Lepton flavor violating decay of true muonium: $(\mu^+\mu^-) \to \mu^\pm e^\mp$

Ryotaro Minato (Yokohama National University)

Collaborators: Akira Sato (Osaka University), Ryosuke Suda (Saitama University), Masato Yamanaka (Hiroshima Institute of Technology)

arXiv:2507.01193

Lepton Flavor Violation

Lepton Flavor Violation (LFV)

Standard model: Exact conservation of lepton flavor

→Evidence for BSM (e.g., Neutrino Oscillations).

$$\mu^+ \rightarrow e^+ \ \overline{\nu_\mu} \ \nu_e$$
$$L_\mu: -1 = 0 + (-1) + 0$$
$$L_e: 0 = (-1) + 0 + 1$$

$$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$$
$$L_\mu: -1 \neq 0$$
$$L_e: 0 \neq -1$$

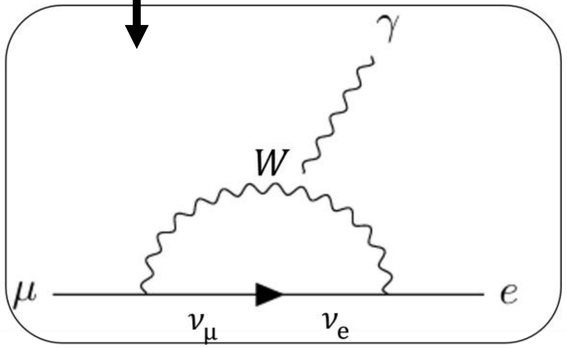
Not conserved

Charged Lepton Flavor Violation (CLFV)

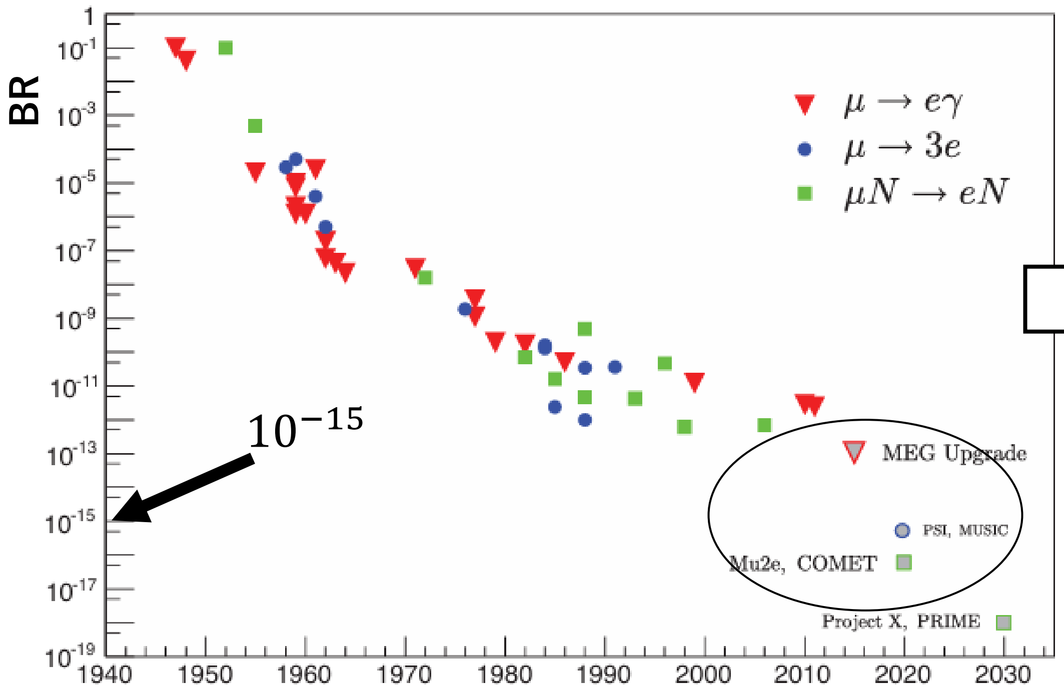
Haven't discovered yet, Evidence of New Physics (NP)

$$\mu^+ \rightarrow e^+ \gamma$$
$$L_\mu: -1 \neq 0$$
$$L_e: 0 \neq -1$$

$BR(\mu \rightarrow e\gamma) < 10^{-54}$
(SM+ν oscillation)



Extremely small without NP!



