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A heavy little Higgs and a light Z' under the radar

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Abstract

The original littlest Higgs model with universal fermion couplings is found to be consistent with precision electroweak data but is strongly constrained by Tevatron limits on the predicted centi-weak Z' boson. A possible signal observed by CDF at 240 GeV is consistent with the predicted Z', and a region below 150 GeV is largely unconstrained by collider data.

<u>Introduction:</u> Little Higgs models address the fine tuning problem posed by quadratically divergent one loop corrections to the Higgs boson mass in the SM (Standard Model) by identifying the Higgs as a pseudo-Nambu-Goldstone boson which only acquires a cutoff sensitive mass at two loop order. Pioneering studies of the original $SU(5)/SO(5)$ littlest Higgs model[1] found that constraints from precision EW (electroweak) data[2, 3, 4, 5] and collider limits on the predicted Z' boson[6] force the model into a region where fine-tuning re-emerges, engendering many variants of the original model.[7] Here we present EW fits of the original model that are consistent with the precision data and in which the Higgs mass is not fine-tuned. Good fits, with χ^2 values two to three units below the SM fit and fine tuning above 10% (and often of order one), occur for values of the $SU(5)$ breaking condensate f between 0.5 and 3 TeV. The best of these fits prefer $f \simeq 1 \pm 0.5$ TeV, as orginally envisioned in [1], while unexpectedly favoring large values of the Higgs boson mass, from $\sim 0.3 - 1$ TeV.

A signature prediction of the fits is a light Z' boson, below $\simeq$ 500 GeV and possibly as light as O(100) GeV, with centi-weak coupling to quarks and leptons. CDF[8] and D0[9] limits currently provide the strongest constraints, excluding much of the region allowed by the EW fits. An excess at 240 GeV in the e^+e^- mass spectrum observed by CDF[8] is consistent with the Z' predicted by the EW fits. The excess is nominally 3.8σ, with 0.6% probability (2.5σ) to be due to a chance fluctuation anywhere in the 150-1000 GeV mass range. If confirmed as a Z' boson, it would correspond in the LH (littlest Higgs) model to a symmetry breaking scale $f \simeq 1.5$ TeV. The CDF and D0 studies have comparable sensitivity, since D0 considered a larger data sample while CDF had a larger acceptance, and the CDF excess is outside the D0 allowed region. Future Tevatron and LHC data will determine if the excess is a fluctuation or a real signal. The model can be tuned to suppress Z' production arbitrarily, but without a physical basis from the UV completion it would be strongly disfavored unless a signal emerges at or near the present limits.

Following [3] we assume universal fermion charge assignments for the two $U(1)$ gauge groups embedded in the global $SO(5)$: the first two SM families have the same $U(1)_i$ charges as the third family, fixed by gauge invariance of the top quark Yukawa interaction specifed in the original model[1] and the absence of mixed $SU(2)_L - U(1)_i$ anomalies. The results differ from earlier studies[3, 5] chiefly because the EW fits are performed with complete scans of both the SM and LH parameters. Earlier studies fixed the SM parameters at their SM best fit values and/or did not scan on all LH parameters. We find that the LH best fit typically occurs at different values of the SM parameters than the SM best fit, and that important cancellations emerge if all LH parameters are scanned. Current data is more restrictive than the data used in earlier studies — in addition to more precise measurements of the top and W masses, low energy data[10, 11] and Tevatron limits on Z' production now impose stronger constraints. ZFITTER[12] is used for the SM corrections, and experimental correlations are included.[13]

