Search for Lepton Flavor Violation in the Higgs Boson Decay at a Linear Collider

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in collaboration with

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Introduction
Motivation 1: MSSM with large $m_{SUSY}$

- In SUSY model, LFV is expected to be found. — but it has not been found yet.
- Is it because of heavy $m_{SUSY}$?
  \[ \text{Br}(\ell_j \rightarrow \ell_i \gamma), \text{Br}(\ell_j \rightarrow 3\ell_i) \propto \left(1/m_{SUSY}^4\right). \]
  — In such a case, what is the signature of the new physics?
- Higgs mediated LFV Babu Kolda, Ellis Dedes Raidal, Kitano Koike Komine Okada
  \[ \text{Br}(\ell_j \xrightarrow{h,H,A} 3\ell_i) \propto \left(1/m_A^4\right)(\tan^6 \beta) \]

LFV process =

$\ell_j \xrightarrow{\gamma,Z} \ell_i$

$\ell_j \xrightarrow{h,H,A} \ell_i$

\[ \kappa_{ji} = f(|\mu|/m_{SUSY}). \]
Motivation 2: Higgs sector in MSSM

The Linear Collider (LC) will make the precision study of $h$. We here deal with search for LF violating decay process. This process suggests that two (or more) Higgs doublet couple to the charged lepton sector.

Direct search for the LF violating Higgs coupling and the indirect measurement of it should be complementary to each other.
**Model:** the effective theory below $m_{\text{SUSY}}$ in the model with large $m_{\text{SUSY}}$

- Lagrangian — leptonic Yukawa

$$-\mathcal{L} \supset Y_{\ell_i} \bar{\ell}_{R_i} \left( \delta_{ij} \Phi_1^0 + \epsilon_{ij} \Phi_2^0 \right) \ell_{L_j} + \text{H.c.}$$

$\simeq$ (mass term) + (flavor diagonal interactions)

$$+ \frac{m_{\ell_i} \kappa_{ij}}{v \cos^2 \beta} \bar{\ell}_{R_i} \ell_{L_j} \left[ \cos(\beta - \alpha)h - \sin(\beta - \alpha)H - iA \right]$$

+ (charged Higgs term) + H.c.,

---

The LFV Higgs decay arise since two Yukawa matrices ($Y_{\ell_i} \delta_{ij}$ and $Y_{\ell_i} \epsilon_{ij}$) can not be diagonalized simultaneously.
Bound on $|\kappa_{32}|^2$ from LFV processes

Branching ratio for $h \rightarrow \tau^+ + \mu^-$ is estimated as

$$\text{Br}(h \rightarrow \tau^\pm + \mu^\mp) \simeq \frac{1}{N_c} \frac{m_\tau^2}{m_b^2} \frac{\cos^2(\beta - \alpha)}{\sin^2 \alpha \cos^2 \beta} |\kappa_{32}|^2.$$  

Throughout this talk, we assume

- Nearly **decoupling region**, $\sin(\alpha - \beta) \sim -1$ ($m_A \gg m_h$).
- Large $\tan \beta$, $\tan \beta = 60$. 
Bound on $|\kappa_{32}|^2$ from LFV processes

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  \]

- Throughout this talk, we assume
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  - Large $\tan \beta$, $\tan \beta = 60$.

- The bound on $|\kappa_{32}|^2$ from $\tau \rightarrow \mu \eta$ (Belle)
  
  \[
  \text{Br}(\tau \rightarrow \mu \eta) \simeq 8.4 \times \frac{G_F^2 m_\mu^2 m_\tau^7 \tau \tau}{768 \pi^3 m_A^4} |\kappa_{32}|^2 \tan^6 \beta < 3.4 \times 10^{-7},
  \]
  \[
  |\kappa_{32}|^2 < 0.3 \times 10^{-6} \times \left( \frac{m_A}{150 \text{[GeV]}} \right)^4 \times \left( \frac{60}{\tan \beta} \right)^6.
  \]
Parameter space which we explore

We consider the situation

- LFV\(\gamma\) is suppressed,
  \[ m_{\text{SUSY}} = m_{\tilde{l}}, m_{\tilde{\nu}}, M_{1,2} \sim \mathcal{O}(1) \text{ TeV}. \]

