Lepton Flavor Violation

in

Long-Baseline Experiments

Sato , Joe
(Saitama U)

1 Introduction

○ Solar neutrino, Atmospheric neutrino, Reactor neutrino

◇ Massive Neutrinos

◇ Lepton Mixing

○ Massive Neutrino

Massive but Very Tiny $\Longrightarrow$ Seasaw Mechanism   and/or $\cdots$

○ Lepton Mixing

Large Mixing $\Longrightarrow$ Interactions with Large Lepton Flavor Violation (LFV)

and/or $\cdots$

$\Downarrow$

Large Lepton Flavor Viiolating Process in Our World !?

○ Yes, MSSM with Seasaw (ν_R) Borzumati and Masiero, Hisano *et. al.*

Large Flavor Changing Slepton Mass thorough renormalization

even if universal scalar mass(m_0^2) at GUT scale(M_G)

(Dirac) Neutrino Yukawa couplings

$$W = f_\nu^{ij} \bar{N}_i L_j H_u$$

$$\begin{aligned}
\mu \frac{d(m_{\tilde{L}}^2)_{ij}}{d\mu} &= \left(\mu \frac{d(m_{\tilde{L}}^2)_{ij}}{d\mu}\right)_{\rm MSSM} (= 0) \\
&+ \frac{1}{16\pi^2} \left[m_{\tilde{L}}^2 f_\nu^\dagger f_\nu + f_\nu^\dagger f_\nu m_{\tilde{L}}^2 + 2(f_\nu^\dagger m_{\tilde{\nu}}^2 f_\nu + \tilde{m}_{H_u}^2 f_\nu^\dagger f_\nu + A_\nu^\dagger A_\nu) \right]_{ij}
\end{aligned}$$

SUSY breaking $m_{\tilde{L}}^2$ scalor lepton doublet

$m_{\tilde{\nu}}^2$ right-handed sneutrino

$\tilde{m}_{H_u}^2$ doublet Higgs

$$U^{Dirac^T} f_\nu^{ij} V^{Dirac^*} = \mathrm{diag}(f_{\nu 1}, f_{\nu 2}, f_{\nu 3})$$

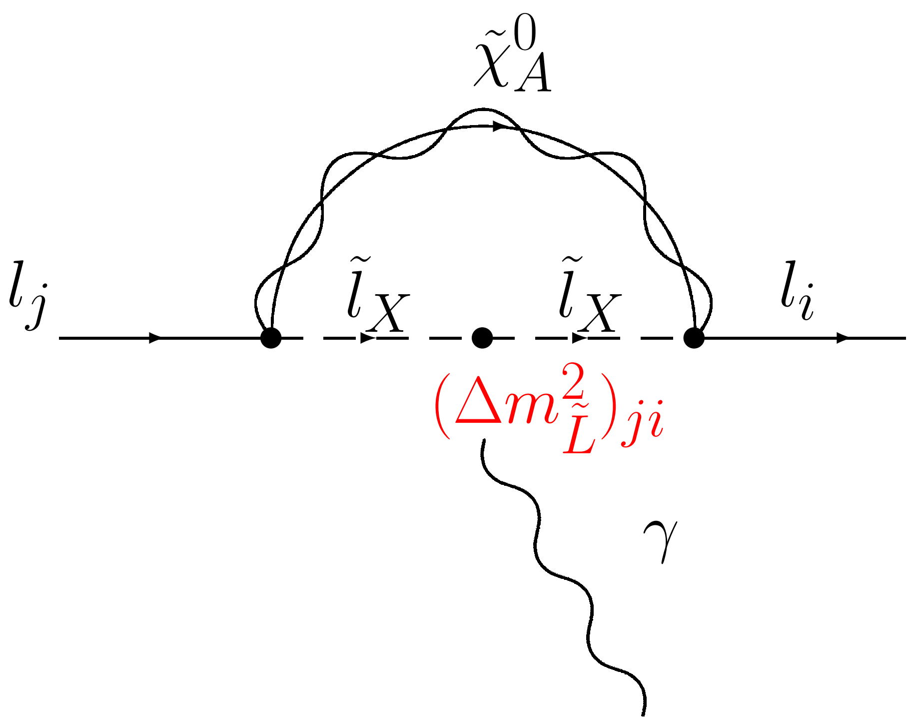
Approximately (a_0:: universal A term)

$$(\Delta m^2_{\tilde{L}})_{ij} \simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(f_\nu^\dagger f_\nu)_{ij}\log\frac{M_G}{M_R}$$

$$\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}U_{ik}^{Dirac}U_{jk}^{Dirac*}|f_{\nu k}|^2\log\frac{M_G}{M_R}$$

