Signature of the Minimal Supersymmetric Standard Model with Right-Handed Neutrinos in Long Baseline Experiments

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(TUM/Saitama)

Based on T. Ota and J.S Phys. Rev. D 71, 096004, 2005

1 Introduction

- Solar neutrino, Atmospheric neutrino, Reactor neutrino
  - ◇ Massive Neutrinos
  - ◇ Lepton Mixing

- Massive Neutrino

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

- Lepton Mixing

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

  and/or $\cdots$

$$\Downarrow$$

Large Lepton Flavor Violating Process in Our World !?

- Yes, MSSM with Seesaw (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

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

$$\mu \frac{d(m_{\tilde{L}}^2)_\alpha^{\ \beta}}{d\mu} = \left(\mu \frac{d(m_{\tilde{L}}^2)_\alpha^{\ \beta}}{d\mu} \right)_{\text{MSSM}} (= 0)$$
$$+ \frac{1}{16\pi^2} \left[m_{\tilde{L}}^2 f_\nu^\dagger f_\nu + f_\nu^\dagger f_\nu m_{\tilde{L}}^2 + 2 (f_\nu^\dagger m_{\tilde{\nu}}^2 f_\nu + \tilde{m}_{H_u}^2 f_\nu^\dagger f_\nu + A_\nu^\dagger A_\nu) \right]_\alpha^{\ \beta}$$

SUSY breaking $m_{\tilde{L}}^2$ scalor lepton doublet
$m_{\tilde{\nu}}^2$ right-handed sneutrino
$\tilde{m}_{H_u}^2$ doublet Higgs

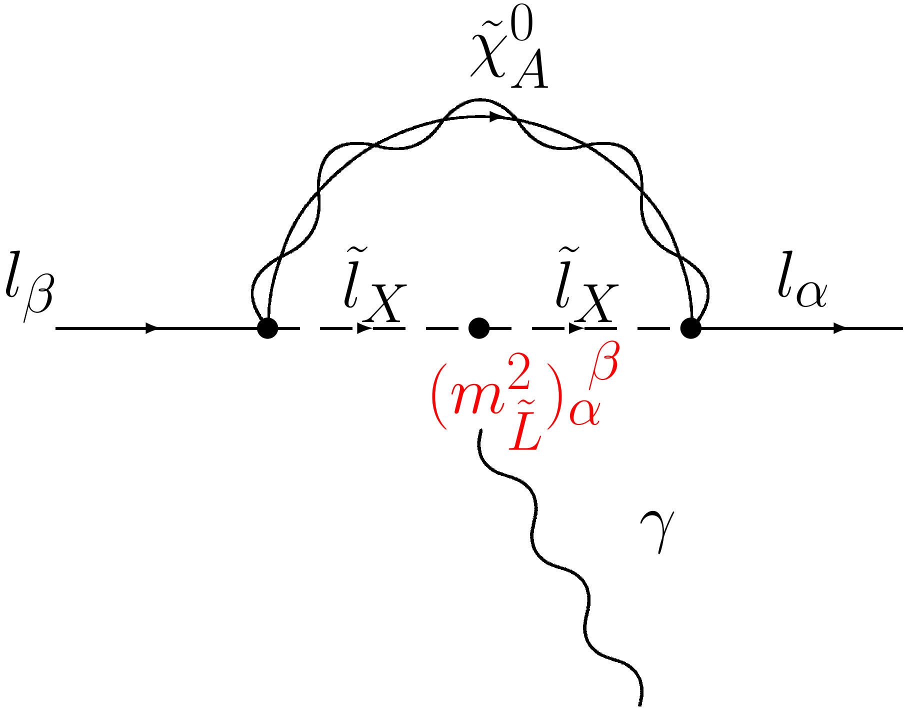
$$V^{Dirac\dagger} f_\nu^{i\beta} U^{Dirac} = \mathrm{diag}(f_{\nu 1}, f_{\nu 2}, f_{\nu 3})$$

Approximately (a_0:: universal A term)

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

$$\Downarrow$$

LFV in the charged-lepton

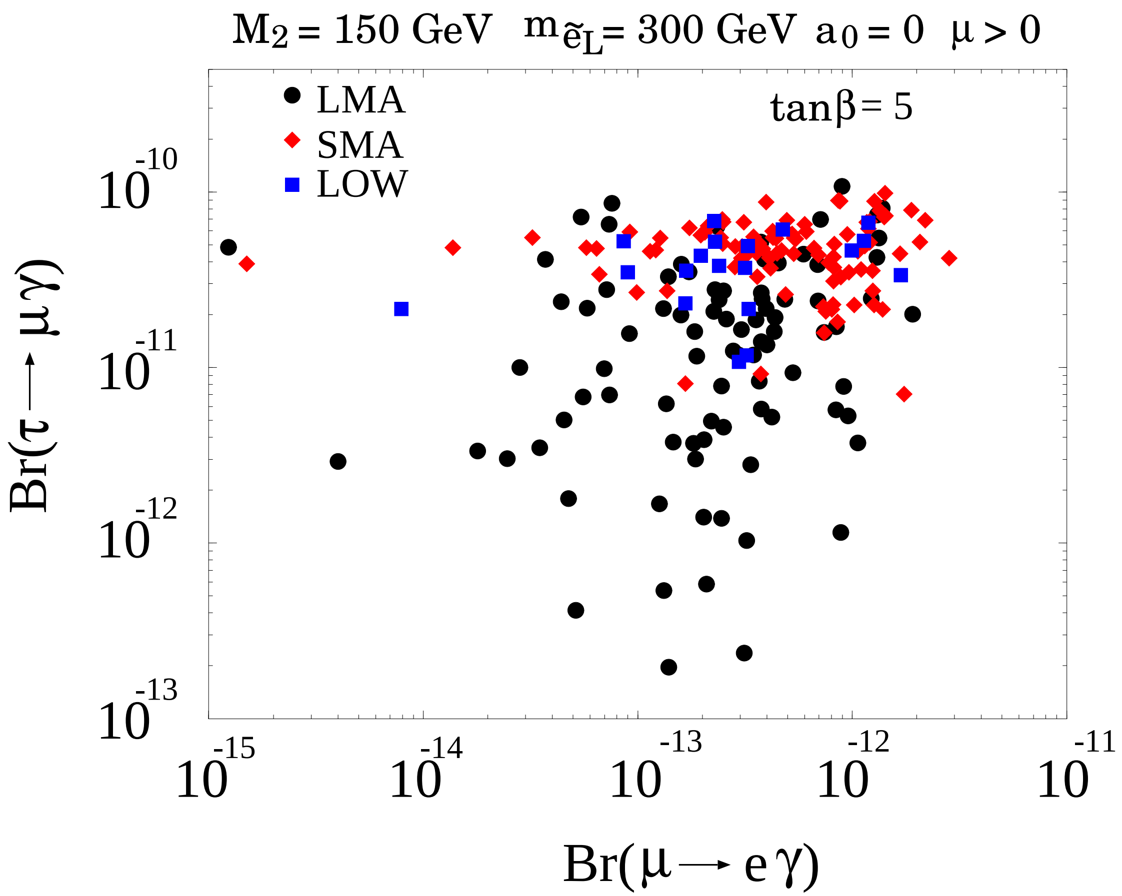


$$\tau \to \mu\gamma \Leftrightarrow (\Delta m^2_{\tilde{L}})_\mu{}^\tau$$

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

Example of Branching Ratio

J.S and K. Tobe



In near future

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

2. New Physics in Neutrino Oscillation Experiments

Quest for LFV

- ○ Precision measurement in (near) future (within 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	$\delta \sim 20°$

- ○ 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 Parametrization

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

Devide into three processes :

Decay (Production), Propagation, Detection

∘ New Physics in Decay

If the type of interaction is same $\Longrightarrow$ Initial State = Flavor Mixed State

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,

Complicated Energy Dependence and Extra Suppression Factor

‘Physical States” (Particle species, helicity, energy, etc.) must be same for interference.

e.g.

