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Phenomenology of mirror fermions in the littlest Higgs model with T-parity

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Abstract: Little Higgs models are an interesting alternative to explain electroweak symmetry breaking without fine-tuning. Supplemented with a discrete symmetry (T-parity) constraints from electroweak precision data are naturally evaded and also a viable dark matter candidate is obtained. T-parity implies the existence of new (mirror) fermions in addition to the heavy gauge bosons of the little Higgs models. In this paper we consider the effects of the mirror fermions on the phenomenology of the littlest Higgs model with T-parity at the LHC. We study the most promising production channels and decay chains for the new particles. We find that the mirror fermions have a large impact on the magnitude of signal rates and on the new physics signatures. Realistic background estimates are given.

Keywords: Beyond Standard Model, Weak Decays.

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1. Introduction

A simple doublet scalar field yields a perfectly appropriate gauge symmetry breaking pattern in the Standard Model (SM). On the other hand, its theoretical shortcomings, such as quadratic divergencies (hierarchy problem) or the triviality of a ϕ^4 theory suggest that it is embedded in a larger scheme. On the other hand, electroweak precision data suggests that up to a scale of about 10 TeV, no new strong interaction is present, indicating that indeed some form of a scalar interaction is required, including the possibility that the (Higgs) scalars are composite. A much investigated option to solve the hierarchy problem are supersymmetric theories; but also models with extra dimensions have been considered.

Recently, an alternative known as the *little Higgs mechanism*,[1], has been proposed where the smallness of the electroweak scale is assured by interpreting the Higgs as a (Pseudo) Goldstone particle of a symmetry breakdown at a scale f. The new gauge bosons and partners of the top quark with a mass of order f cancel the one-loop quadratic corrections to the Higgs mass from Standard Model (SM) particles. A very appealing implementation of the little Higgs concept is the *littlest* Higgs model [2], which extends the SM by a minimal number of gauge bosons and fermions.

However, even though these new particles are weakly coupled, electroweak precision data requires f to be above 5 TeV [3]. On the other hand a scale as low as 1 TeV is required to avoid fine-tuning of the Higgs mass.

A discrete symmetry, called *T-parity*, [5, 4] circumvents these problems. It forbids all tree-level contributions of the new heavy degrees of freedom to electroweak precision observables. The SM fields are T-even, while the new TeV-scale particles are odd. Therefore, the new particles can only be generated in pairs which is reminiscent of R-parity in supersymmetric theories. Besides satisfying the electroweak constraints, T-parity also has

the interesting consequence that the lightest T-odd particle is stable and, if neutral, a good candidate for cold dark matter.

One of the prime objectives of the next generation of colliders, especially the Large Hadron Collider (LHC), is to unravel the physical mechanism of electroweak symmetry breaking. A first study of the phenomenology of the littlest Higgs model with T-parity (LHT) at the LHC presented in ref. [6] yielded attractive production rates for the new particles, see also ref. [7]. The collider phenomenology of little Higgs theories with T-parity has some similarities to supersymmetry. In particular, it involves signatures with missing energy originating from the neutral lightest T-odd particle (LTP), which escapes detection. On the other hand, little Higgs theories usually do not involve a T-odd partner of the gluon, which leads to smaller new physics cross-sections at the LHC compared to supersymmetry.

In this paper, the phenomenology of the littlest Higgs model with T-parity is revisited and in particular the important role of the T-odd fermions (*mirror fermions*) is stressed. Backgrounds from SM sources are investigated in order to arrive at realistic estimates for the observability of the new physics signals of the LHT model. After reviewing the LHT model in section 2, the production processes and signatures for various T-odd particles are studied in detail in sections 3 and 4. Finally, the conclusions are given in section 5.

2. The model

The littlest Higgs model is based on a coset SU(5)/SO(5), i. e. a global SU(5) symmetry that is explicitly broken down to a SO(5) group, with a $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$ subgroup of SO(5) being gauged [2]. The Goldstone modes of the broken SU(5) are implemented in a non-linear sigma model with a breaking scale f. Some of the Goldstone modes only become massive when *both* gauge subgroups are broken. As a consequence of this simultaneous symmetry breaking one-loop quadratic divergencies to the Higgs mass are naturally avoided and their mass get corrections at most at the two-loop level.

The littlest Higgs model can be supplemented by a discrete Z_2 called T-parity [5], with SM particles being even ($T=+1$), and non-SM particles odd ($T=-1$) under this symmetry. The terms of the non-linear sigma model generate masses of order f for the T-odd particles. Rather than giving the whole construction of the model we consider, we refer to [6] for a somewhat detailed description.

