New Physics in Neutrino Oscillation

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○ Motivation

Standard Model must be extended so that Lepton Flavor Violation is included.

Furthermore Large LFV from Oscillation experiment

Large Lepton Flavor Violation must be observed !!

(Very probably) Most studied example

MSSM with RH neutrino (Seesaw Model) Borzumati, Masiero; Hisano et al

Large Flavor Changing Slepton Mass through renormalization

$$W = f_\nu^{i\beta} \bar{N}_i L_\beta H_u$$

$$\mu \frac{d(m_{\tilde{L}}^2)_\alpha{}^\beta}{d\mu} = \left(\mu \frac{d(m_{\tilde{L}}^2)_\alpha{}^\beta}{d\mu} \right)_{\mathrm{MSSM}} (=0)$$

$$+ \frac{1}{16\pi^2} \left[m_{\tilde{L}}^2 f_\nu^\dagger f_\nu + f_\nu^\dagger f_\nu m_{\tilde{L}}^2 + 2 (f_\nu^\dagger m_{\tilde{\nu}}^2 f_\nu + \tilde{m}_{H_u}^2 f_\nu^\dagger f_\nu + A_\nu^\dagger A_\nu) \right]_\alpha{}^\beta$$

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

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

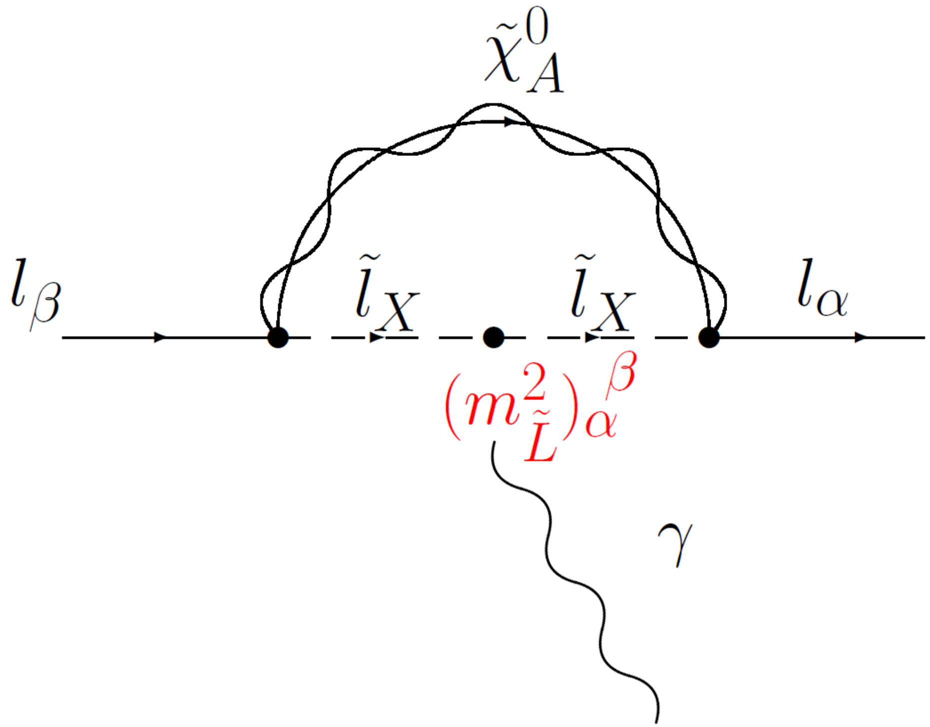
$\tilde{m}_{H_u}^2$ doublet Higgs

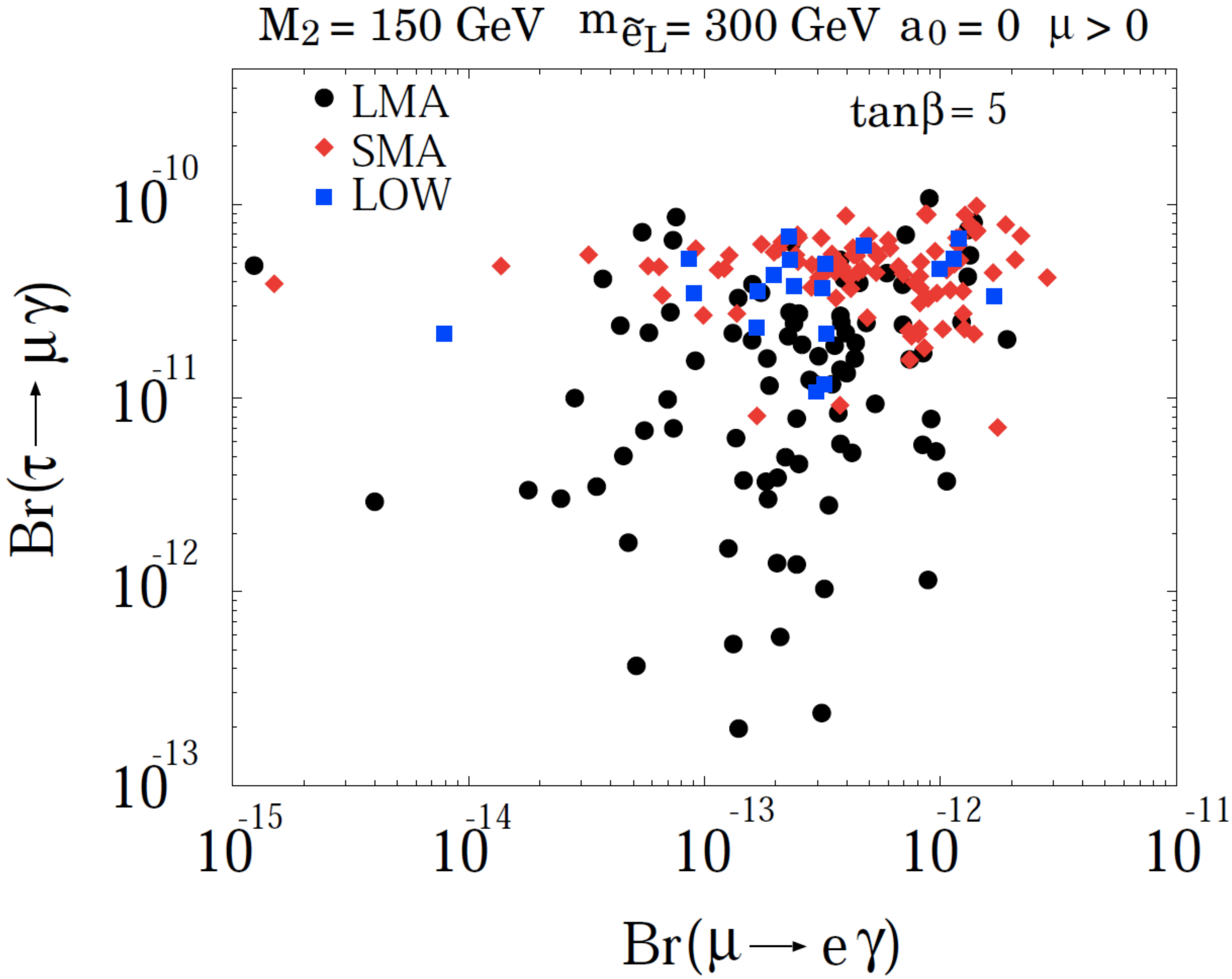
$$V^{Dirac\dagger} f_\nu^{i\beta} U^{Dirac} = \mathrm{diag}(f_{\nu 1}, f_{\nu 2}, f_{\nu 3})$$

Lepton mixing SUSY Breaking Mass

a_0:: universal A term

$$(m^2_{\tilde{L}})_\alpha^{\ \beta} \simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(f_\nu^\dagger f_\nu)_\alpha^{\ \beta}\log\frac{M_G}{M_R}$$
$$\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}U^{Dirac}_{\alpha k}(U^{Dirac*})^{\beta k}|f_{\nu k}|^2\log\frac{M_G}{M_R}$$





Sato, Tobe

Charged Lepton Flavor Violation (cLFV)

Shall we observe soon ?