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

gives distinctive energy dependence. Careful treatment is required.

“Transition probability” for $\bar{\nu}_e \to \bar{\nu}_\mu$ is replaced

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

Tiny Interference

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

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

- New Physics in Matter ⟹ 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. Yamashita
  - ◇ In Principle, Need to Consider Parton Distribution

    Could be Qurak-Flavor Dependent

    e.g. New Physics Sensitive to s-quark

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

⇒ extra energy dependence

  - ◇ Dependence on Interaction Type

    ⟹ Almost no Interference with (V-A)(V+A)

◇ Simple Treatment for (V-A)(V-A), *i.e.* Flavor Mixed State

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

2.2 Classification of New Physics and Constraints

◇The new interaction can be categorized into **3 types**.

▶singlet mediation

$(V-A)(V-A)$ interaction

e.g. $\tilde{l}_{\rm R}$ in $\not{R}_p$ model

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

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

◇ No $SU(2)_L$ counter part ◇ No constraint from charged lepton part

▶doublet mediation

$(V-A)(V+A)$ interaction

e.g. $\tilde{l}_{\rm L}$ in $\not{R}_p$ model

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

◇ Different polarization dependence with the standard one, ◇$SU(2)_L$ counter parts.

▶triplet mediation

$(V-A)(V-A)$ interaction

e.g. box with $\tilde{\chi}$, $\tilde{l}_L$ in SUSY

$$g_{\alpha\beta\gamma\delta}(\bar{l}_\alpha\tau^a C\bar{l}_\beta)(l_\gamma C^\dagger\tau^a l_\delta) = -\frac{1}{2}g_{\alpha\beta\gamma\delta}(\bar{l}_\alpha\tau^a\gamma^\mu l_\delta)(\bar{l}_\beta\tau^a\gamma_\mu l_\gamma) \qquad g_{\alpha\beta\gamma\delta} = g_{\beta\alpha\gamma\delta} = g_{\rho\sigma\delta\gamma}.$$

$$= g_{\alpha\beta\gamma\delta}\left\{(\bar{e}_{\alpha L}C\bar{\nu}_{\beta L} + \bar{\nu}_{\alpha L}C\bar{e}_{\beta L})(e_{\gamma L}C^\dagger\nu_{\delta L} + \nu_{\gamma L}C^\dagger e_{\delta L}) + 2(\bar{\nu}_{\alpha L}C\bar{\nu}_{\beta L})(\nu_{\gamma L}C^\dagger\nu_{\delta L}) + 2(\bar{e}_{\alpha L}C\bar{e}_{\beta L})(e_{\gamma L}C^\dagger e_{\delta L})\right\},$$

◇ $SU(2)_L$ counter part

- Model Independent Constraint on ϵ's

From SU(2) Inverted Process Bergman and Grossmann

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

$$\Longrightarrow \quad \epsilon^s_{e\tau} \lesssim 3.1 \times 10^{-3}, \quad \epsilon^s_{e\mu} \lesssim 5 \times 10^{-5}, \quad \epsilon^s_{\mu\tau} \lesssim 3.2 \times 10^{-3}.$$

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

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

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

2.3 Sensitivity:

★For $(V-A)(V-A)$ interaction type

■In $\nu_\alpha \to \nu_\beta$, 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 $\epsilon \gtrsim \mathcal{O}(10^{-4})$.

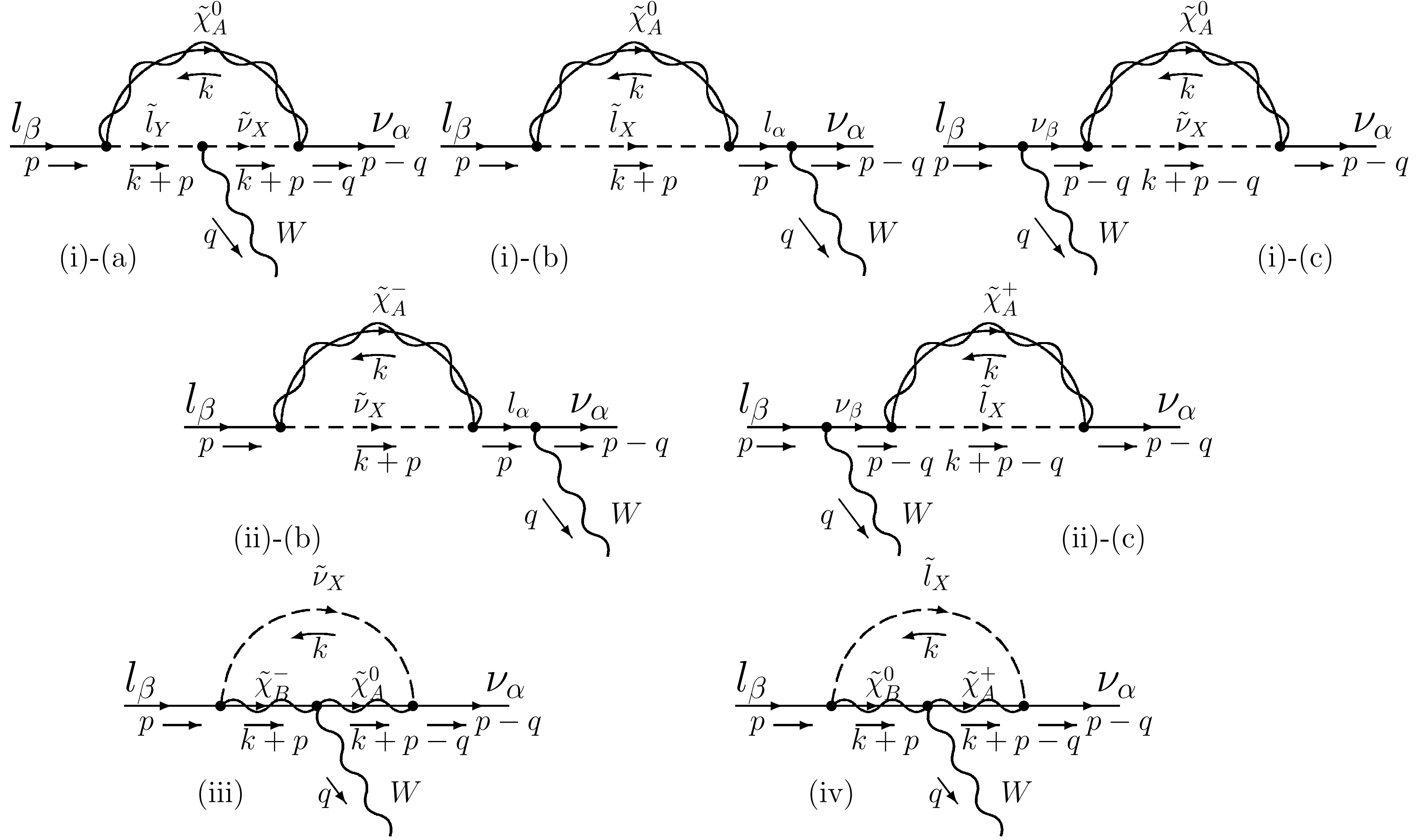
	$\epsilon^{s,m}_{e\mu}$ $(\epsilon^{s}_{\mu e})$	$\epsilon^{s,m}_{e\tau}$	$\epsilon^{s,m}_{\mu\tau}$
$\nu_e \to \nu_\mu$	△	△	×
$\nu_\mu \to \nu_\mu$	×	×	○
$\nu_e \to \nu_\tau$	×	○	△
$\nu_\mu \to \nu_\tau$	×	△	○
$\nu_\mu \to \nu_e$	△	×	×
$\nu_e \to \nu_e$	×	×	×

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

★ Sensitive new physics are different in Nufact and in Conventional Beam.
→ Comparison is important!!

