Lepton Flavor Violating Decay of True Muonium

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Work in Progress

Lepton Flavor Violation

LFV(Lepton Flavor Violation)

Standard model: Exact conservation of lepton flavor

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

$BR(\mu \to e\gamma) < 10^{-54}$
(SM+ν oscillation)
→**extremely small**

CLFV(Charged Lepton Flavor Violation)

If discovered, it would be direct evidence of new physics

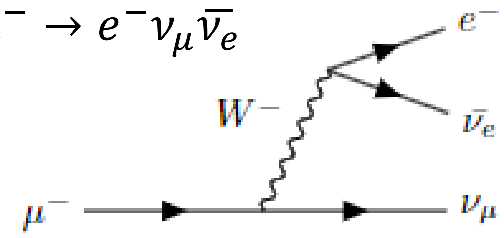
→MEG, SINDRUM, COMET, Mu3e, DeeMe, Mu2e

L_μ: $1 \to 0$
L_e; $0 \to 1$
LFV !

Muon LFV is a hot topic right now!

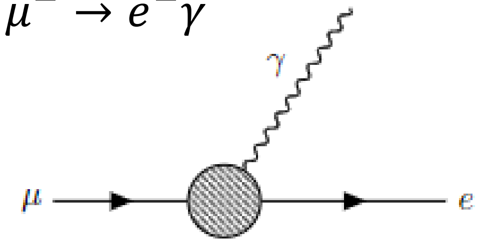
SM

$\mu^- \to e^-\nu_\mu\bar{\nu}_e$

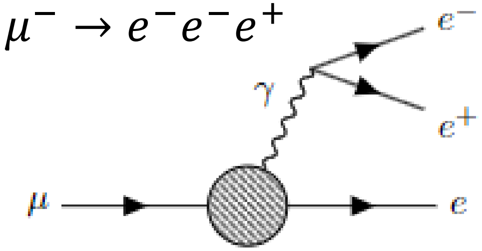


CLFV

$\mu^- \to e^-\gamma$

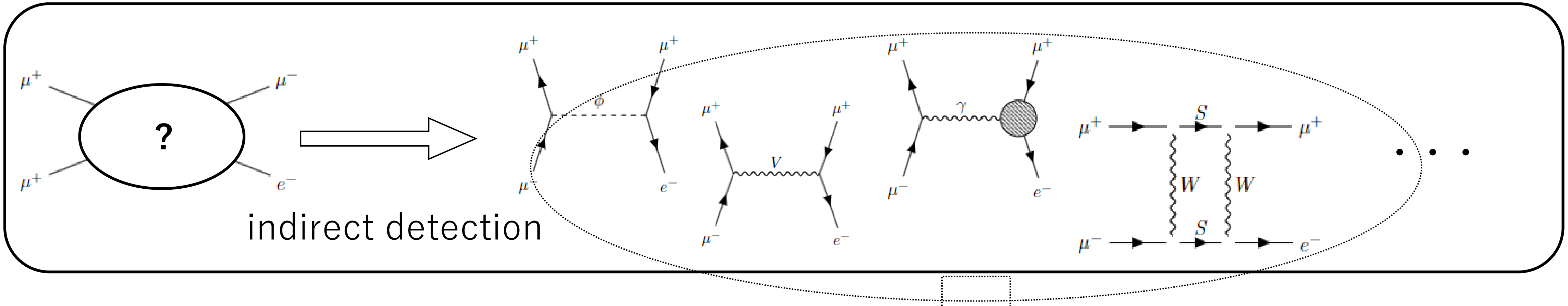


$\mu^- \to e^-e^-e^+$



Motivation

If LFV is observed, how can we identify the underlying physics?



Identify LFV mediator by comparing with other LFV channels.

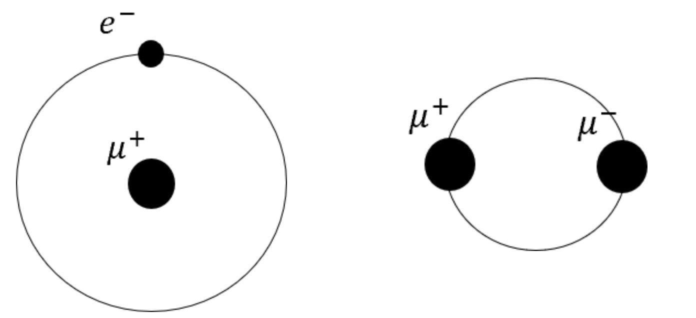
→**The more LFV channels we have, the better.**

$\mu \to e\gamma$
$\mu \to 3e$
…

A new LFV channel : $(\mu^+\mu^-) \to \mu^\pm e^\mp$

Verification of low-energy processes induced by the $\mu\mu\mu e$ operator

What is True Muonium?



