Signatures of Extra Dimensions from Upsilon Decays with a Light Gaugophobic Higgs Boson

Jamison Galloway,1 Bob McElrath,2 and John McRaven1

1Department of Physics, University of California, Davis, CA 95616
2CERN, Geneva 23, Switzerland

(Dated: July 16, 2008)

We explore non-standard Higgs phenomenology in the Gaugophobic Higgs model in which the Higgs can be lighter than the usually quoted current experimental bound. The Higgs propagates in the bulk of a 5D space-time and Electroweak Symmetry Breaking occurs by a combination of boundary conditions in the extra dimension and an elementary Higgs. The Higgs can thus have a significantly suppressed coupling to the other Standard Model fields. A large enough suppression can be found to escape all limits and allow for a Higgs of any mass, which would be associated with the discovery of $W'$ and $Z'$ Kaluza-Klein resonances at the LHC. The Higgs can be precisely discovered at B-factories while the LHC would be insensitive to it due to high backgrounds. In this letter we study the Higgs discovery mode in $\Upsilon(3S)$, $\Upsilon(2S)$, and $\Upsilon(1S)$ decays, and the model parameter space that will be probed by BaBar, Belle, and CLEO data. In the absence of an early discovery of a heavy Higgs at the LHC, A Super-B factory would be an excellent option to further probe this region.

INTRODUCTION

If electroweak symmetry breaking in the Standard Model (SM) arises solely from the presence of a fundamental scalar, the scale of the electroweak interactions requires a severe fine-tuning. The economy of the Higgs mechanism thus comes at the cost of making the SM unnatural. Technicolor models aim to ameliorate this instability by considering the Higgs as a composite state; however, these simplest models are ruled out by their large oblique corrections. A new approach to a composite Higgs is provided by the AdS/CFT correspondence, in particular as represented by Randall-Sundrum (RS1)-type setups. Typically the Higgs has been confined to a particular brane in the 5D picture, thus corresponding to a 4D state of infinite scaling dimension. This, however, is more than is necessary to avoid issues of extreme fine-tuning. Even if the Higgs is localized somewhere near the IR brane of RS1, the corresponding 4D state is interpreted as a composite and can be light with tuning at only the percent level. This particular relaxation of the usual assumptions is the salient feature of the Gaugophobic Higgs model; we consider below (see also for other treatments of a 5D Higgs). The crucial aspect of this model that we exploit is that the Higgs can be made light (e.g. $m_H < 10$ GeV) while simultaneously suppressing its couplings to fermions and weak gauge bosons, such that current experimental constraints are evaded.

THE GAUGEPHOBIC HIGGS MODEL

The Gaugophobic model is described in; here we review only the features important for Higgs production at B-factories. As in RS1, we have a slice of AdS$_5$ with a conformally flat metric (taking $z$ to denote the coordinate of the extra spatial dimension):

$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2).$$

$R$ corresponds to the position of the UV brane and sets the curvature scale of the extra dimension. The second boundary is at $z = R'$ with $R' \gg R$ generating the weak-Planck hierarchy due to the warp factor. $R$ is a free parameter, while $R'$ is set by the masses of the weak gauge bosons. The bulk gauge group $SU(2)_L \times SU(2)_R \times U(1)_X$ is broken to $U(1)_{EM}$ by boundary conditions and a bi-fundamental Higgs with zero $X$ charge. With the Higgs taken to be a bulk field, we choose the three parameters $\beta, m_H, V$ to describe it. In our analysis we parameterize the effect of the Higgs bulk mass $\mu$ by $\beta \equiv \sqrt{4 + \mu^2}$. Conventional RS1 is described by the limit $\beta \to \infty$.

The profile of the vacuum expectation value (VEV) is controlled by UV brane boundary conditions to be

$$v(z) = \sqrt{\frac{2(1 + \beta) \log R'/R \ g V R'}{1 - (R/R')^{2(1+\beta)}}} \ \frac{g_5}{R} \left(\frac{z}{R'}\right)^{2+\beta},$$

where $g$ is the SM $SU(2)$ gauge coupling, and $g_5$ is the 5-dimensional $SU(2)_{L/R}$ gauge coupling. The normalization $V$ of the VEV is chosen such that the SM is recovered as one takes $V \to 246$ GeV: in this limit the gauge boson profiles are flat, with all mass coming from direct overlap with the Higgs. Conversely, in the limit $V \to \infty$ the profiles of the gauge bosons are pushed towards the UV (away from the IR-localized VEV) so that their mass comes entirely from momentum in the fifth dimension. This corresponds to the Higgsless limit; in this case the Kaluza-Klein (KK) scale is lowered, so that the appearance of the weakly-coupled KK states fulfill...
the Higgs boson’s additional role of restoring unitarity in $WW$-scattering.

