PROCEEDINGS OF SCIENCE

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

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A scenario involving lepton-flavor-violating (LFV) interactions, either due to a LFV coupling of a scalar or a vector boson, is an intriguing beyond standard model (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 $\mathcal{L}_{\phi e\mu} = h_{e\mu}\phi\bar{e}(1+\gamma^5)\mu$ + h.c., which turns electron into muon or vice versa through a scalar ϕ, we first derive the $(h_{e\mu}, M_\phi)$ parameter space that can account for experimental measurements of muon anomalous magnetic moment. We propose to probe such a parameter space or that with an even smaller $h_{e\mu}$ by searching for 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 further propose an effective method to discriminate between scalar and vector boson-mediated LFV interactions based on significant differences in their event kinematic distributions.

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1. The lepton-flavor-violating scalar mediator

Various BSM theories involve LFV processes where charged leptons change flavor. LFV searches directly address new physics (NP) in flavor and generations, in which muon-related LFV processes offer potential solutions to the long-standing $g_\mu - 2$ discrepancy. A model of a real scalar mediator ϕ interacting with a pair of oppositely-charged, different-flavored $e^\pm\mu^\mp$ is described as [1]

$$\mathcal{L}_{\phi e\mu} = \sum_{\ell=e,\mu,\tau} g_\ell \phi \bar{\ell}(1+\gamma^5)\ell + h_{e\mu}\phi\bar{e}(1+\gamma^5)\mu + h^*_{e\mu}\phi\bar{\mu}(1-\gamma^5)e \tag{1}$$

where g_ℓ and $h_{e\mu}$ are lepton-flavor-conserving and LFV couplings, respectively. We assume vanishing flavor-diagonal terms, i.e., the Lagrangian contains only LFV $e\mu$ terms. Using Feynman rules from eq. (1), processes $e^+e^- \to e^\pm\mu^\mp\phi$ depend only on $|h_{e\mu}|^2$ and allow for probing positive real LFV couplings. The one-loop contribution to the muon anomalous magnetic moment shown in figure 1 is evaluated as [2] $\Delta a_\mu = (2x_a^2 \log(x_a/(x_a-1)) - 1 - 2x_a)h_{e\mu}^2/(8\pi^2)$ with $x_a = m_\phi^2/m_\mu^2$.

2. Probing the LFV model at Belle II experiment

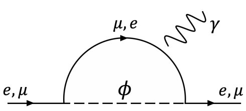

Figure 1: One-loop contribution to a_μ mediated by scalar ϕ.

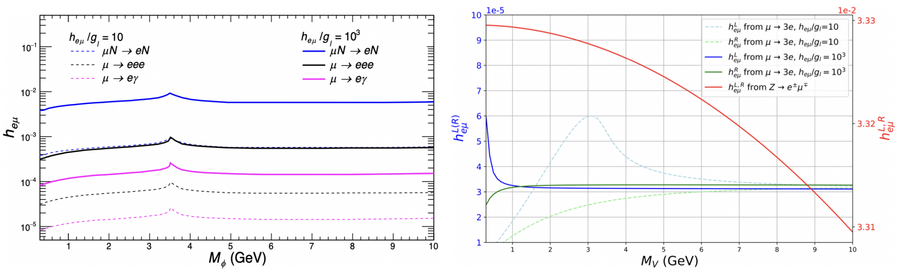

Figure 2: Constraints on LFV couplings mediated by (a) scalar and (b) vector portal scenarios.

Experimental constraints on a flavor-violating boson model depend on the relative strengths of g_ℓ and $h_{e\mu}$ couplings of bosons to leptons. These constraints arise by the effect of the $Z - Z'$ mixing 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, $\mathcal{L}_{\text{int}} = -\bar{\ell}_i\gamma^\lambda\left(\beta^L_{\ell_i\ell_j}P_L + \beta^R_{\ell_i\ell_j}P_R\right)\ell_j Z_\lambda - \bar{\ell}_i\gamma^\lambda\left(h^L_{\ell_i\ell_j}P_L + h^R_{\ell_i\ell_j}P_R\right)\ell_j Z'_\lambda$ where $\beta\ (h)^{(L,R)}_{\ell_i\ell_j}$ are left- (right-handed) Z and Z' couplings, respectively. Figure 2 shows exclusion regions in scalar ϕ [3] and vector V [4] boson masses and LFV couplings for cases with ratios of $h_{e\mu}$ to g_ℓ being 10 and 10^3.

