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Exploring Atmospheric Neutrino Oscillation in JUNO

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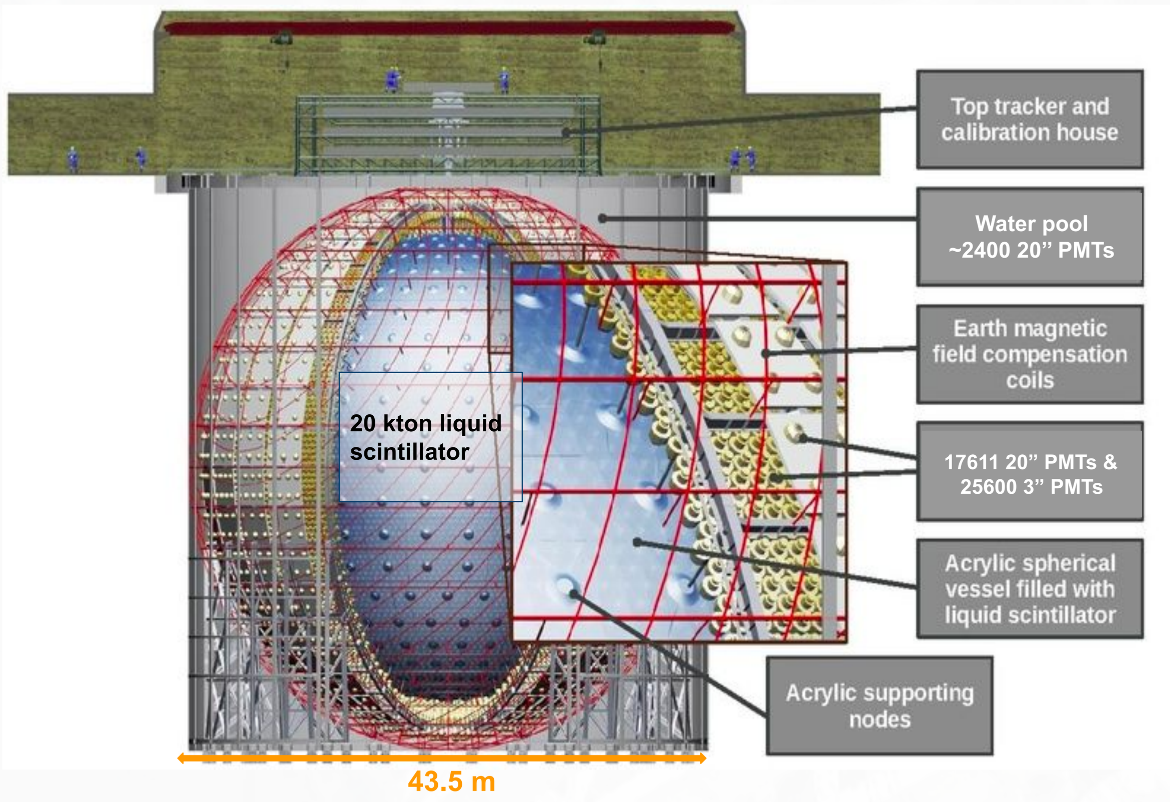
Showcase the status of some key ingredients for NMO measurement with atmospheric neutrino in JUNO

1. The JUNO experiment

The Jiangmen Underground Neutrino Observatory (JUNO) is the first multi-kton liquid scintillator (LS) detector ever built. It will be completed by the end of 2024.



