Revisit Lepton Flavor Violating Deep Inelastic Scattering

Masato Yamanaka (Hosei Univ., Japan)

M. Takeuchi, Y. Uesaka and MY, PLB772 (2017)

Y. Kiyo, M. Takeuchi, Y. Uesaka and MY, JHEP 04 (2022) 044

Y. Kiyo, M. Takeuchi, Y. Uesaka and MY, arXiv:2410.XXXXX

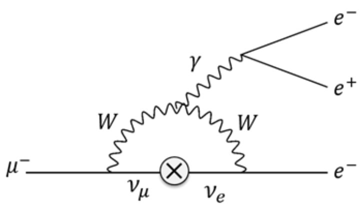
Promising probe -- Lepton Flavor Violation (LFV) --

In the SM

Lepton number is **always** conserved

In the SM with ν oscillation

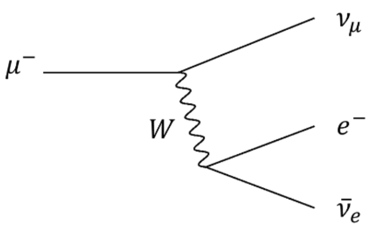
Will be discovered with 10^{55} μ ☺



$\mathrm{BR} \simeq 7.4 \times 10^{-55}$

S. Petcov, Sov. J. Nucl. Phys. (1977)
G. Hernandez-Tome, et al, EPJC (2019)

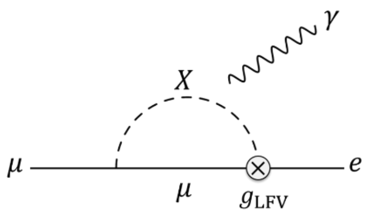
Example: muon decay in SM



μ number $+1 \rightarrow +1$

e number $0 \rightarrow (+1) + (-1)$

Ex.: muon decay in physics beyond SM



μ number $+1 \rightarrow 0$

e number $0 \rightarrow +1$

Promising probe -- Lepton Flavor Violation (LFV) --

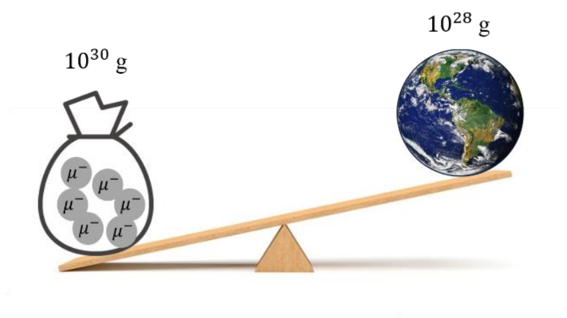
In the SM

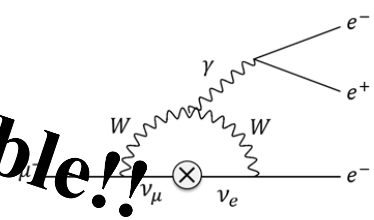
Lepton number is **always** conserved

In the SM with ν oscillation

Will be discovered with 10^{55} μ's

Impossible!!





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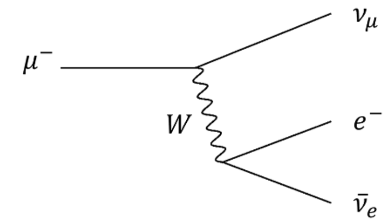

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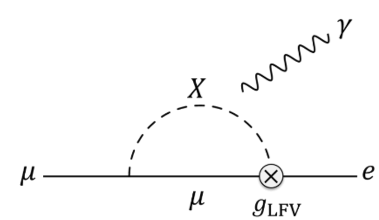


μ number $+1 \rightarrow 0$

e number $0 \rightarrow +1$

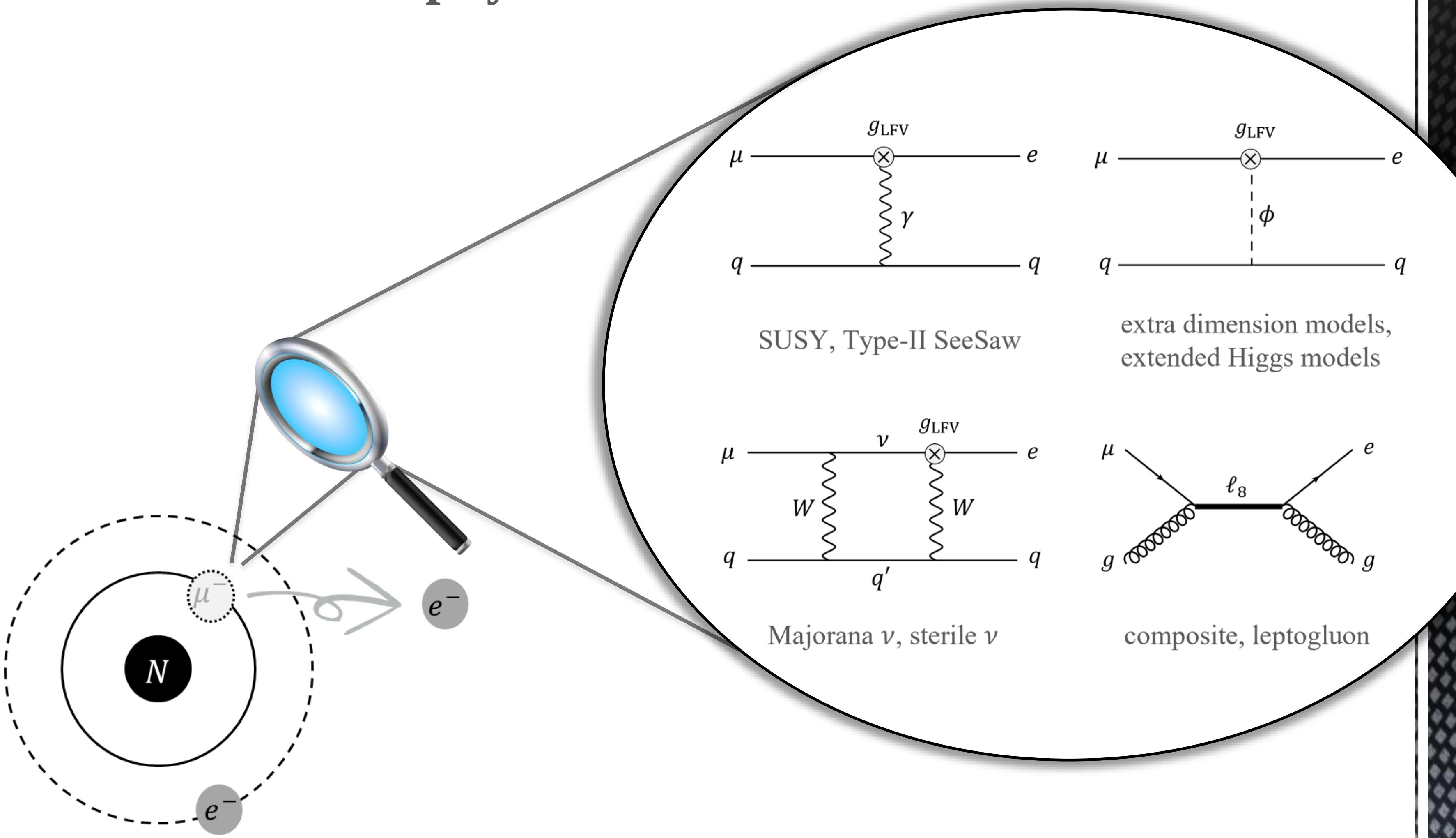
In the physics beyond the SM

-- accessible LFV rate by extra degrees of freedom

(new particles, additional space dimension, …)

