The 3+1 Neutrino Model at NOνA and DUNE

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Neutrino Oscillation

- Neutrino oscillation physics has been around for a long time and is now well documented, culminating with the Nobel Prize for Arthur B. McDonald and Takaaki Kajita in 2015.
- Oscillations are now accepted as the explanation for most of the various neutrino flux problems.
- Parameter degeneracies and the SBL anomaly remain to be solved.
- We introduce one mass and one flavour eigenstate giving the 3+1 (3 active + 1 sterile) case.
- This introduces new parameters, these are: θ_{14}, θ_{24}, θ_{34}, δ_{14}, δ_{34} and Δm^2_{41}.
- The overlaps in probabilities for several sets of oscillation parameters indicate that these will be degenerate for the simulated experiment.
- Thus we have two solutions, true (unprimed) and false (primed):

$$P_{\mu e}(\Delta_{31}, \delta_{13}, \delta_{14}, \theta_{23} \ldots) \approx P'_{\mu e}(\Delta'_{31}, \delta'_{13}, \delta'_{14}, \theta'_{23} \ldots)\,,$$

- Particularly, in some cases the MH-CP degeneracy arises because, a sign flip in Δ_{31} can be compensated by a 180° rotation of δ_{13} and/or δ_{14}.

The Neutrino Mass Hierarchy

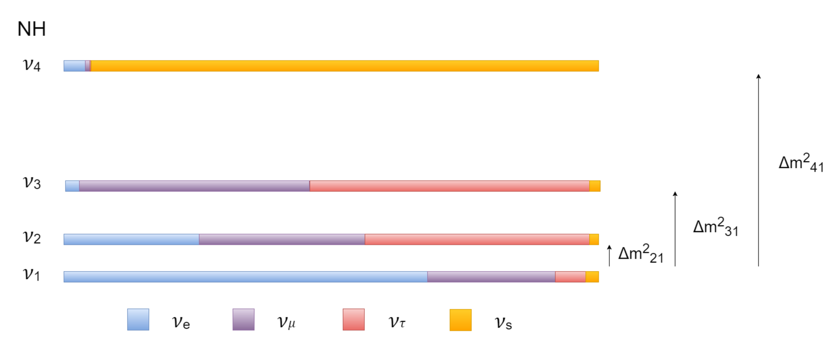

Fig. 1: Schematic of normal hierarchy (NH) with flavour content indicated by colour.

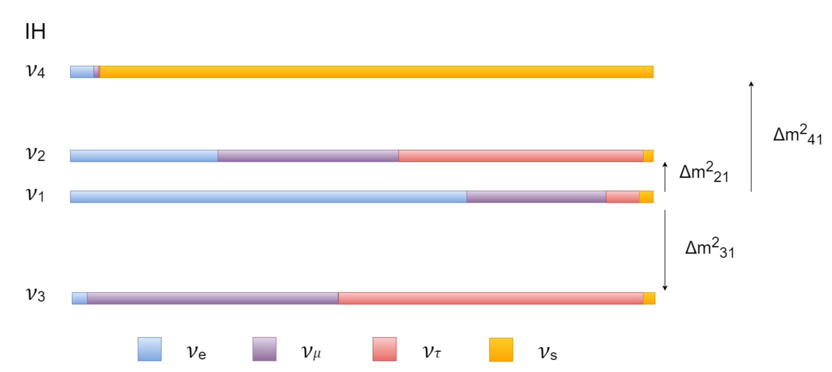

Fig. 2: Schematic of inverted hierarchy (IH) with flavour content indicated by colour.

Experiments

- To simulate we use the GLoBES software as well as additional experiment files [1, 2, 3, 4].
- We focus on the NOνA and DUNE experiments.
- NOνA is the latest long-baseline (LBL) neutrino experiment and should produce promising results in the next few years.
- DUNE is a currently in-development next generation LBL experiment.
- The aim is to see how sensitive NOνA and DUNE are in the 3+1 case.
- We have analysed the best fits from [5] which have now been supplanted.

