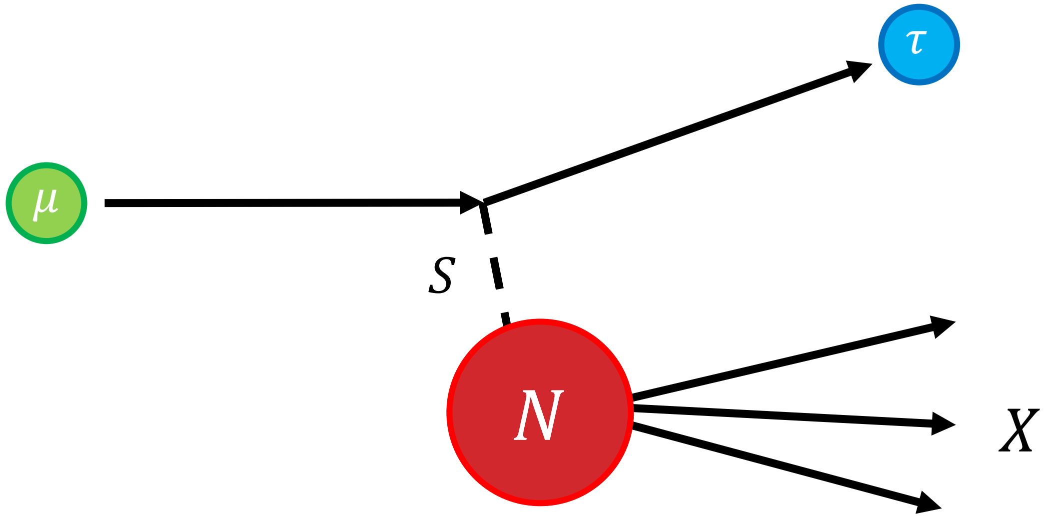
16 / Nov. / 2018 @ KEK, QNP 2018

Charged lepton flavor violation search by lepton-nucleus scattering

M. Takeuchi, YU, & M. Yamanaka, Phys. Lett. B **772**, 279 (2017).
M. Takeuchi, YU, & M. Yamanaka, in progress.



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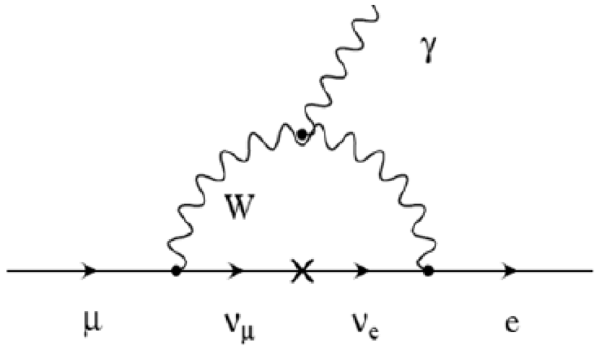
Charged Lepton Flavor Violation (CLFV)

- A probe for new physics -

◆ lepton flavor violation for charged lepton = CLFV
($\mu \to e\gamma$, $\mu \to ee\bar{e}$, $\tau \to e\gamma$, ...)

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

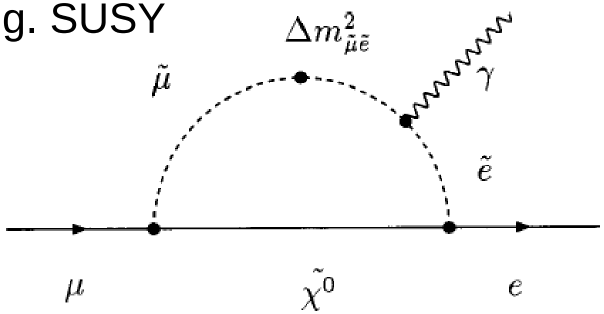


⇨ $\mathrm{Br}(\mu \to e\gamma) \lesssim 10^{-54}$

✓ 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

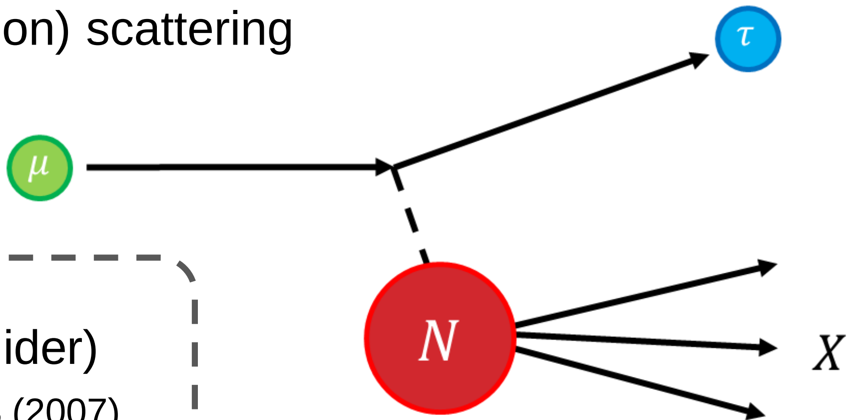
L. Calibbi & G. Signorelli, Riv. Nuovo Cim. **41**, no. 2, 1 (2018).

Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011

$\mu N(eN) \to \tau X$

S.N. Gninenko *et al*., Mod. Phys. Lett. A **17**, 1407 (2002).
M. Sher & I. Turan, Phys. Rev. D **69**, 017302 (2004).

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



Example of experiments

- ✓ Leptoquark search @ HERA (ep collider)
  Aktas *et al*., Eur. Phys. J. C **52**, 833 (2007).