Main goal: Neutrino Mass Ordering (NMO) measurement with 3σ in 6 years through reactor antineutrinos

Focus of this poster:

1. Potential measurement of atmospheric neutrino oscillation with LS detector
2. The matter effects in atmospheric neutrino to boost JUNO's NMO sensitivity
3. Relevant reconstruction status for energy, direction, and particle ID of neutrino at GeV range

3. Analysis workflow

Atmospheric neutrino flux [1]

Oscillation probability

Cross-section in LS GENIE/NuWro/GiBUU

→ pre-reco. expected oscillated spectra

Detector response
- Energy reconstruction
- Direction reco.
- PID reco. of neutrino

Event selection
- Fully / partially contained (FC, PC)
- Muon backgrounds
- Neutral current interaction

Expected spectra with true NMO

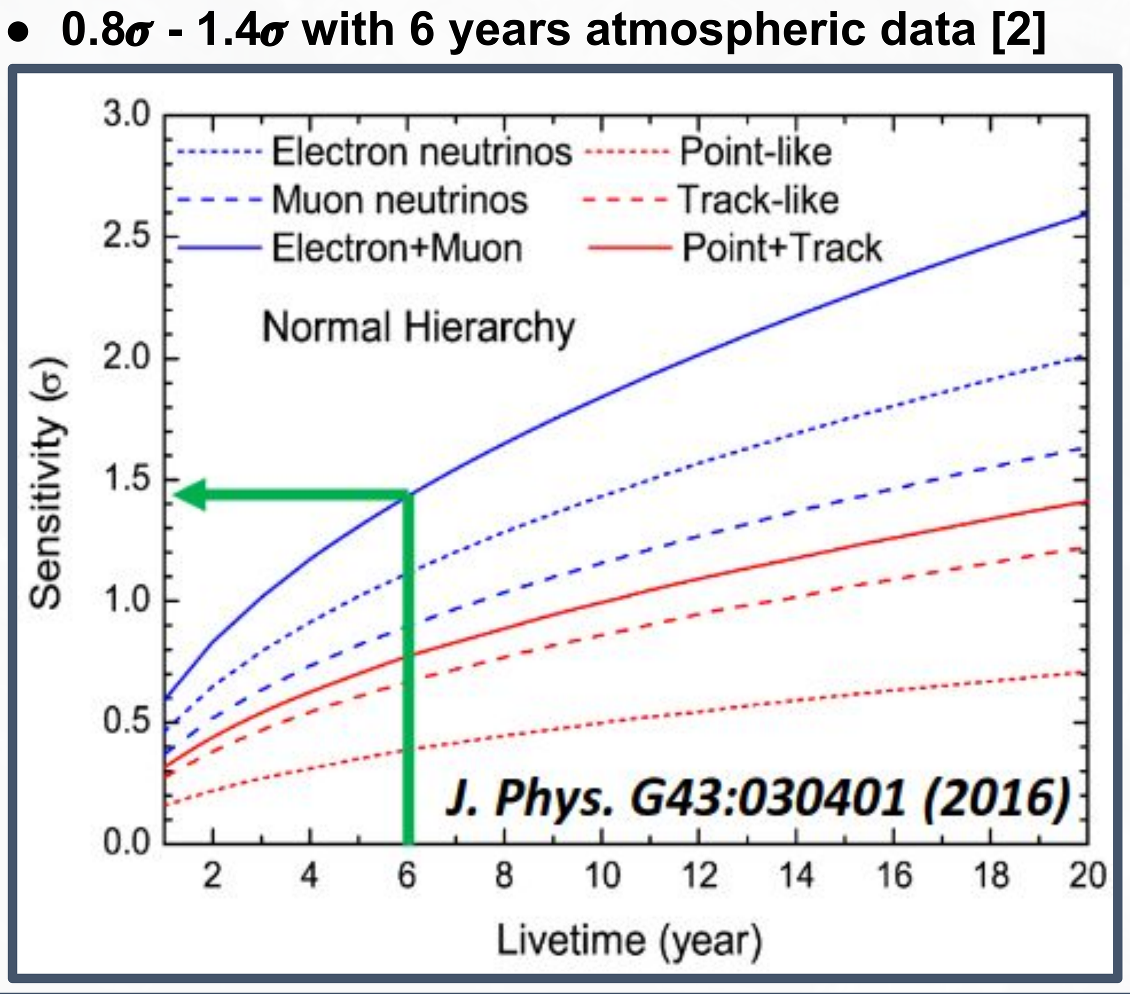
Expected spectra with test NMO

Sensitivity to NMO

Systematics on the flux, cross-section, detector effects, and oscillation parameters

