Importance of second oscillation maxima in probing invisible neutrino decay

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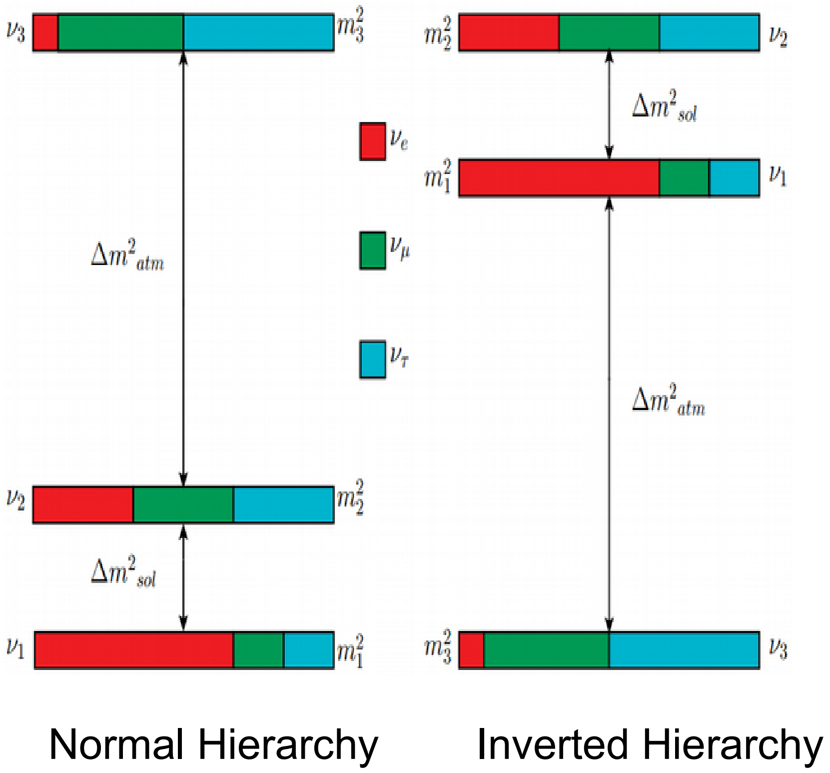
with D. Dutta, S. Goswami, D. Pramanik

Unknowns of 3 Neutrino Paradigm

- **Mass Hierarchy:**
  - Normal Hierarchy(NH)- $\Delta m^2_{21} > 0$, $\boldsymbol{\Delta m^2_{31} > 0}$
  - Inverted Hierarchy(IH)- $\Delta m^2_{21} > 0$, $\boldsymbol{\Delta m^2_{31} < 0}$
- **Octant of θ_{23} :**
  - Lower Octant(LO)-$\boldsymbol{\theta_{23} < 45^o}$
  - Higher Octant(HO)-$\boldsymbol{\theta_{23} > 45^o}$
- **CP violating phase $\boldsymbol{\delta_{CP}}$**



The Detection Channels

- **Long baseline experiments, L ~ 100 km – 1000 km**
- **Oscillation governed by Δm^2_{31}**
- **α, s_{13} << 1**

$$P_{\mu e} = 4 s_{13}^2 s_{23}^2 \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2}$$

$$+ 2\alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin \hat{A}\Delta}{\hat{A}} \frac{\sin(\hat{A}-1)\Delta}{\hat{A}-1}$$

$$+ \alpha^2 \sin^2 2\theta_{12} c_{23}^2 \frac{\sin^2 \hat{A}\Delta}{\hat{A}^2},$$

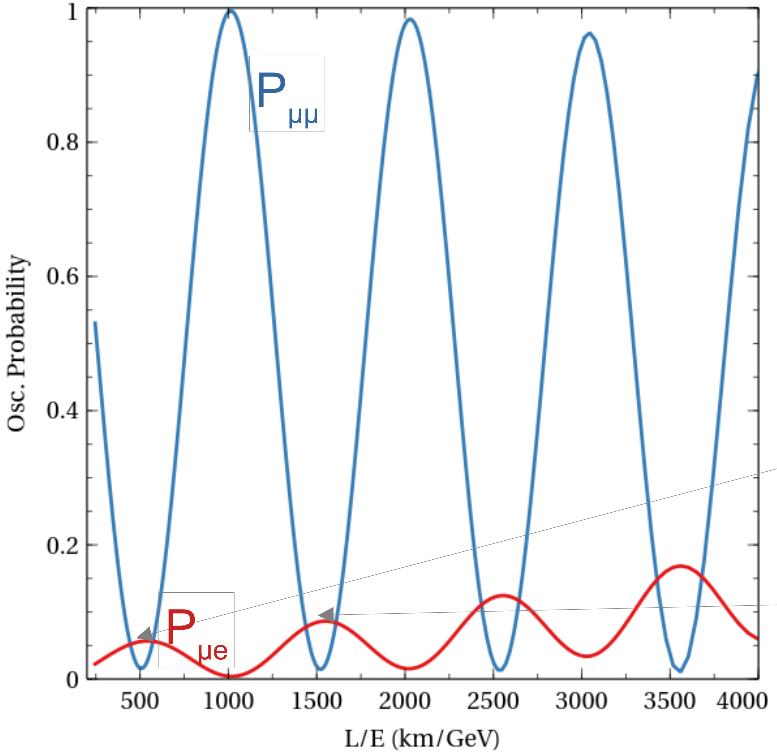
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \text{higher order terms},$$

