A Study on
Muon (Electron) to Tau Conversion
In Deep Inelastic Scattering

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With S.K.'s Transparencies (+mod.)

S.Kanemura, YK, T. Ota, M. Kuze PLB607(2005)165

S.Kanemura, YK, T. Ota, M. Kuze, T. Takai Work in progress

At Workshop of "Flavour in the Era of the LHC",
CERN, November 9th, 2005

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    (a fixed target experiment at ILC)
- Summary

Introduction

Physics Motivation

- 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.

Tau-associated LFV

$\tau \Leftrightarrow e$ & $\tau \Leftrightarrow \mu$

- Tau-associated LFV is interesting in the case of the Higgs mediated LFV, which is proportional to the Yukawa coupling.

  (different behavior from μ e mixing case)
- Tau-associated LFV is less constrained by current data, in comparison to the $\mu \Leftrightarrow e$ mixing

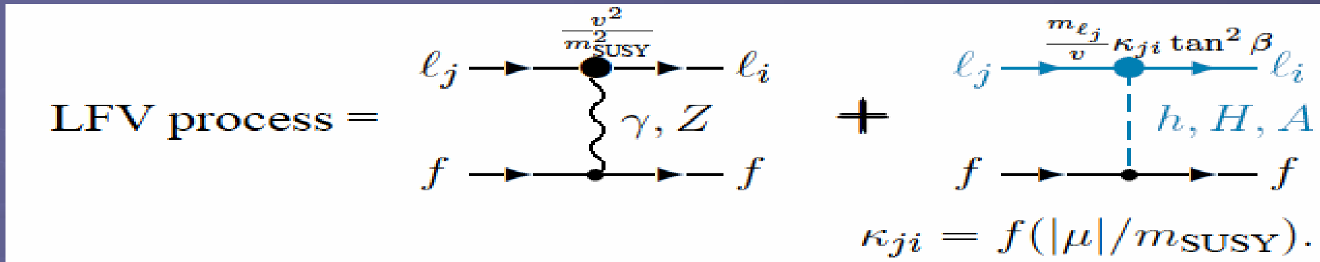
$\mu \to e\gamma$	1.2×10^{-11}
$\mu \to 3e$	1.1×10^{-12}
μ Ti→eTi	6.1×10^{-13}
$\tau \to \mu\gamma$	3.1×10^{-7}
$\tau \to 3\mu$	$(1.4 - 3.1) \times 10^{-7}$
$\tau \to \mu\eta$	3.4×10^{-7}

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. $\mu \to e\gamma$, $\mu \to eee$, ….
- This situation may be explained by 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 :

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

- Higgs mediation :

$$\mathcal{L} = \frac{m_{\ell_i}}{v} \kappa_{ij} (\tan^2 \beta)\, \bar{\ell}_i \ell_j \Phi, \quad (\Phi = h, H, A)$$

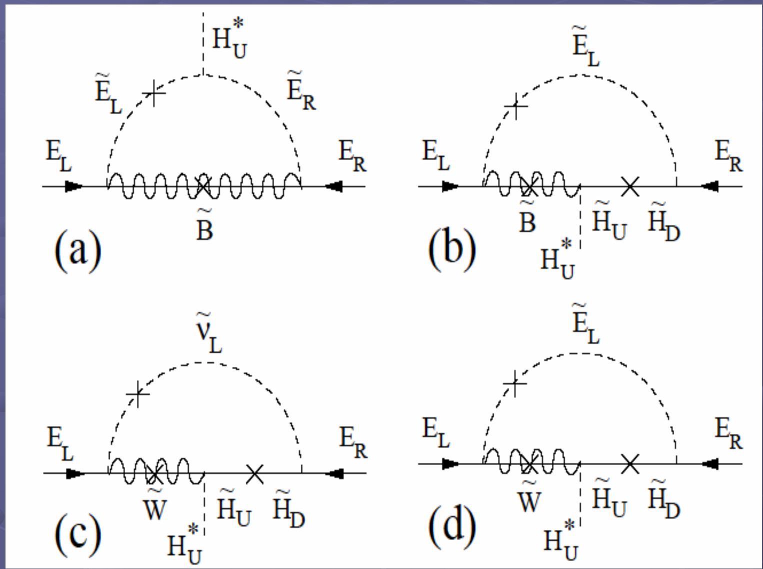
$$\Rightarrow \quad \kappa_{ij} \sim f(|\mu|/M_{SUSY})$$

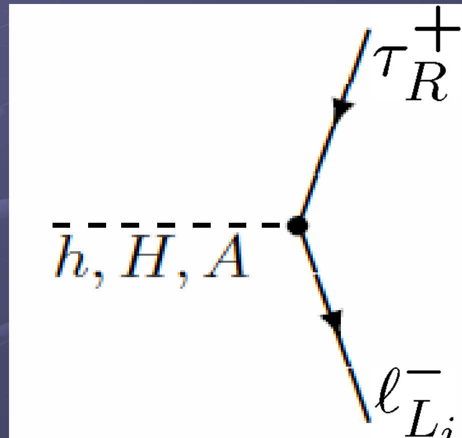
Higgs mediation does not decouple in the large M_{SUSY} limit

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

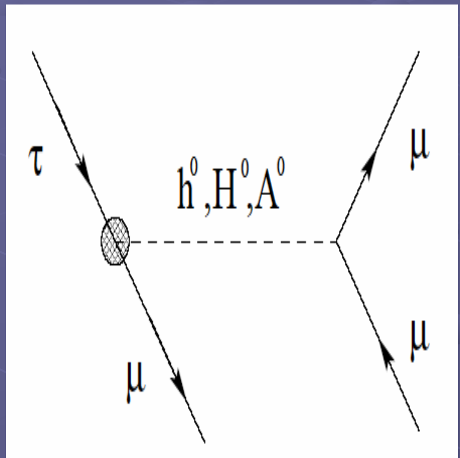
$$\mathcal{L}_{\tau\ell_i} = -\frac{\kappa_{3i} m_\tau}{v\cos^2\beta}\left\{\cos(\alpha-\beta)h^0 + \sin(\alpha-\beta)H^0 - iA^0\right\}(\overline{\tau_R}\ell_{Li})$$

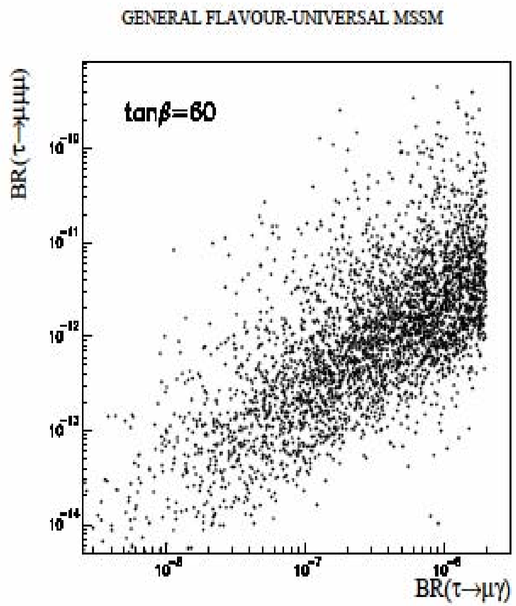
κ ij = Higgs LFV parameter

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

Higgs Mediation vs. 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.

