Distinguishing the Littlest Higgs model with T-parity from supersymmetry at the LHC using trileptons

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Abstract

We analyse hadronically quiet trilepton signatures in the T-parity conserving Littlest Higgs model and in R-parity conserving supersymmetry at the Large Hadron Collider. We identify the regions of the parameter space where such signals can reveal the presence of these new physics models above the Standard Model background and distinguish them from each other, even in a situation when the mass spectrum of the Littlest Higgs model resembles the supersymmetric pattern.
Little Higgs models have emerged recently as a class of alternative new physics schemes for justifying the smallness of the Standard Model (SM) Higgs boson mass [1,2]. Precision electroweak constraints normally imply that the mass scale of the new particles in such theories has to be on the order of several TeV [3], thus leading to a somewhat distasteful degree of fine-tuning. The problem is circumvented through the coinage of an additional discrete symmetry, the so-called T-parity [4,5], whereby all particles in the spectrum are classified as T-even(odd). This allows one to have the Higgs mass protected from quadratic divergences, and at the same time see a spectrum of additional gauge bosons, scalars and fermions, in the mass range of a few hundred GeV’s, with the lightest T-odd particle (LTP) being stable. Although it has been recently pointed out [6] that T-parity can be broken by topological effects arising from anomaly terms, the presence of such effects may not be absolutely certain in an ultraviolet incomplete theory. Therefore, while the consequence of broken T-parity requires careful attention [6,7], it is desirable from a phenomenological point of view to understand the collider signatures of unbroken T-parity as well, together with its distinctive features in relation to other new theories predicting weakly interacting massive particles.

The experimental signals of a scenario with T-parity have close resemblance with those of supersymmetry (SUSY) with conserved R-parity. This is best demonstrated in the context of a simple version of the model, namely, the Littlest Higgs model with T-parity (LHT) [5,8,9]. With the LTP carrying away substantial missing transverse momentum, accompanied by jets and/or leptons rendered hard through the release of energy in the decay of heavy fermions, the LHT, to a first approximation, may indeed look like SUSY. A number of studies have already predicted interesting phenomenological consequences of the LHT, for instance at the Large Hadron Collider (LHC) [8–13]. A few papers have also addressed the question of distinction between the LHT and SUSY at the LHC [14–16] (for non-collider signals, see Ref. [17]). However, there still remains ample need for suggesting new ways of discriminating between the two scenarios. Such a method is proposed in this note, where we emphasise the role played by the non-strongly interacting sectors of such theories, and analyse ‘hadronically quiet’ trilepton signals at the LHC.

Of course, the new particles in SUSY and LHT, whose signals can mimic each other, have different spins. However, extraction of spin information is notoriously difficult at the LHC. Another major difference between the LHT scenario and SUSY lies in the non-existence of a counterpart for the gluino, as the strongly interacting sector is untouched in Little Higgs models which are essentially schemes for stabilisation of the electroweak sector. It has been suggested in this light, for example, in [14], that in the so-called ‘co-annihilation region’, a SUSY scenario produces more multi-jet events compared to the LHT, because of production channels involving a gluino. More importantly, since the gluino is a Majorana fermion, its pair-production followed by cascade decays can produce like- and unlike-sign charginos with equal probability, thus leading to a substantial enhancement of final states with like-sign dileptons. While this can provide a tangible discrimination between the two types of theories, it becomes unavailable if the gluino is far too heavy (say, 2 TeV or more). In such cases, of course, pair-production of same-sign squarks in SUSY and of same-sign heavy quarks in LHT can give rise to like-sign dileptons.
According to a recent study [15], once one filters away the kinematical regions where gluino cascades contribute, the ratio between like- and unlike-sign dileptons is different in the two cases. While such a claim is reassuring, it is better to have some additional discriminating signals, preferably involving the electroweak sector alone. The purpose of this note is to suggest the ‘hadronically quiet’ trilepton channel in this context. It should also be emphasised that we envision a situation where new signals are seen, and some idea about the masses of the new particles is available from the hardness of leptons and/or jets or the missing-$p_T$ distribution.

