Holographic Twin Higgs Model

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We present the first realization of a "twin Higgs" model as a holographic composite Higgs model. Uniquely among composite Higgs models, the Higgs potential is protected by a new standard model (SM) singlet elementary "mirror" sector at the sigma model scale f and not by the composite states at m_{KK}, naturally allowing for m_{KK} beyond the LHC reach. As a result, naturalness in our model cannot be constrained by the LHC, but may be probed by precision Higgs measurements at future lepton colliders, and by direct searches for Kaluza-Klein excitations at a 100 TeV collider.

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Introduction.—The naturalness of the weak scale, i.e., its stability under quantum corrections from higher scales, necessitates physics beyond the standard model (SM) at the TeV scale. The measured mass of the Higgs boson [1] and the absence of any new discovery in the first run of the LHC severely constrain the theory space of such models beyond the SM. Specifically, to survive the experimental bounds, a model has to account for a Higgs mass that is both natural and lighter than the new states that restore naturalness—the top and gauge-boson partners.

The composite Higgs framework [2–6] is a class of models inspired by the naturalness of pion masses in QCD and the "little hierarchy" between their mass and the masses of the other composite states. In analogy, the Higgs boson in composite Higgs models is a pseudo-Nambu-Goldstone boson (PNGB) of a broken global symmetry G/H, just as pions are the PNGBs of chiral symmetry breaking. The Higgs mass and vacuum expectation value (VEV) are both natural and significantly lower than the masses of the other composite states, as required by experiment. The composite Higgs spectrum is nonperturbative and is often calculated using holography [7,8]—the duality of a 5d anti–de Sitter (AdS) geometry to some strongly coupled gauge theory.

In composite Higgs models, the SM states are partially composite, a mix of composite and elementary states. The elementary sector explicitly breaks G, making it an approximate symmetry of the strong sector and generating a loop potential for the PNGB Higgs boson. The Higgs quadratic is generated mostly via top loops, cut off at the scale of fermionic excitations m_ψ where the top partners restore naturalness. It scales naively as $\mu^2 \sim (3/8\pi^2) y_t^2 m_\psi^2$, where y_t is the top Yukawa coupling. Hence, for values of m_ψ larger than 1 TeV, the Higgs potential has to be tuned to get the correct Higgs mass (see [9] where a composite lepton contribution has been considered). Direct searches for vectorlike top partners [10] put a lower limit on m_ψ and therefore on the amount of tuning required to get the correct Higgs potential [11,12]. The future runs of the LHC will probe top partners up to ~2 TeV [13], and the lack of any discovery would be translated to a percent level tuning [11].

A counterexample to this link between LHC nondiscovery and tuning is the possibility that the top partners are light and colorless [14–19]—and cannot be detected at the LHC. The "twin Higgs" model [14–16] is a realization of this idea in which the top partners are singlets of the entire SM gauge group. In this model the gauge symmetry is extended to $(SU(3) \times SU(2) \times U(1))^{\mathrm{SM}} \times (SU(3) \times SU(2) \times U(1))^m$ and the Higgs boson is a PNGB of the breaking of a global $SU(4)/SU(3)$. Additionally, a Z_2 symmetry is postulated, exchanging SM particles with their mirror partners, charged only under the mirror gauge group. The global symmetry breaking pattern in this model ensures that the SM contribution to the Higgs potential is canceled by the contribution of the mirror partners. The effective cutoff in the loops is the mass of the top mirror partner given by $y_t f$, where f is the sigma-model scale. The quadratic term scales as $\mu^2 \sim f^2(3/8\pi^2) y_t^4$ [14], i.e., a factor of $f^2 y_t^2/m_\psi^2$ compared to conventional composite Higgs models.

