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
    - MSSM with large m_{SUSY}
    - LFV via Higgs and LF violating Higgs decay
  - Current experimental bound
  - Branching ratio

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  - Why h? Why linear collider?
  - Strategy

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- Feasibility study
  - *Fake event*

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Introduction

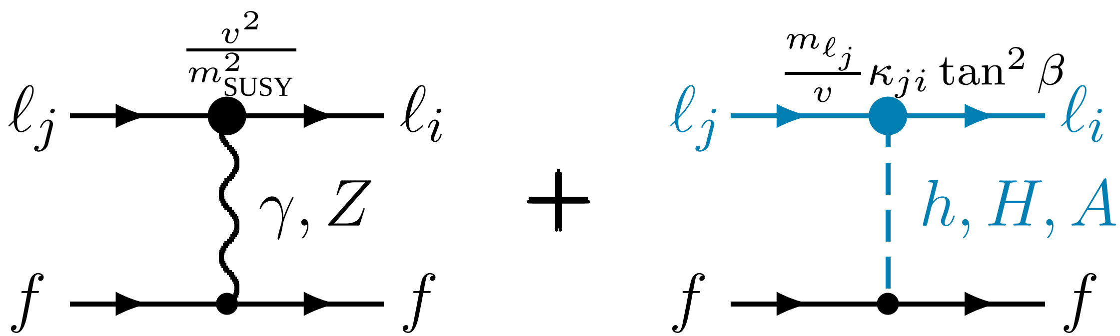
Motivation 1: MSSM with large m_{SUSY}

- In SUSY model, LFV is expected to be found.
  — but it has not been found yet.
- Is it because of heavy m_{SUSY}?
  - $\text{Br}(\ell_j \to \ell_i \gamma)$, $\text{Br}(\ell_j \xrightarrow{\gamma} 3\ell_i) \propto (1/m_{\text{SUSY}}^4)$.

  — In such a case, what is the signature of the new physics?
  - Higgs mediated LFV Babu Kolda, Ellis Dedes Raidal, Kitano Koike Komine Okada

$$\text{Br}(\ell_j \xrightarrow{h,H,A} 3\ell_i) \propto (1/m_A^4)(\tan^6\beta)$$

LFV process =

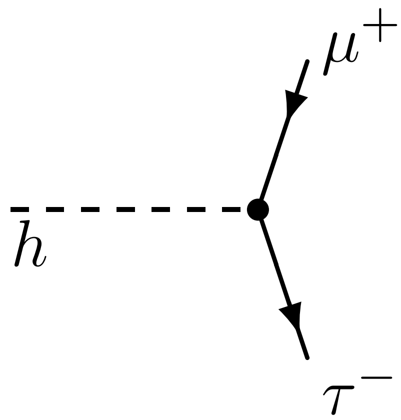


$$\kappa_{ji} = f(|\mu|/m_{\text{SUSY}}).$$

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 $m_{\rm SUSY}$ in the model with large $m_{\rm SUSY}$

- Lagrangian — leptonic Yukawa

loop induced

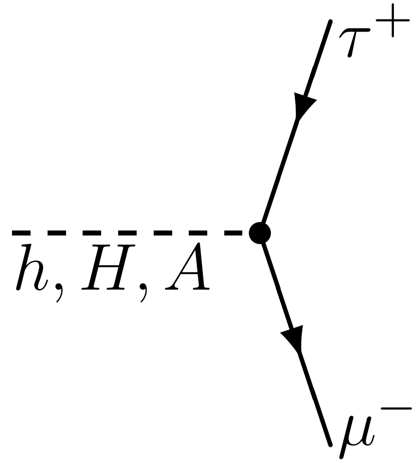
$$-\mathcal{L} \supset Y_{\ell_i} \overline{\ell_{Ri}} \left(\delta_{ij}\Phi_1^0 + \epsilon_{ij}\Phi_2^0\right) \ell_{Lj} + \text{H.c.}$$

$$\simeq (\text{mass term}) + (\text{flavor diagonal interactions})$$

$$+ \frac{m_{\ell_i}\kappa_{ij}}{v\cos^2\beta} \overline{\ell_{Ri}} \ell_{Lj} \left[\cos(\beta-\alpha)h - \sin(\beta-\alpha)H - iA\right]$$

$$+ (\text{charged Higgs term}) + \text{H.c.},$$

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 $h \to \tau^+ + \mu^-$ is estimated as

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

- Throughout this talk, we assume
  - Nearly *decoupling region*, $\sin(\alpha - \beta) \sim -1$ $(m_A \gg m_h)$.
  - Large $\tan\beta$, $\tan\beta = 60$.

