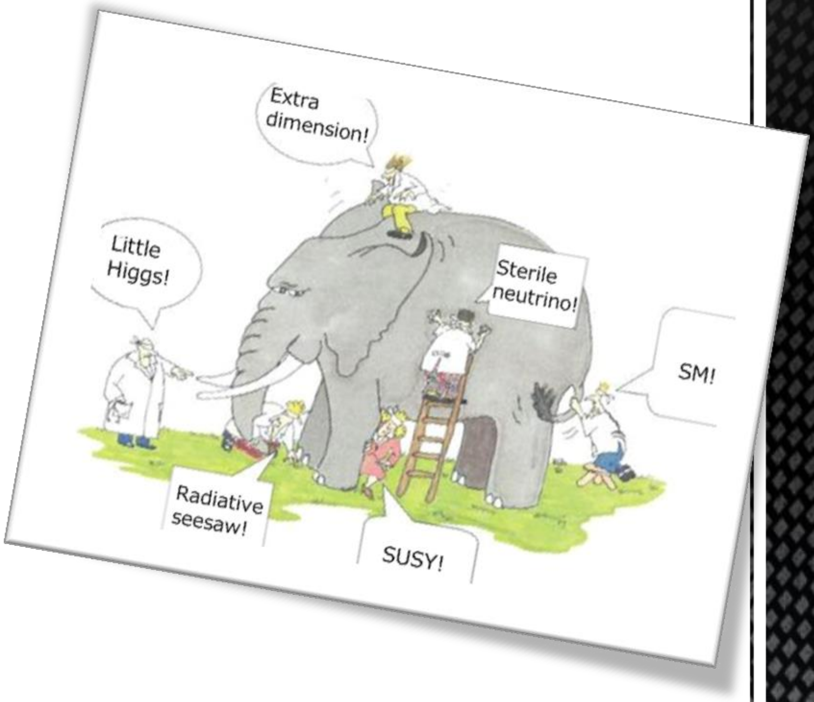
Detailed analysis of lepton flavor violating DIS by (pseudo-)scalar mediator

Masato Yamanaka (NITEP, Osaka City Univ.)

M. Takeuchi, Y. Uesaka and MY, PLB772 (2017)
Y. Kiyo, M. Takeuchi, Y. Uesaka and MY, arXiv:2103.XXXXX
Y. Kiyo, M. Takeuchi, Y. Uesaka and MY, arXiv:2104.XXXXX

Lepton flavor violating deep-inelastic scattering (LFV-DIS)

LFV : not only an evidence, but also a sensitive probe to new physics!

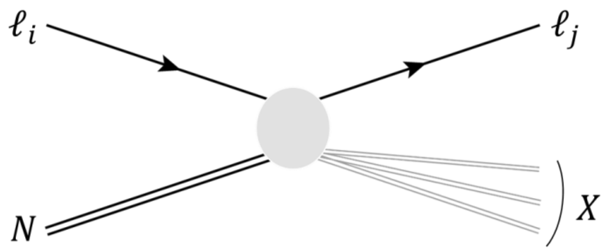


$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \times 10^{-13}$	MEG (2016)
$\mu^+ \to e^+e^-e^+$	$\mathrm{BR} < 1.0 \times 10^{-12}$	SINDRUM (1988)
$\mu \to e$ conversion	$\mathrm{BR} < 7.0 \times 10^{-13}$	SINDRUM-II (2006)

The more LFV processes, the "elephant" is more clearly illustrated!

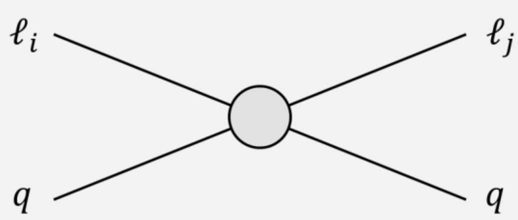
One of the most promising LFV process:
LFV DIS $\ell_i N \to \ell_j X$

- ☐ Clean signal
- ☐ Unique probe to some LFV ope.



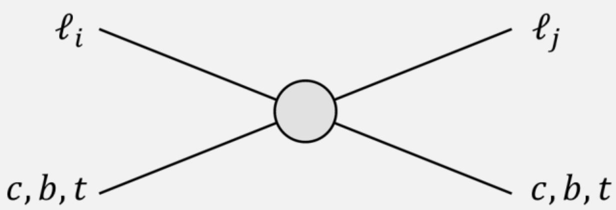
Lepton flavor violating deep-inelastic scattering (LFV-DIS)

<u>Universal</u> $q \in \{u, d, c, s, t, b\}$

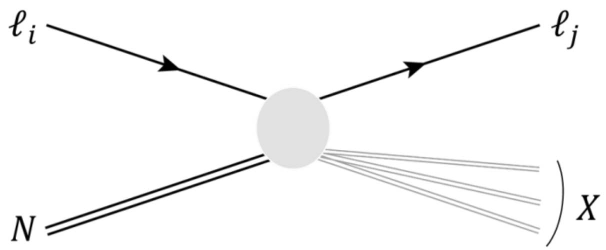


e.g., photonic dipole LFV in SUSY models,
Z' LFV in GUT models, …

<u>Non-Universal</u>



e.g., Higgs LFV in extended Higgs scenarios,
KK boson LFV in extra dimension models, …



