Photon-induced production of the mirror quarks from the LHT model at the LHC

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Abstract

The photon-induced processes at the LHC provide clean experimental conditions due to absence of the proton remnants, which might produce complementary and interesting results for tests of the standard model and for searching of new physics. In the context of the littlest Higgs model with T-parity, we consider the photon-induced production of the mirror quarks at the LHC. The cross sections for various production channels are calculated and a simply phenomenology analysis is performed by assuming leptonic decays.

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1. Introduction

It is well known that the equivalent photon approximation (EPA) can be successfully to describe most of the processes involving photon exchange [1]. A significant fraction of \( pp \) collisions at the LHC will involve quasi-real photon interactions occurring at energies well beyond the electroweak energy scale [2]. Therefore, the LHC can be considered as a high-energy photon-photon or photon-proton collider, which is paid significant attention recently [3].

The photon-induced processes offer a rich and exciting field of research at the LHC [3]. In general, the exclusive two-photon production, \( pp \rightarrow p \gamma \gamma p \rightarrow pXp \), provides clean experimental conditions and well defined final states, which can be selected and precisely reconstructed. Moreover, for the dedicated very forward detectors (VFDs), detection of the two final state protons, scattered at almost zero-degree angle, provides another striking signature, effective also at high luminosity and with large event pile-up [2,4]. Thus, the two-photon production of the charged particle pairs offers interesting potential for signals of new physics beyond the standard model (SM) at the LHC. It has been shown that detection of the supersymmetric charginos, sleptons and the charged Higgs bosons is very unambiguous in two-photon exclusive production, allowing for clear interpretation [5,6]. The exclusive two-photon production of the boson pairs \( WW \) and \( ZZ \) at the LHC provides an excellent way to test the electroweak gauge boson sector [7].

The luminosity and the center-of-mass (c.m.) energy of photon-proton (\( \gamma p \)) collisions are higher than the photon-photon ones at the LHC. This offers interesting possibilities for the study of electroweak interactions and for searching the new physics beyond the SM up to \( TeV \) scale [8]. In contrast to the photon-photon production processes, the photoproduction processes involve topologies with hard jets in the final state. The effect of jet algorithms and the efficiency of event selection was taken into account using a fast simulation of a typical multipurpose LHC detector response [8]. Thus, a large number of \( pp \rightarrow p(\gamma g/q)Y \rightarrow pXY \) processes have sizable cross sections and could be studied during the very low and low luminosity phases of the LHC. So far, the cross sections for many electroweak processes and some new physics processes with their irreducible background
processes are studied in Refs.[7,8,9].

The little Higgs theory [10] is one of the interesting candidates of the new physics beyond the SM. The little Higgs model with T-parity (called the LHT model) [11] is one of the attractive little Higgs models. In this model, particles are divided into T-even and T-odd sectors under T-parity. The T-even sector consists of the SM particles and a heavy top $T_+$, while the T-odd sector contains heavy gauge bosons ($B_H, Z_H, W^\pm_H$), a scalar triplet ($\phi$), and the so-called mirror fermions. These new particles can produce rich phenomenology at present and in future high energy collider experiments [12,13,14,15,16]. Reference [17] has considered photoproduction of pairs of T-odd particles via $e^+e^-$ and $ep$ collisions. As we know, so far, photoproduction and two-photon production of the T-odd particles predicted by the LHT model have not been considered at the LHC, which is the main aim of this paper.

In this paper, we consider the photoproduction and two-photon production processes involved the mirror quarks at the LHC. We show that most of their production cross sections are smaller than those coming from the partonic processes for the mirror quarks at the LHC. However, considering their clean experimental conditions and well defined final states, these production processes should be further studied. The photoproduction and two-photon production processes for the mirror quarks might help to search possible signatures of the LHT model at the LHC.

In the rest of this paper, we will give our results in detail. In section 2, we briefly review the essential features of the LHT model. Photoproduction of the mirror quark associated with a new gauge boson and with a new scalar are discussed in sections 3 and 4, respectively. The cross sections for photoproduction and two-photon production of the mirror quark pairs are calculated in section 5. The simple phenomenology analysis at the LHC are also given in these sections. Finally, we summarize our results and given some discussions in section 6.