In the LHT a global symmetry $SU(5)$ is spontaneously broken down to $SO(5)$ at a scale $f \sim 1$ TeV. An $[SU(2) \times U(1)]^2$ gauge symmetry is imposed, which is simultaneously broken at $f$ to the diagonal subgroup $SU(2)_L \times U(1)_Y$, which is identified with the SM gauge group. This leads to four heavy gauge bosons $W_H^\pm, Z_H, A_H$ with masses $\sim f$ in addition to the SM gauge fields. The SM Higgs doublet is part of an assortment of pseudo-Goldstone bosons which result from the spontaneous breaking of the global symmetry. This symmetry protects the Higgs mass from getting quadratic divergences at one loop, even in the presence of gauge and Yukawa interactions. Electroweak symmetry is broken via the Coleman-Weinberg mechanism and the Higgs mass is generated radiatively, leading naturally to a light Higgs boson. The multiplet of Goldstone bosons contains a heavy $SU(2)$ triplet scalar $\Phi$ as well. In contrast to SUSY, the new states which cancel the quadratically divergent contributions to the Higgs mass due to the top quark, gauge boson and Higgs boson loops, respectively, are heavy fermions, additional gauge bosons and triplet Higgs states.

In order to comply with strong constraints from electroweak precision data on the Littlest Higgs model [3], one imposes T-parity [4] which maps the two pairs of gauge groups $SU(2)_i \times U(1)_i, i = 1, 2$ into each other, forcing the corresponding gauge couplings to be equal, with $g_1 = g_2$ and $g'_1 = g'_2$. All SM particles, including the Higgs doublet, are even under T-parity, whereas the four additional heavy gauge bosons and the Higgs triplet are T-odd. The top quark has two heavy fermionic partners, $T_+$ (T-even) and $T_-$ (T-odd). For consistency of the model, one has to introduce the additional heavy, T-odd vector-like fermions $u^H_i, d^H_i, e^H_i$ and $\nu^H_i (i = 1, 2, 3)$ for each SM quark and lepton field. For further details on the LHT, we refer the reader to Refs. [5, 8, 9, 18]. As shown in Refs. [18–20], a scale $f$ (which dictates the masses of most new particles) as low as 500 GeV is compatible in the LHT with electroweak precision data. Further constraints on the parameters of the LHT come from flavour physics [21].

The masses of the heavy gauge bosons in the LHT are given by

$$m_{W_H} = m_{Z_H} = gf \left(1 - \frac{v^2}{8f^2}\right) \approx 0.65f, \quad m_{A_H} = \frac{fg'}{\sqrt{5}} \left(1 - \frac{5v^2}{8f^2}\right) \approx 0.16f,$$

where corrections of $O(v^2/f^2)$ are neglected in the approximate numerical values. Thus these particles have masses of several hundreds of GeV for $f \sim 1$ TeV, although $A_H$, the heavy partner of the photon, can be quite light, because of the small prefactor, and is usually assumed to be the LTP. The masses of the heavy, T-odd fermions are
determined by general $3 \times 3$ mass matrices in the (mirror) flavour space, $m_{qH,lH}^{ij} \sim \kappa_q^{ij} f$
with $i,j = 1,2,3$. We simplify our analysis by assuming that $\kappa_q^{ij} = \kappa_q \delta^{ij}$. The parameter $\kappa_q \sim \mathcal{O}(1)$ thus determines the masses of the heavy quarks in the following way:

\[ m_{uH} = \sqrt{2} \kappa_q f \left( 1 - \frac{\delta^2}{8 f^2} \right), \quad m_{dH} = \sqrt{2} \kappa_q f. \tag{2} \]

