

$l^J \rightarrow l^I \gamma$ in the Standard Model with general dimension 6 terms

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The discovery of neutrino oscillations opens the road to lepton flavor violation. Observation of charged lepton flavor violation would be a unique probe of new physics beyond the Standard Model. We investigate the possibility of charged lepton flavor violation in the decay $l^J \rightarrow l^I \gamma$ in the extension of the Standard Model with the most general set of operators up to dimension 6.

1 Introduction

The Standard Model (SM) of strong and electroweak interaction is a theory that successfully explains and predict the elementary particles phenomenology. It is considered as a low energy approximation of more fundamental theory. In the SM, the lepton number of each family (lepton flavor) is conserved. On the other hand, the discovery of flavor violation provides a possible hint of new physics beyond the standard model. So far, neutrino oscillations are the only observed example of lepton flavor violation (LFV) that has been observed. It is possible to extend the SM by keeping its gauge symmetry, the particle content and the pattern of spontaneously symmetry breaking by adding new effective operators:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}(\frac{1}{\Lambda^3}) \quad (1)$$

where Λ is large, of the order of the scale of new physics. $Q_k^{(n)}$ denote operators of dimension n and $C_k^{(n)}$ stand for corresponding dimensionless coupling constants (Wilson coefficients). Once the underlying high-energy theory is specified, all the coefficient $C_k^{(n)}$ can be determined by integrating out the heavy fields.

2 The LFV operators of dimension 5 and 6

There is a unique operator of dimension 5 which gives Majorana mass to neutrinos. operators of dimension 6 contribute to charged lepton flavor violation. In Table 1, we collected the independent dimension 6 operators which could contribute to LFV process in the charged lepton sector at tree level or at one-loop level. The complete set of dimension 5 and 6 operators can be found in ¹.

3 $l^J \rightarrow l^I \gamma$ decay

In the SM, all flavor violating effects in the lepton sector are proportional to the very small values of neutrino masses and thus too small to be observed in any foreseeable experiment. In many

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Table 1: Lepton Flavor Violating dimension-6 operators.

$llll$		$llX\varphi$		$ll\varphi^2 D$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\phi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\phi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$			$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$llqq$					
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{eq}	$(\bar{e}_s \gamma^\mu e_t)(\bar{q}_p \gamma_\mu q_r)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s^j q_t^j)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$
				$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

extensions of the SM the effects of new physics can lead to larger and possibly observable LFV effects. It is convenient to parameterize such effect in a model independent in terms of coefficients of dimension 6 operators. We are investigating the possibility of the decay of $l^J \rightarrow l^I \gamma$. The vertices which contribute to such decay is also shown in Fig.1 and 2. Where C_k is dimensionless coupling constants (Wilson coefficient) stand for corresponding Q_k , e.g. $C_{\phi l}^{(1)}$ is dimensionless coupling constant for operator $Q_{\phi l}^{(1)}$. The generic topologies of diagrams contributing to this decay and relevant momenta assignments are shown in Fig.3.

The two dimension 6 operators Q_{eW} and Q_{eB} can give contribution to such decays at tree level. In many extension of the SM, Q_{eW} and Q_{eB} are not generated. If they vanish, flavor violating lepton-photon vertex can still be generated radiatively.

The general form of lepton-photon flavor violation vertex can be written as:

$$V_{ll\gamma}^{JI\mu} = \frac{i}{(4\pi)^2} [\gamma^\mu (F_{VL}^{JI} P_L + F_{VR}^{JI} P_R) + (F_{SL}^{JI} P_L + F_{SR}^{JI} P_R) q^\mu + (F_{TL}^{JI} \sigma^{\mu\nu} P_L + F_{TR}^{JI} \sigma^{\mu\nu} P_R) q_\nu] \quad (2)$$

