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Measurement of Littlest Higgs Model Parameters

J.A. Conley, J.L. Hewett, and M.P. Le
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

The effects of the extended gauge sector present in the Littlest Higgs model in the reactions $e^+e^- \to f\bar{f}$ and $e^+e^- \to Zh$ are examined. We find that the search reach at the 500 GeV ILC essentially covers the entire region where this model is relevant to the hierarchy proble and extends the reach of the LHC. In addition, we show that the ILC allows for an accurate determination of the model parameters, to the precision of a few percent, provided that the LHC measures the mass of the new heavy neutral gauge field.

Little Higgs models [1] feature the Higgs as a pseudo Nambu-Goldstone boson of an approximate global symmetry which is broken by a vev at a scale of a few TeV. The breaking is realized in such a way that the Higgs mass only receives quantum corrections at two loops. In contrast to supersymmetry, the one-loop contribution to the Higgs mass from a SM particle is canceled by a contribution from a new particle of the *same* spin. Little Higgs theories thus predict the existence of new top-like quarks, gauge bosons, and scalars near the TeV scale. Measurement of the couplings of these new particles would verify the structure of the cancelation of the Higgs mass quadratic divergences and prove the existence of the little Higgs mechanism.

The most economical little Higgs model is the so-called "Littlest Higgs" (LH) [1]. This scenario is based on a non-linear sigma model with an $SU(5)$ global symmetry, which is broken to the subgroup $SO(5)$ by a vev f. The natural scale for f is around a TeV; if f is much larger, the Higgs mass must again be finely tuned and this model no longer addresses the hierarchy problem. The $SU(5)$ contains a gauged subgroup $[SU(2) \times U(1)]^2$ which is broken by the vev to the SM electroweak group $[SU(2)_L \times U(1)_Y]$. The global $SU(5)$ breaking leaves 14 massless Goldstone bosons, four of which are eaten by the gauge bosons of the broken gauge groups, giving these gauge bosons a mass of order f. These new bosons correspond to two a heavy neutral bosons, Z_H and A_H, and two heavy charged bosons $W_H^\pm$.

Here, we are mainly concerned with the extended neutral gauge sector, which contains 3 new parameters: f and two mixing angles. Although we focus on the Littlest Higgs model, we note that an enlarged gauge sector with rather generic features is present in all little Higgs scenarios. After EWSB, the mass eigenstates are obtained via mixing

$$\begin{aligned} M^2_{A_L} &= 0, \quad M^2_{Z_L} = m_Z^2 \left[1 - \frac{v^2}{f^2}\left(\frac{1}{6} + \frac{1}{4}(c^2 - s^2)^2 + \frac{5}{4}(c'^2 - s'^2)^2\right) + 8\frac{v'^2}{v^2}\right], \\ M^2_{A_H} &= m_Z^2 s_w^2 \left[\frac{f^2}{5s'^2c'^2v^2} - 1 + \frac{v^2}{2f^2}\left(\frac{5(c'^2 - s'^2)^2}{2s_w^2} - x_H \frac{g}{g'}\frac{c'^2s^2 + c^2s'^2}{cc'ss'}\right)\right], \\ M^2_{Z_H} &= m_W^2 \left[\frac{f^2}{s^2c^2v^2} - 1 + \frac{v^2}{2f^2}\left(\frac{(c^2 - s^2)^2}{2c_w^2} + x_H \frac{g'}{g}\frac{c'^2s^2 + c^2s'^2}{cc'ss'}\right)\right], \end{aligned} \tag{1}$$

with x_H (which is numerically negligible) being given in [2]. The mixing angles

$$s = \frac{g_2}{\sqrt{g_1^2 + g_2^2}} \text{ and } s' = \frac{g'_2}{\sqrt{g_1'^2 + g_2'^2}} \tag{2}$$

relate the coupling strengths of the two copies of $[SU(2) \times U(1)]$. The couplings of the neutral gauge bosons Z_L, A_H, and Z_H to fermions and the light higgs similarly depend on s, s' and f:

$$\begin{aligned} g(A_Lf\bar{f}) &= g_{SM}(Af\bar{f}), \quad g(Z_Lf\bar{f}) = g_{SM}(Zf\bar{f})\left(1 + \frac{v^2}{f^2}a_i(s, s')\right), \quad g(A_Hf\bar{f}) = b_i\frac{g'}{2s'c'}\left(\frac{1}{5} - \frac{1}{2}c'^2\right), \\ g(Z_Hf\bar{f}) &= \pm\frac{gc}{4s}, \quad g(Z_{L\mu}Z_{L\nu}H) = g_{SM}(Z_\mu Z_\nu H)\left(1 + \frac{v^2}{f^2}a(s, s')\right), \end{aligned} \tag{3}$$

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$$g(Z_{L\mu}Z_{H\nu}H) \;=\; \frac{-i}{2}\frac{g^2}{c_W}v\frac{c^2-s^2}{2sc}g_{\mu\nu}, \quad g(Z_{L\mu}A_{H\nu}H) = \frac{-i}{2}\frac{gg'}{c_W}v\frac{c'^2-s'^2}{2s'c'}g_{\mu\nu},$$

where g_{SM} represents the relevant coupling in the SM, and $a(b)_i$ are $\mathcal{O}(1)$ where i labels the fermion species.

