Invisible Neutrino Decay: First vs Second Oscillation

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Invisible neutrino decay

We assume that the ν_3 is unstable and it decays into a sterile neutrino and a singlet scalar with lifetime τ_3. If the new flavour state is ν_s and the mass state is ν_4, we can write as

$$\begin{pmatrix}\nu_\alpha \\ \nu_s\end{pmatrix} = \begin{pmatrix}U & 0 \\ 0 & 1\end{pmatrix}\begin{pmatrix}\nu_i \\ \nu 4\end{pmatrix}. \quad (1)$$

U is the PMNS matrix, and ν_α and ν_i are standard flavour and mass states respectively. We assume,

- Normal hierarchy of the standard neutrinos
- decay eigenstates and the mass eigenstates are same.

Evolution equation in matter:

$$i\frac{d}{dx}\nu_f = \frac{1}{2E}[U\tilde{H}U^\dagger + A]\nu_f, \quad (2)$$

where,

$$\tilde{H} = \begin{pmatrix}0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} - i\frac{m_3}{\tau_3}\end{pmatrix}, \quad (3)$$

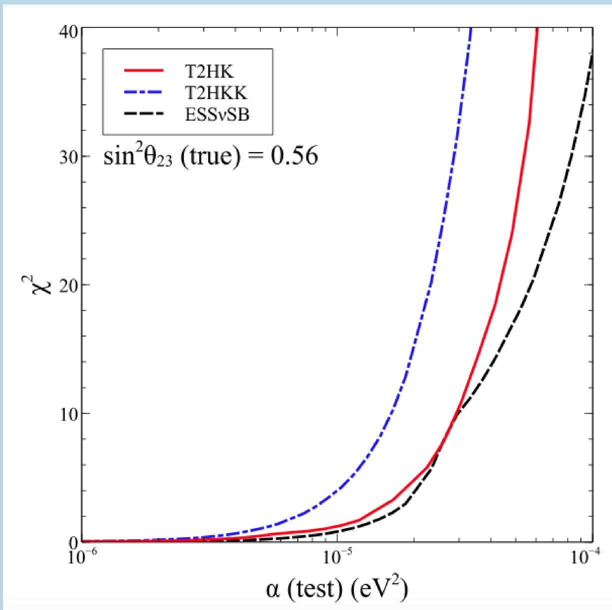
We define, $\alpha = m_3\tau_3$ as the decay rate of the ν_3. The oscillation probability from ν_α to ν_β is then given by,

$$P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha|^2. \quad (4)$$

We calculate this by solving the evolution equation numerically.

Sensitivity

The sensitivity to the decay assuming higher octant true. The important thing to notice is the kink in the sensitivity of ESSνSB, which is a second oscillation maximum experiment. We also note that T2HKK has highest sensitivity whereas the ESSνSB has the lowest.



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Reference

[1] Hyper-Kamiokande Proto Collab. ,*Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande*, , PTEP 2015 (2015) 053C02

[2] Hyper-Kamiokande collaboration., *Physics potentials with the second Hyper-Kamiokande detector in Korea*, PTEP 2018 (2018) 063C01

[3] ESSnuSB collaboration, *A very intense neutrino super beam experiment for leptonic CP-violation discovery based on the European spallation source linac*, Nucl. Phys. B 885 (2014) 127

Simulation details

We considered two experimental configurations which have a detectors at second oscillation maxima, T2HKK [2] and ESSνSB [3]. We also consider T2HK [1] for a comparison which is purely first oscillation maximum experiment.

Exp	L (km)	E (GeV)	Mass (kt)
T2HK	295	0.56	374
T2HKK	295,1100	0.56	187,187
ESSνSB	540	0.35	500

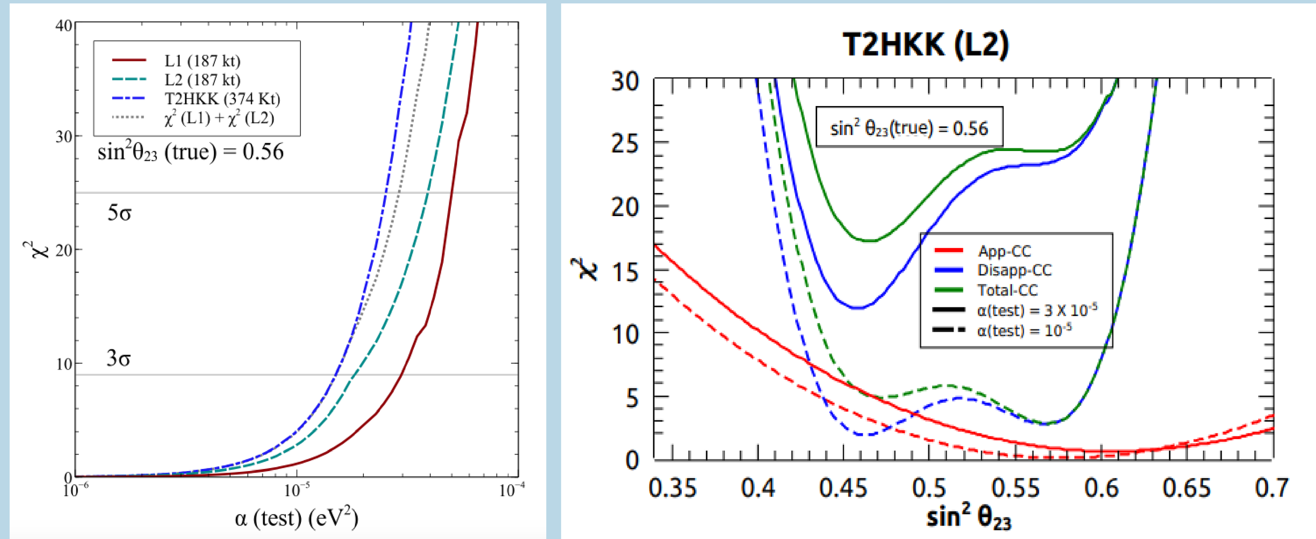
To do our statistical analysis, we use the following χ^2 function