Neutral Lepton Flavor Violation, nLFV, e.g.

$$\pi \to \mu + \nu_e$$

exists ! ?

Ratio against Weak Interaction : ε

$$\frac{\mathrm{Br}(\pi \to \mu\nu_e)}{\mathrm{Br}(\pi \to \mu\nu_\mu)} = \varepsilon^2$$

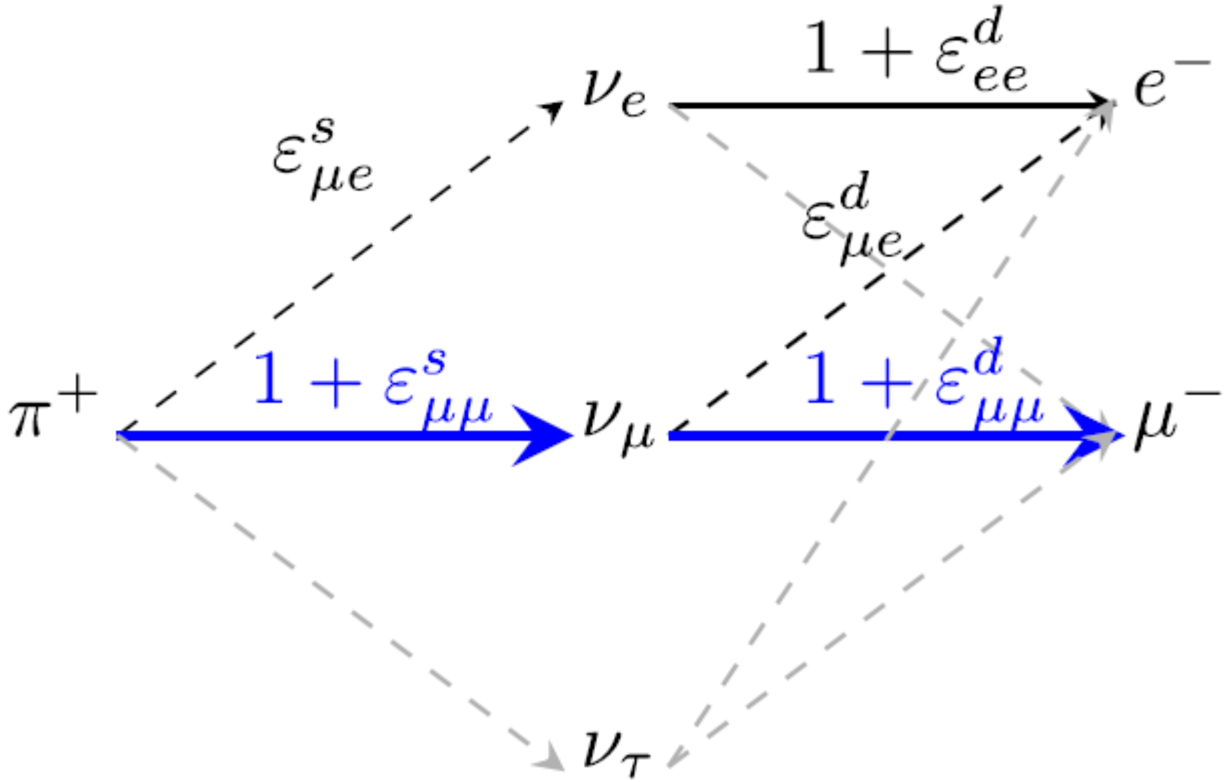
Though this Affects to Universality, only ε^2
since no interference

However,

$$\nu_\mu \to \nu_e$$

Effect on oscillation is ε since it interfere with standard oscillation amplitude

Key idea: flavor state of neutrino is not physical one but intermediate one



We do not observe neutrinos but the phenomenon that

π decays here and an electron is created at the detector

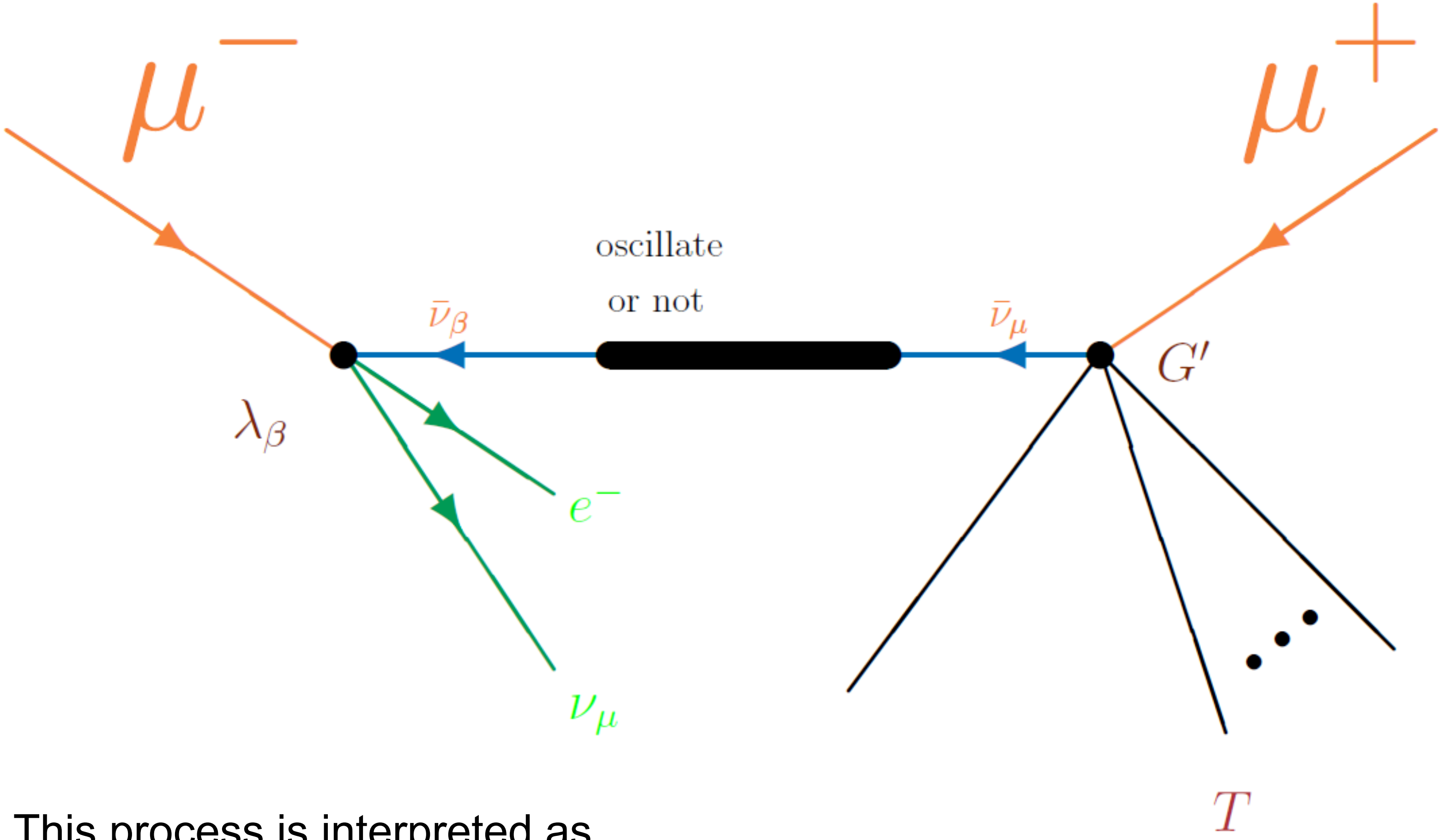
Therefore the oscillation probability is prop to ε

$$|\mathcal{A}(\nu_\mu \to \nu_e) + \mathcal{A}(\nu_e \to \nu_e)|^2 \sim (1+2\varepsilon))|\mathcal{A}(\nu_\mu \to \nu_e)|^2$$

since neutrino is intermediate

Exactly all the physical state must be the same for interference

In Neutrino Factory



This process is interpreted as

$$\nu_e \longrightarrow \nu_\mu$$

Due to interference new physics effect linearly contributes

Formulation

Initial state, s:source

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s |\nu_\beta\rangle$$

$$\sum_{\alpha=e,\mu,\tau} |\nu_\alpha^s\rangle\langle\nu_\alpha^s| \neq 1, \qquad \sum_{\beta=e,\mu,\tau} |\nu_\beta^d\rangle\langle\nu_\beta^d| \neq 1,$$

