The More Minimal 
Supersymmetric Standard Model

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Effective Supersymmetry is presented as a theory of physics above the electroweak scale which has significant theoretical advantages over both the standard model and the Minimal Supersymmetric Standard Model (MSSM). The theory is supersymmetric at short distances but differs significantly from the MSSM. Flavor symmetry violation is intimately related to supersymmetry breaking. There is a new physics scale $\tilde{M} \sim 5–20$ TeV which sets the mass of the first two sparticle families. Supersymmetric sources of CP violation and flavor changing neutral currents for the first two families are suppressed. Effective Supersymmetry can be implemented with automatic suppression of baryon and lepton number violation and a dynamically generated $\mu$ term, while maintaining naturalness in the Higgs sector. There are implications for new particle searches, flavor and CP violation experiments, as well as for the construction of theories of flavor and dynamical supersymmetry breaking.

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1. Introduction

Despite the success of the $SU(2)_L \times U(1)_Y$ theory of electroweak interactions, the mechanism of electroweak symmetry breaking remains obscure. A multitude of models have been constructed to explain this symmetry breaking, but none of them are experimentally confirmed nor theoretically compelling. The three most popular approaches are the standard model, the Minimal Supersymmetric Standard Model (MSSM), and technicolor. Each approach has its virtues as well as its problems. In this Letter we attempt to systematically combine the best features of each of these approaches, while avoiding their respective defects. We employ a “bottom up” line of reasoning, in which we de-emphasize the role of short distance dynamics, instead explaining the physics we observe in terms of “accidental” or “effective” symmetries. Such symmetries are global symmetries obeyed by the lower dimension operators of an effective field theory as a consequence of the gauge symmetry and particle content of that theory, without being symmetries of the fundamental dynamics.

We are prompted by this reasoning to postulate that the world possesses such an effective supersymmetry at scales below 1 TeV, which explains how the electroweak hierarchy can be stable; the meaning of effective supersymmetry will be made more precise below. The theory which we construct (and which we call Effective Supersymmetry) is quite unlike the MSSM, since we require it to possess additional effective symmetries which help to explain the absence of flavor changing neutral currents (FCNC), lepton flavor violation, baryon (B) and lepton (L) number violation, and electric dipole moments (EDMs) of the neutron and electron. Effective Supersymmetry has distinctive theoretical and experimental consequences: there are new interactions for quarks and leptons characterized by an undetermined scale $\Lambda$ and supersymmetry breaks at a scale $\Lambda_{SUSY} \equiv \sqrt{F_s} \leq \Lambda$. The scale $\tilde{M} \equiv F_s/\Lambda$ is fixed to be 5–20 TeV. It is the existence of these new scales above $M_W$ which makes an analysis of effective symmetries both nontrivial and fruitful. Between the scales $\Lambda$ and $\tilde{M}$ the particle content of the effective theory is that of the MSSM, with SUSY spontaneously broken. However most of the scalar fields which would be present in the MSSM have a mass of size $\tilde{M}$—in particular, all of the sparticles of the first two generations. The SUSY partners with masses below a TeV consist of the gluinos, charginos, neutralinos and third family squarks and sleptons.

The line of reasoning leading to Effective Supersymmetry begins with an examination of the strong and weak points of the three basic electroweak symmetry breaking models.

1.1. The Standard Model

There are no compelling discrepancies between the standard model and experiment. Furthermore no \textit{ad hoc} global symmetries are required to explain the absence of proton decay, lepton number violation, and the observed pattern of extremely small FCNC—all of
these features result from accidental symmetries of the renormalizable operators allowed by gauge invariance. This is a very beautiful feature of the standard model, but as an effective theory one must assume that non-renormalizable operators (which do not enjoy the accidental symmetries) are greatly suppressed or absent from the theory.

The standard model has another remarkable feature: Tr $Y = 0$, where $Y$ is the generator of hypercharge on the left handed fermions. This allows charge quantization to be explained via gauge unification into a non-Abelian symmetry $\mathcal{G}$. Major deficiencies of the standard model include its lack of explanations for the absence of strong CP violation, and the tremendous hierarchy between the weak and Planck scales. Also unexplained are the patterns of lepton and quark masses and mixing angles built into the Yukawa interactions; the Yukawa couplings have been regarded as “flavor spurions” parameterizing the low energy effects of the breaking of chiral flavor symmetries at short distance (see for example [2]). Each of these deficiencies may imply new physics at scales (perhaps much) higher than the electroweak scale. However the most serious criticism of the standard model is that it cannot be valid above a scale of about 1 TeV, without an unnatural cancellation between short and long distance contributions to the Higgs mass $\mathcal{M}$.

