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Flavour Physics in the Littlest Higgs Model with T-Parity

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We present the results of an extensive analysis of flavour physics in both quark and lepton sectors, in the Littlest Higgs model with T-parity (LHT). In the quark sector, we identify some interesting scenarios for new mirror quark masses and V_{Hd} mixing matrix that satisfy the existing experimental constraints from K and B physics and simultaneously allow large New Physics effects in rare decays and CP-violating observables. In the lepton sector, where flavour violation in the Standard Model is highly suppressed by small neutrino masses, LHT effects turn out to be naturally huge and could be seen in the near future measurements of lepton flavour violating decays.

1 The LHT Model

The Standard Model (SM) is in excellent agreement with the results of particle physics experiments, in particular with the electroweak (ew) precision measurements, thus suggesting that the SM cutoff scale is at least as large as 10. Having such a relatively high cutoff, however, the SM requires an unsatisfactory fine-tuning to yield a correct ($\approx 10^2$) scale for the squared Higgs mass, whose corrections are quadratic and therefore highly sensitive to the cutoff. This *little hierarchy problem* has been one of the main motivations to elaborate models of physics beyond the SM. While Supersymmetry is at present the leading candidate, different proposals have been formulated more recently. Among them, Little Higgs models play an important role, being perturbatively computable up to about 10 and with a rather small number of parameters, although their predictivity can be weakened by a certain sensitivity to the unknown ultra-violet (UV) completion of these models.

In Little Higgs models [1] the Higgs is naturally light as it is identified with a Nambu-Goldstone boson (NGB) of a spontaneously broken global symmetry. An exact NGB, however, would have only derivative interactions. Gauge and Yukawa interactions of the Higgs have to be incorporated. This can be done without generating quadratically divergent one-loop contributions to the Higgs mass, through the so-called *collective symmetry breaking*. Collective symmetry breaking (SB) has the peculiarity of generating the Higgs mass only when two or more couplings in the Lagrangian are non-vanishing, thus avoiding one-loop quadratic divergences. This mechanism is diagrammatically realized through the contributions of new particles with masses around 1, that cancel the SM quadratic divergences.

The most economical, in matter content, Little Higgs model is the Littlest Higgs (LH) [2], where the global group $SU(5)$ is spontaneously broken into $SO(5)$ at the scale $f \approx \mathcal{O}(1)$ and the ew sector of the SM is embedded in an $SU(5)/SO(5)$ non-linear sigma model. Gauge and Yukawa Higgs interactions are introduced by gauging the subgroup of $SU(5)$: $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$, with gauge couplings respectively equal to g_1, g_1', g_2, g_2'. The key feature for the realization of collective SB is that the two gauge factors commute with a different $SU(3)$ global symmetry subgroup of $SU(5)$, that prevents the Higgs from becoming massive when the couplings of one of the two gauge factors vanish. Consequently, quadratic corrections to the squared Higgs mass involve two couplings and cannot appear at one-loop. In the LH model, the new particles appearing at the scales are the heavy gauge bosons $(W_H^\pm, Z_H, A_H)$ the heavy top (T) and the scalar triplet Φ.

