Probing scalar-mediator quark couplings via CLFV lepton-nucleon scattering
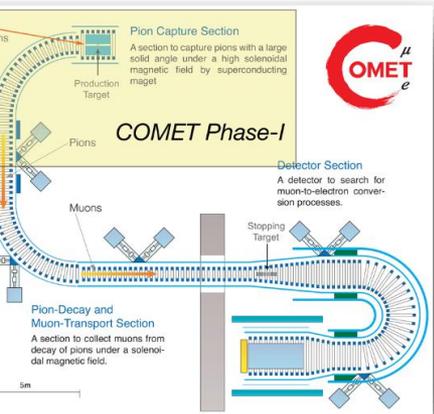
Masato Yamanaka (Hiroshima Institute of Technology)

LFV processes involving quarks (gluon)
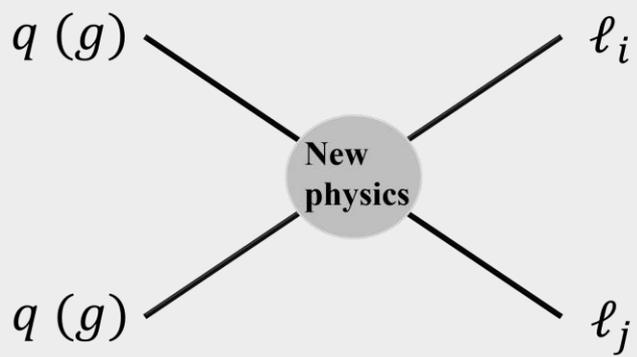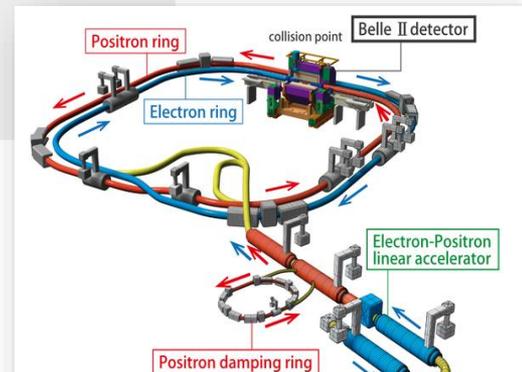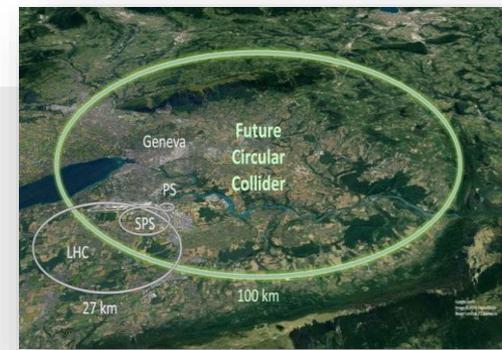
LFV processes involving quarks (gluon)

$$pp \to \ell_i \ell_j @\text{LHC}$$

$$K \to \mu e, D \to \tau e, B \to \tau e, \ldots$$

$\to e^- \text{ conversion}$

$q (g)$ ℓ_i

New physics

$q (g)$ ℓ_j

$\to e\pi, \tau \to \mu\pi\pi, \ldots$

COMET Phase-I

Future Circular Collider
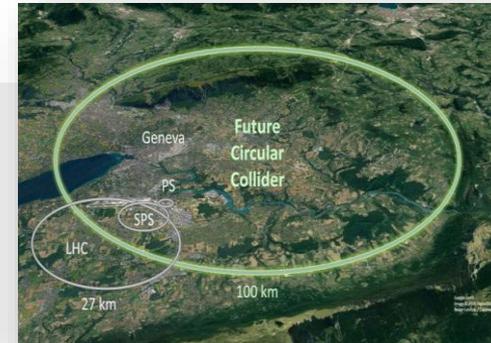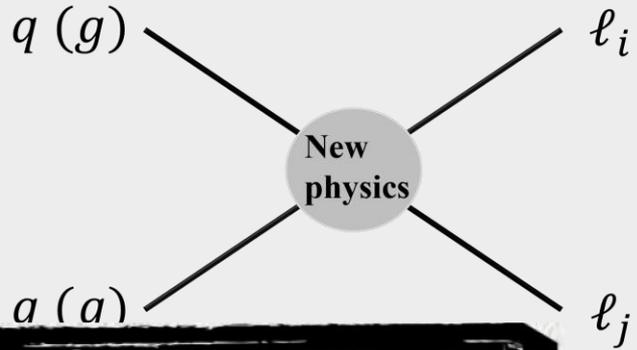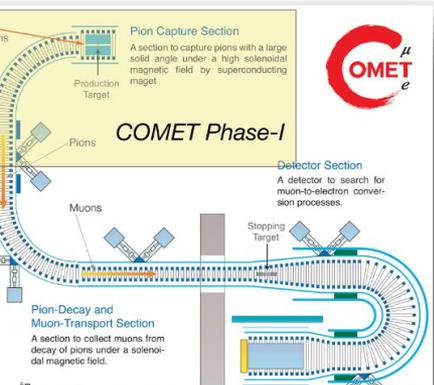
Uncovering the LFV mediator (mass, mediator-quark (gluon) interaction, etc)

Revealing the underlying new physics!

LFV-DIS: Promising process to search for LFV

$$\ell_i + N \to \ell_j + X \quad (N: \text{nucleon}, \ X: \text{hadron})$$

□ Many experiments for cross check (LHeC, ν-factory, ILC, …)

□ Complementary with τ hadronic LFV ($\tau \to e\pi\pi$, etc) and LFV at LHC ($pp \to \mu\tau$, etc)

□ Probe to the chirality of LFV ope. using polarized beam

□ Large number of event $\propto$ (beam intensity N_{ℓ_i}) $\times$ (nucleon density~ mole number)
        @fixed target exp.

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- Large number of event $\propto$ (beam intensity N_{ℓ_i}) $\times$ (nucleon density$\sim$ mole number) @fixed target exp.

- **Probe to the LFV mediator-quark (quark) interaction**

LFV interaction (toy model)

Applicable to a variety of models

(extended) Higgs model, leptoquark, R-parity violating SUSY, flavor sym., extra dimension model, etc.

☐ LFV mediator : scalar

☐ Scenario : mediator dominantly couples with heavy fermion

$$\mathcal{L}_S = -\sum_{i,j}\left(\rho_{ij}^S \bar{\ell}_j P_L \ell_i \phi_S + h.c.\right) - \sum_q \rho_{qq}^S \bar{q} q \phi_S$$
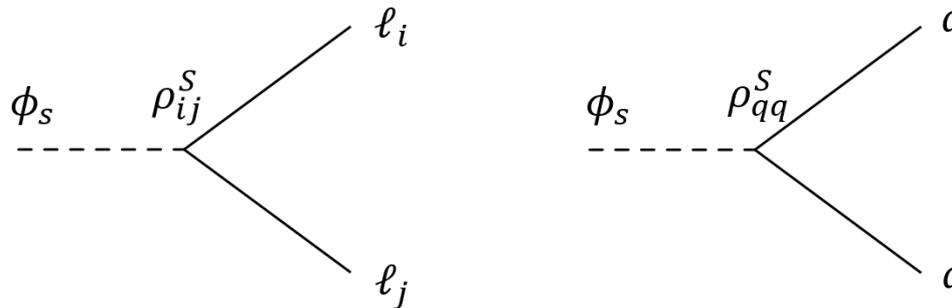
Coupling with quarks (flavor diagonal only)

A) Proportional to quark mass $\rho_{cc}^S : \rho_{bb}^S : \rho_{tt}^S = m_c : m_b : m_t$

B) Couple with one flavor only   example : $\rho_{bb}^S \neq 0, \;\; \rho_{cc}^S = \rho_{tt}^S = 0$