Robert H. Bernstein, Peter S. Cooper, Jul 22, 2013

- MEG
- COMET
- Mu3e
- Mu2e
- …

Proposal new CLFV channel

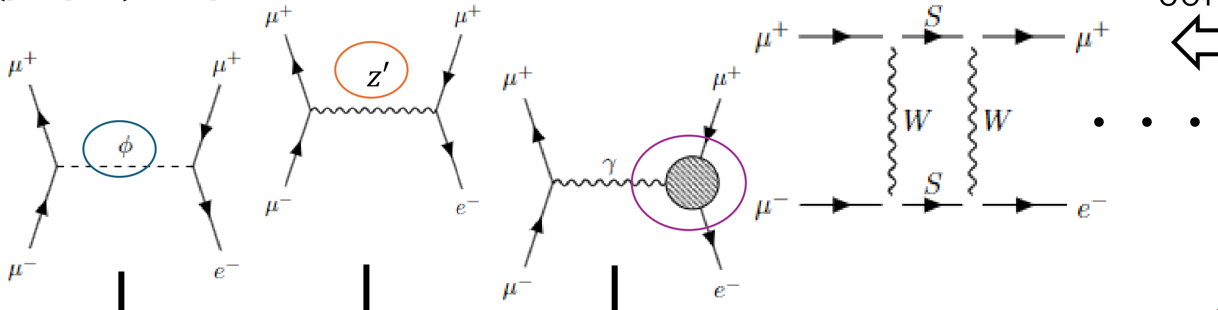
Work: Propose new CLFV channel : $(\mu^+\mu^-) \to \mu^\pm e^\mp$

→Calculation both of $\mu\mu\mu e$ four-fermi operator and dipole operator

Motivation

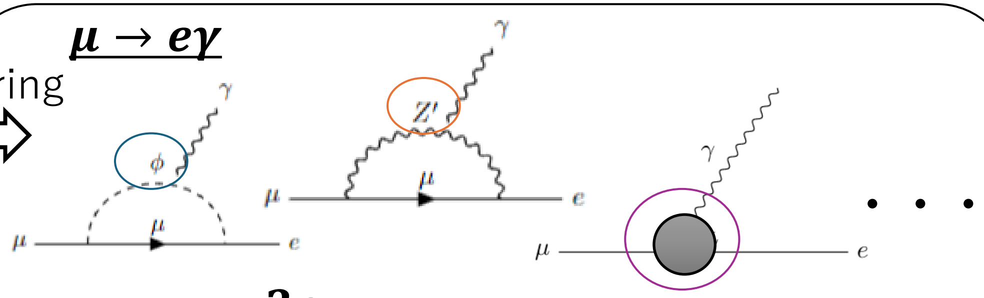
New particles through intermediate states, don't appear directly

$(\mu^+\mu^-) \to \mu^\pm e^\mp$



comparing

$\mu \to e\gamma$



$\mu \to 3e$

$\mu - e$ conversion ・・・

…

Extract underlying physics by comparing with other channels

→**Exploring many CLFV channels complementally is important**

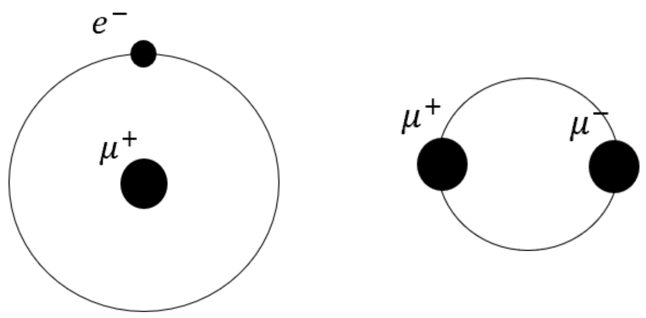
What is True Muonium?

True Muonium ($\mu^+\mu^-$) : $\mu^+\mu^-$ bound state

(Muonium (μ^+e^-) : μ^+e^- bound state)

→**Decay process of True Muonium**

Muonium True Muonium



$0.053\ nm$ $0.00051\ nm$

- Experimentally undiscovered→Production processes are proposed

Candidates for production processes

1 Collider-Based Approaches

- LHCb ($pp \to \eta X, \eta \to (\mu^+\mu^-)\gamma$)
  Cid Vidal et al., 2019
- DIMUS ($\mu^+\mu^- \to (\mu^+\mu^-)$)
  Fox et al., 2022
- Belle II ($e^+e^- \to (\mu^+\mu^-)$)
  Gargiulo et al., 2025

2 Fixed-Target Experiments

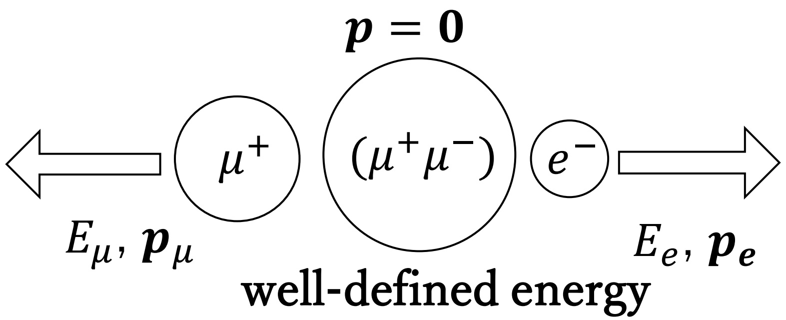
- HPS ($eZ \to (\mu^+\mu^-)$ X)
  Banburski & Schuster, 2012

3 Low-Energy $\mu^+\mu^-$ Recombination

- LEMA ($\mu^+\mu^- \to (\mu^+\mu^-)\gamma$)
  Itahashi et al., 2015

Why True Muonium?