The gauge bosons are formed from the gauge bosons of the two SU(2) and U(1) groups, which in the following are indicated by subscripts 1 and 2, respectively:

$$W_L^a = \tfrac{1}{\sqrt{2}}(W_1^a + W_2^a), \qquad \text{(T-even)} \tag{2.1}$$

$$B_L = \tfrac{1}{\sqrt{2}}(B_1 + B_2), \tag{2.2}$$

with masses from usual electroweak symmetry breaking, and

$$W_H^a = \tfrac{1}{\sqrt{2}}(W_1^a - W_2^a), \qquad \text{(T-odd)} \tag{2.3}$$

$$B_H = \tfrac{1}{\sqrt{2}}(B_1 - B_2), \tag{2.4}$$

with masses of order f generated from the kinetic term of the non-linear sigma model. After electroweak symmetry breaking, the light gauge bosons mix to form the usual physical states of the SM, $A_L = c_{\rm W} B_L - s_{\rm W} W_L^3$, $Z_L = s_{\rm W} B_L + c_{\rm W} W_L^3$ and $W_L^\pm = (W_L^1 \mp W_L^2)/\sqrt{2}$. Similarly, a small mixing of order $\mathcal{O}(v^2/f^2)$ is introduced between B_H and $W_H^0 \equiv Z_H$ through electroweak symmetry breaking. In this work, this mixing and all other terms of order $\mathcal{O}(v^2/f^2)$ will be consistently neglected. In this case, the masses of the T-odd gauge bosons are

$$M_{W_H^\pm} = M_{Z_H} = gf, \qquad M_{B_H} = \frac{g'}{\sqrt{5}} f, \tag{2.5}$$

with $W_H^\pm = (W_H^1 \mp W_H^2)/\sqrt{2}$. The B_H is always lighter than the other T-odd gauge bosons and thus a good candidate for the LTP (lightest T-odd particle) and dark matter.

T-parity also requires a doubling of the fermion sector associating to each T-even (SM) fermion a T-odd fermion. F_H (mirror fermion). These 'partners' get masses [8]

$$m_{f_{H,i}} = \sqrt{2}\kappa_i f, \tag{2.6}$$

where the Yukawa couplings κ can in general depend on the fermion species i. The κ can also generate flavor changing interactions, but this will not be studied in this paper.

The implementation of the mass terms for the mirror fermions also introduces T-odd SU(2)-singlet fermions, which may receive large masses and do not mix with the SU(2)-doublets f_H. Here it is therefore assumed that these extra singlet fermions have large masses and decouple from phenomenology at the LHC.

The top sector requires an additional T-even fermion t'_+ and one T-odd fermion t'_- to cancel quadratic divergencies to the Higgs mass. Their masses are

$$m_{\rm t} = \frac{\lambda_1 \lambda_2 v}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \qquad m_{t'_+} = \sqrt{\lambda_1^2 + \lambda_2^2}\, f, \qquad m_{t'_-} = \lambda_2 f. \tag{2.7}$$

The Yukawa couplings $\lambda_{1,2}$ are constrained by the top mass $m_{\rm t}$, but one has the freedom to choose

$$s_\lambda \equiv \frac{\lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} = \frac{m_{t'_-}}{m_{t'_+}}. \tag{2.8}$$

The decay modes of the T-odd gauge bosons and mirror fermions are summarized in table 1 for $f = 1\,\text{TeV}$, degenerate $\kappa_f = 0.5$ and $s_\lambda = 1/\sqrt{2}$.

3. T-odd production at LHC

In this section we consider the (pair) production of the various T-odd particles at the LHC. Our work completes the previous studies in ref. [6] and stresses the role of the T-odd fermions. Some preliminary results in this direction were also presented in ref. [7].