A fundamental dichotomy haunts modifications of the standard model: new particles and interactions at the TeV scale which cure the naturalness problem risk destroying the accidental symmetries of the standard model which are so successful in explaining phenomenology.

1.2. The Minimal Supersymmetric Standard Model (MSSM)

The MSSM [4] has 122 free parameters [5] which, not surprisingly, can be chosen to agree with experiment. However the model provides no explanation for experimentalists’ failure to observe B or L violation, large FCNC, or EDMs—these features arise by a conspiratorial adjustment of parameters, often with an appeal to new exact and approximate global symmetries. It does not address the origin of the scale of weak symmetry breaking, nor the scale of soft supersymmetry (SUSY) breaking. Its best feature is that it is natural up to extremely short distances [26]: with any cutoff below $M_{pl}$ all quantum corrections to MSSM parameters are smaller than the parameters themselves.

1.3. Dynamical Electroweak Symmetry Breaking

Technicolor [8] aims to eliminate the need for unnatural scalars below $M_{pl}$. This model takes as its inspiration QCD—which naturally explains the small ratio $\Lambda_{QCD}/M_{pl}$ in terms of nonperturbative dynamics—and postulates that the small number $M_W/M_{pl}$ is similarly generated nonperturbatively by new strong interactions. However it is not apparent how
to construct an experimentally acceptable renormalizable model without re-introducing scalars. Thus viable models tend to suffer from the disease they sought to cure.

2. Effective Supersymmetry

We desire a theory that incorporates all of the positive attributes listed above: nonperturbative generation of the electroweak hierarchy, unifiable weak hypercharge, accidental B and L symmetries, suppression of FCNC and CP violation, and agreement with experiment. We now present the details of our argument that a minimal extension of the standard model that incorporates these successful features is Effective Supersymmetry.

2.1. The Observed Spectrum and Naturalness

We begin by adopting fundamental scalar fields and Yukawa interactions which have the virtue of being successful at reproducing the intricate pattern of masses and mixing angles observed in Nature, and which can be made consistent with precision electroweak measurements. Once light scalar fields are admitted to the theory, the large hierarchy between the weak and Planck scales can be stable against radiative corrections if one embraces supersymmetry as well.

It is important for our subsequent discussion to address the question of how much supersymmetry is enough to maintain naturalness. As was pointed out when the MSSM was introduced in [6], exact supersymmetry is not absolutely necessary: a theory with soft SUSY violating operators at the weak scale is sufficient for maintaining naturalness up to the GUT scale. However, from a low energy (e.g. effective field theory) point of view—for which the GUT scale is irrelevant—naturalness can be maintained even with hard (dimension 4) SUSY violation up to a scale significantly higher than the “t Hooft scale”, \( \sim 1 \text{ TeV} \). Such an effective theory must derive from a more fundamental theory which is supersymmetric at high energies, and so the effective theory can be thought of as the result of integrating out heavy particles from a softly broken supersymmetric theory.

In an attempt to raise the naturalness scale above 1 TeV, the first problem one encounters is the possibility of a tree-level Fayet-Iliopoulos term \( \Box \) for weak hypercharge, which contributes directly to the Higgs mass squared \( \Box \). To prevent such a term with a natural coefficient of \( M^{2}_{pl} \) in the full theory, we deduce that

\[
\text{Tr} \ Y = 0 , \tag{2.1}
\]

where the trace is over all particles below the Planck scale. Thus this nontrivial constraint (which is satisfied by the standard model) is not only required for the gauge symmetry

\[1\] The importance of the Fayet-Iliopoulos term was emphasized in [10], in the context of naturalness of SUSY GUTS.
To be unifiable, but is also a prerequisite for maintaining naturalness. Preventing such a term in the full theory is not sufficient, however, since integrating out heavy particles can induce a (finite) $U(1)_Y$ Fayet-Iliopoulos term proportional to $(\alpha_1/4\pi)\text{Tr} Y M_h^2$, where $M_h^2$ is the mass squared matrix of any heavy scalars one has integrated out. Assuming that the scale $M_h$ is much greater than 1 TeV, it follows that naturalness restricts the heavy spectrum to satisfy

$$\text{Tr}(Y M_h^2) \simeq 0 ; \quad (2.2)$$

this constraint can be satisfied if the heavy particles transform as multiplets of a non-Abelian global symmetry that contains $Y$ (such as $SU(5)$), or if $M_h$ is proportional to some charge $Q$ which has no $Q^2Y$ anomaly, such as $Q = (B - L)$. Given eq. (2.1), it follows that the low energy spectrum will also exhibit traceless hypercharge; eq. (2.2) then prohibits generation of a Fayet-Iliopoulos term in the effective theory proportional to $(\alpha_1/4\pi)M_h^2$ (where $M_h$ serves as the cutoff of the effective theory).

