Studies of Strong Electroweak Symmetry Breaking at Photon Colliders

Kingman Cheung

Dept. of Physics & Astronomy, Northwestern University, Evanston, Illinois 60208, USA

Abstract

It has recently been shown that the studies of strongly-interacting electroweak symmetry breaking (EWSB) at photon colliders, via photon splitting into $W$ pair followed by longitudinal $W$-boson scattering, could be possible. Here we present a signal-background analysis for the scattering channels $W^+_L W^-_L \rightarrow Z_L Z_L$ and $W^+_L W^-_L \rightarrow W^+_L W^-_L$ with background coming from the standard model (SM) production of $\gamma \gamma \rightarrow WWZZ$ and $WWWW$, respectively. We illustrate the analysis using the SM with a heavy Higgs boson ($m_H \approx 1$ TeV) to represent a typical strongly-interacting EWSB model and the SM with a light Higgs boson ($m_H \approx 0.1$ TeV) to represent the background. We come up with a set of kinematic acceptance to enhance the signal-to-background ratio. Extension of the kinematic acceptance to other strongly-interacting EWSB models is then trivial, and the signal cross sections for various EWSB models are calculated. We found that it is very feasible to probe the EWSB sector at a photon collider of center-of-mass energy of 2 TeV with a luminosity of just 10 fb$^{-1}$.

*Internet address: cheung@nuhep.phys.nwu.edu
I Introduction

So far very little is known about the electroweak symmetry-breaking (EWSB) sector, except that it gives masses to the vector bosons via spontaneous symmetry breaking, and also gives masses to fermions via Yukawa couplings. In the minimal standard model (SM) a scalar Higgs boson is responsible for electroweak symmetry-breaking but its mass is not determined by the model. If in the future no Higgs boson is found below 800 GeV, the heavy Higgs scenario ($\approx 1$ TeV) will imply a strongly-interacting Higgs sector because the Higgs self-coupling $\lambda \sim m_H^2$ becomes strong \[1\]. However, there is no evidence to favor models with a scalar Higgs boson, so any models that can break the electroweak symmetry the same way as the single Higgs boson does can be a candidate for the EWSB sector.

One of the best ways to uncover the underlying dynamics of the EWSB sector is to study the longitudinal vector boson scattering \[1, 2\]. The Equivalence Theorem \[1\] recalls, at high energy, the equivalence between the longitudinal component ($W_L$) of the vector bosons and the corresponding Goldstone bosons ($w$) that were “eaten” in the Higgs mechanism. These Goldstone bosons originate from the EWSB sector so that their scattering must be via the interactions of the EWSB sector, and therefore the $W_L W_L$ scattering can reveal the dynamics of the EWSB.

Experimentally, the search for the Higgs boson at high energy colliders are so far all negative. Probing the EWSB sector at TeV regime is one of the major goals of all the future supercolliders. Ever since the cancellation of the Superconducting Super Collider, every other opportunity to study EWSB should be explored. Recently, the upgraded Tevatron draws some interests in probing for the Higgs boson. But studies showed that the machine is marginal for discovering the intermediate mass Higgs boson \[3\], not to mention the heavy Higgs boson or the strong EWSB sector. The best opportunity will be at the Large Hadron Collider with a center-of-mass energy 10–14 TeV and a peak luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. The $e^+e^-$ and $e^-e^-$ machines at 1.5–2 TeV also provide possibilities to probe the strong
EWSB sector.

With the idea of laser backscattering [4] it is relatively inexpensive to convert a linear $e^+e^-$ or $e^-e^-$ collider into a $\gamma\gamma$ collider. The resulting photon beams are very monochromatic carrying about 0.8 of the energy of the parent electron beams. Also, polarized laser and electron beams can be employed to further increase the monochromaticity of the photon beam. For a general review of physics potentials at high energy photon colliders please refer to Refs. [5, 6].

Since photon couples to $W^*$ boson with a coupling strength $g$, same order as the fermion-$W$ coupling, we expect the effective $W$ luminosity inside photons to be of the same order as the luminosity inside electrons or quarks. It was shown in Ref. [7] that the effective $W$ luminosity inside a photon has a $\log(s/m^2_W)$ enhancement at very high energy and is given by

$$f_{W/\gamma}(x) = \frac{\alpha}{\pi} \left[ \frac{1-x}{x} + \frac{x(1-x)}{2} \left( \log \frac{s(1-x)^2}{m^2_W} - 2 \right) \right]. \quad (1)$$

Note that the first term in Eqn. (1) is very close to the $W$ luminosity inside an electron.

Previously, all studies of EWSB in $\gamma\gamma$ collisions concentrate on the loop processes $\gamma\gamma \rightarrow W_LW_L$ and $Z_LZ_L$ [8]. Unfortunately, the background from $\gamma\gamma \rightarrow W_TW_T$ is almost three orders of magnitude larger than the $W_LW_L$ signal. Although the signal-to-background ratio can be improved by requiring the final state $W$ bosons away from the beam, it hardly reduces the $W_TW_T$ background to the level of the $W_LW_L$ signal. On the other hand, both the $\gamma\gamma \rightarrow ZZ$ signal and background are absent on tree level. But the box diagram contribution to $Z_TZ_T$ has been shown to be very significant at the large $m(ZZ)$ region, so the $Z_TZ_T$ background is dominant over the $Z_LZ_L$ signal in the search of the SM Higgs boson for $m_H \gtrsim 350$ GeV and also in probing other strong EWSB signals [9]. Unless the polarizations of the final state $ZZ$ and $WW$ pair can be differentiated, it is very hard to use these loop processes to probe the strong EWSB sector.