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

(Muonium: μ^+e^- bound state)

→**Decay process of True Muonium**

・Experimentally undiscovered→Production processes are proposed

Candidates for production processes

1 ： Electron-positron accelerator collisions ($e^+e^- \to (\mu^+\mu^-)$) [1]

2 ： Collision with a fixed target ($eZ \to (\mu^+\mu^-)$ X, Jlab HPS, CERN DIRAC) [2]

3 ： Meson decay ($\eta \to (\mu^+\mu^-)\gamma$, $K_L \to (\mu^+\mu^-)\gamma$) [3](LHCb)

4 ： $\mu^+\mu^-$collision ($\mu^+\mu^- \to (\mu^+\mu^-)\gamma$, $\gamma\mu^+\mu^- \to (\mu^+\mu^-)2\gamma$, $\mu^+\mu^-\mu^+ \to (\mu^+\mu^-)\gamma$) [4]

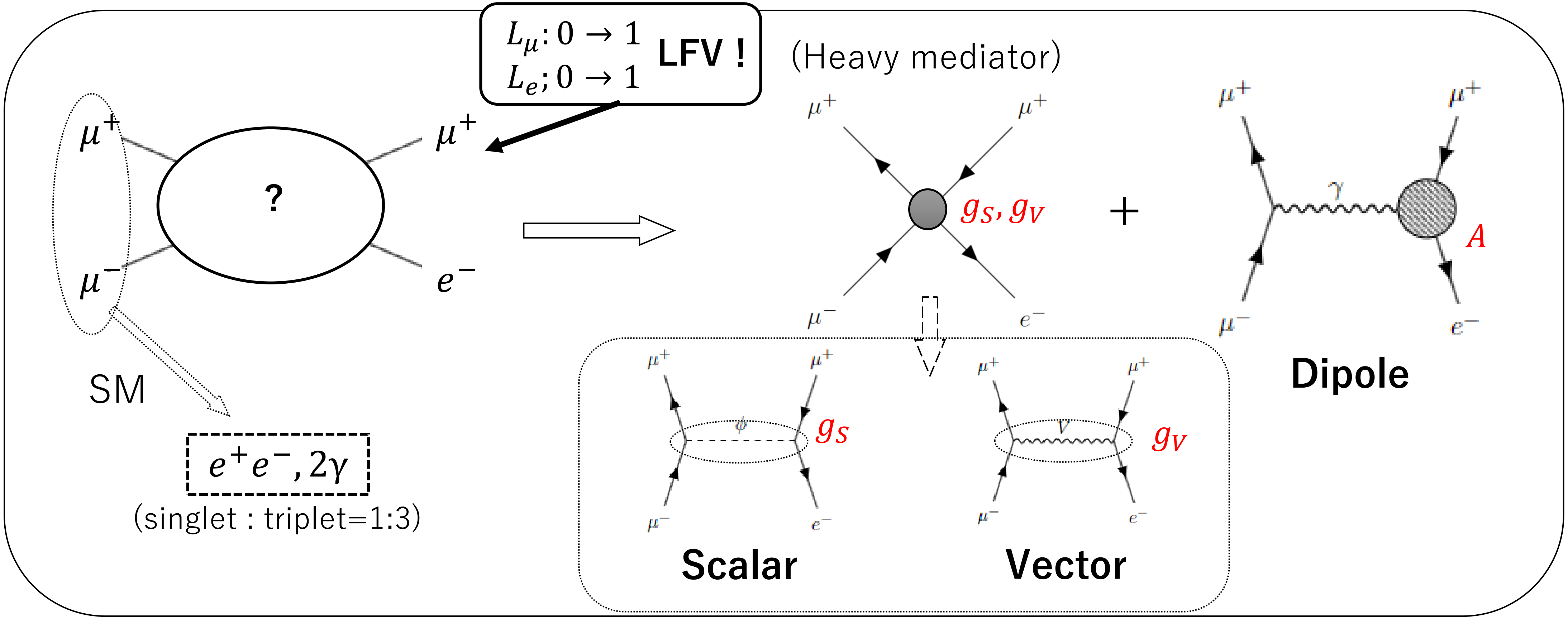
Why True Muonium?