Lepton flavor violating deep-inelastic scattering (LFV-DIS)

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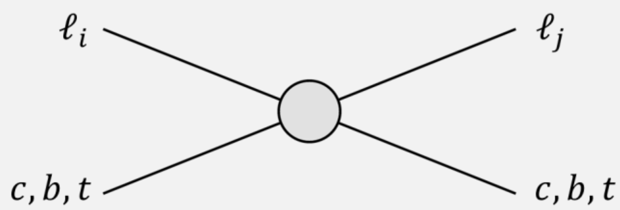
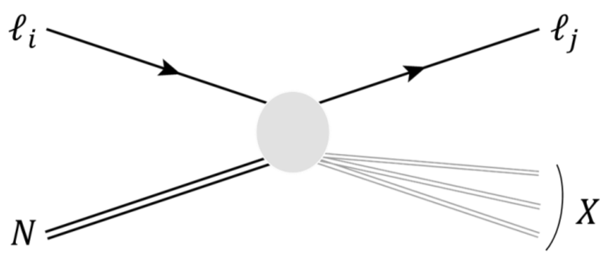


e.g., Higgs LFV in extended Higgs scenarios,
KK boson LFV in extra dimension models, …

No exotic signals@LHC implies that new physics so-weakly couples with valence quarks

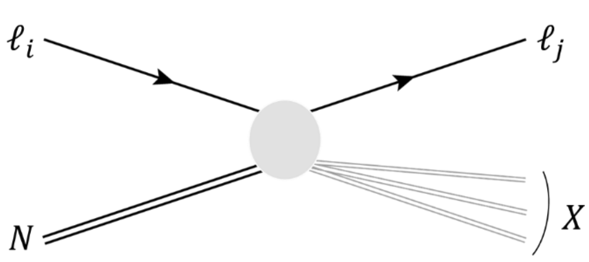
Quite difficult to directly probe the LFV operators involving heavy quarks



Precisely connect the LFV parameter and the LFV-DIS for flavor non-universal LFV mediator

Subprocess of LFV-DIS $\ell_i N \to \ell_j X$

Take into account the (1) ϕgg coupling (2) quark-number conservation



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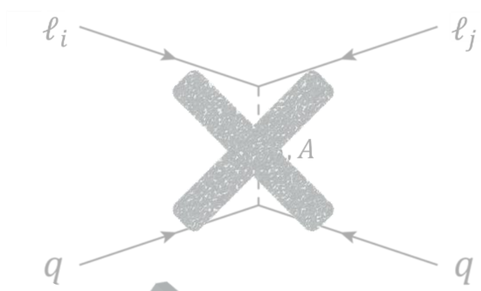

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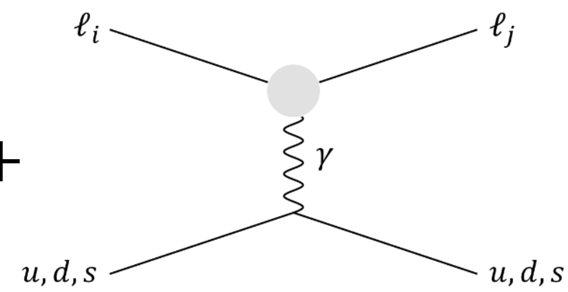
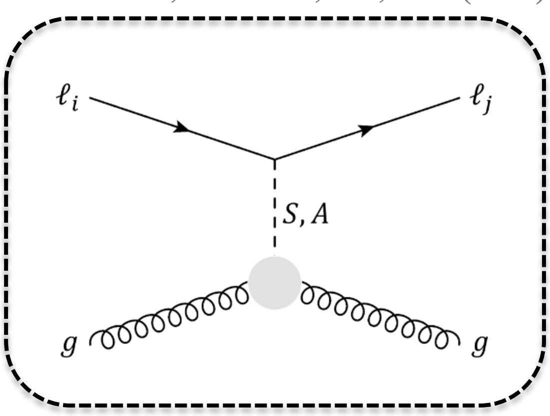


Improved handling

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

ACOT scheme [PRD50 (1994)]



