Atmospheric neutrino reconstruction in JUNO

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On behalf of the JUNO collaboration

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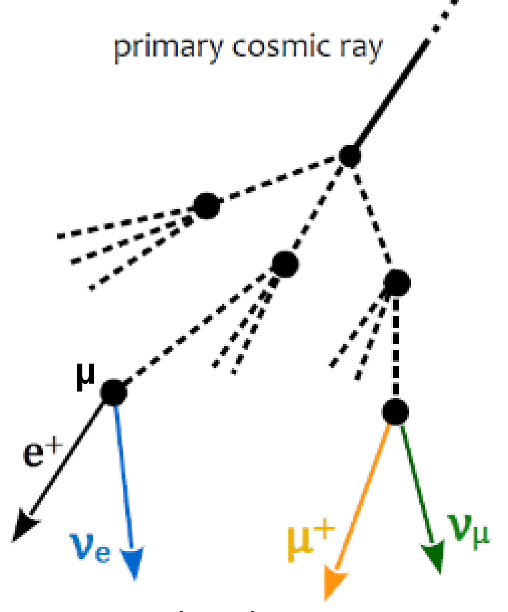
Why Atmospheric Neutrinos in JUNO?

- JUNO will be largest ever build liquid scintillatior (LS) detector
- Enhance JUNO sensitivity to neutrino mass ordering (NMO) via combined analysis with reactor anti-neutrinos.
- Provide the first flux measurement with a large liquid scintillator detector and in the sub-GeV energy region.
- Accessible from the first year of data taking, with O(10) events/day.

Atmospheric Neutrinos in a Nutshell

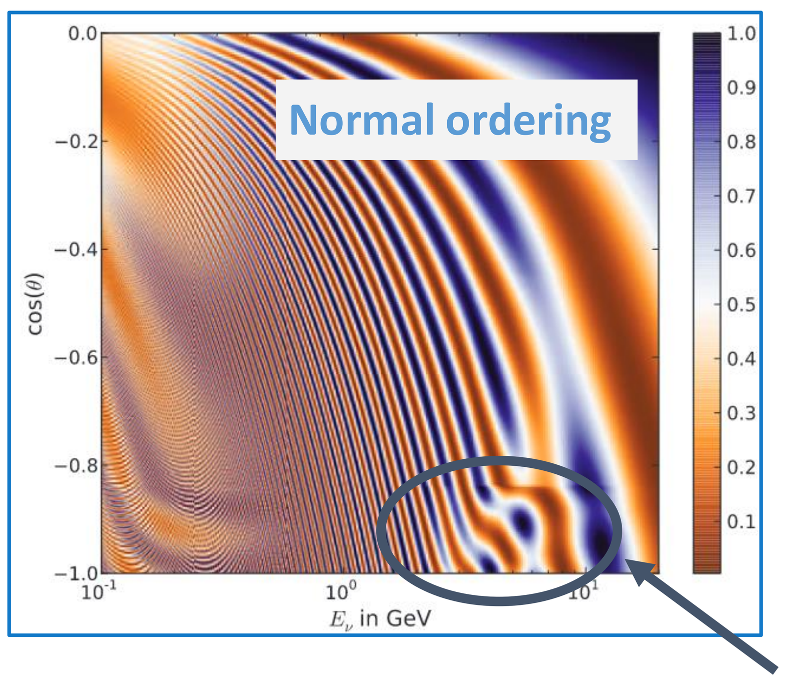
Source:

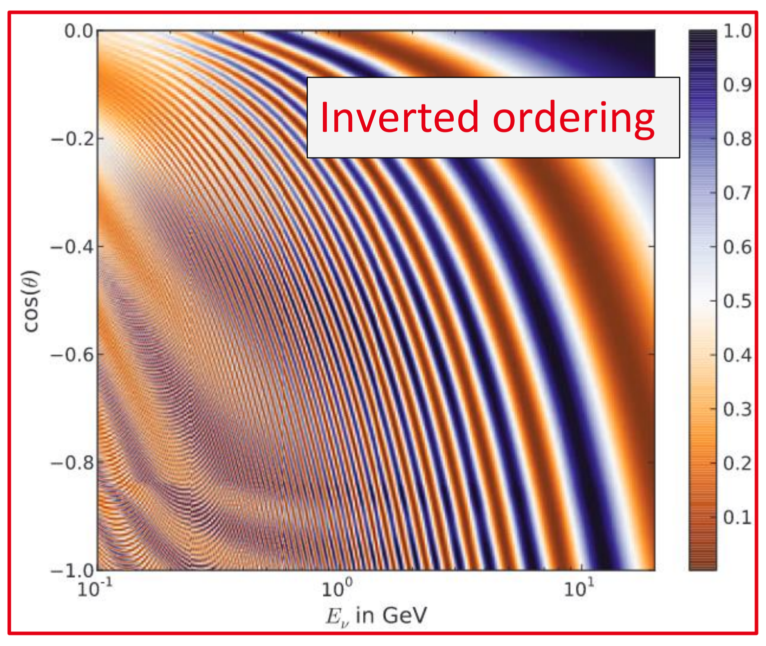
Initiated by primary cosmic rays hitting the atmosphere