・Difficulty of muon acceleration　・Small background

- Introduction
- **Interaction Lagrangian**
- Numerical result, background

Types of Operator

・Scalar, Vector, Dipole-type operator



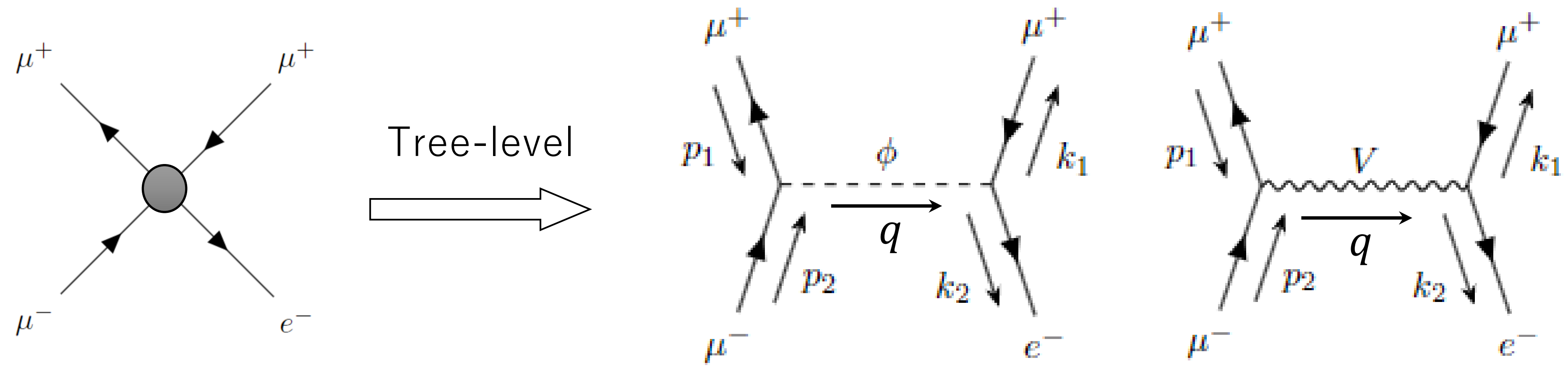
Evaluate the BR as a function of g_S, g_V, A

⇩ 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.



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

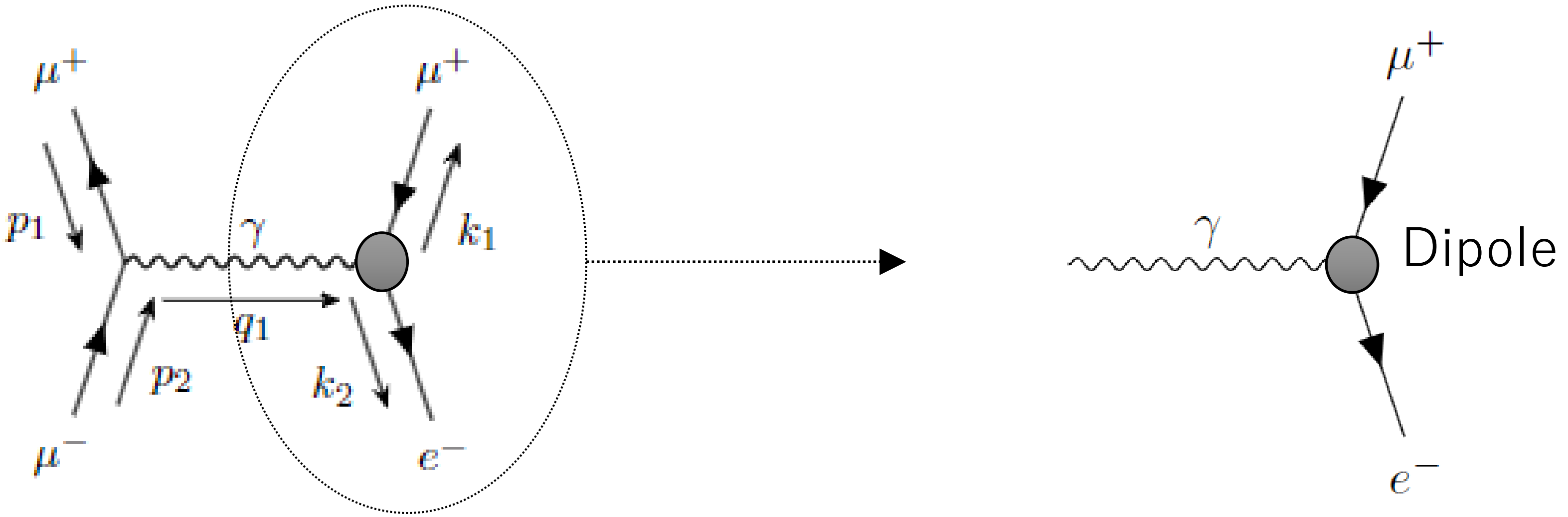
$$\mathcal{L}_{\text{int}}^{(S)} \supset -\frac{1}{\Lambda^2}\left[g_{SLL}(\bar{\psi}_\mu P_L \psi_\mu)(\bar{\psi}_e P_L \psi_\mu) + g_{SRR}(\bar{\psi}_\mu P_R \psi_\mu)(\bar{\psi}_e P_R \psi_\mu)\right]$$