2. The essential features of the LHT model

In this section, we briefly review the essential features of the LHT model studied in Refs.[11,12], which are related to our calculation. The LHT model is based on a
SU(5)/SO(5) global symmetry breaking pattern, which gives rise to fourteen Number- 
Goldstone (NG) bosons. Four of the fourteen NG bosons are eaten by the T-odd heavy 
gauge bosons \((B_H, Z_H, W^\pm_H)\) associated with the gauge symmetry breaking \([SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2 \rightarrow SU(2)_L \times U(1)_Y\) at the scale \(f\). The remaining NG bosons 
decompose into a T-even doublet \(H\), considered to be the SM Higgs doublet, and a 
complex T-odd \(SU(2)\) triplet \(\Phi\)

\[
H = \left( \begin{array}{c}
-i \frac{\pi^+}{\sqrt{2}} \\
\nu + h + i \pi^0
\end{array} \right), \quad \Phi = \left( \begin{array}{cc}
-i \phi^{++} & -i \phi^0 \\
-i \phi^+ + i \phi^0 & -i \phi^+ + i \phi^0
\end{array} \right).
\]

(1)

Here \(h\) is the physical Higgs field and \(\nu = 246\, GeV\) is the electroweak scale. The \(\pi^{0,\pm}\) 
are absorbed by the SM gauge bosons \(W^\pm\) and \(Z\) after electroweak symmetry breaking 
\((EWSB)\). There is an relation between the T-odd triplet and the T-even Higgs boson 
masses, which is approximately expressed as [12]

\[
M_\phi = \frac{\sqrt{2} m_H}{\nu} f,
\]

(2)

where \(f\) is the scale parameter of the gauge symmetry breaking of the LHT model. At 
the leading order, the components \(\phi^+, \phi^-, \phi^0, \) and \(\phi^p\) of the triplet scalar \(\Phi\) have same 
mass, i.e. \(M_{\phi^+} = M_{\phi^-} = M_{\phi^0} = M_{\phi^p} = M_\Phi\).

After taking into account \(EWSB\), at the order of \(\nu^2/f^2\), the masses of the T-odd set 
of the \(SU(2) \times U(1)\) gauge bosons are given by

\[
M_{B_H} = \frac{g' f}{\sqrt{5}} [1 - \frac{5 \nu^2}{8 f^2}], \quad M_{Z_H} \approx M_{W_H} = gf [1 - \frac{\nu^2}{8 f^2}],
\]

(3)

Where \(g'\) and \(g\) are the SM \(U(1)_Y\) and \(SU(2)_L\) gauge coupling constants, respectively. 
Because of the smallness of \(g'\), the gauge boson \(B_H\) is the lightest T-odd particle, which 
is stable, electrically neutral, and weakly interacting particle. Thus, it can be seen as an 
attractive dark matter candidate [12]. Certainly, if the T-parity is violated by anomalies, 
the lightest T-odd gauge boson \(B_H\) can decay into the SM gauge boson pairs \(WW\) and 
\(ZZ\) [18,19].

To avoid severe constraints and simultaneously implement T parity, one needs to 
double the SM fermion doublet spectrum [11, 12]. The T-even combination is associated
with the SM $SU(2)_L$ doublet, while the $T$-odd combination is its $T$-parity partner, which are called the mirror fermions. Assuming there is flavor universal and diagonal Yukawa coupling $k$, the mirror quarks for different generations will be degenerate in mass, and the masses of the up- and down-type mirror fermions can be written as [13]

$$M_{U_H} \approx \sqrt{2}kf (1 - \frac{\nu^2}{8f^2}), \quad M_{D_H} \approx \sqrt{2}kf.$$  

Being $f \geq 500$GeV, it is clear from Eq.(4) that there is $M_{U_H} \approx M_{D_H}$. Thus, we can assume the mirror quarks degenerating in mass and take $M_{Q_H} = M = \sqrt{2}kf$. This means that the mirror quarks have no contributions to the flavor changing processes, which is the minimal flavor violation (MFV) limit of the LHT model [20]. In this paper, we will focus our attention on production of the first and second generation mirror quarks via photon interactions at the LHC and assume that the value of the coupling constant $k$ is in the range of 0.5 $\sim$ 1.5.