Advantages over the rare decay searches of τ

- ✓ <u>high-intensity muon/electron beam</u>
- ✓ 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

$\mu N(eN) \to \tau X$ by higgs exchange

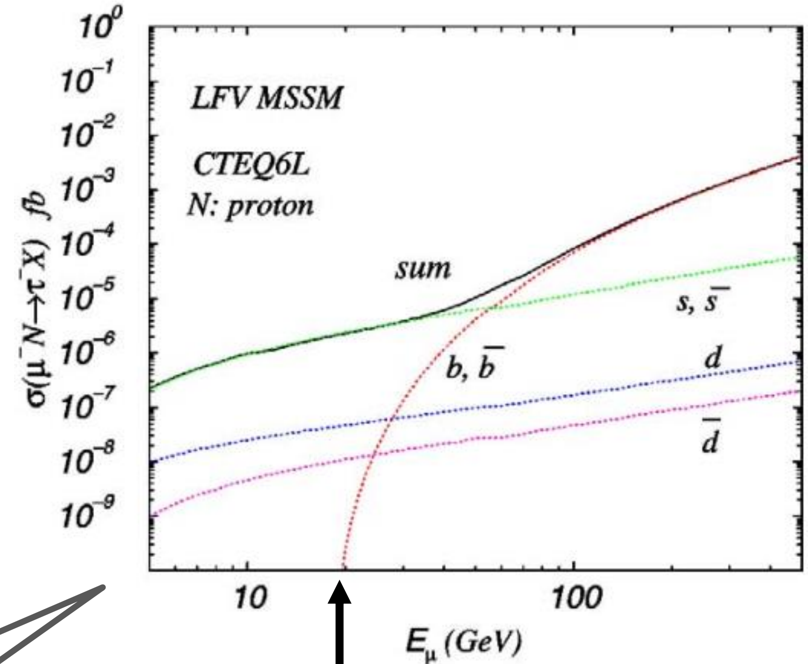
previous work : S. Kanemura *et al*., Phys. Lett. B **607**, 165 (2005).

- 4-Fermi CLFV int. induced by heavy higgs
- subprocess is $\ell q \to \tau q$
- 5-flavor PDF

$\bar{\tau}\ell\bar{q}q$

$$\frac{d^2\sigma_{\ell N\to\tau X}}{dxdy} = \sum_q \frac{d^2\hat{\sigma}_{\ell q\to\tau q}}{dxdy} f_q(x, Q^2)$$

cross section



"threshold" of *b*-quark

b-quarks in nucleon give significant contribution for $E_\ell > 50$GeV

Questions for previous analysis

1. the cross section was estimated with bottom PDF

- subprocess : $\ell b \to \tau b$

⇨ 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

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

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 ($\ell g \to \tau g$) would be important.

- No need to create heavy states in the final state

Subprocesses we consider

initial parton

previous work

$\ell q \to \tau q$ — quark

our work

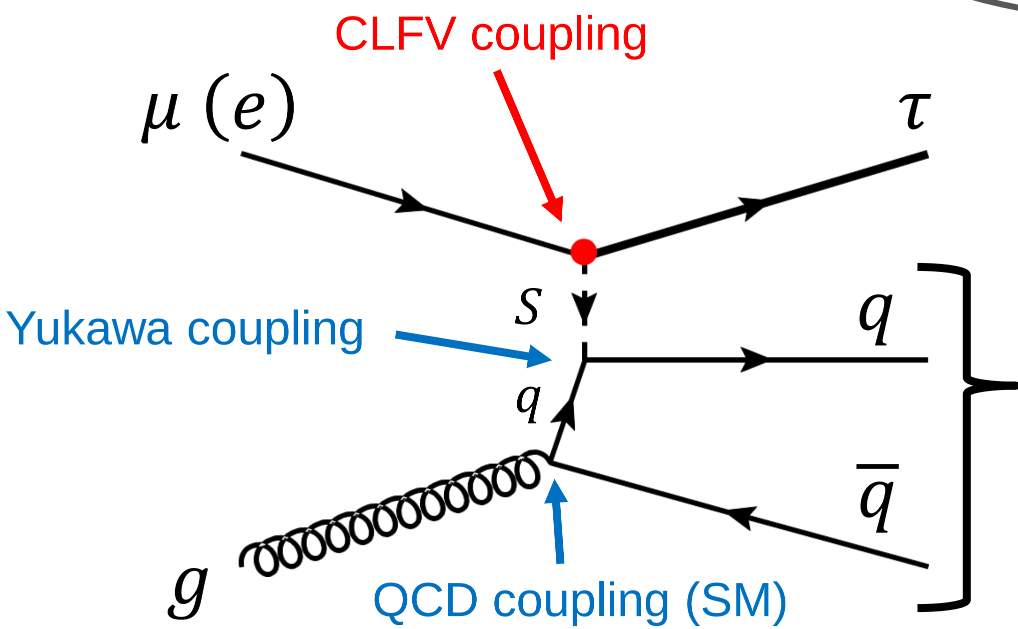
① $\ell g \to \tau q\bar{q}$ ② $\ell g \to \tau g$ — gluon

1. explicitly treat $q\bar{q}$ as final state to consider the phase space suppression
   ⇨ more quantitative near $q\bar{q}$ threshold