Similarly, masses of the heavy leptons in the spectrum are determined by a common parameter $\kappa_l$. We further assume that the values for $\kappa_{q,l}$ are not close to the upper bound $\kappa \leq 4.8$ (for $f = 1$ TeV) obtained from 4-fermion operators [18] and that limits of $m > \mathcal{O}(100$ GeV) from direct searches at the Large Electron Positron (LEP) collider apply to the mirror fermions in the LHT. Thus our analysis takes $\kappa_{q,l}$ in the range $0.2 \lesssim \kappa_{q,l} \lesssim 2$, thereby allowing all new heavy fermions to have masses ranging from several hundreds of GeV to a TeV, for $f \sim 1$ TeV. For our analysis we have used $\kappa_l = 0.4$, with $\kappa_q = 1$ and 1.5. This yields masses of the heavy leptons and quarks which are spaced relative to each other in a way often encountered in SUSY for sleptons and squarks, so that the situation where one spectrum fakes the other at colliders is best addressed. A value of $\kappa_l \lesssim 0.2$ leads to a heavy neutrino LTP, whose phenomenology is somewhat different from that of SUSY with a neutralino LSP.

Thus $f$, together with $\kappa_{q,l}$, determines the part of the LHT spectrum relevant for us. The mass of the triplet scalar $\Phi$ is related to the doublet Higgs mass by

\[ m_\Phi = \sqrt{2} m_H \frac{f}{v}. \tag{3} \]

We will take $m_H = 120$ GeV throughout this paper. Two more dimensionless parameters $\lambda_1$ and $\lambda_2$ appear in the top quark sector; the top mass being given by $m_t = (\lambda_1/\sqrt{1 + R^2})v$ and $R = \lambda_1/\lambda_2$. The masses of the two heavy partners of the top quark, $T_+$ and $T_-$, can be expressed as

\[ m_{T_+} = \lambda_2 \sqrt{1 + R^2} f, \quad m_{T_-} = \lambda_2 f. \tag{4} \]

We use $m_t = 171.4$ GeV in our analysis and set $R = 1$, although this does not have any significant bearing on our analysis.

Hadronically quiet final states comprising of trileptons can be produced in an LHT scenario via $qq' \rightarrow W_H^\mp Z_H$ (see Figure 1(a)). The most obvious way to trileptons from this is $W_H^\mp \rightarrow A_H W^\pm \rightarrow A_H l^\pm \nu_l$, and $Z_H \rightarrow A_H Z \rightarrow A_H l^\pm l^\mp$. However, the SM backgrounds, of which WZ-production is the dominant source, need to be eliminated, the easiest way being to disallow events with the invariant mass of any two opposite-sign leptons in the neighbourhood of the $Z$-mass. While this takes away many signal events, one can still have trileptons if the T-odd heavy leptons are lighter than the $Z_H$. In that case, the decay channel $Z_H \rightarrow l_H^{\pm} l_H^{\mp}$ followed by $l_H^{\pm} \rightarrow A_H l^\pm$ opens up, and the trilepton events can be quite copious in such a region of the parameter space. As an example, one can see that for $\kappa_l = 0.4$ and $f = 500$ GeV one has $m_{Z_H} = 317$ GeV, $m_{l_H^{\pm}} = 283$ GeV and $m_{A_H} = 65$ GeV. We shall comment later on the case where a real $l_H$ cannot be produced in $Z_H$-decays.

\[ ^1 \text{We also performed the same analysis for higher } \kappa_l \text{ values (} \kappa_l = 1 \text{) and found the event rates both in the LHT and SUSY to be too small to be observable after the cuts. We will discuss this point later.} \]
Figure 1: Representative leading order Feynman graphs contributing to the pair production of $W^\pm Z_H$ in the LHT (a) and to $\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ in SUSY (b) at the LHC.

