

T-parity odd heavy leptons at LHC

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Abstract

Little Higgs models with T-parity can easily satisfy electroweak precision tests and at the same time give a stable particle which is a candidate for cold dark matter. In addition to little Higgs heavy gauge bosons, this type of models predicts a set of new T-odd fermions, which may show quite interesting signatures at colliders. We study purely leptonic signatures of T-odd leptons at the Large Hadron Collider (LHC).

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I. INTRODUCTION

The Standard Model (SM), when put in a more general context, is affected by the hierarchy problem, since within the SM the Higgs boson gets a quadratically divergent contribution to its mass if the model is considered as an effective theory only valid up to some high energy scale. If one considers a situation in which physics is perturbative, precision electroweak physics indicates that the Higgs mass cannot be very large and that the effective cutoff is preferably heavier than $5 - 10$ TeV [1]. This requires a fine tuning from the eventual scale of new physics to the electroweak scale. Little Higgs models are effective theories based on the non-linear sigma model structure where the Higgs field is a Nambu-Goldstone Bosons (NGB) of a global symmetry which is spontaneously broken at some higher scale by an expectation value f (for a review, see [2] and references therein). The Higgs field acquires its mass through symmetry breaking at the electroweak scale and, protected by the approximate global symmetry, it remains light. The original Little Higgs models, however, are disfavoured by electroweak precision tests [3], which push the scale f above few TeV thus restoring the fine tuning problem. On the other hand, models with an extra parity (called T-parity [4]) are in agreement with present constraints while allowing a scale f which is sufficiently light to be in the LHC range and solve the little hierarchy problem [5]. T-parity is also motivated by the fact that it offers a stable candidate for dark matter [6]. Generic little Higgs theories predict, at a scale of the order of 1 TeV, new particles responsible for cancelling the standard model quadratic divergences at 1-loop: heavy weak gauge bosons, new heavy scalars, new fermions that are partners of the top quark and partners of the light fermions. These new particles are charged under the T-parity. In addition there are also T-odd doublet partners for every standard model fermionic doublets. As a typical example we consider the Littlest Higgs model with T-parity (LHT). In this work, we study the possibility of observing the T-odd heavy leptons in the single ($pp \rightarrow \ell_H \bar{\nu}_H$) and pair production ($pp \rightarrow \ell_H \bar{\ell}_H$) of heavy charged T-odd leptons at LHC. In particular, we will focus on the purely leptonic decay modes. The ($pp \rightarrow \nu_H \bar{\nu}_H$) production, even though it may give rise to a four charged lepton channel, is less interesting because the smaller cross section, together with small leptonic branching ratios, renders the signal too feeble at the LHC.

Our paper is organised as follows: in section II we discuss the main features of the model we have considered for our analysis and also our framework for event generation and detector

simulations. In section III we compute the production of single charged T-odd lepton in the channel $pp \rightarrow \ell_H \bar{\nu}_H$. In section IV we discuss pair production of T-odd charged leptons. In section V we discuss the pair production of T-odd neutral leptons. Finally we conclude in section VI with the summary of the results.

II. T-ODD LEPTONS IN LHT

In the following, we briefly review the main features of the Littlest Higgs model with T-parity and in particular of the T-odd heavy fermions. The model is based on a $SU(5)$ global symmetry, of which a $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ subgroup is gauged. A discrete parity (T-parity) exchanges the two $[SU(2) \times U(1)]$ groups. At the scale f , the global symmetry is spontaneously broken down to a $SO(5)$ group resulting in 14 massless Nambu-Goldstone (NG) bosons and the gauged symmetry is reduced to its diagonal $SU(2)_L \times U(1)_Y$ subgroup identified with the standard model gauge group. The lightest heavy gauge boson, A_H , is the partner of the photon and is generally the lightest stable T-odd particle in the model.

The implementation of T-parity in the fermion sector requires that each standard model fermion doublet is replaced by the fields F_i ($i = 1, 2$) [4, 7], where each F_i is a doublet under one $SU(2)_i$ and a singlet under the other. T-parity simply exchanges F_1 and F_2 . The T-even combination of F_i is identified with the standard model fermion doublet while the other (T-odd) one is its heavy partner (F_H). Mass terms for these T-odd heavy fermions are generated by Yukawa interactions with additional T-odd $SU(2)$ singlet fermions. Assuming a universal and flavour diagonal Yukawa coupling κ_ℓ , for l_H and ν_H (the T-odd heavy partners of the standard model leptons), we have the following masses

$$m_{l_H} = \sqrt{2}\kappa_l f, \quad m_{\nu_H} = \sqrt{2}\kappa_l f \left(1 - \frac{v^2}{8f^2}\right); \quad (1)$$

as the scale f is typically of the order 500 GeV or larger, it is clear that the T-odd heavy partners have nearly equal masses as they are only split by v^2/f^2 effects. With the simplifying assumption of universal and flavour diagonal Yukawa couplings we therefore have only two free parameters: the new mass scale f and the flavour independent Yukawa coupling κ_ℓ . We use in the following the Feynman rules of mirror fermions in accordance with [8]. These modifications in the couplings of T-odd fermions provide the correct result at the

order v^2/f^2 for the cancellation of the divergences in Z-penguin diagrams in various flavour changing decays. The Yukawa coupling κ_ℓ in general depends on flavour and this can in turn generate Lepton Flavour Violation (LFV) in this class of models [9]. For our analysis we will assume that κ_ℓ is flavour blind and universal, hence it does not give rise to new sources of flavour violation.

A. Calculation and event generation details

The cross-sections and branching ratios for T-odd lepton production and decays have been calculated with CalcHEP v2.5.4 [10]. For this purpose we have used the modified LHT model file provided in [11]. In the modified model file we included the changes in the Feynman rules of mirror fermions in accordance with [8]¹. The LHC cross-sections were calculated for the center of mass energy of 10 and 14 TeV. We have used CTEQ6L PDFs (parton distribution functions) with QCD coupling scale set to $\sqrt{\hat{s}}$.

