(A Path Towards) Determining the Neutrino Mass Hierarchy

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What are Neutrinos?

- Tiny, almost massless neutrally charged leptons
- Only interact via the weak force
- Propagate in mass eigenstates which undergo mixing – neutrino oscillations

- Open Questions in neutrino physics:
  - Is there a fourth “sterile” neutrino?
  - Are neutrinos Majorana or Dirac?
  - Do neutrinos violate CP symmetry?
  - How do neutrinos acquire mass?
  - What is the mass ordering?

Flavor Eigenstates

Mass Eigenstates

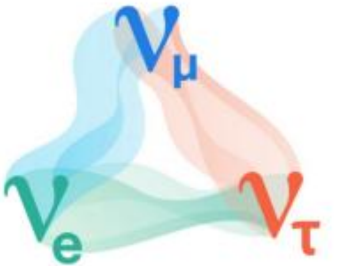

Image by Symmetry Magazine

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{U_{\mathrm{PMNS}}}_{\text{Mixing Matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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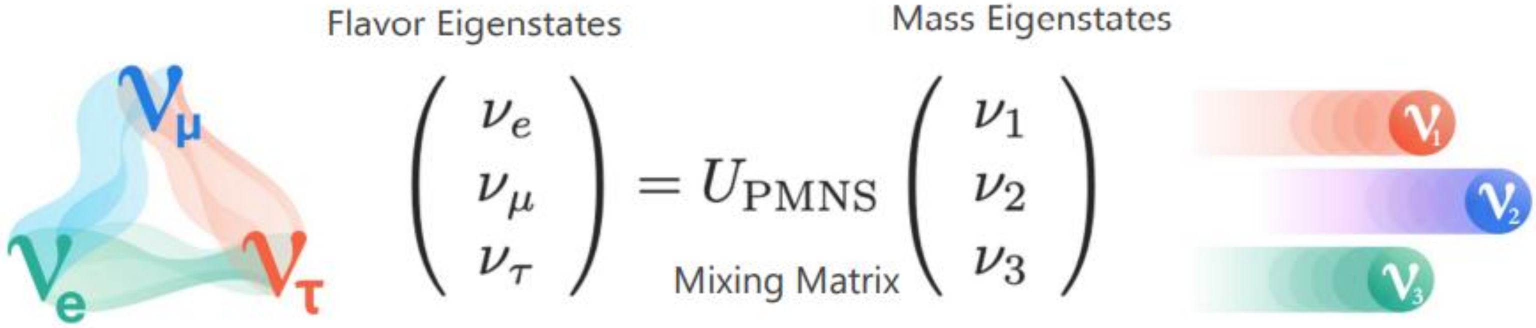
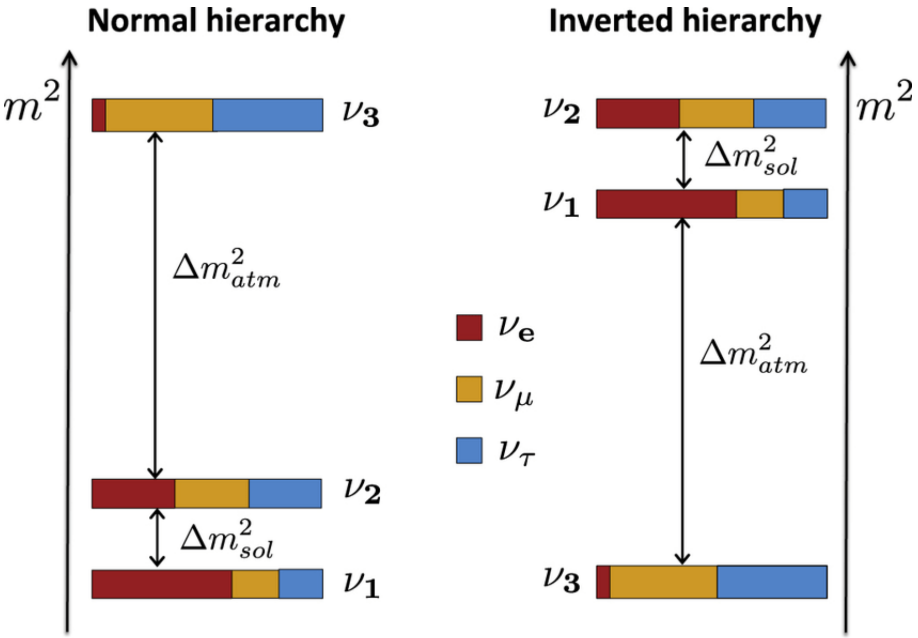


Image by Symmetry Magazine

NOvA–T2K Joint Analysis (2024). *Joint Analysis Results*.
Presentation, 16 February 2024. PDF presentation

What is the Neutrino Mass Hierarchy (and how can we determine it)?