3.1 Heavy gauge bosons

In ref. [6], the production of heavy T-odd gauge bosons was computed including the s-channel gauge boson contributions only, figure 1 (a–c). It was found that the cross-sections can be sizeable, of the order $\mathcal{O}(0.1\text{ pb})$, for $f < 1\,\text{TeV}$. However, for perturbative Yukawa

Particle	Mass m [GeV]	Width Γ [GeV]	Decay modes	
$W_H^\pm$	647	0.056	$W_H^\pm \to W^\pm B_H$	100%
Z_H	647	0.051	$Z_H \to h^0 B_H$	100%
B_H	154	—	—	
u_H	705	0.36	$u_H \to B_H u$	50%
			$\to W_H^+ d$	33%
			$\to Z_H u$	17%
d_H	705	0.36	$d_H \to B_H d$	50%
			$\to W_H^+ u$	33%
			$\to Z_H d$	17%
t'_-	1000	1.25	$t'_- \to B_H t$	100%

Table 1: Tree-level masses, widths and main branching ratios of the T-odd states at Born level for $f = 1\,\text{TeV}$, $\kappa_f = 0.5$ and $s_\lambda = 1/\sqrt{2}$. Corrections of order $\mathcal{O}(v^2/f^2)$ are neglected.

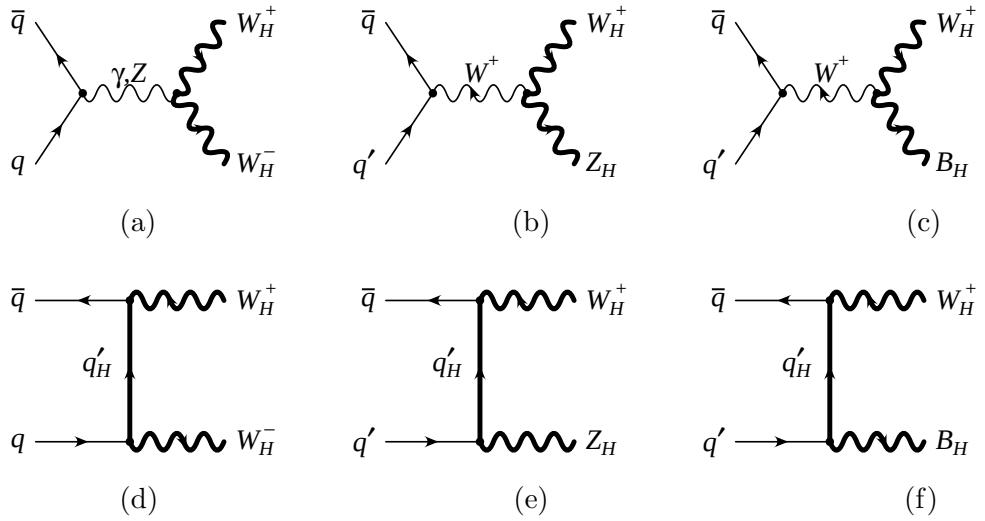

Figure 1: Production diagrams for T-odd gauge bosons at LHC. Thick lines indicate T-odd propagators.

couplings $\kappa_f \lesssim 1$, the mirror fermions cannot be much heavier than the heavy gauge bosons, and thus never decouple from the production process. Thus the t-channel mirror fermion exchange, figure 1 (d–f), is also important.

To study this effect of the mirror fermions for heavy gauge boson production, the Feynman rules for the littlest Higgs model with T-parity [9, 6, 10] have been implemented in CompHEP [11]. The package CompHEP was then used to generate numerical results for production cross-sections and decay modes of the T-odd heavy gauge bosons.

It turns out that the t-channel contributions interfere destructively with the s-channel diagrams, as may be expected by unitarity, thus resulting in lower cross-sections for gauge boson production, see figure 2. For typical values $\kappa \sim \mathcal{O}(1)$, the LHC production cross-sections are reduced by about one order of magnitude relative to the situation without the t-channel diagrams ($\kappa \to \infty$). As a consequence, the expected heavy gauge boson

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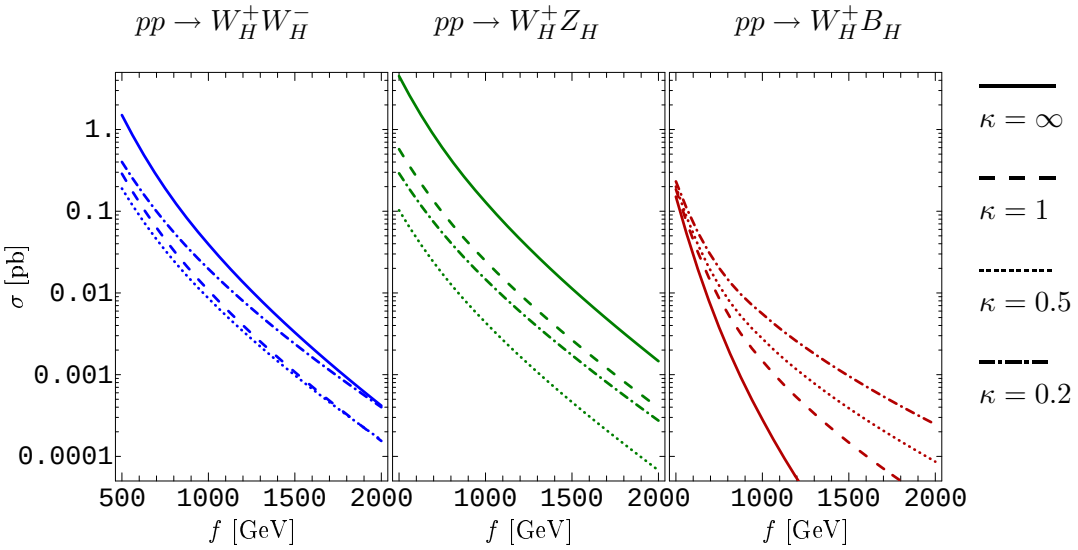

