Higgs mediated CLFV processes
\( \mu N(eN) \rightarrow \tau X \) via gluon operators

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Analysis on CLFV scattering \( \mu N(eN) \rightarrow \tau X \) including
(1) new subprocess \( \ell g \rightarrow \tau g \) \( (\ell \ni e, \mu) \)
(2) quark number conserving subprocess \( \ell g \rightarrow \tau q\bar{q} \)
Search for tau CLFV through $eN(\mu N)$ scattering

- Today’s topic: tau CLFV via Higgs

- A promising way to search for tau CLFV:

  \[ \ell + N \rightarrow \tau + X \quad (N: \text{Nucleus}) \]

- Many exp. launch, e.g., $\nu$-factory, ILC, LHeC, etc.

- Can reach high sensitivity beyond the Belle-II sensitivity limit for tau CLFV

Results hold for any CLFV mediators mainly interacting with heavy fermions e.g., heavy Higgs, flavon, leptoquark, ...
Search for tau CLFV through $eN(\mu N)$ scattering

Precisely relate the LFV parameter and the event rate of $\ell N \to \tau X$

- A promising way to search for tau CLFV:
  $$\ell + N \to \tau + X \ (N: \text{Nucleus})$$

- Many exp. launch, e.g., $\nu$-factory, ILC, LHeC, etc.

- Can reach high sensitivity beyond the Belle-II sensitivity limit for tau CLFV
Prior to the analysis on $\ell N \rightarrow \tau X$, answer easy quiz questions!
Higgs production@LHC

Which is dominant sub-process?
Higgs production@LHC

- Which is dominant sub-process?

- New sub-process for $eN (\mu N) \rightarrow \tau X$

- Dominant sub-process for fixed target exp.
Higgs production@LHC

Which is correct sub-process?
Higgs production@LHC

Which is correct sub-process?

Correct quark final state sub-process with quark-number conservation

Not $\ell q \rightarrow \tau q$!

Threshold and cross section are corrected

e.g., $E_{e(\mu)}^{\text{beam}} > 19$ GeV for $\ell b \rightarrow \tau b$

$E_{e(\mu)}^{\text{beam}} > 55$ GeV for $\ell g \rightarrow \tau b\bar{b}$
Aim of this work and outline

Reformulation of CLFV lepton-nucleus scattering taking into account
(1) new sub-process  $\ell g \rightarrow \tau g$
(2) quark-number conservation sub-process  $\ell g \rightarrow \tau q \bar{q}$

Outline
- Formulation of effective coupling and cross section
- Numerical analysis
- Summary
Formulation of effective coupling and cross section

- Lagrangian
- $hgg$ effective coupling
- Cross section
Lagrangian for $\ell g \to \tau g$ and $\ell g \to \tau q\bar{q}$

Important: momentum transfer dependence of $h_{gg}$ effective coupling

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{CLFV},$$
$$\mathcal{L}_{SM} = -\sum_{q} y_{q} h \bar{q} q + g_{hgg} h G_{\mu\nu}^{a} G^{a\mu\nu},$$
$$\mathcal{L}_{CLFV} = -\rho_{ij} \bar{\ell}_{j} P_{L} \ell_{i} h - \rho_{ji} \bar{\ell}_{j} P_{R} \ell_{i} h$$

$\rho_{ij}, \rho_{ji}$: LFV parameter ($i,j$ : flavor index)

Current bound $\sqrt{|\rho_{\ell\tau}|^2 + |\rho_{\tau\ell}|^2} = 2.4 \times 10^{-3}$

Note: stronger than the Belle-II sensitivity for tau CLFV search
Higgs-gluon-gluon coupling

**hgg effective coupling**

\[
g_{hgg} = \sum_{q=c,b,t} \frac{\alpha_s}{8\pi v} \frac{4m_q^2}{q_h^2} \left[ 1 + \left( 1 - \frac{4m_q^2}{q_h^2} \right) f\left( \frac{4m_q^2}{q_h^2} \right) \right]
\]

\[
f(r) = -\frac{1}{4} \log^2 \left[ -\frac{1 + \sqrt{1 - r}}{1 - \sqrt{1 - r}} \right] \quad (r < 0)
\]