-- not only evidence, but also sensitive to the extra degrees

How to unravel the physics behind the LFV



Unknown particle **indirectly** appears in LFV reactions

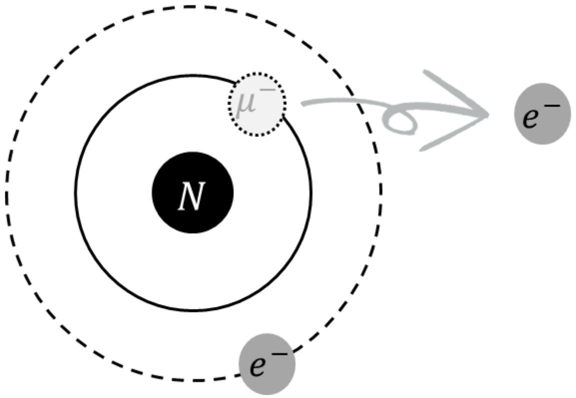
Not appeared in direct observables

How to unravel the physics behind the LFV

Important and necessary

1. **Many LFV observables as possible**
   to draw "unknown" from various angles

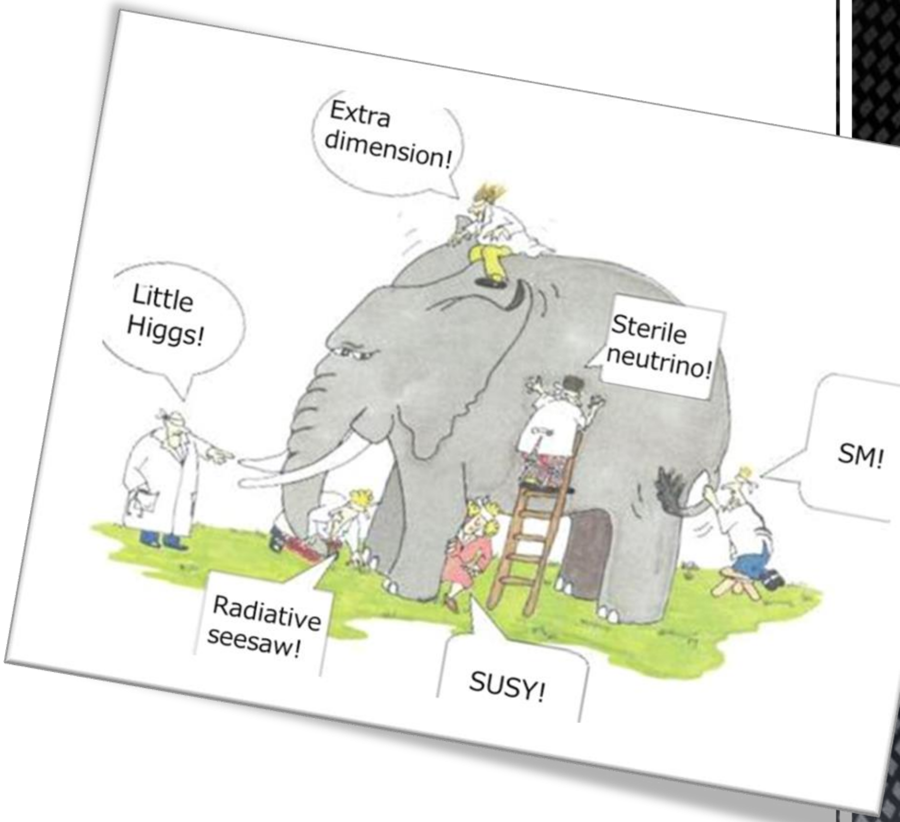
2. **Accurate connection** between LFV
   parameters and observables



Unknown particle **indirectly** appears
in LFV reactions

Not appeared in direct observables

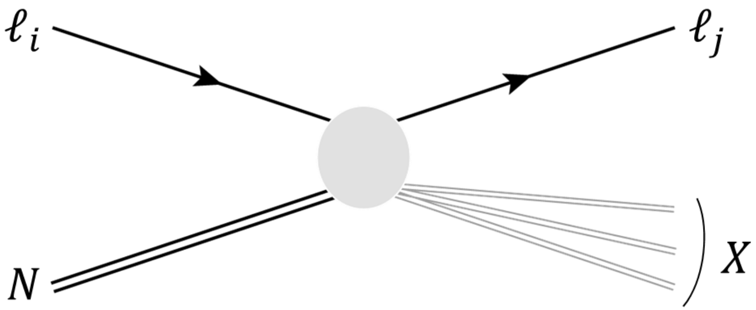
The more LFV processes,
the "elephant" is more clearly illustrated!



Lepton Flavor Violating Deep-Inelastic Scattering (LFV-DIS)

LFV-DIS: Promising process to search for LFV

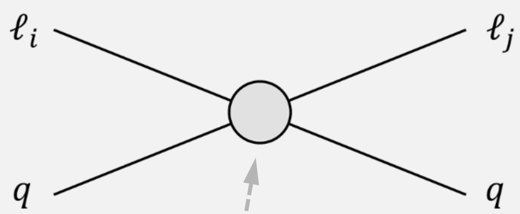
$\boldsymbol{\ell_i + N \to \ell_j + X}$ ($\boldsymbol{N}$: **nucleon**, **X**: **hadron**)



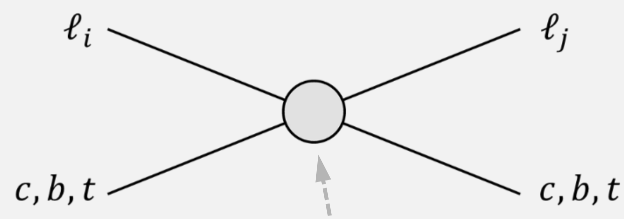
- Many experiments for cross check (LHeC, ν-factory, ILC, …)
- Complementary with τ hadronic LFV ($\tau \to e\pi\pi$, etc) and LFV at LHC ($pp \to \mu\tau$, etc)
- Probe to the chirality of LFV ope. using polarized beam
- Large number of event $\propto$ (beam intensity N_{ℓ_i}) $\times$ (nucleon density~ mole number)
  @fixed target exp.

Types of interaction between LFV mediator and quarks

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

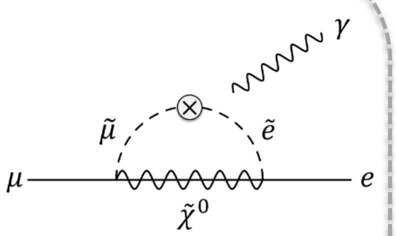


Non-Universal



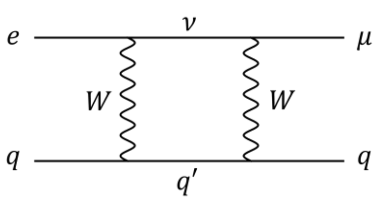
Photonic dipole type

(SUSY, type-II SeeSaw models, etc)



Box type

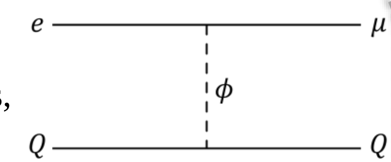
(sterile neutrino models, etc)



etc

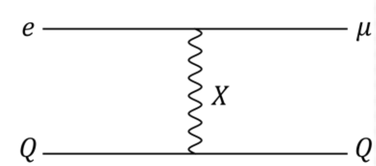
Higgs LFV

(Extended Higgs models, etc)



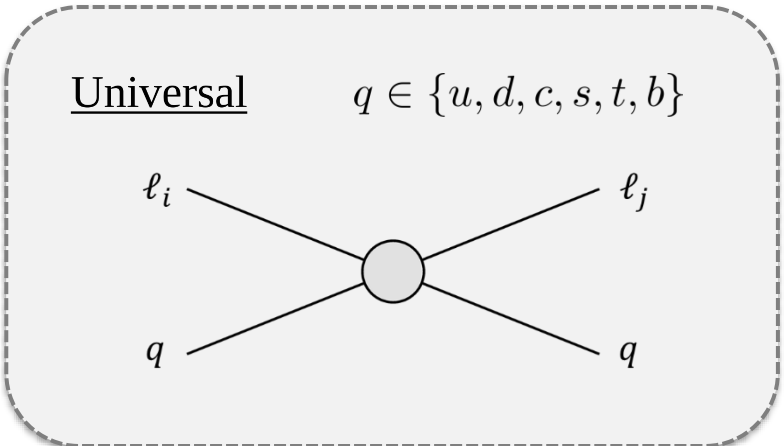
Massive gauge boson

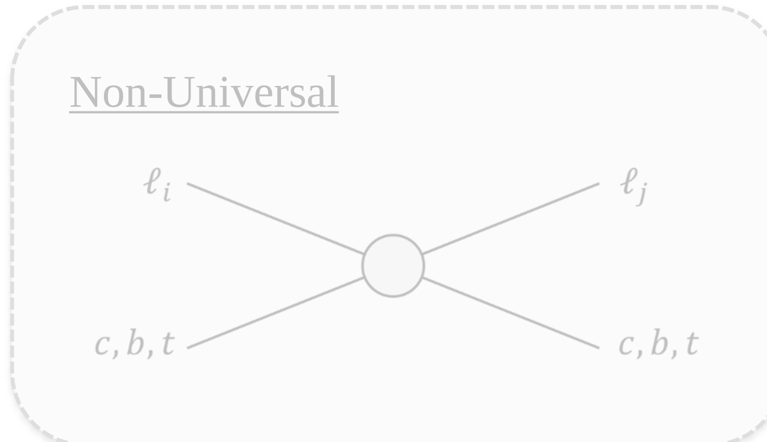
(Extra dimension models, Flavor symmetry models, etc)



etc

Flavor universal interaction type





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

Parton distribution function (PDF)

