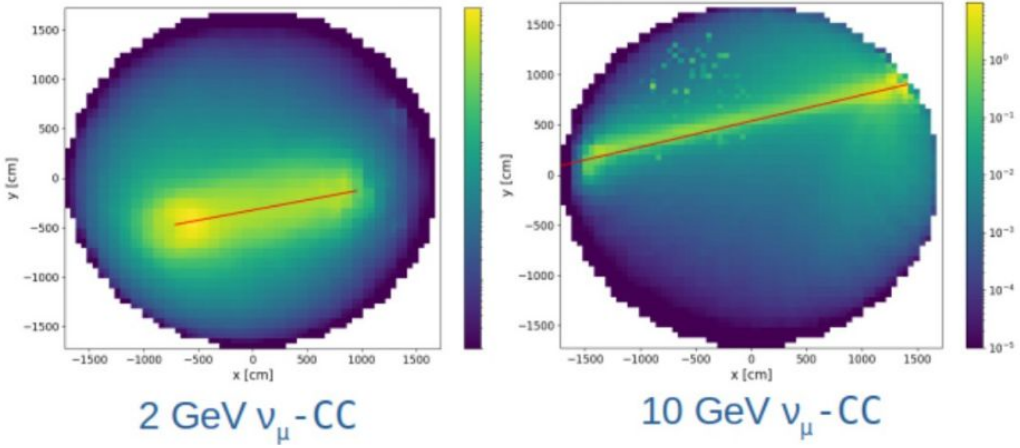
- For E > 3 GeV, angular resolution is around or better than 10 degrees
- Performance with generators GENIE, NuWro found to be comparable

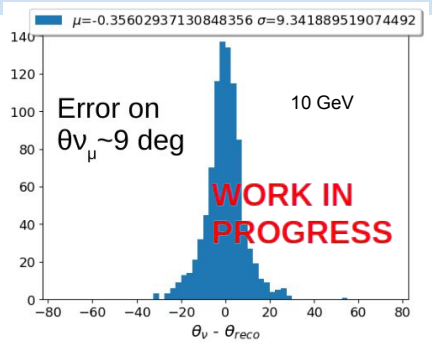
Direction reconstruction

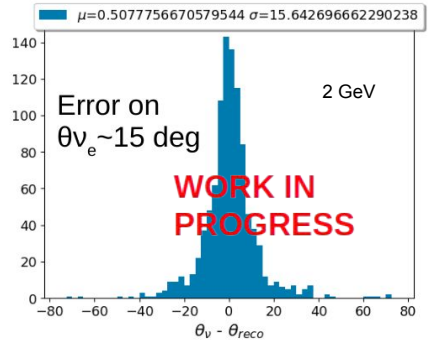
Compare with the traditional method: based on reference point in space and time, likelihood approach is adopted using the first hit time at PMTs and characterizing photon production, propagation, and detection

ML-method works better (specially for electron neutrinos) because this algorithm only uses charge and time (no extra features), but similar order of magnitude

