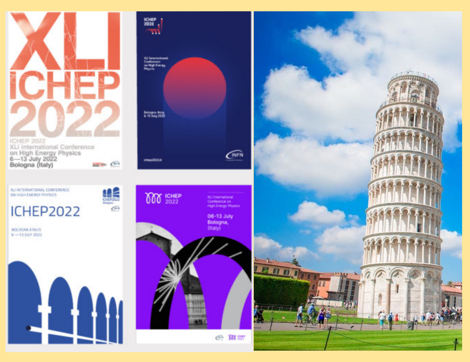

Constraints on lepton-flavor-violating scalar portal using the Belle II result in the search for $e^+e^- \to e^\pm\mu^\mp$ + invisible with $\mathcal{L}$ = 276 pb^{-1}

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Abstract

Lepton-flavor-violating (LFV) scalar portal is an interesting mechanism that connects the dark sector to the visible one. This mechanism leads to a rich phenomenology including an extra contribution to muon anomalous magnetic moment desirable for alleviating the discrepancy between the updated SM prediction and the combined results of Fermilab and BNL measurements. With the low-energy effective coupling $\mathcal{L}_{\phi\mu e} = -y_{\mu e}(\bar{e}_L\mu_R\phi + \bar{\mu}_R e_L\phi^*)$, which turns muon into electron or vice versa through the scalar ϕ, we derive the $(y_{\mu e}, m_\phi)$ parameter space that could account for the discrepancy mentioned above. Furthermore, we calculate the cross section $e^+e^- \to e^-\mu^+\phi^*, e^+\mu^-\phi$ induced by $\mathcal{L}_{\phi\mu e}$ and SM vertices. Using Belle II model-independent 90% C.L. upper limit on ε (efficiency) × $\sigma(e^+e^- \to e^\pm\mu^\mp + \text{invisible})$ with $\mathcal{L} = 276\ \text{pb}^{-1}$ [1], we obtain the corresponding upper limit for $y_{\mu e} \times \sqrt{\varepsilon.\text{Br}(\phi \to \text{invisible})}$. For ε = 1% and Br($\phi \to$ invisible) = 1, we found that for $m_\phi < 4$ GeV, the 90% C.L. upper limit for $y_{\mu e}$ is already in the favorable parameter range to account for the measured g_μ − 2. We stress that explicit details of scalar portal models would determine Br($\phi \to$ invisible) while the efficiency factor ε requires a detailed experimental analysis. Here we meant to point out that the search for $e^+e^- \to e^\pm\mu^\mp + \text{invisible}$ could yield very interesting constraints on LFV scalar portal models. Hence a model-dependent experimental analysis is also very worthwhile.

1. Introduction

Acting as the backbone of particle physics, SM is the most triumphant theoretical model to date. The conservation of lepton flavor as a natural consequence of the SM gauge invariance and renormalization is responsible for the smallness of lepton flavor violations in charged lepton interactions.

The nature of LFV interactions is directly related to the form of the interaction vertex and the mass scale of particles. The typical LFV processes are searched in a variety of scenarios beyond SM:

(a) converting one type of charged lepton to another [2],

(b) converting one charged-lepton type to another charged-antilepton type [3].

Fig. 1 gives examples for the LFV search of Muonium to Antimuonium conversion [4].

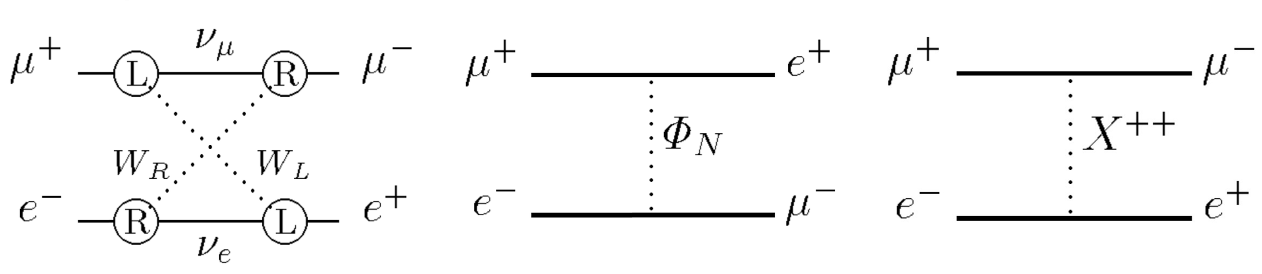

Fig. 1: The FLV models for Mu-$\overline{\text{Mu}}$ conversion.

