Maximally Natural Supersymmetry

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(Received 23 May 2014; published 9 September 2014)

We consider 4D weak scale theories arising from 5D supersymmetric (SUSY) theories with maximal Scherk-Schwarz breaking at a Kaluza-Klein scale of several TeV. Many of the problems of conventional SUSY are avoided. Apart from 3rd family sfermions the SUSY spectrum is heavy, with only ∼50% tuning at a gluino mass of ∼2 TeV and a stop mass of ∼650 GeV. A single Higgs doublet acquires a vacuum expectation value, so the physical Higgs boson is automatically standard-model-like. A new $U(1)'$ interaction raises m_h to 126 GeV. For minimal tuning the associated Z', as well as the 3rd family sfermions, must be accessible to LHC13. A gravitational wave signal consistent with hints from BICEP2 is possible if inflation occurs when the extra dimensions are small.

DOI: 10.1103/PhysRevLett.113.111802 PACS numbers: 12.60.Jv, 12.15.-y, 14.80.Da, 14.80.Rt

The LHC has set stringent limits on the masses of SUSY particles and deviations in Higgs properties, implying a tuning of electroweak symmetry breaking (EWSB) at the percent level or worse for traditional SUSY models [1–6]. This undermines the motivation for SUSY as the solution to the hierarchy problem and the case for discovery of SUSY at the LHC or proposed future colliders. Given the importance of this issue for current and future searches for new physics, we examine the possibility of constructing natural, untuned theories. We find a promising example in theories where some particles propagate in a 5th dimension of physical length $\pi R \sim \mathrm{TeV}^{-1}$ and SUSY is broken by the boundary conditions (BCs) for these bulk fields [7–21]. This mechanism is known as Scherk-Schwarz SUSY breaking (SSSB), and the key features of these models are (i) the theory is never well approximated by a 4D theory with soft supersymmetry breaking, and many problems of the minimal supersymmetric standard model (MSSM) and its extensions are avoided. (ii) The Higgsinos, gauginos, and the 1st and 2nd family sfermions propagate in the 5th dimension and obtain SSSB masses of size $1/2R$. (iii) The 3rd family is localized on a 4D brane to protect the 3rd generation squarks from a large tree-level SSSB mass, thus realizing a natural SUSY spectrum [22–24] and significantly easing collider bounds. The super softness of SSSB [25–31] prevents large logs in the loop-level mediation of SUSY breaking, further protecting the weak scale and suppressing the tendency of the gluino to pull up the stop mass [2,3]. (iv) Only a single Higgs doublet H_u acquires a vacuum expectation value (VEV) and has Yukawa couplings. The μ and b terms are not needed, and the physical Higgs boson is automatically SM-like. (v) An additional SUSY breaking sector is necessarily present for radius stabilization with zero cosmological constant (CC), and SUSY breaking in this sector can naturally be driven by SSSB. Higher dimensional couplings of the MSSM fields to this sector play a crucial role in EWSB and collider phenomenology. (vi) A $U(1)'$ broken in this additional sector raises the Higgs boson mass to 126 GeV through an unusual nondecoupling D term, with a Z' mass of order $1/R$.

The pattern of localization of matter and Higgs multiplets and the mechanism driving EWSB, generating Yukawa couplings, and accommodating the observed physical Higgs mass lead to important differences from previously studied models of near-maximal SSSB near the TeV scale [7–21] and models obtaining a realistic spectrum from nonmaximal SSSB at scales $1/R \gg \mathrm{TeV}$ [32–34].

Natural spectrum from Scherk-Schwarz.—SSSB can be described by periodicity conditions for bulk fields involving a symmetry twist with an R-symmetry group action [35,36]. SSSB is nonlocal from the higher-dimensional perspective, and is of an exceptionally soft type, similar to finite-temperature breaking of SUSY. In our case the twists will be maximal, ± 1, and the underlying nongravitational sector can be described as a 5D gauge theory compactified on a $S^1/(Z_2 \times Z_2')$ orbifold. The 5th dimension is parameterized by $y \in [0, \pi R]$, and branes sit at the inequivalent fixed points 0 and πR.