$\nu_{\mu,e}$: π and K decays

Oscillations of atmospheric neutrinos : $P_{\nu\mu \to \nu\mu}$ Normal (NO) vs Inverted (IO) ordering





Oscillation probability depends on energy and zenith angle

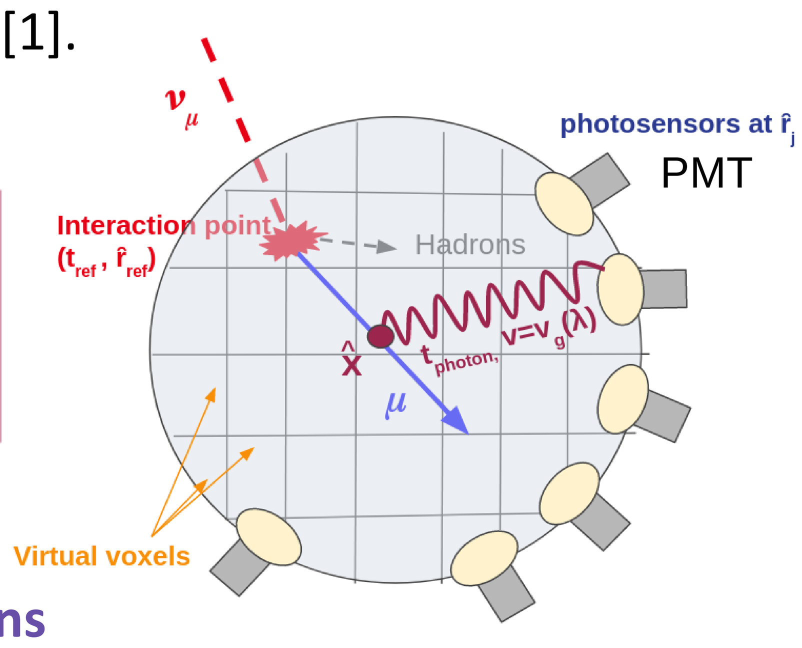
Neutrinos propagate through the Earth -> matter effects modify the oscillation pattern

Topological Reconstruction (directionality)

Idea: Reconstruct the photon emission probability distribution based on the detected hit charges and times [1].

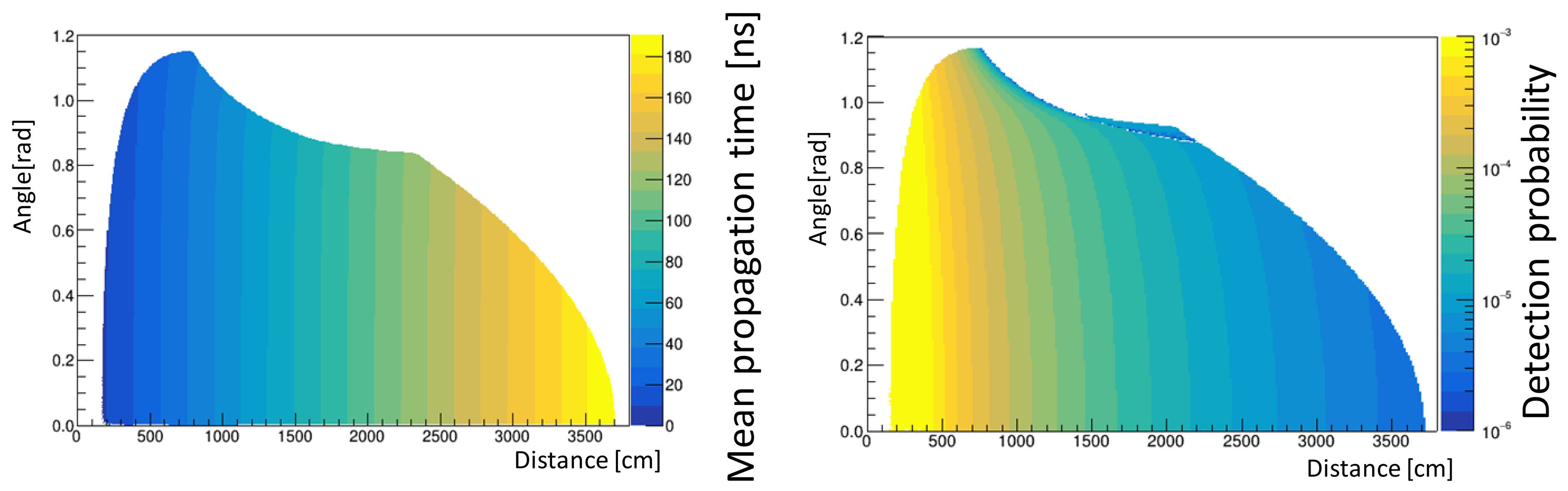
*[1] H. Rebber et al. 2021 JINST **16** P01016*

