

## Dark matter in the little Higgs model under current experimental constraints from the LHC, Planck, and Xenon data Postprint

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### Abstract

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### Full Text

### Preamble

#### Dark matter in little Higgs model under current experimental constraints from LHC, Planck and XENON

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### Abstract

We examine the status of dark matter (heavy photon) in the littlest Higgs model with T-parity (LHT) in light of the new results from the LHC Higgs search, the Planck dark matter relic density and the XENON100 limit on the dark matter scattering off the nucleon. We obtain the following observations: (i) For the LHC Higgs data, the LHT can well be consistent with the CMS results but disfavored by the ATLAS observation of diphoton enhancement; (ii) For the dark matter relic density, the heavy photon in the LHT can account for the Planck data for the small mass splitting of mirror lepton and heavy photon; (iii) For the dark matter scattering off the nucleon, the heavy photon can give a spin-independent cross section below the XENON100 upper limit for  $m_{AH} > 95$  GeV ( $f > 665$  GeV); (iv) A fit using the CMS Higgs data gives the lowest

chi-square of 2.63 (the SM value is 4.75) at  $f = 1120$  GeV and  $m_{AH} = 170$  GeV (at this point the dark matter constraints from Planck and XENON100 can also be satisfied). Such a best point and its nearby favored region (even for  $f$  values up to 3.8 TeV) can be covered by the future XENON1T (2017) experiment.

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## INTRODUCTION

To solve the fine-tuning problem of the standard model (SM), the little Higgs theory [1] is proposed as a kind of electroweak symmetry breaking mechanism accomplished by a naturally light Higgs boson. The littlest Higgs model (LH) [2] provides an economical realization for this theory. Further, to relax the constraints from the electroweak precision data [3], a discrete symmetry called T-parity is introduced to the LH [4, 5]. The LH with T-parity (LHT) predicts a heavy photon as a candidate for the weakly interacting massive particle (WIMP) dark matter (DM), whose relic density, direct detection, indirect detection and phenomenology at the LHC have been intensively studied [6, 7].

Very recently, some experiments have made significant progress, which allow for a test for new physics like the LHT. On the one hand, for the dark matter the Planck collaboration [8] released its relic density as  $\Omega_{\text{ch}}^2 \pm = 0.1199 \pm 0.0027$  (in combination with the WMAP data [9]) and the CDMS II direct detection experiment has reported three WIMP-candidate events corresponding to a WIMP around 8.6 GeV [10]. However, such a CDMS result is in tension with other direct detection results like the latest XENON100 results [11], which provided the most stringent upper limits on the spin-independent WIMP-nucleon scattering cross section for a WIMP above 7 GeV.

On the other hand, for the Higgs search the CMS and ATLAS collaborations have announced observation of a Higgs-like boson around 125 GeV [12-15]. This observation is supported by the Tevatron search which showed a 3.1 excess at  $M_h = 125$  GeV [16]. The properties of this observed particle are well consistent with the SM Higgs boson for most of the search channels. Note that the Higgs diphoton rate from ATLAS is sizably larger than the SM expectation,  $1.6 \pm 0.3$  [14], but the central value of CMS is smaller than the SM prediction,  $0.77 \pm 0.27$  [15]. The Higgs properties in the LHT have been studied in [17-20] and the diphoton rate was found to be always suppressed (in contrast to the low energy supersymmetric models which can either enhance or suppress the diphoton rate [21]).

In this work we examine the status of dark matter (heavy photon) in the LHT under the latest experimental constraints from the LHC Higgs result, the Planck DM relic density and the XENON100 (2012) limit on the DM-nucleon scattering. In Sec. II we recapitulate the dark matter sector in the LHT. In Sec. III we examine the status of dark matter (heavy photon) in light of the latest experimental results. Finally, we give our conclusion in Sec. IV.