- Measuring oscillation parameters only gives us the absolute value for the square mass difference
- Already know m_2 is larger than m_1
- Know absolute value for Δm^2_{32}
- Therefore 2 scenarios: m_3 is larger than m_2 (NO)
- Or m_3 is smaller than m_2 (IO)
- Absolute values for mass splitting parameter change slightly depending on the hypothesis chosen
- With enough precision, can favour one over other



https://tritonstation.com/2021/08/14/the-neutrino-mass-hierarchy-and-cosmological-limits-on-their-mass/

Current Experimental Results

- Oscillations dependent on square mass difference:

$$P_{\mu\to\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}.$$

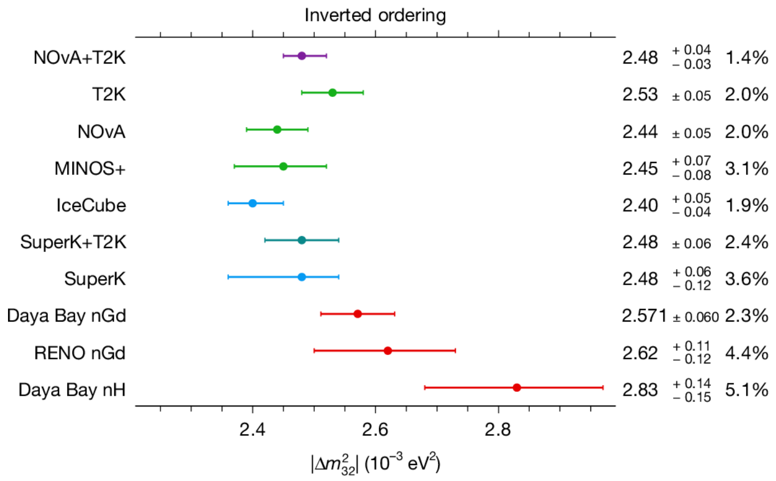
  - Where:

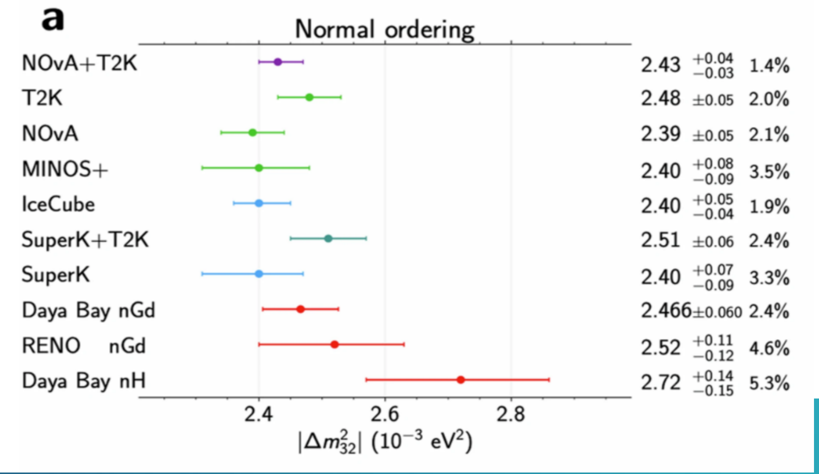
$$\Delta_{ij} \equiv \Delta m^2_{ij} L/2E.$$

Baird, M. D. (2015). *An Analysis of Muon Neutrino Disappearance from the NuMI Beam Using an Optimal Track Fitter*. PhD thesis, Indiana University.