Similar signals in SUSY are well-studied by now at hadron colliders [22, 23]; the main production channel in a minimal model being $qq' \rightarrow \tilde{\chi}^\pm_1\tilde{\chi}^0_2$ (see Figure 1(b)), with $\tilde{\chi}^\pm_1 \rightarrow \nu_l l^\pm \rightarrow \nu_l l^\pm \tilde{\chi}^0_1$ and $l^\pm \rightarrow l^\pm l^\pm \tilde{\chi}^0_1$. The signals are not affected by the invariant mass cut so significantly as in the case of LHT. This feature (namely, the susceptibility to invariant mass cut) itself enables discrimination between the two scenarios. However, as we shall see below, clear quantitative distinction can be made from the predicted strength of the signal as a whole.

The other major source of trileptons can be the production of heavy quarks followed by their cascade decays into leptons via $W^\pm H$ or $Z_H$ decays. The SUSY counterpart of such processes will be the production of squarks followed by their cascade decays into leptons via chargino and neutralino decays. Such processes will be accompanied by two jets, but if these jets are extremely soft, they can escape detection and therefore such events can be misidentified as hadronically quiet. As we shall see later, our jet recognition criteria disallow such final states, and thus one can fully concentrate on final states which genuinely originate in the electroweak sector.

To see whether the LHT signal may be mimicked by the corresponding supersymmetric signal, one has to go to situations where their particle spectra have a close correspondence. It is assumed that the masses of the particles produced in the hard scattering, and that of the invisible particle (LTP/LSP) in the final state, can be extracted from various kinematic distributions. These masses, it has been claimed, can be estimated at the LHC.
up to an uncertainty of about $20 - 30$ GeV for SUSY particles [24]. These references also indicate that the uncertainty can be much less in situations where the masses are correlated, as in a supergravity scenario. It is not unreasonable to expect a similar level of precision in the case of the LHT where the masses of $W_H, Z_H$ and $A_H$ are all related to the parameter $f$.

At each chosen value of $(f, \kappa_q, \kappa_l)$ in our analysis, we equate the masses of the squarks and sleptons to those of the heavy quarks and leptons determined by the relations given in Eq. (2). Next, we try to align the heavy gauge boson masses in Eq. (1) to those of the low-lying neutralinos and charginos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$) which play a crucial role in the production of trileptons. This is best done in a minimal SUSY scenario where the gaugino masses ($M_1, M_2$) are not constrained by the requirement of unification at a high scale. $M_1$, the Bino mass, is set equal to $m_{A_H}$. Next, we set a correspondence between $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0})$ and $(m_{W_H}, m_{Z_H})$ for both the cases where the former pair is dominated by the Wino and the Higgsino. This is done by adopting two scenarios, namely, (a) $M_1 = m_{A_H}, M_2 = m_{Z_H}$ and $\mu = 1.5$ TeV (henceforth to be called the SS1 scenario), and (b) $M_1 = m_{A_H}, \mu = m_{Z_H}$ and $M_2 = 1.5$ TeV (henceforth to be called the SS2 scenario). The physical chargino and neutralino states are subsequently obtained by diagonalisation of the respective mass matrices, and, as seen in Table 1, they indeed demonstrate a very close resemblance of the spectra between LHT and SUSY.

We assume $M_3$ to be 5 TeV, thus decoupling the gluinos as desired. For the sake of simplicity, we set all the trilinear couplings ($A$) to zero, except $A_t$, which we tune to get the lighter CP-even Higgs mass $m_H = 120$ GeV as in the case of the LHT. Our analysis is not affected by this tuning. Note that it is not possible to match all particles in the minimal supersymmetric standard model (MSSM) into corresponding states in the LHT and vice-versa; for instance, the heavy quarks $T_{\pm}$ do not have a counterpart in the MSSM. On the other hand, there are no states in the LHT that would correspond to the heavier chargino and neutralinos. Furthermore, the rest of the Higgs sector (the charged scalar, the heavier neutral scalar and the pseudoscalar in SUSY, and the triplet states in LHT) does not correspond similarly. This, too, does not affect the signals under consideration here. Finally, we use $\tan \beta = 10$ and $m_A = 850$ GeV throughout for the calculations in the MSSM.