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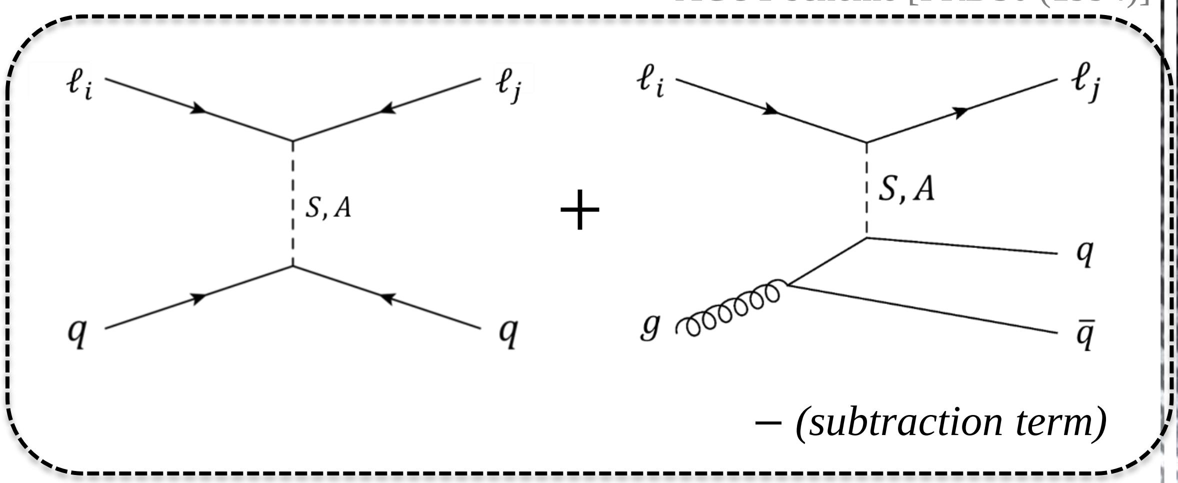


Cross section

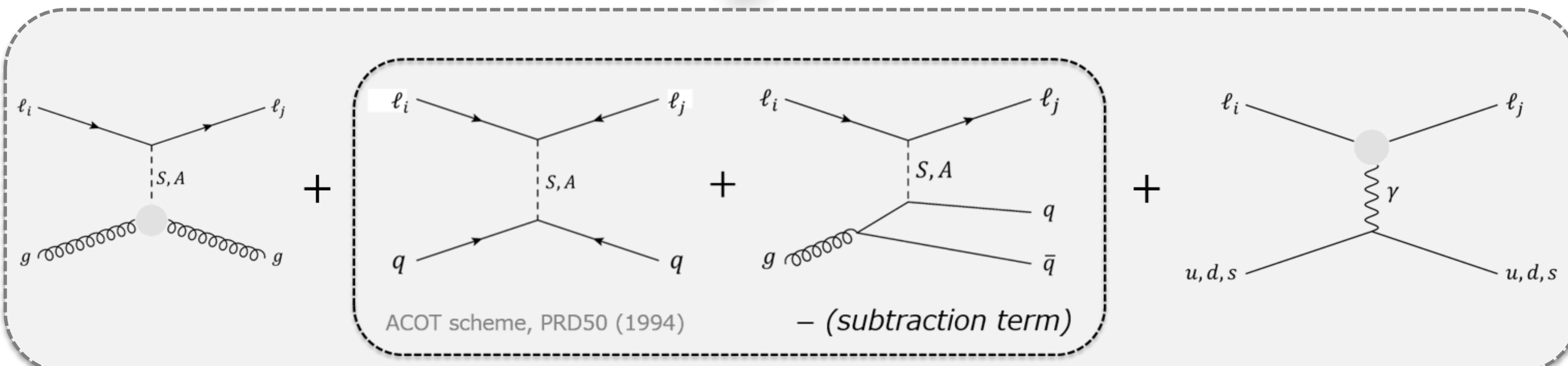
See e.g. T. Stavreva, F. I. Olness, et al, PRD85 (2012)
M. Takeuchi, Y. Uesaka, M.Y., PLB772 (2017)

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

x : Bjorken variable
y : measure of inelasticy

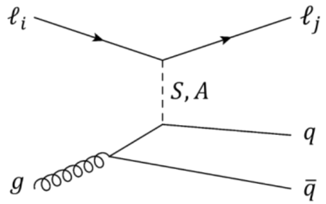
$$\sigma_{\ell_i N \to \ell_i X} = \sum_{\hat{p}=g,q} \int dxdy \int_0^1 d\xi \frac{d^2\hat{\sigma}_{\ell_i \hat{p} \to \ell_j \hat{X}}}{dxdy} f_{\hat{p}}\left(\xi_{\hat{p}}, Q^2\right)$$

PDF (function of ξ, not x!)



ACOT scheme M. Aivazis, J. Collins, F. Olness, W. Tung, PRD50 (1994)

LFV DIS associated with heavy quark@Leading order



- Momentum fraction : $\xi = \frac{Q^2 + w^2}{Q^2} x$
- Momentum transfer : $Q^2 = -(p_i - p_f)^2$
- Transition amplitude of leptonic part : L_{ij}^X

Cross section $$\frac{d\hat{\sigma}^X_{g\to qq}}{dxdy} = \frac{1}{32\pi^2}\left(\frac{y}{\xi}\right)\frac{L_{ij}^X W_{qq}^X}{(Q^2 + m_X^2)^2}$$

Transition amplitude of hadronic part for $Q^2 \gg m_q^2$

Divergence!

$$W_{qq}^X(\xi) \approx 2\pi|\rho_{qq}^X|^2\,\theta(\xi - x_m)\left(\frac{\alpha_s T_F}{2\pi}\right)\left[\left(\frac{x}{\xi}\right)^2 + \left(1 - \frac{x}{\xi}\right)^2\right]\ln\left(\frac{Q^2}{m_q^2}\right) + \mathcal{O}(m_q^0)$$

