Phenomenology of a Constrained Standard Model from an Extra Dimension

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We describe a highly predictive model for supersymmetry breaking in 5 dimensions. We develop its phenomenology and the capabilities for discovery and measurement at various colliders.

I. INTRODUCTION AND THEORETICAL MOTIVATION

Supersymmetry (SUSY) is the leading candidate for physics beyond the Standard Model (SM) because it stabilizes the Higgs mass against quadratically divergent radiative corrections. Since no evidence for superpartners has been found, supersymmetry cannot be exact. Breaking supersymmetry in an experimentally viable way is therefore the premiere stumbling block towards constructing realistic low energy supersymmetric models.

The usual approach to breaking supersymmetry is to write a low energy effective theory, the minimal supersymmetric standard model (MSSM), with mass and coupling terms that break supersymmetry "softly". This soft breaking introduces over a hundred new parameters with no *a priori* guidance as to their size. The vast majority of this parameter space is excluded by stringent experimental constraints on flavor-changing neutral current processes. Furthermore, an extra Higgs doublet (supermultiplet) is necessary for consistency of the model, allowing the supersymmetry-preserving mass term $\mu H_u H_d$ in the superpotential. Electroweak symmetry breaking requires μ of order the electroweak scale, and there is no understanding why this *supersymmetric* mass term should be of the same order as the soft supersymmetry *breaking* mass terms. Thus, there are strong motivations to look for an organizing principle associated with supersymmetry breaking that can naturally explain the size and pattern of superpartner masses.

II. OVERVIEW OF MODEL

Recently, a new approach to low energy supersymmetry has been given by Barbieri, Hall, and Nomura [1]. Unlike the usual approach of postulating a low energy effective theory with so-called "soft" supersymmetry breaking terms added by hand, the entire SM is supersymmetrized in *five* dimensions. This means there are not only complete ($\mathcal{N}=1$ in 4D) supermultiplets consisting of the SM fields and their superpartners, but also a "mirror" set of supermultiplets consisting of mirror SM fields and their mirror superpartners. This is required since supersymmetry in 5D has double the number of supercharges than in 4D; i.e., an $\mathcal{N}=1$ supermultiplet in 5D has the field content of a single $\mathcal{N}=2$ supermultiplet in 4D, which is equivalent to *two* $\mathcal{N}=1$ supermultiplets in 4D.

The 5D spacetime is assumed to be compactified on an $S_1/(Z_2 \times Z_2')$ orbifold. Thus, the physical space is a line segment with two ends – the orbifold fixed points. At each fixed point the 5D fields can transform as either even or odd under the Z_2 symmetry associated with that fixed point, as shown in Fig. 1. The field content can be readily recognized as that of massless $\mathcal{N}=2$, 4D hypermultiplets and vector multiplets. The Kaluza-Klein (KK) reduction of this theory to 4D yields wave functions as sines and cosines of integer and half-integer multiplets of the size of the extra dimension, R, with a mass spectrum given in Fig. 2 (solid lines). Note that no supersymmetry is preserved across the entire dimension, and thus the zero modes consist *only* of

$$\begin{array}{ccc} & \psi_M(+,+) & \\ \phi_M(+,-) & & \phi_M^{c\dagger}(-,+) \\ & \psi_M^{c\dagger}(-,-) & \end{array} \qquad \begin{array}{ccc} & \psi_H(+,-) & \\ \phi_H(+,+) & & \phi_H^{c\dagger}(-,-) \\ & \psi_H^{c\dagger}(-,+) & \end{array} \qquad \begin{array}{ccc} & A^\mu(+,+) & \\ \lambda(+,-) & & \psi_\Sigma(-,+) \\ & \phi_\Sigma(-,-) & \end{array}$$

FIG. 1: Quantum numbers of the matter, Higgs and gauge multiplets under the two orbifoldings: (ψ_M, ϕ_M, ψ_M^c, ϕ_M^c) are the matter (fermions, sfermions, mirror fermions, mirror sfermions), (ψ_H, ϕ_H, ψ_H^c, ϕ_H^c) are the (Higgsinos, Higgs scalars, mirror Higgsinos, mirror Higgs scalars), and (A^μ, λ, ψ_Σ, ϕ_Σ) are the (gauge bosons, gauginos, adjoint fermions, and adjoint scalars). The (±,±) labels refer to the (Z_2, Z_2') parity properties, and thus determine the allowed wave functions of these fields.

