Investigating the Impact of Detector Modeling Uncertainties on Machine Learning Reconstruction in Neutrino Experiments

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Neutrinos are chargeless particles that very rarely interact with other matter, making it difficult to detect them and the oscillations between their three flavors. Many open questions remain about neutrinos, including what their masses are and whether they play a role in explaining the matter-antimatter asymmetry in the universe. To detect these particles, we use large Liquid Argon Time Projection Chambers (LArTPC) which produce high resolution images of the charge deposits that result from neutrino interactions in the detector medium. Interpreting these images can be improved by implementing machine learning (ML) models, such as NuGraph2, a graph neural network (GNN) that performs categorization on the deposited charge. ML models train on simulated data, but differences between the detector simulation and real data present a challenge when applying the efficiencies of the model to real data. We evaluated the impact of such differences in the detector's charge response on NuGraph2's ability to accurately categorize charge into particles. We found that NuGraph2 presents a detector modeling uncertainty of less than 7%, comparable with traditional reconstruction methods, suggesting that this algorithm is robust and can effectively be used on experimental data collected by the detector.

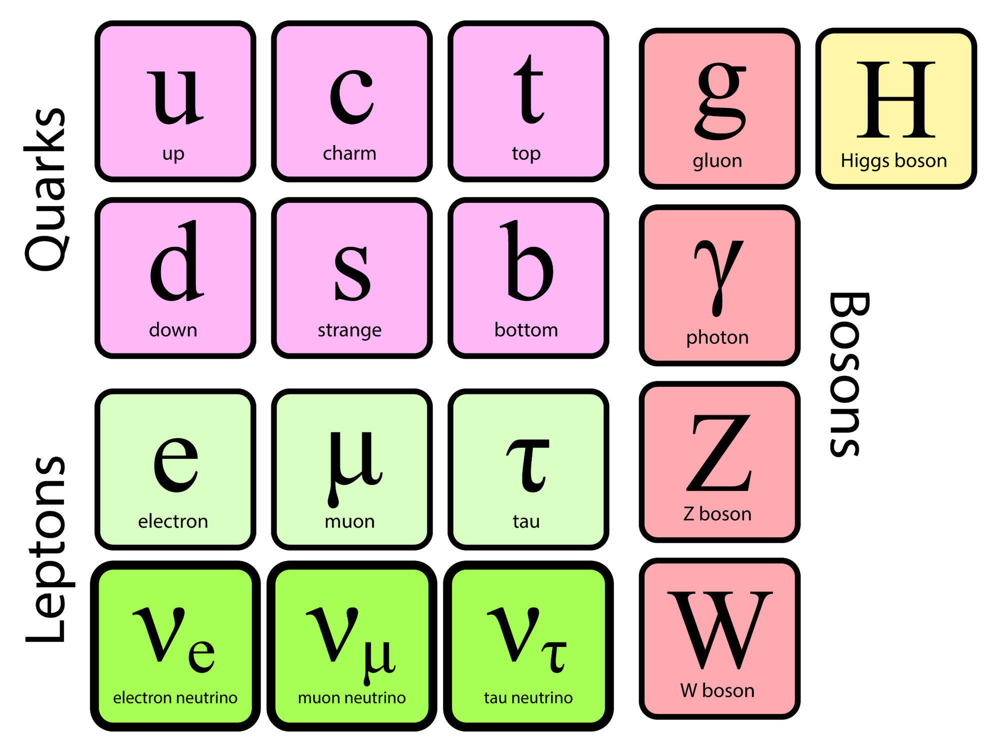
What are Neutrinos?

Neutrinos are the lightest massive particles in the Standard Model of particle physics.

