Oscillation-enhanced search for new interaction with neutrinos

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1. Introduction

∘ Precision measurement on

JHF-SK !? Nufact !?

$\boldsymbol{\delta m^2}$	:	Atmospheric	3%
$\boldsymbol{\sin^2 2\theta_{23}}$	:	neutrino anomaly	1%
$\boldsymbol{U_{e3}(\theta_{13})}$	:	Last Mixing	$\boldsymbol{\sim 0.01}$
$\boldsymbol{\sin\delta}$	:	CP Violation	$\boldsymbol{\delta}$ $\sim$20°

∘ Lepton Flavor Changing Interactions in Models for Neutrino Osicllation.

Can we observe ?

$\Longrightarrow$ We may find the effect of new physics.

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

Let's study this possibility!!

2. Measurement of Neutrino Oscillation

- What we really measure?

e.g. in Neutrino Factories

Muons decay

and

Wrong sign muons appear

$\Longrightarrow$ Fig.1

- We know there is a weak interaction::

Wrong sign muons

suggest the neutrino oscillation

$\Longrightarrow$ Fig.2

- If there is an interaction,

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

it gives the same signal.

$\Longrightarrow$ Fig. 3

We cannot distinguish these contribution!!!

$\Downarrow$

Grossman

Interference

between several contributions.

