Charged lepton flavor violation for a probe to the neutrino masses and their hierarchy

Masato Yamanaka (Hosei Univ.)

Neutrino oscillation and LFV

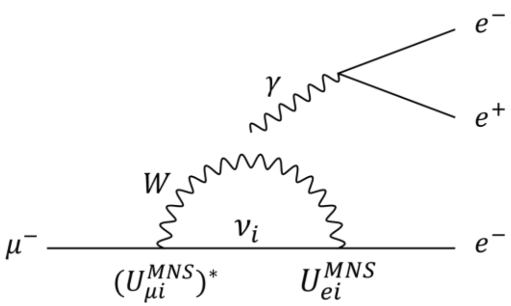
Neutrino oscillation calls new physics beyond the standard model (SM)

<u>SM</u>

Lepton number is **always** conserved

<u>SM + ν oscillation</u>

Will be discovered with 10^{55} μ ☺



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

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

NuFIT 5.2 (2022)

with SK atmospheric data	Normal Ordering (best fit) bfp $\pm1\sigma$	Normal Ordering (best fit) 3σ range	Inverted Ordering ($\Delta\chi^2 = 6.4$) bfp $\pm1\sigma$	Inverted Ordering ($\Delta\chi^2 = 6.4$) 3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
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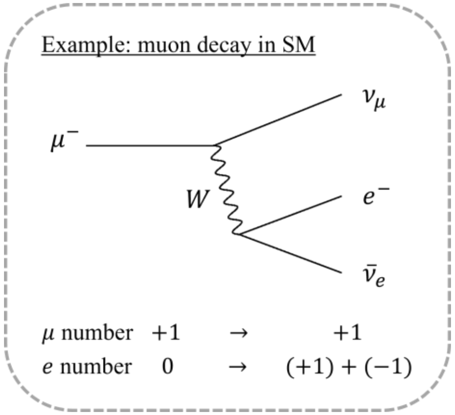

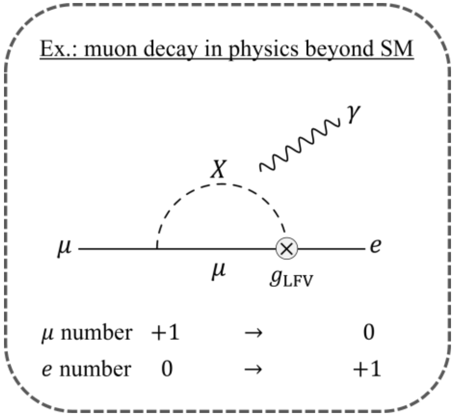

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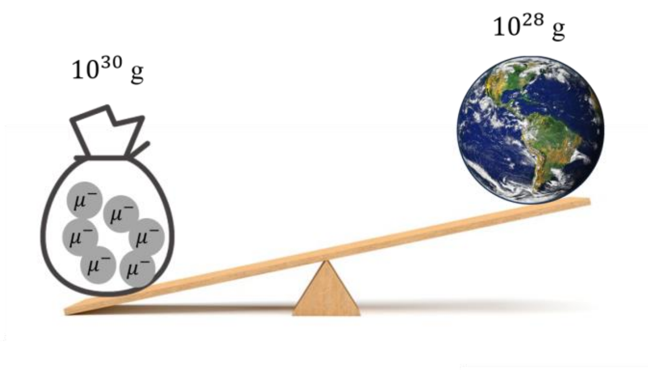
Lepton number is always conserved

SM + ν oscillation

Will be discovered with $10^{55}\,\mu$ **Impossible!!**



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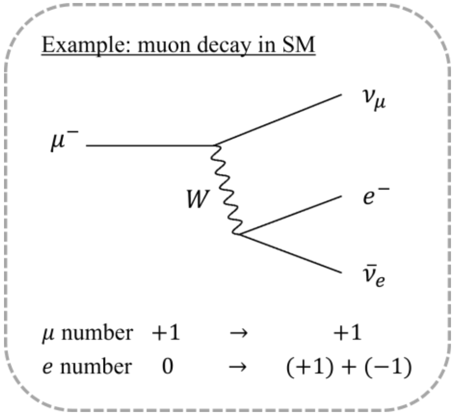

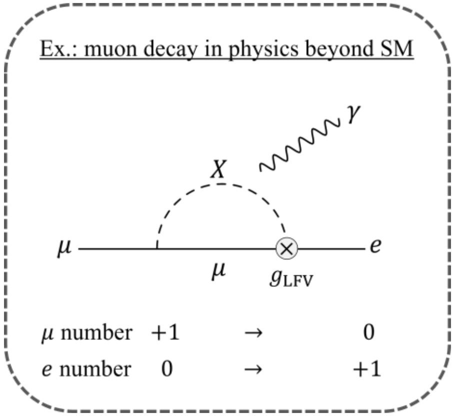

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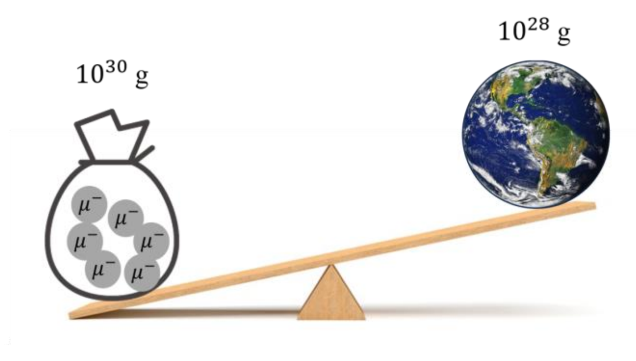


In the physics beyond the SM

-- accessible LFV rate by extra degrees of freedom

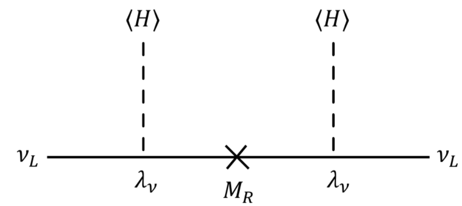
(new particles, additional space dimension, …)