Electroweak Fits: The global $SU(5)$ contains a gauged $SU(2)_1 \times SU(2)_2 \times U(1)_1 \times U(1)_2$ subgroup with coupling constants g_1, g_2, g_1', g_2'. The breaking to $SO(5)$ with condensate f gives masses to a combination of the $SU(2)_i$ and $U(1)_i$ gauge bosons, while the orthogonal $SU(2) \times U(1)$ is subsequently broken by a doublet Higgs boson vev (vacuum expectation value), $v = 247$ GeV, induced by the one loop effective potential. Detailed descriptions are given in [1] and [2]. For the EW fit the salient features are (1) changes in Z boson interactions from $Z - Z'$ mixing and (2) custodial $SU(2)$ breaking from a triplet Higgs boson vev, from the shift in m_Z due to $Z - Z'$ mixing, and from mixing between the left chirality t_L quark and its t_L' partner. We scan the usual SM parameters, $\Delta\alpha^{(5)}$, α_S, m_t, and m_H, and the LH parameters which affect the fit: the triplet Higgs vev, v', the sine of the $t_L - t_L'$ mixing angle, s_L, and the cosines of the $SU(2)_i$ and $U(1)_i$ mixing angles, c and c', related to the SM EW couplings by $g = sg_1 = cg_2$ and $g' = s'g_1' = c'g_2'$. The universal fermion $U(1)$ charge assignments are $y_1 = (2/5)y_{SM}$ and $y_2 = (3/5)y_{SM}$.[3] The correction to the Z coupling for fermion f with SM coupling $g_f = t_{3f} - s_W^2 q_f$ is then

$$\delta g_f = \frac{v^2}{2f^2}\left\{t_{3f}\left[c^2(1-2c^2) + 5(c'^2 - \eta')(1-2c'^2)\right] - 5q_f(c'^2 - \eta')(1-2c'^2)\right\} \tag{1}$$

where t_{3f} and q_f are the weak isospin and charge of fermion f, $s_W^2 = \sin^2\theta_W$, and $\eta' = 2/5$ follows from the universal charge assignment. Corrections to the low energy parameters are

$$s_*^2(0) = s_W^2\left\{1 - \frac{v^2}{2f^2}\left[c^2 + 5(c'^2 - \eta')(1-2\eta')\left(1 - \frac{1}{s_W^2}\right)\right]\right\} \tag{2}$$

and

$$\delta\rho_* = \frac{5}{4}\frac{v^2}{f^2}(1-2\eta')^2 - 4\frac{v'^2}{v^2} \tag{3}$$

These results are consistent with [2, 3].[1]

The fits are performed subject to three conditions. First, requiring $|v'| < |v^2/4f|$ ensures positivity of the triplet Higgs mass. Second, since the coefficient a of the quadratically divergent term in the one loop gauge boson effective potential is expected to be of order one, we require $1/5 < a < 5$, where a is determined by[2]

$$a = \frac{m_H^2}{4m_Z^2}\,\frac{c^2c'^2}{s_W^2c^2 + c_W^2c'^2}\,\frac{1}{1 + |4v'f/v^2|}. \tag{4}$$

Third, fine tuning of the Higgs mass should be no less than 10%,

$$\delta_{FT} = \frac{m_H^2}{(3m_t^2m_t'^2/2\pi^2v^2)\ln(4\pi f/m_{t'})} > 0.1 \tag{5}$$

[1]Sign errors in eq. (3.10) of [2] do not propagate to the the appendix of [2] which we have verified.

[2]The potential eq. (4.16) of [2] reverses $g_1 \leftrightarrow g_2$ and $g_1' \leftrightarrow g_2'$ relative to eq.(4.7) of [1]; we follow [1].