It was suggested in Refs. [8, 10] that longitudinal $W$-boson scattering in $\gamma\gamma$ collisions, which is analogous to those considered at hadronic and $e^+e^-$ colliders, might be useful for
probing the EWSB sector. The schematic diagram for the longitudinal $W$-boson scattering is depicted in Fig. 1. An advantage of this process is that tagging the spectator $W$ bosons, in addition to the strongly-scattered vector bosons, can eliminate all the backgrounds from $\gamma\gamma \rightarrow W_{T}W_{T}$ and $Z_{T}Z_{T}$. It was also shown in Ref. [10] that the cross sections for the signal of various strongly-interacting EWSB models are large enough to be observable. But at that time, backgrounds from the SM have not been calculated, so it is not possible to draw any conclusions. Nevertheless, according to a preliminary result [11], the SM backgrounds from $\gamma\gamma \rightarrow WWZZ$ and $WWW\!\!W$ are manageable with respect to the signals. It is the purpose of this paper to investigate independently the possibility.

The calculation of signals for various models has been given in Ref. [10], in which the method of effective $W$ luminosity inside a photon is used. This method has a disadvantage that the kinematics of the spectator $W$ bosons cannot be calculated exactly, so any acceptance cuts on the spectator $W$ bosons are unrealistic. The way we do here is to carry out exact calculations for the processes $\gamma\gamma \rightarrow WWZZ$ and $WWW\!\!W$. The heavy Higgs boson, which is considered as a typical strong EWSB model, can be incorporated consistently into the SM by putting the Higgs-boson mass $m_{H}$ very large, say 1 TeV, and therefore it can be calculated exactly; while for other EWSB models we still have to rely on the method of effective $W$ luminosity, in which the luminosity function is folded with the subprocess cross section. But based on the fact that the kinematics of the spectator $W$ bosons is insensitive to different strong EWSB models, we expect that the tagging efficiencies of the spectator $W$ bosons, which we can obtain consistently for the heavy Higgs model from the exact calculations of $\gamma\gamma \rightarrow WWZZ$ and $WWW\!\!W$, can be applied trivially to other strong EWSB models. In Secs. II and III, we confront the heavy Higgs-boson signal against the SM background in the channels $\gamma\gamma \rightarrow WWZZ$ and $WWW\!\!W$, respectively. We come up with a favorable set of acceptance cuts to enhance the signal-to-background ratio and also obtain the tagging efficiencies for the spectator $W$ bosons. We then apply these tagging efficiencies to other EWSB models in Sec. IV.
Before we proceed, let us define the signal and background more precisely. The background is essentially the expectation from the SM with a very light Higgs boson. Cross sections of the processes $\gamma\gamma \rightarrow WWZZ$ and $WWWW$ with a light Higgs boson ($m_H = 0.1$ TeV) then represent the backgrounds. On the other hand, the signal can be considered as enhancement over the SM expectation. As we mentioned before, the calculation of the heavy Higgs-boson signal can be incorporated consistently into the SM by putting $m_H$ very large, say 1 TeV. The signal is then defined as the difference between the following cross sections $\sigma(m_H = 1\ TeV) - \sigma(m_H = 0.1\ TeV)$. Signal for other models is calculated by folding the subprocess cross sections $\hat{\sigma}(W_L^+ W_L^- \rightarrow Z_L Z_L, W_L^+ W_L^-)$ with the effective $W$ luminosity inside a photon, which is given in Eqn. (I).

We first concentrate on the channel $\gamma\gamma \rightarrow WWZZ$ because it is relatively simple in the sense that the $ZZ$ pair must come from the longitudinal $W$-boson scattering while the final state $W$ bosons are the spectators. It is therefore straightforward to implement the acceptance cuts on the strongly-scattered $Z$ bosons and on the spectator $W$ bosons, separately. However, for the channel $\gamma\gamma \rightarrow WWWW$ it is more complicated to implement the kinematic cuts because it is ambiguous to determine which $W$ bosons come out from the strong scattering region and which $W$ bosons are the spectators. We adopt the following procedures. We reorder the $W$ bosons according to the absolute values of their rapidities. Those two with smallest absolute rapidities are the bosons coming out from the strong scattering region, while those two with largest absolute rapidities are the spectators.

The organization is as follows. In the next section, we present the signal-background analysis for the channel $\gamma\gamma \rightarrow WWZZ$. In Sec. II, we repeat the same analysis for the channel $\gamma\gamma \rightarrow WWWW$. In Sec. IV, we calculate the signal for various strongly-interacting EWSB models. We reserve Sec. V for discussions and conclusions.
We illustrate in this section the signal-background analysis for the channel $\gamma\gamma \rightarrow WWZZ$, with the signal of a 1 TeV Higgs boson defined by

$$\sigma(m_H = 1 \text{ TeV}) - \sigma(m_H = 0.1 \text{ TeV})$$

and the background is represented by $\sigma(m_H = 0.1 \text{ TeV})$. Typical Feynman diagrams for the process $\gamma\gamma \rightarrow WWZZ$ are shown in Fig. 2. The complete set of Feynman diagrams contains the heavy Higgs-boson signal that we are considering (e.g., in Fig. 2(a)). This is the reason why we said above that the heavy Higgs-boson signal can be incorporated consistently into the SM. We use the package MADGRAPH [12] to generate the complete set of Feynman diagrams and the fortran code for the squared amplitude. Totally, there are 74 Feynman diagrams in the unitary gauge. We present the total cross sections for the process $\gamma\gamma \rightarrow WWZZ$ versus the center-of-mass energies of the $\gamma\gamma$ system with $m_H = 0.1$ and 1 TeV in Fig. 3. Enhancement of the total cross section due to the heavy-Higgs-boson exchange is only significant for $\sqrt{s_{\gamma\gamma}} \gtrsim 1.5$ TeV. Therefore, in the following we choose $\sqrt{s_{\gamma\gamma}} = 2$ TeV to illustrate the confrontation of the heavy Higgs-boson signal against the background. Later, we also show the results for other center-of-mass energies.