## II. THE LITTLEST HIGGS MODEL WITH T-PARITY

This model [2] consists of a nonlinear sigma model with a global SU(5) symmetry which is broken down to SO(5) by a vacuum expectation value (VEV)  $f$ . A subgroup  $[SU(2) U(1)]^2$  of SU(5) is gauged. T-parity is an automorphism which exchanges the  $[SU(2) U(1)]$  and  $[SU(2) U(1)]$  gauge fields. While all the SM particles are T-even, the new gauge bosons ( $W_H, Z_H, A_H$ ) and the triplet scalar ( $\Phi, \Phi, \Phi, \Phi$ ) are T-odd, whose masses are given by:

$$m_{W_H} \approx m_{Z_H} = gf \left( 1 - \frac{v^2}{8f^2} \right), \quad m_{A_H} \approx g' f \frac{v^2}{8f^2}, \quad m_{\Phi} \approx \sqrt{2} \frac{m_h f}{v}$$

where  $h$  and  $v$  are respectively the SM-like Higgs boson and its vacuum expectation value (vev). The relation between  $G_F$  and  $v$  is modified from its SM form and reads as [18]:

$$v \approx v_{SM} \left( 1 + \frac{v^2}{12f^2} \right)$$

where  $v_{SM} = 246$  GeV is the SM Higgs vev. The heavy photon  $A_H$  is typically the lightest T-odd state and thus can serve as a candidate for dark matter.

In the top quark sector, there are a T-even partner (denoted as  $T$ ) and a T-odd partner (denoted as  $T^-$ ). The T-even one mixes with the top quark and cancels the quadratic divergent contribution of the top quark to the Higgs boson mass. The mixing can be parameterized by  $r = \frac{f}{v}$  where  $\lambda_1$  and  $\lambda_2$  are two dimensionless top quark Yukawa couplings. The masses of the T-even partner and the T-odd partner are given by:

$$m_T = \frac{f}{\sqrt{2}} \sqrt{\lambda_1^2 + \lambda_2^2}, \quad m_{T^-} = \lambda_2 f$$

For each SM quark (lepton), a heavy mirror quark (lepton) with T-odd quantum number is added in order to preserve T-parity. Their masses are given by:

$$m_{u_{Hi}} = 2\kappa_{qi} f \left( 1 - \frac{v^2}{8f^2} \right), \quad m_{d_{Hi}} = 2\kappa_{qi} f$$

$$m_{\nu_{Hi}} = 2\kappa_{li} f \left( 1 - \frac{v^2}{8f^2} \right), \quad m_{l_{Hi}} = 2\kappa_{li} f$$

where  $\lambda_{\{qi\}}$  and  $\lambda_{\{li\}}$  with  $i = 1, 2, 3$  are the eigenvalues of the mirror quark and lepton mass matrices, respectively.

For the SM down-type quarks (leptons), the Higgs couplings in LHT have two different cases [18]:

- **LHT-A:**  $\mathcal{L} \supset -\frac{m_d}{v} \left(1 - \frac{v^2}{2f^2}\right) h\bar{d}d$
- **LHT-B:**  $\mathcal{L} \supset -\frac{m_d}{v} \left(1 - \frac{v^2}{f^2}\right) h\bar{d}d$

The relation of down-type quark couplings also applies to the lepton couplings.

In our analysis we use MicrOMEGAs3.2 to calculate the relic density and the cross section between DM and nucleon [22]. The CalcHEP LHT model files are provided by [23]. We add the Higgs couplings to the u-quark, d-quark and electron, and modify the Z and W couplings to mirror fermions. In addition, we assume the interactions between the mirror fermions and the SM fermions are diagonal.

Some typical Higgs and DM couplings are given by [18, 24, 25]:

$$\begin{aligned}
h\bar{u}_{Hi}u_{Hi} &: \frac{m_{u_{Hi}}}{v} \left(1 - \frac{3v^2}{2f^2}\right), & hA_H A_H &: -\frac{g'^2}{2}v \left(1 - \frac{v^2}{3f^2}\right) \\
hW^+W^- &: \frac{2m_W^2}{v} \left(1 - \frac{v^2}{4f^2}\right) g_{\mu\nu}, & h\bar{u}u &: -\frac{m_u}{v} \left(1 - \frac{v^2}{2f^2}\right) \\
h\bar{t}t &: -\frac{m_t}{v} \left(1 - \frac{v^2}{f^2}\right), & h\bar{l}_{Hi}l_{Hi} &: -\frac{m_{l_{Hi}}}{v} \left(1 - \frac{v^2}{2f^2}\right) \\
Z\nu_{Hi}\bar{\nu}_{Hi} &: \frac{g'}{10}\gamma^\mu P_L, & A_H\bar{u}_i u_{Hi} &: -\left(\frac{g'}{10} + g\right)\gamma^\mu P_L \\
A_H\bar{\nu}_i\nu_{Hi} &: -\left(\frac{g'}{10} + g\right)\gamma^\mu P_L, & Wl_{Hi}\bar{\nu}_{Hi} &: \frac{g}{\sqrt{2}}\gamma^\mu P_L
\end{aligned}$$

where  $P_L = (1 - \gamma_5)/2$  and  $x_H = \frac{5gg'}{4(5g^2 - g'^2)}$ .

### III. DARK MATTER IN LHT UNDER CURRENT EXPERIMENTAL CONSTRAINTS

#### A. Implication of LHC Higgs data on LHT parameter space

In our calculations, the Higgs mass is fixed as 125.5 GeV, and the new free parameters are  $f$ ,  $r$ ,  $\_ \{li\}$ ,  $\_ \{qi\}$ . The electroweak precision data favor  $f > 50$  GeV and  $0.5 < r < 2$  [26]. We assume that the three generations of mirror quarks (leptons) are degenerate in mass, namely  $\_ \{l1\} = \_ \{l2\} = \_ \{l3\}$  and  $\_ \{q1\} = \_ \{q2\} = \_ \{q3\}$ . For  $\_ \{qi\} < 0.45$ , the mirror quark is lighter than the heavy gauge bosons  $W_H$  and  $Z_H$ , and thus its only decay mode is the two-body decay into  $A_H$  and a SM quark. The ATLAS and CMS collaborations have analyzed jets plus missing transverse momentum signal, and not yet found any hints of new physics [27, 28]. Therefore, we take  $0.45 < \_ \{qi\} < 1$  conservatively. In addition, we impose the LEP limits on the masses of charged leptons which are required to be larger than 105 GeV [29].

We consider the relevant QCD and electroweak corrections using the code Hdecay [30]. For the Higgs productions and decays, the LHT gives the corrections by directly modifying the Higgs couplings to the relevant SM particles. For the loop-induced decays  $h \rightarrow gg$  and  $h \rightarrow \gamma\gamma$ , the LHT gives the partial corrections via the reduced  $h \bar{t}t$  and  $hWW$  couplings, respectively. Besides,  $h \rightarrow gg$  can get contributions from the loops of heavy partner quark  $T$  and mirror up-type quarks. In addition to the loops of the heavy quarks involved in the  $h \rightarrow gg$ , the decay  $h \rightarrow \gamma\gamma$  can be also altered by the loops of  $W_H$ ,  $\Phi_{\pm}$  and  $\Phi_{\pm\pm}$  in the LHT. The doubly charged  $\Phi_{\pm\pm}$  contributions are enhanced by a relative factor 4 in the amplitude, but can still be ignored due to the very small coupling  $h\Phi_{\pm}\Phi_{\pm}$  (in contrast to the type II seesaw model whose doubly charged scalar can give the dominant contributions to the decay  $h \rightarrow \gamma\gamma$  [31]). Since the mirror charged lepton, the mirror down-type quark and the top partner  $T$  do not have tree-level couplings to the Higgs boson, they do not contribute to  $h \rightarrow gg$  and  $h \rightarrow \gamma\gamma$  at leading order. For  $m_h = 125.5$  GeV, the decay  $h \rightarrow A_H A_H$  is kinematically forbidden in the LHT (such an invisible decay was possible in some supersymmetric models [32]).

The decays  $h \rightarrow gg$  and  $h \rightarrow \gamma\gamma$  are not sensitive to the mirror quark masses as long as they are much larger than half of the Higgs boson mass. The parameter  $r$  determines the Higgs couplings to  $t$ ,  $T$  and  $m_T$ , and is involved in the calculations of  $h \rightarrow gg$  and  $h \rightarrow \gamma\gamma$ . The  $r$  dependence of the top quark loop and  $T$  quark loop can cancel to a large extent, as can be seen from Eq. (6). Therefore, the Higgs signal rates in many channels are only sensitive to the scale  $f$ .