- In addition to \( t \)-quark, \( c \)-quark and \( b \)-quark also sizably contribute
Cross section

H. Georgi, H. Politzer, PRL36 (1976)

\[ \sigma_{\ell_i N \rightarrow \tau X} = \sum_{\hat{X} = g, q\bar{q}} \int dx dy \int_0^1 d\xi \frac{d^2 \hat{\sigma}_{\ell_i g \rightarrow \tau \hat{X}}}{dxdy} f_g(\xi, Q^2) \]

- Momentum fraction: \( \xi = \frac{Q^2 + w^2}{Q^2} x \)
- Invariant mass of \( q\bar{q} \): \( w^2 = (p_q + p_{q'})^2 \)
- Momentum transfer: \( Q^2 = -(p_i - p_f)^2 \)

\( x \): Bjorken variable
\( y \): measure of inelasticity

Gluon PDF
Numerical analysis

- For Higgs CLFV@fixed target experiments
- For general CLFV mediator@fixed target experiments
- For Higgs CLFV@beam collision experiments

CLFV effective coupling is taken to be current bound:

$$\sqrt{|\rho_{\ell\tau}|^2 + |\rho_{\tau\ell}|^2} = 2.4 \times 10^{-3}$$
Cross section vs beam energy for fixed target exp.

- Large enhancement by the new sub-process $\ell g \rightarrow \tau g$, which is dominant for $E_{\ell}^{Lab} \lesssim 1\, \text{TeV}$

- $\tau b\bar{b}$ channel starts to be relevant at $E_{\ell}^{Lab} \approx 500\, \text{GeV}$ (estimated in previous works as $E_{\ell}^{Lab} \approx 50\, \text{GeV}$)
Cross section vs beam energy for fixed target exp.

Event rate/year \((T_m: \text{target mass})\)

\[
N \simeq 6 \times 10^{-16} \, N_{\ell_i} \left( \frac{\sigma_{\ell_i N \to \tau X}}{1 \, \text{fb}} \right) \left( \frac{T_m}{1 \, \text{g cm}^{-2}} \right)
\]

For CLFV mediator = Higgs

\(O(10)\) event@ILC \((N_e \simeq 10^{22}/\text{year})\)

\(O(1)\) event@\(\nu\) factory \((N_\mu \simeq 10^{20}/\text{year})\)
Cross section vs beam energy for fixed target exp.

Event rate/year \((T_m: \text{target mass})\)

\[
N \simeq 6 \times 10^{-16} N_{\ell_i} \left( \frac{\sigma_{\ell_i \rightarrow \tau X}}{1 \text{ fb}} \right) \left( \frac{T_m}{1 \text{ g cm}^{-2}} \right)
\]

For a mediator interacting with gluon

\(O(10^5)\) event@ILC \((N_e \simeq 10^{22}/\text{year})\)

\(O(10^4)\) event@\(\nu\) factory \((N_\mu \simeq 10^{20}/\text{year})\)
Cross section vs collision energy for collider exp.

- $\ell g \to \tau g$
- $\ell g \to \tau t\bar{t}$
- $\ell g \to \tau b\bar{b}$
- $\ell g \to \tau c\bar{c}$

- $\tau t\bar{t}$ channel dominates over others for $\sqrt{s} \gtrsim 1$ TeV
- Important to correctly calculate the cross section with q-number conservation
- Assuming $\mathcal{O}(1000)$ fb$^{-1}$/year, $\mathcal{O}(10)$ event/year@VLHeC
Summary

- Study tau LFV as it is relatively less constrained and sizable effects could be expected

- Focusing on the tau LFV by mediators mainly interacting with heavy fermions

- Reformulation of $\ell N \rightarrow \tau X$ taking into account important ingredients
  
  1. gluon contribution $\ell g \rightarrow \tau g$
  2. q-number conservation $\ell g \rightarrow \tau q\bar{q}$

- Future experiments (COMPASS, ILC, LHeC, $\nu$ factory, etc) could shed light on the tau LFV
Thank you very much!
Backup slides
Cross sections for each PDF