Signature of the MSSM with $\nu_R s$ in a long baseline experiment

Results are shown in part in the proceedings for the conference NuFACT04, [arXiv:hep-ph/0410408]

Paper is in progress [arXiv:hep-ph/0502***]

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Contents

- Introduction
  - cLFV: lepton flavor violation in charged lepton sector
  - nLFV: lepton flavor violation with neutrinos
- Model independent analysis
  - Feasibility study to detect nLFV signals
- In the MSSM with $\nu_{Rs}$,
  - not only cLFV but also nLFV are induced.
  - Correlation between cLFV and nLFV
  - Size of nLFV couplings. — Detectable or not?
- Summary
Introduction: LFV

- In the SM, there is no LFV. In the SM with $m_\nu$, it is small.

- In the MSSM with $\nu_R$s, it can be large

  - The large mixings of neutrinos may imply the large cLFV ...

  $$(m_{L}^2)_{\beta}^{\alpha} \simeq -\frac{(6 + a_0^2)m_0^2}{16\pi^2}(Y_{\nu}^\dagger Y_{\nu})_{\beta}^{\alpha} \ln \frac{M_X}{M_R},$$

  $${\text{Br}}(l_{\alpha} \rightarrow l_{\beta}\gamma) \simeq \frac{\alpha^3}{G_F^2} \left(\frac{m_{L}^2}{m_{\text{SUSY}}^8}\right)^{\alpha} \tan^2 \beta.$$}

  Cheng Li (1977), Petcov (1977), Marciano Sandra (1977), Shrock Lee (1977)

LFV in charged lepton sector (cLFV)

\[ M_2 = 150 \text{ GeV} \quad m_{\tilde{e}_L} = 300 \text{ GeV} \quad a_0 = 0 \quad \mu > 0 \]

\[ \tan^2 \beta \]

One example numerical study
Sato Tobe (2000)

The future experiments
\[ \text{Br}(\mu \rightarrow e \gamma) > 10^{-14}, \]
\[ \text{Br}(\tau \rightarrow \mu \gamma) > 10^{-8}, \]
\[ \text{Br}(\mu \rightarrow e \text{ conv.}) > 10^{-18}. \]

The search for the cLFV is promising experiments.
— However, we here consider an alternative process.
**LFV interaction with neutrinos (nLFV)**

We here discuss a process with the neutrino flavor violation, such as

\[ \mu^- \rightarrow \nu_\tau e^- \bar{\nu}_e, \quad \nu_\alpha e^- \rightarrow \nu_\beta e^-, \quad \nu_\alpha d \rightarrow \ell_\beta u. \]

These processes affect the neutrino oscillation experiments.

Gonzalez-Garcia Grossman Gusso Nir (2001)
Gago Guzzo Nunokawa Teves Zukanovich Funchal (2001)
Huber Schwetz Valle (2002)
Fogli Lisi Mirizzi Montanino (2002)

Can we detect these effects in oscillation experiments?
— Yes, we can, but it depends on the type and size of nLFV interaction.

TO Sato Yamashita (2001)

In the MSSM+$\nu_R$, what is the typical size of nLFV couplings?
— We show the correlation between nLFV and cLFV.
Model independent approach
Standard Oscillation $\nu_\mu \rightarrow \nu_\tau$
Standard Oscillation $\nu_\mu \rightarrow \nu_\tau$

\[
\mathcal{A}(\mu \rightarrow \nu_\mu \bar{\nu}_e e) \times \mathcal{A}(\nu_\mu \xrightarrow{\text{osc}} \nu_\tau) \times \mathcal{A}(\nu_\tau d \rightarrow \tau u)
\]
Standard Oscillation $\nu_\mu \rightarrow \nu_\tau$

$$
|A(\mu \rightarrow \nu_\mu \bar{\nu}_e e) \times A(\nu_\mu \overset{\text{osc}}{\rightarrow} \nu_\tau) \times A(\nu_\tau d \rightarrow \tau u)|^2
$$
Standard Oscillation $\nu_\mu \rightarrow \nu_\tau$

\[ \left| A(\mu \rightarrow \nu_\mu \bar{\nu}_e e) \times A(\nu_\mu \overset{\text{osc}}{\rightarrow} \nu_\tau) \times A(\nu_\tau d \rightarrow \tau u) \right|^2 \]

\[ \Gamma_{\text{SM}}(\mu \rightarrow \nu_\mu \bar{\nu}_e e) \times P_{\nu_\mu \rightarrow \nu_\tau} \times \sigma_{\text{SM}}(\nu_\tau d \rightarrow \tau u) \]
Oscillation with nLFV interactions

\[ \nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau \]