→Compared to $\mu^+\mu^-$ Collisions



・Clear signal of $(\mu^+\mu^-) \to \mu^\pm e^\mp$

(Back-to-back, $E_\mu \simeq 5m_\mu/4$, $|\boldsymbol{p}_\mu| \simeq 3m_\mu/4$, $E_e \simeq 3m_\mu/4$, $|\boldsymbol{p}_e| \simeq 3m_\mu/4$)

→**Identification by the angular, timing, and momentum of μ, e**

・Early-stage accessible

Can be observed before construction of muon acceleration systems

・Magnetic fields provide unique insights into new physics (future work)

As seen in muonium–antimuonium conversion rate depends on external field.

(K. Horikawa and K. Sasaki, 1996)

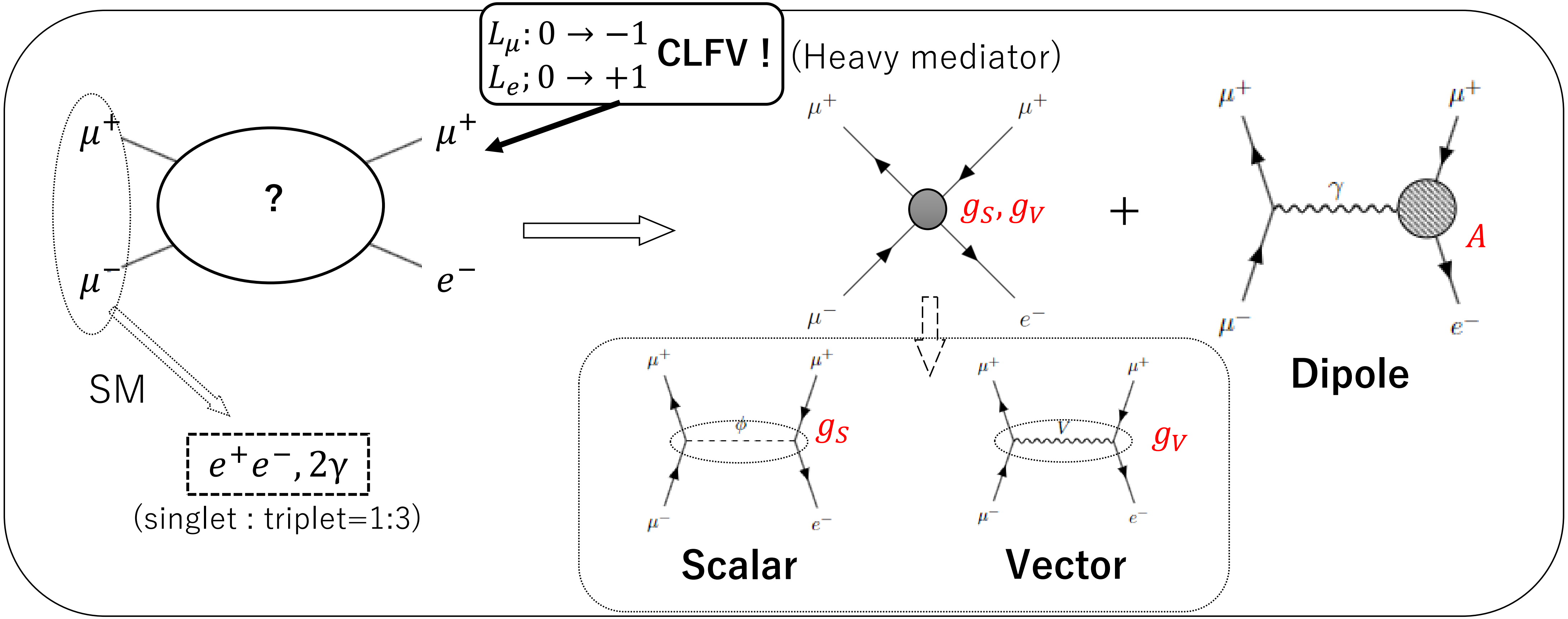
- Introduction

- **Interaction Lagrangian**

- Numerical result

Types of Operator

・ Scalar, Vector, Dipole-type operator



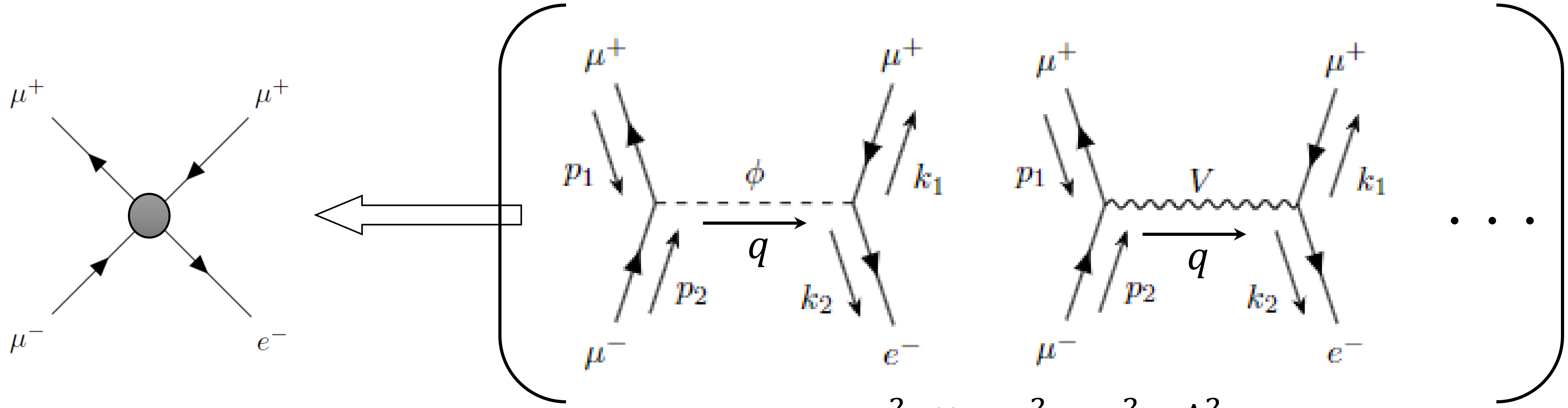
Evaluate the BR as a function of g_S, g_V, A

Chirality (L,R)

$(g_{SLL}, g_{SRR} g_{VLL}, g_{VRR}, g_{VRL}, g_{VLR}, A_L. A_R)$