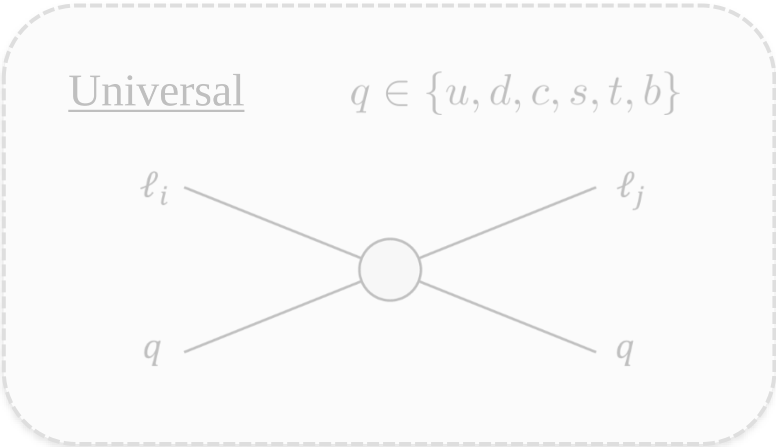
Familiar scheme using subprocess
with massless valence quarks

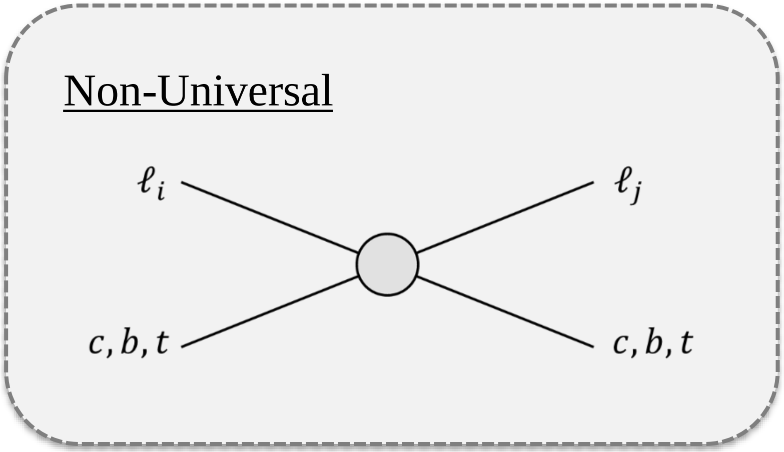
x : Bjorken variable

y : scattering inelasticity

S. Gninenko, M. Kirsanov, et al, MPLA (2002),
M. Sher, I. Turan, PRD (2004),
A. Abada, V. Romeri, A. Teixeira, JHEP (2016),
and so on

Flavor non-universal interaction type





Aim **Precisely connect LFV parameters and DIS observables**

No heavy quarks in nucleon ⟹ **What is subprocess for $eN \to \tau X$?**

Inaccessible t-threshold due to too heavy ⟹ **How to identify the interaction and mediator mass?**

LFV interaction and cross section

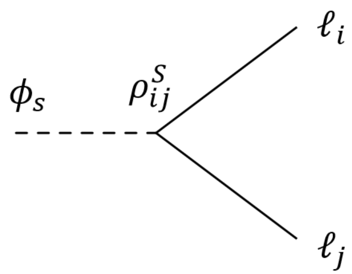
LFV interaction (toy model)

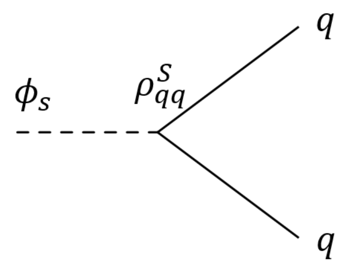
Applicable to a variety of models

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

- LFV mediator : scalar
- Scenario : mediator dominantly couples with heavy fermion

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





<u>Coupling with quarks</u> (flavor diagonal only)

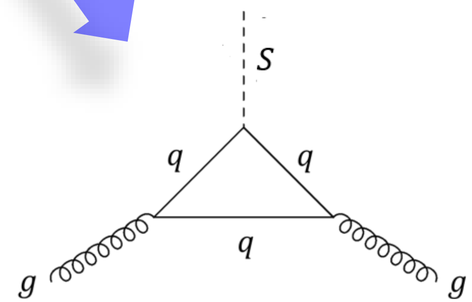
A) Proportional to quark mass $\rho^S_{cc} : \rho^S_{bb} : \rho^S_{tt} = m_c : m_b : m_t$

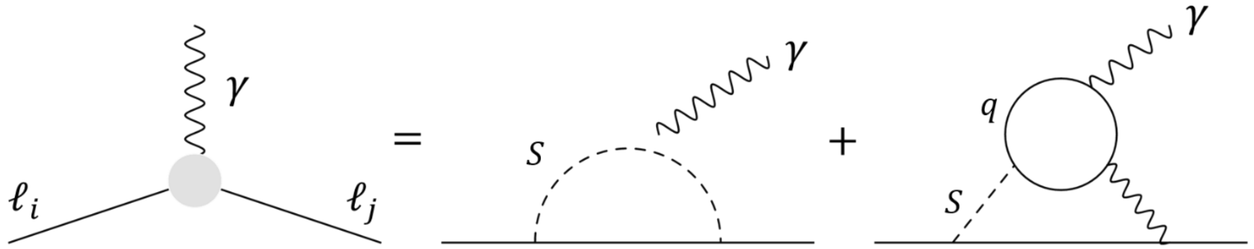
B) Couple with 1 flavor only example : $\rho^S_{bb} \neq 0, \;\; \rho^S_{cc} = \rho^S_{tt} = 0$

LFV interaction (toy model)