LFV mediator-gluon effective interaction

$$\mathcal{L}_S = -\sum_{i,j} \left(\rho_{ij}^S \bar{\ell}_j P_L \ell_i \phi_S + h.c. \right) + \sum_q \rho_{qq}^S \bar{q} q \phi_S \quad + \text{QCD}$$

$$g_{Sgg} = \sum_{q=c,b,t} \frac{\alpha_s \rho_{qq}^S}{8\pi m_q} \frac{4m_q^2}{q_S^2} \left[1 + \left(1 - \frac{4m_q^2}{q_S^2} \right) f\left(\frac{4m_q^2}{q_S^2} \right) \right]$$

$$4m_q^2/q_S^2 \to -\infty$$

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

2/3

Couple with one quark flavor only

Same as SM Yukawa
(thin solid: each contribution)
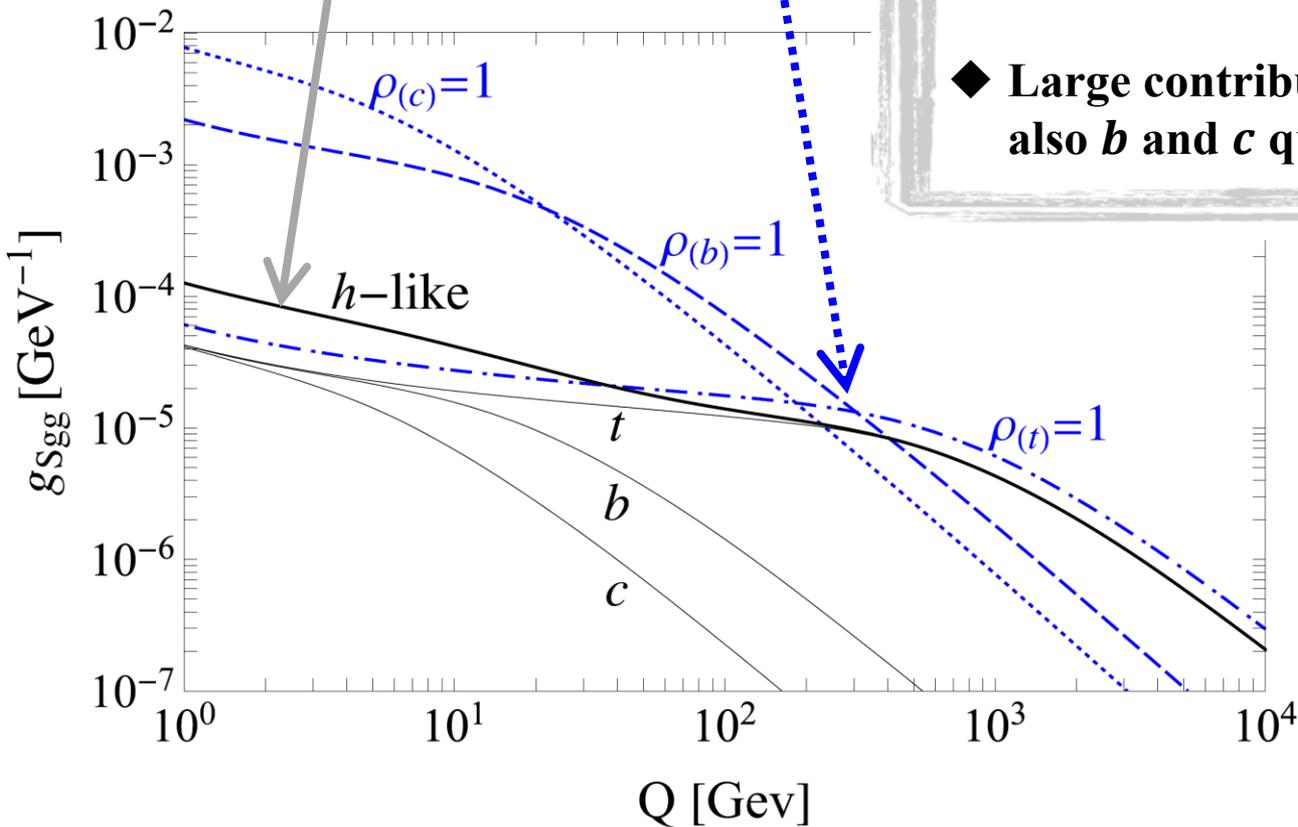
◆ **Strong dependence on momentum transfer, reflecting m_q and types of interaction**

◆ **Large contribution from not only t quark, also b and c quarks**
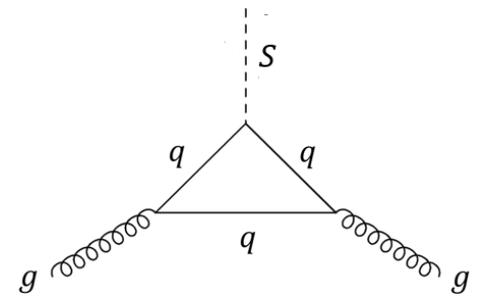
Cross section for $\ell_i g \to \ell_j g$

$$\sigma_{\ell_i N \to \tau X} = \sum_{\hat{p}=g,q} \int dx\, dy \int_0^1 d\xi_{\hat{p}} \frac{d^2 \hat{\sigma}_{\ell_i \hat{p} \to \tau \hat{X}}}{dx\, dy} f_{\hat{p}}(\xi_{\hat{p}}, Q^2)$$

Parton distribution function (PDF)

Subprocess cross section

$$\frac{d^2 \hat{\sigma}_{\ell_i g \to \ell_j g}}{dx\, dy} = \frac{|g_{S g g}|^2}{8\pi \hat{s}} \frac{Q^4}{(Q^2 + m_S^2)^2} \left[\left(|\rho_{ij}|^2 + |\rho_{ji}|^2 \right)(Q^2 + m_i^2 + m_j^2) + 4\mathrm{Re}\,(\rho_{ij}\rho_{ji})\, m_i m_j \right]$$
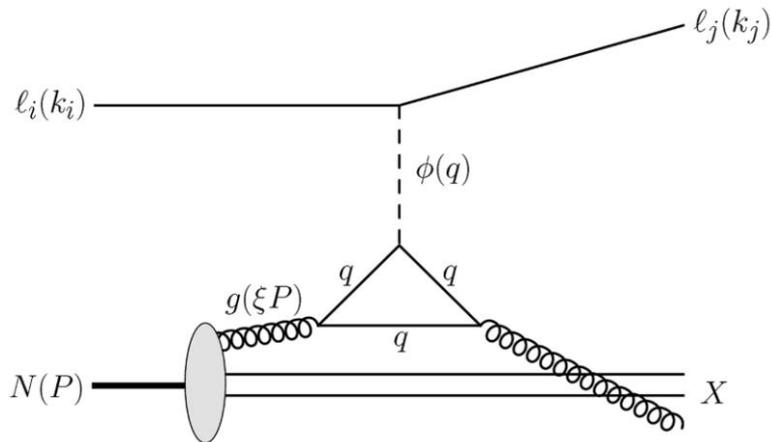
x : Bjorken variable

y : measure of inelasticy

$\xi_{\hat{p}}$: momentum fraction

$Q^2 = -\left(k_i - k_j\right)^2$: momentum transfer

Discriminating the types of mediator-quark coupling

Discriminating resolution for

$\underline{h\text{-like scenario}}$

$$\rho_{qq}^{S} = m_q/v \quad (\text{SM Yukawa})$$

$\underline{b\text{-only scenario}}$

$$\rho_{bb}^{S} \neq 0, \;\; \rho_{cc}^{S} = \rho_{tt}^{S} = 0$$

$\underline{\text{Interaction of LFV mediator}}$

$$\mathcal{L}_S = -\sum_{i,j} \left(\rho_{ij}^{S} \bar{\ell}_j P_L \ell_i \phi_S + h.c. \right) - \sum_{q} \rho_{qq}^{S} \bar{q} q \phi_S$$