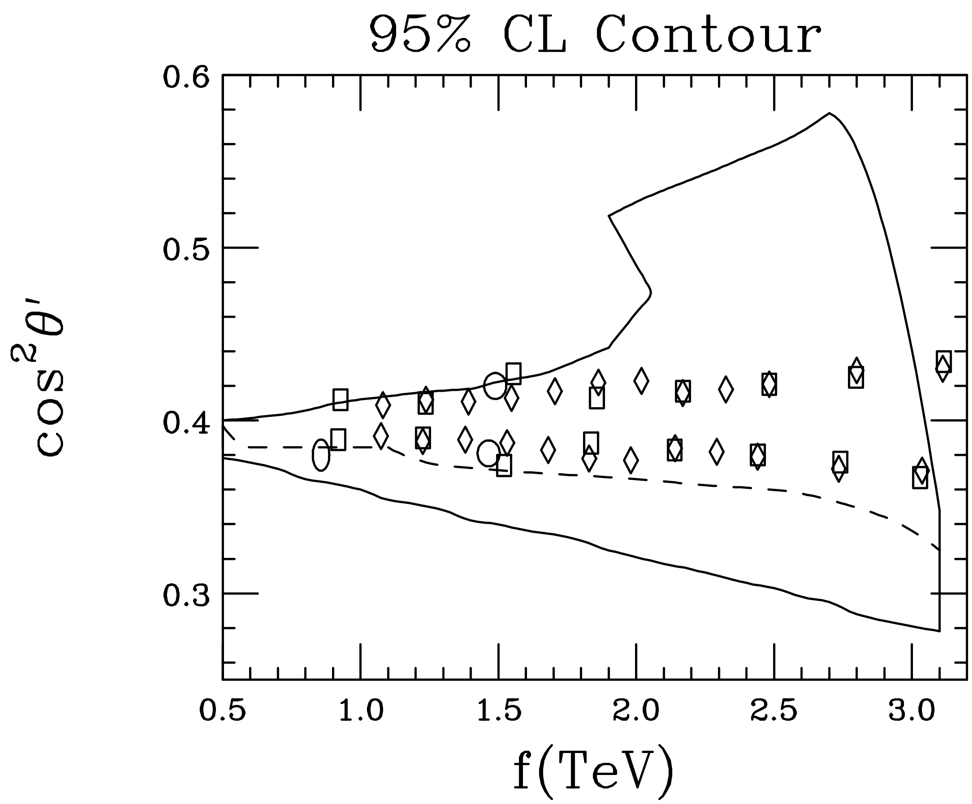

Figure 1: 95% CL contour for EW fits satisfying boundary conditions. The dashed line marks the best fit. Diamonds and boxes are from D0 and CDF limits on Z' production, the two circles correspond to the CDF excess at 240 GeV, and the ellipse represents an example below the Tevatron search region.

where $m_{t'}^2 = m_t^2 f/(s_L v - s_L^2 f)$. Following [2, 3] we also restrict θ and θ' to $s, c, s', c' \geq 0.1$ to keep the gauge coupling constants from becoming unreasonably large.

The 95% CL contour in the $f - c'$ plane is shown in figure 1. The dashed line is the trajectory of the best fit. The global best fit is at $f = 1$ TeV with $\chi^2 = 15.5$ (three units below the best SM fit with $\chi^2 = 18.6$), with m_H from $\simeq 600$ to 800 GeV and δ_{FT} from 0.34 to 1.4. This is as good as it gets for any model that does not explicitly address the 3.2σ A_{LR} - A_{FB}^b discrepancy, since all other data agrees as well or better than chance with the SM.[14] The 95% contour is defined relative to the LH best fit ($\Delta\chi^2 = 5.99$ for 2 degrees of freedom), a more restrictive criterion than the earlier studies. For instance, in [3] the 95% limit was defined by $\Delta\chi^2 = 8$ relative to the SM best fit and $f = 1$ TeV was found to be at the 95% limit, which translates to 11 χ^2 units above our best fit at $f = 1$ TeV. The lower χ^2 is the result of scanning on the SM parameters and s_L as well as c, c', and v'.

The narrowing of the contour below 2 TeV is due to more precise low energy data from atomic parity violation[10] and Möller scattering[11], not available to the earlier studies. The dominant $U(1)$ correction to δg_f is suppressed both at $c'^2 = 2/5$ and $c'^2 = 1/2$ but only at $c'^2 = 2/5$ for $s_*^2(0)$. The low energy measurements then exclude $c'^2 \simeq 1/2$ below but not above 2 TeV, because they are less precise than the Z-pole data so that their relative effect diminishes at large f. If the low energy data is omitted, the upper limit on c'^2 also increases to $\sim 1/2$ at $f \simeq 1$ TeV.