The event simulations always refer to the 14 TeV case: the signal events were generated using CalcHEP v2.5.4 and were interfaced to PYTHIA 6.4.21 [12] by Les Houches Event interface (LHE) [13]. The ISR/FSR switches in PYTHIA were kept on in the simulations. In order to make more realistic estimates we have further passed the events through the fast ATLAS detector simulator ATLFAST [14] for realistic detector effects. ATLFAST identifies isolated leptons, b and τ jets. It also reconstructs missing energy. The jets in ATLFAST are reconstructed using a simple cone algorithm. The SM backgrounds, on- and off-shell W production and ZZ production, were generated using PYTHIA 6.4.21 and were further processed through ATLFAST. The WWW events were generated using MADGRAPH [15] and were interfaced to PYTHIA 6.4.21 for ISR/FSR effects via LHE. The events thus generated were further passed through ATLFAST.

B. Decay of T-odd leptons

The input parameters of the LHT model that are relevant for our analysis are the scale f and the coupling κ_ℓ . As can be seen from Figure 1, in the region $\kappa_\ell < 0.46$, the branching

¹ The revised LHT model files can be obtained from <http://deandrea.home.cern.ch/deandrea/LHTmod1.tgz>.

ratios are:

$$BR(\ell_H \rightarrow A_H \ell) = 1, \quad BR(\nu_H \rightarrow A_H \nu) = 1. \quad (2)$$

For $\kappa_\ell > 0.46$, the leptons became heavier than the gauge bosons W_H and Z_H and other modes start opening up: when $\kappa_\ell \geq 0.5$, the dominant decay modes become $\ell_H \rightarrow W_H \nu$ and $\nu_H \rightarrow W_H \ell$. It is known that in this range ($\kappa_\ell \geq 0.5$) W_H decays to $W A_H$ with almost 100% branching ratio [16, 17].

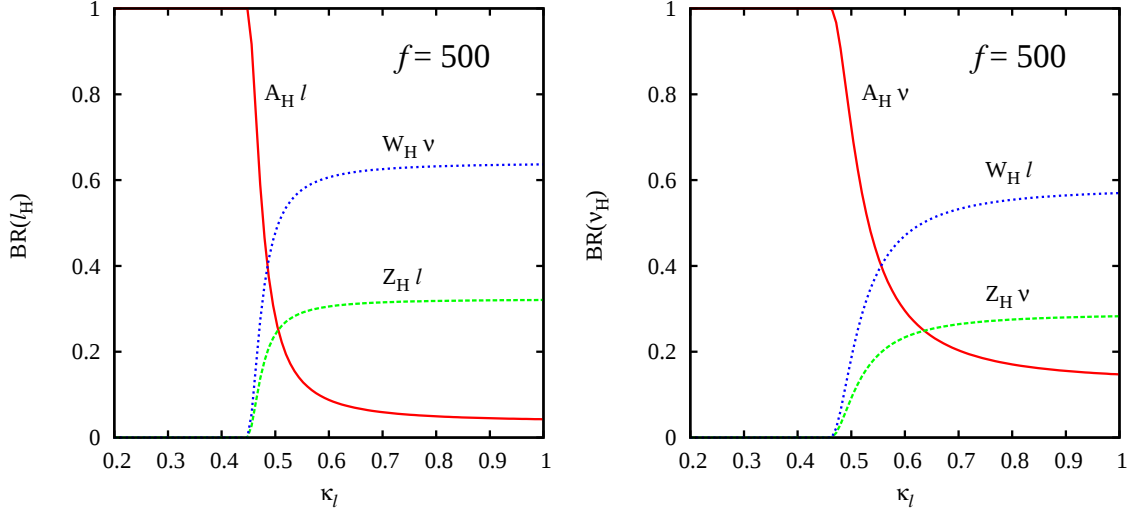


FIG. 1: Branching ratios of ℓ_H (left) and ν_H (right) as a function of κ_ℓ for fixed f . As can be seen from these figures the branching ratios in channel $(\ell_H, \nu_H) \rightarrow (\nu, \ell) W_H$ grow until $\kappa_\ell = 0.55$ (note this decay mode is responsible for tripleton signal) and then flatten out. The above branching fractions remain the same for nearly all values of f .

We show the dependence of the T-odd lepton branching ratios on the symmetry breaking scale f in Figure 2 for charged T-odd lepton (ℓ_H) and in Figure 3 for neutral T-odd lepton (ν_H) for some indicative values of κ_ℓ . Considering the SM W decaying leptonically, the dominant decay chains in the region $\kappa_\ell \geq 0.5$ (with a combined probability of about 12% each) are:

$$\begin{aligned} \ell_H^\pm &\rightarrow W_H^\pm (\rightarrow W^\pm A_H) \nu \rightarrow \ell^\pm \cancel{E}_T, \\ \nu_H^\pm &\rightarrow W_H^\pm (\rightarrow W^\pm A_H) \ell^\mp \rightarrow \ell^\pm \ell^\mp \cancel{E}_T. \end{aligned} \quad (3)$$