Scalar, Vector-type Operator (Four-Fermi)

Heavy mediator can be treated as contact interactions.



$q^2 \ll m_\phi{}^2, m_V{}^2 \sim \Lambda^2$

(Λ: Scale of NP)

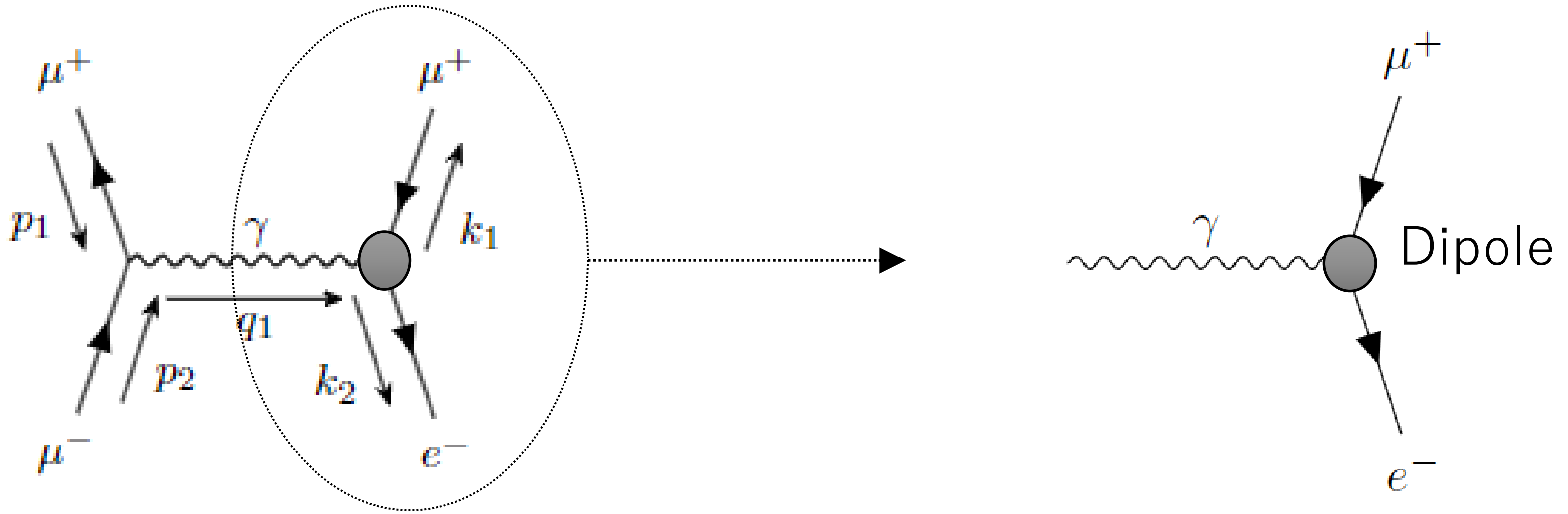
$$\mathcal{L}_{\text{int}}^{(S)} \supset -\frac{1}{\Lambda^2}\left[g_{SLL}(\bar{\psi}_\mu P_L \psi_\mu)(\bar{\psi}_e P_L \psi_\mu) + g_{SRR}(\bar{\psi}_\mu P_R \psi_\mu)(\bar{\psi}_e P_R \psi_\mu)\right]$$

$$\mathcal{L}_{\text{int}}^{(V)} \supset -\frac{1}{\Lambda^2}\left[g_{VLL}(\bar{\psi}_e \gamma^\mu P_L \psi_\mu)(\bar{\psi}_\mu \gamma_\mu P_L \psi_\mu) + g_{VRR}(\bar{\psi}_e \gamma^\mu P_R \psi_\mu)(\bar{\psi}_\mu \gamma_\mu P_R \psi_\mu)\right.$$
$$\left. + g_{VRL}(\bar{\psi}_e \gamma^\mu P_R \psi_\mu)(\bar{\psi}_\mu \gamma_\mu P_L \psi_\mu) + g_{VLR}(\bar{\psi}_e \gamma^\mu P_L \psi_\mu)(\bar{\psi}_\mu \gamma_\mu P_R \psi_\mu)\right]$$