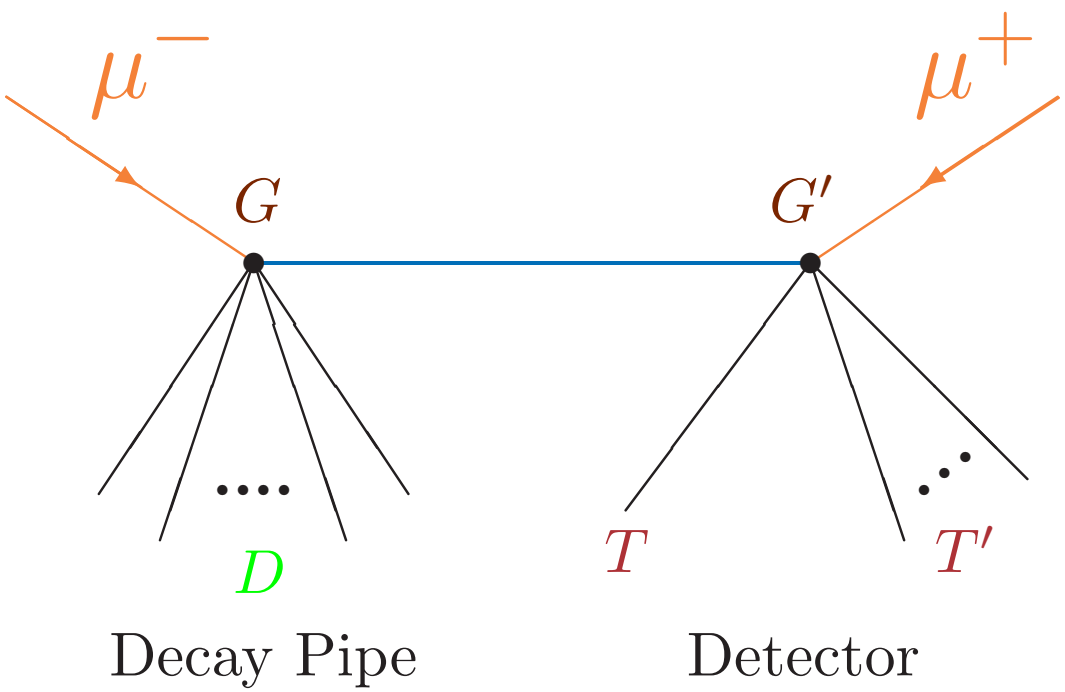


Fig.1 What we really observe

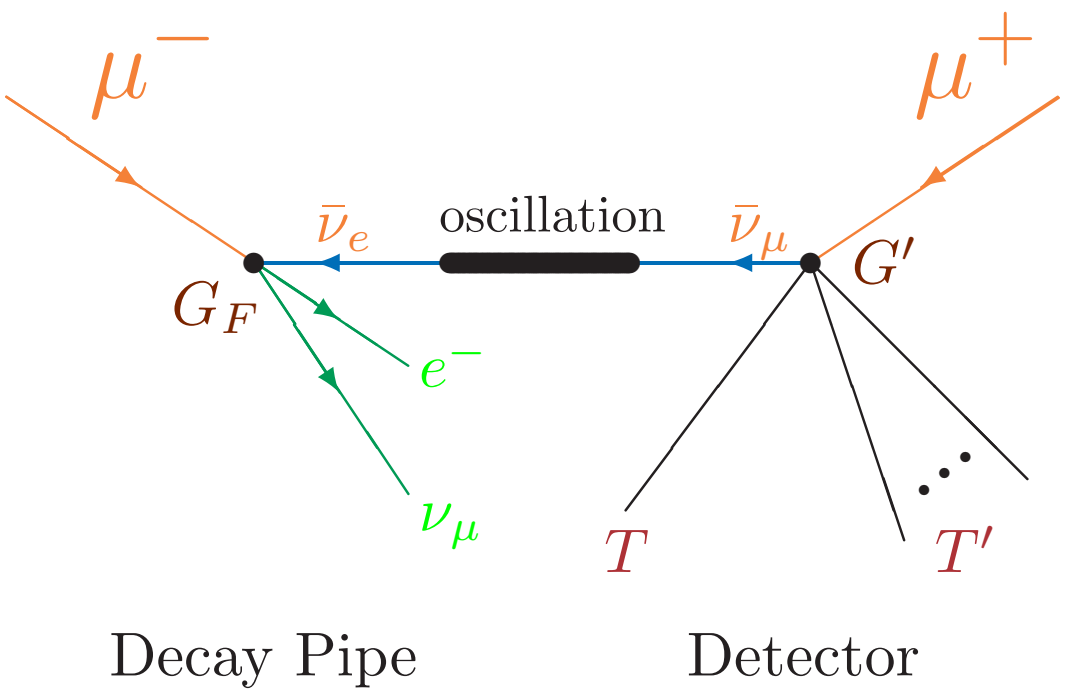


Fig.2 Interpretation by Weak Process

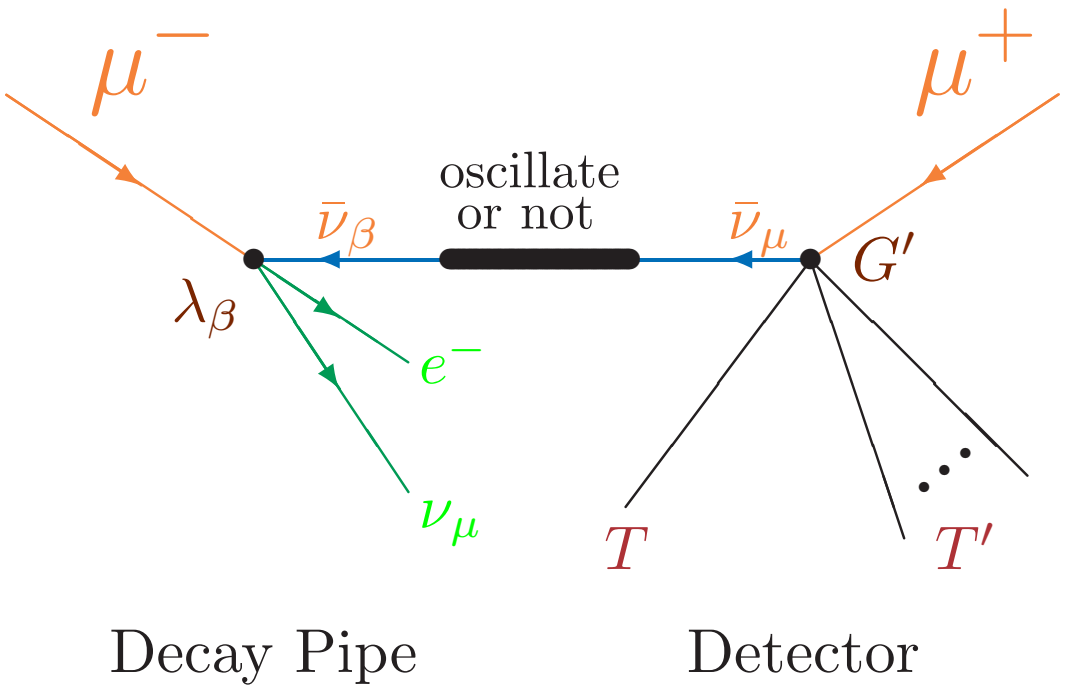
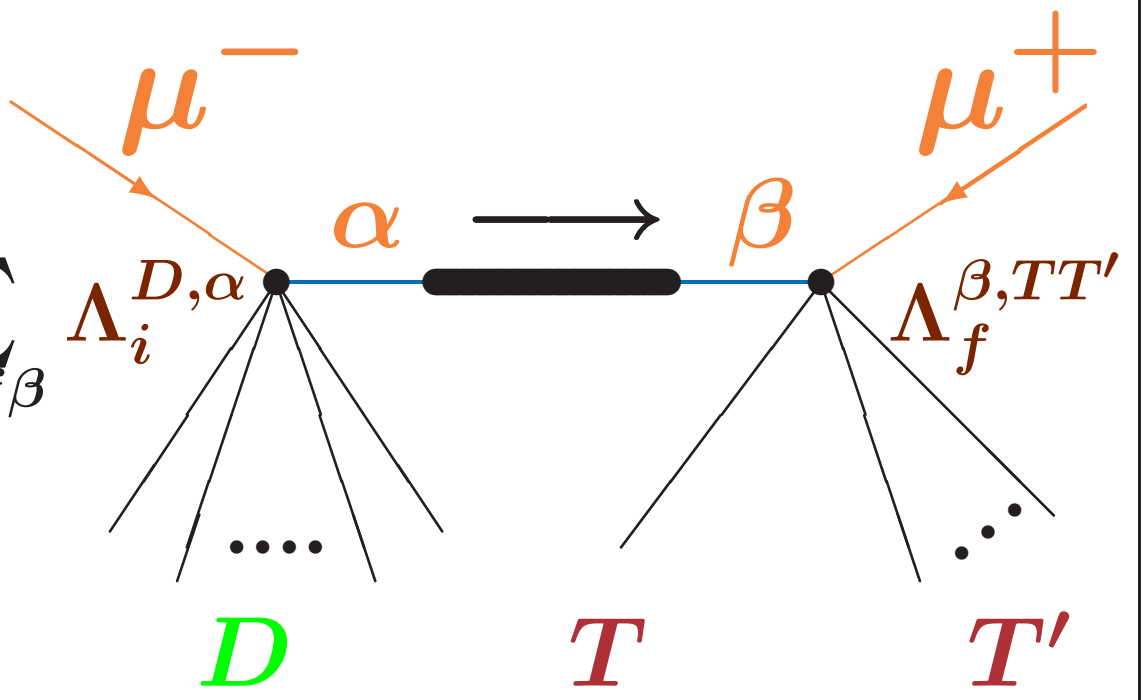
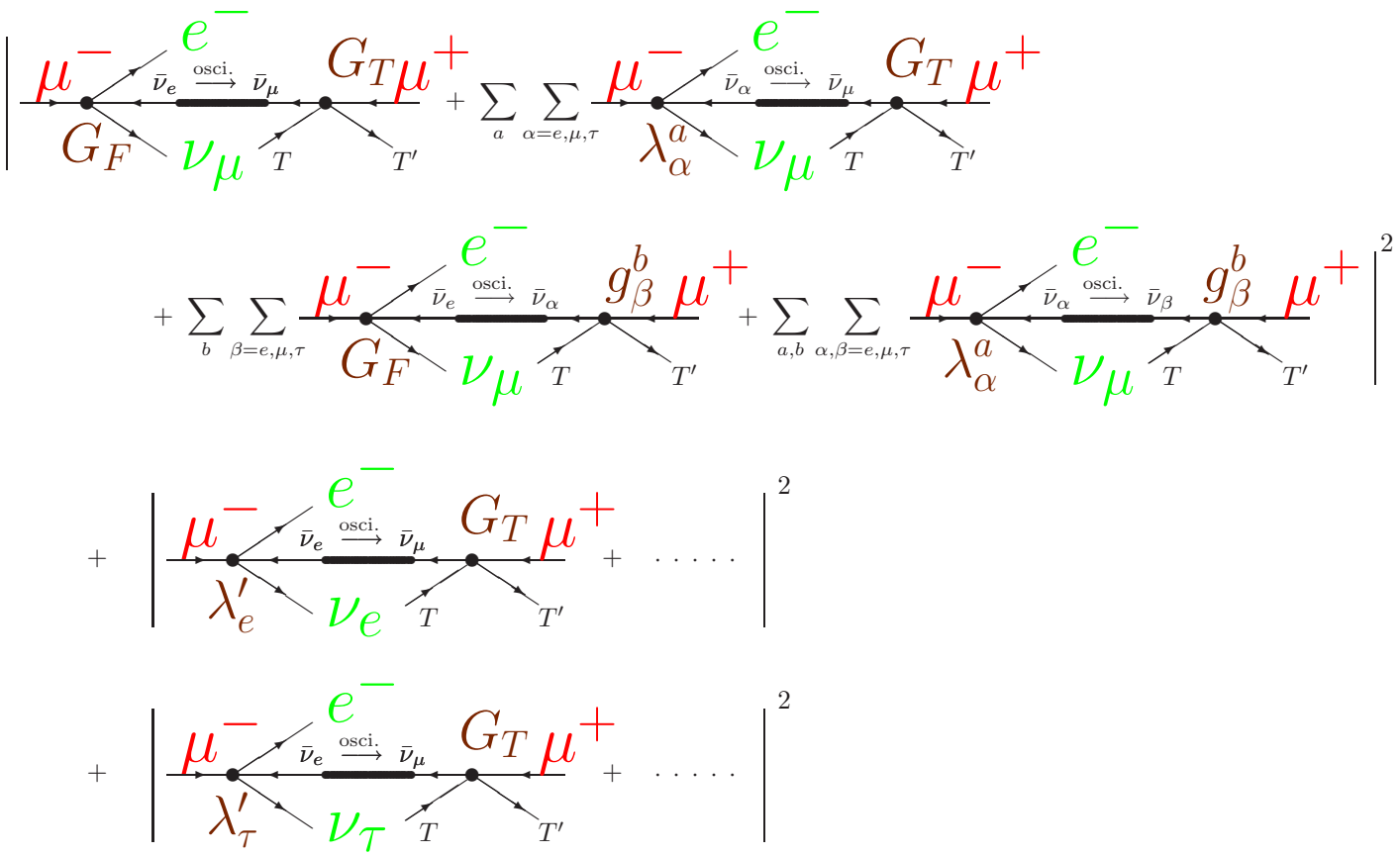