In the LH model, significant corrections to ew observables come from tree-level heavy gauge boson contributions and the triplet vacuum expectation value (vev) which breaks the custodial $SU(2)$ symmetry. Consequently, ew precision tests are satisfied only for quite large values of the New Physics (NP) scale $f \geq 2-3$ [3,4], unable to solve the little hierarchy problem. Motivated by reconciling the LH model with ew precision tests, Cheng and Low [5] proposed to enlarge the symmetry structure of the theory by introducing a discrete symmetry called T-parity. T-parity acts as an automorphism which exchanges the $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ gauge factors. The invariance of the theory under this automorphism implies $g_1 = g_2$ and $g_1' = g_2'$. Furthermore, T-parity explicitly forbids the tree-level contributions of heavy gauge bosons and the interactions that induced the triplet vev. The custodial $SU(2)$ symmetry is restored and the compatibility with ew precision data is obtained already for smaller values of the NP scale, $f \geq 500$ [6]. Another important consequence is that particle fields are T-even or T-odd under T-parity. The SM particles and the heavy top T_+ are T-even, while the heavy gauge bosons $W_H^\pm, Z_H, A_H$ and the scalar triplet Φ are T-odd. Additional T-odd particles are required by T-parity: the odd heavy top T_- and the so-called mirror fermions, i.e., fermions corresponding to the SM ones but with opposite T-parity and $\mathcal{O}(1)$ mass. Mirror fermions are characterized by new flavour interactions with SM fermions and heavy gauge bosons, which involve two new unitary mixing matrices, in the quark sector, analogous to the Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM} [7]. They are V_{Hd} and V_{Hu}, respectively involved when the SM quark is of down- or up-type, and satisfying $V_{Hu}^\dagger V_{Hd} = V_{CKM}$ [8]. Similarly, two new mixing matrices, $V_{H\ell}$ and $V_{H\nu}$, appear in the lepton sector, respectively involved when the SM lepton is charged or a neutrino and related to the PMNS matrix [9] through $V_{H\nu}^{\dagger}V_{H\ell} = V_{PMNS}^{\dagger}$. Both V_{Hd} and $V_{H\ell}$ contain 3 angles, like V_{CKM} and V_{PMNS}, but 3 (non-Majorana) phases [10], i.e. two additional phases relative to the SM matrices, that cannot be rotated away in this case.

Because of these new mixing matrices, the LHT model does not belong to the Minimal Flavour Violation (MFV) class of models [11, 12] and significant effects in flavour observables are possible. Other LHT peculiarities are the rather small number of new particles and parameters (the SB scale f, the parameter x_L describing T_+ mass and interactions, the mirror fermion masses and V_{Hd} and $V_{H\ell}$ parameters) and the absence of new operators in addition to the SM ones. On the other hand, one has to recall that Little Higgs models are low energy non-linear sigma models, whose unknown UV-completion introduces a theoretical uncertainty reflected by a left-over logarithmic cut-off dependence [13, 14] in $\Delta F = 1$ processes.

2 LHT Flavour Analysis

Several studies of flavour physics in the LH model without T-parity have been performed in the last four years [15]. Without T-parity, mirror fermions and new sources of flavour and CP-violation are absent, the LH model is a MFV model and NP contributions result to be very small.

More recently, flavour physics analyses have been also performed in the LHT model, for both quark [8, 14, 16] and lepton sectors [17, 18]. In this model, new mirror fermion interactions can yield large NP effects, mainly in K and B rare and CP-violating decays and in lepton flavour violating decays.

2.1 LHT Analysis in the Quark Sector

In [14, 16] we have studied in the LHT model B and K meson mixings, CP-violation, rare decays and the radiative decay $B \to X_s\gamma$. We have imposed well known experimental constraints and estimated LHT effects in those observables that are not yet measured or still very uncertain. We have considered several scenarios for the structure of the V_{Hd} matrix and the mass spectrum of mirror quarks in order to gain a global view over possible LHT signatures. The parameters f and x_L have been fixed to $f = 1$ and $x_L = 0.5$ in accordance with ew precision tests [6]. The CKM parameters entering the analysis have been taken from tree level decays only, where NP effects can be neglected. In order to simplify the numerical analysis we have set all non-perturbative parameters to their central values, while allowing ΔM_K, ε_K, ΔM_d, ΔM_s, $\Delta M_s/\Delta M_d$ and $S_{\psi K_S}$ to differ from their experimental values by ±50%, ±40%, ±40%, ±40%, ±20% and ±8%, respectively. This rather conservative choice guarantees that important effects are not missed.

