Probing neutrino decay scenarios by hyper-kamiokande and its second detector in korea

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Abstract

We study the signatures of decaying neutrino scenario in T2HKK experiment. Considering a combination of disappearance and appearance channels, for a normal mass ordering and assuming that the heaviest neutrino eigenstate decays, we show by performing an $\Delta\chi^2$ analysis, that the ν_3 lifetime divided by its mass can be constrained to $\tau_3/m_3 > 1.14 \times 10^{-10}\,\mathrm{s/eV}$ 95% CL (Preliminary).
We also perform a combined analysis of T2HKK and T2HK experiments, aiming to obtain a stronger bound. The effect of neutrino decay on the determination of oscillation parameters, $\sin^2\theta_{23}$ and Δm^2_{31}, will be discussed.

Formalism

We assum that the neutrino interaction with a Majoron J which is responsible for neutrino decay

$$\mathcal{L}_{\text{int}} = \frac{1}{2}(g_s)_{ij}\bar{\nu}_i\nu_j J + i\frac{1}{2}(g_p)_{ij}\bar{\nu}_i\gamma_5\nu_j J,$$

$$(\nu \to \nu + \phi, \text{ or } \bar{\nu} \to \bar{\nu} + \phi) \quad (\nu \to \bar{\nu} + \phi \text{ or } \bar{\nu} \to \nu + \phi)$$

the visible decay would affect the observable events at the detector, as they have less energy than the parent particle, we expect a pileup of events at low energies.

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

$$H = U\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta_{21} & 0\\ 0 & 0 & \Delta_{31} - i(\Gamma_3/2)\end{bmatrix}U^\dagger + \begin{bmatrix}V_m(x) & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

adding the decay effect

Due to the long base-line...

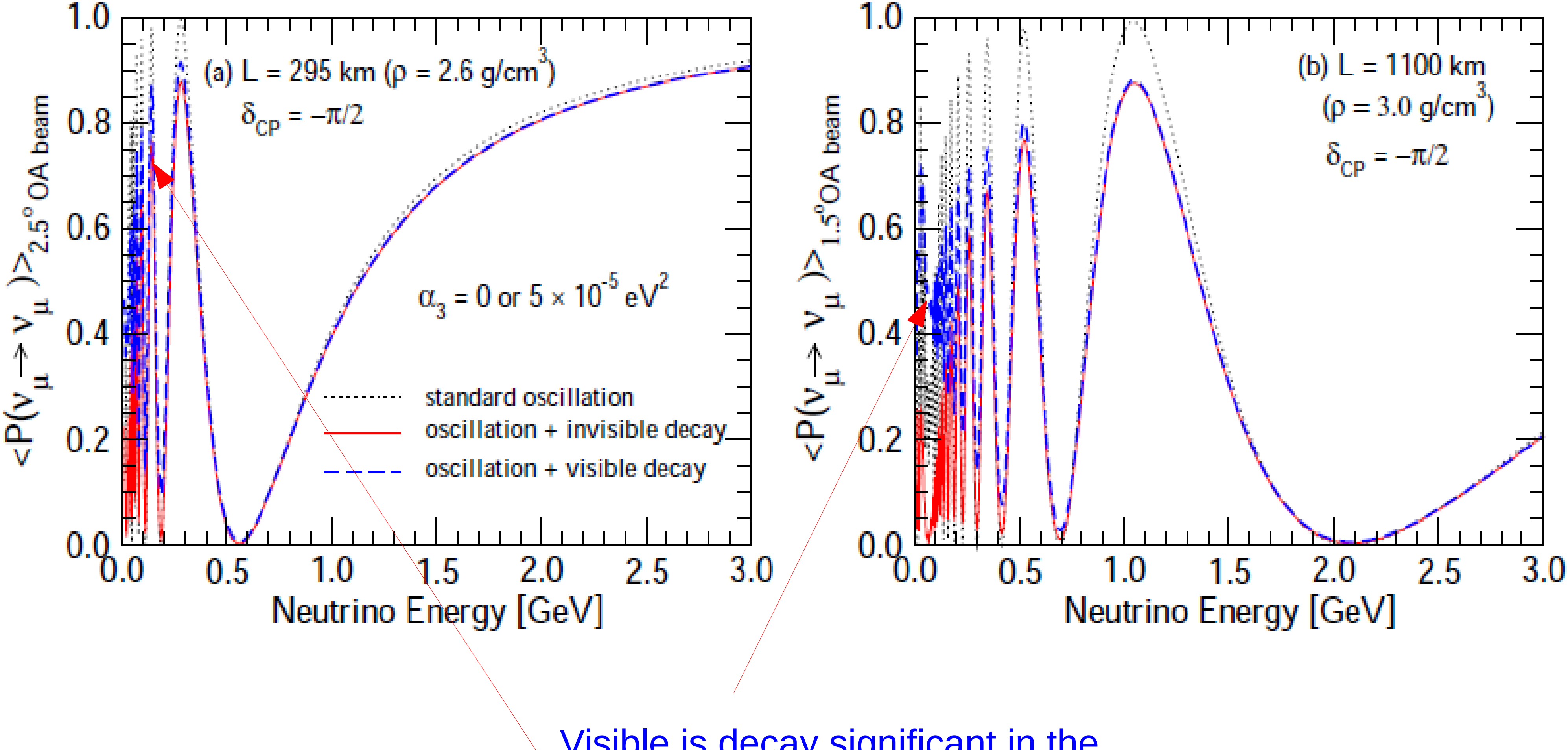
$$P^{rs}_{\alpha\beta}(E_\alpha, E_\beta) = \left|\sum_i U^{(s)}_{\beta i}U^{(r)*}_{\alpha i}\exp\left[-i\frac{m_i^2 L}{2E_\alpha}\right]\exp\left[-\frac{\alpha_i L}{2E_\alpha}\right]\right|^2 \delta(E_\alpha - E_\beta)\delta_{rs} +$$

