Charged lepton flavor violation search by lepton-nucleus scattering

M. Takeuchi, YU, & M. Yamanaka, in progress.

Yuichi Uesaka
Saitama Univ.
Charged Lepton Flavor Violation (CLFV)
- A probe for new physics -

- lepton flavor violation for charged lepton = \textbf{CLFV}
  \((\mu \rightarrow e\gamma, \mu \rightarrow ee\bar{e}, \tau \rightarrow e\gamma, \ldots)\)

- forbidden in SM
- contribution of neutrino mixing → very small

  \(\text{Br}(\mu \rightarrow e\gamma) \lesssim 10^{-54}\)
  ✓ cannot be observed by current technology

- enhanced in many theories beyond SM
  e.g. SUSY

✓ Searches for CLFV can access new physics with little SM backgrounds.
## Current Limits of CLFV processes


<table>
<thead>
<tr>
<th>Reaction</th>
<th>Present limit</th>
<th>C.L.</th>
<th>Experiment</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \rightarrow e^+\gamma$</td>
<td>$&lt; 4.2 \times 10^{-13}$</td>
<td>90%</td>
<td>MEG at PSI</td>
<td>2016</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+e^-e^+$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
<td>90%</td>
<td>SINDRUM</td>
<td>1988</td>
</tr>
<tr>
<td>$\mu^-\text{Ti} \rightarrow e^-\text{Ti}$</td>
<td>$&lt; 6.1 \times 10^{-13}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>1998</td>
</tr>
<tr>
<td>$\mu^-\text{Pb} \rightarrow e^-\text{Pb}$</td>
<td>$&lt; 4.6 \times 10^{-11}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>1996</td>
</tr>
<tr>
<td>$\mu^-\text{Au} \rightarrow e^-\text{Au}$</td>
<td>$&lt; 7.0 \times 10^{-13}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>2006</td>
</tr>
<tr>
<td>$\tau \rightarrow e\gamma$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2010</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\gamma$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2010</td>
</tr>
<tr>
<td>$\tau \rightarrow eee$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
<td>90%</td>
<td>Belle</td>
<td>2010</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
<td>90%</td>
<td>Belle</td>
<td>2010</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0e$</td>
<td>$&lt; 8.0 \times 10^{-8}$</td>
<td>90%</td>
<td>Belle</td>
<td>2007</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\mu$</td>
<td>$&lt; 1.1 \times 10^{-7}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2007</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho^0e$</td>
<td>$&lt; 1.8 \times 10^{-8}$</td>
<td>90%</td>
<td>Belle</td>
<td>2011</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho^0\mu$</td>
<td>$&lt; 1.2 \times 10^{-8}$</td>
<td>90%</td>
<td>Belle</td>
<td>2011</td>
</tr>
</tbody>
</table>
\[ \mu N(eN) \rightarrow \tau X \]


- CLFV process in lepton-nucleus(neucleon) scattering
  - sensitive to \((\bar{\tau}\ell)(\bar{q}q)\) coupling

**Example of experiments**

- Leptoquark search @ HERA \((ep\) collider\)

**Advantages over the rare decay searches of \(\tau\)**

- high-intensity muon/electron beam
- sensitive to interactions which cannot be explored by tau decay \((e.g. \bar{\tau}\mu\bar{c}u)\)
- polarized beam to investigate detailed information of new physics

In this talk, let us consider the case that the mediated scalar couples strongly to heavy quarks
\( \mu N(eN) \rightarrow \tau X \) by higgs exchange


- 4-Fermi CLFV int. induced by heavy higgs
- subprocess is \( \ell q \rightarrow \tau q \)
- 5-flavor PDF

\[
\frac{d^2 \sigma_{\ell N \rightarrow \tau X}}{dx dy} = \sum_q \frac{d^2 \hat{\sigma}_{\ell q \rightarrow \tau q}}{dx dy} f_q(x, Q^2)
\]

