EFFECTIVE SUPERSYMMETRY AND B-FACTORY PHYSICS

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I describe a low-energy effective field theory called Effective Supersymmetry which is a possible description of physics just above the electroweak scale. This effective theory is supersymmetric at short distances but differs significantly from the MSSM, offering several theoretical and phenomenological advantages. I focus on new physics in the B system.

1 Introduction and Conclusions

There are three well-known paradigms for the physics of electroweak symmetry breaking. Loosely speaking these are

- Standard Model

  This class includes all non-supersymmetric models in which electroweak symmetry breaking arises through the vacuum expectation value of a scalar electroweak doublet field, which appears fundamental at the electroweak scale. (This allows for "composite" Higgs fields, provided the scale of compositeness is significantly above the weak scale).

- Minimal Supersymmetric Standard Model (MSSM)

  This class is identical to the Standard Model with the addition of (spontaneously broken) low-energy supersymmetry. Note that the constraints of supersymmetry require at least two light Higgs fields to explain masses for both up type quarks and down type quarks and leptons.

- Dynamical Symmetry Breaking (DSB)

  This class includes all models which lack electroweak charged scalars of the type described above. The typical theory of this type is technicolor, and includes "top-color" assisted technicolor theories as described in other talks at this conference.

Although each of the above classes includes models that are renormalizable, and hence candidates for physics up to arbitrarily high energies, for our purposes we will view them all as *effective* theories, arising as the low energy limit of physics at an energy scale much greater than the weak scale. This means that the Lagrangians for these theories implicitly include all operators consistent with the appropriate symmetries, with the effects of operators of dimension larger than 4 suppressed by this high energy scale.

Each of these classes of models has strong and weak points, some of which are summarized below:

- Standard Model

  Not surprisingly these models do particularly well at accommodating the spectrum of fermion masses and mixing angles, as well as giving good agreement with precision electroweak data. In addition, and most importantly for our purposes here, these models provide an understanding of the smallness of any Baryon (B) and Lepton (L) number violation, as well as the absence of large flavor changing neutral currents (FCNC) and weak CP (CP) violation: each of these four items can be understood as a consequence of an *accidental symmetry* that the model possesses. That is, all operators of dimension less than or equal to 4 consistent with the gauge invariance and particle content of the model *also* respect these symmetries. Thus any violations of these symmetries must arise through higher dimension operators whose effects are automatically suppressed by a high energy scale. For example, an operator which violates baryon number must include at least three quarks (by color gauge invariance), and therefore at least one more fermion by Lorentz invariance, which is an operator of at least dimension six, and hence suppressed by at least two powers of the high energy scale.

  The major deficiency of the Standard Model is the unnaturalness of the weak scale relative to this new high energy scale (which may be as large as the Planck scale, or possibly a smaller intermediate scale).

- MSSM

  This model was first introduced to cure the principal defect of the Standard Model, namely the unnaturally light Higgs field—the introduction of supersymmetry protects the mass of this field from large radiative corrections. However this benefit comes at a huge price—all of the accidental symmetries of the standard model which explained the smallness of B and L violation, the near absence of FCNC and weak CP violation are no longer present. The MSSM must assume either fine tunings of a large number of couplings (nearly 100!) or some unspecified pattern of global symmetries at high energy. [a]

- DSB

  As is well known these models deal effectively with naturalness of electroweak symmetry breaking by eliminating light scalars altogether. In addition B and L arise as accidental symmetries much as they do in the standard model. The weak points are equally well known—the masses and mixing angles of the observed quarks and leptons are difficult to obtain, and FCNC require speculative dynamics to suppress. Lastly weak CP violation is difficult to reconcile with experiment.

The goal of effective supersymmetry [1] is to construct a natural effective field theory which incorporates each of the strong points from the three model categories listed above, while avoiding each of the weak points. The key features that we want to incorporate are: naturalness of

[a] Models of gauge-mediated supersymmetry breaking attempt to achieve this pattern by having SUSY breaking couple weakly, and nearly universally to all quark and lepton fields.

the effective theory; insensitivity to new physics at high energies; and accidental symmetries of the low energy effective theory.