We use the CalcHEP 2.5.i [25] model file for the LHT written by the authors of Ref. [11] to calculate cross-sections and branching fractions. For the subsequent simulations, the cross-sections generated with CalcHEP are then interfaced into PYTHIA 6.410 [26]. The cross-sections and branching fractions for the MSSM are calculated directly in PYTHIA. The parton densities for the calculation of cross-sections at the LHC are evaluated at leading order using CTEQ6L [27] with renormalisation and factorisation scale fixed by $\mu_R = \mu_F = \sqrt{s}$.

In Figure 2, we plot the pair production cross-sections at the LHC for $W_H^+ Z_H$ with

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2 The states $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ should be close to each other in mass (like $W_H$ and $Z_H$), but considerably heavier than $\tilde{\chi}_1^0$ (like $A_H$). Matching the LHT spectrum, controlled by the parameter $f$, in this manner is not possible with $\mu \lesssim M_1$. Consequently, $\tilde{\chi}_1^0$ remains Bino-dominated in our analysis.
\[ \kappa_l = \kappa_q = 1 \]

| \( f \) | \( m_{A_H} \) | \( m_{Z_H} \) | \( m_{\tilde{d}_H} \) | \( m_{\tilde{u}_H} \) | \( m_{\tilde{t}_1} \) | \( m_{\tilde{t}^\pm} \) | Case | \( m_{\tilde{\chi}^0_1} \) | \( m_{\tilde{\chi}^0_2} \) | \( m_{\tilde{\chi}^\pm_1} \) |
|-------|--------|--------|--------|--------|--------|--------|-------|--------|--------|--------|
| 500   | 66.2   | 316.7  | 707.1  | 685.7  | 707.1  | 685.7  | SS1   | 65.9   | 314.9  | 314.9  |
| 1000  | 150.2  | 648.3  | 1414.2 | 1403.5 | 1414.2 | 1403.5 | SS2   | 149.8  | 645.0  | 645.0  |
| \( \kappa_l = 0.4, \kappa_q = 1 \) | | | | | | | | | |
| 500   | 66.2   | 316.7  | 707.1  | 282.8  | 274.2  | SS1   | 65.9   | 314.9  | 314.9  |
| 1000  | 150.2  | 648.3  | 1414.2 | 565.7  | 561.4  | SS2   | 148.9  | 645.6  | 646.0  |

Table 1: LHT and SUSY mass spectrum in GeV for fixed \( f, \kappa_l \) and \( \kappa_q \). The Higgs mass and top mass are taken to be \( m_H = 120 \) GeV and \( m_t = 171.4 \) GeV, respectively. SUSY masses are obtained by fixing \( M_1 = m_{A_H}, M_2 = m_{Z_H} \) and \( \mu = 1500 \) GeV for scenario SS1, whereas for SS2 \( M_1 = m_{A_H}, \mu = m_{Z_H} \) and \( M_2 = 1500 \) GeV. The other SUSY parameters are \( \tan \beta = 10 \) and \( m_A = 850 \) GeV. Note that sfermion masses are taken to be exactly equal to the respective mirror fermion masses and \( M_3 = 5000 \) GeV.