The mirror quarks can couple to ordinary quarks mediated by the T-odd gauge bosons and at higher order by the scalar triple $\Phi$, which are parameterized by two $CKM$-like unitary mixing matrices $V_{H_u}$ and $V_{H_d}$. They satisfy $V_{H_u}^+V_{H_d} = V_{CKM}$, in which the $CKM$ matrix is defined through flavor mixing in the down-type quark sector [15,20]. The coupling expressions, which are related our calculation, are given in Ref.[15]. Using these Feynman rules, we can calculate the production cross sections of the mirror quarks via $\gamma p$ and $\gamma\gamma$ collisions at the LHC.

From the above discussions, we can see that the cross sections for photoproduction and two-photon production of the mirror quarks are generally dependent on the model parameters $f$, $k$, $(V_{H_u})_{ij}$ and $(V_{H_d})_{ij}$. The matrix $V_{H_d}$ can be parameterized in terms of three mixing angles and three phases, which can be probed by the flavor changing neutral current ($FCNC$) processes in K and B meson systems, as discussed in detail in Refs.[15,20]. To avoid any additional free parameters introduced and to simply our calculation, we take the structure of the mixing matrix $V_{H_d}$ as $V_{H_d} = I$, which means $V_{H_u} = V_{CKM}^+$ and the mirror quarks have no impact on the $FCNC$ processes.

3. Photoproduction of the mirror quark associated with a $T$-odd gauge boson
From the above discussions, we can see that the mirror quark can be produced associated with a T-odd gauge boson via the subprocess $q \gamma \rightarrow Q_H B_H (Z_H$ or $W_H)$ at the LHC. The relevant Feynman diagrams are depicted in Fig.1.

![Feynman diagrams](image)

Figure 1: Feynman diagrams for photoproduction of the mirror quark associated with a new gauge boson.

Using the relevant Feynman rules given in Ref.[15], the corresponding scattering invariant amplitudes can be written as

$$M_{ij}^B = -\frac{i e^2}{10 C_W} q_i V_{ij} \bar{u}(P_Q) \left[ \frac{\epsilon^j_L(P_Q + P_q)}{\hat{s}} + \frac{\epsilon^j_A(P_B - P_q + M)}{t_B - M^2} \right] u(P_q),$$  \hfill (5)

$$M_{ij}^Z = \pm \frac{i e^2}{2 S_W} q_i V_{ij} \bar{u}(P_Q) \left[ \frac{\epsilon^j_L(P_z + P_q)}{\hat{s}} + \frac{\epsilon^j_A(P_Z - P_q + M)}{t_Z - M^2} \right] u(P_q),$$  \hfill (6)

$$M_{ij}^W = \frac{i e^2}{\sqrt{2} S_W} V_{ij} \bar{u}(P_Q) \left\{ \frac{\epsilon^j_L(P_{\gamma} + P_q)}{\hat{s}} + \frac{\epsilon^j_A(P_W - P_q + M)}{t_W - M^2} \right\} u(P_q).$$  \hfill (7)

Where $\hat{s} = (P_\gamma + P_q)^2$, $\hat{t}_B = (P_B - P_q)^2$, $\hat{t}_Z = (P_Z - P_q)^2$, $\hat{t}_W = (P_W - P_q)^2$, and $\hat{t}_W^2 = (P_Q - P_q)^2$. $i$ represents the SM light quark $u$, $c$, $d$, or $s$, and $q^j$ represents the corresponding electric charge. $j$ is the family indexes for the mirror quarks and $M$ is the
mass of the mirror quark. \( S_W = \sin \theta_W \), \( C_W = \cos \theta_W \), and \( \theta_W \) is the Weinberg angle. \( \varepsilon_1 \) is the polarization vector of the photon \( \gamma \) and \( \varepsilon_2 \) is the polarization vector of the gauge boson \( Z_H, B_H, \) or \( W_H \). \( P_L = (1 - \gamma_5)/2 \) is the left-handed projection operator. For the up-type quark \( u \) or \( c \), the \( CKM \)-like matrix element \( V_{ij} \) is \((V_{Hu})_{ij}\), while for the down-type quark \( d, s, \) or \( b \), \( V_{ij} \) is \((V_{Hd})_{ij}\). In Eq.(6), “±” represent the up- and down-type quarks, respectively.

