Probing lepton-flavor-violating processes in e^+e^- colliders

Lam Thi To Uyen and Guey-Lin Lin

Institute of Physics, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan

Abstract

Scenario with a lepton-flavor-violating (LFV) interaction, either due to a LFV coupling of a scalar or a vector boson, is an intriguing BSM phenomenon. This LFV coupling in the presence of muons leads to a rich phenomenology including an extra contribution to muon anomalous magnetic moment. With the low-energy effective coupling $\mathcal{L}_{\phi e\mu} = \phi\bar{e}(g_{e\mu} + h_{e\mu}\gamma^5)\mu$ + h.c., which turns e into μ or vice versa through a scalar ϕ, we first derive the ($h_{e\mu}$, M_ϕ) parameter space that can account for experimental measurements of muon anomalous magnetic moment. We propose to probe such a parameter space or that with a even smaller $h_{e\mu}$ by searching for the background-free processes of same-sign, same-flavor final-state lepton pairs $e^+e^- \to e^\pm\mu^\mp\phi \to e^\pm e^\pm\mu^\mp\mu^\mp$ at Belle II experiment. Assuming such final states are detected by Belle II, we propose an effective method to further discriminate between scalar and vector boson-mediated LFV interactions based on significant differences in their event kinematic distributions.

1. Introduction

In SM, lepton flavors are expected to be conserved. However, no fundamental symmetry is associated with their conservation. Some theories of physics BSM incorporate LFV processes, such as rare μ decays, charge-changing $\mu \to e$ conversion, indicating that charged leptons can change their flavor during interactions.

LFV search directly addresses new physics (NP) of flavor and generations. Muon-related LFV processes are of current interest as they could potentiall account for the long-standing $g_\mu - 2$ discrepancy.

Belle-II and BaBar are outstanding lepton colliders searching for LFV processes, giving stringent constraints at different levels of NP.

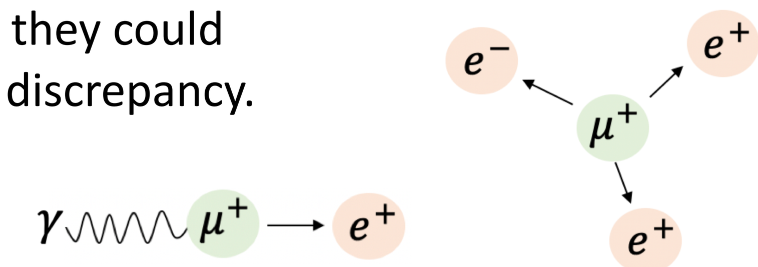

Fig. 1: Some examples of LFV processes.

2. The lepton-flavor-violating scalar mediator

A real scalar mediator ϕ interacts with a pair of oppositely-charged, different-flavored leptons ($e^\pm\mu^\mp$) in the limit of GeV-scale ϕ masses [1],

$$\mathcal{L}_{\phi e\mu} = \sum_{\ell=e,\mu,\tau} y_\ell \bar{\ell}_L \phi \ell_R + y_{e\mu}\bar{e}_L\phi\mu_R + y_{\mu e}\bar{\mu}_L\phi e_R + \text{h.c.}, \quad (1)$$

where y_ℓ and $y_{e\mu(\mu e)}$ are lepton-flavor-conserving (LFC) and LFV couplings, respectively. Or

$$\mathcal{L}_{\phi e\mu} = \phi\bar{\ell}(g_\ell + h_\ell\gamma^5)\ell + \phi\bar{e}(g_{e\mu} + h_{e\mu}\gamma^5)\mu + \phi\bar{\mu}(g^*_{e\mu} - h^*_{e\mu}\gamma^5)e, \quad (2)$$

where $g_\ell(h_\ell) = (y_\ell \pm y^*_\ell)/2$, $g_{e\mu}(h_{e\mu}) = (y_{e\mu} \pm y^*_{\mu e})/2$. Assuming flavor diagonal terms are vanishing, both processes $e^+e^- \to e^\pm\mu^\mp\phi$ only depend on $\left(|g_{e\mu}|^2 + |h_{e\mu}|^2\right)$. We then essentially probe LFV coupling by taking $g_{e\mu} = h_{e\mu} = f$ with f a positive real number.