Equation 2 shows that for generic choices of s and s', $M_{A_H}/M_{Z_H} \simeq s_w m_Z/\sqrt{5}m_W \simeq 1/4$. This light A_H is responsible for the most stringent experimental constraints on the model [3]. As a result, phenomenologically viable variations of the Littlest Higgs models typically decouple the A_H by modifying the gauge structure of the theory. To gain some understanding of models in which the A_H decouples we take two approaches in our analysis: one is to choose a parameter value ($s' = \sqrt{3/5}$) for which the coupling of A_H to fermions vanishes. Another is to artificially take $M_{A_H} \to \infty$ while letting all other quantities in the theory take on their usual, parameter-dependent values. While not theoretically consistent, this approach gives us a more general picture of the behavior of models in which the A_H decouples.

We first examine the process $e^+e^- \to f\bar{f}$, where all of the LH neutral gauge bosons participate via s-channel exchange. We first study the constraints on the model from LEP II, taking as our observables the normalized, binned angular distribution and total cross section for $e^+e^- \to b\bar{b}\, c\bar{c}$ and $\ell\bar{\ell}$ with $l = e$, μ, or τ. We use $\sqrt{s} = 200$ GeV and an integrated luminosity of 627 pb^{-1}. For the detection efficiencies, we take $\epsilon_e = 97\%$, $\epsilon_\mu = 88\%$, $\epsilon_\tau = 49\%$, $\epsilon_b = 40\%$, and $\epsilon_c = 10\%$ [4]. For the ILC, in addition to the above mentioned observables, we also include the angular binned left-right asymmetry A_{LR} for each fermion pair. We use the energy $\sqrt{s} = 500$ GeV, an integrated luminosity of 500 fb^{-1}, and detection efficiencies of take $\epsilon_e = 97\%$, $\epsilon_{\mu,\tau} = 95\%$, $\epsilon_b = 60\%$, and $\epsilon_c = 35\%$ [5].

The exclusion region at LEP II (taking $s' = s/2$) and the 5σ search reach at the ILC for various values of s' are shown in Fig. 1. We find that the search region at $\sqrt{s} = 1$ TeV reaches to somewhat higher values of the parameter s, but has essentially the same reach for f as the 500 GeV results. The 5σ discovery contour for the Z_H at the LHC, as computed by an ATLAS based analysis [6], is included in the figure for comparison.

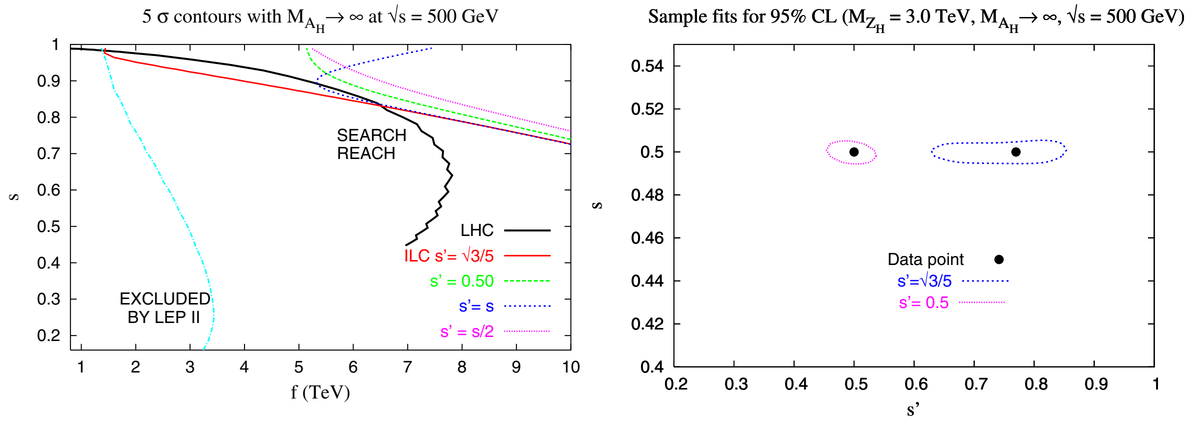

Figure 1: (left) LEP II exclusion region and ILC 5σ search reach in the $s - f$ parameter plane for various values of s'. The LHC result [6] is included for comparison. (right) 95% CL sample fits to the data points ($s = 0.5$, $s' = 0.5$) and ($s = 0.5$, $s' = \sqrt{3/5}$), at a 500 GeV ILC, taking $M_{Z_H} = 3.0$ TeV.