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- Throughout this talk, we assume
  - Nearly *decoupling region*, $\sin(\alpha - \beta) \sim -1 \ (m_A \gg m_h)$.
  - Large $\tan \beta$, $\tan \beta = 60$.
- The bound on $|\kappa_{32}|^2$ from $\tau \to \mu\eta$ (Belle)

$$\mathrm{Br}(\tau \xrightarrow{h,H,A} \mu\eta) \simeq 8.4 \times \frac{G_F^2 m_\mu^2 m_\tau^7 \tau_\tau}{768\pi^3 m_A^4} |\kappa_{32}|^2 \tan^6 \beta < 3.4 \times 10^{-7},$$

$$|\kappa_{32}|^2 < 0.3 \times 10^{-6} \times \left(\frac{m_A}{150[\mathrm{GeV}]}\right)^4 \times \left(\frac{60}{\tan \beta}\right)^6 .$$

Parameter space which we explore

We consider the situation

- LFV$_\gamma$ is suppressed,
  — $m_{\text{SUSY}} = m_{\tilde{l}}, m_{\tilde{\nu}}, M_{1,2} \sim \mathcal{O}(1)$ TeV.
- However, κ_{32} is not so small, Brignole Rossi
  — $R \equiv \mu / m_{\text{SUSY}} \sim \mathcal{O}(10) \to \mu \sim \mathcal{O}(10)$ TeV.
- and we require $m_h \sim$ 120-130 GeV,
  — $m_{Q,U,D}, A_{t,b} \sim \mathcal{O}(1\text{-}10)$ TeV.

One example — Reference values

$$m_{\tilde{l}_i} = m_{\tilde{\nu}_i} = M_1 = M_2 = 2 \text{ TeV}, \mu = 25 \text{ TeV},$$
$$m_Q = 10 \text{ TeV}, m_U = m_D = A_t = A_b = 8 \text{ TeV},$$
$$\tan\beta = 60.$$

This parameter choice yields $\boxed{|\kappa_{32}|^2 = 8.4 \times 10^{-6}, m_h = 123 \text{ GeV}}$

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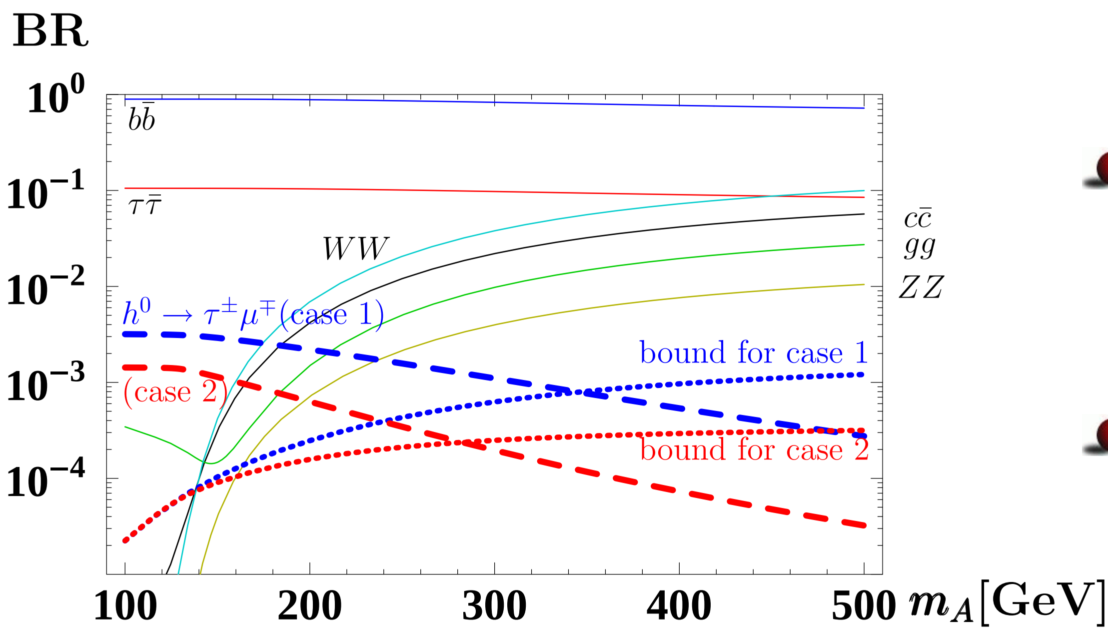
  — $m_{Q,U,D}, A_{t,b} \sim \mathcal{O}(1\text{-}10)$ TeV.