The 2σ favored region on $h_{e\mu}$ - M_ϕ parameter space that accounts for the deviation between theoretical prediction [2] and experimental measurement [3] is shown by the cyan band in Fig. 5.

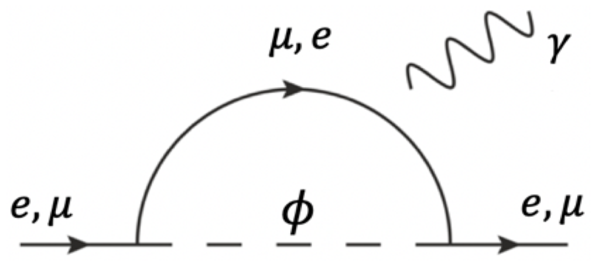

Fig. 2: One-loop diagram to a_μ mediated by the scalar ϕ.

The BSM contributions to $\Delta a_\mu = (g_\mu - 2)/2$ given by the one-loop diagram in Fig. 2 can be evaluated as [4] $\Delta a_\mu = \{2x_a^2\log[x_a/(x_a-1)] - 1 - 2x_a\}h^2_{e\mu}/8\pi^2$ where $x_a = m^2_\phi/m^2_\mu$.

3. The existing constrains on LFV scalar and vector searches

Constrains on LFV mediators depend on the relative strength of LFC g_ℓ and LFV $h_{e\mu}$ couplings of bosons to leptons.

Motivated by the effect of Z-Z' mixing, $\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix}\begin{pmatrix} \hat{Z} \\ \hat{Z}' \end{pmatrix}$ with Z' boson arising from an extra U(1)$'$ symmetry, existing constraints on LFV vector coupling can be derived after diagonalizing interactions of $\hat{Z}$ and $\hat{Z}'$ with charged leptons [5],

$$\mathcal{L}_{\text{int}} = -\bar{\ell}_i\gamma^\lambda\left(\beta^L_{\ell_i\ell_j}P_L + \beta^R_{\ell_i\ell_j}P_R\right)\ell_j Z_\lambda - \bar{\ell}_i\gamma^\lambda\left(h^L_{\ell_i\ell_j}P_L + h^R_{\ell_i\ell_j}P_R\right)\ell_j Z'_\lambda \quad (3)$$

where $\beta^{L,R}_{\ell_i\ell_j}$ and $h^{L,R}_{\ell_i\ell_j}$ are left- (right-handed) Z and Z' couplings, respectively.

Fig. 3 shows the exclusion region in scalar and vector boson masses and LFV coupling for cases of $h_{e\mu}/g_\ell = 10, 10^3$.

