Decoherence in Neutrino Oscillations at INO

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T2K and NOνA Disagree on $\sin^2\theta_{23}$

- T2K experiment [PRL **112** (2014) 061802] observed maximal disapperance of ν_μ. This implies

$$|U_{\mu 3}|^2 = \cos^2\theta_{13}\sin^2\theta_{23} = 0.5,$$

  leading to $\sin^2\theta_{23} = 0.514$.
- When they do a combined analysis of their disappearance and appearance data [PRD **91** (2015) 072010], they obtain $\sin^2\theta_{23} = 0528^{+0.055}_{-0.038}$.
- NOνA experiment on the other hand prefers a non-maximal value for $\sin^2 2\theta_{23}$ [PRL **118** (2017) 151802].

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} \quad \text{or} \quad \sin^2\theta_{23} = 0.624^{+0.022}_{-0.030}$$

Tangential Comment on T2K measurement of $\sin^2\theta_{23}$

- In their most recent published analysis, T2K [PRL **118** (2017) 151801] T2K have two solutions, which are essentially degenerate:
  1. NH, $\sin^2\theta_{23} = 0.532$ and $\delta_{\rm CP} = -102^\circ$,
  2. IH, $\sin^2\theta_{23} = 0.534$ and $\delta_{\rm CP} = -80^\circ$.
- For the above value of $\sin^2\theta_{23}$, we have

$$4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = 0.997,$$

  which is less than half a percent away from maximal disappearance.
- But, why does the best fit of $\sin^2\theta_{23}$ occur at 0.534 rather than 0.514 as was claimed from the analysis of only disappearance data.
- Adding the ν_e appearance data is pushing $\sin^2\theta_{23}$ higher.
- Question: Why does the data prefer this solution rather than one with $\sin^2\theta_{23} = 0.514$ and $\delta_{\rm CP} = -90^\circ$?

Who is Right?

- Possibility-1: $\sin^2 2\theta_{23}$ is maximal. Then we can expect a correction for NOνA.
- Possibility-2: $\sin^2 2\theta_{23}$ is non-maximal. Then we can expect a correction from T2K. Also this is a more interesting possibility from various other points of view (especially for model builders).
- Possibility-3: May be the results of both T2K and NOνA are correct. This is the point of view of Coelho, Mann and Bashar [PRL **118** (2017) 221801].
- They argued that T2K and NOνA have different baselines and also their fluxes peak at different energies.
- To maximise their oscillation signals, they were each designed so that $\Delta m^2_{31} L/E \sim 1$ for both of them.
- But, if there is physics other than oscillation, then values of parameters derived using oscillation formula will differ in the two cases.

What is this Other Physics?

- This other physics can depend purely on energy (as for example the matter term in MSW effect).
- Or it can depend purely on baseline, i.e. the distance of travel of the neutrino or equivalently its time of travel.
- Or it can depend on both but in a form different from that of oscillations.
- Here we limit ourselves to the first two types.

Energy Dependent Solution on One Slide

- Let us suppose there is an MSW like matter term $A_{\rm NP}$ for ν_μ propagation. We want to obtain

$$\sin^2 2\theta_{23}^m = \frac{(\Delta_{31}\sin 2\theta_{23})^2}{[(\Delta_{31}\cos 2\theta_{23} - A_{\rm NP})^2 + (\Delta_{31}\sin 2\theta_{23})^2]} = 0.96,$$

for $\sin 2\theta_{23} = 1.0$, $\Delta_{31} = 2.5 \times 10^{-3}$ eV^2.

- This simple calculation shows that we need $A_{\rm NP} \simeq A_{\rm MSW}$ to achieve the desired change through MSW-like energy dependent terms.
- A more complete analysis, with the same philosophy, was done in Liao, Marfatia and Whisnant [PLB **767** (2017) 350] and they reach the same conclusion.
- Advertisement: Poster by M. Nizam where he studied the ability of INO to constrain $A_{\rm NP}$.

Baseline Dependent Solutions

- The formalism of neutrino oscillations assume that, once produced, a neutrino remains in a perfect superposition of two (or three) mass eigenstates.
- Superposed quantum states, especially in atomic physics, show that perfect superposition does not last for ever.
- Their interaction with environment leads to loss of superposition or decoherence.
- The time evolution equation, including such dissipative interactions with environment, is

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho],$$

where ρ is the neutrino density matrix.
- Based on some general requirements, it can be shown that the operator $\mathcal{D}$ can be parametrized by a single decoherence parameter Γ in the case of two flavour oscillations (three decoherence parameters in three flavour oscillations).

