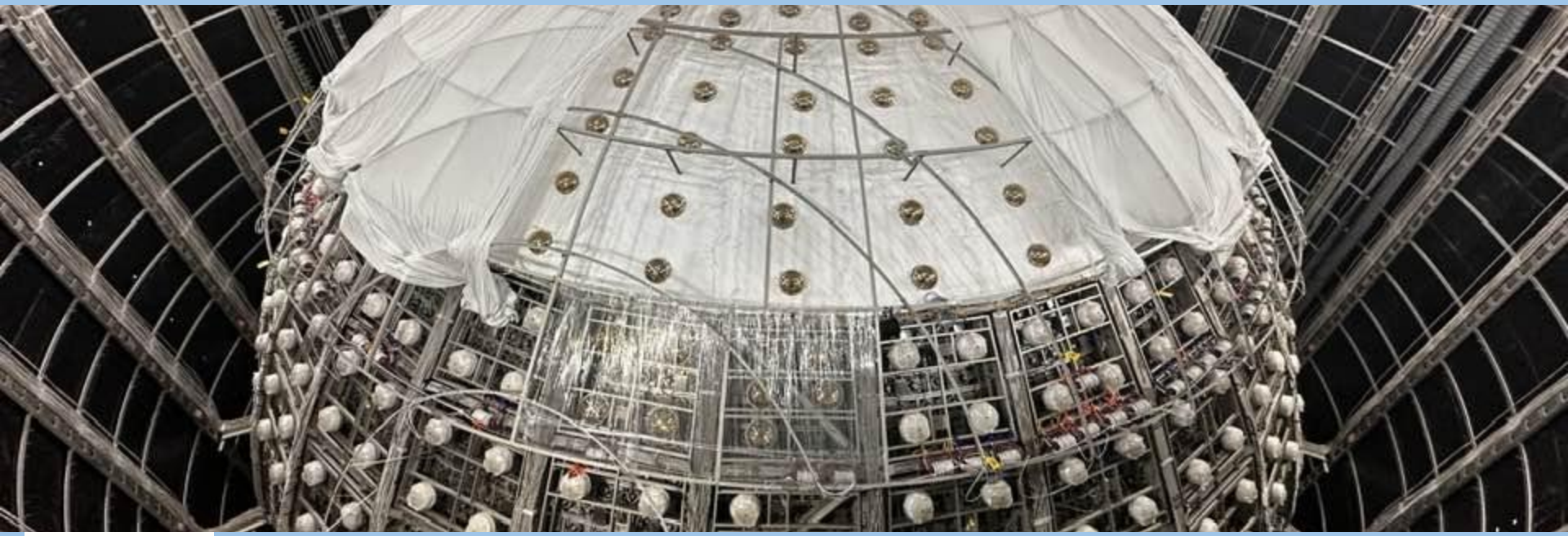
Atmospheric neutrinos in JUNO



Marta Colomer Molla
On behalf of the JUNO Collaboration

ICRC 2025, 15th July, Geneva

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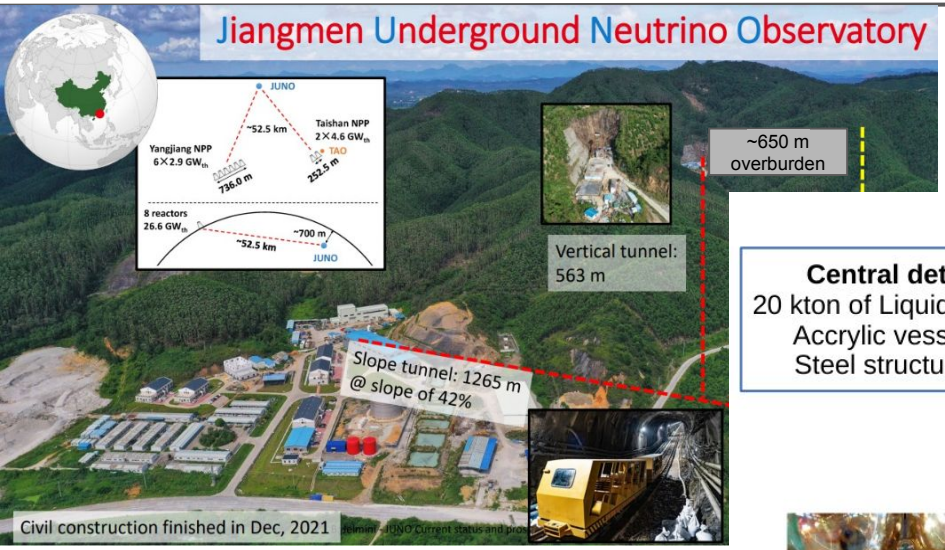
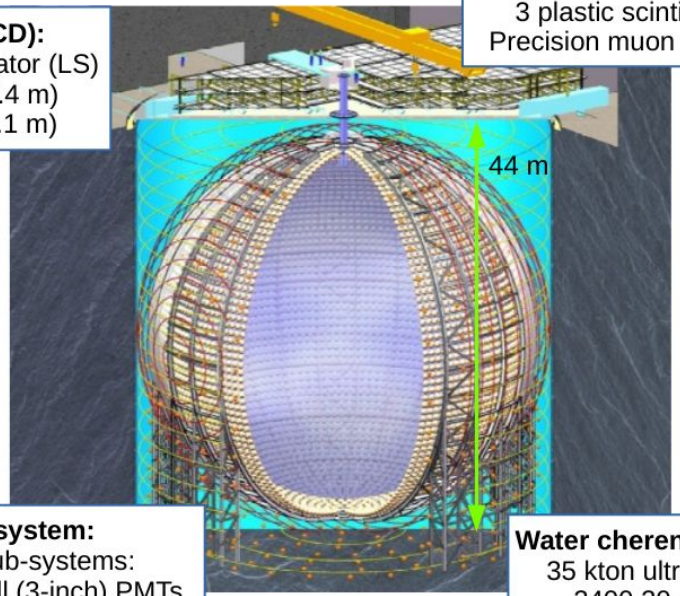
The Jiangmen Underground Neutrino Observatory (JUNO)



Central detector (CD):
20 kton of Liquid Scintillator (LS)
Accrylic vessel (ϕ 35.4 m)
Steel structure (ϕ 40.1 m)