2. include the new subprocess with gluon
   ⇨ enhancement of total cross section

① $\ell g \to \tau q\bar{q}$

instead of $lq \to \tau q$



w : mass of $q\bar{q}$

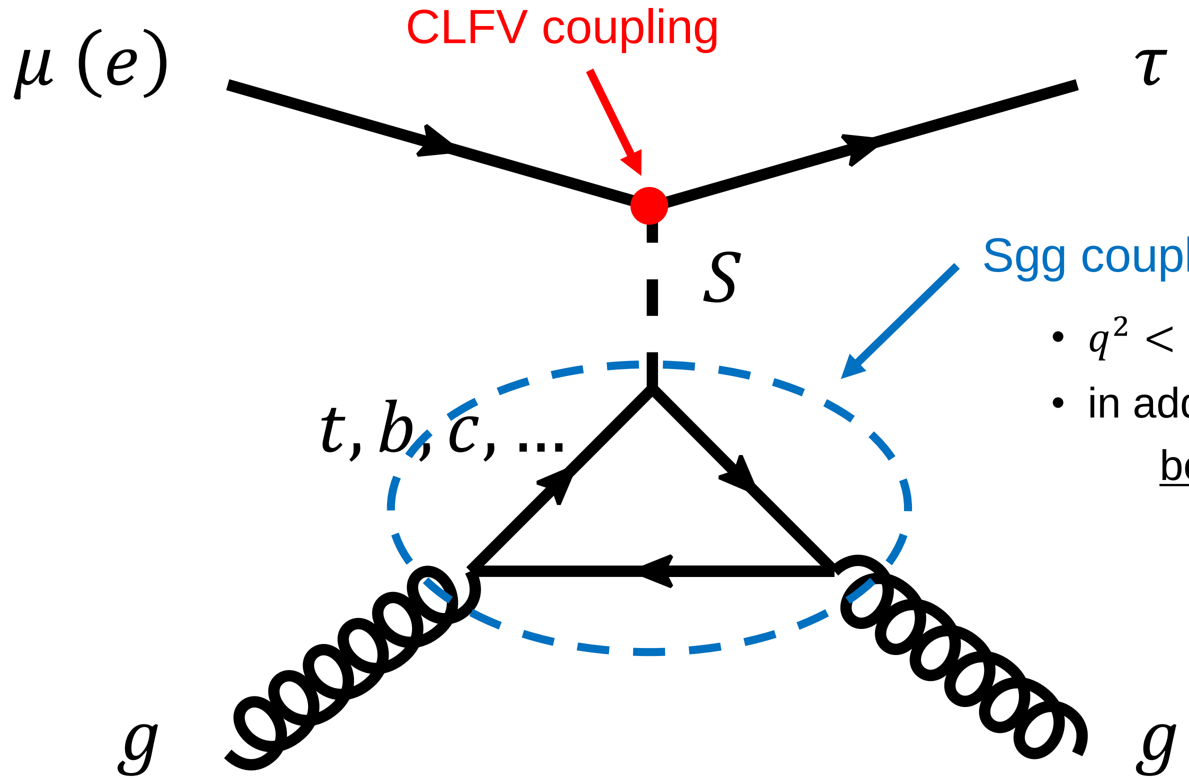
$$w^2 > \left(p_q + p_{\bar{q}}\right)^2 > \left(2m_q\right)^2$$

$$\frac{d^2\sigma^q_{\ell p\to\tau X}}{dxdy} = \int_{\frac{Q^2+4m_q^2}{Q^2}x}^{1} d\xi\, \frac{d^2\sigma_{\ell g\to\tau q\bar{q}}(\xi)}{dxdy} f_g(\xi, Q^2)$$

- We can take into accout the “mass” of heavy quarks explicitly.

② $\ell g \to \tau g$

new "**gluon subprocess**"



Sgg coupling via quark loop

- $q^2 < 0$
- in addition to top contribution,
  <u>bottom & charm are also important</u>

$$\frac{d^2\sigma^g_{\ell p\to\tau X}}{dxdy} = \frac{d^2\sigma_{\ell g\to\tau b\bar{b}}(x)}{dxdy} f_g(x, Q^2)$$

Example 1 : 125GeV higgs LFV

$$\mathcal{L}_I = \mathcal{L}_I^{\mathrm{SM}} + \mathcal{L}_I^{\mathrm{CLFV}}$$

$$\mathcal{L}_I^{\mathrm{SM}} = -\sum_q \frac{m_q}{v} h\bar{q}q$$

$$\mathcal{L}_I^{\mathrm{CLFV}} = -h\bar{\tau}(\rho_{i\tau}P_L + \rho_{\tau i}P_R)\ell_i + \mathrm{H.c.}$$

➢ **constraint by searches for rare decays of higgs**

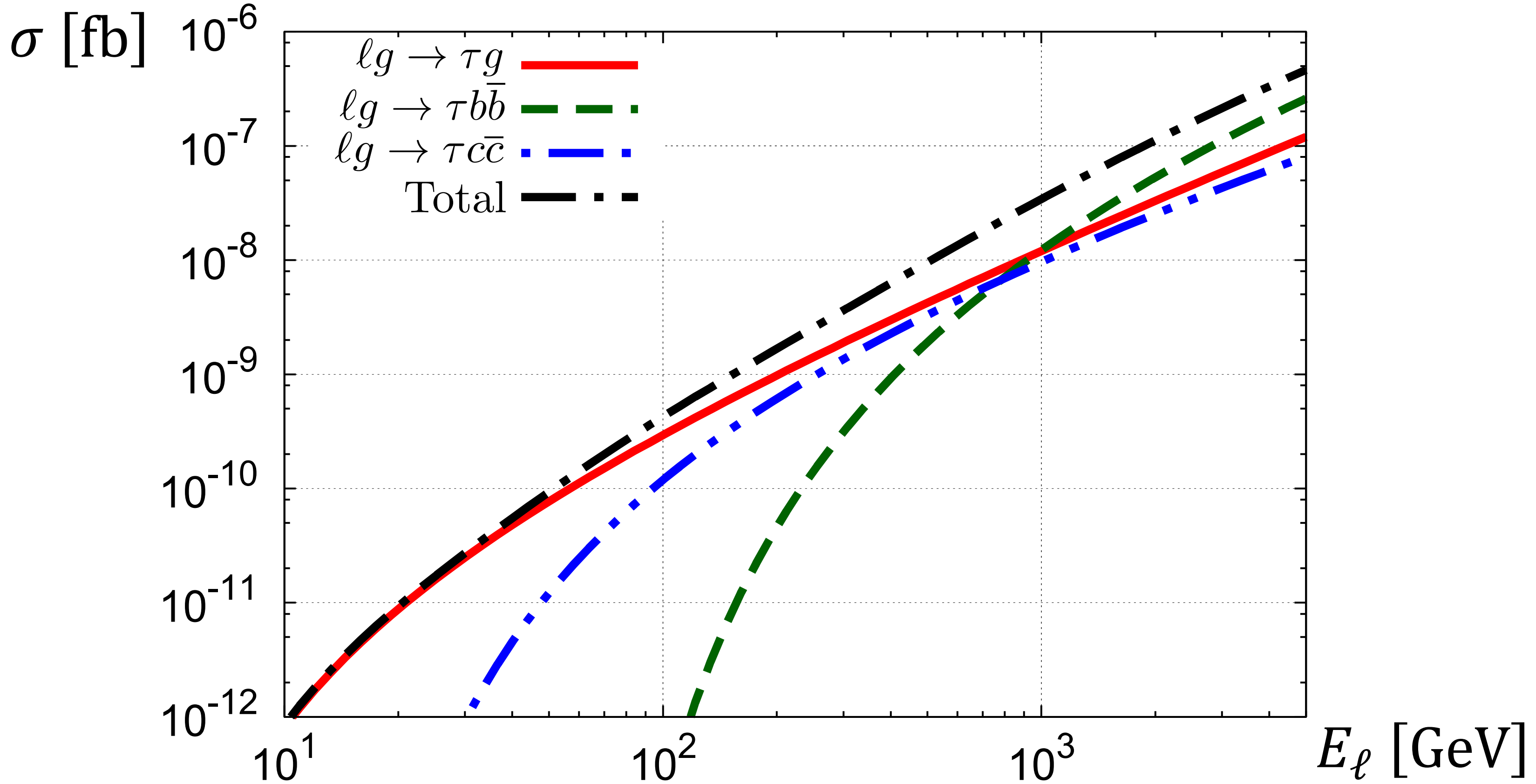
$$Br(h \to \tau e) < 6.1 \times 10^{-3} \Rightarrow \sqrt{|\rho_{\tau e}|^2 + |\rho_{e\tau}|^2} < 2.3 \times 10^{-3}$$