We have now determined the available parameter space accessible to the ILC and not already excluded by LEP II. It remains to ask, given the existence of an LH model with parameters in this accessible range, how accurately would the ILC be able to measure them? To answer this we perform some sample fits employing a χ-square analysis. We use the same set of observables as before, and now take M_{Z_H}, s, and s' as our free parameters. We choose a generic data point (s, s', M_{Z_H}) and use it to calculate the observables, which we then fluctuate according to statistical error. We assume that the Large Hadron Collider would have determined M_{Z_H} relatively well, to the order of a few percent for $M_{Z_H} < 5 - 6$ TeV; we thus fix M_{Z_H} and perform a 2-variable fit to s and s'. Figure 1 shows the results of this fit for two sample data points. For both cases, the determination of s is very accurate, due to the strong dependence of the $Z_H f\bar{f}$ couplings on this parameter.

In order to confirm that the LH model is the correct description of TeV-scale physics, it is important to measure the new particle couplings to the Higgs. Here we are concerned with the coupling of the Z_H to the Higgs boson, which can be tested via the process $e^+e^- \to Z_L h$. In the LH model, in this process from SM expectations arise from three sources: Z_H and A_H exchange in the s-channel and the deviation of the $Z_L Z_L h$ coupling from its SM value.

We then repeat our analysis using the process $e^+e^- \to Z_L h$ and taking the total cross section as our observable with $m_h = 120$ GeV. We assume that at a $\sqrt{s} = 500$ GeV ILC this cross section will be measured to an accuracy of 1.5% [5]. A χ-squared analysis is carried out as before and our results for the ILC search reach in the LH parameter space are displayed in Fig. 2.

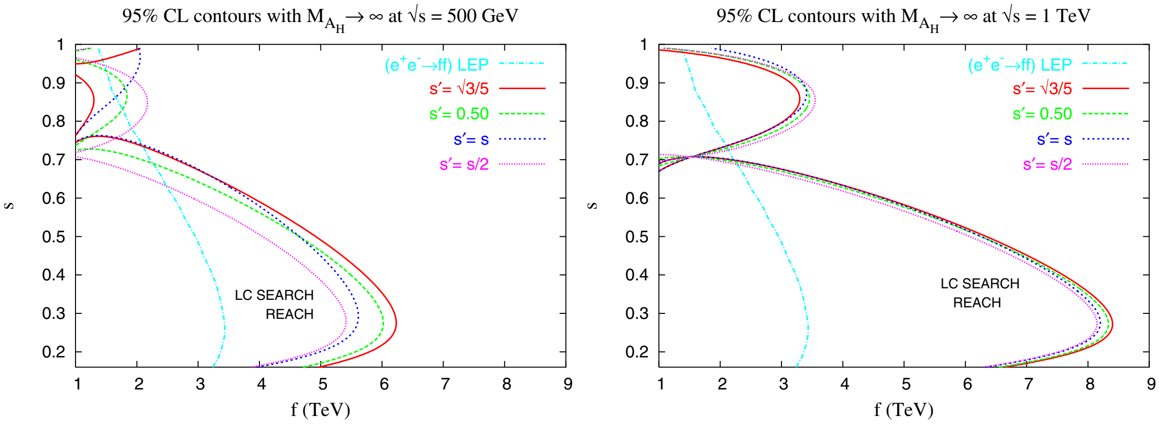

Figure 2: The ILC 95% CL search reach in the $s - f$ parameter plane from the process $e^+e^- \to Z_L h$ for various values of s', taking $\sqrt{s} = 500$ GeV, and 1 TeV in the right, left panel, respectively. The LEP II exclusion region from $e^+e^- \to f\bar{f}$ is shown for comparison.

In summary, we find that the reaction $e^+e^- \to f\bar{f}$ at a $\sqrt{s} = 500\ GeV$ ILC is sensitive to essentially the entire parameter region where the Littlest Higgs model is relevant to the gauge hierarchy problem. It also provides an accurate determination of the fundamental model parameters, to the precision of a few percent, provided that the LHC measures the mass of the heavy neutral gauge field. Additionally, we verified that the couplings of the extra gauge bosons to the light Higgs can be observed from the process $e^+e^- \to Zh$ for a significant region of the parameter space. Further details of our analysis can be found in [7].

0.1. Acknowledgments

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