Measurement of lepton flavor violating Yukawa couplings at ILC

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- Summary

SK, Ota,
Takasugi, Tsumura

SK, Kuno, Kuze, Ota

Introduction

- LFV is a clear signal for physics beyond the SM.
- Neutrino oscillation may indicate the possibility of LFV in the charged lepton sector.
- In new physics models, LFV can naturally appear.
  - SUSY (slepton mixing) Borzumati, Masiero

    Hisano et al.
  - Zee model for the ν mass Zee
  - Models of dynamical flavor violation Hill et al.

In this talk, we discuss tau-associated LFV in SUSY models

τ⇔e & τ ⇔μ

- The Higgs mediated LFV is proportional to the Yukawa coupling ⇒ Tau-associated LFV processes.

  Different behavior from μe mixing case.
- It is less constrained by current data as compared to the μ⇔e mixing

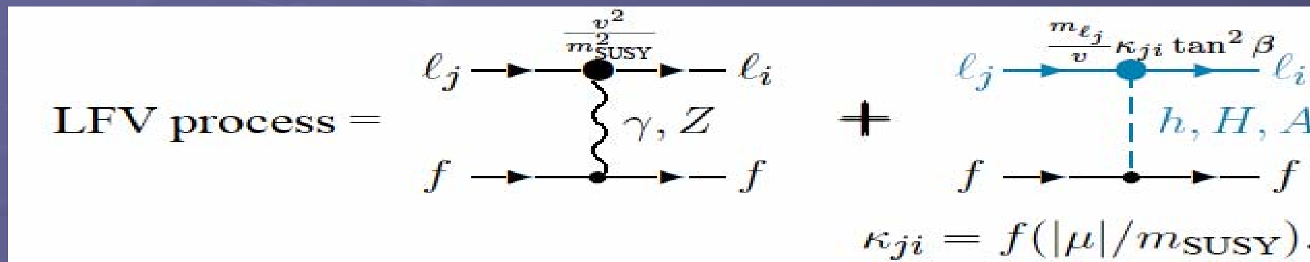
$\mu \to e\gamma$	1.2×10^{-11}
$\mu \to 3e$	1.1×10^{-12}
$\mu Ti \to eTi$	6.1×10^{-13}
$\tau \to \mu\gamma$	3.1×10^{-7}
$\tau \to 3\mu$	$1.4\text{-}3.1 \times 10^{-7}$

LFV in SUSY

- It is known that sizable LFV can be induced at loop due to slepton mixing
- Up to now, however, no LFV evidence has been observed at experiments. $\mu \to e\gamma$, $\mu \to eee$, ….
- Large M_{SUSY}? so that the SUSY effects decouple?

Even in such a case, we may be able to search LFV through the Higgs boson mediation, which does not necessarily decouple for a large M_{SUSY} limit

Decoupling property of LFV



- Gauge mediation :

$$\mathcal{L} = \frac{m_{\ell_i}}{M^2_{SUSY}} \bar{\ell}_i \sigma^{\mu\nu} \ell_j F_{\mu\nu}$$

- Higgs mediation :

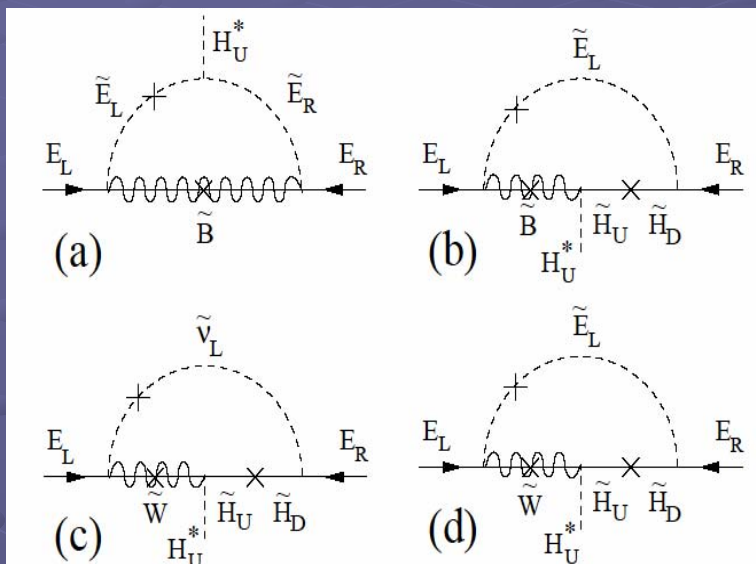
$$\mathcal{L} = \frac{m_{\ell_i}}{v} \kappa_{ij} (\tan^2\beta)\, \bar{\ell}_i \ell_j \Phi, \quad (\Phi = h, H, A)$$
$$\Rightarrow \quad \kappa_{ij} \sim f(|\mu|/M_{SUSY})$$

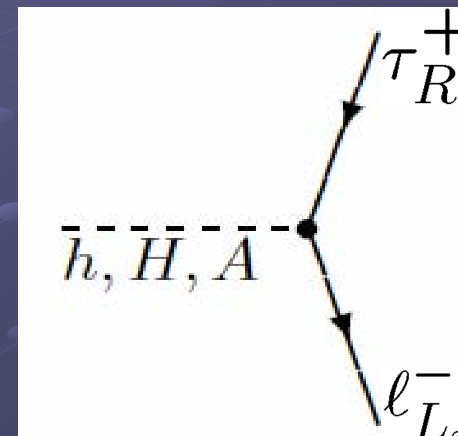
Higgs mediation does not decouple in the large M_{SUSY} limit

LFV Yukawa coupling

Babu, Kolda;
Dedes,Ellis,Raidal;
Kitano, Koike, Okada

Slepton mixing induces LFV in SUSY models.





$\ell_{Li} = e_L$ and μ_L

$$\mathcal{L}_{\tau\ell_i} = -\frac{\kappa_{3i} m_\tau}{v \cos^2\beta}\left\{\cos(\alpha-\beta)h^0 + \sin(\alpha-\beta)H^0 - iA^0\right\}(\overline{\tau_R}\ell_{Li})$$

Kij = Higgs LFV parameter

$$\kappa_{ij} \simeq \epsilon_{ij} = f(m_{\tilde{l},\tilde{\nu}}, M_{1,2}, \mu).$$

A source of slepton mixing in the MSSM+RN

- Slepton mixing induces both the Higgs mediated LFV and the gauge mediation.
- Off-diagonal elements can be induced in the slepton mass matrix at low energies, even when it is diagonal at the GUT scale.
- RGE

$$\frac{\mathrm{d}(m^2_{\tilde{L}})_{ij}}{\mathrm{d}\ln\mu} = \mathrm{diag} + \frac{1}{(4\pi)^2}\left\{m^2_{\tilde{L}}Y^\dagger_\nu Y_\nu + Y^\dagger_\nu Y_\nu m^2_{\tilde{L}} + 2\left(Y^\dagger_\nu m^2_{\tilde{\nu}} Y_\nu + m^2_{H_u} Y^\dagger_\nu Y_\nu + A^\dagger_\nu A_\nu\right)\right\}_{ij}$$

Experimental bound on κ_{32}, κ_{31}

The strongest bound on κ_{32} comes from the $\tau \to \mu\eta$ result.

