Non-universal Z′ Coupling to Flavour Violating Decays $\tau \to \mu\phi/e\phi$

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Introduction

Motivated by the recent experimental evidences of lepton flavour violating (LFV) decays at the LHC, researchers have found a new way to comment on the new physics (NP). The LFV decays are not allowed in standard model (SM) due to the lepton number conservation law, so a small hint of these decays may provide a good agreement with the theory of beyond SM.

In this paper, we are interested to study LFV decay channel i.e. $\tau \to l\phi$ (where $l = \mu,\ e$) which includes the interaction between two different leptons μ-τ and μ-e. Here, ϕ is a vector meson with polarization vector ϵ. We discuss the coupling of non-universal Z′ boson with μ and τ as well as μ and e in Left-Right (LR) Z′ model. In LR model [1], the electroweak gauge group is given by $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The weak interaction symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$ breaks into SM gauge group $SU(2)_L \times U(1)$ by two processes: either both parity and symmetry breaks in same stage or parity breaks before gauge symmetry. In the second case, the parity breaking at first step would manifest as different gauge couplings $g_L \neq g_R$. Here the gauge couplings for leptons are given as $g_L = \frac{e}{2\sqrt{2C_W}}$, $g_R = -\frac{e}{4\sqrt{2C_W}}$ [2]. When non-universal interaction is written in mass eigenstates, the LFV coupling vertex like Z′μτ, Z′eτ etc arise in the corresponding decay channels. In the next section we reproduce the formalism of effective Hamiltonian in Z model, Z′ model and then combine the branching ratios. In section 3, we calculate the branching ratios considering the contribution of both Z boson and Z′ boson, and vary LFV gauge couplings of leptons with the mass of Z′ boson i.e. $M_{Z'}$.

Theoretical Framework

Let us consider the LFV $\tau \to l\phi$ decay in Z-mediated FCNC model. In this case, the effective Hamiltonian can be written as [3]:

$$H_{eff}^{Z} = \frac{G_F}{\sqrt{2}} U_{\tau l} (\bar{\mu}\gamma^{\mu}(1-\gamma_5)\tau) \times (\bar{s}\gamma_{\mu}(C_V^s - C_A^s\gamma_5)s), \quad (1)$$

where, $C_{V,A}^s$ are the vector and axial vector couplings of $s\bar{s}$ quarks to Z boson. Using matrix element $\langle\phi(p',\epsilon)|\bar{s}\gamma^{\mu}s|0\rangle = f_\phi m_\phi \epsilon^{\mu}$, where f_ϕ is decay constant of ϕ meson and ϵ is its polarization vector, amplitude can be written as

$$\mathcal{M}(\tau \to l\phi) = \frac{G_F}{\sqrt{2}} U_{\tau l} C_V^s f_\phi m_\phi \times (\bar{\mu}\gamma^{\mu}(1-\gamma_5)\tau)\epsilon_{\mu}, \quad (2)$$

here, $f_\phi = 0.231$GeV and the coupling constants of leptons (e, μ, τ) to Z boson are $U_{\tau\mu} = 1.295 \times 10^{-3}$ and $U_{\tau e} = 1.28 \times 10^{-3}$. Neglecting the final state lepton mass, the branching ratio for $\tau \to l\phi$ decay mode can be written as

$$\mathcal{B}r_Z(\tau \to l\phi) = \frac{G_F^2}{16\pi}|U_{\tau l}|^2 (C_V^s)^2 f_\phi^2 m_\phi^2 m_\tau \tau_\tau \times \left(1 - \frac{m_\phi^2}{m_\tau^2}\right)^2 \left(2 + \frac{m_\tau^2}{m_\phi^2}\right), \quad (3)$$

τ_τ, m_τ and m_ϕ are lifetime, mass of τ lepton and mass of ϕ meson respectively.

Now we consider the non-universal LR Z′ model where $g_L = 0.1222$ and $g_R = -0.0611$. Neglecting Z-Z′ mixing effect for three body LFV decays we have [2],

$$Br(l_i \to 3l_j) = \frac{\tau_i m_i^5}{1536\pi^3 M_{Z'}^4} \times \left[\left\{2\left(g_L^j\right)^2 + \left(g_R^j\right)^2\right\}\left(g_L^{ij}\right)^2 + \left\{\left(g_L^j\right)^2 + 2\left(g_R^j\right)^2\right\}\left(g_R^{ij}\right)^2\right], \quad (4)$$

where, τ_i, m_i are lifetime, mass of the charged lepton l_i, and $g_{L,R}^{ij}$ are LFV coupling constants of leptons to Z′ boson. Presuming that one of $g_{L,R}^{ij}$ is nonzero at a time we estimate the range of the coupling constants from the current experimental upper limits [4] of three body LFV decays.