Degeneracies in Probability (3ν)

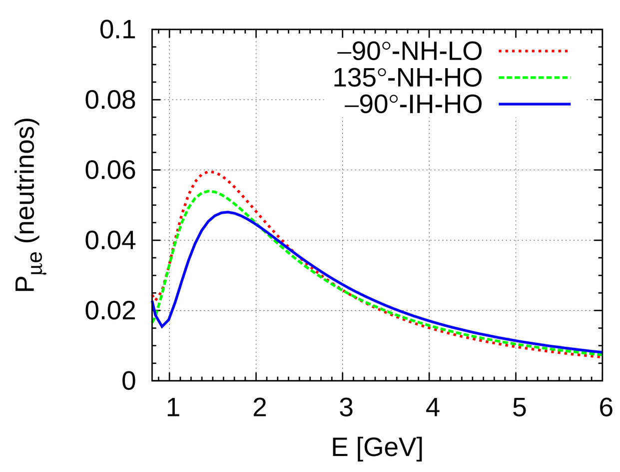

Fig. 3: Probability degeneracies at NOνA for neutrinos.

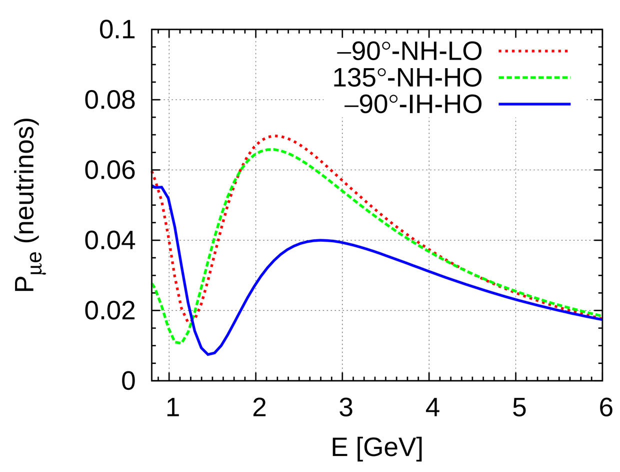

Fig. 5: Probability degeneracies at DUNE for neutrinos.

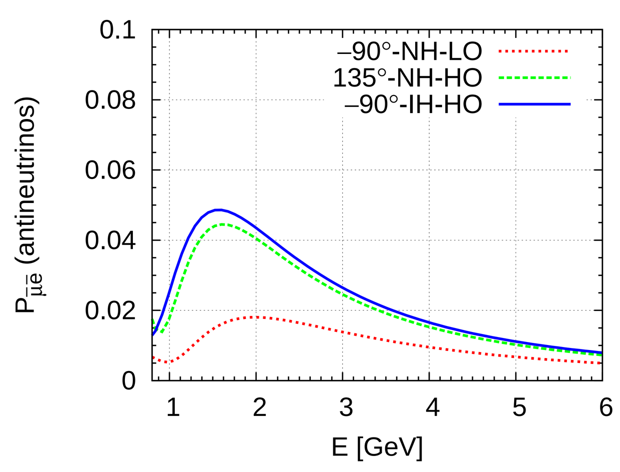

Fig. 4: Same as Fig. 3. but for antineutrinos.

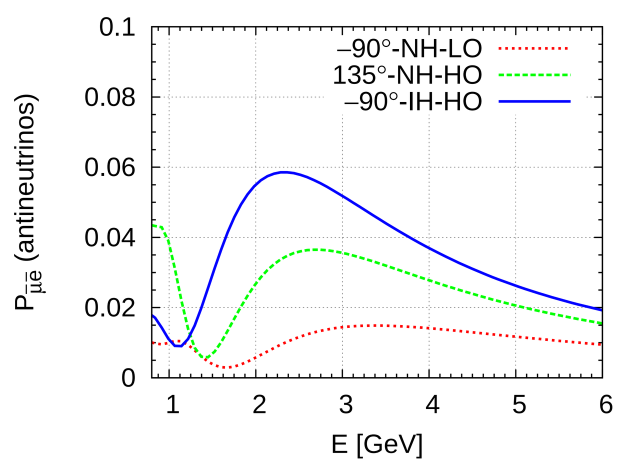

Fig. 6: Same as Fig. 5. but for antineutrinos.