1.1 Effective Supersymmetry

Although I will not present the details of the construction of the effective field theory here, the basic features are easy to describe. Firstly, taking our cue from the success of the Standard Model at accommodating the quark and lepton masses, we will assume our low energy theory contains a fundamental Higgs field (again, fundamental here means in the sense described above—it may very well be the case that such a field has internal structure at some much higher energy). If we wish to impose naturalness of our theory we are immediately confronted with the need to stabilize the Higgs field mass squared (which sets the scale of electroweak symmetry breaking): without any further assumptions the natural size of the Higgs field mass would be the characteristic high energy scale of our effective theory, which is much larger than the weak scale (*e.g.* the GUT or Planck scales). In order to protect the Higgs mass squared and keep this scalar field light we will also impose supersymmetry at high energies. Of course our low energy effective theory will need to break supersymmetry spontaneously to describe our apparently non-supersymmetric world.

So far this model is similar to the MSSM. However we need to avoid the deficiencies of the MSSM, notably the absence of a set of accidental symmetries to suppress B, L, and weak CP violation, as well as FCNC. Note that the "dangerous" operators are those involving squarks and sleptons (the new particles beyond those of the standard model). But in fact those operators dangerous for B, L and weak CP violation require at least two families of squarks and sleptons, while those that give unacceptable flavor changing neutral currents require one of the first two family squarks or sleptons. Thus if we eliminate the first two families of squarks and sleptons from our low energy effective theory, we will have achieved our goal of incorporating an appropriate set of accidental symmetries. Note that this set is smaller than that of the Standard Model, but is large enough to forbid the operators that are most dangerous.

Supersymmetry of course requires that these first two families of squarks and sleptons must be present at high energies, so that an absence in the effective theory must be a consequence of their large masses. Since the corresponding quarks and leptons are very light, this implies that the first two generations must couple strongly to supersymmetry breaking. However our effective theory can't look arbitrarily non-supersymmetric: some remnant of spontaneously broken supersymmetry is necessary to keep the Higgs field naturally light. Since the first two generations are only very weakly coupled to the Higgs, this constraint allows SUSY breaking in this sector to be relatively large; an explicit computation shows that the first two family squarks and sleptons can be as heavy as 25 TeV without making the effective theory unduly unnatural. Similar arguments require that the effective theory also contain the fermionic partners of the gauge bosons, the gauginos. [b] Lastly, the fermionic partners of the Higgs fields, the higgsinos, must also be light.

Why not make the third family squark and sleptons heavy as well? For the third family sleptons and right-handed down type squark, this is indeed possible, since these particles are also weakly coupled to the Higgs. However the top squark (and the left handed bottom squark, which is connected by electroweak symmetry transformations) are strongly coupled to the Higgs and consequently must be lighter than a TeV.

The result is that, from the point of view of a low energy effective field theory, at energies less than several tens of GeV we have a theory which contains the usual fields of the Standard Model, along with a left and right handed top squark, a left handed bottom squark, gauginos and higgsinos. This theory possesses enough of the accidental symmetries of the standard model

[b] Actually the gluino mass is not directly constrained by this analysis. However current realizations of effective supersymmetry have all gauginos light.

Table 1: CP asymmetries measured in B decays

Decay	Quark Process	Parameters
$B_d^0 \to \pi^+\pi^-$	$\bar{b} \to \bar{u}u\bar{d}$	$\sin 2(\alpha - \theta_d)$
$B_d^0 \to D^+D^-$	$\bar{b} \to \bar{c}c\bar{d}$	$-\sin 2(\beta + \theta_d)$
$B_d^0 \to \psi K_s$	$\bar{b} \to \bar{c}c\bar{s}$	$-\sin 2(\beta + \theta_d + \omega)$
$B^\pm \to D_{\mathrm{CP}} K^\pm$ $B_d^0 \to D_{\mathrm{CP}} K^*$	$\bar{b} \to \bar{c}u\bar{s}, \bar{u}c\bar{s}$	$\gamma - \omega \equiv$ $\gamma' + \delta$
$B_s^0 \to \psi\phi$	$\bar{b} \to \bar{c}c\bar{s}$	$\sin 2(\delta - \theta_s)$
$B_s^0 \to D_s^\pm K^*$	$\bar{b} \to \bar{c}u\bar{s}, \bar{u}c\bar{s}$	$\gamma' - \delta + 2\theta_s$

such that, if the scale of the effective theory is sufficiently high, the smallness of B, L and CP violating interactions and FCNC is automatic.

