

Sensitivity of INO ICAL to neutrino mass hierarchy and θ_{23} octant in presence of invisible neutrino decay in matter

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Introduction

The proposed India-based Neutrino Observatory will house a 50 kton magnetised Iron Calorimeter (ICAL) detector to detect atmospheric neutrinos and probe the Earth matter effects on their propagation. Although the main goal of ICAL is to determine neutrino mass hierarchy, it will perform precision measurements on the 2–3 oscillation parameters θ_{23} and $|\Delta m_{32}^2|$ also. The detector optimised to detect muons of a few GeV energy is most sensitive to the charged current (CC) interactions of ν_μ and $\bar{\nu}_\mu$ with the iron target which will produce hadrons and μ^- or μ^+ in the final state. The charge of the muon can be identified well since ICAL is a magnet. This, along with excellent muon resolutions and a large detector mass makes it suitable to determine mass hierarchy, irrespective of δ_{CP} . ICAL being an atmospheric neutrino experiment has the advantage to probe a wide range of L/E , where L is the distance travelled by a neutrino and E its energy. This along with the aforementioned attributes makes it a good detector to study exotic physics phenomena like invisible neutrino decay. Here we present a study on the sensitivity of 500 kton year exposure of ICAL to the invisible decay of the mass eigen state ν_3 in the presence of Earth matter effects. Only the charged current (CC) interactions of atmospheric ν_μ and $\bar{\nu}_\mu$ are analysed. The analysis with observed muon energy in the range 0.5–25 GeV would give a constraint of $\tau_3/m_3 > 1.51 \times 10^{-10}$ s/eV at 90% CL with this exposure. Here τ_3 is the lifetime and m_3 is the mass of ν_3 . The precision on $\alpha_3 \equiv m_3/\tau_3$ and the effect of a non-zero α_3 on the precision measurement of $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ are also studied. The presence of decay affects the oscillation amplitude rather than its phase, it is seen that the precision on $\sin^2 \theta_{23}$ worsens whereas that on $|\Delta m_{32}^2|$ is not much affected. Sensitivity to hierarchy also worsens slightly in the presence of the invisible decay of ν_3 when all parameters are known precisely. For $\alpha_3 \leq 1 \times 10^{-5}$ eV², θ_{23} octant sensitivity improves (worsens) in the presence of invisible decay if θ_{23}^{true} is in the first (second) octant.

Decay of neutrinos

- Observations of neutrino oscillations have proved that neutrinos have mass even though very tiny (\sim eV). Hence they could decay.
- An interesting possibility : A neutrino decays into another neutrino and a scalar (or a Majoron) $\nu \rightarrow \nu' + \phi$, where ϕ can be a scalar or pseudo-scalar massless boson.
- Invisible decays : decay products in the final state are unobservable (a sterile neutrino and the scalar or pseudo-scalar massless boson ϕ). Visible decays : final state contains active neutrinos.
- Parametrisation of decay of each neutrino mass eigen state ν_i , where $i = 1, 2, 3$: ratio of τ_i and m_i , where τ_i is the lifetime and m_i is the mass of each ν_i ; respectively.

Invisible decay of ν_3

- Invisible neutrino decay + 2-flavour vacuum oscillations:
$$i \frac{d}{dx} \nu_f = U \left[\frac{\Delta m_{32}^2}{2E} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} - i \frac{\alpha_3}{2E} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \right] U^\dagger \nu_f, \text{ where } \alpha_3 = \frac{m_3}{\tau_3}$$

$$(eV^2), \nu_f = \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}, U = \begin{pmatrix} c_{23} & s_{23} \\ -s_{23} & c_{23} \end{pmatrix}; c_{23} \equiv \cos \theta_{23} \text{ and } s_{23} \equiv \sin \theta_{23}.$$

The ν_μ survival probability : $P(\nu_\mu \rightarrow \nu_\mu) = [\cos^2 \theta_{23} + \sin^2 \theta_{23} \exp^{-\frac{\alpha L}{2E}}]^2 - 4 \cos^2 \theta_{23} \sin^2 \theta_{23} \exp^{-\frac{\alpha L}{2E}} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right)$, where L is the distance travelled by the neutrinos. Decay affects the amplitude of the oscillation but not its frequency.