Our 5D bulk is supersymmetric and contains the SM gauge fields, the first two families, and a pair of distinct Higgs hypermultiplets, H_u, H_d [see Fig. 1(a)]. As the minimal SUSY in five dimensions corresponds to $N = 2$ 4D SUSY, the superpartners of these bulk states fill out $N = 2$ 4D multiplets, with each 5D vector implying both a 4D vector and chiral supermultiplet in the adjoint representation, $V^a_{5\mathrm{D}} = \{V^a_{4\mathrm{D}}, \bar{\Sigma}^a\}$ (with physical fields V^a_μ, λ^a and $\bar{\sigma}^a, \bar{\lambda}^a$) while the matter fields are hypermultiplets consisting of 4D chiral and antichiral multiplets $\Phi^i_{5\mathrm{D}} = \{\phi^i, \bar{\phi}^i\}$ (physical fields φ_i, ψ_i and $\bar{\varphi}_i, \bar{\psi}_i$) [37–41].

The two Z_2 actions at 0 and πR, break 5D SUSY to two *different* and incompatible $N = 1$ 4D SUSYs, thus

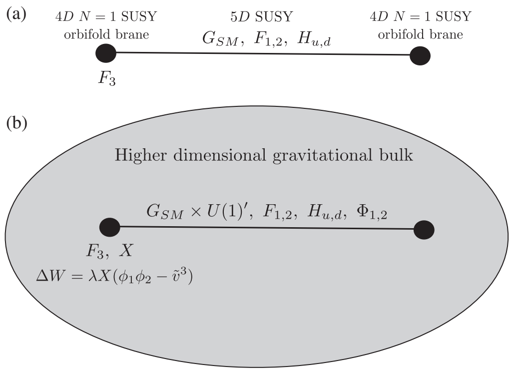

FIG. 1. (a) Schematic of the minimal model. In five dimensions are the SM gauge fields, the first two families $F_{1,2}$, Higgs doublets $H_{u,d}$, and superpartners implied by 5D SUSY. The 3rd generation chiral multiplets are brane localized. SUSY is broken nonlocally by BCs. (b) Full model including embedding in yet higher-dimensional bulk. The 5D $U(1)'$ is broken via y-dependent VEVs (driven by the brane-localized superpotential ΔW) of bulk fields, $\Phi_{1,2}$, of charges ± 1. After SSSB, $F_X \sim 1/R^2$ is induced for X, a brane-localized singlet field.

breaking SUSY completely in the 4D effective theory; the component field BCs are summarized in Table I. At $y=0$ we localize the 3rd generation fields. As the fixed points preserve only $N=1$ 4D SUSY, these states are simply 4D chiral multiplets with no additional partners, and a localized Yukawa superpotential for up-like states is allowed

$$\delta(y)H_u(y)\left(\frac{\tilde{y}_t}{M_5^{1/2}}Q_3U_3^c+\frac{\tilde{y}_c}{M_5^{3/2}}Q_2(y)U_2^c(y)+\cdots\right), \quad (1)$$

where $\tilde{y}_i$ are dimensionless and the Yukawa couplings to bulk 1st or 2nd generations are naturally suppressed compared to the brane-localized 3rd generation. We later return to the down-type Yukawa couplings.

There is no need for a μ term linking H_uH_d to lift the Higgsinos. Instead, SSSB gives the Higgsinos a large $1/2R$ mass by marrying ψ_{h_u} with $\bar{\psi}_{h_u}$. The SSSB BCs lift the Higgsinos while making no contribution to the scalar Higgs masses, avoiding the usual source of tree-level tuning.