3 LFV Effect in MSSM with Right-Handed Neutrinos

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



(i)-(a) (i)-(b) (i)-(c)

(ii)-(b) (ii)-(c)

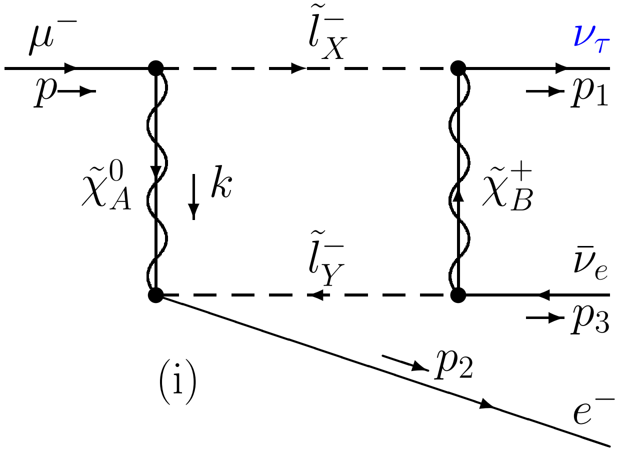
(iii) (iv)

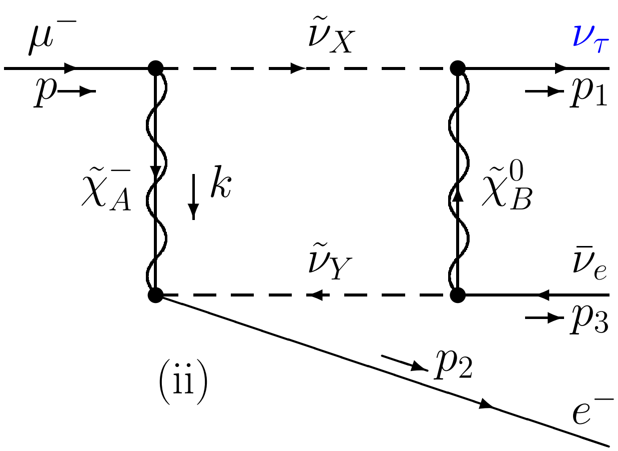
○ $\bar{\nu}_\gamma \; l^-_\gamma$ attaced.

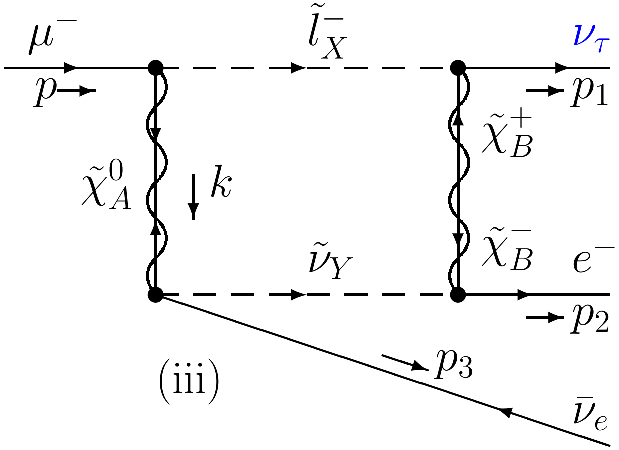
○SU(2) limit, Divergence cansels among them

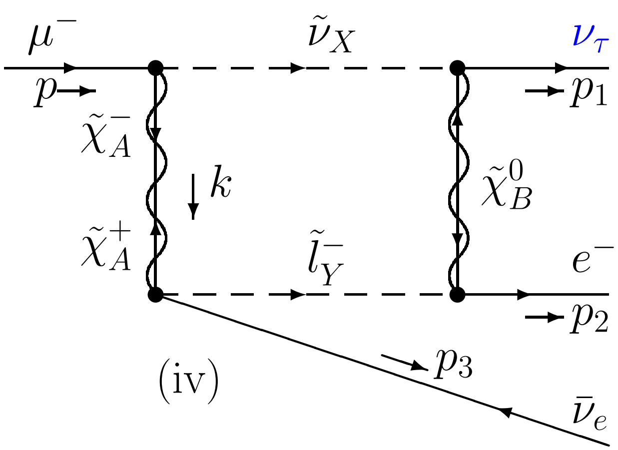
○ $\mathcal{L} = F(q^2)\bar{\nu_\alpha}\gamma^\mu l_\beta l_\gamma \gamma_\mu \nu_\gamma,\;\; F(q^2) = \mathrm{C} + Aq^2$, C vanishes in SU(2) limit