The sensitivity to $e\mu$ flavor-violating interactions is studied at Belle II, which is an energy asymmetric detector of 7 GeV e^- and 4 GeV e^+. 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 $\phi \to e^\mp\mu^\pm$, are essentially BG free. Applying BG free with 95% CL and kinematical cuts [5] for final-state leptons, the upper bound on $h_{e\mu}$ for $e^+e^- \to e^\mp\mu^\pm\mu^\pm e^\mp$ is shown in figure 3. At $\mathcal{L} = 1\ \text{fb}^{-1}$, the Belle II limit on $h_{e\mu}$ for $1 \le M_\phi/\text{GeV} \le 8$ already touches the 2σ parameter region

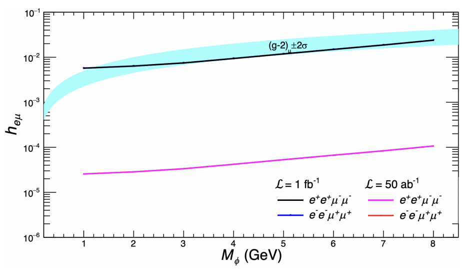

Figure 3: Constraints on $h_{e\mu}$ of LFV searches at Belle II experiment.

favored by the $g_\mu - 2$ anomaly. The sensitivity is inversely proportional to the square root of the luminosity. With a higher luminosity, one can probe the LFV model significantly below the favored parameter region for muon anomalous magnetic moment. In the case of observing the same-sign lepton pairs, it is possible to distinguish between scalar and vector LFV scenarios.

3. Discriminating scalar from vector boson portals in LFV processes.

The cumulative mass distribution as a function of the non-resonant $e\mu$ invariant mass, $K^i(M_{e^\mp\mu^\pm}) = \sum_i N^i_{e^\mp\mu^\pm B}/N^{\text{total}}_{e^\mp\mu^\pm B}$ [6] (with $B = \phi, V$) is exploited to distinguish LFV scalar ϕ from vector V models. Here, $N^{i\,(\text{total})}_{e^\mp\mu^\pm B}$ represent the number of events in a certain i and the total mass range, respectively. $K^i(M_{e^\mp\mu^\pm})$ is useful due to significant differences between peak event rates in different scenarios. Figure 4 shows the case of $K(M_{e^-\mu^+})$ with statistical errors in binned histograms, each with a bin width of 2σ, with σ the recoil mass resolution.

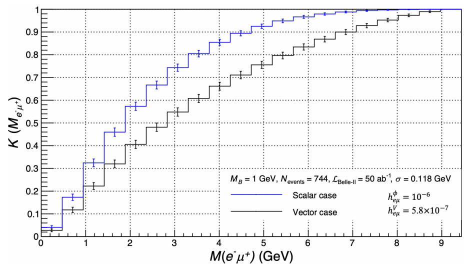

Figure 4: Cumulative mass distribution of $e^+e^- \to e^-\mu^+B$ at M_B= 1 GeV, $\mathcal{L}$ = 50 ab^{-1}.

Quantitatively, the ordering $K^\phi(M_{e^\mp\mu^\pm}) > K^V(M_{e^\mp\mu^\pm})$ is observed in this simulation. The function $K^\phi(M_{e^\mp\mu^\pm})$ increases more rapidly in the middle range of $M_{e^\mp\mu^\pm}$ due to the larger event rates of scalar LFV scenario in this mass range. Consequently, LFV scalar and vector boson scenarios can be distinguished at the Belle II detector.

4. Summary and conclusions

We study the Belle II sensitivity to the $e\mu$ flavor-violating scalar boson model. The sensitivity to the LFV Yukawa coupling $h_{e\mu}$ of processes $e^+e^- \to e^\pm\mu^\mp\phi \to e^\pm e^\pm\mu^\mp\mu^\mp$ for $\mathcal{L}$ = 1 fb^{-1} at Belle II can already approach the favorable parameter range accounting for the measured $g_\mu - 2$ anomaly in the mass range of $1 \leq M_\phi/\text{GeV} \leq 8$. At high luminosity, we could potentially search for the NP. Particularly, the sensitivity for full Belle II luminosity of 50 ab^{-1} to $h_{e\mu}$ is still below the current LFV constraints. The cumulative mass distribution is proposed to distinguish between LFV scenarios involving scalar and vector bosons with statistical uncertainties taken into account.

References

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