- However, \(\kappa_{32}\) is not so small, Brignole Rossi
  \[ R \equiv \mu / m_{\text{SUSY}} \sim \mathcal{O}(10) \rightarrow \mu \sim \mathcal{O}(10) \text{ TeV}. \]

- and we require \(m_h \sim 120-130\) GeV,
  \[ m_{Q,U,D}, A_t, A_b \sim \mathcal{O}(1-10) \text{ TeV}. \]

One example — Reference values

\[
\begin{align*}
  m_{\tilde{l}_i} &= m_{\tilde{\nu}_i} = M_1 = M_2 = 2 \text{ TeV}, \\
  \mu &= 25 \text{ TeV}, \\
  m_Q &= 10 \text{ TeV}, \\
  m_U &= m_D = A_t = A_b = 8 \text{ TeV}, \\
  \tan \beta &= 60.
\end{align*}
\]

This parameter choice yields \(|\kappa_{32}|^2 = 8.4 \times 10^{-6}, m_h = 123 \text{ GeV}\).
We consider the situation

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  \[ m_{Q, U, D}, A_t, A_b \sim \mathcal{O}(1-10) \text{ TeV}. \]

The other example — Reference values

\[
\begin{align*}
  m_{\tilde{l}_{Li}} &= m_{\tilde{\nu}_i} = 1.2 \text{ TeV}, & m_{\tilde{l}_{Ri}} &= 0.8 \text{ TeV}, \\
  M_1 &= 1 \text{ TeV}, & M_2 &= 0.8 \text{ TeV}, & \mu &= 10 \text{ TeV}, \\
  m_Q &= 5 \text{ TeV}, & m_U &= m_D = A_t = A_b = 3 \text{ TeV}, & \tan \beta &= 60.
\end{align*}
\]

This parameter choice yields \[ |\kappa_{32}|^2 = 3.8 \times 10^{-6}, m_h = 123 \text{ GeV} \]
Reference values:
\[ |\kappa_{32}|^2 = 8.4 \times 10^{-6}, \]
\[ |\kappa_{32}|^2 = 3.8 \times 10^{-6}. \]

When \( m_A \) is large, the experimental bound is relaxed, \( \text{BR}(\tau^\pm \mu^\mp) \) is allowed,

keeping \( m_h \sim 123 \text{ GeV} \)
\[ \sin(\alpha - \beta) \simeq -1, \]
\[ \sigma_{hZ} \sim 220[\text{fb}]. \]
Our Points
We focus on $h \rightarrow \tau^\pm + \mu^\mp$ process search at a LC.
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Why lightest Higgs?

- First object to be found
  Its mass will be thoroughly determined.
- Nealy decoupling region, $\sigma \propto \sin^2(\alpha - \beta)$.
Our Points

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  - First object to be found
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  - Nealy decoupling region, \( \sigma \propto \sin^2(\alpha - \beta) \).

- Why linear collider?
  - Clear signal, Precision measurement
    - It is important to reduce the backgrounds.
    - The Higgs-strahlung is preferable in the Higgs production processes to determine \( m_h \) and \( \sqrt{s} \) with high precision.
Higgs production process

In low $\sqrt{s}$ region, the Higgs-strahlung is dominant.

In 2HDM, $\sigma = \sigma_{\text{SM}} \times \sin^2(\alpha - \beta)$. 
Using $Z$-recoil, we can identify the process as the Higgs-mediated one.

- $p_\tau$ is reconstructed by using $\sqrt{s}$, $m_h$, $m_Z$ and $p_\mu$.

It is not necessary to measure $p_\tau$. 
Using $Z$-recoil, we can identify the process as the Higgs-mediated one.

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It is not necessary to measure $p_\tau$.

- We assume $L = 1,000 \text{ fbarn}^{-1}$, optimally tuned $\sqrt{s}$.