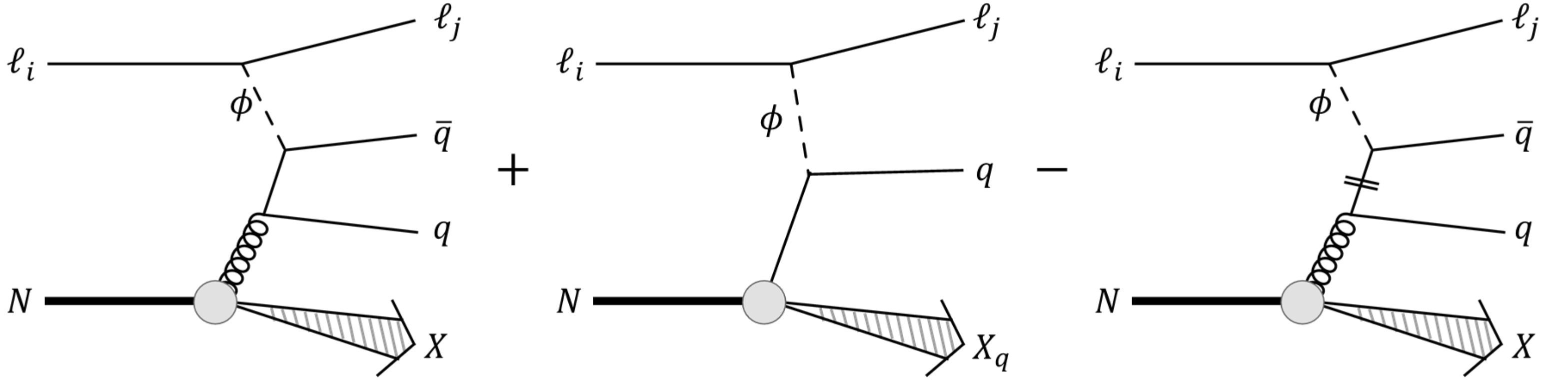
Heavy quark PDF is constructed by renormalizing such divergence with QCD corrections

R. Ellis, W. Stirling, B. Webber, *QCD and collider physics*

Subprocess $\ell_i b \to \ell_j b$ should be employed with the heavy quark PDF for $Q^2 \gg m_q^2$

ACOT scheme

M. Aivazis, J. Collins, F. Olness, W. Tung, PRD50 (1994)



Scheme with $m_q \neq 0$

Scheme with $m_q = 0$

Subtraction contribution to cancel double counting

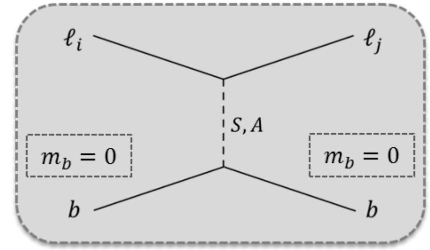
Scheme formula interpolating two different energy scales ($Q^2 \sim 4m_q^2$ and $Q^2 \gg m_q^2$)

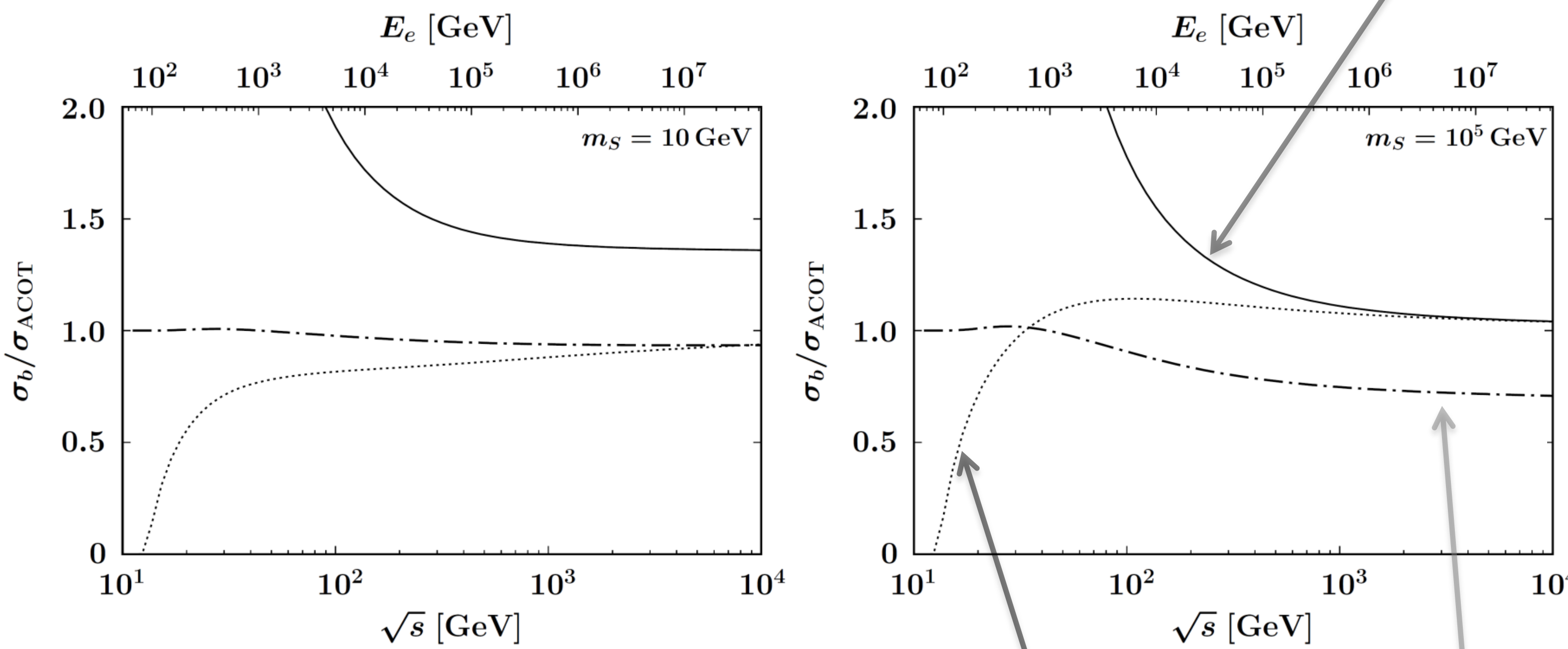
$$\frac{d^2\sigma}{dxdy} = \int_0^1 d\xi \left\{ \frac{d^2\hat{\sigma}_{\ell_i g\to\ell_j q\bar{q}}}{dxdy} f_g(\xi, Q^2) + \frac{d^2\hat{\sigma}_{\ell_i q\to\ell_j q}}{dxdy} f_q(\xi, Q^2) + \frac{d^2\hat{\sigma}_{\ell_i \bar{q}\to\ell_j \bar{q}}}{dxdy} f_q(\xi, Q^2) \right.$$