$$\Downarrow$$

LFV in the charged-lepton

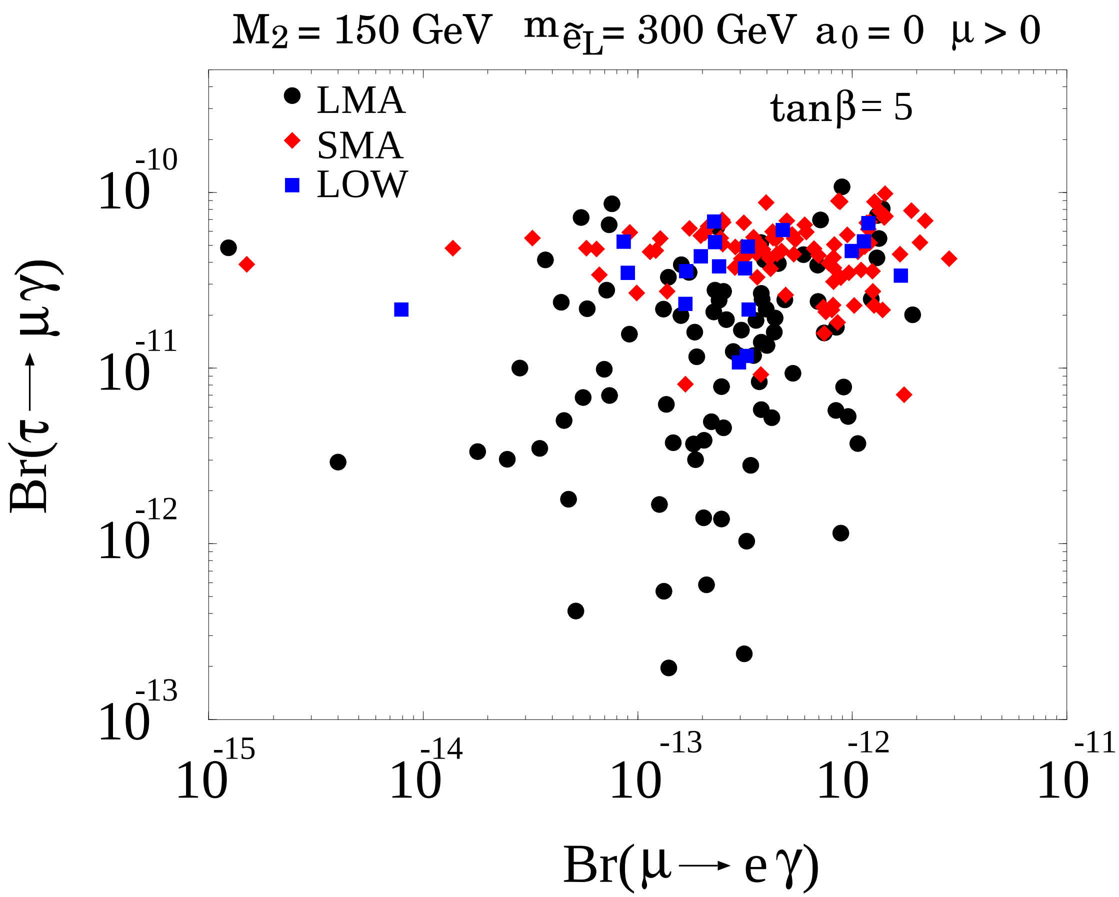


$\tau \to \mu\gamma \Leftrightarrow (\Delta m^2_{\tilde{L}})_{32}$

$\mu \to e\gamma \Leftrightarrow (\Delta m^2_{\tilde{L}})_{21}$

Example of Branching Ratio

J.S and K. Tobe



In near future

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-14} \text{ PSI}$$
$$\mathrm{R}(\mu \to e \text{ in Al}) \sim 10^{-16} \text{ MECO}$$
$$\mathrm{R}(\mu \to e \text{ in Ti}) \sim 10^{-18} \text{ PRISM}$$

2. New Physics in Neutrino Oscillation Experiments

Quest for LFV

- Precision measurement in (near) future (witihn three-generation)

JHF-SK !? Nufact !?

δm^2_{31}	:	Atmospheric	3%
$\sin^2 2\theta_{23}$	:	neutrino anomaly	1%
$U_{e3}(\theta_{13})$	:	Last Mixing	~ 0.01
$\sin\delta$	:	CP Violation	$\delta \sim 20^\circ$

- Neutrino masses $\Longrightarrow$ LFV Interactions

$\Longrightarrow$ Observable Effect in Oscillation Experiments ?

We may see the effect of new physics.

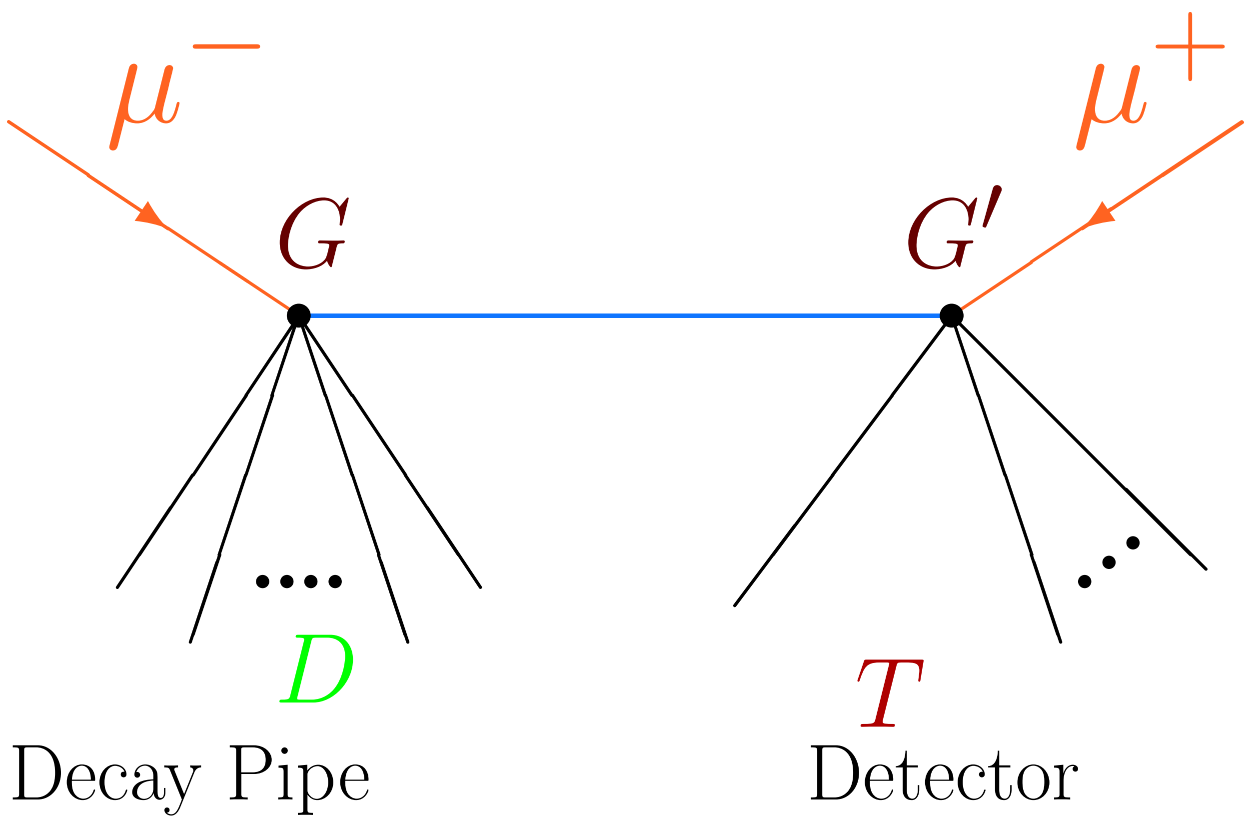
Gonzalez-Garcia, *et. al*, **Gago**, *et.al*, **Ota**, *et al*, **Huber**, *et.al*, **and so on.**