Octant Sensitive Terms

$$\Delta = \Delta m^2_{31} L/4E$$

Hierarchy Sensitive Terms

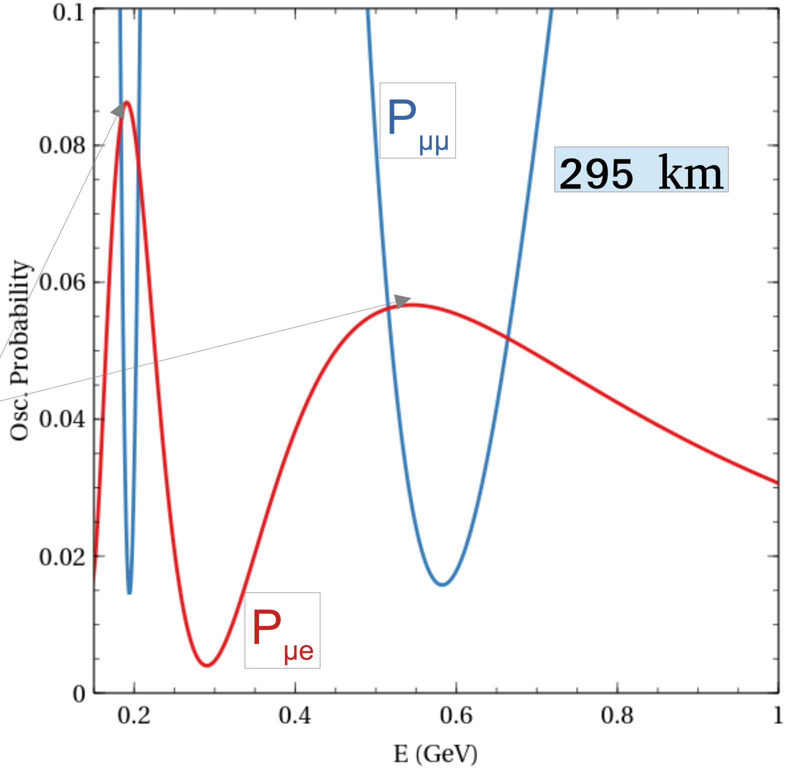
Oscillation Maxima



Osc max for $P_{\mu e}$ minima for $P_{\mu\mu}$ and vice-versa

First Oscillation Maxima

Second Oscillation Maxima



$\sin^2(\Delta m^2_{31} L/4E) = 1$ $\qquad$ $\Delta m^2_{31} L/4E = n\pi/2$

Experimental Details

Experiment	Baseline Length	Peak Energy	Oscillation Maxima
T2HK	295 km	0.6 GeV	First Oscillation Maxima
T2HKK	295 km (L1) ; 1100 km (L2)	0.6 GeV	Hybrid Setup. Both oscillation maxima
ESSνSB	540 km	0.35 GeV	Second Oscillation Maxima

Why Neutrino Decay?

- If neutrinos have mass, there is a possibilty they can decay

The stability of neutrino can be tested experimentally

The possibility of pure neutrino decay excluded at 4σ by Super-K.

Decay along with oscillation is still a possible scenario.

Neutrino Decay

Visible Decay

Final State is flavour state.
They can be detected.

Helicity conserving decay

$$\nu_j \rightarrow \nu_i + J$$

Helicity non-conserving decay

$$\nu_j \rightarrow \bar{\nu}_i + J$$

Invisible Decay

Final state is sterile.
Final state below threshold of experiment.

In our case

$$\nu_j \rightarrow \nu_s + J$$

Constraints on Invisible Neutrino decay

MINOS	$\tau_3 / m_3 > 2.1 \times 10^{-12}$ s/eV	$\alpha_3 < 3.13 \times 10^{-4}$ eV^2
T2K	$\tau_3 / m_3 \sim 7.8 \times 10^{-13} - 8.3 \times 10^{-12}$ s/eV	$\alpha_3 \sim 7.9 \times 10^{-5} - 8.4 \times 10^{-4}$ eV^2
MINOS + T2K	$\tau_3 / m_3 > 2.8 \times 10^{-12}$ s/eV	$\alpha_3 < 2.35 \times 10^{-4}$ eV^2
LBL + Atm	$\tau_3 / m_3 > 2.9 \times 10^{-10}$ s/eV	$\alpha_3 < 2.27 \times 10^{-6}$ eV^2
SOLAR	$\tau_2 / m_2 > 9 \times 10^{-5}$ s/eV	$\alpha_2 < 7.3 \times 10^{-12}$ eV^2
ICE CUBE	$\tau / m >$ 10 s/eV	$\alpha < 6.58 \times 10^{-17}$ eV^2
SN1987	$\tau / m > 10^5$ s/eV	$\alpha < 6.58 \times 10^{-21}$ eV^2
CMB	$\tau / m > 10^{11}$ s/eV	$\alpha < 6.58 \times 10^{-27}$ eV^2

Framework of Neutrino Decay

$\alpha = \tau_3 / m_3$

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\left[\frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix} - i\frac{\alpha}{2E}\begin{pmatrix}0&0&0\\0&0&0\\0&0&1\end{pmatrix}\right]U^\dagger + \begin{pmatrix}A&0&0\\0&0&0\\0&0&0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$A = 2\sqrt{2}G_F n_e E$

We solve this equation numerically to get $P_{\mu e}$ and $P_{\mu\mu}$ for our analysis

The vacuum oscillation probability:

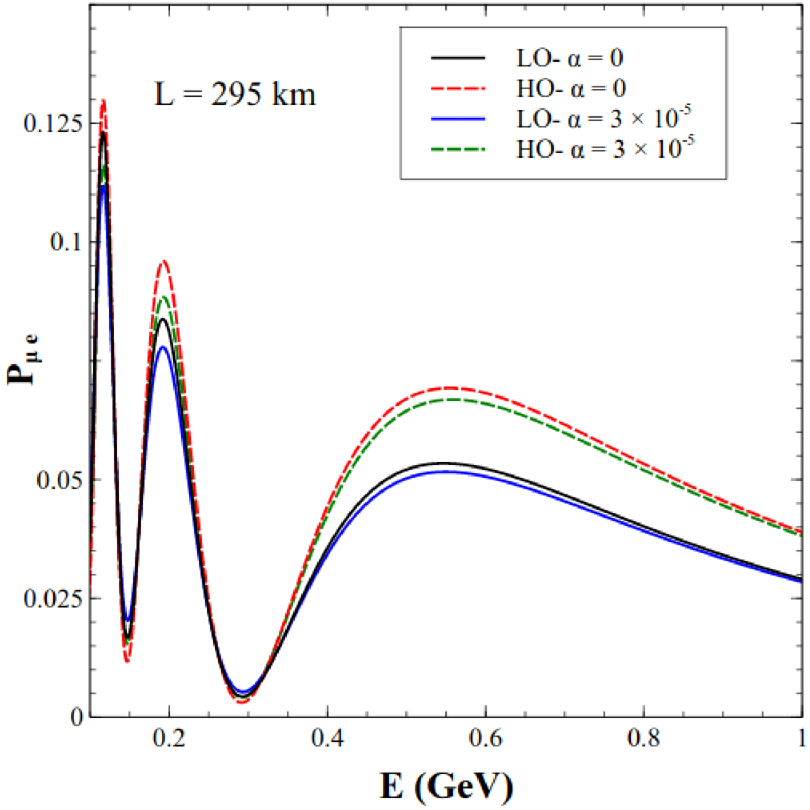
$$P_{\mu\mu} = \left[1 - \sin^2\theta_{23}\left(1 - e^{-\frac{\alpha L}{E}}\right)\right]^2 - \sin^2 2\theta_{23}\, e^{-\frac{\alpha L}{2E}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