$$\left. - \left(\frac{d^2\hat{\sigma}_{\ell_i q\to\ell_j q}}{dxdy} + \frac{d^2\hat{\sigma}_{\ell_i \bar{q}\to\ell_j \bar{q}}}{dxdy} \right) \frac{\alpha_s}{2\pi} \int_\xi^1 \frac{dz}{z} f_g(z, Q^2) P_{gq}(\xi/z) \ln\left(\frac{Q^2}{m_q^2}\right) \right\}$$

Subtraction part

Scheme dependence on LFV-DIS

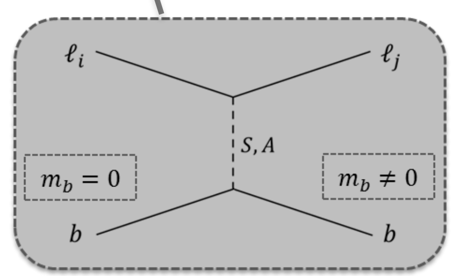


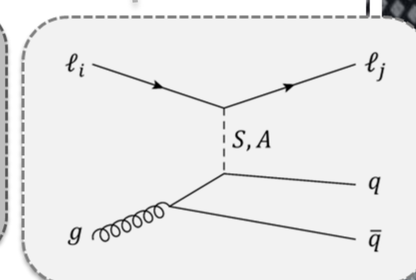


- Finite m_b effect even far above the $b\bar{b}$ threshold

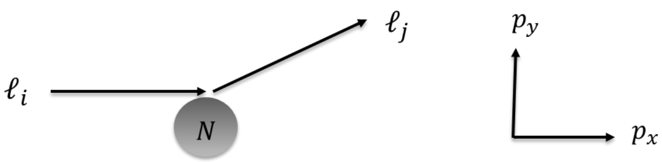
- **<u>ACOT scheme</u>: Indispensable for LFV-DIS mediated by scalar, especially for small m_S**

- <u>$\ell_i g \to \ell_j b\bar{b}$</u> : Acceptable alternative at the scale of next(-next) generation experiments