Wave Packet Decoherence

- This decoherence is to be contrasted with wave packet decoherence which worried people ever since neutrino oscillations were considered.
- Since the neutrino energy must span both mass eigenstates m_1 and m_2, the propagating neutrino must be viewed as a wave packet, which is a superposition of the wave packets of two mass eigenstates.
- Since the two masses are different, the mean speed of the of the two mass eigenstate wave packets are different. If you wait long enough (or if the baseline is long enough) the overlap between the two wave packets will be lost. This is called wave packet decoherence.
- For ultra-relativistic neutrinos, such as reactor or long baseline neutrinos, these effects are negligible.
  For example, see Section 8.2 of the book *Fundamentals of Neutrino Physics and Astrophysics* by Giunti and Kim.

Survival Probability with Decoherence

- Lisi, Marrone and Montanino [PRL **85** (2003) 093006] derived the muon neutrino survival probability assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23}\left[1 - \exp^{-\Gamma L}\cos\left(\frac{\Delta_{31} L}{2E}\right)\right].$$

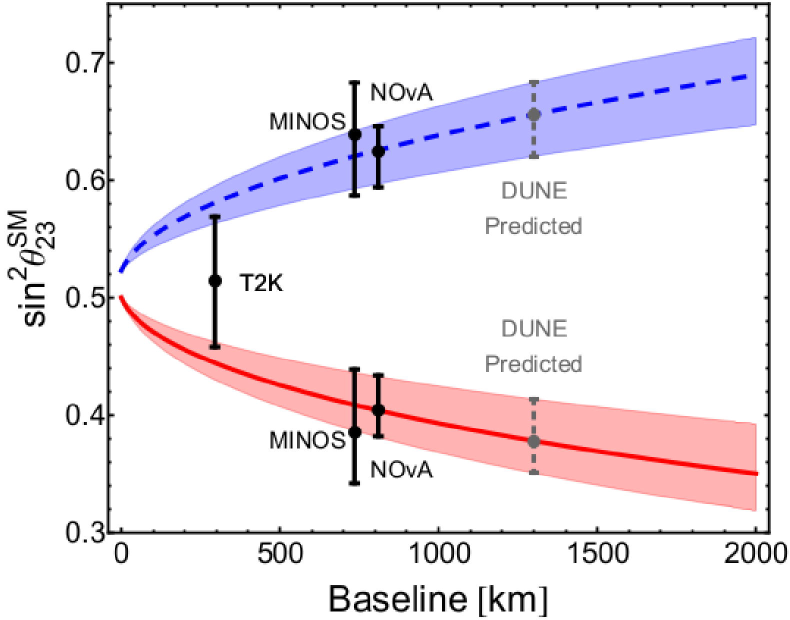
- They made a fit to the Super-Kamiokande data using the above expression. The best fit point occured for $\Gamma = 0$. They also obtained the 90% upper limit

$$\Gamma \leq 3.5 \times 10^{-23}\ \mathrm{GeV}.$$

- The factor $\exp(-\Gamma L)$ makes it look like the expression for neutrino decay. However, in the case of neutrino decay, the whole oscillating factor gets multiplied by $\exp(-\Gamma L)$. For a discussion of decoherence in decaying and oscillating neutral mesons, see A. K. Alok, S. Banerjee and SUS, PLB **749** (2015) 94.

Decoherence in Three Flavour Oscillations

- Extension to three flavours in vacuum or in constant matter density is straight forward. The corresponding expressions are given in the paper of Coelho *et. al.* mentioned before.
- In three flavours, there are three decoherence parameters Γ_{21}, Γ_{31} and Γ_{32}, which modulate the corresponding oscillating term $\cos(\Delta_{ij} L/2E)$.
- Solar neutrino data and KamLAND data show that Γ_{21} is negligibly small. [G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, PRD **76** (2007) 033006].
- Coelho *et. al.* assumed $\Gamma_{31} = \Gamma_{32} = \Gamma$ and showed that the non-maximail $\sin^2 2\theta_{23}$ preferred by NOνA disappearance data can be explained if we assume $\sin^2 2\theta_{23} = 1$ and $\Gamma = (2.3 \pm 1.1) \times 10^{-23}$ GeV.


