Measurement of Heavy Gauge Bosons in Little Higgs Model with T-parity at ILC

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The Littlest Higgs Model with T-parity is one of the attractive candidates of physics beyond the Standard Model. One of the important predictions of the model is the existence of new heavy gauge bosons, where they acquire mass terms through the breaking of global symmetry necessarily imposed on the model. The determination of the masses are, hence, quite important to test the model. In this paper, the measurement accuracy of the heavy gauge bosons at ILC is reported.

1 Introduction

There are a number of scenarios for new physics beyond the Standard Model. The most famous one is the supersymmetric scenario. Recently, alternative one called the Little Higgs scenario has been proposed [1, 2]. In this scenario, the Higgs boson is regarded as a pseudo Nambu-Goldstone boson associated with a global symmetry at some higher scale. A $Z_2$ symmetry called T-parity is imposed on the models to satisfy constraints from electroweak precision measurements [3, 4, 5]. Under the parity, new particles are assigned to be T-odd (i.e. with a T-parity of $-1$), while the SM particles are T-even. The lightest T-odd particle is stable and provides a good candidate for dark matter. In this article, we focus on the Littlest Higgs model with T-parity as a simple and typical example of models implementing both the Little Higgs mechanism and T-parity.

In order to test the Little Higgs model, precise determinations of properties of Little Higgs partners are mandatory, because these particles are directly related to the cancellation of quadratically divergent corrections to the Higgs mass term. In particular, measurements of heavy gauge boson masses, Little Higgs partners for gauge bosons, are quite important. Since heavy gauge bosons acquire mass terms through the breaking of the global symmetry, precise measurements of their masses allow us to determine the most important parameter of the model, namely the vacuum expectation value of the breaking.

We studied the measurement accuracy of masses of the heavy gauge bosons at the international linear collider (ILC). In addition, the sensitivity to the vacuum expectation value (f) was estimated. In this paper, the status of the study is shown, and the detail of this study is described in [6].

2 Representative point and target mode

In order to perform a numerical simulation at ILC, we need to choose a representative point in the parameter space of the Littlest Higgs model with T-parity. Firstly, the model parameters should satisfy the current electroweak precision data. In addition, the cosmological
observation of dark matter relics also gives important information. Thus, we consider not only the electroweak precision measurements but also the WMAP observation [7] to choose a point in the parameter space. We have selected a representative point where Higgs mass and \( f \) are 134 GeV and 580 GeV, respectively. At the representative point, we have obtained \( \Omega_{\text{DM}}h^2 \) of 1.05. The masses of the heavy gauge bosons are \((M_{A_H}, M_{W_H}, M_{Z_H}) = (81.9 \text{ GeV}, 368 \text{ GeV}, 369 \text{ GeV})\), where \( A_H \), \( Z_H \), and \( W_H \) are the Little Higgs partners of a photon, \( Z \) boson, and \( W \) boson, respectively. Here, \( A_H \) plays the role of dark matter in this model [8, 9]. Since all the heavy gauge bosons are lighter than 500 GeV, it is possible to generate them at ILC.

There are four processes whose final states consist of two heavy gauge bosons: \( e^+e^- \rightarrow A_H A_H, A_H Z_H, Z_H Z_H, \) and \( W_H^+ W_H^- \). The first process is undetectable, thus not considered in this article. The cross sections of the other processes are shown in Table 1. Since \( M_{A_H} + M_{Z_H} \) is less than 500 GeV, \( A_H Z_H \) can be produced at the \( \sqrt{s} = 500 \text{ GeV} \). At \( \sqrt{s} = 1 \text{ TeV} \), we can observe \( W_H^+ W_H^- \) with large cross section. We, hence, concentrate on \( e^+e^- \rightarrow A_H Z_H \) at \( \sqrt{s} = 500 \text{ GeV} \) and \( e^+e^- \rightarrow W_H^+ W_H^- \) at \( \sqrt{s} = 1 \text{ TeV} \). Feynman diagrams for the signal processes are shown in Fig. 1. Note that \( Z_H \) decays into \( A_H h \), and \( W_H^\pm \) decays into \( A_H W^\pm \) with almost 100% branching fractions.