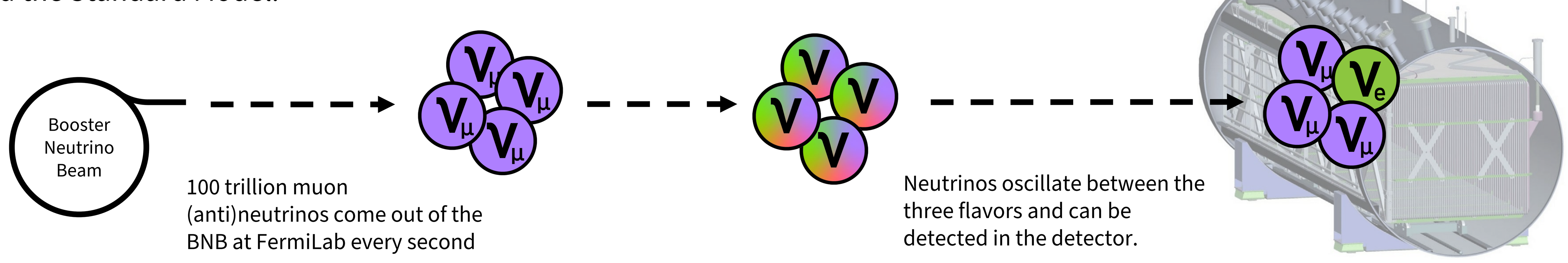
As they propagate, they can oscillate between the three flavors:

- Electron neutrino, ν_e
- Muon neutrino, ν_μ
- Tau neutrino, ν_τ

Measuring neutrino properties with increasing precision may help explain the matter/anti-matter asymmetry in the universe and explore physics beyond the Standard Model.



The Standard Model of particle physics consists of leptons, quarks, and bosons. Each flavor of neutrino is associated with a charged lepton.



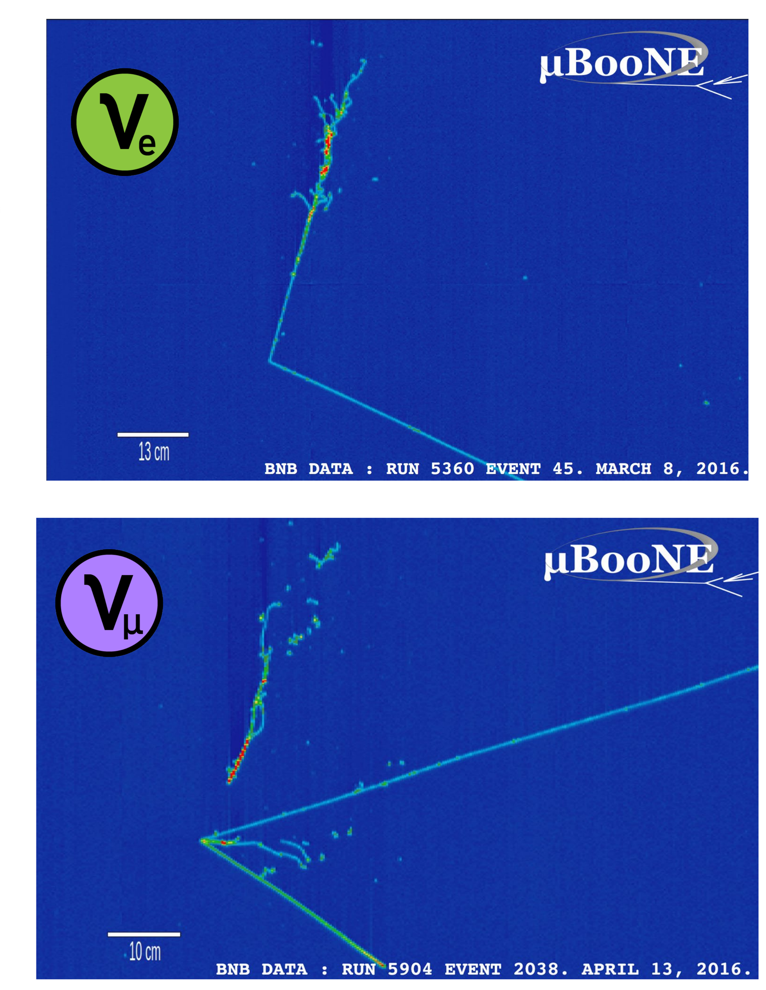
100 trillion muon (anti)neutrinos come out of the BNB at FermiLab every second

Neutrinos oscillate between the three flavors and can be detected in the detector.