Top Tracker:
3 plastic scintillator layers
Precision muon tagging (veto)

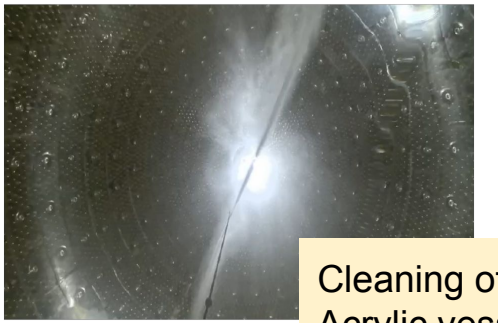


Light detection system:
>40000 PMTs in 2 sub-systems:
large (20-inch) and small (3-inch) PMTs

Water cherenkov detector:
35 kton ultra-pure water
2400 20-inch PMTs

JUNO status: detector filling and commissioning

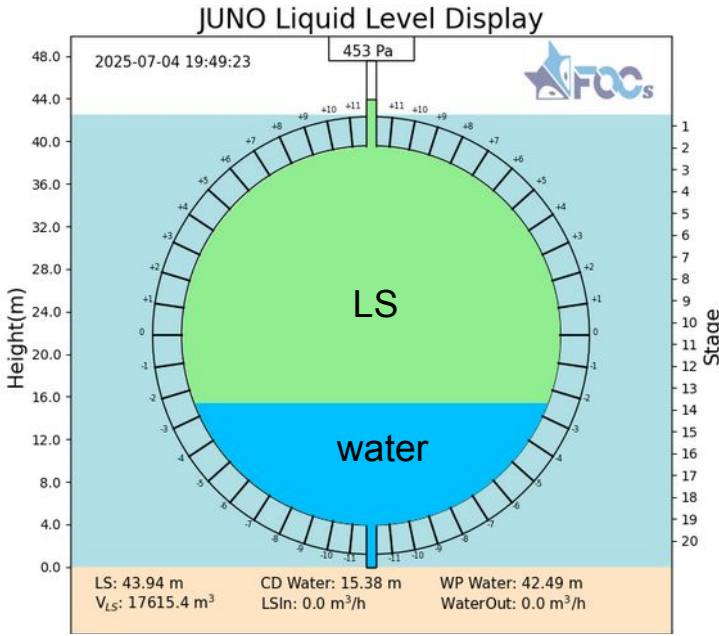
1st Dec. 2024 Installation finished



Cleaning of CD Acrylic vessel

18th Dec. 2024 – 1st Feb. 2025: Water filling

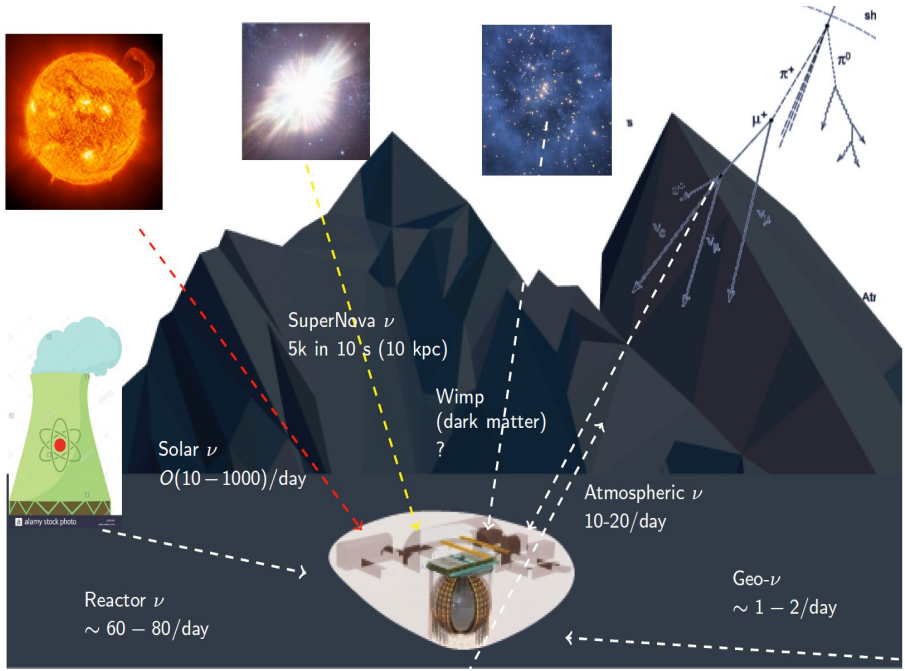
7th Feb. 2025 – today: Liquid Scintillator (LS) filling



Talk by Cong Guo on 17th July

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 — Talk by A. Gavrikov tomorrow
  - Geo-neutrinos
  - Supernova burst neutrinos
  - Supernova relic neutrinos — Talk by Yufeng Li tomorrow
  - Exotic neutrinos
  - Nucleon decay
  - ...

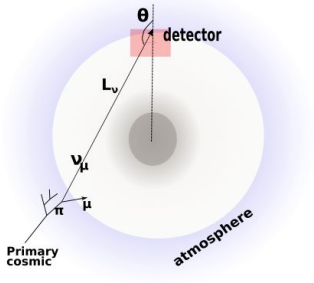


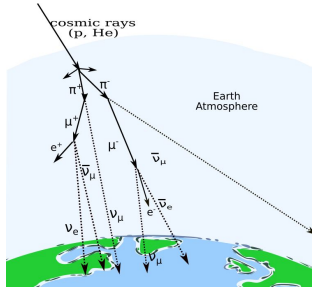
Atmospheric neutrino oscillations

- Atmospheric neutrinos (of several GeV) going through Earth's matter undergo the MSW effects

  -> they offer complementary channel to measure the NMO

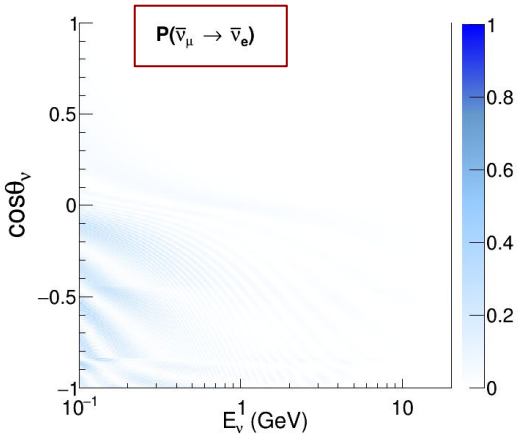
- Matter effects depend on the neutrino energy, incident angle, and type
- Oscillation probabilities under MSW effect are affected by the NMO

