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Charged Lepton Flavor Violation in the Standard Model with Dimension-6 Operators

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We study the lepton flavor violating effects in the charged lepton sector of the Standard Model (SM) extensions. We use model- independent parametrization of New Physics effects, where the SM is extended by the full basis of the dimension-5 and -6 operators constructed of the SM fields and preserving its gauge symmetries. We investigate the tree and one loop predictions to the radiative lepton decays and also the 3-body flavor violating charged lepton decays at tree level. We discuss how their decay rates can be correlated.

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1. Introduction

The Standard Model (SM) is often considered to be only an effective approximation of some more fundamental theory, valid at much higher energy scales. The hint how this fundamental theory may look like can come from the flavor structure of the SM. Depending on the specific realization of New Physics, various patterns of the relative size of amplitudes of the flavor violating decays can emerge. The current experiments already palace strong constraints on many models beyond the SM. We investigate lepton flavor violation(LFV) processes in terms of coefficients of higher dimension operators which are suppressed by power of Λ and are added to the SM Lagrangian:

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathscr{O}\left(\frac{1}{\Lambda^3}\right). \tag{1.1}$$

Here $\mathscr{L}_{\rm SM}^{(4)}$ is the usual renormalizable part of the SM Lagrangian, $Q_k^{(5)}$ is the Weinberg operator giving rise to neutrino masses, $Q_k^{(6)}$ denote dimension-6 operators, and $C_k^{(n)}$ stand for the corresponding dimensionless coupling constants. There are 59 independent dimension-6 operators, only much less numerous subset of them is important for LFV processes in charged lepton sector, so our numerical analysis is quite predictive.The list of dimension-5 and 6 operators is given in [1].

We computed the complete set of the tree-level and one loop contributions to the radiative lepton decays $\ell \to \ell' \gamma$ as well as to Lepton Electric Dipole Moments(EDMs) and Anomalous Magnetic Moments(AMMs). We also obtained the formula for all various of the three body charged lepton decay rates and for flavor violating Z boson decays to lepton pairs[2]. The derived expression allowed us to obtain model independent bounds on the Wilson coefficients of LFV operators. Having such bounds can significantly simplify and speed up the comparison with experiment the specific models of New Physics, as now the predicted by them values of Wilson coefficients need to be calculated in terms of parameters of such models.The obtained expressions can correlate, in this paper we focus on radiative lepton decay and three body charged lepton flavor violation and as an example show how they can correlate.

2. Lepton Flavor Violation in the SM with Dimension-6 operators

In this section we present some of our results for lepton flavor violating effects in the charged lepton sector of the SM extensions. We have calculated the decay rates of the several experimentally best constrained observables , expressing the final formulae for them in terms of Wilson coefficients multiplying the effective operators. We discuss how combining various processes could help us finding correlations(or cancellations) between different LFV couplings.

The effective flavor violating lepton-photon vertex as follows,

$$\begin{aligned} V_{\ell\ell\gamma}^{fi\,\mu} &= \frac{i}{\Lambda^2}[\gamma^\mu(F_{VL}^{fi}P_L + F_{VR}^{fi}P_R) + (F_{SL}^{fi}P_L + F_{SR}^{fi}P_R)q^\mu \\ &+ i(F_{TL}^{fi}\sigma^{\mu\nu}P_L + F_{TR}^{fi}\sigma^{\mu\nu}P_R)q_\nu] \end{aligned} \tag{2.1}$$

Only tensor form-factors F_{TL} and F_{TR} contribute to physical observables.

The general form of the $\ell_i \to \ell_f \gamma$ branching ratio is given by:

$$\mathrm{Br}\left[\ell_i \to \ell_f \gamma\right] = \frac{m_i^3}{16\pi\Lambda^4\Gamma_{\ell_i}} \left(\left|F_{TR}^{fi}\right|^2 + \left|F_{TL}^{fi}\right|^2 \right). \tag{2.2}$$

where Γ_{ℓ_i} is the total decay width of decaying lepton, $\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3}$ and Γ_τ also includes the hadronic channels. Only the operators Q_{eW} and Q_{eB} can give contribution to the $\ell_i \to \ell_f \gamma$ at tree level, if their coefficients are comparable to other Wilson coefficients of the dimension 6 operators, they dominate the effective photon-lepton vertex, with the form factors simply given by:

$$F_{TR}^{fi} = F_{TL}^{if\star} = v\sqrt{2}\left(c_W C_{eB}^{fi} - s_W C_{eW}^{fi}\right) \equiv v\sqrt{2} C_\gamma^{fi}. \tag{2.3}$$

