The decay $h \to \mu\tau$ in the Littlest Higgs Model with T-parity

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Abstract. We calculate the one loop contributions to $h \to \mu\tau$ decay in the littlest Higgs model with T-parity. We include mirror fermions and odd gauge bosons loops. We find that for a special choice of the mixing matrix of mirror fermion $k_{ii} = 0.2$ and $k_{ii} = 0.45$, the branching fraction is the order $10^{-3} - 10^{-2}$ and $10^{-2} - 10^{-1}$, respectively, with an energy scale $f = 0.5 - 2$ TeV. However, our results are a function of the square of the product of mixing matrices $|V_{H\mu}^\dagger V_{H\tau}|^2$.

1. Introduction

Some months ago, the CMS experiment [1] reported a 2σ excess in a search for $h \to \mu\tau$ decay, corresponding to an integrated luminosity of 19.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The corresponding branching ratio reported is $Br(h \to \tau\mu) = 0.84^{+0.39}_{-0.37} \%$, while ATLAS [2] observed only a small excess in one of the signal regions and reported the upper limit $Br(h \to \tau\mu) = 0.77 \pm 0.62\%$ (1.2σ). These results provide great motivation for the search of physics beyond the Standard Model (SM). In the SM the neutral flavour changing processes (NFCP) are not induced at tree level. However, in some SM extensions NFCP are associated with heavy particles, thus the $h \to \mu\tau$ decay could be induced at one loop level. In this regard, in the effective lagrangian approach $Br(h \to \tau\mu) = 10^{-1} - 10^{-2}$ was reported in [3], whereas in the generic supersymmetric SM without R parity [4] the branching ratio can exceed $10^{-5}$ [4]. This last result is in agreement with [5], where the off-diagonal $\ell\ell h$ boson vertex was induced by one-loop electroweak corrections in the SM framework, in which one right-handed neutrino for each family has been introduced. Moreover, the study of this process in the Simplest little Higgs Model has also been reported in [6] they found that $Br(H \to \mu\ell) \sim 10^{-12}$ as low as and $Br(H \to \tau\ell)$ is enhanced by a factor of order 300. In this work, we present the results of $h \to \tau\mu$ decay in the littlest Higgs model (LHM) with T-parity [7], induced only by a heavy $W_H^\pm$ boson. The LHM with T parity is a minimal version of a type of models known as Little Higgs Model [8], which are characterized by a global $SU(5)$ and gauge $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ symmetries and they are spontaneously broken at scale $f \sim O(\text{TeV})$. In this model, the Higgs boson is considered as pseudo-Goldstone boson; an important aspect of the model is that it remains protected from quadratic divergences and thus this model offers an alternative to the hierarchy problem. Nevertheless, the LHM with
T parity is affected by electroweak precision tests [9], which led to the inclusion of the so called T-parity and in consequence not only the number of parameters are reduced, but also the scale energy \( f \) can be relaxed considerably.

This paper is organized as follows. In section 2, we briefly review the LHM with T parity and show the relevant couplings of the Higgs boson that are necessary for our work. In section 3, we present our calculations for \( h \to \mu\tau \) decay at one loop level. Numerical results and analysis are given in Section 4 and finally, our conclusions are given in Section 5.

2. Littlest Higgs Model with T-Parity Framework

The Littlest Higgs Model [10] is based on a non-linear sigma model with global \( SU(5) \) symmetry, which is spontaneously broken down to \( SO(5) \) via the vacuum expectation value of the scalar field \( \Sigma \). On other hand, the sub group \( [SU(2) \otimes U(1)]^2 \) is contained in \( SU(5) \), but \( \Sigma_0 \) at the scale \( f \) breaks the gauge symmetry to the diagonal odd-T group \( SU(2) \otimes U(1) \), which is identified with the SM gauge group; in other words \( [SU(2) \otimes U(1)]^2 \to SU(2) \otimes U(1). \)

The gauge-kinetic Lagrangian of LHM is

\[
\mathcal{L} = \frac{1}{2} f^2 \text{Tr} |D_{\mu}\Sigma|^2 \tag{1}
\]

were \( f = \frac{\Lambda}{4\pi} \) is the collective symmetry breaking scale, \( \Lambda \) the cut off of the model, and the covariant derivative is given by

\[
D_{\mu}\Sigma = \partial_{\mu}\Sigma - \sum_{j=1}^{2} \left\{ ig_j W_j^a \left( Q_j^a \Sigma + \Sigma Q_j^a T \right) + ig'_j B_j \left( Y_j \Sigma + \Sigma Y_j T \right) \right\} \tag{2}
\]

\( Q_j^a \) and \( Y_j \) are generators of the gauged symmetries, \( g_j \) and \( g'_j \) are coupling constants. The breaking \( SU(5) \to SO(5) \) generates 14 Goldstone bosons, 4 of which are eaten to give mass to 4 linear combinations of the gauge fields (see next subsection).