Two interesting scenarios have been identified. In the first one (B-scenario)

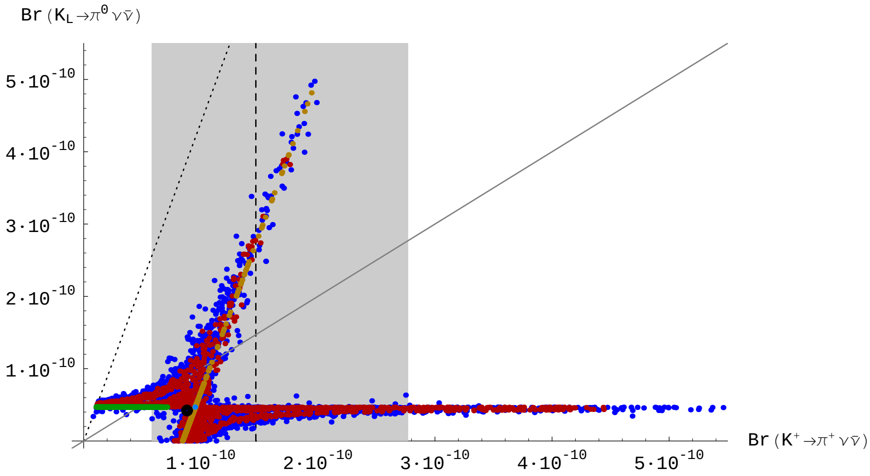

Figure 1: *$Br(K_L \to \pi^0\nu\overline{\nu})$ as a function of $Br(K^+ \to \pi^+\nu\overline{\nu})$. The shaded area represents the experimental 1σ-range for $Br(K^+ \to \pi^+\nu\overline{\nu})$. The model-independent Grossman-Nir bound [19] is displayed by the dotted line, while the solid line separates the two areas where $Br(K_L \to \pi^0\nu\overline{\nu})$ is larger or smaller than $Br(K^+ \to \pi^+\nu\overline{\nu})$.*

large enhancements in B physics are possible, while in the second one (K-scenario) important effects appear in K observables. They are both characterized by the quasi-degeneracy of the first two mirror quark generations ($m_{H1} \simeq m_{H2} \simeq 500$, $m_{H3} \simeq 1000$), as required by ΔM_K and ε_K constraints. The new mixing angles in V_{Hd} are chosen to satisfy the hierarchy $s^d_{23} \ll s^d_{13} \leq s^d_{12}$ in B-scenario and the hierarchy $s^d_{23} \simeq s^d_{13} < s^d_{12} = 1/\sqrt{2}$ in K-scenario. Moreover, the two additional phases of V_{Hd}, whose impact is numerically small, have been set to zero. In addition, in order to explore all possible LHT effects, we have performed a general scan over mirror quark masses and V_{Hd} parameters. In the following scatter plots, B- and K-scenarios and general scan are respectively displayed as green, brown and blue points, while red points correspond to a less general scan over V_{Hd} parameters at fixed mirror masses ($m_{H1} = 400$, $m_{H2} = 500$, $m_{H3} = 600$).

The main results of our LHT analysis [14, 16] in the quark sector are:

- The most evident departures from the SM predictions are found for CP-violating observables that are strongly suppressed in the SM. These are the branching ratio for $K_L \to \pi^0\nu\overline{\nu}$ (Fig. 1) and the CP-asymmetry $S_{\psi\phi}$, that can be enhanced by an order of magnitude relative to the SM predictions. Large departures from SM expectations are also possible for $Br(K_L \to \pi^0\ell^+\ell^-)$ (Fig. 2), $Br(K^+ \to \pi^+\nu\overline{\nu})$ (Fig. 1) and the semileptonic CP-asymmetry $A^s_{\rm SL}$, that can be enhanced by an order of magnitude w.r.t the SM.

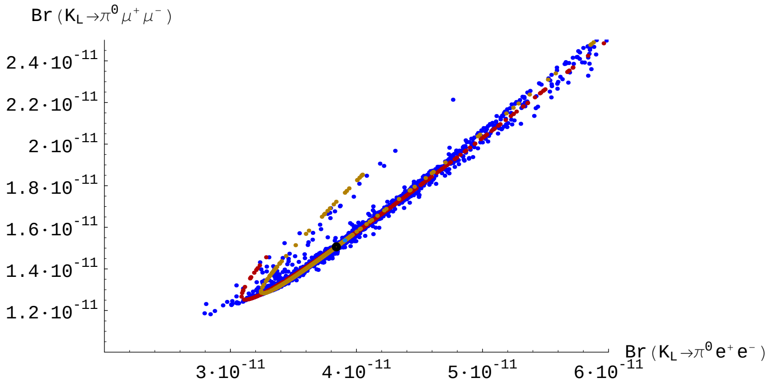

Figure 2: *$Br(K_L \to \pi^0\mu^+\mu^-)$ as a function of $Br(K_L \to \pi^0 e^+e^-)$.*