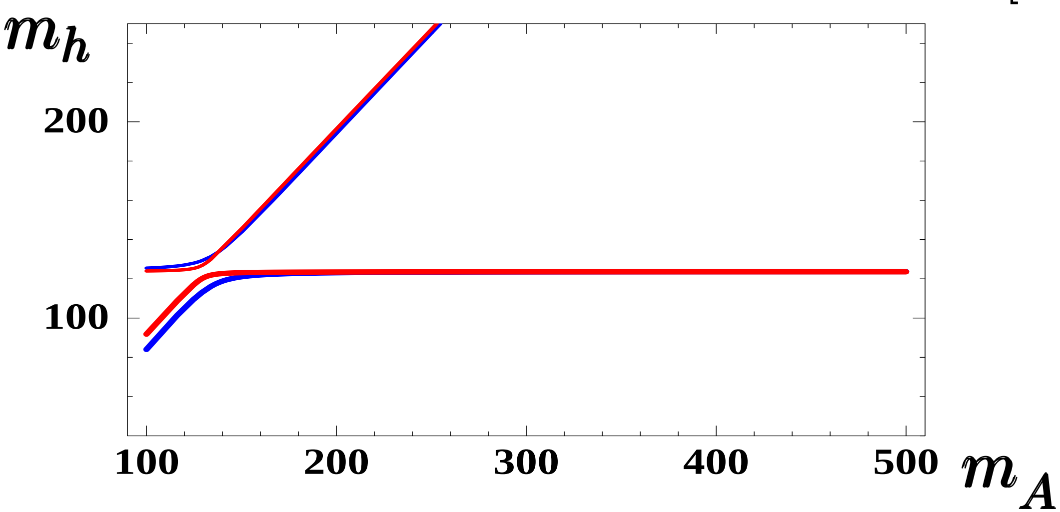
The other example — Reference values

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

This parameter choice yields $|\kappa_{32}|^2 = 3.8 \times 10^{-6}, m_h = 123$ GeV

Branching ratio





- 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, BR$\mathcal{O}(10^{-4})$ is allowed,
- keeping $m_h \sim 123$ GeV
  $\sin(\alpha - \beta) \simeq -1$,
  — $\sigma_{hZ} \sim 220$[fb].

Our Points

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  - First object to be found
    Its mass will be thoroughly determined.
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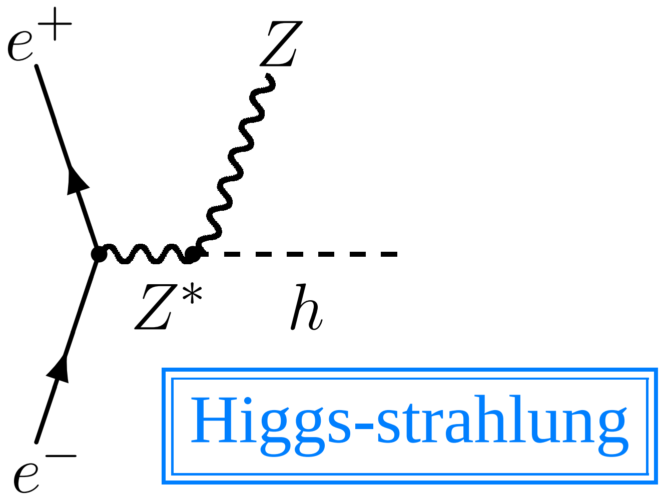
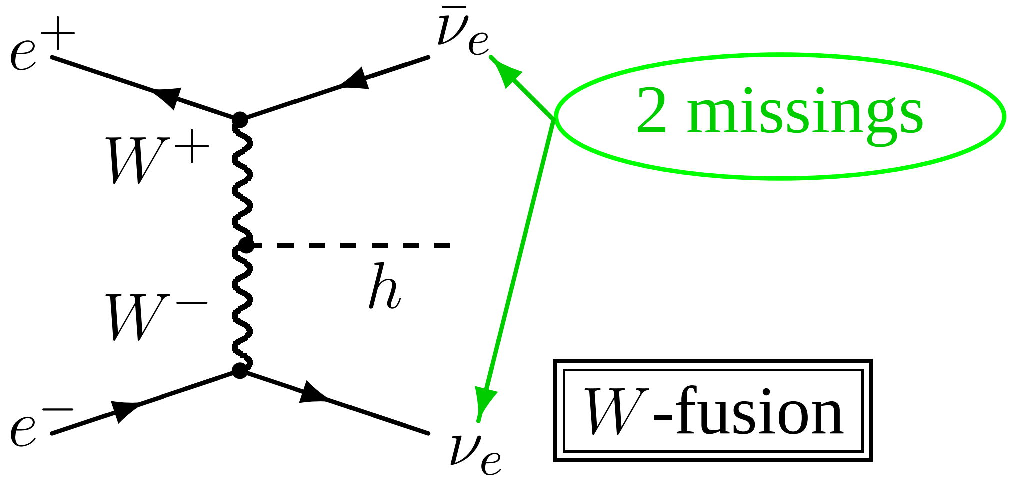
- Why lightest Higgs?
  - First object to be found
    Its mass will be thoroughly determined.
  - Nealy decoupling region, $\sigma \propto \sin^2(\alpha - \beta)$.
- Why linear collider?
  - Clear signal, Precision measurement