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

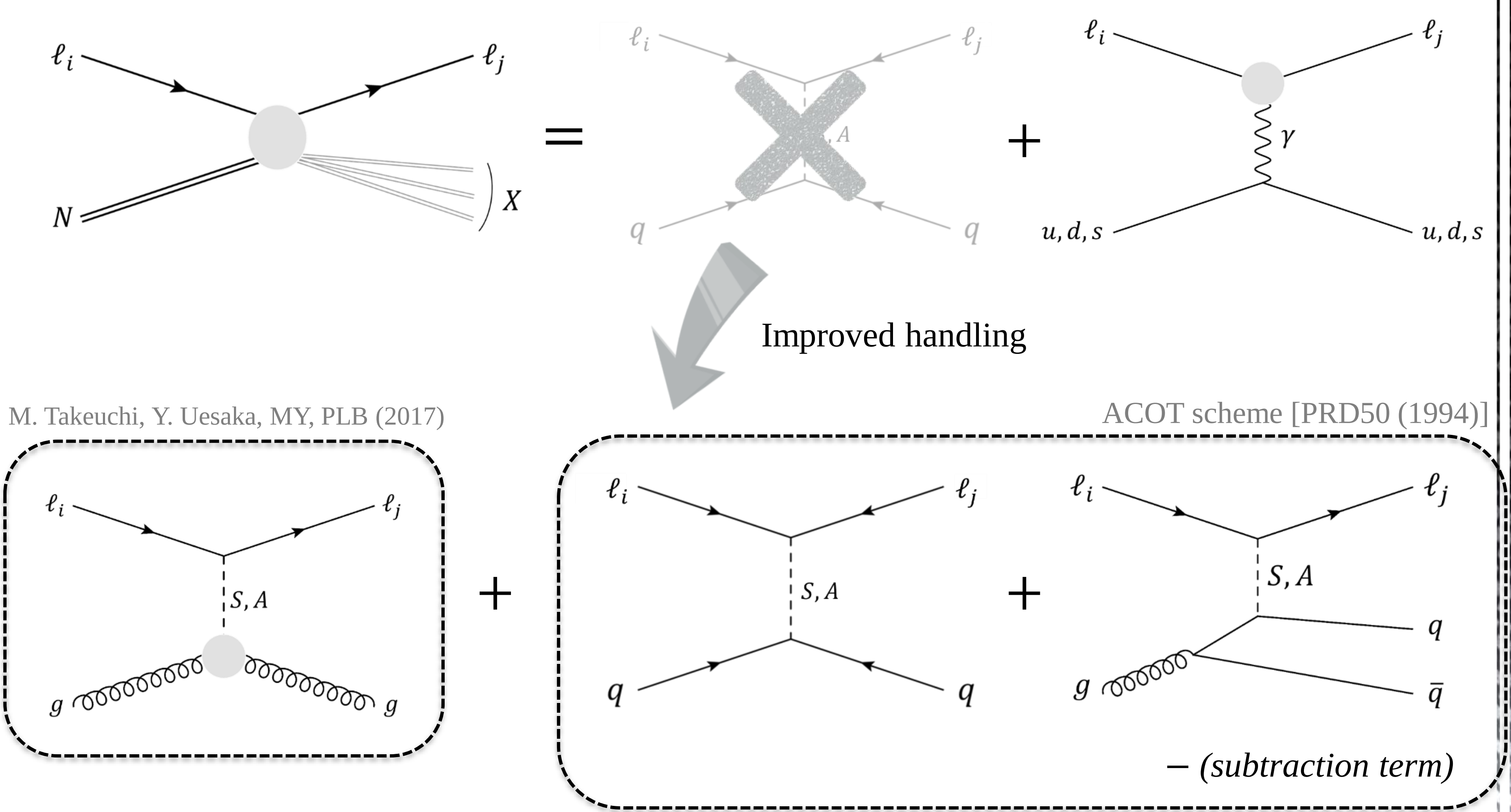
Two types of effective LFV interaction from the coupling with fermions





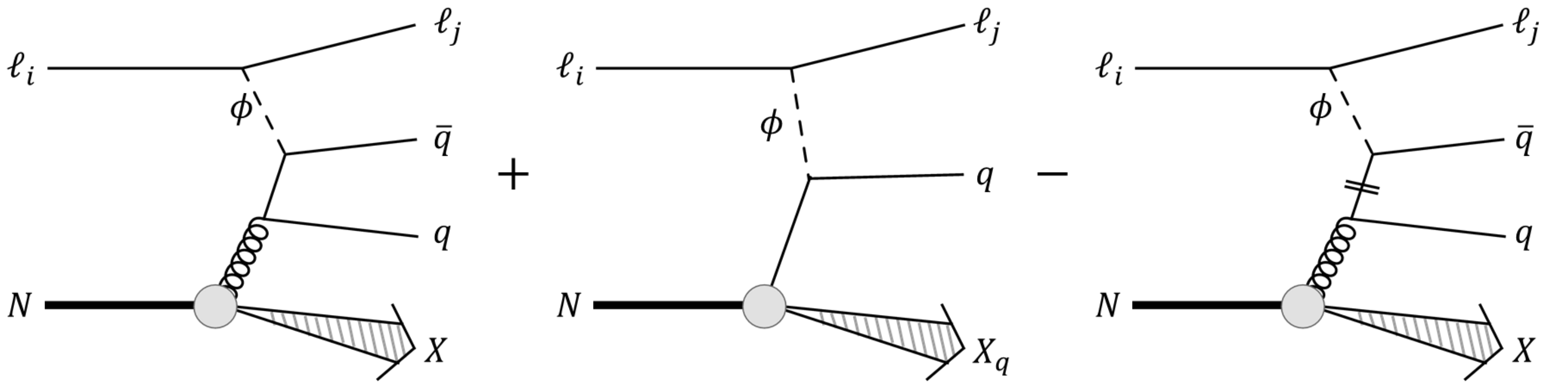
Subprocess of LFV-DIS $\ell_i N \to \ell_j X$

Take into account the (1) $\phi g g$ coupling (2) quark-number conservation



ACOT scheme

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



contribution with $m_q \neq 0$

contribution with $m_q = 0$

Subtraction contribution to cancel double counting

Subprocess associated with c, b, t @low Q^2

Lowest-order subprocess due to Q-number conservation

amplitude $\propto \ln(Q^2/m_q^2)$

Subprocess associated with c, b, t @high Q^2

Subprocess described by c, b, t PDF

c, b, t PDF : constructed by renormalizing divergent part for $Q^2 \gg m_q^2$ with QCD correction

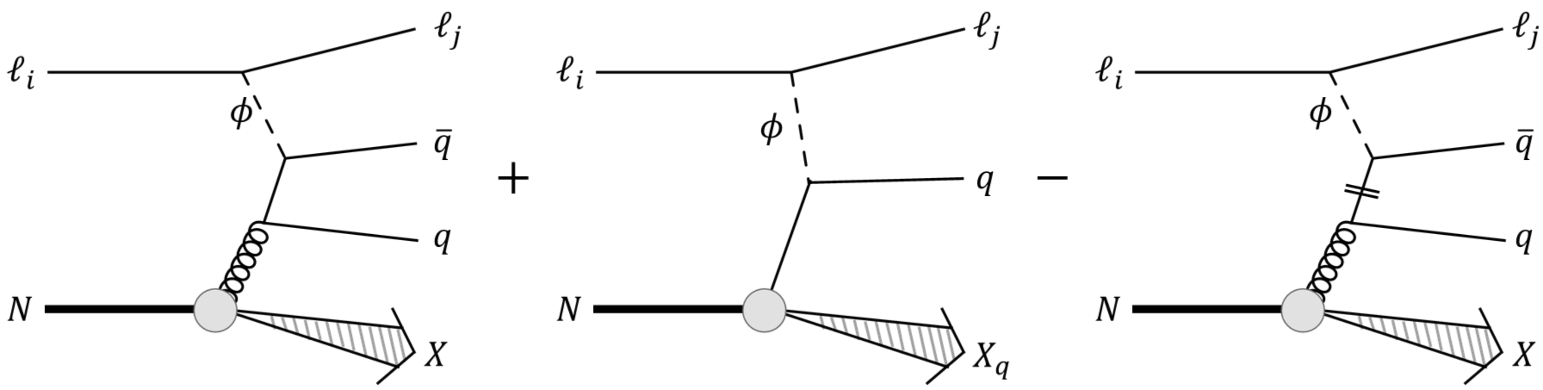
Scheme for DIS XS with Q-number conservation and Q-mass

Scalar structure function involving ACOT

arXiv:2107.10840

ACOT scheme

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



contribution with $m_q \neq 0$

contribution 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

Cross section

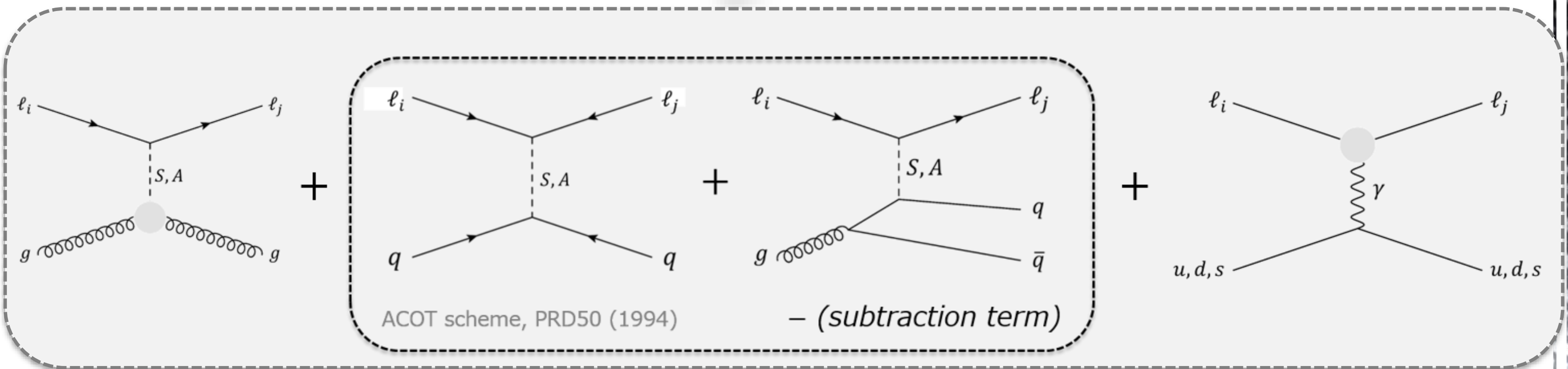
See e.g. T. Stavreva, F. I. Olness, et al, PRD85 (2012)
M. Takeuchi, Y. Uesaka, M.Y., PLB772 (2017)