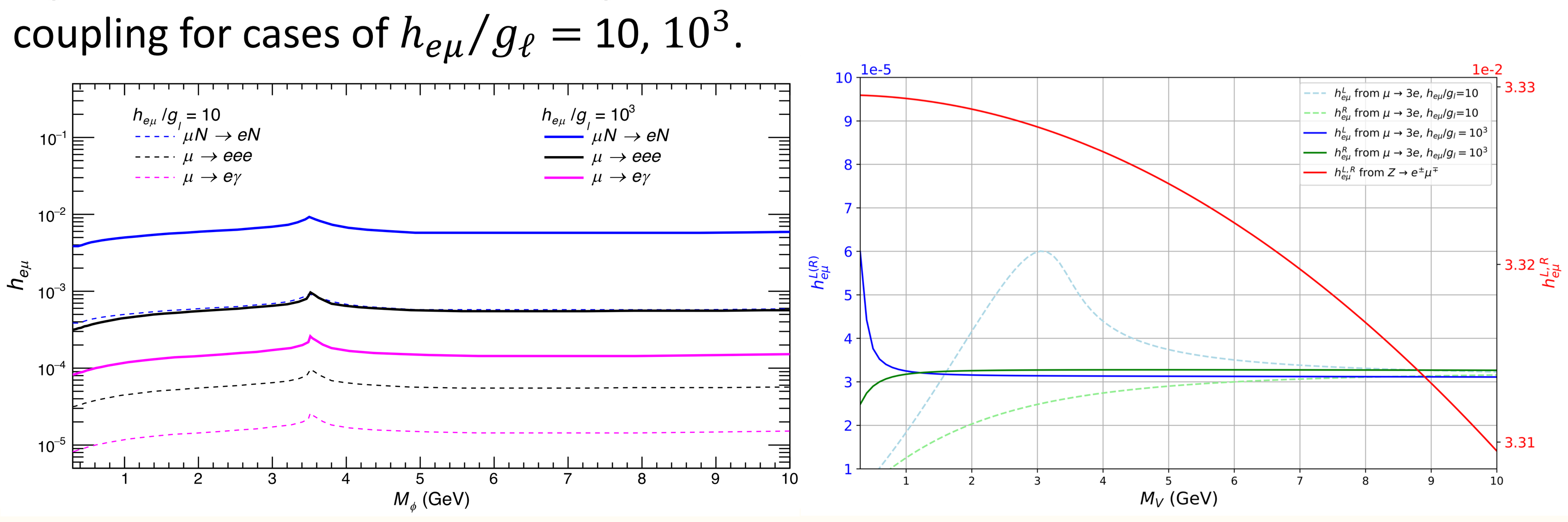

Fig. 3: Constraints on LFV couplings mediated by (a) scalar and (b) vector portals scenarios.

Tree-level flavor-changing decays of $\mu \to e\gamma$ and $\mu \to 3e$ give the most stringent bounds $h^\phi_{e\mu} \lesssim 1.17 \times 10^{-5}$ and $h^V_{e\mu} \lesssim 1.3 \times 10^{-5}$ in LFV scalar [6] and vector [5] searches, respectively, for $h_{e\mu}/g_\ell = 10$ in the range of boson masses $\lesssim 8$ GeV.

4. Probing the LFV model at Belle II experiment

The sensitivity to $e\mu$ flavor-violating interactions is probed at Belle II, which is an energy asymmetric detector of 7 GeV e^- and 4 GeV e^+ with $E_{\text{C.M}}$ = 10.58 GeV.

Final-state same-sign lepton pairs in processes $e^+e^- \to e^\mp\mu^\pm\phi \to e^\mp\mu^\pm\mu^\pm e^\mp$, where ϕ decays into $e^\mp\mu^\pm$, are essentially BG free.

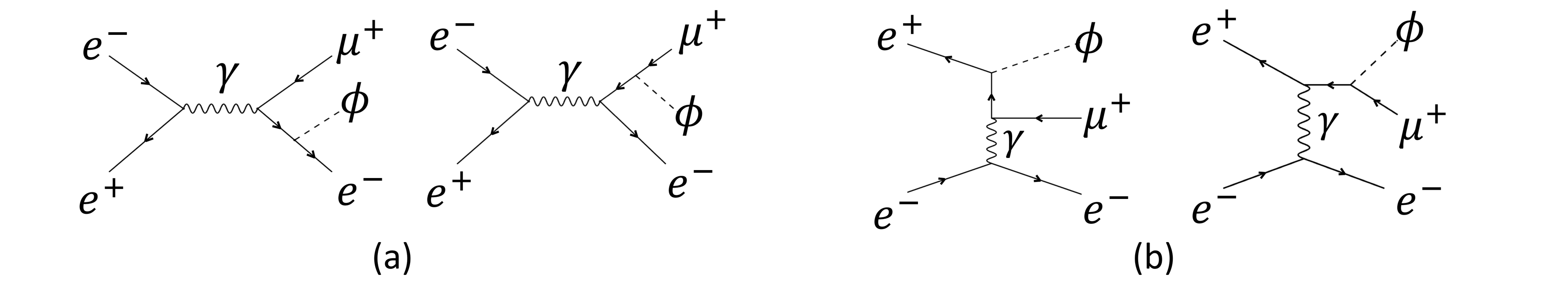

Fig. 4: Feynman diagrams for (a) s-channel, (b) t-channel LFV process $e^+e^- \to e^-\mu^+\phi$. For $e^+e^- \to e^+\mu^-\phi$ we replace e^- to e^+ and μ^+ to μ^- in these diagrams.

Using BG free with 95% CL of 3 events for a Poisson signal and kinematical cuts [7] for the final-state leptons, the upper bound on $h_{e\mu}$ is shown in Fig. 5.

At $\mathcal{L} = 1$ fb^{-1}, the Belle II limit on $h_{e\mu}$ for $1 \le M_\phi/\text{GeV} \le 8$ already touches 2σ parameter region favored by $g_\mu - 2$.

Under recent LFV constraints, such signatures can be searched at full Belle II luminosity, potentially discerning scalar from vector LFV scenarios.