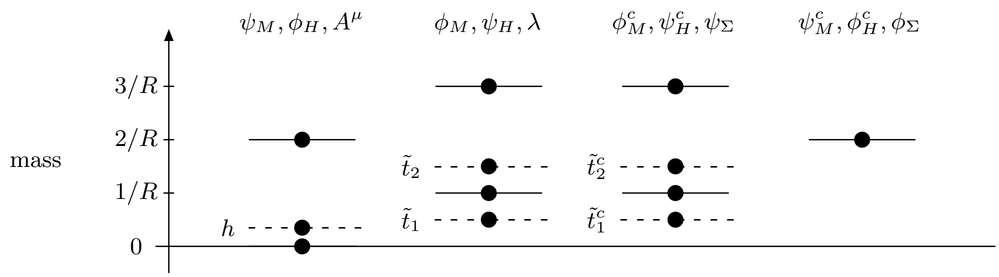

FIG. 2: Tree-level KK mass spectrum of the matter, Higgs and gauge multiplets. Physical light Higgs and top squarks mass eigenstates are shown in dashed lines.

SM fields. There is no μ term in this model, due to $\mathcal{N} = 1$ SUSY in 5D. The lightest Higgsinos and one Higgs doublet are massive, since they are odd under one or both of the Z_2's.

An interesting feature of this model is that the Higgs effective potential can be calculated essentially in terms of a single free parameter R, which comes from the loop contribution through the top Yukawa coupling. The only scale in the model, $1/R$, can be determined by the minimization condition of the Higgs effective potential, which gives $1/R \sim 370$ GeV [2]. This allows us to predict the physical Higgs boson mass as well as the superparticle and KK tower masses. The predicted Higgs mass is $m_h = (127 \pm 8)$ GeV. At the first excited level, there are two superparticles for each SM particle. Their masses shift from $1/R$ by electroweak breaking effects, such as fermion masses. The largest effect appears in the top squark sector, giving top squarks of masses $1/R \pm m_t \sim 210, 540$ GeV. The mass spectrum of the light Higgs and stops is also shown in Fig. 2 as dashed lines. Although possible additional brane localized interactions could shift the value of $1/R$ by as much as a few tens of percent, the Higgs and stop mass prediction is much less sensitive to the UV physics. The observation of the light stop, described below, and the measurement of its mass in the predicted range would be an unmistakable signature of this model.

III. DISCUSSION OF PHENOMENOLOGY

The low energy effective theory *below* $\sim 2/R$ consists of one Higgs doublet and two superpartners for each SM particle. The light Higgs has SM-like Yukawa couplings and WWh, ZZh gauge couplings. It can be produced at Tevatron Run II via the usual associated production of Wh or Zh, with the Higgs decays into $b\bar{b}$ or $\tau\bar{\tau}$. At LHC, $gg \to h \to \gamma\gamma$ would be the discovery channel for the light Higgs. However, the top Yukawa coupling could have a $O(10\%)$ deviation from the SM value due to the fact that it is a brane-localized interaction, which could be measured in a TeV scale e^+e^- collider via $t\bar{t}h$ associated production [3].

One characteristic feature of this model is that the two degenerate light stops [1] ($\tilde{t}_1$) with mass $m_{\tilde{t}_1} = 1/R - m_t$ are the LSPs, and are stable[2] if R-parity is exact. Since the stop carries color charge, once produced, it captures (anti)quarks in the detector matter to form a super-hadron. The lowest mass states [4] are $T^+ = \tilde{t}_1\bar{d}$, $T^0 = \tilde{t}_1\bar{u}$ and their charge conjugate states T^-, $\bar{T}^0$. Both neutral and charged states are sufficiently stable inside the detector since the β-decay of T^+ into T^0 is suppressed by the small mass splitting between them. $T^\pm$ appears as a stiff charged track with little hadron calorimeter activity, and hits the muon chamber. A heavy $T^\pm$ can be distinguished from a muon via large dE/dx or time-of-flight. T^0 and $\bar{T}^0$ could be identified as missing energies as they traverse the detector with little interactions.

The other supersymmetric particles (besides the heavier stop) are almost degenerate in mass: $\sim 1/R$, with small mass splittings coming from electroweak corrections or additional unknown brane kinetic terms. All of them cascade decay into stop LSPs. Squarks mostly decay via the channel

$$\tilde{q} \to q\tilde{g} \to q\tilde{t}_1 t \to q\tilde{t}_1 bW^\pm \to q\tilde{t}_1 b(l\nu/jj'), \tag{1}$$

where $\tilde{g}$ in the first step can be either on-shell or off-shell. The b-jet from the top decay and the leptons/jets from the W decay are energetic, while q from the original $\tilde{q}$ decay is usually soft because of relatively small

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[1] In the following, we use the symbol $\tilde{t}_1(\tilde{t}_2)$ to denote both degenerate light (heavy) stops.
[2] The cosmological constraints on an absolutely stable stop could be relaxed if we allow small R-parity violation.

mass splitting between the squark and gluino. For $\tilde{q}_L$, another decay channel

$$\tilde{q}_L \to q'\tilde{W}^{\pm} \to q'\tilde{t}_1 b \tag{2}$$

could be important (although suppressed by the weak coupling) if the heavy gluino is off-shell in process (1).

