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Flavor Violation at the LHC

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Abstract

In this talk, we discuss a way of establishing lepton flavor violation (LFV) at the Large Hadron Collider(LHC). The existence of massive right-handed neutrinos can explain neutrino oscillations via the seesaw mechanism and can induce a sizeable LFV in low energy supersymmetry. We use $\tilde{\chi}_2^0 - \tilde{\chi}_1^0 - \tilde{\tau}_1$ system to study the invariant masses of two hadronically decaying taus ($\tau_h\tau_h$) and one hadronically decaying tau plus a muon ($\tau_h\mu$) from $\tilde{\chi}_2^0$ in scenarios with LFV. The $\tau_h\mu$ invariant mass (where μ emerges from the τ decay) can arise even withoul LFV. We use a transfer function utilizing the ditau mass distribution to extract the LFV $\tau_h\mu$ signal. The proposed technique can also be applied for a LFV $\tau_h e$ search and any model.

Keywords: flavor violation, supersymmetry, collider

1. Introduction

The neutrino oscillation data suggest that we have neutrino mixing matrix, the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix [1], just like the CKM mixing matrix in the quark sector. The light neutrino masses are usually generated via the seesaw mechanism, involving heavy Majorana masses for right handed neutrinos. These heavy right handed neutrinos are introduced as additions to the SM quarks and leptons. The Type -I seesaw formula for the light neutrino mass matrix with three generations is given by [2]

$$m_\nu = -\mathcal{M}_D^T(\mathcal{M}_R)^{-1}\mathcal{M}_D, \tag{1}$$

where $\mathcal{M}_D$ is the Dirac neutrino mass matrix and $\mathcal{M}_R$ is the Majorana matrix, which consists of three right handed neutrinos (ν^c). The heavy masses at the scale v_{B-L} corresponding to a new local $B-L$ symmetry of weak interactions. Typically this mass scale is around the GUT scale for natural values of couplings. The neutrino mixing angles in such schemes emerge jointly from two sources: (i) mixings among the right handed neutrinos in $\mathcal{M}_R$ and (ii) mixings among different generations in the Dirac mass matrix $\mathcal{M}_D$. The charged lepton sector can also contribute to the MNSP matrix.

The neutrino flavor mixings induced by the seesaw mechanism can generate lepton flavor violating (LFV) effects. Such effects are extremely small in any process due to a power suppression factor $(1/v_{B-L})^2$ within the minimally extended SM to accommodate the seesaw mechanism. However, this situation changes in the presence of low energy SUSY. The power suppression factor for LFV effects, $(1/M_{\rm SUSY})^2$, becomes small which lead to observable LFV effects at low energies [3]. In low energy SUSY, the lepton flavor violation (LFV) can be induced in the slepton sector. The flavor violation then get transferred via one loop diagrams involving the exchange of gauginos to the charged leptons where the suppression is $\sim (1/M_{\rm SUSY})^2$. The experimental evidence for neutrino oscillation indicates that there might very well be LFV in the presence of low energy SUSY. Searches for LFV processes such as $\tau \to \mu\gamma$ and/or $\mu \to e\gamma$ can therefore inform us about the ν^c mixings in $\mathcal{M}_R$ and/or family mixings in $\mathcal{M}_D$.

Motivated by this natural occurrence of LFV due to neutrino oscillation, in this talk, we study the prospect of establishing LFV in the slepton sector at the Large Hadron Collider (LHC) using mass reconstruction tech-

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niques. Instead of using any particular scenario to generate the LFV in the leptonic sector, we use a bottom up approach so that this study can be applied to any model of LFV.

We investigate a decay chain involving the sleptons since the slepton-neutralino and slepton-chargino interactions carry the information of LFV. In non-LFV scenarios, the final states possess taus when staus are the lighter of sleptons and in such scenarios the $M_{\tau\tau}$ distribution shows a clear endpoint and peak. However, when LFV is present, the decay modes $\tilde{\chi}_2^0 \to \tau\mu\tilde{\chi}_1^0$ and/or $\tilde{\chi}_2^0 \to \tau e\tilde{\chi}_1^0$ can show up. The authors of [4] proposed a search for the LFV signal by looking for an excess in OS μ-$\tau_{\rm h}$ over OS e-$\tau_{\rm h}$ events with no LFV decays in the e-$\tau_{\rm h}$ channels. In this talk, we discuss a complementary method using a "transfer" function, which can be used for the μ-$\tau_{\rm h}$ and e-$\tau_{\rm h}$ LFV channels simultaneously [5].