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.

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

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

For κ_{31}, similar bound is obtained.

Current Data

Mode	Belle (90% CL)	Babar (90% CL)
$\tau^- \to e^- \pi^0$	1.9×10^{-7}[2]	
$\tau^- \to e^- \eta$	2.4×10^{-7}[2]	
$\tau^- \to e^- \eta'$	10×10^{-7}[2]	
$\tau^- \to \mu^- \pi^0$	4.1×10^{-7}[2]	
$\tau^- \to \mu^- \eta$	1.5×10^{-7}[2]	
$\tau^- \to \mu^- \eta'$	4.7×10^{-7}[2]	
$\tau^- \to e^- \pi^+ \pi^-$	8.4×10^{-7}[3]	1.2×10^{-7}[4]
$\tau^- \to e^- \pi^+ K^-$	5.7×10^{-7}[3]	3.2×10^{-7}[4]
$\tau^- \to e^- K^+ \pi^-$	5.6×10^{-7}[3]	1.7×10^{-7}[4]
$\tau^- \to e^- K^+ K^-$	3.0×10^{-7}[3]	1.4×10^{-7}[4]
$\tau^- \to \mu^- \pi^+ \pi^-$	2.8×10^{-7}[3]	2.9×10^{-7}[4]
$\tau^- \to \mu^- \pi^+ K^-$	6.3×10^{-7}[3]	2.6×10^{-7}[4]
$\tau^- \to \mu^- K^+ \pi^-$	15.5×10^{-7}[3]	3.2×10^{-7}[4]
$\tau^- \to \mu^- K^+ K^-$	11.7×10^{-7}[3]	2.5×10^{-7}[4]
$\tau^- \to e^- e^+ e^-$	3.5×10^{-7}[5]	2.0×10^{-7}[6]
$\tau^- \to e^- \mu^+ \mu^-$	2.0×10^{-7}[5]	3.3×10^{-7}[6]
$\tau^- \to \mu^- e^+ e^-$	1.9×10^{-7}[5]	2.7×10^{-7}[6]
$\tau^- \to \mu^- \mu^+ \mu^-$	2.0×10^{-7}[5]	1.9×10^{-7}[6]
$\tau \to e\gamma$	3.9×10^{-7}[7]	
$\tau \to \mu\gamma$	3.1×10^{-7}[8]	6.8×10^{-8}[9]

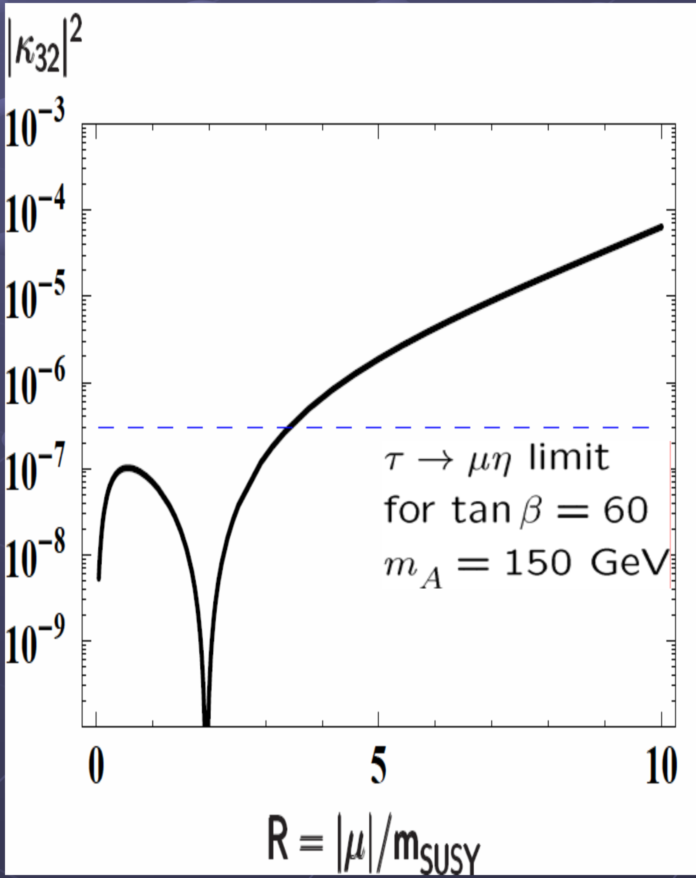
Decoupling property of the Higgs LFV coupling (κ ij)

Consider that MSUSY is as large as O(1) TeV with a fixed value of | μ |/MSUSY

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 future colliders

- Tau rare decays at B factories.

$\tau \to e \pi \pi \quad (\mu \pi \pi)$

$\tau \to e \eta \quad (\mu \eta)$

$\tau \to \mu ee \quad (\mu \mu \mu)$, ...

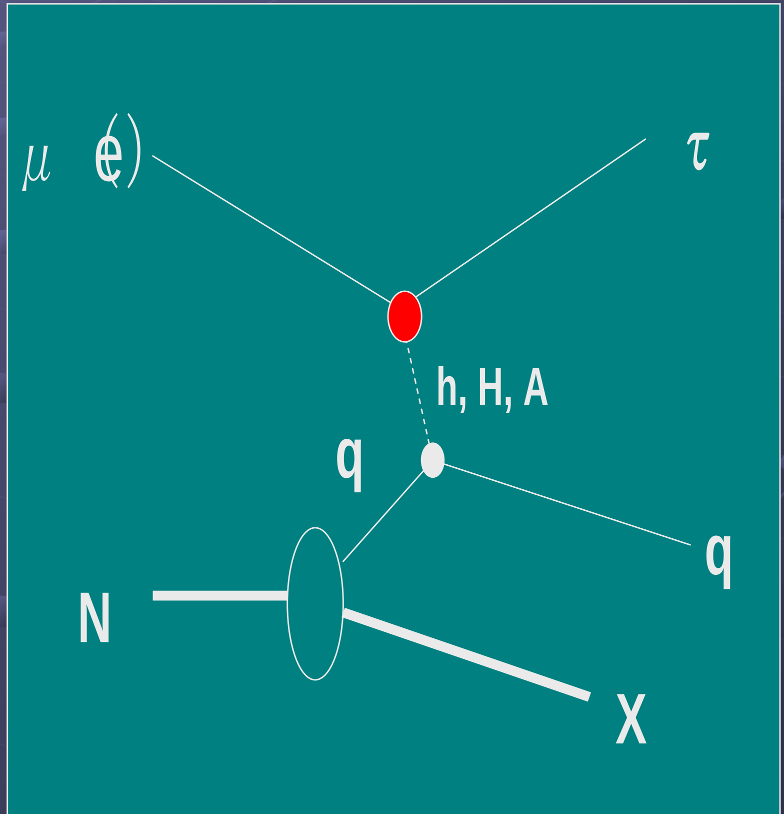
$\mathrm{Br}(\tau \to \mu\eta)$
$\sim \mathrm{Br}(\tau \to e\eta) \sim 3 \times 10^{-7}$

In near future, super B-factories may improve the upper limits by about one order of magnitude.