We will look at some kinematic variables to enhance the signal-to-background ratio. Thanks to some intensive studies of longitudinal vector boson scattering at hadronic super-colliders [13, 14], we can borrow their strategies. The strongly-scattered $Z_L$ bosons should have larger transverse momentum and larger invariant mass $m(ZZ)$ in the central rapidity region than the $Z$ bosons from the background; while the spectator $W$ bosons, coming from the photon splitting, tend to be in the forward rapidity region. Therefore, we begin with the acceptance cuts

$$m(ZZ) > 500 \text{ GeV} \quad \text{and} \quad |y(Z)| < 1.5$$

(3)
on the strongly-scattered $ZZ$ pair, and the basic acceptance to tag both spectator $W$ bosons:

$$p_T(W) > 25 \text{ GeV} \quad \text{and} \quad |y(W)| < 3.$$ 

(4)
These spectator $W$ bosons have to be tagged in order to eliminate the $\gamma\gamma \to W_TW_T$ or $Z_T Z_T$ backgrounds. We use a wide rapidity coverage of 3 because we expect that the spectator $W$ bosons for the signal are very forward but they can hardly go beyond $|y(W)| = 3$ in rapidity at $\sqrt{s_{\gamma\gamma}} = 2$ TeV, as indicated in Fig. 4. To demonstrate the fact that the spectator $W$ bosons for the signal are more forward than those for the background, we show the rapidity distribution of the more-forward $W$ boson for the case of $m_H = 1$ TeV and for the background ($m_H = 0.1$ TeV) in Fig. 4. From the figure it is advantageous to require at least one of the spectator $W$ bosons in the forward rapidity region defined by

$$1.5 < |y(W)| < 3.0 .$$

We also look at the transverse momentum $p_T$ distribution of the $Z$ bosons, as we expect that the strongly-scattered $Z$ bosons should have larger $p_T$ than the $Z$ bosons from the background. We show the distribution of the $\min(p_T(Z_1), p_T(Z_2))$ in Fig. 5. From the figure, a $p_T$ cut of

$$p_T(Z) > 250 \text{ GeV}$$

can further improve the signal-to-background ratio. We summarize in Table I the cross sections for various combinations of the cuts in Eqns. (3), (4), (5), and (6). In fact, we can gain in the signal-to-background ratio by tightening the $p_T(Z)$ cut or by imposing other cuts, e.g. $\Delta p_T(ZZ) = |\vec{p}_T(Z_1) - \vec{p}_T(Z_2)| > 600$ GeV, but at the same time we are losing signal events. We also show in Table I the significance of the signal defined by $S/\sqrt{B}$, where $S$ and $B$ are the number of signal and background events with an integrated luminosity of 10 fb$^{-1}$.

Next, we estimate the tagging efficiencies for the spectator $W$ bosons. The acceptance cuts on the spectators are given in Eqns. (4) and (5). The efficiency can be calculated from Table I. The last second row shows the cross sections with all acceptance cuts imposed; while the last row shows the cross sections with the acceptance cuts on $Z$ bosons only. The tagging efficiency of the spectator $W$ bosons for the signal is then

$$\frac{\sigma({\text{signal}})_{\text{last second row}}}{\sigma({\text{signal}})_{\text{last row}}} = \frac{10.8 \text{ fb}}{13.6 \text{ fb}} = 79\% .$$
This efficiency is applied in Sec. IV to estimate the cross sections for other strong EWSB models.

\section{\gamma\gamma \rightarrow WWWW}

The complete set of Feynman diagrams and the fortran code for the squared amplitude are also generated by MADGRAPH [12]. There are totally 240 contributing Feynman diagrams in the unitary gauge. As explained in the Introduction, this channel is more complicated because of various combinations. It can have enhancement from the strong scattering channels $W_L^+ W_L^+ \rightarrow W_L^+ W_L^+$ and $W_L^- W_L^- \rightarrow W_L^+ W_L^-$. According to Ref. [10], the signal for the like-charge channels is substantially smaller than the signal for the opposite-charge channel. The dominance of the opposite-charge channel over the like-charge channels is due to the presence of a s-channel resonance in the opposite-charge channel and the absence of any doubly-charged resonance in the like-charge channels. Therefore, for the following we only concentrate on the opposite-charge scattering channel.