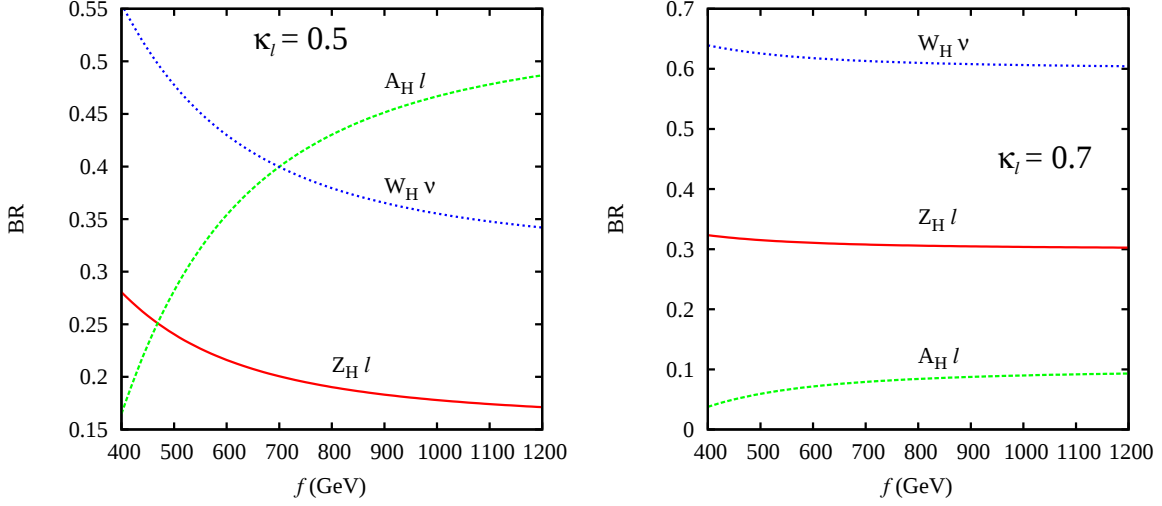


FIG. 2: Branching ratios of ℓ_H decay as a function of f .

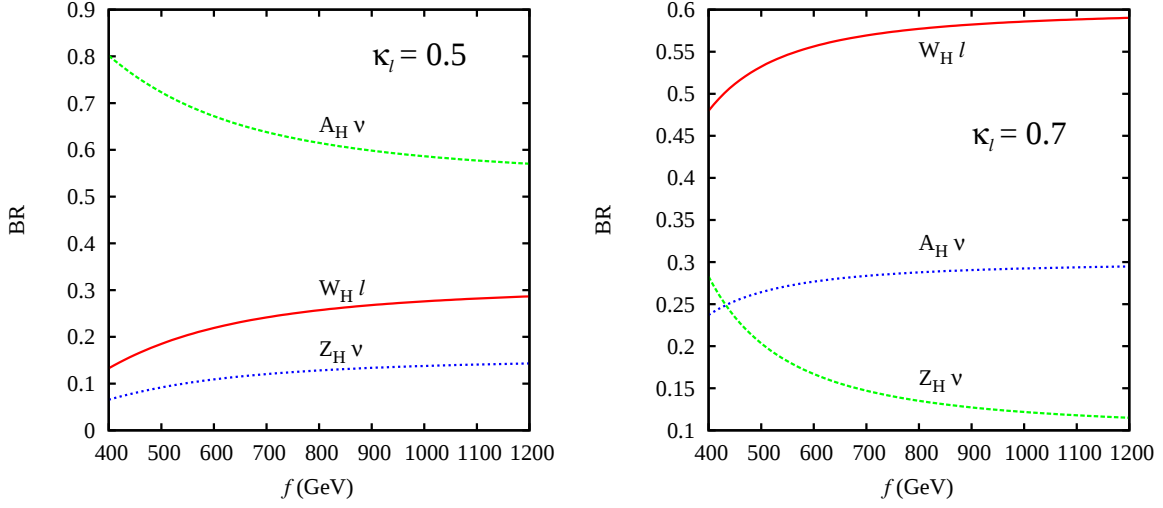


FIG. 3: Branching ratios of ν_H decay as a function of f .

Note that we are considering the decay chains with only leptons² in the final state, the reason being that with purely leptonic final state it is easier to suppress the backgrounds coming from $t\bar{t}$ and other QCD processes by imposing jet veto on the events. Armed with the information about the possible decay channels of T-odd leptons, in next sections we will discuss the production of these heavy leptons at LHC.

² By leptons in our analysis we mean electrons and muons.

III. SINGLE CHARGED T-ODD LEPTON PRODUCTION ($pp \rightarrow \ell_H \bar{\nu}_H$)

In a reasonable range of parameters of the LHT model, it is possible to produce a single charged T-odd lepton in association with the T-odd heavy neutrino at LHC. Initially LHC is expected to run at low energy $\sqrt{s} = 7$ TeV where it is expected to collect a small luminosity $\mathcal{L} < 100 \text{ pb}^{-1}$. This energy will be upgraded to $\sqrt{s} = 10$ TeV with an expected integrated luminosity of the order $\mathcal{L} = \mathcal{O}(100) \text{ pb}^{-1}$, before reaching the design energy of 14 TeV. In Figure 4 we have shown the production cross-sections of $pp \rightarrow \ell_H \bar{\nu}_H$ for the center of mass energy of 10 and 14 TeV. Depending on the energy, it can exceed a picobarn in part of the (f, κ_ℓ) parameter space.

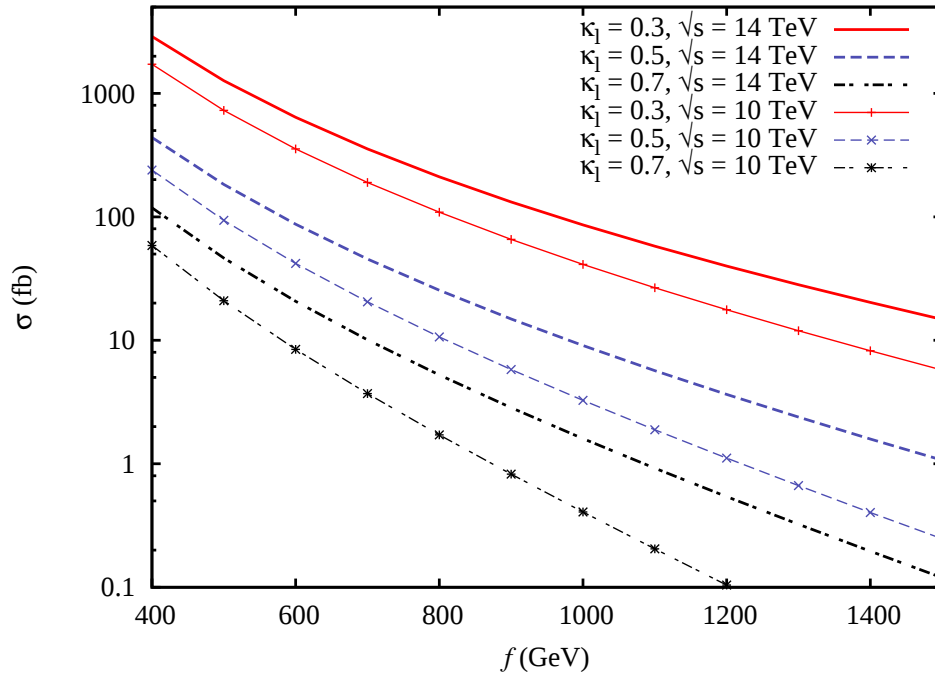


FIG. 4: LHC production cross-sections for the process $pp \rightarrow \ell_H \nu_H$ for the options of centre of mass energy of 14 TeV and 10 TeV, and for different benchmark points as a function of f .