- We here discuss the other possibilities.
  - The DIS process μ N (eN)$\to \tau$ X at a fixed target experiment at a neutrino factory and a LC

Search for LFV Yukawa Coupling

- $\mu N \rightarrow \tau X$ DIS process at future a neutrino factory (or a muon collider) , about 10^{20} muons/year of energy 50 GeV (or 100-500GeV) can be available.
- $eN \rightarrow \tau X$ DIS process at a LC (Ecm=500GeV L=10^{34}/cm^2/s), 10^{22} electrons/year of 250 GeV electrons available. (a fixed target option at ILC).



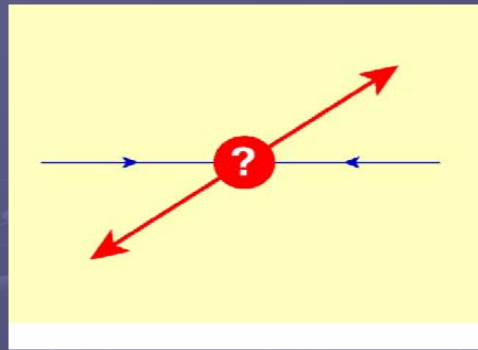
NuFACT at J-PARC

Muon beam at
Neutrino Factory :
Energy = 20-50 GeV
Intensity = 10^{20} /year

PRISM for
mu-e conversion
experiment ($<10^{-18}$)

A Linear Collider (ILC)

e^+e^- collision



ILC (former JLC, TESLA, NLC)

1st stage

$\sqrt{s} = 220 - 500\text{GeV}$ $\int L = 50 - 500\text{fb}^{-1}$

2nd stage

$\sqrt{s} = 500 - 1500\text{GeV}$ $\int L = 500 - 1000\text{fb}^{-1}$

Roadmap report JLC

Constraints of New Physics on the τ μ coupling from Data

$$\mathcal{L} \sim \frac{4\pi}{\Lambda^2}(\bar{\mu}\Gamma\tau)(\bar{q}^{\alpha}\Gamma q^{\beta})$$

$$\Gamma = (1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu})$$

- Scalar coupling $\tau \to \mu\ \pi\ \pi$ $\Lambda \sim 2.6$ TeV
- Pseudo scalar coupling $\tau \to \mu\ \eta$ ~ 12 TeV
- Vector $\tau \to \mu\ \rho$ ~ 12 TeV
- Pseudo vector $\tau \to \mu\ \pi$ ~ 11

Black, Han, He, Sher, 2002

Cross Sections with Effective Couplings

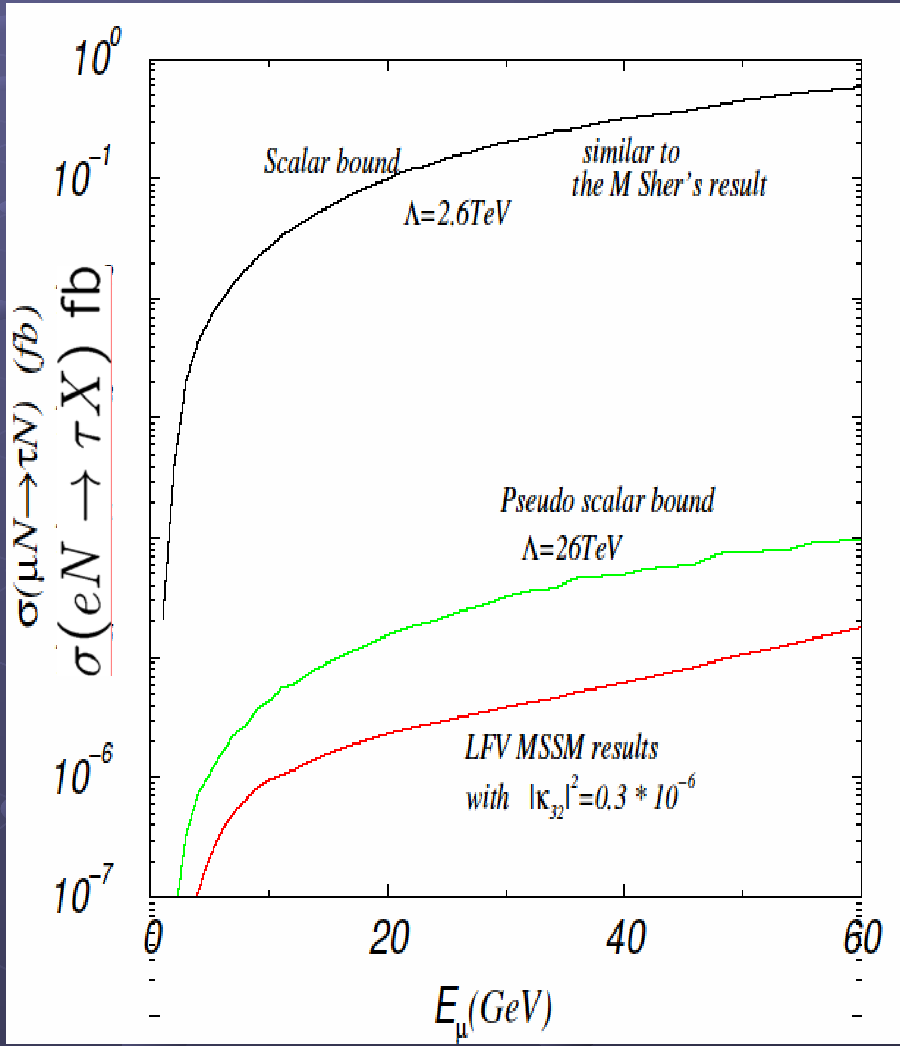
Scalar coupling

---several 10^{-1} fb

- In SUSY,

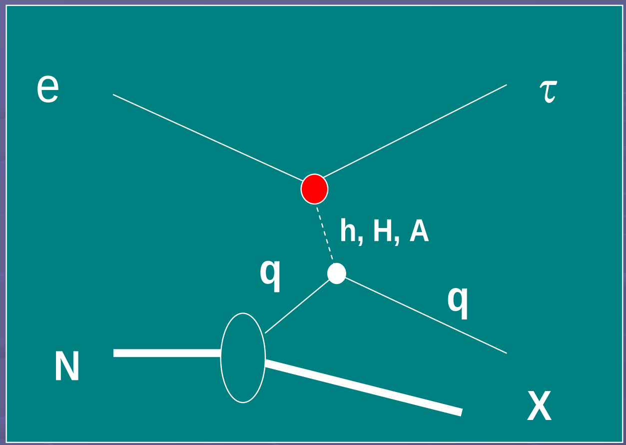
  scalar coupling = pseudo scalar coupling which makes the cross section 10^{-4}-10^{-5} smaller than scalar coupling bound