Only the formfactors F_{TL} and F_{TR} contribute to $l^J \rightarrow l^I \gamma$ decay². Below we list the 1-loop results for F_{TL} , F_{TR} formfactors resulting from diagrams with respective gauge bosons in the loop:

$$\begin{aligned}
 F_{TL}^{ZJI} &= \frac{e^3 m_J (1+2s_W^2-4s_W^4)}{6s_W^2 M_W^2} \delta^{IJ} + \frac{4e[(C_{\phi l}^{(1)JI} + C_{\phi l}^{(3)JI})m_J(1+s_W^2) - C_{\phi e}^{JI}m_I(\frac{3}{2}-s_W^2)]}{3M^2} \\
 F_{TR}^{ZJI} &= \frac{e^3 m_I (1+2s_W^2-4s_W^4)}{6s_W^2 M_W^2} \delta^{IJ} + \frac{4e[(C_{\phi l}^{(1)JI} + C_{\phi l}^{(3)JI})m_I(1+s_W^2) - C_{\phi e}^{JI}m_J(\frac{3}{2}-s_W^2)]}{3M^2} \\
 F_{TL}^{WJI} &= -\frac{5e^3 m_J}{12s_W^2 M_W^2} \delta^{IJ} - \frac{5em_J [C_{\phi l}^{(3)JI} + C_{\phi l}^{(3)IJ*}]}{3M^2} \\
 F_{TR}^{WJI} &= -\frac{5e^3 m_I}{12s_W^2 M_W^2} \delta^{IJ} - \frac{5em_I [C_{\phi l}^{(3)JI} + C_{\phi l}^{(3)IJ*}]}{3M^2} \\
 F_{TL}^{G^0IJ} &= F_{TR}^{G^0IJ} = 0 = F_{TL}^{G^\pm JI} = F_{TR}^{G^\pm JI} = F_{TL}^{WGJI} = F_{TR}^{WGJI} = 0
 \end{aligned}$$

Conclusion

We are investigating the predictions for charged lepton flavor violation in the extension of the SM up to dimension 6 operators. Operators of dimension 6 can contribute to the $l^J \rightarrow l^I \gamma$ decay at one loop level. Any observation of CLFV would be a clear hint for physics beyond the SM.