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

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

Cross section (fixed target)

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



✓ $\ell g \to \tau g$ is important for $E_\ell < 1\text{TeV}$

- 7.8 times larger ($E_\ell = 50\text{GeV}$)
- 1.8 times larger ($E_\ell = 500\text{GeV}$)

$\boldsymbol{eN \to \tau X}$

ILC : $E_e = 500\text{GeV}, N_e = 10^{22}/\text{year}$
(dentity of target ~ $100\text{g} \cdot \text{cm}^{-2}$) ⇨ $\mathcal{O}(10)$ events/year

Example 2 : “heavy scalar” LFV

Toy model :

$$\mathcal{L}_I = -\rho(\bar{\tau}e)S - y\left(\bar{b}b\right)S$$

S : scalar (mass : m_S)

ρ, y : couplings

⇩ integrate out S

$$\mathcal{L}_{\rm eff} = C_{4F}(\bar{\tau}e)\left(\bar{b}b\right) + C_G(\bar{\tau}e)G^a_{\mu\nu}G^a_{\mu\nu}$$

$$C_{4F} \sim \frac{\rho y}{m_S^2}$$

$$C_G \sim \frac{\alpha_S}{12\pi m_b}\frac{\rho y}{m_S^2}$$

✓ C_G is limited by rare decay searches of τ

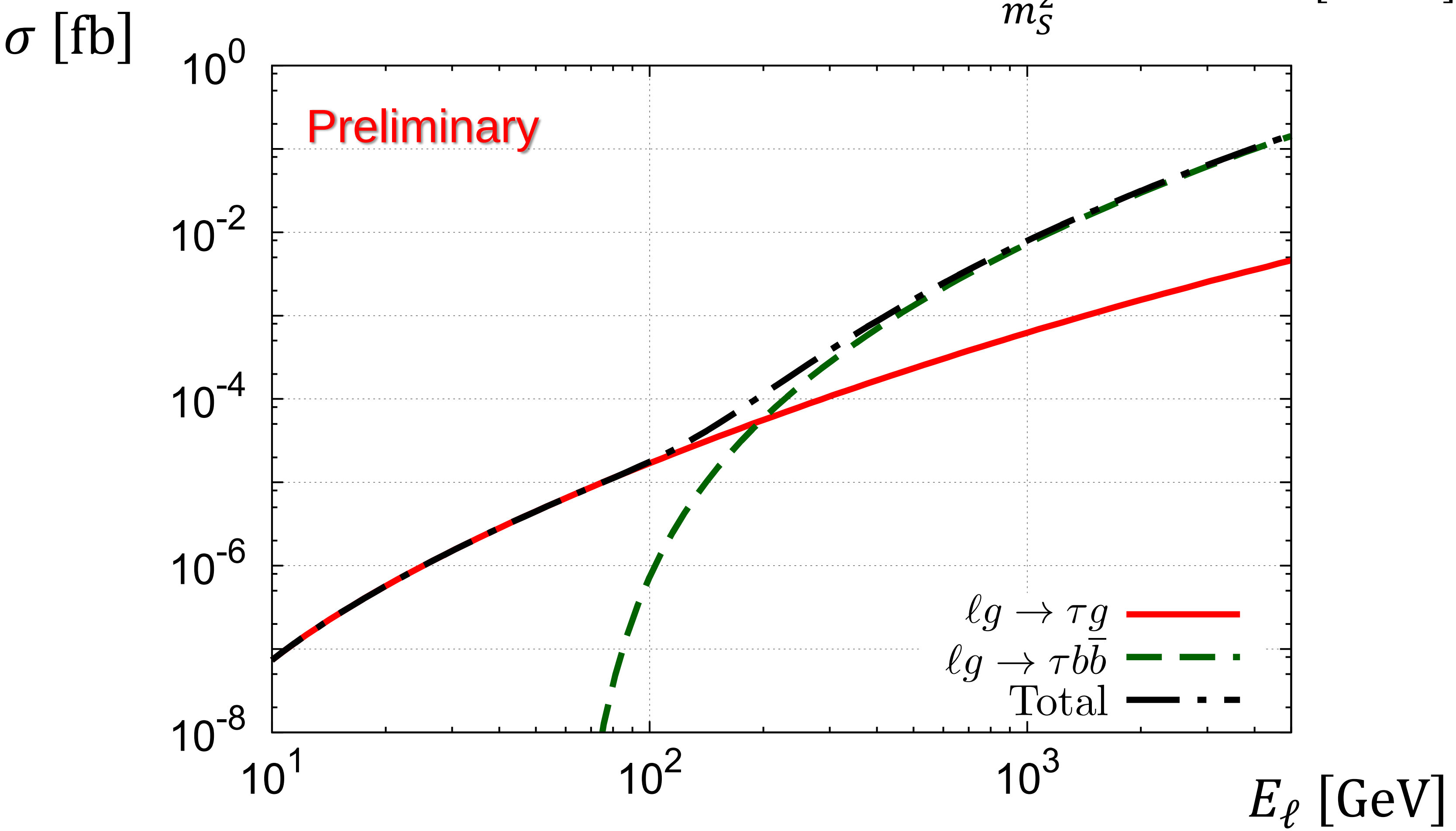
cf. A. Celis, V. Cirigliano, E. Passemar, PRD**89** 095014 (2014).