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

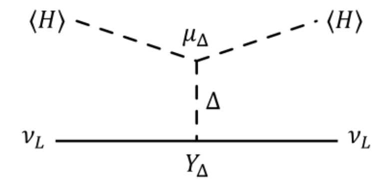
ν mass generation scenarios

(1) Tree-level mass generation

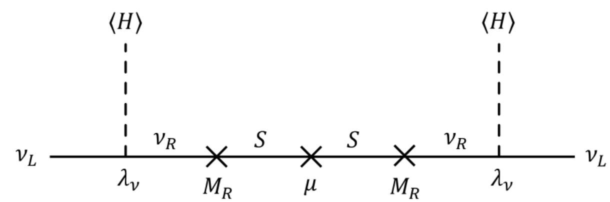
Type-I (-II, -III) Seesaw
Inverse Seesaw
Linear Seesaw
High- (Low-, middle-) scale Seesaw, etc
[with or without SUSY, extra dimension, etc]



Type I Seesaw



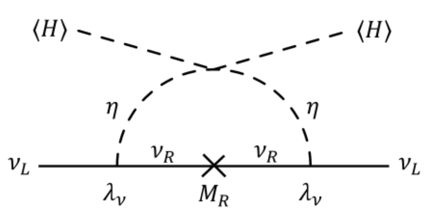
Type II Seesaw



Inverse Seesaw

(2) loop-level mass generation

Scotogenic
Leptoquark
Zee-Babu
R-parity violating SUSY, etc
[1-loop, 2-loop, 3-loop, …]



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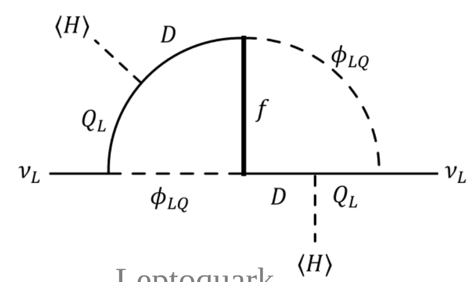

Leptoquark

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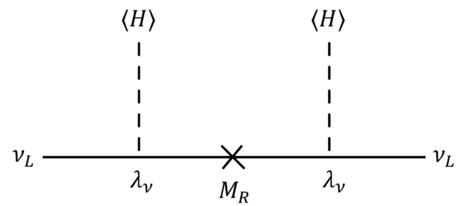

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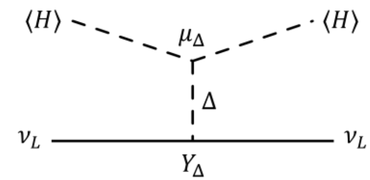

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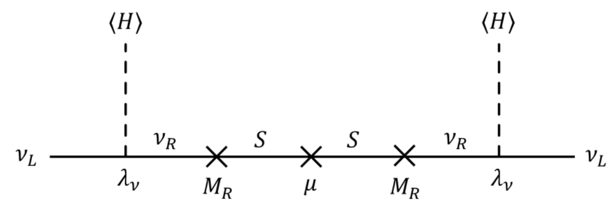

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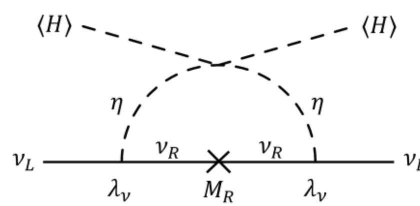

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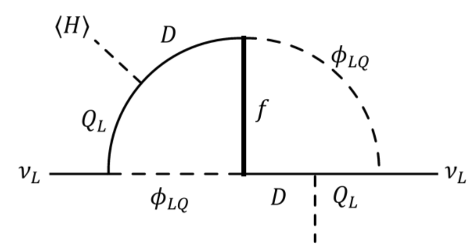


Leptoquark

Find intrinsic patterns of correlation of observables for these scenarios!

How to unravel the physics behind the LFV

Unknown particle **indirectly** appears in LFV reactions

Not appeared in direct observables

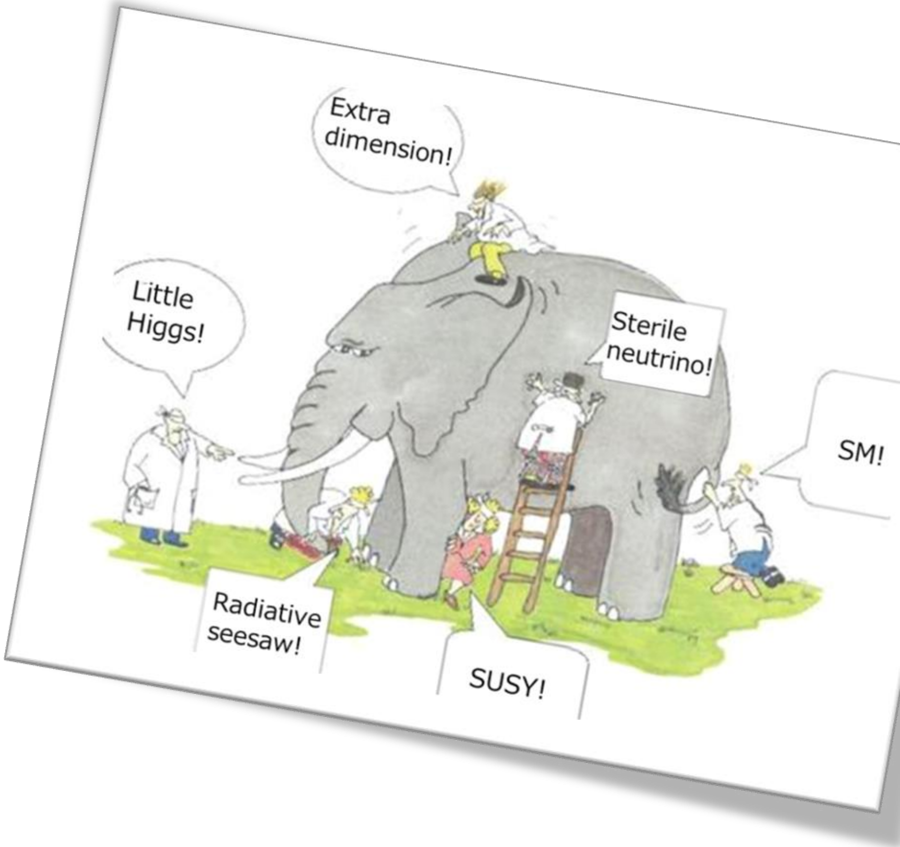
Many LFV observables as possible to draw "unknown" from various angles

