Associated production of a photon with dark matter pair at the ILC within the Littlest Higgs model with T-parity

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Abstract

Within the context of the Littlest Higgs model with T-parity, the heavy photon ($A_H$) is supposed to be an ideal dark matter (DM) candidate. One direct proof of validity of the model is to produce the heavy photon at collider. In this paper, we investigate the associated production of a photon with heavy photon pair at the planned international $e^+e^-$ linear collider (ILC), i.e., $e^+e^- \rightarrow A_H A_H \gamma$ and show the distributions of the transverse momenta of the photon. The numerical results indicate that the heavy photon production rate could reach several $fb$ at the low mass parameter space and the characteristic signal is a single high energetic photon and missing energy, carried by the heavy photons. All in all, it can be good chance to observe the heavy photon via this process with the high yearly luminosity of the ILC.

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The predictions of the standard model (SM) of particle physics, including the strong and electroweak interactions, are in accordance with the data coming from all the experiments within the error tolerance so far. All the facts indeed strengthen our confidence in the SM. However, there are still some problems existing in the framework of the SM. For example, there exits the famous hierarchy problem. Meanwhile, SM can’t provide an appropriate candidate of the DM. These facts mean that the explanation provided by the SM should not be the end of the story and it will let a little room for the new physics beyond the SM. As mentioned above, the new physical models are needed to solve the fine-tuning problem and provide the candidates of the DM. There are many new physics models that have been proposed, such as: Little Higgs models\cite{1, 2} with T-parity (LHT)\cite{3, 4}, supersymmetry (SUSY) models with R-parity\cite{5}, etc. These models could solve the above problems successfully.

In the original little Higgs models (LHM), there is a spontaneously broken global symmetry. The interactions of two sets cause the explicitly broken of the global symmetry, with each set preserving an unbroken subset. Higgs arises as an exact pseudo-Nambu-Goldstone boson (PNGB) when either set of couplings vanishes. The hierarchy problem is explained by introducing new heavy particles at the TeV scale, with the identical spins of the corresponding SM particles (opposite to the scenario in SUSY). The quadratic divergences of the Higgs boson mass are canceled by these new particles at one-loop level. However, the original LHM still suffer severe constraints from precision electroweak fits that are derived from the corrections of the tree-level interactions. To evade the issue, a $Z_2$ discrete symmetry designated as T-parity (mimic R-parity in SUSY) is brought in. In LHT, particles of SM have the even T-parity, while all new gauge bosons and scalar triplets have the odd T-parity. In the above arrangement, it is completely natural to eliminate the contributions at tree-level. Another benefit of the LHT is that the particles with odd T-parity must be pair-produced and then cascade decay down to the lightest T-odd particle (LTP), so the LTP is guaranteed to be stable.

The Littlest Higgs model with T-parity\cite{6, 7} is such a type model. In this model, there is a neutral LTP: heavy photon $A_H$ with an odd T-parity. If the T-parity was conservation, it would be stable. It also has the following characters: non-luminous, non-relativistic, non-baryonic, and electrically neutral.\cite{8, 9, 10, 11, 12} The heavy photon indeed satisfies all standards of the cold DM, so it could be regarded as a perfect candidate of DM naturally. Experimentally searching heavy $A_H$ gauge boson and some other special particles\cite{13, 14} would provide direct evidence for judging validity of the model. Because all the new particles are so heavy that they escaped detection in prior colliders. By a general analysis, their masses, may be in TeV regions, so that one can expect to observe them at the high energy colliders, e.g., the large hadron collider (LHC) and the ILC. The production of heavy photon pair at the LHC, $pp \rightarrow A_H A_H + X$ has been discussed in the Ref.\cite{6}. In fact, the LHC might be difficult to confirm a theory, but feasible to rule out a model as
long as the signal predicted by the model does not show up at the required region. If we want to better understand the properties of the Littlest Higgs model with T-parity, we need to study the production of these particles at the ILC because of the clean background. In our previous work, we have studied $e^+e^- \rightarrow A_H A_H$ at the ILC in the Littlest Higgs model with T-parity. However, because the interactions between SM particles and heavy photons are weakness, the detection of above process is difficult. In this work, we analyze associated production of a photon with dark matter pair at the ILC, that is, $e^+e^- \rightarrow A_H A_H \gamma$, where typical collider signals are a single high energetic photon and missing energy, carried by the heavy photons.