2.1 Interference between

Oscillation Amplitude $\mathcal{A}$ and New-Physics Amplitude $\mathcal{E}$

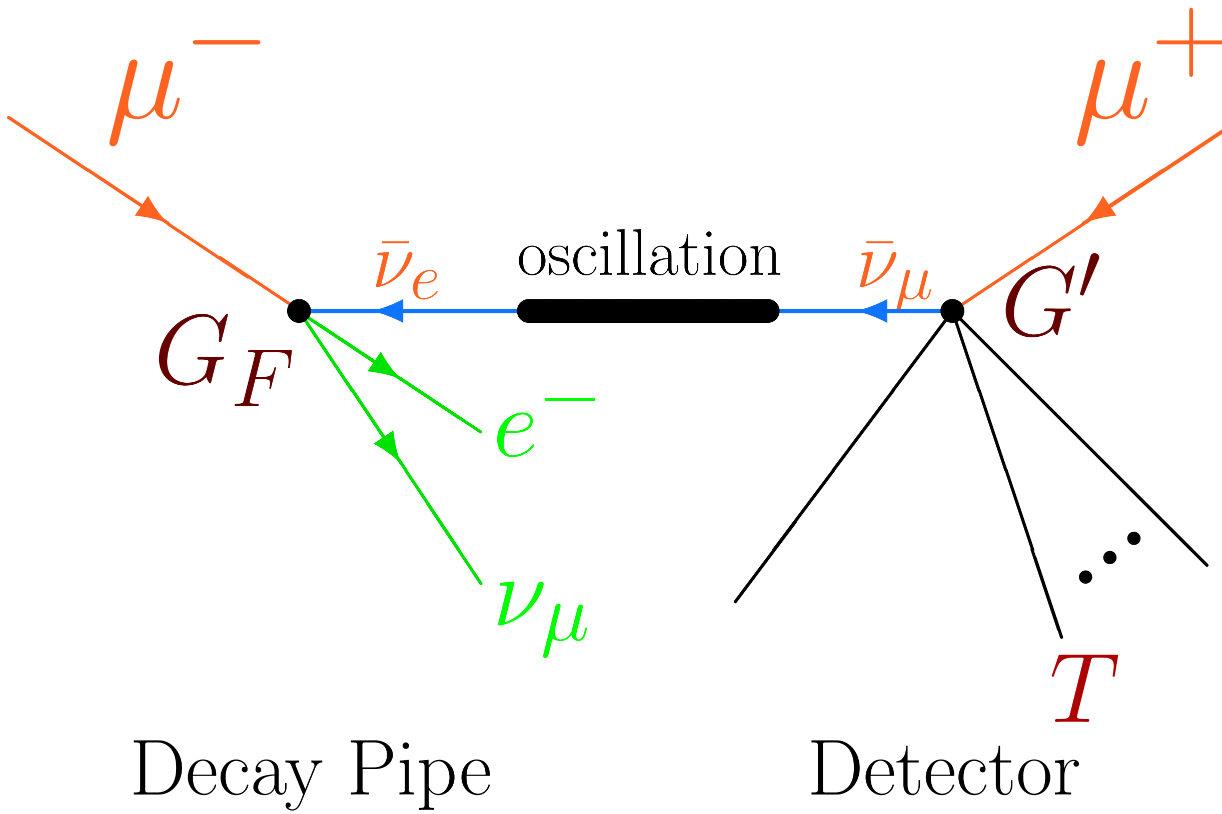
∘ What we really measure? e.g. in Neutrino Factories