- $\mu^+ \to e^+\gamma$
- $\mu^- \to e^-$ conversion in nuclei
- $\mu^- e^- \to e^- e^-$ in muonic atom
- $\tau \to 3\mu, \tau \to e\pi\pi, \tau \to \mu\gamma, \ldots$, etc

Accurate connection between LFV parameters and observables

- Characteristic signatures for each LFV operator
- Dependences on experimental stage
- Ratios and correlations of BRs etc

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



Outline

1. Introduction

2. Lepton flavor violating processes

3. ν mass generation scenarios and LFV

4. Summary

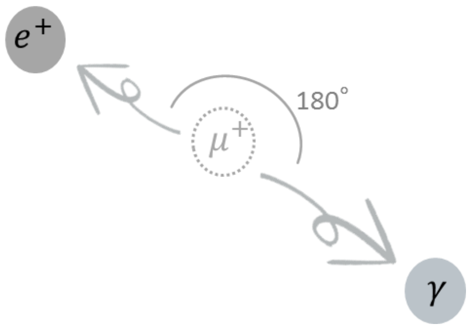
Lepton flavor violating processes

Radiative decay $\ell_i \to \ell_j \gamma$

Signal

-- back-to-back $e(\mu) + \gamma$,

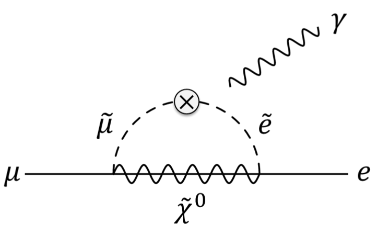
-- $\sum E = m_\mu$ (for $\mu \to e\gamma$) , $\sum E = m_\tau$ (for $\tau \to \ell_j\gamma$)



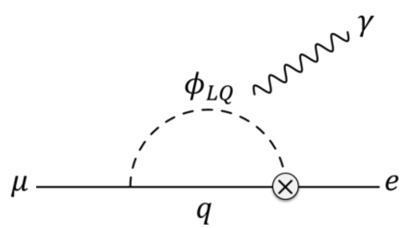
Experimental status

Process	BR limit	Future
$\mu \to e\gamma$	4.2×10^{-13} MEG (2016)	6.0×10^{-14} MEG II
$\tau \to e\gamma$	3.3×10^{-8} BABAR (2010)	9.0×10^{-9} Belle II
$\tau \to \mu\gamma$	4.2×10^{-8} Belle (2021)	6.9×10^{-9} Belle II

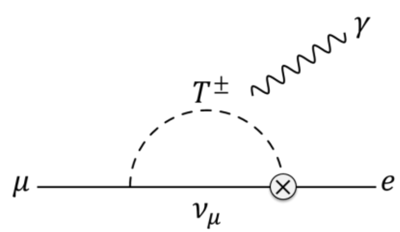
Probe to various models beyond the SM



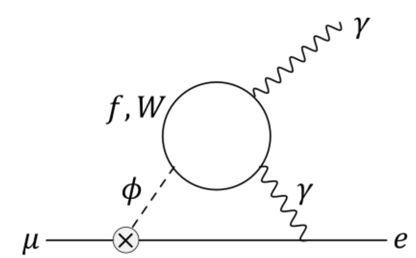
SUSY (+ Type-I SeeSaw)



Leptoquark, GUT models



Type-II SeeSaw, extended Higgs models



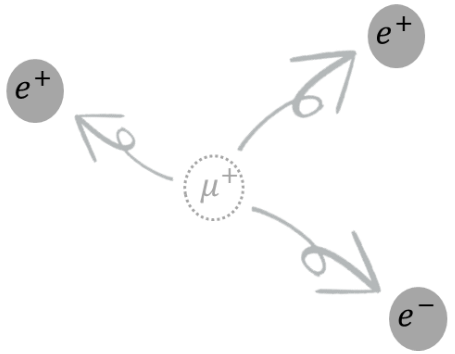
Higgs LFV, extended Higgs models

3 lepton decay $\ell_i \to \ell_j \ell_k \ell_k$

Signal

-- $\sum E_e = m_\mu$ (for $\mu \to eee$) , $\sum E_\ell = m_\tau$ (for $\tau \to \ell_j \ell_k \ell_k$)

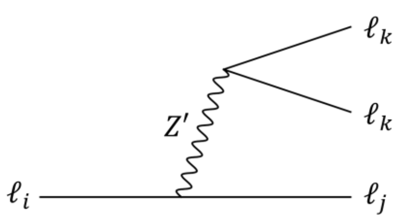
-- spatial momenta $\sum \overrightarrow{p_e} = \vec{0}$, time coincidence $\Delta t_{eee} = 0$