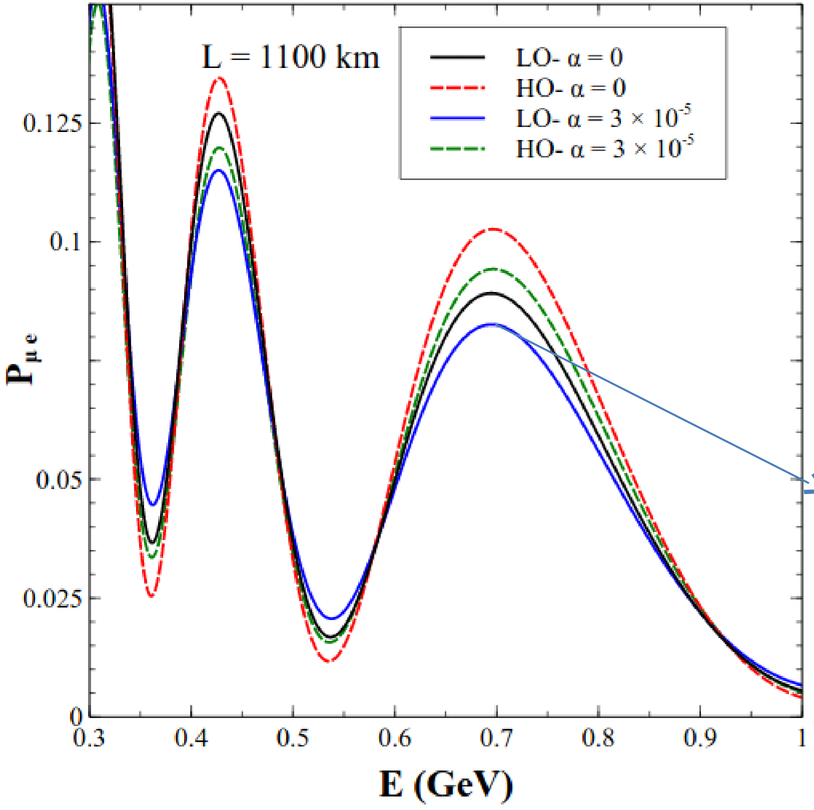
Supression factor proportional to $\alpha L/E$

$L_{2nd} \sim 3 \times L_{1st}$
(effect of decay greater)

Appearance Channel

θ_{23} (LO) = 40°
θ_{23} (HO) = 51°

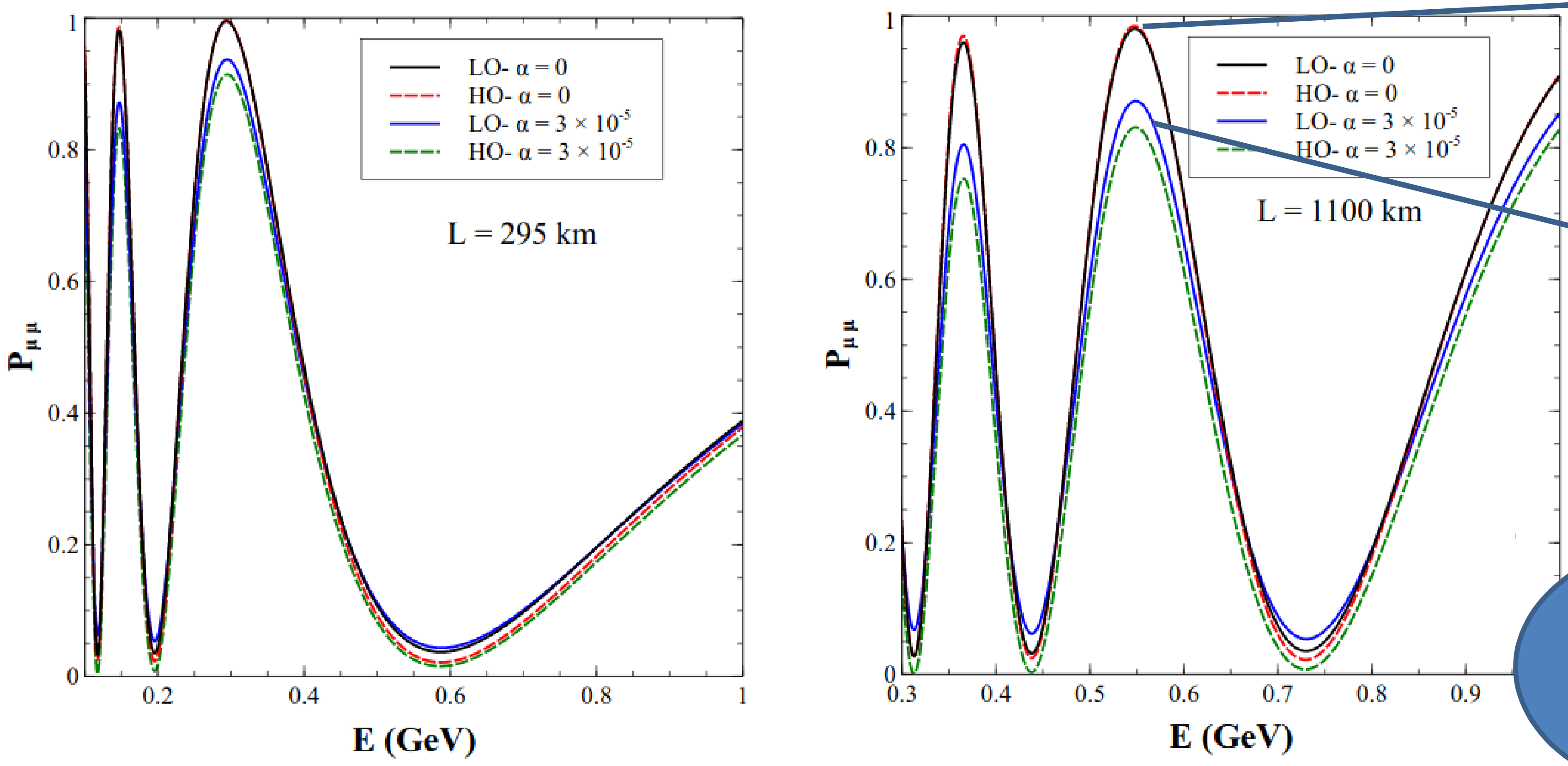




Octant band width similar.