The decay chains depend on the parameter region: as discussed in the previous section, in the region $\kappa_\ell < 0.46$ the T-odd leptons decay directly in the heavy photon, $\ell_H \rightarrow A_H \ell$ and $\nu_H \rightarrow A_H \nu$. For $\kappa_\ell \geq 0.5$ the T-odd leptons decay mainly via heavy charged W_H 's, as in eqns (3). These two regions of parameter space give different signatures, therefore we will discuss them separately in next sub-sections.

A. $\kappa_\ell < 0.46$

In this region the T-odd leptons decay with 100% branching ratio to the heavy photon and the corresponding SM lepton. The heavy neutrinos, therefore, decay invisibly: this gives rise to the signature of a single isolated charged lepton with missing energy ($\ell^\pm \cancel{E}_T$). The dominant SM background for this signature comes from the on- and off-shell W production:

- on-shell W production, $pp \rightarrow W^\pm \rightarrow \ell^\pm \bar{\nu}$.
- off-shell W production $pp \rightarrow W^\pm Z$ with the W going to leptons and the Z decaying invisibly via $Z \rightarrow \nu \bar{\nu}$.

This signature has been already analysed in [18, 19]. They argued that it may be possible to reduce the backgrounds by using high $\cancel{E}_T$ cuts and by using the transverse mass cuts. The transverse mass is defined as follows:

$$m_T = \sqrt{2p_T^\ell E_T^{miss}(1 - \cos(\phi))} , \quad (4)$$

where ϕ is the angle between the transverse momentum of the lepton p_T^ℓ and the transverse component of missing energy.

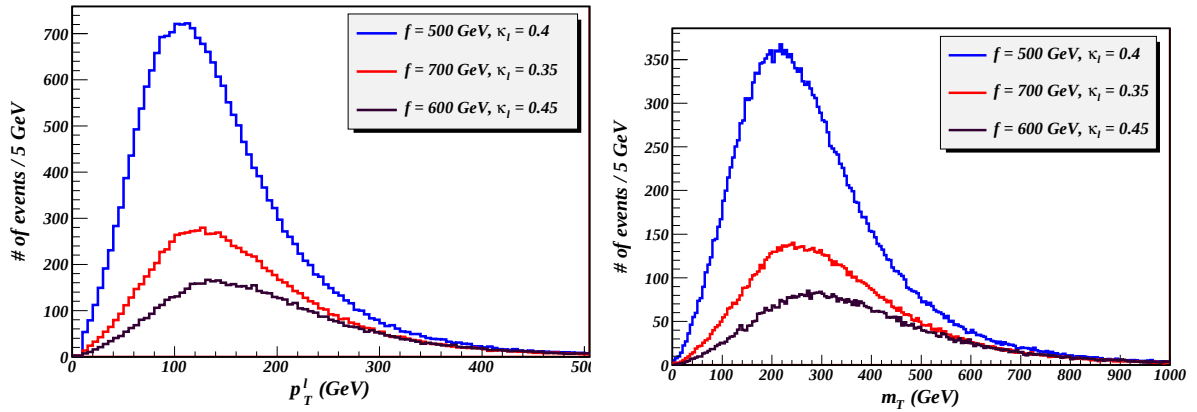


FIG. 5: p_T^ℓ distribution (left) and m_T distribution (right) for LHT. The model parameters are given in legends. In these distributions we have taken the LHC luminosity to be $\mathcal{L} = 100 \text{ fb}^{-1}$.

In order to perform the analysis we impose the following *pre-selection cuts*:

- (a) jet veto: we reject events having any resolved jet. By resolved jet we mean a jet that is visible in the detector. For this we veto an event having a jet with $p_T > 30$ GeV and rapidity $|\eta| < 3$.
- (b) exactly one charged lepton with $p_T^\ell > 10$ GeV and $|\eta| < 3$.

The p_T^ℓ and m_T distributions after the *preselection cuts* for signal events are given in Fig 5.

Parameters $\Rightarrow$	SM	SM	$f = 700$	$f = 600$	$f = 500$	$f = 600$	$f = 700$
Cuts $\Downarrow$	on shell	off shell	$\kappa_\ell = 0.4$	$\kappa_\ell = 0.4$	$\kappa_\ell = 0.4$	$\kappa_\ell = 0.45$	$\kappa_\ell = 0.35$
σ (fb)			114.8	212.8	433	133.55	195.16
Presel. cuts	1.7×10^9	6.1×10^4	5823.1	11067.9	22882.8	6800.5	10072.7
$p_T^\ell > 100$ GeV	4.9×10^5	2137.4	4916.4	8656.8	15652.2	5687.9	7852.9
$m_T > 200$	3.16×10^5	1818	4849.8	8481.5	15212.2	5604.8	7689
$m_T > 300$	8.17×10^4	451	3623.8	5722.9	8887.6	4138.4	5157.2
$m_T > 400$	2.72×10^4	147	2343.7	3335	4593	2664.7	3001.2
$p_T^\ell > 200$ GeV	2.82×10^4	147.9	2350.1	3351.6	4607.1	2673.1	3011.3
$m_T > 300$	2.82×10^4	146.8	2349.2	3350.3	4604.5	2672.2	3009.2
$m_T > 400$	2.72×10^4	139.4	2278.7	3238.2	4422	2592	2904.7
$p_T^\ell > 300$ GeV	3026.7	26.8	866.2	1074.2	1284.3	966.5	949.6
$m_T > 400$	30.3	0.26	8.7	10.7	12.8	9.7	9.5
$S/\sqrt{B}$ (10 fb $^{-1}$)	-	-	5	6.2	7.3	5.5	5.4
$S/\sqrt{B}$ (100 fb $^{-1}$)	-	-	15.6	19.5	23.2	17.5	17.2

