A GRAVITY DUAL OF SINGLE-SECTOR SUPERSYMMETRY BREAKING

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We present a five-dimensional gravitational dual of "single-sector" models of supersymmetry breaking which are models that contain no messenger sector and naturally explain the scale of supersymmetry breaking and the fermion mass hierarchy. Inspired by flux-background solutions of type IIB supergravity, supersymmetry is broken by a metric background that deviates from AdS_5 in the infrared. The first and second generation sfermions directly feel the supersymmetry breaking and obtain masses of order 10 TeV, while the gauginos and third generation sfermions are elementary states that obtain soft masses of order 1 TeV at the loop level via direct gauge mediation. This particle spectrum leads to distinctive signatures at the LHC, similar to the usual gauge mediation with a neutralino NLSP that decays promptly to a gravitino LSP.

1 Introduction

Recently, gauge/gravity duality ideas based on the AdS/CFT correspondence in type IIB string theory [1] have been used to give a four-dimensional (4D) holographic description for models in a warped extra dimension. [2] This has led to the remarkable result that strongly coupled 4D gauge dynamics can be modeled with a five-dimensional (5D), weakly coupled gravitational theory. In this approach, classical field theory computations are able to capture the dominant effects of the strongly coupled 4D theory.

Warped extra dimension models have been used to break supersymmetry, [3] where the warp factor is used to generate a low SUSY-breaking scale which is then identified as a dynamical supersymmetry breaking (DSB) scale. In these previous models boundary conditions were used to break supersymmetry. In the present work, we pursue this idea of relating the warp factor with a dynamically generated scale in the context of realistic, strongly coupled 4D SUSY gauge theories, softly broken by the effects of DSB. A simple 5D gravitational dual will be described that will allow previously "incalculable" particle mass spectra to be calculated.

Supersymmetry will be broken by considering an effective 5D model that is motivated from a ten-dimensional (10D) type IIB supergravity solution,[4] which is obtained by perturbing the well-known Klebanov-Strassler supersymmetric background,[5] using techniques developed in Ref.[6] The effective deformed nonsupersymmetric 5D background metric is obtained from a dimensional reduction of the 10D metric, and the resulting 5D geometry will be parametrized as[7]

$$ds^2 = A^2(z)(-dt^2 + d\vec{x}^2 + dz^2) \ , \tag{1}$$

where the warp factor is

$$A^2(z) = \frac{1}{(kz)^2}\left[1 - \epsilon\left(\frac{z}{z_1}\right)^4\right] \ , \tag{2}$$

k is the AdS curvature scale, and $z_0 \leq z \leq z_1$ with z_0, z_1 the positions of the (ultraviolet) UV and (infrared) IR branes respectively. The parameter ϵ is related to variables in the original 10D solution (see Ref. [7]), although for our phenomenological purposes we only need assume it to be an arbitrary but small, positive parameter. The $\epsilon \to 0$ limit is just a slice of AdS_5, which is the 5D background setup used in the Randall-Sundrum model.[8]

2 A 5D Gravity Model

The MSSM fields are assumed to propagate in the bulk with metric (1). In the supersymmetric limit ($\epsilon \to 0$) these 5D fields propagate in a slice of AdS and satisfy nontrivial boundary conditions.[9] Upon compactification to four dimensions, the massless zero modes of the Kaluza-Klein towers are identified with the 4D MSSM fields. Since the warp factor is used to set the scale of supersymmetry breaking, the Higgs fields need not be localized on the IR brane and in fact they are assumed to be confined on the UV brane where their masses are protected by supersymmetry.

2.1 Fermion masses

Consider the SM fermions, where each fermion is embedded into its own 5D Dirac spinor. The zero mode profile for each fermion i is given by $f_i(z) \propto z^{\frac{1}{2}-c_i}$, where the exponent depends on a bulk mass parameter c_i. For $c_i > 1/2$ ($c_i < 1/2$) the zero mode is localized near the UV (IR) brane.[9] The wavefunction overlap of the fermion zero modes with the UV-confined Higgs fields $z_0 = 1/k$, leads to the 4D Yukawa couplings[7]

$$Y_\psi = Y_\psi^{5D} k \sqrt{\frac{1/2 - c_L}{(kz_1)^{1-2c_L} - 1}} \sqrt{\frac{1/2 + c_R}{(kz_1)^{1+2c_R} - 1}} \ , \tag{3}$$