Dipole-type Operator

Dipole-type operator + gauge interaction

・Strong complementarity with $\mu \to e\gamma$ searches



$$\mathcal{L}_{\rm int}^{(D)} \supset -e\bar{\psi}_\mu\gamma^\mu A_\mu\psi_\mu - \frac{v_{Higgs}}{\Lambda^2}(A_L\bar{\psi}_e\sigma^{\mu\nu}P_L\psi_\mu F_{\mu\nu} + A_R\bar{\psi}_e\sigma^{\mu\nu}P_R\psi_\mu F_{\mu\nu})$$

・Introduction

・Interaction Lagrangian

・**Numerical result**

Result (single operator)

Upper Limit of BR

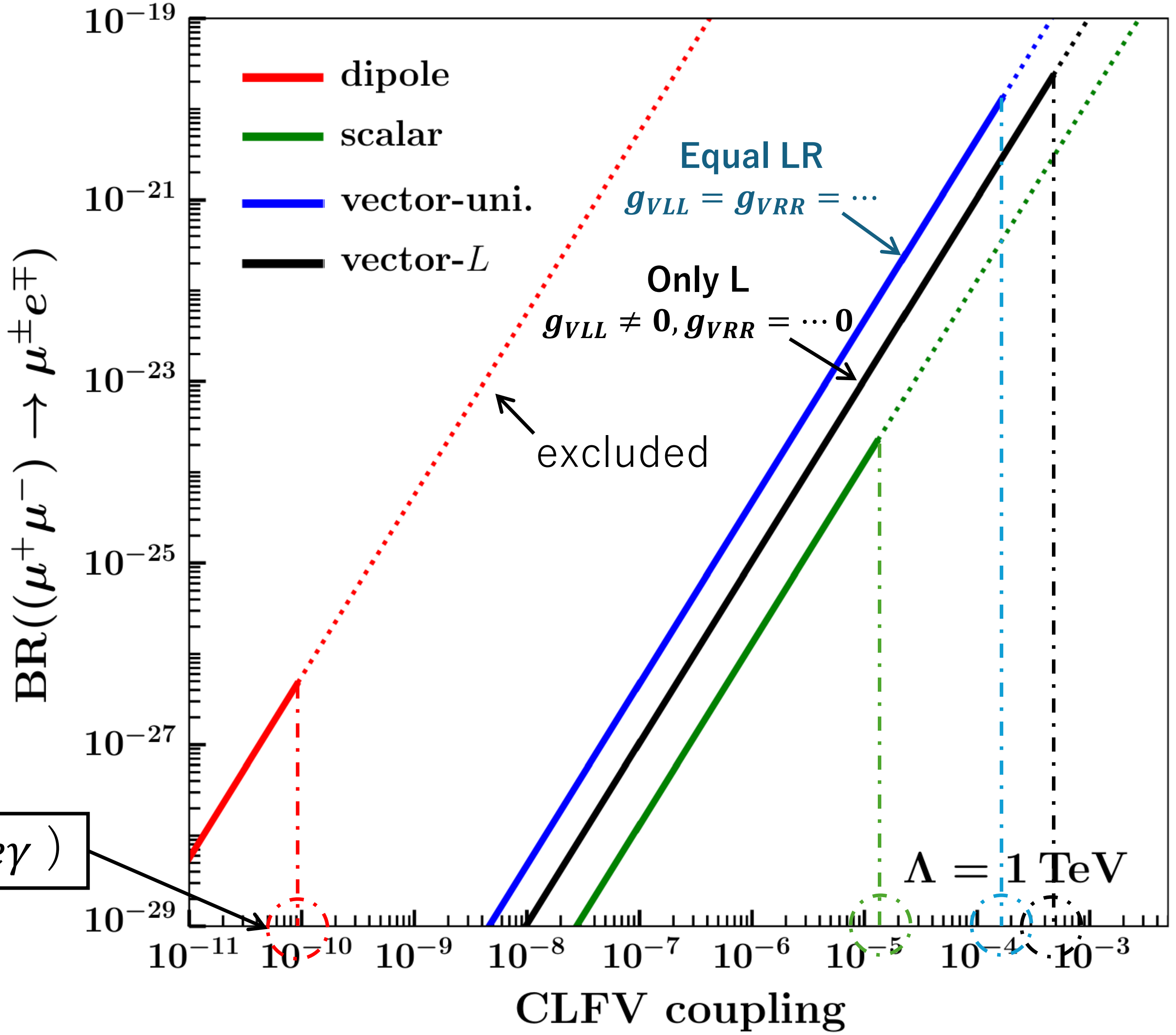
$A_L \to BR(\mu\mu \to \mu e) \sim 10^{-27}$
$g_S \to BR(\mu\mu \to \mu e) \sim 10^{-24}$
$g_V \to BR(\mu\mu \to \mu e) \sim 10^{-20}$

$$\boxed{N_{\mathrm{TM}} = \mathrm{BR}^{-1} \approx 5.2 \times 10^{19}}$$

5.2×10^{19} True Muonium may enable CLFV tests!