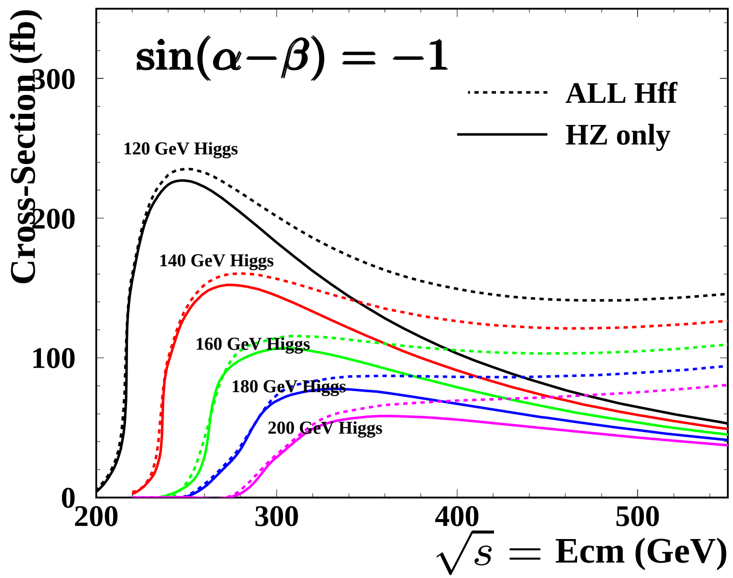
    It is important to reduce the backgrounds.

    The Higgs-strahlung is preferable in the Higgs production processes to determine m_h and $\sqrt{s}$ with high precision.

Higgs production process

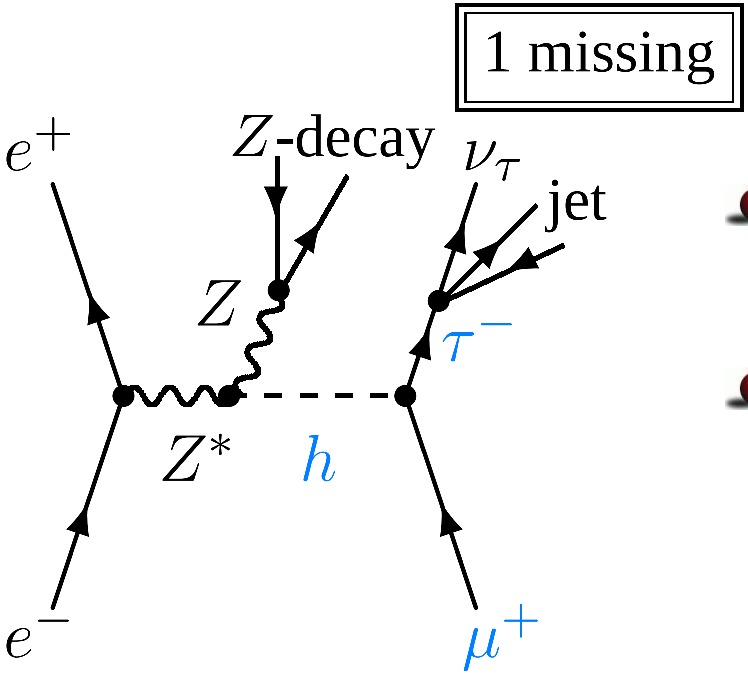






- In low $\sqrt{s}$ region, the Higgs-strahlung is dominant.
- In 2HDM, $\sigma = \sigma_{\rm SM} \times \sin^2(\alpha - \beta)$.

Strategy



- Using Z-recoil, we can identify the process as the Higgs-mediated one.
- p_τ is reconstructed by using $\sqrt{s}$, m_h, m_Z and p_μ.

  It is not necessary to measure p_τ.