4. Atmospheric sensitivity to neutrino mass ordering

- **0.8σ - 1.4σ with 6 years atmospheric data [2]**



References

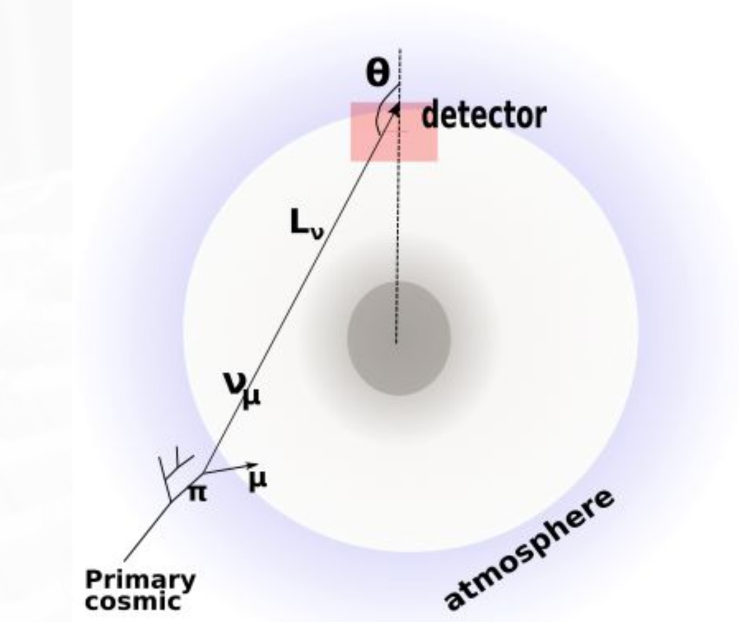
[1] M. Honda et.al. *Phys. Rev. D92, 023004 (2015)*
[2] JUNO Collaboration, *J. Phys. G43:030401 (2016)*
[3] Z. Yang et.al. *Phys.Rev.D* 109 (2024) 5, 052005