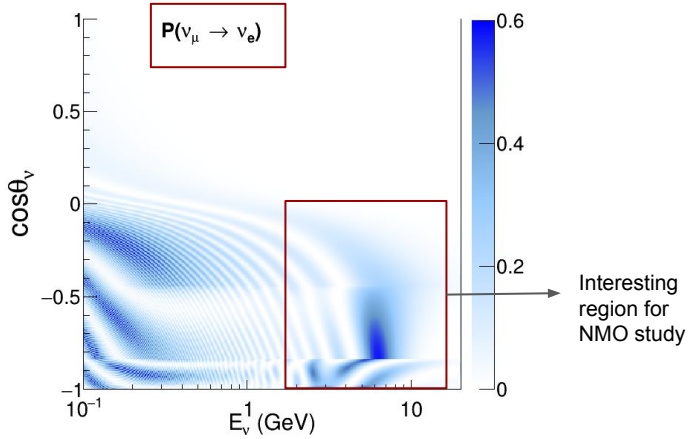




With normal ordering (NO): $m_3 > m_2 > m_1$

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

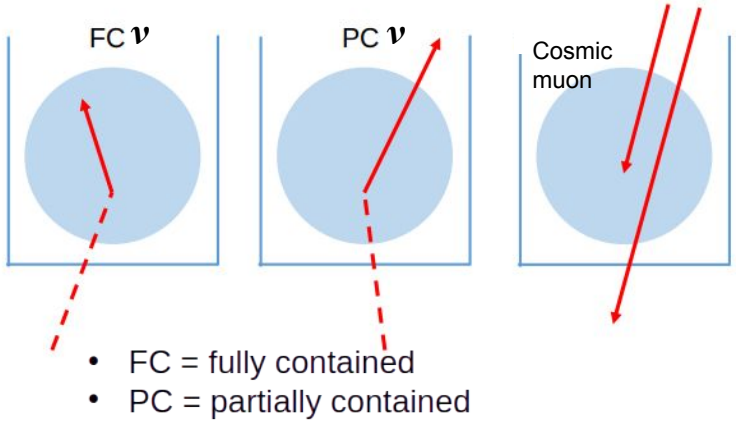




Cosmic muons vs. atmospheric neutrinos

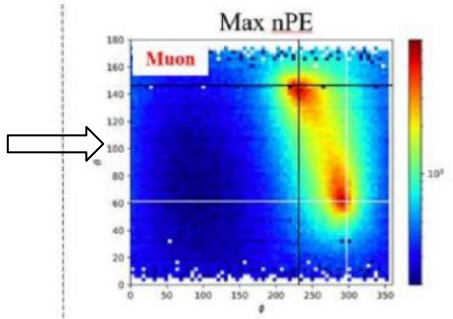
~650 m rock overburden suppress muon background
Expected muon rate ~ 5 Hz
Neutrino interactions in JUNO LS ~ 10/day

Correlation between CD and WP and TT are used to suppress most of the muons

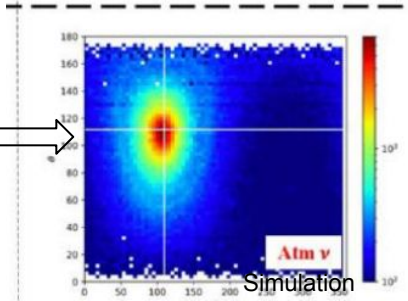


Remaining muons can be removed using PMT features (charge and time patterns)