Final state d:detection

$$\langle\nu_\alpha^s|\nu_\beta^s\rangle \neq \delta_{\alpha\beta}, \qquad \langle\nu_\alpha^d|\nu_\beta^d\rangle \neq \delta_{\alpha\beta}.$$

$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle\nu_\alpha|$$

Not diagonal

Hamiltonian

$$\tilde{V}_{\mathrm{MSW}} = a_{\mathrm{CC}} \begin{pmatrix} 1+\varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ \varepsilon_{e\mu}^{m*} & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{e\tau}^{m*} & \varepsilon_{\mu\tau}^{m*} & \varepsilon_{\tau\tau}^m \end{pmatrix}$$

$$H_{\alpha\beta} = \frac{1}{2E}\left[U_{\alpha j} \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix}_{jk} (U^\dagger)_{k\beta} + (\tilde{V}_{\mathrm{MSW}})_{\alpha\beta} \right]$$

Matter effect also changed

Transition Probability

$$\begin{aligned} P_{\nu_\alpha^s \to \nu_\beta^d} &= |\langle\nu_\beta^d| e^{-iHL} |\nu_\alpha^s\rangle|^2 \\ &= |(1+\varepsilon^d)_{\gamma\beta} (e^{-iHL})_{\gamma\delta} (1+\varepsilon^s)_{\alpha\delta}|^2 \\ &= |[(1+\varepsilon^d)^T e^{-iHL} (1+\varepsilon^s)^T]_{\beta\alpha}|^2, \end{aligned}$$

ε Upper limit on

From Universality $< \mathcal{O}(10^{-3})$

ε : interfere with Weak Interaction

ε^2 : no interference with Weak Interaction

From c LFV SU(2) weak relation !?

$\mu \to e\gamma$ ⇒ $\nu_\mu \leftrightarrow eW$ $(+W\bar{e}\nu_e$ matter effect $\varepsilon^m_{e\mu}$)