PDF : CTEQ6L



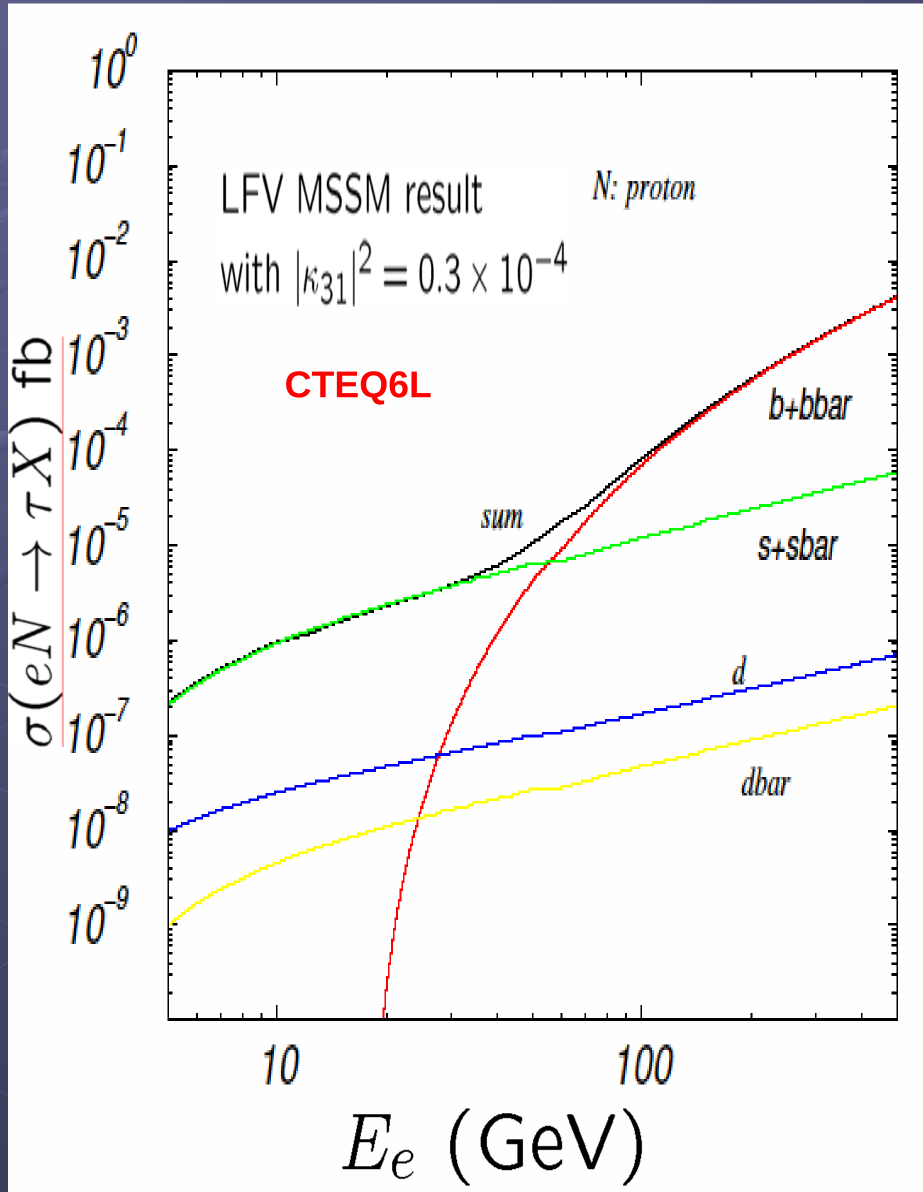
DIS Cross Section

Higgs mediated process



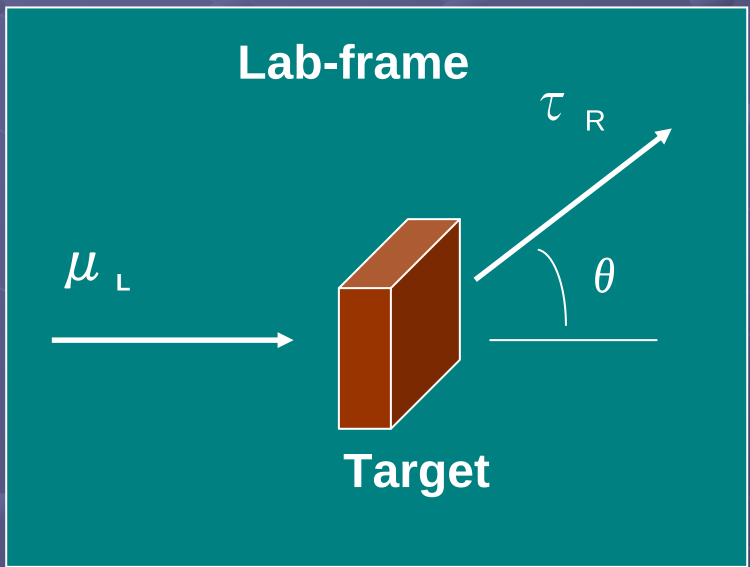
- Each sub-process $\mu(e)q \rightarrow \tau\ q$ is proportional to the down-type quark masses.
- For the energy > 60 GeV, the total cross section is enhanced due to the b-quark sub-process