PoS(ICRC2023)1189



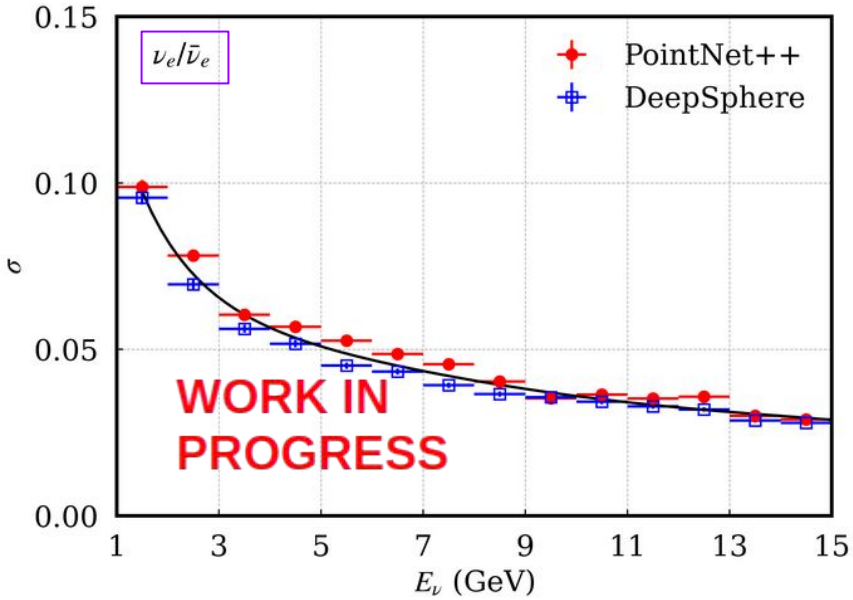


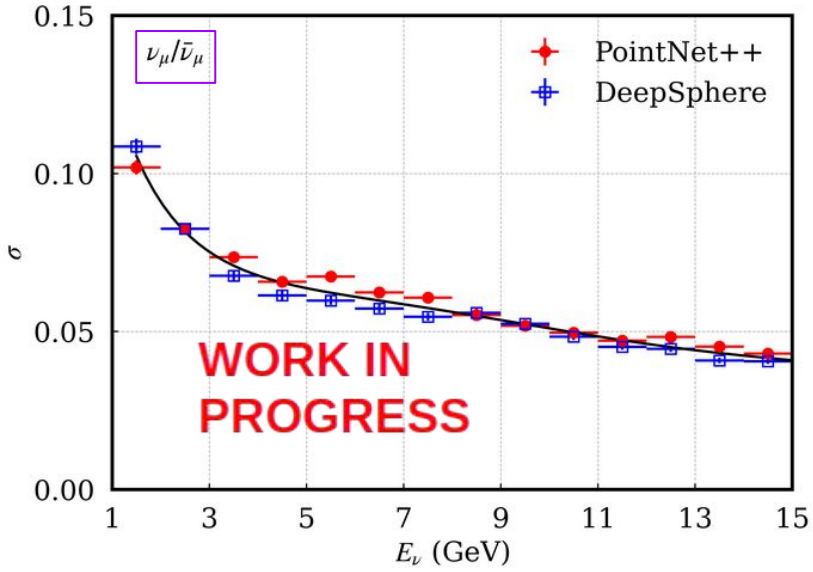


Energy reconstruction

at E > 3 GeV

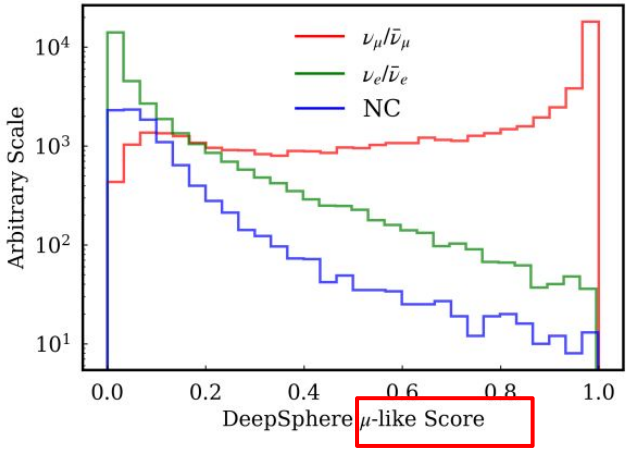
- For electron neutrino, better than 6%,
- For muon neutrino, better than 8%

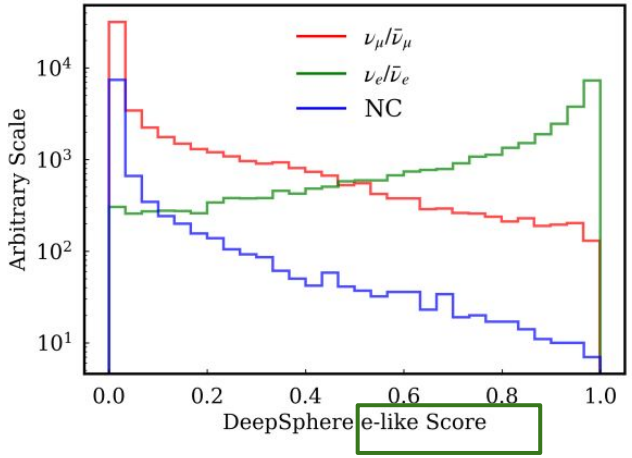




Neutrino flavor identification

- The topology information (of events are reflected in the PMT waveforms
- **PMT waveform features of Prompt trigger** information are used for ML model training to classify **μ**-like, ***e***-like or **NC**-like events