- Current limits on τ_3/m_3 , where τ_3 and m_3 are the lifetime and mass of ν_3 respectively : From MINOS combined charged current (CC) and neutral current (NC) analysis $\rightarrow \tau_3/m_3 > 2.8 \times 10^{-12}$ (s/eV) at 90% CL.

Invisible decay and oscillation in 3-flavour matter

- $i \frac{d\tilde{\nu}}{dt} = \frac{1}{2E} [U M^2 U^\dagger + A_{CC}] \tilde{\nu}$, where, $M^2 = \text{diag}(\mathbf{0}, \Delta m_{21}^2, \Delta m_{32}^2 - i\alpha_3)$ is the mass matrix modified to take into account the decay of the heaviest mass eigen state ν_3 , $\tilde{\nu}^T = (\nu_e \nu_\mu \nu_\tau)$, E = neutrino energy, α_3 = decay constant in units of eV² and U is the 3×3 neutrino mixing matrix. The mixing matrix :
$$U = \begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -C_{23}S_{12} - S_{23}S_{13}C_{12}e^{i\delta} & C_{23}C_{12} - S_{23}S_{13}S_{12}e^{i\delta} & S_{23}C_{13} \\ S_{23}S_{12} - C_{23}S_{13}C_{12}e^{i\delta} & -S_{23}C_{12} - C_{23}S_{13}S_{12}e^{i\delta} & C_{23}C_{13} \end{pmatrix} \text{ where } c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}; \theta_{ij} \text{ is the mixing angle between two mass eigenstates } i \text{ and } j; i, j = 1, 2, 3 \text{ and } \delta \text{ is the CP violating (Dirac) phase.}$$
- Matter term : $A_{CC} = 2\sqrt{2}G_F n_e E = 7.63 \times 10^{-5} \text{ eV}^2 \rho(\text{gm/cc}) E(\text{GeV})$, where, G_F is the Fermi constant and n_e is the electron number density in matter and ρ is the matter density.

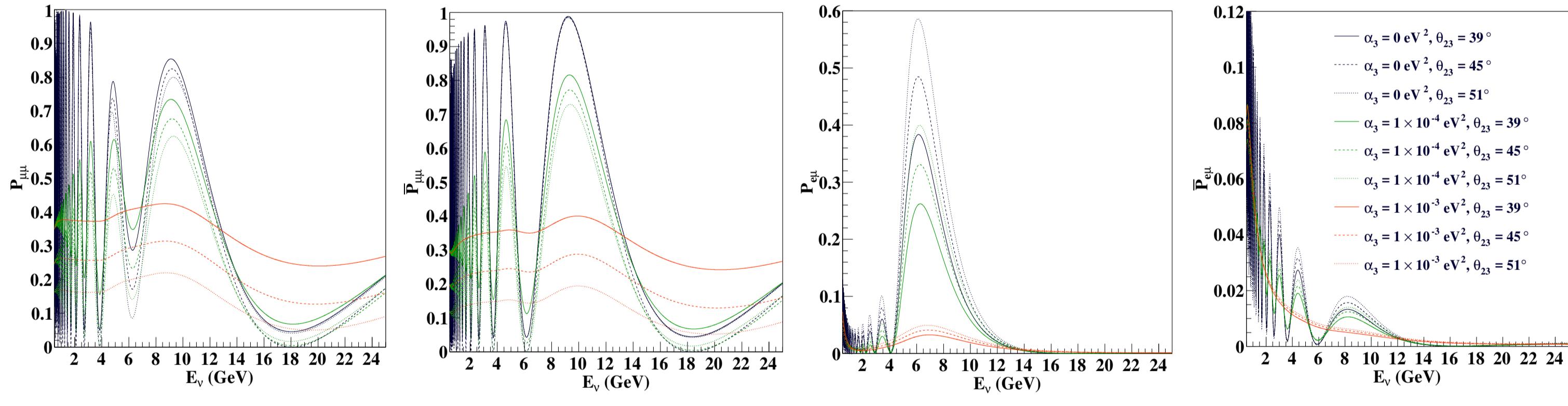


Figure 1: 3-flavour matter oscillation probabilities $P_{\mu\mu}$, $\bar{P}_{\mu\mu}$, $P_{e\mu}$ and $\bar{P}_{e\mu}$ with $\alpha_3 = 0, 1 \times 10^{-4}$ and 1×10^{-3} eV² and $\theta_{23} = 39^\circ, 45^\circ$ and 51° , for $L = 9700$ km in the energy range $E_\nu = 0.5$ –25 GeV and true NH.