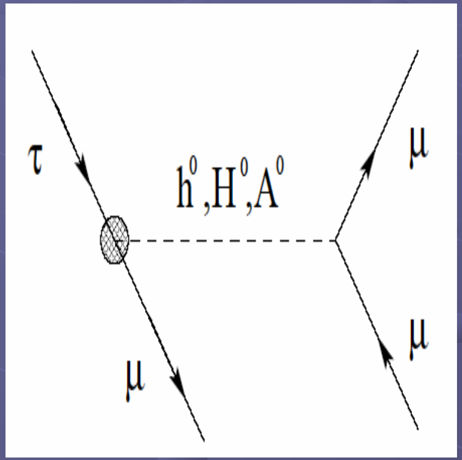
$$\mathrm{Br}(\tau \xrightarrow{A} \mu\eta) \simeq \frac{9G_F^2(F_\eta^8)^2 m_\eta^4 m_\tau^3 \tau_\tau}{128\pi} \frac{1}{m_A^4} |\kappa_{32}|^2 \tan^6\beta < 3.4 \times 10^{-7}$$

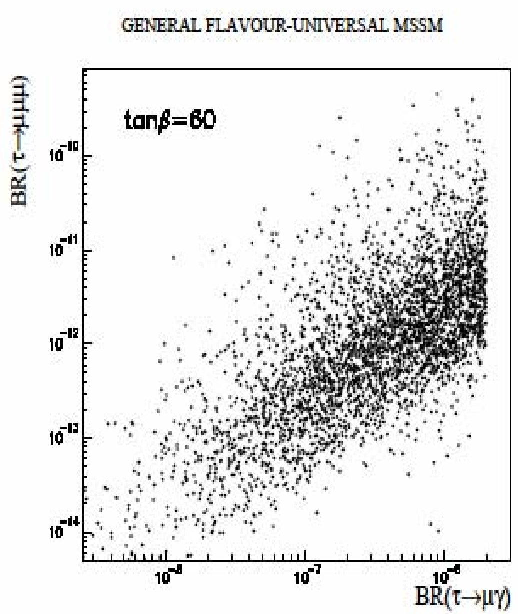
$$|\kappa_{32}|^2 < 0.3 \times 10^{-6} \times \left(\frac{m_A}{150[\mathrm{GeV}]}\right)^4 \times \left(\frac{60}{\tan\beta}\right)^6 .$$

For κ_{31}, similar bound is obtained.

The correlation between the Higgs mediation and the gauge mediation

For relatively low m_{SUSY}, the Higgs mediated LFV is constrained by current data for the gauge mediated LFV.





Scatter plot of Higgs-mediated $\mathrm{Br}(\tau \to 3\mu)$ against $\mathrm{Br}(\tau \to \mu\gamma)$ in GFU-MSSM.
$m_0^{\tilde{q}}, m_0^{\tilde{l}}, m_0^{H_d}, m_0^{H_u} < 700$ GeV

$\mathrm{Br}(\tau \to \mu\gamma)$ strongly constrains $\mathrm{Br}(\tau \xrightarrow{\text{Higgs}} 3\mu)$.

Dedes Ellis Raidal

For $m_{SUSY} >$ O(1)TeV, the gauge mediation becomes suppressed, while the Higgs mediated LFV can be large.

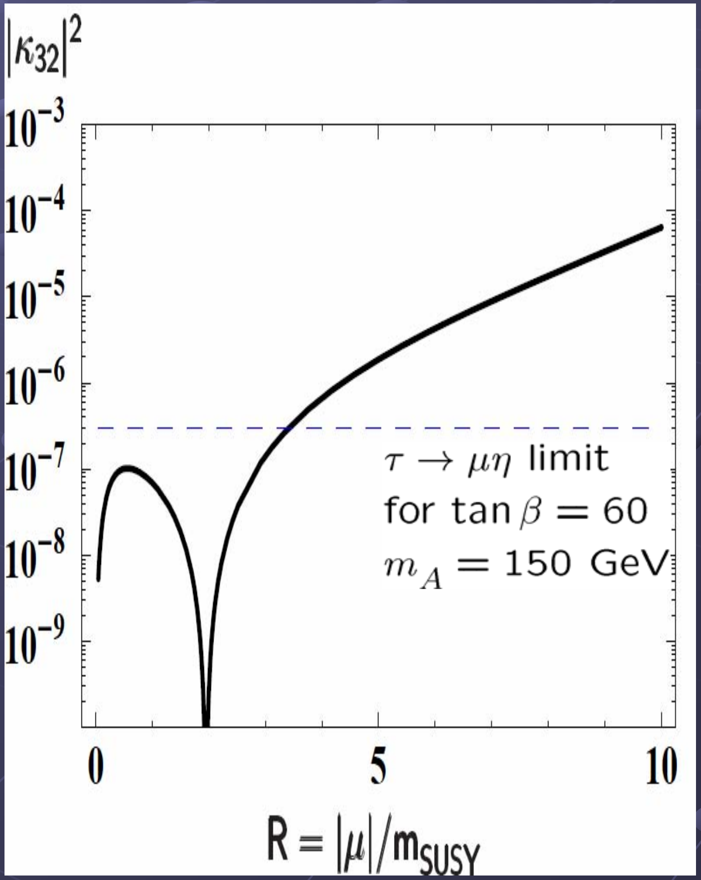
Decoupling property of the Higgs LFV coupling (κ_{ij})

Consider that M_{SUSY} is as large as O(1) TeV with a fixed value of $|\mu|/M_{SUSY}$

Gauge mediated LFV is suppressed, while the Higgs-LFV coupling κ_{ij} can be sufficiently large .

Babu,Kolda;
Brignole, Rossi

$m_{SUSY} \sim$ O(1) TeV



$$\mathrm{Br}(\tau \to \mu\eta) \sim \mathrm{Br}(\tau \to e\eta) \sim 3 \times 10^{-7}$$

Search for Higgs mediated τ- e & τ- μ mixing at ILC

- Tau's rare decays at B factories.