$\nu_e \leftrightarrow \mu W$ $(+W\bar{u}d$ $\pi \to \mu + \nu_e)$

$\varepsilon^{s,d}_{\mu e}$

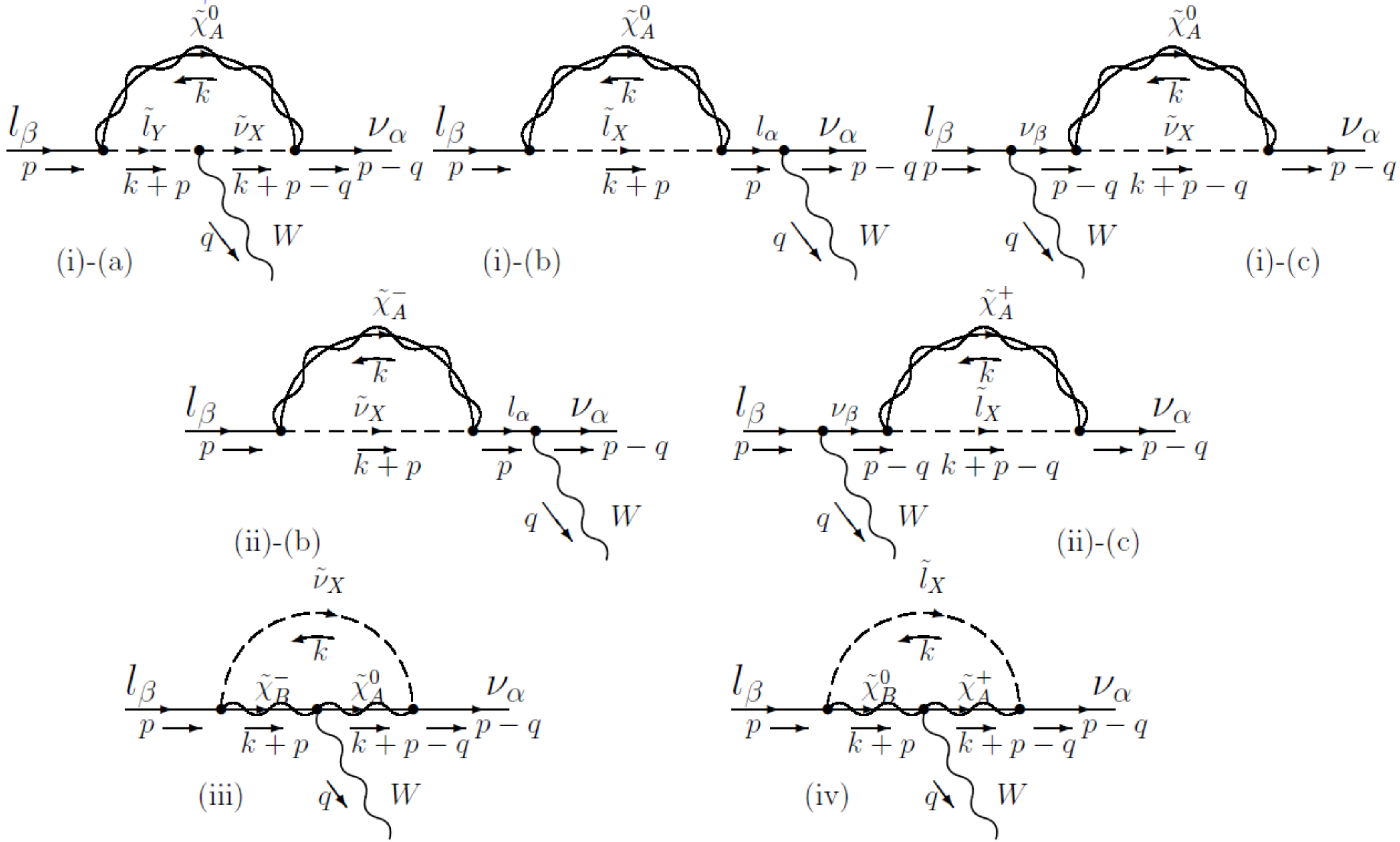
Naively same limit !? ε^2

However, contribution from Box and tree

⇒ Model dependent

MSSM with RH neutrino (Seesaw Model)の例 Ota,Sato

Example of $\epsilon^{s}_{\beta\alpha}$ (Source): W-penguin diagrams

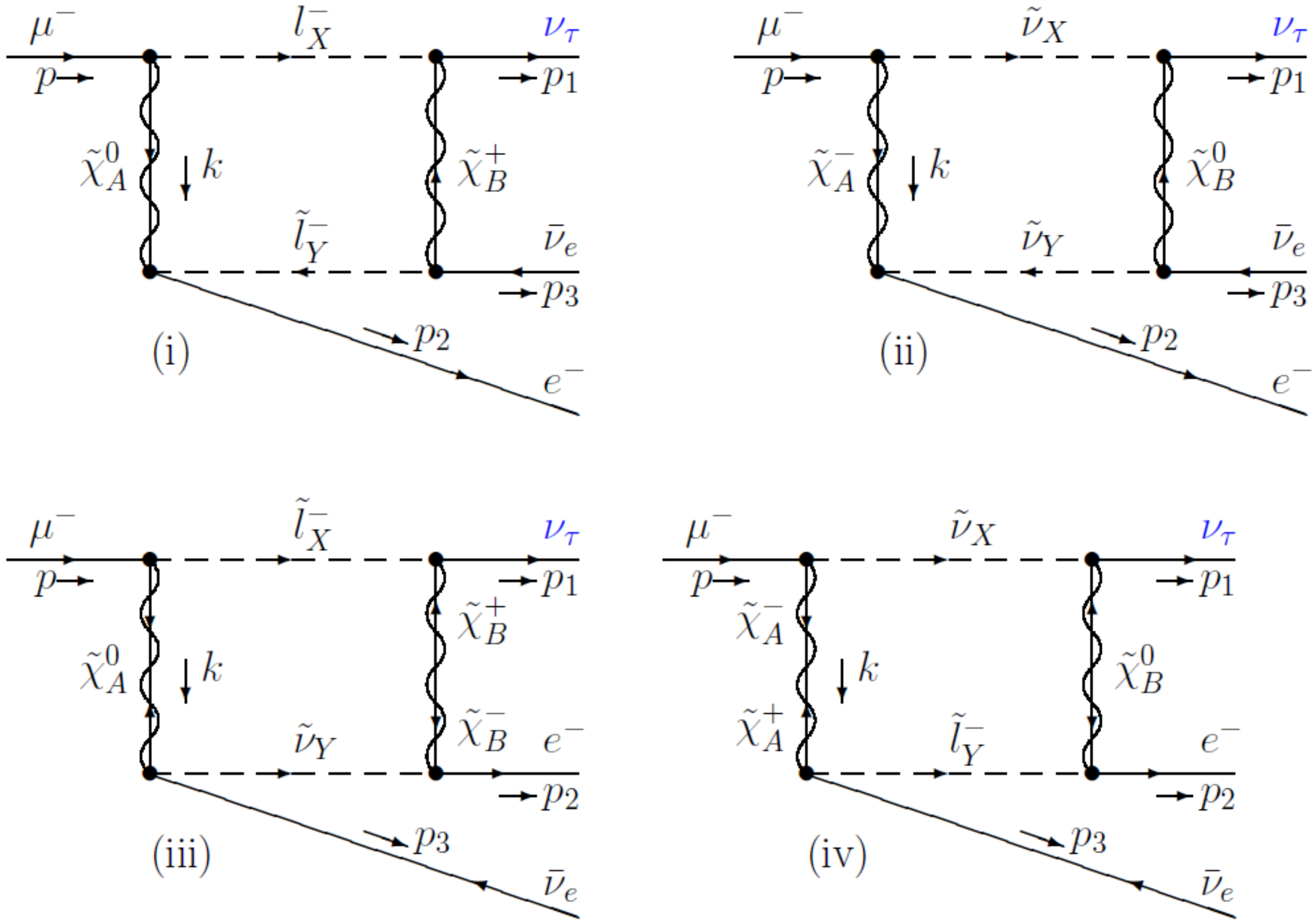


○ $\bar{\nu}_\gamma$ l^-_γ attaced.

○SU(2) limit, Divergence cansels among them

MSSM with RH neutrino (Seesaw Model)の例 Ota,Sato

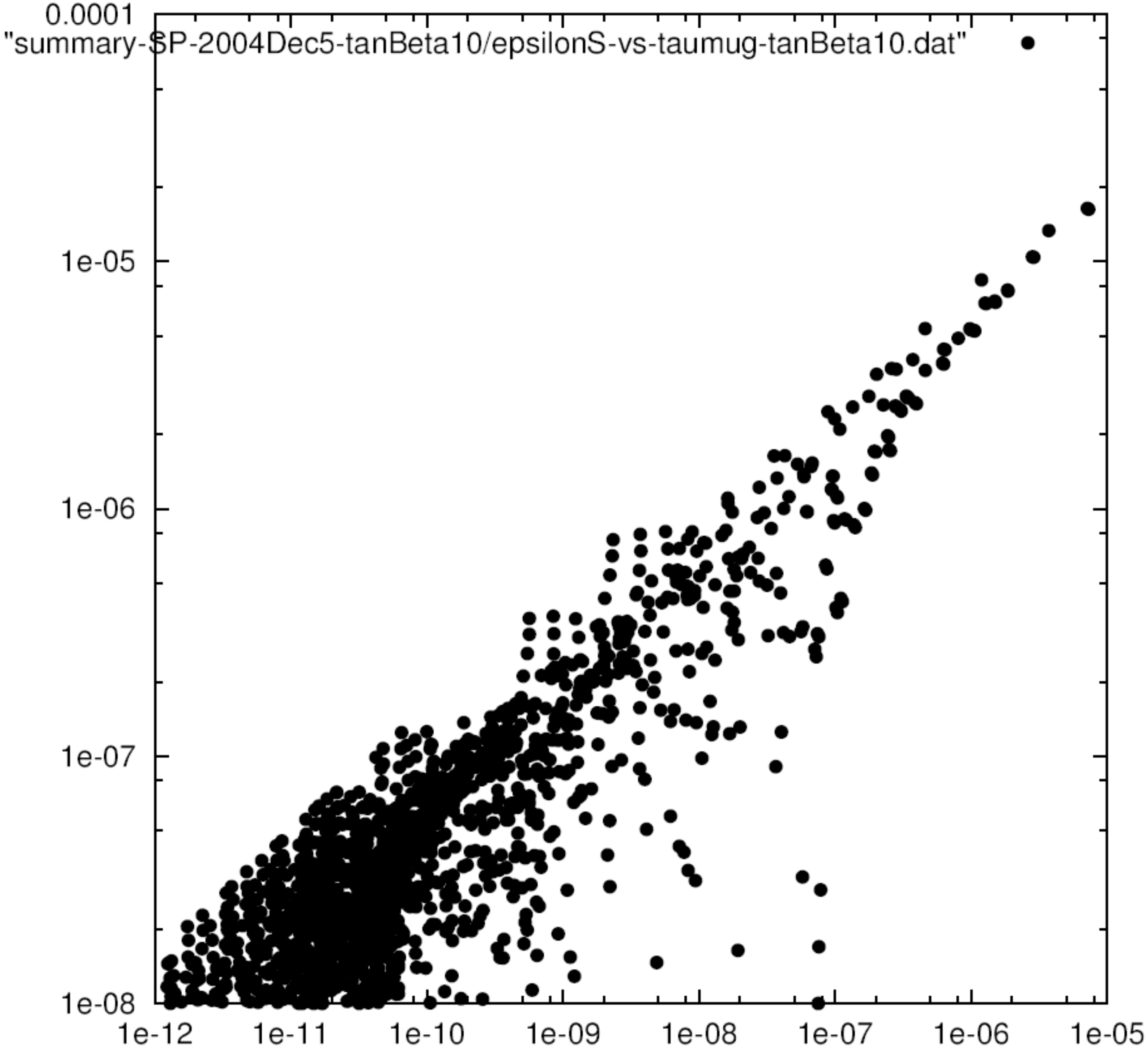
Box diagrams for $\epsilon^s_{\mu\tau}$



- ○ Calculation straightforwad
- ○ For $\epsilon^s_{\mu e}$ there are other graphs.