The LHC results so far have shown no deviation from the SM prediction. The direct searches have raised the bounds of the gluino mass to be more than 1.9 TeV at ATLAS [6] and 1.6 TeV at CMS [7]. It is important to note that the constraints on the non-colored SUSY particles with smaller mass gaps and tau final states are not good [8]. In this talk, we will use the scenarios with mostly τs in the final states.

The talk is organized as follows. In section 2 we discuss further the origins of LFV terms in SUSY, as well as our particular implementation of such LFV terms for this study. In section 3 we discuss the possible signals and associated measurements leading to the estimation of the non-LFV background. In section 4 we propose a technique to estimate this background and extract the effects of LFV. Finally, we present our conclusions in section 5.

2. Origin of LFV

LFV effects can be generated by the neutrino seesaw mechanism in SUSY in a very simple way. Suppose, we have the mSUGRA [9] boundary condition at the GUT scale and thus, there is no flavor violation anywhere except in the Yukawa couplings. It should be noted that in the absence of neutrino masses, there is only one leptonic Yukawa matrix, Y_l, for the charged leptons which will not induce any flavor violation in the slepton sector in mSUGRA models. However, to satisfy the neutrino mixing data, the right handed neutrinos have masses of order v_{B-L} which is lower than M_G and the right handed neutrino masses need to be $\sim 10^{12} - 10^{15}$ GeV. The soft masses of the sleptons will feel the effects of LFV in the neutrino Yukawa sector through the renormalization group evolution in the momentum regime $v_{B-L} \leq \mu \leq M_G$ where the ν^c fields are active. At the scale v_{B-L}, the slepton mass matrix looses universality in flavor, and this non-universality will sustain at the weak scale. If we use flavor violating Majorana couplings, we find the following flavor violating soft terms for trilinear couplings and slepton masses:

$$\begin{aligned} \Delta m^2_{ij}(i\neq j) &\simeq \frac{-3(m_0^2+A_0^2)}{32\pi^4}[Y_\nu^\dagger Y_\nu f^\dagger f \\ &+ f^\dagger f Y_\nu^\dagger Y_\nu]_{ij}\left(\ell n\frac{M_G}{M_{B-L}}\right)^2 \end{aligned} \tag{2}$$

$$\begin{aligned} A_{\ell ij}(i\neq j) &\simeq \frac{-3}{64\pi^4}[A_\ell(Y_\nu^\dagger Y_\nu f^\dagger f \\ &+ f^\dagger f Y_\nu^\dagger Y_\nu)]_{ij}\left(\ell n\frac{M_G}{M_{B-L}}\right)^2 . \end{aligned} \tag{3}$$

If we use flavor violating Dirac couplings, we find the following flavor violating soft terms for slepton masses:

$$\Delta m^2_{ij}(i\neq j) \simeq -\frac{1}{8\pi^2}(3m_0^2+A_0^2)(Y_\nu^\dagger Y_\nu)_{ij}\left(\ell n\frac{M_G}{M_{B-L}}\right) . \tag{4}$$

We see that the amount of LFV is model depenedent. We simply introduce a term by hand which causes LFV within the charged slepton mass matrix to capture this flavor violation effect and try to see the effect at the LHC. The charged slepton mass matrix is a 6x6 matrix and is given by

$$\mathcal{M}^2_{\tilde{\ell}} = \begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^2_{LR} \\ \mathcal{M}^2_{LR} & \mathcal{M}^2_{RR} \end{pmatrix}, \tag{5}$$

where $\mathcal{M}^2_{LL}$ represents the 3x3 matrix for soft masses for left sleptons, $\mathcal{M}^2_{RR}$ represents the 3x3 matrix for soft masses for right sleptons, and $\mathcal{M}^2_{LR}$ represents the diagonal matrix with elements $m_l(A_l+\mu\tan\beta)$, where A_l is the trilinear soft mass term and m_l is the diagonal charged lepton mass ($Y_l v_d$) for generation l. In mSUGRA,

$$\mathcal{M}^2_{LL} = \mathcal{M}^2_{RR} = m_0^2\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{6}$$

and $A_l = A_0$. When off-diagonal elements in $\mathcal{M}^2_{LL,LR,RR}$ are present, the effects of LFV can emerge. When we diagonalize the above mass matrix to obtain the mass eigenstates of sleptons, if there is no such off-diagonal LFV element in $\mathcal{M}^2_{LL,LR,RR}$, then thre is no flavor violation. One typical example of flavor violation in the context of mSUGRA model is shown in fig.2.

If the second lightest neutralino, $\tilde{\chi}_2^0$, is produced at the LHC from the cascade decays of squarks or direct