Liquid Argon Time Projection Chambers (LArTPC)

Neutrinos interact with Argon atoms and release an array of different particles depending on the type of neutrino and interaction mode. Unique signatures of ionization charge (free electrons) are left behind in the detector. LArTPCs produce high-resolution images of these ionization signatures.

Scan the QR code for an animation of the detection process

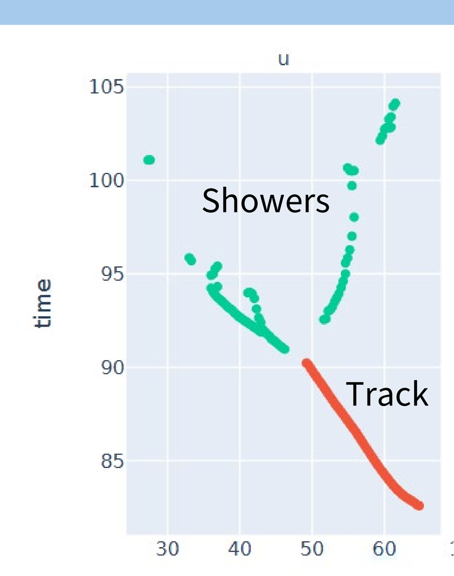


MicroBooNE event displays for an electron neutrino (top) and muon neutrino (bottom) interaction. They highlight the difference between showers (e & γ) and tracks (μ). There is also a visible gap in the photon shower compared to the electron shower.

NuGraph2

NuGraph2 is a graph neural network (GNN) that takes the charge deposits from the neutrino interaction as input. Based on its training on simulated data, it can perform predictions about whether each charge deposit belongs to a cosmic ray or one of 5 different particle types:

- Minimally Ionizing Particle (μ)
- Highly Ionizing Particle (p)
- Electromagnetic Shower (e, photon)
- Michel Electron (muon decay)
- Diffuse (other small charge deposits)

