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Distinct signals of the gauge-Higgs unification in e^+e^- collider experiments

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ABSTRACT

Effects of Kaluza–Klein excited neutral vector bosons (Z' bosons) in the gauge-Higgs unification on $e^+e^- \to \bar{q}q, \ell^+\ell^-$ cross sections are studied, particularly in future e^+e^- collider experiments with polarized beams. Significant deviations in the energy and polarization dependence in $\sigma(\mu^+\mu^-)$, the lepton forward–backward asymmetry, $R_b(\mu) \equiv \sigma(\bar{b}b)/\sigma(\mu^+\mu^-)$ and the left–right asymmetry from the standard model are predicted.

With the establishment of the standard model (SM) by the discovery of the Higgs boson, searching for physics beyond the SM and understanding the electroweak phase transition have become a few of the main topics in particle physics. Not only large hadron colliders, but also e^+e^- colliders play an important role for this purpose. In this letter we study distinct signals of the gauge-Higgs unification (GHU) [1–10] in the future e^+e^- collider experiments.

In GHU the Higgs boson is a part of the extra-dimensional component of the gauge potentials, appearing as a fluctuation mode of an Aharonov–Bohm (AB) phase θ_H in the fifth dimension. As a consequence the Higgs couplings HWW, HZZ and Yukawa couplings deviate from those in the SM in a universal manner [11]. They are suppressed by a common factor $\cos\theta_H$;

$$\frac{g^{GHU}_{HWW}}{g^{\rm SM}_{HWW}}, \frac{g^{\rm GHU}_{HZZ}}{g^{\rm SM}_{HZZ}}, \frac{y^{\rm GHU}_{\bar{f}f}}{y^{\rm SM}_{\bar{f}f}} \simeq \cos\theta_H \ . \tag{1}$$

For $\theta_H = \mathcal{O}(0.1)$, probable values in the model, the deviation of the couplings amounts to $1 - \cos\theta_H = \mathcal{O}(0.005)$, and is small. At the ILC at $\sqrt{s} = 250$ GeV, the ZZH coupling can be measured in the 0.6% accuracy with 2 ab^{-1} data [12]. Another prominent feature of the model is that the first Kaluza–Klein (KK) excited states of the neutral gauge bosons, Z', have large couplings to right-handed components of quarks and leptons, viable signals of which can be seen in hadron collider experiments [8,10].

The main purpose of this letter is to check the effect of such Z' bosons using lepton collider experiments in the past and future. We first examine the GHU model with precision measurements in LEP1 experiment at $\sqrt{s} = M_Z$, and LEP2 experiments for 130 GeV $\le \sqrt{s} \le$ 207 GeV. Then we predict several signals of Z' bosons in GHU in e^+e^- collider experiments designed for future with collision energy $\sqrt{s} \ge 250$ GeV with polarized electron and positron beams.

The GHU model we consider is the $SO(5) \times U(1)_X$ gauge theory in the Randall–Sundrum warped space with metric $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $(0 \le |y| \le +L)$ where k is the AdS_5 curvature. The warp factor $z_L \equiv e^{kL}$ is large ($\gg 1$). $SO(5)$ symmetry is broken to $SO(4) \simeq SU(2)_L \times SU(2)_R$ by the orbifold boundary conditions at $y = 0$ and L. The $SO(5)/SO(4)$ part of the gauge fields, $A^{\hat{a}}_y$ $(a = 1 \sim 4)$, plays the role of the Higgs field in the SM. $SU(2)_R \times U(1)_X$ symmetry is spontaneously broken to $U(1)_Y$ by a brane-localized scalar field at $y = 0$. Finally the $SU(2)_L \times U(1)_Y$ symmetry is dynamically broken to $U(1)_{\rm em}$ by the Hosotani mechanism.

5D fields are expanded in KK series. In particular, there are four KK towers of the neutral vector bosons, $\gamma^{(m)}$, $Z^{(m)}$, $Z_R^{(n)}$ and $A^{\hat{4}(n)}$ $(m = 0, 1, 2, \cdots, n = 1, 2, 3 \cdots)$ where $\gamma^{(0)}$ and $Z^{(0)}$ correspond to the photon and Z boson, respectively. These fields except for $A^{\hat{4}}$ couple to the SM fields and can be observed as neutral Z' vector bosons.

In addition to the quark–lepton multiplets in the vector representation of $SO(5)$, N_F dark fermions in the spinor representation are introduced. As a consequence the electroweak symmetry breaking is achieved at the one loop level. The Higgs boson, which is massless at the tree level, acquires a finite mass m_H, independent of the cutoff scale. The gauge hierarchy problem is thus solved [2].

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There remain two free parameters, N_F and z_L. Given N_F and z_L, the effective potential $V_{\rm eff}(\theta_H)$ is fixed. From the location of the minimum of $V_{\rm eff}(\theta_H)$, the value θ_H is determined. There is the property called the universality such that many of the physical quantities are determined by θ_H, but do not depend on N_F and z_L independently. In the following we take $N_F = 4$ and parameterize the model by θ_H.