Constrains for CLFV coupling by MEG ($\mu \to e\gamma$)

→Dipole is most suppressed because of $\mu \to e\gamma$ at tree-level contribution



The MEGII collaboration .2024

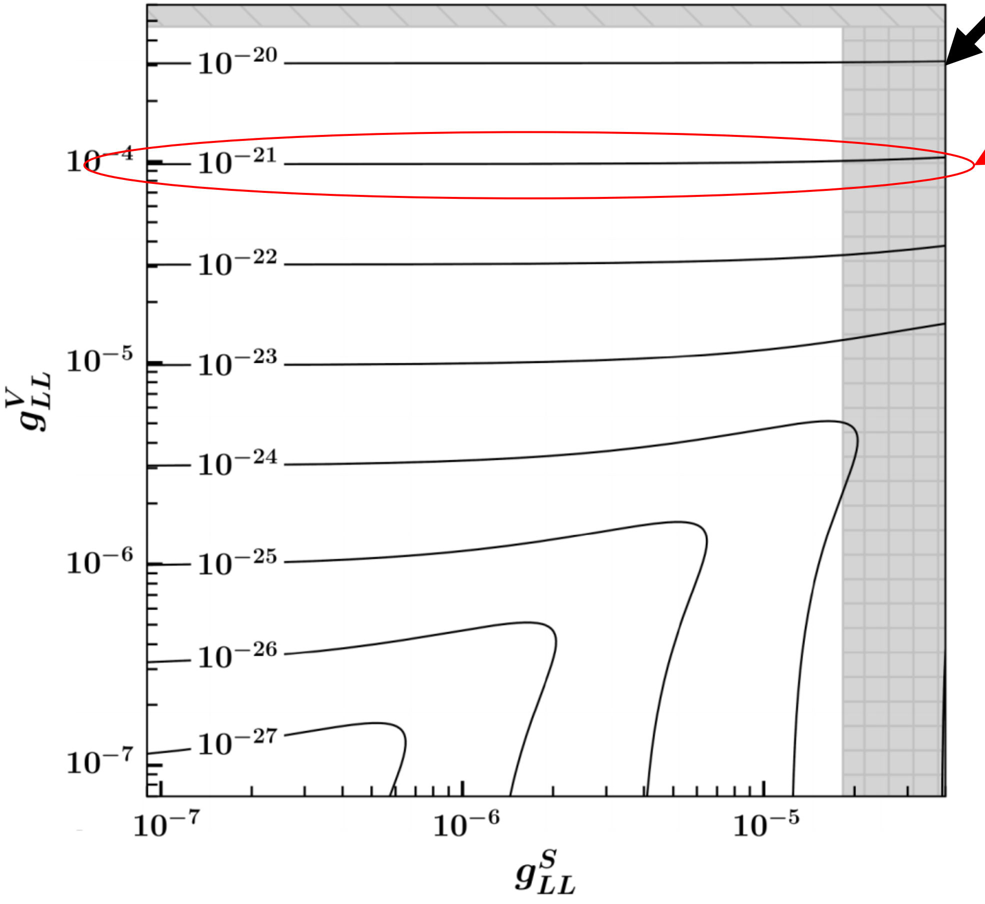
Result (multiple operator)

(e.g. scalar-vector interference)

Contour: $BR = 10^{-20}, 10^{-21}, \cdots$
Shaded: excluded by MEG II
Only two shown couplings are nonzero

$BR = 10^{-20}$

This contour cannot determine g^S parameters.



Draw similar $g_S - g_V$ contour

- One contour ≠ one solution → **degeneracy**
- Combine with other CLFV observables
  - $\mu^+ e^- \to \mu^+ \mu^-$ at a collider is observed
  - $\mu^+ \to e^- \gamma$, $\mu^+ \to e^+ e^- e^+$ ... are not
- separate scalar-vector contributions comparing two $g_S g_V$ contours (collider cross section + BR of TM CLFV)

→Break degeneracies and pin down the operator.