- \( \mu^- \rightarrow W \)
- \( e^- \rightarrow \nu_e \)
- \( e^- \rightarrow W \rightarrow \tau^- \)
- \( d \rightarrow u \)
Oscillation with nLFV interactions

\[ \nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau \]

nLFV interaction

\[ \nu_\tau \xrightarrow{\text{no oscillation}} \nu_\tau \]
Oscillation with nLFV interactions

\[ \nu_\mu \overset{\text{oscillation}}{\rightarrow} \nu_\tau \]

+ nLFV interaction

\[ \nu_\tau \overset{\text{no oscillation}}{\rightarrow} \nu_\tau \]

\[ 2 \]

Signature of the MSSM with \( \nu_R \)s in a long baseline experiment – p.9/20
Oscillation with nLFV interactions

\[
\left| \begin{array}{c}
\nu_\mu \xrightarrow{\text{osc}} \nu_\tau \\
\end{array} \right|^2 + 2 \text{Re} \left[ \left( \begin{array}{c}
\nu_\mu \xrightarrow{\text{osc}} \nu_\tau \\
\end{array} \right)^* \left( \begin{array}{c}
n_\text{LFV} \nu_\tau \xrightarrow{\text{no osc}} \nu_\tau \\
\end{array} \right) \right] = \Gamma_{\text{SM}} \times \left( P_{\nu_\mu \rightarrow \nu_\tau} + 2 \text{Re} \left[ \epsilon_{\mu \tau}^s A^* (\nu_\mu \xrightarrow{\text{osc}} \nu_\tau) A (\nu_\tau \xrightarrow{\text{no osc}} \nu_\tau) \right] \right) \times \sigma_{\text{SM}},
\]

where \( \epsilon_{\mu \tau}^s \equiv \frac{A(\mu \rightarrow \nu_\tau \bar{\nu}_e e)}{A_{\text{SM}}} \).

- The oscillation probability is modified by the interference term due to the nLFV interaction.
- The size of the interference term is \( \mathcal{O}(\epsilon_{\mu \tau}^s) \), not \( \mathcal{O}(|\epsilon_{\mu \tau}^s|^2) \).
  — This interference effect can occur only in the oscillation process.
Search for the effect of $\epsilon^s_{\mu\tau}$ in $\nu_\mu \rightarrow \nu_\tau$

- Necessary (muon)$\times$(detector size) for 90% CL detection of nLFV.
  normalized at $10^{21} \times 100$[kton]
  - $\nu_\mu \rightarrow \nu_\tau$ channel
  - $\epsilon^s_{\mu\tau} = 3 \times 10^{-3} e^{i \frac{\pi}{2}}$
  - 10% ambiguity is considered in the oscillation parameters, $\Delta m^2$s and $\theta$s, and the CP-phase $\delta$ is treated as a free parameter.

$$\mu^- \xrightarrow{G_F} \nu_\mu \xrightarrow{\text{osc.}} \nu_\tau \rightarrow \tau^-$$
$$\mu^- \xrightarrow{\epsilon^s_{\mu\tau} G_F} \nu_\tau \xrightarrow{\text{no osc.}} \nu_\tau \rightarrow \tau^-$$

- The energy dependence of this signal is $1/E_\nu$.
It is quite different from the standard oscillation effect($\propto 1/E^2_\nu$).
Oscillation with nLFV interactions

The other diagrams which contribute to $\mathcal{A}(\mu + I \rightarrow \tau + F)$

- no oscillation
- nLFV at detection $\propto \epsilon_{\mu\tau}^d G_F$
- nLFV in matter effect $\propto \epsilon_{\mu\tau}^m G_F$

Signature of the MSSM with $\nu_F$'s in a long baseline experiment – p.12/20
Summary of the model independent analysis

Detectable signal ...

In $\nu_\alpha \rightarrow \nu_\beta$ channel, we can extract the nLFV signals only with $\epsilon^{s,m,d}_{\alpha\beta}$.