In order to raise the naturalness scale of the effective theory above the 't Hooft scale, quadratic divergences must cancel at least to order $\alpha/4\pi$ in the effective theory. This is tantamount to requiring that all one-loop quadratic divergences cancel in the limit that the Yukawa couplings of all the quarks and leptons, with the exception of the top, are set to zero. (An exception occurs in the large tan $\beta$ regime with two light Higgs doublets, in which case the bottom Yukawa coupling must be retained as well). This is possible so long as the spectrum below $\sim 1$ TeV includes left- and right-handed top squarks, a left handed bottom squark, Higgsinos, a bino and a wino, all with dimension 4 interactions as given by SUSY, up to order $\alpha/4\pi$ corrections. Although not required for one-loop naturalness, theories with light winos and binos typically have a light gluino as well. Note that both the up- and down-type Higgsinos are required to maintain gauge invariance in the effective theory due to the triangle anomaly, even if there is only a single light scalar Higgs doublet.

We conclude that the above spectrum provides a minimal effective supersymmetry at low energy which eliminates one-loop quadratic corrections to the Higgs mass squared. Two-loop graphs give 20 TeV for the scale where naturalness would break down without a supersymmetric spectrum. The scale $\tilde{M}$ of the first and second generation sparticles must therefore satisfy

$$\tilde{M} \lesssim 20 \text{ TeV} . \quad (2.3)$$

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2 This bound assumes that contributions to the Higgs mass from 2-loop diagrams computed with a cutoff $\tilde{M}$ should be $\lesssim M_Z$. Our bound is less stringent than the 2–5 TeV bound given in ref. [10] because our bottom-up approach does not assume the SUSY breaking parameters are generated at the Planck scale, and so does not include the effects of renormalization group running from $M_{GUT}$.
2.2. The electroweak hierarchy

While supersymmetry stabilizes the electroweak hierarchy, it does not explain it. Technicolor offers the most compelling explanation for this hierarchy, namely that it arises from dynamical symmetry breaking. Therefore we extend the gauge symmetries of effective supersymmetry to $G \times SU(3) \times SU(2) \times U(1)$, where $G$ is a gauge group containing new strong interactions—which we call “superglue”—which generates the observed hierarchy nonperturbatively. The agreement between precision electroweak experiments and standard model calculations implies that the scale of these new superglue interactions must be well above $M_W$, and that superglue interactions decouple. Because of the necessary relation between the scale of weak symmetry breaking and SUSY breaking, we postulate that superglue is responsible for breaking both symmetries: the potential for the Higgs scalar is determined by supersymmetry breaking terms. Note that the SUSY breaking and electroweak breaking scales, although related, may be proportional to different powers of the superglue scale, such as occurs in SUSY breaking models where non-renormalizable terms in the superpotential are responsible for supersymmetry breaking (see, e.g. [11]).

An important consequence of enlarging the standard model gauge group is that in general there are new accidental symmetries. Thus the symmetry group above $\Lambda$ is $G \times SU(3) \times SU(2) \times U(1) \times A$, where $A$ is the group of such accidental symmetries; the imposition of $G$ gauge symmetry can make $A$ much larger than the accidental symmetry group of the MSSM and can account for a number of the standard model’s successes which are quite mysterious in the MSSM.

2.3. Flavor Changing Neutral Current Constraints

In supersymmetric theories with new interactions for the first two families at a scale $\Lambda$, the existence of non-renormalizable FCNC operators suppressed by powers of $\Lambda$ typically constrain this scale to be larger than several hundred TeV. However the constraints become much more severe with softly broken SUSY, which allows FCNC through super-renormalizable interactions in the form of squark masses and trilinear squark couplings. In the absence of any compelling model of flavor that suppresses these dangerous interactions, a straightforward explanation for why FCNC are not observed is that the squarks and sleptons which mediate FCNC are heavy and have decoupled from low energy physics [12]. The large approximate flavor symmetry we observe in the world then becomes an accidental symmetry as it is in the standard model, rather than the result of conspiratorial short distance physics.

To suppress CP conserving FCNC without any universality [9] or alignment [13] in this way requires the first and second family squarks and sleptons to have masses of size $\tilde{M}$ satisfying [12,14,15]

$$\tilde{M} \gtrsim 50 \text{ TeV}.$$ (2.4)
If all CP violating phases are maximally large, suppression of CP violating $\Delta S = 2$ interactions imposes a stronger bound\(^3\),

\[ \tilde{M} \gtrsim 600 \text{ TeV} \quad (2.5) \]

On the other hand, naturalness (eq. (2.3)) requires the first two families of squarks and sleptons to be lighter than $\sim 20$ TeV and constrains the remaining spectrum below $\sim 1$ TeV as described in §2.1.