TABLE I: Results of the simulations for the signal $\ell^\pm \cancel{E}_T$. The numbers of events, after sequentially imposing the cuts mentioned in the text, are for an LHC luminosity $\mathcal{L} = 100 \text{ fb}^{-1}$. The most efficient cut is $p_T^\ell > 300$ GeV, for which we also give $S/\sqrt{B}$ for different LHC luminosities. Note that a cut at the same level on m_T is practically ineffective as the two quantities are strongly correlated. Harder cuts, for example $m_T > 400$ GeV, start affecting more the signal events, therefore reducing $S/\sqrt{B}$.

As can be seen from the results given in Table I the backgrounds are huge as compared to signal. To extract signal from such huge backgrounds, we try to impose additional cuts. In

the case of the LHT model, the charged lepton comes from the decay of heavy T-odd lepton and hence would have a relatively high p_T as compared to SM leptons. Hence, to further reduce the SM backgrounds we have used the following secondary cuts:

- p_T^ℓ cut: we imposed three different values, namely 100 GeV, 200 GeV and 300 GeV, in order to test the efficacy of such cut. As we are looking at the signal of single lepton with $\cancel{E}_T$ hence $\cancel{E}_T = p_T^\ell$.
- transverse mass (m_T) cut: we considered cuts of 200 GeV, 300 GeV and 400 GeV.

The final summary table after implementing all the above mentioned cuts on signal and backgrounds is given in Table I. It is to be noted that the p_T^ℓ and m_T distributions and cuts are strongly correlated as they are related by eqn (4). The most efficient cut is $p_T^\ell > 300$ GeV, for which we listed the significance. In all the analysed benchmark points, a discovery is possible for $\mathcal{L} = 10 \text{ fb}^{-1}$. Harder cuts would reduce the signal and the overall statistics too much, therefore reducing the significance.

B. $\kappa_\ell \geq 0.5$

When $\kappa_\ell > 0.46$ the production cross-sections are typically smaller due to the larger mass of the leptons, however the region $\kappa_\ell \geq 0.5$ can give interesting signatures at the LHC due to the presence of multiple leptons in the final state. The reason for this being that in this region the T-odd leptons decay primarily via a charged W_H , which subsequently decays to W and A_H . Following the decay chains in eqns (3), we can get the following signature (triple leptons):

$$pp \rightarrow \ell_H \nu_H \rightarrow \ell^\pm \ell^\mp \ell^\pm \cancel{E}_T, \quad (5)$$

with a probability of about 1.5 %. This is a very interesting signature where the SM background is relatively small and can be easily controlled. The SM backgrounds for triple leptons can be:

- $pp \rightarrow W^\pm Z$ where both W and Z decay leptonically, $W^\pm \rightarrow \ell^\pm \bar{\nu}$ and $Z \rightarrow \ell \bar{\ell}$.
- $pp \rightarrow W^\pm W^\pm W^\mp$ where all the W 's decay leptonically, $W^\pm \rightarrow \ell^\pm \bar{\nu}$.

In order to study the signal in this region of the LHT parameter space with respect to the possible backgrounds at LHC we implemented the following *pre-selection cuts*:

- (a) jet veto: we apply a veto on events having a jet with $p_T > 30$ GeV within a rapidity of $|\eta| < 3$.
- (b) we demand that there are exactly three leptons, with only two of same charge, with $p_T > 20$ GeV and $|\eta| < 3$.
- (c) minimum $\cancel{E}_T$ threshold of 30 GeV.

In addition to the above mentioned *pre-selection cuts*, to reduce the SM backgrounds we use the following secondary cuts:

- invariant mass of the same sign leptons $|m_{\ell\pm\ell\mp} - m_Z| > 10$ GeV. This will reduce the backgrounds coming from leptons originating from a Z.
- we demand that $|m_T(\ell \cancel{E}_T) - m_W| > 15$. This will reduce the SM backgrounds coming from W 's.
- cut on $\cancel{E}_T$ at 100 GeV: higher values for the cut would reduce too much the signal and the overall statistics. This cut could be helpful in reducing the backgrounds because, in the SM, $\cancel{E}_T$ comes from neutrinos and hence could be relatively soft as compared to LHT models where $\cancel{E}_T$ comes from heavy photons (A_H) can hence could be relatively hard.

Process $\Rightarrow$	LHT	LHT	Background	Background
Cuts $\Downarrow$	$f = 500, \kappa_\ell = 0.5$	$f = 500, \kappa_\ell = 0.55$	WZ	WWW
Preselection cuts	39.1	102.9	14961.6	86.5
$ m_{\ell\pm\ell\mp} - m_Z > 10$ GeV	27.5	75.4	1032.2	65.9
$ m_T(\ell \cancel{E}_T) - m_W > 15$ GeV	26.1	72.2	609.1	56.25
$\cancel{E}_T > 100$ GeV	16.1	47.8	58.9	15.3
$S/\sqrt{B}$	1.9	5.5		

TABLE II: *Efficiency of cuts on signal and background for the trilepton mode at LHC. The figures in the Table are number of events after each subsequent cut, assuming the integrated luminosity of LHC to be $\mathcal{L} = 300 \text{ fb}^{-1}$.*

At this point we would like to note that Datta *et.al.* [17] have also analysed the same signature (trilepton) and have used similar kind of cuts to reduce the SM backgrounds. They implemented the $\cancel{E}_T > 100$ GeV cut before implementing a $m_T(\ell \cancel{E}_T)$ (transverse mass) cut and have indicated substantial reduction in the backgrounds by imposing the m_T cut. We disagree from their results as m_T and $\cancel{E}_T$ are strongly correlated and hence one does not get any substantial reduction in backgrounds by implementing a $\cancel{E}_T$ cut first and then imposing a m_T cut. Accordingly we have implemented the m_T cut first to reduce the backgrounds arising from W -bosons. We have later imposed the $\cancel{E}_T$ cut to further reduce the backgrounds. We have estimated signal and major backgrounds for the above mentioned cuts in the trilepton mode: the results of our analysis are summarised in table II. We see that, even though the backgrounds are easily controlled, due to the small statistics, very large luminosities would be required at LHC in order to discover this channel.