In this Letter, we UV complete the twin Higgs idea in the composite Higgs framework using the holographic approach with gauge-Higgs unification [4–7] where the composite states are related to the Kaluza-Klein (KK) tower of excitations in a Randall-Sundrum (RS) setting (for other UV completions see Refs. [20,21]). This is a first realization of "neutral naturalness" [16] as a bona-fide composite Higgs model, i.e., a natural composite Higgs model that cannot be excluded at the LHC. The main feature of this model is that unlike other composite Higgs models, naturalness is restored by the "mirror partners" at the sigma model scale f, and m_{KK} can lie out of the LHC reach without tuning. The mirror partners in this model arise as a new elementary sector related to the SM by the Z_2 symmetry. Using the holographic approach, the Higgs potential is fully solvable—there are no logarithmic divergences and the dynamics is well defined up to the strong coupling scale. The spectrum consists of the SM particles, the mirror partners, and KK excitations with various SM and mirror quantum numbers.

As in the original twin Higgs model [14], our model requires an additional Z_2-breaking contribution to get the correct Higgs potential and to lift the mirror photon and the mirror partners of light states—in order to avoid potential constraints from cosmology [22,23]. We suggest a mechanism to generate this contribution by postulating a soft Z_2 breaking in the strong sector, i.e., in the bulk and on the IR brane. We calculate the Z_2-breaking contribution to the Higgs potential using holography.

We assume that the Z_2 symmetry is an exact symmetry of the elementary sector, as in the original twin Higgs model [14]. We do not seek a geometric origin for this discrete symmetry in this work, unlike in the Orbifold Higgs model [16].

The model.—In this section we construct the holographic twin Higgs model. At its basis is an elementary sector containing both the SM and mirror degrees of freedom that mix with composites from the strong sector. The 5d dual of this picture is a RS framework with UV and IR branes, located at $z = L_0$ and at $z = L_1$. The low energy Lagrangian will contain only the states that have Neumann boundary conditions on the UV brane—SM and mirror sectors. The scales of the gauge and fermion excitations are $m_\rho \approx m_\psi \approx m_{\rm KK} = (2/L_1)$. [In other composite Higgs models, the fermion excitations can be lighter than the gauge excitations to avoid tensions between naturalness [5,11] and electroweak precision data (EWPD), not present in our model.]

The bulk symmetry of the model is $SU(7)\times SO(8)$ corresponding to the global symmetry in the original twin Higgs model [14], enlarged to accommodate an unbroken custodial symmetry [24]. We choose SU(7) instead of the $SU(6)\times U(1)$ in Ref. [14] in order to avoid tree-level kinetic mixing between the neutral gauge bosons and their mirror partners. The bulk symmetry is broken on the IR brane into $SU(7)\times SO(7)$ with the Higgs boson as a PNGB in the $SO(8)/SO(7)$ coset. The symmetry on the UV brane is $(SU(3)\times SU(2)\times U(1)_Y)^{\rm SM}\times(SU(3)\times SU(2)\times U(1)_Y)^m$.

The essence of the twin Higgs model is the Z_2 mirror symmetry, exchanging the SM and the mirror sectors. This symmetry is imposed on the UV brane, i.e., as the symmetry of the elementary sector. It corresponds to the discrete subgroup of the bulk symmetry exchanging the two $SO(4)$s in $SO(8)$, and the two $SU(3)\times U(1)$s in $SU(7)$. The mirror partners introduced by this Z_2 symmetry protect the Higgs potential from radiative corrections.

We choose the boundary conditions on the UV brane so that the conserved $U(1)$s (hypercharge and mirror hypercharge) are generated by

$$Y = T_R^3 + \frac{4}{3}T^7, \qquad Y^m = T_{mR}^3 + \frac{4}{3}T_m^7, \tag{1}$$

where T_R^3 and T_{mR}^3 are the generators of $U(1)_R$, $U(1)_{R^m}\subset SO(8)$ and T^7 and T_m^7 are the generators of $U(1)_7$, $U(1)_7^m \subset SU(7)$.

The Higgs boson is nonlinearly realized in the vector representation $\mathbf{8_v}$:

$$\Sigma = e^{-i\sqrt{2}T^a(h^a/f)}(0,0,0,0,0,0,0,1)^{\intercal}, \tag{2}$$

where T^a are 4 broken generators charged under $SU(2)^{\rm EW}$. The other 3 broken generators are eaten by the mirror gauge bosons.