χ^2 analysis with charged current ν_μ and $\bar{\nu}_\mu$ events

- No. of CC ν_μ events : $\frac{d^2 N}{dE_\nu d \cos \theta_\mu} = t \times n_d \times \int dE_\nu d \cos \theta_\nu d\phi_\nu \times \left[P_{\mu\mu} \frac{d^3 \Phi_\mu}{dE_\nu d \cos \theta_\nu d\phi_\nu} + P_{e\mu} \frac{d^3 \Phi_e}{dE_\nu d \cos \theta_\nu d\phi_\nu} \right] \times \frac{d\sigma_\mu(E_\nu)}{dE_\mu d \cos \theta_\mu}$, where n_d = the number of targets in the detector, σ_μ = differential neutrino interaction cross section in terms of the energy and direction of the charged current lepton, Φ_μ and Φ_e : fluxes of ν_μ and ν_e and $P_{\alpha\beta}$: oscillation probability $\nu_\alpha \rightarrow \nu_\beta$ in matter modified with α_3 . Similarly for anti-neutrinos. CID efficiency taken into account.
- Bins of $(E_\mu^{obs}, \cos \theta_\mu^{obs}, E_{had}^{obs})$ (3D); $E_\mu^{obs} = 0.5$ –25 GeV, $\cos \theta_\mu^{obs} = [-1, 1]$ and $E_{had}^{obs} = 0$ –15 GeV.
- Systematic uncertainties : $\pi_1 = 20\%$ flux normalisation error, $\pi_2 = 10\%$ cross section error, $\pi_3 = 5\%$ tilt error, $\pi_4 = 5\%$ zenith angle error, $\pi_5 = 5\%$ overall systematics, $\pi_6 = 2.5\%$ $\Phi_{\nu_\mu}/\Phi_{\bar{\nu}_\mu}$ ratio. Only 5 uncertainties separately for ν and $\bar{\nu} \rightarrow 10$ pulls; 6th uncertainty as a constraint $\rightarrow 11$ pulls.
- $\chi^2 = \min_{\xi_1^\pm, \xi_6} \sum_{i=1}^{N_{\nu_\mu}^{obs}} \sum_{j=1}^{N_{\cos \theta_\mu}^{obs}} \left(\sum_{k=1}^{N_{had}^{obs}} \left(T_{ij(k)}^+ - D_{ij(k)}^+ \right) - D_{ij(k)}^+ \ln \left(\frac{T_{ij(k)}^+}{D_{ij(k)}^+} \right) \right)^2 + 2 \left[\left(T_{ij(k)}^- - D_{ij(k)}^- \right) - D_{ij(k)}^- \ln \left(\frac{T_{ij(k)}^-}{D_{ij(k)}^-} \right) \right] + \sum_{l=1}^5 \xi_l^2 + \sum_{l=1}^5 \xi_l^2 + \xi_6^2$

χ^2 analysis

- $\chi^2_{ICAL} = \chi^2_{11} + \chi^2_{prior}$. Here i, j, k sum over muon energy, muon angle and hadron energy bins. The number of predicted events with systematic errors in each bin are:

$$T_{ij(k)}^\pm = T_{ij(k)}^{0\pm} \left(1 + \sum_{l=1}^5 \pi_{ij(k)}^{l\pm} \xi_l^\pm \pm \pi_6 \xi_6 \right)$$

Parameter	True value	Marginalization range
θ_{13}	8.5°	[7.80°, 9.11°]
$\sin^2 \theta_{23}$	0.5	[0.39, 0.64]
Δm_{32}^2	2.3663×10^{-3} eV ²	[2.3, 2.6] $\times 10^{-3}$ eV ² (NH)
$\sin^2 \theta_{12}$	0.304	Not marginalised
Δm_{21}^2	7.6×10^{-5} eV ²	Not marginalised
δ_{CP}	0°	Not marginalised

Table 1: Marginalisation done in 3σ ranges of the parameters. NH is the true hierarchy.