Figure 2: The cross sections for the photoproduction of the mirror quarks associated with the new gauge bosons \((B_H, Z_H, W_H)\) as functions of the coupling constant \( k \) for the scale parameter \( f = 500\text{GeV} \).

After calculating the cross section \( \hat{\sigma}_{ij}^G(\hat{s}) \) \((G = Z_H, B_H, \) or \( W_H)\) for the subprocess \( q\gamma \rightarrow Q_H B_H(Z_H \) or \( W_H)\), the effective cross section \( \sigma_G \) at the LHC can be obtained by folding \( \hat{\sigma}_{ij}^G(\hat{s}) \) with the parton distribution functions \( (PDFs) \)

\[
\sigma_G = \sum_{i,j} \int_{x_{\text{min}}}^{1} \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} dx d\tau f_{q_i/p}(x, \mu) f_{\gamma/p}(\tau) \hat{\sigma}_{ij}^G(\hat{s})
\]

with \( x_{\text{min}} = (M_Q + M_G)^2/S \), \( \tau_{\text{min}} = (M_Q + M_G)^2/Sx \), \( \tau_{\text{max}} = (1 - m/\sqrt{S})^2 \) and \( \hat{s} = x\tau S \), in which the c.m. energy \( \sqrt{S} \) is taken as 14TeV for the LHC. \( m \) is the proton mass. In our numerical calculation, we will use \( CTEQ6L PDF[21] \) for the quark distribution
\( f_{q/p}(x, \mu_F) \) and assume that the factorization scale \( \mu_F \) is of order \( \sqrt{s} \). The photon distribution function \( f_{\gamma/p}(\tau) \) is assumed that it only is the elastic components of the equivalent photon distribution of the proton, which has been extensively studied in Refs. [1, 22, 23].

Figure 3: (a) Same as Fig. 2 but for \( f = 1 TeV \). (b) Same as Fig. 2 but for \( f = 1.5 TeV \).

In Fig. 2, Fig. 3(a), and Fig. 3(b) we plot the cross sections for photoproduction of the mirror quark associated with the new gauge bosons as functions of the parameter \( k \) for three values of the scale parameter \( f \). In these three figures we have taken the values of the \( CKM \) matrix elements \( (V_{CKM})_{ij} \) given in Ref. [24], in which \( V_{CKM} \) is constructed based on the parameterization [25]. One can see from these figures that, although there is the relation \( M_{B_H} < M_{Z_H} \simeq M_{W_H} \), the cross section \( \sigma_{W_H} \) is most large and the cross section \( \sigma_{B_H} \) is smaller than \( \sigma_{W_H} \) or \( \sigma_{Z_H} \). This is because the coupling constants of the new gauge boson \( B_H \) to the mirror quarks and ordinary quarks are smaller than those for the new gauge bosons \( Z_H \) and \( W_H \). Furthermore, for the subprocess \( q\gamma \to Q_H'W_H \), there is an extra Feynman diagram as shown in Fig. 1(c) contributing to the cross section \( \sigma_{W_H} \). For \( 0.6 \leq k \leq 1.4 \) and \( 500 GeV \leq f \leq 1500 GeV \), the values of the effective production cross sections \( \sigma_{B_H}, \sigma_{Z_H}, \) and \( \sigma_{W_H} \) are in the ranges of \( 1.6 \times 10^{-2} fb \sim 2.6 fb, 7.5 \times 10^{-2} fb \sim 11 fb, 0.36 \times 10^{-2} fb \sim 82 fb \), respectively.