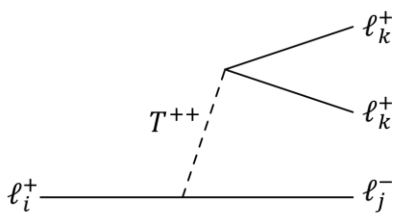
Experimental status

Process	BR limit		Future	
$\mu \to eee$	1.0×10^{-12}	SINDRUM (1988)	1.0×10^{-16}	Mu3e
$\tau \to eee$	2.7×10^{-8}	Belle (2010)	4.7×10^{-10}	Belle II
$\tau \to \mu\mu\mu$	1.8×10^{-8}	Belle (2010)	2.9×10^{-10}	Belle II
$\tau \to \mu ee$	1.5×10^{-8}	Belle (2010)	2.3×10^{-10}	Belle II

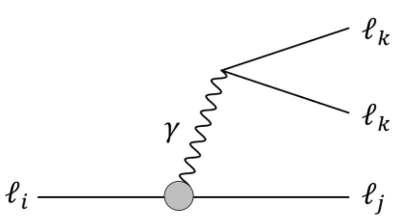
Probe to various models beyond the SM



GUT models, Little Higgs, extra dimension models



Type-II SeeSaw, extended Higgs models



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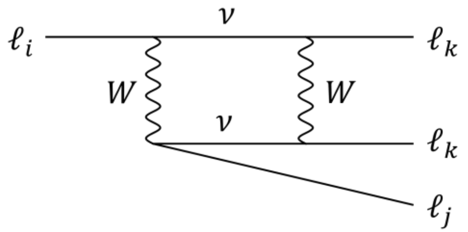
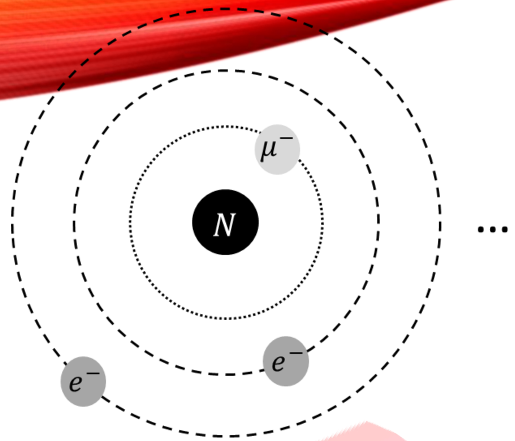


νMSM, sterile ν

LFV processes in muonic atom



Muonic atom

-- bound state of muon μ^- and nucleus N

-- fate of muon in the SM

(1) muon decay in orbit

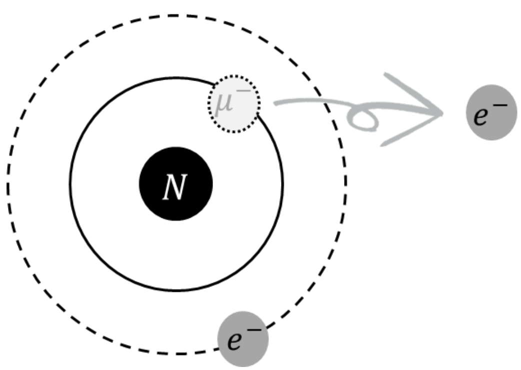
$$(\mu^- N(A,Z)) \rightarrow e^- + \bar{\nu}_e + \nu_\mu + N(A,Z)$$

(2) muon capture

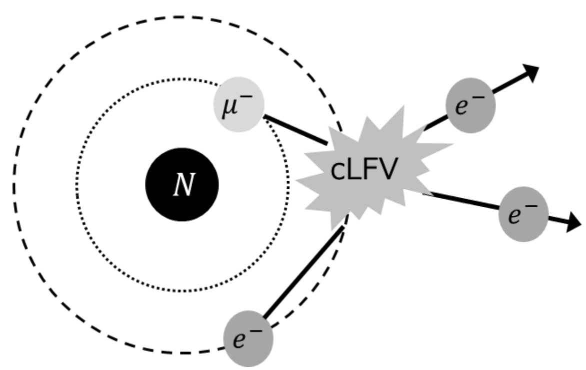
$$(\mu^- N(A,Z)) \rightarrow \nu_\mu + N'(A,Z-1)$$

If LFV mediator couples with nucleon

If LFV mediator couples mainly with leptons



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



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

And also

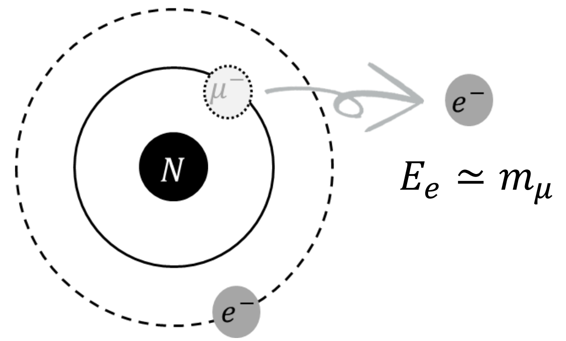
- $\mu^- \rightarrow e^+$ conversion
- $\mu^- \rightarrow e^- \gamma$ in muonic atom
- $\mu^- \rightarrow eX$ (X: light boson)

$\mu^- \rightarrow e^-$ conversion in muonic atom

J. Steinberger and H. Wolfe, Phys. Rev. (1955)

Signal

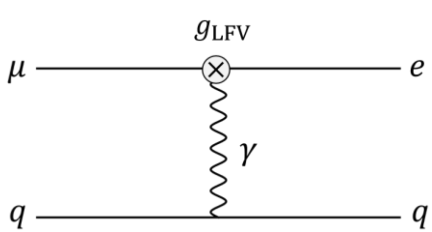
-- Monoenergetic electron $E_e \simeq 105$ MeV