Sensitivity to α_3 , octant of θ_{23} and precision measurement of various parameters

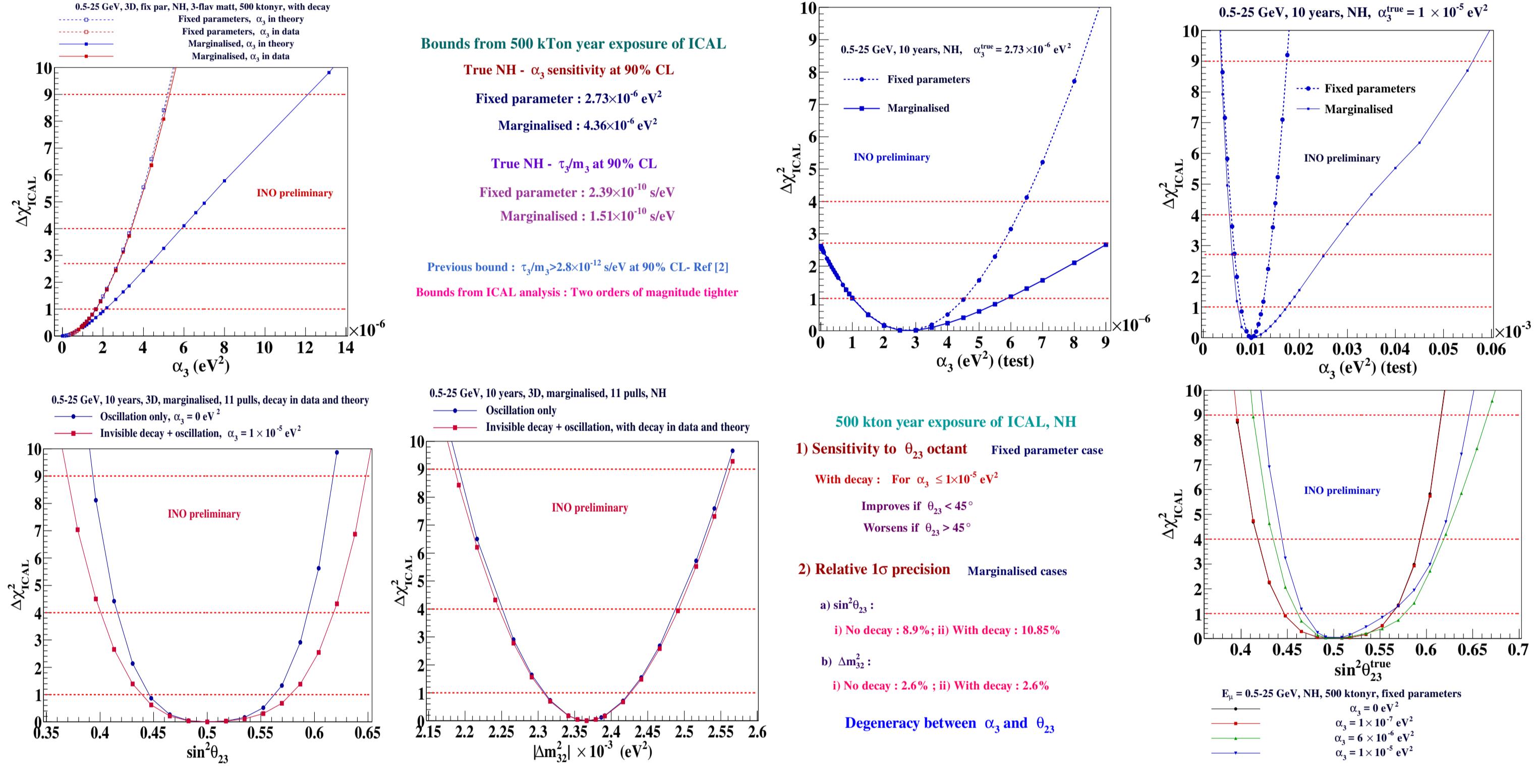


Figure 2: (Top panels) Expected sensitivity of ICAL to invisible decay of ν_3 and precision on α_3 (eV²). (Bottom panels) Precision on $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ and sensitivity to θ_{23} octant without and with decay for 500 kTon year exposure and true NH.