For \( k > 0.5 \), the mirror quark is heavy enough to decay into \( T \)-odd gauge boson plus an ordinary fermion. The branching ratios of the possible two-body modes of the
mirror quarks $U_H$ and $D_H$ are discussed in Refs.[13,26]. The different chain decays of the mirror quark can give different experimental signatures at the LHC, which have been extensively studied. The up- and down-type mirror quarks mainly decay into $dW_H^+$ and $uW_H^-$, respectively. For $0.6 \leq k \leq 1.4$ and $f = 1 TeV$, the values of the branching ratios $Br(U_H \to dW_H^+)$ and $Br(D_H \to uW_H^-)$ are all about 57% [26]. To simply our phenomenology analysis, we only consider the signatures induced by the decay modes $uW_H^-$ and $dW_H^+$ and take these two decay modes as $jW_H$, in which $j$ indicates a light-flavor jet $u$, $c$, $d$, or $s$. Furthermore, we will assume that T-parity is strictly conserved and the T-odd gauge boson $B_H$ can be seen as missing energy.

From the above discussions, we can see that photoproduction of the mirror quark associated with the T-odd gauge boson at the LHC can give the following final states

$$q\gamma \to Q_H B_H \to jW_H B_H \to jW B_H B_H \to j\nu\ell B_H B_H, \quad (9)$$
$$q\gamma \to Q_H Z_H \to jW_H Z_H \to jW H B_H B_H \to j\nu\ell b\bar{b} B_H B_H, \quad (10)$$
$$q\gamma \to Q_H W_H^\pm \to jW_H^\pm W_H^\mp \to jW^\pm W^\mp B_H B_H \to j\ell^+\ell^−\nu\ell B_H B_H. \quad (11)$$

In the above processes, we have assumed that the T-odd gauge bosons $W_H$ and $Z_H$ mainly decay into $WB_H$ and $HB_H$, respectively. For the Higgs boson mass $M_H \leq 120 GeV$, its dominant decay channel is $H \to b\bar{b}$. In order to ensure the cleanest event signature, only fully leptonic decay modes of the gauge boson $W$ are considered. It is obvious that the chain decay processes (9), (10), and (11) can lead to the $l^\pm + jet + \not\!E_T$, $l^\pm + jets + \not\!E_T$, and $l^+l^- + jet + \not\!E_T$ signatures. The production rates for these three kinds of the signatures can be easily estimated by multiplying the overall decay branching ratios to the effective production cross sections for the above processes. For example, the production rate of the $l^\pm + jet + \not\!E_T$ signature can be written as: $\sigma_{B_H} \times Br(Q_H \to jW_H) \times Br(W_H \to WB_H) \times Br(W \to l\nu_l) \approx \sigma_{B_H} \times 0.57 \times 1 \times 0.32 \approx 0.18\sigma_{B_H}$. The number of the raw signal events generated per year at the LHC are given in Fig.4, in which we have taken the scale parameter $f = 500 GeV$ and the yearly integrated luminosity $\mathcal{L} = 100 fb^{-1}$. One can see from this figure that there will be several and up to hundreds of these kinds of the signal events to be generated at the LHC per year.
Figure 4: The number of the raw signal events versus the parameter $k$ for $f = 500GeV$ and $L = 100fb^{-1}$.

In general, the photoproduction signals at the LHC have two kinds of backgrounds: irreducible and reducible backgrounds, which have very similar final states or same final states as the signal, and come from the photoproduction processes and the parton-parton interaction processes, respectively. During the phase of the low luminosity, one can use the large rapidity gap (LRG) way to distinguish the photoproduction signal from the reducible backgrounds [6,7,8,9]. At high luminosity (general about $100fb^{-1}$) the reducible backgrounds can be suppressed by using the dedicated very forward detectors (VFDs). Applying the acceptance cuts, one can significantly suppress the irreducible backgrounds coming from the SM photoproduction processes, such as $q\gamma \rightarrow jW, q\gamma \rightarrow q'WH, q\gamma \rightarrow q'W^{\pm}W^{\mp}$, etc. To be certain, a detailed simulation is needed, which has been extensively studied in Refs.[7,8,9] and is beyond the scope of this paper.