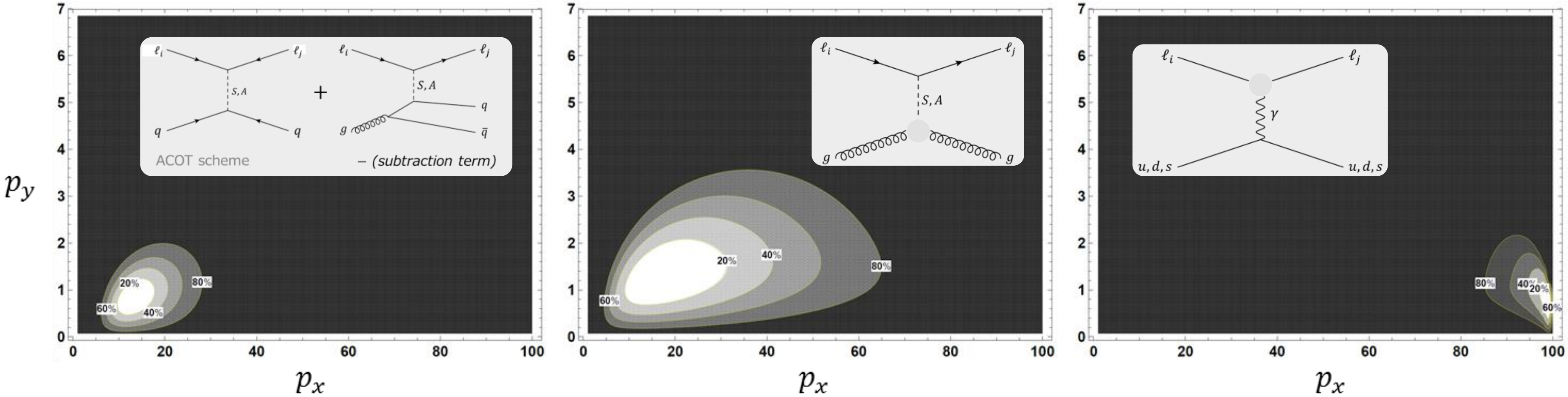




Momentum distribution

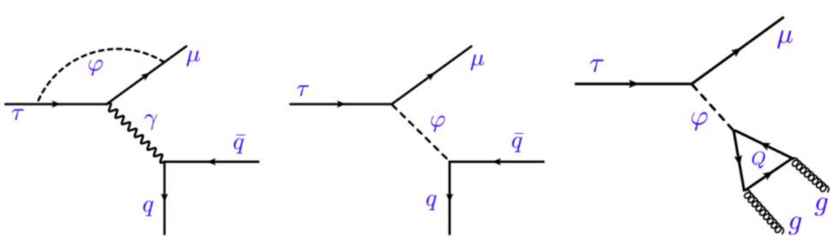


Beam energy = 100 GeV, m_S = 10 GeV

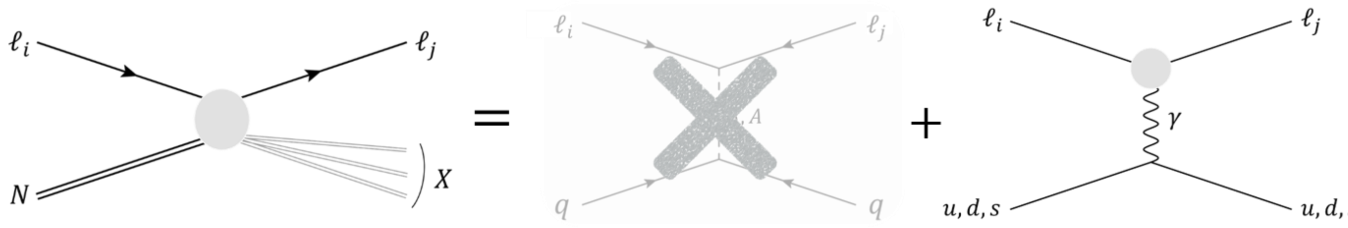


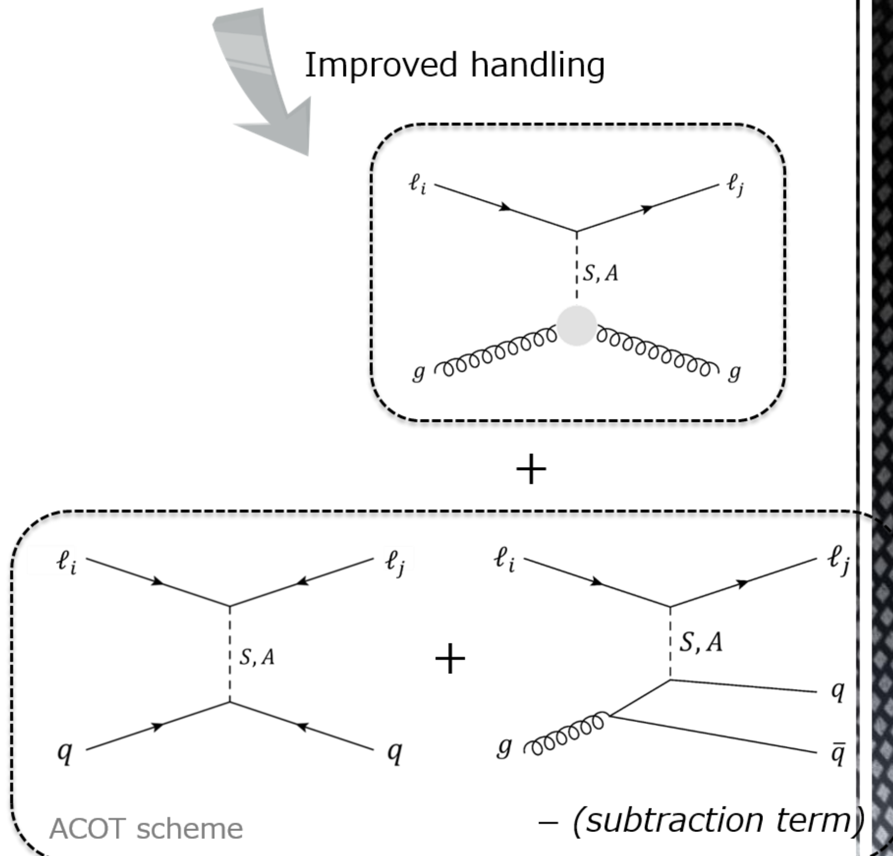
- Completely different distribution for each subprocess
- Sensitive probe to the interactions of mediator and quark/gluon/photon
- Synergy with τ LFV decay