Summary

- Proposed a new CLFV reaction: $(\mu^+\mu^-) \to \mu^\pm e^\mp$.
- 5.2×10^{19}True Muonium may enable CLFV tests
- Evaluate contribution of interference between multiple operators

Future Work

- Investigate singlet and triplet-specific reactions.
- Consider mediators not constrained by $\mu \to e\gamma$ (e.g., sterile ν)
- Explore off-shell photon dipole interactions constrained by $\mu \to 3e$

→**Precise calculations more clearly shed light on the physics behind CLFV**

Working Hypothesis

(1) **four Fermi effective operator**

- **scalar LR universal (scalar)**

  $(g_S = g_{SLL} = g_{SRR} \neq 0)$

- **vector LR universal (vector-uni)**

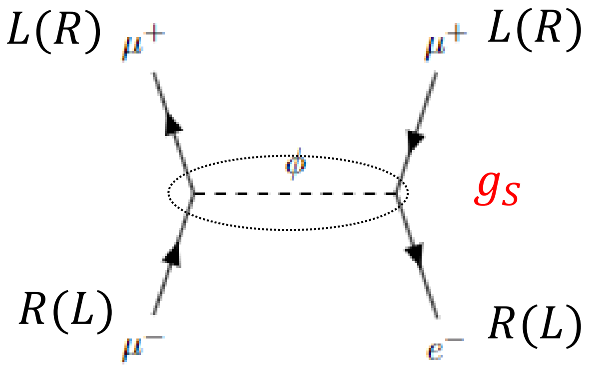
  $(g_V = g_{VLL} = g_{VRR} = g_{VLR} = g_{VRL} \neq 0)$

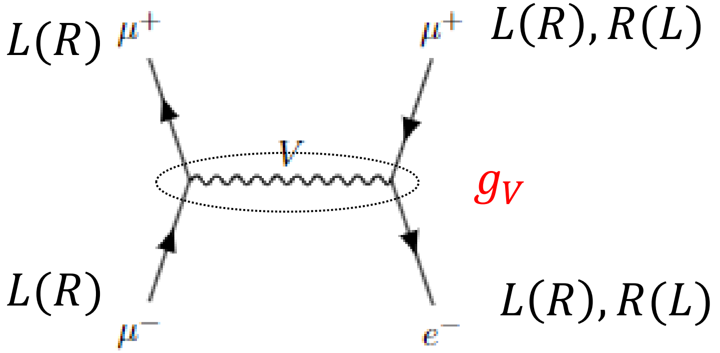
- **vector L only (vector-L)**

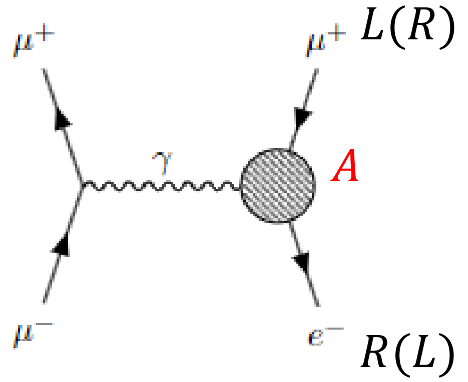
  $(g_{VLL} \neq 0,\ g_{VRR} = g_{VLR} = g_{VRL} = 0)$

(2) **dipole operator LR universal (dipole)**

$(A = A_L = A_R \neq 0)$







Branching Ratio

Branching ratio $(m_e \sim 0)$

$$BR(\mu\mu \to \mu e) = \frac{\Gamma(\mu\mu \to \mu e)}{\Gamma(\mu\mu)}$$

$$= \left(\frac{1[TeV]}{\Lambda}\right)^4 [6.54 \times 10^{-15}(|g_{SLL}|^2 + |g_{SRR}|^2) + 1.05 \times 10^{-13}(|g_{VLL}|^2 + |g_{VRR}|^2)$$
$$+ 8.93 \times 10^{-14}(|g_{VLR}|^2 + |g_{VRL}|^2) + 4.20 \times 10^{-14} Re\left(g_{VLL}g^*_{VLR} + g_{VRR}g^*_{VRL}\right)$$
$$+ 2.81 \times 10^{-7}\left(|A_L|^2 + |A_R|^2\right) + (\text{SVD interference terms})].$$

Constraints from MEG + MEG II Experiments

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$$BR(\mu \to e\gamma) < 3.1 \times 10^{-13}$$

$$\Downarrow \quad (\Lambda \sim 1[TeV])$$

$$\underline{g_{SLL}^2 + g_{SRR}^2 \lesssim 3.35 \times 10^{-10}, \quad g_V^2 \lesssim 2.72 \times 10^{-8}\ (\text{uni})}$$
$$\underline{g_{VLL}^2 \lesssim 2.18 \times 10^{-7}\ (\text{L}), \quad A_L^2 + A_R^2 \lesssim 1.64 \times 10^{-20}}$$

Upper Limit of Coupling Constant

Constraints from MEG + MEG II

$BR(\mu \to e\gamma) < 3.1 \times 10^{-13}$

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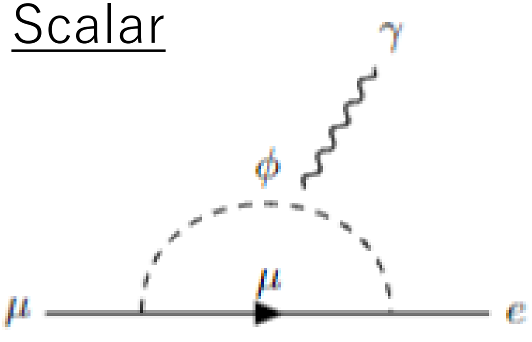
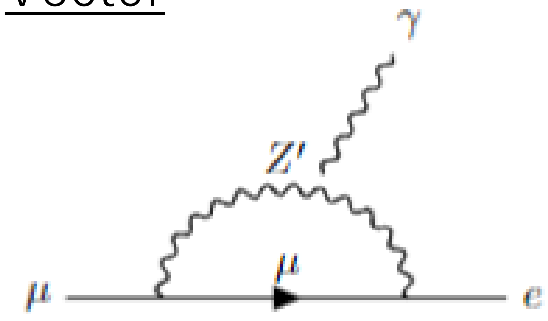
Scalar



