Incorporating Inelasticity Reconstruction into Neutrino Mass Ordering Studies with IceCube

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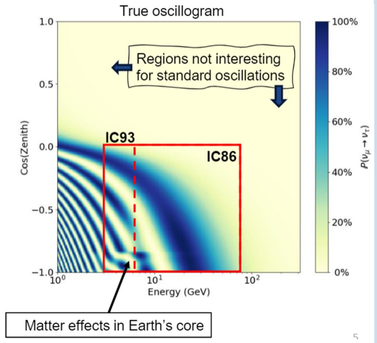
Abstract

Atmospheric muon neutrinos and antineutrinos passing through the Earth experience matter effect induced oscillations, due to the interior structure of the Earth, which only affect neutrinos or antineutrinos depending on the true neutrino mass ordering (NMO). By leveraging the fact that more neutrinos are expected to be detected than antineutrinos in IceCube DeepCore, the detector can be used to probe the NMO. However, the fact that the mean inelasticity of neutrinos and antineutrinos are different has not yet been exploited to statistically separate neutrinos and antineutrinos for IceCube DeepCore, and could be used for the IceCube Upgrade. To this end, new inelasticity reconstructions were developed using two dimensional convolutional neural networks along with a model aggregating boosted decision tree for DeepCore and a graph neural network for the Upgrade. This poster will show how these reconstruction algorithms were developed and their performance. We then use these new inelasticity reconstructions as a fourth binning variable and calculate new sensitivities to determine how much of an impact this new reconstruction could have on the determination of the NMO with IceCube.

Introduction

IceCube DeepCore (IC86) is a more densely instrumented infill of the IceCube Neutrino Observatory that detects neutrinos with energies as low as a few GeV [1]. The IceCube Upgrade (IC93), a seven string infill to DeepCore, will lower the energy threshold of the detector [2].



IceCube can measure neutrino oscillations by counting muon neutrino and antineutrino charged current events (tracks) and other interactions (cascades) [3].

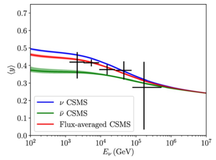
Matter resonance in oscillations will only occur for neutrinos or antineutrinos, depending on the neutrino mass ordering (NMO).

$$P_{\mu e} \approx 4 s_{13}^2 s_{23}^2 \frac{\sin^2(A-1)\Delta}{(A-1)^2}, \text{ asymmetric about } \theta_{23} = 45^\circ$$

$$A = \pm \frac{2E}{\Delta m_{31}^2} (7.56 \times 10^{-14} eV) \left(\frac{\rho(x)}{g/cm^3}\right) Y_e(x)$$

$$y = \frac{Energy\ of\ the\ Hadronic\ Cacsade}{Energy\ of\ the\ Neutrino}$$

The average inelasticity for neutrinos and antineutrinos is different, which can allow us to separate neutrinos from antineutrinos statistically [4, 5].



Conclusion

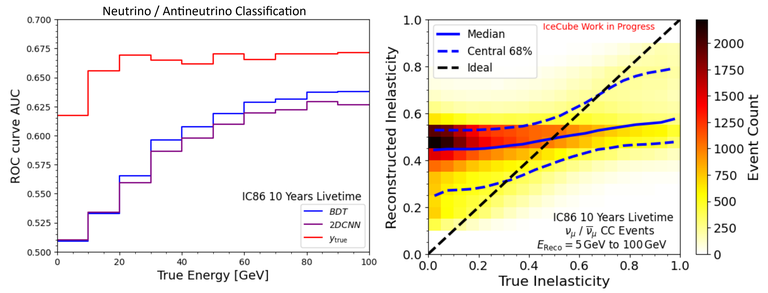
Two inelasticity reconstructions have been developed for DeepCore and the Upgrade. Both have limited performance below 30 GeV, with significant improvement above 30 GeV. Nevertheless we find that incorporating inelasticity as a fourth binning parameter increases the sensitivity to the neutrino mass ordering, for both mass orderings and detector configurations.