A. Celis, V. Cirigliano, E. Passemar, PRD89 (2014)
T. Husek, K. Monsalvez-Pozo, J. Portoles, JHEP01 (2021)



Summary





- LFV-DIS: Promising process to search for LFV

- **Analysis on LFV-DIS taking into account important ingredients**

  (1) gluon contribution $\ell_i g \to \ell_j g$

  (2) ACOT scheme

- Heavy quark effects (q-number conservation and finite mass) and the gluon contribution could change the cross section by an order

- Different distributions in each subprocess enable to identify the LFV operator

Backup slides

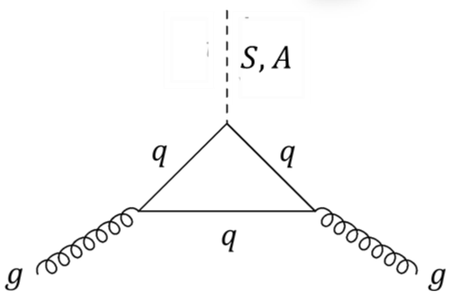
LFV DIS mediated by (pseudo-)scalar

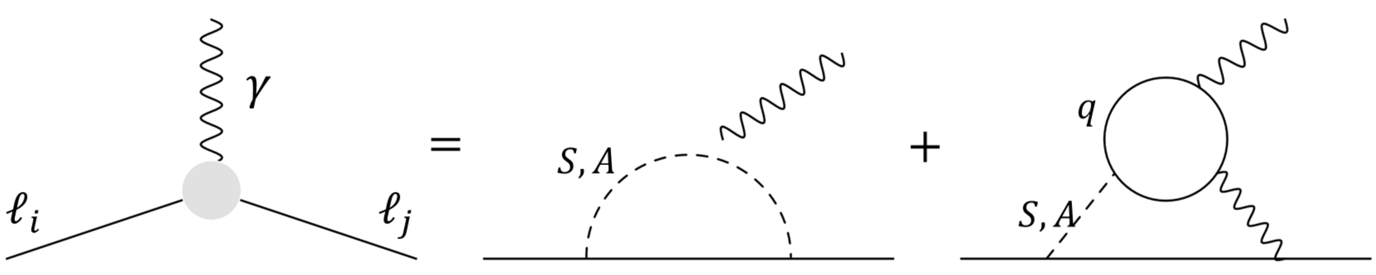
A simplest extension for interactions of CLFV (pseudo-)scalar

$$\mathcal{L}_{\rm CLFV} = \sum_{X=S,A}\left(-\rho^X_{ij}\bar{\ell}_j P_L \ell_i \phi_X - \rho^X_{ji}\bar{\ell}_j P_R \ell_i \phi_X\right) + h.c.$$

$$\mathcal{L}_q = -\rho^S_{qq}\bar{q}q\phi_S - \rho^A_{qq}\bar{q}\gamma^5 q\phi_A + h.c.$$

ρ_{ij}, ρ_{ji} : CLFV parameter
(i, j : flavor index)



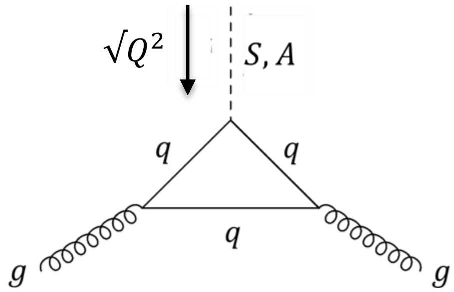


$\phi_{S(A)}gg$ effective coupling

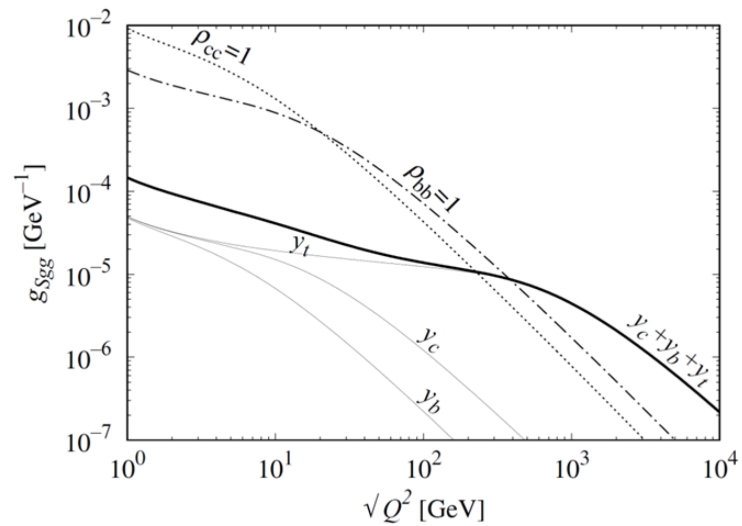
$(a)\ \rho_{cc}^{S(A)} = 1,\ \rho_{bb}^{S(A)} = \rho_{tt}^{S(A)} = 0$