  $\tau \rightarrow e\pi\pi$ ($\mu\pi\pi$)

  $\tau \rightarrow e\eta$ ($\mu\eta$)

  $\tau \rightarrow \mu e e$ ($\mu\mu\mu$), ….

$$\mathrm{Br}(\tau \to \mu\eta) \sim \mathrm{Br}(\tau \to e\eta) \sim 3 \times 10^{-7}$$

  In near future, τ rare decay searches may improve the upper limit by about 1 order of magnitude.

- We here discuss the other possibilities.
  - Higgs decays into a tau-mu or tau-e pair
  - The DIS process e N $\rightarrow \tau$ X

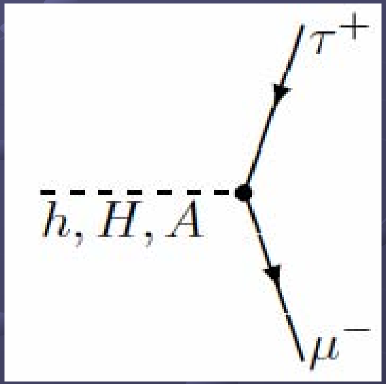
    by a fixed target experiment at ILC

The LFV Higgs boson decay

LFV Higgs boson decays

After the Higgs boson is discovered, we can consider the possibility to measure the LFV Yukawa couplings directly from the decay of the Higgs bosons.

- LHC   Assamagan et al; Brignole, Rossi
- LC   SK, Matsuda, Ota, Shindou, Takasugi, Tsumura

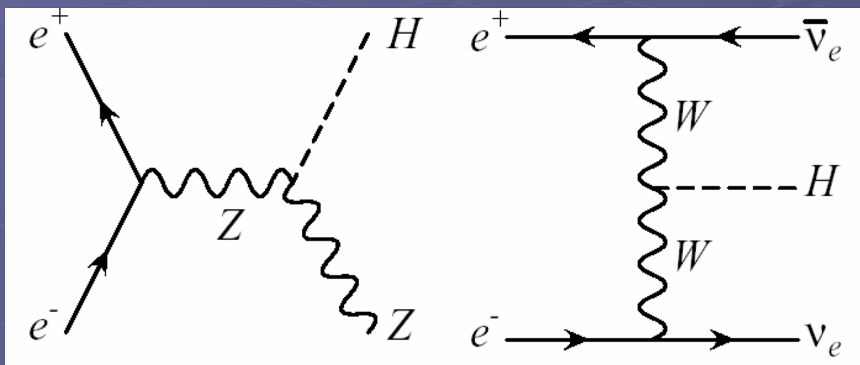


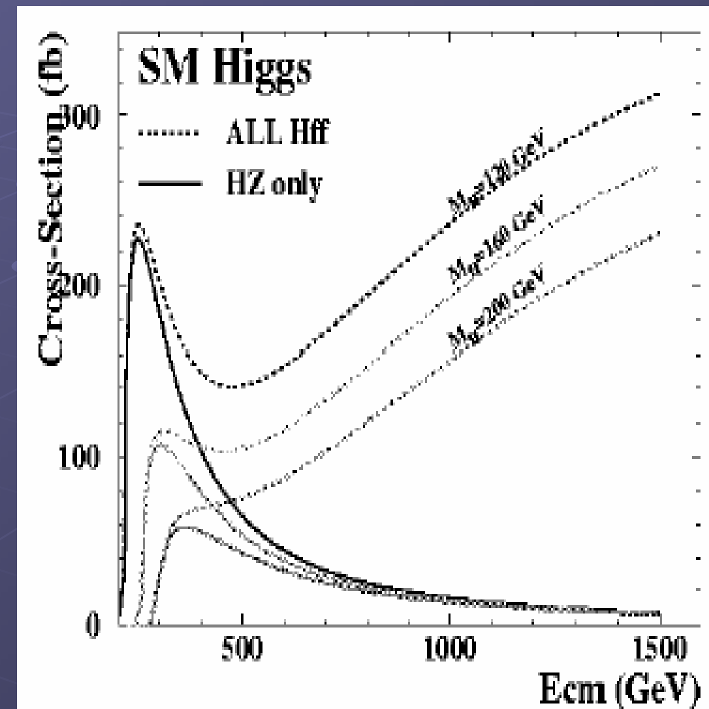
Search for h →τμ (τe) at a LC:

- Simple kinematic structure (Esp. Higgssrahlung process)
- Precise measurement of the lightest Higgs boson:
  property (m_h,Γ,σ,Br,…) will be thoroughly measured
- Less backgrounds

Higgs Production at a LC

via gauge interaction





$$\sigma \sim 200\ \text{fb}$$

At low energies, the Higgsstrahlung process is dominant.

In 2HDM (MSSM), $\sigma = \sigma_{\text{SM}} \times \sin^2(\alpha - \beta).$

Decay branching ratios

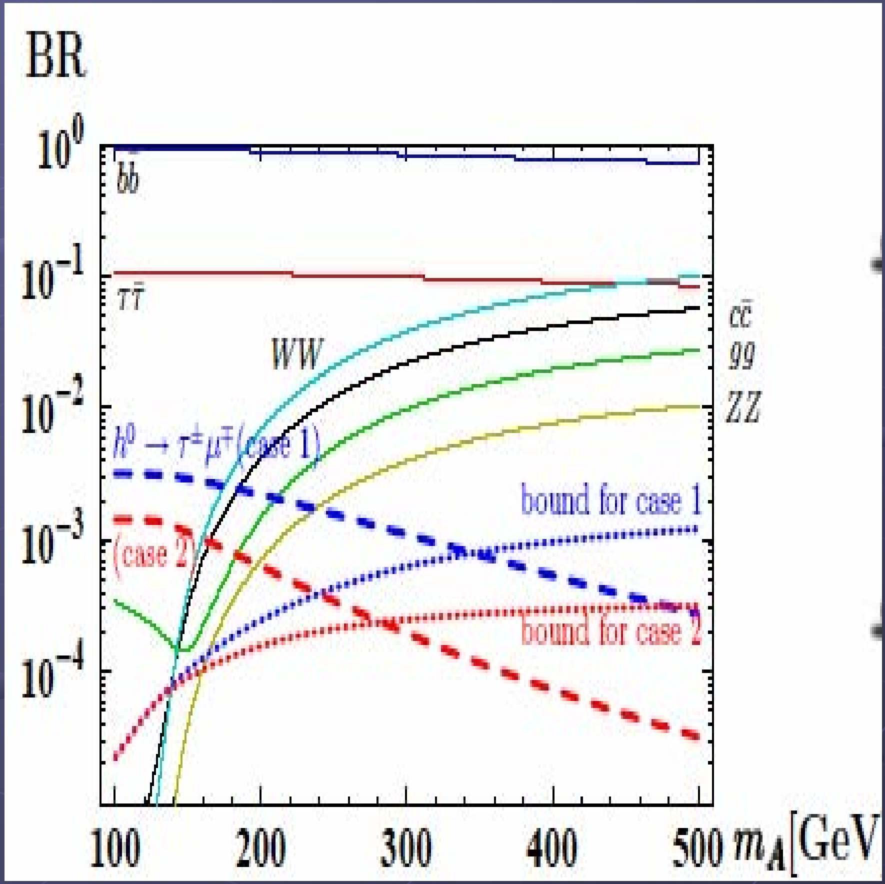
$$\mathrm{Br}(h \to \tau^{\pm} + \mu^{\mp}) \simeq \frac{1}{N_c}\frac{m_\tau^2}{m_b^2}\frac{\cos^2(\beta-\alpha)}{\sin^2\alpha\cos^2\beta}|\kappa_{32}|^2 .$$