Since we are going to impose very different acceptance cuts on the strongly-scattered $W$ bosons and the spectator $W$ bosons, we have to distinguish them. As mentioned in the Introduction, we reorder the absolute rapidities of the $W$ bosons according to $|y(W_1)| < |y(W_2)| < |y(W_3)| < |y(W_4)|$. We then assume the first two $W$ bosons with smallest absolute rapidities to be the strongly-scattered $W$ bosons as we expect them to be central; while the last two $W$ bosons with largest absolute rapidities to be the spectators as we expect them to be forward. We proceed closely as in Sec. III. We impose the acceptance cuts

\begin{align}
    m(WW) > 500 \text{ GeV} \quad \text{and} \quad |y(W)| < 1.5
\end{align}

on the strongly-scattered $W$ bosons, and the basic cuts

\begin{align}
    p_T(W_{sp}) > 25 \text{ GeV} \quad \text{and} \quad |y(W_{sp})| < 3
\end{align}
to tag both spectator $W$ bosons. We put a “sp” in the subscript to indicate that they are the spectator $W$ bosons. We also require at least one forward spectator $W$ boson in the rapidity region defined by:

$$1.5 < |y(W_{sp})| < 3,$$

since we expect that the behavior of the spectator $W$ bosons here is the same as the spectator $W$ bosons in the $ZZ$ channel. Then we looked at the $p_T$ distribution of the strongly-scattered $W$ bosons to determine the value needed to further suppress the background and we have chosen

$$p_T(W) > 250 \text{ GeV}.$$  

We summarize the cross sections for various combinations of the cuts in Table II, which is similar to Table I. The tagging efficiency of the spectator $W$ bosons for this channel is

$$\frac{\sigma(\text{signal})_{\text{last second row}}}{\sigma(\text{signal})_{\text{last row}}} = \frac{20.2 \text{ fb}}{25.6 \text{ fb}} = 79\%,$$

which happens to be the same as the $ZZ$ channel within the first two significant digits.

**IV Signal for Strong EWSB Models**

Description of some strongly-interacting EWSB models and the amplitude function predicted by each of the models can be found in Ref. [13]. Here we calculate the signal cross sections for various models by the method of effective $W$ luminosity, in addition to the heavy Higgs-boson model that we have studied in the Secs. [I] and [II]. Each of the $W_LW_L$ scattering amplitudes grows with energy until reaching the resonances, e.g. a technirho. The presence of the resonances (scalar or vector) is the natural unitarization to the scattering amplitudes, except that there might be slight violation of unitarity around the resonance peak. After the resonance, the scattering amplitudes will stay below the unitarity limit. The models can be classified according to the spin and isospin properties of the resonance fields, which are to
unitarize the $W_LW_L$ scattering amplitudes. There are scalar-like, vector-like, and nonresonant models. For scalar-like models we employ the SM with a 1 TeV Higgs boson, the model with a chirally-coupled scalar of mass $m_S = 1$ TeV and width $\Gamma_S = 350$ GeV, and $O(2N)$ model with the cutoff $\Lambda = 2$ TeV. For the vector-like models we choose the chirally-coupled vector field (technirho) of masses $m_\rho = 1.2$ and $1.5$ TeV, and $\Gamma_\rho = 0.5$ and $0.6$ TeV, respectively. In the extreme case of no light resonance (nonresonant model), unitarity is likely to be saturated before reaching the lightest resonance. Here we employ the Low Energy Theorem (LET)-derived amplitude function, $A(s,t,u) = s/v^2$, for the nonresonant model and extrapolate it to high energy. We might have to worry about unitarity violation in the scattering amplitudes. Let us take a look at the LET-derived amplitude. From the partial wave analysis, the only nonzero partial wave coefficients $a^I_J$ are $a^0_0$, $a^1_1$, and $a^2_0$. Among the nonzero $a^I_J$'s, $a^0_0$ saturates the unitarity ($|a^I_J| < 1$) at the lowest energy $4\sqrt{\pi}v \approx 1.7$ TeV, which is the center-of-mass energy of the $W_LW_L$ system. So for $\gamma\gamma$ colliders of 1.5–2 TeV that we are considering, unitarity violation should not happen, and therefore we simply extrapolate the LET amplitudes without any unitarization. Later, we also extend the results to $\sqrt{s_{\gamma\gamma}} = 3$ TeV. But for simplicity we leave out the unitarization procedures so that our results for $\sqrt{s_{\gamma\gamma}} \gtrsim 2$ TeV might slightly over-estimate the actual cross sections, or in other words, they represent some upper bounds for the cross sections.

Before we present the results for the signals, let us examine the validity of the method of effective $W$ luminosity by comparing the heavy Higgs-boson signal obtained by the exact calculation and by the method of effective $W$ luminosity. In Secs. I and II, we already have the results for the exact calculations of the 1 TeV Higgs-boson signal at $\sqrt{s_{\gamma\gamma}} = 2$ TeV, which are listed in Tables I and II. We first compare the $Z_LZ_L$ channel. Using the method of effective $W$ luminosity the signal is given by

$$\sigma(s_{\gamma\gamma}) = \int dx_1 dx_2 f_{W/\gamma}(x_1) f_{W/\gamma}(x_2) \hat{\sigma}(W_L^+W_L^- \to Z_LZ_L, \hat{s} = x_1 x_2 s_{\gamma\gamma}), \quad (13)$$