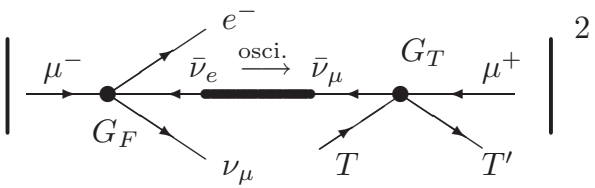
Fig.3 Same Signal!!

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

$$\sum_{D;TT'} \left| \sum_{i\alpha;f\beta} \right|^2$$

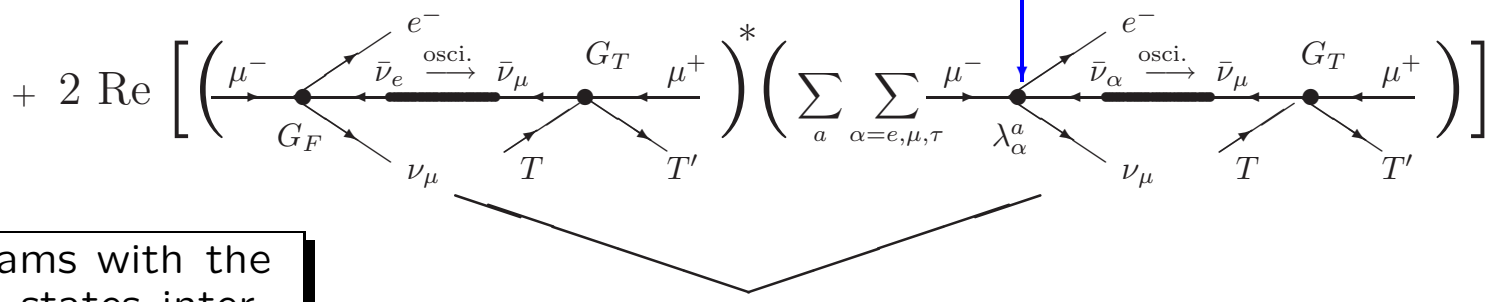



μ^-
e^-
$\bar{\nu}_e$
osci.
$\bar{\nu}_\mu$
$G_T\mu^+$
G_F
ν_μ
T
T'
$+\sum_a \sum_{\alpha=e,\mu,\tau}$
μ^-
e^-
$\bar{\nu}_\alpha$
osci.
$\bar{\nu}_\mu$
$G_T\ \mu^+$
λ^a_α
ν_μ
T
T'
$+\sum_b \sum_{\beta=e,\mu,\tau}$
μ^-
e^-
$\bar{\nu}_e$
osci.
$\bar{\nu}_\alpha$
g^b_β
μ^+
G_F
ν_μ
T
T'
$+\sum_{a,b}\ \sum_{\alpha,\beta=e,\mu,\tau}$
μ^-
e^-
$\bar{\nu}_\alpha$
osci.
$\bar{\nu}_\beta$
g^b_β
μ^+
λ^a_α
ν_μ
T
T'
2
$+$
μ^-
e^-
$\bar{\nu}_e$
osci.
$\bar{\nu}_\mu$
$G_T\ \mu^+$
$+\ \cdots\cdots$
λ'_e
ν_e
T
T'
2
$+$
μ^-
e^-
$\bar{\nu}_e$
osci.
$\bar{\nu}_\mu$
$G_T\ \mu^+$
$+\ \cdots\cdots$
λ'_τ
ν_τ
T
T'
2
$+\ \cdots\cdots$



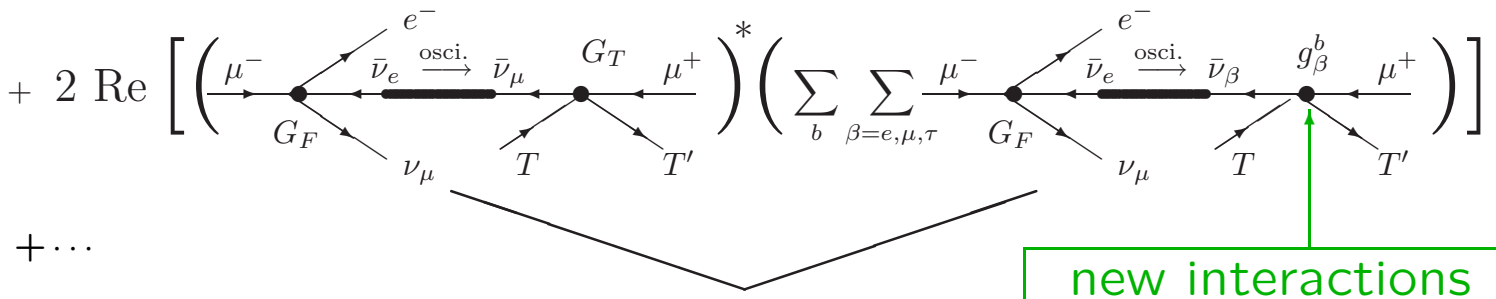
■ main term

new interactions in muon decay



The diagrams with the same final states interfere each other.

