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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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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 $\mathcal{L}_{\phi\mu e} = -y_{\mu e}\left(\bar{e}_L\mu_R\phi + \bar{\mu}_R e_L\phi^*\right)$, which turns muon into electron or vice versa through the scalar ϕ, we derive the $\left(y_{\mu e}, m_\phi\right)$ parameter space that could account for the discrepancy mentioned above. Furthermore, we calculate the cross section induced by $\mathcal{L}_{\phi\mu e}$ and SM vertices. Using Belle II model-independent 90% C.L. upper limit on ε(efficiency)$\times\sigma\left(e^+e^- \to e^\pm\mu^\mp + \text{invisible}\right)$ with $\mathcal{L} = 276\,\text{pb}^{-1}$ [1], we obtain the corresponding upper limit for $y_{\mu e} \times \sqrt{\varepsilon.Br\left(\phi \to \text{invisible}\right)}$ with ε the signal efficiency. With the assumption of $Br\left(\phi \to \text{invisible}\right) = 1$ and the implementation of ECL selection criteria for the signal reconstruction of processes $e^+e^- \to e^\pm\mu^\mp\phi$, we found that for $0.5 \le m_\phi \le 8$ GeV, the sensitivity to $y_{\mu e}$ has not yet reached the favorable parameter range to account for the measured $g_\mu - 2$. We stress that explicit details of scalar portal models would determine $Br\left(\phi \to \text{invisible}\right)$ while the detection efficiency requires a detailed experimental analysis. We point out that the search for $e^+e^- \to e^\pm\mu^\mp$ + invisible in Belle II is limited by the rather large rapidities (in absolute value) of final-state leptons. This indicates that the searches for similar processes induced by LFV scalar portal models in fixed-target experiments will be more promising.

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1. Introduction

Acting as the backbone of particle physics, SM is the most successful theoretical model to date. The conservation of lepton flavor as a natural consequence of the SM gauge invariance and renormalizability 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. Typical LFV processes have been searched for in a variety of scenarios beyond SM, which are (i) converting one type of charged lepton to another, (ii) converting one charged-lepton type to another charged-antilepton type. Prominently, muon-related LFV processes are of current interest because they could potentially shed light on the long-standing discrepancy of $g_\mu - 2$ between theoretical predictions and experimental measurements [2].

2. The lepton-flavor-violating mediator

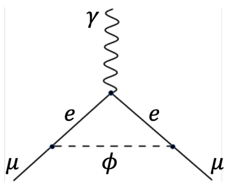
We consider a model in which a spin-0, complex scalar mediator ϕ interacts with a pair of oppositely-charged, different-flavored leptons ($e^\pm\mu^\mp$) for sub-GeV ϕ satisfying $m_\phi \gg m_\mu$ [3]

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

where $\ell_{L,R} = P_{L,R}\ell$ (with $\ell = e, \mu$) are left- and right-handed leptonic ℓ states. Here, ϕ interacts with the P_R operator as a convention and non-zero values of the $y_{\mu e}$ are taken only for a flavor-changing pair. A 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. It is of interests to find out if the presence of muons in the LFV vertices below the electroweak scale could be probed effectively either at forward-backward asymmetric e^+e^- collider or at fixed target experiments. Results of these experiments will be very relevant to the interpretation of anomaly in $g_\mu - 2$.

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 combined measurement of BNL and Fermilab is shown by the pink band in Fig. 3. The BSM contribution to the magnetic moment of muons $\Delta a_\mu = \left(g_\mu - 2\right)/2$ is given by the one-loop diagram depicted by Fig. 1 [4]



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

Figure 1: The contribution of one-loop diagram to a_μ^{SM} mediated by the scalar ϕ in the LFV model.

where $F(\kappa,\lambda) = \frac{1}{2}\int_0^1 dx \frac{x^2(1+\kappa-x)}{(1-x)\left(1-\lambda^2 x\right)+(\kappa\lambda)^2 x}$ with $\kappa = m_e/m_\mu$ and $\lambda = m_\mu/m_\phi$.

The pink band in Fig. 3 gives $y_{\mu e} \simeq \left[2.40\times10^{-3}, 6.31\times10^{-2}\right]$ 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. 2. For its charge-conjugated process $e^+e^- \to e^-\mu^+\phi^*$, we replace e^+ to e^- and μ^- to μ^+ in these diagrams.

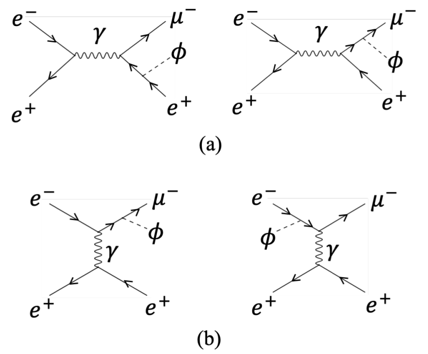


Figure 2: Feynman diagrams for (a) s-channel, (b) t-channel LFV process $e^+e^- \to e^+\mu^-\phi$.