where $f_{W/\gamma}(x)$ is the effective $W$ luminosity inside a photon given in Eqn. (1) and $\hat{\sigma}(\hat{s})$ is
given by
\[
\hat{\sigma}(\hat{s}) = \int d(PS) \frac{1}{2\lambda^{1/2}(\hat{s}, m_W^2, m_W^2)} \left| \mathcal{M}(W_L^+W_L^- \rightarrow Z_LZ_L) \right|^2,
\]
where \(\lambda(x, y, z) = (x^2 + y^2 + z^2 - 2xy - 2yz - 2zx)\) and \(PS\) is the phase space factor including the symmetry factor of 1/2. The scattering amplitude \(\mathcal{M}\) is written as
\[
\mathcal{M}(W_L^+W_L^- \rightarrow Z_LZ_L) = A(\hat{s}, \hat{t}, \hat{u}),
\]
where \(\hat{s}, \hat{t},\) and \(\hat{u}\) in the above equation refer to the \(W_L^+W_L^-\) system and \(A(\hat{s}, \hat{t}, \hat{u})\) is the amplitude function predicted by each strong EWSB model. For the heavy Higgs-boson model \(A(\hat{s}, \hat{t}, \hat{u})\) is given by
\[
A(\hat{s}, \hat{t}, \hat{u}) = -\frac{m_H^2}{v^2} \left(1 + \frac{m_H^2}{s - m_H^2 + im_H \Gamma_H \theta(\hat{s})}\right),
\]
where \(v \approx 246\) GeV and \(\theta(\hat{s}) = 1\) (0) for \(\hat{s} > 0\) (otherwise). \(\Gamma_H\) is the decay width of the Higgs boson and we take \(\Gamma_H = 0.5\) TeV for \(m_H = 1\) TeV. With only the acceptance cuts in Eqns. (3) and (6) on the strongly-scattered \(Z\) pair at \(\sqrt{s_{\gamma\gamma}} = 2\) TeV, the method of effective \(W\) luminosity gives \(\sigma(\gamma\gamma \rightarrow W_{sp}W_{sp}Z_LZ_L) = 12.7\) fb, which is within 7% of the result (13.6 fb) for the exact calculation. For the \(W_L^+W_L^-\) channel we do similar comparison. The scattering amplitude \(\mathcal{M}(W_L^+W_L^- \rightarrow W_L^+W_L^-)\) is again expressed in term of the amplitude function:
\[
\mathcal{M}(W_L^+W_L^- \rightarrow W_L^+W_L^-) = A(\hat{s}, \hat{t}, \hat{u}) + A(\hat{t}, \hat{s}, \hat{u}).
\]
With the acceptance cuts in Eqns. (8) and (11) on the strongly-scattered \(W/W\) pair at \(\sqrt{s_{\gamma\gamma}} = 2\) TeV, the method of effective \(W\) luminosity gives \(\sigma(W^+W^- \rightarrow W_{sp}^+W_{sp}^-W_L^+W_L^-) = 29.0\) fb, which is still within 15% of the result (25.6 fb) for the exact calculation. Therefore, we have justified here the validity of the method of effective \(W\) luminosity with the acceptance cuts: \(m(WW/ZZ) > 500\) GeV, \(|y(W/Z)| < 1.5\), and \(p_T(W/Z) > 250\) GeV on the strongly-scattered \(W/Z\) bosons. We do expect that the approximation works better at very large invariant mass and central rapidity phase space region. From now on, we use the method of effective \(W\) luminosity to calculate the signal for various models including the heavy Higgs boson.
With the 79% tagging efficiency of the spectator $W$ bosons for both $W_L^+W_L^- \rightarrow Z_LZ_L$ and $W_L^+W_L^- \rightarrow W_L^+W_L^-$ channels, we show the cross sections of the signal for various models at $\sqrt{s_{\gamma\gamma}} = 2$ TeV and the significance of each in Table II. From Table II, we can see that both channels are very sensitive to the presence of scalar-like resonances, but $W_L^+W_L^-$ channel is far more sensitive to the presence of vector-like resonances than the $Z_LZ_L$ channel. On the other hand, in the extreme case of no light resonances, the $Z_LZ_L$ channel is enhanced more than the $W_L^+W_L^-$ channel by about 50%.