- Better energy resolution allows better precision on mass splitting measurement
- Majority of this precision is statistically limited (need more data!), however, systematics play a part too

The NOvA Collaboration., The T2K Collaboration. Joint neutrino oscillation analysis from the T2K and NOvA experiments. Nature 646, 818–824 (2025). https://doi.org/10.1038/s41586-025-09599-3





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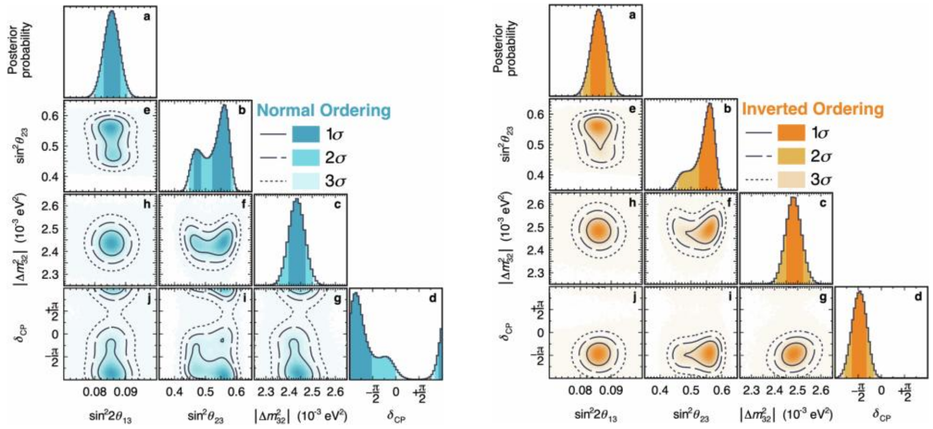
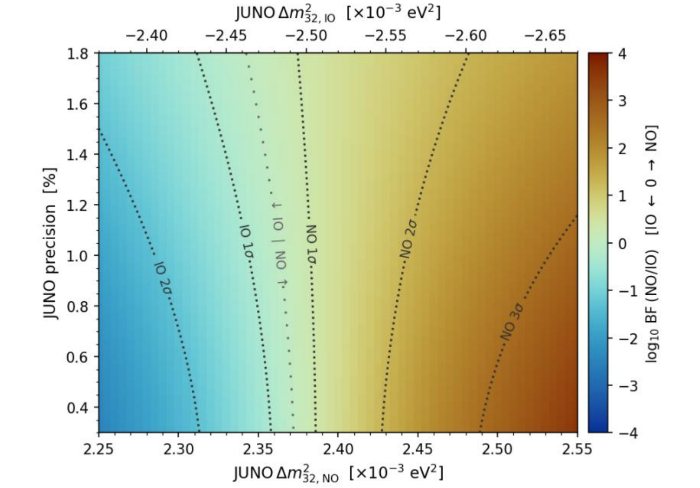
International Collaboration

- NOvA's issues still exist with parameter degeneracy (and data taking)
- JUNO is much less statistically limited
- Note that in central region of "Crystal Ball Plot", JUNO precision is subdominant uncertainty to NOvA
- NOvA-T2K joint analysis changes preference (although both experiments individually favour NO, joint fit weakly favours IO due to parameter degeneracies)

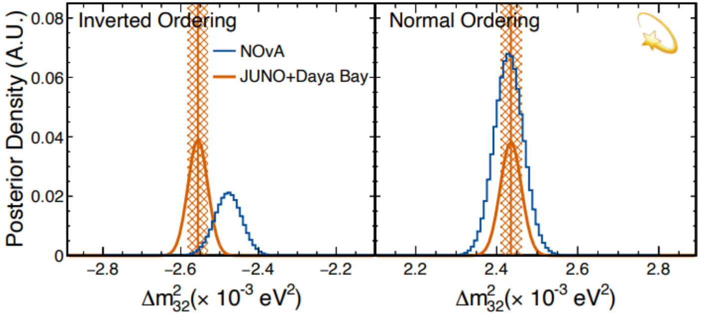




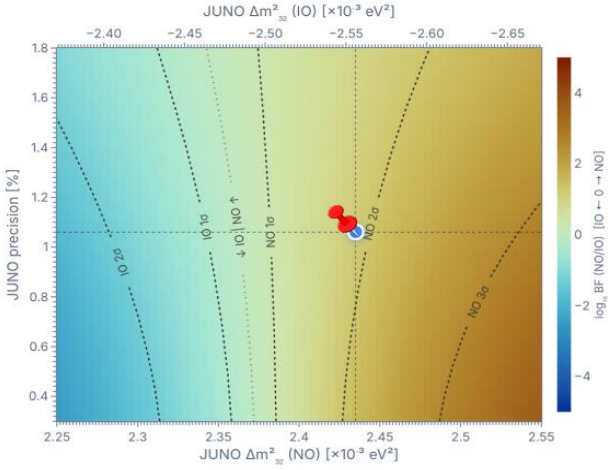
NOvA Collaboration (2026). *Determining Neutrino Mass Ordering with NOvA and Upcoming JUNO Measurements.* arXiv:2606.14121 [hep-ex]