One way to implement T-parity is by the following requirement on the fields, \( W_{1}^a \leftrightarrow W_{2}^a \), \( B_{1} \leftrightarrow B_{2} \). In this way, the gauge kinetic lagrangian (1) is invariant under T-parity and the heavy gauge bosons are odd while the SM ones are even, obtaining a reduction in the total number of model parameters; in particular, for the gauge sector \( g_1 = g_2 = \sqrt{2} g \) and \( g'_1 = g'_2 = \sqrt{2} g' \), where \( g \) and \( g' \) would shortly be identified with the SM \( SU(2) \) and \( U(1) \) gauge couplings, respectively.

2.1. Gauge Boson Sector

The T-odd bosons acquire mass at order \( O(v^2/f^2) \) in the expansion of the Eq. (1) and the mass spectrum is given by

\[
M_{W_H}^2 = fg \left( 1 - \frac{v^2}{f^2} \right), \quad M_{W_H} = M_{Z_H}, \quad M_{A_H} = \frac{fg'}{\sqrt{5}} \left( 1 - \frac{5v^2}{8f^2} \right), \tag{3}
\]

and \( v \) can be given by \( v \simeq v_{SM}(1 + \frac{v_{SM}^2}{f^2}) \), where \( v_{SM} = 246 \text{ GeV} \).

The mass of the even-T bosons is generated by the second breaking of the symmetry \( SU(2)_L \otimes U(1)_Y \to U(1)_{EM} \), which takes place via the usual Higgs mechanism. In this case the mass of the bosons is given as a small correction; however, the relations of SM for the masses of gauge bosons are satisfied at tree level.
2.2. Fermion Sector

For the implementation of parity-T in the fermion sector we introduce mirror fermions. This is done by including fermion doublets in $SU(5)$ and a right handed multiplet $\Psi_R$ of $SO(5)$ is introduced,

$$L_{\text{mirror}} = -\kappa_{ij} f \left( \bar{\Psi}_i^j \xi + \bar{\Psi}_i^j \Sigma_0 \Omega \xi^j \right) \Psi_R^i,$$

(4)

where the sum runs over the generation indices $i, j = 1, 2, 3$, $\kappa_{ij}$ is a mixing matrix and $\Psi$ are the fermion multiplets. After expansion of Eq. (4), we obtain expressions for the masses of mirror leptons and neutrinos, and neutrino couplings with Higgs boson are given according to

$$m_{\nu_H} = \sqrt{2} k_{ii} f, \quad m_{l_H} = \sqrt{2} k_{ii} f \left( 1 - \frac{v^2}{f^2} \right), \quad h\bar{\nu}_H \nu_H \sim i\kappa_{ii} \frac{v}{\sqrt{2}},$$

(5)

On the other hand, in Ref. [11] it is discussed in detail the existence of two unitary mixing matrices $V_{H\ell}$ and $V_{H\nu}$; this is one of the principal ingredients in the mirror fermionic sector. These matrices are associate with the heavy bosons and satisfy the relation $V_{H\nu}^\dagger V_{H\ell} = V_{PMNS}$, were $V_{PMNS}$ is the Pontecorvo-Maki-Nakagata-Saki (PMNS) matrix, which contains information on the mixture (flavour violating) of the quantum heavy states with SM fermions when they interact through heavy gauge bosons $W_H$, $Z_H$ or $A_H$.

As we saw, the heavy charged leptons are predicted by the LHM with T parity; however, they do not have direct couplings with the Higgs boson, and we do not consider these couplings in our calculations. The coupling of leptons and mirror neutrinos with heavy bosons $W_H$ [12] and the coupling between Higgs boson and heavy bosons $W_H$’s are given respectively by

$$\bar{\nu}_H^j W_H^{\mu+} \ell^j \sim \frac{ig}{\sqrt{2}} (V_{H\ell})_{ij} \gamma^\mu P_L, \quad hW_H^{\mu+} W_H^\mu \sim -\frac{ig^2}{2} g^{\mu\nu},$$

(6)

were $P_L = \frac{1}{2}(1 - \gamma_5)$.