The χ^2 minimum is quite shallow as a function of f and m_H. It varies by no more than 1.2 χ^2 units between $f = 0.5$ and 3 TeV, with the upper limit set by the fine tuning requirement. For the global best fit, at $f = 1$ TeV and $m_H = 600$ GeV, the χ^2 varies by ≤ 0.9 for m_H betweem 325 GeV and 1 TeV, with the lower limit again set by δ_{FT}.

The Centi-Weak Z' Boson: A characteristic prediction emerging from the fits is a light, narrow Z' boson, between ~ 100 and 500 GeV, with a suppressed coupling to SM quarks and leptons that reduces the effect of $Z - Z'$ mixing. The mass and coupling strength are

$$m_{Z'} = \frac{s_W}{\sqrt{5} s' c'} \frac{f}{v} m_Z, \tag{6}$$

$$r_{Z'} \equiv \frac{g_{Z'}}{g_Z} = \frac{s_W (c'^2 - \eta')}{s' c'}, \tag{7}$$

where $\mathcal{L}_{Z'ff} = g_{Z'} \overline{f} y_f \not{Z}' f$ with $y_f = q_f - t_{3f}$. Measurements of $m_{Z'}$ and $g_{Z'}$ then determine f and θ' up to a twofold ambiguity. Collider limits on Z' production further constrain the parameter space, while a Z' discovery would enable more detailed tests of the model.

The boxes (CDF[8]) and triangles (D0[9]) in figure 1 represent 95% CL limits on narrow Z' boson production. For each Z' mass the upper limit on $\sigma_{Z'} BR(e^+e^-)$ implies an upper limit on $r_{Z'}$ that implies the upper and lower limits on c'^2 shown in the figure.[3] The limits are strong because a Z' coupled to hypercharge has a large (15%) e^+e^- branching ratio.

Using the CDF excess at 240 GeV to illustrate a possible signal, we estimate $\sigma BR(e^+e^-) \simeq$ 42 fb from the data.[4] For the LH Z' we have $\sigma BR(e^+e^-) = 122\, r_{Z'}^2$ pb, which implies $r_{Z'} = 0.019$. Equations (6-7) then have two solutions for f and c'^2, plotted as circles in figure 1, at (1.47 TeV, 0.38) and (1.49 TeV, 0.42). The latter is at the edge of the 95% contour, while the former, with $\chi^2 = 16.0$, is only 0.5 χ^2 units above the global minimum and 2.6 units below the SM best fit. A fit with these parameters is compared with the SM best fit in table 1. Because the Higgs triplet and the top partner both effect the fit predominantly

[3]Collider cross sections are computed with Madgraph v4[15] with K-factor $K = 1.3$.

[4]The quoted net signal efficiency[8] at $m_{e^+e^-} = 150$ GeV is $\epsilon_{\rm TOT} = 0.27$. The net efficiency at 240 GeV increases in proportion to the acceptance of the CDF fiducial region, to $\epsilon_{\rm TOT} = 0.32$, since trigger and other instrumental efficiencies for electrons in the fiducial region vary slowly between 150 and 240 GeV. Taking the interval $m_{e^+e^-} = 240\,{\rm GeV} \pm 2\sigma_{m_{e^+e^-}}$ where the CDF resolution at 240 GeV is $\sigma_{m_{e^+e^-}} = 5.4$ GeV, we find 32 signal and 70 background events from figure 1 of [8], reproducing the quoted 3.8σ nominal signficance. The total signal cross section for 2.5 fb^{-1} is then $\simeq 42$ fb.

via the oblique parameter T, the fit sees v' and s_L as a single parameter.[5] Together with the $SU(2)$ mixing angle c the LH fit then has two more parameters than the SM fit, and the χ^2 confidence level, CL$(16.0, 11) = 0.14$, is comparable to the SM, CL$(18.6, 13) = 0.14$. The fine-tuning condition is robustly satisfied, $\delta_{\rm FT} = 0.9$, and the coefficient of the effective potential is $a = 0.6$. The masses of the Higgs boson, top partner, triplet Higgs and W' are respectively 0.82, 2.1, 6.9 and 3.0 TeV. Since the χ^2 minimum is quite flat, discovery of a centi-weak Z' will not determine the masses of the other particles in the model, but the fit would then imply relationships between the masses and other parameters that can be tested.

