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Measurements of model parameters in the Littlest Higgs model with T-parity in ILC

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Summary. — The Littlest Higgs model with T-parity is one of the attractive candidates for physics beyond the standard model. In the model, we study production processes of new gauge bosons at the international linear collider (ILC). Through Monte Carlo simulations of the production processes, we show that the heavy gauge boson masses can be determined very accurately at the ILC for a representative parameter point of the model. From the simulation result, we also discuss the determination of other model parameters at the ILC.

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1. – Introduction

The Little Higgs model [1,2] has been proposed for solving the little hierarchy problem. In this scenario, the Higgs boson is regarded as a pseudo Nambu-Goldstone (NG) boson. The global symmetry breaking is specially arranged to cancel quadratically divergent corrections to the Higgs mass term at 1-loop level. As a result, the scale of new physics can be as high as 10 TeV without a fine-tuning on the Higgs mass term. In order to avoid electroweak precision constraints, the implementation of the Z_2 symmetry called T-parity to the model has been proposed [3]. In this study, we focus on the Littlest Higgs model with T-parity as a simple and a typical example of the model.

In order to test the model, determinations of properties of Little Higgs partners are mandatory, because these particles are directly related to the cancellation of quadratically divergent terms. In particular, measurements of heavy gauge boson masses are quite important because these masses arise from the vacuum expectation value (VEV) of the global symmetry breaking which is the most important parameter of the model.

TABLE I. – *Representative point used in our simulation study.*

f	m_h	λ_2	κ_l	$m_{A_{\rm H}}$	$m_{W_{\rm H}}$	$m_{Z_{\rm H}}$	m_Φ
580 (GeV)	134 (GeV)	1.5	0.5	81.9 (GeV)	368 (GeV)	369 (GeV)	440 (GeV)

Furthermore, because the heavy photon is a candidate for dark matter [4, 5], the determination of its property gives a great impact not only on particle physics but also on astrophysics and cosmology. The International Linear Collider (ILC) will provide an ideal environment to measure the properties of heavy gauge bosons [6]. We study the sensitivity of the measurements to the Little Higgs parameters at the ILC based on a realistic Monte Carlo simulation [7]. We have used MadGraph [8] and Physsim [9] to generate signal and Standard Model (SM) events, respectively. In this study, we have also used PYTHIA6.4 [10], TAUOLA [11] and JSFQuickSimulator [12].

2. – Littlest Higgs model with T-parity

The Littlest Higgs model with T-parity is based on a non-linear sigma model describing an $SU(5)/SO(5)$ symmetry breaking with a VEV, $f \sim \mathcal{O}(1)$ TeV. An $[SU(2)\times U(1)]^2$ subgroup in the $SU(5)$ is gauged, which is broken down to the SM gauge group $SU(2)_L \times U(1)_Y$. Due to the presence of the gauge and Yukawa interactions, the $SU(5)$ global symmetry is not exact and the SM doublet and triplet Higgs bosons (H and Φ) arise as pseudo NG bosons. The triplet Higgs boson mass is given by $m_\Phi = \sqrt{2} m_h f/v$, where m_h is the SM Higgs mass and $\langle H\rangle = (0, v/\sqrt{2})^T$. The triplet Higgs boson is T-odd, while the SM Higgs is T-even.

This model contains gauge fields of the gauged $[SU(2)\times U(1)]^2$ symmetry; the linear combinations $W^a = (W^a_1 + W^a_2)/\sqrt{2}$ and $B = (B_1 + B_2)/\sqrt{2}$ correspond to the SM $SU(2)_L$ and $U(1)_Y$ gauge bosons. The other linear combinations $W^a_{\rm H} = (W^a_1 - W^a_2)/\sqrt{2}$ and $B_{\rm H} = (B_1 - B_2)/\sqrt{2}$ are additional gauge bosons called heavy gauge bosons, which acquire masses of $\mathcal{O}(f)$ through the $SU(5)/SO(5)$ symmetry breaking. After the electroweak symmetry breaking, the neutral components of $W^a_{\rm H}$ and $B_{\rm H}$ are mixed with each other and form mass eigenstates $A_{\rm H}$ and $Z_{\rm H}$. The masses of heavy gause bosons are given by $m_{W_{\rm H}} \simeq m_{Z_{\rm H}} \simeq gf$ and $m_{A_{\rm H}} \simeq \sqrt{0.2} g' f$, where g (g') is the $SU(2)_L$ ($U(1)_Y$) gauge coupling constant. Heavy gauge bosons behave as T-odd particles, while SM gauge bosons are T-even.

To implement T-parity, two $SU(2)$ doublets $l^{(1)}$ and $l^{(2)}$ are introduced for each SM lepton. The quantum numbers of $l^{(1)}$ and $l^{(2)}$ under the $[SU(2)\times U(1)]^2$ are $(\mathbf{2}, -3/10; \mathbf{1}, -1/5)$ and $(\mathbf{1}, -1/5; \mathbf{2}, -3/10)$, respectively. The $l_{\rm SM} = (l^{(1)} - l^{(2)})/\sqrt{2}$ gives the left-handed SM lepton and another linear combination $l_{\rm H} = (l^{(1)} + l^{(2)})/\sqrt{2}$ is vector-like T-odd partner. The masses depend on $\kappa_l : m_{e_{\rm H}} \simeq m_{\nu_{\rm H}} \simeq \sqrt{2}\kappa_l f$. In addition, new particles are also introduced in quark sector. (For details, see ref. [13].)