In the quark sector the SM states Q_L, t_R, b_R (and their mirror partners) are embedded in Ψ_Q, Ψ_t, Ψ_b bulk multiplets—in the $\mathbf{8_v}$, $\mathbf{1}$, $\mathbf{28}$ representations of $SO(8)$ and in the $\mathbf{7}$ of $SU(7)$. (In the analogous 4D picture, the elementary states mix with the appropriate components of the composite multiplets $\Psi_{Q/t/b}$ [7].) Each quark multiplet has a bulk mass as well as boundary conditions and mass terms on the UV and IR branes that respect their symmetries.

In the 5D picture, only the SM fields and their mirror partners have Neumann b.c. on the UV brane. (See the Supplemental Material [25] for a detailed account of the breaking patterns and branching rules in our model.) On the IR brane, Ψ^Q is decomposed into the $\mathbf{1}$ and the $\mathbf{7}$ of $SO(7)$. Both of these components have Neumann b.c. for the left handed chirality and we can write the IR mass term as $m_q^1\Psi_L^{Q_1}\Psi_R^t$, where $\Psi_L^{Q_1}$ is the $SO(7)$ singlet component of Ψ_L^Q.

The top sector holographic Lagrangian [4,7], is given by

$$L = \overline{\Psi_L^Q}\not{p}(\Pi_0^Q(p)+\Pi_1^Q(p)\Sigma\Sigma)\Psi_L^Q + \overline{\Psi^t}_R\not{p}\Psi_R^t + \overline{\Psi_L^Q}M_t(p)\Sigma\Psi_R^t, \tag{3}$$

where $M_Q(p)$, $\Pi_0^Q(p)$, and $\Pi_1^Q(p)$ are calculated holographically [7]. The top mass and its contribution to the Higgs potential are given by

$$m_t = \frac{1}{2}\frac{v}{f}\frac{M_t(p\to 0)}{\sqrt{\Pi_0^Q(p\to 0)}},$$

$$V(h) = -\frac{1}{8\pi^2 f^2}2N_c\int p^3 dp\left[\log\left(1+\frac{M_t^2(p)}{2p^2\Pi_0^Q(p)}\sin^2\frac{h}{f}\right) + 2\log\left(1+\frac{\Pi_1^Q(p)}{2\Pi_0^Q(p)}\sin^2\frac{h}{f}\right)+(\sin\leftrightarrow\cos)\right], \tag{4}$$

where $v\equiv f\sin(\langle h\rangle/f)$ is the usual Higgs VEV. The $(\sin\leftrightarrow\cos)$ part is the mirror partner contribution. The SU(2) gauge contribution can be calculated in a similar way [4], while the contribution of the hypercharge boson is an order of magnitude smaller.

The value of $m_{\rm KK}/f$ required to reproduce the top mass is set by the bulk masses c_q and c_u of Ψ_Q, Ψ_t, and the IR mass m_q^1. In Fig. 1 we plot the typical Higgs mass generated by the top and gauge sector as a function of $m_{\rm KK}/f$ for

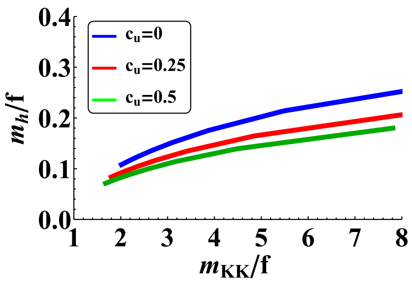

FIG. 1 (color online). The Higgs mass generated by the top and gauge sector. The weak dependence of the Higgs potential on m_{KK}/f is a unique feature of the twin Higgs approach.

several values of c_u. In our choice of the parameter space t_R is mostly composite, i.e., $c_u > 0$. The resulting Higgs mass is typically $m_h \sim 0.2f$, but the VEV is too high: $v = (1/\sqrt{2})f$.