International Collaboration

- NOvA’s issues still exist with parameter degeneracy (and data taking)
- JUNO is much less statistically limited
- Note that in central region of “Crystal Ball Plot”, JUNO precision is subdominant uncertainty to NOvA
- JUNO offset: $\lambda \sim 0.12 \pm 0.005 \times 10^{-3}\mathrm{eV}^2$
- Joint fit with JUNO favours NO at around 1.88σ
- Bayes factor for Normal/Inverted Preference with Daya Bay data: 15.74 (94% / 6% posterior)

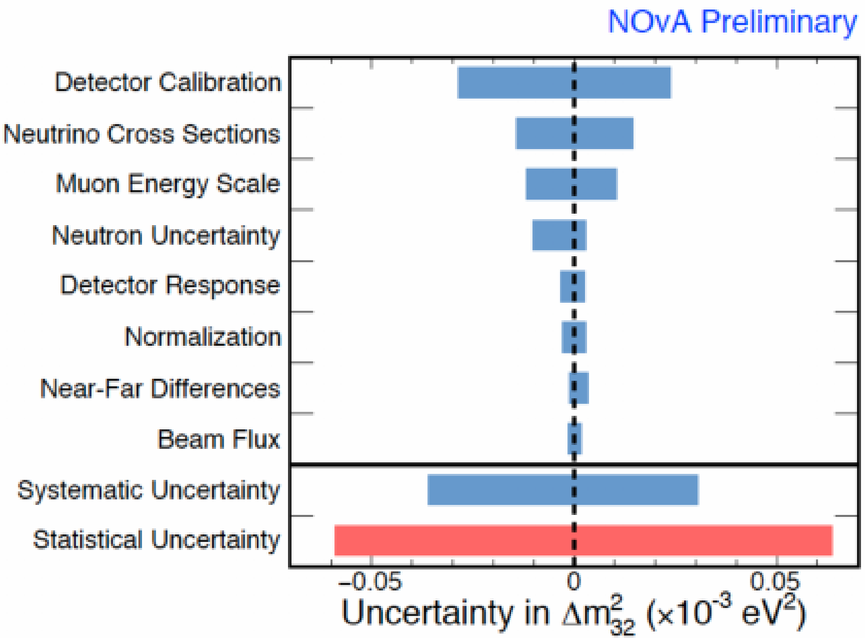


Exp.	JUNO*	NOvA
Δm^2_{32} NO	2.435	2.431
Δm^2_{32} IO	-2.556	-2.479
Precision	1.05%	1.4%



So, What Next?

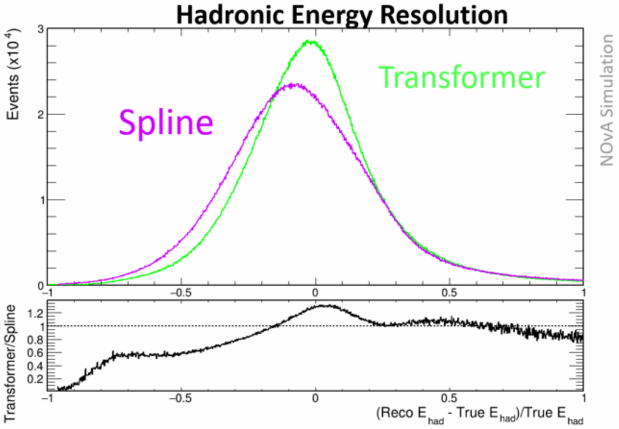
- Main goal: increase precision of measurement
- Statistics: hard with current experiments, next gen will go some way on this end.
- Systematics: biggest source of uncertainty that we can fix without taking more data.
- Dominant systematic for oscillation analysis: detector calibration
- Traditional method – spline, straight line fit to single measured variable
- Alternative methods now being explored utilising ML Energy Estimators (with access to more parameters)
- Recent acquisition of test beam also helps better characterise our detector