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

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

$$\mathrm{Br}(\tau \xrightarrow{A} \mu\eta) \simeq \frac{9G_F^2(F_\eta^8)^2 m_\eta^4 m_\tau^3 \tau_\tau}{128\pi}\frac{1}{m_A^4}|\kappa_{32}|^2\tan^6\beta < 3.4\times 10^{-7}$$

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



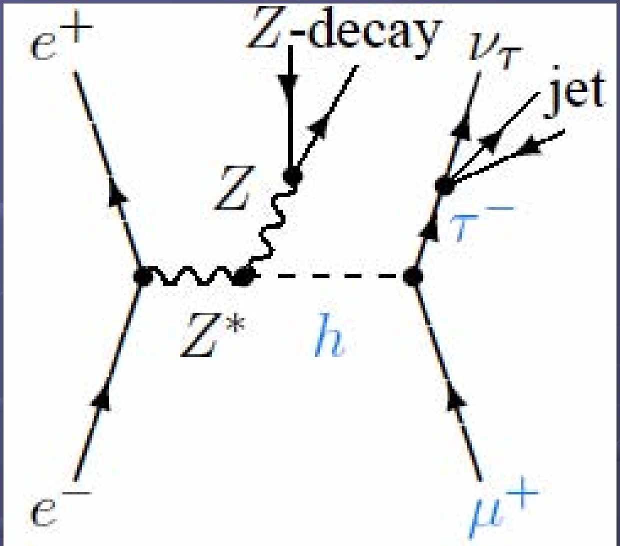
When m_A is large,
the experimental bound is relaxed,
and branching ratio of
10^(-4)-10^(-3) is allowed.

Signal

The process can be identified by using Z recoil:

- The τ momentum is reconstructed by using E_{cm}, m_h, p_Z and p_μ

  It is not required to measure τ



- The # of the signal event

$$N_{\text{signal}} = L \times \sigma(e^+e^- \to hZ) \times \mathrm{Br}(h \to \tau\mu) \times \epsilon$$

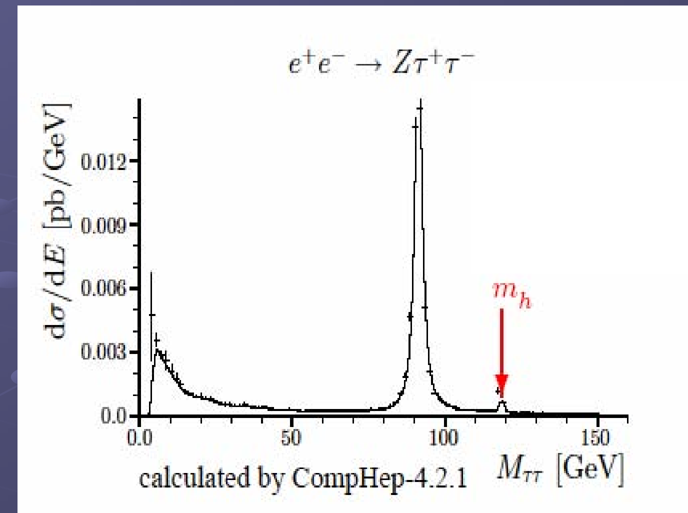
$$\epsilon = \begin{cases} \mathrm{Br}(Z \to \ell^+\ell^-) & (\sim 7\%) \\ \mathrm{Br}(Z \to jj) & (\sim 73\%) \end{cases}$$

11 event for leptonic decay of Z
118 event for hadronic decay

$L = 1000\mathrm{fb}^{-1}$, $\sqrt{s}$: optimally tuned,
$|\kappa_{32}|^2 = 8.4 \times 10^{-6}$

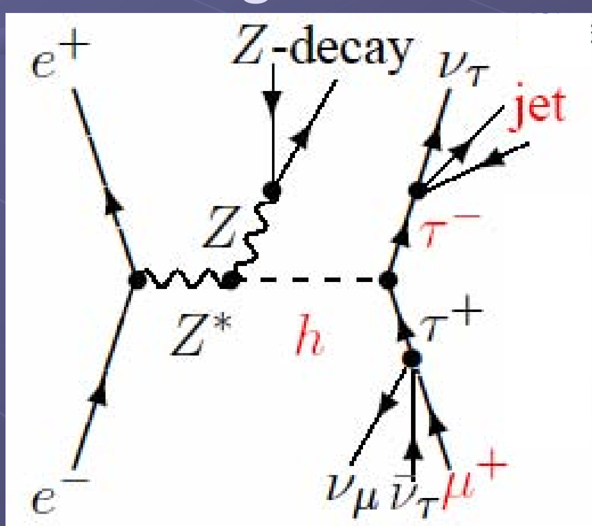
Backgrounds

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



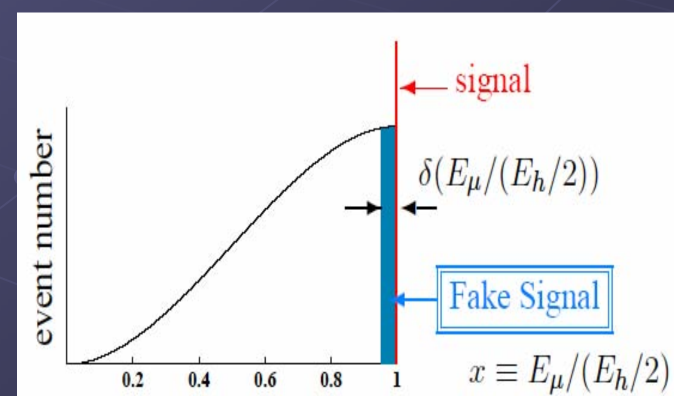
The background is huge, but most of them can be cut by appropriate kinematic cuts.