### Table 1: Cross sections for the production of heavy gauge bosons.

| \( \sqrt{s} \) (GeV) | \( e^+e^- \rightarrow A_H Z_H \) (fb) | \( e^+e^- \rightarrow Z_H Z_H \) (fb) | \( e^+e^- \rightarrow W_H^+ W_H^- \) (fb) |
|----------------------|------------------|------------------|------------------|
| 500                  | 1.91             | -                | -                |
| 1 TeV                | 7.42             | 110              | 277              |

Figure 1: Diagrams for signal processes; (a) \( e^+e^- \rightarrow A_H Z_H \) and (b) \( e^+e^- \rightarrow W_H^+ W_H^- \).

### Simulation tools

We have used MadGraph [10] to generate \( e^+e^- \rightarrow A_H Z_H \) at \( \sqrt{s} = 500 \text{ GeV} \), while \( e^+e^- \rightarrow W_H^+ W_H^- \) at \( \sqrt{s} = 1 \text{ TeV} \) and all the standard model events have been generated by Phyxsim [11]. We ignored the initial- and final-state radiation, beamstrahlung, and the beam energy spread for study of \( e^+e^- \rightarrow A_H Z_H \) at \( \sqrt{s} = 500 \text{ GeV} \), whereas their effects were considered for study of \( e^+e^- \rightarrow W_H^+ W_H^- \) at \( \sqrt{s} = 1 \text{ TeV} \) where the beam energy spread is set to 0.14% for the electron beam and 0.07% for the positron beam. The finite crossing angle between the electron and positron beams was assumed to be zero. In both event generators, the helicity amplitudes were calculated using the HELAS library [12], which allows us to deal with the effect of gauge boson polarizations properly. Parton showering and hadronization have been carried out by using PYTHIA6.4 [13], where final-state tau leptons are decayed by TAUOLA [14] in order to handle their polarizations correctly. The generated Monte Carlo events have been passed to a detector simulator called JSFQuickSimulator, which implements the GLD geometry and other detector-performance related parameters [15].
4 Analysis

In this section, we present simulation and analysis results for heavy gauge boson productions. The simulation has been performed at $\sqrt{s} = 500$ GeV for the $A_HZ_H$ production and at $\sqrt{s} = 1$ TeV for the $W^+W^-$ production with an integrated luminosity of 500 fb$^{-1}$.

4.1 $e^+e^- \rightarrow A_HZ_H$ at 500 GeV

$A_H$ and $Z_H$ are produced with the cross section of 1.9 fb at the center of mass energy of 500 GeV. Since $Z_H$ decays into $A_H$ and the Higgs boson, the signature is a single Higgs boson in the final state, mainly 2 jets from $h \rightarrow b\bar{b}$ (with a 55% branching ratio). We, therefore, define $A_HZ_H \rightarrow A_HA_Hbb$ as our signal event. For background events, contribution from light quarks was not taken into account because such events can be rejected to negligible level after requiring the existence of two $b$-jets, assuming a $b$-tagging efficiency of 80% for $b$-jets with 15% probability to misidentify a $c$-jet as a $b$-jet. This $b$-tagging performance was estimated by the full simulation, assuming a typical ILC detector. Signal and background processes considered in this analysis are summarized in Table 2. Figure 2 shows a typical $A_HZ_H$ event seen in the detector simulator.

The clusters in the calorimeters are combined to form a jet if the two clusters satisfy $y_{ij} < y_{\text{cut}}$. $y_{ij}$ is defined as

$$y_{ij} = \frac{2E_iE_j(1 - \cos \theta_{ij})}{E_{\text{vis}}^2},$$

(1)

where $\theta_{ij}$ is the angle between momenta of two clusters, $E_i(j)$ are their energies, and $E_{\text{vis}}$ is the total visible energy. All events are forced to have two jets by adjusting $y_{\text{cut}}$. We have selected events with the reconstructed Higgs mass in a window of 100 – 140 GeV. Since Higgs bosons coming from the $WW$ fusion process have the transverse momentum ($p_T$) mostly below W mass, $p_T$ is required to be above 80 GeV in order to suppress the $\nu\nuh \rightarrow \nu\nubb$ background. Finally, multiplying the efficiency of double $b$-tagging ($0.8 \times 0.8 = 0.64$), we are left with 272 signal and 5,419 background events as shown in Table 2, which corresponds.