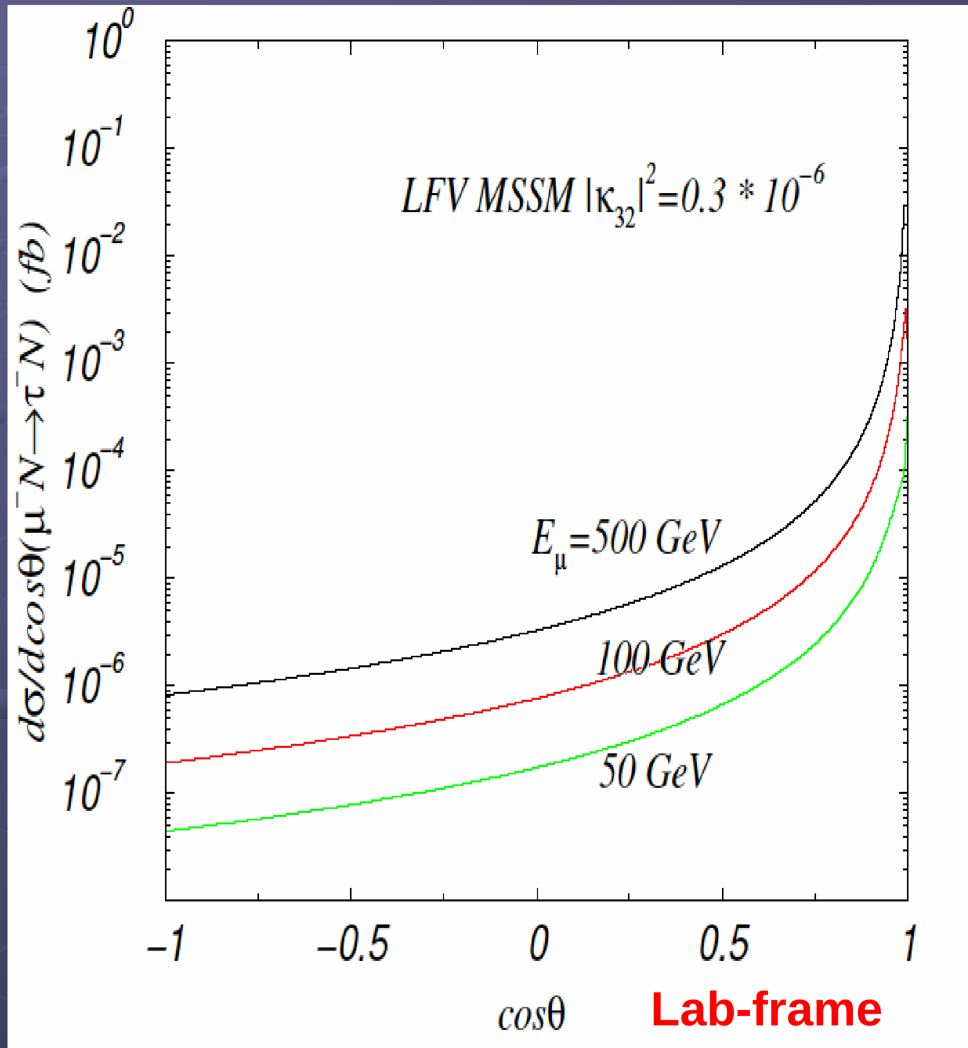
E ＝50 GeV 10^{-5}fb
100 GeV 10^{-4}fb
250 GeV 10^{-3}fb



Angular Distribution (Higgs Mediation)

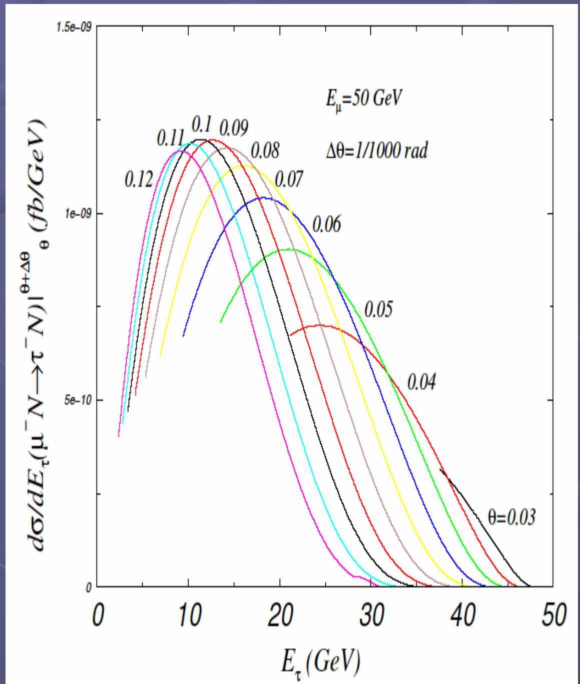
Higgs mediation
→ chirality flipped
→ $(1-\cos\theta_{CM})$



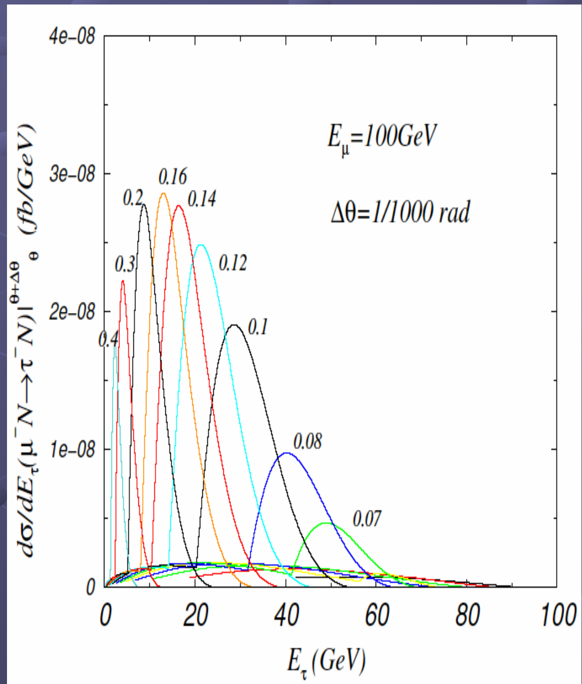


Energy Distribution at Different Angles

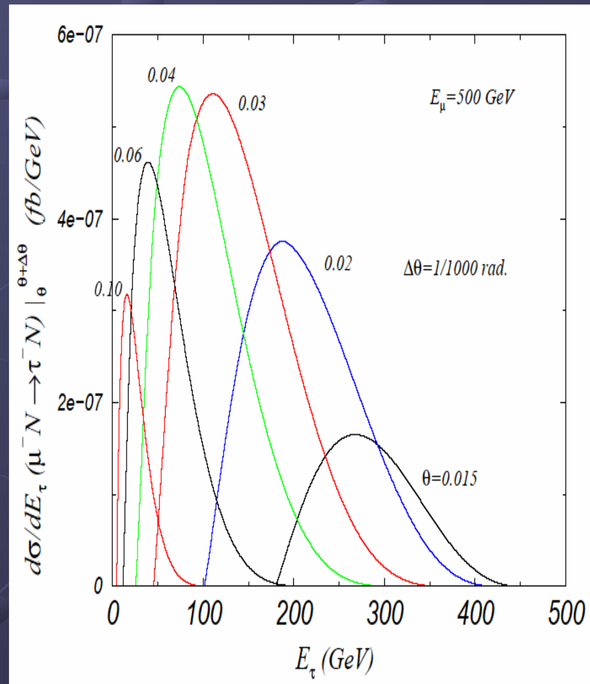
- From a left-handed μ_L beam, τ_R is emitted to the backward direction due to $(1 - \cos\theta_{CM})$ nature in CM frame.
- In Lab-frame, tau is emitted forward direction with some P_T.