TABLE I. BCs at $y=(0,\pi)$ for bulk fields of a complete model with $+$ indicating Neumann BCs and $-$ indicating Dirichlet BCs. Only the $(+,+)$ fields have a zero mode, and the KK mass spectrum ($n\geq 0$) is $m_n=n/R$ for $(+,+)$ fields, $(2n+1)/2R$ for $(+,-)$ and $(-,+)$, and $(n+1)/R$ for $(-,-)$. $\psi_{F_{1,2}}$ stands for all 1st and 2nd generation fermions; φ_{F_i} their 4D $N=1$ sfermion partners; barred states are the extra 5D $N=1$ SUSY partners.

	$(+,+)$	$(+,-)$	$(-,+)$	$(-,-)$
V^a_{5D}	V^a_μ	λ^a	$\bar{\lambda}^a$	$\bar{\sigma}^a$
$H_{u,d}$	$h_{u,d}$	$\psi_{h_{u,d}}$	$\bar{\psi}_{h_{u,d}}$	$\bar{h}_{u,d}$
$F_{i=1,2}$	ψ_{F_i}	φ_{F_i}	$\bar{\varphi}_{F_i}$	$\bar{\psi}_{F_i}$
$\Phi_{1,2}$	$\psi_{\Phi_{1,2}}$	$\varphi_{1,2}$	$\bar{\varphi}_{1,2}$	$\bar{\psi}_{\Phi_{1,2}}$

After SSSB the brane-localized scalars pick up, at 1-loop, finite positive soft SUSY-breaking masses

$$\delta\tilde{m}_i{}^2 \simeq \frac{7\zeta(3)}{16\pi^4R^2}\left(\sum_{I=1,2,3}C_I(i)g_I^2+C_t(i)y_t^2\right), \quad (2)$$

with $C(U_3)=\{4/9,0,4/3,1\}$, $C(D_3)=\{1/9,0,4/3,0\}$, $C(E_3)=\{1,0,0,0\}$, $C(L_3)=\{1/4,3/4,0,0\}$, $C(Q_3)=\{1/36,3/4,4/3,1/2\}$, and for the Higgs bulk scalar zero mode $C(H_{u,d})=\{1/4,3/4,0,0\}$ [7]. Because of the nonlocal nature of SSSB there are no cutoff-dependent log enhancements of the effective 4D soft terms.

In addition to the positive 1-loop EW contribution Eq. (2), the Higgs soft mass $\tilde{m}^2_{H_u}$ receives a comparable negative contribution at 2-loops from the t-$\tilde{t}$ sector. Reference [12] performed a 2-loop 5D calculation of this term, and we have used RG methods to determine the leading 3-loop $\log(m_tR)$-,$\log(m_{\tilde{t}_1}/m_t)$-enhanced corrections, which are numerically important in determing the fate of EWSB [42]. As shown in Fig. 2, these minimal contributions do not so far lead to EWSB. Nevertheless, the model has attractive features: Compared to 4D theories the Higgs soft mass is more screened from SUSY-breaking as Eq. (2) involves a finite 1-loop factor with no log enhancement, SUSY breaking for all but the 3rd generation and Higgs scalar zero mode is direct and universal, and Higgsinos are heavy without a large μ term.

Successful EWSB and Higgs Mass.—Other faults remain in this model, and we find their solution plays a major role for EWSB and experimental signatures. First, our 5D theory is an effective theory which must be cutoff at a scale M_5. The bulk 5D gauge couplings are dimensionful ($1/g^2_{I,4}=\pi R/g^2_{I,5}$ up to small brane-kinetic-term corrections), and 5D perturbative unitarity bounds for g_3 require $\pi M_5R \lesssim 25$ [43,44]. NDA strong coupling estimates for the brane-localized Yukawa couplings give a similar bound [45].