Muons decay and Wrong sign muons appear



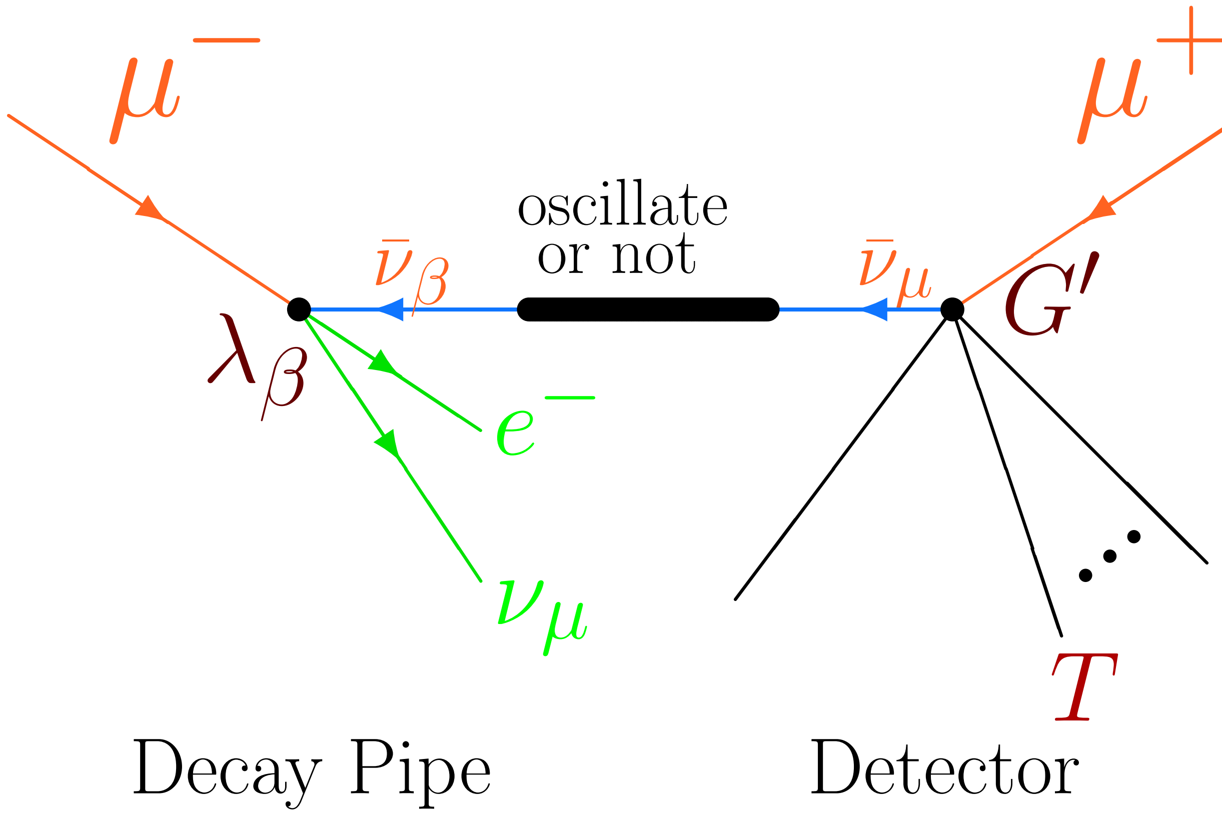
◦ We know there is a weak interaction::