An event is classified to the category with the largest score by default

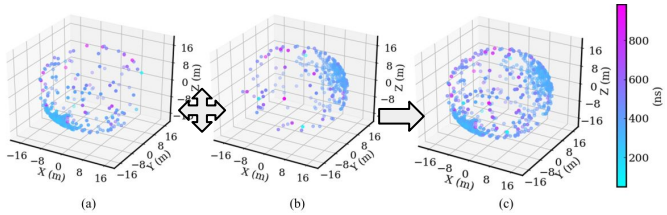
arXiv:2503.21353[hep-ex]

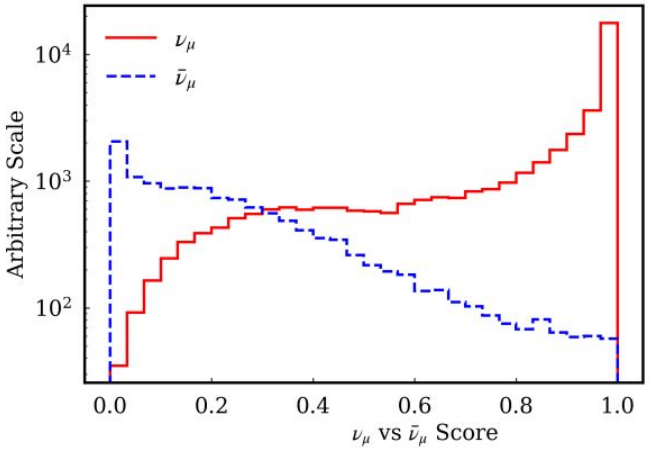
Neutrino vs antineutrino

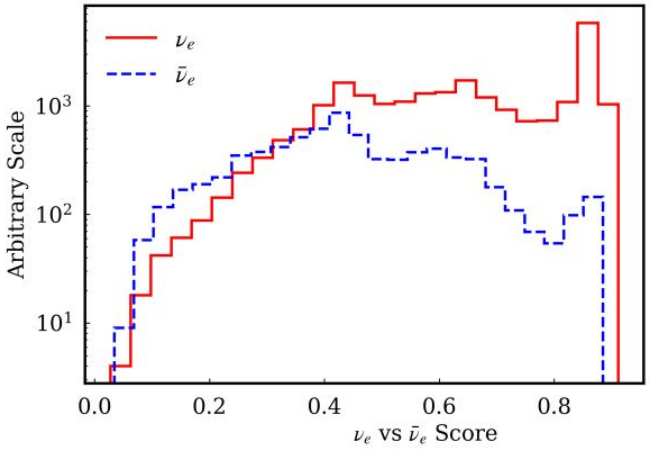
Antineutrino interactions tend to produce more primary neutrons than neutrino interaction

For training ML, in addition to PMT waveform information of prompt trigger, neutron information from delayed triggers is used

- With energy between 2-2.7 MeV
- delayed time between 10 μs and 1 ms







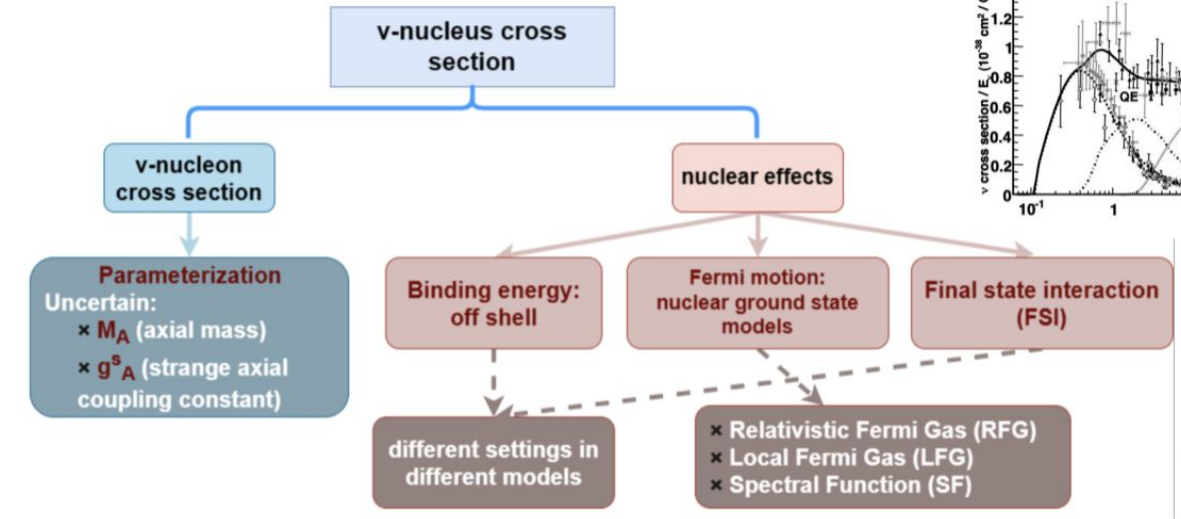
marges multiple delayed triggers into one, summing up charges and take first hit time of earliest