For $\tilde{b}_L$, a particular decay channel

$$\tilde{b}_L \to \tilde{t}_1 W^{\pm} \to \tilde{t}_1(l\nu/jj') \tag{3}$$

dominates when the process (1) is suppressed by the small mass splitting $m_{\tilde{b}_L} - m_{\tilde{g}}$.

For sleptons, a decay similar to (1) occurs through neutral Wino and Bino:

$$\tilde{l} \to l\tilde{W}^0/\tilde{B}^0 \to l\tilde{t}_1 t \to l\tilde{t}_1 b W^{\pm} \to l\tilde{t}_1 b(l\nu/jj'). \tag{4}$$

However, $\tilde{l}_L$ can also decay via the lepton analogue of (2), which is comparable with (4) for $m_{\tilde{W}} < m_{\tilde{l}}$ and dominates if $m_{\tilde{W}} > m_{\tilde{l}}$.

The gluino can decay via $\tilde{g} \to t\tilde{t}_1,\ b\tilde{b}_L,\ q\tilde{q}_L,\ q\tilde{q}_R$, either on-shell or off-shell, with subsequent decays of the t, $\tilde{b}_L$, $\tilde{q}_L$ or $\tilde{q}_R$ as described above. The generic decay products would be $\tilde{t}_1$+b+$(l\nu/jj')$+soft jet/lepton. Decays through $b\tilde{b}_L$ could lead to $\tilde{t}_1$+$(l\nu/jj')$+soft b if the $\tilde{b}_L$ decays via (3), or $\tilde{t}_1$+b+soft jet is also possible if $\tilde{q}_L$ decays via (2).

There are three *Dirac* neutralinos/charginos, in contrast with the usual MSSM with four Majorana neutralinos and two Dirac charginos. The mass eigenstates are usually a mixture of gauginos and Higgsinos, with a small mass splitting of roughly 12 GeV (18 GeV) between the lightest one and the two heavier neutralinos (charginos) [1]. The dominant decay channel for charginos is $\chi^{\pm} \to b\tilde{t}_1$, leading to a clean signal of (track or missing energy)+b jet. Neutralinos decay similarly to gluinos or via $\chi^0 \to \chi^{\pm}W^{\mp}$ with subsequent decays of $\chi^{\pm}$ and $W^{\mp}$.

The heavier stop $\tilde{t}_2$ with mass $m_{\tilde{t}_2} = 1/R + m_t$ can decay via

$$\tilde{t}_2 \to \tilde{t}_1 Z \to \tilde{t}_1(2l/2\nu/2j),\ \ \tilde{t}_2 \to \tilde{t}_1 h \to \tilde{t}_1 b\bar{b},\ \ \tilde{t}_2 \to \tilde{b}_L W^{\pm} \to \tilde{t}_1 2(l\nu/jj')\ +\ [b \text{ if } \tilde{b}_L \text{ decays via (1)}]. \tag{5}$$

The heavy Higgs, with mass $m_H \sim 2/R$, decays through $t\bar{t}$ like a usual heavy SM Higgs, while $H \to WW$ is forbidden due to the non-conservation of the fifth dimensional momentum. The discovery of the KK tower of SM particles (heavy quarks, leptons, gauge bosons and their mirror partners) would be strong evidence for the existence of TeV-scale extra dimensions. However, they are unlikely to be pair-produced at a TeV-scale e^+e^- collider. For a hadron collider, the cascade decay chain is complicated and it is hard to distinguish the signal from the large background. The discussion of the phenomenology of the heavier states is therefore left out in the current work.

IV. EXPERIMENTAL CAPABILITIES

A. Tevatron Run II

A heavy, stable charged particle (CHAMP) such as the $T^+(T^-)$ predicted by the model will move slowly through the detector after it has been produced, losing large amounts of energy via ionization as it travels. The CDF Run I search [5] for these types of particles was based on the measurement of this energy loss by the tracking system. The search found no evidence for the production of CHAMPS, and lower mass limits of ∼200 GeV were set in the context of a heavy quark model [6]. The limit in the context of SUSY models with a long-lived stop is currently being evaluated.