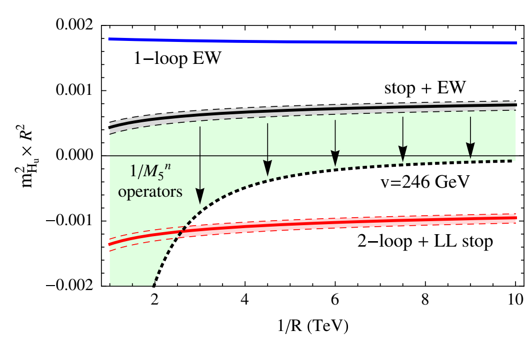

FIG. 2 (color online). Contributions to the Higgs soft mass $m^2_{H_u}$ in units of $1/R^2$. The positive 1-loop electroweak contribution (blue) and the negative 2-loop + leading log top-stop sector contribution (red) combine to give a positive mass squared (black). Contributions from higher-dimension operators of Eq. (4) can lead to successful EWSB, indicated by the dotted black curve. The dashed bands show the uncertainty for $\overline{\mathrm{MS}}$ top mass $m_t(M_t)=160^{+5}_{-4}$ GeV.

This cutoff is large enough to justify the 5D viewpoint and the parametrization of UV effects in terms of higher dimensional operators, but the weakness of gravity in the low energy 4D theory, $M_{\rm pl} \gg M_5$, must still be explained. The two controllable possibilities of which we are aware are (a) to embed the 5D theory in a 10 or 11D string or M-theory where some or all of the extra 5 or 6 purely gravitational dimensions are "large," similar to the original brane-world proposal of Refs. [46–49] [see Fig. 1(b)]. Since our fundamental scale is $M_5 \gtrsim 30$ TeV, $n \geq 2$ extra dimensions is safe from cosmological, astrophysical, and laboratory constraints. (b) To utilize a little-string-theory construction with tiny string coupling [50].

Second, the radius R is unstabilized. Moreover, SSSB without radius stabilization is of no-scale type with zero CC at tree level [39,51–54], and, generally, radius stabilization yields a deep negative CC of order $\sim -1/R^4$ [55–61]. An additional positive SUSY breaking sector can tune the minimum to zero CC, and will generally involve a brane-localized field X with an F term, $F_X \sim 1/R^2$ [42].

With this additional brane-localized SUSY breaking $F_X \neq 0$, the Kahler operators

$$\Delta\mathcal{K}_{m_H^2} = \delta(y)\frac{c_H}{M_5^3}X^\dagger X H_u^\dagger H_u, \tag{3}$$

$$\Delta\mathcal{K}_{m_{\tilde{t}}^2} = \delta(y)X^\dagger X\left(\frac{c_Q}{M_5^2}Q_3^\dagger Q_3 + \frac{c_U}{M_5^2}U_3^{c\dagger}U_3^c\right), \tag{4}$$

can alter the H_u soft mass and trigger EWSB, either directly for $\Delta\mathcal{K}_{m_H^2}$ or radiatively through 1-loop stop corrections for $\Delta\mathcal{K}_{m_{\tilde{t}}^2}$. When the 5D picture is under good control, $(\pi R M_5) \gtrsim 10$, the contribution from $\Delta\mathcal{K}_{m_{\tilde{t}}^2}$ dominates. As illustrated in Fig. 2, we find that for $F_X \sim 1/R^2$, and for $c_Q, c_U \sim 1$ this shift is sufficient to trigger EWSB at scales $1/2R \gtrsim 2$ TeV. The tuning involved will be seen to be exceptionally mild for present collider limits. Additional higher dimensional operators including brane-localized derivative operators, which may be present at tree level or radiatively generated [40,62–67] do not significantly affect the Higgs zero mode.