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

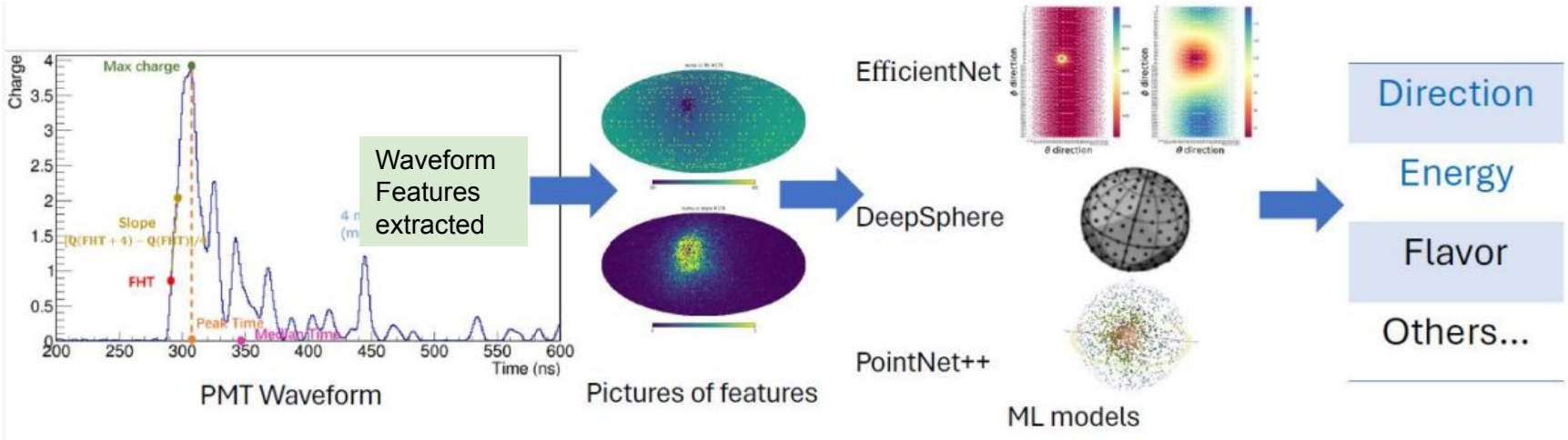


Additional Veto PMTs on WP wall to improve muon veto

- 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

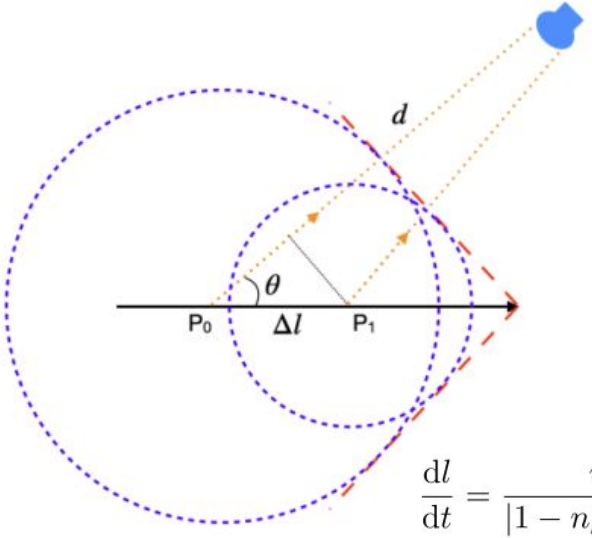
Multipurpose reconstruction method

- Waveform features are extracted: first hit time, NPE, slope…
- Feed these information to Machine Learning models, trained to reconstruct the neutrino events

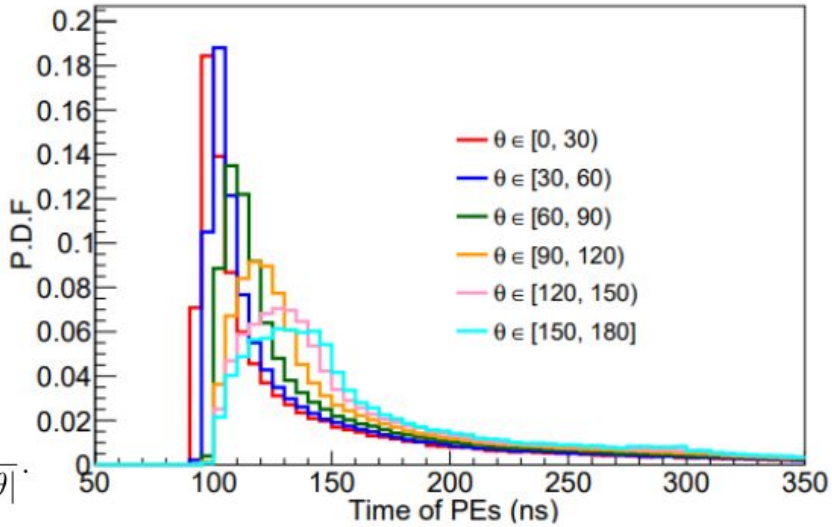


Direction reconstruction

- 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

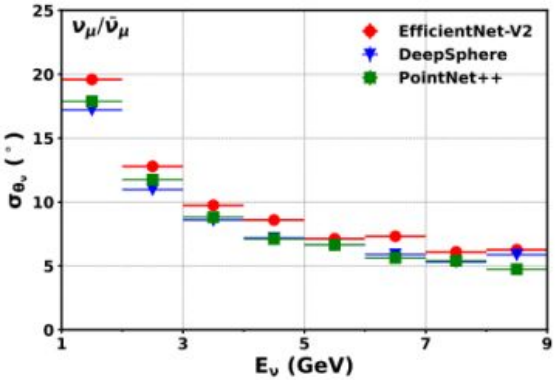


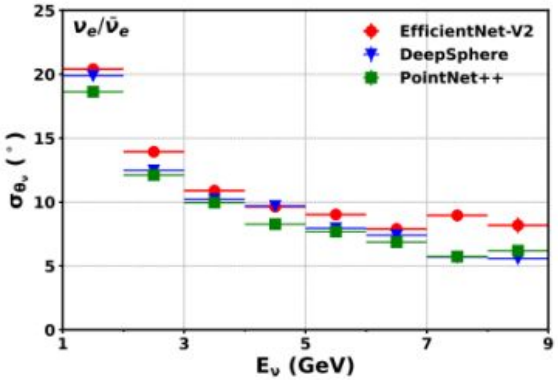
$$\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{v}{|1 - n\beta\cos\theta|}.$$

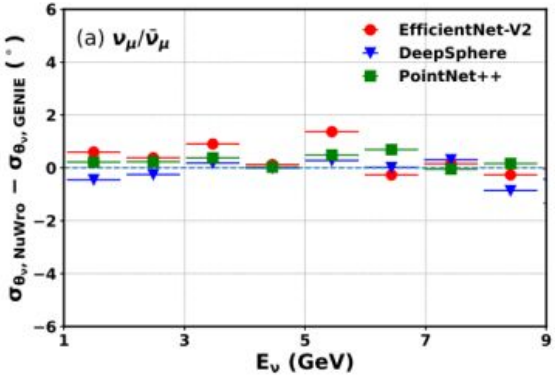


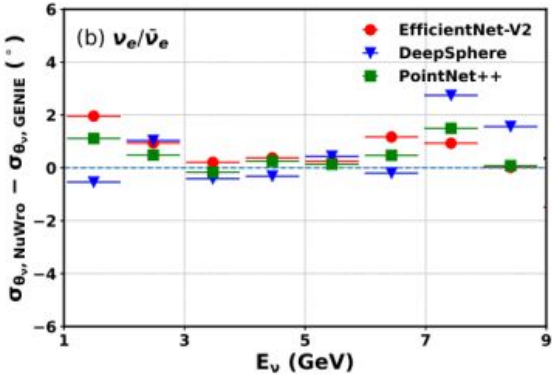
Particle directionality information is encoded within the PMT waveform

Angular resolution









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

- For Eν > 3 GeV, angular resolution is around <~ 10 deg
- Interaction model impact: Performance with GENIE and NuWro found to be comparable

Direction reconstruction

Compare with the traditional method: likelihood method to use the light pattern observed in the PMTS to reconstruct the emission probability -> trace back the particle trajectory -> angle