Validation of these results is currently ongoing. Incorporating systematics into the Upgrade NMO analysis is required for final sensitivities. In addition, we plan to set performance benchmarks for future inelasticity reconstruction efforts and directly link this progress to an improved NMO sensitivity.

References

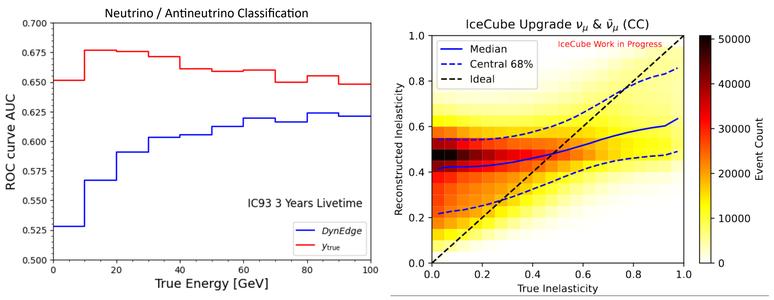
1) IceCube Collaboration, M. G. Aartsen et al. Journal of Instrumentation 9 no. 03, (Mar, 2014) P03009–P03009.
2) IceCube Collaboration, M. G. Aartsen et al. POS ICRC 2019 (2019) 1031
3) IceCube Bollaboration, R. Abbasi et al. arXiv:2305.16514
4) IceCube Collaboration, M. G. Aartsen et al. Phys. Rev. D 99 (Feb, 2019) 032004.
5) M. M. Devi et al. Journal of High Energy Physics 2014 no. 10, (Oct, 2014).
6) IceCube Collaboration, POS ICRC 2023 (2023) 1129
7) IceCube Collaboration, R. Abbasi et al. arxiv:2304.12236.

DeepCore Inelasticity Reconstruction



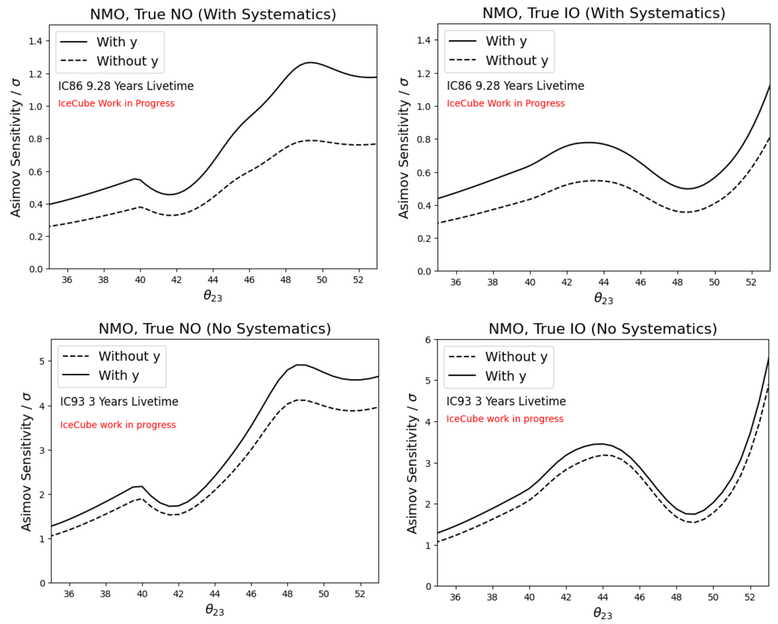
Below 30 GeV the performance degrades rapidly, but there is still some neutrino / antineutrino classification power.