Prominently, muon-related LFV processes are of current interest because they could potentially shed light on the long-standing discrepancy of g_μ −2 between theoretical predictions and experimental measurements.

2. The lepton-flavor-violating mediator

We consider a model in which a spin-0, complex scalar mediator ϕ interacts with a pair of oppositely-charged, different-flavored leptons ($e^\pm\mu^\mp$) in the limits of the sub-GeV ϕ masses, $m_\phi \gg m_\mu$ [5]

$$\mathcal{L}_{\phi\mu e} = -y_{\mu e}(\bar{e}_L\mu_R\phi + \bar{\mu}_R e_L\phi^*) \qquad (1)$$

where $\ell_L = P_L\ell$, $\ell_R = P_R\ell$ (with $\ell = e, \mu$) are the left- and right-handed chiral lepton ℓ states. Here, ϕ interacts with the P_R operator as a convention and the non-zero values of the coupling $y_{\mu e}$ are assumed only for a flavor-changing pair.

A suggested scalar mediator in the proposed LFV model which couples chirally to different flavor lepton pairs is a viable portal between DM and the visible sector.

Current searches for LFV often involve the productions and subsequent LFV decays of low energy muons such as $\mu^+ \to e^+\gamma$, and $\mu^+ \to e^+e^+e^-$ with branching ratios of the order $10^{-13} - 10^{-12}$ [6]. One of the diagrams for these decays is shown in Fig. 2.

In general, the presence of muon in the LFV vertices below the electroweak scale could be probed effectively at the forward-backward asymmetries of e^-e^+ collider, which interprets the existence of new physics regarding the $g_\mu - 2$.

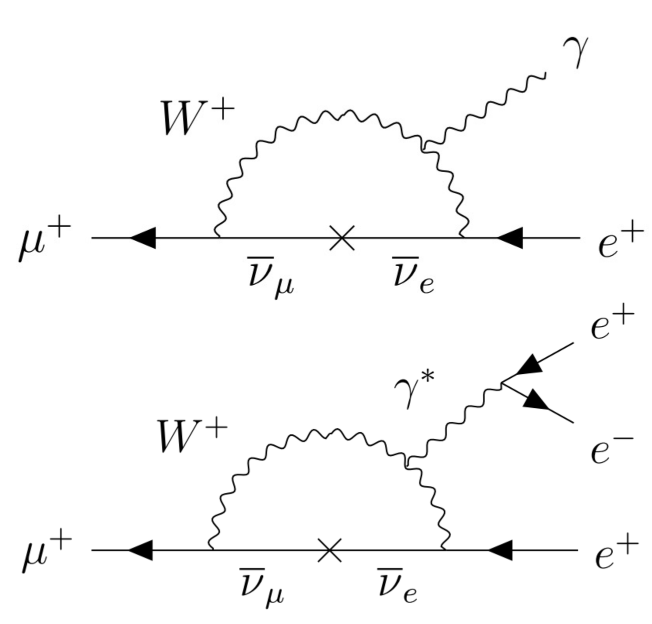

Fig. 2: The loop diagrams of $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$ mediated by the neutrino flavor mixing.

3. A hint for the puzzle of muon anomalous magnetic moment

The 2σ favored region on $y_{\mu e} - m_\phi$ parameter space that accounts for the deviation between the theory prediction and BNL + Fermilab measurement is shown by the pink band in Fig. 5.