4. Photoproduction of the mirror quark associated with a T-odd scalar

The LHT model predicts the existence of a complex T-odd triplet scalar $\Phi$ with the mass in the range of $350GeV \sim 1400GeV$ for $m_H = 120GeV$ and $500GeV \leq f \leq 2000GeV$. At the leading order, its components $\phi^{\pm}, \phi^{0}$, and $\phi^{p}$ have the same mass and
can be produced via the parton-parton collision processes at the LHC, which have been discussed in Ref.[27]. It has been shown that the production cross sections are much small. Although the T-odd scalar couples to ordinary quark and the mirror quark at the order $v^2/f^2$ [15], to compare the photoproduction with the partonic production of the T-odd scalars, we consider photoproduction of the T-odd scalars in this section. The relevant Feynman diagrams are shown in Fig.5.

![Feynman diagrams](image)

Figure 5: Feynman diagrams for photoproduction of the mirror quark in association with a T-odd scalar.

Using the relevant Feynman rules given in Ref.[15], the invariant scattering amplitudes for photoproduction of the T-odd scalars can be written as

$$M_{\phi^\pm} = -\frac{e^2 V_{ij} \nu^2}{6\sqrt{2}S_W} f \bar{u}(P_Q)\{\frac{iefP_L}{S_W(t_\phi - M_{W_H}^2)} + \frac{MP_L}{2fM_{W_H}}[q^i(P_q + P_\gamma)\frac{\tilde{s}}{2\tilde{s}} + \frac{P_{\gamma}^\mu}{t_\phi - M_{\phi^\pm}^2}]\}u(q),$$

$$M_{\phi^0} = \frac{e^2 q^iV_{ij} \nu^2}{12\tilde{s}} \left[\frac{1}{\sqrt{10}C_W M_{B_H}} + \frac{1}{\sqrt{2}S_W M_{Z_H}}\right]M\bar{u}(P_Q)[P_L(P_q + P_\gamma)f]u(P_q).$$

where $\tilde{s} = (P_q + P_\gamma)^2$.

Our numerical results are given in Fig.6, in which we have plotted the production cross sections as functions of the coupling constant $k$ for the scale parameter $f = 500 GeV$ and the other relevant free parameters are taken to be same as section 3. One can see from this figure that the production cross section is indeed much small. In most of the parameter space of the LHT model, the value of the total cross section for photoproduction of the T-odd scalar in association with the mirror quark is smaller than $0.01 fb$. However, compared that of partonic production of the T-odd scalar associated the T-odd gauge
boson, its background is also very small, which mainly comes from the photon-induced processes.

In most of the parameter space of the LHT model, the T-odd scalars $\phi^\pm$ and $\phi^p$ mainly decay into $W^\pm B_H$ and $HB_H$, respectively. For $m_H = 120 GeV$, $k = 1$ and $f = 1 TeV$, there are $Br(\phi^\pm \rightarrow W^\pm B_H) \simeq 1$ and $Br(\phi^p \rightarrow HB_H) \simeq 1$. Thus, photoproduction of the T-odd scalars at the LHC can give the following final states:

\begin{equation}
q\gamma \rightarrow Q_H \phi^p \rightarrow jW_H HB_H \rightarrow jWHB_H B_H \rightarrow j\ell\nu_\ell\bar{b}\bar{b}B_H B_H,
\end{equation}

\begin{equation}
q\gamma \rightarrow Q'_H \phi^\pm \rightarrow jW_H^\mp W^\pm B_H \rightarrow jW^\mp W^\pm B_H B_H \rightarrow jl^+l^-\nu_\ell\bar{\nu}_\ell B_H B_H,
\end{equation}

which can induce the $l^\pm + jets + \not{E}_T$ and $l^+l^- + jet + \not{E}_T$ signatures. The first kind of signatures is same as that of Eq.(10) and the second is same as that of Eq.(11). Thus, we have to say that it is more difficult to detect the possible signatures of the mirror quark via the subprocess $q\gamma \rightarrow Q_H \Phi$ than via the subprocess $q\gamma \rightarrow Q'_H W_H$.