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

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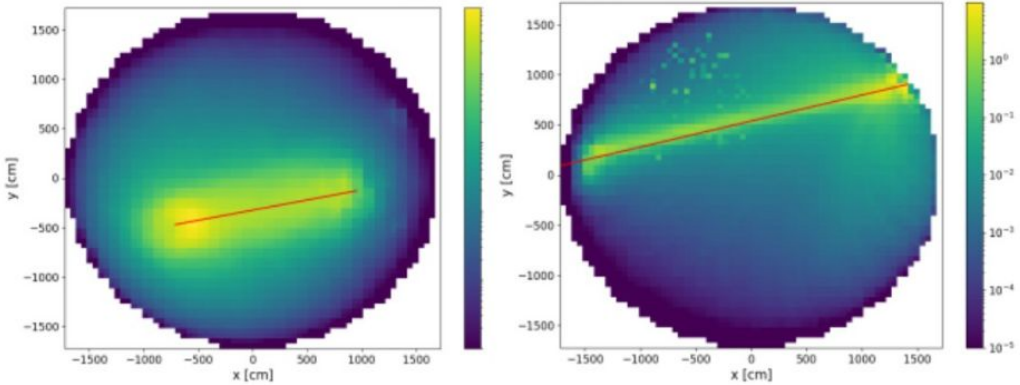
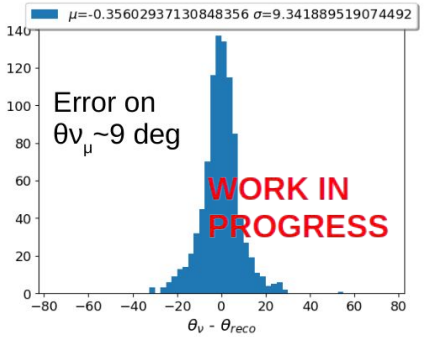
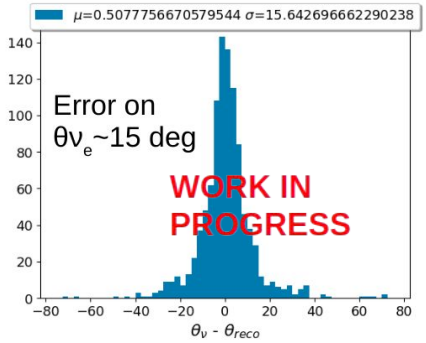


