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Top Quark Properties in Little Higgs Models

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We study the shifts in the gauge couplings of the top quark induced in the Littlest Higgs model with and without T parity. We find that the ILC will be able to observe the shifts throughout the natural range of model parameters.

1. INTRODUCTION

Identifying the mechanism which breaks electroweak symmetry and generates fermion masses is one of the main physics goals for both the LHC and the ILC. Studies of the top quark have the potential to illuminate this issue; since it is the heaviest of the Standard Model (SM) fermions, the top is expected to couple strongly to the symmetry-breaking sector. Consequently, the structure of that sector can have significant, potentially observable effects on the properties of the top. For example, it is well known that the vector and axial $t\bar{t}Z$ form factors receive large corrections (of order 5-10%) in certain models of dynamical electroweak symmetry breaking [1]. At future colliders such as the LHC and the ILC, we will be able to pursue a program of precision top physics, similar to the program studying the Z at LEP and SLC. In this manuscript, we study the corrections to the top quark properties in "Little Higgs" models of electroweak symmetry breaking [2], and compare the expected deviations from the SM predictions with expected sensitivities of experiments at the LHC and the ILC.

In the Little Higgs models, electroweak symmetry is driven by the radiative effects from the top sector, including the SM-like top and its heavy counterpart, a TeV-scale "heavy top" T. Probing this structure experimentally is quite difficult. While the LHC should be able to discover the T quark, its potential for studying its couplings is limited [3, 4]. Direct production of the T will likely be beyond the kinematic reach of the ILC. However, we will show below that the corrections to the gauge couplings of the SM top, induced by its mixing with the T, will be observable at the ILC throughout the parameter range consistent with naturalness. Measuring these corrections will provide a unique window on the top sector of the Little Higgs.

Many Little Higgs models have been proposed in the literature. We will consider two examples in this study, the "Littlest Higgs" model [5], and its variation incorporating T parity [6].

2. THE LITTLEST HIGGS

As our first example, consider the $SU(5)/SO(5)$ Littlest Higgs (LH) model [5]. Since the original model turned out to be severely constrained by precision electroweak data [7], we focus on the version with a reduced gauge group, $SU(2) \times SU(2) \times U(1)$, which is significantly less constrained. We follow the conventions and notation of Ref. [3]. The new TeV-scale states are the gauge bosons $W_H^{\pm}, W_H^3$, a vector-like weak-singlet quark T (the "heavy top"), and a weak-triplet scalar field ϕ. The model is parametrized by the symmetry breaking scale f (assumed to be of order 1 TeV), the $SU(2)$ mixing angle ψ, the htT coupling constant λ_T, and the triplet vacuum expectation value (vev) v'.

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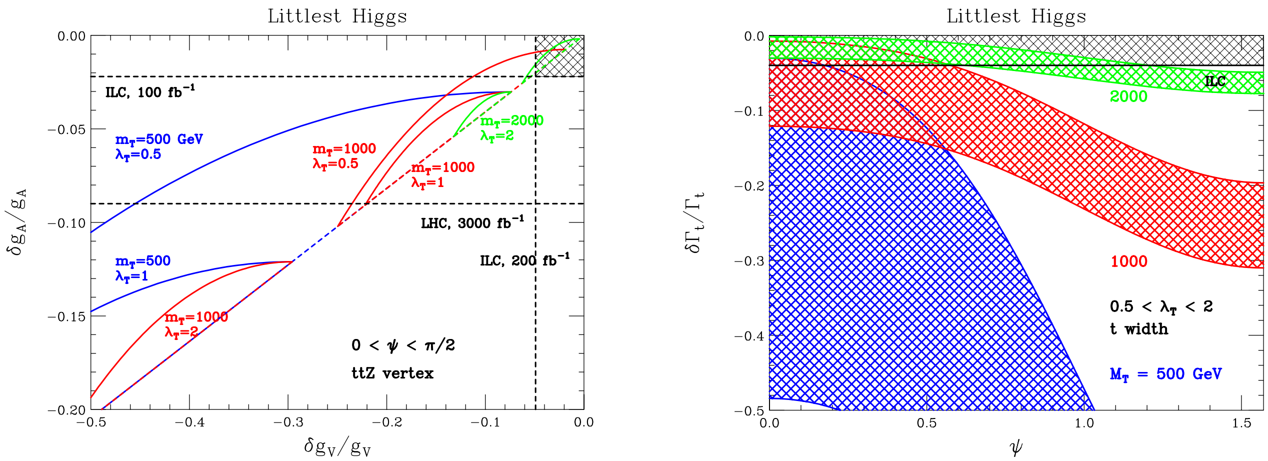