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





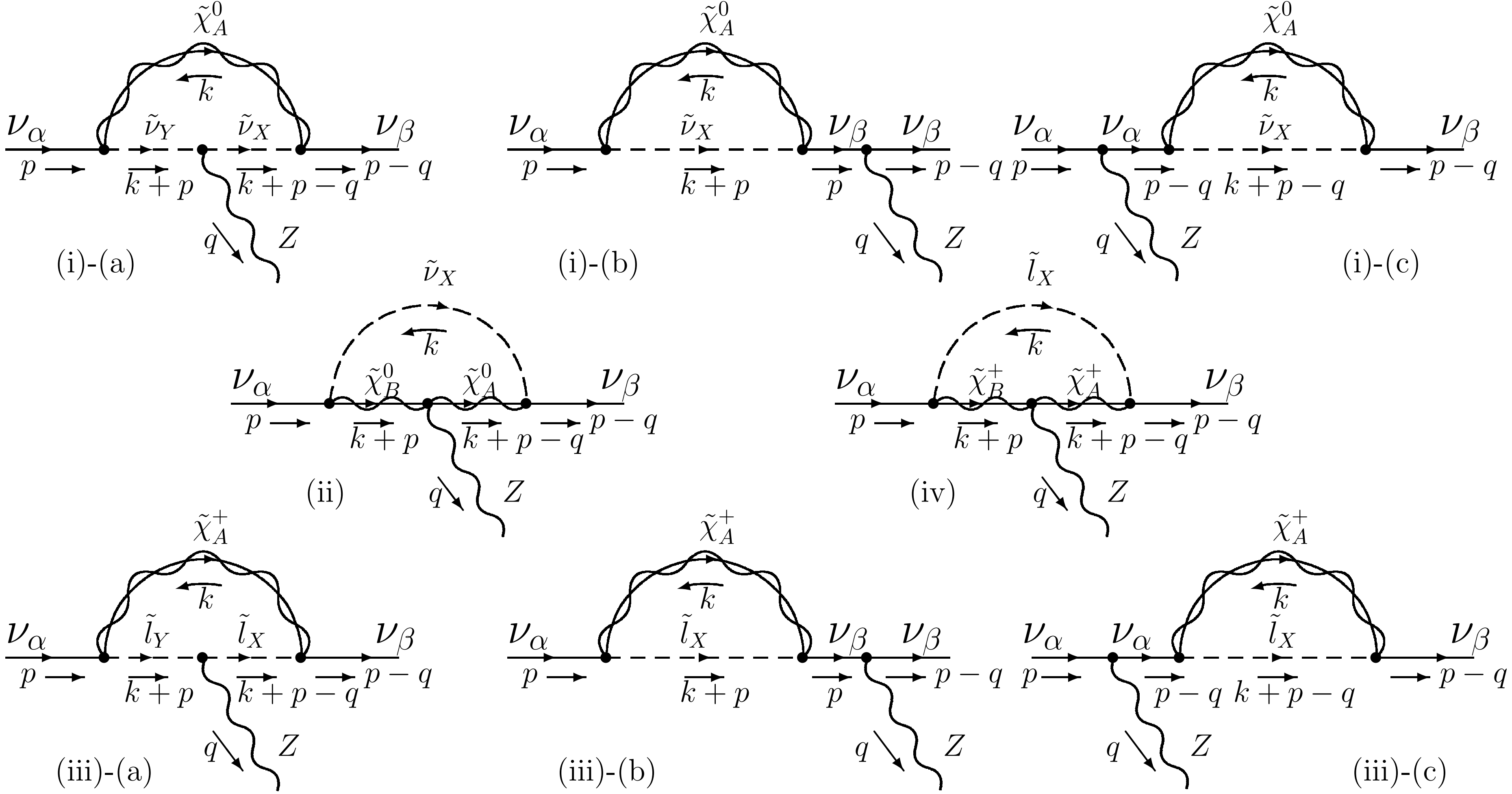




○ Calculation straightforwad

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

Examples of $\epsilon^m_{\beta\alpha}$ (Matter Effect): Z-Penguin diagrams



○$\bar{e}e, \bar{u}u, \bar{d}d$ attaced.

○ SU(2) limit, Divergence cansels among them

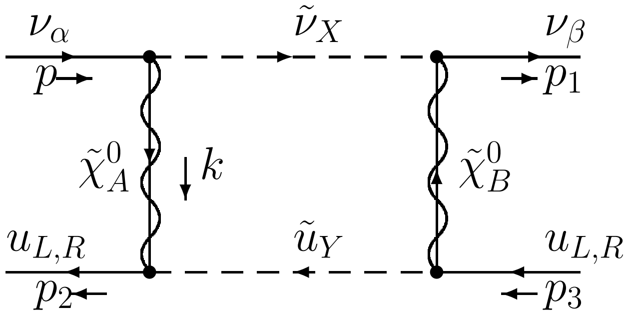
○$\mathcal{L} = G(q^2)\bar{\nu_\beta}\gamma^\mu l \nu_\alpha Z_\mu$, $G(q^2) =$ C' $+A'q^2$, C' vanishes in SU(2) limit

○ To calculate the real rate, (i)-(b) and (iii)-(b) should be omitted —> later discussion

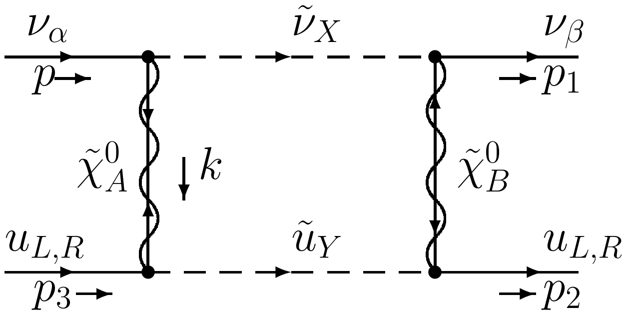
- No photon penguin contribution due to neutrality of matter

Box diagrams for $\epsilon^{m}_{\beta\alpha}$

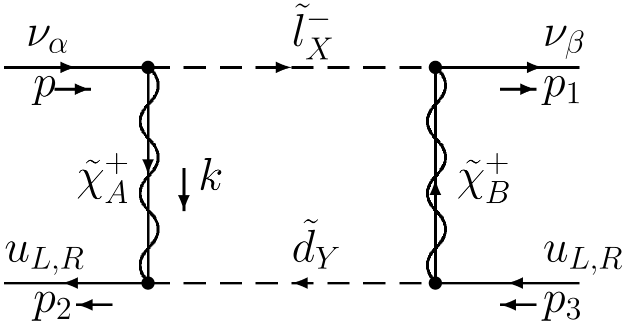
For up-type quark



$(\text{i})_{L,R}$



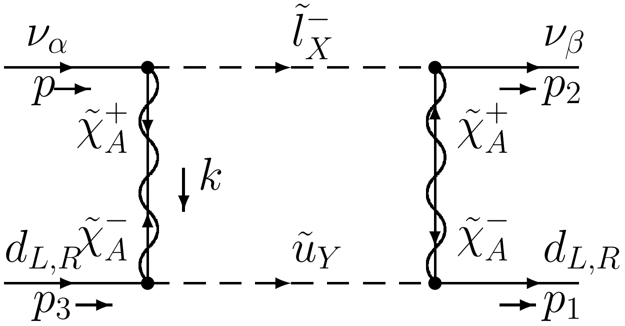
$(\text{ii})_{L,R}$



$(\text{iii})_{L,R}$

For down-type quark

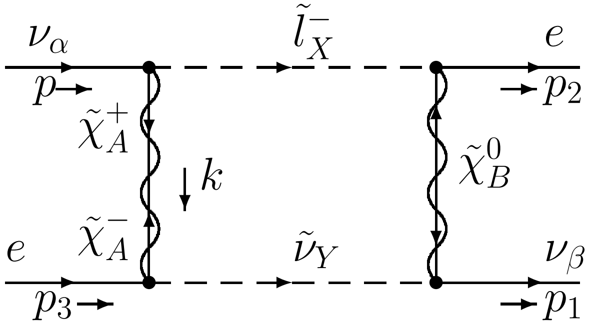
- Neutralino contribution :: same as those for the up-type quark (i) & (ii).
- Chargino cntribution :: slightly different from that for the up-type quark.



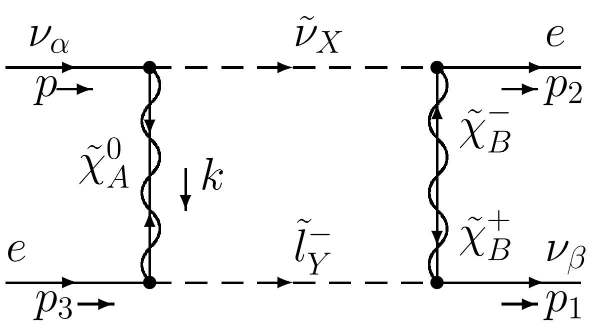
(iii’)

For electron

Two more diagrams in addition to (i), (ii), and (iii')



(iv)

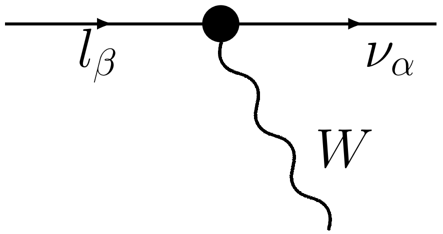


(v)

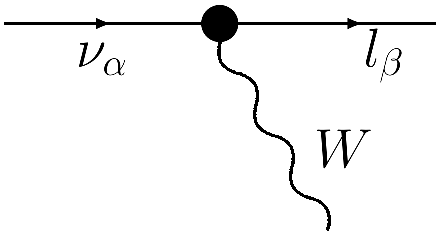
○ For$\alpha = \mu$, $\beta = \tau$, (iv) and (v) :: negligibly small