The other ingredient that establishes the profile (2) is the Higgs quartic coupling $\lambda$, which is confined to the IR brane to ensure that electroweak symmetry breaking takes place there. We trade this parameter for the mass $m_H$ of the physical Higgs mode via the effective potential’s minimization condition, in the same way as in the SM. The couplings between the Higgs and other states is provided by the overlap of the corresponding 5D profiles, so field localization governs interaction strength.

The light fermions in the model are arranged in doublets of the bulk gauge group. The 5D fermions must be vector-like due to the nature of the 5D realization of the Dirac algebra, so that bulk mass terms are allowed for them and will dictate their localization. They each have dimensionless bulk masses $c_L$ and $c_R$ for the left- and right-handed pieces as well as a UV kinetic term to split the masses within a given multiplet. The inclusion of the third quark generation requires more care, however, since the heavy top quark requires a large overlap with the Higgs VEV. With the top and bottom arranged together in doublets, this would lead to an unacceptable deviation in the $Z\bar{b}_Lb_L$ coupling. We choose to solve this problem as in [6] where non-universal corrections to the $Z$-couplings are avoided by representing the left-handed bottom quark in a bi-doublet of the bulk $SU(2)_L \times SU(2)_R$. The total field content of the third generation thus contains the new fields $T$ and $X$, where the quantum numbers of the $T$ allow it to mix with $t$. The new exotic quark $X$ has electric charge $5/3$ so won’t mix with the other fields. The lowest lying $X$ state enters at $m_X \sim 1$ TeV.

PARAMETER SPACE AND CONSTRAINTS

The Gaugephobic model is described by the five parameters shown in Table I with the ranges we considered. In Fig. 1 we scan over the parameter space imposing the constraints in this section. We find that all of the Higgs couplings are suppressed in this model.

![Figure 1](image-url)

**FIG. 1:** $\xi^2$ vs. $V$. As $V \to 246$ GeV from above the SM is approached, i.e. $g_{HZZ} \to g_{H^{SM}ZZ}$ while as $V$ is increased the gauge bosons decouple from the Higgs.

**TABLE I:** Range of the scanned parameter space with the AdS scale set by $R^{-1} = 10^8$ GeV. The range of $\beta$ is chosen to localize the Higgs VEV towards the IR brane, while the range of $V$ is chosen to interpolate between the SM and “almost Higgsless” limits. The bulk mass for the left- and right-handed bottom quark are constrained by the required precision of their coupling to the $Z$.

| Parameter | Range |
|-----------|-------|
| $m_b$ [GeV] | [0, 10] |
| $\beta$ | [2, 10] |
| $V$ [GeV] | [250, 1500] |
| $c_L(b)$ | [0, 0.5] |
| $c_R(b)$ | [-0.79, -0.7] |

In Fig. 1 we scan over the parameter space imposing the parameters shown in Table I, with the ranges we considered. We apply constraints in this section. We find that all of the Higgs couplings are suppressed in this model.

LEP searched for the Higgs in the Higgsstrahlung mode in which it is radiated off a $Z$ boson through the $HZZ$ coupling. By decoupling the Higgs from the $Z$, LEP would have a sufficiently small rate that it could not discover the Higgs [10]. We apply the decay mode independent bound on the Higgsstrahlung cross section. This limit varies by a factor of two as a function of mass; we apply $\xi^2_{HZZ} < 2 \times 10^{-2}$ which is the upper bound for the limit in the range $2m_b < m_H < m_{\tau (3)}$, where we define the suppression relative to the SM of $Z$ bosons and bottom quarks as

$$\xi^2_{HZZ} \equiv \left( g_{HZZ} / g_{H^{SM}ZZ} \right)^2; \quad \xi^2_{bbH} \equiv \left( y_b / y_b^{SM} \right)^2,$$

with $g_{HZZ}$ denoting the $H \to ZZ$ coupling and $y_b$ the bottom Yukawa. These suppression factors are shown in Fig. I and are uncorrelated with the Higgs mass. The LEP constraint depends only on the $HZZ$ coupling and is independent of other modifications which would change the Higgs decays.