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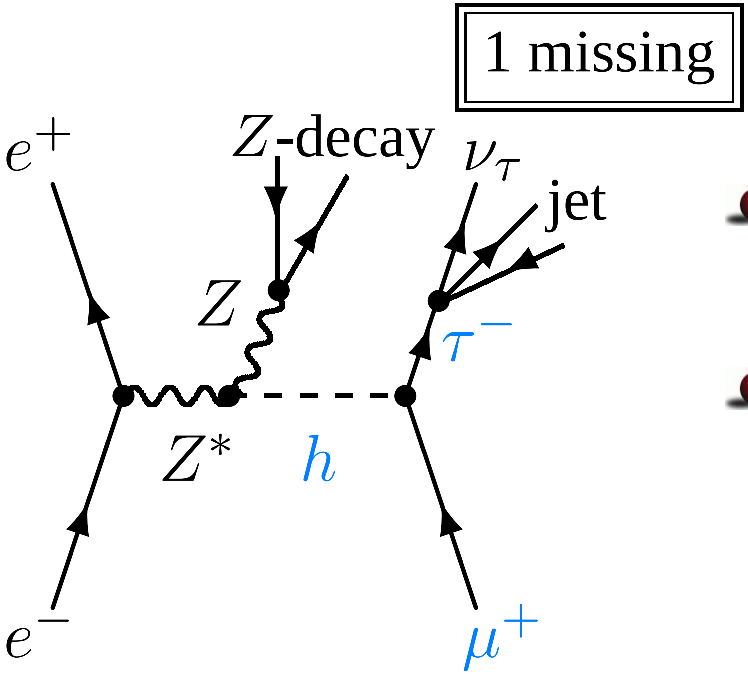

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- We assume $L = 1{,}000$ fbarn^{-1}, optimally tuned $\sqrt{s}$.
- The number of event for BR $= 7 \times 10^{-4}$ is estimated as

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

$$\epsilon \equiv \text{Br}(Z \to ee, \mu\mu) \simeq 0.07.$$

Feasibility Study

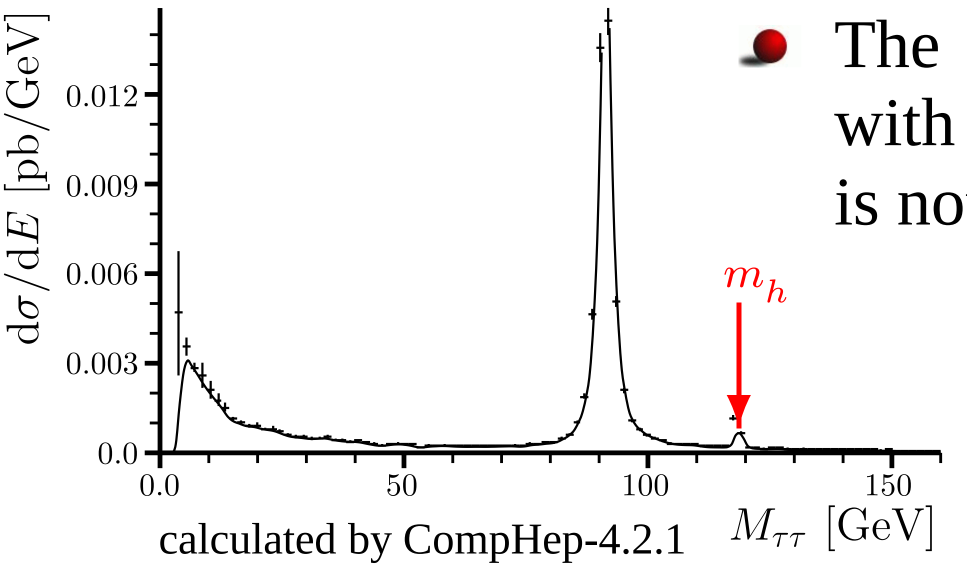
Backgrounds

- We introduce the invariant mass cut to reduce the backgrounds which do not include the lightest Higgs boson.