Fake signal



with

$$p_{\mu^+} \simeq p_{\tau^+}$$



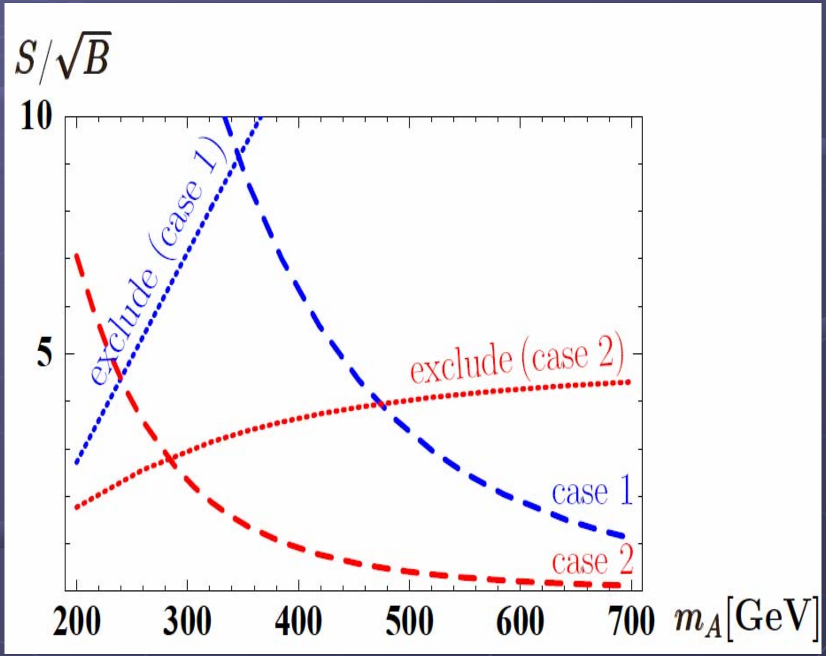
In order to reduce the fake signal events, it is important to determine E_h with high precision from p_Z, E_{cm}, p_μ.

Feasibility of h →τμ

- Resolution of Z momentum: $\delta \sim 0.3\sqrt{E_Z}$ GeV (jj), $\sim 0.1\sqrt{E_Z}$ GeV $(\ell\ell)$

- Signal / Fake
  118 / 230 events
  (Z →jj、 δ = 3 GeV)
  11 / 8 events
  (Z→ll, δ = 1GeV)

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



For some limited parameter region,
h → τμ （τe） can be tested at a LC.

Case of the general two Higgs doublet model

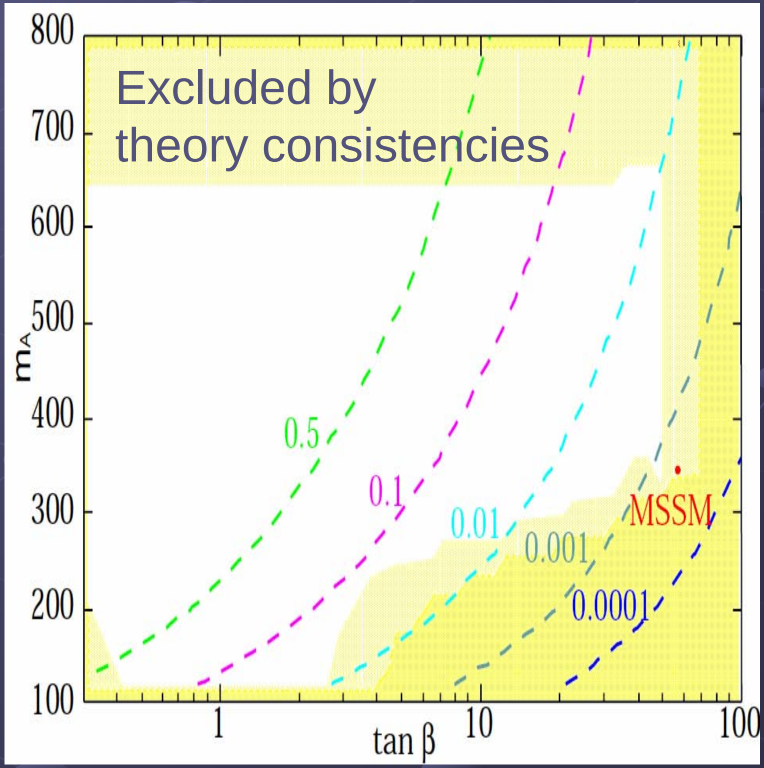
SK, Ota, Tsumura, in preparation

Under the constraint from theoretical consistencies such as vacuum stability and perturbative unitarity, and also that from the LEP precision data and tau LFV rare decay data, the maximum value of Br(h→μτ) can be very large in the low tanβ region.

$$\mathrm{Br}(\tau \xrightarrow{A} \mu\eta) \simeq \frac{9G_F^2 (F_\eta^8)^2 m_\eta^4 m_\tau^3 \tau_\tau}{128\pi} \frac{1}{m_A^4} |\kappa_{32}|^2 \tan^6\beta < 3.4 \times 10^{-7}$$

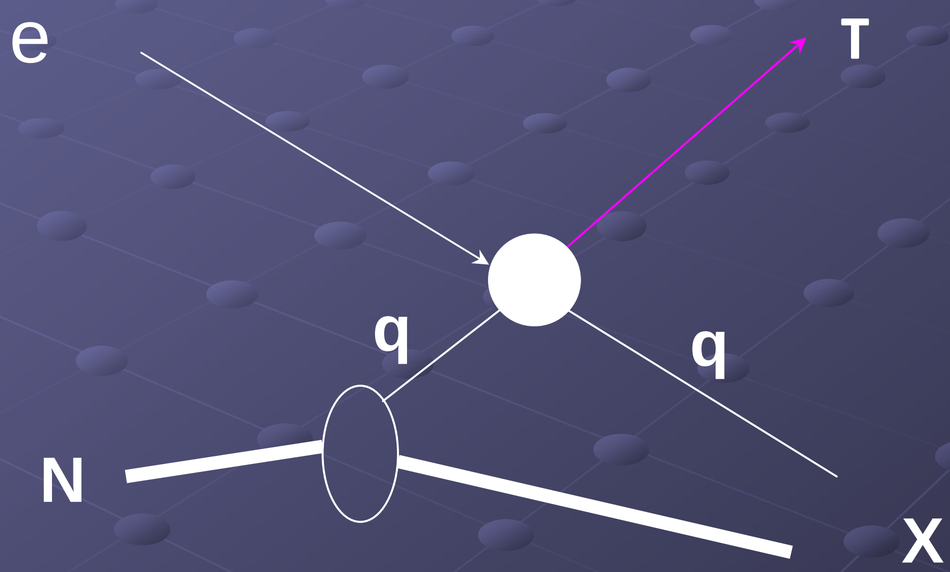
$$|\kappa_{32}|^2 < 0.3 \times 10^{-6} \times \left(\frac{m_A}{150[\mathrm{GeV}]}\right)^4 \times \left(\frac{60}{\tan\beta}\right)^6 .$$

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



ILC can largely improve the LFV coupling in low tanβ region.