\( b \)-quarks in nucleon give significant contribution for \( E_\ell > 50 \text{GeV} \)

"threshold" of \( b \)-quark

Cross section graph
Questions for previous analysis

1. the cross section was estimated with bottom PDF
   • subprocess: $\ell b \rightarrow \tau b$

   In the region near the “bottom threshold”, 5-flavor PDF is valid?
   • The final state must be $b\bar{b}$, due to bottom # conservation.
   • We cannot ignore phase space suppression by mass of final state.

   threshold for fixed target experiment

   $\tau b : E_\ell > 19$GeV   $\tau b\bar{b} : E_\ell > 55$GeV

2. subprocesses were only reactions with quarks

   If CLFV is induced by mediation of
   “particle which couples strongly to heavy quarks” (like higgs),
   the subprocess with gluon ($\ell g \rightarrow \tau g$) would be important.

   • No need to create heavy states in the final state
Subprocesses we consider

previous work \( \ell q \rightarrow \tau q \)

our work

1. \( \ell g \rightarrow \tau q\overline{q} \)
2. \( \ell g \rightarrow \tau g \)

1. explicitly treat \( q\overline{q} \) as final state to consider the phase space suppression
   more quantitative near \( q\overline{q} \) threshold

2. include the new subprocess with gluon
   enhancement of total cross section
We can take into account the “mass” of heavy quarks explicitly.
2. $\ell g \rightarrow \tau g$

- CLFV coupling
- Sgg coupling via quark loop
  - $q^2 < 0$
  - In addition to top contribution, bottom & charm are also important

\[
\frac{d^2\sigma_{\ell p \rightarrow \tau X}}{dx dy} = \frac{d^2\sigma_{\ell g \rightarrow \tau b\bar{b}}(x)}{dx dy} f_g(x, Q^2)
\]
Example 1: 125GeV higgs LFV

\[ \mathcal{L}_I = \mathcal{L}_{I}^{\text{SM}} + \mathcal{L}_{I}^{\text{CLFV}} \]

\[ \mathcal{L}_{I}^{\text{SM}} = - \sum_{q} \frac{m_q}{v} h \bar{q} q \]

\[ \mathcal{L}_{I}^{\text{CLFV}} = - h \bar{\tau} (\rho_{i\tau} P_L + \rho_{\tau i} P_R) \ell_i + \text{H. c.} \]

- constraint by searches for rare decays of higgs

\[ Br(h \rightarrow \tau e) < 6.1 \times 10^{-3} \]
\[ \Rightarrow \sqrt{|\rho_{\tau e}|^2 + |\rho_{e\tau}|^2} < 2.3 \times 10^{-3} \]

\[ Br(h \rightarrow \tau \mu) < 2.5 \times 10^{-3} \]
\[ \Rightarrow \sqrt{|\rho_{\tau \mu}|^2 + |\rho_{\mu \tau}|^2} < 1.4 \times 10^{-3} \]

CMS Collab., CMS-PAS-HIG-17-001.
Cross section (fixed target)

\[ \sqrt{|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2} = 2.3 \times 10^{-3} \]

\( \ell g \rightarrow \tau g \) is important for \( E_\ell < 1 \) TeV

\( eN \rightarrow \tau X \)

ILC: \( E_e = 500 \) GeV, \( N_e = 10^{22} \)/year

( density of target ~ 100 g \cdot cm^{-2} )

\( \mathcal{O}(10) \) events/year
Example 2: “heavy scalar” LFV

Toy model:

\[ \mathcal{L}_I = -\rho (\bar{\tau}e)S - y (\bar{b}b)S \]

\( S \) : scalar (mass : \( m_S \))
\( \rho, y \) : couplings

integrate out \( S \)

\[ \mathcal{L}_{\text{eff}} = C_{4F} (\bar{\tau}e)(\bar{b}b) + C_G (\bar{\tau}e)G_{\mu\nu}G^{\mu\nu} \]

\[ C_{4F} \sim \frac{\rho y}{m_S^2} \]
\[ C_G \sim \frac{\alpha_S}{12\pi m_b} \frac{\rho y}{m_S^2} \]