■ Interference $\sim \mathcal{O}(\lambda)$



+ ···

■ Interference $\sim \mathcal{O}(g)$

new interactions in detection process

Remarks

◇ For interference to occur, all states including invisible states must be same!!!!
Even if we have

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

there is NOT interference with main mode.

◇ "States" means "Physical States", i.e.
Particle species, helicity, energy, and so on.
$\Longrightarrow$

$$L = \lambda(\bar{e}_R\gamma_\mu\mu_R)(\bar{\nu}_\mu\gamma^\mu\nu_e),$$

gives distinctive energy dependence.
Careful treatment is required.
"Transition probability" for $\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$ is replaced

$$\begin{aligned} & P(\bar{\nu}_e \longrightarrow \bar{\nu}_\mu; E_\mu, E_\nu) \\ = & \int_{e,\nu_\mu} |A_L T_{\bar{\nu}_e\bar{\nu}_\mu} A_D + A_R T_{\bar{\nu}_e\bar{\nu}_\mu} A_D|^2 \\ = & \int_{e,\nu_\mu} \{|A_L|^2 + 2\mathrm{Re}(A_L^* A_R) + |A_R|^2\} |T_{\bar{\nu}_e\bar{\nu}_\mu} A_D|^2 \end{aligned}$$

$A_{L(R)}$: μ Decay Amplitude
$T_{\bar{\nu}_\alpha\bar{\nu}_\beta}$: ν transition Amplitude
A_D : μ CreationneAmplitude

On the other hand,

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

gives same energy dependence at decay site.

$$\Downarrow$$

Simple treatment Grossman

Initial flavor state:

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

$$\epsilon^s_{e\mu} = \lambda / G_F$$

Gago, *et al*, Huber, *et al*

◇ Similar mechanism works for extra (flavor changing) matter effect,

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

◇ Same things happen at detector side. E.g.

$$L = \lambda(\bar{\nu}_e \gamma_\mu \mu)(\bar{d}\gamma^\mu u).$$

However, parameterization is very difficult!!!

In principle, we can parameterize their effect using parton distribution

($\Rightarrow$ extra energy dependence)

in model dependent way, e.g.

$$\propto \epsilon^d_{\alpha\beta;q} q(x, y)$$

if new interaction does not see the difference between quraks, we can use $\epsilon^d_{\alpha\beta}$

◇ Transition rate depends not only on the magnitude but also the phase of extra couplings.

fake CP violation, Gonzalez-Garcia, *et al*

3. Sensitivities

◇ Plots' shapes are well understood by high energy expansion of oscillation probabilities:

$$P_\epsilon \sim \frac{L^\beta}{E^\alpha}$$

$$\xi^2 \sim \frac{L^{(2\beta-4)}}{E^{(2\alpha-5)}}$$

◇ If all mixing parameters are known EXACTLY, extra couplings are very well explored.

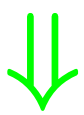
However, $\alpha \geq 2$, these effects are "renormalized" into the mixing parameters.

◇ Extra couplings can give $\alpha = 1$, that is,

1/E

dependence on

"Transition Probability".



Stable Sensitivity!!!

◇ Sensitivity $\propto |\epsilon|^2$.
Also depends on the phase of ϵ's.

◇ To see $\epsilon_{\alpha\beta}$, use $\nu_\alpha \longrightarrow \nu_\beta$.

(In other appearance channels they $1/E^2$ dependence and vulnerable against parameter uncertainties.)

◇ In disappearance channel, also $1/E$ dependence.

"statistically" promising.

("systematically" ???)

◇ Sensitive new physics are different in Nufact and in Conventional Beam.

$\longrightarrow$ Comparison is important!!

Numerical calculations:

◇Oscillation parameters that we take here:

$$\sin\theta_{12} = \frac{1}{2}, \quad \sin\theta_{23} = \frac{1}{\sqrt{2}}, \quad \sin\theta_{13} = 0.1,$$
$$\delta m^2_{21} = 5 \times 10^{-5}, \qquad \delta m^2_{31} = 3 \times 10^{-3},$$
$$\delta = \frac{\pi}{2}.$$

*We assume 10% uncertainty in each parameter including the Earth matter.

◇The figures indicate the necessary data size (muon number $\times$ detector mass) to distinguish the observation with the standard model assumption at 90% confidence level.

▶Concretely,

$$\chi^2_{90\%} < \chi^2 \equiv \sum_i^{\text{bin}} \frac{\left| N_i^{\text{NP}} - N_i^{\text{SM}} \right|^2}{N_i^{\text{SM}}} = N_\mu M_{\text{det}} X^2$$