Upgrade Inelasticity Reconstruction



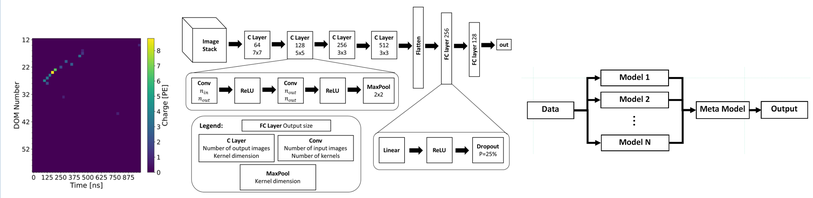
The reconstruction for the upgrade shows improved performance at low energies compared to DeepCore.

NMO Sensitivities with Inelasticity

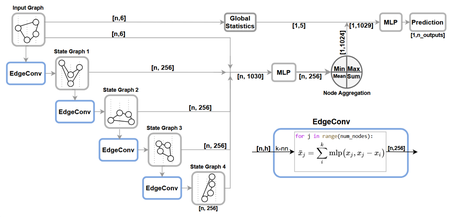


Improvements in the NMO sensitivity can be seen for both IceCube DeepCore and the IceCube Upgrade.

Reconstruction Models

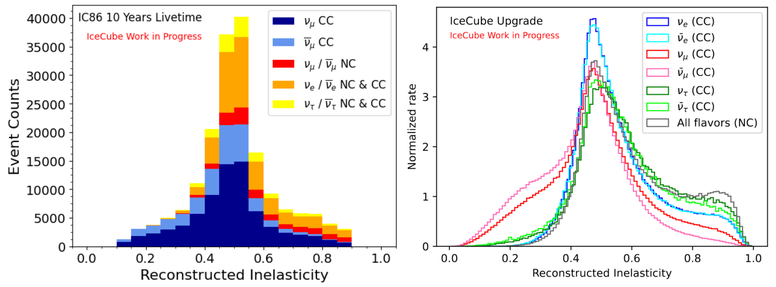


The DeepCore reconstruction uses three two dimensional CNNs fed into a BDT [6].



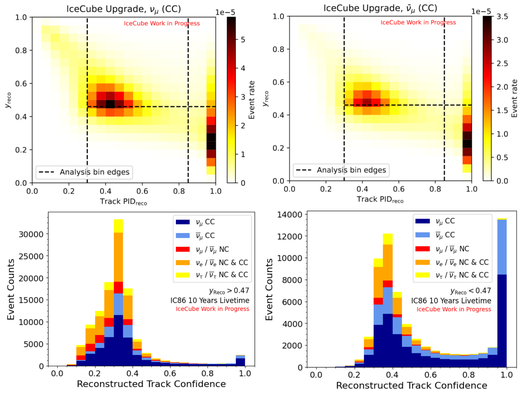
The Upgrade reconstruction utilizes DynEdge, a GNN based model [7]. Both reconstructions are trained on track events.

Cascade Performance



Even though the models have only been trained on track events, expected features of other interactions can be seen: e.g. more cascade events reconstructed at high inelasticity.

Binning with Inelasticity



The track confidence score (PID) and the reconstructed inelasticity are anticorrelated.

To help prevent unpopulated bins, each of the two inelasticity bins is assigned it's own PID binning.

DeepCore Binning

Parameter	Binning
y	[0.0, 0.47]
PID	[0.0, 0.55, 1.0]
Energy	5GeV to 100GeV, 12 Log Bins
Cos (Zenith)	-1.0 to 0.0, 10 linear bins

Parameter	Binning
y	[0.47, 1.0]
PID	[0.0, 0.25, 1.0]
Energy	5GeV to 100GeV, 12 Log Bins
Cos (Zenith)	-1.0 to 0.0, 10 linear bins

Upgrade Binning

Parameter	Binning
PID and y	PID < 0.3, [0.3, 0.85, 1.0]PID X [0.0, 0.46, 1.0]y
Energy	5GeV to 100GeV, 12 Log Bins
Cos(Zenith)	-1.0 to 0.0, 10 linear bins