LO with decay not degenerate with no-decay

Disappearance Channel

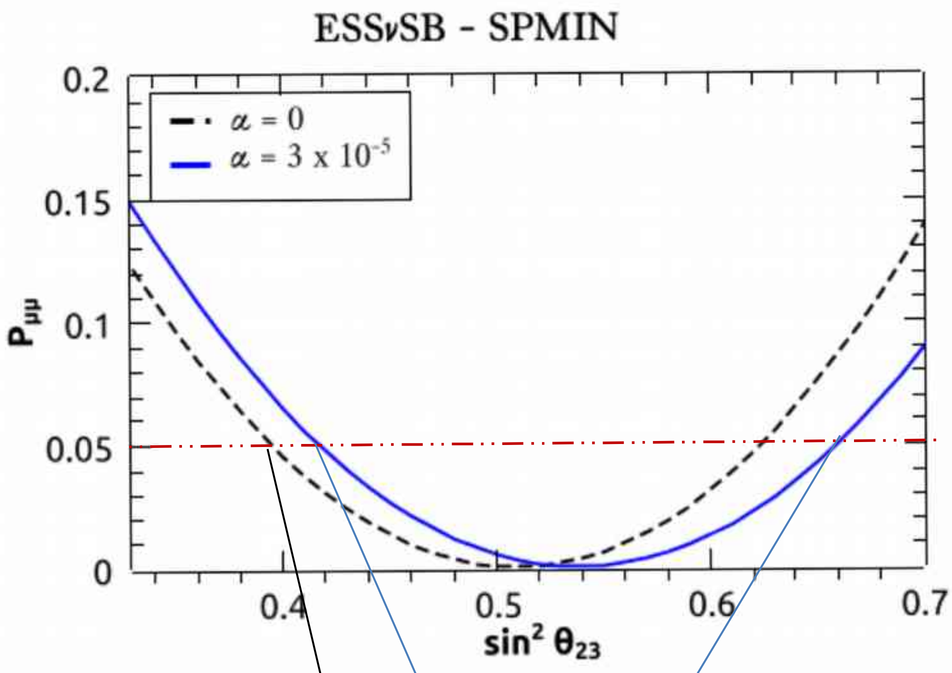


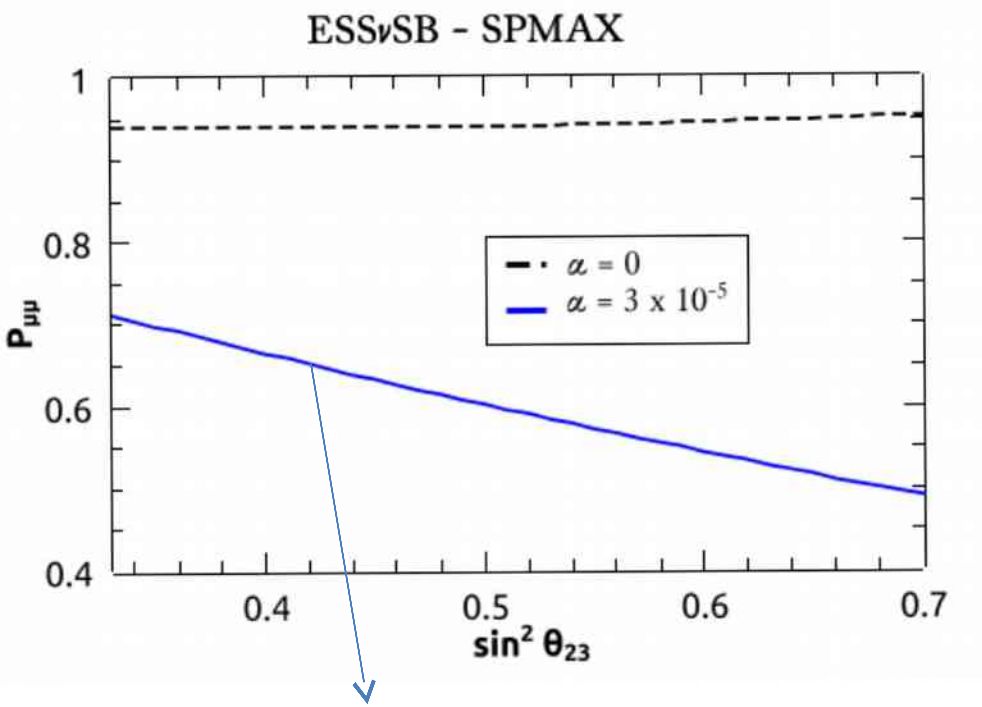
LO and HO overlap

LO and HO separate in presence of decaay

Octant sensitivity in $P_{\mu\mu}$ channel

Dependence on θ_{23}



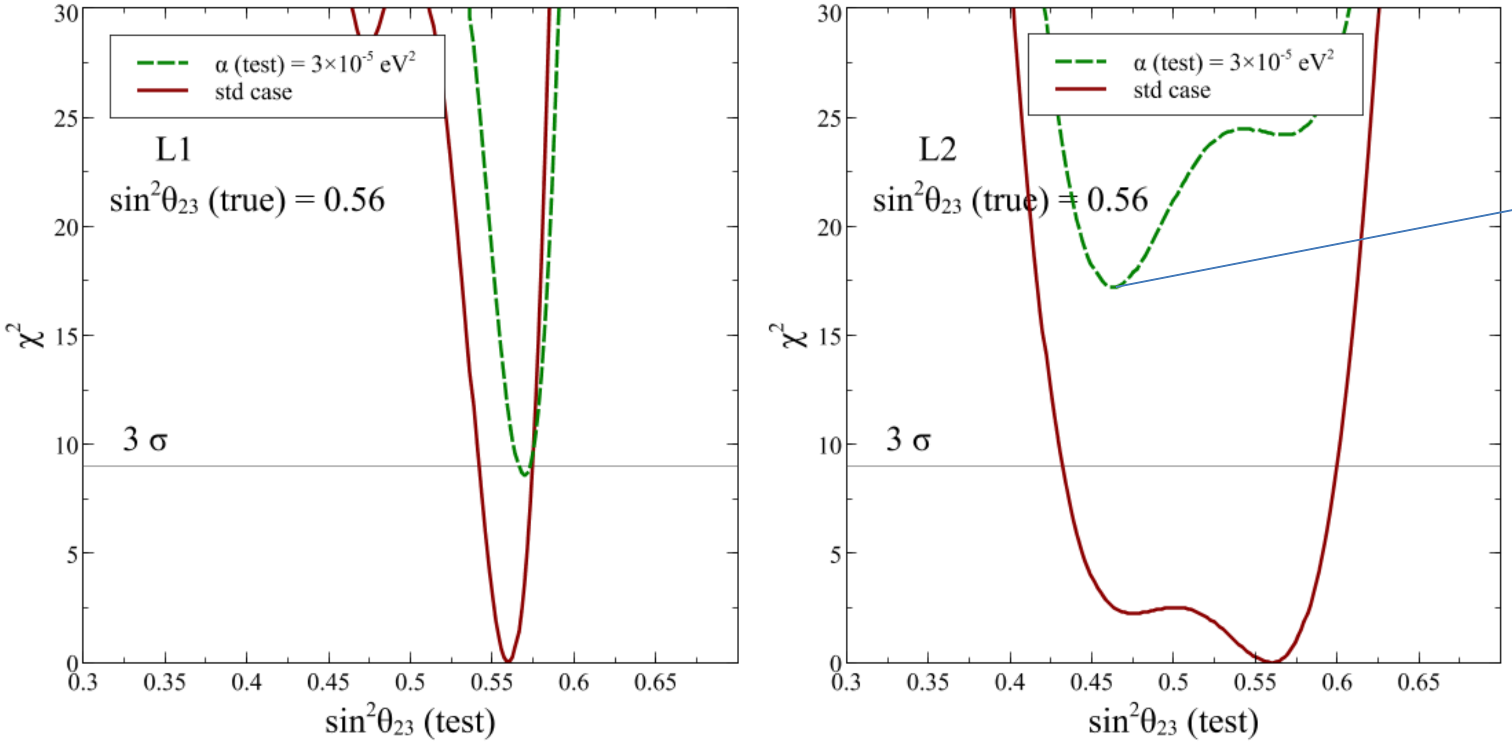


Two degenerate solutions in opposite octants

Constant decreasing curve
The lowest θ_{23} is preferable

First vs Second Osc Max at fixed θ_{23}

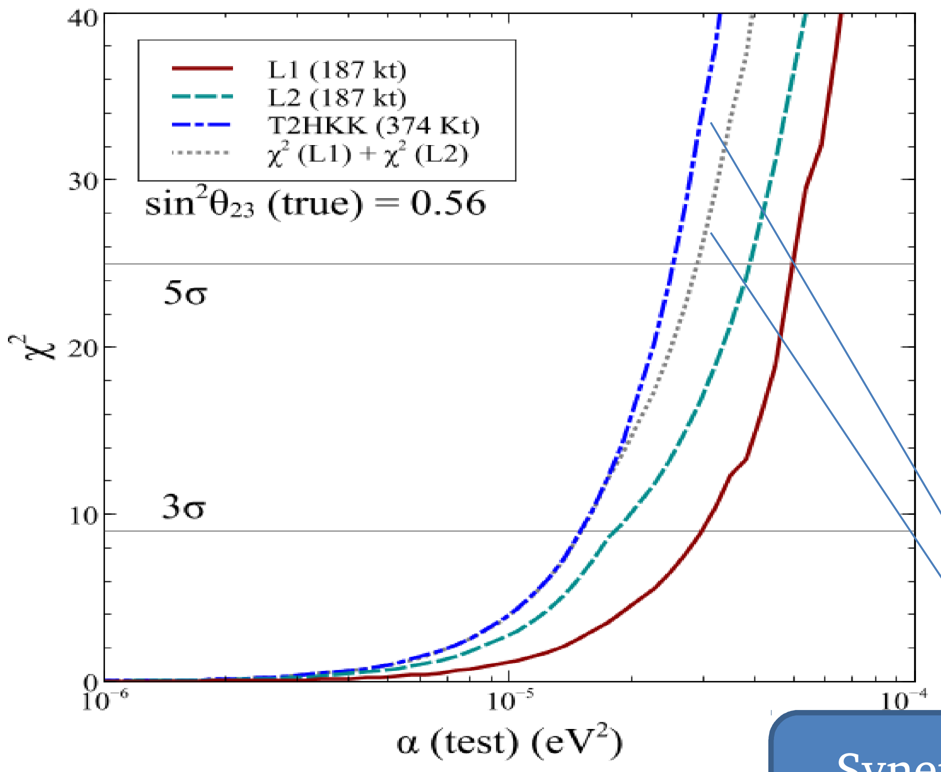