$$\left|U^{(r)}_{\alpha i}\right|^2\left|U^{(s)}_{\beta f}\right|^2\left(\frac{1 - e^{-\alpha_i L/E_\alpha}}{E_\alpha}\right)\frac{x^2_{if}}{(x^2_{if} - 1)}F^{rs}_g(E_\alpha, E_\beta) \times \Theta_H(E_\alpha - E_\beta)\,\Theta_H(x^2_{if}E_\beta - E_\alpha)$$

See A.Gago 1705.03074

Probabilities

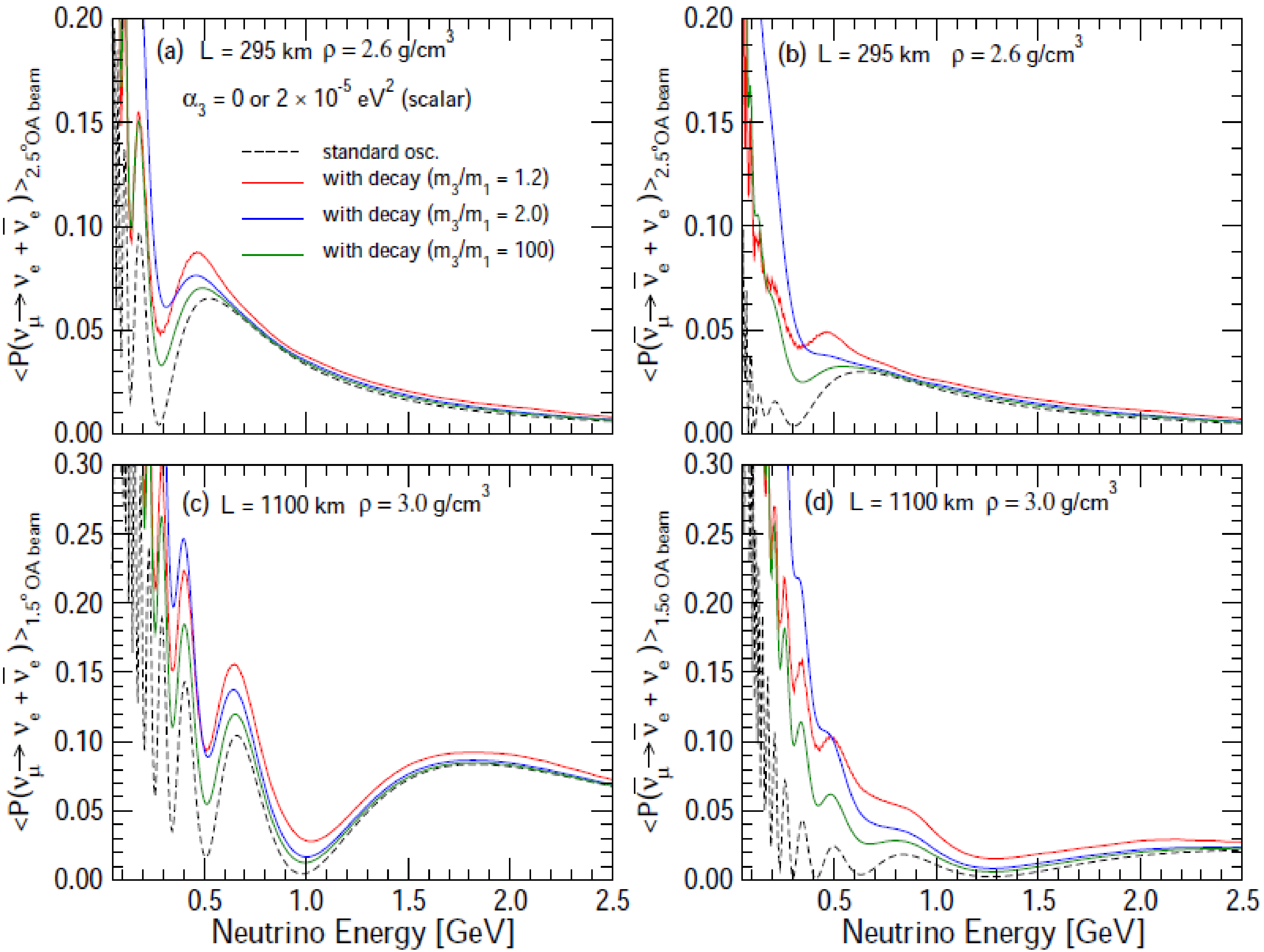
Disappearence channel $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$



