Breaking the Neutrino Mass Hierarchy Problem

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Introduction

Neutrinos have had, arguably, more impact in the development of particle physics than any other single particle ever. With the historical beta decay anomaly and Fermi's four-point interaction [1], the world was introduced with a new kind of interaction - Weak Interaction. After around 90 years of proposing a new particle, *neutrino*, we have only just managed to determine that they are massive [2, 3]. But there are still plenty of undetermined facets about this elusive particle: the exact mass is unknown, the exact nature - Dirac or Majorana - is unknown, the three flavour states of neutrino are mixed but not all of the parameters governing the mixing $\left(\theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{31}, \delta_{CP}\right)$ are known with precision at experiments yet.

The neutrino oscillation experiments around the globe have become more and more precision driven over the years to resolve these underlying issues. In this paper we use GLoBES package [4, 5], to simulate the current and future long baseline neutrino oscillation experiments, studying the physics potential and optimising the experiments.

Sign-degeneracy problem in Δm^2_{31}

Among several problems neutrino oscillation physics face, both in theory as well as experiments, the determination of mass hierarchy is a very important problem. Physics of Neutrinoless double beta decay and various mass models of neutrinos depends on the mass hierarchy of neutrinos. Neutrino oscillation experiments run all over the globe to find the mass hierarchy but as seen in the 3-flavour neutrino oscillation probability expression,

$$\begin{aligned}\mathbb{P}_{\alpha\beta} &= \delta_{\alpha\beta} \\ &- 4\sum_{\mathrm{j>i}} \mathbb{R}e\left(U^*_{\alpha\mathrm{j}} U_{\beta\mathrm{j}} U_{\alpha\mathrm{i}} U^*_{\beta\mathrm{i}}\right) \sin^2\left(\frac{\Delta m^2_{\mathrm{ij}}}{4E} L\right) \\ &+ 2\sum_{\mathrm{j>i}} \mathbb{I}m\left(U^*_{\alpha\mathrm{j}} U_{\beta\mathrm{j}} U_{\alpha\mathrm{i}} U^*_{\beta\mathrm{i}}\right) \sin^2\left(\frac{\Delta m^2_{\mathrm{ij}}}{4E} L\right)\end{aligned}$$

it doesn't give masses explicitly. Instead it depends only on the mass-squared differences, Δm^2_{ij}. The three flavour mixing depends on the three mixing angles of which θ_{13} is not known precisely but is close to zero, and the octant of θ_{23} is not known. The mixing also depends on two mass-squared differences of which the sign of Δm^2_{31} is not known. These results are summarised below as measured in the experiments till date [6].

Parameter	Best-fit	3σ
$\Delta m^2_{21}[10^{-5} eV^2]$	7.37	6.93-7.96
$\lvert\Delta m^2_{31}\rvert[10^{-3} eV^2]$	2.56(2.54)	2.45-2.69(2.42-2.66)
$\sin^2\theta_{12}$	0.297	0.250-0.354
$\sin^2\theta_{23}, \Delta m^2_{31(32)} > 0$	0.425	0.381-0.615
$\sin^2\theta_{23}, \Delta m^2_{32(31)} < 0$	0.589	0.384-0.636
$\sin^2\theta_{13}, \Delta m^2_{31(32)} > 0$	0.0215	0.0190-0.0240
$\sin^2\theta_{13}, \Delta m^2_{32(31)} < 0$	0.0216	0.0190-0.0242
δ/π	1.38 (1.31)	2σ: (1.0-1.9) (2σ:(0.92-1.88))

TABLE I: Neutrino mixing parameters best fit

We consider T2K & NOνA experiments to tackle the ambiguousness in mass hierarchy due to indetermination of sign of Δm^2_{31}. T2K & NOνA are both off-axis beam experiment to study the neutrino oscillation physics. Such experiments prefer off-axis beam because a narrow energy band is obtained at the oscillation maximum.

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Sensitivity tests in T2K and NOνA

We study the sensitivity of the two experiments, T2K [7–9] & NOνA [10, 11], towards measuring the sign of Δm^2_{31} for different values of θ_{13}. The fluxes and cross-sections have been calculated and listed in [12, 13].

Minimising the χ^2 for the given PDG values in Table 1 as true values give different local minimum at different true values of θ_{13}. χ^2 is plotted against θ_{13} to see which experiment has better resolution among these two to resolve sgn(Δm^2_{31}).

Results & Conclusion

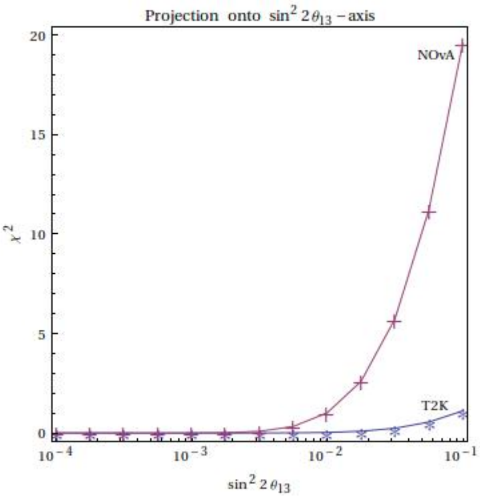

FIG. 1: Mass hierarchy sensitivity at T2K & NOνA

The results clearly show that for larger values of θ_{13}, the NOνA experiment has more ambiguity towards a conclusive sgn(Δm^2_{31}). T2K is much more sensitive in the similar regions which is visible in the form of smaller χ^2. Still, it is not possible to say, at present, whether T2K will resolve the sign-degeneracy or not. Better experiments like T2HKK, DUNE, etc have been proposed which will hopefully provide positive results. Also, a lot of research is going on for the theoretically possible Neutrino Factories which are more powerful probes than other Neutrino Oscillation experiments. Further, simulations of Neutrino Factories is possible but their experimental realisation is a far-fetched dream at present.

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