With the Higgs decoupled from the $Z$, the next most relevant constraints come from radiating the Higgs off $b$ quarks. For $2m_b < m_H < 2m_{\tau}$, the SM Higgs was first ruled out by ARGUS [11] in the channels $B \to KH$ and $B \to K^*H$ with the assumption that $m_b = 50$ GeV. However today we know from CDF and D0 [12] that $m_t = 172$ GeV, which strongly enhances this branching ratio. For a SM Higgs in this mass range, these channels would be dominant [13] because of an $m_t^2$ enhancement in the rate:

$$\frac{\Gamma(b \to Hs)}{\Gamma(b \to c\ell\nu)} =$$

$$\frac{27\sqrt{2}}{64\pi^2} G_F m_b^3 \left( 1 - \frac{m^2_H}{m^2} \right)^2 \frac{V_{tb}^* V_{tb}}{V_{cb}} \left( \frac{m_t}{m_b} \right)^4.$$
where \( f(m_c/m_h) \approx 0.5 \) is the dimensionless phase space factor for \( b \to c\tau\nu \). We use this standard result to approximate the rate even in this model. New contributions coming from KK quarks will contain suppression not only from the top Yukawa couplings, but also from both gauge couplings appearing in the diagram: the overall suppression from these three couplings makes their contribution substantially smaller than Eq. 3. The exotic \( X \) quark does not contribute to this process. Thus to avoid regions that are tightly constrained to have an extremely weak Higgs coupling, we prefer \( m_H > 2m_t \). However, as can be seen in Fig. 1, the couplings of the Higgs become arbitrarily small as \( V \to \infty \), so that a large enough VEV could provide an adequate suppression in the top Yukawa coupling to explain the observed rate. With the measured value \( \mu \) of \( B \to s\mu^+\mu^- \) and assuming \( BR(H \to \mu^+\mu^-) = 5\% \), the Gaugephobic Higgs with \( m_H < 2m_t \) is allowed when \( V > 3.1 \) TeV. At this point we have a suppression of the top Yukawa coupling \( \xi_{tH}^2 \sim 10^{-5} \) while \( \xi_{bH}^2 \sim 10^{-4} \).

For \( m_H > 2m_t \) the most probable mode to search is in \( \Upsilon(nS) \to \gamma H \) where \( n = 1, 2, 3 \), which we discuss in detail in the next section. Since the \( HZZ \) constraints are taken into account, the Gaugephobic Higgs also has suppressed couplings to \( b \) quarks and therefore \( \Upsilon \)'s. This mode was not as vigorously pursued as Higgsstrahlung and \( B \) meson decays because there is sufficient theoretical uncertainty in the predictions for this mode. Even including these uncertainties, this mode only barely reached the expected SM level. Therefore LEPI data was used to rule out the SM Higgs in the \( m_B - m_K < m_H < M_\Upsilon \) region instead. Searches were performed by the CLEO collaboration using \( \Upsilon(1S) \) decays to mono-energetic photons [15]. They limit

\[
BR(\Upsilon(1S) \to \gamma H) < 0.4\%; \quad 8.4\text{GeV} < M_H < 9.4\text{GeV}
\]

The CUSB Collaboration measured the entire photon spectrum from Upsilon decays [16]. They rule out earlier claims from Mark III [17] and Crystal Ball [18] of evidence for Higgs resonances at 2.2 GeV and 8.3 GeV respectively. This limit just barely reaches the SM expectation \( BR(\Upsilon \to \gamma H) \sim 2 \times 10^{-4} \) for \( M_H \to 0 \) and worsens to limit \( BR(\Upsilon \to \gamma H) < 1.5 \times 10^{-3} \) as \( M_H \) increases.

Finally the ARGUS collaboration searched for a monochromatic photon line [19] in the ranges

\[
BR(\Upsilon(1S) \to \gamma H) < 0.1\%; \quad 2.1\text{GeV} < m_H < 8.9\text{GeV}
\]

\[
BR(\Upsilon(2S) \to \gamma H) < 0.5\%; \quad 3.2\text{GeV} < m_H < 9.5\text{GeV}
\]

where the limits quoted are at the lowest \( m_H \) and worsen slightly for higher \( m_H \).