Wrong sign muons suggest the neutrino oscillation



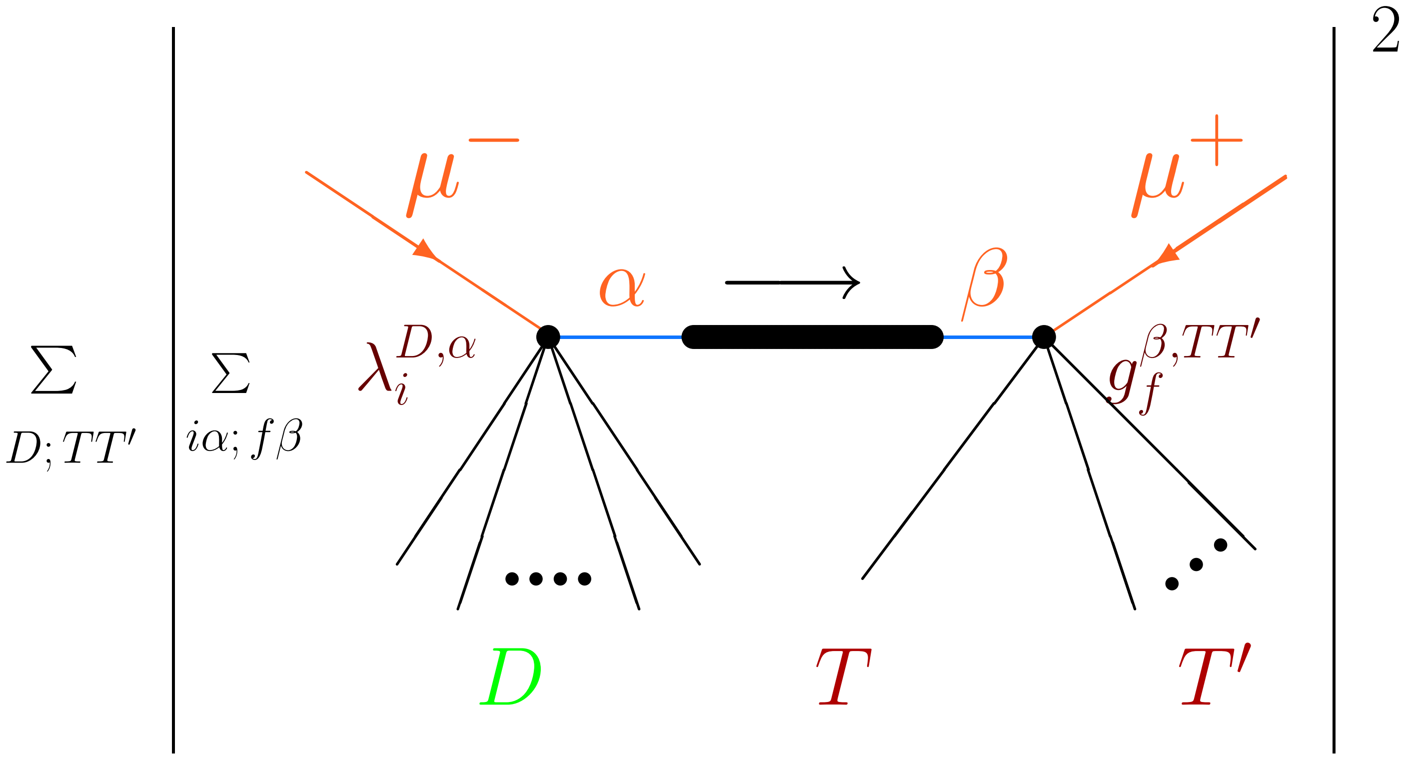
- If there is an interaction,

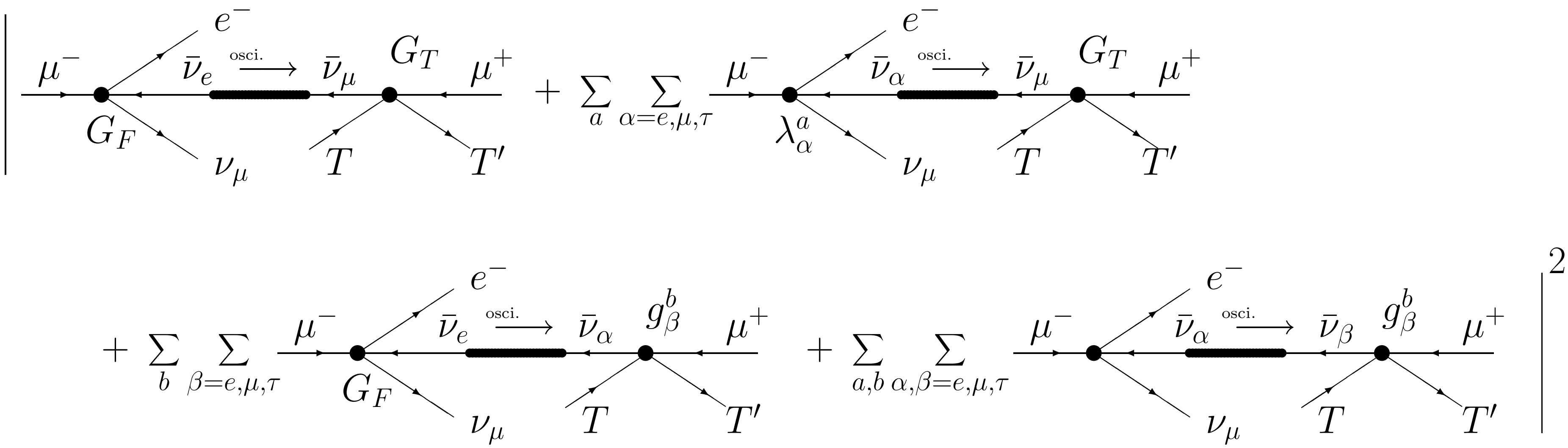
$$L = \lambda(\bar{e}\gamma_\mu \mu)(\bar{\nu}_\mu \gamma^\mu \nu_\beta),$$
$$\beta \neq e,$$



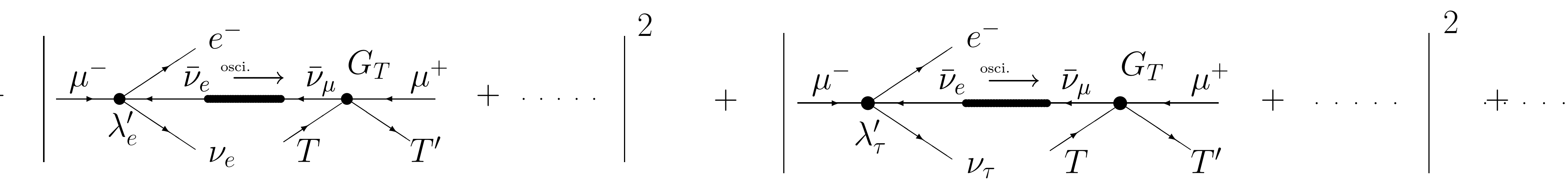
Same Signal $\Longrightarrow$ Interference

Transition rate for "$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$"

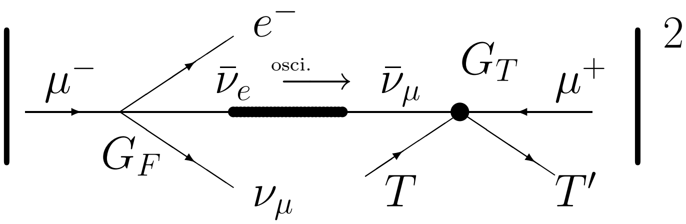




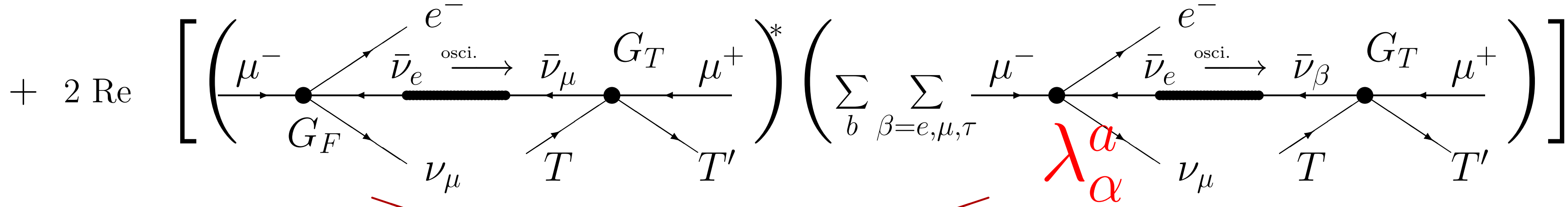
Interference



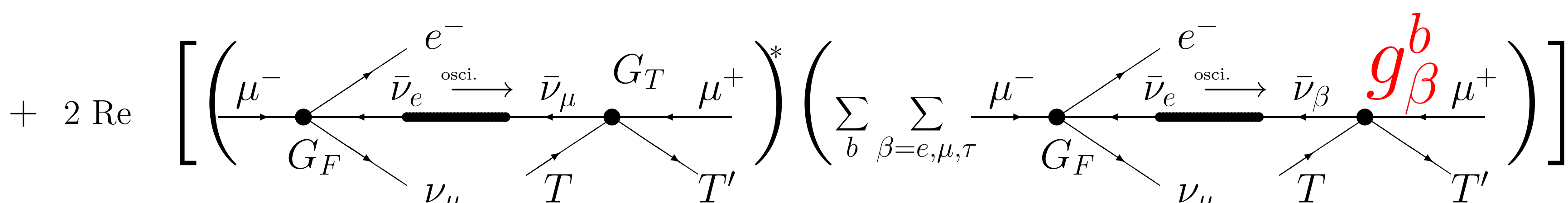
No Interference



and propergation term



Interference $\sim O(\lambda)$ :: linear dependence



Interference $\sim O(g)$ :: linear dependence

2.2 Parametrization

∘ New Physics in Decay $\Longrightarrow$ Initial State = Flavor Mixed State

If the type of interaction is same

e.g., new physics in muon decay

$$L = \lambda(\bar{e}_L \gamma_\mu \mu_L)(\bar{\nu}_\mu \gamma^\mu \nu_\mu),$$

Initial flavor state: Grossman

$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1 \\ \epsilon^s_{e\mu} \\ 0 \end{pmatrix}, \qquad \epsilon^s_{e\mu} = \lambda / G_F$$