Degeneracies in Probability (4ν)

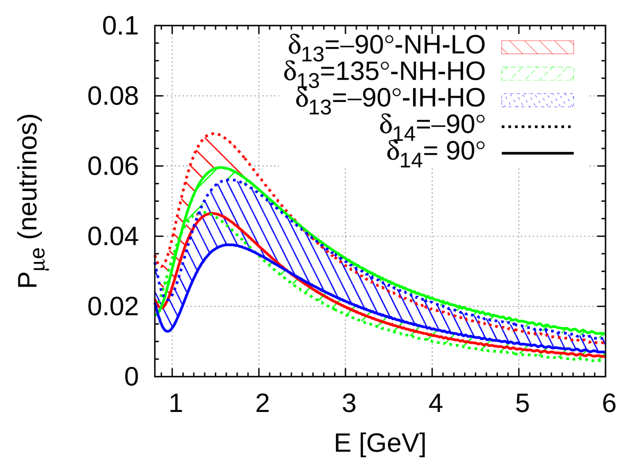

Fig. 7: Same as Fig. 3. but with a light sterile neutrino.

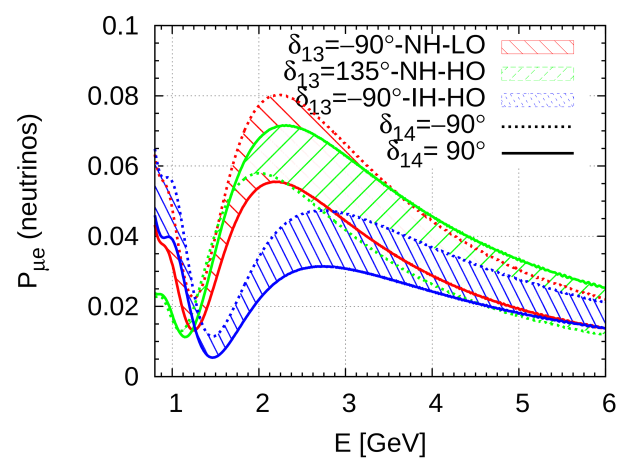

Fig. 9: Same as Fig. 5. but with a light sterile neutrino.

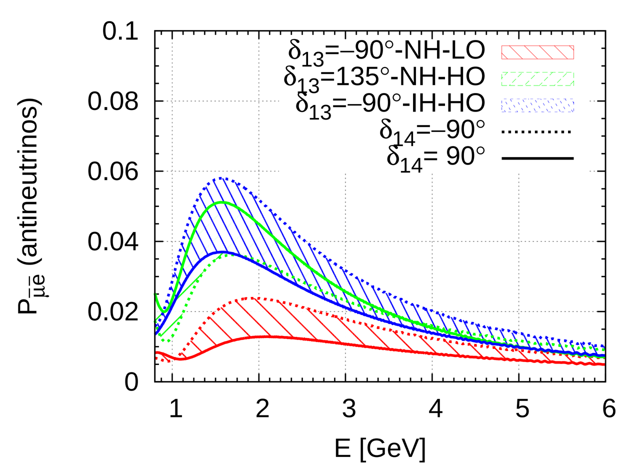

Fig. 8: Same as Fig. 7. but for antineutrinos.

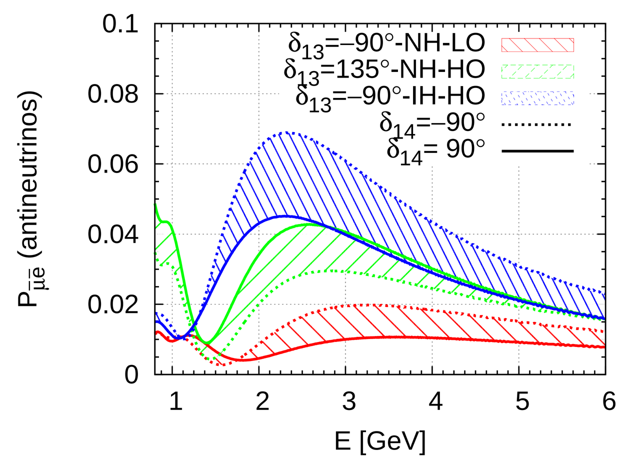

Fig. 10: Same as Fig. 9. but for antineutrinos.