Visible is decay significant in the low energy < 0.5 GeV

Probabilities

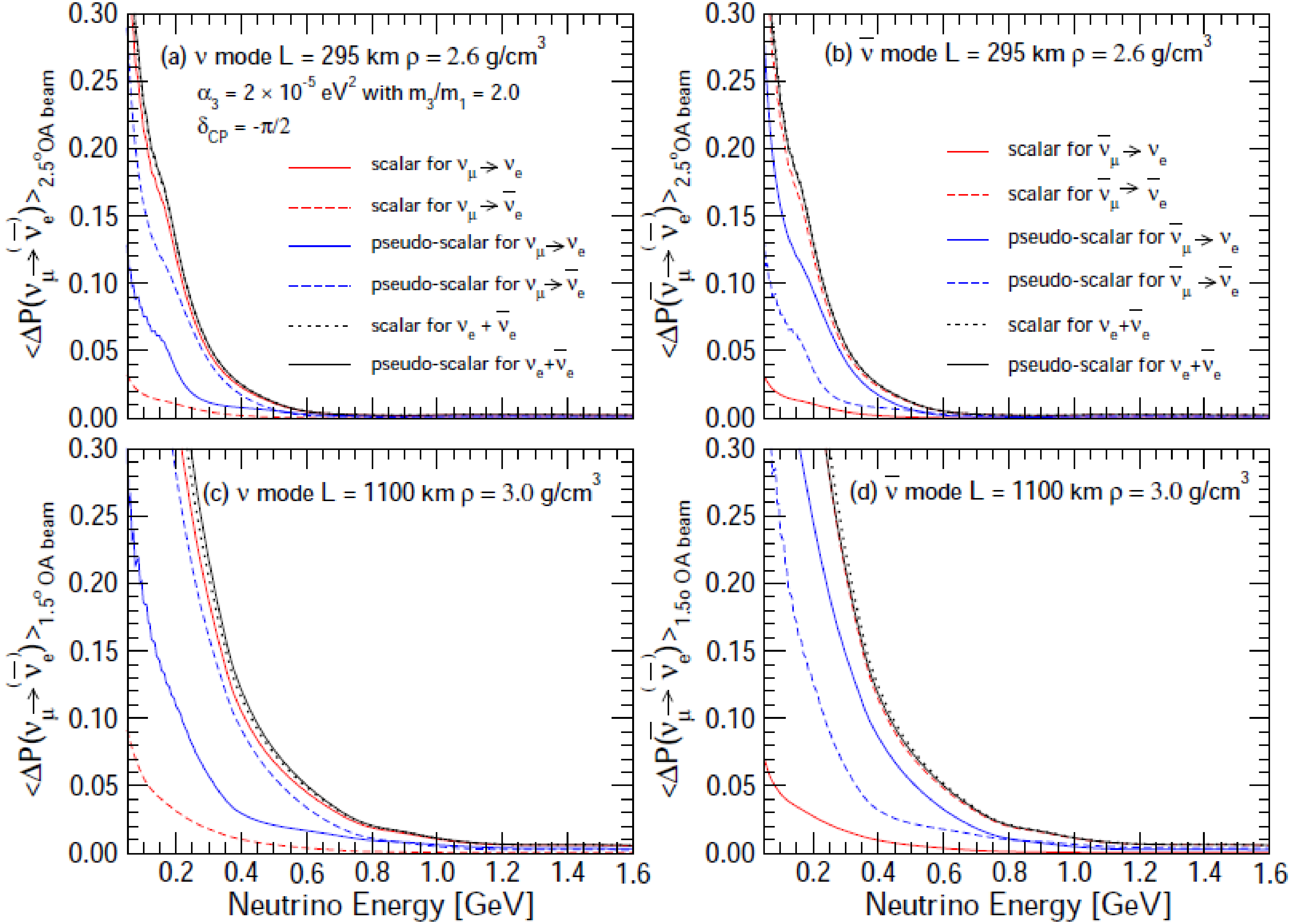
Appearence channel $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$



Visible decay on the appareance channel
is more significative

Probabilities

$$\Delta P(\nu_\mu \to \nu_e; E_{\nu_e}) \equiv P_{\text{eff}}^{\text{osc+decay}}(\nu_\mu \to \nu_\beta; E_{\nu_e}) - P_{\text{inv}}(\nu_\mu \to \nu_e; E_{\nu_e}),$$



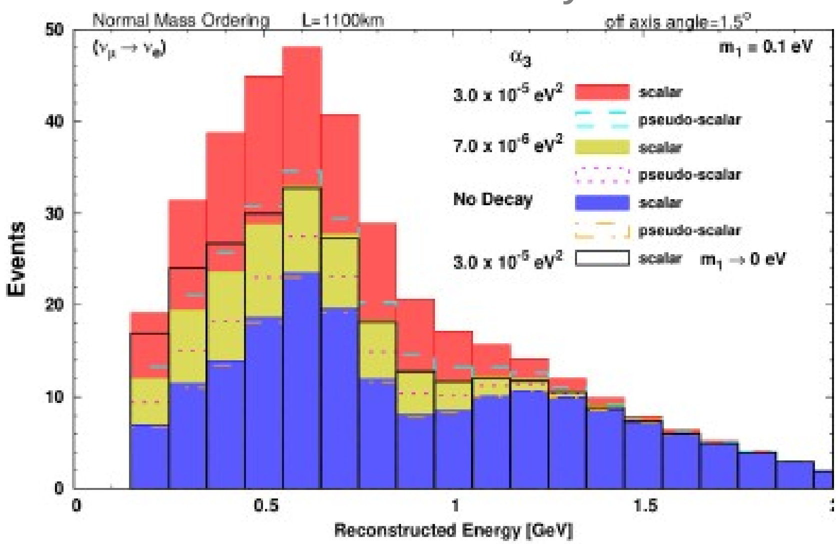
Visible decay significant in the
low energy < 0.6 GeV