As expected, m_h is only weakly dependent on m_{KK} because the quadratic divergence is cut off at the scale of the mirror partners rather than at the compositeness scale. For this reason, we avoid the generic tuning in composite Higgs models $\Delta > (m_{\mathrm{KK}}/400\ \mathrm{GeV})^2$ [11] and m_{KK} can be naturally high. Nevertheless, an additional term is required to obtain a small v/f. This introduces a mild tuning, also present in composite Higgs models [11] and the original twin Higgs model [14]. The additional term is

$$V_s(h) = \mu_{s1}^2 f^2 \sin^2\frac{h}{f} - \mu_{s2}^2 f^2 \sin^2\frac{h}{f}\cos^2\frac{h}{f}. \qquad (5)$$

To understand the tuning in this model, it is useful to approximate the top and gauge contribution as $V(h) \approxeq -\alpha \sin^2(h/f)\cos^2(h/f)$. With this approximation we can calculate the VEV and the tuning analytically:

$$\frac{v^2}{f^2} = \frac{\alpha + \mu_{s2}^2 f^2 - \mu_{s1}^2 f^2}{2(\alpha + \mu_{s2}^2 f^2)}, \qquad \Delta \approxeq \frac{f^2}{2v^2} \qquad (6)$$

with the tuning defined as [26]

$$\Delta = \max\left(\frac{\partial \log m_Z}{\partial \log \mu_{s1}}, \frac{\partial \log m_Z}{\partial \log \mu_{s2}}\right) \approx \frac{\partial \log m_Z}{\partial \log \mu_{s1}}. \qquad (7)$$

While μ_{s1}^2 is tuned to $\alpha + \mu_{s2}^2$, μ_{s2}^2 is required to increase the generated quartic so that the mass of the Higgs boson is 125 GeV, especially for small m_{KK}/f. For large f (and m_{KK}) the tuning is milder than in Eq. (6) due to an additional $\sin^4(h/f)$ term in the top contribution of Eq. (4) that scales as $\log(m_{\mathrm{KK}}/v)$ [4,14]. We plot the tuning calculated using the full potential of Eq. (4) in Fig. 2. We note that the μ_{s1} term is a Z_2 breaking term, akin to the one in Ref. [14], and the μ_{s2} term is Z_2 conserving.

To generate these terms we postulate a soft Z_2 breaking in the strong sector. This can be used to keep the light mirror sector (the mirror partners of light states) independent of SM parameters. In this way, the model is potentially unconstrained by cosmological bounds, for instance, the Planck limit on the effective number of neutrinos [23]. Additionally, our model allows various dark matter scenarios within the light mirror sector. In the next section we describe the holographic Z_2 breaking pattern.

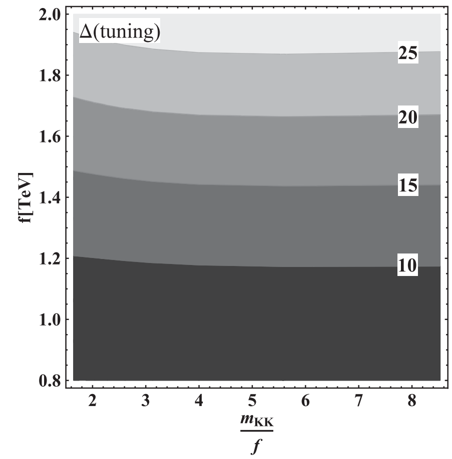

FIG. 2. The degree of tuning between the SM and the additional $V_s(h)$ contributions as a function of the pion scale f and the ratio (m_{KK}/f).