Discriminating the types of mediator-quark coupling

Discriminating resolution for

<u>h-like scenario</u>

$$\rho_{qq}^{S} = m_q/v \quad \text{(SM Yukawa)}$$

<u>b-only scenario</u>

$$\rho_{bb}^{S} \neq 0, \ \ \rho_{cc}^{S} = \rho_{tt}^{S} = 0$$

Couplings from projected experimental sensitivity $\mathrm{BR}(\tau \to e\pi\pi) = 5 \times 10^{-10}$

<u>h-like scenario</u>

$$\sqrt{|\rho_{e\tau}|^2 + |\rho_{\tau e}|^2} = 3.6 \times \left(\frac{m_S}{1\,\mathrm{TeV}}\right)^2$$

<u>b-only scenario</u>

$$\rho_{bb}\sqrt{|\rho_{e\tau}|^2 + |\rho_{\tau e}|^2} = 0.21 \times \left(\frac{m_S}{1\,\mathrm{TeV}}\right)^2$$

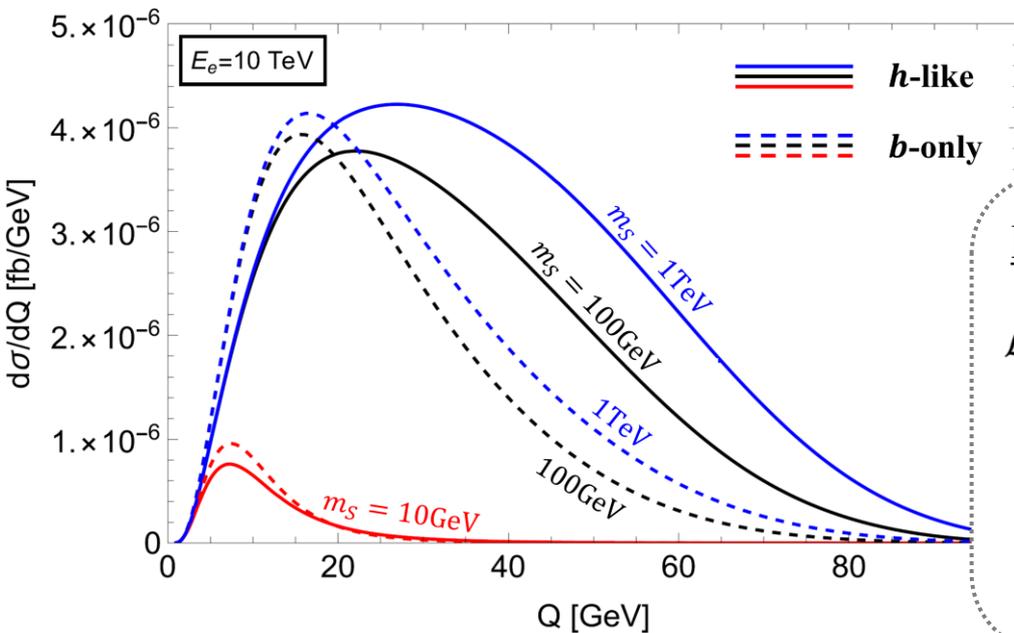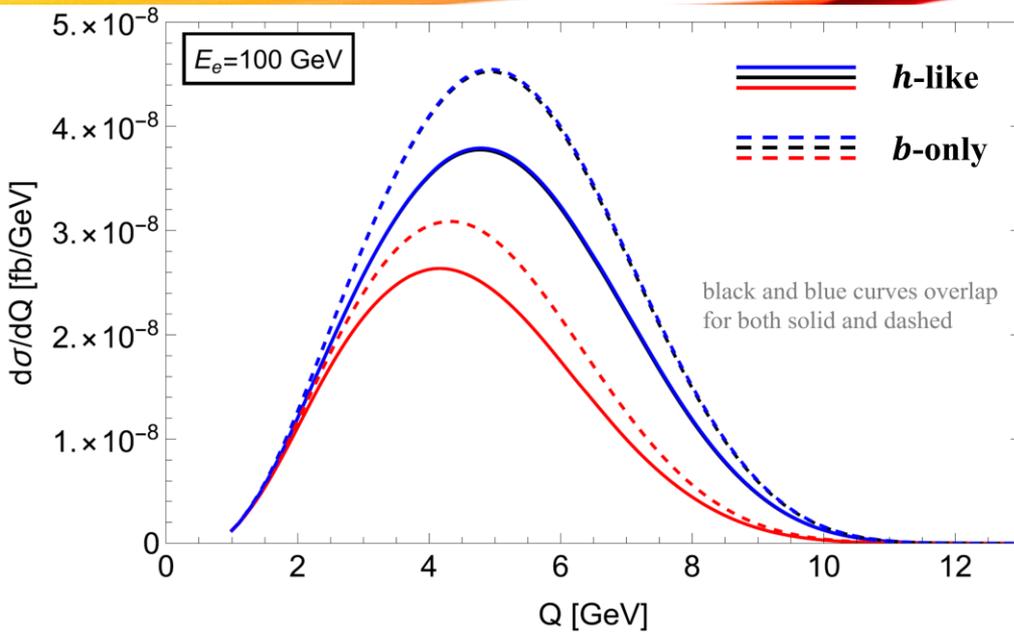# Discriminating the types of mediator-quark coupling

Discriminating resolution for

<u>h-like scenario</u>
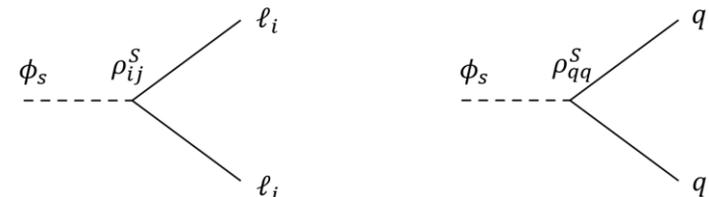
$$\rho^S_{qq} = m_q/v \quad \text{(SM Yukawa)}$$