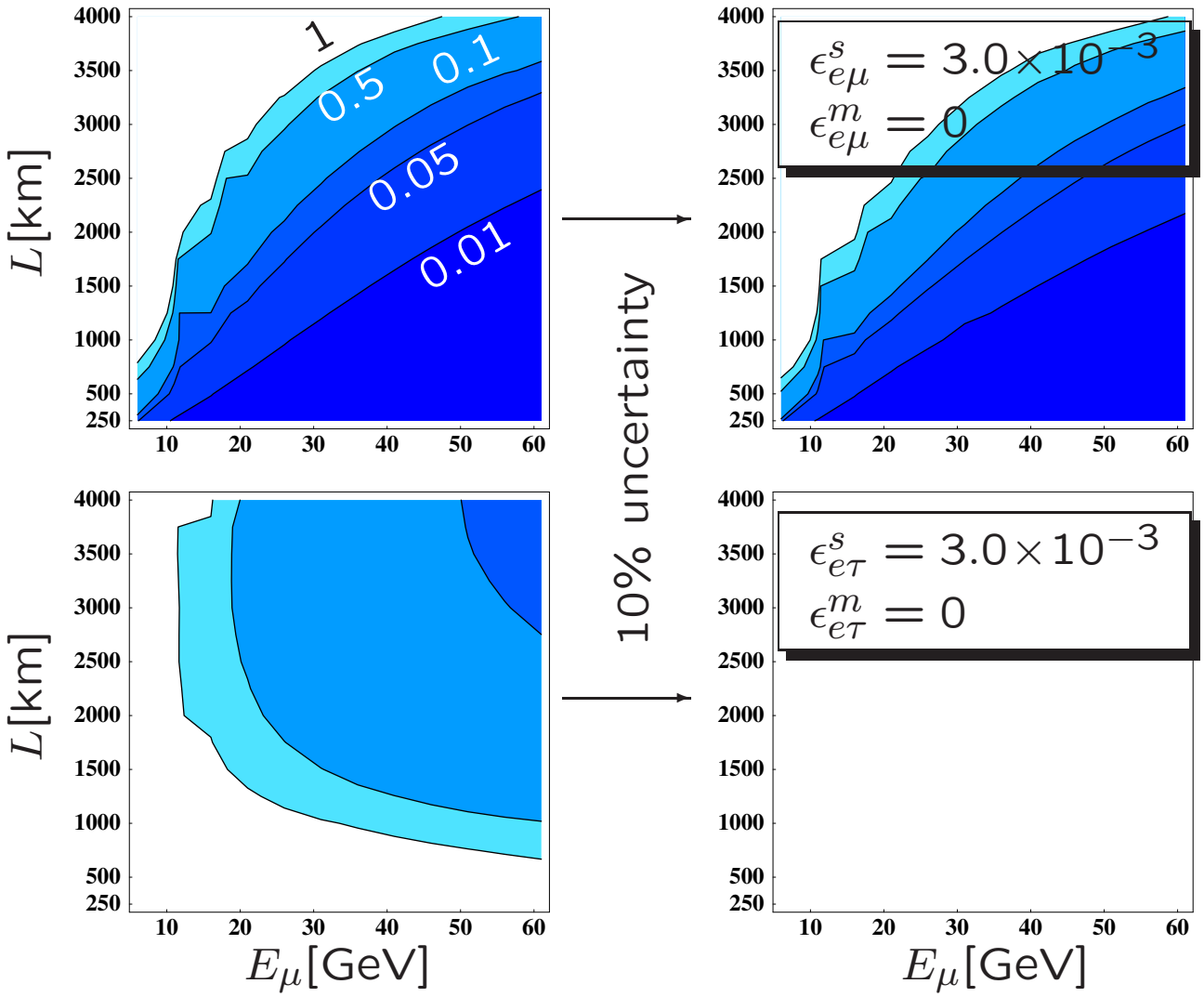
$$N_\mu M_{\text{det}} > \frac{\chi^2_{90\%}}{X^2}$$

In each E_μ and L, this value is ploted.

$\nu_e \to \nu_\mu$ **channel,** $\left\|\epsilon^{s,m}_{\alpha\beta}\right\| = 3\times10^{-3}$**,** $(V-A)(V-A)$ **type**

◇ The effects induced by $\epsilon^{s,m}_{e\mu}$ and $\epsilon^{s,m}_{e\tau}$ are large enough to be observed.

◇ However, the $\epsilon^{s,m}_{e\tau}$ effects have the same energy dependence as the main contribution of the standard oscillation. The errors of the oscillation parameters absorb the $\epsilon^{s,m}_{e\tau}$ effects.



★ In this channel, the singlet mediated $\epsilon^s_{e\mu}$ is forbidden. The $\epsilon^s_{e\mu}$ effects are strongly constrained by the counter part process.

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

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

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

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

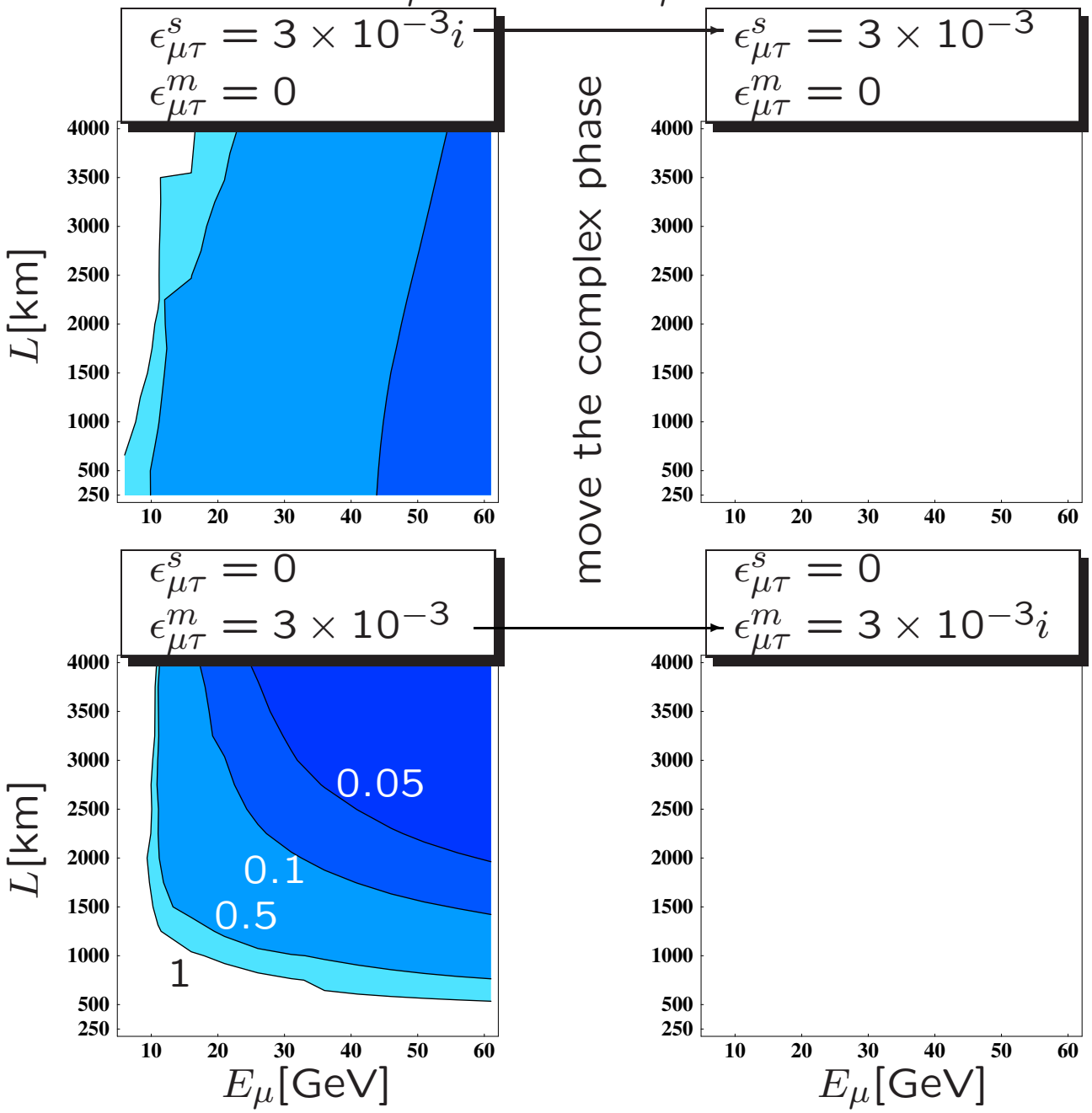
$\nu_e \to \nu_\mu$ channel, $\epsilon_{e\mu}$ terms in high energy