The BSM contribution to $\Delta a_\mu = (g_\mu - 2)/2$ is given by the one-loop diagram depicted by Fig. 3 [7]. Hence

$$\Delta a_\mu = \frac{y_{\mu e}^2}{4\pi^2}\frac{m_\mu^2}{m_\phi^2}F(\kappa,\lambda) \qquad (2)$$

with $F(\kappa,\lambda) = \frac{1}{2}\int_0^1 dx\, \frac{x^2(1+\kappa-x)}{(1-x)(1-\lambda^2 x)+(\kappa\lambda)^2 x}$

where $\kappa = m_e/m_\mu$ and $\lambda = m_\mu/m_\phi$.

For $m_\phi \gg m_\mu$, Eq. (2) can be written as $\Delta a_\mu = \frac{y_{\mu e}^2}{24\pi^2}\frac{m_\mu^2}{m_\phi^2}$.

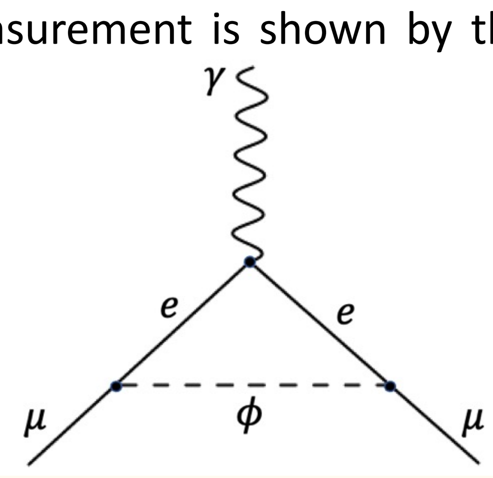

Fig. 3. The contribution of one-loop diagram to a_μ^{SM} mediated by the scalar ϕ in the LFV model.

The pink band in Fig. 5 gives $y_{\mu e} \approx [2.40\times10^{-3}, 6.31\times10^{-2}]$ in the m_ϕ region of $[0.5, 8]$ GeV, which could account for the anomaly in $g_\mu - 2$.

4. Probing the LFV model at Belle II experiment

Belle II experiment has obtained limits for the LFV μe coupling as a by-product of an optimized analysis for the main search for $U(1)_{L_\mu - L_\tau}$ gauge boson Z' [1]. The searched signature is a μe pair accompanied by the missing energy. A model independent limit on $\varepsilon\times\sigma(e^+e^- \to e^\pm\mu^\mp$+ invisible) with ε the signal efficiency is obtained. Using this limit, we study the constraint on the Yukawa coupling $y_{\mu e}$ described by Eq. (1) as a function of m_ϕ. The LFV processes considered are $e^+e^- \to e^+\mu^-\phi$ illustrated in Fig. 4 and its charge-conjugated process $e^+e^- \to e^-\mu^+\phi^*$.