This paper is arranged as follows. The numerical results of the production rate and the distributions of the transverse momenta are given in Sec. II where all input parameters are explicitly listed. Our analysis of various aspects and conclusions are presented in the final section.

1 Theoretical formulation and numerical results

We know the Littlest Higgs model with T-parity is based on a non-linear $\sigma$-model describing a global $SU(5)/SO(5)$ symmetry breaking, which takes place at an energy scale $\Lambda \sim 4\pi f \sim 10$ TeV. The vacuum expectation value (VEV) that causes the breaking is characterized by the direction of the form

$$
\Sigma_0 = \begin{pmatrix}
1 & 1 \\
1 & 1 \\
1 & 1
\end{pmatrix}.
$$

(1)

The vacuum also breaks the assumed embedded local gauge symmetry $[SU(2) \times U(1)]^2$ subgroup down to the diagonal subgroup. One set of $SU(2) \times U(1)$ acquire masses of order $f$

$$
W_H^0 = \frac{1}{\sqrt{2}}(W_1^0 - W_2^0), \quad M_{W_H^0} = gf,
$$

(2)

$$
B_H = \frac{1}{\sqrt{2}}(B_1 - B_2), \quad M_{B_H} = \frac{g'}{\sqrt{5}}f,
$$

(3)

the other set remaining massless before Electroweak Symmetry Breaking (EWSB) is identified as the SM electroweak gauge fields $SU(2)_L \times U(1)_Y$.

After EWSB, the VEV of the Higgs will shift the mass eigenstates of the heavy gauge boson sector. The new heavy mass eigenstates $A_H$, $Z_H$ and $W_H^\pm$ could be written as

$$
W_H^\pm = \frac{1}{\sqrt{2}}(W_H^1 \mp iW_H^2),
$$

$$
Z_H = \sin \theta_H B_H + \cos \theta_H W_H^3,
$$

$$
A_H = \cos \theta_H B_H - \sin \theta_H W_H^3,
$$

(4)
the masses of the new heavy gauge bosons receive corrections of order \( v^2/f^2 \) and could be written as

\[
M(Z_H) = M(W^\pm_H) = gf(1 - \frac{v^2}{8f^2}) \approx 0.65f, \\
M(A_H) = \frac{fg'}{\sqrt{5}}(1 - \frac{5v^2}{8f^2}) \approx 0.16f,
\]

where \( g \) and \( g' \) are the gauge couplings of the SM \( SU(2)_L \) and \( U(1)_Y \) respectively. So the mass of the \( A_H \) is distinctively smaller than other T-odd particles, which are generically of level \( f \). With the T-parity, \( A_H \) is a weakly interacting stable neutral particle. It provides a natural candidate of the weakly-interacting massive particle (WIMP)\[16\] cold DM.

The mirror fermions, acquire masses through a Yukawa-type interaction

\[
\kappa f (\bar{\Psi}_2 \xi \Psi' + \bar{\Psi}_1 \Sigma_0 \Omega \xi \dagger \Omega \Psi')
\]

whereas \( \Psi_1, \Psi_2 \) are the fermion doublets and \( \Psi' \) is a doublet under \( SU(2)_2 \).

One fermion doublet \( \Psi_H = \frac{1}{\sqrt{2}}(\Psi_1 + \Psi_2) \) gets a mass \( \kappa f \). \( f \) is a scale parameter and takes the value of 1000. Concretely, the T-odd heavy partners of the SM leptons get the following masses \( \sqrt{2} \kappa_l f \)\[17\], where the \( \kappa_l \) is the independent Yukawa coupling of flavor. The T-odd heavy lepton will be supposed to surpass 300 GeV to evade the colored T-odd particles from being detected in the squark searches at the Tevatron.