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

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

$\nu_\mu \to \nu_\mu$ **channel,** $\left|\epsilon^{s,m}_{\alpha\beta}\right| = 3\times10^{-3}$**,** $(V-A)(V-A)$ **type**

◇ The analytic expression shows that only the effects originated from Im$[\epsilon^s_{\mu\tau}]$ and Re$[\epsilon^m_{\mu\tau}]$ are effective.

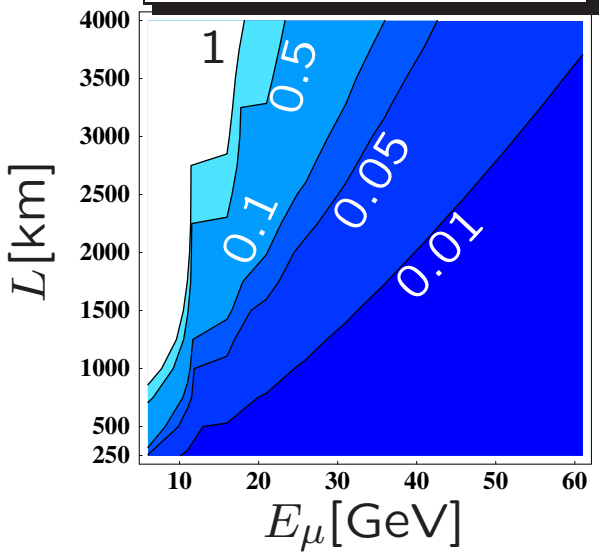


★The observability of the new interactions strongly depends on their phase.

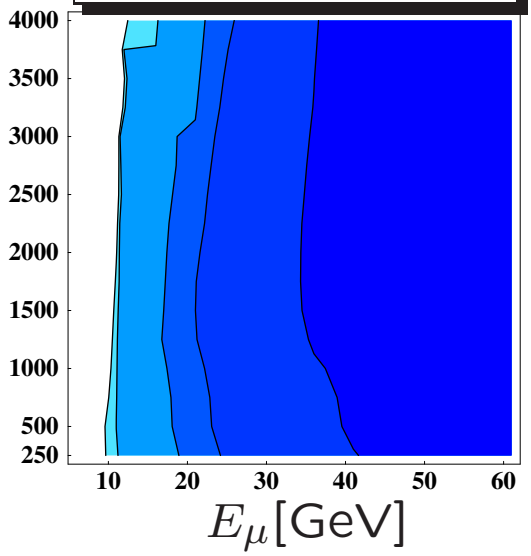
$\nu_\mu \to \nu_\tau$ **channel,** $\left|\epsilon^{s,m}_{\alpha\beta}\right| = 3 \times 10^{-3}$, $(V-A)(V-A)$ type

◇The statistical error gives the appearance channel an advantage over disappearance channel.

$\epsilon^s_{\mu\tau} = 3 \times 10^{-3} i$
$\epsilon^m_{\mu\tau} = 0$



$\epsilon^s_{\mu\tau} = 0$
$\epsilon^m_{\mu\tau} = 3 \times 10^{-3}$



◇ The technologies for ν_τ detection are under R&D.