Appendix

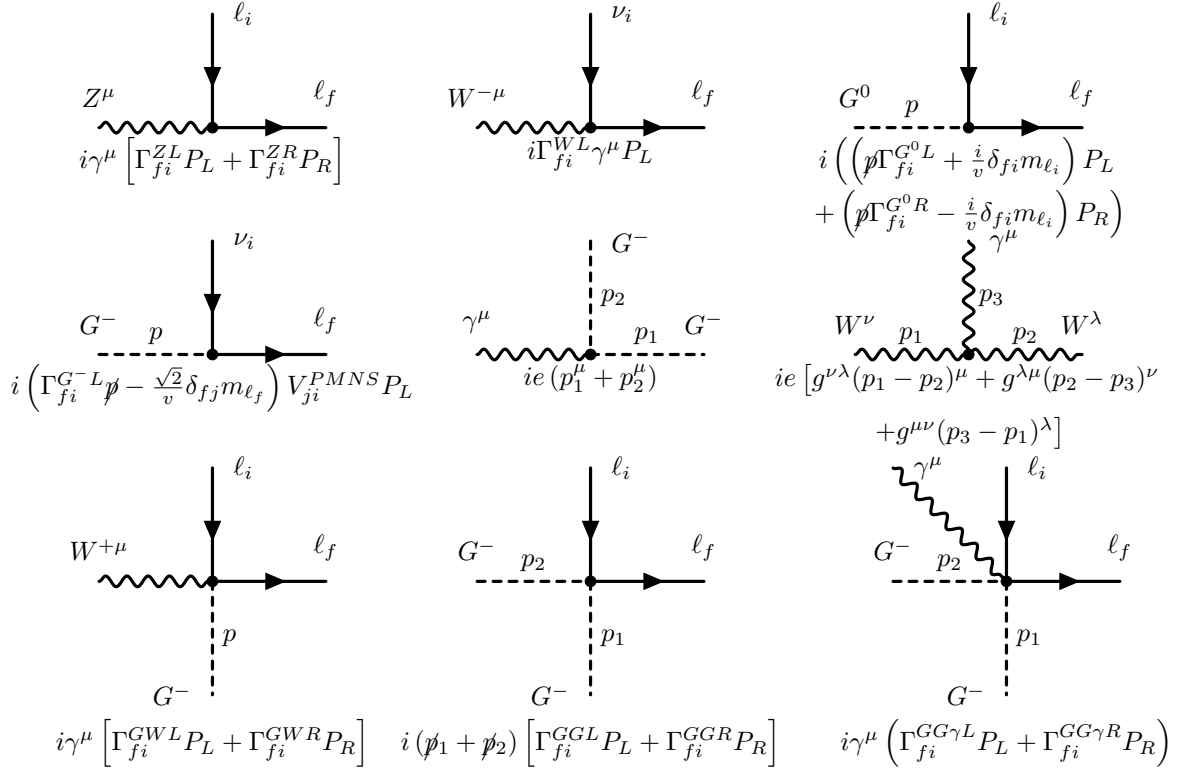


Figure 1: Vertices of diagrams contributing to $\ell^I \rightarrow \ell^J \gamma$ decay.

Where,

$$\begin{aligned}
 \Gamma_{fi}^{ZL} &= \frac{e}{2s_W c_W} \left(\frac{v^2}{M^2} \left(C_{\phi l}^{(1)fi} + C_{\phi l}^{(3)fi} \right) + (1 - 2s_W^2) \delta_{fi} \right), \\
 \Gamma_{fi}^{ZR} &= \frac{e}{2s_W c_W} \left(\frac{v^2}{M^2} C_{\phi e}^{fi} - 2s_W^2 \delta_{fi} \right), \\
 \Gamma_{fi}^{WL} &= -\frac{e}{\sqrt{2}s_W} \left(\frac{v^2}{M^2} C_{\phi l}^{(3)fj} + \delta_{fj} \right) V_{ji}^{PMNS}, \\
 \Gamma_{fi}^{G^0 L} &= \frac{iv}{M^2} \left(C_{\phi l}^{(1)fi} + C_{\phi l}^{(3)fi} \right), \\
 \Gamma_{fi}^{G^0 R} &= \frac{iv}{M^2} C_{\phi e}^{fi}, \quad \Gamma_{fi}^{G^- L} = -\frac{v\sqrt{2}}{M^2} C_{\phi l}^{(3)fj}, \\
 \Gamma_{fi}^{GWL} &= -\frac{ev}{M^2 s_W} C_{\phi l}^{(1)fi}, \quad \Gamma_{fi}^{GWR} = -\frac{ev}{M^2 s_W} C_{\phi e}^{fi}, \\
 \Gamma_{fi}^{GGL} &= -\frac{e}{M^2} \left(C_{\phi l}^{(1)fi} - C_{\phi l}^{(3)fi} \right), \quad \Gamma_{fi}^{GGR} = -\frac{e}{M^2} C_{\phi e}^{fi}, \\
 \Gamma_{fi}^{GG\gamma L} &= -\frac{2e}{M^2} \left(C_{\phi l}^{(1)fi} - C_{\phi l}^{(3)fi} \right), \quad \Gamma_{fi}^{GG\gamma R} = -\frac{2e}{M^2} C_{\phi e}^{fi},
 \end{aligned} \tag{3}$$