The Lagrangian for effective four fermion coupling with Z′-mediated FCNC could be written as [2],

$$\mathcal{L}_{4f} = \frac{1}{2M_{Z'}^2}\left[g_L^{\tau l}\left(\bar{l}\gamma^{\mu}P_L\tau\right) + g_R^{\tau l}\left(\bar{l}\gamma^{\mu}P_R\tau\right)\right] \times \sum_q \left[g_L^q\left(\bar{q}\gamma_{\mu}P_L q\right) + g_R^q\left(\bar{q}\gamma_{\mu}P_R q\right)\right], \quad (5)$$

where, q = quarks, l = leptons. The branching ratio for the decay mode $\tau \to l\phi$ (*l*= *e*, *μ*) through Z′-mediated FCNC is given by

$$\mathcal{B}r_{Z'}(\tau \to l\phi\,) = \frac{m_\tau \tau_\tau f_\phi^2}{64\pi M_{Z'}^4}(g_V^s)^2[(g_L^{\tau l})^2 + (g_R^{\tau l})^2] \times \left(1 - \frac{m_\phi^2}{m_\tau^2}\right)^2 \left(m_\phi^2 + \frac{m_\tau^2}{2}\right). \qquad (6)$$

So, the total branching ratio considering both Z- and Z′-mediated FCNC can be written as

$$\mathcal{B}r_{total}(\tau \to l\phi\,) = \mathcal{B}r_Z + \mathcal{B}r_{Z'} = \frac{m_\tau \tau_\tau f_\phi^2}{8\pi} \times \left(1 - \frac{m_\phi^2}{m_\tau^2}\right)^2 \left(m_\phi^2 + \frac{m_\tau^2}{2}\right)\left[\{G_F^2 |U_{\tau l}|^2 (C_V^s)^2\} + \left\{\frac{(g_V^s)^2}{8M_{Z'}^4}[(g_L^{\tau l})^2 + (g_R^{\tau l})^2]\right\}\right]. \qquad (7)$$

Result and Discussion

The whole formalism in section 2 shows that Z′ may contribute to the LFV channels. Eq. (4) constrains the LFV coupling constants $g_{L,R}^{ij}$. As these coupling constants are dependent on the mass of Z′ boson, so we can vary $g_{L,R}^{ij}$ with $M_{Z'}$. There are lot of direct and indirect searches going on for the discovery of Z′ boson but till now its exact mass is not predicted. Different accelerators [5] gives model dependent lower bound around $M_{Z'} \sim 500$ GeV. Recently ATLAS collaboration gives the limit of $M_{Z'} \sim 1.90$ TeV [6] as well as, in CMS, various searches have found $M_{Z'} \sim 3.15$ TeV [7]. Oda *et al.* [8] have predicted the upper bound as $M_{Z'} \sim 6000$ GeV. Here we use the mass of Z′ boson within a range between 500-6000 GeV. The variation curve for $g = (g_L^{\tau l})^2 + (g_R^{\tau l})^2$ vs. $M_{Z'}$ is given in Fig.1.

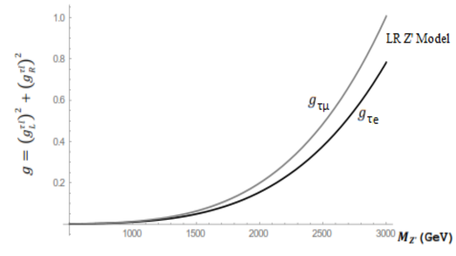

Fig.1

Next we calculate the branching ratio for the decay mode $\tau \to l\phi$ considering Z and Z′ contribution by putting the values of $g_{L,R}^{ij}$ in eq. (7). The experimental upper limit and our obtained results are summarized in Table.1. From Table.1 we see that the values of branching ratio

Table.1

	$Br(\tau \to \mu\phi)$	$Br(\tau \to e\phi)$
Experimental upper limit	8.4×10^{-8}	3.1×10^{-8}
$\mathcal{B}r_Z$	1.42×10^{-9}	1.39×10^{-9}
$\mathcal{B}r_{Z'}$	3.03×10^{-8}	3.89×10^{-8}
$\mathcal{B}r_{total}$	3.169×10^{-8}	4.03×10^{-8}

are enhanced due to introducing the new gauge boson Z′. Our predicted branching ratio for $\tau \to \mu\phi$ decay satisfies the experimental limit whereas for $\tau \to e\phi$ decay, it is little bit higher than the experimental limit. Further, we calculate the ratio of $\mathcal{B}r_{total}(\tau \to \mu\phi\,)$ to $\mathcal{B}r_{total}(\tau \to e\phi\,)$ which is given by $\mathcal{R}_{\mu e}^{\tau} = \mathcal{B}r_{total}(\tau \to \mu\phi\,)/\mathcal{B}r_{total}(\tau \to e\phi\,) = 0.786$. The value of $\mathcal{R}_{\mu e}^{\tau}$ should be 1 in SM as there is no space for LFV in SM. But here we get the value smaller than 1. So, we conclude that the lepton flavor is not conserved here. From the above discussion it is clear that LFV decays are much probable in Z′ model. We expect that these decays would provide useful tool for new tests of lepton non-universality and to explore new physics beyond SM in near future.

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