IV. PAIR PRODUCTION OF CHARGED T-ODD LEPTONS ($pp \rightarrow \ell_H \bar{\ell}_H$)

In Figure 6 we show the production cross-section for $pp \rightarrow \ell_H \bar{\ell}_H$ as a function of the symmetry breaking scale f for some indicative values of κ_ℓ and for center of mass energy of 10 and 14 TeV. As can be seen from Figures 4 and 6 the production cross-section for pair of charged T-odd leptons is relatively smaller than the process we have discussed in the previous section. The reason for this being that in the channel discussed in the previous section we also have to consider the charged conjugate process. The signature for $pp \rightarrow \ell_H \bar{\ell}_H$ in the $\kappa_\ell < 0.46$ region of the parameter space is two opposite sign leptons and $\cancel{E}_T$. As analysed in Ref. [18], in this case it is relatively easier to suppress backgrounds as compared to single charged lepton with $\cancel{E}_T$. For $\kappa_\ell > 0.46$, the decay chains in eqn 3 would also give rise to the same signature. However, the effective cross-section in this case would be too small considering the branching ratio of $\ell_H \rightarrow W_H \nu$ and, after the decay $W_H \rightarrow W A_H$, of the leptonic decay of the W . Therefore in our analysis we will restrict ourselves to the charged pair channel with $\kappa_\ell < 0.46$.

The main backgrounds to opposite sign lepton pair and $\cancel{E}_T$ signal can come from:

- $pp \rightarrow W^+ W^- \rightarrow \ell^\pm \ell^\mp \cancel{E}_T$ where the charged gauge boson decays leptonically.
- $pp \rightarrow Z Z \rightarrow \ell^\pm \ell^\mp \cancel{E}_T$ where one of the Z 's decays leptonically and the other invisibly.

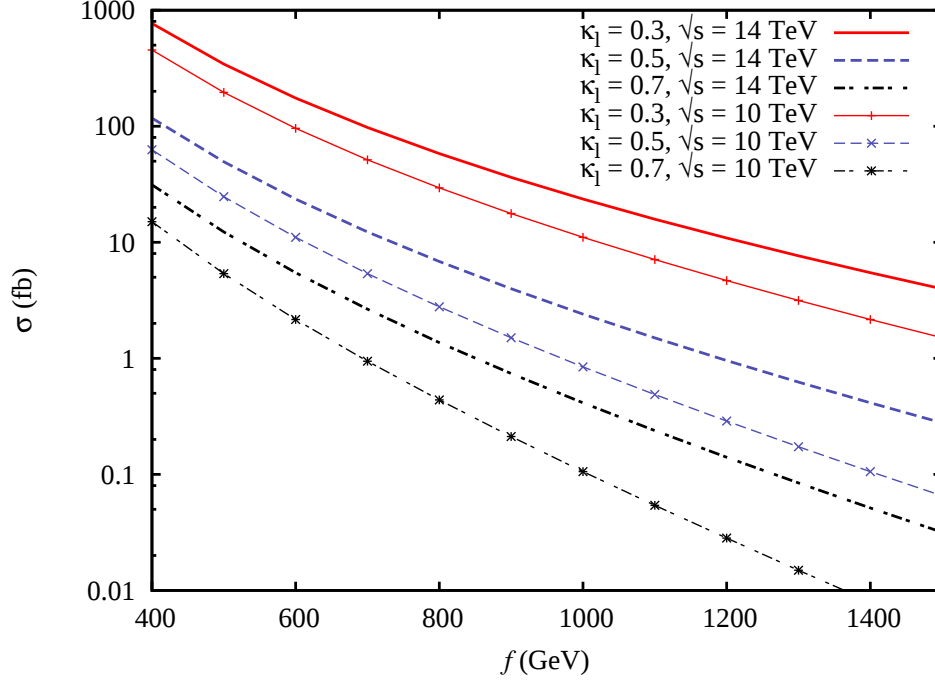


FIG. 6: LHC production cross-sections for the process $pp \rightarrow \ell_H \bar{\ell}_H$.

We propose to use following *pre-selection cuts*:

- (a) jet veto: veto events having jets with $p_T > 30$ GeV and $|\eta| < 3$.
- (b) exactly two leptons of opposite charge. The leptons must be visible in the detector so we require them to have $p_T > 10$ GeV and $|\eta| < 3$.
- (c) missing energy threshold $\cancel{E}_T > 30$ GeV.

The results of the signal and background events after imposing *pre-selection cuts* are given in Table III. As can be seen from the table the background events surviving the *pre-selection cuts* are orders magnitude greater than the signal events. More cuts are therefore necessary in order to improve the signal as compared to backgrounds. To device the *secondary cuts* we have plotted the $\cancel{E}_T$ and dilepton invariant mass ($m_{\ell\ell}$) distributions for some signal point and backgrounds in Figure 7. We also define the two dilepton transverse invariant mass as [18]:

$$m_T^{2\ell} = \sqrt{2p_T^{2\ell} \cancel{E}_T (1 - \cos\phi)} , \quad (6)$$

where $p_T^{2\ell}$ is the sum of the transverse momenta of the two leptons. The $m_T^{2\ell}$ distribution