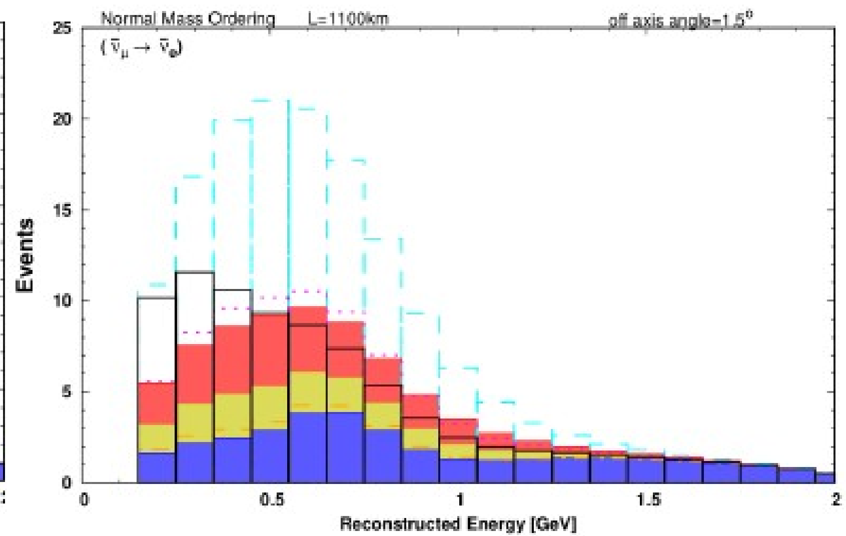
Expected number of events

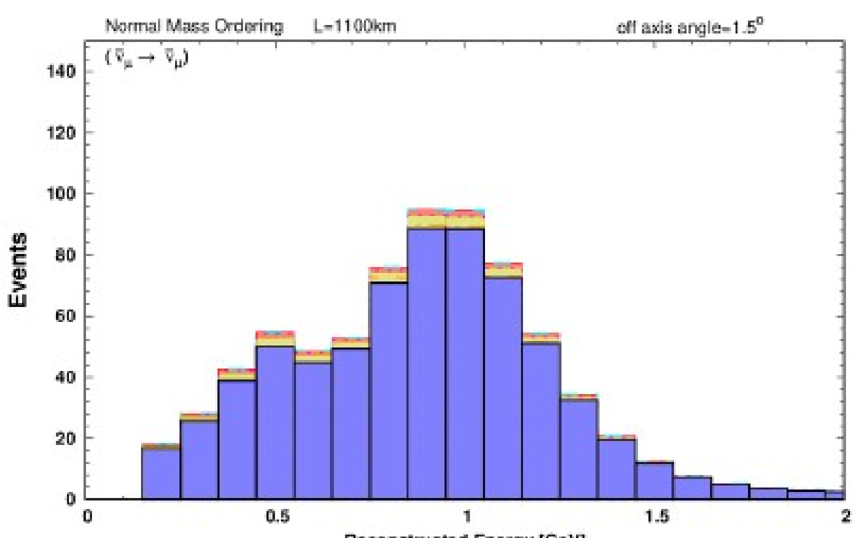
Running time, Effective Flux, Cross section

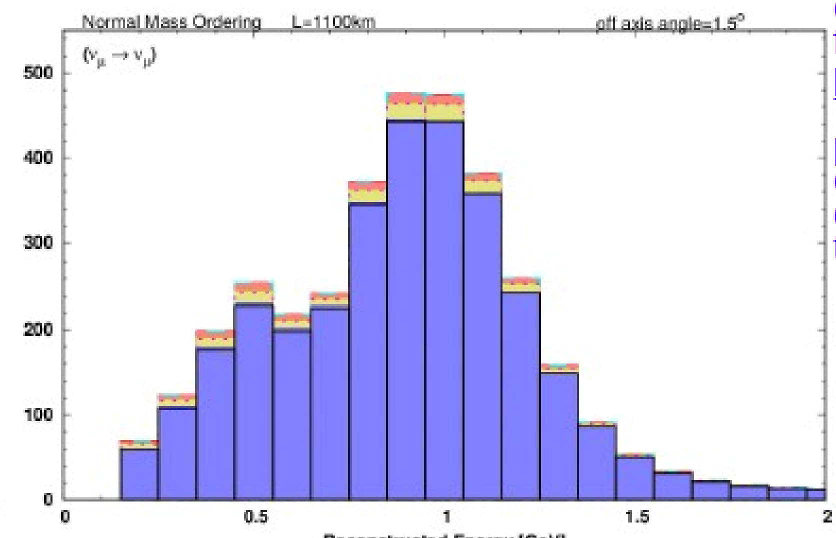
$$N_i = n_N T \int_{E_{rec,i}^{min}}^{E_{rec,i}^{max}} \epsilon(E_{rec}) dE_{rec} \int_{E_\beta^{min}}^{E_\beta^{max}} dE_\alpha \phi_\alpha^{sr}(E_\alpha) P_{\alpha\beta}^{sr}(E_\alpha E_\beta) \sigma(E_\beta) Res(E_\alpha, E_{rec})$$

Efficiency, Probability, Resolution function









The observable effect of visible neutrino decay on the events distribution is a pile-up of events at low energy as expected from the effective probability above. The neutrinos were produced in some energy and then decayed arriving to the detector.