$$e^+ + e^- \to Z\tau\tau \to Z\tau\mu + \nu_\mu\nu_\tau$$

$$e^+ + e^- \to ZWW \to Z\tau\mu + \nu_\mu\nu_\tau$$

$e^+e^- \to Z\tau^+\tau^-$

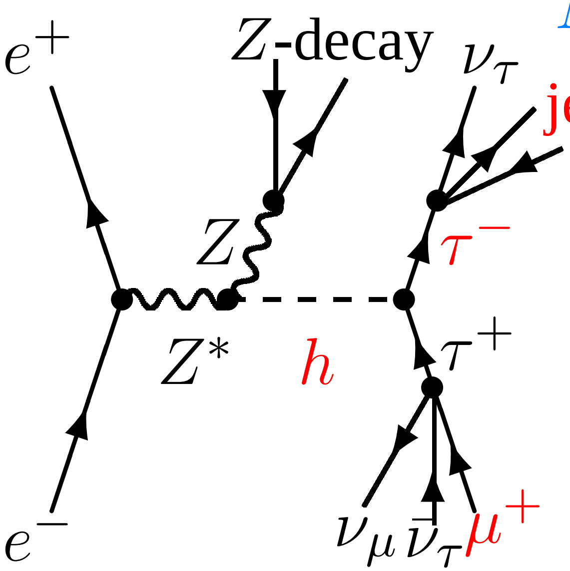


calculated by CompHep-4.2.1

- The number of backgrounds with $M_{\tau\mu} \neq m_h$ is huge but it is not serious.

Backgrounds — Fake signal —

- The most serious background is induced by the tau-pair production throught the Higgs decay.



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

$\sim$270 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

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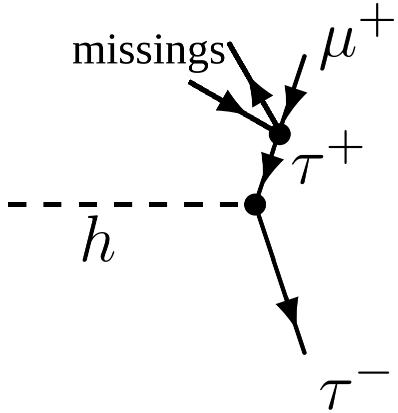
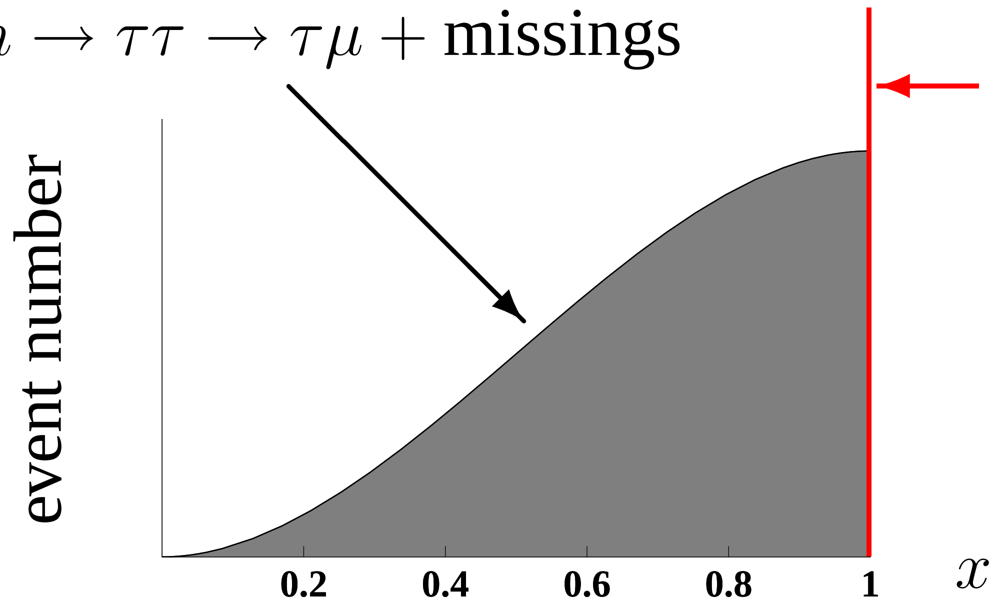
- The muon from tau tends to be emitted to the same direction of the parent tau.
- The energy of muon tends to distribute around the parent tau's.