In this model, the coupling terms that heavy photon interact with SM fermion and T-odd fermion, the SM photon interact with T-odd fermions are shown as:\[6, 7\]

\[
A^\mu_H \bar{L}_i L_j : i \frac{e}{\sqrt{4} \pi f} (S_W - 5C_W(\frac{e}{e})^2 x_h) \gamma^\mu P_L \delta_{ij}, \\
A^\mu \bar{L}_i \tilde{L}_j : i e \gamma^\mu \delta_{ij},
\]

where \( \tilde{L} \) is the heavy T-odd lepton and \( L \) is the SM lepton. \( e = \sqrt{4\pi/\alpha} \), where \( \alpha \) is the fine-structure constant and take the value\[18\] of 1/128. \( x_h = \frac{5}{4} \frac{g' f}{g - g'} \), \( v = 2 M_W S_W \), \( P_L = \frac{1 - \gamma_5}{2} \) is the left-handed chiral projection operator. \( S_W \) and \( C_W \) are sine and cosine of the Weinberg angle respectively, \( M_W \) is the mass of SM W gauge boson.

At the tree-level, the Feynman graphs for the process of \( e^+ e^- \rightarrow A_H A_H \gamma \) are shown in Fig. \[\text{Fig. 1}\]

According to the Feynman graphs in Fig. \[\text{Fig. 1}\] we can directly write the explicit amplitude of
take two groups of values:

Concretely, in order to expose possible dependence of the cross section on these parameters, we let the center-of-mass frame $P_{1M3}$, $P_{1M4}$, $P_{1M5}$, $P_{1M6}$ vary in the ranges 100 to 250 GeV in Fig. 2 and 100 to 300 GeV in Fig. 3. The final numerical results of the cross sections are illustrated in Fig. 2 and Fig. 3.

From these figures, we can observe that the dependence of production rate on heavy photon

\[ M = M_a + M_b + M_c + M_d + M_e + M_f, \]

\[ M_a = -i \frac{e^3}{16 \pi^2} (S_W - 5C_W \frac{\bar{q} \gamma^2 q}{q^2})^2 \frac{1}{P_{5M2}^2 - m_L^2} \frac{1}{P_{1M3}^2 - m_H^2} \bar{\nu}_e (P_2) \gamma^\mu (P_{5M2} + m_L) \gamma^\nu P_L (P_{1M3} + m_e) \gamma^\mu P_L u_\nu - (P_1) \epsilon_\mu (P_3) \epsilon_\nu (P_4) \epsilon_\rho (P_5), \]

\[ M_b = -i \frac{e^3}{16 \pi^2} (S_W - 5C_W \frac{\bar{q} \gamma^2 q}{q^2})^2 \frac{1}{P_{5M2}^2 - m_L^2} \frac{1}{P_{1M4}^2 - m_H^2} \bar{\nu}_e (P_2) \gamma^\mu (P_{5M2} + m_L) \gamma^\nu P_L (P_{1M4} + m_e) \gamma^\mu P_L u_\nu - (P_1) \epsilon_\mu (P_3) \epsilon_\nu (P_4) \epsilon_\rho (P_5), \]

\[ M_c = -i \frac{e^3}{16 \pi^2} (S_W - 5C_W \frac{\bar{q} \gamma^2 q}{q^2})^2 \frac{1}{P_{5M2}^2 - m_L^2} \frac{1}{P_{1M5}^2 - m_H^2} \bar{\nu}_e (P_2) \gamma^\mu (P_{5M2} + m_L) \gamma^\nu P_L (P_{1M5} + m_e) \gamma^\mu P_L u_\nu - (P_1) \epsilon_\mu (P_3) \epsilon_\nu (P_4) \epsilon_\rho (P_5), \]

\[ M_d = -i \frac{e^3}{16 \pi^2} (S_W - 5C_W \frac{\bar{q} \gamma^2 q}{q^2})^2 \frac{1}{P_{5M2}^2 - m_L^2} \frac{1}{P_{1M3}^2 - m_H^2} \bar{\nu}_e (P_2) \gamma^\mu (P_{5M2} + m_L) \gamma^\nu P_L (P_{1M3} + m_e) \gamma^\mu P_L u_\nu - (P_1) \epsilon_\mu (P_3) \epsilon_\nu (P_4) \epsilon_\rho (P_5), \]