$Y^L_{\mu\mu}$ $Y^L_{\mu e}$

$\boxed{\mathcal{L}_{Sint} = -\bar{\psi}_i Y_{ij} \psi_j \phi + h.c.}$

Vector



$Q^L_{\mu\mu}$ $Q^L_{\mu e}$

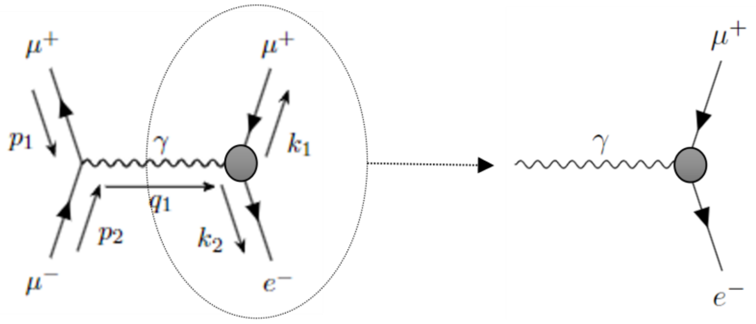
$\boxed{\mathcal{L}_{Vint} = -\bar{\psi}_i Q_{ij} \gamma^\mu \psi_j Z'_\mu + h.c.}$

(Four-Fermi)

$$\frac{g_{SLL}}{\Lambda^2} = \frac{Y^L_{\mu e} Y^L_{\mu\mu}}{m_\phi^2}$$

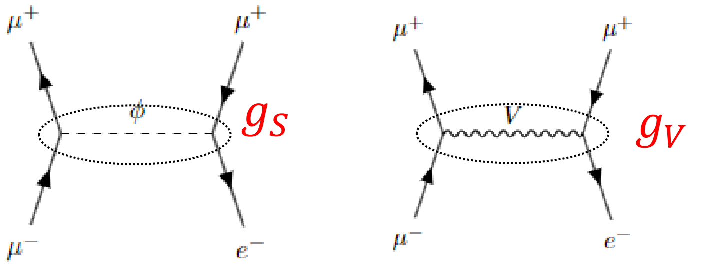
$$\frac{g_{VLL}}{\Lambda^2} = \frac{Q^L_{\mu e} Q^L_{\mu\mu}}{m_{Z'}^2}$$

Dipole



$A_L^2 + A_R^2 \lesssim 1.64 \times 10^{-20}$

Scalar, Vector



$g_{SLL}^2 + g_{SRR}^2 \lesssim 3.35 \times 10^{-10}$

$g_V^2 \lesssim 2.72 \times 10^{-8}$ (uni)

$g_{VLL}^2 \lesssim 2.18 \times 10^{-7}$ (L)

$(\Lambda \sim 1[TeV])$

Vector-universal vs Vector-left

Assuming $g_V^{(vector-uni)} = g_{VLL}^{(vector-L)}$

Vector-universal

Vector-left

$$BR(\mu\mu \to \mu e) = \frac{\Gamma(\mu\mu \to \mu e)}{\Gamma(\mu\mu)}$$
$$= \left(\frac{1[TeV]}{\Lambda}\right)^4 [6.54 \times 10^{-15}(|g_{SLL}|^2 + |g_{SRR}|^2) + 1.05 \times 10^{-13}(|g_{VLL}|^2 + |g_{VRR}|^2)$$
$$+ 8.93 \times 10^{-14}(|g_{VLR}|^2 + |g_{VRL}|^2) + 4.20 \times 10^{-14} Re\left(g_{VLL}g^*_{VLR} + g_{VRR}g^*_{VRL}\right)$$
$$+ 2.81 \times 10^{-7}\left(|A_L|^2 + |A_R|^2\right) + (\text{SVD interference terms})].$$

$$\boxed{BR(vector-uni) \sim BR(vector-L) \times 8}$$

→Enhanced around a digit by interference terms

・On the other hand, scalar and dipole are different factor of two simply

Estimated Number of Muons Produced

$\underline{3 \times 10^{15}\ \mu^-/s,\ 2 \times 10^{15}\ \mu^+/s}$ are expected produced
at the muon production point of the muon collider

$\rightarrow$ $10^{22}\ \ \mu\ /\ year$ can produced

C. Accettura et al, 2025

$\Updownarrow$

$$\boxed{N_{\mathrm{TM}} = \mathrm{BR}^{-1} \approx 5.2 \times 10^{19}}$$

If an efficient method for generating True Muonium,
CLFV decay proposed in this study could be discovered!