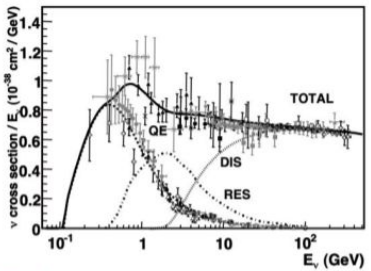
arXiv:2503.21353[hep-ex]

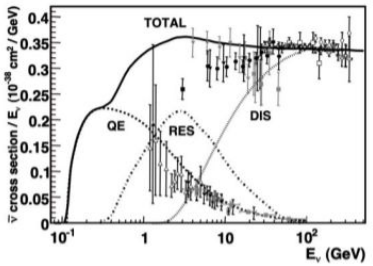
Interaction models

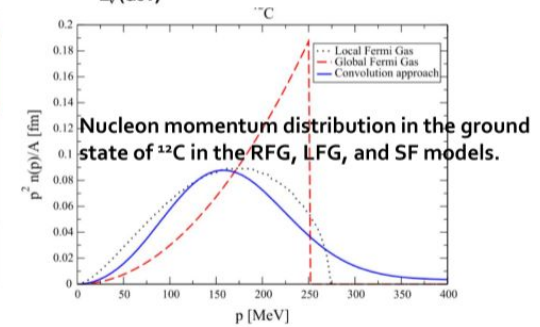
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

Brief summary of GeV neutrino interaction models









- GeV neutrino interaction is model dependent! Existing generators at JUNO:
  - GENIE/NuWro/GiBUU
  - NEUT incorporation in progress
- We are working on the latest versions of the generators, within the Gev v-A high-eNergY MEDium Effect (GANYMEDE) working group

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Major improvements in detector response

Detector response	Previous estimate	New developments	New features used
Event selection	ν_e: Evis > 1 GeV $Y_{vis} = E_{had}/E_{vis} < 0$ ν_μ: $L\mu > 5$ m	**$E_{vis} > 1$ GeV** ~30% more statistics	
Reconstruction (energy and direction)	**$\sigma_{Evis} = 1\%/\sqrt{E_{vis}}$** **$\nu_e$: $\sigma_{\theta\nu e} = 10^\circ$** **$\nu_\mu$: $\sigma_{\theta\mu} = 1^\circ$**	E_ν reconstruction instead of E_{vis} **$\sigma_{\theta\nu} < 10^\circ$ ($E_\nu > 4$ GeV)** E_ν dependent	ML-based on PMT features: first hit time, time and charge at peak in waveform
Particle identification	**NC/CCν_e/CCν_μ → 100%** neutrino / anti-neutrino: → based on michel electron N_e and Y_{vis}	**80–95% efficiency** E_ν dependent **60% ~80% efficiency:** better separation neutrino / anti-neutrino	ML-based on PMT features for primary triggers and neutron (secondary) triggers

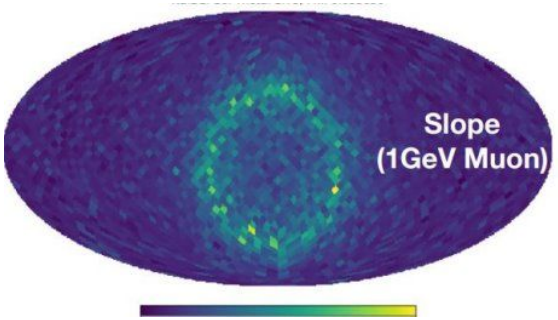
New analysis of atmospheric neutrino in progress!