5. Pair production of the mirror quarks via $\gamma g$ and $\gamma \gamma$ collisions
At the LHC, the mirror quarks can be produced in pairs via exchanging the T-odd gauge bosons ($B_H$ and $Z_H$) and gluon exchange. It has been shown that, as long as their masses are not too large, the mirror quarks can be copiously produced in pairs [13]. However, the mirror quarks can also be produced in pairs via $\gamma g$ and $\gamma\gamma$ collisions at the LHC. To completely consider of the mirror quarks, we will consider their photon-induced production in this section. The relevant Feynman diagrams are displayed in Fig.7, in which Fig.7a is similar to that for the SM process $g\gamma \rightarrow t\bar{t}$ and Fig.7b is similar to that for the two-photon production of the supersymmetric pairs or the top quark pairs.

![Feynman diagrams for the photon-induced production of the mirror quark pair.](image)

Figure 7: Feynman diagrams for the photon-induced production of the mirror quark pair.

![Production cross sections induced by $\gamma g$ (a) and $\gamma\gamma$ (b) collisions versus $f$ value for different values of $k$.](image)

Figure 8: The production cross sections induced by $\gamma g$ (a) and $\gamma\gamma$ (b) collisions versus $f$ value for different values of $k$.

It is obvious that the pair production cross sections of the mirror quarks are only dependent on the scalar parameter $f$ and the coupling parameter $k$. In Fig.8(a) and Fig.8(b) we present the cross sections induced by $\gamma g$ and $\gamma\gamma$ collisions versus $f$ value for different values of the parameter $k$. One can see from these figures that the photon-induced production of the mirror quark pairs are mainly generated by the subprocess
$g\gamma \rightarrow Q_H Q_H$ and the effective cross section $\sigma_{g\gamma}$ is larger than $\sigma_{\gamma\gamma}$ at least by three orders of magnitude. Certainly, this is because the gluon luminosity is much larger than the photon luminosity and the coupling of the gluon to the mirror quarks is stronger than that for the photon. For $k = 0.6$ and $500GeV \leq f \leq 1500GeV$, the values of the cross section $\sigma_{g\gamma}$ is in the range of $2.1 \times 10^{-3} fb \sim 87.5 fb$.

If we assume that the mirror quark decays into $W_j (j=u, c, d, \text{ or } s)$ and focus our attention only on the pure leptonic decay modes for the $SM$ gauge boson $W$, then pair production of the mirror quark can induce the $l^+l^- + jets + E_T$ signature. The total number of this kind of signal are given in Fig.9 for $f = 500GeV$, in which we have taken the integral luminosity $\mathcal{L} = 100 fb^{-1}$ and $Br(Q_H \rightarrow W_H j) \simeq 57\%$. One can see from this figure that there will be several and up to hundreds of the $l^+l^- + jets + E_T$ signal events to be generated at the $LHC$ per year.

![Figure 9: The number of the $l^+l^- + jet + E_T$ signature events for $f = 500GeV$ and $\mathcal{L} = 100 fb^{-1}$.](image)

The reducible $SM$ backgrounds of pair production of the mirror quark via $\gamma p$ and $\gamma\gamma$ interactions mainly come from $t\bar{t}$, which both top quarks decay leptonically, and $W^+W^- jj$, which the two jets originate from initial-state radiation. Although the re-
ducible background is several orders of magnitude larger than the signal, one expects that it can be reduced to the same level as the irreducible background by using LRG condition and the dedicated VFDs [6,7,8,9]. The irreducible backgrounds mainly come from the photon-induced processes $\gamma g \rightarrow t\bar{t}$ and $\gamma\gamma \rightarrow t\bar{t}$. The ratio of the signal over the square root of the background $R = S/\sqrt{B}$ (called the statistical significance) is given in Fig.10 in which we have taken $f = 500 GeV$ and $\mathcal{L} = 100 fb^{-1}$. One can see from this figure that, with reasonable values of the free parameters, the values of $R$ can be significantly large.