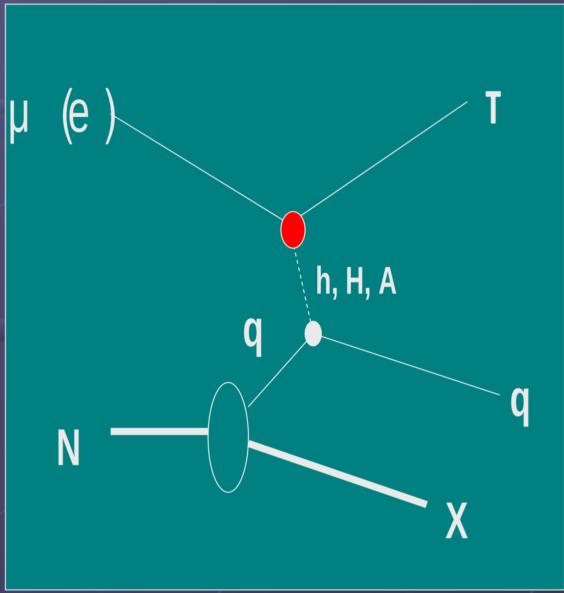
The DIS process $eN \to \tau X$



Alternative process for search of the Higgs LFV coupling

- At future ν factories (μ colliders) , 10^20 muons of energy 50 GeV (100-500GeV) can be available. DIS μ N→τ X process

M. Sher; SK et al

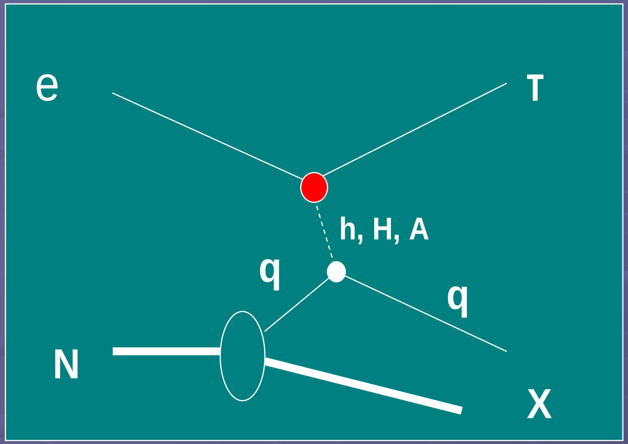


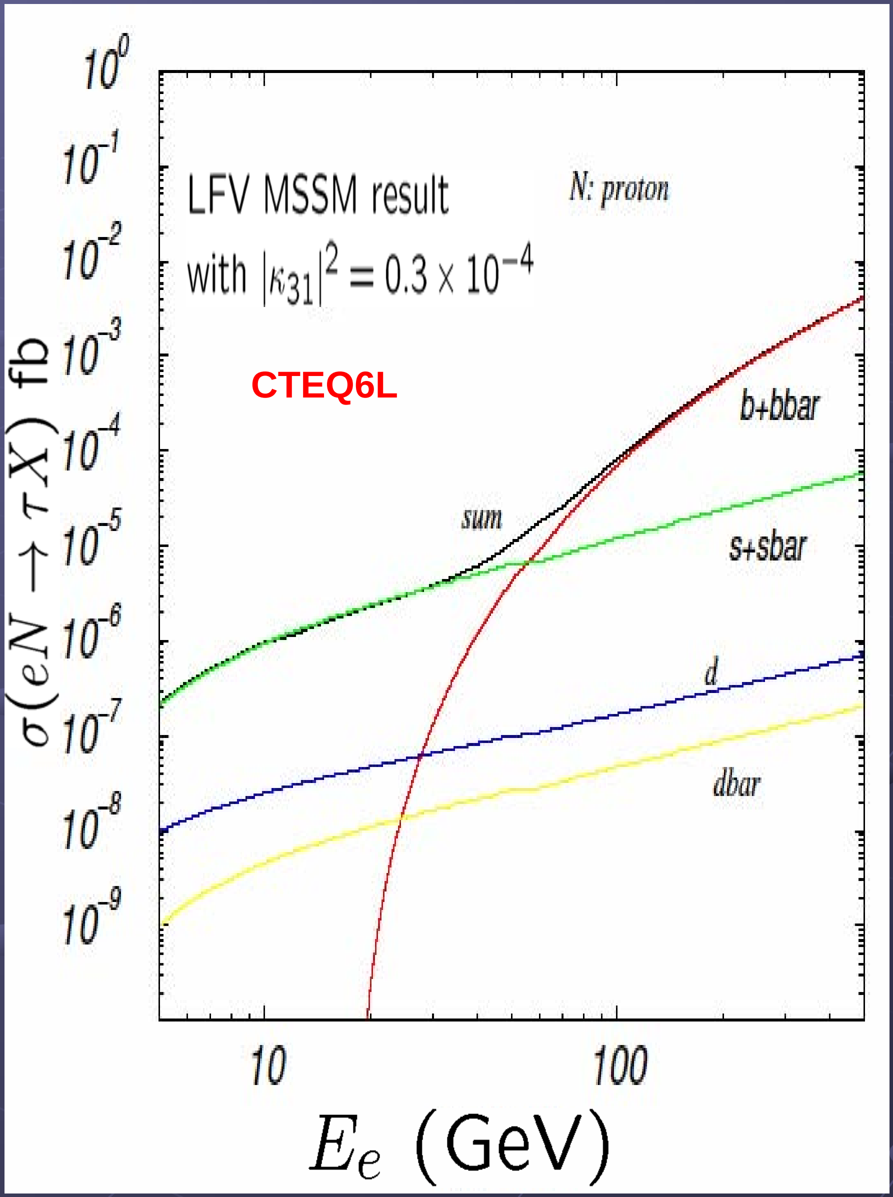
- At a LC (Ecm=500GeV L=10^34/cm^2/s) 10^22 of 250GeV electrons available. DIS process e N→τ X process