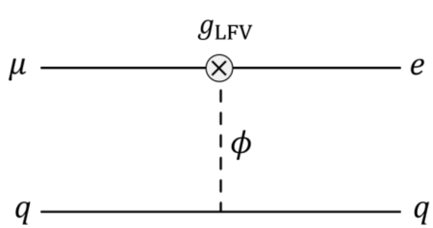
Experimental status

Process	BR limit	Future
$\mu^- \mathrm{Au} \rightarrow e^- \mathrm{Au}$	7.0×10^{-13} SINDRUM (2006)	N/A
$\mu^- \mathrm{Ti} \rightarrow e^- \mathrm{Ti}$	4.3×10^{-12} SINDRUM (2006)	N/A
$\mu^- \mathrm{Al} \rightarrow e^- \mathrm{Al}$	N/A	$a\ few \times 10^{-17}$ COMET, Mu2e
$\mu^- \mathrm{Si} \rightarrow e^- \mathrm{Si}$	N/A	1.0×10^{-14} DeeMe

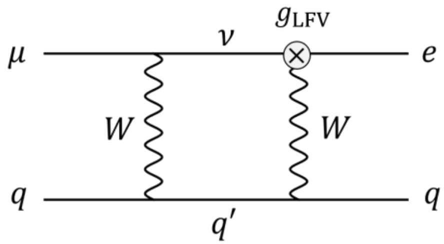
Probe to various LFV operators (pure leptonic operator, unlike $\mu \rightarrow e$ conv.)



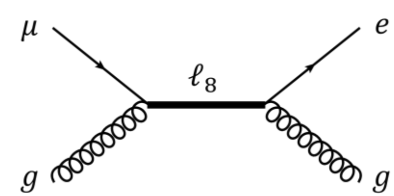
SUSY, Type-II SeeSaw



extra dimension models, extended Higgs models



Majorana ν, sterile ν



composite, leptogluon

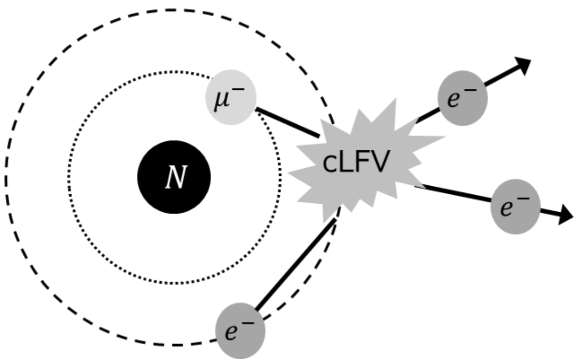
$\mu^- e^- \to e^- e^-$ in muonic atom

M. Koike, Y. Kuno, J. Sato, MY, PRL (2010)

Signal

-- back-to-back di-electron of $E_e \simeq m_\mu/2$

-- time coincidence $\Delta t_{ee} = 0$

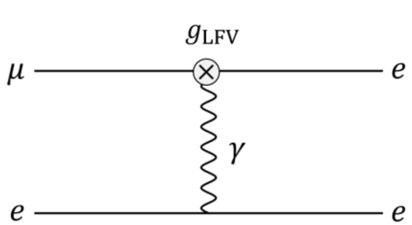


Experimental status

-- Limit: N/A (New process!)

-- included in physics programs of COMET (& Mu2e?)

Probe to various LFV operators (pure leptonic operator, unlike $\mu \to e$ conv.)



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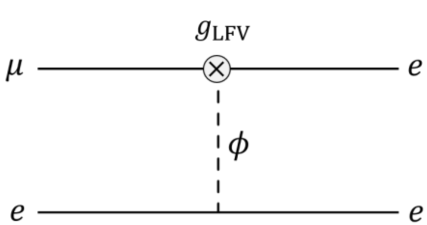
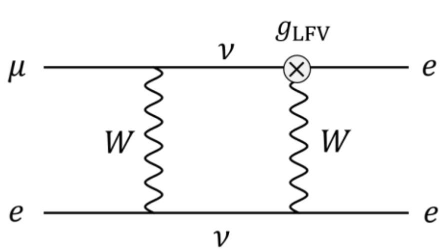
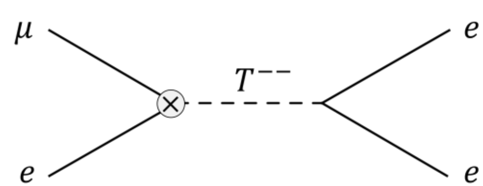


extra dimension models,
little Higgs models

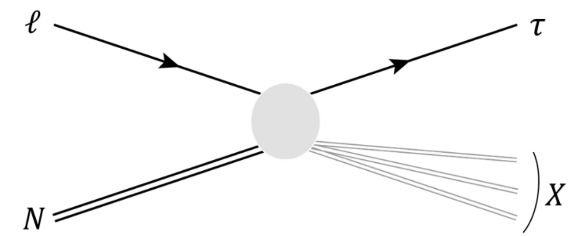


νMSM, sterile ν



extended Higgs models

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



<u>Signal</u>

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

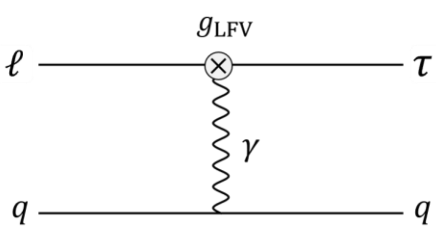
<u>Experimental status</u>

-- Limit: HERA exp.