$E_\mu = E_h/2 - \mathcal{O}(m_\tau^2/E$

$x \equiv E_\mu/(E_h/2)$

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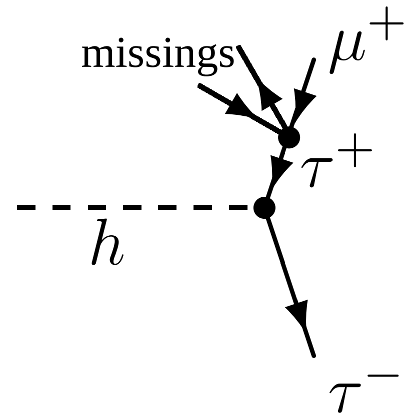
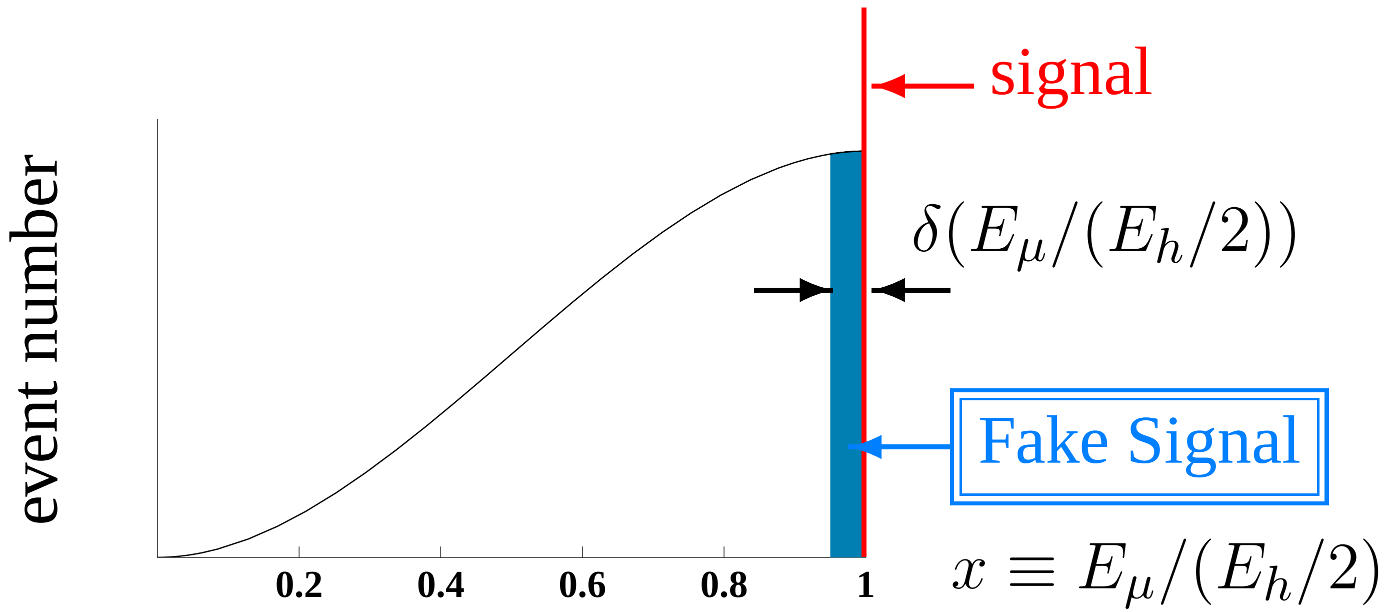
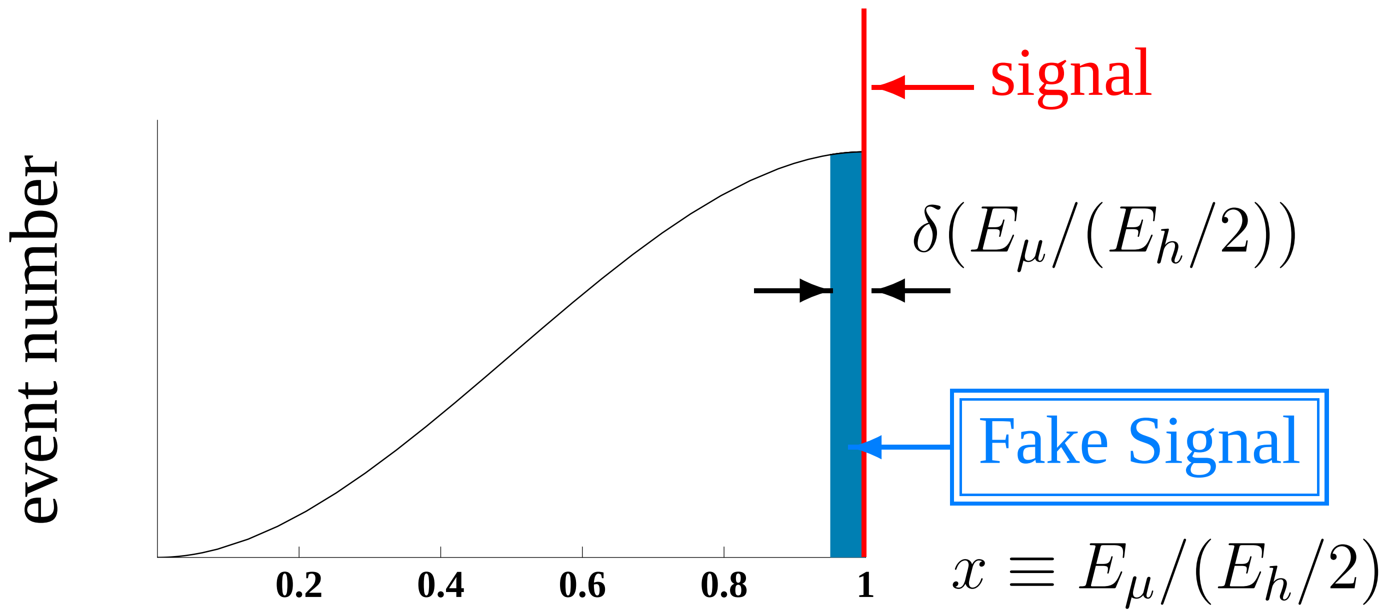