A fixed target experiment option of ILC

Enhancement of cross section in SUSY

Higgs mediated process



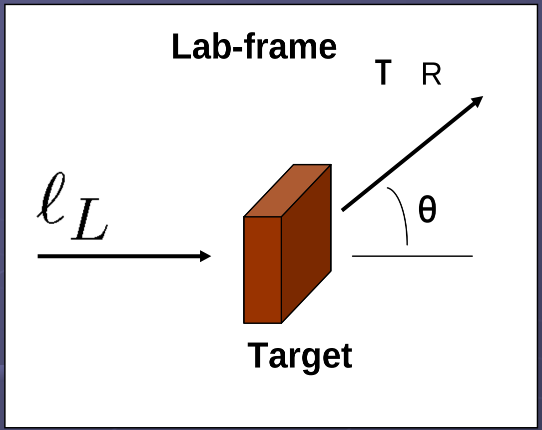


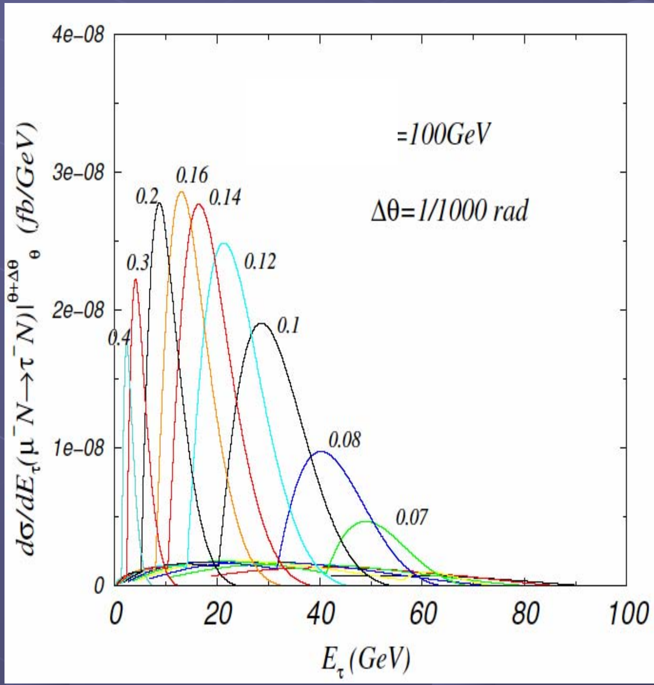
- Each sub-process
  e q →τq
  is proportional to the down-type quark masses.
- For the energy > 60 GeV, the total cross section
  is enhanced due to
  the b-quark sub-process

  E = 50 GeV 10^(-5)fb
  100 GeV 10^(-4)fb
  250 GeV 10^(-3)fb

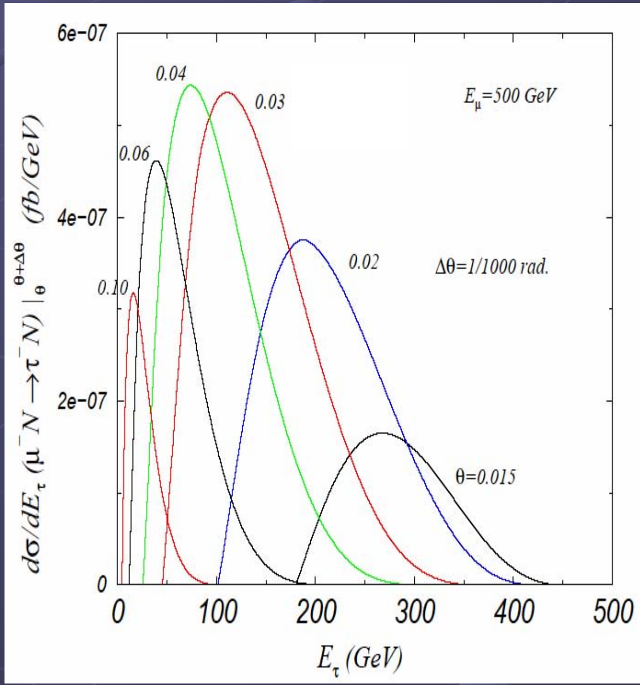
Energy distribution for each angle

- From the e_L beam, τ_R is emitted to the backward direction due to $(1-\cos\theta_{CM})^2$ nature in the CM frame.
- In Lab-frame, tau is emitted forward direction but with large angle with a P_T.





E = 100 GeV



E = 500 GeV

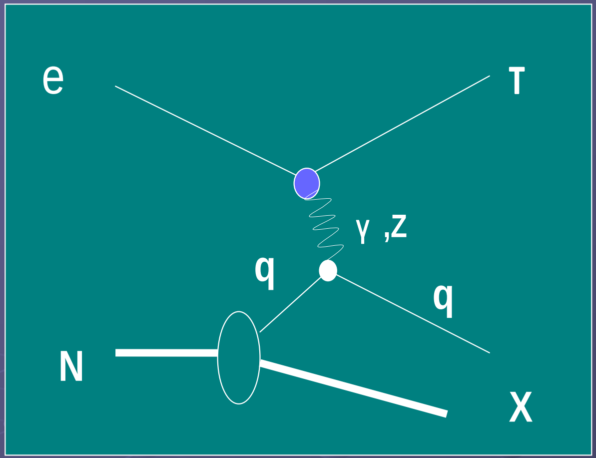
Contribution of the gauge boson mediation