\[ M_e = -i \frac{e^3}{16 \pi^2} (S_W - 5C_W \frac{\bar{q} \gamma^2 q}{q^2})^2 \frac{1}{P_{5M2}^2 - m_L^2} \frac{1}{P_{1M4}^2 - m_H^2} \bar{\nu}_e (P_2) \gamma^\mu (P_{5M2} + m_L) \gamma^\nu P_L (P_{1M4} + m_e) \gamma^\mu P_L u_\nu - (P_1) \epsilon_\mu (P_3) \epsilon_\nu (P_4) \epsilon_\rho (P_5), \]

\[ M_f = -i \frac{e^3}{16 \pi^2} (S_W - 5C_W \frac{\bar{q} \gamma^2 q}{q^2})^2 \frac{1}{P_{5M2}^2 - m_L^2} \frac{1}{P_{1M5}^2 - m_H^2} \bar{\nu}_e (P_2) \gamma^\mu (P_{5M2} + m_L) \gamma^\nu P_L (P_{1M5} + m_e) \gamma^\mu P_L u_\nu - (P_1) \epsilon_\mu (P_3) \epsilon_\nu (P_4) \epsilon_\rho (P_5), \]

where $P_{5M2} = P_5 - P_2$, $P_{1M3} = P_1 - P_3$, etc. The $\epsilon$s are the polarization vectors for the final gauge bosons.

With the above production amplitude, we can obtain the production cross section of the process and the distributions of the transverse momenta of $A_H$ through the Monte Carlo method.

There are also three free parameters involved in the production amplitudes: the energy of the center-of-mass frame $\sqrt{s}$, the heavy photon mass $m_{AH}$ and the mass of heavy lepton $m_L$. Concretely, in order to expose possible dependence of the cross section on these parameters, we take two groups of values: $\sqrt{s} = 500, 1000$ GeV, $m_L = 300, 500, 700$ GeV respectively, we also let $m_{AH}$ vary in the ranges 100 to 250 GeV in Fig. 2 and 100 to 300 GeV in Fig. 3. The final numerical results of the cross sections are illustrated in Fig. 2 and Fig. 3.

From these figures, we can observe that the dependence of production rate on heavy photon
Figure 2: The dependence of the cross section of $e^+e^- \rightarrow A_H A_H \gamma$ on heavy photon mass $m_{A_H}$ (100~250 GeV) for $\sqrt{s}=500$ GeV and $m_{\tilde{\ell}}=300, 500, 700$ GeV at the ILC.

Figure 3: The dependence of the cross section of $e^+e^- \rightarrow A_H A_H \gamma$ on heavy photon mass $m_{A_H}$ (100~300 GeV) for $\sqrt{s}=1000$ GeV and $m_{\tilde{\ell}}=300, 500, 700$ GeV at the ILC.
mass is quite strong, the cross section magnitude has a slide of above one order when $m_{AH}$ arises from 100 GeV to 225 GeV, naturally since the phase space is depressed rigorously by large $m_{AH}$. The dependence of the cross section on $\sqrt{s}$ is obvious: when $\sqrt{s}$ becomes large, the cross section increases evidently. The relations between the cross section and $m_{L}$, on the other hand, have a little complications, when $\sqrt{s}$ equals 500 GeV, $m_{L}$ becomes large, the cross section decreases, but when $\sqrt{s}$ equals 1000 GeV, that is no longer the case, specific relations can be obtained from Fig. 3. We also find that the production rate of $e^+e^- \rightarrow A_H A_H \gamma$ is much larger than $e^+e^- \rightarrow A_H A_H [15]$ of the same parameters. Despite depressions from the three-body phase space and the $\tilde{Y}$ factor, the extra items which contain $m_{L}$ in the numerators of the Eq. (8) enhance the final results strongly.

In Fig. 4 and Fig. 5 with $\sqrt{s}=500$ GeV, we present the transverse momentum distributions of final photon for $m_{AH}=100$ and 200 GeV, respectively. We can find that the differential cross section with the small transverse momentum of final photon make the main contribution to the cross section of $e^+e^- \rightarrow A_H A_H \gamma$.