3. – Simulation study

The representative point $(f, m_h, \lambda_2, \kappa_l)$ used in our simulation study is shown in table I where λ_2 is an additional Yukawa coupling in the top sector. The model parameter satisfies not only the current electroweak precision data but also the WMAP observation [14].

TABLE II. – *Cross sections for the production of heavy gauge bosons.*

$\sqrt{s}$	$e^+e^- \to A_{\rm H}Z_{\rm H}$	$e^+e^- \to Z_{\rm H}Z_{\rm H}$	$e^+e^- \to W_{\rm H}^+W_{\rm H}^-$
500 GeV	1.91 (fb)	—	—
1 TeV	7.42 (fb)	110 (fb)	277 (fb)

Furthermore, no fine-tuning is needed at the sample point to keep the Higgs mass on the electroweak scale [15, 16]. Heavy leptons are heavier than heavy gauge bosons.

In the model, there are four processes whose final states consist of two heavy gauge bosons: $e^+e^- \to A_{\rm H}A_{\rm H}$, $A_{\rm H}Z_{\rm H}$, $Z_{\rm H}Z_{\rm H}$, and $W_{\rm H}^+W_{\rm H}^-$. The first process is undetectable. At the representative point, the largest cross section is expected for the fourth process (See table II.) On the other hand, because $m_{A_{\rm H}} + m_{Z_{\rm H}}$ is less than 500 GeV, the second process is important at the $\sqrt{s} = 500$ GeV. We, hence, concentrate on $e^+e^- \to A_{\rm H}Z_{\rm H}$ at $\sqrt{s} = 500$ GeV and $e^+e^- \to W_{\rm H}^+W_{\rm H}^-$ at $\sqrt{s} = 1$ TeV with an integrated luminosity of 500 fb^{-1}. Feynman diagrams for the signal processes are shown in fig. 1.

3˙1. *The $A_{\rm H}Z_{\rm H}$ production.* – We define $A_{\rm H}Z_{\rm H} \to A_{\rm H}A_{\rm H}h \to A_{\rm H}A_{\rm H}bb$ as our signal event. The $A_{\rm H}$ and $Z_{\rm H}$ boson masses can be estimated from the edges of the distribution of the reconstructed Higgs boson energies.

The energy distribution of the reconstructed Higgs bosons with remaining backgrounds is depicted in fig. 2(a). The signal distribution after backgrounds have been subtracted is shown in fig. 2(b). The endpoints have been estimated by fitting the distribution with a lineshape determined by a high statistics signal sample. The fit resulted in $m_{A_{\rm H}}$ and $m_{Z_{\rm H}}$ being 83.2 ± 13.3 GeV and 366.0 ± 16.0 GeV, respectively.

3˙2. *The $W_{\rm H}W_{\rm H}$ production.* – We have used 4-jet final states, $W_{\rm H}^+W_{\rm H}^- \to A_{\rm H}A_{\rm H}W^+W^- \to A_{\rm H}A_{\rm H}qqqq$, as the signal. The masses of $A_{\rm H}$ and $W_{\rm H}$ bosons can be determined from the edges of the reconstructed W energy distribution. The energy distribution is depicted in fig. 3(a). After subtracting the backgrounds from fig. 3(a), the distribution has been fitted with a lineshape determined by a high statistics signal sample as shown in fig. 3(b). The fitted masses of $A_{\rm H}$ and $W_{\rm H}$ bosons are 81.58 ± 0.67 GeV and 368.3 ± 0.63 GeV, respectively. Using the process, it is also possible to confirm that the spin of $W_{\rm H}^{\pm}$ is consistent with one and the polarization of $W^{\pm}$ from the $W_{\rm H}^{\pm}$ decay is dominantly longitudinal. Furthermore, the gauge charges of the $W_{\rm H}$ boson could be also measured using a polarized electron beam. Figure 4 shows the probability contours for masses of $A_{\rm H}$ and $W_{\rm H}$ at 1 TeV together with that of $A_{\rm H}$ and $Z_{\rm H}$ at 500 GeV. The mass resolution improves dramatically at $\sqrt{s} = 1$ TeV, compared to that at $\sqrt{s} = 500$ GeV.

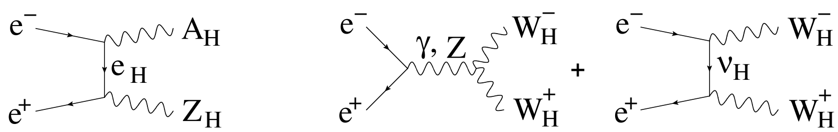

Fig. 1. – Diagrams for signal processes; $e^+e^- \to A_{\rm H}Z_{\rm H}$ and $e^+e^- \to W_{\rm H}^+W_{\rm H}^-$.