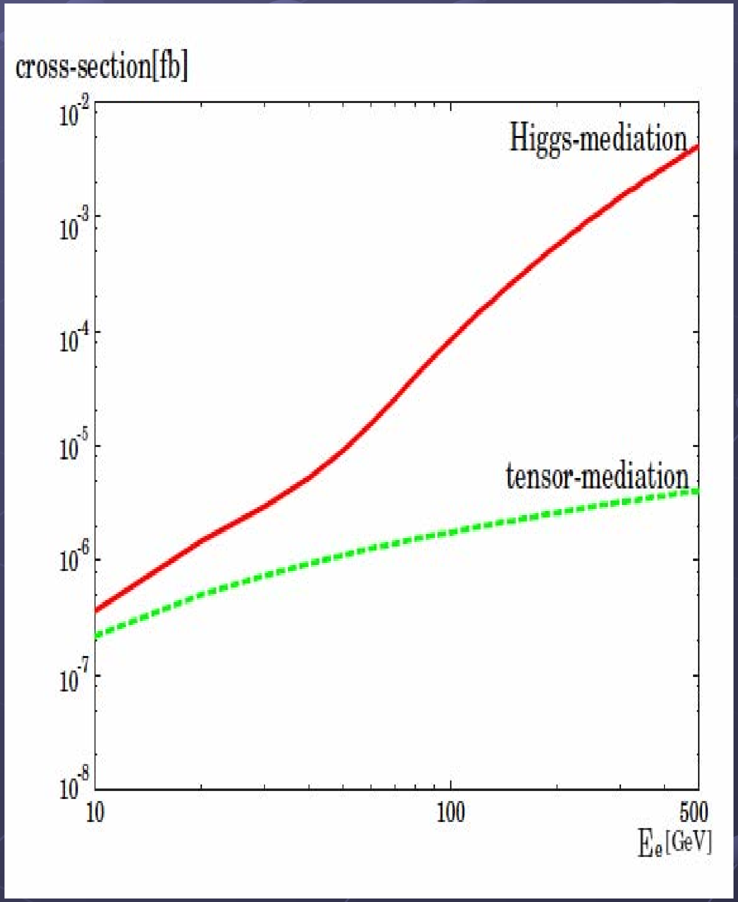
$$Br(\tau \to e\gamma) < 3 \times 10^{-7} \text{ (Belle)}$$

τ→eγ results gives the upper bound on the tensor coupling, therefore on the e N →τX cross section

Gauge coupling
⇒ No bottom Yukawa enhancement

At high energy
DIS e N →μX process is more sensitive to the Higgs mediation than the gauge mediation.





Number of taus

$E_e = 250$ GeV,

$L = 10^{34}$ /cm^2/s, $\Rightarrow$ 10^{22} electrons

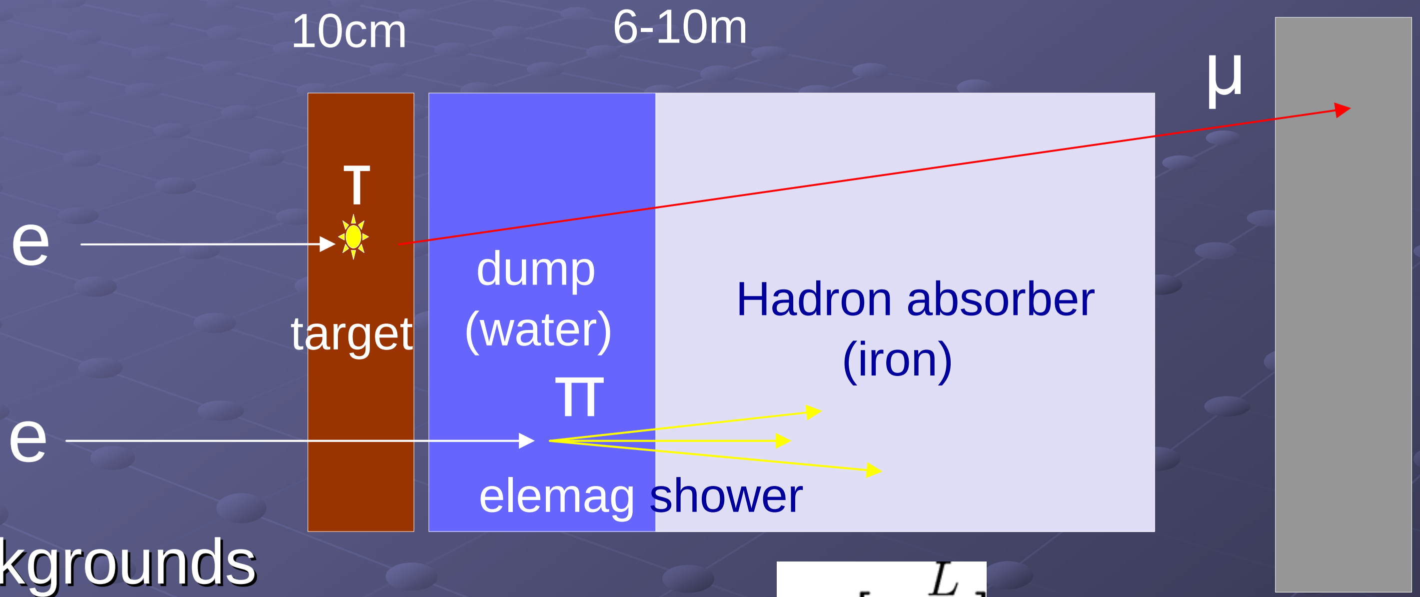
In a SUSY model with $|\kappa_{31}|^2 = 0.3\times10^{-6}$:

$\sigma = 10^{-3}$ fb

10^5 of τleptons are produced for the target of $\rho = 10$ g/cm^2

Naively, non-observation of the high energy muons from the tau of the $e\,N \to \tau\,X$ process may improve the current upper limit on the e-τ-Φcoupling^2 by around 4 orders of magnitude

- High energy muon from tau is a signal
- Geometry (picture)   ex) target ρ=10g/cm^2



$$exp[-\frac{L}{\lambda_0}]$$

- Backgrounds
  - Pion punch-through
  - Muons from Pion decay-in-flight
  - Muon from the muon pair production
  - …….

Realistic Monte Carlo simulation is in preparation. GEANT,…

SK, Y. Kuno, M. Kuze, T. Ota, T. Takai

Summary 1

- We discussed LFV in the Higgs coupling
  - Direct search via the decay process $h \to \tau\mu$ at a LC
  - DIS process $e\, N \to \tau X$ by using the high energy electron beam of a LC with a fixed-target.
- $h \to \tau\mu$ at a LC:
  - The backgrounds can be reduced by kinematic cuts
  - The signal may be detectable, if the LFV Higgs coupling κ_{32} is as large as its upper bound from the $\tau \to \mu\eta$ result.
  - Such a significant κ_{32} can be realized when M_{SUSY} is as large as TeV with μ/M_{SUSY} being O(1-10).
  - In the general 2HDM, larger significance is obtained under the current experimental constraint.

Summary 2

- DIS process $e\ N \to \tau X$:
  - Possibility of a fixed target experiment at a LC
  - For E > 60 GeV, the cross section is enhanced due to the sub-process of Higgs mediation with sea b-quarks
  - At a LC with Ecm=500GeV ⇒ σ = 10^(-3) fb

  L=10^34/cm^2/s ⇒ 10^22 electrons available

  ⇨ 10^5 of taus are produced for ρ=10 g/cm^2

  - Non-observation of the signal (high-energy muons) would improve the current limit by 10^4.
  - Realistic simulation: work in progress.