<u>b-only scenario</u>

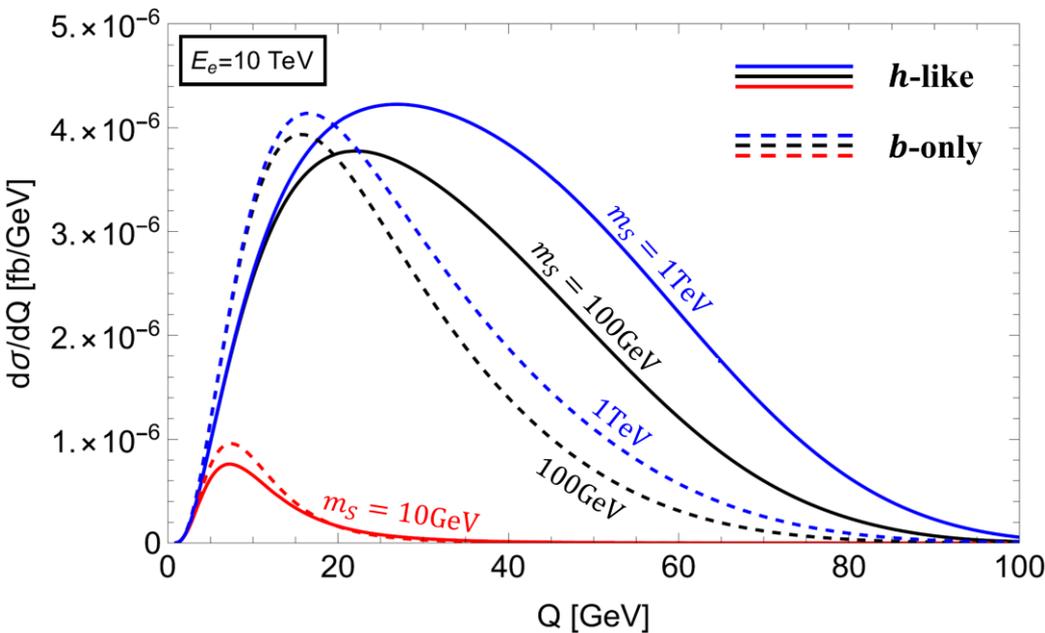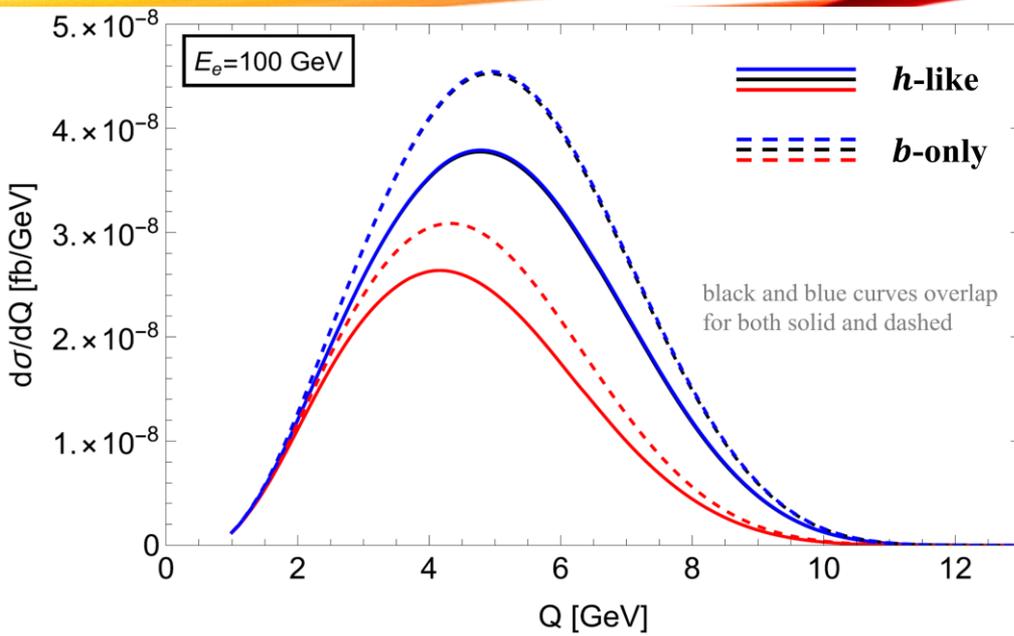$$\rho^S_{bb} \neq 0, \;\; \rho^S_{cc} = \rho^S_{tt} = 0$$
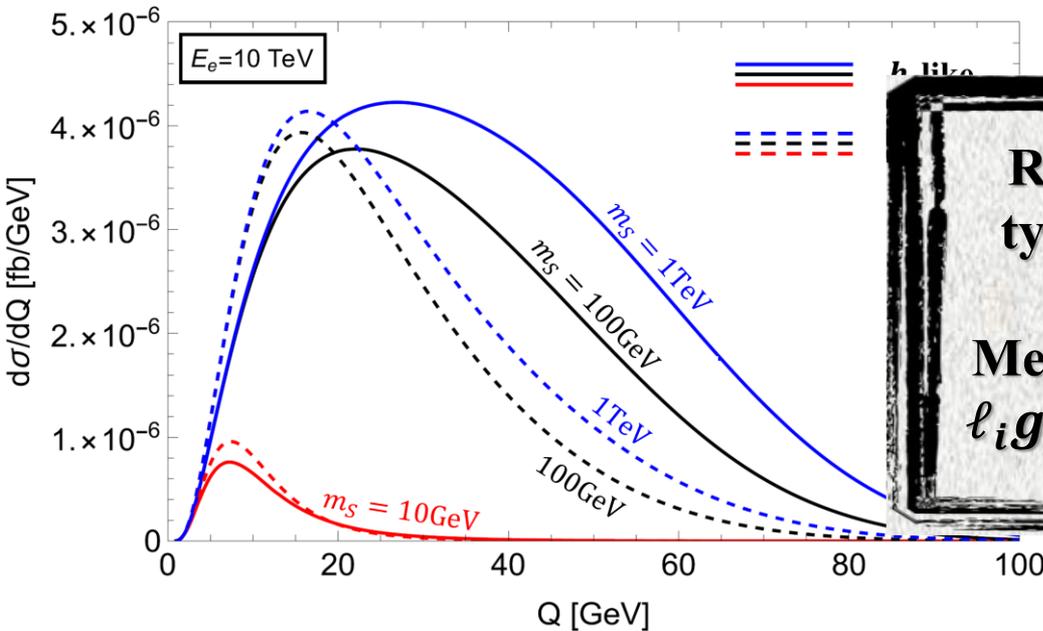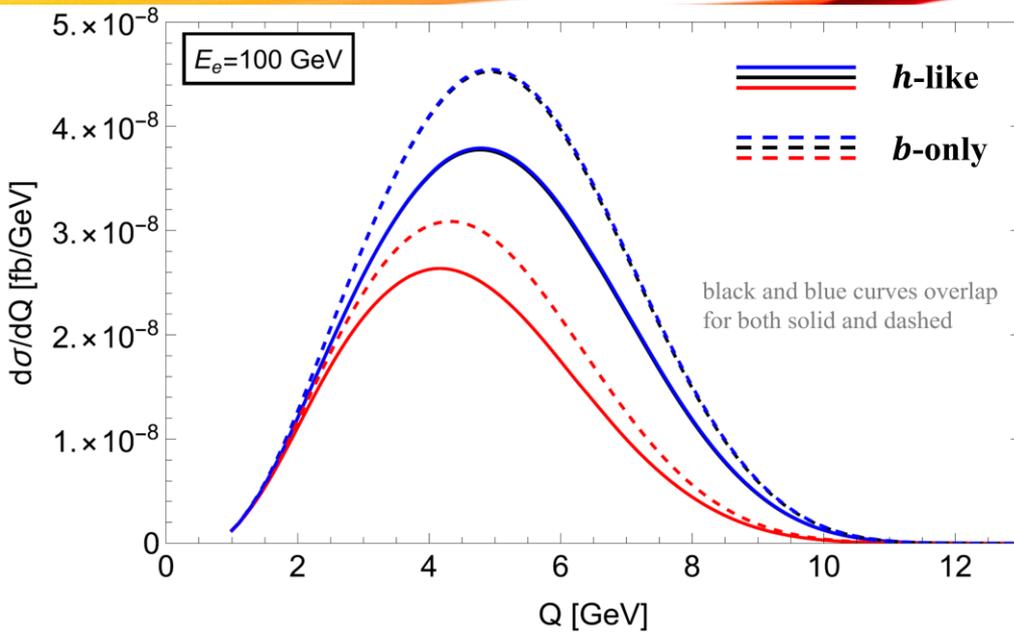
Reliable and promising probe to the types of mediator-quark interaction!