Although the energy of photon colliders is limited by the Next Linear Collider designs, it is still instructive to show the signal and background cross sections at other center-of-mass energies. However, there is a technical difficulty that the tagging efficiency for the spectator $W$ bosons by the cuts in Eqns. (4) and (5) is likely to vary with the center-of-mass energies. From Fig. II, we know that there are hardly any signal and background events beyond $|y(W_{sp})| = 3$ at $\sqrt{s_{\gamma\gamma}} = 2$ TeV, due to the finite $W$-boson mass. However, we do expect that for $\sqrt{s_{\gamma\gamma}} > 2$ TeV the spectator $W$ bosons can go further out in the forward rapidity region and we verified that at $\sqrt{s_{\gamma\gamma}} = 3$ TeV the signal events can go up to about $|y(W_{sp})| = 3.5$ with a substantial number of them beyond $|y(W_{sp})| = 3$; while the majority of the background events are still within $|y(W_{sp})| < 3$. Therefore, in order to maintain a large ($\approx 80\%$) tagging efficiency at $\sqrt{s_{\gamma\gamma}} = 3$ TeV, we have to extend the forward rapidity coverage from 3 to 3.5, while such an extension in the rapidity coverage should not affect significantly the background cross section since the majority of the background events are within $|y(W_{sp})| < 3$. Therefore, we expect that at different $\sqrt{s_{\gamma\gamma}}$ we have to adjust the rapidity coverage for the spectator $W$ bosons in order to maintain a large tagging efficiency. Instead of presenting our summary curves with different cuts at different center-of-mass energies, we adopt the following, for simplicity. We calculate the background for $\sqrt{s_{\gamma\gamma}} = 1 - 3$ TeV with the same acceptance cuts: $m(ZZ/WW) > 500$ GeV, $|y(Z/W)| < 1.5$, and $p_T(Z/W) > 250$ GeV on the strongly-scattered $Z/W$ bosons, and $p_T(W_{sp}) > 25$ GeV, $|y(W_{sp})| < 3$, and requiring at least one forward spectator $W$ boson in the range $1.5 < |y(W_{sp})| < 3$ for the spectator $W$ bosons.
Whether or not extending the rapidity coverage should not change the background cross sections significantly since the majority of the background events are within $|y(W_{sp})| < 3$. On the other hand, the cross sections for various models at $\sqrt{s_{\gamma\gamma}} = 1 - 3$ TeV are calculated with only the acceptance cuts on the strongly-scattered $W/Z$ bosons and then multiplied by a constant 79% tagging efficiency to represent the effect of tagging the spectator $W$ bosons. Although the 79% tagging efficiency is only valid for $\sqrt{s_{\gamma\gamma}} = 2$ TeV with the rapidity coverage up to 3, we do expect that similar tagging efficiencies can be obtained by extending the rapidity coverage, which depends on $\sqrt{s_{\gamma\gamma}}$, from 3 gradually to 3.5 at $\sqrt{s_{\gamma\gamma}} = 3$ TeV; while this extension in rapidity coverage should not affect the background cross sections significantly. The cross sections for various models in the channels $W^+_L W^-_L \to Z_L Z_L$ and $W^+_L W^-_L \to W^+_L W^-_L$ are shown in Fig. 6(a) and (b), respectively. The backgrounds from the SM production of $\gamma\gamma \to WWZZ$ and $WWW WW$ with $m_H = 0.1$ TeV are also shown. The 79% tagging efficiency of the spectator $W$ bosons for both $Z_L Z_L$ and $W^+_L W^-_L$ channels has been multiplied in the signal curves of Figs. 6(a) and (b). From Figs. 6(a) and (b), the $Z_L Z_L$ channel seems doing better than the $W^+_L W^-_L$ channel, as the $\gamma\gamma \to WWZZ$ background can be suppressed below most of the signal curves except for the models of heavy vector resonance and of LET. This is due to the fact that the cross section for $\gamma\gamma \to WWWWW$ receives many contributions that are not sensitive to the Higgs-boson mass. Obviously, the higher the center-of-mass energies, the better is the possibility of probing the strongly-interacting EWSB scenario. At $\sqrt{s_{\gamma\gamma}} = 1.5$ TeV, although the signal-to-background ratio is greater than 1 for both channels and for most of the models, the number of the signal events might be too small for any practical observation, unless a very high luminosity can be achieved, say 100 fb$^{-1}$. For $\sqrt{s_{\gamma\gamma}} \gtrsim 2$ TeV the cross sections for the signal are much larger and a large signal-to-background ratio is still maintained, so the feasibility to probe the EWSB improves significantly. According to Table III, a center-of-mass energy $\sqrt{s_{\gamma\gamma}}$ of 2 TeV with an integrated luminosity of 10 fb$^{-1}$ is already sufficient to probe the strong EWSB scenario. However, for the present highest energy $e^+e^-$ collider designs of 1.5 TeV it can
at most be converted to a photon collider of energy about 1.2 TeV and this is certainly not enough to probe the EWSB at TeV regime.

V Discussions

So far we have performed the signal-background analysis with the assumptions of a perfect monochromatic $\gamma\gamma$ collider, and ignoring any QCD-related backgrounds and the decays of the vector bosons. We are going to discuss them in order. First, we discuss the decays of the vector bosons. Since it is necessary to identify the $W$ and $Z$ bosons, only the decay modes, in which the $W$ and $Z$ bosons can be fully reconstructed, are considered. Therefore, for the $W$ bosons coming out from the strong-scattering region it has to decay hadronically; while the $Z$ bosons can decay into hadrons and leptons. The combined branching ratio for the strongly-scattered $WW$ pair is $[\text{Br}(W \to q\bar{q})]^2 = (0.7)^2 \approx 0.5$; while that for the $ZZ$ pair is $[\text{Br}(Z \to q\bar{q}, \ell\bar{\ell})]^2 = (0.8)^2 \approx 0.6$. Furthermore, we also have to identify the spectator $W$ bosons with full reconstruction so as to eliminate the QCD backgrounds. The branching ratio for the spectator $W$ bosons is then $(0.7)^2 \approx 0.5$. In total, we have a combined branching ratio of 25% (30%) for the $W^+_LW^-_L$ ($Z_LZ_L$) channel. It implies that after we take into account of the decay branching ratios the signal and background cross sections in Table III are quartered and the significance of the signal is halved, which does not affect our conclusion that a 2 TeV photon collider with a luminosity of 10 fb$^{-1}$ is sufficiently feasible to probe the EWSB sector. QCD backgrounds should not be serious since we always require to identify the $W$ and $Z$ bosons by fully reconstructing their masses. By reconstruction, most of the backgrounds from QCD production of jets are eliminated. Production of $\gamma\gamma \to t\bar{t}t\bar{t}$ might be a possible background, but the presence of the $b$-jets and the top-mass reconstruction can help eliminating this background.