$(b)\ \rho_{bb}^{S(A)} = 1,\ \rho_{cc}^{S(A)} = \rho_{tt}^{S(A)} = 0$

$(c)\ \rho_{cc}^{S(A)} = y_c,\ \rho_{bb}^{S(A)} = y_b,\ \rho_{tt}^{S(A)} = y_t$

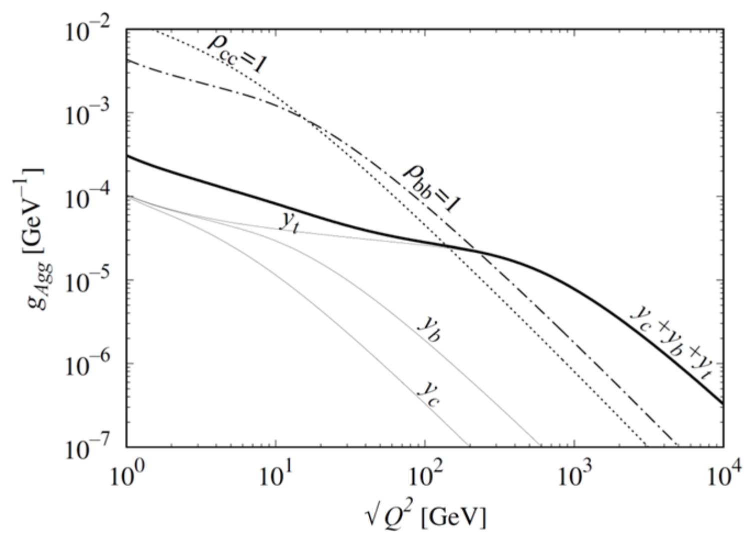


$$\mathcal{L}_G = g_{Sgg}\phi_S G^a_{\mu\nu}G^{a\mu\nu} + g_{Agg}\phi_A G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

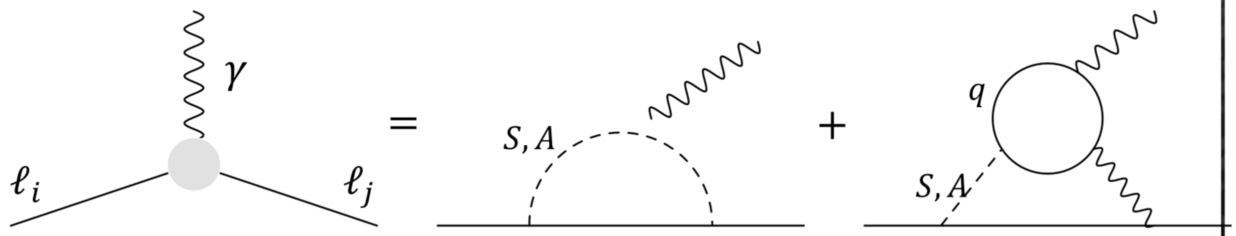


Carefully handle following points to determine LFV ope.

- Strong dependence of momentum transfer
- Pattern of mediator-quark interaction
- Sizable contributions of c- and b-quarks in addition to t-quark



Photonic dipole



$$\mathcal{L}_{\text{dipole}} = -\frac{e}{2} m_j \sum_{X=S,A} \left(A^X_{ij} \bar{\ell}_j \sigma^{\mu\nu} P_L \ell_i F_{\mu\nu} + A^X_{ji} \bar{\ell}_j \sigma^{\mu\nu} P_R \ell_i F_{\mu\nu} \right)$$

$$A_{ij} = \frac{1}{16\pi^2 v^2} \left(A_1 + A_2^{t,b} + A_2^W \right)$$

e.g. coefficients in 2HDM as a function of scalar mass

Sensitive to models and mediator mass

Event rate via the dipole operator is useful for model discrimination

m_ϕ [GeV]	125	200	300	400	500
$10^3 \times \tilde{A}_1^f(r_{\tau/\phi})$	2.0025	0.8872	0.4345	0.2605	0.1747
$10^3 \times \tilde{A}_2^{t,H}(r_{t/\phi})$	6.2431	4.6631	3.4720	2.7435	2.2504
$10^3 \times \tilde{A}_2^{t,A}(r_{t/\phi})$	8.9039	6.5746	4.8361	3.7840	3.0785
$10^3 \times \tilde{A}_2^{b,H}(r_{b/\phi})$	0.0407	0.0208	0.0114	0.0073	0.0052
$10^3 \times \tilde{A}_2^{b,A}(r_{b/\phi})$	0.0508	0.0255	0.0138	0.0088	0.0062
$10^3 \times \tilde{A}_{2,\phi}^W(r_{W/\phi})$	-14.0380	-8.8698	-5.1773	-2.9841	-1.5079