Examples of $\epsilon^d_{\alpha\beta}$ (Detection) : W-penguin diagrams

Naively,



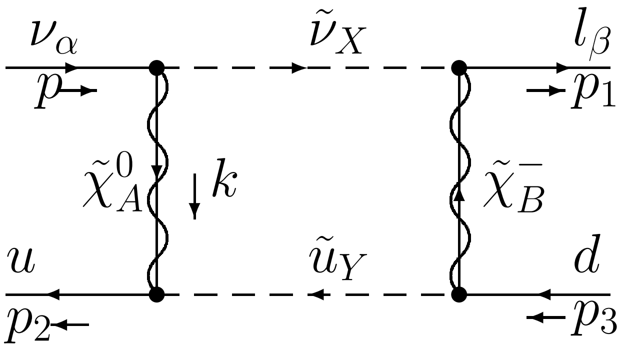
$= \mathrm{i}\epsilon^s_{\beta\alpha} G_F$



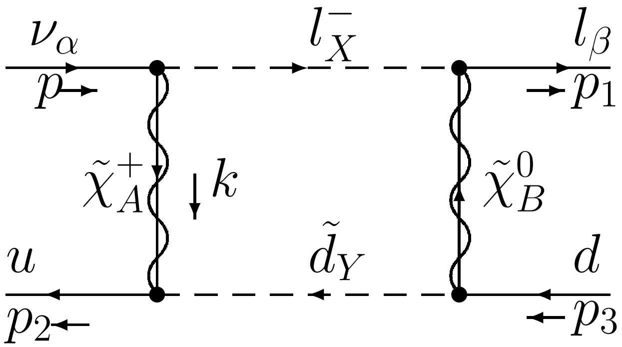
$= \mathrm{i}\epsilon^d_{\alpha\beta} G_F = \mathrm{i}\epsilon^{s*}_{\beta\alpha} G_F$

However, to calculate the rate some graphs should be omitted —> later discussion

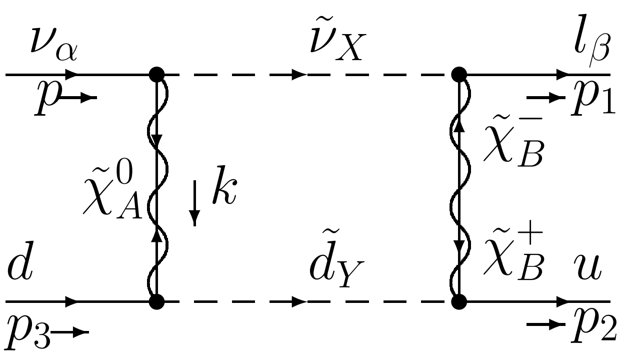
Box diagrams for $\epsilon^{d}_{\alpha\beta}$



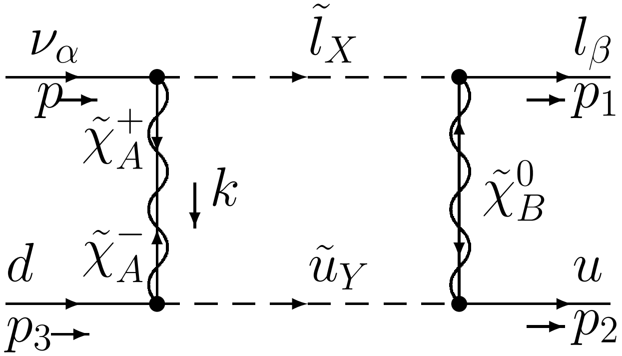
(i)



(ii)



(iii)



(iv)

To calculate the rate, we have pay attention to

(1) Off-shell neutrino
(2) Double counting

(1) Off-shell

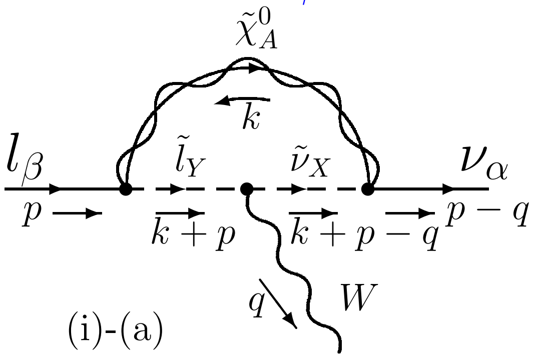
- How to understand the "Off shell amplitude"?

Note that all diagrams for ϵ's have off shell neutrino external lines.
since for oscillation, from uncertainty principle,

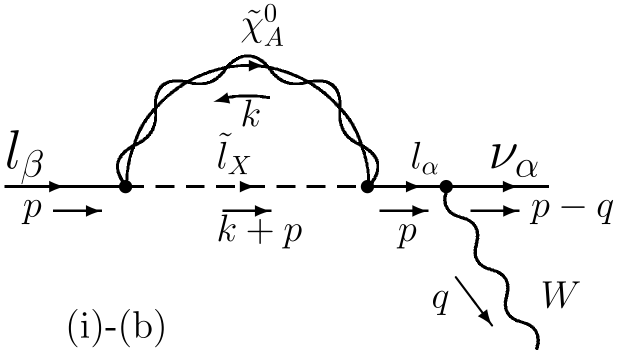
$$\delta p \sim \frac{1}{\delta x} >> \frac{1}{L} \sim \frac{\Delta m^2}{p}$$
$$\Longrightarrow \delta p^2 >> \Delta m^2 \qquad (< p^2 >>> m^2)$$

For neutrino internal line we should treat neutrinos as massless.

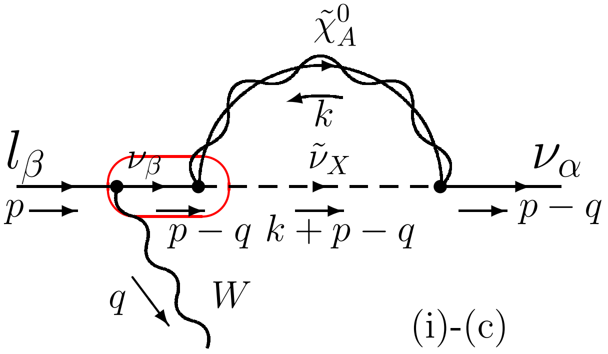
Example of $\epsilon^{s}_{\beta\alpha}$ (Source): W-penguin diagrams



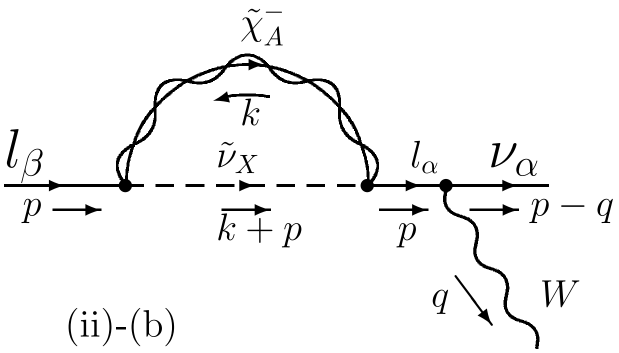
(i)-(a)



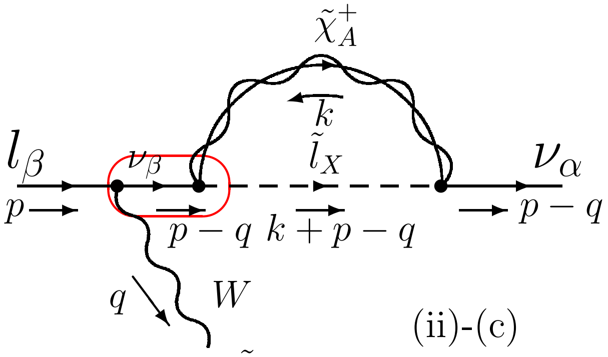
(i)-(b)