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

$$\Rightarrow \frac{\rho y}{m_S^2} < 1.8 \times 10^{-6}\ [\mathrm{GeV}^{-2}]$$

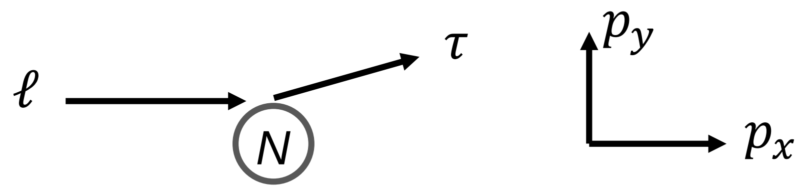
Cross section (fixed target)

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



$\boldsymbol{eN \to \tau X}$ **:** ILC : $E_e = 250\mathrm{GeV}, N_e = 10^{22}/\mathrm{year}$ (density of target $\sim 100\mathrm{g}\cdot\mathrm{cm}^{-2}$) ⇨ $\mathcal{O}(10^5)$ events/year

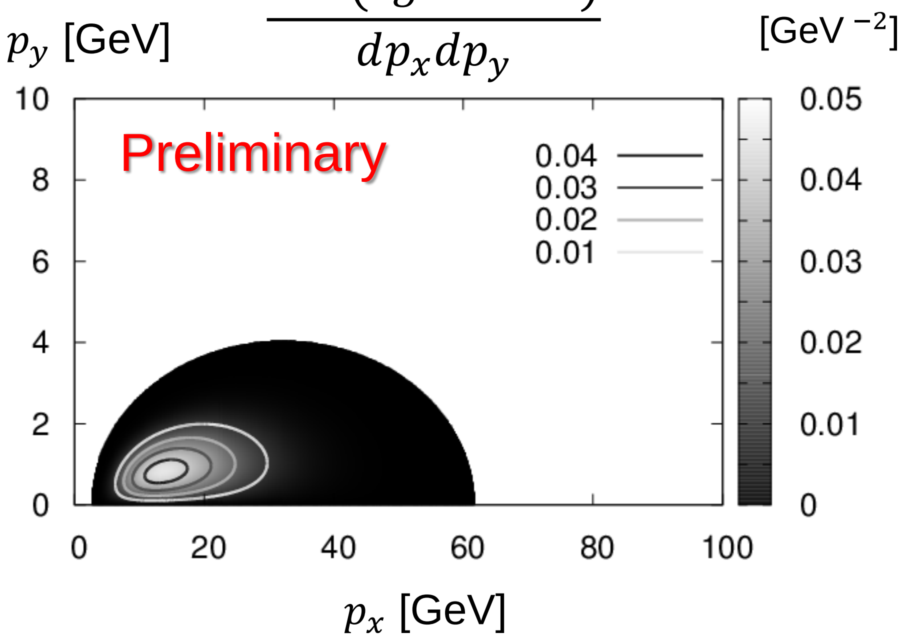
Momentum distribution of emitted τ



$E_e = 100\text{GeV}$

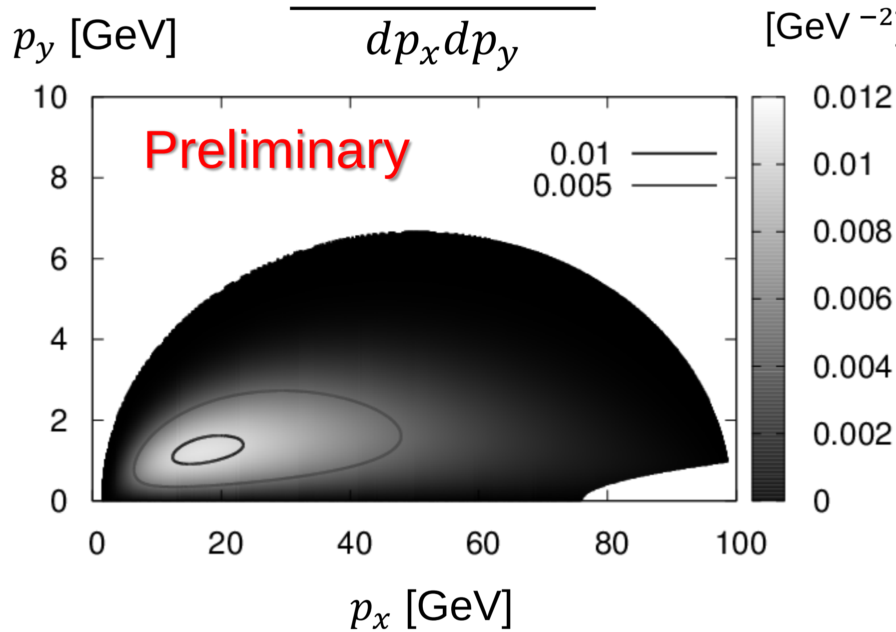
① $\ell g \to \tau b\bar{b}$

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



② $\ell g \to \tau g$