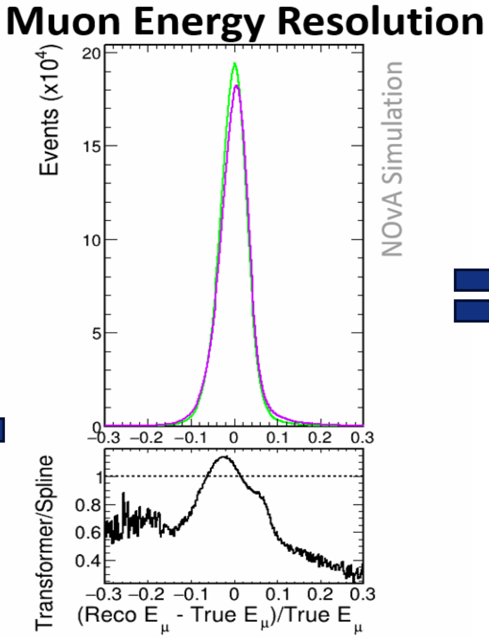


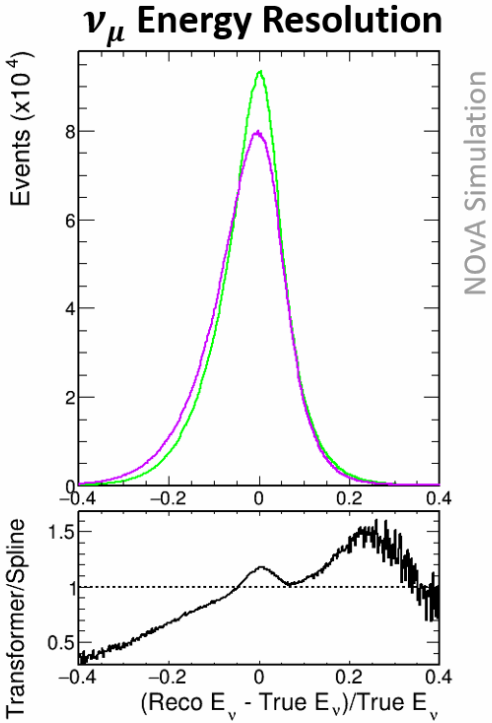
Bian, J. (2018). *Results and Prospects from NOvA*. **Proceedings of the 20th International Workshop on Neutrinos — PoS(NuFACT2018)**.

Early Results are Promising!

- Mass splitting is sensitive to the muon disappearance channel
- Important to be able to effectively characterise energy of muon neutrino interactions







Figures from: Transforming the ν World: A New Multivariate Transformer Energy Estimator for NOvA (Neutrino 2026 Poster)

Summary

- Neutrino Mass Hierarchy determination is limited by precision of global mass splitting measurements

- By utilising ML techniques, NOvA can reduce its systematic uncertainty on their measurement

- Acquisition of Test Beam can further help characterise our detector response to specific particles

- These techniques can be adopted moving forward by next gen experiments (e.g. DUNE), with higher statistics

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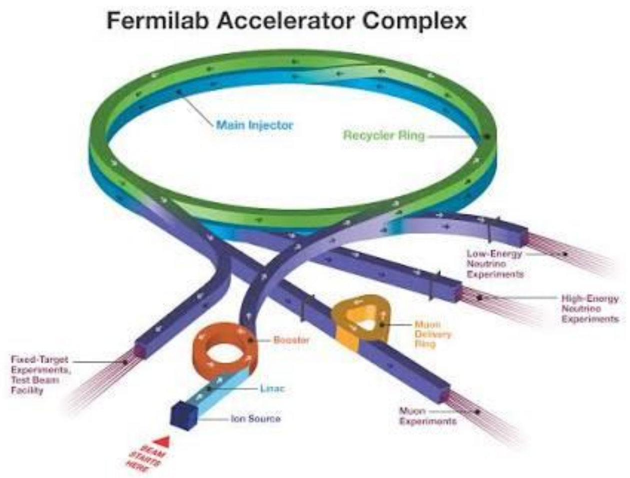
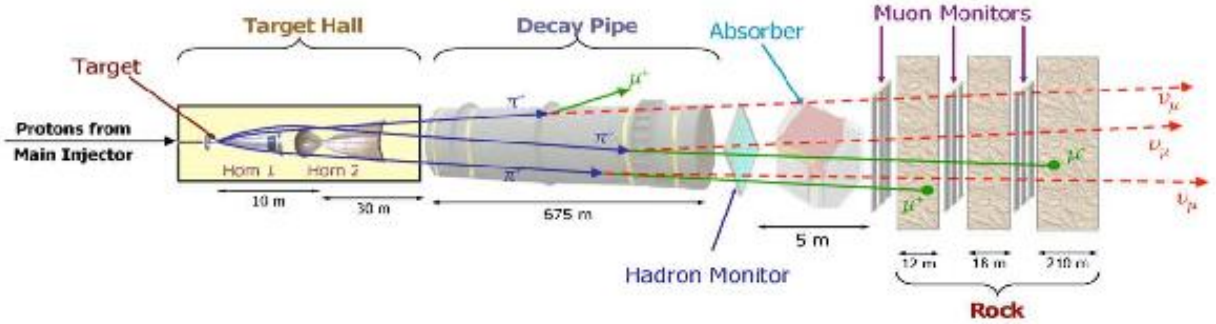
Backups