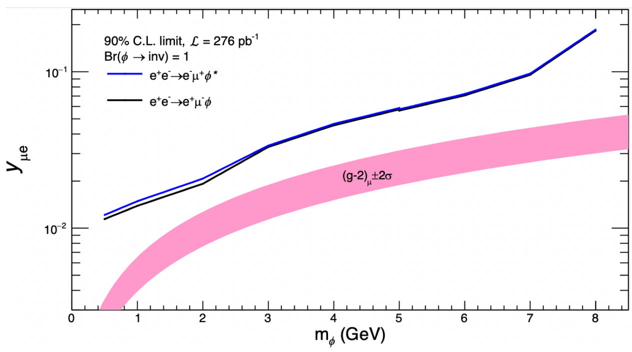


Figure 3: The constraint on $y_{\mu e}$ as a function of m_ϕ from the LFV searches at Belle II experiment.

The signal cross section is a function of $y_{\mu e}$ and m_ϕ. Using the Belle II 90% C.L. limit on $\varepsilon\times\sigma$ ($e^+e^- \to e^\pm\mu^\mp\phi$) at the $\mathcal{L} = 276$ pb^{-1} and the assumed branching ratio Br ($\phi \to$ invisible) = 1, the upper bound on $y_{\mu e}$ for the mass range of $m_\phi \leq 8$ GeV is shown in Fig. 3. The simulation package CalcHEP [5] with cuts of CleanedTracks selection criteria [6] for the ECL angular acceptance of leptons, the transverse momentum of the final-state dilepton and the recoil mass resolution within event windows is employed as an effective tool to calculate the cross section. It is seen that, with $\mathcal{L}$ = 276 pb^{-1}, the Belle II limit on $y_{\mu e}$ for $m_\phi \leq 8$ GeV has not reached the 2σ parameter region favored by $g_\mu - 2$ measurement. The severe cuts of the candidate reconstruction which remove the majority of signal events in the region between the barrel and endcaps of the ECL are responsible for this result. The LFV signal contributions from t-channel before selection criteria are much larger than s-channel by roughly 4 orders of magnitude. They are however heavily affected by the above cuts. At an e^+e^- collider, the tracking volume surrounded by the cylindrical ECL parallel to the colliding beam cannot effectively capture the signals along beam direction and its vicinity. Taking advantage of the enhanced scatterring cross section, fixed-target detectors with higher luminosities are instead more promising to probe LFV boson over a large recoil mass range.

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 $e^+e^- \to e^+\mu^-\phi$, $e^+e^- \to e^-\mu^+\phi^*$. 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. 4 that $y\,(e^+, \mu^-)$ 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. We stress that such parity violation effects should be probed in fixed-target experiments due to large rapidity magnitudes of final state leptons.

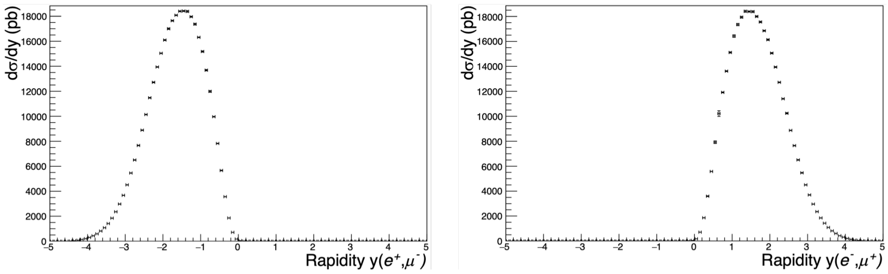


Figure 4: The rapidity distributions in t-channel contributions to LFV processes $e^+e^- \to e^+\mu^-\phi$ (left) and $e^+e^- \to e^-\mu^+\phi^*$ (right) for the $m_\phi = 1$ GeV.

6. Summary and conclusions

We have used Belle II limit on $\varepsilon \times \sigma$ $(e^+e^- \to e^\pm\mu^\mp$ + invisible) at $\mathcal{L} = 276$ pb^{-1} to probe LFV scalar portal model. The upper limit on LFV Yukawa coupling $y_{\mu e}$ described by Eq. (1) was derived by using Belle II 276 pb^{-1} result on $e^+e^- \to e^-\mu^+(e^+\mu^-)$ + invisible. The forward-backward asymmetry for the angular distribution of the momentum sum $P_{e^\pm} + P_{\mu^\mp}$ is shown in Fig. 4, where such a parity-violating effect arises from t-channel diagrams in Fig. 2. For Br $(\phi \to$ invisible) = 1, we found that the 90% C.L. upper limit for $y_{\mu e}$ has not yet reached the favorable parameter range to account for the measured $g_\mu - 2$. This is due to the geometrical limitation of the ECL at an asymmetric lepton collider, which is not optimized for detecting very forward or backward leptonic final states. Fixed-target experiments are expected to be more promising for performing LFV scalar searches.

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