Analysis Method

The $\Delta\chi^2$ function

$$\Delta\chi^2 = \sum_{e=f,n}\left[\sum_i \frac{\left(N^{obs}_{e,i} - \alpha N^{fit}_{e,i}\right)^2}{N^{fit}_{e,i} + (\epsilon N^{fit}_{e,i})}\right] + \left(\frac{1-\alpha}{\sigma_\alpha}\right)^2$$

$n \rightarrow$ near detector

$f \rightarrow$ far detector

$\sigma_\alpha = 2\%$

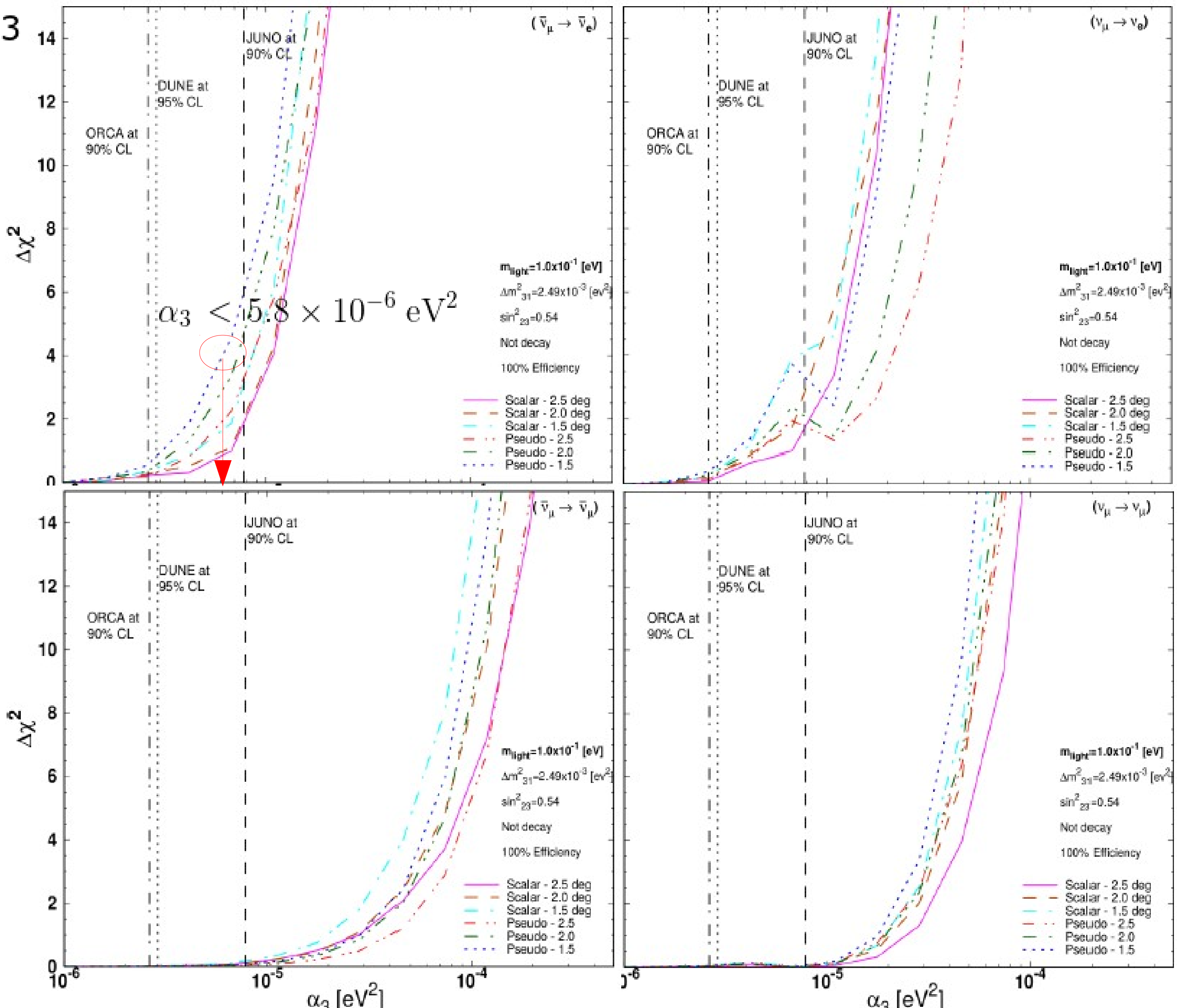
$\epsilon = 3\%$

$N^{obs}_{e,i}$ Observed number of events (simulated) in the energy bin

$N^{fit}_{e,i}$ Fitted number of events (theoretically expected) in the energy bin