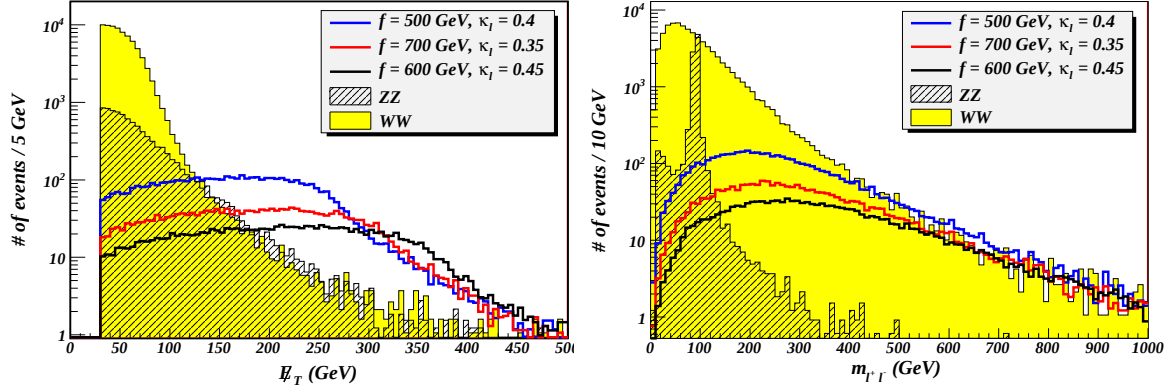


FIG. 7: E_T distribution (left) and lepton invariant mass ($m_{\ell\bar{\ell}}$) distribution (right) for the process $pp \rightarrow \ell_H \bar{\ell}_H \rightarrow \ell\bar{\ell} + E_T$ with LHC luminosity of 100 fb^{-1} , including backgrounds. The model parameters are given in the legends.

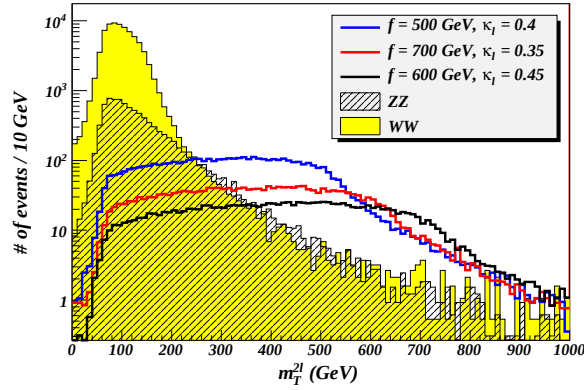


FIG. 8: $m_T^{2\ell}$ distribution for the process $pp \rightarrow \ell_H \bar{\ell}_H \rightarrow \ell\bar{\ell} + E_T$ with LHC luminosity of $\mathcal{L} = 100 \text{ fb}^{-1}$, including backgrounds.

is shown in Figure 8. By observing these distributions we propose to use the following secondary cuts:

- $E_T > 100 \text{ GeV}$.
- the invariant mass of the lepton pair is away from m_Z , $|m_{\ell\bar{\ell}} - m_Z| > 10 \text{ GeV}$. This reduces the backgrounds where a lepton pair originates from Z-decay.
- transverse mass cut, $m_T^{2\ell} > 200 \text{ GeV}$.

The summary of our results for some particular sets of input parameters (f, κ_ℓ) is shown in

Model parameters $\Rightarrow$	SM	SM	$f = 500$	$f = 600$	$f = 700$	$f = 600$	$f = 700$
Cuts $\Downarrow$	WW	ZZ	$\kappa_\ell = 0.4$	$\kappa_\ell = 0.35$	$\kappa_\ell = 0.3$	$\kappa_\ell = 0.45$	$\kappa_\ell = 0.35$
σ (fb)			117.6	97.5	97.58	36.27	53.48
Pre-selection cuts	7.67×10^4	9316.8	4738	3918.9	3993.4	1449.5	2142.8
$\cancel{E}_T > 100$ GeV	1994.1	1672.8	3669	3071.7	3065.5	1247.6	1767.3
$ m_{\ell\bar{\ell}} - m_Z > 10$ GeV	1814.1	233.7	3496.7	2942.1	2869.3	1216.2	1710.7
$m_T^{2\ell} > 200$ GeV	1419.2	210.4	3433.6	2890.8	2869.3	1202.9	1687.8
$S/\sqrt{B}(1 \text{ fb}^{-1})$			8.5	7.1	7.1	3	4.2
$S/\sqrt{B}(3 \text{ fb}^{-1})$			14.9	12.4	12.4	5.2	7.3
$S/\sqrt{B}(10 \text{ fb}^{-1})$			26.9	22.6	22.5	9.4	13.2

TABLE III: Results of the simulations in the channel $\ell^+\ell^- \cancel{E}_T$. The above numbers indicate the number of events after imposing of sequential selection cuts as defined in the text for an LHC luminosity $\mathcal{L} = 100 \text{ fb}^{-1}$. We have also given the significance $S/\sqrt{B}$ after the cuts for various integrated luminosities.

Table III. The $\cancel{E}_T$ and $m_{\ell\bar{\ell}}$ cuts are very effective in reducing the WW and ZZ cuts without affecting the signal. Therefore, this channel offers a powerful discovery potential even at integrated luminosity as low as 1 fb^{-1} .

V. PAIR PRODUCTION OF NEUTRAL T-ODD LEPTONS ($pp \rightarrow \nu_H \bar{\nu}_H$)

For completeness, we discuss here the pair production of heavy neutral T-odd leptons. The production cross-sections $pp \rightarrow \nu_H \bar{\nu}_H$, shown in Figure 9, are of the same order as the ones in the previous section. However, for $\kappa_\ell < 0.46$ the neutral leptons decay invisibly into neutrino and heavy photon, thus not leaving any signatures. On the other hand, for $\kappa_\ell > 0.46$, the decay chain in eqn 3 gives rise to a very clean four lepton channel. The rate of such events, however, is very small due to the smallness of the cross-sections and the suppression of the branching ratios.

In the SM, four leptons can arise from:

- $pp \rightarrow W^\pm W^\mp Z$ with the gauge bosons decaying leptonically.

