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

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We investigate a possibility of precision measurements for parameters of the Littlest Higgs model with T-parity at the International Linear Collider (ILC). The model predicts new gauge bosons which masses strongly depend on the vacuum expectation value that breaks a global symmetry of the model. Through Monte Carlo simulations of production processes of new gauge bosons, we show that these 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.

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 associated with a global symmetry at some higher scale. Though the symmetry is not exact, its breaking is specially arranged to cancel quadratically divergent corrections to the Higgs mass term at 1-loop level. This is called the Little Higgs mechanism. As a result, the scale of new physics can be as high as 10 TeV without a fine-tuning on the Higgs mass term. Due to the symmetry, the scenario necessitates the introduction of new particles. In addition, the implementation of the Z_2 symmetry called T-parity to the model has been proposed in order to avoid electroweak precision measurements [3]. In this study, 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 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 (VEV) of the breaking. 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. However, it is difficult to determine the properties of heavy gauge bosons at the Large Hadron Collider, because they have no color charge [6].

On the other hand, the ILC will provide an ideal environment to measure the properties of heavy gauge bosons. We study the sensitivity of the measurements to the Little Higgs

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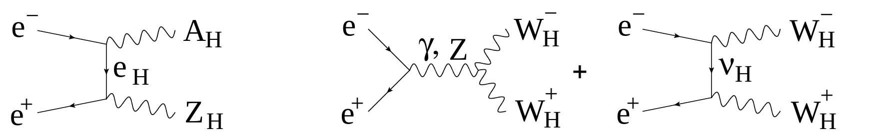

Figure 1: Diagrams for signal processes; $e^+e^- \to A_\mathrm{H}Z_\mathrm{H}$ and $e^+e^- \to W_\mathrm{H}^+W_\mathrm{H}^-$.

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 which implements the GLD geometry and other detector-performance related parameters [12].

2 Model

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 $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$ subgroup in the SU(5) is gauged, which is broken down to the SM gauge group $\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$. Due to the presence of the gauge and Yukawa interactions, the SU(5) global symmetry is not exact. The SM doublet and triplet Higgs bosons (H and Φ) arise as pseudo NG bosons in the model. The triplet Higgs boson is T-odd, while the SM Higgs is T-even.

This model contains gauge fields of the gauged $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$ symmetry; The linear combinations $W^a = (W_1^a + W_2^a)/\sqrt{2}$ and $B = (B_1 + B_2)/\sqrt{2}$ correspond to the SM gauge bosons for the $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ symmetries. The other linear combinations $W_\mathrm{H}^a = (W_1^a - W_2^a)/\sqrt{2}$ and $B_\mathrm{H} = (B_1 - B_2)/\sqrt{2}$ 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_H^a and B_H are mixed with each other and form mass eigenstates A_H and Z_H. The heavy gauge bosons (A_H, Z_H, and W_H) 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 gauged $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$ symmetry are $(\mathbf{2}, -3/10; \mathbf{1}, -1/5)$ and $(\mathbf{1}, -1/5; \mathbf{2}, -3/10)$, respectively. The linear combination $l_{SM} = (l^{(1)} - l^{(2)})/\sqrt{2}$ gives the left-handed SM lepton. On the other hand, another linear combination $l_\mathrm{H} = (l^{(1)} + l^{(2)})/\sqrt{2}$ is vector-like T-odd partner which acquires the mass of $\mathcal{O}(f)$. The masses depend on the κ_l: $m_{e_\mathrm{H}} = \sqrt{2}\kappa_l f, m_{\nu_\mathrm{H}} = (1/2)(\sqrt{2} + \sqrt{1 + c_f})\kappa_l f \simeq \sqrt{2}\kappa_l f$. In addition, new particles are also introduced in quark sector. (For details, see Ref. [13].)

3 Simulation study

The representative point used in our simulation study is $(f, m_h, \lambda_2, \kappa_l)$ = (580 GeV, 134 GeV, 1.5, 0.5) where (m_{A_H}, m_{W_H}, m_{Z_H}, m_Φ) = (81.9 GeV, 368 GeV, 369 GeV, 440 GeV) and 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]. Furthermore, no fine-tuning is needed at the sample point to keep the Higgs mass on the electroweak scale [15, 16].

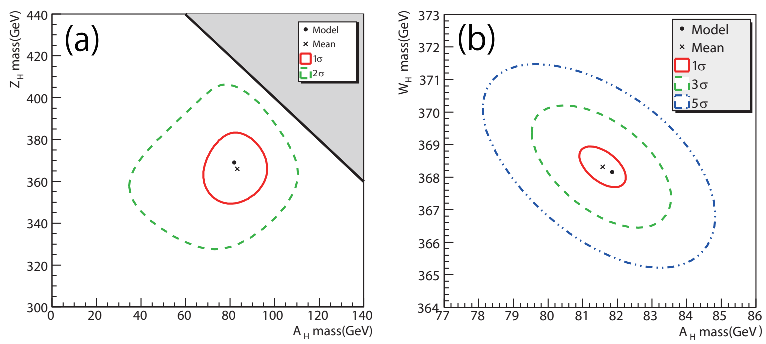

Figure 2: Probability contours corresponding to (a) 1- and 2-σ deviations from the best fit point in the $A_{\rm H}$ and $Z_{\rm H}$ mass plane, and (b) 1-, 3-, and 5-σ deviations in the $A_{\rm H}$ and $W_{\rm H}$ mass plane. The shaded area in (a) shows the unphysical region of $m_{A_{\rm H}} + m_{Z_{\rm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

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, which is open at $\sqrt{s} > 1$ TeV. On the other hand, because $m_{A_{\rm H}} + m_{Z_{\rm H}}$ is less than 500 GeV, the second process is important already 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. Feynman diagrams for the signal processes are shown in Fig. 1.

For the $A_{\rm H}Z_{\rm H}$ production at $\sqrt{s} = 500$ GeV with an integrated luminosity of 500 fb^{-1}, 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 endpoints have been estimated by fitting the distribution with a line shape 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.

For the $W_{\rm H}W_{\rm H}$ production at $\sqrt{s} = 1$ TeV with an integrated luminosity of 500 fb^{-1}, we have used 4-jet final states, $W_{\rm H}^+W_{\rm H}^- \to A_{\rm H}A_{\rm H}W^+W^- \to A_{\rm H}A_{\rm H}qqqq$. The masses of $A_{\rm H}$ and $W_{\rm H}$ bosons can be determined from the edges of the W energy distribution. 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 2 shows the probability contours for the 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.

4 Conclusion

The Littlest Higgs Model with T-parity is one of the attractive candidates for physics beyond the SM. We have shown that the masses of the heavy gauge bosons can be determined very accurately at the ILC. It is important to notice that these masses are obtained in a model-independent way, so that it is possible to test the Little Higgs model by comparing them with the theoretical predictions. 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 $\sqrt{s} = 500$ GeV and 0.1% at $\sqrt{s} = 1$ 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 $\sqrt{s} = 500$ GeV and 1 TeV, κ_l could be obtained within 9.5% and 0.8% accuracies, respectively.

Finally, We have also found that the thermal abundance of dark matter relics can be determined to 10% and 1% levels at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV, respectively. These accuracies are comparable to those of current and future cosmological observations such as the PLANCK satellite [17], implying that the ILC experiment will play an essential role to understand the thermal history of our universe.

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