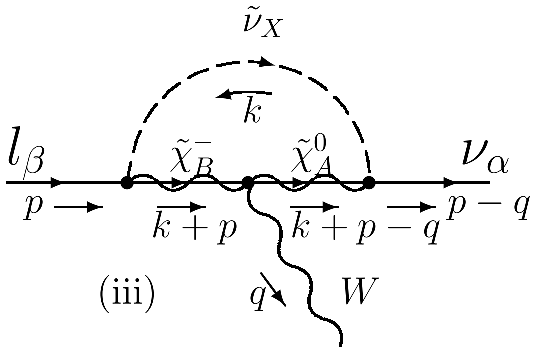
(i)-(c)



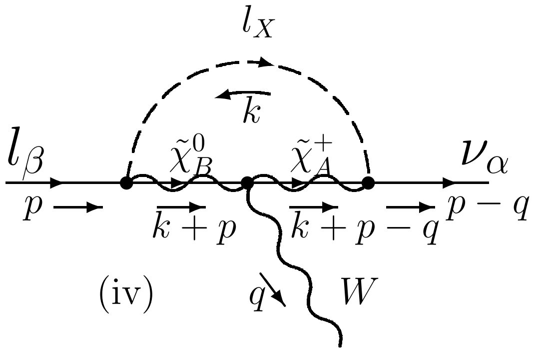
(ii)-(b)



(ii)-(c)



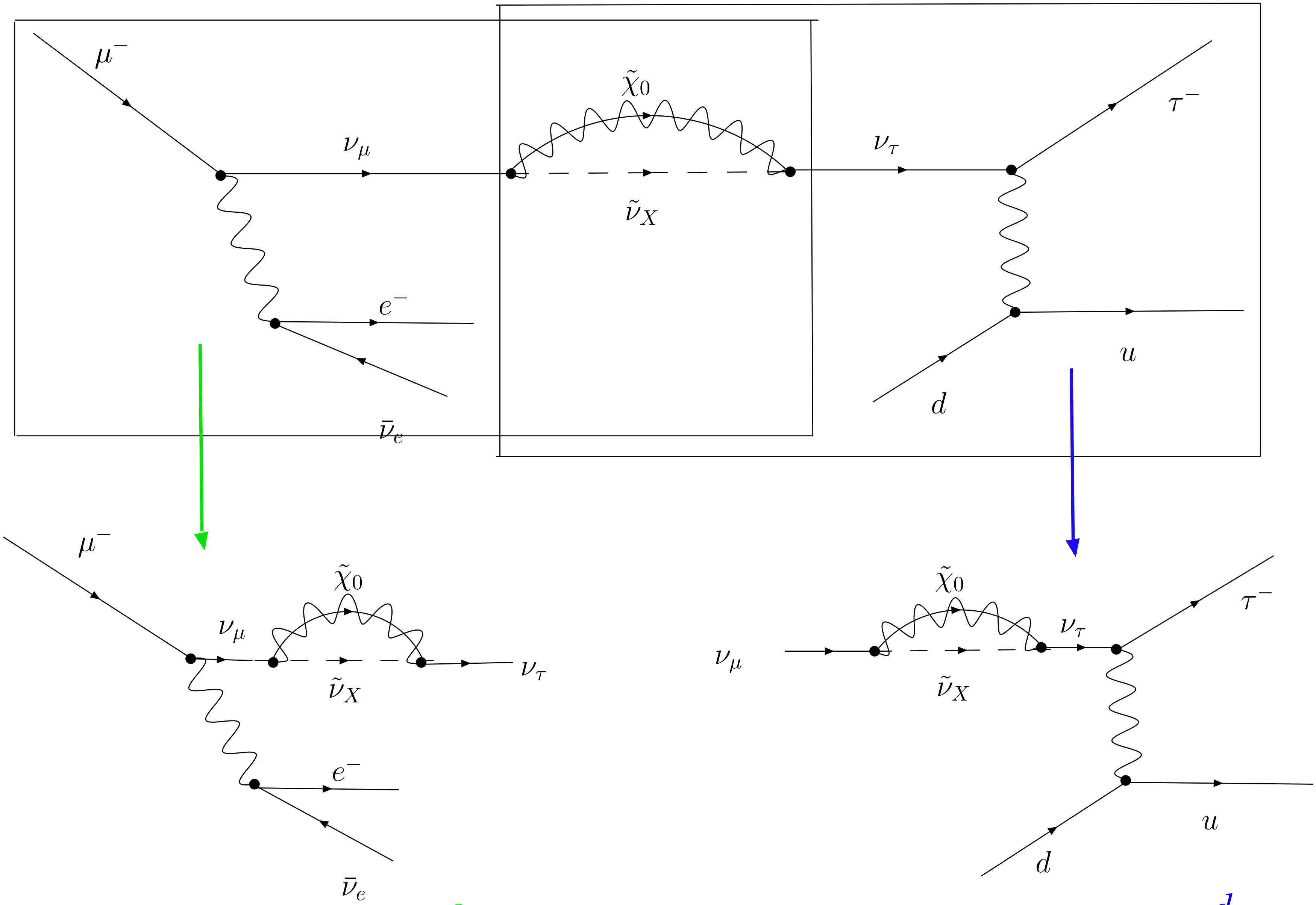
(iii)



(iv)

$$\frac{(p-q)^2}{(p-q)^2 - m^2_{\nu_\beta}} \Longrightarrow 1 \text{ (Specific here)} \quad \neq \frac{m^2_{\nu_\alpha}}{m^2_{\nu_\alpha} - m^2_{\nu_\beta}} \text{ (“Usual” case)}$$