- 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

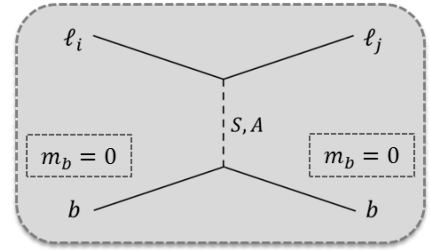
$$\sigma_{\ell_i N \to \ell_i X} = \sum_{\hat{p}=g,q} \int dxdy \int_0^1 d\xi \frac{d^2\hat{\sigma}_{\ell_i \hat{p} \to \ell_j \hat{X}}}{dxdy} f_{\hat{p}}\left(\xi_{\hat{p}}, Q^2\right)$$

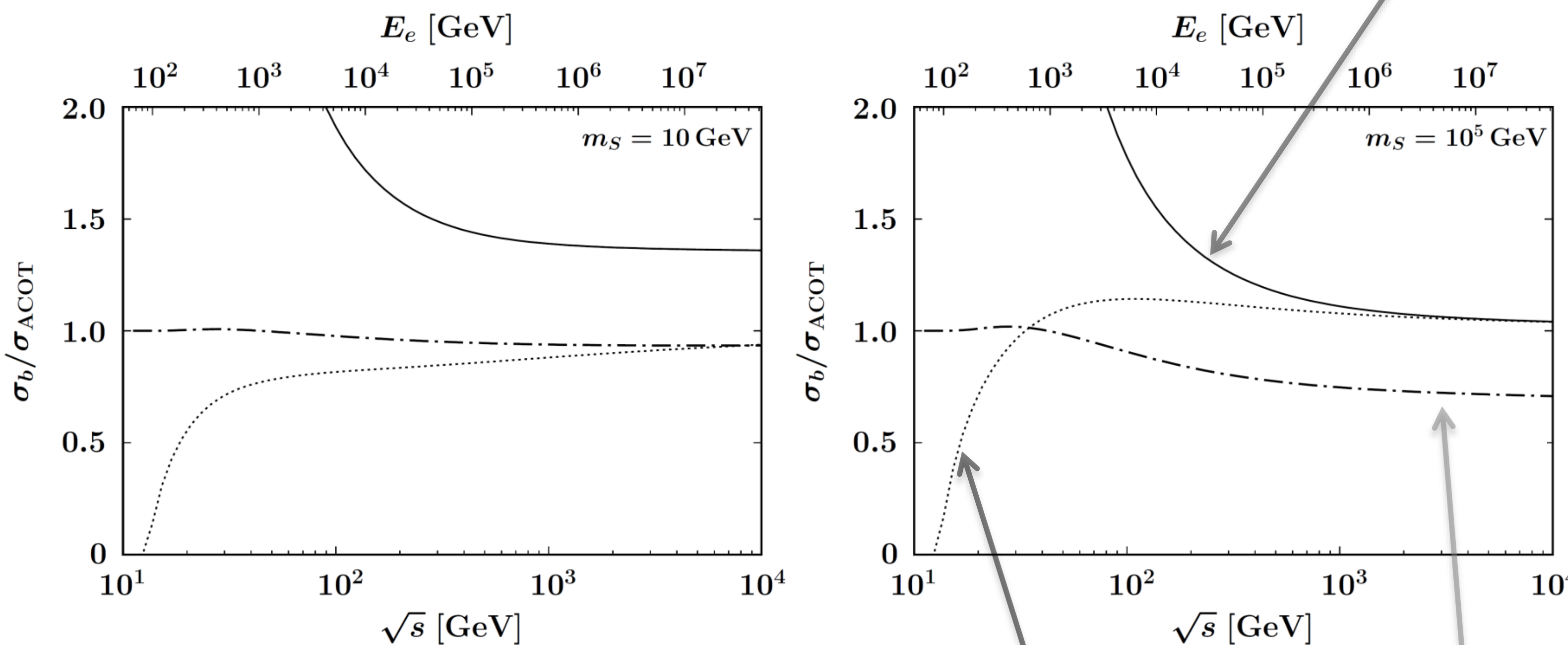
PDF (function of ξ, not x!)

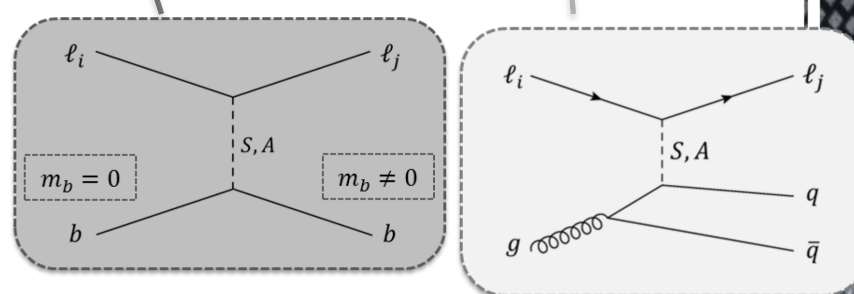


Numerical analysis

Scheme dependence on LFV-DIS

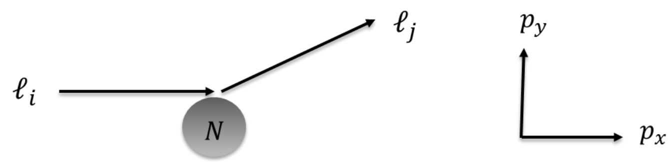




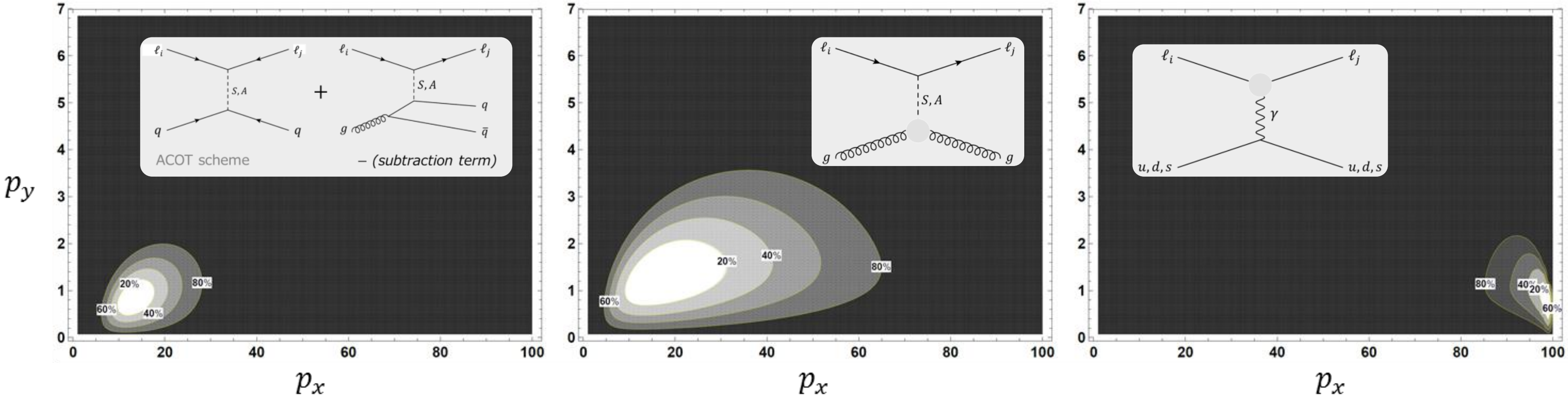


- Finite m_b effect even far above the $b\bar{b}$ threshold
- **ACOT scheme: Indispensable for LFV-DIS mediated by scalar, especially for small m_S**
- $\ell_i g \to \ell_j b\bar{b}$: Acceptable alternative at the scale of next(-next) generation experiments