![Figure 10: The statistical significance $R$ as a function of the parameter $k$ for $f = 500 GeV$.](image)

The numerical results of Fig.10 are obtained in the case of no any cut applied. Similar with Refs.[7,8,9], if we apply acceptance cuts on the final state particles, the irreducible backgrounds can be significantly suppressed and the value of $R$ should be enhanced. Thus, the possible signals of the mirror quarks might be detected via $g\gamma$ collision at the LHC.

6. Conclusions and discussions

The photon-induced processes at the LHC provide clean experimental conditions due to absence of the proton remnants. Well defined final states can be easily selected and precisely reconstructed. To some extend, the LHC can be considered as a high-energy $\gamma - \gamma$ or $\gamma - p$ collider, which offer interesting possibilities for studying the electroweak
sector and for searching new physics up to $TeV$ scale. One expects that the $\gamma - \gamma$ or $\gamma - p$ collision at the $LHC$ should give complementary and interesting results for the tests of the $SM$ and for searching of new physics. Thus, considering production of new particles via $\gamma - \gamma$ or $\gamma - p$ collision at the $LHC$ is very interesting. It will be helpful to detect the possible signatures of new physics models at the $LHC$.

The $LHT$ model is one of the attractive little $Higgs$ models that is not only consistent with electroweak precision tests but also predicts the existence of the heavy $T$-odd $SU(2)$ doublet fermions, which are called the mirror fermions of the $SM$ fermions. These new particles might produce the observability signatures in future high energy collider experiments. In this paper, we consider the photon-induced production of the first and second generation mirror quarks and further discuss its possible signatures at the $LHC$.

The effective production cross sections of the mirror quarks at the $LHC$ via the subprocesses $q\gamma \to Q_H B_H(Z_H)$, $q\gamma \to Q'_H W^\pm_H$, $q\gamma \to Q'_H \phi^\pm$, $q\gamma \to Q_H \phi^p$, $g\gamma \to Q_H Q_H$, and $\gamma\gamma \to Q_H Q_H$ are calculated. Our numerical results show that the values of cross sections for all of these production channels are strongly dependent on the scale parameter $f$ and the coupling parameter $k$. Their values decrease quickly as $f$ and $k$ increase. However, as long as the mirror quark is not too heavy, i.e. the parameters $f$ and $k$ are not too large, it can be significantly produced via some of these processes at the $LHC$.

For example, for $0.6 \leq k \leq 1$ and $500GeV \leq f \leq 1500GeV$, the cross section value of the subprocess $q\gamma \to Q'_H W^+_H$ is larger than $0.1 fb$ and can reach $82 fb$, and the value of the cross section for the subprocess $qg \to Q_H Q_H$ is in the range of $2.1 \times 10^{-3} fb \sim 88 fb$.

The different chain decay channels of the mirror quark can give different experimental signatures. The possible signatures of the mirror quarks generated from the partonic processes have been studied in Ref.[13]. Considering the domainant decay channels of the mirror quarks, the possible signatures generated by the photon-induced processes are also discussed in this paper. We find that some of the photon-induced processes can produce the same signals as those for the partonic processes. However, because of the clean experimental conditions and the well defined final states, they might be easily detected. For the photon-induced signatures, most of the backgrounds coming from the partonic
interactions, called reducible background, can be significantly omitted by using the $LRG$ technique and the dedicated $VFD$s. The irreducible background generated by $\gamma - \gamma$ or $\gamma - p$ interaction can be largely suppressed by applying acceptance cuts. Certainly, it should be further studied.

All of our numerical results are obtained in the case of only considering the elastic photon contributions. If the contributions of the inelastic photons are included, the corresponding cross sections are increased by about a factor of three [2]. It is obvious that the irreducible backgrounds are also increased. Furthermore, the strong interactions between protons, the so called rescattering effects, can suppress the photon-induced cross sections, which depends on the invariant mass of the exclusively produced state, such as $Q_H W_H$ or $Q_H Q_H$. This kind of correction effects is ignored in our numerical results. In our simply phenomenology analysis, we have taken the T-odd gauge boson $B_H$ as missing energy. If we assume the the T-parity is violated, then $B_H$ can decay into $WW$ and $ZZ$ pairs, which can induce different signatures.

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