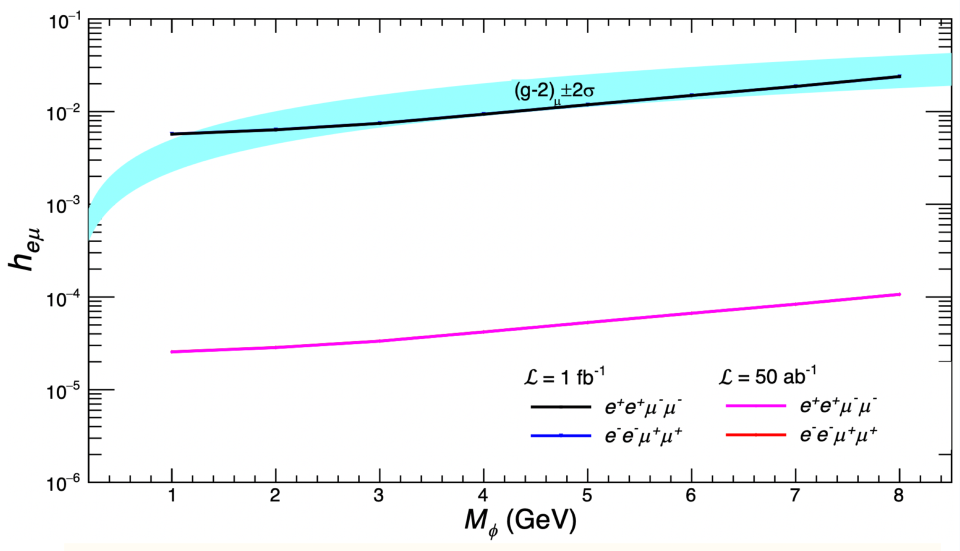

Fig. 5: Constraints on $h_{e\mu}$ as a function of M_ϕ from LFV searches at Belle II experiment.

5. The discrimination of the scalar boson from the vector boson portal in LFV processes

The cumulative mass distribution [8] $K^i\left(M_{e^\mp\mu^\pm}\right) = \sum_i N^i_{e^\mp\mu^\pm B}/N^{\text{total}}_{e^\mp\mu^\pm B}$(with $B = \phi, V$) is exploited to distinguish between LFV scalar ϕ and vector boson V models. Here, $N^i_{e^\mp\mu^\pm B}$ is the number of events in a certain mass interval and $N^{\text{total}}_{e^\mp\mu^\pm B}$ is the total number of events, respectively. $K^i(M_{e^\mp\mu^\pm})$ is useful due to significant differences between peak event rates in different scenarios.

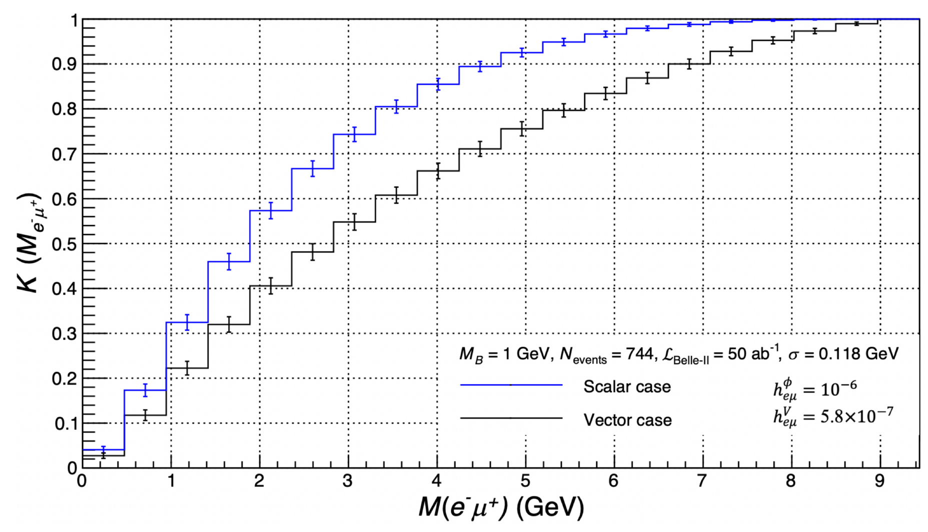

Fig. 6: Cumulative mass distribution of LFV search $e^+e^- \to e^-\mu^+B$ for M_B = 1 GeV at $\mathcal{L}$ = 50 ab^{-1}.