With first two family squark masses of $\sim 20$ TeV, and with the mild assumptions of squark university or alignment at the 20% level and CP violating phases of $O(0.1)$, it is possible to satisfy the FCNC and CP constraints. Specific models of the flavor hierarchy may produce more universality or alignment, and restrict new CP violation as well \cite{16}, for instance in the model of ref. \cite{14} FCNC are adequately suppressed if the first two family squarks have 5 TeV masses.

We conclude that with top, left handed bottom squark, chargino, and neutralino masses below 1 TeV, and the first two family squark and slepton masses in the range $\tilde{M} = 5\text{--}20$ TeV \(^4\), we are able to combine two of the best features of the MSSM and standard model respectively: naturalness of the electroweak symmetry breaking scale, and suppression of FCNC. A nontrivial constraint on the heavy spectrum of the theory is eq. (2.2), which can result from either the accidental symmetry group $A$, or from a coupling between sparticles and SUSY breaking dynamics which is proportional to a charge $Q$ without a $Q^2Y$ anomaly. We show below that this novel spectrum can be achieved by having the first two families of squarks and sleptons couple directly to the SUSY breaking dynamics, while the third family does not.

2.4. CP Violation

Effective Supersymmetry also cures the SUSY CP problem. The MSSM with universal soft masses has two CP violating phases which are strongly constrained by the absence of observable EDMs \cite{17}; with non-universal masses the number of independent CP violating phases increases to 43 \cite{5}. However if the first two families of sparticles are heavier than $\sim 10m_{\tilde{g}}$ (where $m_{\tilde{g}}$ is the gluino mass) while third family squarks are heavier than $\sim 550$ GeV \cite{12,14}, then none of these phases lead to unacceptable EDMs for the electron or the neutron, even if CP violation is maximal. On the other hand this may allow detectable CP violation at the $B$ factory or in top production. We discuss this further at the end of this Letter where we explore experimental implications of Effective Supersymmetry.

\(^3\) The bounds (2.4) and (2.5) are approximate. There are $O(1)$ uncertainties due to unknown short distance physics and to long distance QCD.

\(^4\) In many clever models with highly restrictive global symmetries, even lighter squark masses are acceptable. We disregard this possibility since such symmetries appear contrived.
2.5. B violation

In the standard model, the observed stability of nucleons is explained by an accidental baryon number symmetry. Such an explanation is lacking in the MSSM where disastrous dimension 4 and 5 B violating operators have to be excluded by the imposition of global symmetries. The dimension 5 operators are particularly troublesome as they have to be suppressed by a scale greater than $M_{pl}$ to be phenomenologically acceptable.

If we adopt the standard model solution, and B conservation arises as an accidental symmetry, we must assume that the new gauge group $G$ forbids dimension 4 and 5 B violating operators in the full theory. Since at least two generations are necessary to construct any dimension 4 or 5 B violating operator, this suggests that at least the first two generations of quark superfields carry $G$ charges. The new gauge sector $G$ includes the superglue interactions responsible for $SU(2) \times U(1)$ and SUSY breaking, but may include additional gauge interactions. In one realization of Effective Supersymmetry, $G$ is just the superglue group, and the first two quark and lepton generations are composites of constituents that carry superglue (explaining why they couple more strongly to SUSY breaking than the third family). Another possibility is that there is a spontaneously broken gauge interaction—either an Abelian or non-Abelian gauged flavor symmetry—which communicates SUSY breaking in the superglue sector to the quarks and leptons, and that this messenger interaction forbids low dimension B violating operators. In the next section we outline examples of these two realizations of Effective Supersymmetry. In both cases we obtain the squark spectrum advocated above, and suppression of B violation can be automatic.

2.6. L violation

The observed conservation of $e$, $\mu$, and $\tau$ lepton numbers is well explained in the standard model, where the lepton flavor symmetries are an accidental consequence of the gauge structure of the theory. In contrast, the gauge symmetries of the MSSM allow dimension 2, 3, and 4 lepton violating operators in the form of misaligned slepton mass matrices, as well as superpotential terms of the form $LH_u$, $QDL$ and $LLE$ ($L, E, Q, D$ and $H_u$ are the lepton doublet, conjugate electron, quark doublet, conjugate down-type quark, and up-type Higgs superfields respectively). These last three operators violate overall lepton number and can contribute to neutrino masses, while all of the operators can contribute to $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$. As in the case of FCNC discussed above, lepton violation in the slepton mass matrices is sufficiently suppressed if the first two generations of sleptons have masses $\gtrsim 4$ TeV \cite{3}. The absence of the dimension 3 and 4 superpotential operators above the scale $\Lambda$ can be understood once again if lepton flavor symmetries are part of the accidental symmetry group $\mathcal{A}$ of the full theory. This requires that an appropriate combination of the $L, E$ and $H_u$ fields transform under the group $G$. 
2.7. $SU(2) \times U(1)$ breaking

In addition to third generation squarks, gauginos and Higgsinos, the low energy Effective Supersymmetry spectrum must include at least one light scalar Higgs doublet, but not necessarily both doublets of the MSSM. In one composite realization of Effective Supersymmetry described in the next section, the $H_d$ doublet has a mass of the same scale, $\tilde{M}$, as the heavy squarks. This leads to a naturally large value for $\tan \beta$, of size $\sim \tilde{M}/M_W \sim O(100)$.