In the allowed region c' and $r_{Z'}$ are related by $|c'^2 - 2/5| \simeq |r_{Z'}|$. Future Tevatron and LHC data can determine if the excess at 240 GeV is a real signal or, if not, can tighten the limits on c'^2 to the point of implausibility, unless it can be physically motivated by a UV completion of the model. Current CDF and D0 limits on $|r_{Z'}|$ range from $\simeq 0.01$ to $\simeq 0.04$ for $m_{Z'}$ from 150 to 500 GeV. The limit scales with the integrated luminosity like $L^{-\frac{1}{4}}$. With $L = 10$ fb^{-1} the CDF and D0 limits could tighten by 30% and 15% respectively, and it should be possible to vet the nominal 3.8σ CDF signal at 240 GeV.

To illustrate the sensitivity of the LHC we consider $m_{Z'} = 240$ GeV. We require $p_T > 25$ GeV and $|\eta| < 2.4$ for e^+ and e^-, and assume 65% efficiency within the fiducial region, as aready achieved by ATLAS in an early study of the Z boson[16]. The e^+e^- fractional mass resolution, $\hat{\sigma}_m = \sigma_m/m$, is parameterized by $d_m = \hat{\sigma}_m/0.02$, since $\hat{\sigma}_m \simeq 2\%$ for CDF at 240 GeV, a figure that will eventually be surpassed by ATLAS and CMS. The signal region is defined as $m_{Z'} \pm 2\,\sigma_m$. At $\sqrt{s} = 7$ TeV the CDF 3.8σ excess would then have a significance of $5.6\sigma \cdot \sqrt{(L/d_m)}$ with L expressed in fb^{-1}. For $\sqrt{s} = 7$ TeV and $L = d_m = 1$ the expected 95% CL exclusion limit is $r_{Z'} < 0.012$, and for $\sqrt{s} = 13$ TeV with $L = 100$ and $d_m = 1/2$ it is $r_{Z'} < 0.0026$.

The Tevatron Z' limits constrain the model for $m_{Z'} \geq 150$ GeV, corresponding to $f \gtrsim 920$ GeV, but the region within the 95% EW contour below 900 GeV is largely unconstrained. Excellent EW fits exist down to $f = 500$ GeV, corresponding to $m_{Z'} = 85$ GeV, although the expansion in v^2/f^2 and the leading order treatment of $Z - Z'$ mixing used here and in the earlier studies may be unreliable at such low values. Comparing the approximate results with a calculation to all orders in v^2/f^2 and with exact diagonalization of the $Z - Z'$ mass matrix, we find that the corrections are reliable at the O(10%) level for $f \gtrsim 1$ TeV, as expected for an expansion in v^2/f^2.[6] Small errors due to the approximations will cause small shifts in the values of the parameters at which the best fits occur but do not significantly alter the confidence levels. A separate analysis of the very low f region will be presented elsewhere.

[5]However we must vary v' and s_L separately to verify the boundary conditions, equations (4-5).

[6]The approximate treatment of $Z - Z'$ mixing is acceptable even for $m_{Z'} = 150$ GeV, because the factor $c'^2 - \eta' \simeq 1/5$ in the off-diagonal matrix element offsets the dangerous factor 1/5 in $m_{Z'}^2$ (see equation (6)).