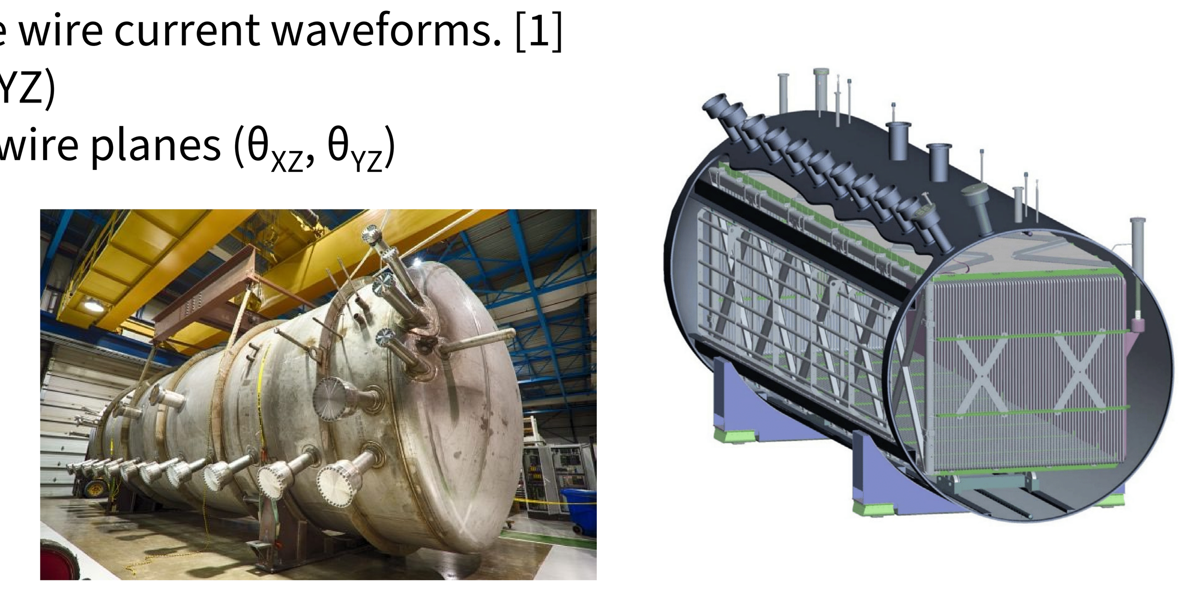


NuGraph2 U-plane prediction of particle categories from Run 6999, Subrun 11, Event 595 of the MicroBooNE open data release. Adapted from [2].

Wire Modifications on the MicroBooNE Detector

Differences between the detector simulation and real data have been quantified. We can create more realistic simulated data by representing these as modifications on the wire current waveforms. [1]

- Track positions (X, YZ)
- Track angles w.r.t. wire planes (θ_{XZ}, θ_{YZ})
- Charge scaling ($\frac{dE}{dx}$)



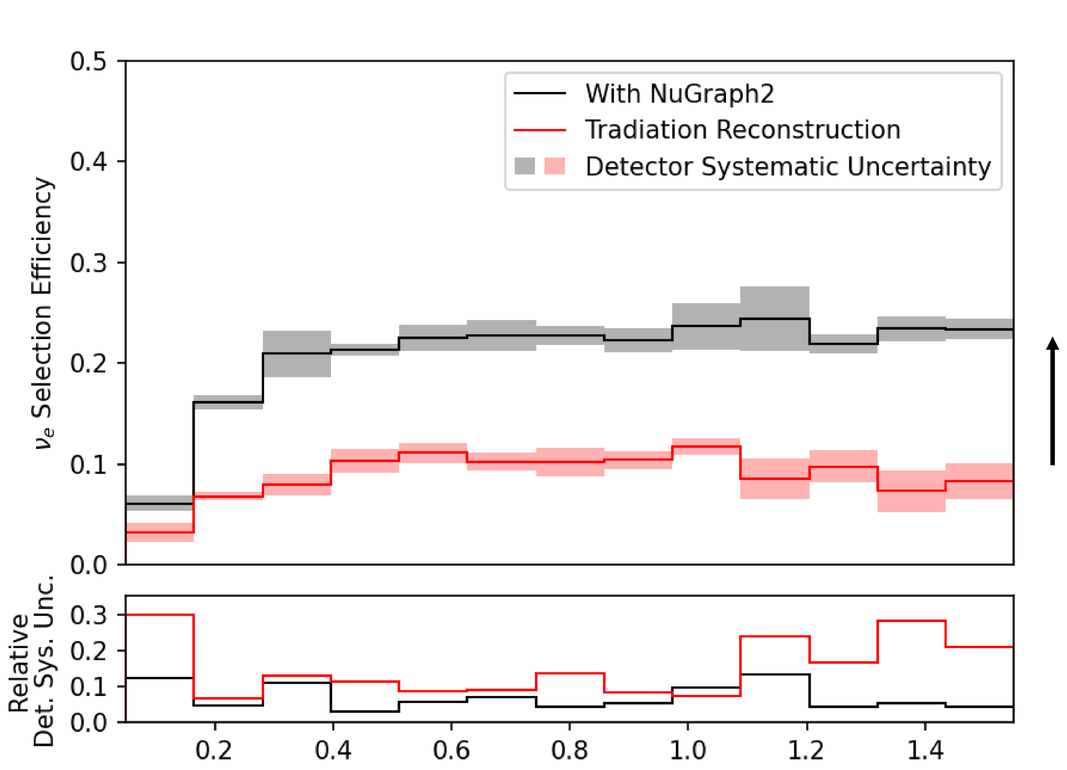
Images of the MicroBooNE LArTPC Detector. Image of the cryostat (left) and CAD diagram (right). Copied from microboone.fnal.gov/images-videos/