Figure 1: The corrections to the $t\bar{t}Z$ axial and vector couplings (left panel) and the top width Γ_t (right panel) in the $SU(5)/SO(5)$ Littlest Higgs model. The regions in which the ILC would observe no deviation from the SM are shaded.

It can be shown that $v' \sim v^2/f \ll v$, where $v = 246$ GeV is the SM Higgs vev. In this analysis, we will set $v' = 0$, since the effects of a non-vanishing v' on the observables considered here are numerically small. Instead of f, we will use the more physical quantity, the heavy top mass m_T, in our plots; these are related by $m_T/f = (\lambda_t^2 + \lambda_T^2)/\lambda_T$, where $\lambda_t \approx 1$ is the SM top Yukawa. Naturalness arguments put an upper bound on this parameter, $m_T \lesssim 2$ TeV.

Corrections to the gauge couplings of the top quark in the LH model arise from two sources: the mixing of the (left-handed) top with the heavy top T, and the mixing of the SM gauge bosons $W^\pm, Z^0$ with their heavy counterparts, $W_H^\pm$ and W_H^3. Using the superscripts “t” and “g” to denote the contributions from these two sources, the corrections to the $t\bar{t}Z$ coupling can be written as

$$\delta g_R^{Z\mathrm{t}} = 0, \qquad \delta g_R^{Z\mathrm{g}} = \frac{v^2}{4f^2}\frac{c_\psi^2 s_\psi^2}{c_W^2 - s_W^2} g_R^Z,$$
$$\delta g_L^{Z\mathrm{t}} = \frac{\lambda_T^2 v^2 g_A^Z}{m_T^2}, \qquad \delta g_L^{Z\mathrm{g}} = \frac{v^2}{4f^2}\left[2g_A^Z s_\psi^4 + g_R^Z \frac{c_\psi^2 s_\psi^2}{c_W^2 - s_W^2}\right]. \tag{1}$$

Here, $g_{L,R}^Z$ are the SM left- and right-handed $t\bar{t}Z$ couplings, $g_V^Z = (g_R^Z + g_L^Z)/2$ and $g_A^Z = (g_R^Z - g_L^Z)/2$ are their vector and axial combinations, c_W, s_W are respectively the cosine and sine of the weak mixing angle, and $s_\psi \equiv \sin\psi$, $c_\psi \equiv \cos\psi$. The predicted shifts in the $t\bar{t}Z$ axial and vector couplings for $m_T = 0.5, 1.0$, and 2.0 TeV, and $\lambda_T = 0.5, 1, 2$, are plotted in Fig. 1 (left panel), along with the experimental sensitivities expected at the LHC [8] and the ILC [1]. The mixing angle ψ is varied between 0 and $\pi/2$. Note that the shifts have a definite sign. While only a rather small part of the parameter space is accessible at the LHC even with 3000 fb^{-1} integrated luminosity, the ILC experiments will be able to easily observe the shifts in most of the parameter space preferred by naturalness considerations.