$$\chi^2 = 2\sum_i\left(N^i_test - N^i_{true} + N^i_{true}ln\left(\frac{N^i_{true}}{N^i_{test}}\right)\right) \quad (5)$$

We also considered the systematic uncertainties using pull method.

Synergy between first and second oscillation maxima

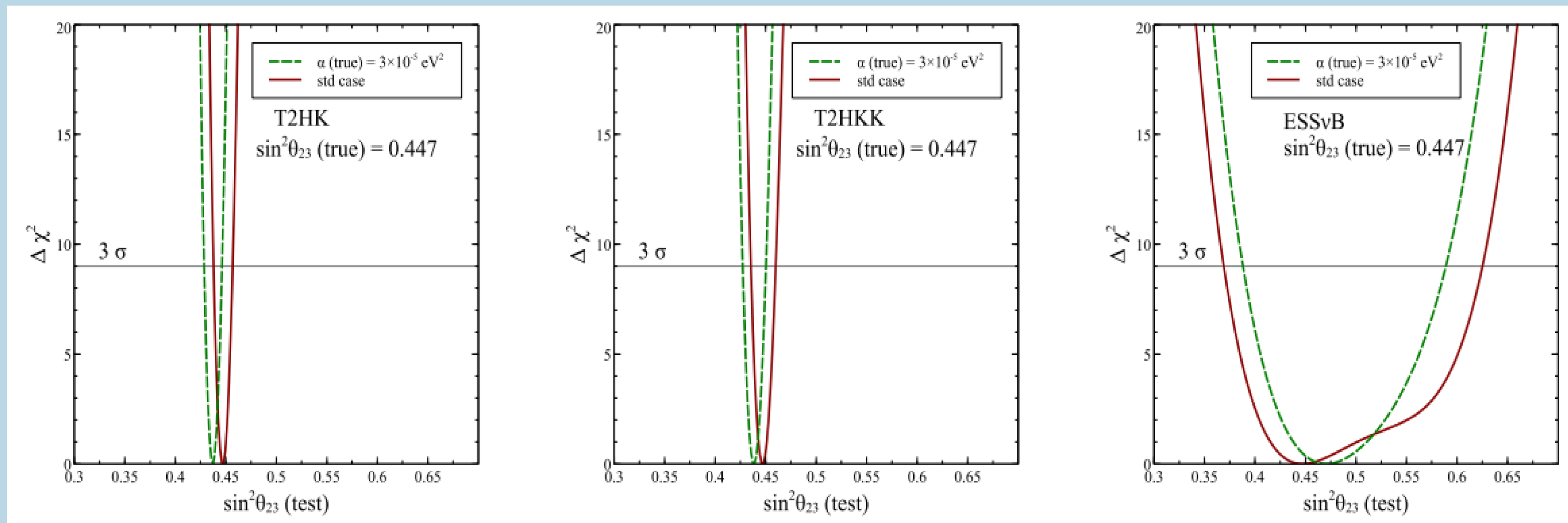
In the left panel we show the effect of two detectors of the T2HKK. L1 (295 km) and L2 (1100 km) are two detectors, The important point to note from this figure, is that the sum of the χ^2 of the two detectors is less than the actual sensitivity of the combined experiment, we call this synergy between the two detectors.



The synergy is due to the interplay between appearance and disappearance. channels shown in the right fig. The disappearance gives best fit in the wrong octant. For lower values, appearance dominates and for higher values, diasappearance wins. Thus, there is a discontinuity in the sensitivity curve. For the T2HKK, the first detector constrains θ_{23} in the right octant, thus the synergy.

Role of decay in θ_{23} measurement

Dark red curves represents the standard case with no decay. In the cases of green curves, we assume decay in the simulated data, but not in the fit.



We see that for the lower octant, the best-fits for the θ_{23} shift towards lower values for the cases of T2HK and T2HKK, however, when purely second oscillation maximum experiment is considered like ESSνSB, the best-fit shifts towards a higher value of θ_{23}.