Sensitivity to neutrino mass hierarchy in the presence of decay

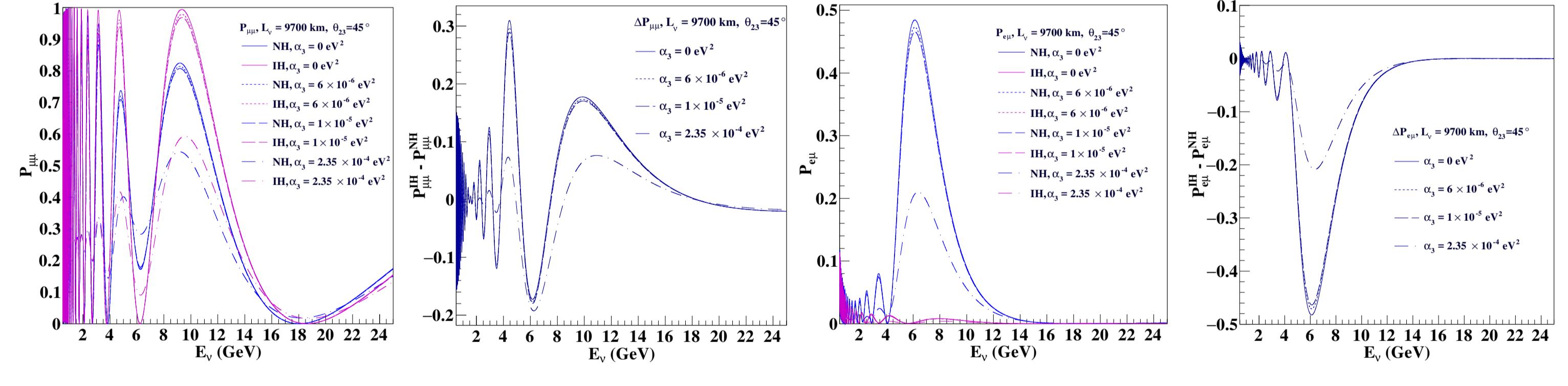


Figure 3: (Left set) $P_{\mu\mu}$ and $\Delta P_{\mu\mu}$, (right set) $P_{e\mu}$ and $\Delta P_{e\mu}$ for NH and IH and different values of α_3 .

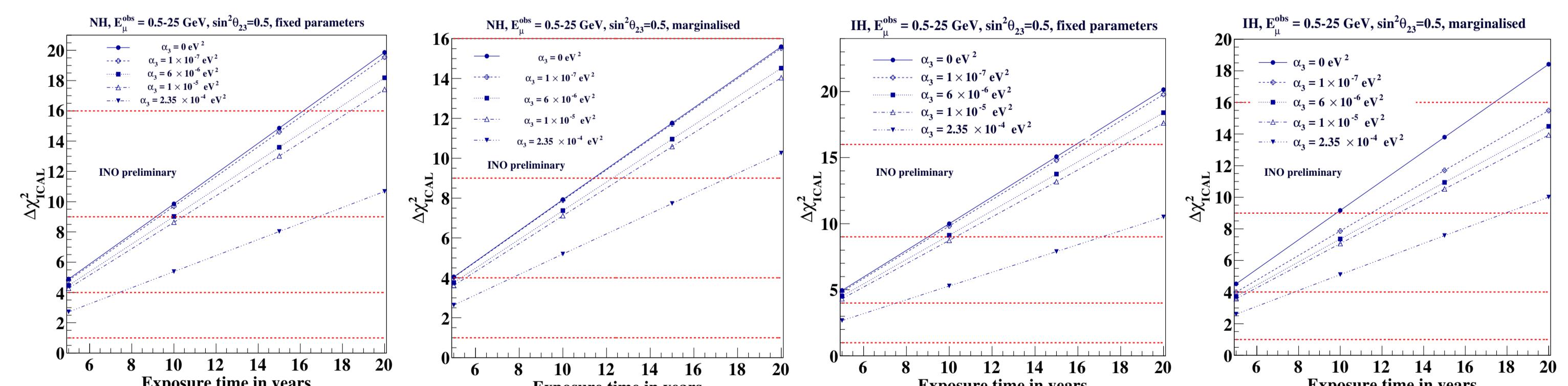


Figure 4: Sensitivity to neutrino mass hierarchy assuming (left set) true NH and (right set) true IH, with different α_3 values for true $\theta_{23} = 45^\circ$. Y-axes are not the same.

Acknowledgements and References

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