2.8. Summary

We conclude that Effective Supersymmetry can realize the best features of the standard model, the MSSM, and technicolor and its variants, with the following features:

1. The world is supersymmetric above $\sim 20$ TeV;
2. A new gauge group $G$ exists which contains a strongly interacting “superglue” sector that nonperturbatively generates the SUSY symmetry breaking scale $\sqrt{F_s}$ as well as the $SU(2) \times U(1)$ symmetry breaking scale. The only constraint on $\Lambda$ and $F_s$ is $\tilde{M} \sim 5$–20 TeV, where $\tilde{M} \equiv F_s/\Lambda$;
3. Above the scale $\Lambda$ matter fields (or their constituents, in a composite model) carry $G$ interactions which forbid renormalizable B and L violating operators, as well as dimension 5 B violation.
4. The first two generations couple more strongly to SUSY breaking than the third, and the respective squarks and sleptons are heavy, with masses at the scale $\tilde{M}$;
5. The top squarks and left-handed bottom squarks are much lighter, with masses $\lesssim 1$ TeV.
6. The weak gauginos and higgsinos also have masses $\lesssim 1$ TeV;
7. Naturalness allows the gluino to be heavier than 1 TeV. However if we assume that the gluino is an elementary particle which is weakly coupled at high energies, then it can not be strongly coupled to SUSY breaking and will also be lighter than $\sim 1$ TeV.
8. Only one linear combination of the two Higgs doublets of the MSSM need appear in the effective theory below $\tilde{M}$, while the upper bound on the lightest Higgs scalar is $\approx 120$ GeV (as in the MSSM).
9. The tau sleptons and right-handed bottom squark masses may be light, or as heavy as $\tilde{M}$; however the constraint (2.2) must be satisfied.

With these features, Effective Supersymmetry allows a natural gauge hierarchy, while succeeding where the MSSM fails: namely by simultaneously explaining how the world can be supersymmetric at high energies while looking so much like the standard model at low energies. Effective Supersymmetry ameliorates the MSSM’s serious problems with FCNC and excessive weak CP violation without assuming universality in the squark sector. Furthermore, it provides a simple framework for understanding the suppression of
B and L violation. In the next section we describe two different realizations of Effective Supersymmetry.

3. Realizations of Effective Supersymmetry

There are at least two distinct ways to implement Effective Supersymmetry: either the first two generations are composite with constituents that carry superglue, or else the matter fields are fundamental and communicate with the superglue sector through some gauged flavor symmetry with the first two generations coupling more strongly to SUSY breaking than the third. We now sketch these two realizations.

3.1. Effective Supersymmetry with composite quarks and leptons

The minimal extended gauge interaction necessary to implement Effective Supersymmetry is superglue alone. Then, as discussed above, B can arise as an accidental symmetry above $\Lambda$ if the first two generations of squarks and sleptons are composed of constituents carrying superglue; accidental L conservation requires a more model dependent charge assignment. The effective theory below the scale $\Lambda$ contains the superfields of the MSSM as well as superfields responsible for SUSY breaking, and operators of higher dimension suppressed by powers of $\Lambda$. The effective Kähler potential arising from nonperturbative dynamics is generic, containing all operators allowed by symmetry. In contrast the effective superpotential is known to be non-generic [18]. In order to suppress Fayet-Iliopoulos terms, we will assume the accidental approximate symmetry group $A$ contains a non-Abelian factor with hypercharge as a subgroup, which implies eq. (2.2). Thus $\text{Tr} \ Y$ must vanish separately on both the fundamental and composite particle sectors.

In the following discussion we demonstrate that Effective Supersymmetry can be realized if we assume that the gauge fields, the top and left-handed bottom superfields, and the up-type Higgs are neutral under superglue; the remaining particles in the effective theory below $\Lambda$ (those of the MSSM) are composites of preons which carry superglue. (There are at least six possibilities for which of the Higgs and third family particles are elementary, e.g. the $\bar{\tau}$ and $H_d$ superfields could also be elementary). In addition we assume that supersymmetry breaking has a weakly coupled, O’Raifeartaigh-like description in the infrared, as occurs in some dynamical SUSY breaking models [11,19,20].