3. $h \rightarrow \bar{\tau}\mu$ Decay

In general, there are four diagrams contributing at this order to the process $h \rightarrow \bar{\tau}\mu$, see Figure 1. In this paper we present the results for the contributions with $W_H$ bosons and a mirror neutrino in the loop. The couplings with heavy particles and SM particles used to perform this calculation are given in the equations (5) and (6).

**Figure 1.** Feynman diagrams for the decay $h \rightarrow \bar{\tau}\mu$ in the LHM with T parity. Where we sum over the generation indices $i = 1, 2, 3$. 
We consider two complementary diagrams for each diagram considered in Figure (1), in order to remove the divergences. In complementary diagrams, we note that the largest contribution will come from that in which the matrix element is proportional to the mass of the tau. To solve the integrals we use the method called Feynman parametrization.

4. Results and Analysis

In general, the transition amplitude is expressed as follows

\[ iM = i (\mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3) = i \pi(p_2, m_\tau) (A + iB \gamma_5) u(p_1, m_\mu), \]  

(7)

where \( A \) and \( B \) are structure functions which depend on the scale energy \( f \); we plot their behavior in Figure 2, for two different values of \( \kappa_{ii} \). A kinematical study is done in [13] for the permitted limits and it was found that \( \kappa_{ii} \leq 0.45 \) it is a good limit, and excludes \( \kappa_{ii} \leq 0.1 \), since in this case the quark partners become lighter than the heavy photon \( A_H \) and therefore stable.

On the other hand, the numerical value of the masses in Eq. (5) are dependent on the energy scale considered and on the parameter \( \kappa_{ii} \). In our calculations we choose \( 0.5 \text{ TeV} \leq f \leq 2 \text{ TeV} \), because when we include the symmetry T parity in LHM the constraints are mitigated with electroweak precision data, starting at a scale of 500 GeV [14]. Although the most recent data cover up to \( 25 \text{ fb}^{-1} \) analyzed [15] for Higgs searches in CMS and ATLAS, they excluded parameter space regions at 95% and 99% CL respectively; the exclusion limit for \( f \) is \( f \geq 607 \text{ GeV} \).

In the following analyses we have used \( \kappa_{ii} = 0.2 \) and \( \kappa_{ii} = 0.45 \). In Figure 2 we present our results as a function of the product \( V_{H\mu}^* V_{H\tau} \) mixing matrices.

\[ \begin{align*}
\text{Figure 2. Structure functions A and B as a function of the symmetry breaking scale f. We have used } \kappa_{ii} = 0.2 \text{ (black line) and } \kappa_{ii} = 0.45 \text{ (blue line). The mixing matrices are in general arbitrary.}
\end{align*} \]

In our case the decay width has the form,

\[ \Gamma = \frac{m_h}{8\pi} \sqrt{\lambda} \left\{ A^2 \left( 1 - \left( \frac{m_\mu + m_\tau}{m_h} \right)^2 \right) + B^2 \left( 1 - \left( \frac{m_\tau - m_\mu}{m_h} \right)^2 \right) \right\}, \]

(8)

where \( \lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz \). We will calculate the fraction of the total decay using the experimental results shown in Table 1.

\[ \text{1 We have seen that } \kappa_{ij} \text{ is a free parameter of the model, making the fermion spectrum dependent on this value besides the scale } f. \]
Table 1. Experimental values of the decay width of the Higgs boson in different channels [16].

| $X\bar{X}$  | $b\bar{b}$ | $\tau^+\tau^-$ | $WW^*$ | $ZZ^*$ | $gg$ | $\gamma\gamma$ |
|----------|----------|----------------|--------|--------|------|--------------|
| $\Gamma(h \to X\bar{X})\text{MeV}$ | $4.2^{+7.3}_{-2.6}$ | $0.3^{+1.0}_{-0.7}$ | $1.2^{+0.5}_{-0.4}$ | $0.14^{+0.06}_{-0.04}$ | $0.20^{+0.16}_{-0.09}$ | $0.04^{+0.05}_{-0.02}$ |

Finally, we plot the branching ratio in Figure 3. We can see that the branching ratio of $h \to \mu\tau$ decay can reach an order of $10^{-1}$ for $\kappa_{ii} = 0.45$ (blue line) in agreement with the results of CMS and ATLAS experiments; for $\kappa_{ii} = 0.2$ (black line) we get branching ratio up $10^{-2}$, these results are in the energy range allowed by the LHM with T parity.