Additionally, there is an important indirect constraint from the coupling of the \( Z \) to \( b \) quarks, \( g_{Zbb} \): for left-handed \( b \)'s this is constrained to be within \( \sim 0.25\% \) of its SM value [9] while for the right-handed fields the constraint is relaxed to \( \sim 30\% \) [20]. This accuracy is possible only with the third generation incorporated in the representations described above, and even then provides a stringent condition on the bulk masses of those fields.

We point out that a complete analysis of electroweak precision parameters is lacking for this model. However it has been shown that in the Higgsless limit, the large contributions to the \( S \)-parameter typical of Technicolor models can in fact be cancelled in a holographic model by an appropriate “de-localization” (i.e. tuning of the bulk masses) of the bulk fermions [21]. The effect of de-localization on our results is small: we have confirmed numerically that adding restrictions to the localization of the light fermions does not qualitatively change our results.

**A LIGHT HIGGS IN \( \Upsilon \) DECAYS**

At low masses, the Gaugephobic Higgs is produced by radiation from the heaviest fermion available. Data with heavy fermions comes dominantly from producing \( \Upsilon \) and \( J/\Psi \) resonances. BaBar has collected 30.2 fb\(^{-1}\) on the \( \Upsilon(3S) \) and 14.45 fb\(^{-1}\) on the \( \Upsilon(2S) \), complementing the 3 fb\(^{-1}\) collected by Belle, and older results from CLEO.

The Higgs is radiated from vector resonances \( V \to \gamma H \) [14]. The photon is monochromatic with an energy

\[
E_{\gamma} = \frac{M^2_V - M^2_H}{2M_V}
\]

because the Higgs is extremely narrow (\( \Gamma_H < 1 \) MeV) for these masses. The relative rate assuming a Coulomb-like potential for the \( b\bar{b} \) state is [14]

\[
\frac{\Gamma(\Upsilon \to H\gamma)}{\Gamma(\Upsilon \to \mu\mu)} = \frac{G_F m^2_H}{\sqrt{2\pi}a} \left( 1 - \frac{m^2_H}{m^2_V} \right) \xi^2_{Hbb}\epsilon; \quad (6)
\]

\[
BR(\Upsilon \to H\gamma) \approx 1 \times 10^{-4} \left( 1 - \frac{m_H}{m^2_V} \right) \xi^2_{Hbb}\epsilon, \quad (7)
\]

where \( \xi_{Hbb} \) is the suppression relative to the SM. The factor \( \epsilon \) includes any next-to-leading order corrections, most notably the leading one-loop QCD correction [22, 23, 24] and relativistic correction [25]. All of these corrections reduce the branching ratio to Higgs over the entire mass range, but there is considerable uncertainty as to how to combine the various contributions. See [20] for further discussion. Since these two corrections are coming respectively from hard and soft gluon effects, we simply combine the two to find the approximate branching fraction for \( \Upsilon(3S) \to H\gamma \) shown in Fig. 2. The relative uniformity of this plot reflects the fact that the suppression of the bottom Yukawa coupling has little direct dependence on the mass of the physical Higgs. Numerical differences between this rate for the \( 3S \) state and the same rate for the lighter \( n = 1, 2 \) resonances can be determined.
from the difference in the partial width $\Gamma(\Upsilon \to \mu \mu)$ of each.

Unfortunately the $\Upsilon(4S)$ data is almost useless in the Wilczek mode because its width is so much larger. For the $\Upsilon(4S)$ data to be competitive with $\Upsilon(3S)$ data, one needs approximately $\Gamma(\Upsilon(4S))/\Gamma(\Upsilon(3S)) \simeq 1000$ times more data because the $\Upsilon(4S)$ is above threshold for decay into a pair of $B$ mesons and consequently has a very large width. However, one can profitably search for a Higgs in $B$ meson decays using $\Upsilon(4S)$ decays, albeit with reduced kinematic reach $m_H < 4.8$ GeV.

CONCLUSIONS

A light Higgs boson is experimentally excluded only when its couplings to other SM fields are sufficiently large. There still exists a class of viable models in which these couplings are suppressed in an “almost Higgsless” scenario, allowing for the potential discovery of a light Higgs at B-Factories. This discovery would be associated with the discovery at the LHC of heavy $Z'$ and $W'$ Kaluza-Klein resonances and no Higgs. We show the range of viable parameters within the Gaugephobic Higgs model. For a Higgs lighter than 10 GeV, the relevant signal would be an excess of monochromatic photons in $\Upsilon(nS)$ data, associated with a pair of heavy fermions such as charm or tau. A Higgs lighter than the $B$ meson is much more tightly constrained to be nearly Higgsless, and can be discovered in $B \to KH$ using $\Upsilon(4S)$ data.