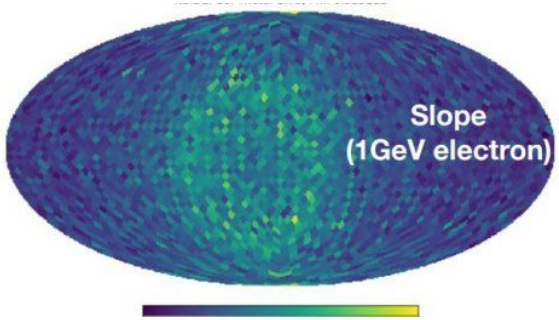
Summary and conclusions

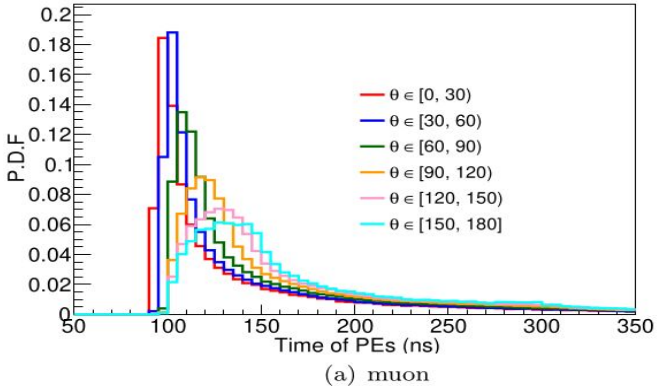
- The large homogeneous liquid scintillator (LS) detectors are capable of reconstruct the energy, direction and PID of GeV energy neutrinos
- The high efficiency of neutron capture rate in LS is advantageous to separate neutrinos from antineutrinos in JUNO
- Atmospheric neutrino study in JUNO is promising to boost the overall NMO sensitivity of JUNO
- A new atmospheric neutrino study in JUNO is ongoing with the latest and realistic detector response, the paper will appear soon.
- LS filling of JUNO is now ongoing and half of the filling already done, stay tuned for exciting results from commissioning, full water phase, and mixed phase data.

Thank you!

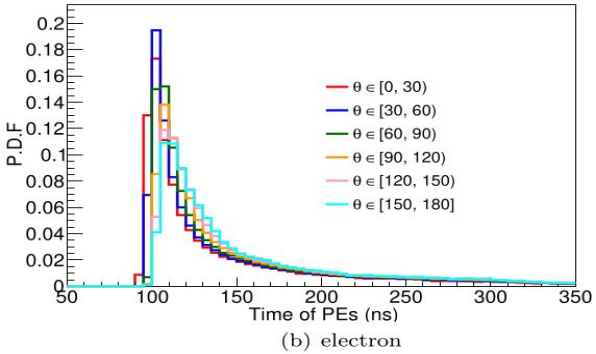
‘Slope’ of waveform in flavor identification