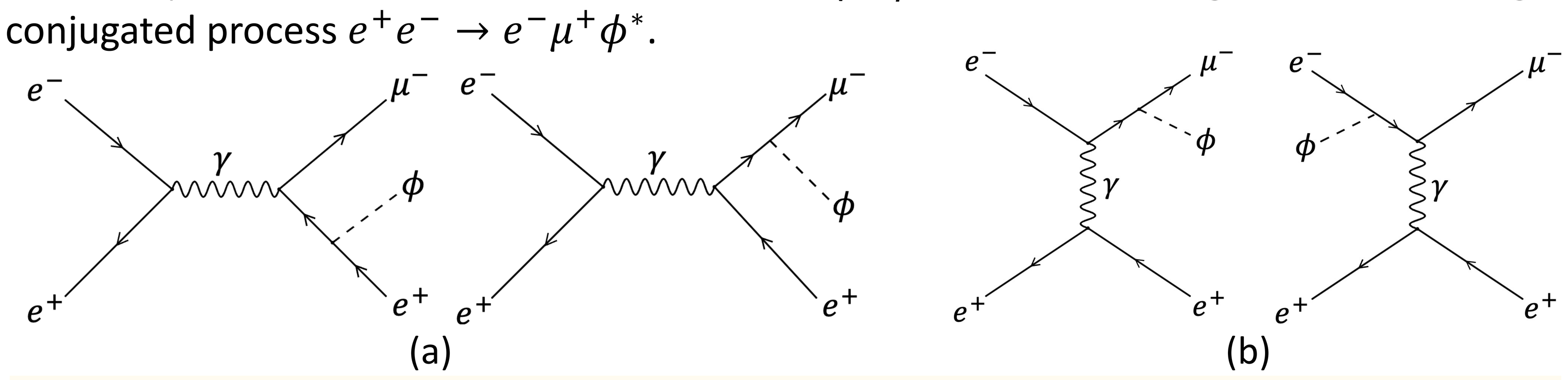

Fig. 4. Feynman diagrams for (a) *s*-channel, (b) *t*-channel LFV process $e^+e^- \to e^+\mu^-\phi$. For $e^+e^- \to e^-\mu^+\phi^*$ we replace e^+ to e^- and μ^- to μ^+ in these diagrams.

The signal cross section is a function of $y_{\mu e}$ and m_ϕ. Using the Belle II 90% CL limit on $\varepsilon\times\sigma(e^+e^- \to e^\pm\mu^\mp\phi)$ at the $\mathcal{L} = 276\ \text{pb}^{-1}$, the upper bound on $y_{\mu e}$ for the mass range of $m_\phi \le 8$ GeV is shown in Fig. 5. The efficiency ε = 1% and branching ratio Br($\phi \to$ invisible) = 1 are assumed in the plot and the simulation package CalcHEP [8] is employed as an effective tool to calculate the cross section.

The constraint on $y_{\mu e}$ with LFV processes of $e^+e^- \to e^-\mu^+\phi^*, e^+\mu^-\phi$ becomes less stringent as m_ϕ increases. It is seen that, with just $\mathcal{L} = 276\ \text{pb}^{-1}$, the Belle II limit on $y_{\mu e}$ for m_ϕ < 4 GeV already touches the 2σ parameter region favored by $g_\mu - 2$ measurement.

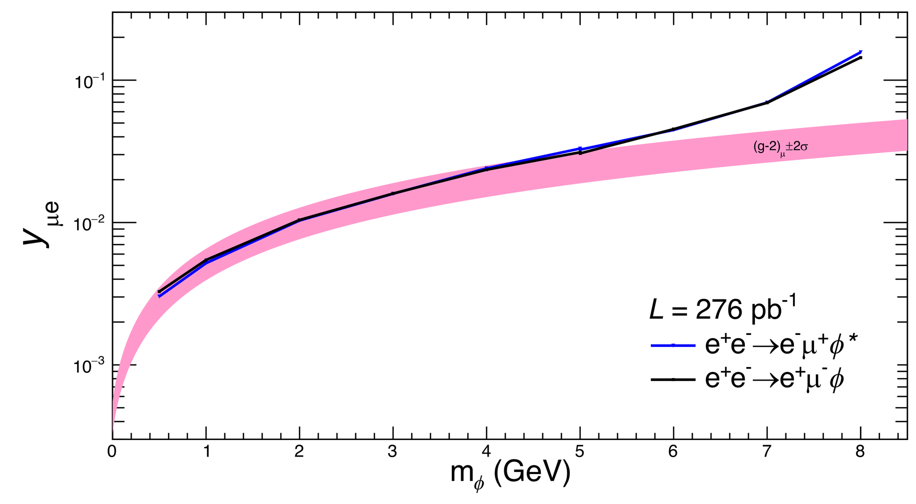

Fig. 5. The constraint on $y_{\mu e}$ as a function of m_ϕ from the LFV searches at Belle II experiment.

5. Parity violation with final-state leptons in LFV processes

It is useful to probe this violation in the coupling between the scalar mediator ϕ and the μe pair by considering the angular distributions of final-state leptons in the LFV processes $e^+e^- \to e^+\mu^-\phi$, $e^+e^- \to e^-\mu^+\phi^*$.