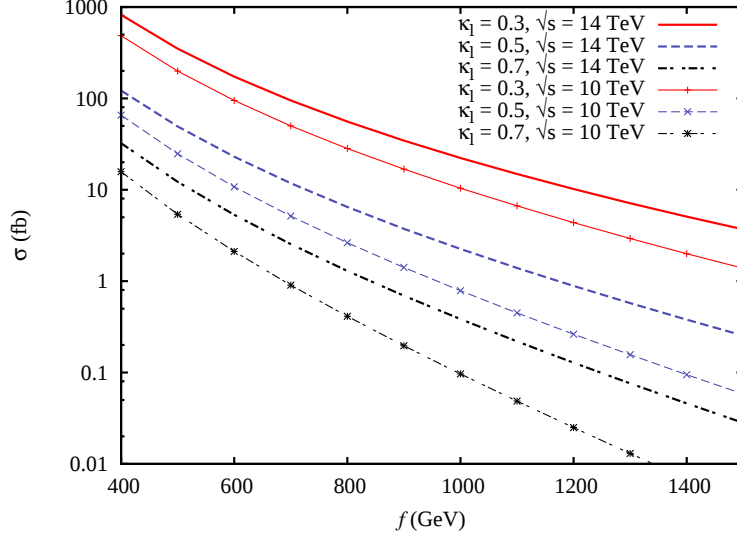


FIG. 9: LHC production cross-sections for the process $pp \rightarrow \nu_H \bar{\nu}_H$ for the options of centre of mass energy of 14 TeV and 10 TeV, and for different benchmark points as a function of f .

- $pp \rightarrow ZZZ$ with two Z 's decaying via $Z \rightarrow \ell^\pm \ell^\pm$ and third Z decaying via $Z \rightarrow \nu \bar{\nu}$.
- $pp \rightarrow ZZ$ with each of Z decaying leptonically.

The *pre-selection* cuts we used are:

- exactly four charged leptons, two each of same charge with $p_T^\ell > 15$ GeV and $|\eta| < 3$.
- jet veto: no jet with $p_T > 30$ GeV and $|\eta| < 3$ in the event.

The *secondary* cuts imposed to reduce backgrounds are :

- invariant mass of the same sign leptons $|m_{\ell^\pm \ell^\mp} - m_Z| > 10$ GeV. This will reduce the backgrounds coming from leptons originating from a Z .
- we demand that $|m_T(\ell \cancel{E}_T) - m_W| > 15$. This will reduce the SM backgrounds coming from W 's.
- cut on $\cancel{E}_T$ at 100 GeV: higher values for the cut would reduce too much the signal and the overall statistics.

The results of our simulations are summarized in Table IV. As in the trilepton case, the small statistics requires very large integrated luminosities in order to observe this channel, even though the backgrounds are easily controlled.

Parameter set $\Rightarrow$	$f = 500$	$f = 500$	SM	SM	SM
Cuts $\Downarrow$	$\kappa = 0.5$	$\kappa = 0.55$	ZZW	ZZZ	ZZ
σ (fb)	49.3	33.5			
Pre-selection	2.1	29.6	14.9	2.7	44.9
$ m_{\ell^+\ell^-} - m_Z > 10$ GeV	1.5	19.7	6.9	0.4	9.8
$ m_T(\ell \cancel{E}_T) - m_W > 15$ GeV	1.3	19	6.1	0.3	8.4
$\cancel{E}_T > 100$ GeV	0.7	12.1	2.4	0.2	5.6
$S/\sqrt{B}$	0.2	4.2			

TABLE IV: Number of signal and background events for $\mathcal{L} = 300 \text{ fb}^{-1}$.

VI. CONCLUSIONS

In this work we have discussed the phenomenology of T-parity odd heavy leptons at the LHC in the Littlest Higgs model as a sample of the corresponding phenomenology for typical Little Higgs models with T-parity. This type of models predicts a set of new T-odd fermions in addition to the heavy gauge bosons of the Little Higgs model. We have studied T-odd charged lepton single and pair production at the LHC and their purely leptonic decays. Production of a pair of heavy neutrinos, when giving visible leptonic signatures, have a too feeble rate to be detected. Those channels are very clean at the LHC due to the absence of jets which can rid of most of the QCD background. In the single charged channel, the production cross-sections at LHC are large and can be more than a picobarn in part of the (f, κ_ℓ) parameter space. For $\kappa_\ell < 0.46$ the heavy leptons decay only to the heavy photon A_H and the corresponding standard model lepton. This yields the single lepton signature $\ell^\pm \cancel{E}_T$, which can be discovered at LHC over the background with an integrated luminosity of around 10 fb^{-1} both for the 10 TeV and the 14 TeV centre of mass energy options. When $\kappa_\ell > 0.46$ the production cross-sections are typically small due to the larger mass of the heavy leptons, and decay modes involving the heavy W_H and Z_H bosons open up. For $\kappa_l > 0.5$ this gives rise to a trilepton signature, however it is suppressed by small branching ration and therefore a high integrated luminosity of 300 fb^{-1} is necessary for the observation of such channel.

The process $pp \rightarrow \ell_H \bar{\ell}_H$ has a smaller production cross-section which is typically in

the 100 femtobarn region, however it is easier to detect over the backgrounds due to the presence of two opposite charge leptons in the final state. For $\kappa_l < 0.46$, the dilepton plus missing energy ($\ell^+\ell^- \cancel{E}_T$) signal can be easily detected at LHC over the background, and an integrated luminosity of 1 to 3 fb^{-1} is sufficient for the discovery.

In summary, for small values of the Yukawa coupling κ_l , the T-odd heavy leptons of T-parity little Higgs models are easily detectable at the LHC due to the purely leptonic signatures. This provides is a new handle to test this type of models with a few spectacular channels that can be studied even in the early stage of the LHC running, with clear and visible signatures over the background. For larger Yukawa couplings, the purely leptonic signal is suppressed by branching ratios, therefore requiring very large integrated luminosities for the detection. In this case, semi-leptonic decays may be interesting, however we leave their study to future work.

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