Both the CDF and DØ detectors have been upgraded in preparation for Run II. The CDF upgrade includes a time-of-flight (TOF) detector [7]. With the TOF one can measure directly that a CHAMP moves more slowly than a lighter particle at the same momentum. Furthermore, TOF can distinguish between heavy and light particles at higher momentum than is possible with energy-loss measurements. The CDF CHAMP search at Run II will therefore be based on measurements made by the TOF system. DØ plans to use dE/dx at the trigger level and their muon system for TOF [8].

Studies have been performed using Pythia [9] and the full CDF detector simulation to produce CHAMP Monte Carlo samples. The transverse momentum (p_T) distribution for a 200 GeV CHAMP is shown in Figure 3a. The p_T is large, almost always greater than 50 GeV. The pair production of CHAMPs will thus leave two high-p_T tracks in the detector as a signature. In order to take advantage of this fact a high-p_T two-track trigger has been developed to select events from the Run II data. The trigger requires 2 isolated tracks with $p_T > 10$

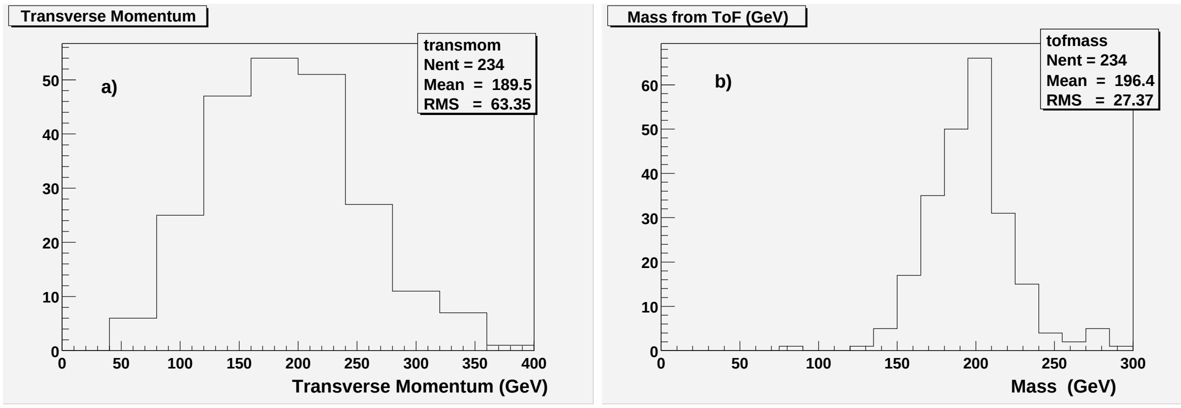

FIG. 3: Monte Carlo distributions for a 200 GeV CHAMP at Run II of the Tevatron. (a) The transverse momentum after detector simulation. (b) The mass after detector simulation. This mass has been reconstructed by combining the momentum measurement with the TOF information.

GeV. For a 200 GeV CHAMP, the trigger has been found to be 37% efficient and the rate from background (after subtracting the rate from other triggers) has been estimated to be less than 10 nb at the nominal Run II luminosity of $10^{32}\ cm^{-2}s^{-1}$. Most signal events which fail this trigger do so because one or both of the CHAMPs in an event do not go through the fiducial tracking volume. In order to increase the trigger efficiency, a high p_T single track trigger is also being developed.

Events that are selected by the triggers will be analyzed to identify particles with a large TOF. This information can then be used with the momentum obtained from the tracking system to measure the mass of the particle in question. Figure 3b shows this measured mass for a 200 GeV CHAMP Monte Carlo sample and demonstrates that such particles can be reconstructed with a resolution of about 25 GeV. The dominant effect is the uncertainty inherent in measuring the transverse momentum for tracks with very little curvature.

In this model, the cross section for the pair production of light stops is about 0.6 pb [10], leading to about 600 events per year at nominal luminosity.[3] Triggerable events would have one or two high-p_T isolated tracks; events with two neutral T^0 from direct production might be impossible to trigger on unless other appreciable activity is present. The scalar nature of the top squark could be confirmed by the angular distribution of the differential cross section $\mathrm{d}\sigma/\mathrm{d}\cos\theta$. The measurement of the light stop mass in the predicted range with twice the standard cross section would be compelling evidence for this model.

The cross section for $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$ production ranges from 0.1 to 1 pb in this model [11]. The final decay products always include two $\tilde{t}_1$, which can be triggered on as discussed above. In addition, there will be other objects that can be used to distinguish these events from direct stop pair production. These include two energetic b jets (except for the case of $\tilde{b}_L$ which decay via Eq. (3)), possible energetic leptons, $\not{E}_T$ (from neutrinos), and jets coming from decays of the intermediate W. Alternative triggers based on these objects should be useful in selecting events containing two neutral T^0, although distinguishing the signal from background requires detailed study. Finally, the production of sleptons, gauginos and higher mass states is less promising at the Tevatron in Run II.