(2) Double counting

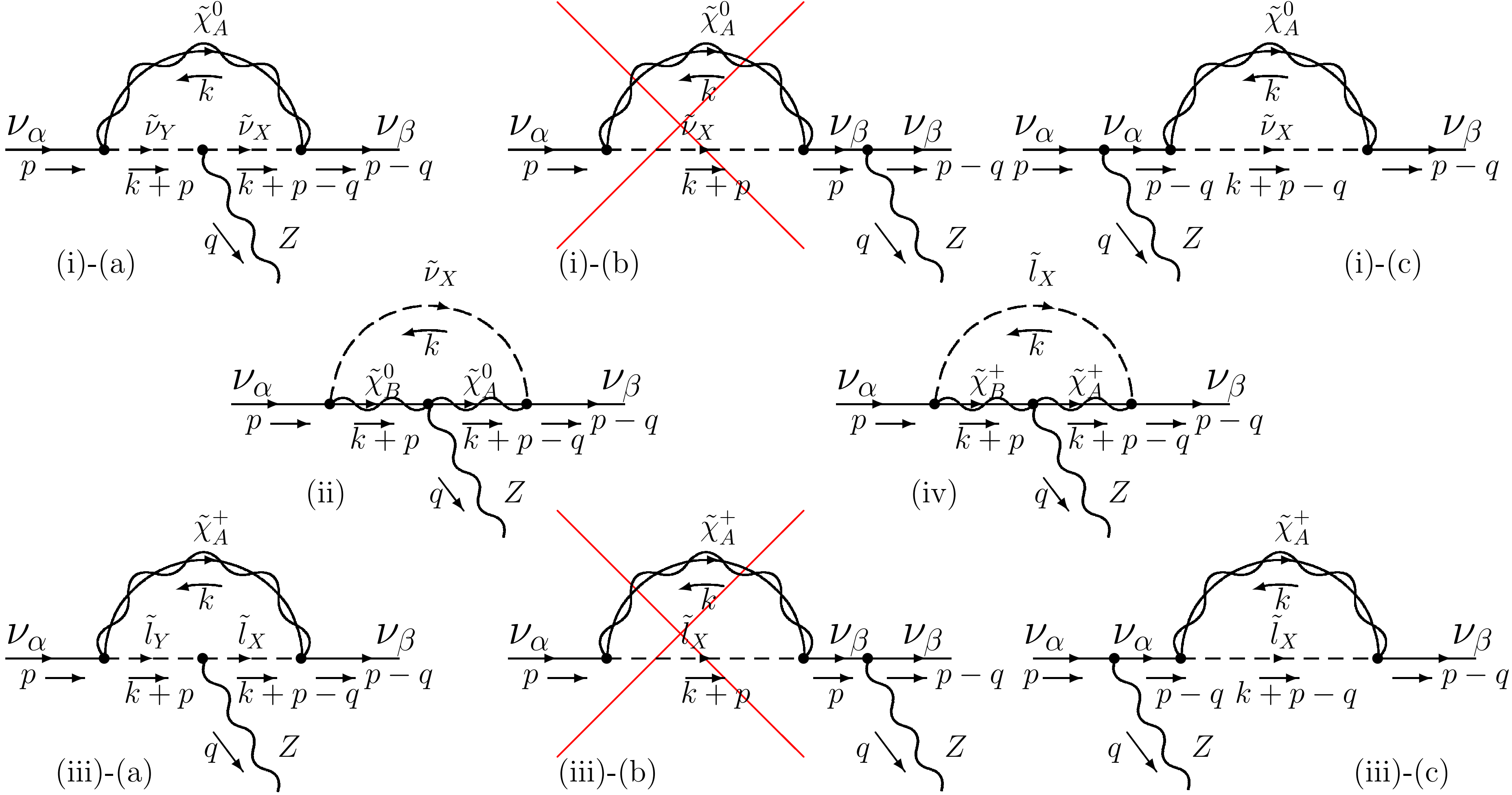


Contribution to ϵ^s

Contribution to ϵ^d

To calculate both means doubly counting one amplitude.

Examples of $\epsilon^{m}_{\beta\alpha}$ (Matter Effect): Z-Penguin diagrams



Not to include the contribution from (i)-(b) and (iii)-(b)

Similar aguement holds for ϵ^{d} (Detection process)

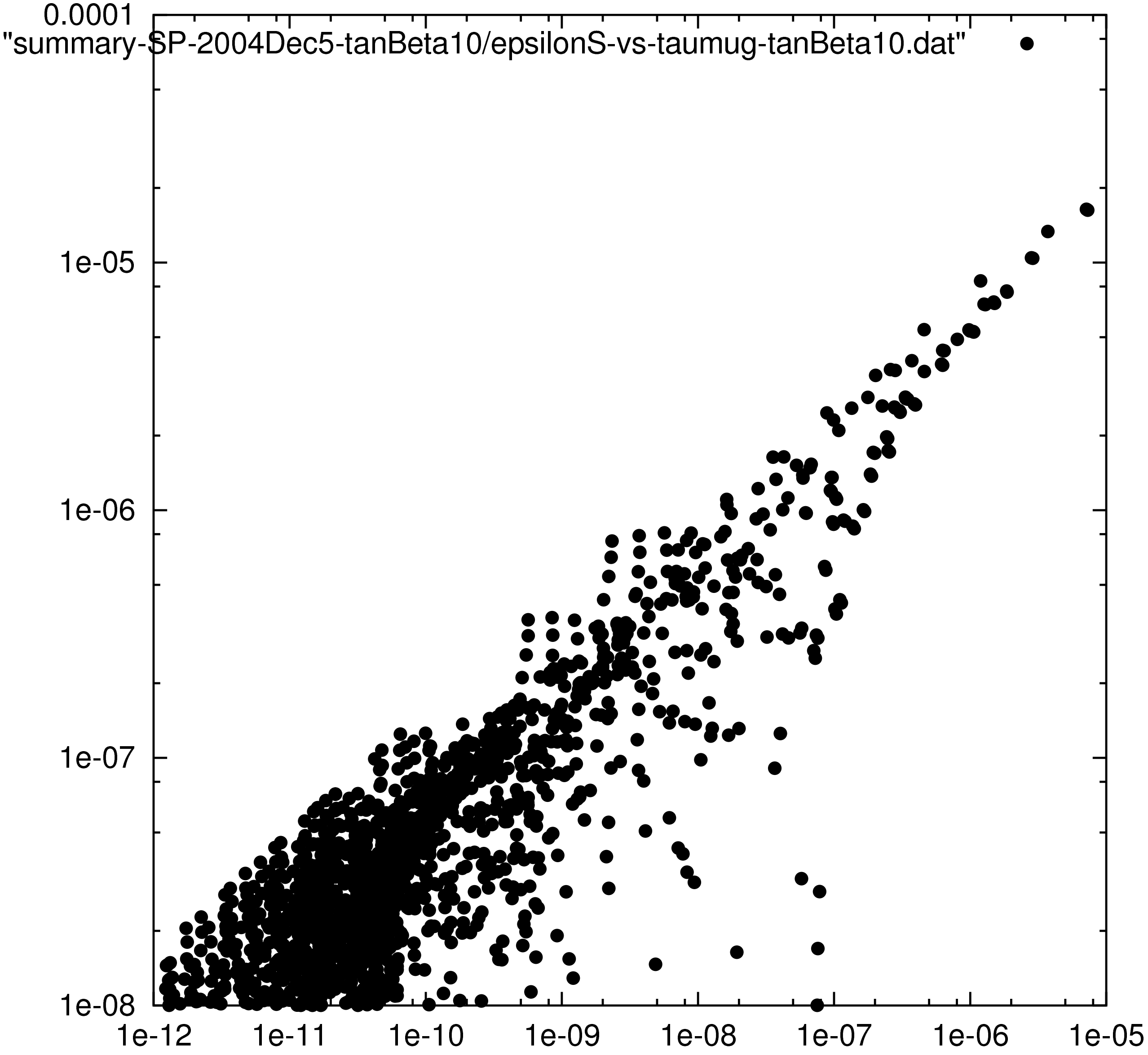
Predictions of Minimal Supersymmetric Standard Model with Right-Handed Neutrinos

◇ SUGURA-like boundary condition

Universal scalar mass $m_0 = 100 \sim 1000\text{GeV}$
Universal A term $a_0 = 0$
Universal gaugeino mass $M_{1/2} = 100 \sim 1000\text{GeV}$