Pure Electron State $\Longrightarrow$ Mixed with Muon State

Otherwise, T.Ota, J.S, and N. Yamashita

Complicated Energy Dependence and Extra Suppression Factor

$\Longrightarrow$ Very Probably, No Need to Take into account

∘ New Physics in Matter $\Longrightarrow$ Shift of Matter Effect Gago, *et al* Huber, *et al*

$$H \quad += \quad \begin{pmatrix} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}.$$

∘ New Physics in Detection Process T. Ota, J.S, and N. Yanashita

Exactly, Need to Consider Parton Distribution

However Simple Treatment Could be done, *i.e.* Flavor Mixed State

$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1 \\ \epsilon^d_{e\mu} \\ 0 \end{pmatrix}$$

∘ ϵ's of $O(10^{-4})$ Can be reach Gonzalez-Garcia, *et. al*, Gago, *et.al*, Ota, *et al*, Huber, *et.al*,

- Model Independent Constraint on ϵ's

  From SU(2) Inverted Process Bergman and Grossmann

  e.g. $\mu^- \to e^- \nu_\tau \bar{\nu}_e \quad \Leftrightarrow \tau^- \to \mu^- e^- e^+$

  $\Longrightarrow \quad \epsilon^s_{\mu\tau} \leq 3 \times 10^{-3}$

  factor 2-3 (T. Ota, J.S, N.Yamashita) or maybe 10 (P. Huber and J.W.Valle)

  could be multiplied since SU(2) is broken

- Strong Correlation between Some of LFV Effect and Mixing Parameters

$\nu_e \to \nu_\mu$ channel, $\epsilon_{e\tau}$ terms in high energy

$$
\begin{aligned}
\Delta P_{\nu_e\to\nu_\mu}\{\epsilon_{e\tau}\} &= 2 s_{23} s_{2\times 23} s_{2\times 13} \\
&\times \Bigg[c_{13}^2 \left(s_\delta \mathrm{Re}[\epsilon_{e\tau}^s] - c_\delta \mathrm{Im}[\epsilon_{e\tau}^s]\right) \left(\frac{\bar{a}}{4E_\nu}L\right) \left(\frac{\delta m_{31}^2}{4E_\nu}L\right)^2 \\
&\quad + c_{13}^2 \left(c_\delta \mathrm{Re}[\epsilon_{e\tau}^s] + s_\delta \mathrm{Im}[\epsilon_{e\tau}^s]\right) \\
&\qquad \left\{ 1 - \frac{1}{2}\left(\frac{\bar{a}}{4E_\nu}L\right)^2 - s_{13}^2 \left(\frac{\bar{a}}{4E_\nu}L\right)\left(\frac{\delta m_{31}^2}{4E_\nu}L\right) \right\} \left(\frac{\delta m_{31}^2}{4E_\nu}L\right)^2 \\
&\quad - c_{13}^2 \left(s_\delta \mathrm{Re}[\epsilon_{e\tau}^m] + c_\delta \mathrm{Im}[\epsilon_{e\tau}^m]\right) \left(\frac{\bar{a}}{4E_\nu}L\right) \left(\frac{\delta m_{31}^2}{4E_\nu}L\right)^2 \\
&\quad - \frac{1}{3} s_{13}^2 \left(c_\delta \mathrm{Re}[\epsilon_{e\tau}^m] - s_\delta \mathrm{Im}[\epsilon_{e\tau}^m]\right) \\
&\qquad \left\{ \left(\frac{\bar{a}}{4E_\nu}L\right) + 2\left(\frac{\delta m_{31}^2}{4E_\nu}L\right) \right\} \left(\frac{\bar{a}}{4E_\nu}L\right) \left(\frac{\delta m_{31}^2}{4E_\nu}L\right)^2 \Bigg]
\end{aligned}
$$

■All terms are proportional to E_ν^{-2} or more lower power terms. This energy dependence is the same as the main oscillation terms.

$$
s_{23}^2 s_{2\times 13}^2 \left(\frac{\delta m_{31}^2}{4E_\nu}L\right)^2
$$

$\nu_e \to \nu_\mu$ channel, $\epsilon_{e\mu}$ terms in high energy

$$
\begin{aligned}
\Delta P_{\nu_e\to\nu_\mu}\{\epsilon_{e\mu}\} = 2 s_{23} s_{2\times 13} \\
\times \Bigg[& \left(s_\delta \mathrm{Re}[\epsilon^s_{e\mu}] - c_\delta \mathrm{Im}[\epsilon^s_{e\mu}]\right) \left\{1 - \frac{2}{3}\left(\frac{\bar{a}}{4E_\nu}L\right)^2\right\} \left(\frac{\delta m^2_{31}}{4E_\nu}L\right) \\
& - \left(c_\delta \mathrm{Re}[\epsilon^s_{e\mu}] + s_\delta \mathrm{Im}[\epsilon^s_{e\mu}]\right) \left\{1 - \frac{1}{3}\left(\frac{\bar{a}}{4E_\nu}L\right)^2\right\} \left(\frac{\bar{a}}{4E_\nu}L\right) \left(\frac{\delta m^2_{31}}{4E_\nu}L\right) \\
& + 2 c^2_{23} \left(s_\delta \mathrm{Re}[\epsilon^m_{e\mu}] + c_\delta \mathrm{Im}[\epsilon^m_{e\mu}]\right) \left(\frac{\bar{a}}{4E_\nu}L\right) \left(\frac{\delta m^2_{31}}{4E_\nu}L\right)^2 \\
& + 2 \left(c_\delta \mathrm{Re}[\epsilon^m_{e\mu}] - s_\delta \mathrm{Im}[\epsilon^m_{e\mu}]\right) \left\{1 - \frac{1}{3}\left(\frac{\bar{a}}{4E_\nu}L\right)^2\right\} \left(\frac{\bar{a}}{4E_\nu}L\right) \left(\frac{\delta m^2_{31}}{4E_\nu}L\right) \Bigg] \\
& \qquad + \mathcal{O}(1/E^2)
\end{aligned}
$$