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



Conclusion

- $\ell N \to \tau X$ 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

$\ell q \to \tau q$ ⇨ ① $\ell g \to \tau q\bar{q}$ ② $\ell g \to \tau g$

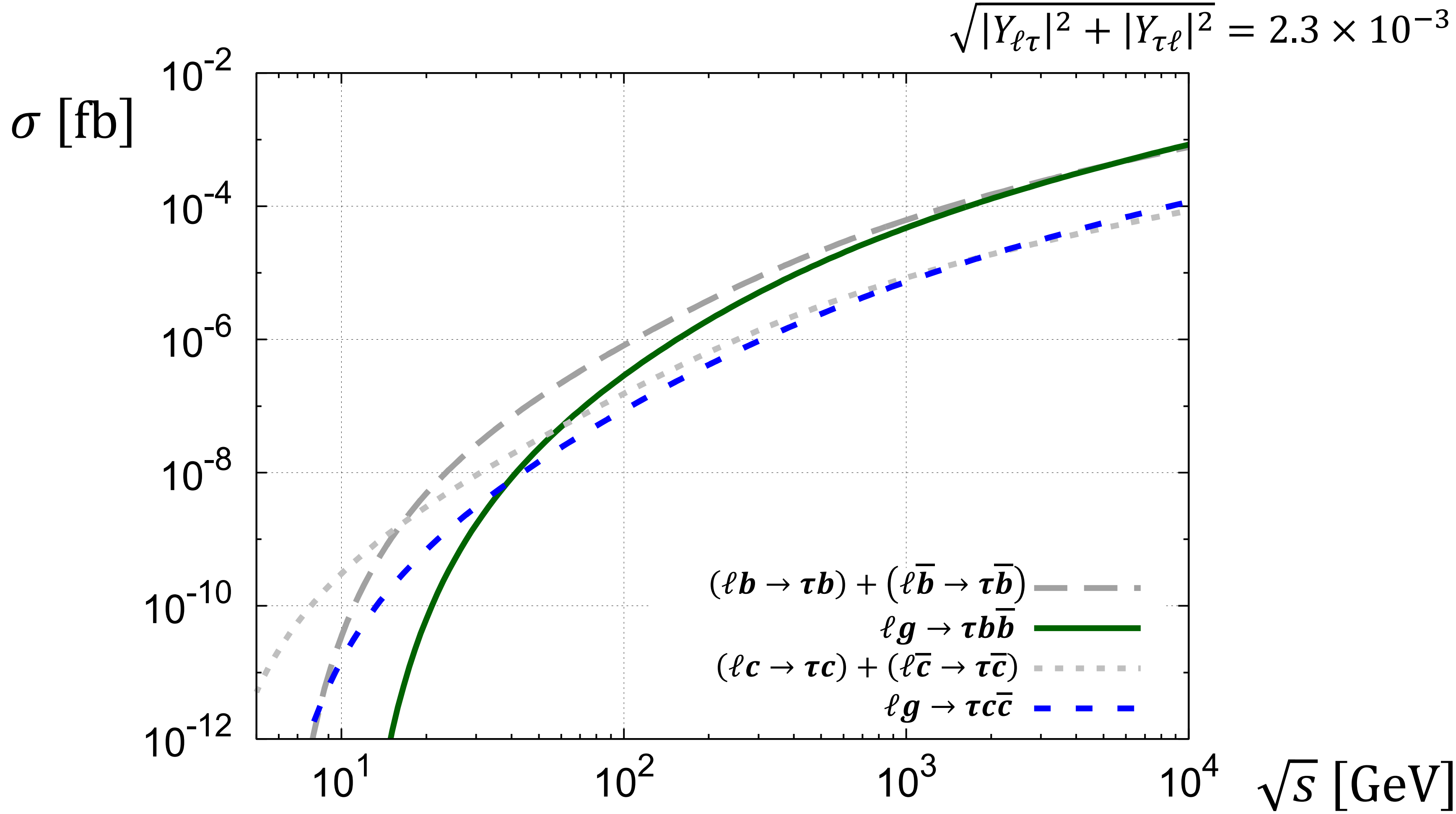
    - explicitly consider the mass of a quark-pair in the final state
    - newly consider gluon subprocess

⇩

  - ✓ gluon subprocess is dominant for $E_\ell \lesssim 1$TeV
  - ✓ future experiments (e.g. ILC) can search for CLFV with tau !

Backup

Comparison of $\ell g \to \tau q\bar{q}$ & $\ell q \to \tau q$



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

(couplings)

$$\mathcal{L}^{h}_{CLFV} = -h\overline{\ell_j}\left(Y_{ij}P_L + Y_{ji}P_R\right)\ell_i$$