\( \kappa_q = 1 \) and \( \kappa_q = 1.5 \), as functions of the LHT scale \( f \). As we vary \( f \) and scan the LHT spectrum, the cross-sections for \( \tilde{\chi}^\pm_1 \tilde{\chi}^0_2 \)-production have also been calculated (both for SS1 and SS2), the SUSY spectrum being matched at each point as described above. The difference between the LHT and the SS1 cross-section can be partially attributed to the vector \textit{vis-a-vis} fermionic final states in the respective signals. A further suppression of the SS2 cross-section in comparison to that of SS1 is also noticeable. This is because for SS2 the couplings involved in the \( t \)- and \( u \)-channels are predominantly Yukawa in nature and thus suppressed for light quarks from the proton beams, while for SS1 the gauge coupling \( g_2 \) plays the vital role (see Figure 1(b)). The cross-section enhancement with increased \( \kappa_q \), i.e. increased masses for the mirror quarks, shows that we are in a region of the parameter space where the not so unusual destructive interference between the \( s \)- and \( t \)-channel processes in Figure 1(a) becomes less effective with increase in \( \kappa_q \) [10, 11]. A similar interference effect occurs for the SS1 case in Figure 1(b). Therefore, the relative difference between SS1 and SS2 increases when going from lighter to heavier squarks when increasing \( \kappa_q \). In the case of SS2, with Higgsino dominated charginos and neutralinos, it is mainly the \( s \)-channel diagram in Figure 1(b) which contributes, so that there is very little difference between the cross-sections for the two values of \( \kappa_q \).

While the production cross-sections are controlled by the parameter \( \kappa_q \) for a fixed \( f \), the decay rates are primarily governed by \( \kappa_l \), see also Ref. [13]. In Figure 3(a-c) we plot the branching fractions of the particles produced in the initial hard scattering for LHT, SS1 and SS2, respectively, as functions of \( \kappa_l \), with the SUSY spectrum appropriately matched.
Figure 2: Pair production cross-sections at the LHC of $W_H^\pm Z_H$ (LHT) and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ (SUSY) for $\kappa_q = 1$ (left panel) and $\kappa_q = 1.5$ (right panel). The solid (black) line represents the cross-section in the LHT. The dashed (red) line correspond to the SUSY scenario SS1 ($M_2 < \mu$) and the dash-dotted (blue) line to the SUSY scenario SS2 ($\mu < M_2$). For each value of $f$ the mass spectra in the two SUSY cases have been matched to the LHT spectrum as described in the text.

In Figure 3(a) (3(b)), we see that the leptonic branching fractions are larger for $W_H^\pm (\tilde{\chi}_1^\pm)$ or $Z_H (\tilde{\chi}_2^0)$ up to $\kappa_l = 0.44$. This is because the masses of the heavy leptons (sleptons) are smaller than the masses of the heavy gauge bosons (chargino and neutralino). Above $\kappa = 0.44$, the decays are purely into the LTP (LSP) and a gauge boson or a Higgs. In case of SS1, as the produced particles are gaugino dominated, their decays are governed by gauge couplings, whereas for SS2 the produced particles being Higgsino dominated, it is the Yukawa coupling which enters in the decay. This explains why the leptonic branching fractions for SS1 (Figure 3(b)) are higher compared to SS2 (Figure 3(c)).

The event analysis is performed with PYTHIA at the parton level, turning off initial- and final-state radiation. To select our final trilepton states, we apply the following cuts on our sample events:

- In order that the events are hadronically quiet, we reject jets having $p_T > 30$ GeV and $|\eta_j| < 2.7$. This reduces the $t\bar{t}$ background considerably [23].
- Each lepton should have $p_T > 25$ GeV and $|\eta_l| \leq 2.5$, to ensure that they lie within the coverage of the detector.
- $\Delta R_{ll} \geq 0.2$, (where $(\Delta R)^2 = (\Delta \eta)^2 + (\Delta \phi)^2$) such that the leptons are well resolved in space.
Figure 3: LHT and SUSY branching fractions for the produced particles as a function of $\kappa_l$ for fixed $f = 500$ GeV and $\kappa_q = 1$. Panel (a) represents the LHT and panels (b) and (c) correspond to SUSY scenario SS1 ($M_2 < \mu$) and SS2 ($\mu < M_2$), respectively.
A missing transverse energy cut, $E_T^\gamma \geq 100$ GeV has been employed to suppress the SM background.