- The branching ratios for $B_{s,d} \to \mu^+\mu^-$ and $B \to X_{s,d}\nu\overline{\nu}$, instead, are modified by at most 50% and 35%, respectively, and the effects of new electroweak penguins in $B \to \pi K$ are small, in agreement with the recent data. The new physics effects in $B \to X_{s,d}\gamma$ and $B \to X_{s,d}\ell^+\ell^-$ turn out to be below 5% and 15%, respectively, so that agreement with the data can easily be obtained.

- Small, but still significant effects have been found in $B_{s,d}$ mass differences. In particular, a 7% suppression of ΔM_s is possible, thus improving the compatibility with the recent experimental measurement [20].

- The possible "discrepancy" [21–23] between the values of $\sin 2\beta$ following directly from $A_{\rm CP}(B_d \to \psi K_S)$ and indirectly from the analysis of the unitarity triangle involving only tree-level processes, and in particular $|V_{ub}|$, can be cured within the LHT model thanks to a new phase $\varphi_{B_d} \simeq -5^o$.

- The universality of new physics effects, characteristic for MFV models, can be largely broken, in particular between K and $B_{s,d}$ systems. NP effects, in fact, are typically larger in K system where the SM contribution is CKM-suppressed. In particular, sizable departures from MFV relations between $\Delta M_{s,d}$ and $Br(B_{s,d} \to \mu^+\mu^-)$ and between $S_{\psi K_S}$ and the $K \to \pi\nu\overline{\nu}$ decay rates are possible.

2.2 LHT Analysis in the Lepton Sector

In contrast to rare K and B decays, where the SM contributions play an important and often dominant role in the LHT model, the smallness of ordinary neutrino masses