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

V. Khachatryan *et al*. [CMS Collab.], Phys. Lett. B **763**, 472 (2016).

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

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

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

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

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

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

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

stronger limit than higgs rare decay's

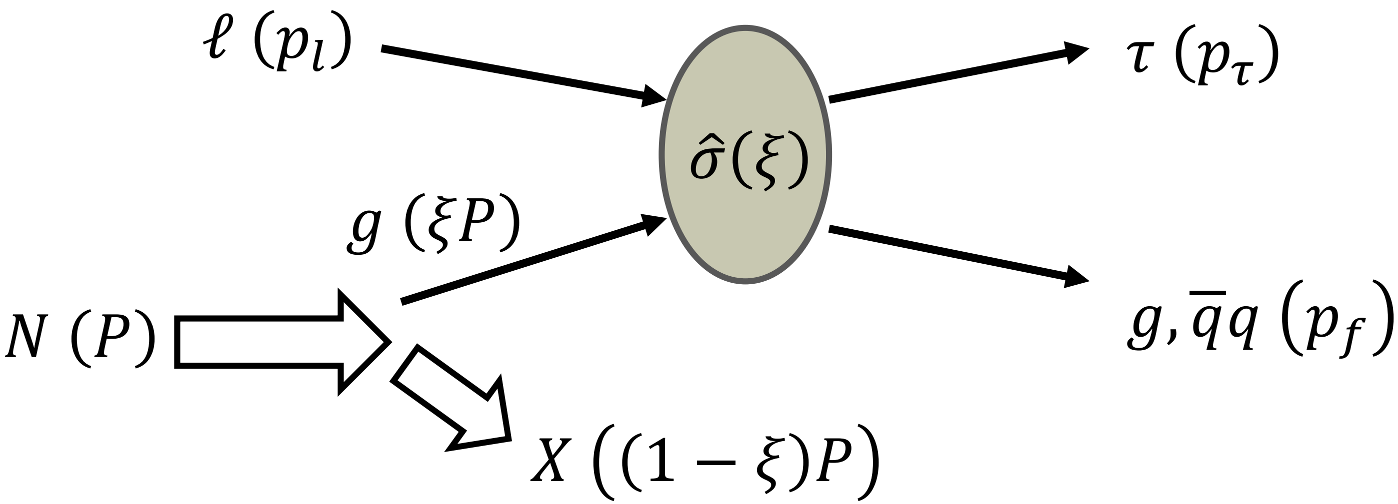
relatively small

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 $\hat{\sigma}$

ξ : momentum fraction



2. integration weighted by PDF

f_g : グルーオンPDF

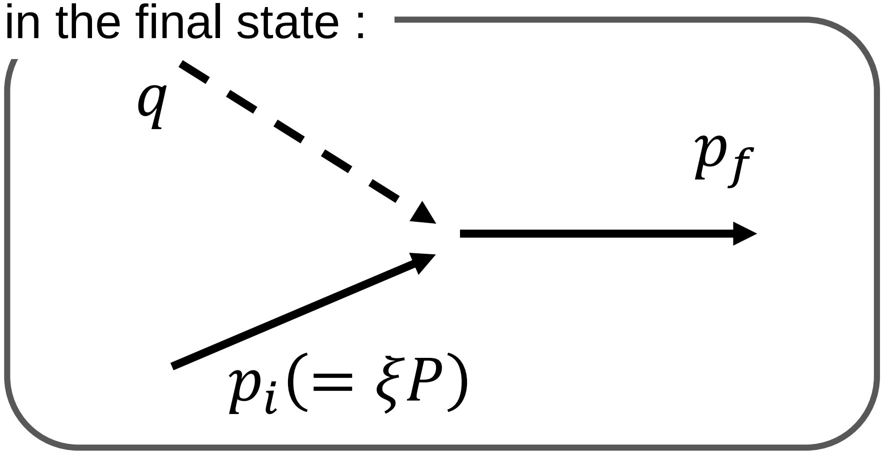
$$\frac{d^2\sigma_{\ell N\to\tau X}}{dxdy} = \sum_{\hat{X}} \int_{\xi_{\min}}^{1} d\xi\, \frac{d^2\hat{\sigma}_{\ell g\to\tau\hat{X}}(\xi)}{dxdy} f_g(\xi, Q^2)$$

x : Bjorken variable y : inelaticity (the ranges of x, y are restricted by τ mass)

C.H. Albright, C. Jarlskog, Nucl. Phys. B **84**, 467 (1975).

Relation between x & ξ

case of one parton in the final state :



by momentum conservation

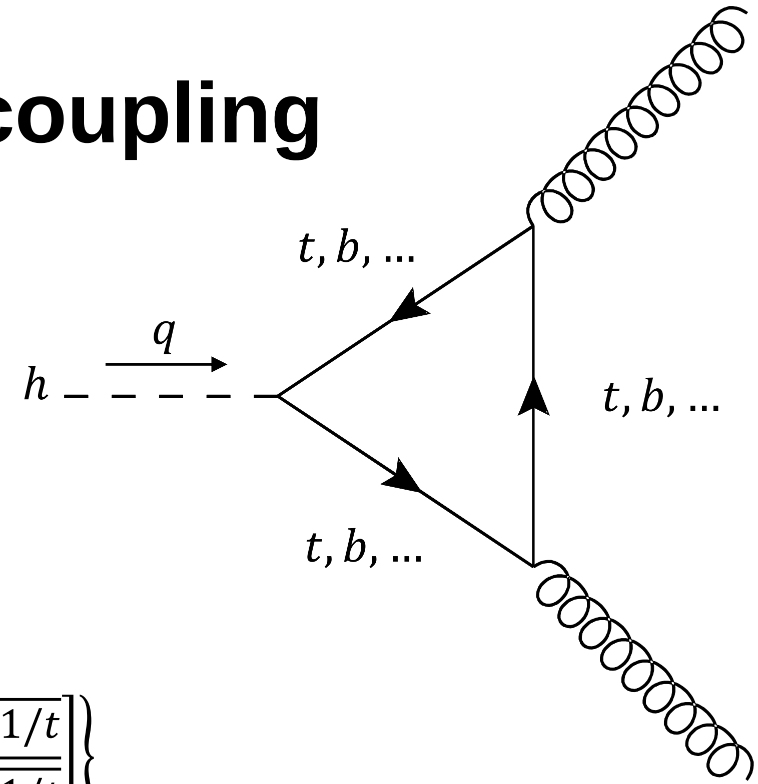
$$p_f^2 = (p_i + q)^2$$

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

$$\Rightarrow \quad \xi = \frac{Q^2 + p_f^2}{Q^2} x \qquad \left(x = \frac{Q^2}{2P \cdot q} \right)$$

$\xi = x$ if $p_f^2 = 0$

Higgs-glu-glu coupling



- higgs couples to gluon via quark loop

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

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

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

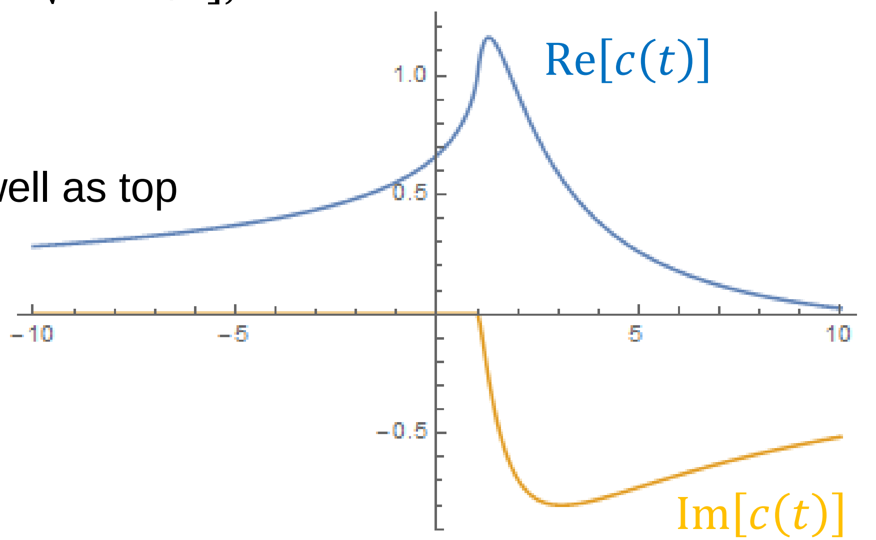
- Here, the region of $q^2 < 0$ is needed.