Results

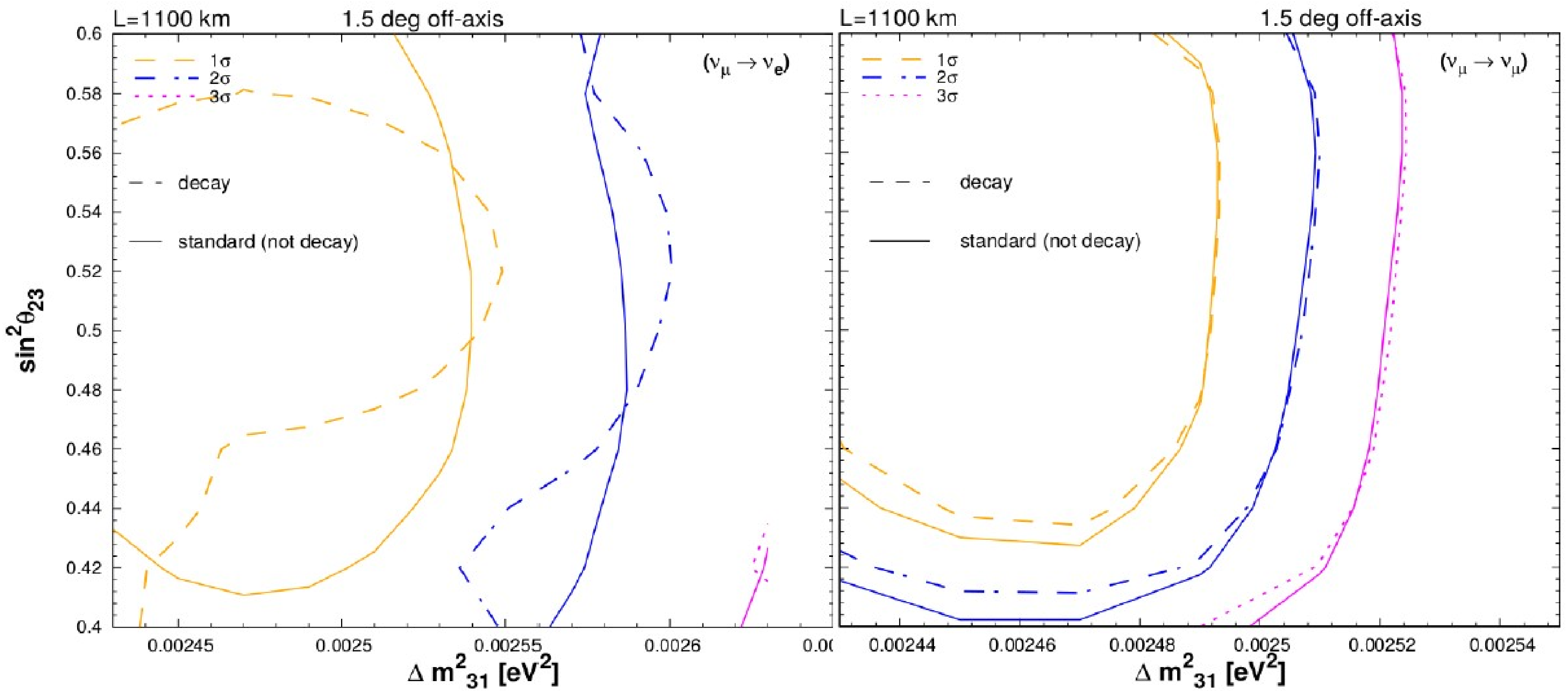
Bound on α_3



$$\alpha_3 < 5.8 \times 10^{-6}\ \text{eV}^2 \longrightarrow \tau_3/m_3 > 1.14 \times 10^{-10}\ \text{s/eV}$$

Results

Determination oscillation parameters by T2HKK



Conclusions

We have studied the event distribution on T2HKK in the scenario where neutrinos decay visibly, in the oscillation channels $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$. A binned $\Delta\chi^2$ analysis on the number of events has been performed. We found that T2HKK alone can constrain the decay lifetime of neutrino state ν_3 to $\alpha_3 < 5.8 \times 10^{-6}\ \mathrm{eV}^2$ which correspond to $\tau_3/m_3 > 1.14 \times 10^{-10}\ \mathrm{s/eV}$ at 95% CL.

A strongest limit on ν_3 is expected by considering the second detector, (work in progress).

Also it has been shown that the determination of oscillation parameters in T2HKK is robust whether the neutrinos decay (with a lifetime allowed by the current bounds) or not.

THANKS
GRACIAS
OBRIGADO

$$\frac{dP_{\text{vis}}^{\nu_\alpha^A \to \nu_\beta^B}(E_{\nu_\alpha}, E_{\nu_\beta})}{dE_{\nu_\beta}} = Q_{\alpha\beta}^{AB}(E_{\nu_\alpha}, E_{\nu_\beta}) \frac{d}{dE} \Gamma_{\nu_3^A \to \nu_1^B}(E_{\nu_\alpha}, E_{\nu_\beta}),$$