Measure the $d\sigma/dQ$ for the subprocess $\ell_i g \to \ell_j g$ with increasing beam energy

Discriminating the types of mediator-quark coupling

Important point for discrimination

Shift of peak position of $d\sigma/dQ$

From the difference of Q at which the effective coupling g_{Sgg} begins to drop

$\left(\right.$ Convolution with PDF is sensitive to the difference of Q $\left.\right)$
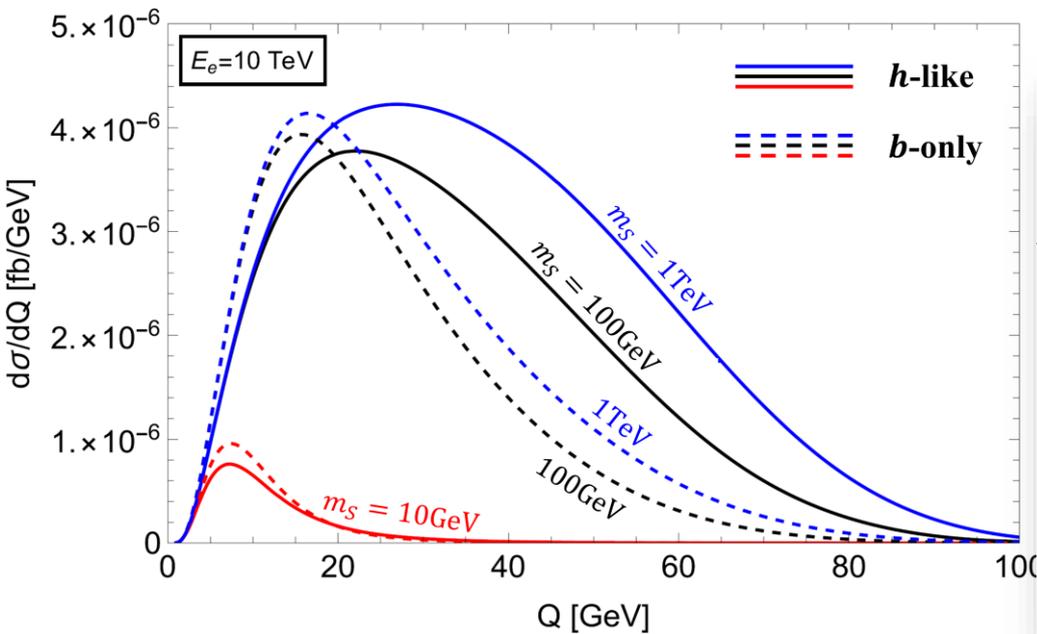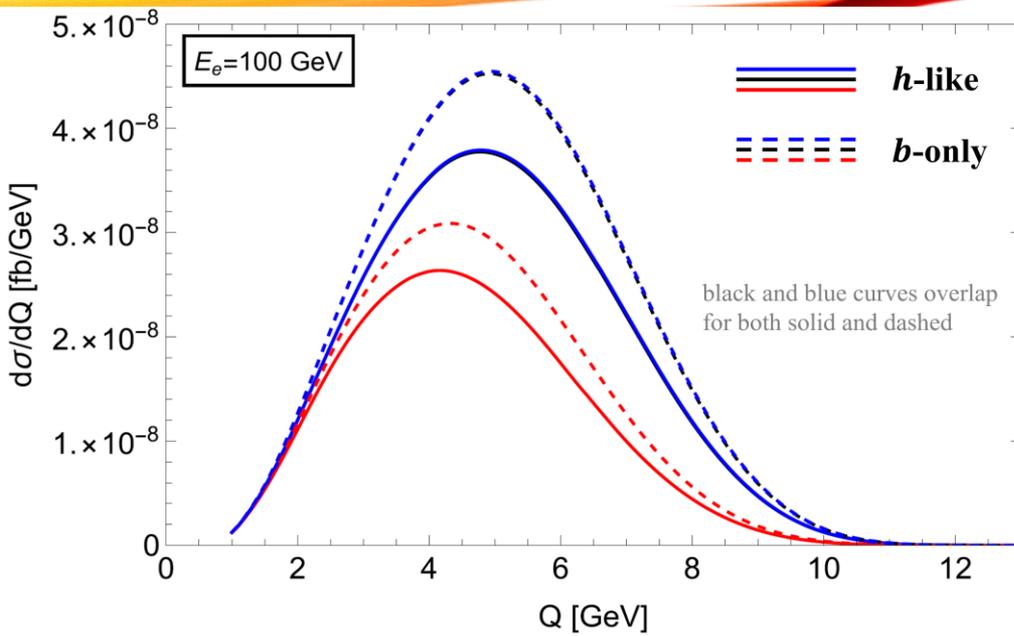
Discriminating the types of mediator-quark coupling

Important point for determination of m_S

For smaller m_S

Peak position of $d\sigma/dQ$ ⬅

Magnitude of $d\sigma/dQ$ ⬇

$\left(\begin{array}{l} c\text{-quark contribution is picked up by small} \\ Q, \text{which drops faster than heavier quarks} \end{array}\right)$

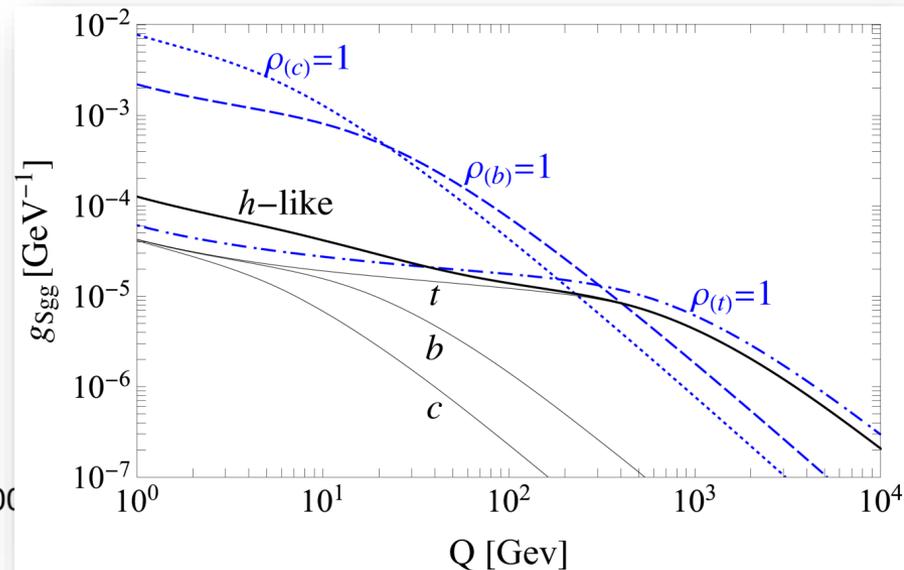Plot labels: E_e=100 GeV; **h-like**; **b-only**; black and blue curves overlap for both solid and dashed; $d\sigma/dQ$ [fb/GeV]; Q [GeV]

E_e=10 TeV; **h-like**; **b-only**; m_S = 1TeV; m_S = 100GeV; 1TeV; 100GeV; m_S = 10GeV; $d\sigma/dQ$ [fb/GeV]; Q [GeV]