2 Discussions and conclusions

The combination of cosmology and high energy collider [19, 20] seems to be a good idea. Astrophysical observations provide a way to study the characteristics of DM, however, the exact properties of a DM particle need to be determined by the DM factories, that is to say, the LHC and the ILC. Because of relatively clean background, the ILC is more appropriate for accurate examinations. So this paper is a proper supplement to Refs. [6, 21]. Finally, the heavy photon is the LTP and must be produced in pairs, constraint from the final state phase space of $A_H A_H \gamma$ is alleviated compared with other heavy T-odd particles pair production, since heavier T-odd particles
Figure 5: The distributions of the transverse momenta of final photon for the process $e^+e^- \rightarrow A_H A_H \gamma$ for $\sqrt{s}=500$ GeV and $m_{A_H}=200$ GeV.

are too heavy to be pair-produced in the first stage of the ILC with $\sqrt{s}=500$ GeV. It may imply that if the Littlest Higgs model with T-parity applies, $A_H A_H \gamma$ would be detected at earliest time at the ILC.

One factor strongly complicates the investigation of dark matter in the collider experiments is that DM particles do not carry either electric or color charge. In the collider experiments, the direct detection of DM at a collider is very difficult, DM would be like neutrinos and therein they would escape the detector without depositing energy in the experimental devices, causing an obvious imbalance of momentum and energy in collider events. In this paper, unlike the radiative production of heavy photons in $e^+e^-$ annihilation of six-dimensional SUSY QED\cite{22}, the signal of the heavy photon pair can be observed as missing momentum recoiling against the detected photon by measuring the energy deposited in each calorimeter cell of a detector. In the SM, the main irreducible background originates from the reaction $e^+e^- \rightarrow \bar{\nu}\nu \gamma$. This reaction is dominated by the t-channel W exchange contribution at the energies well above the Z peak. The background cross section at the ILC ($\sqrt{S}=500$ GeV) with no polarization was provided in Ref. \cite{23}, which is treated as the function of the DM mass, and has a rather large value. Nevertheless, the rate predicted of $e^+e^- \rightarrow A_H A_H \gamma$ may well be observable. Experiments at the ILC can search for $A_H A_H \gamma$ signature as an excess over the SM background $\nu\bar{\nu}\gamma$. If all of the background caused by SM neutrinos and the uncertainties were been subtracted and the vector sum of all the transverse momenta still not equal to zero, we could believe that something invisible is produced, the undetected particle(s) may be the DM candidate(s) (such as a heavy photon).

The second problem we have to solve is how to distinguish the heavy photon of the Littlest Higgs model with T-parity from other type DM production at the ILC, e.g., the lightest neutralino...
(\tilde{\chi}_1^0) of SUSY with R-parity, the gravitino of SUSY [24], the heavy neutrinos of new generations [25], etc. Since different DM particles have different reaction channels and probabilities to be detected by the detectors of the ILC, which offer a way to distinguish the $A_H$ from other DM candidates.

Tree-level production of $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$ [25] in the MSSM [27, 28] with R-parity, $e^+e^- \rightarrow \Psi_g \bar{\Psi}_g \gamma$ within SUSY [29], $e^+e^- \rightarrow \nu \bar{\nu} \gamma$ [30] of the new generations have been studied in detail in the relative papers respectively. The other way to the model discrimination is by detecting and measuring the shape of the photon spectrum in the events with WIMP production. [31] Readers who are interested in and want to know more about the issue can see these papers and we don’t discuss the problem more.

As a conclusion, our calculations indicate that the production rate of $e^+e^- \rightarrow A_H A_H \gamma$ could reach several $fb$ in the relatively low mass parts of the allowed parameter space. That is to say, thousands of signal events would be produced one year via the $A_H A_H \gamma$ production mode at the ILC thanks to its high energy and yearly luminosity (500 $fb^{-1}$ at 500 GeV first and 1000 $fb^{-1}$ at 1000 GeV later). The advantage of analyzing such processes at the ILC is obvious because the hadronic background is very suppressed and the amount of signals may be practically observable. Therefore, associated production of a photon with heavy photon pair at the ILC might be a promising signal for the Littlest Higgs model with T-parity and a proper way to detect the DM.

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