$$Q_{\alpha\beta}^{AB}(E_{\nu_\alpha}, E_{\nu_\beta}) \equiv \sum_{I=1}^{3} \sum_{J=1}^{3} \sum_{M=1}^{3} \sum_{N=1}^{3} \left(\tilde{U}^{(A)}\right)_{I\alpha}^{-1} \left(\tilde{U}^{(A)}\right)_{M\alpha}^{-1*} \hat{U}_{\beta J}^{(B)} \hat{U}_{\beta N}^{(B)*} \tilde{C}_{I3}^{(A)} \tilde{C}_{M3}^{(A)*} \left(\hat{C}^{(B)}\right)_{1J}^{-1} \left(\hat{C}^{(B)}\right)_{1N}^{-1*}$$
$$2E_{\nu_\beta} \times \frac{\left[(E_\beta/E_\alpha)\tilde{\alpha}_{<IM>} - \hat{\alpha}_{<JN>}\right] - i\left[(E_\beta/E_\alpha)\Delta\tilde{m}_{IM}^2 - \Delta\hat{m}_{JN}^2\right]}{\left[(E_\beta/E_\alpha)\tilde{\alpha}_{<IM>} - \hat{\alpha}_{<JN>}\right]^2 + \left[(E_\beta/E_\alpha)\Delta\tilde{m}_{IM}^2 - \Delta\hat{m}_{JN}^2\right]^2}$$
$$\times \left\{ \exp\left[-i\frac{\Delta\hat{m}_{JN}^2 L}{2E_\beta}\right] \exp\left[-\frac{\hat{\alpha}_{<JN>}L}{2E_\beta}\right] - \exp\left[-i\frac{\Delta\tilde{m}_{IM}^2 L}{2E_\alpha}\right] \exp\left[-\frac{\tilde{\alpha}_{<IM>}L}{2E_\alpha}\right] \right\}, \qquad \text{(A.6)}$$

$$\frac{d}{dE}\Gamma_{\nu_3^r \to \nu_1^s}(E_{\nu_\mu}, E_{\nu_\beta})$$
$$= \frac{\alpha_3}{E_{\nu_\alpha}^2} \frac{x_{31}^2}{(x_{31}^2 - 1)} \Theta_H(E_{\nu_\alpha} - E_{\nu_\beta})\, \Theta_H(x_{31}^2 E_{\nu_\beta} - E_{\nu_\alpha})\; F_g^{rs}(E_{\nu_\alpha}, E_\beta),$$

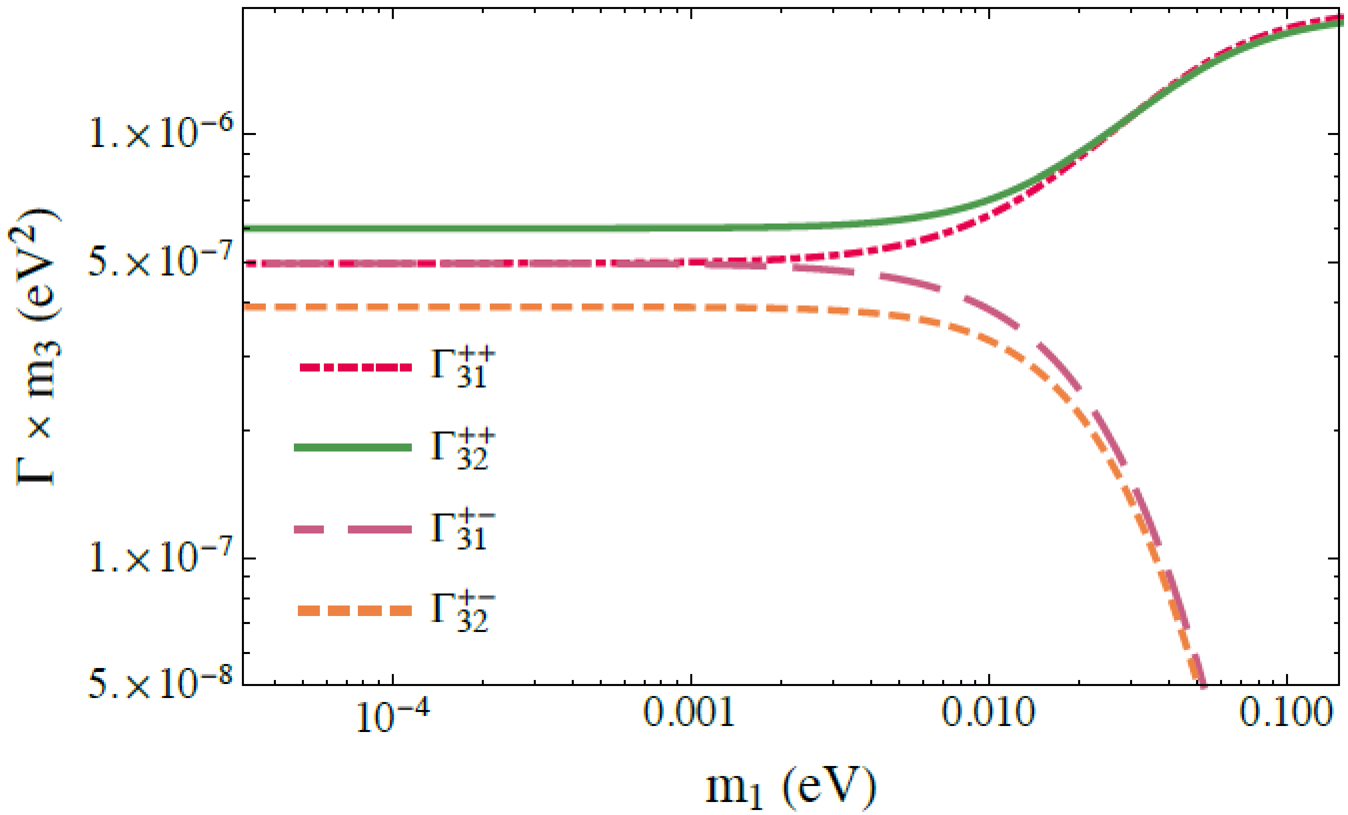
$$F_{g_s}^{\pm\pm}(E_{\nu_\alpha}, E_{\nu_\beta}) = \frac{1}{E_{\nu_\alpha} E_{\nu_\beta}} \frac{(E_{\nu_\alpha} + x_{if} E_{\nu_\beta})^2}{(x_{if}+1)^2},$$