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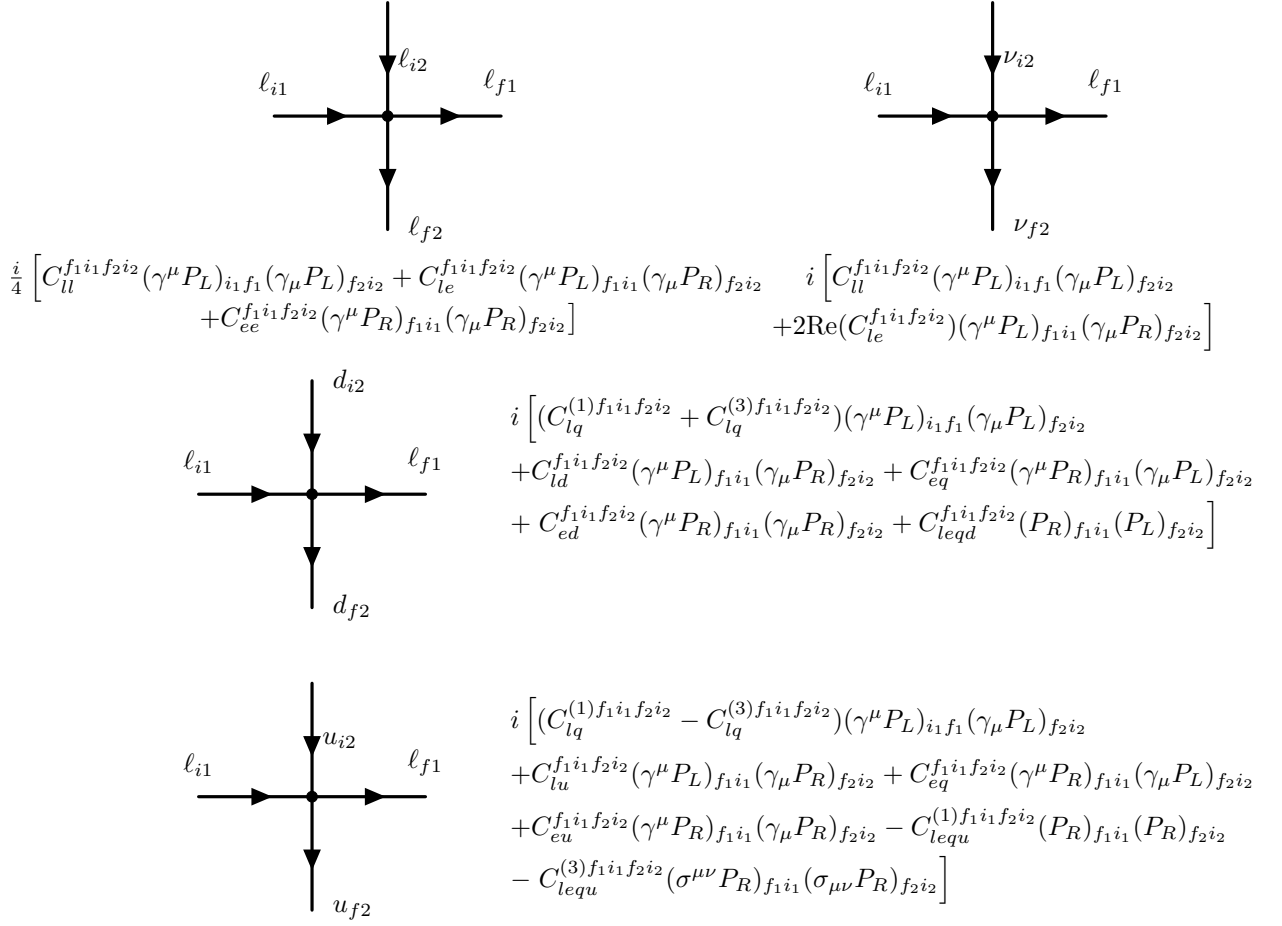


Figure 2: Four-fermion vertices of diagrams contributing to $\ell^I \rightarrow \ell^J \gamma$ decay.

References

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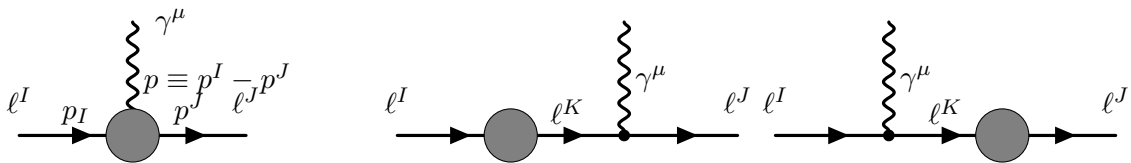


Figure 3: Topologies of diagrams contributing to $l^I \rightarrow l^J \gamma$ decay.