2 GeV ν_μ-CC

10 GeV ν_μ-CC

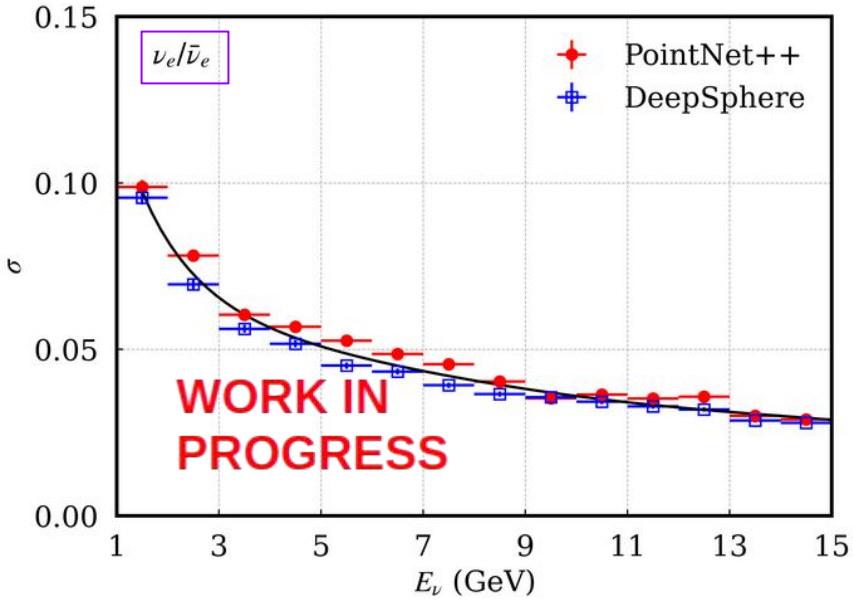


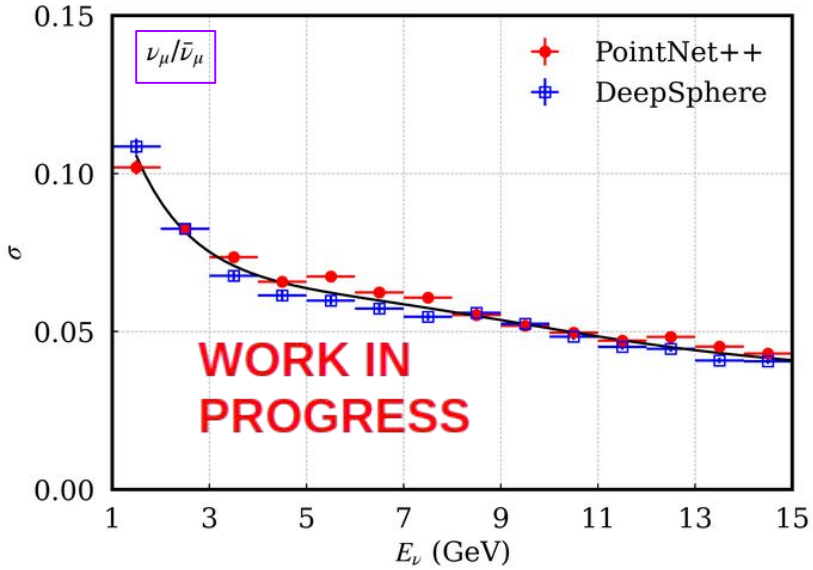


Energy reconstruction

At Eν > 3 GeV

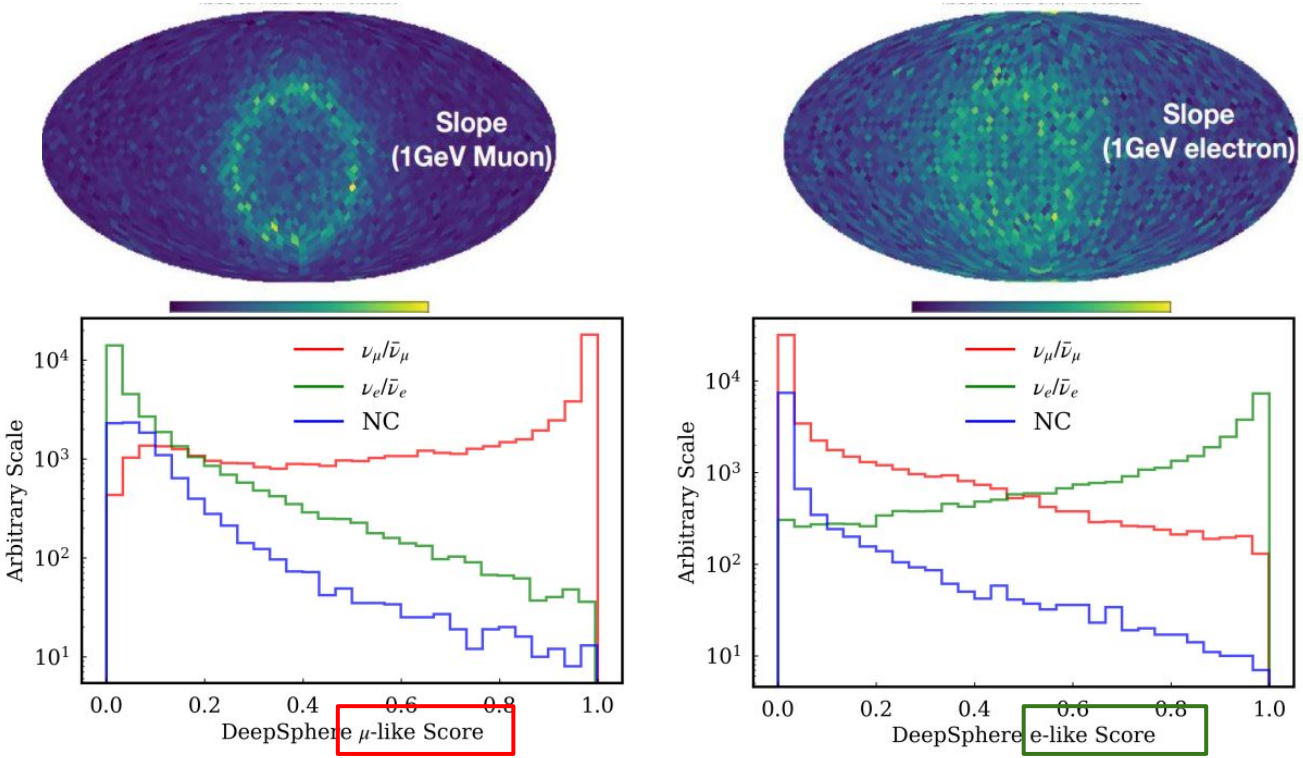
- For electron neutrino, better than 6%,
- For muon neutrino, better than 8%





Neutrino flavor identification

- The event topology information is reflected in the PMT waveforms
- **PMT waveform features (prompt trigger)** are used to classify: **μ**-like, ***e***-like and **NC**-like



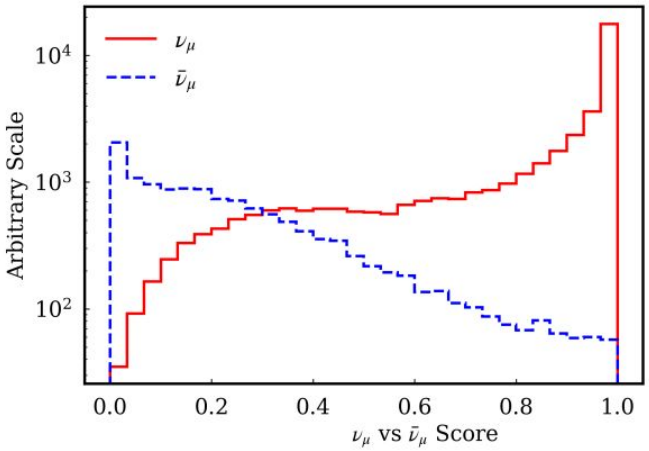
arXiv:2503.21353[hep-ex]

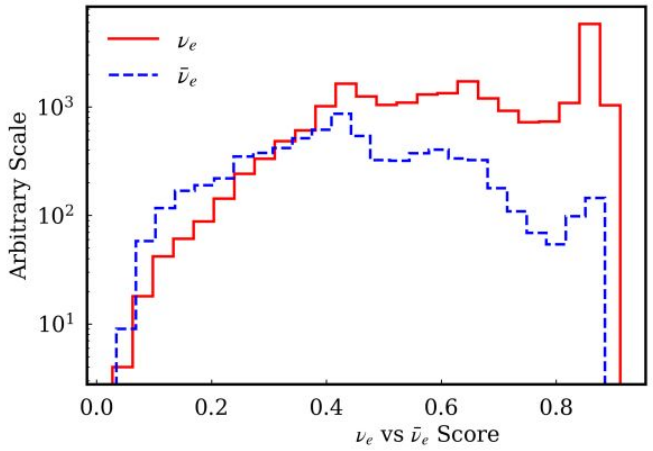
Neutrino vs antineutrino

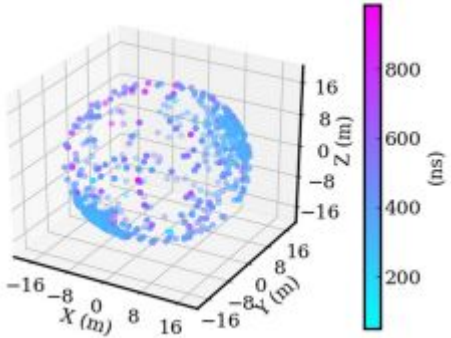
- Antineutrinos transfer less energy to hadrons (less hadronic interaction): encoded in PMT waveform
- Antineutrino interactions tend to produce more primary neutrons than neutrino interaction:

In addition to PMT waveform information of prompt trigger, neutron information from delayed triggers is also used

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







arXiv:2503.21353[hep-ex]