decay	$f = 1000$	$f = 500$	exp. upper bound
$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$ $(1 \cdot 10^{-11})$	$1.2 \cdot 10^{-11}$ $(1 \cdot 10^{-11})$	$1.2 \cdot 10^{-11}$ [24]
$\mu^- \to e^-e^+e^-$	$1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$	$1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$	$1.0 \cdot 10^{-12}$ [25]
$\mu\text{Ti} \to e\text{Ti}$	$2 \cdot 10^{-10}$ $(5 \cdot 10^{-12})$	$4 \cdot 10^{-11}$ $(5 \cdot 10^{-12})$	$4.3 \cdot 10^{-12}$ [26]
$\tau \to e\gamma$	$8 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$1.1 \cdot 10^{-7}$ [27]
$\tau \to \mu\gamma$	$8 \cdot 10^{-10}$ $(8 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$4.5 \cdot 10^{-8}$ [28]
$\tau^- \to e^-e^+e^-$	$7 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$7 \cdot 10^{-8}$ $(7 \cdot 10^{-8})$	$2.0 \cdot 10^{-7}$ [29]
$\tau^- \to \mu^-\mu^+\mu^-$	$7 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$7 \cdot 10^{-8}$ $(6 \cdot 10^{-8})$	$1.9 \cdot 10^{-7}$ [29]
$\tau^- \to e^-\mu^+\mu^-$	$5 \cdot 10^{-10}$ $(5 \cdot 10^{-10})$	$6 \cdot 10^{-8}$ $(6 \cdot 10^{-8})$	$2.0 \cdot 10^{-7}$ [30]
$\tau^- \to \mu^-e^+e^-$	$5 \cdot 10^{-10}$ $(5 \cdot 10^{-10})$	$6 \cdot 10^{-8}$ $(5 \cdot 10^{-8})$	$1.9 \cdot 10^{-7}$ [30]
$\tau^- \to \mu^-e^+\mu^-$	$5 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$5 \cdot 10^{-14}$ $(5 \cdot 10^{-14})$	$1.3 \cdot 10^{-7}$ [29]
$\tau^- \to e^-\mu^+e^-$	$5 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$5 \cdot 10^{-14}$ $(4 \cdot 10^{-14})$	$1.1 \cdot 10^{-7}$ [29]
$\tau \to \mu\pi$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	$2 \cdot 10^{-7}$ $(1 \cdot 10^{-7})$	$4.1 \cdot 10^{-7}$ [31]
$\tau \to e\pi$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	$2 \cdot 10^{-7}$ $(1 \cdot 10^{-7})$	$1.9 \cdot 10^{-7}$ [31]
$\tau \to \mu\eta$	$6 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$6 \cdot 10^{-8}$ $(5 \cdot 10^{-8})$	$1.5 \cdot 10^{-7}$ [31]
$\tau \to e\eta$	$6 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$6 \cdot 10^{-8}$ $(5 \cdot 10^{-8})$	$2.4 \cdot 10^{-7}$ [31]
$\tau \to \mu\eta'$	$7 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$8 \cdot 10^{-8}$ $(8 \cdot 10^{-8})$	$4.7 \cdot 10^{-7}$ [31]
$\tau \to e\eta'$	$7 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$8 \cdot 10^{-8}$ $(7 \cdot 10^{-8})$	$1.0 \cdot 10^{-6}$ [31]
$K_L \to \mu e$	$4 \cdot 10^{-13}$ $(2 \cdot 10^{-13})$	$3 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$4.7 \cdot 10^{-12}$ [32]
$K_L \to \pi^0\mu e$	$4 \cdot 10^{-15}$ $(2 \cdot 10^{-15})$	$5 \cdot 10^{-16}$ $(5 \cdot 10^{-16})$	$6.2 \cdot 10^{-9}$ [33]
$B_d \to \mu e$	$5 \cdot 10^{-16}$ $(2 \cdot 10^{-16})$	$9 \cdot 10^{-17}$ $(9 \cdot 10^{-17})$	$1.7 \cdot 10^{-7}$ [34]
$B_s \to \mu e$	$5 \cdot 10^{-15}$ $(2 \cdot 10^{-15})$	$9 \cdot 10^{-16}$ $(9 \cdot 10^{-16})$	$6.1 \cdot 10^{-6}$ [35]
$B_d \to \tau e$	$3 \cdot 10^{-11}$ $(2 \cdot 10^{-11})$	$3 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$1.1 \cdot 10^{-4}$ [36]
$B_s \to \tau e$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$3 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	—
$B_d \to \tau\mu$	$3 \cdot 10^{-11}$ $(3 \cdot 10^{-11})$	$3 \cdot 10^{-10}$ $(3 \cdot 10^{-10})$	$3.8 \cdot 10^{-5}$ [36]
$B_s \to \tau\mu$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$3 \cdot 10^{-9}$ $(3 \cdot 10^{-9})$	—

Table 1: *Upper bounds on LFV decay branching ratios in the LHT model, for two different values of the scale f, after imposing the constraints on $\mu \to e\gamma$ and $\mu^- \to e^-e^+e^-$. The numbers given in brackets are obtained after imposing the additional constraint $R(\mu Ti \to e Ti) < 5 \cdot 10^{-12}$. The current experimental upper bounds are also given.*

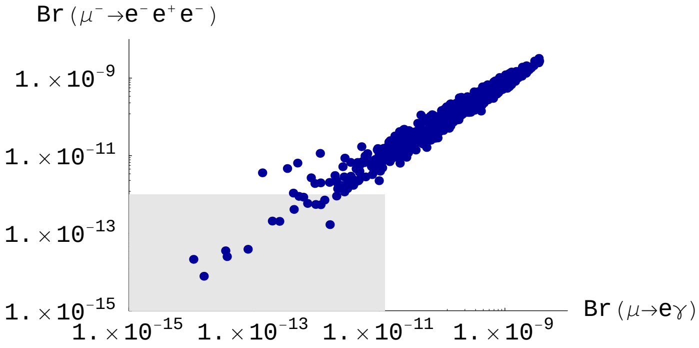

Figure 3: *Correlation between the branching ratios for $\mu \to e\gamma$ and $\mu^- \to e^- e^+ e^-$ from a general scan over the LHT parameters. The shaded area represents present experimental upper bounds.*

assures that mirror fermion contributions to lepton flavour violating (LFV) processes are by far the dominant effects. Moreover, the absence of QCD corrections and hadronic matrix elements allows in most cases to make predictions entirely within perturbation theory.