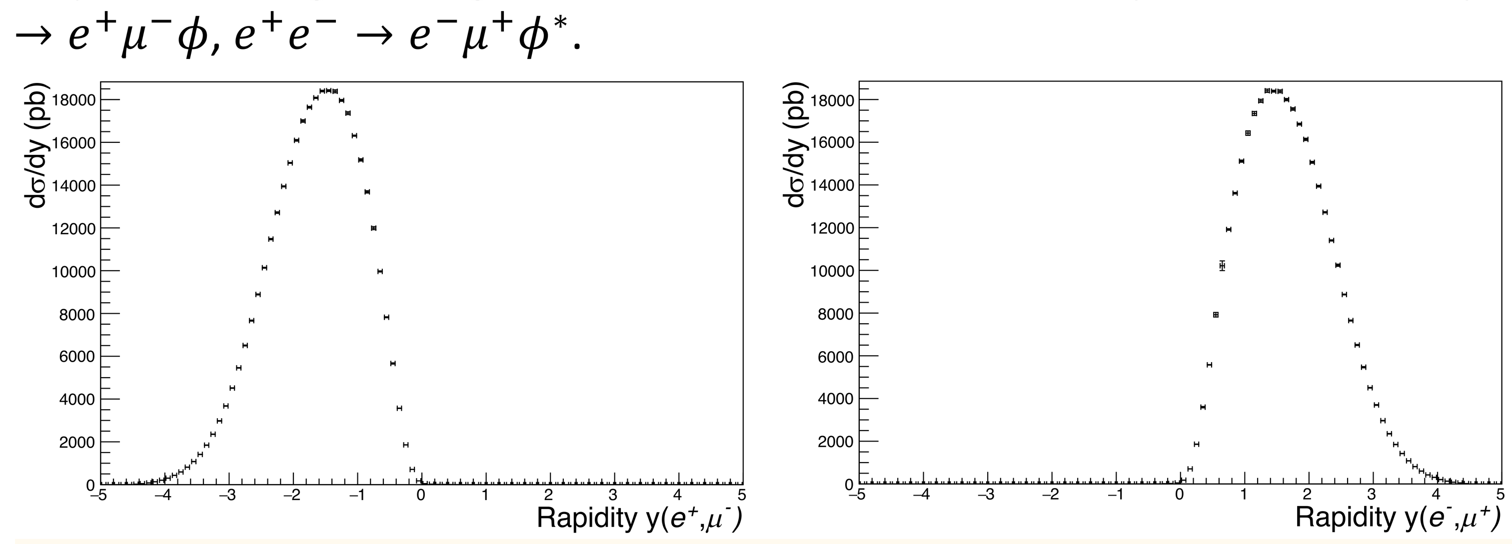

Fig. 6: The e, μ rapidity distributions in *t*-channel contributions to LFV processes $e^+e^- \to e^+\mu^-\phi$ (left) and $e^+e^- \to e^-\mu^+\phi^*$ (right) for the m_ϕ= 1 GeV.

The *t*-channel contributions to LFV processes $e^+e^- \to e^+\mu^-\phi$ and $e^+e^- \to e^-\mu^+\phi^*$ are parity-violating. One can see from Fig. 6 that y(e^+, μ^-) is always negative for the former process and always positive for the latter process. We note that the *s*-channel contributions are parity-conserving while the interference contributions are negligible compared to *t*-channel contributions.

6. Summary and conclusions

- We use Belle II limit on $\varepsilon\times\sigma(e^+e^- \to e^\pm\mu^\mp$+ invisible) at $\mathcal{L} = 276\ \text{pb}^{-1}$ to probe LFV scalar portal model.
- We have derived the upper limit on LFV Yukawa coupling $y_{\mu e}$ described by Eq. (1) with the processes $e^+e^- \to e^-\mu^+\phi^*, e^+\mu^-\phi$ for $\mathcal{L} = 276\ \text{pb}^{-1}$ at Belle II experiment.
- The forward-backward asymmetry for the angular distribution of the momentum sum $P_{e^\pm} + P_{\mu^\mp}$ is shown in Fig. 6. Such a parity-violating effect arises from *t*-channel diagram in Fig. 4.
- For ε = 1% and Br($\phi \to$ invisible) = 1 , we found that for m_ϕ = 4 GeV, the 90% C.L. upper limit for $y_{\mu e}$ already touches the favorable parameter range to account for the measured $g_\mu - 2$.

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