MSSM with RH neutrino (Seesaw Model)の例

Ota,Sato



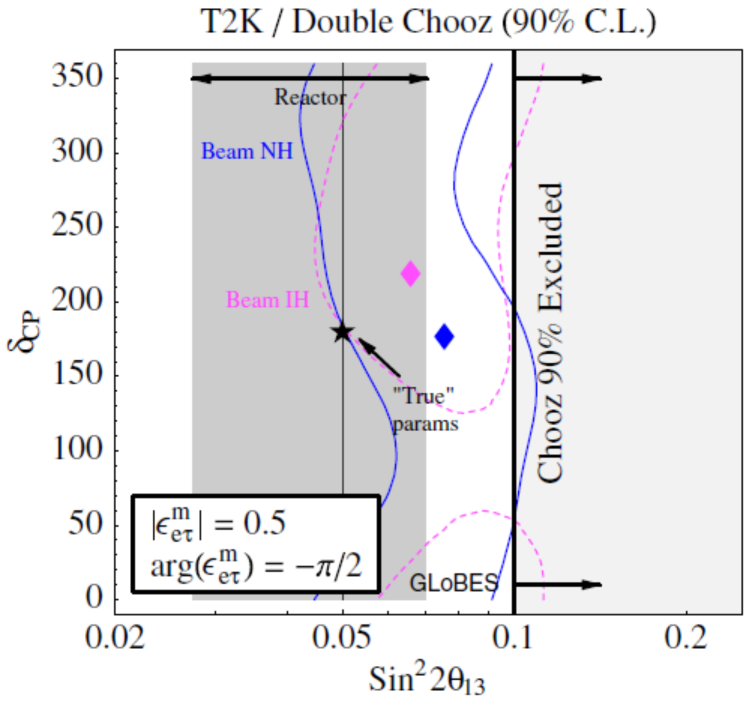
Strong corelation with cLFV

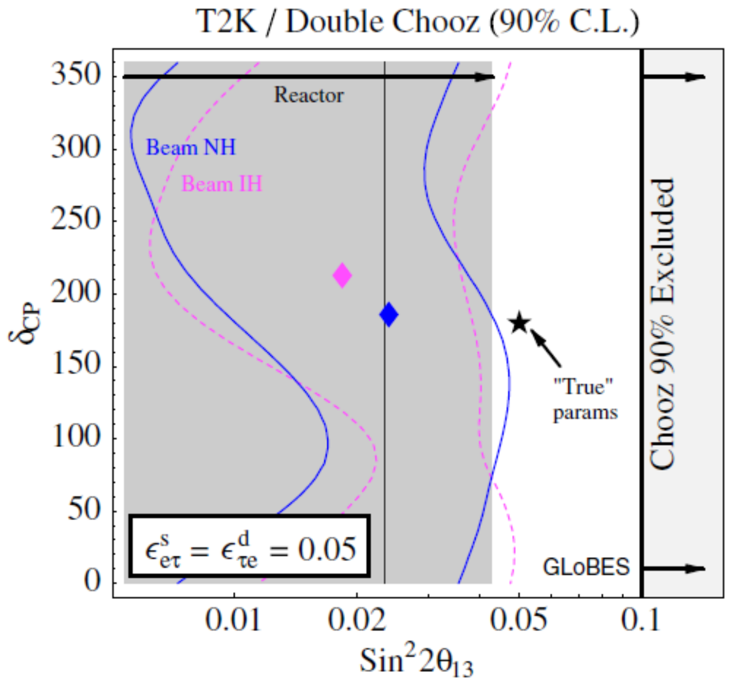
$\mathrm{Br}(\tau \to \mu\gamma)$

Tree contribution bay be large. Then …

If quite large, three generation assumption may cause a contradiction !?
Extreme Examples: Reactor vs Long baseline