Data with no-decay

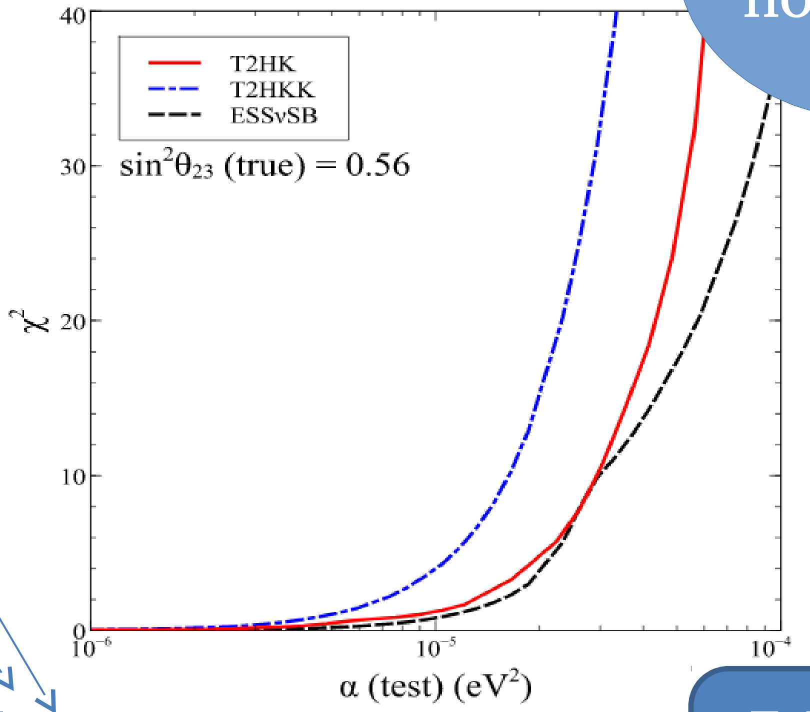


α can be resolved at C.L. > 3σ

Second oscillation maxima better for fixed θ_{23}

Capabiility to test α



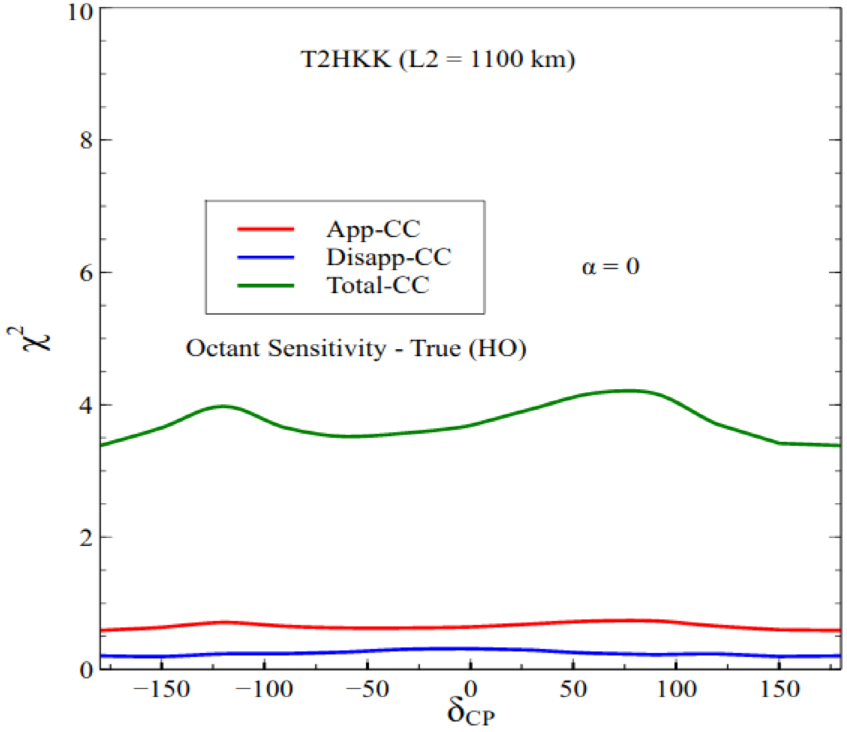


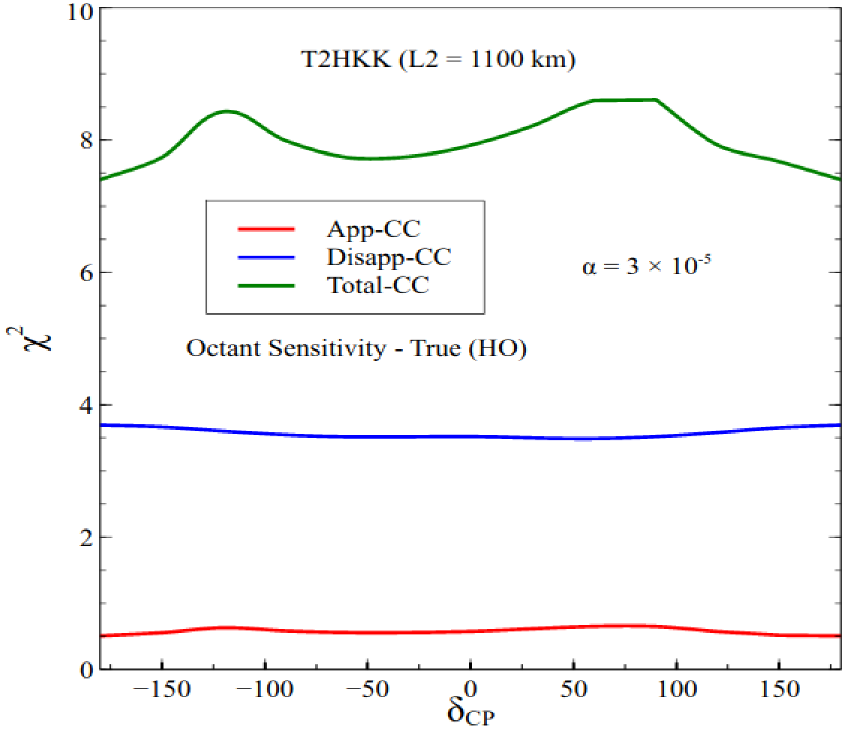
Data with no-decay

Synergy between L1 and L2

T2HKK has best sensitivty

Octant Sensitivity





Disappearance channel do not contribute

Disappearance channel contribution significantly enhanced

Summary of Results