The summed finite 1-loop results for F_{TL}, F_{TR} form-factors for the $\ell_i \to \ell_f \gamma$ decay can be written down as:

$$\begin{aligned} F_{TL}^{fi} &= \frac{4e}{(4\pi)^2}\left[\frac{C_{\phi l}^{(1)fi} m_f(1+s_W^2) - (C_{\phi l}^{(3)fi} m_f + C_{\phi e}^{fi} m_i)(\frac{3}{2} - s_W^2)}{3} + \sum_{k=1}^{3} C_{\ell e}^{fkki} m_K\right], \\ F_{TR}^{fi} &= \frac{4e}{(4\pi)^2}\left[\frac{C_{\phi l}^{(1)fi} m_i(1+s_W^2) - (C_{\phi l}^{(3)fi} m_i + C_{\phi e}^{fi} m_f)(\frac{3}{2} - s_W^2)}{3} + \sum_{K=1}^{3} C_{\ell e}^{kifk} m_K\right]. \end{aligned}$$

Operators of dimension-6 also give contributions to decay of heavy charged lepton into three lighter charged lepton. We obtain the branching ratios for decay of heavy charged lepton to three lepton of the same flavor,

$$\begin{aligned} \mathrm{Br}(\ell_i \to \ell_f \ell_f \overline{\ell}_f) &= \frac{m_i^5}{12288\pi^3\Lambda^4\Gamma_{\ell_i}} \left(4\left(|C_{VLL}|^2 + |C_{VRR}|^2 + |C_{VLR}|^2 + |C_{VRL}|^2\right)\right. \\ &+ \left. |C_{SLR}|^2 + |C_{SRL}|^2 + 48X_\gamma\right). \end{aligned} \tag{2.4}$$

where X_γ denotes the photon contribution and Γ^{ℓ_i} is the total decay width of the initial lepton. The photon penguin contribution reads:

$$\begin{aligned} X_\gamma &= -\frac{16ev}{m_i}\mathrm{Re}\left[\left(2C_{VLL} + +C_{VLR} - \frac{1}{2}C_{SLR}\right)C_{\gamma R}^\star\right. \\ &+ \left.\left(2C_{VRR} + C_{VRL} - \frac{1}{2}C_{SRL}\right)C_{\gamma L}^\star\right] \\ &+ \frac{64e^2v^2}{m_i^2}(\log\frac{m_i^2}{m_f^2} - \frac{11}{4})(|C_{\gamma L}|^2 + |C_{\gamma R}|^2), \end{aligned}$$

The quantities C_X read as:

$$\begin{aligned} C_{VLL} &= 2\left((2s_W^2 - 1)\left(C_{\phi\ell}^{(1)fi} + C_{\phi\ell}^{(3)ji}\right) + C_{\ell\ell}^{fiff}\right), \\ C_{VRR} &= 2\left(2s_W^2 C_{\phi e}^{fi} + C_{ee}^{fiff}\right), \\ C_{VLR} &= -\frac{1}{2}C_{SRL} = \left(2s_W^2\left(C_{\phi\ell}^{(1)ji} + C_{\phi\ell}^{(3)fi}\right) + C_{le}^{fiff}\right), \\ C_{VRL} &= -\frac{1}{2}C_{SLR} = \left((2s_W^2 - 1)C_{\phi e}^{fi} + C_{\ell e}^{fffi}\right), \\ C_{\gamma L} &= 2\sqrt{2}C_\gamma^{if*}, \\ C_{\gamma R} &= 2\sqrt{2}C_\gamma^{fi}. \end{aligned} \tag{2.5}$$

We can check potential correlation between obtained expressions. Many dimension-6 operators contribute to both expressions for radiative lepton decays and for the three-body charged lepton decays. Thus, their decay rates can be correlated. The ratio of both decay rates in case in which only C_γ^{fi} is non-zero depends solely on SM parameters and is given by $1/(\frac{\alpha}{3\pi}(\log\frac{m_i^2}{m_f^2}-\frac{11}{4}))$. It is interesting (particularly for projecting new experiments which would measure each of the decays separately) how strongly this ratio could be modified by contributions other then photon penguin.

The ratio of both decays is independent of the scale Λ of NP and depend only on the ratios of Wilson coefficients. Thus, given a specific model, one can determine the branching ratio for one process in terms of the other one independently of the scale of New Physics.

As an example, let's assume that only the Wilson coefficients C_γ^{if}, $C_{\varphi e}^{fi}$ and $C_{\varphi\ell}^{(1)fi}$ do not vanish. In Fig. 1 we show the ratios $\mathrm{Br}\left[\ell_i \to \ell_f \gamma\right]/\mathrm{Br}\left[\ell_i \to \ell_f \ell_f \bar{\ell}_f\right]$ as a function of $\frac{C_{\varphi e}^{fi}}{C_\gamma^{fi}}$ and $\frac{C_{\varphi\ell}^{(1)fi}}{C_\gamma^{fi}}$. The value predicted in the photon-penguin domination scenario responds to point $(0,0)$ in each plot. As one can see, contributions from other operators can change this ratio even by factor of 2. Several other correlations discussed in [2].