where Y_ψ^{5D} is a 5D Yukawa coupling. This expression is used to solve for the c parameters using the values of the 4D Yukawa couplings and assuming $10^{-3} \leq Y_\psi^{5D} k \leq 1$. The results are listed in Table 1. Indeed it is seen from these values that the lighter generations are closer to the IR brane while the third generation is UV-localized. Since each SM fermion is contained in a chiral supermultiplet, the corresponding scalar superpartner will be localized at the same place in the supersymmetric limit. In the deformed case, the scalar localization is qualitatively unchanged. This is because the profile is only modified in the IR, where the deformation is noticeable.

Note that it is necessary to allow a small hierarchy in the 5D Yukawa couplings, in order to avoid FCNC's from the squarks. Essentially, the c's must be degenerate among first and second generation quarks in order for the corresponding squarks to be degenerate. This also helps to avoid naturalness constraints from hypercharge Fayet-Illiopoulos D-terms.[7]

Table 1: Standard Model $\overline{\text{MS}}$ running fermion masses at the scale m_Z with the corresponding c values and 5D Yukawa couplings (in units of k) for the case of UV Higgses and $\tan\beta = 10$.

	$\bar{m}(m_Z)$	c_L	$-c_R$	Y^{5D}
e	0.503 MeV	0.350	0.350	1
μ	103.9 MeV	0.467	0.467	1
τ	1.75 GeV	0.601	0.601	1
d	3.9 MeV	0.456	0.456	0.059
s	67.6 MeV	0.456	0.456	1
b	2.9 GeV	0.69	0.648	1
u	1.7 MeV	0.456	0.456	0.0025
c	0.58 GeV	0.456	0.456	0.849
t	166 GeV	0.69	5.341	1

2.2 Scalar masses

The scalar superpartner masses are related to the fermion mass spectrum. The zero mode profile of a bulk scalar field is given at leading order by $f_i(z) \propto z^{b_i-1}$, where the exponent depends on a mass parameter b_i of the 5D model. By supersymmetry [9]

$$b_i = \frac{3}{2} - c_i, \tag{4}$$

which explicitly shows that once the SM fermion localization is set by c_i, the localization of the scalar zero mode is then fixed. The values $b_i < 1$ ($c_i > 1/2$) correspond to a UV-localized mode, whereas $b_i > 1$ ($c_i < 1/2$) is IR-localized. Clearly it is the IR-localized scalar modes that are sensitive to the SUSY-breaking background because the deformation is only appreciable near the IR brane.

In the supersymmetry-breaking background (1) the scalar zero modes will obtain a mass. The scalar mass squared as a function of the localization parameter b is given by [7]

$$\widetilde{m}^2 = \epsilon \frac{(1-b)(b+10)}{(kz_1)^4} \frac{(kz_1)^{1+b} - (kz_1)^{1-b}}{(kz_1)^{1-b} - (kz_1)^{b-1}} k^2 + \mathcal{O}(\epsilon^2) \ . \tag{5}$$

This expression simplifies in the limit $kz_1 \gg 1$. For $b > 1$ the scalar mass simply becomes

$$\widetilde{m} \approx \sqrt{\epsilon(b-1)(b+10)}\, z_1^{-1} \ , \tag{6}$$

while for $0 < b < 1$ we have the approximation:

$$\widetilde{m} \approx \sqrt{\epsilon(1-b)(b+10)}\,(kz_1)^{b-1} z_1^{-1} \ . \tag{7}$$

Thus we see that for an IR-localized field ($b > 1$) the scalar mass becomes of order the IR scale z_1^{-1}, while for $b \ll 1$ and $kz_1 \sim 10^{13}$ the scalar mass is much less than a GeV.