ACKNOWLEDGEMENTS

We thank Christophe Grojean, Jack Gunion, Damien Martin, and John Terning for discussions. The work of J.G. and J.M. is supported by the US Department of Energy under contract DE-FG03-91ER40674.

[1] S. Weinberg, Phys. Rev. D 13, 974 (1976); S. Weinberg, Phys. Rev. D 19, 1277 (1979); L. Susskind, Phys. Rev. D 20, 2619 (1979).
[2] M. E. Peskin and T. Takeuchi, Phys. Rev. Lett. 65, 964 (1990); B. Holdom and J. Terning, Phys. Lett. B 247, 88 (1990); M. Golden and L. Randall, Nucl. Phys. B 361, 3 (1991).
[3] J. M. Maldacena, Adv. Theor. Math. Phys. 2, 231 (1998) [Int. J. Theor. Phys. 38, 1113 (1999)] [arXiv:hep-th/9711200].
[4] L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999) [arXiv:hep-ph/9905221].
[5] R. Contino and A. Pomarol, JHEP 0411, 058 (2004) [arXiv:hep-th/0406257].
[6] G. Cacciapaglia, C. Csaki, G. Marandella and J. Terning, JHEP 0702, 036 (2007) [arXiv:hep-ph/0611358].
[7] M. A. Luty and T. Okui, JHEP 0609, 070 (2006) [arXiv:hep-ph/0609274]; H. Davoudiasl, B. Lilley and T. G. Rizzo, JHEP 0608, 042 (2006) [arXiv:hep-ph/0508279].
[8] C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. Lett. 92, 101802 (2004) [arXiv:hep-ph/0308038]; C. Csaki, C. Grojean, J. Hubisz, Y. Shirman and J. Terning, Phys. Rev. D 70, 015012 (2004) [arXiv:hep-ph/0310355].
[9] K. Agashe, R. Contino, L. Da Rold and A. Pomarol, Phys. Lett. B 641, 62 (2006) [arXiv:hep-ph/0605341].
[10] R. Barate et al. [LEP Working Group for Higgs boson searches], Phys. Lett. B 565, 61 (2003) [arXiv:hep-ex/0306033] and references therein.
[11] M. S. Alam et al., Phys. Rev. D 40, 712 (1989) [Erratum-ibid. D 40, 3790 (1989)].
[12] W. M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006).
[13] B. Grinstein, L. J. Hall and L. Randall, Phys. Lett. B 211, 363 (1988).
[14] F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
[15] D. Besson et al. [CLEO Collaboration], Phys. Rev. D 33, 300 (1986).
[16] F. Franzini et al., Phys. Rev. D 35, 2883 (1987).
[17] R. M. Baltrusaitis et al. [MARK-III Collaboration], Phys. Rev. Lett. 56, 107 (1986).
[18] C. Peck et al. [Crystal Ball Collaboration], Report No. SLAC-PUB-3380; DESY 84-064 (unpublished).
[19] H. Albrecht et al. [ARGUS Collaboration], Phys. Lett. B 154, 452 (1985).
[20] D. Choudhury, T. M. P. Tait and C. E. M. Wagner, Phys. Rev. D 65, 053002 (2002) [arXiv:hep-ph/0109097].
[21] G. Cacciapaglia, C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. D 71, 035015 (2005) [arXiv:hep-ph/0409126]; R. Foadi, S. Gopalakrishna and C. Schmidt, Phys. Lett. B 606, 157 (2005) [arXiv:hep-ph/0409296].
[22] R. Barbieri, R. Gatto, R. Kogerler and Z. Kunszt, Phys. Lett. B 57, 455 (1975).
[23] M. I. Vysotsky, Phys. Lett. B 97, 159 (1980).
[24] P. Nason, Phys. Lett. B 175, 223 (1986).
[25] I. G. Aznauryan, A. S. Bagdasaryan, and N. L. Ter-Isaakyan, Sov. J. Nucl. Phys. 36, 743 (1982).
[26] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, *The Higgs Hunter’s Guide* (Perseus Publishing, Cambridge, MA, 1990).