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

Dipole-type Operator

Dipole-type operator + gauge interaction

dipole-type loop that induces $\mu \to e\gamma$.



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

→Evaluate the BR as a function of $g_{SLL}, g_{SRR}, g_{VLL}, g_{VRR}, g_{VRL}, g_{VLR}, A_L, A_R$

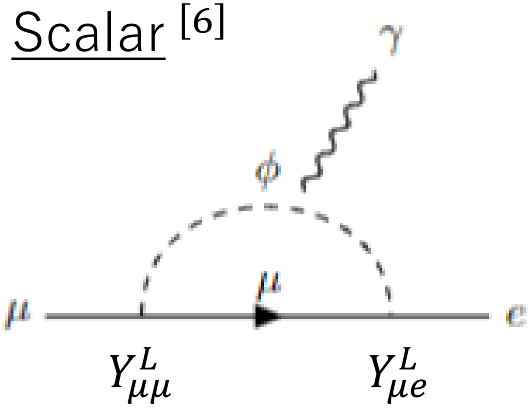
- Introduction
- Interaction Lagrangian
- **Numerical result, background**

Upper Limit of Coupling Constant

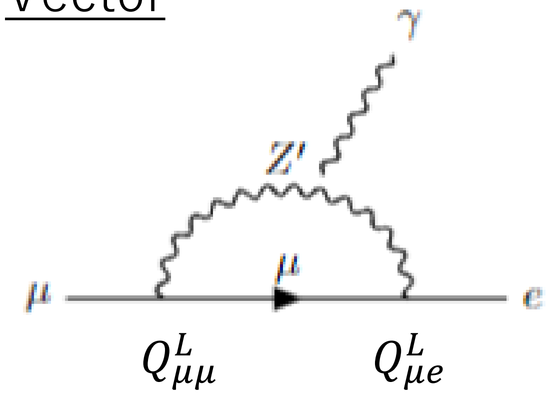
Constraints from MEG+MEG II [5]

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

Scalar [6]



Vector [7]



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

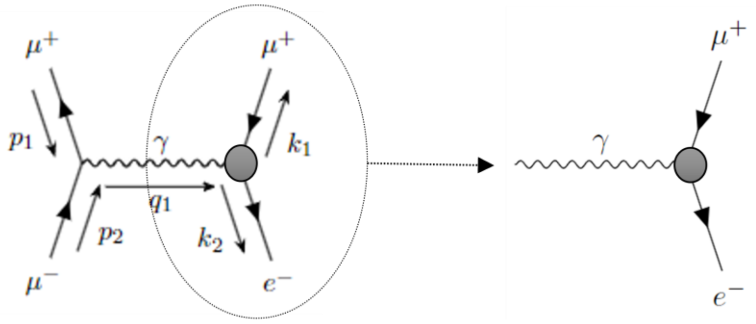
$\mathcal{L}_{Vint} = -\bar{\psi}_i Q_{ij} \gamma^\mu \psi_j Z'_\mu + h.c.$

(Four-Fermi)