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



reference time and vertex: $(t_{ref}, \hat{r}_{ref})$

Analytical probability density functions (based on scintillation and optical properties):

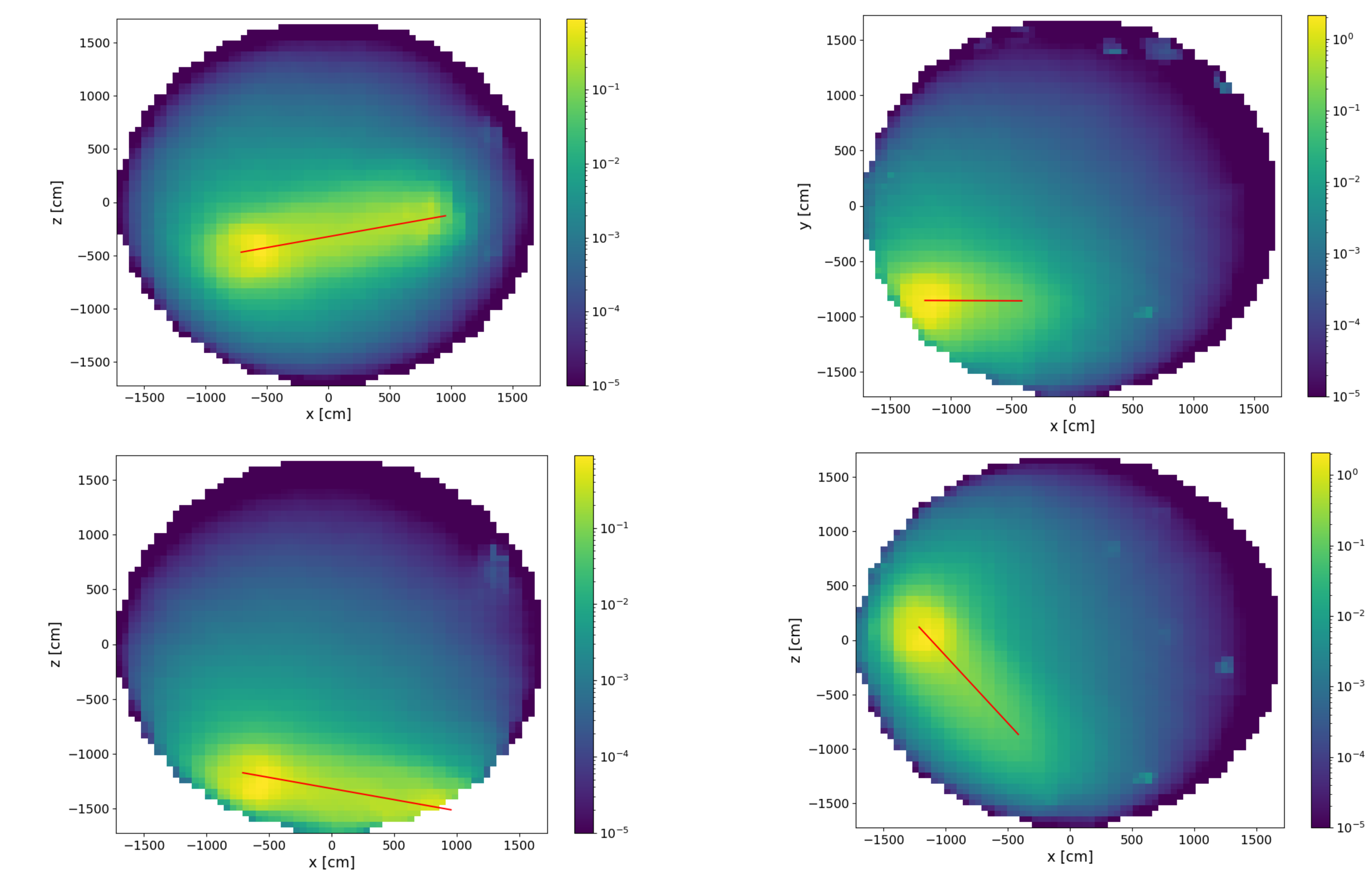


Results:

Example: two ν_μ charged current events of ~3 GeV
- t_{ref} smeared by PMT transit time spread (TTS)
- $\hat{r}_{ref}$ smeared by vertex uncertainty of 25 cm

Includes: full simulation with electronics effects + waveform reconstruction

Case 1: hadron energy is negligible | **Case 2: hadron energy is non negligible**



Legend:
– muon track (Monte Carlo)

-> Promising direction reconstruction performance for GeV events

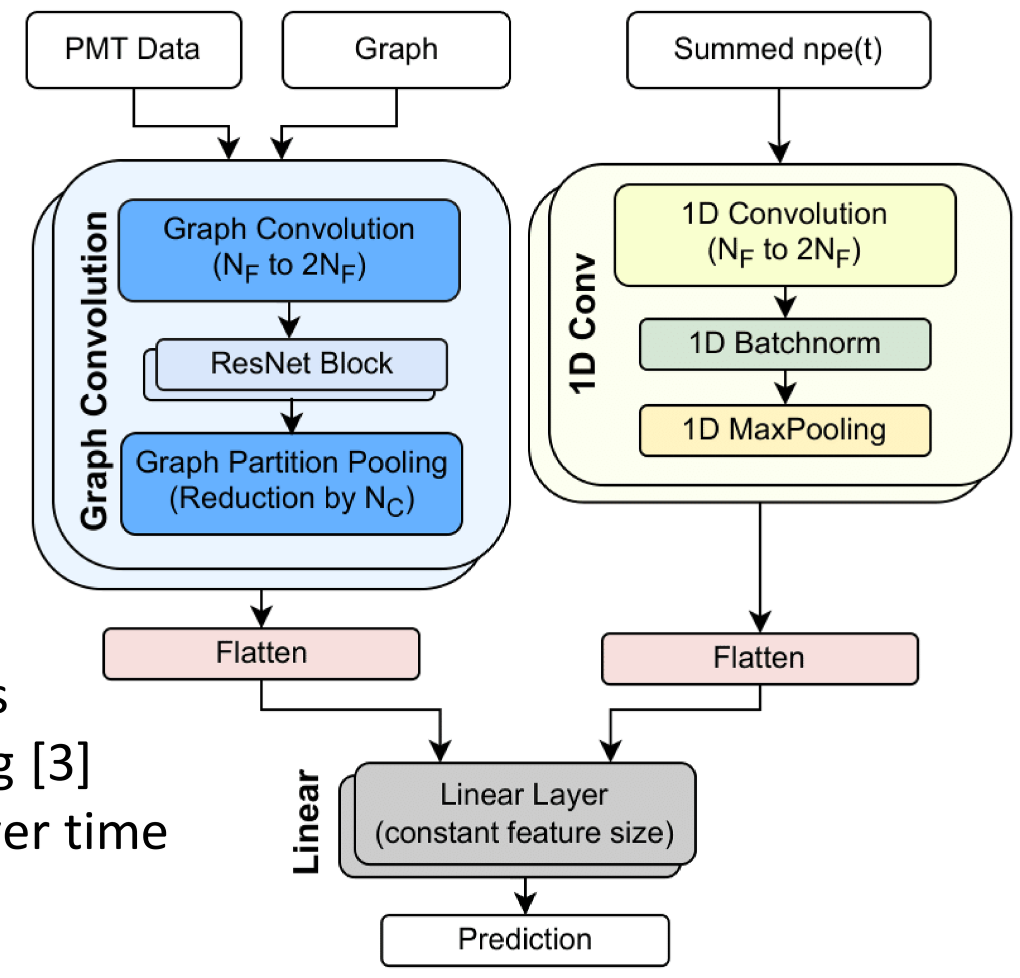
Energy Reconstruction with Graph Convolution Neural Networks (GCNN)

Graph Convolution:
- Graph represents detector geometry -> one node = one photomultiplier (PMT)
- Convolution based on Kipf and Welling [2]

$$h_i^{(l+1)} = \sigma\left(b^{(l)} + \sum_{j \in N(i)} \frac{1}{c_{ij}} h_j^{(l)} W^{(l)}\right)$$