From Eq. (4), the values of b_i are determined by the fermion spectrum of Table 1. We then apply (5) to obtain the squark and slepton mass spectrum. The AdS curvature scale is set by requiring $m_P^2 \simeq M_5^3/k$ where M_5 is the 5D Planck scale. Choosing $k \sim 0.1 M_5$ requires $k \simeq 10^{-3/2} m_P = 7.7 \times 10^{16}$ GeV. Consequently the model parameters are set to

$$\pi kR = 28.42, \quad \epsilon = 0.05, \quad \tan\beta = 10, \quad z_0 = k^{-1}, \quad z_1 = (ke^{-\pi kR})^{-1} = (35\ \text{TeV})^{-1}. \tag{8}$$

The first two generations of squarks and sleptons obtain masses of order 1/10 to 1/20 the Kaluza-Klein mass scale,

$$m_{\text{KK}} = \pi z_1^{-1} = 110\ \text{TeV}, \tag{9}$$

but the third generation masses are much smaller. As expected since the third generation fermions are near the UV brane in order to have a large overlap with the Higgs, the corresponding supersymmetry-breaking masses are phenomenologically unacceptable. However by considering the dual 4D theory we will show that there is a gauge-mediated contribution that gives rise to acceptable third generation squark and slepton masses.

2.3 Relation to 4D single-sector models

Interestingly, the holographic 4D dual of the 5D gravity model is remarkably similar to models constructed purely in four dimensions. In particular, the authors of the "single-sector" models [11,12] consider a class of theories in which DSB can be argued convincingly, and in which the first two generations of the MSSM arise as composite states ($P\bar{U}$) of a strongly coupled gauge theory. The fields $\bar{U}$ acquire large F-terms, so that the composites ($P\bar{U}$) feel the SUSY-breaking directly. The first and second generation scalars get large masses, whereas the fermion composites remain massless due to chiral symmetries. Since the $\bar{U}$ fields also carry Standard Model charges, they communicate SUSY-breaking to the rest of the MSSM through gauge mediation. The scalar masses for the first and second generation composite scalars ($P\bar{U}$) are given by $m_\phi^2 \sim F^2/M^2$, where the messenger scale M is the scale of the strong internal dynamics, corresponding to the Kaluza-Klein scale (9) in the gravitational dual.

Taking into account the parameters chosen in (8), the messenger scale is thus

$$M = 110 \text{ TeV}. \tag{10}$$

We will assume $F \approx M$, as is common in theories where the messengers couple strongly to the DSB sector. We also require a large enough F/M in order to have a viable spectrum, and this too leads to $F \approx M$. In particular, we choose $F/M = 90$ TeV.

The other ingredient that is needed to compute the effects of gauge mediation is the number of messengers, N_m. In practice we set $N_m = 2$, since this gives rise to an attractive LHC phenomenology and satisfies the experimental constraints that will be discussed below. We note that the $B\mu$ term and A terms are generated radiatively, with the boundary condition that they vanish at the messenger scale (10). This is fairly constraining and significantly influences the model parameters. In particular, the model is adjusted so as to obtain viable electroweak symmetry breaking and the lightest Higgs mass.

2.4 The particle mass spectrum

In Table 2 we show the complete soft mass spectrum using the two-loop RGE code Softsusy[10], for the values of the parameters given in (8), and $\mu < 0$ for the Higgsino mass parameter. Boundary conditions are imposed at the messenger scale (10), and the bulk soft masses calculated from (5) are added in quadrature to the gauge mediation masses at that scale. Softsusy automates a self-consistent determination of the thresholds for the superpartner spectrum, taking into account one- and two-loop effects. The gravitino mass is obtained from the standard formula $m_{3/2} = F/(\sqrt{3}\, m_P) = 2.35$ eV.

Note that these are only the masses for the lightest modes, which are zero modes in the AdS_5 limit. The Kaluza-Klein modes are at the $\mathcal{O}(100)$ TeV scale. The heavy first and second generation scalar masses arising from the bulk 5D calculation represent nonperturbative masses in the 4D dual theory that are difficult to calculate directly in the strongly coupled gauge theory.

2.5 LHC signal

The gravitino is the LSP, which means that in the single sector model the lightest neutralino, $\tilde{\chi}_1^0$, is the NLSP. Because the messenger scale is relatively low, the decay length of $\tilde{\chi}_1^0$ is less

Table 2: Particle mass spectrum of the example single-sector model described in the text.