Figure 2: Cross-sections for T-odd heavy vector boson production at the LHC as a function of the symmetry breaking scale f, and for several values of the T-odd fermions Yukawa coupling κ.

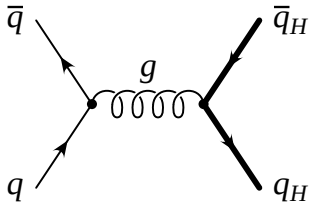

Figure 3: QCD production diagram for T-odd mirror quarks at LHC. Thick lines indicate T-odd propagators.

cross-sections are only several fb for all possible final states $W_H^+ W_H^-$, $W_H^+ Z_H$ and $W_H^+ B_H$. The identification of new physics processes of that size at the LHC relies strongly on the presence of leptons in the signature. $W_H^\pm$ bosons decay into leptons $l = e, \mu$ with a branching ratio of about 20%. Folding in that branching ratio further reduces the signal cross-section. Large backgrounds from SM gauge boson pair production and $t\bar{t}$ production make the identification of a signal process with $\mathcal{O}$(fb) cross-section practically impossible.

3.2 Mirror quarks

While the mirror quarks effectively lead to a reduction of the T-odd gauge boson production at the LHC, the mirror quarks can also be produced directly with large cross-sections through gluon exchange, see figure 3. In addition, there are also subdominant weak production diagrams. Due to the strongly interacting production amplitude, the cross-section for mirror quarks is typically larger than for T-odd vector bosons, see figure 4. Since for generation- and flavor-independent κ all mirror quarks, except the top partners, have almost degenerate masses, the production cross-sections are also independent of the mirror quark flavor.

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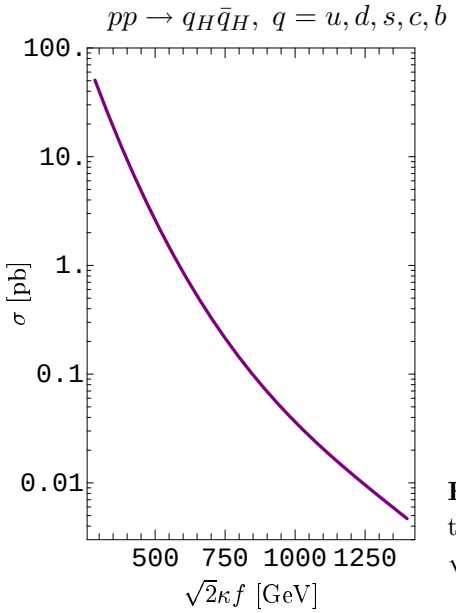

Figure 4: Cross-sections for T-odd mirror quark production at the LHC as a function of the quark mass $m_{q_H} \sim \sqrt{2}\kappa f$.

For sufficiently large masses of the heavy T-odd quarks, they decay into T-odd vector bosons. This leads to signatures that are similar to supersymmetric theories, where squarks with large production cross-sections decay via charginos and neutralinos. However, for a realistic assessment of the discovery potential of the LHC for the T-odd quarks, the production rates and relevant SM backgrounds need to be studied in more detail.

In the following the specific scenario with $f = 1\,\text{TeV}$, $\kappa = 0.5$ for all T-odd fermion flavors, and $s_\lambda = 1/\sqrt{2}$ will be considered as a concrete example to analyze the discrimination of the mirror fermions signal against SM backgrounds. The relevant T-odd particle masses in this scenario are $M_{W_H^\pm} = M_{Z_H} = 647\,\text{GeV}$, $M_{B_H} = 154\,\text{GeV}$, $m_{q_H} = 705\,\text{GeV}$ for $q = u, d, s, c, b$ and $m_{t'_-} = 1000\,\text{GeV}$.