NuMI Beam

https://www.fnal.gov/pub/science/particle-accelerators/accelerator-complex.html

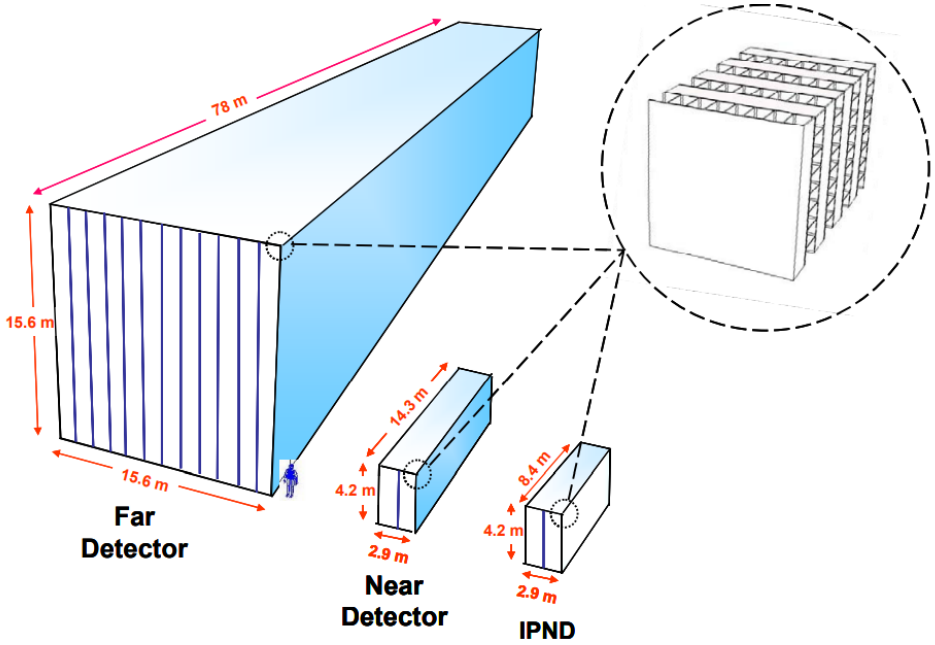


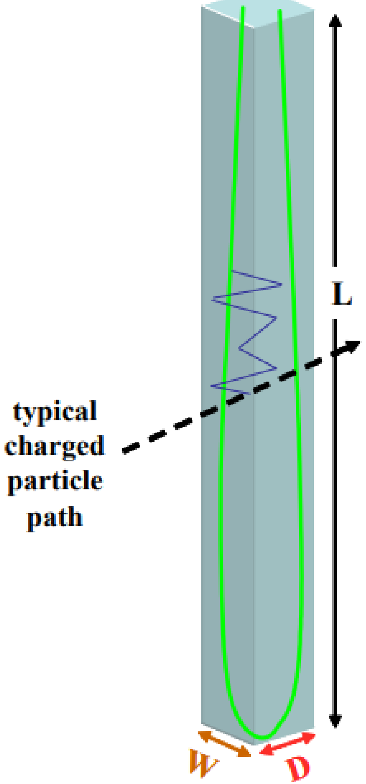
- Neutrinos at Main Injector
- High energy protons fired at graphite target
- Pions, kaons produces
- Decay in flight to muons and muon neutrinos



P. Adamson et al. “The NuMI Neutrino Beam”. In: Nucl. Instrum. Meth. A 806 (2016),pp. 279–306. doi: 10.1016/j.nima.2015.08.063. arXiv: 1507.06690 [physics.acc-ph].