(a) muon

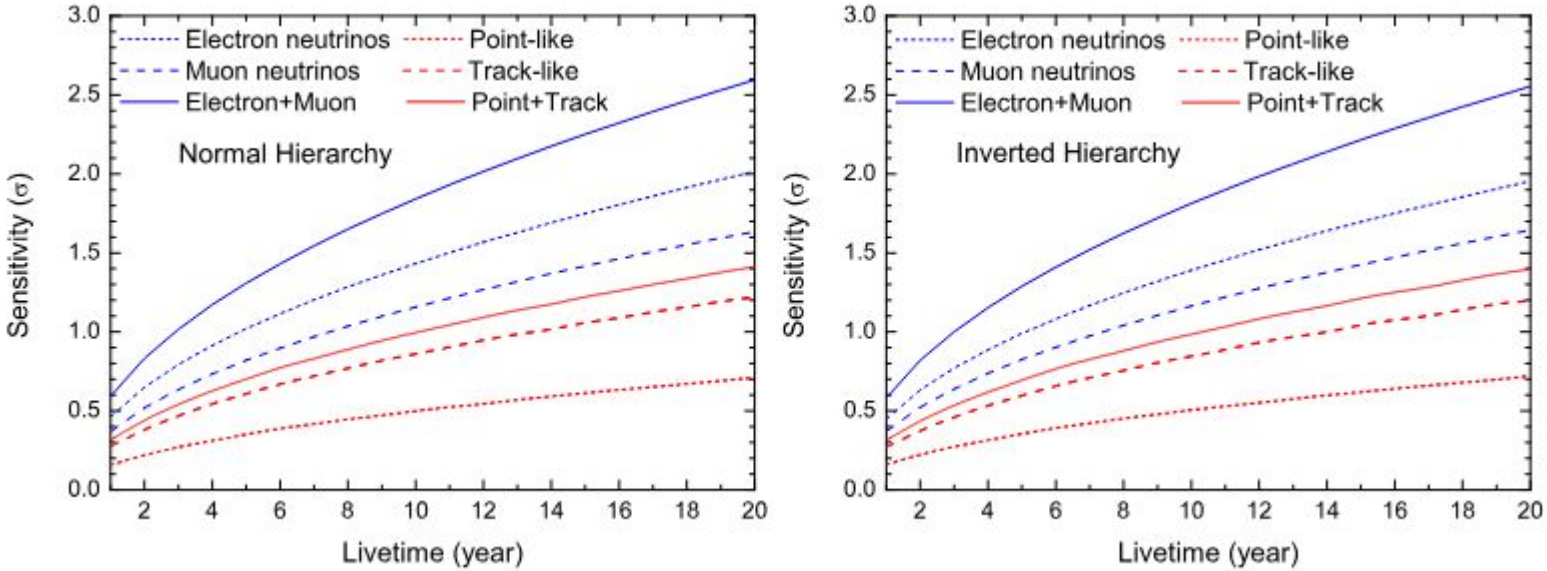


(b) electron

- Electron showers are spatially more confined than muon tracks
- This is reflected in PMT waveform charge evolution, particularly in the rising slope over time

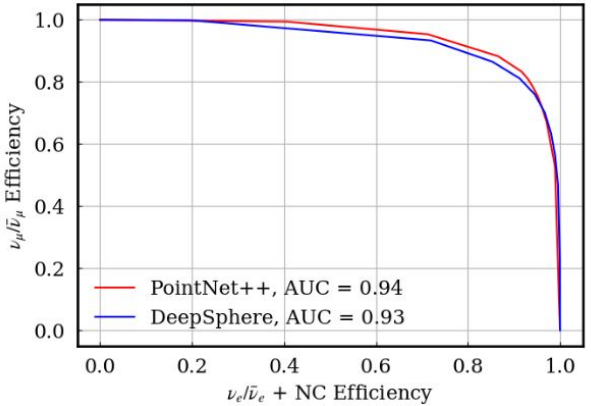
JUNO's NMO sensitivity with atmospheric neutrino