(a) $\boldsymbol{pp \to q_H q_H \to q q' W_H^\pm B_H \to jj\,l + \not{E}_T}$. Here j indicates a (light-flavor) jet, $l = e, \mu$ an identified lepton, and $\not{E}_T$ stands for missing transverse energy. Since signatures with only hadronic objects in the final state are very challenging to select from the backgrounds, only leptonic decays of the $W_H^\pm$ are considered here. The major SM background for the $jj\,l + \not{E}_T$ signature comes from $pp \to W^+W^- \to q\bar{q}' l^\pm \nu_l$ production.

Here the signal and background have been calculated with CompHEP, where also off-shell effects have been included in the computation of the $q\bar{q}' l^\pm \nu_l$ background. Since the SM background is several orders of magnitude larger than the signal, the signal-to-background ratio needs to be improved with suitable selection cuts. The result is summarized in table 2. Generally, a lower threshold for the transverse energy $E_{T,j}$ of the jets needs to be applied. Since the jet originating from the mirror squark decay into B_H is expected to be relatively hard, a rather strong cut of 200 GeV is imposed on the transverse energy of the hardest jet. Furthermore, the jets are required to be in the central region with rapidity $\eta_j < 2.5$ and the jets must be separated in solid angle to be identifiable as two individual jets. Due to the large mass of the B_H, which are the stable LTPs in this scenario, the signal is

Cut	Signal $pp \to q_H q_H \to jj\, l + \not{E}_T$	Background $pp \to q\bar{q}' l^\pm \nu_l \to jj\, l + \not{E}_T$	S/B
	55 fb	IR-div.	
$E_{T,j_1} > 200\,\text{GeV}$, $E_{T,j_2} > 50\,\text{GeV}$, $\eta_j < 2.5$, $\angle(j_1, j_2) > 30°$	23 fb	3.5 pb	6.6×10^{-3}
$\not{E}_T > 400\,\text{GeV}$	11 fb	31 fb	0.3
$E_{T,l} > 50\,\text{GeV}$	8 fb	15 fb	0.5

Table 2: Signal and background rates for the process $pp \to q_H q_H \to q q' W_H^\pm B_H \to jj\, l + \not{E}_T$ with incremental application of signal selection cuts. "IR-div." indicates that without any jet separation cuts, the SM background is not infrared safe at fixed order Born approximation and thus no number can be given here.

characterized by large missing transverse energy $\not{E}_T$, so that a cut on this variable is very effective to reduce the SM backgrounds. Furthermore, since the W boson from the W_H decay is strongly boosted, the final state lepton tends to be relatively hard, so that a cut on the lepton transverse energy is useful.

We have checked that the statistical significance of the signal cannot be improved by varying the values of the cuts in the table. Even after the relatively aggressive cuts in table 2, the signal-to-background ratio is still smaller than one, making a meaningful measurement of the T-odd production process difficult, but not impossible. With $30\,\text{fb}^{-1}$, a statistical significance of nine standard deviations could be achieved, but systematic uncertainties might affect this substantially.

(b) $\boldsymbol{pp \to q_H q_H \to qq W_H^+ W_H^- \to jj\, l^+ l^- + \not{E}_T}$. With an additional lepton in the final state, this process might be better separable from the SM background than process (a). The main SM backgrounds are $t\bar{t}$, where both top quarks decay leptonically, and W^+W^-jj, where the two jets originate from initial-state radiation. Note that also for the signal, additional hard jets stemming from initial-state radiation are expected [13].

As before, the signal has been calculated with CompHEP, while the SM background was simulated with MADGRAPH [12]. Again, the SM background is several orders of magnitude larger than the signal, but can be improved with the cuts listed in table 3. In addition to kinematic cuts, b-tagging also helps to reduce the $t\bar{t}$ background, since only little heavy flavor content is expected in the signal. According to ref. [14], a b-tagging efficiency of 90% with an impurity of 25% is assumed. The other selection cuts are similar to the ones used in table 2, with the jet cone size defined as $\Delta R_{jj} = \sqrt{(\Delta\eta_{jj})^2 + (\Delta\phi_{jj})^2}$, where $\Delta\phi_{jj}$ is the azimuthal angle between the two jets. It turns out that the signal-to-background ratio remains well below one after application of the selection cuts, and moreover the signal statistics are very low. Therefore this channel does not look promising as a discovery mode for the LHT model at the LHC.