The bottom and tau Yukawa couplings also result from F_X via the Kahler terms [68]

$$\delta(y)[H_u(y)^\dagger X^\dagger]\left(\frac{\tilde{y}_b}{M_5^{5/2}}Q_3 D_3^c + \cdots\right). \tag{5}$$

The 1st and 2nd generation down-type Yukawa couplings can be generated by similar higher dimensional Kahler operators or by superpotential couplings to $h_u^\dagger$ on the $y = \pi$ brane [14]. Therefore, H_d need not obtain a VEV, a dramatic simplification of the Higgs sector only possible because the cutoff scale is so low. Although H_d must be present to avoid a quadratically divergent Fayet-Illiopoulos (FI) term [16,69,70], unlike the MSSM there is no need for there to be μ or B_μ terms that link H_u to H_d. The simplest option is to impose an unbroken Z_2 symmetry on H_d which forbids these unnecessary terms and eliminates potentially dangerous flavor-changing effects; H_d is a stable (neutral) particle in the spectrum in addition to the LSP, as in the inert doublet models [71–74].

For $m_{\tilde{t}_1} \gtrsim 3.5$ TeV, the radiative contributions to the physical Higgs mass may be large enough to accommodate $m_h = 126$ GeV [75]. For lighter stops, we obtain $m_h = 126$ GeV with a nondecoupling D term (as only $\langle H_u\rangle \neq 0$, a NMSSM-like singlet interaction SH_uH_d cannot be employed as in Ref. [76]). Specifically, we introduce a bulk $U(1)'$ gauging a subgroup of right-handed $SU(2)$ generated by T_{3R} under which H_u (and H_d) transform [the $U(1)'$ is anomaly-free if three light RHD neutrino superfields are introduced in the bulk; we find our theory allows a novel theory of neutrino mass generation [42]]. To avoid suppression of the quartic, the breaking of the new gauge group must couple to large SUSY breaking F terms [77–79]. It is natural to associate the breaking of the $U(1)'$ with the same dynamics that generates F_X, with the resulting Z' mass $\sim 1/R$.

A simple model where F_X is induced by SSSB and is associated with the breaking of the $U(1)'$ is obtained by introducing bulk hypermultiplet fields $\phi_{1,2}$ charged $\pm\frac{1}{2}$ under the $U(1)'$ with SSSB BCs given in Table. 1 and a brane-localized superpotential

$$\Delta W = \frac{\lambda}{M_5}X(\phi_1(y)\phi_2(y) - \tilde{v}^3)\delta(y). \tag{6}$$

This leads to spontaneous breaking of the $U(1)'$ in the D-flat direction with a y-dependent profile for $\langle\phi_{1,2}\rangle$ and a brane-localized $F_X = M_5/(\lambda\pi R)$. This positive SUSY breaking contribution to the radion potential can be tuned to allow stabilization with zero CC. We find that for $m_{\tilde{t}} \gtrsim 650$ GeV$(m_{\tilde{t}} \gtrsim 1$ TeV$)$ and $m_Z' \lesssim 2/R$, the $U(1)'$ D term can yield $m_h = 126$ GeV with $g_X < 1 (g_X < g_2)$. The $U(1)'$ sector also contributes to the Higgs soft mass. The contribution is not well approximated by the truncated lightest KK modes; we evaluate it in the 5D theory and find for $m_{Z'} \gtrsim 1/R$ the contribution favors EWSB and numerically approaches

$$\delta m_{H_u}^2[U(1)'] \approx -10^{-3}g_X^2 m_{Z'}^2. \tag{7}$$

Phenomenology and Variations.—The theory has a rich phenomenology, and a variety of new physics signatures are accessible to LHC14 in the low-fine-tuning parameter region. Here we provide just a brief summary of the main features [42]. The spectrum of new (nongravitational) states is illustrated in Fig. 3, where we have shown values with minimal fine-tuning consistent with current bounds.