$$F_{g_s}^{\pm\mp}(E_{\nu_\alpha}, E_{\nu_\beta}) = \frac{(E_{\nu_\alpha} - E_{\nu_\beta})}{E_{\nu_\alpha} E_{\nu_\beta}} \frac{(x_{if}^2 E_{\nu_\beta} - E_{\nu_\alpha})}{(x_{if}+1)^2},$$

$$F_{g_p}^{\pm\pm}(E_{\nu_\alpha}, E_{\nu_\beta}), = \frac{1}{E_{\nu_\alpha} E_{\nu_\beta}} \frac{(E_{\nu_\alpha} - x_{if} E_{\nu_\beta})^2}{(x_{if}-1)^2},$$

$$F_{g_p}^{\pm\mp}(E_{\nu_\alpha}, E_{\nu_\beta}) = \frac{(E_{\nu_\alpha} - E_{\nu_\beta})}{E_{\nu_\alpha} E_{\nu_\beta}} \frac{(x_{if}^2 E_{\nu_\beta} - E_{\nu_\alpha})}{(x_{if}-1)^2},$$

$$x_{if} \equiv m_f/m_i = m_3/m_1$$



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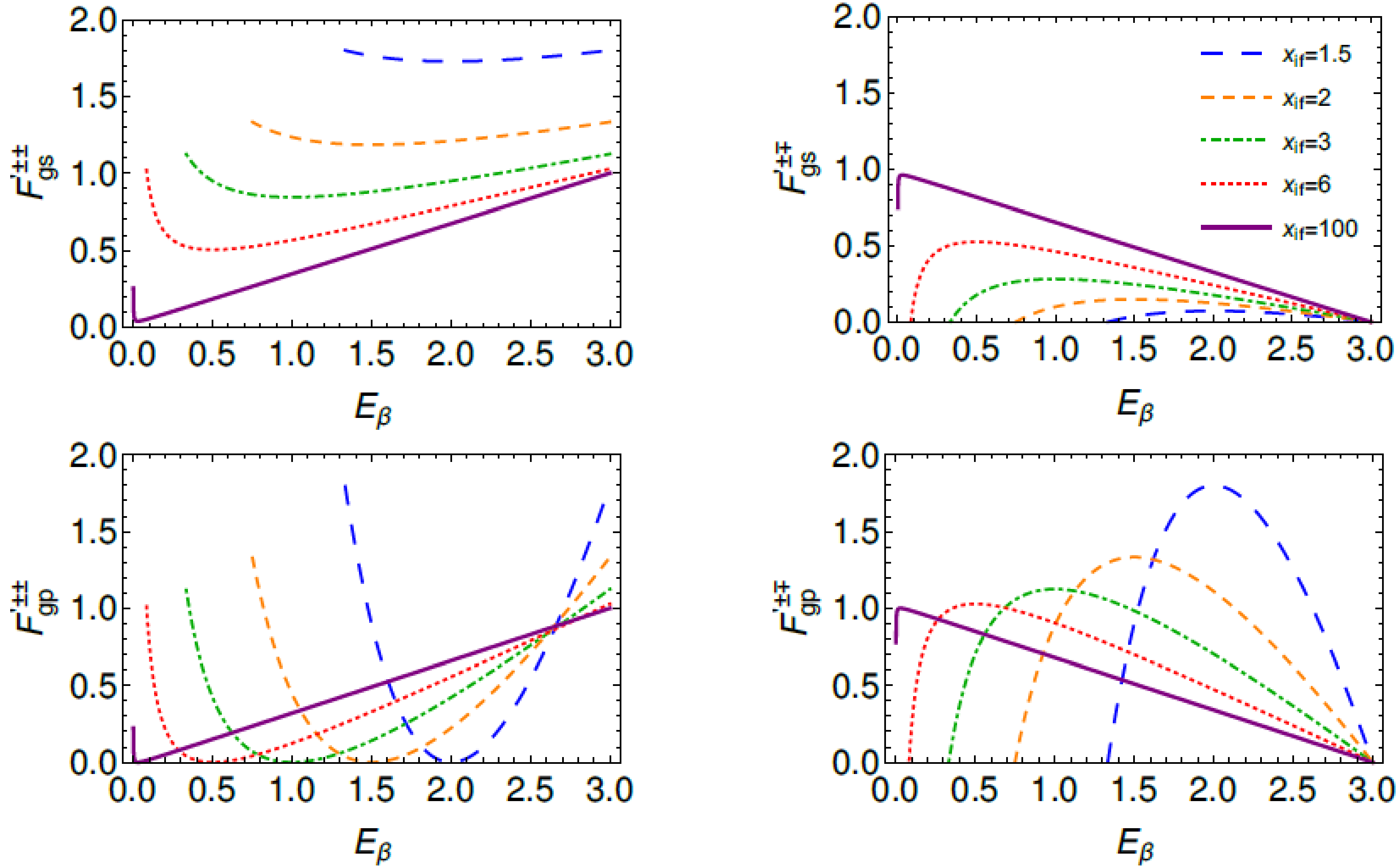

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