$\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_{eL}$	10160, 10150, 10160 GeV
$\tilde{\mu}_L$, $\tilde{\mu}_R$, $\tilde{\nu}_{\mu L}$	5145, 5130, 5145 GeV
$\tilde{d}_L$, $\tilde{d}_R$, $\tilde{u}_L$, $\tilde{u}_R$	5905, 5885, 5970, 5890 GeV
$\tilde{s}_L$, $\tilde{s}_R$, $\tilde{c}_L$, $\tilde{c}_R$	5905, 5885, 5970, 5890 GeV
$\tilde{g}$	1615 GeV
$\tilde{b}_1$, $\tilde{b}_2$, $\tilde{t}_1$, $\tilde{t}_2$	1354, 1369, 1253, 1369 GeV
$\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_{\tau L}$	511, 630, 633 GeV
$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$	478, 593 GeV
$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$	288, 480, 511, 598 GeV
h^0, A^0, H^0, $H^{\pm}$	115, 646, 646, 651 GeV
$\tilde{G}$	2.35 eV

than 1 mm. This leads to the signal $pp \to 2\gamma + \not{E}_T$ (two hard photons and missing transverse energy) at the LHC. The study of the diphoton signal can be performed using PYTHIA (version 64.08).[13]

Most of the background in the diphoton channel can be removed by cuts on $\not{E}_T$ and p_T, since Standard Model diphoton events are predominantly of low p_T and $\not{E}_T$. Hence we impose the following kinematic cuts to reduce background:

$$p_{T,\gamma} \geq 40 \text{ GeV}, \qquad \not{E}_T \geq 60 \text{ GeV}. \tag{11}$$

The results are shown in Fig. 1. It can be seen that backgrounds (dashed) are orders of magnitude smaller than the signal (solid). With 1-10 fb^{-1} of data, virtually no background events occur. The simple $p_{T,\gamma}$ and $\not{E}_T$ cuts (11) suffice to remove virtually all SM backgrounds for the diphoton plus missing energy signal. Discovery of the example model within the first 10 fb^{-1} of well-understood data is a certainty, and would occur during the first few years of the LHC experiment.

3 Conclusion

We have presented a 5D dual gravity model of 4D single-sector supersymmetry breaking models. These models naturally explain the scale of supersymmetry breaking and the fermion mass hierarchy without invoking a messenger sector. They lead to a distinctive particle spectrum consisting of heavy ($\mathcal{O}(10\,\text{TeV})$) first and second generation squark and slepton masses. The remaining sparticles are lighter ($\mathcal{O}(\text{TeV})$) so that at low energies only the gluinos, charginos, neutralinos and third generation squarks and sleptons will be accessible at the LHC. The LSP is the gravitino. The most striking signal at the LHC is from diphotons and missing energy, which will be easily detectable after 1-10 fb^{-1} of "well-understood" data is accumulated.

The dual 4D interpretation of our model is that the first two generations of fermions and bosons would be composite states of some strongly coupled gauge theory ("superglue") that is responsible for both the scale of supersymmetry breaking via dimensional transmutation and the fermion mass hierarchy via large anomalous dimensions for fermionic operators in the gauge theory. The remaining particles are elementary fields that couple weakly to the composite supersymmetry breaking sector. This holographic interpretation is qualitatively identical to single-sector models that were explicitly constructed in four dimensions[11,12]. Our 5D model not only has a calculational advantage over 4D strongly coupled gauge theories, where at best only naive dimensional analysis estimates are possible, but also uses the AdS/CFT correspondence to identify the ratio of the Planck scale to the scale of supersymmetry breaking with the warp factor and the fermion mass hierarchy as arising from wavefunction overlap in the bulk.

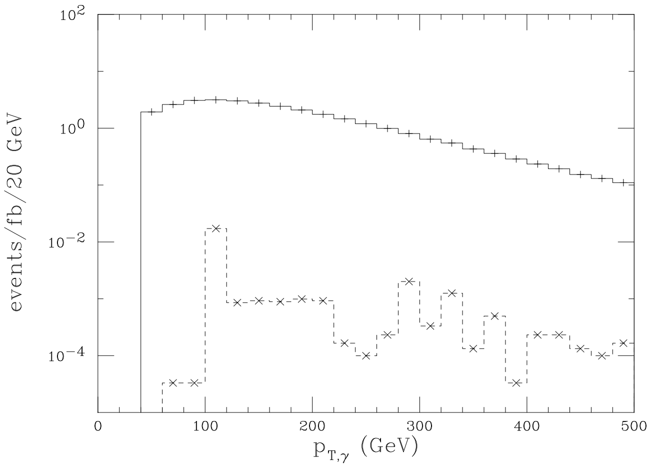

Figure 1: Comparison of the single-sector diphoton signal (solid) to background (dashed) where cuts (11), have been made, removing virtually all the background.

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