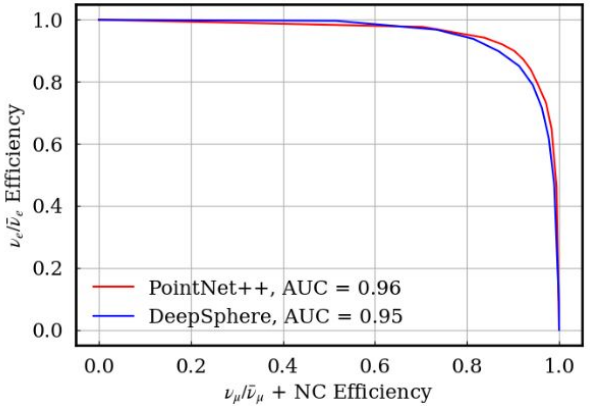
J. Phys. G 43 (2016) 030401

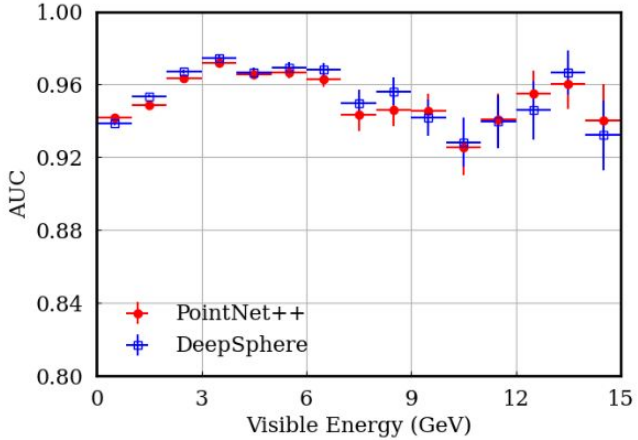


Performance of flavor identification method

More steeper the Receiver operating characteristic (ROC), better the separation





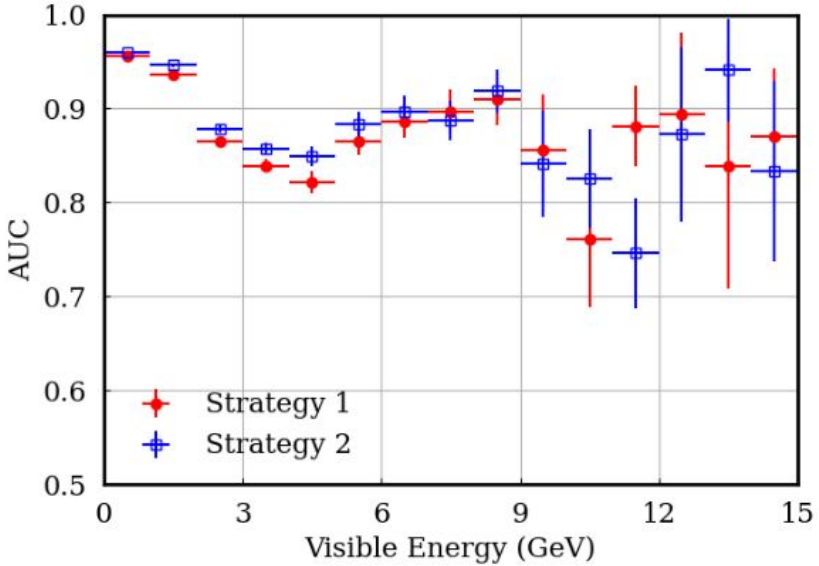


- The performance of two different ML models are similar
- For oscillation analysis the score can be tuned depending on the requirement

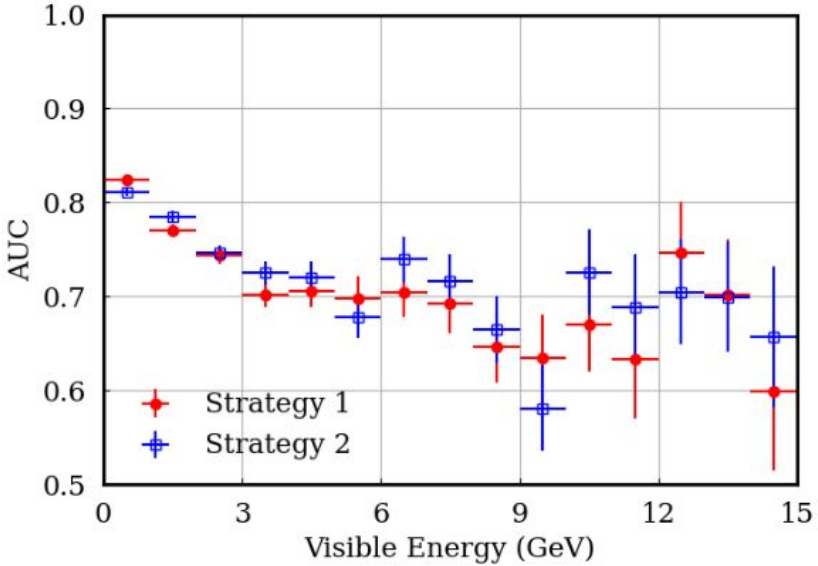
arXiv:2503.21353[hep-ex]

Performance of the PID reconstruction

arXiv:2503.21353[hep-ex]



(a) $\nu_\mu/\bar{\nu}_\mu$ identification



(b) $\nu_e/\bar{\nu}_e$ identification