KOPP, LINDNER, OTA, AND SATO



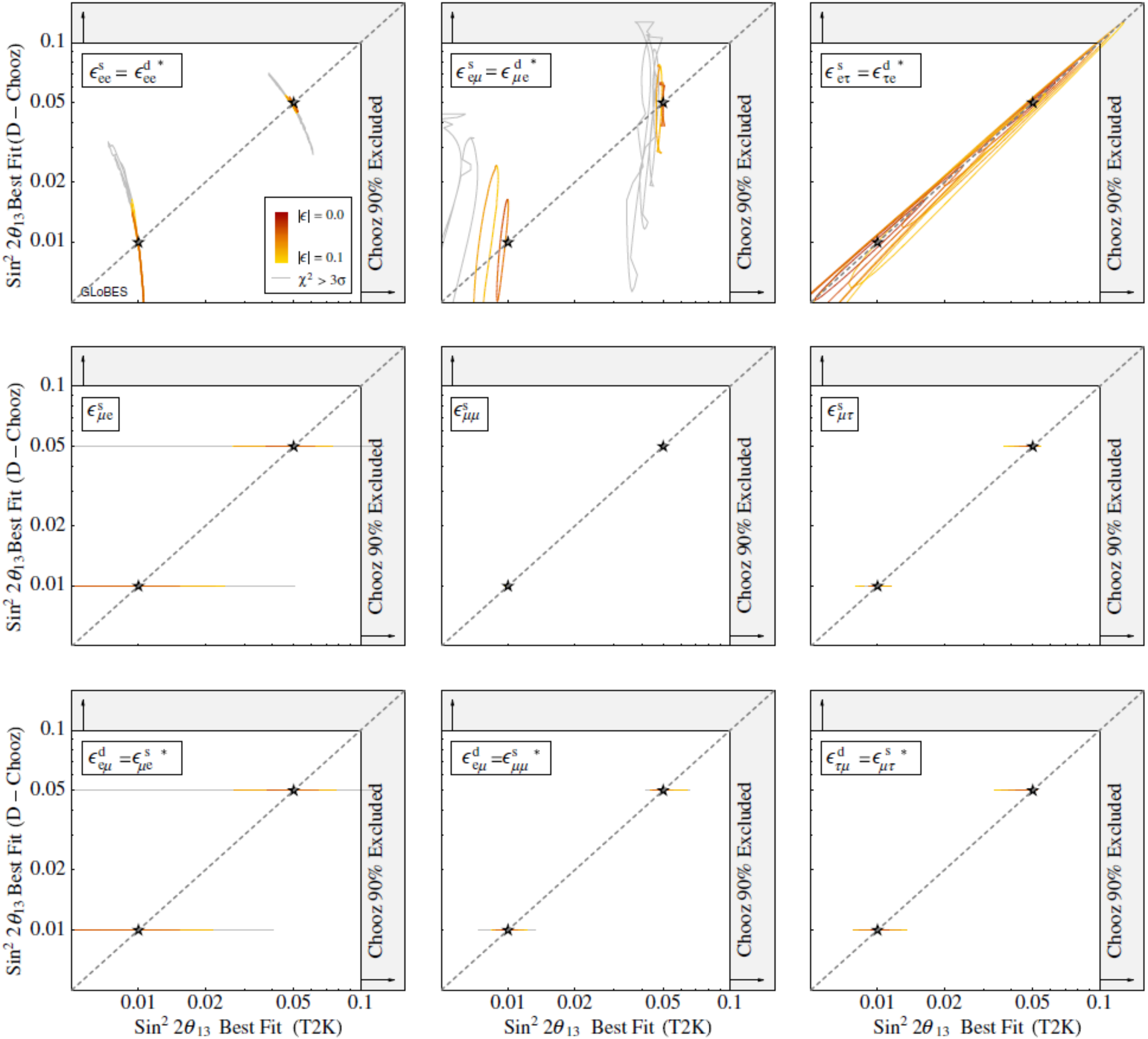


Matter effect only
Long baseline
gives incorrect
value

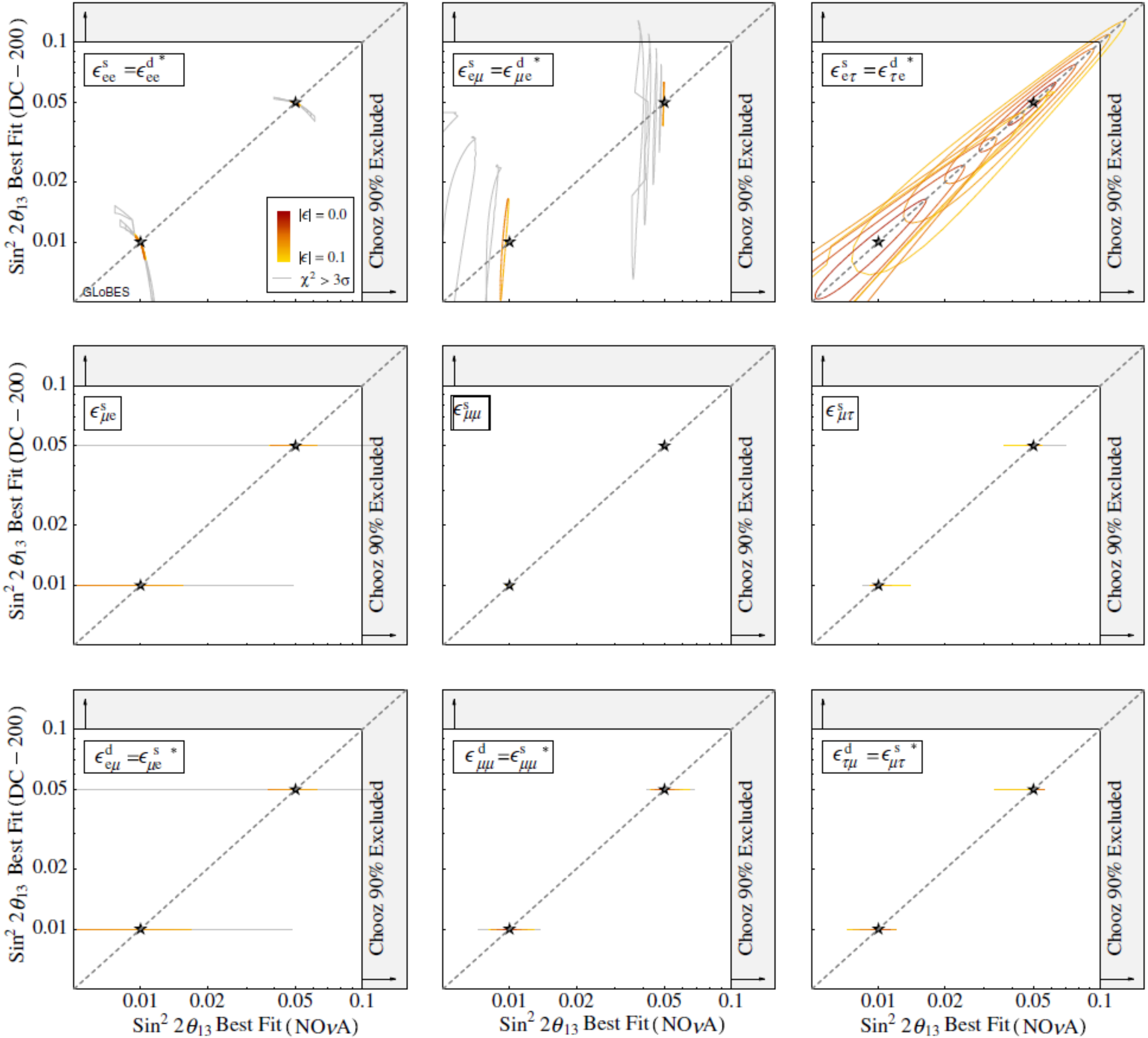
Initial and final
Both give incorrect value