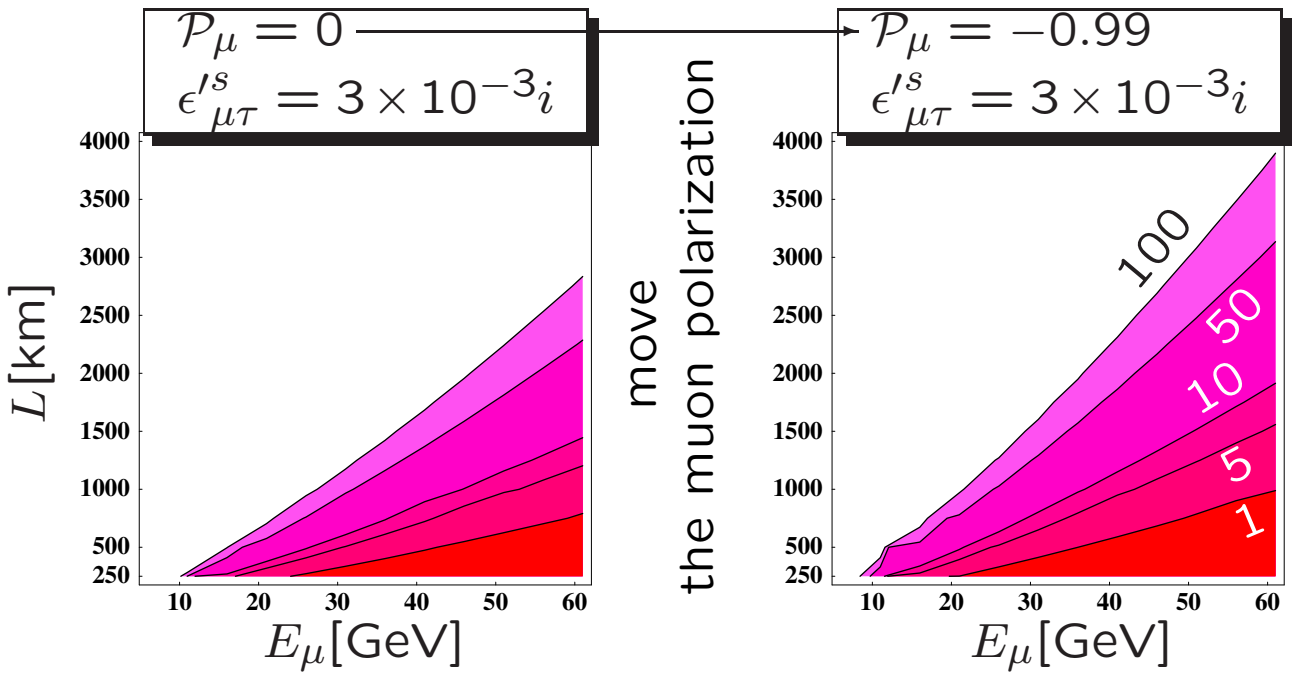
▼

★ The CERN is now putting two experiments that aim at $\nu_\mu \to \nu_\tau$ into practice. **ICARUS** and **OPERA**

◇ **Doublet mediated interaction: $\nu_\mu \to \nu_\tau$ channel**

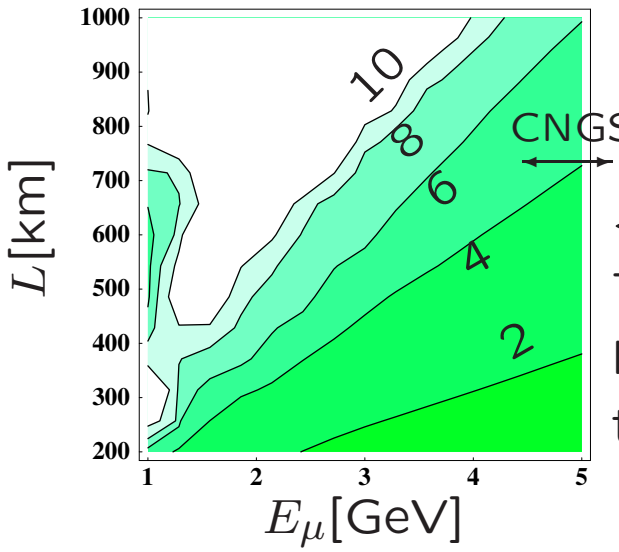
The effect caused by doublet scalar mediation is suppressed by m_e/m_μ.

It has the different feature with the ordinary term in the polarization dependence.



★ Using polarized beam give a little gain, but it is not more than the direct search.

Using the conventional beam: $\nu_\mu \to \nu_\tau$ channel



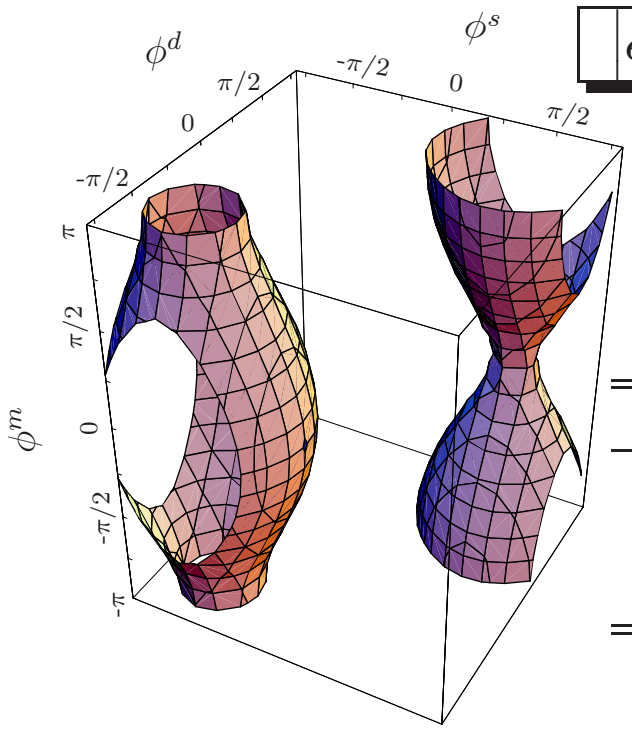
CNGS ⟷ 30GeV

$$\epsilon^s_{\mu\tau} = 3 \times 10^{-3} i$$
$$\epsilon^m_{\mu\tau} = 0$$

◀The unit is 10^5 neutrinos. This is the $\mathcal{O}(10^2)$ times larger exposure than that of the current experiments.

ICARUS and OPERA:

◇ Low statistics make a study of the energy spectra infeasible. We compare the total event number made by the new interaction with the error.



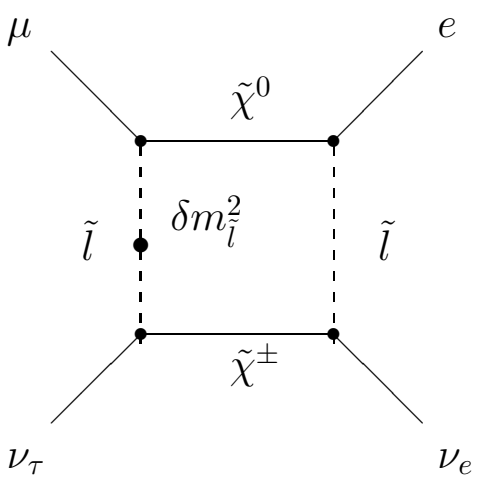
$$|\epsilon^s_{\mu\tau}| = |\epsilon^m_{\mu\tau}| = |\epsilon^d_{\mu\tau}| = 0.01$$

◀The contour denotes that the effect made by new interactions is as large as the 1σ error.

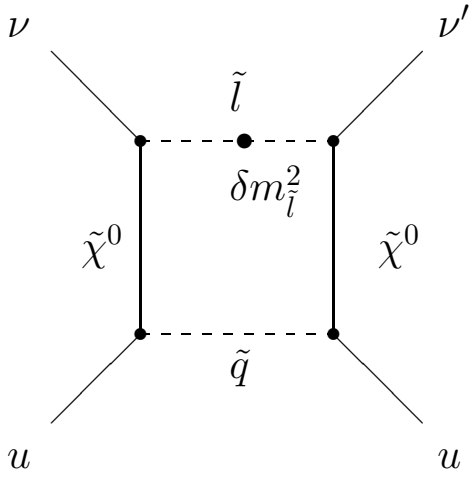
	$N_\tau^{\rm SM}$	$\sigma^2_{\rm sys}$	$\sigma_{\rm tot}$
ICARUS-A	40.4	11	7.4
ICARUS-B	23.5	1.5	5.2
OPERA	16.3	0.75	4.3

4. Examples of Models

◇ SUSY + $\boldsymbol{\nu_R}$.