Estimation of the number of the fake event

- 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

$N_{\text{fake}} \lesssim 1$ events !! $\qquad N_{\text{signal}} \sim 10$ events



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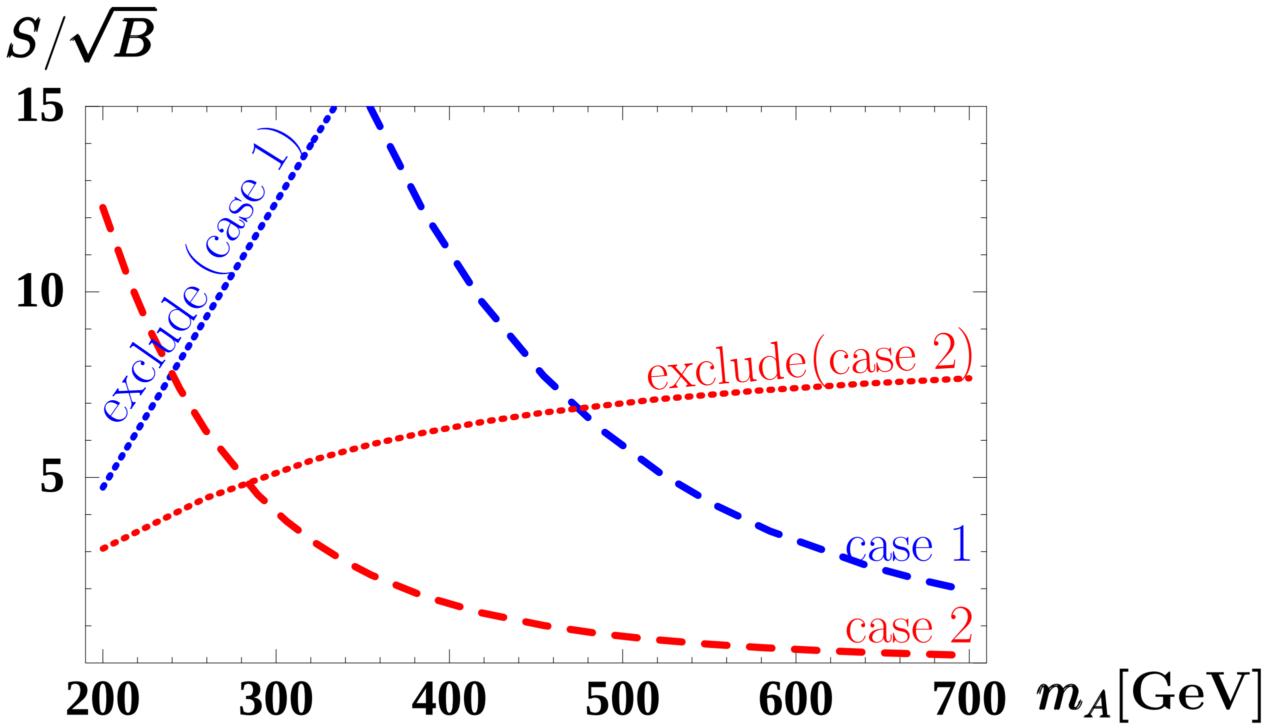
- When we assume $|\kappa_{32}|^2 = 8.4 \times 10^{-6}$, $m_A \gtrsim 350$ GeV, $\tan\beta = 60$, and $\delta(E_h) = 0.1$ GeV,

$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{fake}}}} \gtrsim 10.$$

By adding the $Z \to jj$ channel, we can expect much larger significance.

$S/\sqrt{B}$



- Case 1: $\mu = 25\text{TeV}$, $m_S \sim 2$ TeV $\rightarrow |\kappa_{32}|^2 = 8.4 \times 10^{-6}$,
- Case 2: $\mu = 10\text{TeV}$, $m_S \sim 1$ TeV $\rightarrow |\kappa_{32}|^2 = 3.8 \times 10^{-6}$.

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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 $\tau \to \mu\eta$ 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.