We note that some of the composite Higgs models (CHM) have similar features to those in the GHU. In particular, CHM based on $SO(5)$ gauge group has almost the same gauge structure as the $SO(5) \times U(1)_X$ GHU [4,13]. The $SO(5)$ gauge invariance is reduced to $SO(4)$ by orbifold boundary conditions in both cases. However, there are many differences between the two. The 4D Higgs boson in GHU is a fluctuation mode of the AB phase θ_H in the fifth dimension, but is not a pseudo-Nambu–Goldstone boson supposed in CHM. Secondly, in most of the CHM, $SO(4)$-breaking boundary conditions are imposed on fermion fields by hand to obtain the quark–lepton spectrum. In the GHU theory based on the action principle the $SO(5) \times U(1)_X$ gauge invariance in the bulk and the $SO(4) \times U(1)_X$ gauge invariance on the UV and IR branes are strictly preserved. GHU is more restrictive than CHM, and is powerful to make predictions.

In GHU the relevant parameter for physics of SM particles is θ_H. With θ_H given, the KK spectra of various fields, the couplings of quarks and leptons to KK gauge bosons, and the Higgs couplings are all determined. The Higgs boson mass $m_H \sim 125$ GeV and $m_{KK} = 7 \sim 10$ TeV are naturally realized for $\theta_H \sim 0.1$ without fine-tuning of the parameters. It has been shown that corrections to $H \to \gamma\gamma, Z\gamma$ due to an infinite number of KK states of W, t et al. running in the loop are finite and tiny for $\theta_H \sim 0.1$. It has been recognized that the $SO(5) \times U(1)_X$ GHU in the RS space gives nearly the same phenomenology at low energies as the SM for $\theta_H \lesssim 0.1$.

The phase θ_H in GHU corresponds to the vacuum misalignment angle in CHM. A bound $\theta_H < 0.3$ has been derived in CHM from the S parameter constraint [13,14]. In GHU much stronger constraint $\theta_H \lesssim 0.1$ is obtained from the current non-observation of Z' signals at LHC. It should be stressed in this connection that in GHU in the RS space right-handed quarks and leptons and KK gauge bosons are localized near the IR brane whereas left-handed quarks and leptons are localized near the UV brane so that right-handed quarks and leptons have larger couplings to KK gauge bosons than left-handed quarks and leptons.

Masses and widths of Z' bosons are tabulated in Table 1. Fermion couplings to Z' for $\theta_H = 0.115$, 0.0917 and 0.0737 are given in Tables 2, 3 and 4, respectively. In the evaluation $\sin^2\theta_W = 0.23126$ and $M_Z = 91.1876$ GeV are adopted. The Z couplings of quarks and leptons except for top quark are almost the same as in the SM within the accuracy of one part in 10^4. The deviation of the $Zt\bar{t}$ couplings are less than 1%, whereas the deviation of the $Zb\bar{b}$ couplings are very tiny in GHU.

We evaluate $e^+e^- \to \bar{f}f$ cross sections $\sigma(\bar{f}f)$ where f is a lepton or quark. In addition to leptonic and hadronic cross sections, forward–backward asymmetry defined by

Table 1
Masses and widths of Z' bosons, $Z^{(1)}$, $\gamma^{(1)}$, and $Z_R^{(1)}$ ($N_F = 4$).

θ_H [rad.]	$\frac{z_L}{10^4}$	m_{KK} [TeV]	$m_{Z^{(1)}}$ [TeV]	$\Gamma_{Z^{(1)}}$ [GeV]	$m_{\gamma^{(1)}}$ [TeV]	$\Gamma_{\gamma^{(1)}}$ [GeV]	$m_{Z_R^{(1)}}$ [TeV]	$\Gamma_{Z_R^{(1)}}$ [GeV]
0.115	10	7.41	6.00	406	6.01	909	5.67	729
0.0917	3	8.81	7.19	467	7.20	992	6.74	853
0.0737	1	10.3	8.52	564	8.52	1068	7.92	1058

$$A_{\rm FB} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_{-1}^1 \frac{d\sigma}{d\cos\theta} d\cos\theta}, \tag{2}$$

the ratio of hadronic and leptonic cross sections $R_\mu \equiv \sigma(\bar{q}q)/\sigma(\mu^+\mu^-)$, and the asymmetry of $\sigma(\bar{f}f)$ with right- and left-handed polarized electron beams are investigated.[1]

Cross sections are evaluated to the leading order, which may receive quantum corrections. Such corrections are parametrized as $\sigma \to \delta_{\rm QCD} \cdot \delta_{\rm QED} \cdot \sigma + r_{\rm nf}$ where $\delta_{\rm QCD} = 1 + \mathcal{O}(\alpha_s/\pi)$ and $\delta_{\rm QED} = 1 + \mathcal{O}(\alpha_{EM}/\pi)$ are factorizable QCD and QED corrections, whereas $r_{\rm nf}$ denotes non-factorizable corrections. In this paper we assume that $\delta^{\rm GHU}_{\rm QCD,QED} \simeq \delta^{\rm SM}_{\rm QCD,QED}$ and $r_{\rm nf}$ for both GHU and SM are small. We have taken only the first KK states into account. The second KK states are approximately twice as heavy as the first KK states. The magnitudes of couplings of the second KK states are at most a half of the couplings of the first KK states. Thus the contributions of the second KK states are expected to be small.