$E\mu$ =50 GeV



$E\mu$ =100 GeV



$E\mu$ =500 GeV

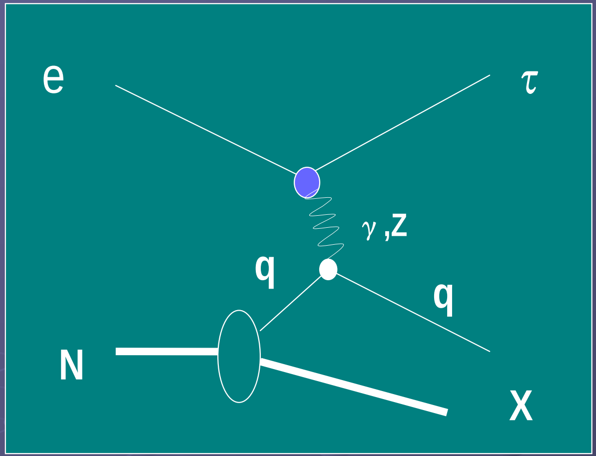
Contribution of
Gauge Boson Mediation

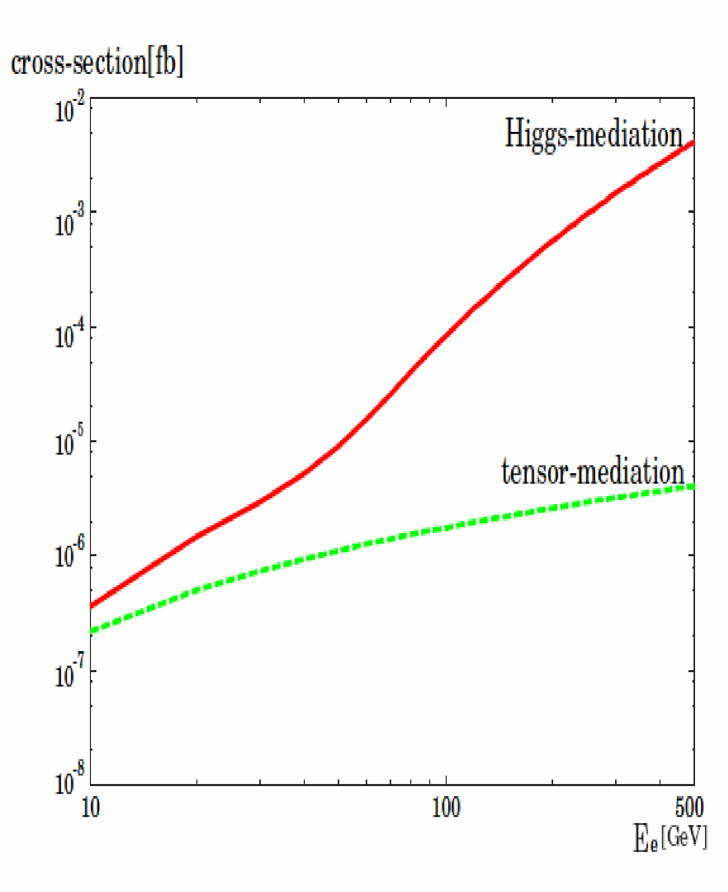
$\tau \to e\gamma$ results gives the upper bound on the tensor coupling, therefore on the $e N \to \tau X$ cross section

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

Gauge coupling
$\Rightarrow$ No bottom Yukawa enhancement

At high energy, $\mu(e)N \to \tau X$ DIS process is more
sensitive to the Higgs mediation than the gauge mediation.





Experiments

Target:
muon beam 100g/cm^2
electron beam 10g/cm^2

- Near future
  - CERN μ beam (200GeV)

Beam	Intensity	Cross section	Signal/year
200GeV μ	10^{14}muons/year	10fb	10^{2}events

  - SLAC LC (50GeV)

50GeV e	10^{21}electrons/year	10^{-1}fb	10^{6}events

- Future
  - Neutrino Factory, muon collider

50GeV μ	10^{20}muons/year	10^{-5}fb	10^{2}events
500GeV μ	10^{20}muons/year	5×10^{-3}fb	5×10^{4}events

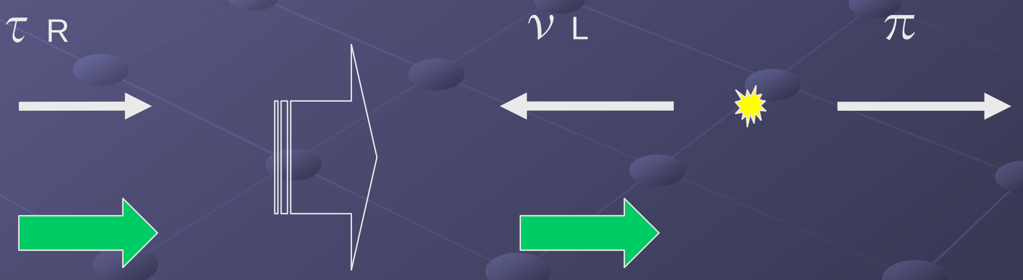
  - ILC fixed target option

250GeV e	10^{22}electrons/year	10^{-3}fb	10^{5}events

Muon beam

Signal

- # of tau for L =10^20 muons
  $|\kappa_{32}|^2 = 0.3 \times 10^{(-6)}$ (from the present limits)
  $E_\mu = 50$ GeV $100 \times \rho$ [g/cm^2] τ's
  100 GeV 1000
  500 GeV 50000
- Hadronic products from tau decays
  $\tau \rightarrow \pi$、 ρ , a1, ... $+$ missings
- Hard hadrons emitted into the same direction as the parent τ's
  $\tau_R \Rightarrow$ backward ν_L + forward π , ρ 、 ....