The theory is mostly protected from precision, flavor, and CP observables, although signatures are possible. While SUSY flavor problems are suppressed by the automatic near degeneracy of 1st and 2nd generation squarks and the

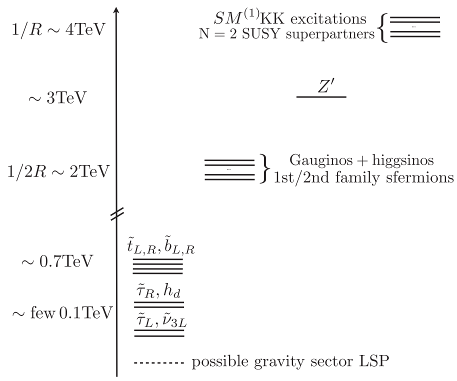

FIG. 3. Schematic spectrum of new states of primary experimental interest.

near-Dirac masses of Higgsinos and gauginos, KK gauge boson exchange can lead to deviations in kaon and especially B_q mixing, and rare decays depending on model-dependent details [80]. The high scale of the KK states and $U(1)'$ sectors, $1/R \sim m_{Z'} \gtrsim 4$ TeV protects from EWPT [45]. Higgs properties are automatically SM-like since only H_u obtains a VEV, and the inert H_d is easily made consistent with limits.

The presence of additional large gravitational dimensions constrains models of inflation and reheating. A detailed treatment is left to future work [42], but we note that a small inflationary energy scale $V_I < M_5^4 \ll M_{\rm pl}^4$ can be consistent with recent hints of observable tensor perturbations [81] if the extra gravitational dimensions and thus the corresponding 4D Planck mass are small during inflation, as in models of rapid asymmetric inflation [82]. In the absence of R-parity violation, the lightest supersymmetric particle (LSP) is stable and may contribute part or all of the observed dark matter density. In some gravitational embeddings there are cosmologically stable light bulk modes of the gravitini, while in others all of the gravitini can be lifted, and the LSP will be a 5D brane-localized state from the MSSM or X sector. The former can be constrained by BBN, CMB, and astrophysical limits on decays between gravitino KK states, while the latter case may have interesting signatures and constraints from direct detection experiment.

The leading signature of this model is sparticle production at the LHC and future colliders. Two important differences from generic natural SUSY phenomenology occur. First, $m_{\tilde{g}} \sim (3-5) m_{\tilde{t}}$ arises without extra tuning, and tuning limits will likely be driven by direct production of 3rd generation sparticles, not gluino production. Second, the absence of a light Higgsino leads to unusual stop and sbottom decay chains. The brane-localized 3rd generation slepton masses are dominantly from higher dimensional operators Eq. (4), so either $\tilde{\tau}_R$ or $\tilde{\nu}_{\tau_L}$ could be the lightest ordinary superpartner (LOSP). Three-body decays of $\tilde{t}$ and $\tilde{b}$ to the LOSP can dilute missing energy signatures and lead to τ-rich final states. Depending on the embedding of the 5D theory in the gravitational dimensions, the LOSP can be collider stable, or decay through prompt or displaced vertices to extra-dimensional-gravitini or other R_p-odd states in the bulk. In another variation, if F_X is generated independently of SSSB, the associated goldstino remains light [83] and ordinary superpartners will decay directly to this state, mimicking more standard natural SUSY signatures. For this short work we take the LHC8 bounds on $\tilde{t} \to t + \text{MET}$ of $m_{\tilde{t}} \gtrsim 650$ GeV [84,85] as a guideline, but we note that limits on the production of 3rd generation squark and gluinos can potentially be substantially eased if the LOSP is a promptly decaying stau [86,87].

The mass and couplings of the new Z' are restricted by the requirement $m_h \approx 126$ GeV, suggesting this state is also likely to be accessible; 8 TeV limits require $m_{Z'} \gtrsim 3$ TeV [88,89].