(c) $\boldsymbol{pp \to q_H q_H \to qq' W_H^\pm Z_H \to qq' W^\pm h^0 B_H B_H \to jj\, bb\, l + \not{E}_T}$. Since the Z_H

Cut	Signal	Background		S/B
	$q_H q_H \to jj\,ll + \not{E}_T$	$t\bar{t} \to jj\,ll + \not{E}_T$	$WWjj \to jj\,ll + \not{E}_T$	
	2.7 fb			
$E_{T,j} > 50\,\text{GeV}$, $E_{T,l} > 10\,\text{GeV}$, $\eta_j < 2.5$, $\Delta R_{jj} < 0.4$	2.2 fb	30 pb	180 fb	8×10^{-5}
$\not{E}_T > 400\,\text{GeV}$	1.0 fb	88 fb	21 fb	0.01
$E_{T,l} > 50\,\text{GeV}$	0.7 fb	46 fb	9 fb	0.013
b-tag veto	0.5 fb	3.2 fb	7 fb	0.03

Table 3: Signal and background rates for the process $pp \to q_H q_H \to qqW_H^+W_H^- \to jj\,l^+l^- + \not{E}_T$ with incremental application of signal selection cuts.

Cut	Signal	Background	S/B
	$q_H q_H \to jj\,bb\,l + \not{E}_T$	$t\bar{t} \to jj\,bb\,l + \not{E}_T$	
	14.0 fb		
$E_{T,j} > 50\,\text{GeV}$, $E_{T,l} > 10\,\text{GeV}$, $\eta_j < 2.5$, $\Delta R_{jj} < 0.4$	13.4 fb	128 pb	1×10^{-4}
$\not{E}_T > 250\,\text{GeV}$	9.8 fb	3.1 pb	3×10^{-3}
$E_{T,l} > 50\,\text{GeV}$	8.4 fb	1.3 pb	6×10^{-3}
b-tag	5.0 fb	770 fb	6×10^{-3}
$100\ \text{GeV} < m_{\text{bb}} < 150\ \text{GeV}$	5.0 fb	65 fb	0.08

Table 4: Signal and background rates for the process $pp \to q_H q_H \to qq' W_H^\pm Z_H \to jj\,bb\,l + \not{E}_T$ with incremental application of signal selection cuts.

boson almost always decays into the (little) Higgs boson h^0, the selection of this signal process needs to make use of the two b jets in the final state. The largest SM background is semileptonic $t\bar{t}$ decays.

Again, CompHEP was used to calculate the signal, while the SM background was simulated with MADGRAPH. For the signal selection procedure, it is assumed that the Higgs boson has already been discovered and its mass measured, so that a cut can be applied on the invariant mass m_{bb} of the two bottom jets stemming from the Higgs. This requires a good identification of the b jets among the four or more jets in the event. Thus b-tagging is mandatory for the signal selection, and it is advantageous to optimize the b-tagging procedure for a high purity of 98%, at an efficiency of 60% [14]. Applying the cuts in table 4, it is found that the signal-to-background ratio stays well below one after application of the selection cuts, so that this channel is also not suitable for new physics discovery in the LHT model.

(d) $\boldsymbol{pp \to t'\_\bar{t}'\_ \to t\bar{t}B_H B_H}$. The final state signature of this process is identical to $t\bar{t}$ production. As an example, the semileptonic decay of the top quark pair is considered,

Cut	Signal $t'_-\bar{t}'_- \to jj\,bb\,l + \not{E}_T$	Background $t\bar{t} \to jj\,bb\,l + \not{E}_T$	S/B
$E_{T,j} > 50\,\text{GeV}$, $E_{T,l} > 10\,\text{GeV}$, $\eta_j < 2.5$, $\Delta R_{jj} < 0.4$	8.2 fb	128 pb	6×10^{-5}
$\not{E}_T > 800\,\text{GeV}$	1.4 fb	3.2 fb	0.4
b-tag	0.8 fb	1.9 fb	0.4

Table 5: Signal and background rates for the process $pp \to t'_-\bar{t}'_- \to t\bar{t}B_HB_H \to jj\,bb\,l + \not{E}_T$ with incremental application of signal selection cuts.

leading to the final state $jj\,bb\,l + \not{E}_T$.