The minimal realization involves a single composite chiral superfield $S$ with effective super- and Kähler potentials

$$W_S = \Lambda^2_{SUSY} S, \quad K_S = SS^\dagger + \frac{a_1}{\Lambda^2} S^3 S^\dagger + \text{h.c.} + \frac{a_2}{\Lambda^2} S^2 S^\dagger^2 + \ldots ,$$  (3.1)
where the \( \{a_i\} \) are \( \mathcal{O}(1) \) coefficients parameterizing unknown strong interaction effects. Note that \( \Lambda_{SUSY}/\Lambda \) is a model dependent parameter which varies from \( \mathcal{O}(1) \) to exponentially small in explicit examples; we treat it as an unknown. The theory breaks supersymmetry with \( \langle F_s \rangle = \Lambda_{SUSY}^2 \), while the scalar components of \( S \) get masses of order \( \tilde{M} \).

The most general Kähler potential for the matter fields in the effective theory below \( \Lambda \) is constructed by the following power counting:

\[
K_0 + \Lambda^2 K_I \left( \frac{c_i}{\Lambda}, \frac{\lambda_i f_i}{4\pi \Lambda} \right),
\]

where \( K_0 \) is the conventional renormalizable kinetic term, and \( K_I \) contains all non-renormalizable interactions. The \( \{c_i\}, \{f_i\} \) are the composite and fundamental superfields (and their conjugates), while the \( \{\lambda_i\} \) are dimensionless couplings between the fundamental fields and the preons in the theory above \( \Lambda \). In addition there may be small spurions associated with approximate symmetries of the preon theory.

We may expand the Kähler potential interactions coupling \( S \) and matter fields in powers of \( S \) as

\[
K_{eff} = \left( \frac{S}{\Lambda} + h.c \right) K^{(1)} + \frac{S^* S}{\Lambda^2} K^{(2)} + \ldots,
\]

where the \( K^{(i)} \) are functions of superfields of the form given in eq. (3.2). Below the scale \( F_s \), \( K^{(1)} \) contributes terms that can be written in supersymmetric form as an effective superpotential (as well as other operators); \( K^{(2)} \) contributes to SUSY violating scalar interactions (masses, trilinear couplings, as well as “hard” SUSY violating couplings).

Interactions between \( S \) and standard model gauge fields are of the form

\[
\left[ n_i \frac{\alpha_i S}{4\pi \Lambda} \mathcal{W}_i \mathcal{W}_i \right]_F,
\]

where \( n_i \) is a numerical factor proportional to the index of the gauge charge in the preon theory above the scale \( \Lambda \); one can easily imagine that the \( n_i \) are as large as \( \mathcal{O}(10) \).

Several salient features of the effective theory below \( \Lambda_{SUSY} \) arising from the operators (3.3) and (3.4) are:

1. \( SU(3) \times SU(2) \times U(1) \) gaugino masses that arise from the operator (3.4) are of size

\[
m_i = n_i (\alpha_i/4\pi) \tilde{M},
\]

with \( \tilde{M} \equiv F_s/\Lambda \).

2. \( LL \) and \( RR \) squark and slepton mass matrices for the first two generations come from a term in \( K^{(2)} \) of the form \( z_{ij} \Phi^*_i \Phi_j \) (where \( z_{ij} = \mathcal{O}(1) \)) which yields

\[
\tilde{m}_{ij} \sim z_{ij} \tilde{M}.
\]
3. Third generation $LL$ and $RR$ squark and slepton masses also arise from $K^{(2)}$ but are suppressed by perturbative couplings to the constituents of $S$—denoted here $\lambda_3$—and are given by $\sim \lambda_3/4\pi \tilde{M}$. For $\lambda_3 \sim 1$, the same size as the top quark Yukawa coupling, third family sparticles have masses over an order of magnitude less than their counterparts from the first two families.

4. SUSY breaking Higgs masses arise from $K^{(2)}$ as well. As $H_u$ is fundamental while $H_d$ is composite, their masses are given by

$$m_{H_d} \sim \tilde{M}, \quad m_{H_u} \sim \frac{\lambda_H}{4\pi} \tilde{M}, \quad (3.7)$$

where $\lambda_H$ parameterizes the coupling of $H_u$ to the constituents of $S$. It follows that there is a single Higgs in the low energy theory:

$$H = \sin \beta H_u + \cos \beta H_d^\dagger \quad (3.8)$$

with

$$\tan \beta \sim \frac{4\pi}{\lambda_H}. \quad (3.9)$$

5. The “$\mu$ term” (which contributes to Higgsino masses) comes from $K^{(1)}$—an example of the Giudice-Masiero mechanism [21]—and is the same size as $m_{H_u}$ given in eq. (3.7).