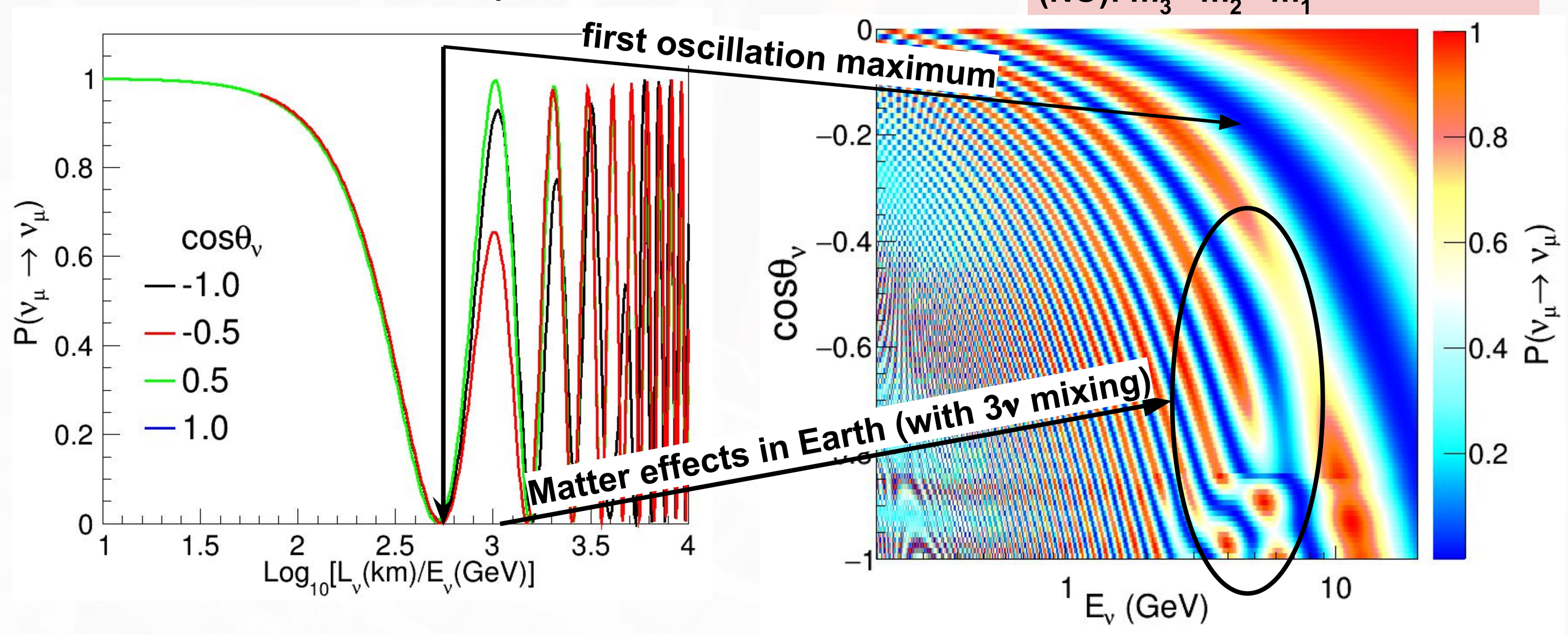
2. Atmospheric neutrino oscillation

Source of atmospheric neutrinos : interactions of cosmic particles in Earth's atmosphere.

Typical range energy : 100 MeV – few TeV, isotropic distribution at E_ν > 3 GeV.