■Some of them depend on E_ν^{-1}. The terms must be robust against the uncertainty of the parameters.

Uncertainty of Mixing Parameter Hide Some of LFV Effect T. Ota, J.S., N.Yamashita

Conversely,

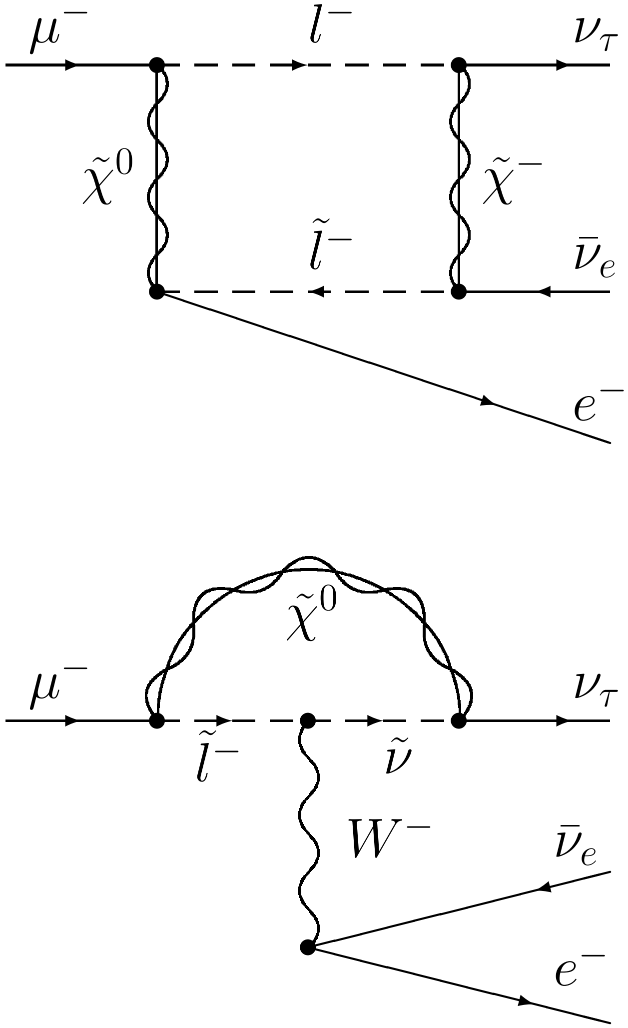
Weak Constraint on LFV Effect may be Obstacle to Determine Mixing Parameters

P. Huber and J.W. Valle

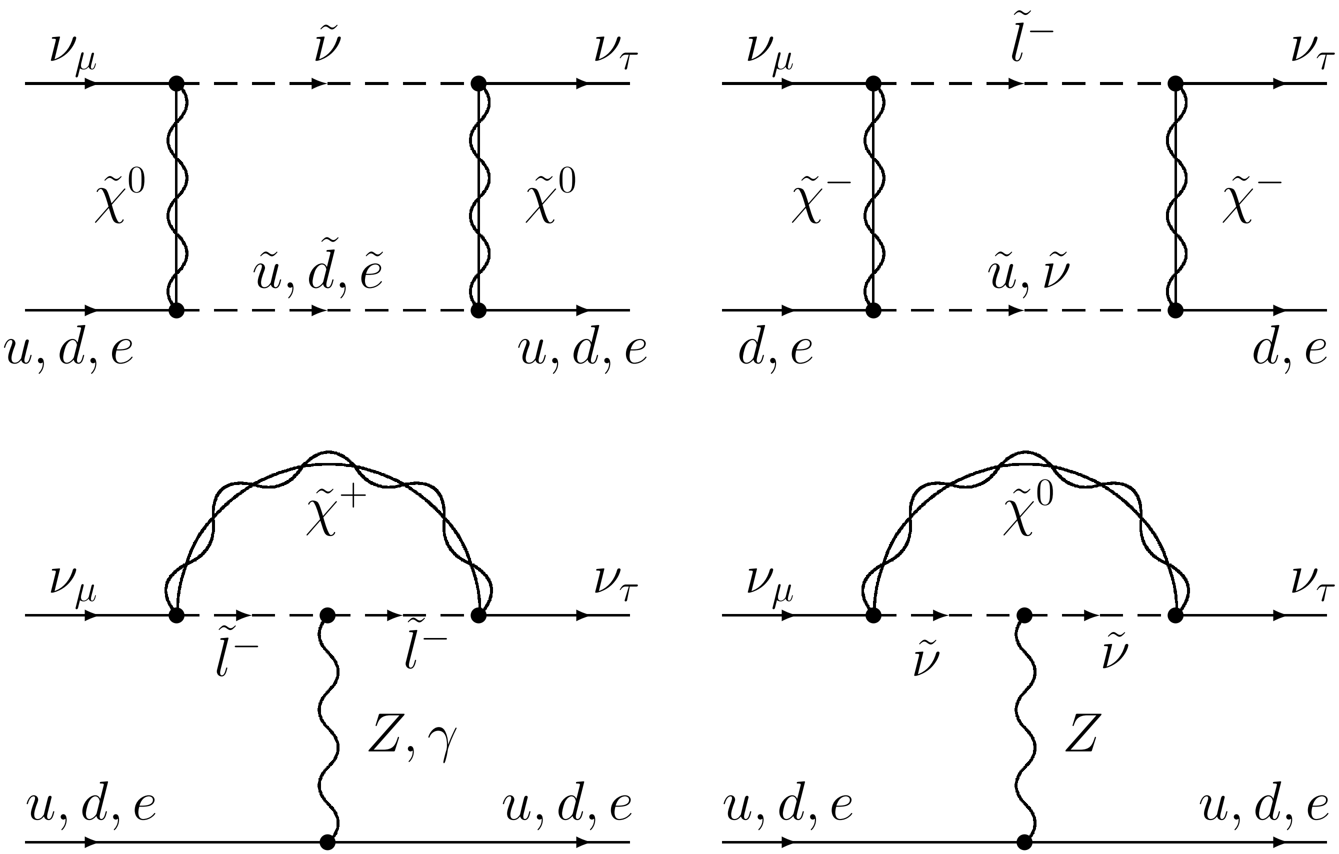
Comparison with Different Modes is Important