Momentum distribution

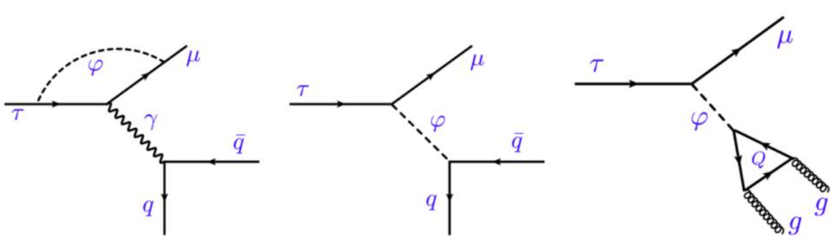


Beam energy = 100 GeV, m_S = 10 GeV

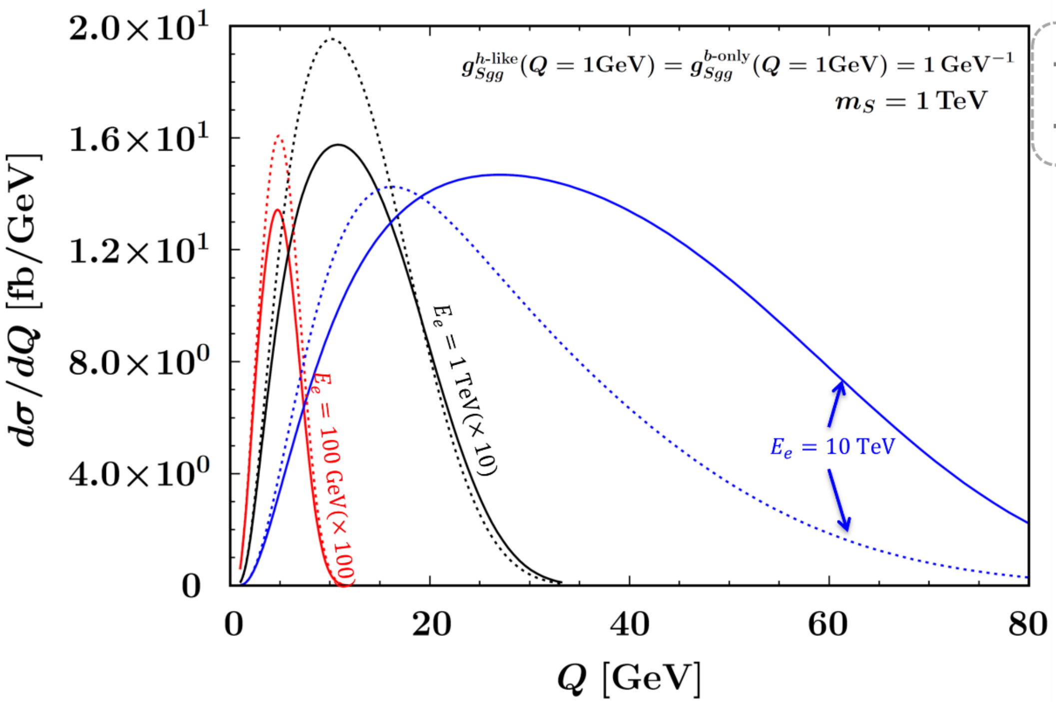


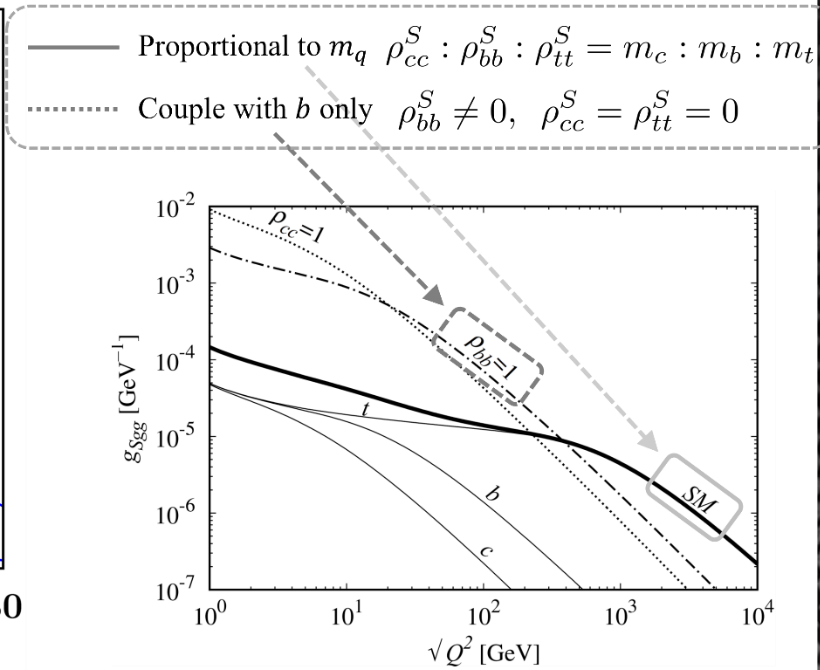
- Completely different distribution for each subprocess
- Sensitive probe to the interactions of mediator and quark/gluon/photon
- Synergy with τ LFV decay

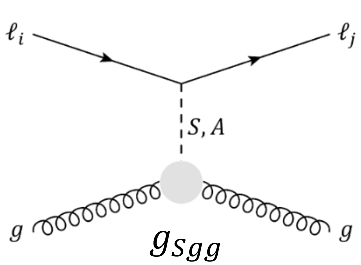
A. Celis, V. Cirigliano, E. Passemar, PRD89 (2014)
T. Husek, K. Monsalvez-Pozo, J. Portoles, JHEP01 (2021)



Interaction between mediator and quarks







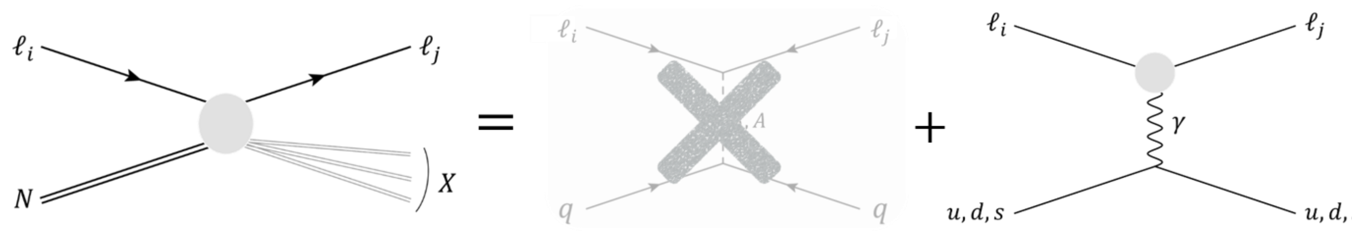
Mediator-gluon-gluon coupling g_{Sgg} strongly depends on