0.7
0.6
0.5
0.4
0.3
$\sin^2\theta_{23}^{SM}$
NOvA
MINOS
DUNE
Predicted
T2K
DUNE
Predicted
MINOS
NOvA
0
500
1000
1500
2000
Baseline [km]

Decoherence Limits from INO-ICAL

- We did a preliminary study of decoherence limits that can be obtained from 10 years of atmospheric data from ICAL.
- Using NUANCE event generator, 500 years of unoscillated atmospheric ν_μ CC events were simulated with $E_\nu : 0.5 - 100$ GeV.
- They were modulated with the two flavour survival probability without decoherence

$$P_{\mu\mu}^{\mathrm{ND}} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta_{31} L}{4E} \right).$$

- The unoscillated events were modulated once more, now with the two flavour survival probability with decoherence

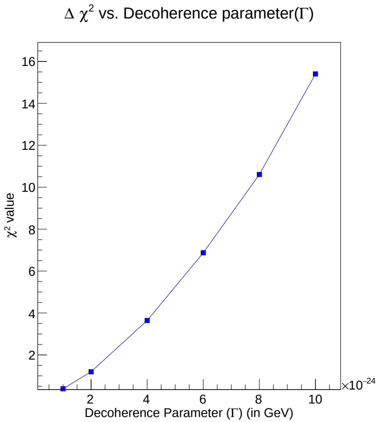
$$P_{\mu\mu}^{\mathrm{WD}} = 1 - \frac{1}{2} \sin^2 2\theta_{23} \left[1 - \exp^{-\Gamma L} \cos \left(\frac{\Delta_{31} L}{2E} \right) \right].$$

- We used the oscillation parameters, $\sin^2 2\theta_{23} = 1$ and $\Delta_{31} = 2.5 \times 10^{-3}$ eV^2.

Decoherence Limits from INO-ICAL

- Both the event samples, without and with decoherence, are binned in $\cos\theta_\mu$ (zenith angle of the muon) and E_μ (the energy of the muon).
- The range of $\cos\theta_\mu$ is $(0.1, 1)$ with bin size 0.025 and the energy bins are taken to be $(1-2, 2-3, 3-4, 4-5, 5-6, 6-7.5, 7.5-9, 9-11, 11-14, 14-20)$ GeV.
- We have computed the χ^2 between the two event samples as a function of Γ and scaled it down for an the exposure of 10 years.
- The plot of χ^2 vs. Γ is given in the next slide. The information on hadron energy is NOT used in generating this plot.

Decoherence Limits from INO-ICAL

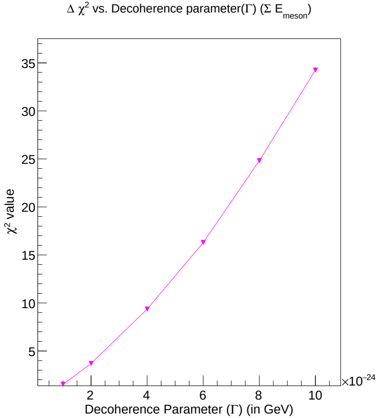


Values of $\Gamma > 7 \times 10^{-24}$ GeV can be ruled out at 3 σ.

Decoherence Limits from INO-ICAL Including Hadron Energy

- Amol, in his talk, demonstrated that the inclusion of hadron energy improves the precision of various quantities in ICAL.
- We included the meson energy as a third independent variable and redid the χ^2. We considerd four hadron energy bins: $(1-2, 2-4, 4-7 \text{ and } 7-11)$ GeV.
- The results show quite an improvement.

Decoherence Limits from INO-ICAL Including Hadron Energy



Now values of $\Gamma > 3 \times 10^{-24}$ GeV can be ruled out at 3 σ.

Conclusions

- Atmospheric Neutrinos of very long pathlengths and high energies are ideal for testing decoherence in oscillations due interactions with environment.
- ICAL, which can make an accurate measurement of the energy and the direction of these high energy muons can put stringent limits on the decoherence parameters.
- Including the hadron energy as a variable in the analysis leads to a marked improvement in the limits. It is possible to set a 3 σ upper limit of $\Gamma \leq 4 \times 10^{-24}$ GeV.
- Recently Coloma, Lopez-Pavon, Martiniz-Soler and Nunokawa have analyzed IceCube/DeepCore data to obtain upper limits on the decoherence parameters (arXiv:1803.04438).