Table 2: Signal and backgrounds processes considered in the $A_HZ_H$ analysis.

| Process | Cross sec. [fb] | # of events | # of events after all cuts |
|---------|-----------------|-------------|---------------------------|
| $A_HZ_H \rightarrow A_HA_Hbb$ | 1.05 | 525 | 272 |
| $\nu\nuh \rightarrow \nu\nubb$ | 34.0 | 17,000 | 3,359 |
| $Zh \rightarrow \nu\nubb$ | 5.57 | 2,785 | 1,406 |
| $tt \rightarrow WWbb$ | 496 | 248,000 | 264 |
| $ZZ \rightarrow \nu\nubb$ | 25.5 | 12,750 | 178 |
| $\nu\nuZ \rightarrow \nu\nubb$ | 44.3 | 22,150 | 167 |
| $\gamma Z \rightarrow \gamma bb$ | 1,200 | 600,000 | 45 |

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to a signal significance of 3.7 (= 272/√5419) standard deviations. The indication of the new physics signal can hence be obtained at √s = 500 GeV.

The masses of $A_H$ and $Z_H$ bosons can be estimated from the edges of the distribution of the reconstructed Higgs boson energies. This is because the maximum and minimum Higgs boson energies ($E_{\text{max}}$ and $E_{\text{min}}$) are written in terms of these masses,

$$E_{\text{max}} = \gamma Z_H E^*_h + \beta Z_H \gamma Z_H p^*_h,$$
$$E_{\text{min}} = \gamma Z_H E^*_h - \beta Z_H \gamma Z_H p^*_h,$$

(2)

where $\beta Z_H (\gamma Z_H)$ is the $\beta (\gamma)$ factor of the $Z_H$ boson in the laboratory frame, while $E^*_h (p^*_h)$ is the energy (momentum) of the Higgs boson in the rest frame of the $Z_H$ boson. Note that $E^*_h$ is given as $(M^2_{Z_H} + M^2_h - M^2_{A_H})/(2M_{Z_H})$.

Figure 3(a) shows the energy distribution of the reconstructed Higgs bosons with remaining backgrounds. The background events are subtracted from Fig. 3(a), assuming that the background distribution can be understood completely. Then, the endpoints, $E_{\text{max}}$ and $E_{\text{min}}$, have been estimated by fitting the distribution with a line shape determined by a high statistics signal sample. The fit resulted in $m_{A_H} + m_{Z_H}$ to be 83.2 ± 13.3 GeV and 366.0 ± 16.0 GeV, respectively, which should be compared to their true values: 81.85 GeV and 368.2 GeV. Figure 3(b) shows the probability contours for the masses of $A_H$ and $Z_H$.

Since the masses of the heavy gauge bosons are from the vacuum expectation value ($f$), $f$ can be determined by fitting the energy distribution of the reconstructed Higgs bosons. Then, $f$ was determined to be $f = 576.0 ± 25.0$ GeV.

4.2 $e^+e^- \rightarrow W^+_H W^-_H$ at 1 TeV

$W^+_H W^-_H$ production has large cross section (277 fb) at ILC with $\sqrt{s} = 1$ TeV. Since $W^\pm_H$ decays into $A_H$ and $Z_H$ with the 100% branching ratio, analysis procedure depends on the $W$ decay modes. In this analysis, we have used 4-jet final states from hadronic decays of $W$.
Table 3: Signal and background processes considered in the $W^+_H W^-_H$ analysis.

| Process | cross sec. [fb] | # of events | # of events after all cuts |
|---------|-----------------|-------------|---------------------------|
| $W^+_H W^-_H \rightarrow A_H A_H qqqq$ | 106.5 | 53,258 | 37,560 |
| $W^+ W^- \rightarrow qqqq$ | 1773.5 | 886,770 | 306 |
| $e^+ e^- W^+ W^- \rightarrow e^+ e^- qqqq$ | 464.9 | 232,442 | 23 |
| $e \nu W \rightarrow e \nu qqqq$ | 25.5 | 12,770 | 3,696 |
| $Z_H H \rightarrow A_H A_H hh$ | 99.5 | 49,757 | 3,351 |
| $\nu \bar{\nu} W^+ W^- \rightarrow \nu \bar{\nu} qqqq$ | 6.5 | 3,227 | 1,486 |

Two $W$ bosons, $W^+_H W^-_H \rightarrow A_H A_H qqqq$. Signal and background processes considered in the analysis are summarized in Table 3.