Experiment(s)	α (eV^2)	τ_3/m_3 (s/eV)
T2HK	$\geq\ 2.42 \times 10^{-5}$	$\leq\ 2.72 \times 10^{-11}$
T2HKK	$\geq\ 1.51 \times 10^{-5}$	$\leq\ 4.36 \times 10^{-11}$
ESSνSB	$\geq\ 2.71 \times 10^{-5}$	$\leq\ 2.43 \times 10^{-11}$
T2HK+ESSνSB	$\geq\ 1.51 \times 10^{-5}$	$\leq\ 4.36 \times 10^{-11}$
T2HKK+ESSνSB	$\geq\ 1.19 \times 10^{-5}$	$\leq\ 5.53 \times 10^{-11}$

Conclusions

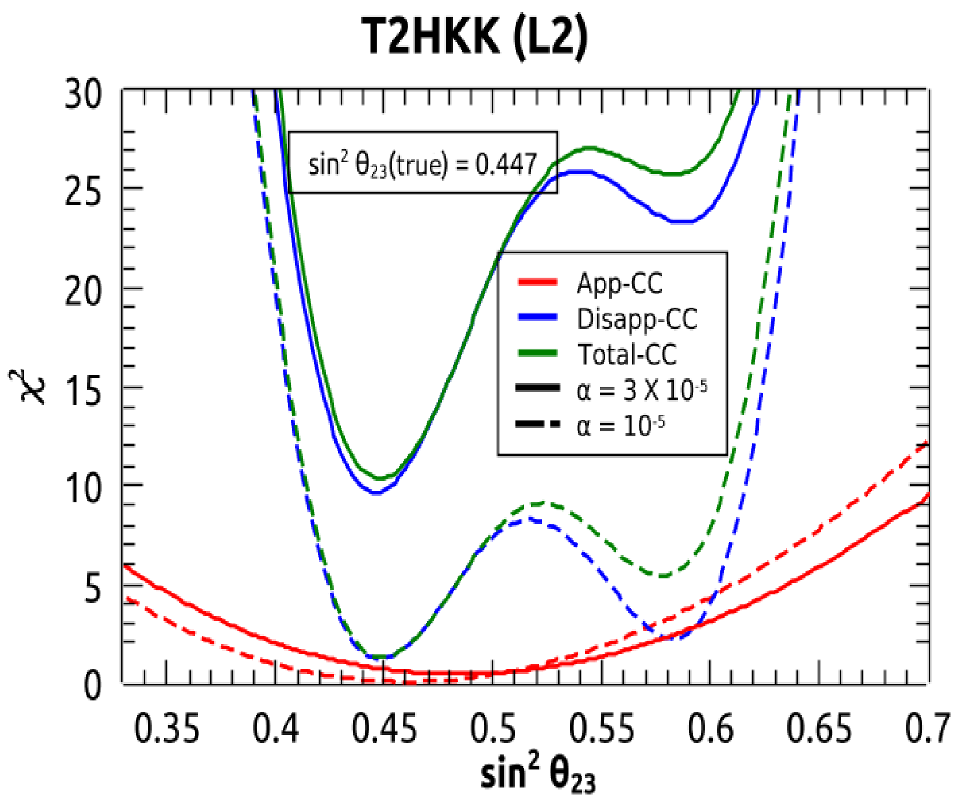
The combination of first and second oscillation maxima is best for decay.