○Similar Effect to $\mu \to e\gamma$

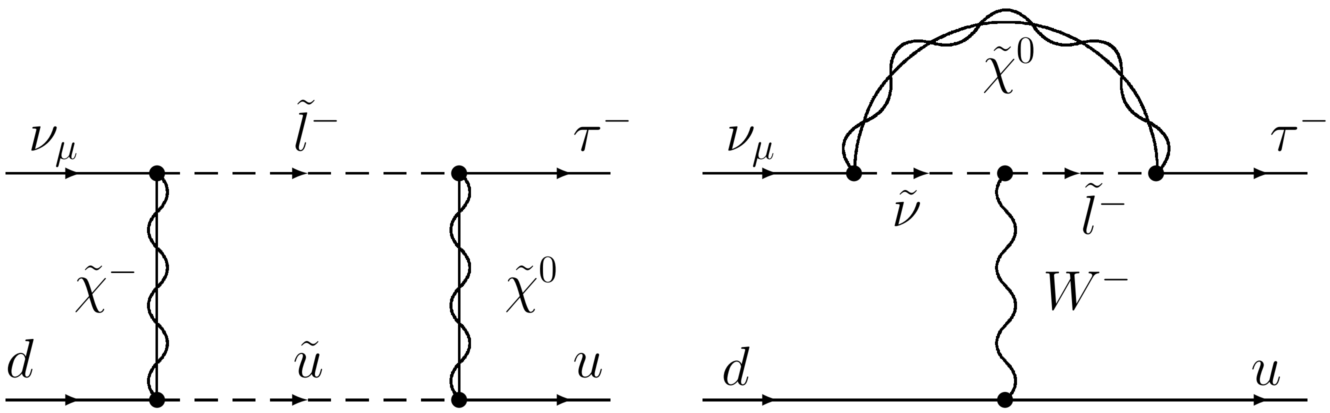
Examples of LFV Interaction in Muon Decay



Examples of LFV Interactions in Matter Effect



Examples of LFV Interaction in a Detection Process



- Amplitude of Graphs $\mathcal{E}$

$$\mathcal{E} \sim \frac{(\Delta m^2_{\tilde{L}})_{\alpha\beta}}{16\pi^2 m^4_{\mathrm{S}}} g^4 \simeq -\frac{(6+a_0^2)}{16\pi^2}(f_\nu^\dagger f_\nu)_{\alpha\beta} \log\frac{M_G}{M_R}\,\frac{g^4}{16\pi^2 m^2_{\mathrm{S}}}$$

and hence

$$\epsilon = \frac{\mathcal{E}}{G_F} \sim -\frac{(6+a_0^2)}{16\pi^2}(f_\nu^\dagger f_\nu)_{\alpha\beta} \log\frac{M_G}{M_R}\ \frac{g^4}{16\pi^2 m_{\rm S}^2 G_F} \sim -\frac{(6+a_0^2)}{16\pi^2}(f_\nu^\dagger f_\nu)_{\alpha\beta} \log\frac{M_G}{M_R}\ \frac{g^2}{16\pi^2}$$

can be $\mathrm{O}(10^{-4})$.

Moreover, Diagrams Contribute Coherently,

Decay, Propagation, Detection,

Factor 10 (?) Enhancement

4 Summary and Duscussion

∘ Explanation for Neutrino Masses and Lepton Mixing

by MSSM with RH Neutrino

$\sim$ Promising

∘ Large LFV Phenomena in Charged Lepton Expected

∘ Similarly, Large LFV Phenomena $O(10^{-3})$in Neutrino Oscillation Experiment

Good News ?   Obstacle ?

Strong Correlation between Some of LFV Effect and Mixing Parameters

Uncertainty of Mixing Parameter Hide Some of LFV Effect T. Ota, J.S., N.Yamashita

Conversely,

Weak Constraint on LFV Effect may be Obstacle to Determine Mixing Parameters

P. Huber and J.W. Valle

$\Longrightarrow$

Comparison between Several Modes,   T.Ota and J.S.

$\nu_\mu \rightarrow \nu_\mu$ (T2K ?) VS $\nu_\mu \rightarrow \nu_\tau$ (OPERA ?)

∘ Advantage over Direct Detection

$\mathcal{S}$: Systematic Error

Direct Detection

$$\epsilon^2 > \mathcal{S} \longrightarrow \epsilon > \sqrt{\mathcal{S}}$$

Oscillation Detection

$$\mathcal{A}\epsilon > \mathcal{S} \longrightarrow \epsilon > \frac{\mathcal{S}}{\mathcal{A}} > \sqrt{\mathcal{S}}$$

$\mathcal{A}^2 > \mathcal{S}$: Always expected

∘ Keep in Mind the Possibility of LFV Interactions