A soft Z_2 breaking in the strong sector.—To softly break Z_2 in the strong sector, we first extend the bulk symmetry by an $O(4)$, so that the full bulk symmetry is $SU(7)\times SO(8)\times O(4)$. The mirror Z_2 that previously acted within $SO(8)\times SU(7)$ now exchanges the two $SU(2)$s in the $O(4)$ as well. This $O(4)$ is spontaneously broken in the bulk to $SU(2)_4 \times U(1)_4^m$, softly breaking the Z_2 as well. $U(1)_4^m$ is broken on the IR brane, serving as an additional source for Z_2 breaking. We modify the UV b.c. so that the hypercharge and mirror hypercharge are

$$Y = T_R^3 + \frac{4}{3}T^7 + T^4, \qquad Y^m = T_{mR}^3 + \frac{4}{3}T_m^7 + T_m^4. \qquad (8)$$

The mirror photon is now massive, due to the breaking of $U(1)_4^m$ on the IR brane. The PNGBs from the $O(4)$ breaking are SM singlets.

The breaking in the bulk is translated to different bulk masses for different components of O(4) multiplets. As a result, Z_2 partners in these multiplets are localized differently in the bulk and have different Yukawa couplings.

We embed the leptons and first two quark generations in the **6** of O(4). They are identified with the $T_m^4 = T^4 = 0$ components of the $SU(2)_4^m \subset O(4)$ triplet within this multiplet. Accordingly, their mirror partners are the $T_m^4 = T^4 = 0$ components of the $SU(2)_4 \subset O(4)$ triplet. The masses of the mirror partners of the light states are then independent of the masses of the SM counterparts, due to the breaking of $O(4)$ (and Z_2) in the bulk.

We now turn to produce the terms from Eq. (5). The Z_2 breaking term is generated by a SM singlet embedded in the **28** of $SO(8)$ and in the **6** of $O(4)$. The singlet is the $T^3_{mR} = 0$ component of the $SU(2)^m_R \subset SO(8)$ triplet and the $T^4_m = 0$ component of the $SU(2)^m_4 \subset O(4)$ triplet. Its mirror partner is also a SM singlet with a different bulk mass due to the $O(4)$ breaking. We assume that it is localized sufficiently far from the IR brane so that it does not contribute to the Higgs potential. To create the Z_2 conserving term we further introduce a SM singlet fermion embedded in the $\mathbf{35_v}$ of $SO(8)$, which is its own mirror partner. The two new multiplets couple on the IR brane.

On the UV brane only the SM singlet components of $\mathbf{28}, \mathbf{35_v}$ have Neumann b.c. for the left handed chirality. The IR brane b.c. are

$$\begin{aligned} &\Psi^{21}_L(+), \qquad \Psi^7_L(+) \in \Psi^{28}_L, \\ \Psi^{27}_R(+), \qquad &\Psi^7_R(+), \qquad \Psi^1_R(+) \in \Psi^{35_v}_R \end{aligned} \tag{9}$$

with an IR mass term $m_7 \bar{\Psi}^7_L \Psi^7_R$. The Higgs potential generated by the new fermions is the one from Eq. (5). The free parameters in this case are the bulk masses and the IR-brane mass, denoted by c_{28}, c_{35v}, and m_7. They are selected to reproduce values of μ_{s1}, μ_{s2} in the relevant range [see Eq. (6)]. The tuning is now given by

$$\Delta = \frac{\partial \log m_Z}{\partial \log \mu_{s1}} \max\left(\frac{\log \mu_{s1}}{\log\{c_i, m_7\}}\right) \tag{10}$$

with typically $[\partial \log \mu_{s1}/\partial \log(c_i, m_i)] < 1$ for $f \sim 1$ TeV in the desired area of the parameter space ($c_{28} > 0$, $c_{35s} < 0$, $m_7 \sim 1$). The new singlets are massless, but can be easily lifted with no consequence to the Higgs potential.

Phenomenology.—Generally in composite Higgs models, bounds on m_{KK} imply lower limits on the amount of tuning in the Higgs potential. The most relevant bounds are from vectorlike quark (VLQ) searches [10,13], which probe the top excitations directly. In particular, for m_{KK} larger than the LHC reach of roughly 2 TeV [13], the tuning is at least at the percent level [11]. The mass of the gauge excitations is constrained by EWPD [11,27], but is only loosely related to the tuning.