Input data:
- First hit time per
- Charge per PMT (Graph)
- Charge VS time distribution (summer over all PMTs)

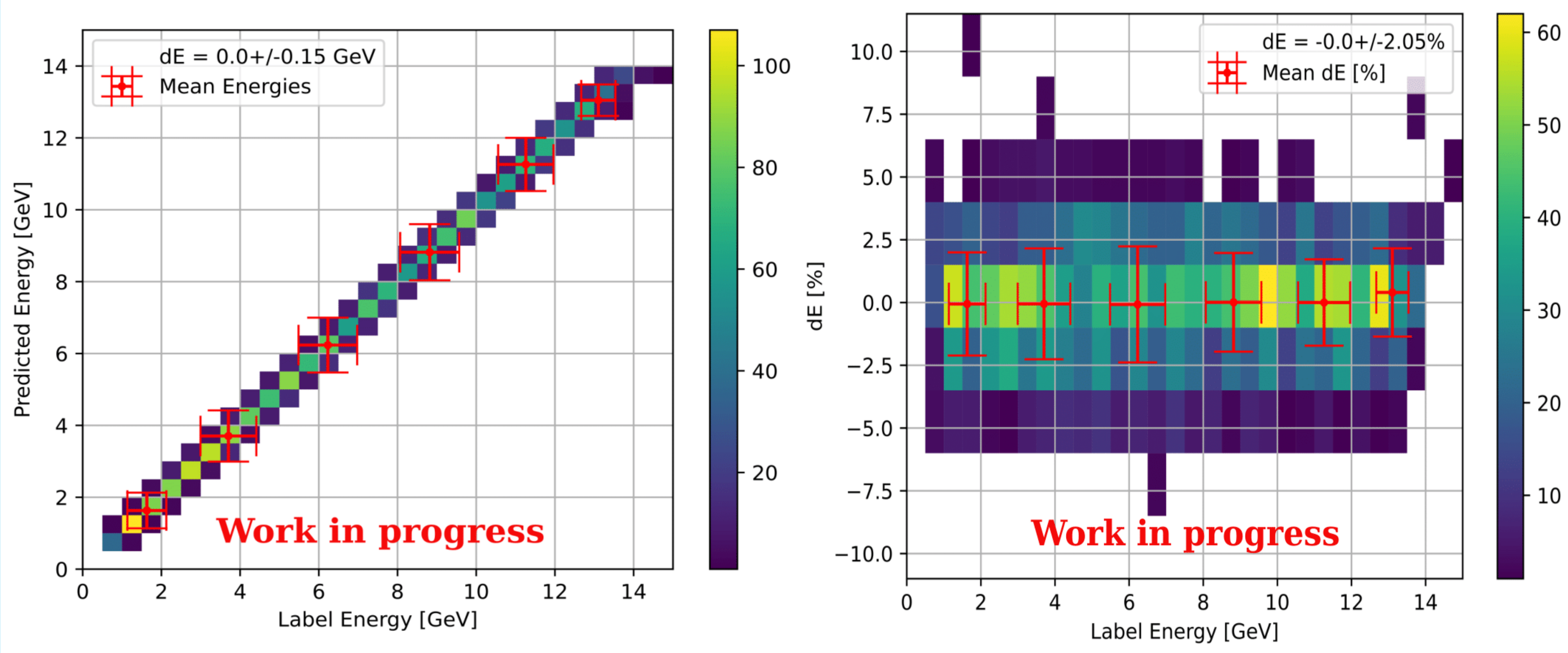
Architecture:
1) Graph Convolution:
- Alternate with ResNet Blocks
- Apply graph partition pooling [3]
2) 1D convolution on charge over time
3) Fully Connected Layers:
- Combine 1) and 2) outputs



[2] Kipf and Welling, arXiv:1609.02907
[3] M. Bachlechner et al., arXiv:2208.05952

Results:

- Reconstruction of the visible energy in energy range [100MeV, 15GeV]
- Offset removed via linear bias correction
- Resolution: dE = (Etrue - Ereco)/Etrue



Resulting energy resolution of ~ 2%

Summary and Outlook

- Energy and direction reconstruction for atmospheric neutrinos are feasible in JUNO -> **oscillation and NMO study ongoing**
- **Ongoing:**
  - Particle identification via machine learning (GCNN).
  - Separate hadronic contribution to improve direction reconstruction