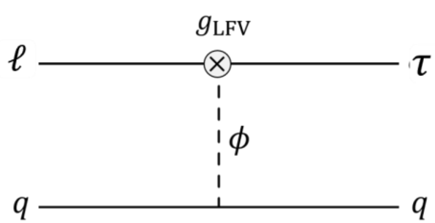
-- Future: EIC, LHeC, ILC, …

$e \to \tau$	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**

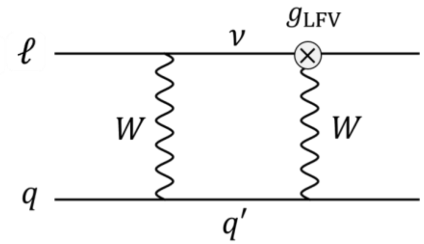
<u>Probe to various models beyond the SM</u>



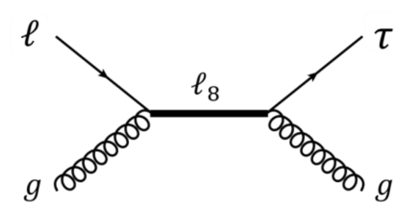
SUSY, Type-II SeeSaw



extra dimension models,
extended Higgs models



Majorana ν, sterile ν



composite, leptogluon

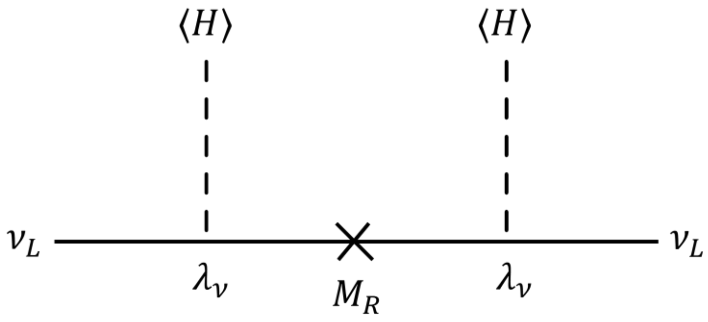
ν mass generation scenarios and LFV

Tree-level m_ν generation: Type-I seesaw

P. Minkowski, PLB (1977)
T. T. Yanagida, Conf.Proc.C (1979)

SM + heavy right-handed neutrinos

- Tiny neutrino mass and mixing for natural size couplings $\lambda \sim \mathcal{O}(1)$
- Baryon asymmetry of the universe via leptogenesis



$$\mathcal{M}_\nu \sim \langle H \rangle^2 \lambda_\nu M_R^{-1} \lambda_\nu^T$$

<u>All of LFV processes</u> experimentally unreachable, $\Gamma_{\rm LFV} \propto \left| m_D M_R^{-2} m_D^\dagger \right|^2$

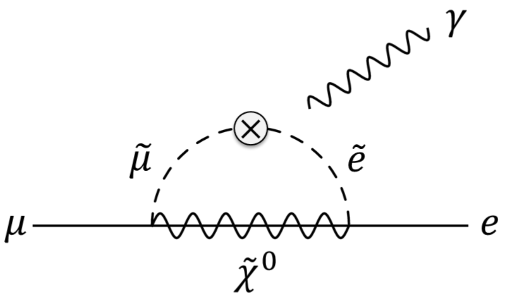
S. Bilenky, S. Petcov, B. Pontecorvo, PLB (1977)
A. Broncano, M. Gavela, E. Jenkins, PLB (2003)

Discovery of LFV ⟶ Rule out the minimal type-I seesaw

Tree-level m_ν generation: Type-I seesaw

SM + heavy right-handed neutrinos + <u>SUSY</u>

- Tiny neutrino mass and mixing for natural size couplings $\lambda \sim \mathcal{O}(1)$
- Baryon asymmetry of the universe via leptogenesis + <u>DM, GUT without desert, etc</u>

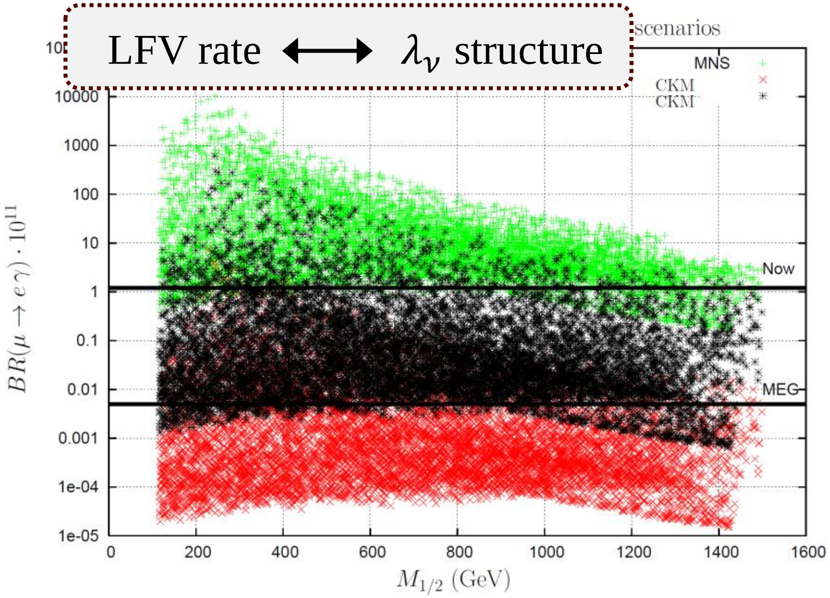


Flavor violating entries in slepton soft-breaking mass from RGE running of λ_ν

$$\left(\Delta m^2_{\tilde{L}}\right)_{ij} = -\frac{\ln\left[M_{\rm GUT}/M_R\right]}{16\pi^2}\left(6m_0^2 + 2A_0^2\right)\left(\lambda_\nu^\dagger \lambda_\nu\right)_{ij}$$

F. Borzumati, A. Masiero, PRL (1986)
J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi, PRD (1996)

LFV rate ⟷ λ_ν structure

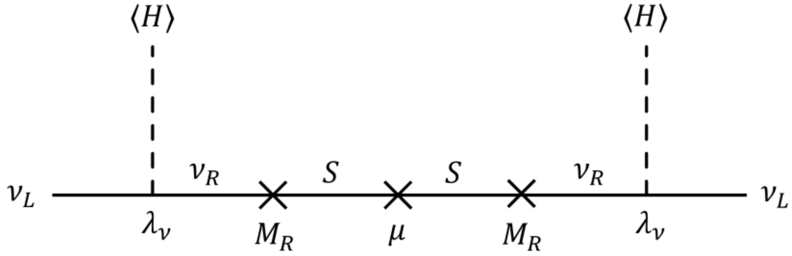


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, PRD (2006)