We analyse only those events where $m_{l^+l^-} > 20$ GeV which ensures the absence of leptons emitted from off-shell photons. An additional cut in the form of $m_{l^+l^-} < m_Z - 15$ GeV or $m_{l^+l^-} > m_Z + 15$ GeV is used, in order to eliminate the SM backgrounds from on-shell Z-bosons. Furthermore, we demand $m_T(E_T^\gamma) < m_W - 15$ GeV or $m_T(E_T^\gamma) > m_W + 15$ GeV to reduce the backgrounds arising from W-bosons [28].

The efficiency of the cuts is shown in Table 2. In Figure 4 we present the variation of the number of trilepton events against the scale $f$ for LHT, SS1 and SS2, after imposing the above event-selection criteria. An integrated luminosity of 300 fb$^{-1}$ at the LHC has been used for obtaining the number of events. This is done for $\kappa_l = 0.4$, with $\kappa_q = 1.0$ and $\kappa_q = 1.5$, respectively. We find that the LHT trilepton event rates remain higher after the cuts in comparison to SS1 and SS2. This is primarily because of the larger cross-sections for the LHT. The SS2 rates are further suppressed in comparison to SS1 because of the small branching fractions for the leptonic decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$.

As mentioned earlier, the production of heavy quarks (squarks), followed by their cascade decays, might also lead to hadronically quiet trilepton events, if the accompanying jets are very soft. We simulated such events and found them to be negligible, since, with such masses as chosen here, the jets in the final state almost always emerge with $p_T > 30$ GeV. Also, in the SUSY cases, the cascade decays of the heavier charginos and neutralinos do not yield a significant number of trileptons after the cuts are imposed.

The number of SM background events surviving the cuts is shown as a flat dotted line in Figure 4. A closer look at the figure shows that the LHT trilepton events can be clearly

| Cuts | LHT       | SS1 | SS2 | Background |
|------|-----------|-----|-----|------------|
| No jet with $p_{Tj} > 30$ GeV and $|\eta_j| < 2.7$, $p_{Tl} > 25$ GeV, $|\eta_l| < 2.5$ and $\Delta R_\ell > 0.2$ and $E_T^\gamma > 30$ GeV | 9292.7 | 1641.4 | 68.1 | 20232.5 |
| $E_T^\gamma > 100$ GeV | 7281.2 | 1187.6 | 49.6 | 1599.9 |
| $m_{l^+l^-} > 20$ GeV | 7085.4 | 1137.5 | 48.1 | 1596.5 |
| $|m_{l^+l^-} - m_Z| > 15$ GeV | 4543.9 | 659.8 | 18.2 | 467.1 |
| $m_T(E_T^\gamma) - m_W| > 15$ GeV | 4246.3 | 606.5 | 17.0 | 263.9 |

Table 2: Efficiency of the cuts on trilepton events at the LHC from $W^+_H Z_H$ (LHT), $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ (SUSY) and from the SM background. The integrated luminosity is assumed to be 300 fb$^{-1}$. The missing energy cut is shown in two stages to convey the usefulness of the finally chosen value $E_T^\gamma > 100$ GeV. The values of the LHT parameters are $f = 500$ GeV, $\kappa_q = 1$ and $\kappa_l = 0.4$. The SS1 and SS2 parameters corresponding to this LHT point are given in Table 1.
Figure 4: Expected $3l + E_T$ event rates after the cuts at the LHC from $W_H^\pm Z_H$ (LHT) and $\tilde{\chi}_i^\pm \tilde{\chi}_j^0$ (SUSY), for scenario SS1 ($M_2 < \mu$) and SS2 ($\mu < M_2$) with $\kappa_l = 0.4$ for $\kappa_q = 1$ (left panel) and $\kappa_q = 1.5$ (right panel). The integrated luminosity is assumed to be 300 fb$^{-1}$. The line-style (colour) conventions for these plots are the same as in Figure 2. The horizontal dotted line represents the SM background of 264 events after all the cuts.