Degenerate Regions

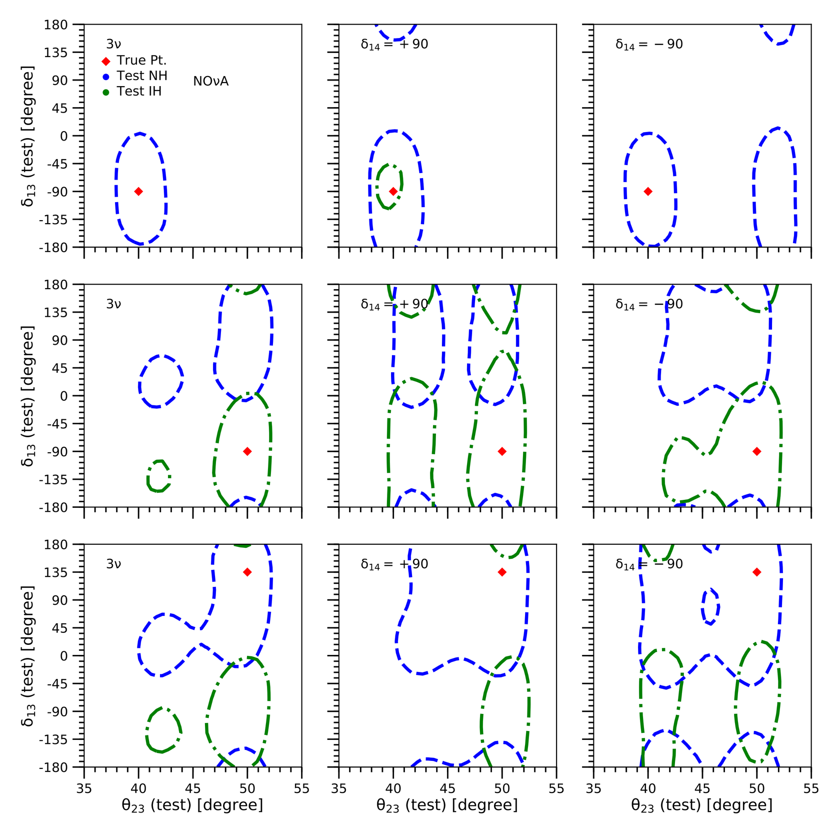

Fig. 11: Contour plots in the test $\theta_{23} - \delta_{13}$ plane for various true values.

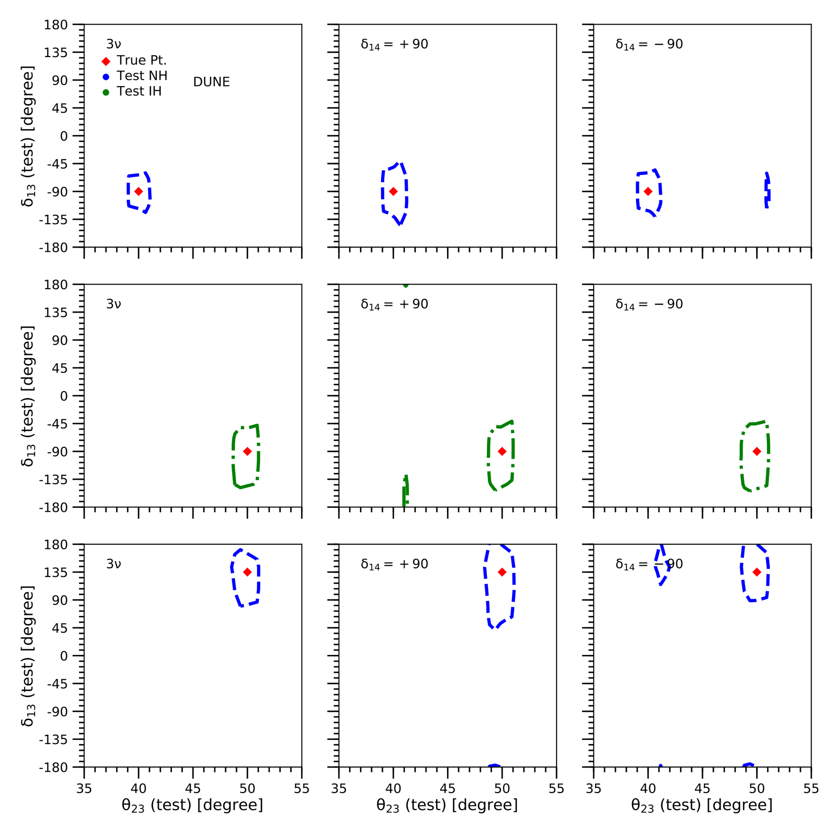

Fig. 13: same as Fig. 11. but for DUNE $5 + \bar{5}$.