Bullock, Hagiwara, Martin

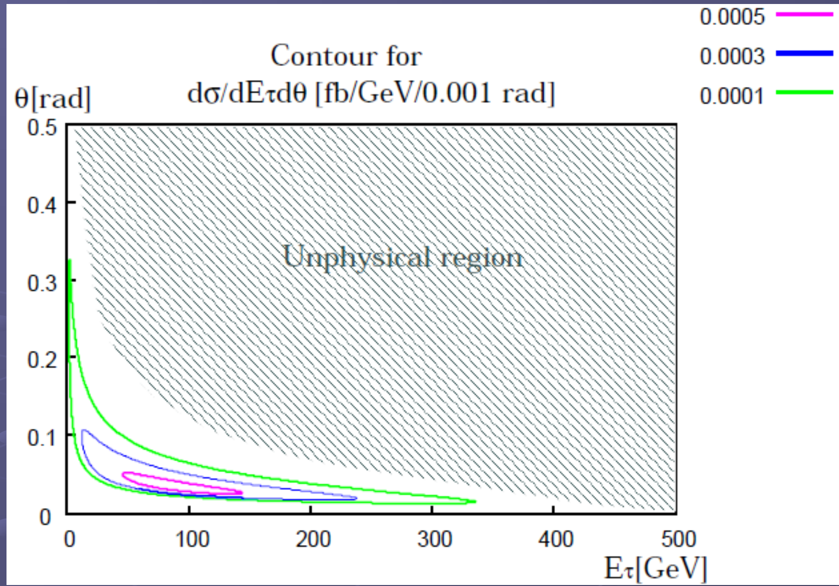
Backgrounds

- Hard hadrons from the target (N) should not be so serious, and smaller for higher energies of the initial muon beam.
- Hard muons from DIS $\mu N \to \mu X$ may fake signal.
  - Rate of mis-ID [machine dependent]
  - Emitted to forward direction without large P_T due to Rutherford scattering
    $1/\sin^4(\theta_{CM}/2)$
  - Energy cuts
- Realistic Monte Carlo simulation is necessary to see the feasibility

Signal $\frac{d^2\sigma}{dE_\tau d\theta}$

$$\mu N \to \tau X$$

Higgs boson mediation

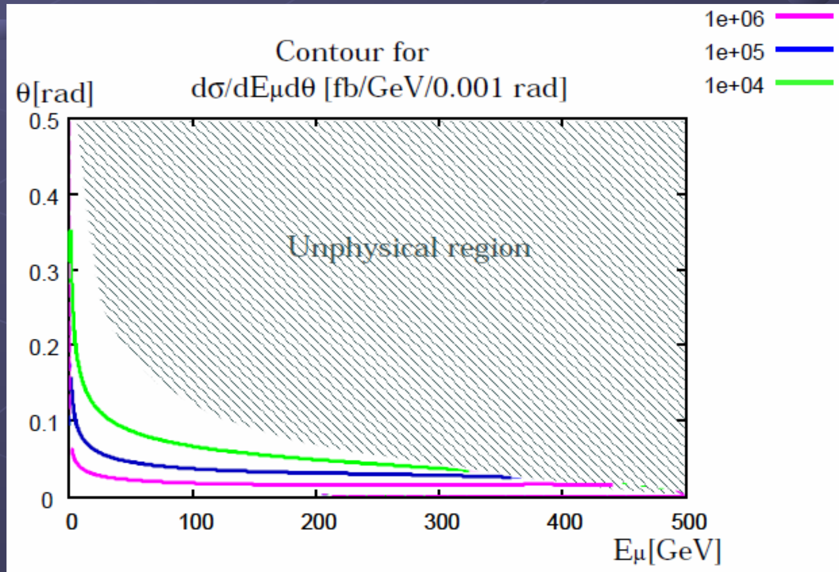


Backgrounds $\frac{d^2\sigma}{dE_\mu d\theta}$

$$\mu N \to \mu X$$

photon mediation

usual DIS



Different distribution

⇒ BG reduction by E_τ, θ_τ cuts

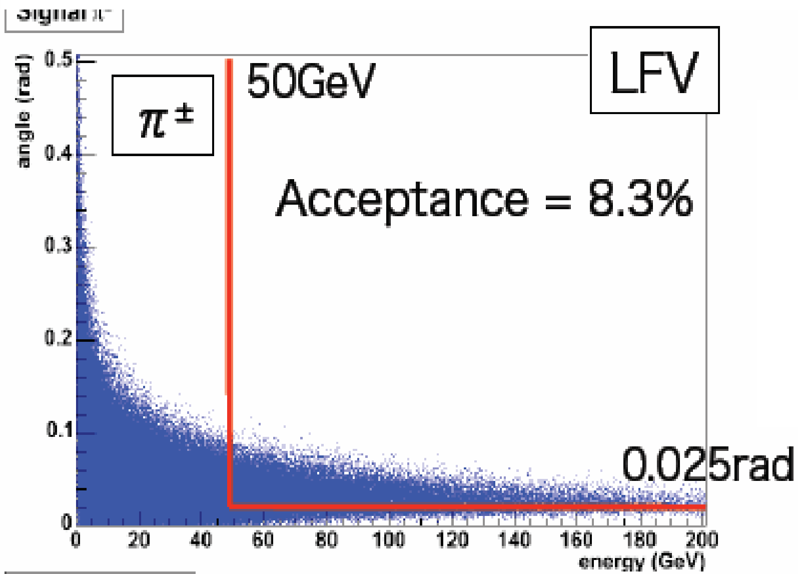
Monte Carlo Simulation

- 500-GeV muon beam
- Generator: Signal Modified LQGENEP (leptoquark generator) Bellagamba et al
  Background LEPTO γ D I S