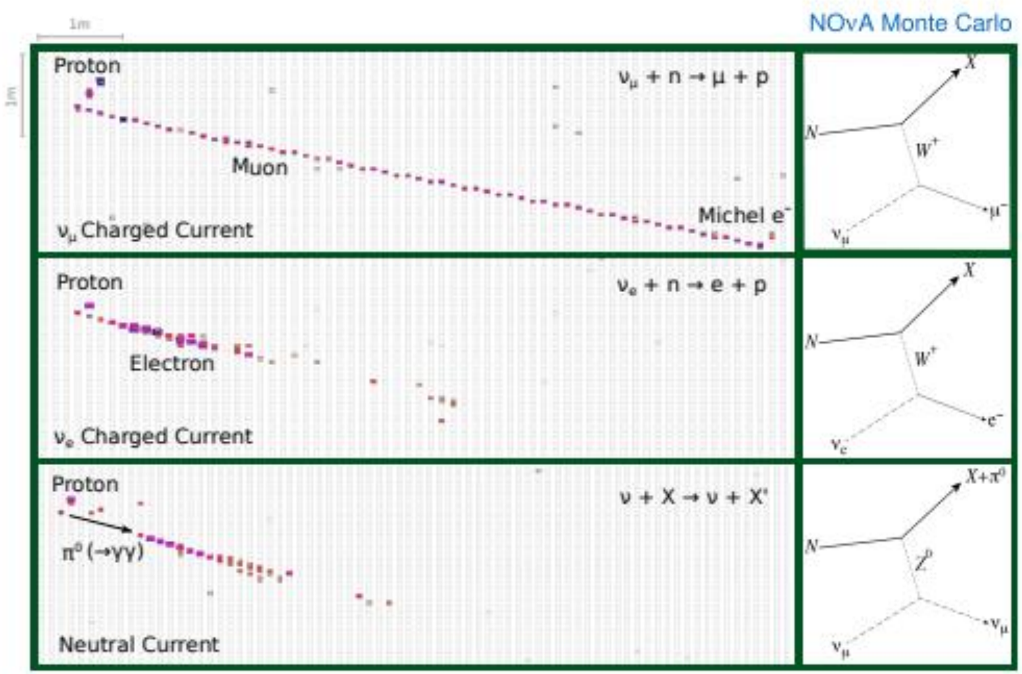
NOvA Detectors





Figures from: The NOvA Technical Design Report (2007)
https://inspirehep.net/files/1e897a237c85bae0087a7f644e9ad832

Example Event in Detector



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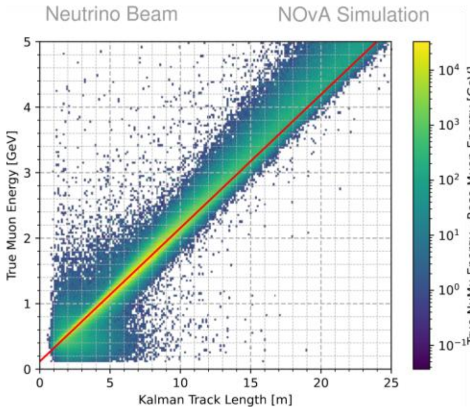
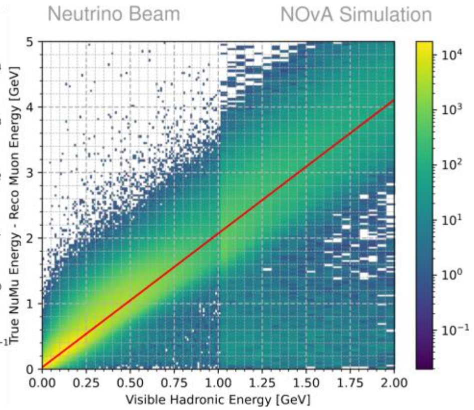
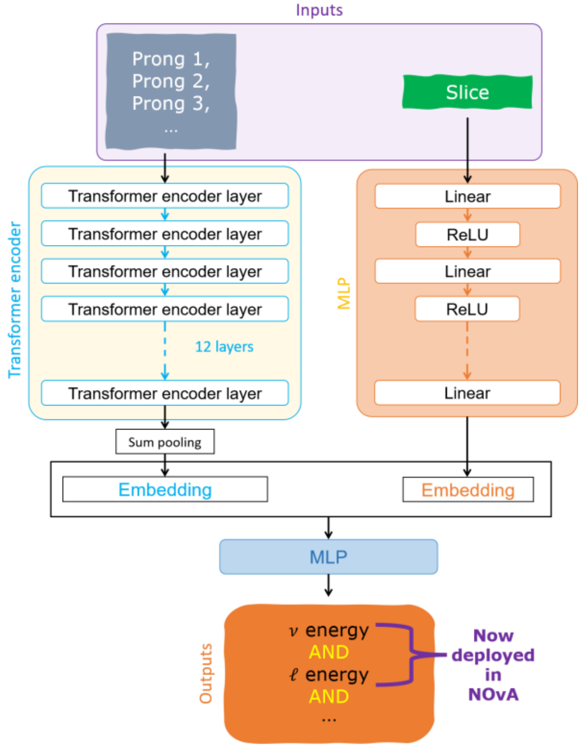
Baird, M., Bian, J., Messier, M., Niner, E., Rocco, D., & Sachdev, K. (2015). *Event Reconstruction Techniques in NOvA*. **Journal of Physics: Conference Series, 664**, 072035. https://doi.org/10.1088/1742-6596/664/7/072035.