NuGraph2 robust against detector variation

Twice as efficient with similar detector uncertainty

Quantifying Detector Uncertainties

Combined with the existing reconstruction pipeline, NuGraph2 supplies us with new parameters to perform a selection for electron neutrinos (ν_e). This improves the efficiency of the selection, and we made sure that this new efficiency doesn't also increase the uncertainty on the efficiency.



Analysis Version	ν_e Selection Efficiency	Absolute Detector Modeling Uncertainty (Weighted Average)	Relative Detector Modeling Uncertainty (Weighted Average)
With NuGraph2 (MCC9.10)	20.9%	1.4%	6.7%
Traditional Reconstruction (MCC9)	9.1%	1.1%	13%

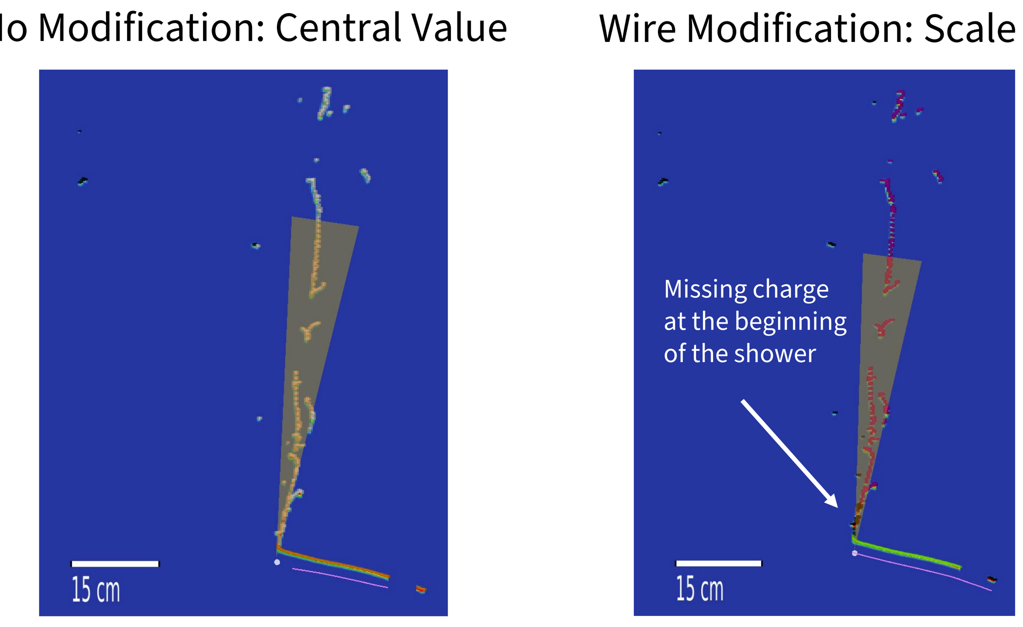
Selection efficiency is the proportion of target events that are successfully selected.

Detector systematic uncertainty is the expected error in the measurement due to mismodeling in the detector simulations.

Looking at Specific Events

No Modification: Central Value

Wire Modification: Scale X



Comparison of the shower reconstruction. Charge is missing from beginning of the shower, indicating a mis-reconstruction due to the detector variation.

Acknowledgements

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References

[1] P. Abratenko et al. (MicroBooNE Collaboration), Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data, The European Physical Journal C 82, 10.1140/epjc/s10052-022-10270-8 (2022).

[2] A. Aurisano, V. Hewes, G. Cerati, J. Kowalkowski, C. S. Lee, W. Liao, D. Grzenda, K. Gumpula, and X. Zhang, Graph neural network for neutrino physics event reconstruction, Phys. Rev. D 110, 032008 (2024).