T2K vs Double Choooz

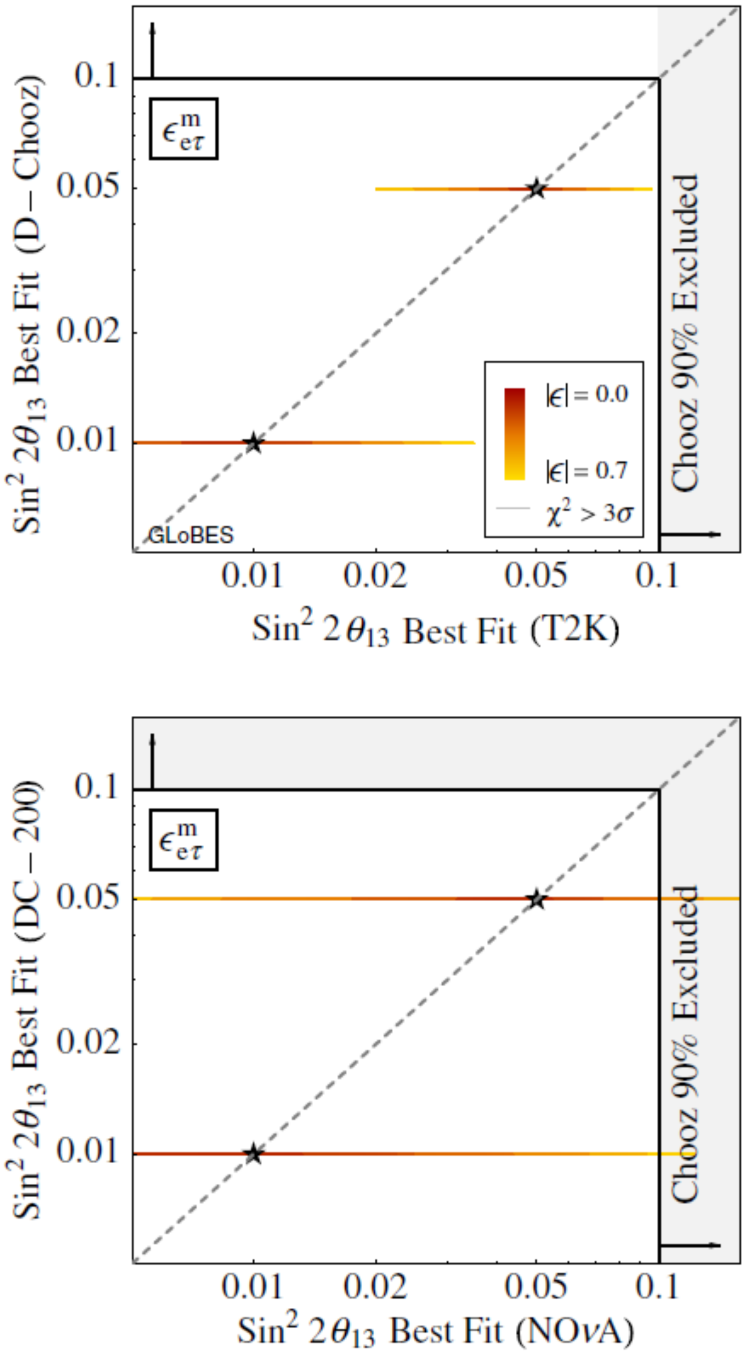
Star : true value

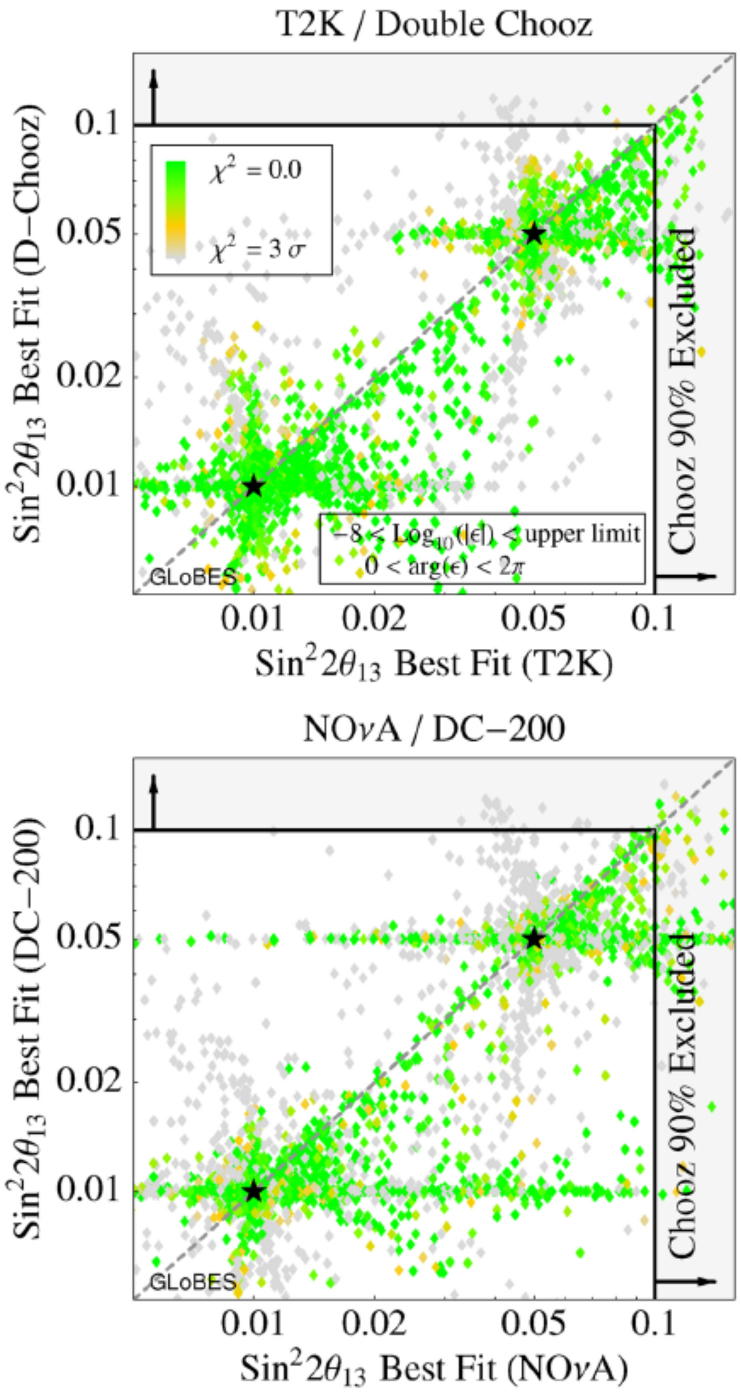


T2K vs NO ν A



$\epsilon^{s}_{ee} = \epsilon^{d\,*}_{ee}$
$\epsilon^{s}_{e\mu} = \epsilon^{d\,*}_{\mu e}$
$\epsilon^{s}_{e\tau} = \epsilon^{d\,*}_{\tau e}$
$\epsilon^{s}_{\mu e}$
$\epsilon^{s}_{\mu\mu}$
$\epsilon^{s}_{\mu\tau}$
$\epsilon^{d}_{e\mu} = \epsilon^{s\,*}_{\mu e}$
$\epsilon^{d}_{\mu\mu} = \epsilon^{s\,*}_{\mu\mu}$
$\epsilon^{d}_{\tau\mu} = \epsilon^{s\,*}_{\mu\tau}$
$|\epsilon| = 0.0$
$|\epsilon| = 0.1$
$\chi^2 > 3\sigma$
GLoBES
Chooz 90% Excluded
$\mathrm{Sin}^2\, 2\theta_{13}$ Best Fit (DC − 200)
$\mathrm{Sin}^2\, 2\theta_{13}$ Best Fit (NOνA)
0.01
0.02
0.05
0.1