✓ \( C_G \) is limited by rare decay searches of \( \tau \)


\[ Br(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8} \]

\[ \frac{\rho y}{m_S^2} < 1.8 \times 10^{-6} [\text{GeV}^{-2}] \]
Cross section (fixed target)

\[ \frac{\rho y}{m_S^2} = 1.8 \times 10^{-6} \text{ [GeV}^{-2}] \]

\( \sigma \text{ [fb]} \)

\[ \begin{array}{c}
\rho y \\
E_\ell \text{ [GeV]} \\
\end{array} \]

\( eN \rightarrow \tau X \):

ILC: \( E_e = 250 \text{GeV}, N_e = 10^{22}/\text{year} \)

(density of target \( \sim 100 \text{g} \cdot \text{cm}^{-2} \)) \( \Rightarrow \mathcal{O}(10^5) \) events/\text{year}
Momentum distribution of emitted $\tau$

$E_e = 100\text{GeV}$

① $\ell g \to \tau b\bar{b}$

$\frac{d^2\sigma(eg \to \tau b\bar{b})}{dp_x dp_y}$

② $\ell g \to \tau g$

$\frac{d^2\sigma(eg \to \tau g)}{dp_x dp_y}$

Preliminary
Conclusion

- $\ell N \rightarrow \tau X$ process
  - one of the promising candidates to study CLFV including tau
    - Here, assuming CLFV yukawa of a scalar, the cross section is estimated.
  - corrections for previous calculation
    - explicitly consider the mass of a quark-pair in the final state
    - newly consider gluon subprocess

- gluon subprocess is dominant for $E_\ell \lesssim 1$TeV
- future experiments (e.g. ILC) can search for CLFV with tau!
Backup
Comparison of $\ell g \rightarrow \tau q \bar{q}$ & $\ell q \rightarrow \tau q$

$\sqrt{|Y_{\ell \tau}|^2 + |Y_{\tau \ell}|^2} = 2.3 \times 10^{-3}$

taking into account phase space suppression in the final state

more quantitative near the threshold
Higgs CLFV

(CLFV = lepton flavor violation in charged lepton sector)

- current constraint for branching ratio

\[ Br(h \to \mu^\pm e^{\mp}) < 3.5 \times 10^{-4} \]
\[ \Rightarrow \sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 5.4 \times 10^{-4} \]

\[ Br(h \to \tau e) < 6.1 \times 10^{-3} \]
\[ \Rightarrow \sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 2.3 \times 10^{-3} \]

\[ Br(h \to \tau \mu) < 2.5 \times 10^{-3} \]
\[ \Rightarrow \sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 1.4 \times 10^{-3} \]

- constraint by other searches (assuming that CLFV is induced by only yukawa with SM higgs)

\[ \mu \to e\gamma : \sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 2.1 \times 10^{-6} \]

\[ \tau \to e\gamma : \sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 1.4 \times 10^{-2} \]

\[ \tau \to \mu\gamma : \sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 1.6 \times 10^{-2} \]

\[ \text{stronger limit than higgs rare decay's} \]
\[ \text{relatively small} \]


CMS Collab., CMS-PAS-HIG-17-001.

When \( h \to \tau \ell \) is observed, we have any ways to crosscheck?
Way to calculate the cross section

1. calculation of cross section of subprocess \( \hat{\sigma} \)

\[ \ell (p_\ell) \quad \rightarrow \quad \hat{\sigma}(\xi) \quad \rightarrow \quad \tau (p_\tau) \]

\[ g (\xi P) \quad \rightarrow \quad \hat{\sigma}(\xi) \quad \rightarrow \quad g, \bar{q}q (p_f) \]

\[ N (P) \quad \rightarrow \quad X ((1 - \xi)P) \]