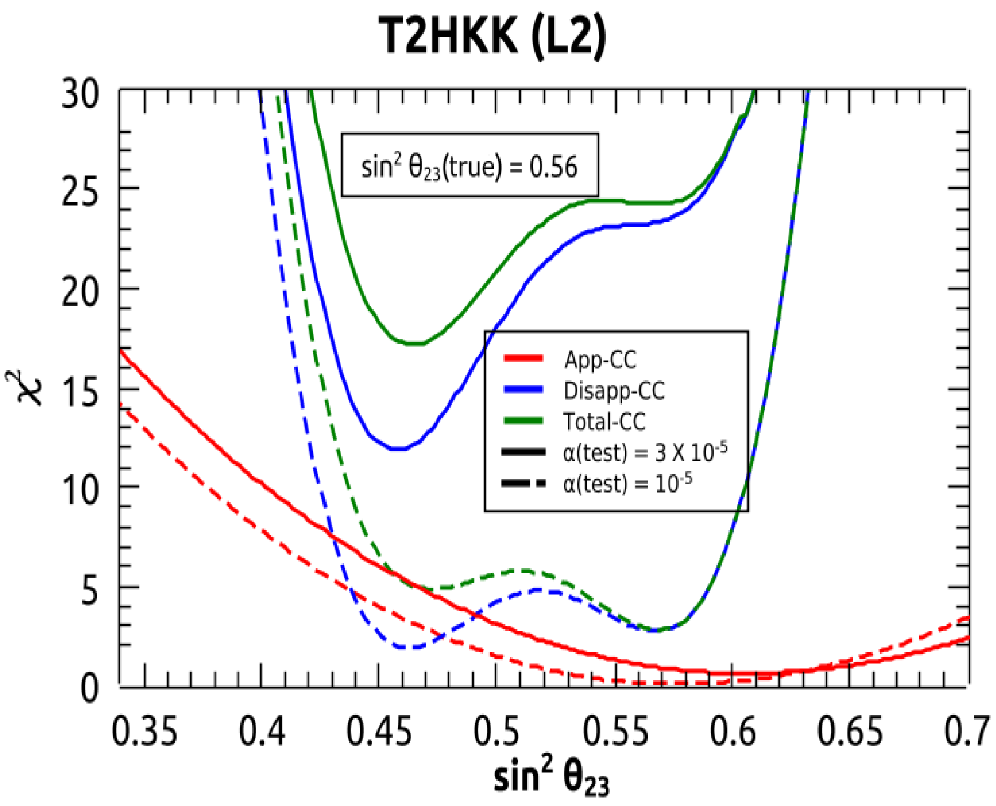
The first oscillation maximum has best θ_{23} precision.

At the second oscillation maximum the sensitivity to decay more because of enhanced baseline (for same energy) and/or lower energy (for same baseline).