In [18] we have studied the most interesting LFV processes: $\ell_i \to \ell_j \gamma$, $\tau \to \ell P$ (with $P = \pi, \eta, \eta'$), $\mu^- \to e^- e^+ e^-$, the six three-body decays $\tau^- \to l_i^- l_j^+ l_k^-$ and the rate for $\mu - e$ conversion in nuclei. We have also calculated the rates for $K_{L,S} \to \mu e$, $K_{L,S} \to \pi^0 \mu e$, $B_{d,s} \to \mu e$, $B_{d,s} \to \tau e$ and $B_{d,s} \to \tau \mu$.

At variance with meson decays, the number of flavour violating decays in the lepton sector, for which significant experimental constraints exist, is rather limited. Basically only the upper bounds on $Br(\mu \to e\gamma)$, $Br(\mu^- \to e^- e^+ e^-)$, $Br(K_L \to \mu e)$ and $R(\mu\text{Ti} \to e\text{Ti})$ can be used in our analysis. The situation may change significantly in the coming years thanks to near future experiments [26, 37–39]. Meanwhile, we have estimated LHT effects, imposing the experimental bounds mentioned above and scanning over mirror lepton masses in the range $[300, 1500]$ and over the parameters of the $V_{H\ell}$ mixing matrix, with the symmetry breaking scale f fixed to $f = 1$ or $f = 500$ in accordance with ew precision tests [6].

We have found that essentially all the rates considered can reach or approach present experimental upper bounds, as shown in table 1. In particular, in order to suppress the $\mu \to e\gamma$ and $\mu^- \to e^- e^+ e^-$ decay rates below the experimental upper bounds (see Fig. 3), the $V_{H\ell}$ mixing matrix has to be rather hierarchical, unless mirror leptons are quasi-degenerate.

Moreover, following the strategy proposed in [40–42] in the supersymmetric framework, we have identified certain correlations between branching ratios that are less

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.4\ldots2.5$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.4\ldots2.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to\mu^-\mu^+\mu^-)}{Br(\tau\to\mu\gamma)}$	$0.4\ldots2.3$	$\sim 2\cdot10^{-3}$	< 0.2
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.3\ldots1.6$	$\sim 2\cdot10^{-3}$	< 0.1
$\frac{Br(\tau^-\to\mu^-e^+e^-)}{Br(\tau\to\mu\gamma)}$	$0.3\ldots1.6$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$1.3\ldots1.7$	~ 5	$0.1\ldots5$
$\frac{Br(\tau^-\to\mu^-\mu^+\mu^-)}{Br(\tau^-\to\mu^-e^+e^-)}$	$1.2\ldots1.6$	~ 0.2	$0.2\ldots20$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-2}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$> 5\cdot10^{-3}$

Table 2: *Comparison of various ratios of branching ratios in the LHT model and in the MSSM without and with significant Higgs contributions.*

parameter dependent than the individual branching ratios and could provide a clear signature of the model. In particular, we find that the ratios $Br(\ell_i \to \ell_j\ell_j\ell_j)/Br(\ell_i \to \ell_j\gamma)$, $Br(\ell_i \to \ell_j\ell_j\ell_j)/Br(\ell_i \to \ell_j\ell_k\ell_k)$ and $Br(\ell_i \to \ell_j\ell_k\ell_k)/Br(\ell_i \to \ell_j\gamma)$ could allow for a transparent distinction between the LHT model and the MSSM (see Table 2).

Finally, we have studied the muon anomalous magnetic moment finding that, even for values of the NP scale f as low as 500, $a_\mu^{\mathrm{LHT}} < 1.2\cdot10^{-10}$. This value is roughly a factor 5 below the current experimental uncertainty [43], implying that the possible discrepancy between the SM prediction and the data cannot be solved in the LHT model.

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