6. The scalar $H_uH_d$ mass term (the “$B\mu$ term”) comes from $K^{(2)}$ with size $\sim \lambda_H/4\pi \tilde{M}^2$.

7. Yukawa interactions can arise from both $K^{(1)}$ and the non-generic superpotential $W$. However the $b$ quark Yukawa coupling is $O(1)$ and must come from $W$.

8. SUSY violating trilinear scalar couplings can come from both $K^{(1)}$ and $K^{(2)}$, with maximum size $\tilde{M}\mu/\Lambda$. (They may be further suppressed by factors of $\lambda/4\pi$ or spurions). Note that these will be quite small for elementary scalar fields such as the top squark. For $\Lambda \gg \tilde{M}$, nonsupersymmetric trilinear terms are suppressed for all scalars, avoiding any problems with vacuum stability [22].

9. The fermion partner of $S$ becomes the massless Goldstino $G$; it serves as the longitudinal modes of the gravitino, which acquires a mass

$$m_{3/2} = \frac{F_s \sqrt{8\pi}}{\sqrt{3}M_{pl}}, \quad (3.10)$$

and has couplings proportional to $1/F_s$.

This theory is a successful realization of Effective Supersymmetry provided that $\tilde{M} = F_s/\Lambda \sim 5$–20 TeV (so that FCNC and CP violation are suppressed), $\lambda_H/4\pi \sim 10^{-2}$ (to provide the correct electroweak scale), and $\lambda_3/4\pi \sim 10^{-1}$ (to ensure a light enough stop). Note that eqs. (3.8), (3.9) imply $\tan \beta = O(100)$ and the light Higgs is mostly $H_u$, which involves no fine tuning in this theory.
3.2. Effective Supersymmetry with gauged flavor interactions

As another realization of Effective Supersymmetry we can consider a theory above the scale \( \Lambda \) in which the ordinary quarks and leptons carry only new weak gauge charges. These new weak interactions would then be responsible for communicating with the strongly interacting sector which breaks supersymmetry. As discussed above, to fully implement Effective Supersymmetry these interactions must serve double duty: they must forbid \( B \) and \( L \) violating renormalizable operators and they must distinguish the coupling of the first two generations to the SUSY breaking sector in a way which keeps the third family squarks light, while allowing the first two family squarks and sleptons to become heavy.

As one concrete example, we may consider a new Abelian gauge symmetry which appears anomalous (with a Green-Schwarz anomaly cancellation mechanism operating near the Planck scale \([23]\)) with only the first two families carrying a non-zero value of this charge. The first two families of squarks and sleptons would then get tree level masses from this \( U(1) \) gauge interaction, while the third family of squarks and sleptons would only receive masses at higher loop order or via supergravity, and would thus be naturally lighter. (Anomalous \( U(1) \)s which communicate non-perturbative SUSY breaking to the ordinary quarks and leptons in this way have recently been introduced in \([24]\).) In these models squarks receive comparable mass contributions from supergravity and this \( U(1) \) interaction. A suitable re-adjustment of the scales and \( U(1) \) charges involved could produce the Effective Supersymmetry spectrum.

4. Implications of Effective Supersymmetry

4.1. Flavor

The large value of \( \tan \beta \) obtainable in Effective Supersymmetry can explain the small \( m_b/m_t \) ratio without fine tuning. Furthermore, since the particles of the first two families carry gauge interactions different from the top, it is natural to try and relate this to an explanation for the lightness of these fermions. It is possible for the Yukawa couplings of the first or first two families to be generated radiatively and derive only from the Kähler potential terms in eq. (3.3). Kähler potential terms can give a contribution to effective fermion-Higgs couplings of order

\[
\lambda_{\text{eff}} \sim \frac{\mu}{\Lambda} \lesssim 10^{-2} . \tag{4.1}
\]

This may explain in part why the first two generations are much lighter than the top. If \( \Lambda \) is too large, Kähler potential contributions to fermion masses are small, and Yukawa

\[\text{[25]}\]

After completion of this work ref. \[25\] appeared, which overlaps with some of the ideas in this section.
interactions in the effective superpotential are required. In any case, flavor textures above \( \Lambda \) need not resemble those of the standard model.

Decoupling of flavor violation is a feature of the standard model, but not of the MSSM. A major advantage of Effective Supersymmetry is suppression of flavor violation for the first two generations. Thus the theory is much less contrained by FCNC and rare decay limits than the MSSM.