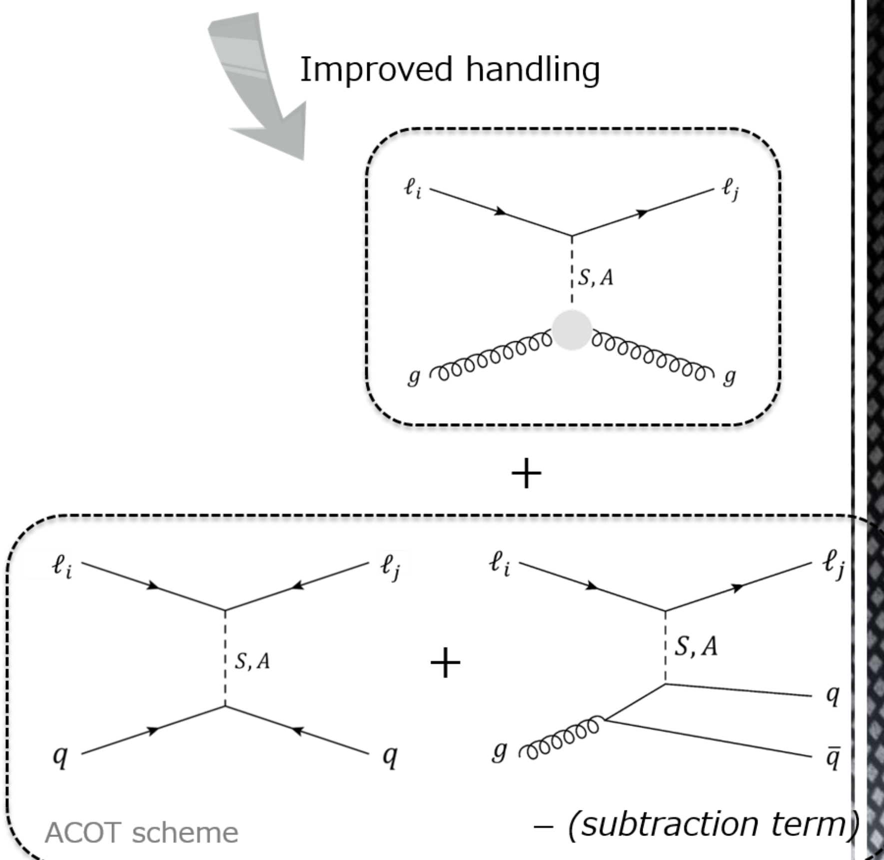
(i) momentum transfer $\sqrt{Q^2}$

(ii) internal quark mass m_q

Differential cross section identifies interaction between mediator and quarks

Summary





- LFV-DIS: Promising process to search for LFV

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

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

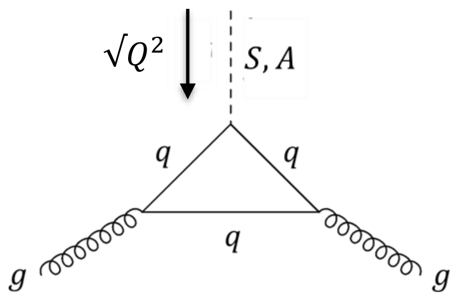
  (2) ACOT scheme

- 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

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



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

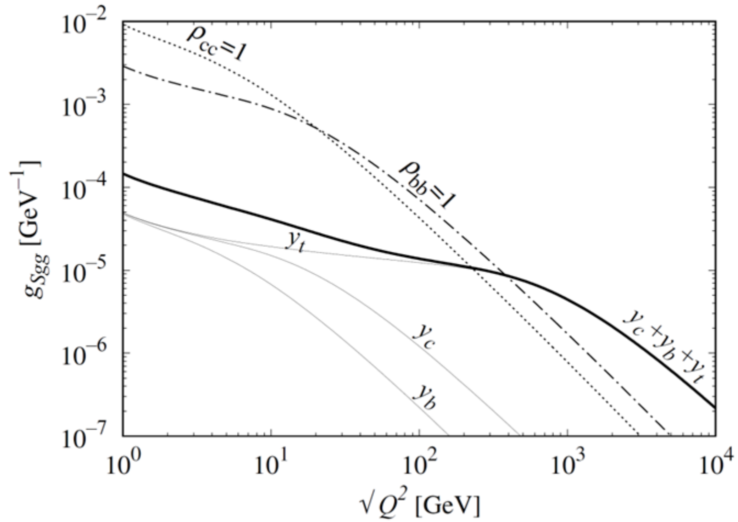
Carefully handle following points to determine LFV ope.

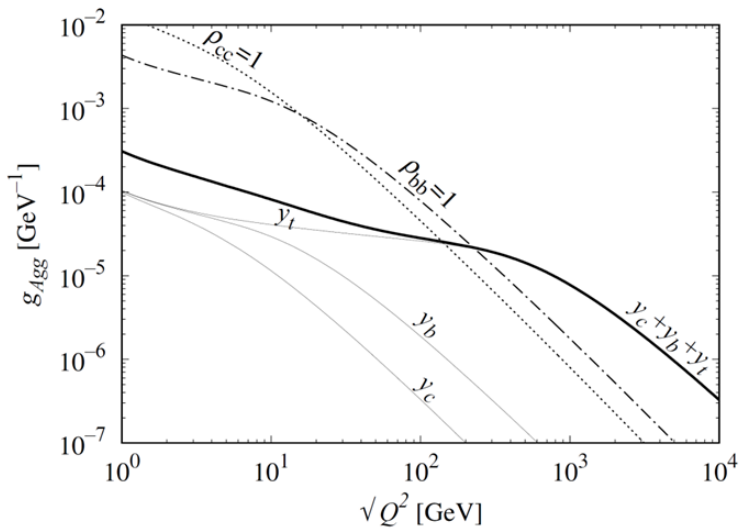
- Strong dependence of momentum transfer
- Pattern of mediator-quark interaction
- Sizable contributions of c- and b-quarks in addition to t-quark

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

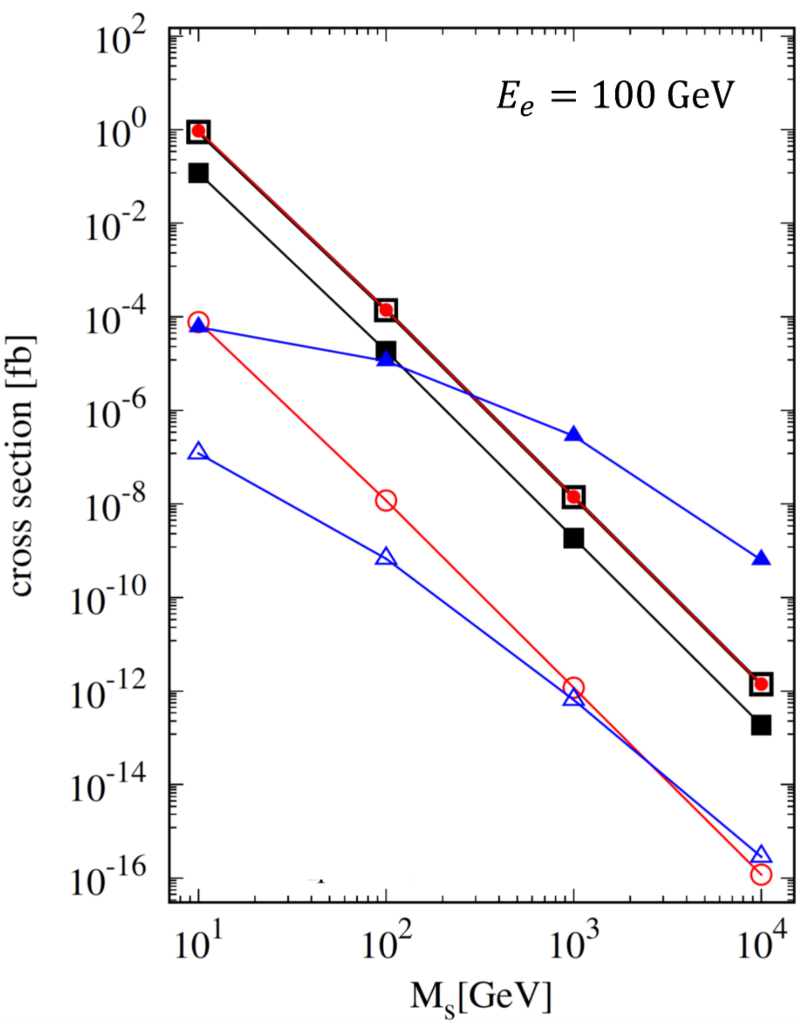
$(b)\ \rho_{bb}^{S(A)} = 1,\ \rho_{cc}^{S(A)} = \rho_{tt}^{S(A)} = 0$