In the LEP1 experiment [15] at the Z-pole ($\sqrt{s} = M_Z$) the measured and fitted values of cross sections, forward–backward asymmetries of charged leptons $A^\ell_{\rm FB}$, $R^0_\ell \equiv \Gamma_{\rm hadrons}/\Gamma_\ell$ ($\ell = e, \mu$) and $R_b \equiv \Gamma_b/\Gamma_{\rm hadrons}$ are given by

$$\sigma^{\rm meas}(\bar{q}q)/\sigma^{\rm fit}(\bar{q}q) = 1.00149 \pm 0.00089, \tag{3}$$

$$A^{\ell\ \rm meas}_{\rm FB}/A^{\ell\ \rm fit}_{\rm FB} = 1.042 \pm 0.058, \tag{4}$$

$$R^{0,\ \rm meas}_\ell/R^{0,\ \rm fit}_\ell = 1.0012 \pm 0.0012, \tag{5}$$

$$A^{b\ \rm meas}_{\rm FB}/A^{b\ \rm fit}_{\rm FB} = 0.956 \pm 0.015, \tag{6}$$

$$R^{\rm meas}_b/R^{\rm fit}_b = 1.002 \pm 0.031, \tag{7}$$

where $\sigma^{\rm fit}(\bar{q}q) = 41.478$ nb, $A^{\ell\ \rm fit}_{\rm FB} = 0.01645$, $R^{0,\rm fit}_\ell = 20.742$, $A^{b\ \rm fit}_{\rm FB} = 0.1038$ and $R^{\rm fit}_b = 0.21579$. In GHU, we obtain

$$\sigma^{\rm GHU}(\bar{q}q)/\sigma^{\rm SM}(\bar{q}q) = 1.00143,\ 1.00098,\ 1.00073, \tag{8}$$

$$A^{\ell\ \rm GHU}_{\rm FB}/A^{\ell\ \rm SM}_{\rm FB} = 0.99571,\ 0.99668,\ 0.99780, \tag{9}$$

$$R^{0\rm GHU}_\ell/R^{0\rm SM}_\ell = 0.99984,\ 0.99989,\ 0.99992, \tag{10}$$

$$A^{b\ \rm GHU}_{\rm FB}/A^{b\ \rm SM}_{\rm FB} = 0.99769,\ 0.99832,\ 0.99887, \tag{11}$$

$$R^{\rm GHU}_b/R^{\rm SM}_b = 1.00019,\ 1.00016,\ 1.00014, \tag{12}$$

for $\theta_H = 0.115$, 0.0917 and 0.0737, respectively. For $\sqrt{s} = M_Z$, cross section is dominated by the Z boson resonance and effects of Z' are very small. Z-boson couplings are very close to the SM value so that the deviation of the cross sections from the SM is very tiny. No significant deviations are seen. In LEP1, the measured $A^b_{\rm FB}$ value deviates from the fit value at nearly 3σ level. In GHU, $A^b_{\rm FB}$ is close to the SM value.

In the LEP2 experiment, cross sections of $\bar{q}q$, $\mu^+\mu^-$ and $\tau^+\tau^-$ for twelve different collision energies $\sqrt{s}$ (130 GeV $\le \sqrt{s} \le 207$ GeV) were measured. For the energy 120 GeV $\lesssim \sqrt{s} \lesssim$ 207 GeV, $\sigma(\bar{q}q)$ is much larger than the cross sections for lepton final states. The average of $\sigma^{\rm exp}/\sigma^{\rm SM}(\bar{q}q)$ is 1.0092 ± 0.0076 [16]. In GHU, we obtain $\sigma^{\rm GHU}/\sigma^{\rm SM}(\bar{q}q) = 0.9975$, 0.9985 and 0.9993 at $\sqrt{s} = 130$ GeV, and 0.9882, 0.9923 and 0.9953 at $\sqrt{s} = 207$ GeV for $\theta_H = 0.115$, 0.0917 and 0.0737, respectively. Using the ratios $\sigma^{\rm exp}/\sigma^{\rm SM}$ we perform the χ^2-test for the $\sigma^{\rm model}/\sigma^{\rm SM}$. When $\sigma^{\rm model} = \sigma^{\rm SM}$, the χ^2-value is χ^2/d.o.f. = 7.3/12. In GHU ($\sigma^{\rm model} = \sigma^{\rm GHU}$), χ^2/d.o.f. = 14.4/12 (p-value is 28%) [11.2/7 (p-value is 13%)], 12.0/12 [8.9/7 (26%)] and 10.6/12 [7.6/7 (37%)]

[1] In the numerical evaluation in this letter we have used the values of the various couplings obtained for $m_H = 126$GeV. With $m_H = 125$GeV the value of $M_{Z'}$, for instance, decreases by 1.3%.