Requiring that the heavy photon is the lightest  $T$ -odd particle, we scan over the parameter space of  $f$ ,  $r$ ,  $\{q_i\}$  and  $\{l_i\}$  in the ranges allowed by the electroweak precision data ( $\{l_i\}$  is not involved in the calculation of the Higgs signal rates). We show the inclusive diphoton signal rate normalized to the SM value in Fig. 1 [Figure 1: see original paper]. From this figure we find that the diphoton rates in the LHT-A and LHT-B are always suppressed, and approach the SM predictions for a large scale  $f$ . The suppression in the former is more sizable than in the latter because the  $h\bar{b}b$  coupling in the LHT-B is suppressed more sizably. Since the ATLAS diphoton data is above the SM value by about 20%, the predicted rates in both the LHT-A and LHT-B are outside the 20% range of the ATLAS data. For the CMS diphoton data which shows no enhancement relative to the SM value, the LHT-A and LHT-B can both give the signal rates in its 10% range. In the following, we will focus on the CMS data instead of combining the two groups' results.

Now we perform a fit to the CMS Higgs data in the LHT-A and LHT-B. We compute the  $\chi^2$  values by the method introduced in [33, 34], with the CMS Higgs data in 9 channels from Fig.4 of [15]. Since the data for different exclusive search channels presented by one collaboration are not independent, we consider the correlation coefficient as in [35, 36]. In Fig. 2 [Figure 2: see original paper] we project the samples on the plane of  $\chi^2$  versus  $f$ . Similar to the diphoton rates, the

$\sigma$  of LHT-A and LHT-B is only sensitive to  $f$ . The  $\sigma$  is larger than the SM value for low values of  $f$ , then becomes smaller than the SM value for intermediate values of  $f$ , and finally approaches the SM value for sufficiently high values of  $f$ . For  $f$  around 1 TeV,  $\sigma$  in the LHT-A and LHT-B reaches the minimal value, which is 2.63 for LHT-A and 3.70 for LHT-B. So we see that the best point favored by the CMS Higgs data is at  $f = 1$  TeV.

We also performed the fit using the ATLAS data [14, 37]. We found that the  $\sigma$  values are much larger than using the CMS data. The main source of large  $\sigma$  comes from the diphoton enhancement [14].

## B. Dark matter relic density and scattering with nucleon

Our results show that the heavy photon relic density and its spin-independent cross section with nucleon are very similar for the LHT-A and LHT-B. So we only present the results for LHT-A. We will display the dark matter relic density and its spin-independent cross section with the nucleon in the parameter space allowed by the CMS Higgs data at 2  $\sigma$  level (as shown in the left panel of Fig. 2, most samples in our scan can survive such a 2  $\sigma$  criterion). The theoretical predictions in the LHT-A will be compared with the relic density data from Planck and the scattering rate limit from XENON100. Also, the future XENON-1T sensitivity will be shown for the LHT-A.

The heavy photon pair-annihilation processes include  $A_H A_H \rightarrow f\bar{f}, ZZ, WW$  which proceed via an s-channel  $h$  exchange, and  $A_H A_H \rightarrow hh$  which proceeds via a 4-point contact interaction, an s-channel  $h$  exchange, and t- and u-channel  $A_H$  exchange. Also,  $A_H A_H \rightarrow f\bar{f}$  can proceed via the t- and u-channel T-odd fermion exchange (including the mirror quark, mirror lepton, top partner  $T$ ), whose contributions to the relic density are generally suppressed by the interactions between the T-odd fermions and SM fermions mediated by the heavy photon. In addition, the mirror lepton can have an important effect on the relic density via the coannihilation processes for the mirror lepton masses close to the heavy photon. However, the other T-odd particles, including the mirror quarks, top partner quark  $T$ , heavy gauge bosons and scalars, do not contribute to the relic density since their masses are much larger than  $A_H$ .