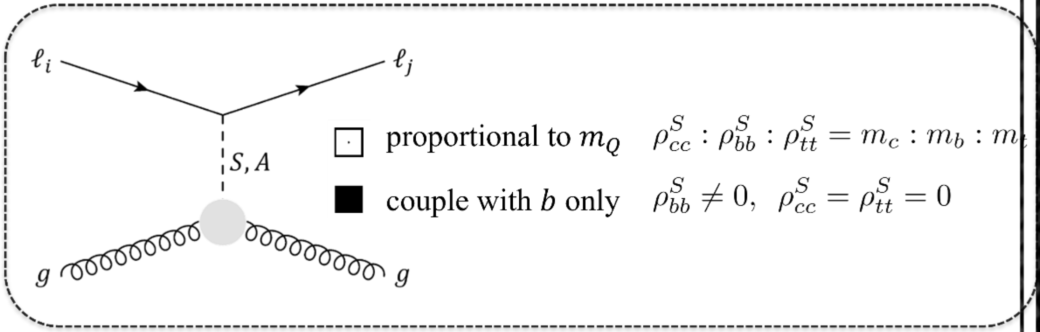
$(c)\ \rho_{cc}^{S(A)} = y_c,\ \rho_{bb}^{S(A)} = y_b,\ \rho_{tt}^{S(A)} = y_t$

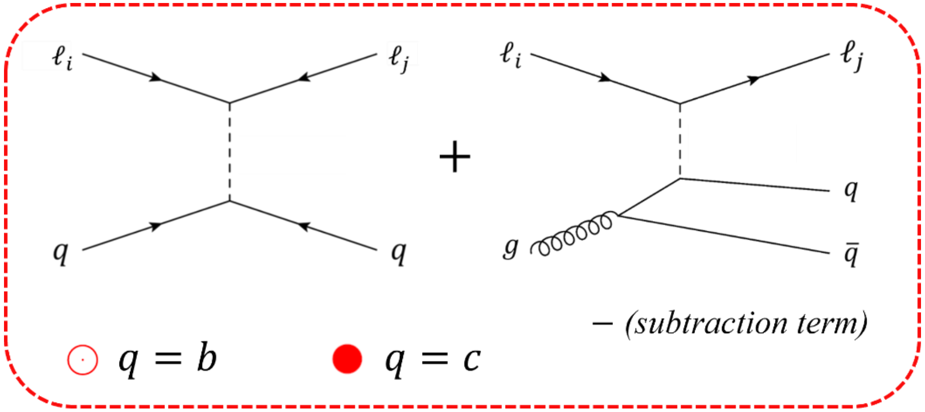


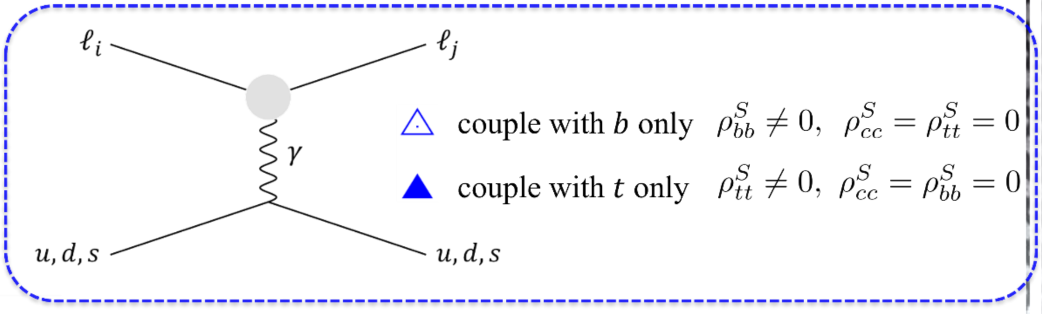


Mediator mass dependence





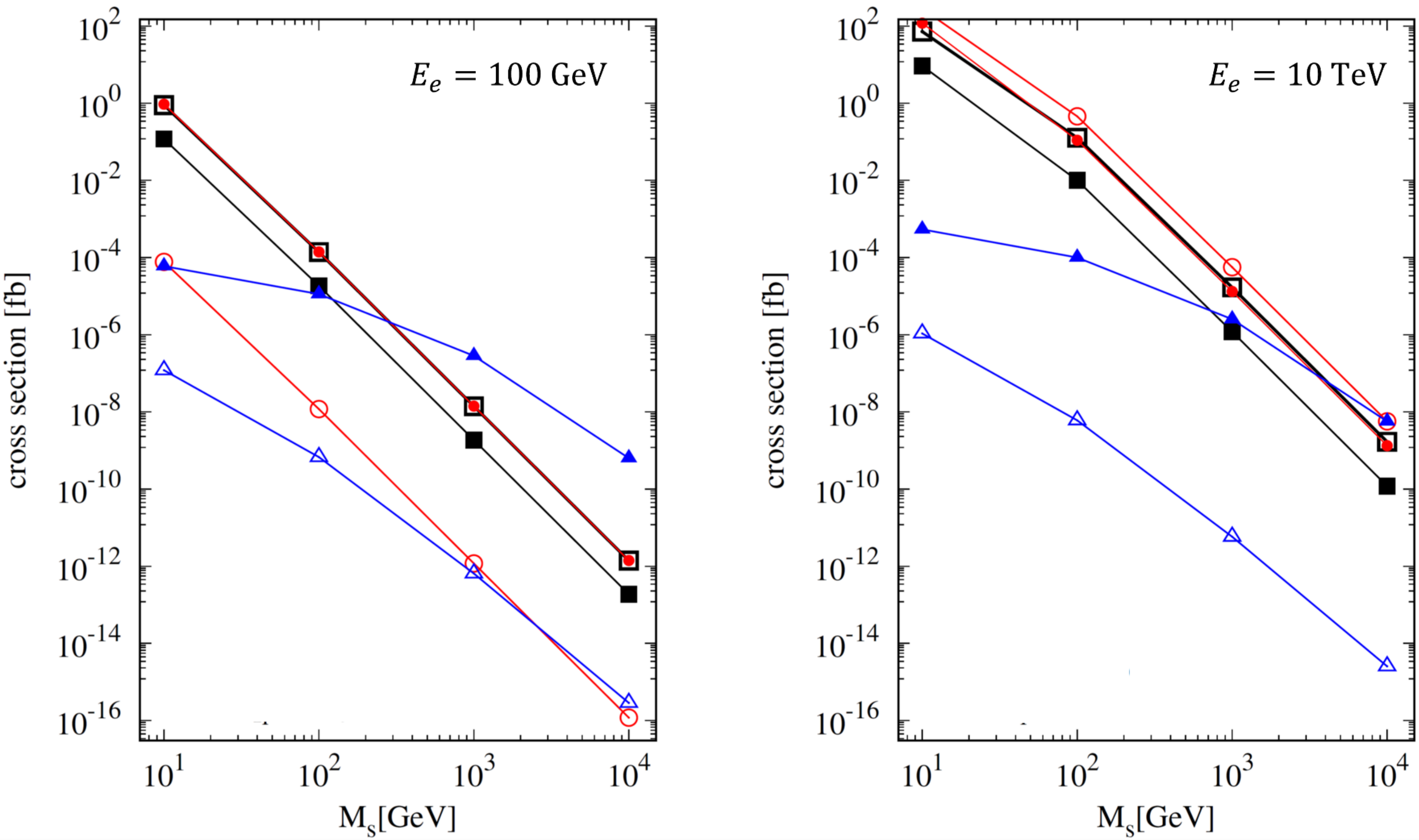




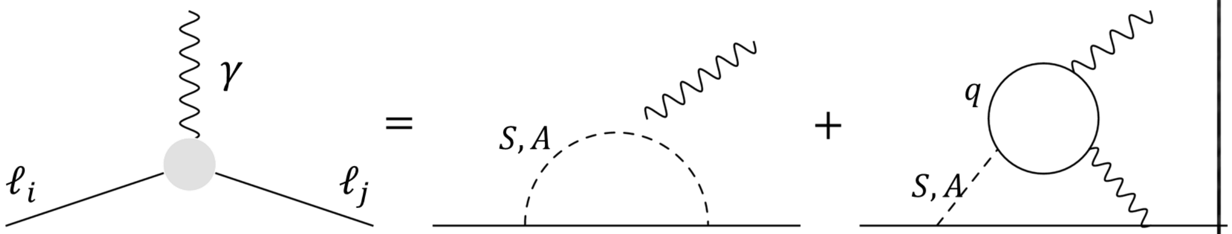
Mediator mass dependence

M_s : measure σ for each subprocess with different E_e

Not sensitive to interaction between Med. and quark …



Photonic dipole



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

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

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