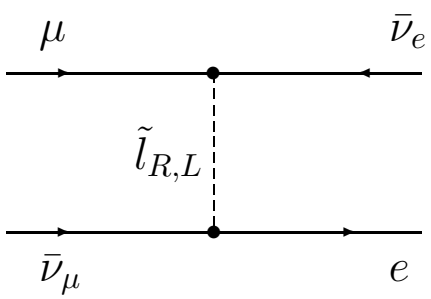
(1)



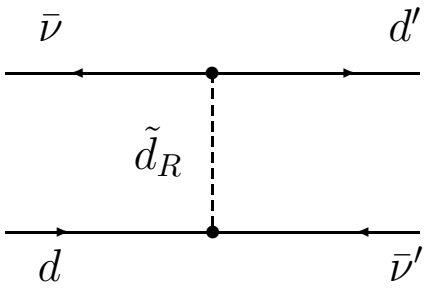
(2)

(1) Muon decay and matter effect.
(2) Pion decay, matter effect and detection process.

◇ R-Parity breaking models



(1)



(2)

(1) Muon decay and matter effect.
(2) Pion decay, matter effect and detection process.

◇ In general, from $SU(2)_L$ invariance,

Singlet type, :((V-A)(V-A)), SUSY+ν_R & R-Parity Br

$$h_{\alpha\beta\gamma\delta}(\bar{l}_\alpha C\bar{l}_\beta)(l_\gamma C^\dagger l_\delta)$$
$$= -\frac{1}{2}h_{\alpha\beta\gamma\delta}(\bar{l}_\alpha\gamma^\mu l_\delta)(\bar{l}_\beta\gamma_\mu l_\gamma)$$
$$= \frac{1}{2}h_{\alpha\beta\gamma\delta}h_{\alpha\beta\gamma\delta}(\bar{e}_{\alpha L}C\bar{\nu}_{\beta L} - \bar{\nu}_{\alpha L}C\bar{e}_{\beta L})(e_{\gamma L}C^\dagger\nu_{\delta L} - \nu_{\gamma L}C^\dagger e_{\delta L}),$$

$$h_{\alpha\beta\gamma\delta} = -h_{\beta\alpha\gamma\delta} = -h_{\alpha\beta\delta\gamma}.$$

Triplet type, :((V-A)(V-A)) SUSY+ν_R

$$g_{\alpha\beta\gamma\delta}(\bar{l}_\alpha\tau^a C\bar{l}_\beta)(l_\gamma C^\dagger\tau^a l_\delta)$$
$$= -\frac{1}{2}g_{\alpha\beta\gamma\delta}(\bar{l}_\alpha\tau^a\gamma^\mu l_\delta)(\bar{l}_\beta\tau^a\gamma_\mu l_\gamma)$$
$$= g_{\alpha\beta\gamma\delta}\left\{(\bar{e}_{\alpha L}C\bar{\nu}_{\beta L} + \bar{\nu}_{\alpha L}C\bar{e}_{\beta L})(e_{\gamma L}C^\dagger\nu_{\delta L} + \nu_{\gamma L}C^\dagger e_{\delta L})\right.$$
$$\left. +2(\bar{\nu}_{\alpha L}C\bar{\nu}_{\beta L})(\nu_{\gamma L}C^\dagger\nu_{\delta L}) + 2(\bar{e}_{\alpha L}C\bar{e}_{\beta L})(e_{\gamma L}C^\dagger e_{\delta L})\right\},$$

$$g_{\alpha\beta\gamma\delta} = g_{\beta\alpha\gamma\delta} = g_{\rho\sigma\delta\gamma}.$$

Doublet type, :((V-A)(V+A)), R-Parity Br

$$f_{\alpha\beta\gamma\delta}(\bar{l}_\alpha e_{\beta R})(\bar{e}_{\gamma R}l_\delta)$$
$$= -\frac{1}{2}f_{\alpha\beta\gamma\delta}(\bar{l}_\alpha\gamma^\mu l_\delta)(\bar{e}_\gamma\gamma_\mu P_R e_\beta)$$
$$= f_{\alpha\beta\gamma\delta}\left\{(\bar{e}_{\alpha L}e_{\beta R})(\bar{e}_{\gamma R}e_{\delta L}) + (\bar{\nu}_{\alpha L}e_{\beta R})(\bar{e}_{\gamma R}\nu_{\delta L})\right\}.$$

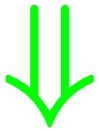
◇ ϵ's $(\epsilon_{\mu\tau})$ can be $O(10^{-2})$ in Singlet type and $O(10^{-3})$ in other types. !!!

5. Summary and Discussion

◇ Effect of new physics in neutrino oscillation experiment

◇

Interference

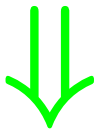


Linear dependence on extra couplings
Oscillation enhanced search of new physics !!

Phase, Interaction type, and so on.

◇

$\mathbf{1/E}$ dependence in oscillation



Stable sensitivity

◇ For $(V-A)(V-A)$ interaction type

■In $\nu_\alpha \longrightarrow \nu_\beta$, the effects induced by $\epsilon^{s,m}_{\alpha\beta}$. The others are too small or easy to be absorbed into the error of the oscillation parameters.

■The expected sensitivity is $\epsilon \gtrsim \mathcal{O}(10^{-4})$.

	$\epsilon^{s,m}_{e\mu}(\epsilon^{s}_{\mu e})$	$\epsilon^{s,m}_{e\tau}$	$\epsilon^{s,m}_{\mu\tau}$
$\nu_e \longrightarrow \nu_\mu$	△	△	×
$\nu_\mu \longrightarrow \nu_\mu$	×	×	○
$\nu_e \longrightarrow \nu_\tau$	×	○	△
$\nu_\mu \longrightarrow \nu_\tau$	×	△	○
$\nu_\mu \longrightarrow \nu_e$	△	×	×
$\nu_e \longrightarrow \nu_e$	×	×	×

◇ In many models $\epsilon_{\mu\tau}$ is large.

$\longrightarrow \tau$ appearance is important !

The CNGS experiments will be able to detect the new interactions with $\epsilon \gtrsim \mathcal{O}(10^{-2})$, depending on their phases.