Assuming Normal Ordering (NO): $m_3 > m_2 > m_1$

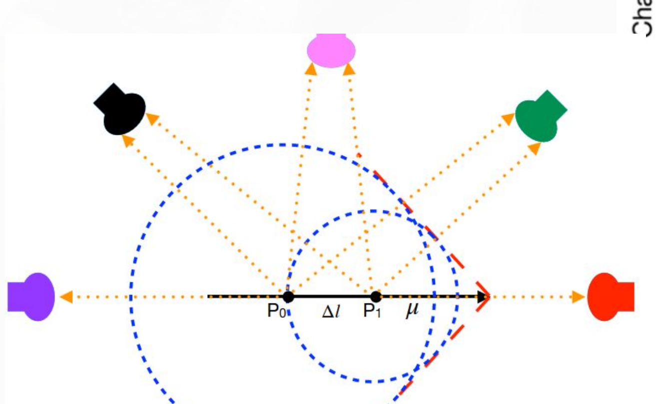


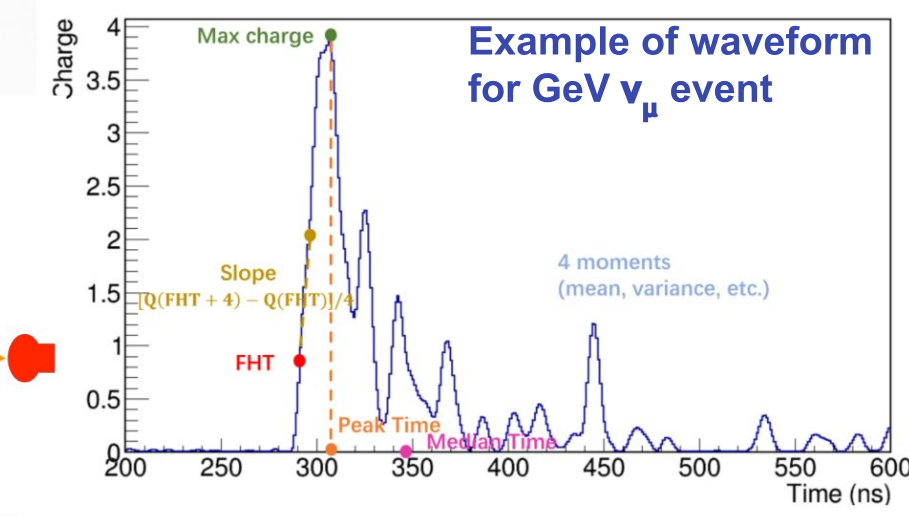


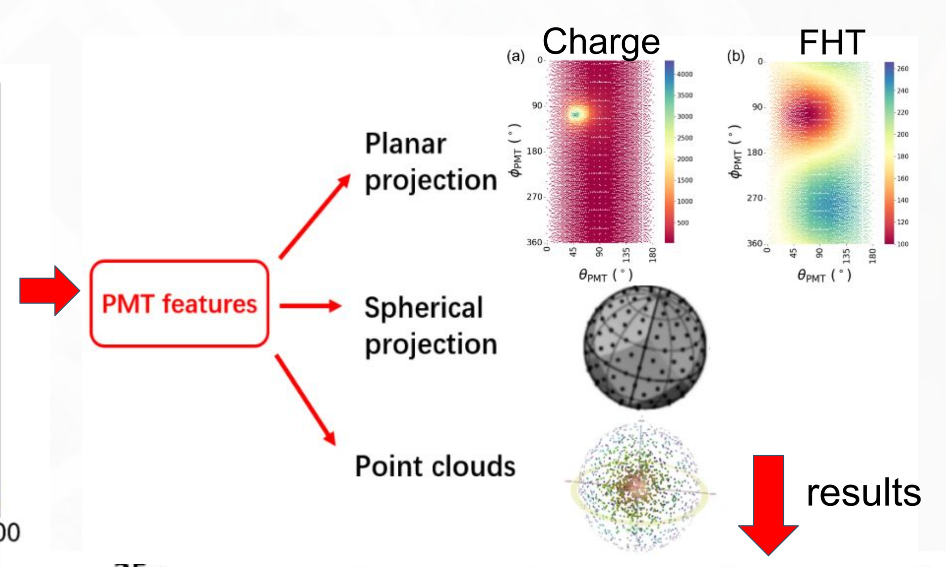
- Matter effects enhance neutrino oscillation and depend on neutrino energy E_ν, direction θ or baseline L_ν, and matter density.
- Neutrino oscillation is modified with matter effect with NO, whereas for IO, matter effects appears in antineutrino oscillation.

5. Directionality reconstruction of GeV neutrinos in JUNO

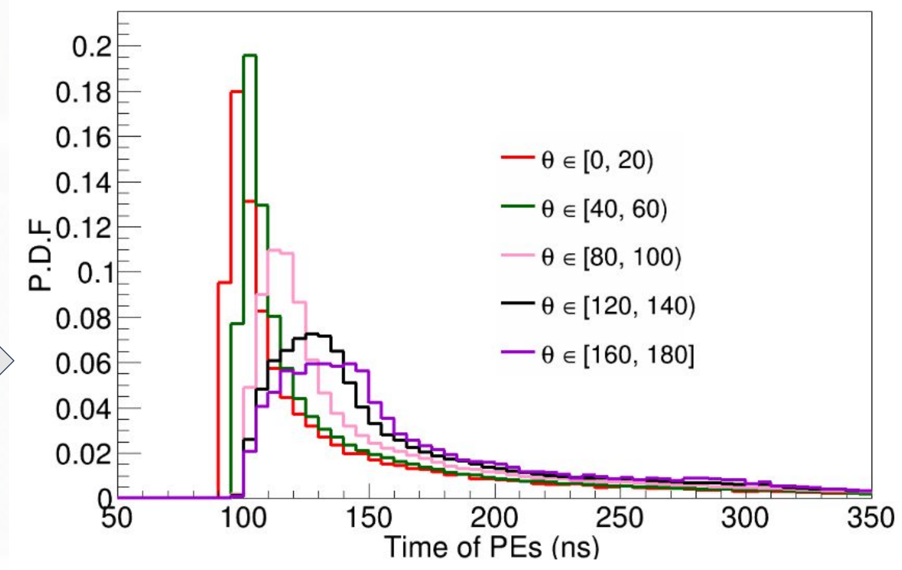
- A novel directionality reconstruction method is developed for the atmospheric neutrino events in large homogeneous LS detectors based on waveform analysis and machine learning (ML) techniques (Efficient-v2, DeepShere, PointNet++) [3].
- Features extracted from each PMT's waveform reflect the event's topological structure and carry information about the event's direction, energy and flavor types: multi-purpose reconstruction.