3. Conclusions

We calculated expressions for several lepton flavor observables in the extended Standard Model with general dimension 6 operators. We discussed the potential correlation between the decay rates of the radiative lepton decays and 3-body flavor violating charged lepton decays. Such correlation could be potentially very important for designing new experiments.

References

[1] B. Grządkowski, M. Iskrzyński, M. Misiak and J. Rosiek, JHEP **1010**, 085 (2010) [arXiv:1008.4884 [hep-ph]].

[2] A. Crivellin, S. Najjari and J. Rosiek, JHEP **1404**, 167 (2014) [arXiv:1312.0634 [hep-ph]].

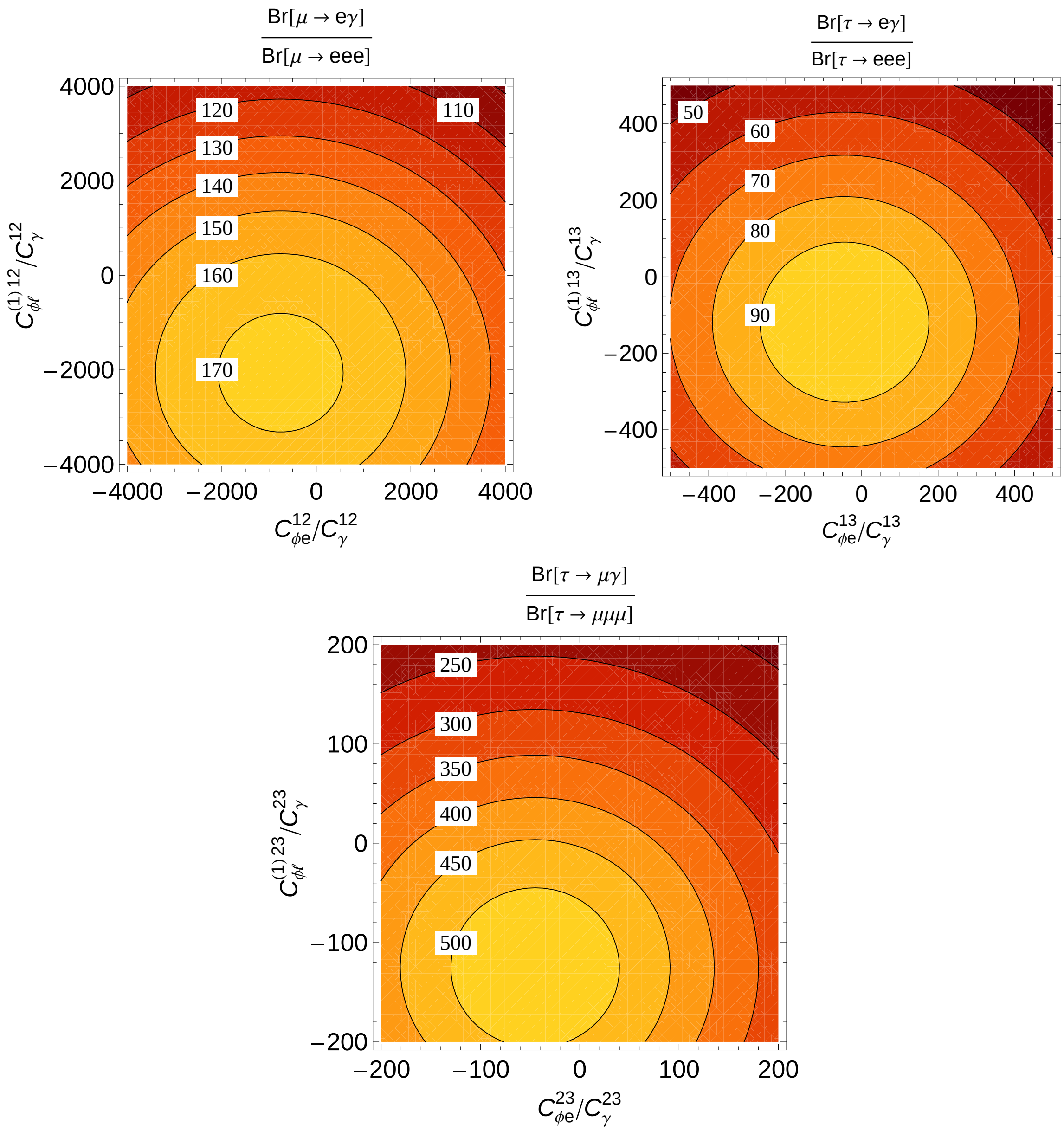

Figure 1: Ratios $\mathrm{Br}[\ell_i \to \ell_f \gamma]/\mathrm{Br}[\ell_i \to \ell_f \ell_f \overline{\ell}_f]$ in the $\frac{C_{\varphi e}^{fi}}{C_\gamma^{fi}}$–$\frac{C_{\varphi\ell}^{(1)\,fi}}{C_\gamma^{fi}}$ plane.