Transformer and Spline Architecture

- Transformer (multivariate analysis):
  - Prongs are reconstructed particles
  - Slice is a selected event in the detector
- Spline: Straight line fit to single variables







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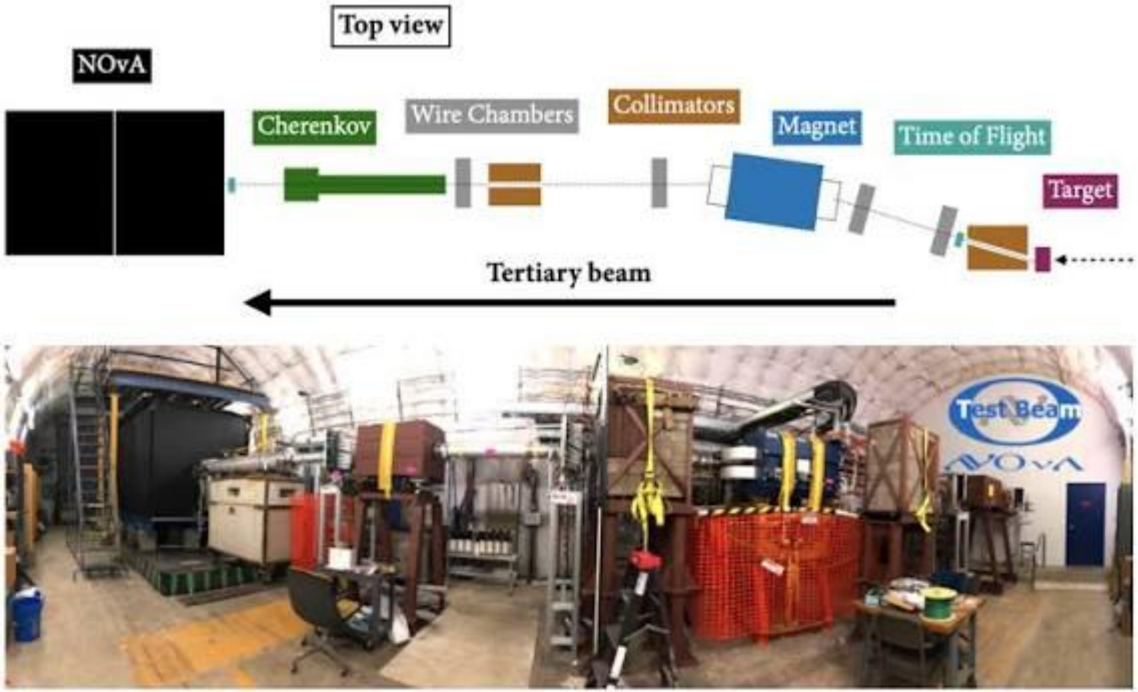
NOvA Test Beam

- Aim: To better characterise detector response to known particles



Wallbank, Michael. (2021). The NOvA Test Beam Program. 188. 10.22323/1.390.0188.