1.2 Implications for B physics

In effective supersymmetry, supersymmetry breaking is significantly different for the third generation than it is for the first two. This effective theory has large flavor violation associated with the third family which is distinctly different from the MSSM. These effects would have notable signatures in experiments involving the B system [2]. For example possible effects in effective supersymmetry which are absent in the MSSM with squark mass alignment include: observable D–$\bar{D}$ mixing; non Standard Model phase relations in B_d–$\bar{B}_d$ and B_s–$\bar{B}_s$ mixing; and non Standard Model phase relations in direct B decays.

To analyze these effects we parameterize all the possible operators that might appear subject to one assumption: processes which occur at tree-level in the standard model are dominated by the standard model. In this case we can choose parameters as [3]:

$$\begin{aligned} \alpha &\equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) & \beta &\equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \\ \gamma &\equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) & \gamma' &\equiv \arg\left(-\frac{V_{tb}V_{ub}^*}{V_{ts}V_{us}^*}\right) \\ \delta &\equiv \arg\left(-\frac{V_{tb}^*V_{ts}}{V_{cb}^*V_{cs}}\right) & \omega &\equiv \arg\left(-\frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*}\right) \end{aligned} \tag{1}$$

With these definitions (and without other assumptions such as CKM unitarity) there are two *identities*:

$$\alpha + \beta + \gamma = \pi; \quad \omega = \gamma - \gamma' - \delta\ . \tag{2}$$

CKM unitarity (which we do *not* impose) would require $\omega = 0$. On the basis of current experimental data the best we can say is $\omega \lesssim 0.2$. In addition to these angles, new physics allows for two independent phases in B–$\bar{B}$ mixing, which we call $\theta_{d,s}$ for the B_d and B_s mixing respectively.

CP asymmetries measured in various B decays will allow the experimental extraction of these parameters. The list in Table 1 displays the parameters measured in several popular processes.

Once these parameters are known, they can be used to distinguish models of new physics. For example, the standard model predicts the angle in $B_d^0 \to D^+D^-$ differs from that in $B_d^0 \to \psi K_s$ by $\pi/2$; measurement of a different angle indicates new physics. The observation of a non-zero ω would be conclusively non-standard model, as would a non-zero θ_d or θ_s. However it is also

Table 2: New B Physics in Effective SUSY

Phenomenon	SUSY (universality)	SUSY (alignment)	Effective SUSY
$D\bar{D}$ mixing	No	Yes	Possible
V_{td}, Δm_B not SM	Possible	Possible ($< 30\%$)	Possible
δ_{KM}, ϵ not SM	Possible	Possible	Possible
New phase in B_d mixing	No	$< \pi/10$	Possible ($< \pi/2$)
New phase in B_s mixing	No	No	Possible ($< \pi/2$)
New phases in B decay	No	No	Possible ($< \pi$)

possible that all new CP violating phases in the B system are small, and yet new physics would still appear through the measurement of the parameters in Table 1. For example, it is possible that the observed CP violation in the neutral K system, ϵ_K, comes not from a phase in the CKM matrix (as in the standard model) but from CP violating couplings of squarks. In this case even though CP violation in the B system might be dominated by the standard model, this would disagree with the CP violation measured in the K system. One of the most interesting possibilities for B physics is the ability to test whether or not the *known* CP violation is really a consequence of the CKM mechanism, or conversely whether new physics influences the K system CP violation. The expectations for a variety of CP violating effects, all of which are absent in the standard model, are shown in Table 2. For comparison I have shown the corresponding expectations for two versions of the MSSM: one in which FCNC are suppressed by assuming all squarks are nearly degenerate (universality) and one in which FCNC are suppressed by assuming that squark mixing angles are proportional to the corresponding quark mixing angles (alignment).

Electroweak symmetry breaking remains a mystery. Effective Supersymmetry, a natural alternative to the MSSM, is one possibility for this physics. It shares with other supersymmetric models the possibility of nonstandard contributions to ϵ_K and B_d–$\bar{B}_d$ mixing, but may also have other, distinct, signatures. Observable possibilities which are precluded in other supersymmetric models (assuming R-parity conservation) include $\mathcal{O}(\pi/2)$ values for the new physics parameters θ_d and θ_s, a 30% effect in $b \to s\ell^+\ell^-$ decays, and large new phases in $b \to s$ penguins. D^0–$\bar{D}^0$ mixing is likely to be much larger than in the standard model but very difficult to observe. Effective field theories of this kind, which couple flavor physics with weak symmetry breaking, are likely to lead to large non-standard model effects in the third family, making B-factories an exciting probe of these fundamental questions.

Acknowledgments

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References

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