Summary and conclusions

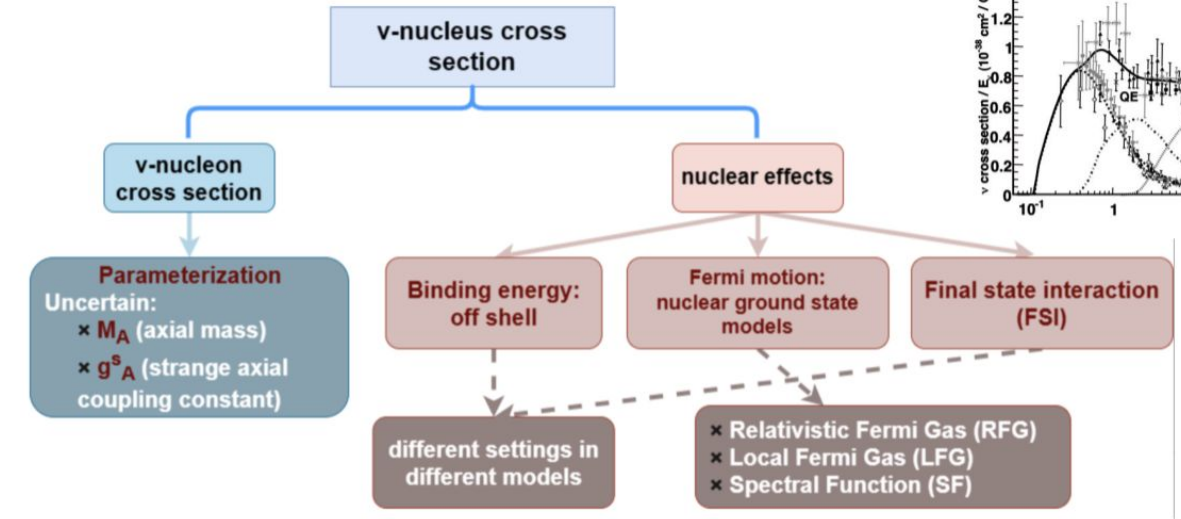
- The large homogeneous liquid scintillator (LS) detectors are capable to reconstruct the energy, direction and type (PID) atmospheric neutrinos
- Atmospheric neutrino study in JUNO is promising to boost the overall NMO sensitivity of JUNO
- New atmospheric neutrino study in JUNO ongoing with the latest and more realistic detector response -> paper coming soon.
- LS filling and commissioning of JUNO is ongoing (15.5/20 kton done), will finish in September -> stay tuned for exciting results

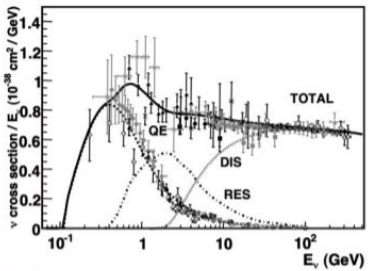
Thank you!

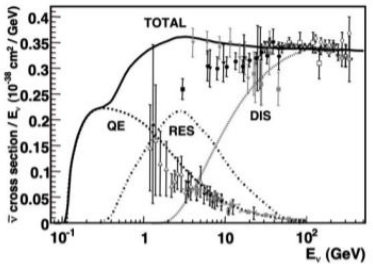
Interaction models

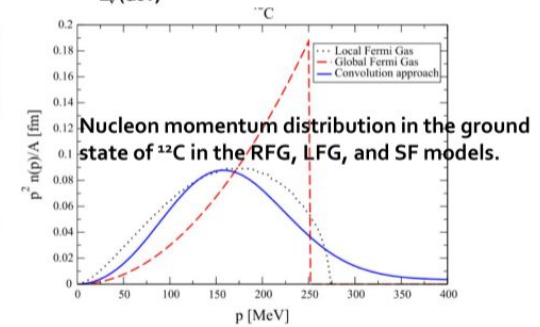
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

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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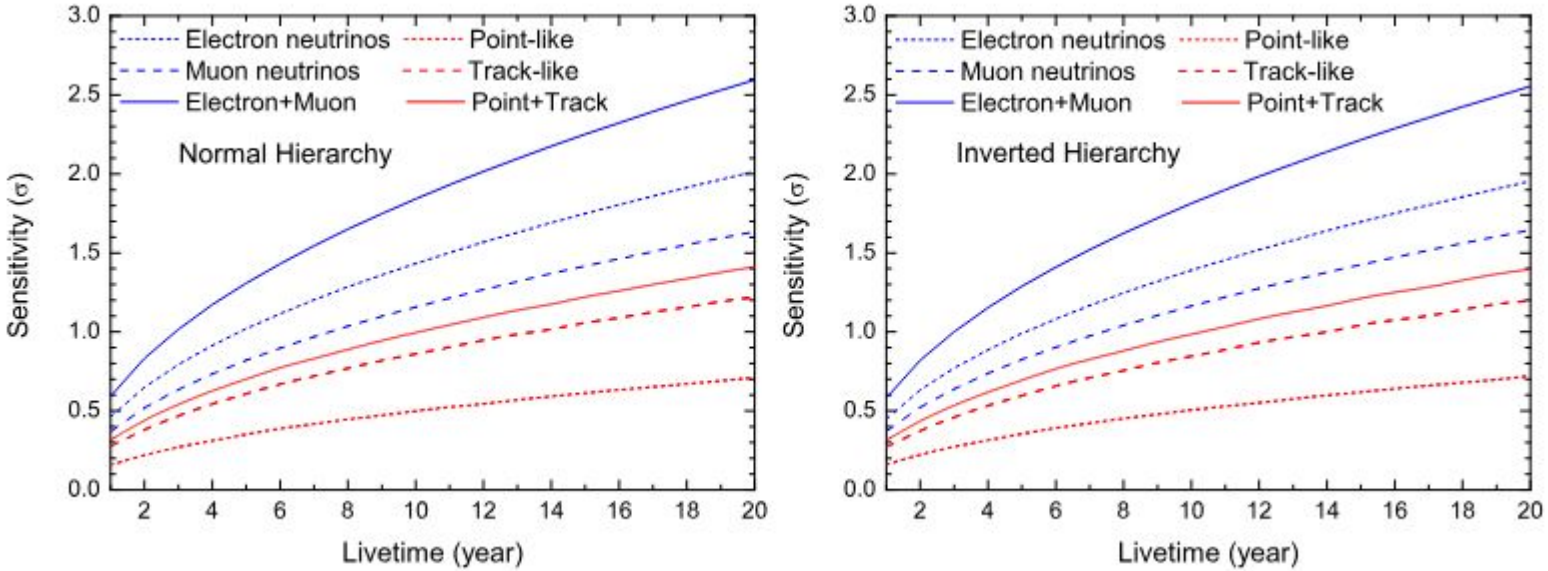
Major improvements in detector response

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!