distinguished, at least at the 6$\sigma$ level, from either of SS1 or SS2, even in the presence of the SM background, up to $f \simeq 1.5$ TeV for $\kappa_q = 1.0$, and $f \simeq 1.7$ TeV for $\kappa_q = 1.5$. Figure 4 also shows that a comparable number of events for LHT and SS1 may only result from widely different values of $f$ (differing by almost 300 GeV or so). Thus, conservatively, the event rates are likely to be still distinguishable if the uncertainty in $f$ is around 200 GeV or less. Actually even with an integrated luminosity of 30 fb$^{-1}$ a differentiation between LHT and SUSY above the SM background could well be possible, although of course with less significance. It should be noted, however, that we did not take into account systematic errors such as uncertainties from higher order QCD corrections, parton distributions, initial- and final-state radiation and detector effects. Only a more detailed and realistic analysis could show whether a distinction between the different models can be made with lower statistics. Moreover, distinguishing between LHT and MSSM will only be feasible, if we already have some knowledge about the mass spectrum in the underlying model. Maybe not enough information on all the masses will be available after the early phase of LHC with 30 fb$^{-1}$ of data. Once we have precise enough information on the relevant masses, LHT and SS1 would be clearly distinguishable by the trilepton yield which, as is clear from Figure 4, would be an order of magnitude higher for LHT than that for SS1 for similar masses. The SS2 events, on the other hand, are going to be well below the backgrounds, for the mass range under investigation here.

A similar study for a higher $\kappa_l$ value, namely, $\kappa_l = 1$ does not yield fruitful results, as in this case the heavy leptons are more massive than the heavy gauge bosons. The
only possible decay modes are $W^\pm_H \to W^\pm A_H$ and $Z_H \to hA_H$. Thus the Higgs boson controls the number of trilepton events in the higher $\kappa_l$ regions. In the LHT, below about $f = 470$ GeV, a Higgs boson with a mass of 120 GeV decays invisibly into two heavy photons about 90% of the times [20], while beyond $f = 470$ GeV, it decays into $b\bar{b}$ with a branching fraction of about 70%. Therefore, there are only a few trilepton events generated via $h \to \tau\bar{\tau} \to l\bar{\nu}_l l\nu_l \tau\bar{\nu}_\tau$. In fact, from Figure 3 it is clear that the above conclusions will remain unaffected for any $\kappa_l$ beyond $\kappa_l > 0.44$, because the mirror leptons remain heavier than the heavy gauge bosons in this $\kappa_l$ region. The trilepton signals from neither LHT nor SUSY (with its slepton masses correspondingly higher) can rise above the SM backgrounds in this region.

Earlier studies have predicted appreciable rates for trilepton signals in SUSY at the Tevatron [22] and the LHC [23]. However, they analysed regions with lower masses than what has been considered here. Since the values of $f$ in the LHT corresponding to such masses are ruled out by precision electroweak observables, such regions are not pertinent to the distinction between the LHT and SUSY scenario. Moreover, the choice of cuts in these studies is different from ours.

Before we end, we want to reiterate that, apart from ensuring $m_{\nu_H} > m_{A_H}$, we have not made any 'tailored' parameter choice. The masses of SUSY particles are kept at par with those of the LHT spectrum in each case, in order to have similar event kinematics. Also, both the cases of gaugino and higgsino domination in the lighter chargino and the second lightest neutralino are included in our study, making the comparisons practically exhaustive.

In conclusion, we have analysed hadronically quiet trilepton events arising in both $T$-parity conserving Littlest Higgs and $R$-parity conserving SUSY models at the LHC. We found a clear excess of trilepton events in the LHT over the corresponding number of events in the two SUSY scenarios with a mass spectrum that matches the one in the LHT. While for $\kappa_l \leq 0.44$, it is possible to rise above the Standard Model backgrounds, such backgrounds become a problem for larger values of $\kappa_l$. Therefore, while the hadronically quiet trilepton signal suggests a promising way of distinguishing between SUSY and LHT, this signal is perhaps best usable if the heavy leptons (sleptons) do not exceed the heavy gauge bosons ($\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$) in mass.

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