B. LHC

Given the factor of seven increase in center of mass energy over Tevatron Run II, the LHC experiments will substantially extend the search for phenomena predicted by this model. In particular, the heavier mass states should be accessible. If the light Higgs is not discovered at the Tevatron it will be uncovered at the LHC in the usual channels. The heavy Higgs discovery should also be possible, as in the SM case, provided enough integrated luminosity is achieved [12]. Nevertheless, prospects for identifying either of these Higgs as unique to this model requires more study. One strategy would search for the heavy Higgs decaying via some of the predicted SUSY states.

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[3] The cross section is twice of that in Ref. [10] because of the multiplicity of the degenerate stops.

Light stop pairs can be produced copiously with a cross section of $\sim$ 150 pb [13]. As at the Tevatron, the charged stop hadrons should give rise to unmistakable detector signatures at the LHC, provided these events are selected by online triggers. For example, muon triggers that require low dE/dx in the tracking chambers might reject these events and thus should be avoided. Sensitivities to stop can be estimated from a CMS collaboration projection for a NLSP stau in GMSB models [14]. For a long-lived stau, the authors utilize the drift tubes in the muon barrel as a time-of-flight detector; the available timing window for this approach requires $1/\beta < 2$. A clear signal is observed: the efficiency grows with stau mass and the backgrounds considered are easily suppressed. For $M(\tilde{\tau}) = 636$ GeV the efficiency is 26%. The $T^{\pm}$ in this model could be identified in a similar fashion provided that they are in a charged state when traversing the muon chamber.

Squarks and gluinos can also be produced copiously and the charged tracks can be used for triggering, as before. In addition, events with neutral stop mesons could create a large $\not\!\!E_T$ event signature and be selected by triggers requiring an associated high-p_T lepton or jet. Even for the heavier stop states, hundreds of events per year could be observed, given the clean signal of $\tilde{t}_2$ decay via Eq. (5). The measurement of the mass difference between $\tilde{t}_2$ and $\tilde{t}_1$ (predicted to be $2m_t$) would be another check of the model. It should be noted that the prediction of doubled cross sections due to degeneracies of the various SUSY states would provide a means for differentiating these signals from typical SUSY models.

C. Linear Collider

A high-energy electron-positron Linear Collider (LC) running at center-of-mass energies of up to 1 TeV, would permit a number of measurements which would be essential to the confirmation of this model. With a mass predicted to be less than 250 GeV, pair production of the light stop would be copious even at a 500 GeV LC. The factor-of-two enhancement of the stop production cross section (due to the presence of the degenerate mirror state) could be measured to a statistical and systematic precision of order 1%. At higher energies, individual thresholds for the full spectrum of particles at the scale of $1/R$ could be detected. The resulting picture – a light stop plus a nearly-degenerate array of sfermions, Higgsino states, and gauginos, with each sfermion exhibiting a precise factor-of-two production rate enhancement – would represent an unambiguous signature for this model. Another unique characteristic – the Dirac nature of the neutralinos and charginos – could be confirmed by studying the helicity dependence of their production cross-sections. The associate production of $\tilde{t}_1\tilde{t}_2$ is possible at a TeV LC via s-channel Z-exchange.

Several other checks of the model, which are not possible at a hadron machine, could be performed at a Linear Collider. As mentioned above, the $O(10\%)$ deviation from the SM top Yukawa coupling could be measured to 1-2σ at a 1 TeV LC [3]. The chiral composition of the stop mass eigenstates could also be confirmed by exploiting the beam polarization. All in all, the ability to individually detect and precisely measure the properties of each of the 1/R-scale states, including those (such as sleptons) which are not accessible to hadron machines, makes the complementary information provided by the LC an essential component of the confirmation of the model's characteristic phenomenology.

V. SUMMARY

We have described a model for supersymmetry breaking in 5 dimensions and developed its phenomenology and the capabilities for discovery and measurement at various colliders. Discovery of the predicted states is possible at the LHC and perhaps at the Tevatron in Run II. The degeneracy of each state leading to factor-of-two enhanced sfermion cross sections could also be measured. However, detailed measurements at a high-energy LC will be necessary to confirm this model. The discovery of the Kaluza-Klein tower of SM particles (heavy quarks, leptons, gauge bosons and their mirror partners) would constitute strong evidence for the existence of TeV-scale extra dimensions.

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