![Figure 3. Branching ratio for decay $h \to \mu\tau$ as a function of the symmetry breaking scale $f$. We have used $\kappa_{ii} = 0.2$ (black line) and $\kappa_{ii} = 0.45$ (blue line).](image)

5. Conclusions and Prospects

We have studied the flavor violating Higgs boson decay to $\mu\tau$, which is induced at one loop level by charged heavy gauge bosons and mirror heavy neutrinos, in the Little Higgs Model with T-parity. For this purpose, we consider symmetry breaking scale $f$ between 500 and 2000 GeV. Moreover, we have used values of $\kappa_{ii} = 0.2$ and $\kappa_{ii} = 0.45$, which was obtained to consider that the mirror quarks are heavier than all the heavy gauge bosons of the LHM with T parity. Our result shows that the branching fraction is of the order $(10^{-3} - 10^{-2})|V_{H_{\mu}}^\dagger V_{H_{\tau}}|^2$ and $(10^{-2} - 10^{-1})|V_{H_{\mu}}^\dagger V_{H_{\tau}}|^2$, but our result decreases when it considers any particular scenario for the mixing matrices. However, there are additional contributions arising from neutral heavy gauge bosons and charged mirror leptons, but it is showed that the charged heavy gauge bosons is the main contribution. The details of these analyses will be reported soon.

6. Acknowledgements

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References

[1] V. Khachatryan et al. [CMS Collaboration], “Search for Lepton-Flavour-Violating Decays of the Higgs Boson”, Phys. Lett. 749, 337 (2015).

[2] G. Aad et al. [ATLAS Collaboration], “Search for Lepton-Flavour-Violating $H \rightarrow \mu\tau$ Decays of the Higgs Boson with the ATLAS Detector”, arXiv:1508.03372 [hep-ex].

[3] J. L. Diaz-Cruz and J. Toscano, “Probing Lepton Flavour Violation with Higgs Boson Decays $H \rightarrow \ell_i + \ell_j$”, Phys.Rev. D62, 116005 (2000).

[4] A. Arhrib, Y. Cheng, O. Kong, “$H \rightarrow \mu\tau$ Decay in Supersymmetry without R-Parity”, Europhys. Lett. 101 (2013) 31003.

[5] A. Pilaftsis, “Lepton Flavor nonconservation in $h^0$ Decays”, Phys. Lett. B285 (1992).

[6] A. Lami and P. Roig, “$H \rightarrow \ell\ell'$ in the Simplest Little Higgs Model”, arXiv:1603.09663v1 [hep-ph] 31 Mar 2016.

[7] N. Arkani, A. G. Cohen, E. Katz and A. E. Nelson, “The Littlest Higgs” JHEP 0207, 034 (2002).

[8] N. Arkani, A. Cohen, and H. Georgi, “Electroweak Symmetry Breaking from Dimensional Deconstruction”, Phys.Lett. B513 (2001).

[9] C. Csaki, J. Hubisz, G. D. Kribs, P. Meade, and J. Terning, “Big Corrections from a Little Higgs”, Phys.Rev. D67 (2003) 115002.
   J. Hewett, F. Petriello, and T. Rizzo, “Constraining the littlest Higgs”, JHEP 0310 (2003) 062.

[10] H. Cheng, I. Low, “TeV Symmetry and the Little Hierarchy Problem”, JHEP 0309, 051 (2003).

[11] J. Hubisz, S. J. Lee and G. Paz, “The flavor of a little Higgs with T-parity”, JHEP 06, 041 (2006), hep-ph/0512169.

[12] M. Blanke et al. “Rare and CP-Violating $K$ and $B$ Decays in the Littlest Higgs Model with T-Parity”, JHEP01 (2007) 066.

[13] Jorgen Reuter, Marco Tonini, Maikel de Vries, “Littlest Higgs with T-parity: Status and Prospects”, arXiv:1310.2918v2[hep-ph] 20 Feb, 2014.

[14] J. Hubisz, P. Meade, A. Noble, and M. Perelstein, “Electroweak Precision Constraints on the Littlest Higgs Model with T Parity”, J. High Energy Phys. 01 (2006) 135.

[15] J. Reuter, M. Tonini and M. de Vries, “Littlest Higgs with T-Parity: Status and Prospects”, JHEP02 (2014) 053.

[16] CMS collaboration, arXiv:1202.1487v1[hep-ex]; arXiv:1202.1488v1.
   ATLAS collaboration, ATLAS-CONF-2012-019, March 7, 2012.
   The TEVNPH Working Group for the CDF and D0 Collaboration, FERMILAB-CONF-12-065-E.