All events have been reconstructed as 4-jet events by adjusting the cut on y-values. In order to identify the two $W$ bosons from $W^+_H$ decays, two jet-pairs have been selected so as to minimize a $\chi^2$ function,

$$
\chi^2 = \frac{(\text{rec} M_{W1} - \text{tr} M_{W})^2}{\sigma_{M_{W}}} + \frac{(\text{rec} M_{W2} - \text{tr} M_{W})^2}{\sigma_{M_{W}}},
$$

where $\text{rec} M_{W1(2)}$ is the invariant mass of the first (second) 2-jet system paired as a $W$ candidate, $\text{tr} M_{W}$ is the true $W$ mass ($80.4$ GeV), and $\sigma_{M_{W}}$ is the resolution for the $W$ mass ($4$ GeV). We required $\chi^2 < 26$ to obtain well-reconstructed events. Since $A_H$ bosons escape from detection resulting in a missing momentum, the missing transverse momentum ($\text{miss}_{p_T}$) of the signal peaks at around $175$ GeV. We have thus selected events with $\text{miss}_{p_T}$ above $84$ GeV. Then, the reconstructed $W$ energy is required to be between $0$ GeV to $500$ GeV. The numbers of events after the selection cuts are shown in Table 3. The number of remaining background events is much smaller than that of the signal.

As in the case of the $A_H Z_H$ production, the masses of $A_H$ and $W_H$ bosons can be determined from the edges of the $W$ energy distribution. Figure 4(a) shows the energy distribution of the reconstructed $W$ bosons. After subtracting the backgrounds from Fig 4(a), the distribution has been fitted with a line shape function. The fitted masses of $A_H$ and $W_H$ bosons are $82.29 \pm 1.10$ GeV and $367.8 \pm 0.8$ GeV, respectively, which are to be compared to their input values: $81.85$ GeV and $368.2$ GeV. Figure 4(b) shows the probability contours for the masses of $A_H$ and $W_H$ at $1$ TeV. The mass resolution improves dramatically at $\sqrt{s} = 1$ TeV, compared to that at $\sqrt{s} = 500$ GeV. Then, $f = 579.7 \pm 1.1$ GeV was obtained by fitting the energy distribution of the reconstructed $W$ bosons.

Summary

The Littlest Higgs Model with T-parity is one of the attractive candidates of physics beyond the Standard Model since it solves both the little hierarchy and dark matter problems simultaneously. One of the important predictions of the model is the existence of new heavy gauge bosons, where they acquire mass terms through the breaking of global symmetry necessarily imposed on the model. The determination of the masses are, hence, quite important to test the model.

We have performed Monte Carlo simulations in order to estimate measurement accuracy of the masses of the heavy gauge bosons at ILC. At ILC with $\sqrt{s} = 500$ GeV, it is possible to produce $A_H$ and $Z_H$ bosons. Here, we can observe the excess by $A_H Z_H$ events in the
Figure 4: (a) The energy distribution of the reconstructed $W$ bosons with remaining backgrounds after the selection cuts. (b) Probability contours corresponding to 1-, 3-, and 5-σ deviations in the $A_H$ and $W_H$ mass-plane.

Higgs energy distribution with the statistical significance of 3.7-sigma. Furthermore, the masses of these bosons can be determined with accuracies of 16.2% for $A_H$ and 4.3% for $Z_H$. Once ILC energy reaches $\sqrt{s} = 1$ TeV, the process $e^+e^- \rightarrow W_H W_H$ opens. Since the cross section of the process is large, the masses of $W_H$ and $A_H$ can be determined as accurately as 1.3% and 0.2%, respectively. Then, the vacuum expectation value, $f$, can be determined with accuracy of 4.3% at $\sqrt{s} = 500$ GeV and 0.2% at 1 TeV.

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