Figs. 6 and 7 show cases of $K(M_{e^-\mu^+})$ with statistical errors in binned histograms, each with a bin width of 2σ, where σ is the recoil mass resolution.

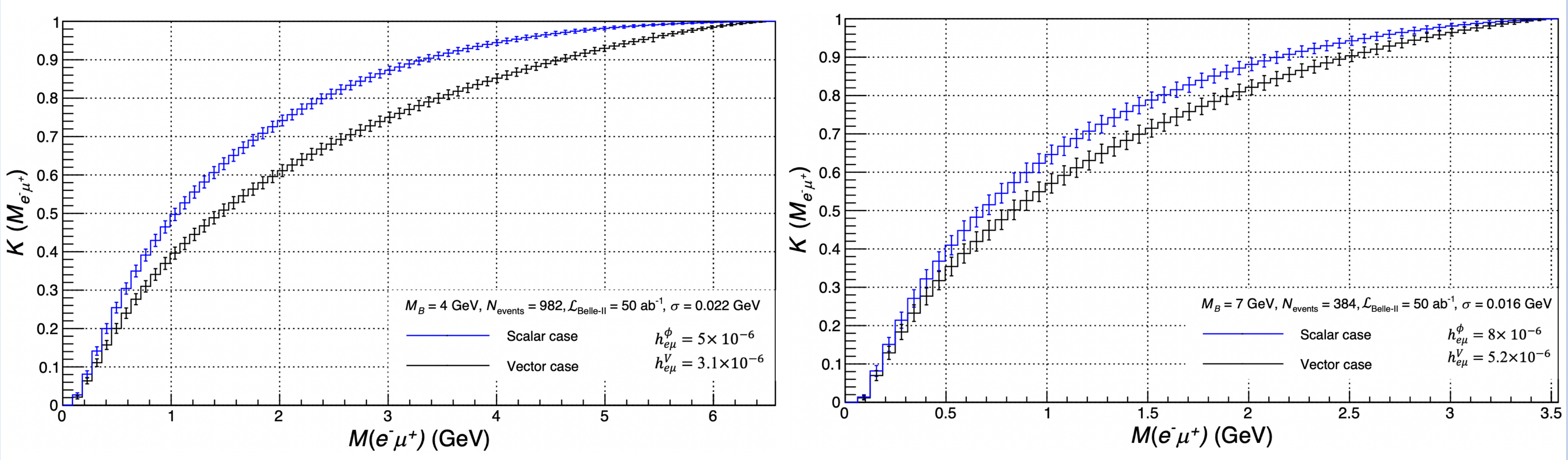

Fig. 7: Cumulative mass distribution of process $e^+e^- \to e^-\mu^+B$ for M_B = 4, 7 GeV at $\mathcal{L}$ = 50 ab^{-1}.

Quantitatively, the ordering $K^\phi\left(M_{e^\mp\mu^\pm}\right) > K^V\left(M_{e^\mp\mu^\pm}\right)$ holds in these simulations. $K^\phi\left(M_{e^\mp\mu^\pm}\right)$ increases faster in the middle of the $M_{e^\mp\mu^\pm}$ range, as scalar LFV event rates increase the fastest in this mass range. So, LFV scalar and vector boson scenarios can be distinguished in the Belle II detector.

6. Summary and conclusions

- Belle II sensitivity has been studied to probe $e\mu$ flavor-violating scalar boson model.
- Sensitivities to LFV Yukawa coupling $h_{e\mu}$ of $e^+e^- \to e^\pm\mu^\mp\phi \to e^\pm e^\pm\mu^\mp\mu^\mp$ for $\mathcal{L} = 1$ fb^{-1} at Belle II can already touch the favorable parameter range accounting for the measured $g_\mu - 2$ in $1 \le M_\phi/\text{GeV} \le 8$.
- At high $\mathcal{L}$, we could potentially search for NP. Particularly, the sensitivity for Belle II full $\mathcal{L}$ to $h_{e\mu}$ is still quite below current LFV constrains.
- Cumulative mass distribution is proposed to discriminate between LFV scenarios involving exchange of scalar and vector bosons, accounting for statistical uncertainties.

7. References

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