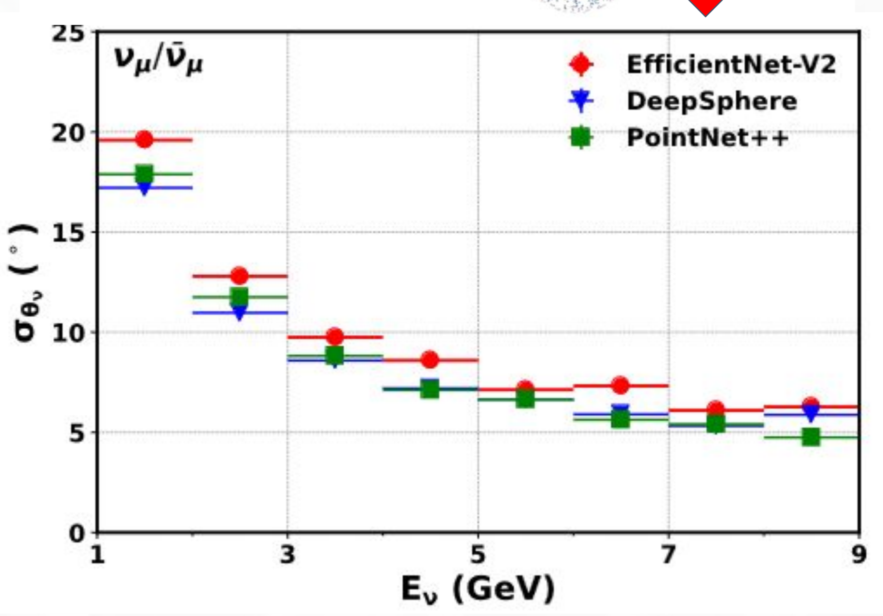






- Scintillation light photon distribution from a charged particle track in space and time is not isotropic
- Photo-electron as a function of time for PMTs at different angles with respect to a muon track





6. Potential improvements towards a realistic estimation

Det. responses	JUNO yellowbook [2]	New Developments	Features used for reco.
Event selection	ν_e: E_{vis} > 1 GeV Y_{vis}= $E_{hadrons}/E_{vis}$ < 0.5 ν_μ: L_μ > 5 m	E_{vis} > 1 GeV – ~30% more statistics	–
Energy	σ_{Evis} = 1%/ $\sqrt{E_{vis}}$	$\sigma_{E\nu}$ – E_ν reconstruction instead of E_{vis}	ML-based on total charge in PMT
Directionality	ν_e : $\sigma_{\theta\nu}$ = 10° ν_μ : $\sigma_{\theta\mu}$ = 1°	$\sigma_{\theta\nu}$ < 10° (E_ν> 4 GeV) – E_ν dependent	ML-based on PMT features such as first hit time, time and charge at peak in waveform
Classification	CC-e / CC-μ / NC 100%	80–95% efficiency – E_ν dependent	ML-based on PMT features as well as event level features (neutron multiplicity, Michel electron, etc.) Poster#500
	ν vs $\bar{\nu}$ Based on Michel electron N_e and Y_{vis}	50% ~80% efficiency – better separation	

Conclusions

1. The methods for reconstructing neutrino energy, direction, and particle identity (flavor and neutrino or antineutrino) in GeV range are developed in JUNO.
2. The atmospheric neutrino data in JUNO has the potential to observe the neutrino oscillation.
3. Atmospheric neutrinos carry the imprints of NMO through different matter effects in neutrino and antineutrino. Therefore, the synergy between reactor and atmospheric neutrino events will boost the sensitivity of JUNO towards neutrino mass ordering.