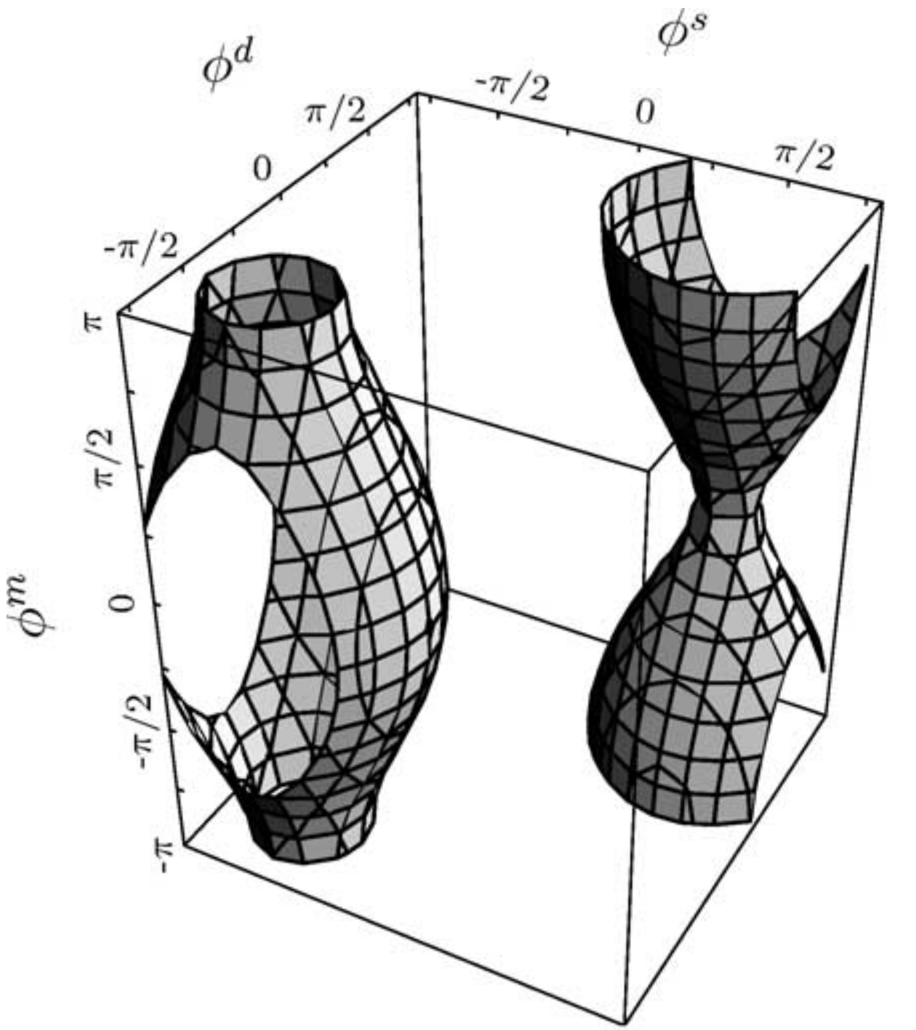


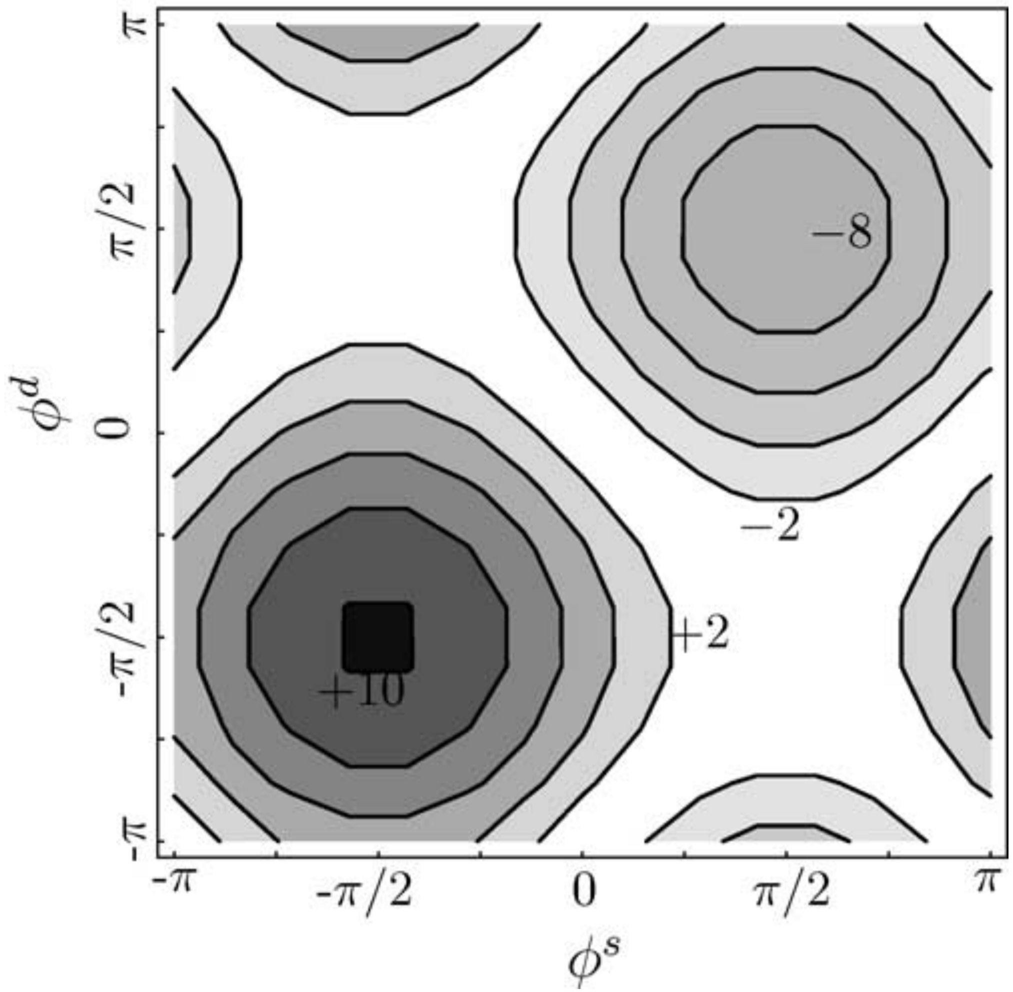
Matter Effect

Randomly generated NSIs

OPERA and ICARUS

T. Ota, J. Sato





Parameters in vase gives different appearance event number from the expectation

$|\epsilon_{\mu\tau}^{s,m,d}|$ are assumed to be 0.01

⟺ 「Contradiction」 with other experiments

Another view point

Too many NSI parameters

Which one is really necessary?
How to define goodness of fit?

Fit with assumption of three generation is not good

MNS matrix is unitary？
12 parameters（=18－1－3－2） in MNS

To know New physics, first we should check if the MNS is unitary！

is it！？

Oscillation probability $P(\nu_\alpha \to \nu_\beta)$ for $E \sim$ O(100) MeV and $L \sim$ O(100) Km

$\delta m_{ij}^2 = m_i^2 - m_j^2$	mass square difference
E	Neutrino energy
L	Distance
$\Delta_{ij} = \frac{\delta m_{ij}^2}{2E} L$	phase of oscillation
$J \equiv \mathrm{Im}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*)$	Jarlskog Parameter (CP measure)

$$
\begin{aligned}
& P(\nu_\mu \to \nu_e) \\
= \; & 4|U_{e3}U_{\mu 3}|^2 \sin^2 \frac{\Delta_{31}}{2} \\
+ \; & 4\mathrm{Re}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) + \frac{\delta m_{21}^2}{\delta m_{31}^2} \Delta_{31} \sin \Delta_{31} \\
- \; & 4\mathrm{Im}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) + \frac{\delta m_{21}^2}{\delta m_{31}^2} \Delta_{31} \sin^2 \frac{\Delta_{31}}{2} \\
- \; & 4\mathrm{Re}(U_{e2}^* U_{\mu 2} U_{e1} U_{\mu 1}^*) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2} \right)^2 \left(\frac{\Delta_{31}^2}{2} \right)^2
\end{aligned}
$$

CPV

$$
\begin{aligned}
\equiv \; & A \sin^2 \frac{\Delta_{31}}{2} \\
+ \; & \frac{B}{2} \Delta_{31} \sin \Delta_{31} \\
+ \; & C \Delta_{31} \sin^2 \frac{\Delta_{31}}{2} \\
+ \; & D \left(\frac{\Delta_{31}^2}{2} \right)^2
\end{aligned}
$$

Up to the leading(second) order of small values,

U_{e3} and $\frac{\delta m_{21}^2}{\delta m_{31}^2}$.

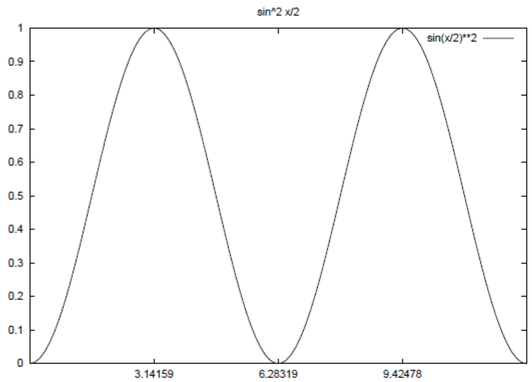
If necessary we should include matter effect

Base function

$$\sin^2\frac{\Delta_{31}}{2},\ \ \Delta_{31}\sin\Delta_{31},\ \ \Delta_{31}\sin^2\frac{\Delta_{31}}{2},\ \ \Delta_{31}^2$$

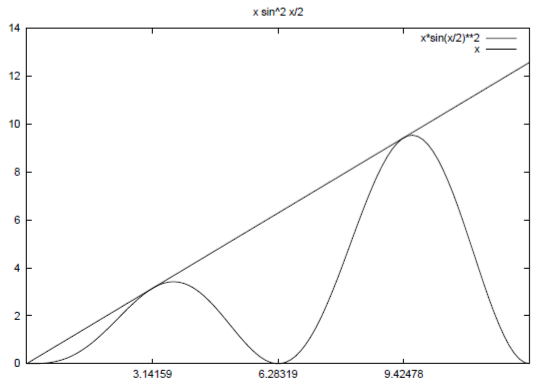
Independent though not diagonal

$\sin^2\frac{\Delta_{31}}{2}$



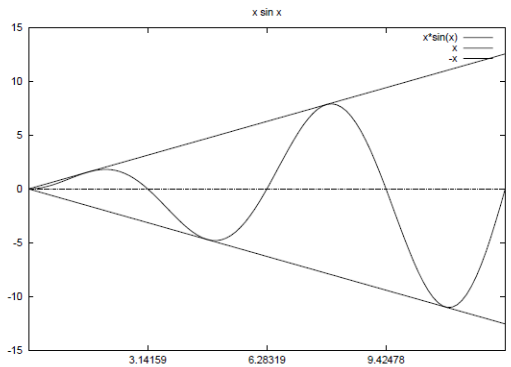
Δ_{31}

$\Delta_{31}\sin^2\frac{\Delta_{31}}{2}$



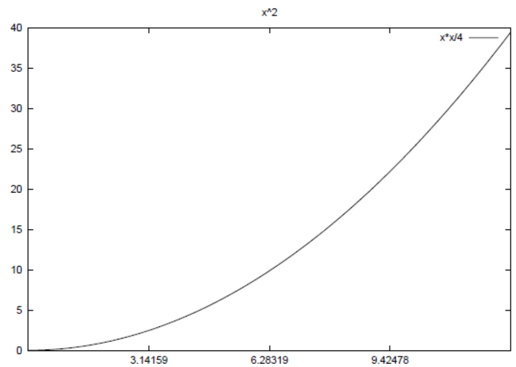
Δ_{31}

$\sin^2\Delta_{31}$



Δ_{31}

Δ_{31}^2



Δ_{31}

Find a value of those coefficients without assumptions of three generation, unitarity etc.

The check if the following holds

$$4AD = B^2 + C^2$$

Required from the unitarity of MNS.
Indeed it is a relation of unitary triangle

Summary

Now We can discuss Appearance events

New Physics Search is within a scope !?
With your model ,calculate ε 's !
Oscillation experiment may check your model faster than LHC !???