In Fig. 3 [Figure 3: see original paper] we project the LHT samples showing the dependence of the heavy photon relic density on  $m_{AH}$  and  $\Delta M$  (the mass splitting between mirror neutrino and heavy photon). We see that in order to account for the DM relic density,  $\Delta M$  must be small and thus the mirror leptons play an important role via the coannihilation processes. For the heavy photon pair-annihilation, there is no s-channel Higgs resonance since the mass splitting of  $2m_{AH}$  and  $m_h$  is much larger than the total width of Higgs. Further, the relevant Higgs and heavy photon couplings are suppressed by a factor of  $1 - O(v^2/f^2)$  (see Eq. 6). Therefore, the cross sections of the heavy photon pair-annihilation are too small to provide the correct relic density of DM, and the mirror leptons have to play an important role via the coannihilation processes.

The heavy photon scattering off the nucleon can occur via exchanging a Higgs boson or a mirror quark. The former will give the dominant contribution to the spin-independent cross section, especially for the Higgs-gluon interaction via the heavy quark loops. For the latter case, since the mirror quarks are much heavier than the heavy photon, we have no enhancement in the propagator [6]. They cannot contribute sizably to the spin-independent cross section due to the small couplings of  $A_H \bar{u} u_H$  and  $A_H \bar{d} d_H$ .

In Fig. 4 [Figure 4: see original paper] we display the scatter plots of the LHT-A parameter space allowed by the CMS Higgs data at 2 level and by the Planck dark matter relic density at 2 level, showing the spin-independent scattering cross section off the nucleon. We see that the spin-independent cross section decreases with increasing  $m_{AH}$ , and is below the upper limit of XENON100 (2012) for  $m_{AH} > 95$  GeV ( $f > 665$  GeV). The best point from the fit of the CMS Higgs data (which also gives the relic density in the 2 range) happens at  $f = 1120$  GeV and  $m_{AH} = 170$  GeV. Such a best point and its nearby favored region (even for  $f$  values up to 3.8 TeV) can be covered by the future XENON1T (2017) experiment.

Finally, in Table I we present the detailed information for two samples (LHT-A P1 and LHT-B P3) which give minimal  $\chi^2$  for the CMS Higgs data and also the best relic density (closest to the measured central value). Also, another two samples (LHT-A P2 and LHT-B P4) for  $f = 800$  GeV are given for comparison. As previously discussed,  $\chi^2$  is sensitive to  $f$  and the relic density is sensitive to  $f$  and  $\mu$ . For the best-fit points,  $\mu_{SI}$  is almost the same in the LHT-A and LHT-B, while the Higgs properties have sizable differences. Especially, the rates for the Higgs signals  $\gamma\gamma$ ,  $ZZ$ , and  $WW$  via the VBF+VH production channel are enhanced in the LHT-B, but suppressed in the LHT-A, which may be useful for distinguishing between the two models.

#### IV. CONCLUSION

The LHT provides a heavy photon as a candidate for weakly interacting massive particle dark matter. In this note we examined the status of such a dark matter candidate in light of the new results from the LHC Higgs search, the Planck dark matter relic density and the XENON100 limit on the dark matter scattering off the nucleon. We scanned over the parameter space in the ranges allowed by the electroweak precision data. By confronting the parameter space with the LHC Higgs data, we found that the LHT can well be consistent with the CMS results but disfavored by the ATLAS observation of diphoton enhancement. Then in the parameter space allowed by the CMS Higgs data at 2 level, we calculated the heavy photon relic density and found that the heavy photon can account for the Planck data for the small mass splitting of mirror lepton and heavy photon. Finally, under the constraints from LHC Higgs and Planck dark matter relic density, we checked the heavy photon scattering off the nucleon and found that the heavy photon can give a spin-independent cross section below the XENON100 upper limit for  $m_{AH} > 95$  GeV ( $f > 665$  GeV). The

whole parameter space allowed by the current experiments (LHC Higgs, Planck, XENON100) can be covered by the future XENON1T (2017) experiment for  $f$  values up to 3.8 TeV.

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