$\rho_{(c)}=1$; $\rho_{(b)}=1$; $\rho_{(t)}=1$; h–like; t; b; c; g_{Sgg} [GeV^{-1}]; Q [Gev]
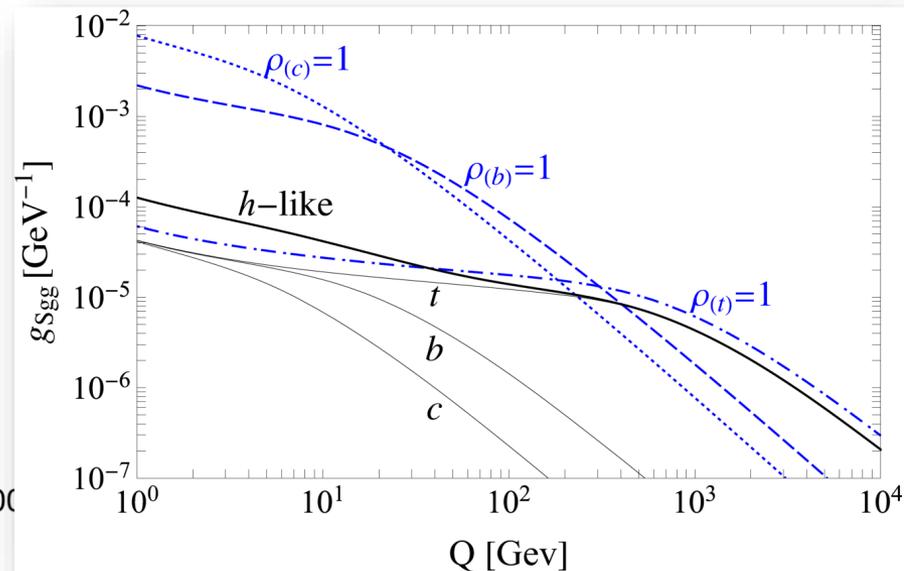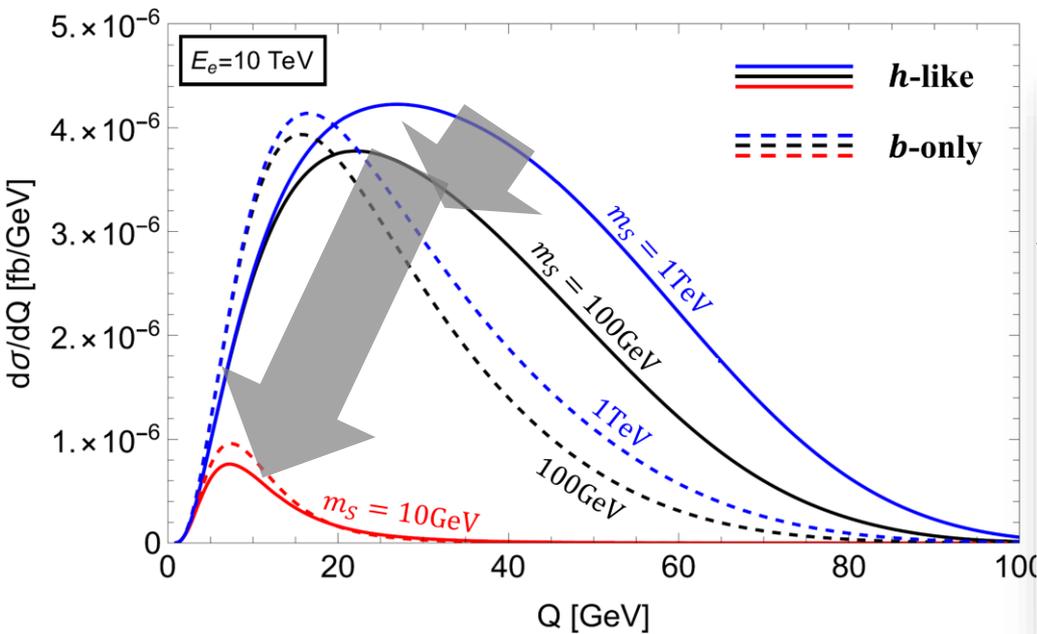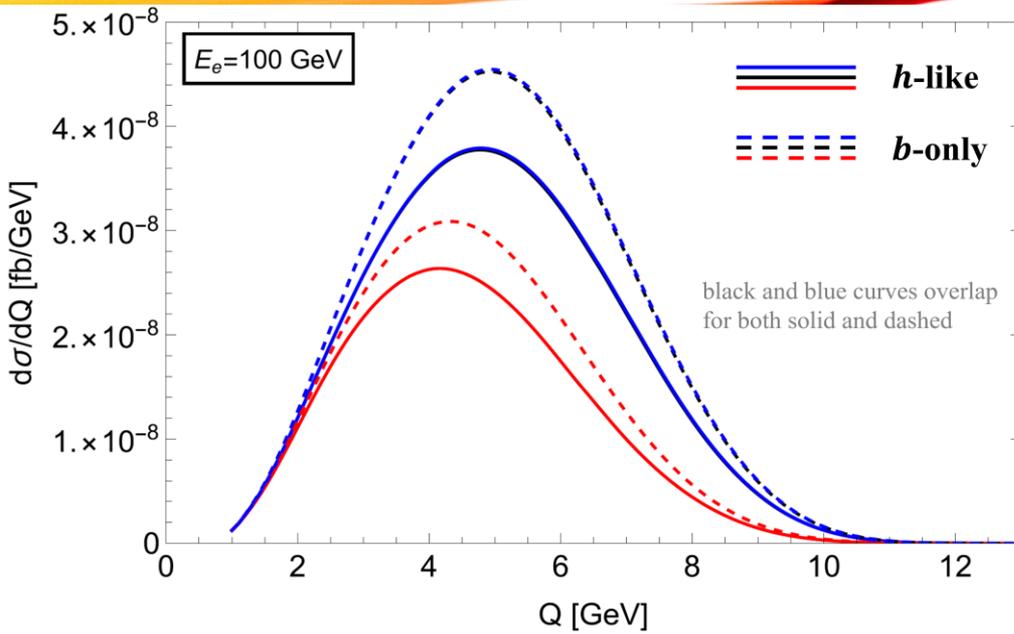
Test for the mass proportionality

Parametrization for the deviation from SM Yukawa

$$\rho_{cc}^{\phi} = \frac{m_c}{v}, \rho_{bb}^{\phi} = \frac{m_b}{v}, \rho_{tt}^{\phi} = \kappa_t^{\phi} \frac{m_t}{v}$$

$d\sigma(\ell_i N \to \ell_j X)/dQ$ at peak position Q^*

Clear sensitivity both of the peak position Q^* and the $d\sigma/dQ$ to κ_t^{ϕ}

Lepton Flavor Violation (LFV)

Not only an evidence, but also versatile probe to new physics

Important mission: How to uncover the LFV mediator-quark (gluon) interaction?

$$pp \rightarrow \ell_i \ell_j @ \text{LHC}$$
$$K \rightarrow \mu e, D \rightarrow \tau e, B \rightarrow \tau e, \dots$$