※ bottom & charm contribution is important as well as top

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

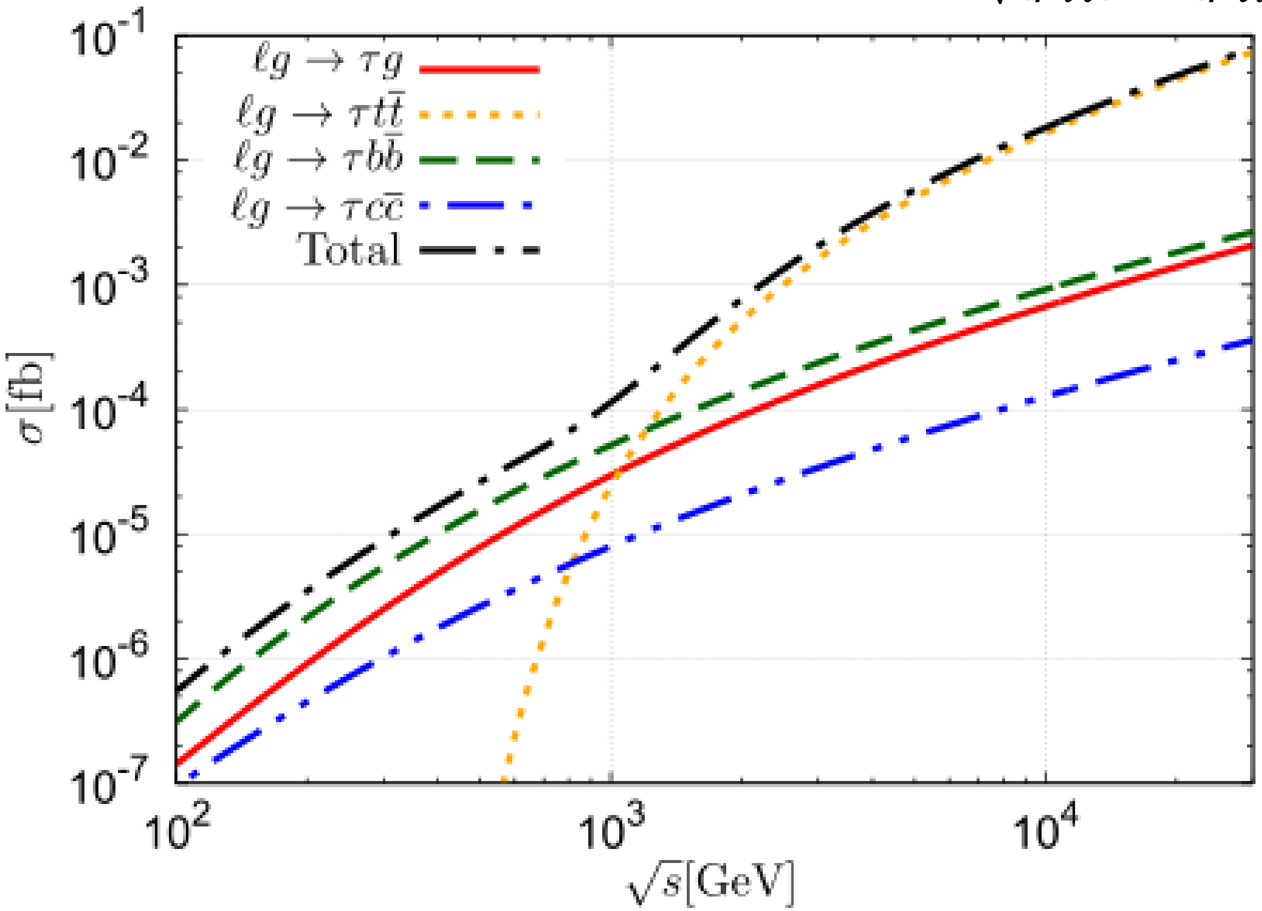
$$\sum_{i=t,b,\ldots} c\left(\frac{q^2}{4m_i^2}\right) \simeq 0.67 + 0.53 + 0.24 + \cdots$$

top bottom charm



Cross section (ℓp collider)

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



- $t\bar{t}$ channel is important in the high energy region

For experimental searches

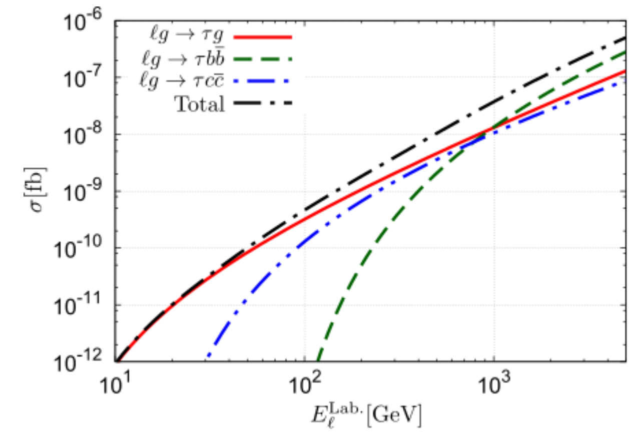
1. fixed target experiment

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_ℓ : produced number of ℓ per year

T_m : mass of target per $\text{cm}^2 \sim 100\text{g} \cdot \text{cm}^{-2}$



$\boldsymbol{eN \to \tau X}$

ILC (PWFA) : $E_e = 500\text{GeV}\ (5\text{TeV}),\ \ N_e = 10^{22}/\text{year}$ ⇨ $\mathcal{O}(10)\ \left(\mathcal{O}(10^3)\right)$ events/year

$\boldsymbol{\mu N \to \tau X}$

neutrino factory : $E_\mu = \mathcal{O}(100)\text{GeV},\ \ N_\mu = 10^{20}/\text{year}$ ⇨ $\mathcal{O}(10^{-1})$ events/year

2. collider experiment

$\boldsymbol{ep \to \tau X}$

TLHeC (VHE-TLHeC) : $\sqrt{s} \simeq 1.3(3.5)\text{TeV}$

Luminocity $\simeq \mathcal{O}(10^3)\ \text{fb}^{-1}/\text{year}$

⇨ $\mathcal{O}(100)$ events