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	Experiment	**SM**	Pull	**LH**	Pull
A_{LR}	0.1513 (21)	0.1480	1.6	0.1477	1.7
A^l_{FB}	0.01714 (95)	0.01644	0.7	0.01639	0.8
$A_{e,\tau}$	0.1465 (33)	0.1480	-0.5	0.1477	-0.4
A^b_{FB}	0.0992 (16)	0.1038	-2.9	0.1036	-2.7
A^c_{FB}	0.0707 (35)	0.0742	-1.0	0.0740	-1.0
Γ_Z	2495.2 (23)	2495.7	-0.2	2496.3	-0.5
R_ℓ	20.767 (25)	20.739	1.1	20.739	1.1
σ_h	41.540 (37)	41.481	1.6	41.480	1.6
R_b	0.21629 (66)	0.21582	0.7	0.21564	1.0
R_c	0.1721 (30)	0.1722	-0.04	0.1723	-0.07
A_b	0.923 (20)	0.935	-0.6	0.935	-0.6
A_c	0.670 (27)	0.668	0.07	0.668	0.08
m_W	80.399 (23)	80.378	0.9	80.392	0.3
A_{PV}	$-131\,(17)\cdot 10^{-9}$	$-156\cdot 10^{-9}$	1.4	$-136\cdot 10^{-9}$	0.3
$Q_W(Cs)$	-73.16 (.35)	-73.14	-0.06	-73.30	0.4
$\Delta\alpha^{(5)}(m_Z)$	0.02758 (35)	0.02768	-0.3	0.2761	-0.09
m_t	173.3 (1.1)	173.3	0.02	173.3	0.02
$\alpha_S(m_Z)$		0.1180		0.1192	
m_H		89		820	
c				0.16	
v' (GeV)				4.2	
s_L				0.0124	
χ^2/dof		18.6/13		16.0/11	
CL(χ^2)		0.135		0.140	
m_H[90%] (Gev)		51 — 152		270 — 1000	
CL(m_H > 114 GeV)		0.24		1	

Table 1: The SM best fit and an LH model fit with $f, c'^2 = 1.47\,\text{TeV}, 0.38$ corresponding to the CDF excess at 240 GeV.

The region $m_{Z'} < 150$ GeV is not strongly constrained because LEPII ran sparsely below 150 GeV, accumulating $3\,\mathrm{pb}^{-1}$ samples at 130 and 136 GeV. For instance, a 140 GeV Z' with $r_{Z'} = 0.02$ corresponding to $f \simeq 860$ GeV and $c'^2 = 0.38$ (marked by the ellipse in figure 1) yields a good EW fit, with $CL(15.6, 11) = 0.16$ compared to the SM fit with $CL(18.6, 13) = 0.14$, and would only shift $\sigma(e^+e^- \to \mu^+\mu^-)$ at 136 GeV by 0.22 fb, well below the 0.67 fb experimental uncertainty.[17] Even at the 95% limit of the EW fit, $c'^2 = 0.365$, the effect is only as big as the experimental uncertainty. The region $f < 900$ GeV within the 95% EW contour is then largely unconstrained by Z' production limits.

Discussion: The LH model can also resolve the conflict with the direct limit on the Higgs mass that arises in the SM fit if the 3.2σ discrepancy between the hadronic and leptonic measurements of $\sin^2\theta_W$ (dominated by A_{LR} and A^b_{FB}) is attributed to underestimated systematic uncertainties in the hadronic asymmetry measurements.[14] The model then provides robust fits of the EW data with CL $\simeq$ 80% (compared to CL $\simeq$ 70% for the SM) while raising m_H well into the allowed region above 114 GeV.

A narrow Z' coupled to hypercharge is also generic in hidden sector models with a $U(1)$ gauge boson,[18] which could have couplings to quarks and leptons of centi-weak strength or less. The fits of the precision EW data suggest that the Z' of the LH model should have centi-weak coupling strength and should emerge at or near the current Tevatron limits, perhaps with a signal resembling the CDF excess at 240 GeV. If no signal is seen, upper limits from the LHC would force the model into an extremely fine-tuned domain unless it can be shown to result naturally from a UV completion. In addition to tightening the existing Tevatron limits for $150 < m_{Z'} < 500$ GeV, searches should be extended as far as possible to Z' masses below 150 GeV, for which there are also excellent fits of the EW data.

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