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

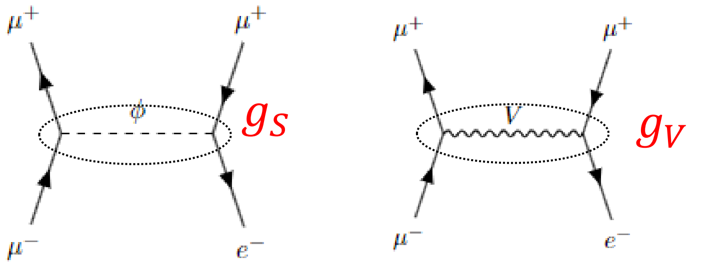
$$\frac{g_{VLL}}{\Lambda^2} = \frac{Q^L_{\mu e} Q^L_{\mu\mu}}{m^2_{Z'}}$$

Dipole [8]



$$A^2_L + A^2_R \lesssim 1.64 \times 10^{-20}$$

Scalar, Vector



$$g^2_{SLL} + g^2_{SRR} \lesssim 3.35 \times 10^{-10}$$
$$g^2_{VLL} + g^2_{VRR} \lesssim 2.18 \times 10^{-7}$$
$$g^2_{VLR} + g^2_{VRL} \lesssim 2.42 \times 10^{-8}$$

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

Branching Ratio Evaluation

Branching ratio(→Ignoring interference terms, $m_e \sim 0$)

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

$$= \left(\frac{1[TeV]}{\Lambda[TeV]}\right)^4 [2.64 \times 10^{-15}(|g_{SLL}|^2 + |g_{SRR}|^2) + 4.22 \times 10^{-14}(|g_{VLL}|^2 + |g_{VRR}|^2) + 3.59 \times 10^{-14}(|g_{VLR}|^2 + |g_{VRL}|^2)$$

$$+1.69 \times 10^{-14}(g_{VLL}g^*_{VLR} + g_{VRR}g^*_{VRL}) + 1.13 \times 10^{-7}(|A_L|^2 + |A_R|^2) + (\text{SVD interference terms})]$$

Constraints from MEG+MEG II Experiments [5]

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

⇩ $(\Lambda \sim 1[TeV])$

$g_{SLL}^2 + g_{SRR}^2 \lesssim 3.35 \times 10^{-10}, \quad g_{VLL}^2 + g_{VRR}^2 \lesssim 2.18 \times 10^{-7}$

$g_{VLR}^2 + g_{VRL}^2 \lesssim 2.42 \times 10^{-8}, \quad A_L^2 + A_R^2 \lesssim 1.64 \times 10^{-20}$

Result

(e.g., Scalar-type
$g_S \equiv g_{SLL} = g_{SRR}$, $g_V = 0$, A=0)