2. integration weighted by PDF

\[
\frac{d^2 \sigma_{\ell N \rightarrow \tau X}}{dx dy} = \sum \int_{\xi_{\text{min}}}^{1} d\xi \frac{d^2 \hat{\sigma}_{\ell g \rightarrow \tau \bar{X}}(\xi)}{dx dy} f_g(\xi, Q^2)
\]

- \( x \): Bjorken variable
- \( y \): inelasticity

( the ranges of \( x, y \) are restricted by \( \tau \) mass )

Relation between $x$ & $\xi$

case of one parton in the final state:

by momentum conservation

$$p_f^2 = (p_i + q)^2$$

$$= 2\xi P \cdot q - Q^2$$

$$\therefore \xi = \frac{Q^2 + p_f^2}{Q^2} x \quad (x = \frac{Q^2}{2P \cdot q})$$

$\xi = x$ if $p_f^2 = 0$
Higgs-glu-glu coupling

- higgs couples to gluon via quark loop

\[ \mathcal{L}_{hgg}^{\text{eff}} = g_{hgg} h G_{\mu\nu}^a G^{a\mu\nu} \]

\[ g_{hgg} = \frac{\alpha_s}{8\pi v} \sum_{i=t,b,...} c \left( \frac{q^2}{4m_i^2} \right) \]

\[ c(t) = \frac{1}{t} \left\{ 1 - \frac{1}{4} \left( 1 - \frac{1}{t} \right) \log^2 \left[ -\frac{1 + \sqrt{1 - 1/t}}{1 - \sqrt{1 - 1/t}} \right] \right\} \]

- Here, the region of \( q^2 < 0 \) is needed.

※ bottom & charm contribution is important as well as top

e.g.) \( Q^2 = -q^2 = (10\text{GeV})^2 \)

\[ \sum_{i=t,b,...} c \left( \frac{q^2}{4m_i^2} \right) \approx 0.67 + 0.53 + 0.24 + ... \]

\[ \text{top, bottom, charm} \]
Cross section (\(\ell p\) collider)

\[\sqrt{|\rho_{\ell\tau}|^2 + |\rho_{\tau\ell}|^2} = 2.4 \times 10^{-3}\]

- The \(t\bar{t}\) channel is important in the high energy region.

[Graph showing cross sections for various processes with \(\ell g \rightarrow \tau g\), \(\ell g \rightarrow \tau t\bar{t}\), \(\ell g \rightarrow \tau b\bar{b}\), and \(\ell g \rightarrow \tau c\bar{c}\) plotted against \(\sqrt{s}\) in GeV.]
For experimental searches

1. fixed target experiment
   
   event number $N$ per year
   
   $$N \simeq 6 \times 10^{-16} \cdot N_\ell \left( \frac{\sigma}{1\text{fb}} \right) \left( \frac{T_m}{1\text{g} \cdot \text{cm}^{-2}} \right)$$
   
   $N_\ell$ : produced number of $\ell$ per year
   $T_m$ : mass of target per $\text{cm}^2 \sim 100\text{g} \cdot \text{cm}^{-2}$
   
   $eN \to \tau X$
   ILC (PWFA) : $E_e = 500\text{GeV (5TeV)}$, $N_e = 10^{22}/\text{year} \Rightarrow \mathcal{O}(10) \left( \mathcal{O}(10^3) \right)$ events/year
   
   $\mu N \to \tau X$
   neutrino factory : $E_\mu = \mathcal{O}(100)\text{GeV}$, $N_\mu = 10^{20}/\text{year} \Rightarrow \mathcal{O}(10^{-1})$ events/year

2. collider experiment
   
   $ep \to \tau X$
   TLHeC (VHE-TLHeC) : $\sqrt{s} \simeq 1.3(3.5)\text{TeV}$
   Luminosity $\simeq \mathcal{O}(10^3) \text{fb}^{-1}/\text{year}$
   $\Rightarrow \mathcal{O}(100)$ events