A perfect monochromatic $\gamma\gamma$ collider might be possible in the future but even the best up-to-date design, the laser backscattering [4], cannot produce perfect monochromaticity. The
energy spectrum of the photon beam with respect to the parent electron beam is continuous with a peak at \( x \approx 0.83 \). Therefore, being more realistic we present the summary curves again but folded with the the luminosity of the photon beam obtained from laser backscattering. The luminosity function for the photon spectrum using unpolarized laser and electron beams is given by

\[
f_{\gamma/e}(x) = \frac{1}{D(\xi)} \left[ 1 - x + \frac{1}{1 - x} - \frac{4x}{\xi(1 - x)} + \frac{4x^2}{\xi^2(1 - x)^2} \right],
\]

where

\[
D(\xi) = (1 - \frac{4}{\xi} - \frac{8}{\xi^2}) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2},
\]

with \( \xi = \frac{4E_0\omega_0}{m_e^2} \), \( x = \omega/E_0 \), \( \omega_0 \) is the energy of the laser photon, \( E_0 \) is the parent electron beam energy, and \( \omega \) is the energy of the converted photon. The allow range of \( x \) is \( 0 \leq x \leq x_{\text{max}} = \xi/(1 + \xi) \). \( \xi \) is chosen to be 4.8 in order to avoid the electron-positron pair creation from the fusion of the laser photon and the converted photon. Once \( \xi \) is chosen, everything is fixed. The luminosity function is folded with the subprocess cross sections as follows:

\[
\sigma(s) = \int dx_1 dx_2 f_{\gamma/e}(x_1) f_{\gamma/e}(x_2) \int dx_3 dx_4 f_{W/\gamma}(x_3) f_{W/\gamma}(x_4) \hat{\sigma}(W^+_L W^-_L \rightarrow Z_L Z_L, W^+_L W^-_L)
\]

(20)

to obtain the cross sections for the signal at the center-of-mass energy \( \sqrt{s} \) of the parent \( e^+e^- \) collider; while the cross section for the SM background is

\[
\sigma(s) = \int dx_1 dx_2 f_{\gamma/e}(x_1) f_{\gamma/e}(x_2) \hat{\sigma}(\gamma\gamma \rightarrow WWZZ, WWWW).
\]

(21)

The results are presented in Fig. 7(a) and (b), respectively, for the \( e^+e^- \rightarrow \gamma\gamma \rightarrow WWZZ \) and \( WWWW \) as a function of the center-of-mass energies of the parent \( e^+e^- \) collider. We have multiplied to the signal curves a constant 79% tagging efficiency to represent the effect of tagging the spectator \( W \) bosons, and the background curves are calculated exactly with all the acceptance cuts. The shape and the relative size of the signal and background curves do not change significantly from Figs. 6 to Figs. 7, in which the photon spectrum is folded. However, the actual values of the cross sections drop substantially, indicating that the
monochromaticity of the photon beams is very important. This is easy to understand that the cross section of the signal increases quite sharply with $\sqrt{s_{\gamma\gamma}}$, as demonstrated in Figs. [1], and therefore the middle to lower end of the photon spectrum by laser backscattering can hardly contribute to the strong EWSB signal. Since only the upper end of the photon spectrum can contribute to the signal, it is necessary to use polarized laser and electron beams to increase the monochromaticity of the colliding photon beams [4]. If the monochromaticity of the photon beam can approach the limit of being perfect about 0.8 of the parent electron-beam energy, an $e^+e^-$ machine of 2.5 TeV would be sufficient to be converted into a 2 TeV photon collider, which has been concluded, in the last section, feasible to probe the strong EWSB scenario. We will not comment any more on what energy of an $e^+e^-$ collider operating in the $\gamma\gamma$ mode is enough to probe the EWSB sector, but only emphasize that $\sqrt{s_{\gamma\gamma}} = 2$ TeV with a luminosity of 10 fb$^{-1}$ is sufficient.

We have presented a signal-background analysis for studying the strong $W_LW_L$ scattering at $\gamma\gamma$ colliders. We confront the signal of various strong EWSB models against the worst irreducible background from the SM production of $\gamma\gamma \to WWZZ$ and $WWWW$. We have demonstrated, with the analysis on the vector-boson level, that with our acceptance cuts the background can be substantially reduced to a level smaller than the signal, and the signal still maintains a very high significance with 10 fb$^{-1}$ luminosity. In principle, a complete Monte Carlo simulation including the decays of the $W/Z$ bosons, the smearing of the momentum of the decay products, and the true detector acceptance is needed to establish the viability. Nevertheless, we have shown, as a first step, that it is very feasible to probe the EWSB by studying the longitudinal $W$-boson scattering (Fig[1]) at photon colliders, provided that the center-of-mass energy of the $\gamma\gamma$ system is of the order 2 TeV with a luminosity of just 10 fb$^{-1}$, or provided that the center-of-mass energy is 1.5 TeV but with a high luminosity of the order 100 fb$^{-1}$.
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Table I: Table showing cross sections (fb) for various combinations of the acceptance cuts in Eqn. (3), (4), (5), and (6) for the channel $\gamma\gamma \rightarrow WWZZ$ at $\sqrt{s_{\gamma\gamma}} = 2$ TeV. In the fourth column the signal is defined as $\sigma(m_H = 1$ TeV) $- \sigma(m_H = 0.1$ TeV). The last column shows the significance $S/\sqrt{B}$ of the signal with an integrated luminosity of 10 fb$^{-1}$.

| No cuts          | $\sigma(m_H = 1$ TeV) | $\sigma(m_H = 0.1$ TeV) | Signal | $S/\sqrt{B}$ |
|------------------|------------------------|--------------------------|--------|-------------|
| (3)+(4)          | 33.7                   | 17.7                     | 16.0   | 12          |
| (3)+(4)+(5)      | 24.8                   | 10.4                     | 14.4   | 14          |
| (3)+(4)+(5)+(6)  | 14.5                   | 3.7                      | 10.8   | 18          |
| (3)+(6)          | 21.8                   | 8.2                      | 13.6   | 15          |