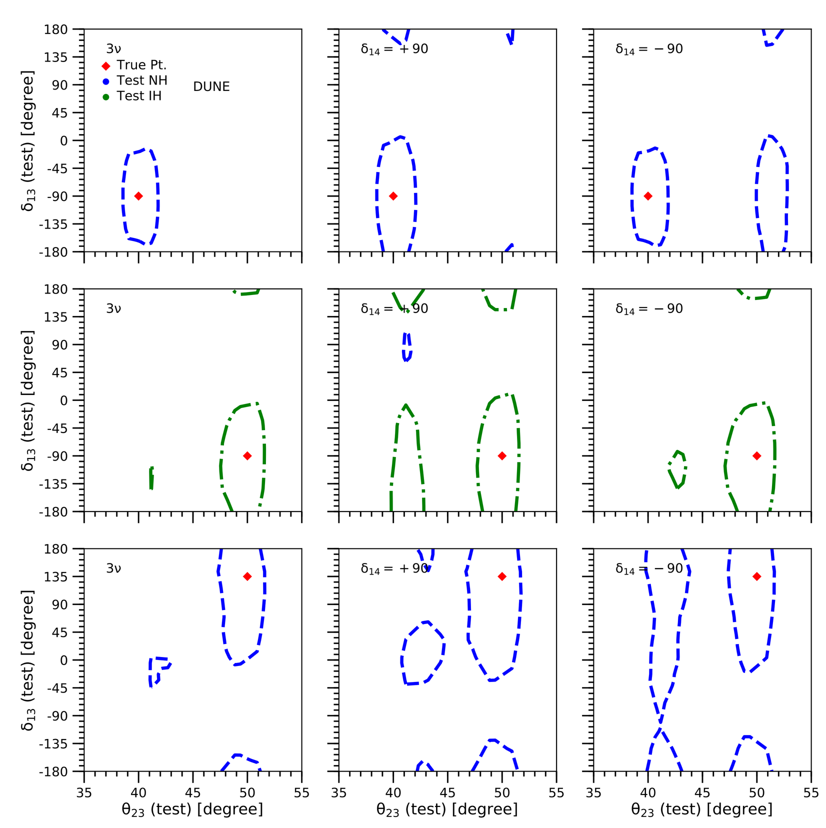

Fig. 12: same as Fig. 11. but for DUNE $2 + \bar{2}$

- In the standard neutrino case (Fig. 11. left column) NOνA can solve the current degeneracies after a full run of 3 years neutrino, 3 years antineutrino $(3 + \bar{3})$.
- In the 3+1 case (blue) there are new wrong octant degenerate regions for most δ_{14} values 90% C.L.
- Additionally, in the 3+1 case, wrong hierarchy degenerate regions appear in the wrong and right octant for all but two of the chosen values.
- These results imply that NOνA still has significant resolution power in a few cases, but this is highly dependent on the sterile parameters.
- After only a partial run, DUNE already has much greater MH resolution than NOνA, though there are still significant wrong octant solutions in the sterile case.
- For the full DUNE $5+\bar{5}$ run very few incorrect regions are left.

- NOνA can resolve the MH and octant degeneracies in the 3ν, $\delta_{13} = -90°$, LO, NH case.
- In the other considered 3ν cases NOνA cannot resolve these alone so may need to be combined with other experiments.
- DUNE can almost completely resolve all of our 3ν cases after only $2 + \bar{2}$ running.
- A full run of DUNE alone can fully resolve the sterile cases we considered, so if degeneracies haven't been solved by the time DUNE is operational, perhaps they'll be solved soon after.

References

[1] Patrick Huber, M. Lindner, and W. Winter. Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator). *Comput. Phys. Commun.*, 167:195, 2005.

[2] Patrick Huber, Joachim Kopp, Manfred Lindner, Mark Rolinec, and Walter Winter. New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator. *Comput. Phys. Commun.*, 177:432–438, 2007.

[3] Patrick Huber, Joachim Kopp, Manfred Lindner, Mark Rolinec, and Walter Winter. "globes: General long baseline experiment simulator". *Computer Physics Communications*, 177(5):439 – 440, 2007.

[4] Patrick Huber, Manfred Lindner, Thomas Schwetz, and Walter Winter. First hint for CP violation in neutrino oscillations from upcoming superbeam and reactor experiments. *Journal of High Energy Physics*, 2009(11):044–044, nov 2009.

[5] P. Adamson et al. Constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in NOνA. 2017.