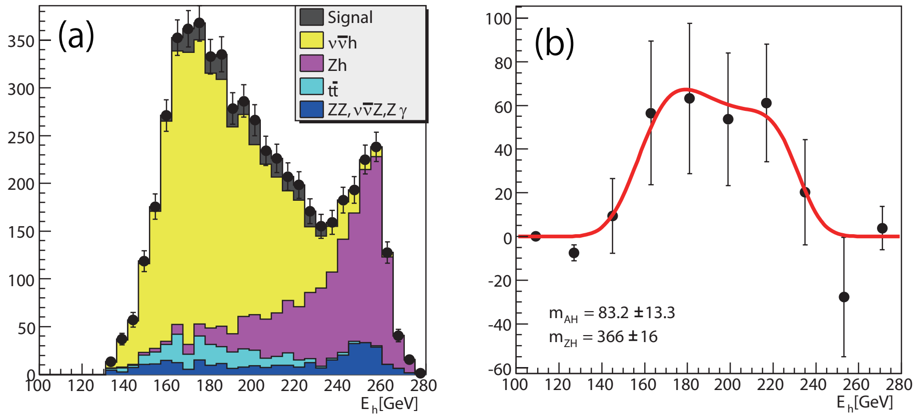

Fig. 2. – (a) Energy distribution of the reconstructed Higgs bosons with remaining backgrounds after the mass cut. (b) Energy distribution of the Higgs bosons after subtracting the backgrounds.

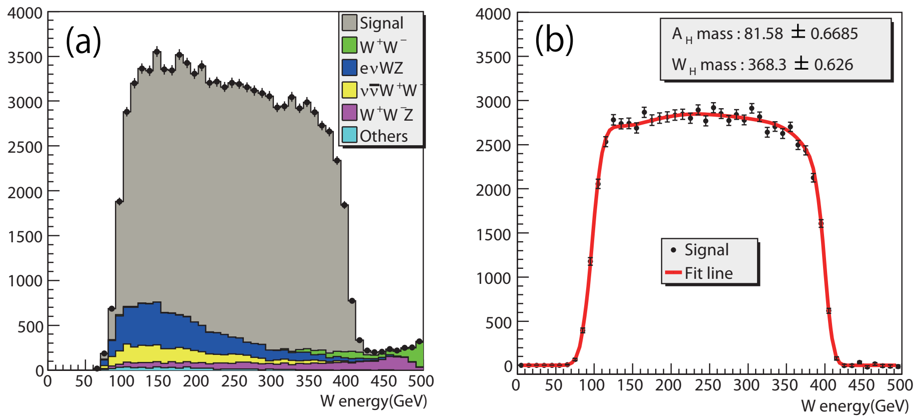

Fig. 3. – (a) The energy distribution of the reconstructed W bosons with remaining backgrounds after the selection cuts. (b) The energy distribution of the W bosons after the subtraction of the backgrounds.

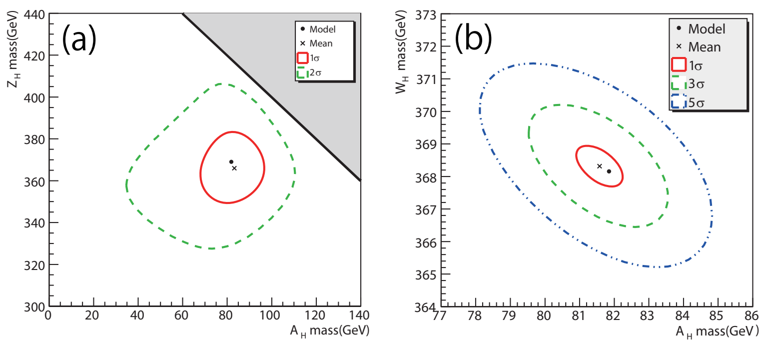

Fig. 4. – Probability contours corresponding to (a) 1- and 2-σ deviations from the best-fit point, and (b) 1-, 3-, and 5-σ deviations. The shaded area in (a) shows the unphysical region of $m_{A_{\rm H}} + m_{Z_{\rm H}} > 500\,{\rm GeV}$.

4. – Conclusions

In the Littlest Higgs model with T-parity, we have shown that the masses of the heavy gauge bosons can be determined very accurately at the ILC. Furthermore, since the masses of the heavy gauge bosons are determined by the VEV f, it is possible to accurately determine f. From the results obtained in our simulation study, it turns out that the VEV f can be determined to accuracies of 4.3% at $\sqrt{s} = 500\,\text{GeV}$ and 0.1% at 1 TeV. Another Little Higgs parameter κ_l could also be estimated from production cross sections for the heavy gauge bosons, because the cross sections depend on the masses of heavy leptons. At the ILC with $\sqrt{s} = 500\,\text{GeV}$ and 1 TeV, κ_l could be obtained within 9.5% and 0.8% accuracies, respectively.

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