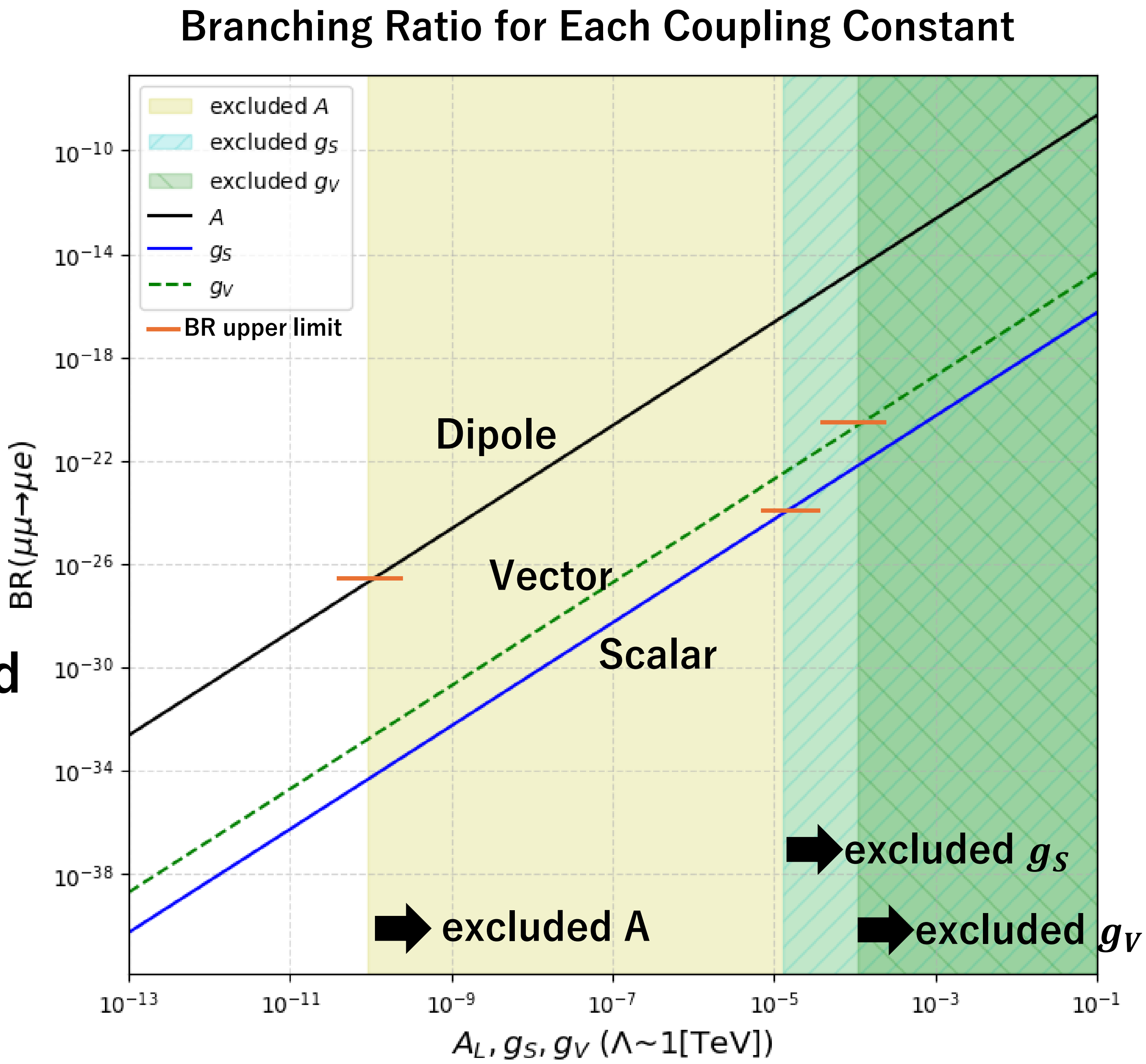
Upper Limit of BR

$$A_L \to BR(\mu\mu \to \mu e) < 10^{-27}$$
$$g_S \to BR(\mu\mu \to \mu e) < 10^{-24}$$
$$g_V \to BR(\mu\mu \to \mu e) < 10^{-21}$$

→ **10^{21} True Muonium could shed light on new way to LFV search!**

muon collider
neutrino factory [9]

Technological improvement enables LFV verification!



Discriminate the signals

Signal

・$\mu^+\mu^- \to \mu^\pm e^\mp$

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

Background

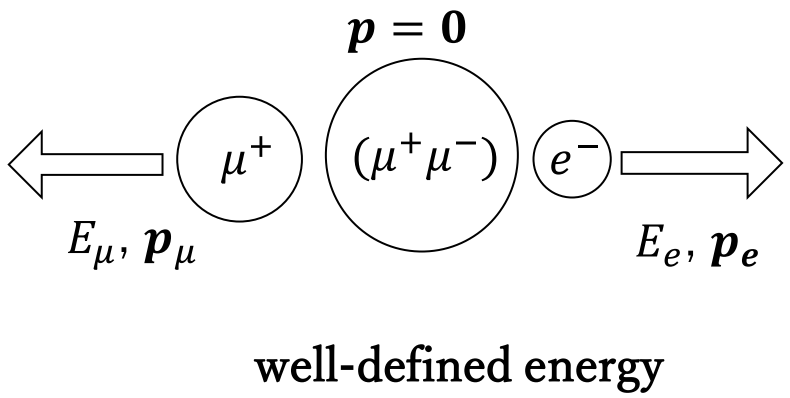
The most problematic

・$\mu^+\mu^- \to e^+e^-\gamma$ $(E_e \simeq 3m_\mu/4)$

・$\mu^+\mu^- \to \mu^+\mu^-$ $(E_\mu \simeq 5m_\mu/4)$

→accidental detection

…etc



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

Summary

- Proposed a new LFV reaction: $(\mu^+\mu^-) \to \mu^\pm e^\mp$.
- Evaluated three operator types: scalar, vector, and dipole.
- $\mathbf{10^{21}}$True Muonium could shed light on new way to LFV search

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**

Reference

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[2] Andrzej Banburski and Philip Schuster .2012
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[5] The MEGIIcollaboration .2024
[6] Yuji Omura, Eibun Senaha, Kazuhiro Tobe .2015
[7] L. Lavoura .2003
[8] Yoshitaka Kuno, Yasuhiro Okada .1999
[9] S. Geer .2010