Signal and background have been computed as above, using b-tagging with 98% purity and 60% efficiency. The main discrimination to the $t\bar{t}$ background is a cut on missing transverse energy, see table 5, which improves the signal-to-background ratio tremendously. However, the resulting signal-to-background ratio is still below one, and the remaining signal rate is small, so that even without considering systematic uncertainties, only a statistical significance of less than three standard deviations is achievable with $30\,\text{fb}^{-1}$.

Other decay chains, such as $pp \to q_Hq_H \to qq'Z_HZ_H$ have large SM background and will not be considered.

4. Mirror leptons and decay signatures

Mirror leptons, the T-odd partners of the leptons, can be produced directly at the LHC through s-channel exchange of SM gauge bosons. However, their production cross-sections are small, below 1 fb for the scenario with $\kappa_l = 0.5$ and $f = 1000\,\text{GeV}$, i.e. $m_{l_H} = 707\,\text{GeV}$. We therefore do not consider the direct production further.

However, the mirror leptons may play an important role in the decay signatures. If the mirror fermions are not degenerate, but for instance T-odd leptons and T-odd quarks have different masses, the experimental signatures can be greatly altered. For example for $\kappa_q = 0.5$ and $\kappa_l = 0.2$, the mirror lepton mass is $m_{l_H} = 283\,\text{GeV}$, and the heavy gauge boson can decay into the mirror leptons, $Z_H \to l^\pm l_H^\mp$. If this decay channel is open, the branching ratio will be almost 100% for all lepton flavors combined. As a consequence, the T-odd quarks can decay through cascades like

$$q_H \to q\,Z_H \to q\,l^\pm l_H^\mp \to q\,l^+l^-\,B_H, \tag{4.1}$$

leading to a signal of opposite-sign same-flavor leptons and missing transverse energy, similar to the situation in mSUGRA scenarios in supersymmetry [15]. Here one can make use of the fact that the main SM backgrounds produces uncorrelated leptons, with the same proportion of same-flavor ($e^+e^-/\mu^+\mu^-$) and opposite-flavor ($e^\pm\mu^\mp$) leptons. If then the opposite-flavor events are subtracted from the total sample, the SM backgrounds are effectively removed, while the little Higgs signal is not affected [15]. However, the statistical

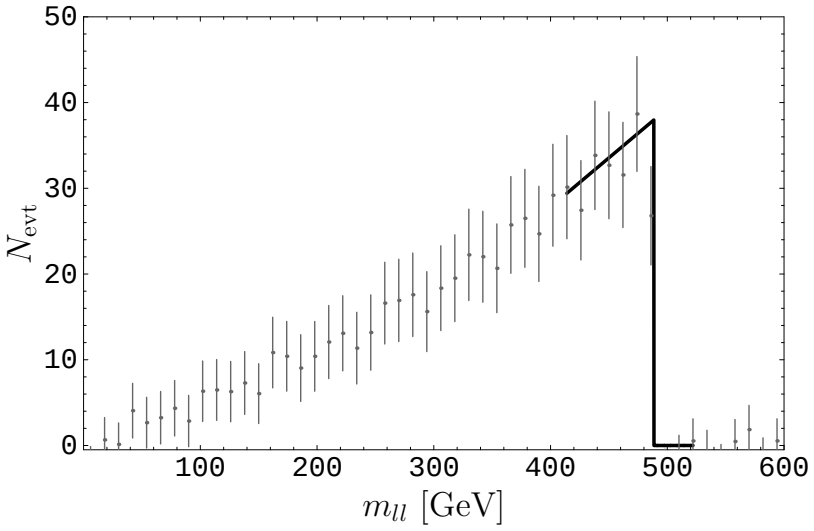

Figure 5: Distribution of the di-lepton invariant mass m_{ll} associated with the decay chain $q_H \to q\,Z_H \to q\,l^{\pm}l_H^{\mp} \to q\,l^+l^-\,B_H$, for the parameter values $f = 1000$ GeV, $\kappa_q = 0.5$ and $\kappa_l = 0.2$. The error bars correspond to the statistical uncertainty for $30\,\mathrm{fb}^{-1}$ luminosity, after subtraction of backgrounds.

noise from the backgrounds is not reduced by this method and still affects the extraction of the signal process.

For the signal selection of the decay chain eq. (4.1), the same cuts as listed in table 3 can be used. Since the decay of one mirror quark already leads to two leptons in the final state, no assumption for the decay of the second mirror quark needs to be made, other than that it leads to the LTP B_H in the final state, which generates missing transverse energy in the signature. This improves the signal statistics compared to the analysis in section 3.2 (b). After application of the cuts in table 3, the signal rate for the process eq. (4.1) is 21 fb, while the SM backgrounds amount to 10 fb. If in addition the different-lepton-flavor subtraction described above is used, the remaining backgrounds are negligible, but introduce some statistical noise. Combining the statistical errors, the new physics signal can be identified in this channel with more than 20 standard deviations with $30\,\mathrm{fb}^{-1}$ luminosity.