The corrections to the $t\bar{b}W$ coupling have the form

$$\delta g_R^{W\mathrm{t}} = 0, \qquad \delta g_R^{W\mathrm{g}} = 0,$$
$$\delta g_L^{W\mathrm{t}} = -\frac{1}{4}\frac{\lambda_T^2 v^2 g^W}{m_T^2}, \qquad \delta g_L^{W\mathrm{g}} = \frac{v^2}{4f^2} g^W s_\psi^2 \left(c_\psi^2 - s_\psi^2 - \frac{c_\psi^2 c_W^2}{c_W^2 - s_W^2}\right), \tag{2}$$

where g^W is the SM $t\bar{b}W$ coupling. These corrections induce a shift in the top width, $\delta\Gamma_t/\Gamma_t = 2\delta g_L^W/g^W$. The induced shift, as a function of the angle ψ, is plotted in the right panel of Fig. 1, where the parameter λ_T is varied between 0.5 and 2 for $m_T = 0.5, 1.0$ and 2.0 TeV. The accuracy of the top width measurement expected at the ILC [1] will allow to observe this effect in most of the natural parameter space.

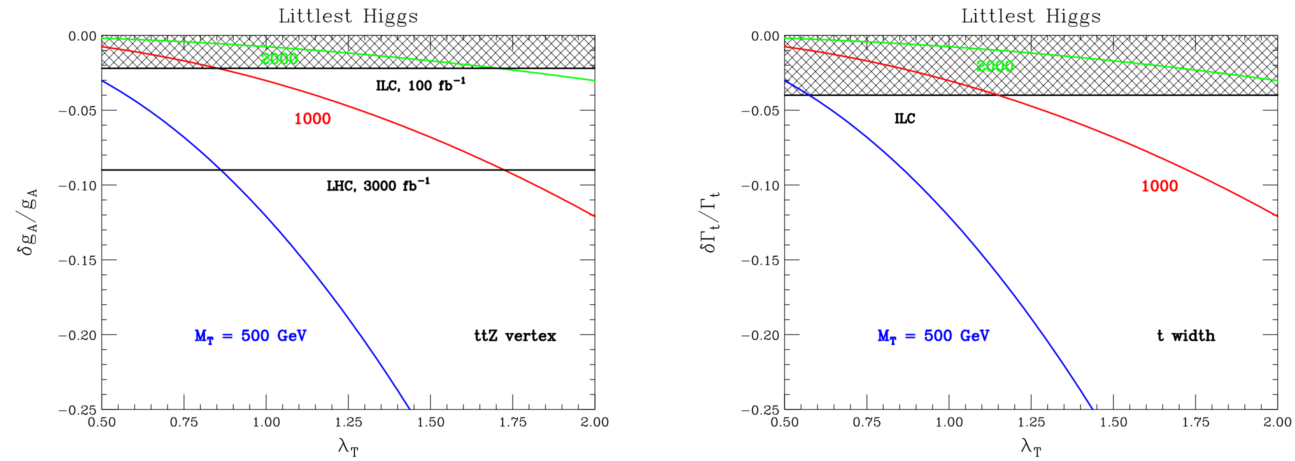

Figure 2: The corrections to the $t\bar{t}Z$ coupling (left panel) and the top quark width (right panel) in the $SU(5)/SO(5)$ Littlest Higgs model with T parity. The regions in which the ILC would observe no deviation from the SM are shaded.

3. LITTLEST HIGGS WITH T PARITY

The LH model can be extended to include a discrete symmetry, T parity [6], which greatly reduces the contributions to precision electroweak observables [9]. The main new feature in this model is the absence of the gauge boson mixing, since light and heavy gauge bosons have opposite charges under T parity. The top-heavy top mixing is still present, however. The resulting corrections to the $t\bar{t}Z$ and $t\bar{b}W$ vertices are identical to the corresponding shifts in the model without T parity, δg_L^{Zt} and δg_L^{Wt}, given in Eqs. (1) and (2). The shift in the axial $t\bar{t}Z$ coupling is plotted in the left panel of Fig. 2. (The shift in the vector coupling is identical up to a sign.) The correction to the top width is shown in the right panel of Fig. 2. Again, both effects should be observable at the ILC.

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