— by using its characteristic energy dependence.
— the nLFV amplitude does not include neutrino oscillation but its final states are the same as the standard one.

At a neutrino factory ($10^{21}$ muons $\times$ 100 kt detector), we have a chance to detect the signal of $|\epsilon^{s,m,d}_{\alpha\beta}| \sim \mathcal{O}(10^{-4})$. 
Summary of the model independent analysis

- Detectable signal ...
  - In $\nu_\alpha \rightarrow \nu_\beta$ channel, we can extract the nLFV signals only with $\epsilon_{s,m,d}^{s,m,d}$.
    - by using its characteristic energy dependence.
    - the nLFV amplitude *does not include neutrino oscillation* but its final states are the same as the standard one.
  - We here deal with $\epsilon_{\mu\tau}^{s,m,d}$ in the $\nu_\mu \rightarrow \nu_\tau$ channel.

- At a neutrino factory ($10^{21}$ muons $\times 100$ kt detector), we have a chance to detect the signal of $|\epsilon_{s,m,d}^{s,m,d}| \sim \mathcal{O}(10^{-4})$.
  - We make a numerical calculation for the size of nLFV couplings $\epsilon_{\mu\tau}^{s,m,d}$ in the MSSM with $\nu_{RS}$. 

In the MSSM with $\nu_{R}$
The origin of the nLFV is the same as that of the cLFV: slepton mixing.

Naively, $\epsilon^{s}_{\mu\tau} \sim \mathcal{O}(10^{-4})$ in nLFV corresponds to $\text{Br}(\tau \rightarrow \mu\gamma) \sim \mathcal{O}(10^{-8})$ in cLFV.

— However, for quantitative analysis, it is necessary to make a numerical calculation ...
Numerical evaluation of $\epsilon^s_{\mu\tau}$ in MSSM $+\nu_R$

and box diagrams ...
Numerical evaluation of $\epsilon^m_{\mu\tau}$ in MSSM+$\nu_R$

and box diagrams ...
Numerical evaluation of $\epsilon_{\mu \tau}^{s,m,d}$ in MSSM $+ \nu_R$

Source \quad Matter \quad Detection

$\mu^-$ \quad $W$ \quad $Z$ \quad $\tau^-$

$\nu_e$ \quad $e^-$ \quad $e^-$ \quad $W$

$W$ \quad $e^-$ \quad $e^-$ \quad $u$

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

$\epsilon_{\mu \tau}^s$ $10^{-5}$

$\epsilon_{\mu \tau}^m$ $10^{-5}$

$\epsilon_{\mu \tau}^d$ $10^{-4}$
Correlation between nLFV and cLFV

- Correlation between the nLFV coupling $\epsilon_{\mu\tau}^s$ and cLFV process $\tau \rightarrow \mu\gamma$.
- With some different $Y_\nu$'s, we scan the $m_0$-$M_{1/2}$ space with $a_0 = 0$, $\tan \beta = 10$, and $\mu > 0$.
- The parameter $\epsilon_{\mu\tau}^s$ is constrained at $\mathcal{O}(10^{-5})$ by the current bound of $\tau \rightarrow \mu\gamma$.
- It is smaller than the naive estimation because of cancellation among diagrams.
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Summary

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- The oscillation enhances the nLFV effect due to interference.
- We evaluate the effective couplings of nLFV which are relevant to $\nu_\mu \rightarrow \nu_\tau$ in the MSSM with $\nu_{Rs}$.
  - $\epsilon_{\mu\tau}^s$, $\epsilon_{\mu\tau}^m$, $\epsilon_{\mu\tau}^d$ where $\epsilon_{\mu\tau}^{s,m,d} \equiv$ exotic/standard
  - Detectable size: $|\epsilon_{\mu\tau}^{s,m,d}| \gtrsim \mathcal{O}(10^{-4})$
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- In the MSSM with $\nu_{Rs}$, these couplings are constrained by the process $\tau \rightarrow \mu \gamma$ as $|\epsilon_{\mu \tau}^{s,m,d}| \lesssim \mathcal{O}(10^{-5})$.
- Other model? — R-parity violation ...
  — CPV MSSM ...
  — $SU(5)$ GUT ...

Signature of the MSSM with $\nu_{Rs}$ in a long baseline experiment – p.21/20