$\mu^- \rightarrow e^-$ conversion

$q\ (g)$ ℓ_i

New physics

$q\ (g)$ ℓ_j

$\tau \rightarrow e\pi, \tau \rightarrow \mu\pi\pi, \dots$
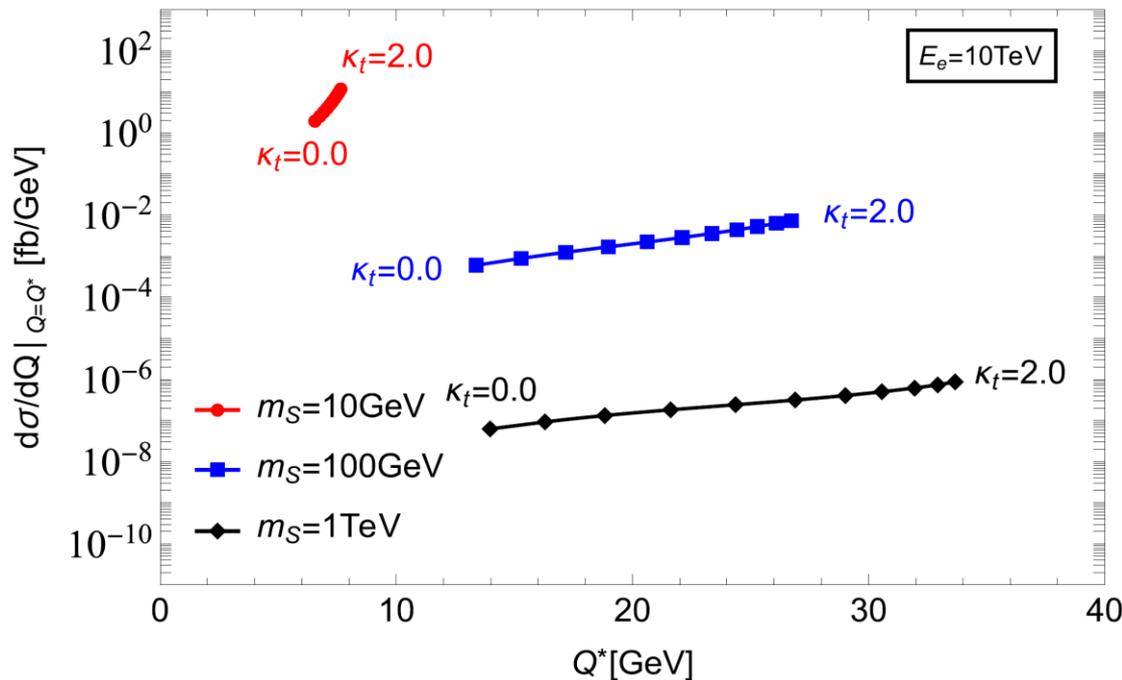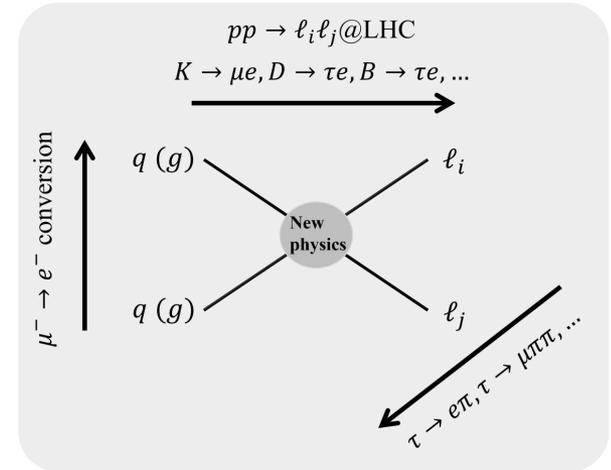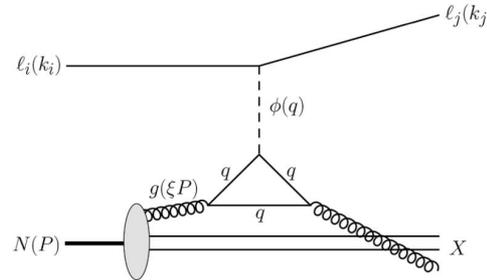
LFV Deep inelastic scattering (LFV-DIS)

Reliable and promising probe to the types of mediator-quark (gluon) interaction!

Key: mediator-gluon effective coupling

Measure the $d\sigma/dQ$ for the subprocess $\ell_i g \rightarrow \ell_j g$ with increasing beam energy!

Backup slides

Complemental probe to $\ell_i\ell_j qq$ ($\ell_i\ell_j gg$)

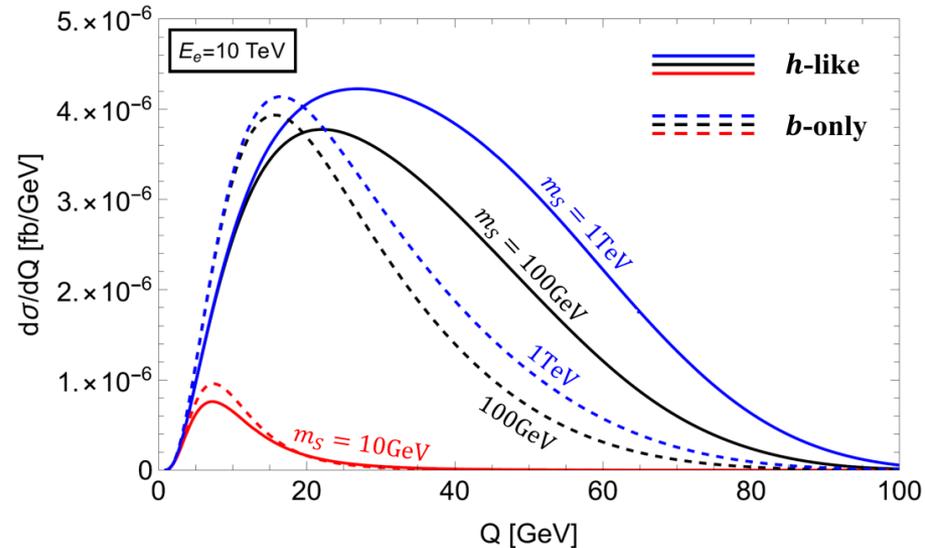| Channel	Upper limit	Experiment	Reference
$\pi^0 \to \mu^\pm e^\mp$	3.59×10^{-10}	KTeV	75
$\eta \to \mu^\pm e^\mp$	6×10^{-6}	Saturne SPES2	76
$K_L^0 \to \pi^0 \mu^\pm e^\mp$	7.56×10^{-11}	KTeV	75
$K_L^0 \to 2\pi^0 \mu^\pm e^\mp$	1.64×10^{-10}	KTeV	75
$K_L^0 \to \mu^+ e^-$	4.7×10^{-12}	BNL E871	74
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	BNL E865, E777	73
$D^+ \to \pi^+ \mu^\pm e^\mp$	3.4×10^{-5}	Fermilab E791	77
$D^+ \to K^+ \mu^\pm e^\mp$	6.8×10^{-5}	Fermilab E791	77
$D^0 \to \mu^\pm e^\mp$	8.1×10^{-7}	BaBar	78
$D_s^+ \to \pi^+ \mu^\pm e^\mp$	6.1×10^{-4}	Fermilab E791	77
$D_s^+ \to K^+ \mu^\pm e^\mp$	6.3×10^{-4}	Fermilab E791	77
$B^0 \to \mu^\pm e^\mp$	9.2×10^{-8}	BaBar (347 fb^{-1})	79
$B^0 \to \tau^\pm e^\mp$	1.1×10^{-4}	CLEO (9.2 fb^{-1})	80
$B^0 \to \tau^\pm \mu^\mp$	3.8×10^{-5}	CLEO (9.2 fb^{-1})	80
$B^+ \to K^+ e^\pm \mu^\mp$	9.1×10^{-8}	BaBar (208 fb^{-1})	81
$B^+ \to K^+ e^\pm \tau^\mp$	7.7×10^{-5}	BaBar (348 fb^{-1})	82
$B_s^0 \to e^\pm \mu^\mp$	6.1×10^{-6}	CDF (102 pb^{-1})	83

Abbreviations: BNL, Brookhaven National Laboratory; CDF, Collider Detector at Fermilab; KTeV, Kaons at the Tevatron.

LFV Deep inelastic scattering $e(\mu)N \to \tau X$

Signal

-- τ with large momentum along the beam-axis
   (highly depends on types of LFV operator)
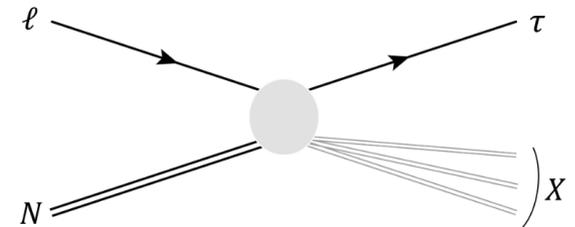
Experimental status

  -- Limit: HERA exp.