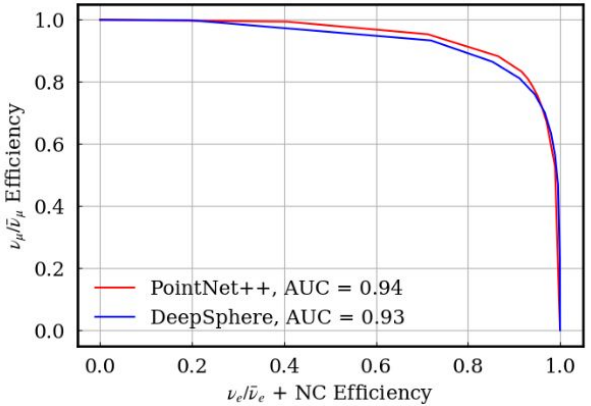
JUNO's NMO sensitivity with atmospheric neutrino

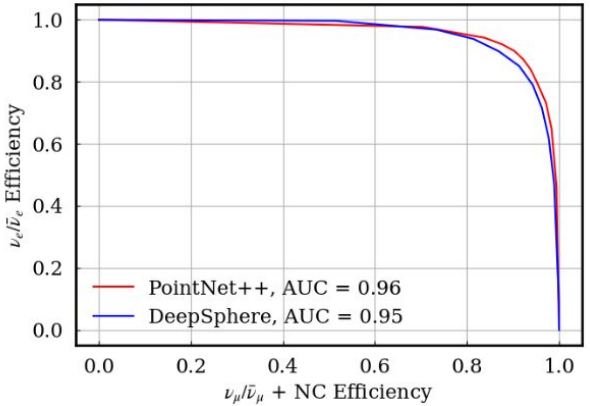
J. Phys. G 43 (2016) 030401

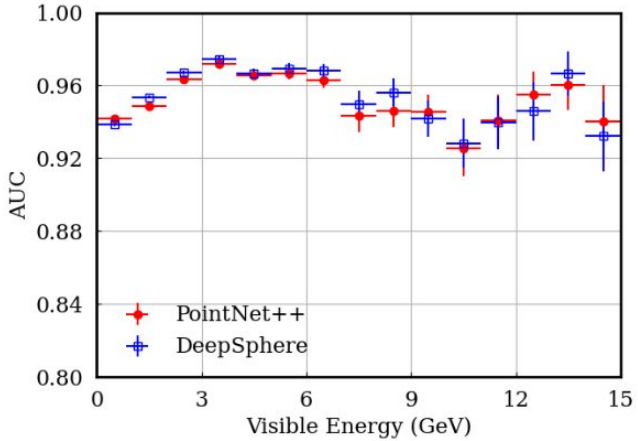


Performance of flavor identification method

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





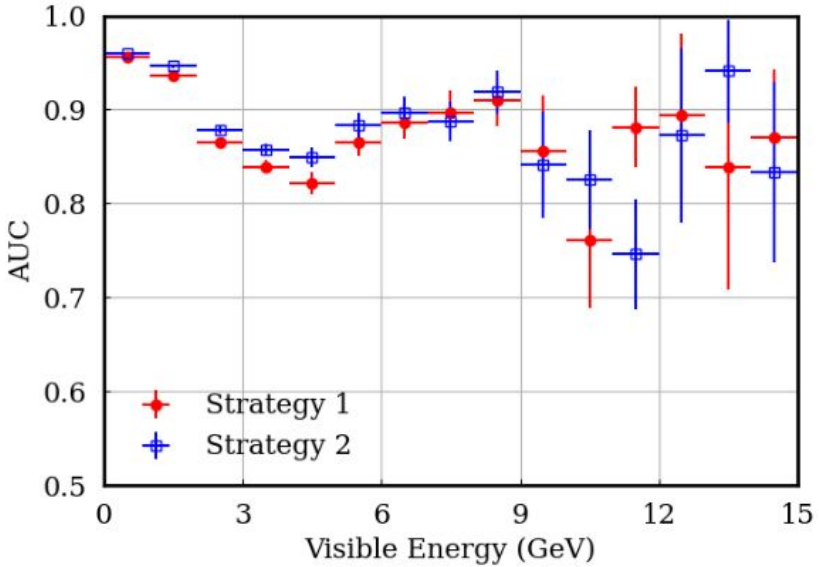


- The performance of two different ML models are similar
- For oscillation analysis the score can be tuned depending on the requirement

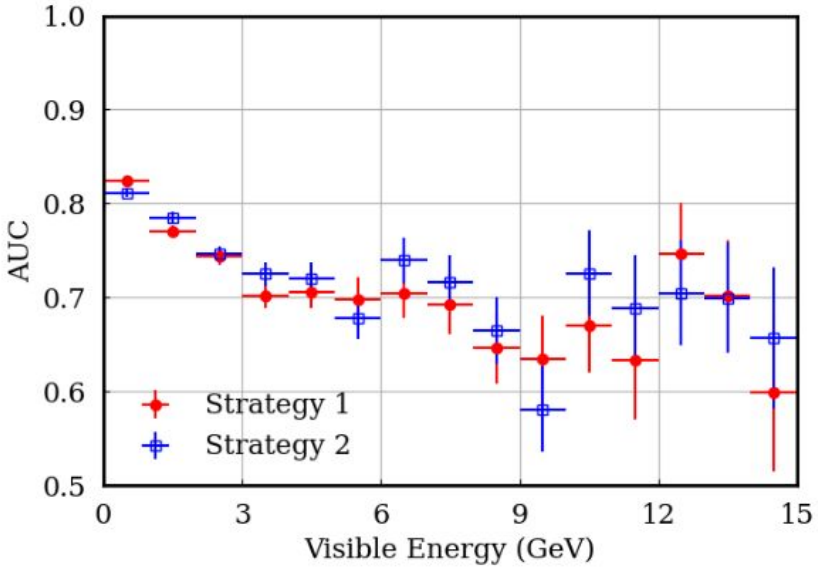
arXiv:2503.21353[hep-ex]

Performance of the PID reconstruction

arXiv:2503.21353[hep-ex]



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



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