- The number of event for $\text{BR} = 7 \times 10^{-4}$ is estimated as

$$ N_{\text{signal}} = L \times \sigma_{Zh} \times \text{Br}(h \rightarrow \tau + \mu) \times \epsilon \sim 10 \text{ events}, $$

$$ \epsilon \equiv \text{Br}(Z \rightarrow ee, \mu\mu) \simeq 0.07. $$
Feasibility Study
We introduce the invariant mass cut to reduce the backgrounds which do not include the lightest Higgs boson.

\[ e^+ + e^- \rightarrow Z\tau\tau \rightarrow Z\tau\mu + \nu_\mu\nu_\tau \]

\[ e^+ + e^- \rightarrow ZWW \rightarrow Z\tau\mu + \nu_\mu\nu_\tau \]

\[ e^+e^- \rightarrow Z\tau^+\tau^- \]

The number of backgrounds with \( M_{\tau\mu} \neq m_h \) is huge but it is not serious.
The most serious background is induced by the tau-pair production through the Higgs decay.

\[ N_{\text{before cut}} = L \sigma_{Zh} \times \text{Br}(h \rightarrow \tau\tau) \times \text{Br}(\tau \rightarrow \mu\nu\bar{\nu}) \times \epsilon \]

\[ \sim 270 \text{ events!!} \]

We can reduce it by using the kinematic cuts.

However, there are the irreducible backgrounds — Fake signal.

Fake signal condition: \( p_{\mu^+} \simeq p_{\tau^+} \)
Estimation of the number of the fake event

Fake signal condition: \( p_{\mu^+} \simeq p_{\tau^+} \)

- The muon from tau tends to be emitted to the same direction of the parent tau.
- The energy of muon tends to distribute around the parent tau’s.

\[ h \rightarrow \tau\tau \rightarrow \tau\mu + \text{missings} \]

\[ E_\mu = E_h/2 - \mathcal{O}(m_\tau^2/E_h) \]

\[ x \equiv E_\mu/(E_h/2) \]
Estimation of the number of the fake event

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\[
\delta(E_\mu/(E_h/2))
\]

\[
\frac{E_\mu}{E_h/2}
\]

\[
x \equiv E_\mu/(E_h/2)
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Estimation of the number of the fake event

In order to reduce the fake events, it is important to determine $E_h$ with high precision.

If we can determine $\delta(E_h)$ within 0.1 GeV, then

\[ N_{\text{fake}} \lesssim 1 \text{ events}!! \]

\[ N_{\text{signal}} \sim 10 \text{ events} \]

\[ x \equiv E_\mu/(E_h/2) \]

\[ \delta(E_\mu/(E_h/2)) \]
Estimation of the number of the fake event

- In order to reduce the fake events, it is important to determine $E_h$ with high precision.
- If we can determine $\delta(E_h)$ within 0.1 GeV, then
  \[ N_{\text{fake}} \lesssim 1 \text{ events} \]
  \[ N_{\text{signal}} \sim 10 \text{ events} \]
- When we assume $|\kappa_{32}|^2 = 8.4 \times 10^{-6}$, $m_A \gtrsim 350$ GeV, $\tan \beta = 60$, and $\delta(E_h) = 0.1$ GeV,
  \[ \frac{N_{\text{signal}}}{\sqrt{N_{\text{fake}}}} \gtrsim 10. \]
  By adding the $Z \rightarrow jjj$ channel, we can expect much larger significance.
Case 1: $\mu = 25\text{TeV}$, $m_S \sim 2\text{ TeV} \rightarrow |\kappa_{32}|^2 = 8.4 \times 10^{-6}$,

Case 2: $\mu = 10\text{TeV}$, $m_S \sim 1\text{ TeV} \rightarrow |\kappa_{32}|^2 = 3.8 \times 10^{-6}$. 
Summary
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We consider the feasibility to observe the LFV Higgs boson decay process, $h \rightarrow \tau \mu$, at a linear collider.
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- Our point is that we can reduce the background by using the precise measurement of the kinematics.
- It is constrained by \( \tau \rightarrow \mu \eta \) search.
  - In MSSM, the significance of the signal can be sizable.
Summary

- We consider the feasibility to observe the LFV Higgs boson decay process, $h \rightarrow \tau \mu$, at a linear collider.
- Our point is that we can reduce the background by using the precise measurement of the kinematics.
- It is constrained by $\tau \rightarrow \mu \eta$ search.
  - In MSSM, the significance of the signal can be sizable.
- The direct measurement of the LF violating Higgs coupling and the indirect measurement of it should be complementary to each other.