Tree-level m_ν generation: Type-I seesaw

SM + heavy RH neutrinos + <u>sterile fermions</u>
(Inverse seesaw) R. Mohapatra, J. Valle, PRD (1986)

- Tiny neutrino mass and mixing for natural size couplings $\lambda \sim \mathcal{O}(1)$ and twofold seesaw
- Baryon asymmetry of the universe via leptogenesis

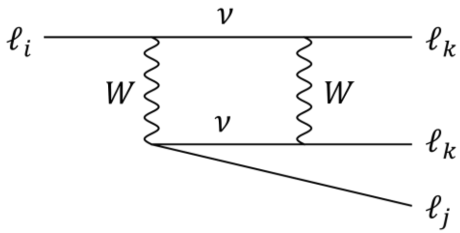


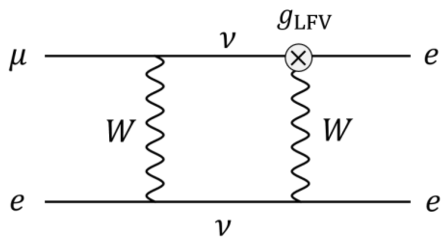
$$\mathcal{M}_\nu \sim \lambda_\nu \langle H \rangle \left(M_R^T\right)^{-1} \mu\, M_R^{-1} \lambda_\nu^T \langle H \rangle \sim \frac{m_D^2}{M_R^2}\mu$$

Flavor violating charged current from non-unitarity of PMNS matrix due to extra mixing of leptons

$$\mathcal{L}_{W^\pm} = -\frac{g_w}{\sqrt{2}} W_\mu^- \sum_{\alpha=1}^{3} \sum_{j=1}^{3+n_S} \mathbf{U}_{\alpha j} \bar{\ell}_\alpha \gamma^\mu P_L \nu_j + \text{H.c.}$$

J. Schechter, J. Valle, PRD (1980)





Tree-level m_ν generation: Type-I seesaw

SM + heavy RH neutrinos + <u>sterile fermions</u> (Inverse seesaw) R. Mohapatra, J. Valle, PRD (1986)

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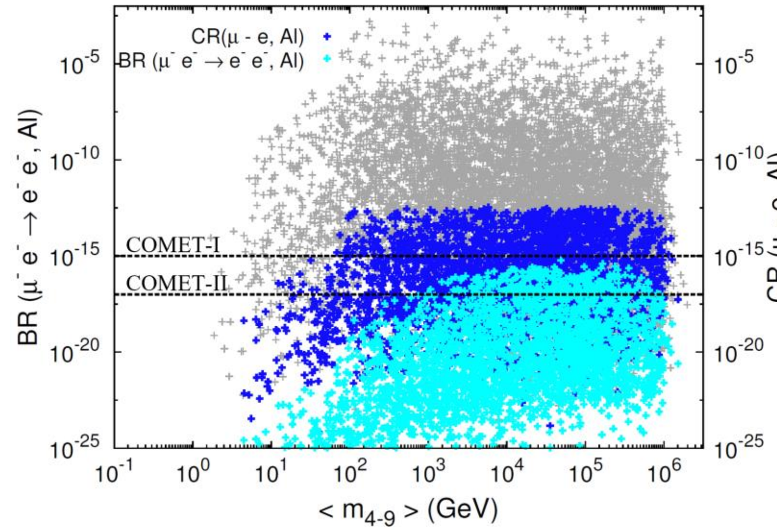
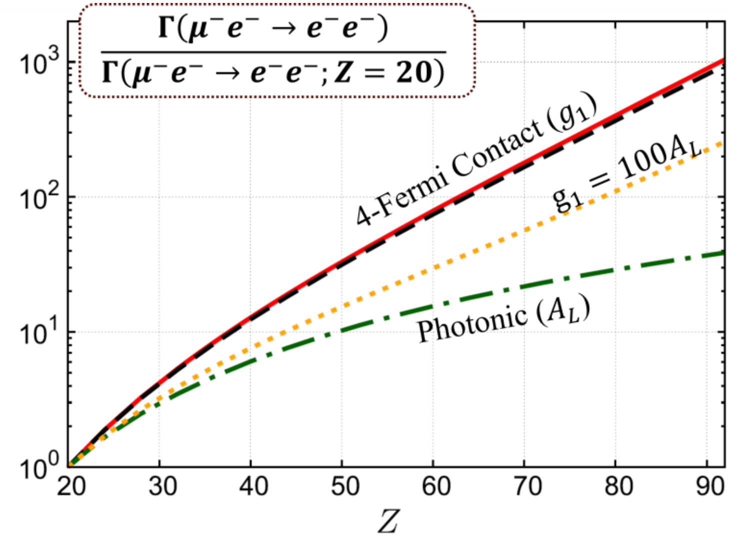


A. Abada, V. Romeri, A. Teixeira, JHEP (2016)

Significant contribution to $\mu^- e^- \to e^- e^-$ and $\mu \to e$ conversion, within reach of COMET and Mu2e



Y. Uesaka, Y. Kuno, J. Sato, T. Sato, MY, PRD (2018)

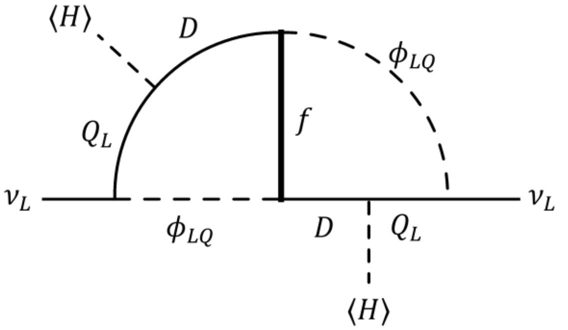
Z dependence of $\mu^- e^- \to e^- e^-$ could discriminate type-I seesaw models (SUSY type-I or inverse seesaw)