Furthermore, the di-lepton invariant mass distribution shown in figure 5 exhibits a distinct upper endpoint at

$$(m_{ll}^{\max})^2 = (m_{Z_H}^2 - m_{l_H}^2)(m_{l_H}^2 - m_{B_H}^2)/m_{l_H}^2 . \tag{4.2}$$

This feature can be used to extract some information about the T-odd particle masses. The spectrum edge can be fitted with a simple triangle-shaped fit function, see figure 5. Assuming $30\,\mathrm{fb}^{-1}$ luminosity, one obtains

$$m_{ll}^{\max} = 488.6^{+5.2}_{-4.4}\ \mathrm{GeV}, \tag{4.3}$$

which is in good agreement with the input value of the underlying model, 488.5 GeV. Due to the relatively small signal cross-section, the statistical error is quite large. It can

be improved by using more luminosity. With a total luminosity of $300\,\mathrm{fb}^{-1}$, the error is reduced to

$$\delta m_{ll}^{\max} = \begin{smallmatrix}+2.1\\-1.7\end{smallmatrix}\ \mathrm{GeV}. \tag{4.4}$$

Still, at this level of precision, systematic errors due to the lepton energy scale uncertainty or due to mistagging can be neglected.

Since eq. (4.2) depends only mildly on m_{l_H} for $m_{B_H} \ll m_{l_H} \ll m_{Z_H}$, the measured endpoint $m_{ll}^{\max}$ gives a rough estimate of the mass difference between the T-odd gauge bosons, $m_{ll}^{\max} \approx m_{Z_H} - m_{B_H}$. In the case of the scenario studied here, $m_{Z_H} - m_{B_H} = 493\,\mathrm{GeV}$, so that this simplified relation holds within statistical errors.

More information about the mass spectrum of the T-odd particle could be obtained by studying invariant mass distributions including the jet originating from the mirror quark decay [15]. However, due to additional jet radiation and ambiguities in the selection of the jet, the kinematic endpoints of these distributions are more smeared out. This fact together with the low signal statistics leads to very large errors for fits to kinematic endpoints of jet-lepton distributions.

5. Conclusion

In this paper we have considered the production and decay of the T-odd heavy particles at LHC in littlest Higgs models with T-parity. This symmetry implies the presence of heavy mirror particles and that the heavy particles can only be pair produced. In the case of heavy gauge bosons, s-channel and t-channel production mechanisms interfere destructively. This reduces the production rate substantially to less than about 0.1 pb and makes this channel almost impossible to observe.

Similarly, the discovery and measurement of T-odd mirror quarks at the LHC is very difficult. We have considered all possible decay chains, but most decay channels are lost in the SM background. Only the channel $pp \to q_H q_H \to q q' W_H^{\pm} B_H \to jj\, l + \not{E}_T$ with a production rate of about 10 fb might be promising, but mandates further study. We discuss to some extent the cuts required to reduce the SM background (see table 2). Although the final state signatures are quite similar to the ones for squark production in the MSSM, the signal rates are typically lower in the LHT models than in the MSSM because there is no partner to the gluon. Recall that in supersymmetric models, the partner of the gluon, the gluino, is typically the primary particle for squark production. This yields larger cross-section and additional hard jets in the final state, which help to discriminate from the background. In LHT models however, the gluon is a has no partner. It should be noted, however, that the somewhat pessimistic results of this section strongly depend on the underlying scenario. For example, by lowering the breaking scale f, the production cross-section of T-odd quarks at the LHC are greatly enhanced. Figure 4 gives a rough picture of the dependence on f; the actual dependence is more complicated because of the intricate energy dependence of the cuts.

Mirror leptons, are only produced through weak processes, but may play a role in the decay signatures of the heavy quarks if they are lighter than the heavy quarks or gauge

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bosons. Then the leptonic branching ratio of the neutral gauge boson Z_H is close to one, with opposite-sign same-flavor leptons. As detailed above, this can be used to effectively suppress the SM background; although some non-negligible statistical noise remains. Moreover, this decay could also yield information about the spectrum of the T-odd particles. Clearly detailed experimental studies along these lines will be required for a more conclusive assessment.

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