Table II: Table showing cross sections (fb) for various combinations of the acceptance cuts in Eqn. (8), (9), (10), and (11) for the channel $\gamma\gamma \rightarrow WWWW$ at $\sqrt{s_{\gamma\gamma}} = 2$ TeV. In the fourth column the signal is defined as $\sigma(m_H = 1$ TeV) $- \sigma(m_H = 0.1$ TeV). The last column shows the significance $S/\sqrt{B}$ of the signal with an integrated luminosity of 10 fb$^{-1}$.

| No cuts          | $\sigma(m_H = 1$ TeV) | $\sigma(m_H = 0.1$ TeV) | Signal | $S/\sqrt{B}$ |
|------------------|------------------------|--------------------------|--------|-------------|
| (8)+(9)          | 80.0                   | 51.9                     | 28.1   | 12          |
| (8)+(9)+(10)     | 64.4                   | 38.9                     | 25.5   | 13          |
| (8)+(10)+(11)    | 34.9                   | 14.7                     | 20.2   | 17          |
| (8)+(11)         | 50.4                   | 24.8                     | 25.6   | 16          |
Table III: Table showing cross sections (fb) for various EWSB models and background at $\sqrt{s_{\gamma\gamma}} = 2$ TeV. The background is calculated exactly with the full set of acceptance cuts, and the signal is calculated by the method of effective $W$ luminosity with only the acceptance cuts on the strongly-scattered $WW/ZZ$ pair and then multiplied by a constant 79% tagging efficiency to represent the effect of tagging the spectator $W$ bosons. The significance is calculated with a luminosity of 10 fb$^{-1}$.

| Model Description                        | $\sigma(Z_LZ_L)$ | $S/\sqrt{B}$ | $\sigma(W_L^+W_L^-)$ | $S/\sqrt{B}$ |
|------------------------------------------|------------------|--------------|-----------------------|--------------|
| (1) 1 TeV Higgs boson                    | 10.1             | 17           | 22.9                  | 19           |
| (2) Chirally-coupled Scalar              |                  |              |                       |              |
| $m_S = 1$ TeV, $\Gamma_S = 0.35$ TeV     | 7.1              | 12           | 11.3                  | 9.3          |
| (3) O(2N)                                | 4.8              | 7.9          | 7.5                   | 6.2          |
| (4) Chirally-coupled vector              |                  |              |                       |              |
| $m_V = 1.2$ TeV, $\Gamma_V = 0.5$ TeV    | 2.1              | 3.5          | 20.7                  | 17           |
| (5) $m_V = 1.5$ TeV, $\Gamma_V = 0.6$ TeV| 0.36             | 0.6          | 4.3                   | 3.6          |
| (6) LET                                  | 2.6              | 4.3          | 1.7                   | 1.4          |
| SM background                            | 3.7              | -            | 14.7                  | -            |
Figures

1. Schematic diagram for longitudinal $W$-boson scattering in $\gamma\gamma$ collisions.

2. Typical Feynman diagrams contributing to the process $\gamma\gamma \to WWZZ$ and $WWWW$: (a) Higgs-boson exchange, (b) non-Higgs-boson exchange.

3. Total cross sections of the process $\gamma\gamma \to W^+W^-ZZ$ versus the center-of-mass energies $\sqrt{s_{\gamma\gamma}}$ of the $\gamma\gamma$ system for $m_H = 1.0$ (solid line) and $0.1$ TeV (dashed line).

4. Absolute rapidity distribution for the more-forward spectator $W$ boson in the process $\gamma\gamma \to WWZZ$ with $m_H = 1$ TeV and $0.1$ TeV at $\sqrt{s_{\gamma\gamma}} = 2$ TeV. Acceptance cuts are in Eqns. (3) and (4).

5. Transverse momentum $p_T$ distribution for the $Z$ boson with smaller $p_T$ in the process $\gamma\gamma \to WWZZ$ at $\sqrt{s_{\gamma\gamma}} = 2$ TeV. Acceptance cuts are in Eqn. (3), (4), and (5).

6. Summary curves for (a) $Z_LZ_L$ channel and (b) $W^+_LW^-_L$ channel: cross sections of the signal for various strong EWSB models and the SM background. The acceptance cuts on the strongly-scattered $ZZ/WW$ pair are $m(ZZ/WW) > 500$ GeV, $|y(Z/W)| < 1.5$, and $p_T(Z/W) > 250$ GeV; while the acceptance cuts on the spectator $W$ bosons are $p_T(W_{sp}) > 25$ GeV and $|y(W_{sp})| < 3$, we also require at least one forward spectator $W$ boson in the rapidity region defined by $1.5 < |y(W_{sp})| < 3$. The 79% tagging efficiency has been multiplied to the signal curves to represent the effect of tagging the spectator $W$ bosons. The models are (1) 1 TeV Higgs boson, (2) chirally-coupled scalar $m_S = 1$ TeV and $\Gamma_S = 0.35$ TeV, (3) $O(2N)$ with $\Lambda = 2$ TeV, (4) chirally-coupled vector $m_V = 1.2$ TeV and $\Gamma_V = 0.5$ TeV, (5) $m_V = 1.5$ TeV and $\Gamma_V = 0.6$ TeV, and (6) LET. The SM background with $m_H = 0.1$ TeV is indicated by (7).

7. Summary curves: same as Fig. 6 but folded with the photon spectrum using unpolarized laser and electron beams by laser backscattering.
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