Radiative m_ν generation: Leptoquark

K. Babu, J. Julio, NPB (2010)

SM + leptoquark ϕ_{LQ} + color octet fermion f

- Tiny neutrino mass and mixing for natural size couplings $\lambda \sim \mathcal{O}(1)$ and loop suppression
- Accounting for $B \to D^{(*)}\tau\nu$ anomaly

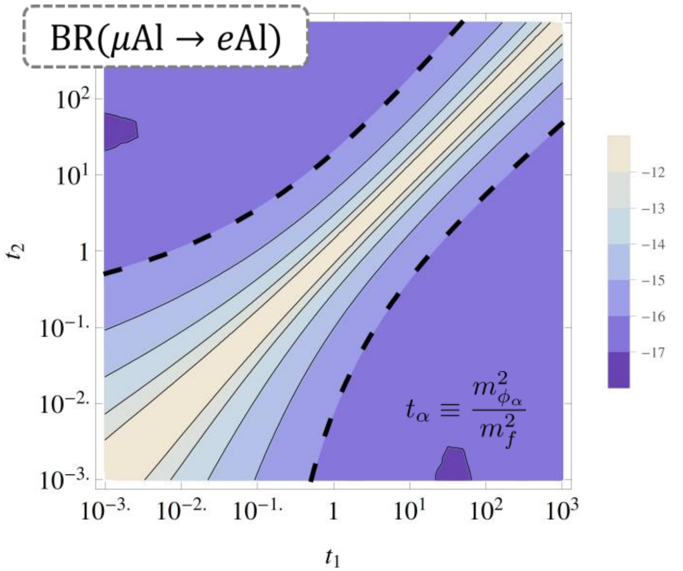


$$\mathcal{M}_\nu \sim 4\frac{m_f m_b^2 V_{tb}^2}{(2\pi)^8}\sum_{\alpha,\beta=1}^{N_\phi}\left(\lambda_{i3\alpha}^{LQ}\lambda_{3\alpha}^{df}\right)(I_{\alpha\beta})\left(\lambda_{j3\beta}^{LQ}\lambda_{3\beta}^{df}\right)$$

P. Angel, Y. Cai, N. Rodd, M. Shcmidt, R. Volkas, JHEP (2014)

Yukawa couplings of SM fermion and leptoquark violates lepton flavor conservation

Leading channel for leptoquark LFV: $\mu \to e$ conversion



Radiative m_ν generation: Leptoquark

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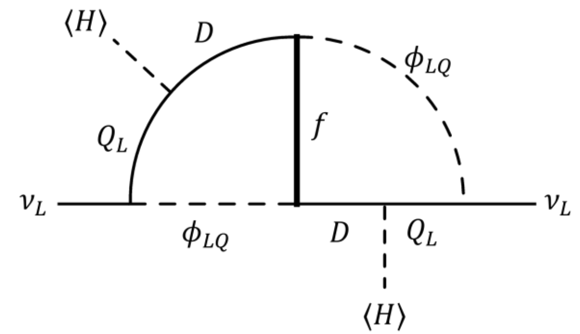
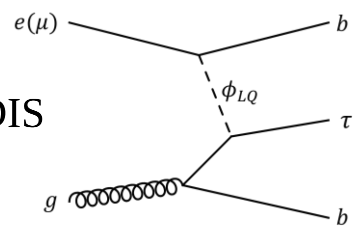


$$\mathcal{M}_\nu \sim 4\frac{m_f m_b^2 V_{tb}^2}{(2\pi)^8}\sum_{\alpha,\beta=1}^{N_\phi}\left(\lambda_{i3\alpha}^{LQ}\lambda_{3\alpha}^{df}\right)\left(I_{\alpha\beta}\right)\left(\lambda_{j3\beta}^{LQ}\lambda_{3\beta}^{df}\right)$$

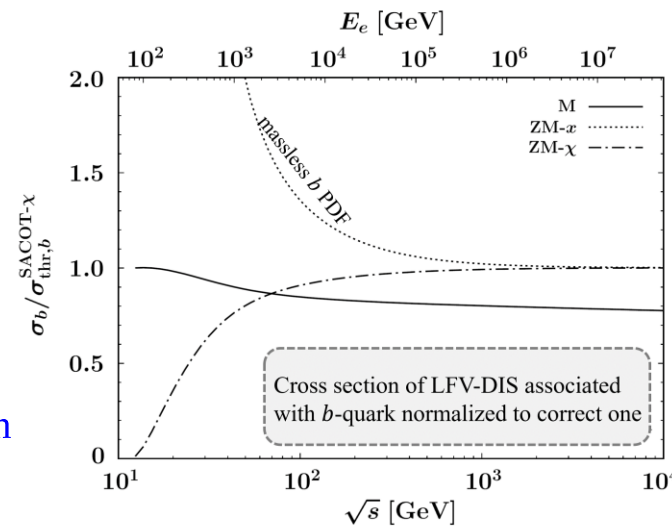
P. Angel, Y. Cai, N. Rodd, M. Shcmidt, R. Volkas, JHEP (2014)

How to check τ LFV?
How to discriminate this scenario from other m_ν generation scenarios?

LFV-DIS



Carefully formulate the DIS cross section associated with heavy quarks



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

Summary

Summary

- Neutrino oscillation calls new physics beyond the SM

- Many ν mass generation scenarios
  Verification $\longleftrightarrow$ Find intrinsic patterns of LFV observables

- **<u>Many LFV observables as possible</u>** to draw “unknown” from various angles

- **<u>Accurate connection</u>** between LFV parameters and observables
  -- $\mu \to e\gamma$ in SUSY type-I seesaw
  -- $\mu \to e$ conv. and $\mu^- e^- \to e^- e^-$ in inverse seesaw
  -- $\mu \to e$ conv. and LFV-DIS in leptoquark-loop generation