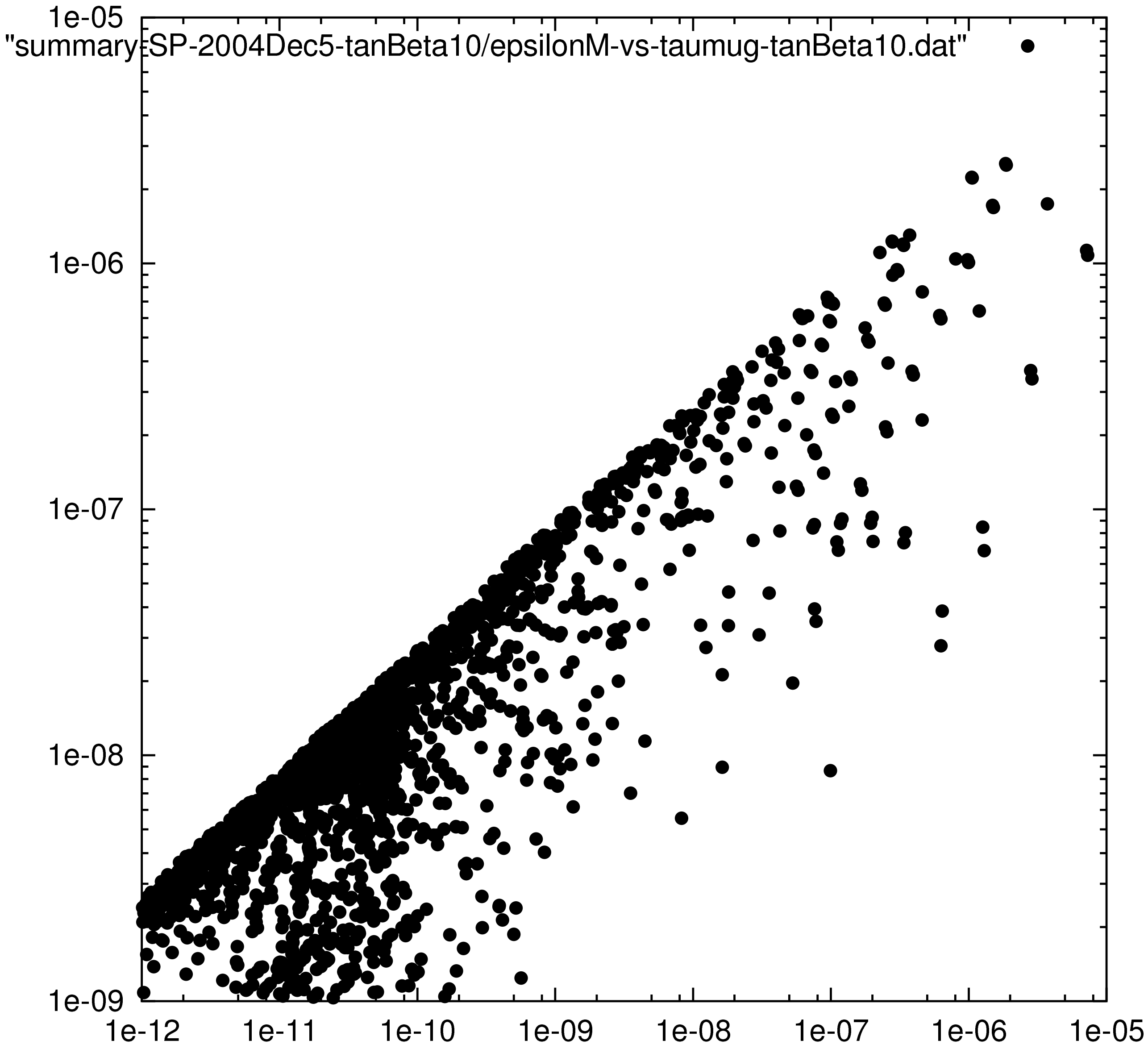
at GUT scale

◇ Masses and Mixings for Quark and Lepton are in the range of experiments



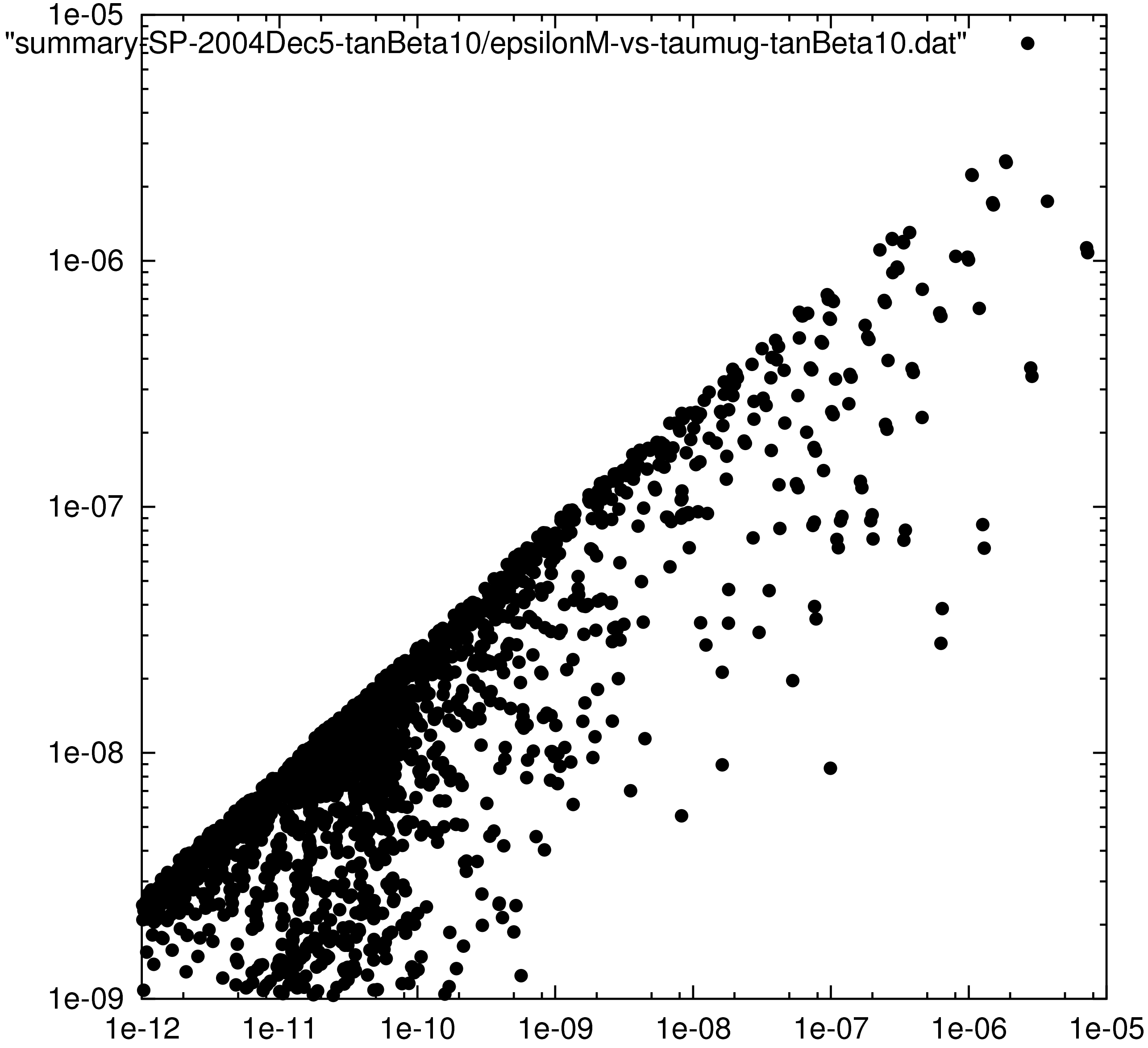
$\mathrm{Br}(\tau \to \mu\gamma)$

Example of nLFV in decay process $\epsilon^{s}_{\mu\tau}$



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

Example of nLFV $\epsilon^{m}_{\mu\tau}$



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

Example of nLFV $\epsilon^{d}_{\mu\tau}$

They are too small to be observed . . .

4 Summary and Discussion

- Explanation for Neutrino Masses and Lepton Mixing

  by MSSM with RH Neutrino

  $\sim$ Promising

- Large LFV Phenomena in Charged Lepton Expected
- However, very small LFV phenomena in Neutral Lepton Sector

(assuming SUGRA-like boundary condition)

Too small to be observed

- Advantage over Direct Detection

Transition Probability $\sim |\mathcal{A} + \epsilon|^2$ $\mathcal{A}$: Oscillation Amplitude

$\mathcal{S}$: Systematic Error

Direct Detection $(|\mathcal{A}| \ll |\epsilon|)$

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

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