The tuning of EWSB in this theory can be quantified by the sensitivity of v to shifts at the scale $1/R$ of the contribution $\Delta m_{\tilde{t}}^2$ to the stop soft masses through the operator Eq. (4) and shifts of the Z' mass,

$$\Delta = \sqrt{\left(\frac{\partial \ln v^2}{\partial \ln \Delta m_{\tilde{t}}^2}\right)^2 + \left(\frac{\partial \ln v^2}{\partial \ln m_{Z'}^2}\right)^2}, \qquad (8)$$

where, for simplicity, we set $\Delta m_{\tilde{q}_3}^2 = \Delta m_{\tilde{u}_3}^2 \equiv \Delta m_{\tilde{t}}^2$. The fine-tuning is shown in Fig. 4, where the stop mass has been fixed as a function of $1/R$ and m_{Z}' to give successful EWSB. For $m_{Z'} \lesssim 1.5/R$, the stop contribution is the dominant source of tuning. Remarkably, at current LHC8 limits the theory is natural with a tuning of ~50%. LHC14 can discover stops at $m_{\tilde{t}} \sim 1.2$ GeV [90], for which the theory is ~20% tuned. For $m_{\tilde{t}_1} \gtrsim 3.5$ TeV, the tuning is still only at

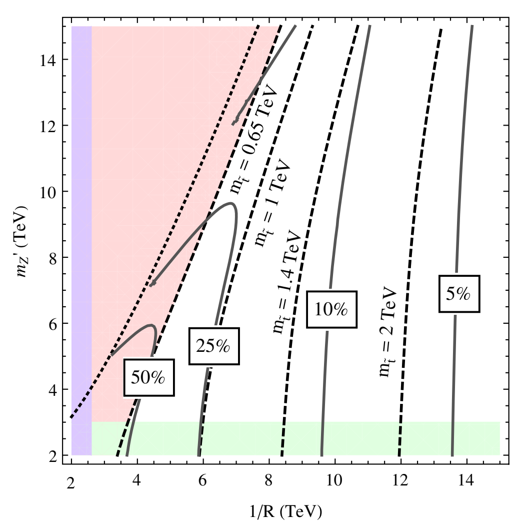

FIG. 4 (color online). Fine-tuning Δ^{-1} (solid lines) as function of $1/R$ and the Z' mass, Eq. (8). Iso-contours of stop mass are dashed. Limits from LHC8 searches for $\tilde{t} \to t + \text{MET}$ [84,85] (red) and Z' resonance searches [88,89] (green) are shaded. Subdominant limits $m_{\tilde{g}} \approx 1/(2R) \gtrsim 1.3$ TeV from $\tilde{g} \to t\bar{t}/b\bar{b} + \text{MET}$ searches (blue) are also shaded [91,92].

the few percent level and $m_h = 126$ GeV might be obtained radiatively [75] without the complications of an extra $U(1)'$ sector—an attractive target for a 100 TeV proton collider.

The production of KK excitations of SM particles would be an important signature of the extra-dimensional nature of this model, but their large mass $\sim 1/R$ and an approximate KK parity make these particles difficult to reach at LHC14. Observing the near degeneracy of gauginos, Higgsinos, and 1st and 2nd generation sfermions would provide an alternative strong indication of the extra-dimensional nature of the theory.

In summary, we have presented a model where SSSB accompanied by a simple mechanism driving EWSB leads to a natural spectrum consistent with Higgs properties and sparticle bounds with fine-tuning better than ~50% even after LHC8 limits. Variations involving different field content and localizations, including interplay with other mechanisms for driving EWSB in SSSB via different bc's [10,11] and quasilocalization of the stop [12–16] or Higgs boson [17–20] deserve further attention as leading candidates for natural theories at LHC14 and future colliders. In an aesthetic direction, the extended gauge structure and extra dimensions suggest interesting possibilities for gauge unification in this model [42].

We thank N. Arkani-Hamed, A. Arvanitaki, M. Baryakhtar, N. Craig, I. Garcia Garcia, T. Gherghetta, E. Hardy, X. Huang, D. E. Kaplan, K. Van Tilburg, J. Wacker, and Y. Zhao for useful discussions. We especially thank DEK for hospitality at JHU during a portion of this work. This work was partially supported by ERC Grant BSMOXFORD No. 228169. K. H. is supported by a NSF Graduate Research Fellowship under Grant No. DGE-0645962 and by the US DOE under Contract No. DE-AC02-76SF00515.

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