4.2. Unification

One of the great successes of the MSSM, the unification of couplings \([6,26]\), can be easily preserved in Effective Supersymmetry. If \( \Lambda \geq M_{\text{GUT}} \), this follows trivially, if the only new particles at \( \tilde{M} \) are the first two generation sparticles. If \( \Lambda < M_{\text{GUT}} \), knowledge of the effective theory above \( \Lambda \) is needed to determine whether coupling constants unify. Even for low \( \Lambda \) the coupling constant unification of the MSSM can be preserved provided that the accidental approximate symmetry group \( \mathcal{A} \) above the scale \( \tilde{M} \) contains a global \( SU(5) \) with the standard model gauge group as a subgroup, and, except for the Higgs doublets, particles come in approximately degenerate \( SU(5) \) multiplets. As discussed above such a scenario is desirable since it explains the absence of the \( U(1)_Y \) \&-term, eq. \((2.2)\), which would destabilize the hierarchy.

4.3. Cosmology

Gravitino properties depend on the scale \( \sqrt{F_s} \), since the gravitino eats the goldstino and acquires the mass given in eq. \((3.10)\). If \( \sqrt{F_s} \lesssim 10^{10} \) GeV, the gravitino is the lightest supersymmetric particle. Cosmological implications of a light gravitino are studied in \([27]\).

With a light top squark and large CP violation in soft supersymmetry breaking terms, the cosmological asymmetry between baryons and anti-baryons can be generated at the electroweak phase transition \([28]\).

4.4. Experimental signatures

The agreement between the standard model and experiment is no coincidence in our theory. Below \( \tilde{M} \) the spectrum of our effective theory is closer to that of the standard model than the MSSM. Deviations from the standard model in flavor changing neutral currents, lepton number violation, and electric dipole moments for the first two generations can be suppressed below any experimental bounds. If there are large CP violating phases, and if the top and/or bottom squarks are lighter than \( \sim 550 \) GeV, it is possible for the neutron EDM to be close to current limits \([12,14,29]\). However a detectable top squark contribution to EDM’s requires large mixing between the left and right handed top squarks, which is very small in many realizations of Effective Supersymmetry (such as in the composite example of section 3.1).
High precision tests of third family couplings and rare $\tau$ and $b$ decay searches could yield evidence for new physics, since some (and perhaps all) third family sparticles are light, with masses $\lesssim 1$ TeV. The weak gauginos and Higgsinos are also lighter than $\sim 1$ TeV. Together these sparticles can contribute to non-standard effects in $b$, $\tau$, and top quark physics. In particular CP violation can be especially interesting at colliders, since there are no longer any EDM constraints on CP violation in soft supersymmetry violating terms.

It is usually assumed that supersymmetry implies a non-minimal Higgs spectrum; however in Effective Supersymmetry, the effective theory below $\tilde{M}$ may have only a single Higgs doublet with standard model couplings. In this case the Higgs mass is nearly the same as in the MSSM with large $\tan \beta$, large $m_A$, and small left-right squark mixing—i.e. between $M_Z$ and $\sim 120$ GeV [4].

Currently most experimental search strategies for sparticles, especially at hadron colliders, rely on the assumption of squark and slepton degeneracy, and so considerable modification will be needed to search for Effective Supersymmetry. For instance most gluino decays will involve third family quarks and a chargino or neutralino.

Standard supersymmetry searches assume that the lightest supersymmetric particle is a stable neutralino. However, for $\sqrt{F_s} \lesssim 10^6$ GeV the neutralino decay to a gravitino and either a photon, a $Z$, or a Higgs would take place within the detector [10].

If the lightest sparticles are found and their interactions are studied, effective supersymmetry predicts their dimension 4 couplings should nearly agree with standard SUSY, since the lightest sparticles are necessarily those with the smallest couplings to the supersymmetry breaking sector. The dimensionless couplings of the heavier sparticles would deviate from SUSY predictions by an amount $F_s/\Lambda^2$.

5. Summary

It is commonly assumed that the MSSM with a desert above $\sim 1$ TeV is the minimal way to reproduce the successes of the standard model and predict the correct value of $\sin^2 \theta_w$, while maintaining naturalness in the electroweak symmetry breaking sector. In the MSSM avoiding FCNC requires very precise squark universality or alignment. We have argued that such a scenario is neither minimal nor necessarily superior. Instead we have advocated that physics beyond the $Z$ be constructed from a low energy, effective field theory perspective. We find that low energy phenomenology favors a scale $\tilde{M} \sim 5$–20 TeV for the first two families of squarks and sleptons, while naturalness favors a scale below 1 TeV for the top and left-handed bottom squarks—implying an intimate connection between the physics of flavor and the supersymmetry breaking mechanism. New gauge interactions for the first two families, which are connected with supersymmetry breaking, can explain such a sparticle spectrum while suppressing B and L violation. Although the effective theory
below \( \bar{M} \) is not at all supersymmetric, quadratically divergent contributions to the Higgs mass approximately cancel. This framework, which we call Effective Supersymmetry, has distinctive features that can be tested at future colliders.

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