  Q^2>1.69GeV^2, σ =0.17 μ b
- MC_truth level analysis

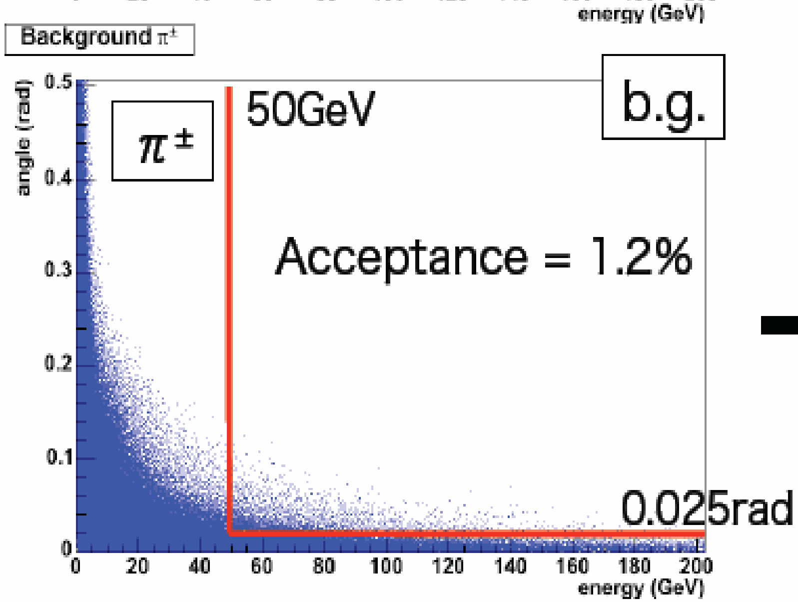
Work in progress

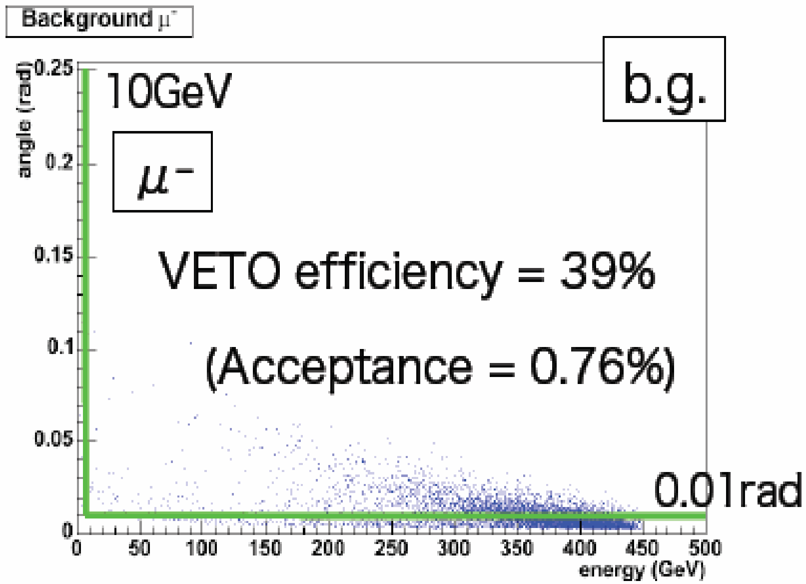
Backgrounds for $\mu N \to \tau X$



$E\pi > 50GeV,$
$\theta\ \pi > 0.025rad$
$\Delta \mu\quad 0.01rad$

Takai





Scattering angle of μ is small, it would be difficult to tag background events for reduction

Electron beam

Number of taus

Ee＝250 GeV,

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

With the present limit of | κ 31 |^2=0.3 $\times$ 10^(-6),

the cross section will be σ = 10^{-3} fb

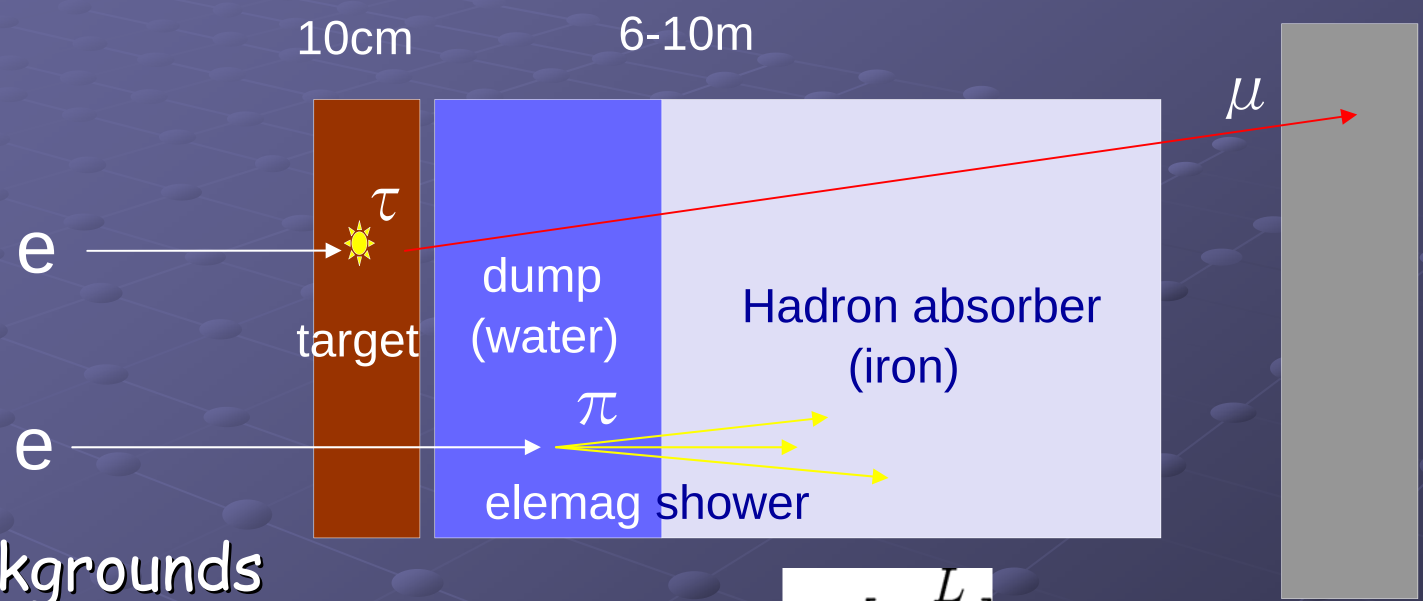
10^5 of τ leptons can be produced for the target of ρ =10 g/cm^2

Naively, non-observation of the high energy muons from the tau of the e N $\rightarrow$ τ X process may improve the current upper limit on the e- τ - Φ coupling^2 by around 4-5 orders of magnitude

Signal/Backgrounds

- Signal: for example, μ from τ in $e N \rightarrow \tau X$
- Backgrounds:
  - Pion punch-through
  - Muons from Pion decay-in-flight
  - Muon from the muon pair production
- Monte Carlo Simulation under study
  - 50GeV electron beam
  - Event Generator Signal: modified LQGENEP
    Background: γ DIS σ =0.04 μb
  - BG absorber, simulation for the pass through
  - Probability of e, π, μ by using GEANT

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



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

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

Monte Carlo simulation by using GEANT

Summary

- We discussed LFV via DIS processes μN (e N) $\rightarrow \tau X$ using high energy muon and electron beams and a fixed target.
- For E > 60 GeV, the cross section is enhanced due to the sub-process of Higgs mediation with sea b-quarks
- DIS $\mu N \rightarrow \tau X$ by the intense high energy muon beam.
  - In the SUSY model, 100-10000 tau leptons can be produced for E_μ =50-500 GeV.
  - No signal in this process can improve the present limit on the Higgs LFV coupling by 10^2 - 10^4.
  - The τ is emitted to forward direction with E_T
  - The signal is hard hadrons from $\tau \rightarrow \pi \nu$、 $\rho \nu$, $a_1 \nu$, ... ,which go along the τ direction.
  - Main background: mis-ID of μ in $\mu N \rightarrow \mu X$....
- DIS process $e N \rightarrow \tau X$:
  - At a LC with Ecm=500GeV $\Rightarrow \sigma$ =10^(-3) fb
    L=10^34/cm^2/s $\Rightarrow$ 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.