The tuning in our model is almost independent of m_{KK} and depends primarily on f (see Fig. 2). This allows us to choose m_{KK} as high as calculability allows us: $(m_{\mathrm{KK}}/f) < 4\pi$. We assume that $m_{\mathrm{KK}} \lesssim 7$ TeV and $f \sim 1$ TeV, so that tuning is $\mathcal{O}(10\%)$.

The electroweak (EW) constraints [11,27] are easily satisfied due to the high scale of excitations ($m_\rho \approx m_{\mathrm{KK}} > 3$ TeV) and due to the custodial symmetry of the bulk and IR brane [5].

The fermion KK excitations include a $2_{7/6}$ VLQ with $m_{7/6} \lesssim 7$ TeV, and a $2_{1/6}$ VLQ with $m_{1/6} \lesssim 10$ TeV. Naturalness does not require these states to lie within the LHC reach, but they are bound to appear in a future 100 TeV collider (see Ref. [28]). We leave the possibility of exotic signals at the LHC, such as quirks [29,30], glueballs [31], and emerging jets [32] for a future study.

In this work we do not specify the flavor structure of the model. As in any other composite Higgs model, flavor bounds can be satisfied by imposing flavor symmetries and we note that flavor violation is already suppressed in our model due to the high KK scale. The mirror contribution to flavor violating processes is expected to be subleading, as it is always mediated by the KK modes.

Additionally, we assume that baryon number is conserved in the composite sector, so that SM and mirror quarks carry identical baryon charges. As the lightest mirror baryon is generically heavier than the proton, no proton decay is induced.

Finally, precision Higgs measurements can produce bounds on f, as in any PNGB Higgs model, due to the modification of all the partial widths by a $1-(v^2/f^2)$ factor. While the LHC can probe f up to 900 GeV [2], future leptonic colliders can produce significantly higher bounds on f [33]. Additionally, the Higgs boson can now decay to mirror quarks, predominately to the mirror-bottom quark, whose Yukawa coupling is $y_{b^m} = (f/v)y_b$. The invisible width $\Gamma_{\mathrm{inv}} \approx 0.5(v^2/f^2)\Gamma^{\mathrm{SM}}_{bb}$ can be probed at future leptonic colliders [33].

Summary and Conclusions.—In this work we presented the holographic twin Higgs model. This model is an implementation of the twin Higgs idea [14] within the composite Higgs framework, set in a 5d AdS background for calculability. The bulk symmetry group is $SU(7)\times SO(8)$, broken on the IR brane into $SU(7)\times SO(7)$ and on the UV brane into $(SU(3)\times SU(2)\times U(1))^{\mathrm{SM}}\times (SU(3)\times SU(2)\times U(1))^m\times Z_2$. The Z_2 symmetry on the UV brane is identified with the bulk symmetry operator exchanging the SM and the mirror sectors.

The contribution to the Higgs potential, generated via SM fermion and gauge loops, is cut off by the mass of the mirror partners rather than by the KK scale, as in the conventional CHM model. As a result, values of m_{KK} beyond the reach of the LHC are natural. However, an additional Z_2-breaking contribution is required to get $v < f$. We introduce a soft Z_2 breaking in the strong sector that is used to generate this contribution, as well as to make the light mirror sector masses and couplings independent of the SM. The Higgs potential is then $\mathcal{O}(10\%)$ tuned to obtain a reasonable $(v/f) \sim \frac{1}{4}$ and the right Higgs mass.

The particle spectrum in our model is as follows. (1) Top and gauge mirror partners: SM singlets with $\mathcal{O}$(TeV) masses. (2) Light mirror states and new singlets: SM singlets, possibly dark matter candidates with arbitrary masses below the EW scale. May be probed as invisible Higgs width at future colliders. (3) KK excitations: vectorlike quarks and heavy gauge bosons, with $\mathcal{O}(5$ TeV) masses, beyond the reach of the LHC. May be probed at a 100 TeV collider.

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