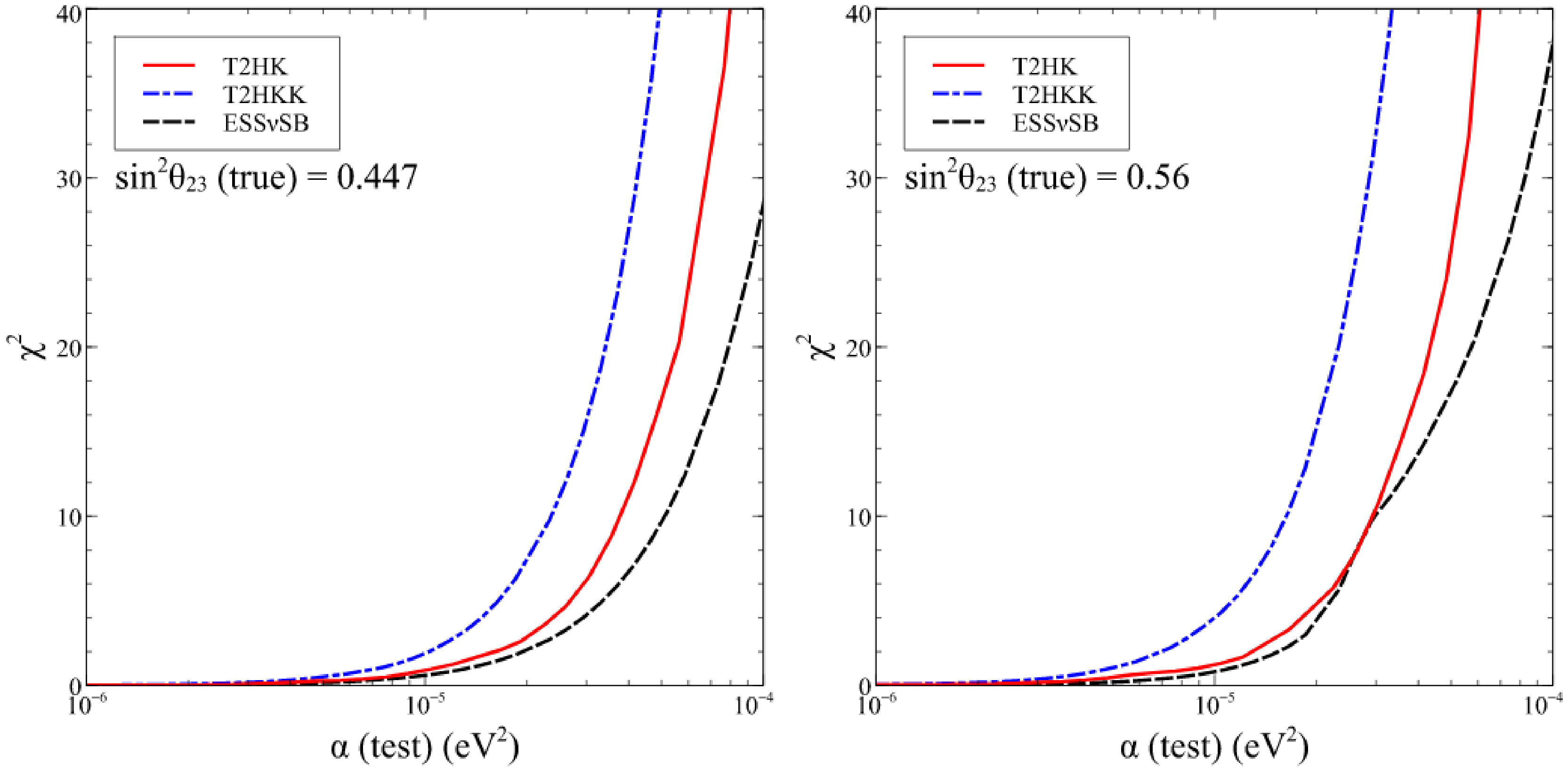
Thank You

Appearance and Disappearance Contributions

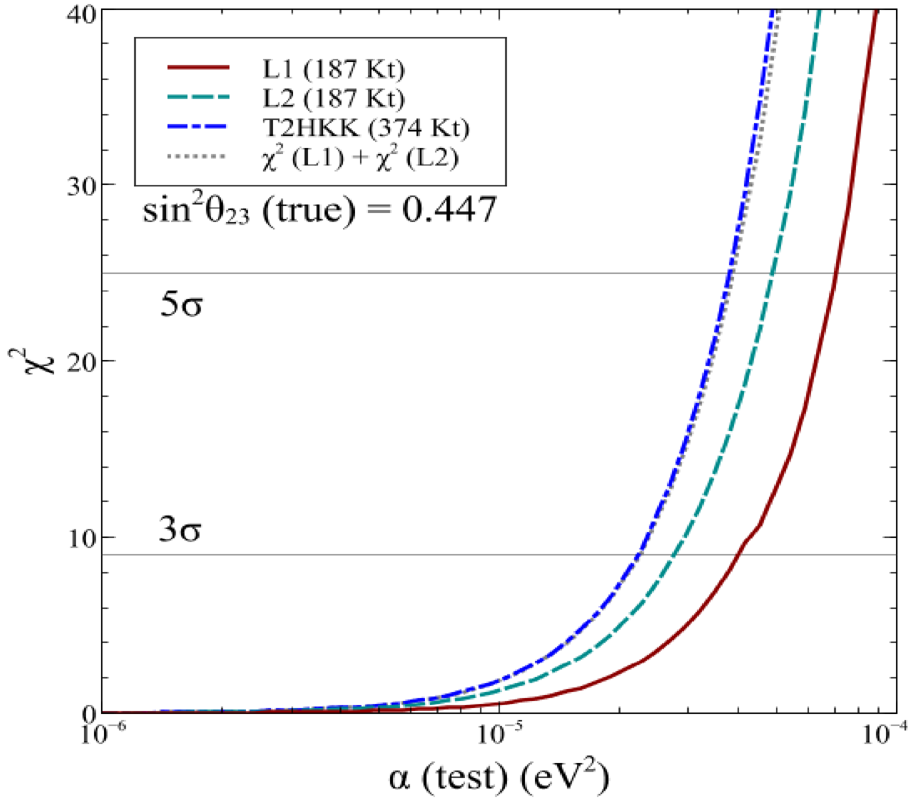


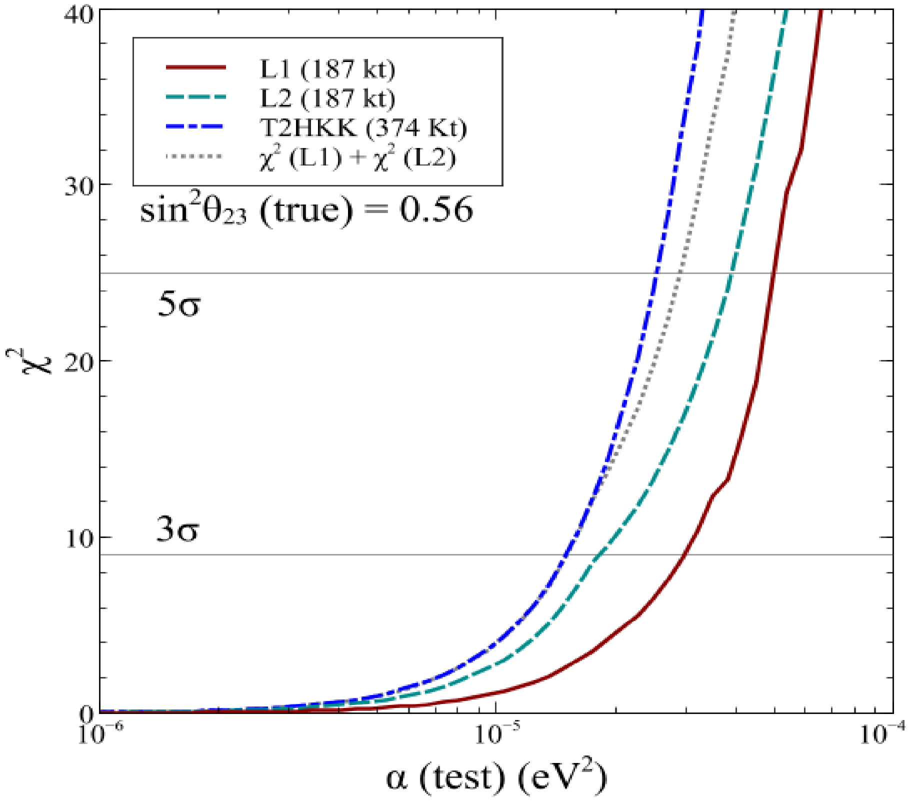


Sensitivity to decay parameter



First vs Second Oscillation Maxima





Oscillation Parameters Used in Analysis

Oscillation parameters	True Values	Marginalization Range
θ_{13}	8.6°	Fixed
θ_{12}	33.82°	Fixed
$\sin^2\theta_{23}$	0.447(LO), 0.56(HO)	0.413 — 0.671
Δm^2_{21} (eV^2)	7.39×10^{-5}	Fixed
$\lvert\Delta m^2_{31}\rvert$ (eV^2)	2.52×10^{-3}	2.3×10^{-3} — 2.6×10^{-3}
δ	-90°	-180° — 180°