  -- Future: EIC, LHeC, ILC, …

|	$e \to \tau$		ZEUS			$F = 0$	
$\alpha\beta$	$S^L_{1/2}$ e^+u_α	$S^R_{1/2}$ $e^+(u+d)_\alpha$	$\tilde{S}^L_{1/2}$ e^+d_α	V^L_0 e^+d_α	V^R_0 e^+d_α	$\tilde{V}^R_0$ e^+u_α	V^L_1 $e^+(\sqrt{2}u+d)_\alpha$
1 1	$\tau \to \pi e$ 0.4 **3.0**	$\tau \to \pi e$ 0.2 2.5	$\tau \to \pi e$ 0.4 4.6	G_F 0.2 3.3	$\tau \to \pi e$ 0.2 3.3	$\tau \to \pi e$ 0.2 2.4	G_F 0.2 1.2
1 2	**3.1**	$\tau \to Ke$ 5 **2.5**	$K \to \pi\nu\bar{\nu}$ 10^{-3} 4.7	$\tau \to Ke$ 3 3.7	$\tau \to Ke$ 3 3.7	**2.7**	$K \to \pi\nu\bar{\nu}$ 2.5×10^{-4} 1.3
1 3	*	$B \to \tau\bar{e}X$ 8 **5.1**	$B \to \tau\bar{e}X$ 8 **5.1**	$B \to l\nu X$ 2 4.6	$B \to \tau\bar{e}X$ 4 4.6	*	$B \to l\nu X$ 2 4.6
2 1	**16**	$\tau \to Ke$ 5 9.2	$K \to \pi\nu\bar{\nu}$ 10^{-3} 12	$\tau \to Ke$ 3 4.9	$\tau \to Ke$ 3 4.9	**6.2**	$K \to \pi\nu\bar{\nu}$ 2.5×10^{-4} 2.6
2 2	$\tau \to ee\bar{e}$ 20 **20**	$\tau \to ee\bar{e}$ 30 **11**	$\tau \to ee\bar{e}$ 66 **12**	$\tau \to ee\bar{e}$ 33 **6.2**	$\tau \to ee\bar{e}$ 33 **6.2**	$\tau \to ee\bar{e}$ 10 11	$\tau \to ee\bar{e}$ 6.1 **4.3**
2 3	*	$B \to \tau\bar{e}X$ 8 16	$B \to \tau\bar{e}X$ 8 16	$B \to l\nu X$ 2 12	$B \to \tau\bar{e}X$ 4 12	*	$B \to l\nu X$ 2 12
3 1	*	$B \to \tau\bar{e}X$ 8 17	$B \to \tau\bar{e}X$ 8 17	V_{ub} 0.2 5.4	$B \to \tau\bar{e}X$ 4 5.4	*	V_{ub} 0.2 5.4
3 2	*	$B \to \tau\bar{e}X$ 8 22	$B \to \tau\bar{e}X$ 8 22	$B \to l\nu X$ 2 7.6	$B \to \tau\bar{e}X$ 4 7.6	*	$B \to l\nu X$ 2 7.6
3 3	*	$\tau \to ee\bar{e}$ 30 **30**	$\tau \to ee\bar{e}$ 66 **30**	$\tau \to ee\bar{e}$ 33 **15**	$\tau \to ee\bar{e}$ 33 **15**	*	$\tau \to ee\bar{e}$ 6.1 15

Probe to various models beyond the SM
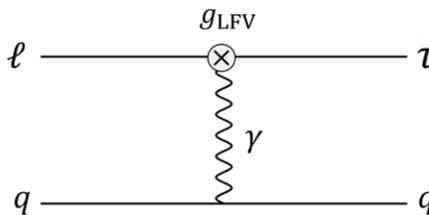
SUSY, Type-II SeeSaw
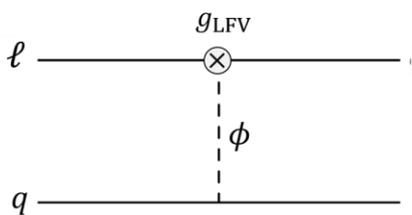
extra dimension models,
extended Higgs models
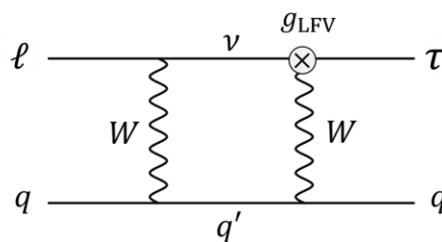
Majorana ν, sterile ν
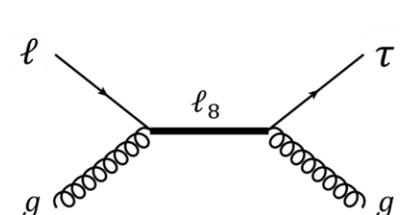
composite, leptogluon

LFV Deep inelastic scattering $e(\mu)N \to \tau X$
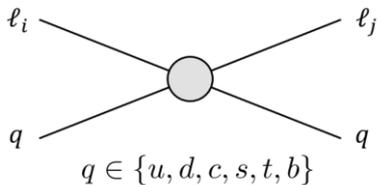
Cross section for $e(\mu)N \to \tau X$

$$\sigma_{\ell_i N \to \tau X} = \sum_{\hat{p}=g,q} \int dx dy \int_0^1 d\xi_{\hat{p}} \frac{d^2 \hat{\sigma}_{\ell_i \hat{p} \to \tau \hat{X}}}{dx dy} f_{\hat{p}}(\xi_{\hat{p}}, Q^2)$$

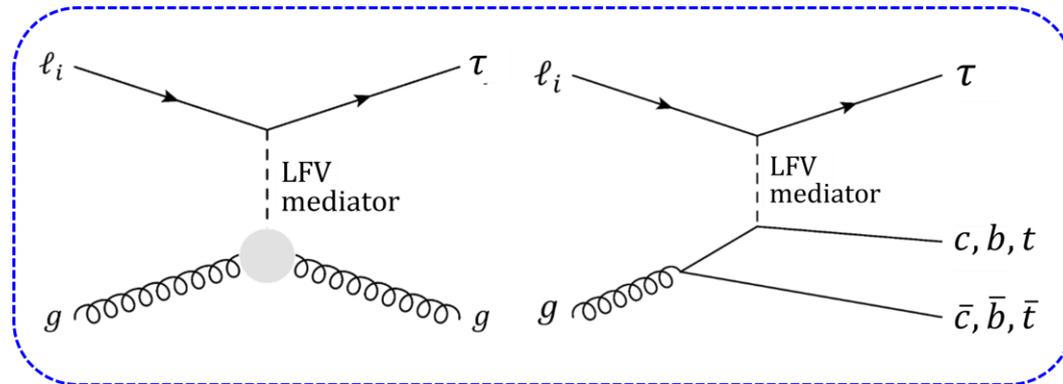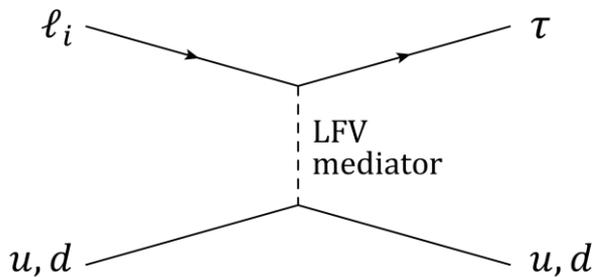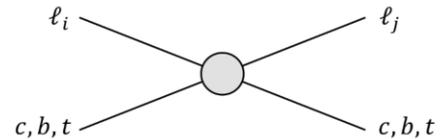Parton distribution function (PDF)

Subprocess cross section

LFV mediator couples universally with all quarks (e.g., GUT Z', dipole LFV, etc)

ℓ_i ℓ_j

q q

$q \in \{u, d, c, s, t, b\}$

LFV mediator couples dominantly with heavy quarks (e.g., Higgs, KK bosons, etc)

ℓ_i ℓ_j

c, b, t c, b, t

Cross section, kinematics, and so on highly depends on types of LFV mediator

M. Takeuchi, Y. Uesaka, MY, PLB (2017)

ℓ_i τ

LFV mediator

u, d u, d

ℓ_i τ

LFV mediator

g g

ℓ_i τ

LFV mediator

g

c, b, t

$\bar{c}, \bar{b}, \bar{t}$

Beam energy = 100 GeV, m_S = 10 GeV