B-Factory Physics from Effective Supersymmetry

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We discuss how to extract non-Standard Model effects from B-factory phenomenology. We then analyze the prospects for uncovering evidence for Effective Supersymmetry, a class of supersymmetric models which naturally suppress flavor changing neutral currents and electric dipole moments without squark universality or small CP violating phases, in experiments at BaBar, BELLE, HERA-B, CDF/D0 and LHC-B.

The principle of naturalness implies that physics beyond the standard model must be present at or below the “t Hooft scale” $4\pi m_W/g_\text{w} \sim 1\text{ TeV}$ \textsuperscript{[1]}. In the next few years several experiments will probe Flavor Changing Neutral Currents (FCNC) and CP violation in the B system, providing both new tests of the Standard Model (SM) and potential clues to new physics up to energies near 1000 TeV. These experiments may be the first to provide evidence for physics beyond the SM. New physics in rare decays of B mesons and in studies of CP violation in the $B_d$ and $B_s$ systems can originate from: two non-SM phases $\theta_{d,s}$ in the $\Delta B = 2$ operators for $B_{d,s}$ mixing; new phases in the $\Delta B = 1$, $b \rightarrow d$ and $b \rightarrow s$ hadronic transitions (“penguins”); disagreement between CP violation in the $B$ system and $\epsilon$ in the kaon system; or departure of $\Delta m_{B_d}$ and/or $\Delta m_{B_s}$ from SM predictions.

In this Letter we show that all of the above effects are likely to occur and may be measurable in a class of theories recently proposed by three of us, called “Effective Supersymmetry” \textsuperscript{[3]}. Effective Supersymmetry is a new approach to the problem of naturalness in the weak interactions, providing an experimentally acceptable suppression of FCNC and electric dipole moments (EDMs) for the first two families while avoiding acceptable suppression of FCNC and electric dipole moments for light quarks and leptons.

We have computed the possible effects on B factory physics from the light gauginos, Higgsinos, and top and bottom squarks. We find different and larger effects are possible than in the MSSM with squark universality \textsuperscript{[3,4]} or alignment \textsuperscript{[5,6]}. Nonuniversal masses for the third generation of squarks and sleptons have also been considered in \textsuperscript{[7,8]}, and the effects of nonuniversal masses and new phases for the third generation of squarks on B physics has been considered previously in the context of grand unified theories \textsuperscript{[9,10]}. B factory experiments will be able to distinguish the effects of the standard model CKM phases \textsuperscript{[11]}

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

from the effects of new physics (such as supersymmetric box and penguin diagrams) \textsuperscript{[11]}. Note that with these definitions there are two identities,

$$\alpha + \beta + \gamma + \pi; \quad \omega = \gamma - \gamma' - \delta .$$

From direct measurements of CKM parameters, and the assumption that there are no new physics contributions to decay amplitudes which can compete with SM tree level processes, $|\omega| \lesssim 0.2$. Note however that $\omega > O(10^{-3})$ requires both CKM non-unitarity and new physics in $K^+K^-$ mixing. CKM unitarity also constrains $|\delta| < 0.03$.

We first consider the effects of new physics through $\Delta B = 2$ operators. Many of the time dependent asymmetries resulting from the interference between $B^0 - \bar{B}^0$ mixing and decay into CP eigenstates \textsuperscript{[12]} are cleanly predicted in the Standard Model as a function of the Cabibbo-Kobayashi-Maskawa (CKM) parameters \textsuperscript{[13]}. While the direct decay amplitudes in table 1 will be dominated by SM physics, the CP violating asymmetries which result from interference between mixing and decay are sensitive to gauginos, Higgsinos, and squarks through box diagrams which can produce nonstandard $\Delta B = 2$ effects.
Table 1. CP asymmetries measured in B decays

| Decay | Quark Process | $A_{CP}$ |
|-------|---------------|----------|
| $B^0_d \rightarrow \pi^+\pi^-$ | $\bar{b} \rightarrow \bar{u}d$ | $\sin 2(\alpha - \theta_d)$ |
| $B^0_s \rightarrow D^+D^-$ | $\bar{b} \rightarrow \bar{c}c\ell\nu$ | $-\sin 2(\beta + \theta_d)$ |
| $B^0 \rightarrow \psi K_s$ | $\bar{b} \rightarrow \bar{c}c\bar{s}$ | $-\sin 2(\beta + \theta_d + \omega)$ |
| $B^{\pm} \rightarrow D_{CP}K^{\mp}$ | $\bar{b} \rightarrow \bar{c}u\bar{s}$, $\bar{u}c\bar{s}$ | $\gamma - \omega \equiv \gamma' + \theta$ |
| $B^0 \rightarrow \psi\phi$ | $\bar{b} \rightarrow \bar{c}c\bar{s}$ | $\sin 2(\delta - \theta_s)$ |
| $B^0_s \rightarrow D^0K^*$ | $\bar{b} \rightarrow \bar{c}u\bar{s}$, $\bar{u}c\bar{s}$ | $\gamma' - \delta + 2\theta_s$ |

This new physics may be parameterized by two phases $\theta_d, \theta_s$:

$$\theta_{d,s} = \frac{1}{2} \arg \left( \frac{\left| \mathcal{B}_{d,s}\right|}{\left| \mathcal{B}_{d,s}\right|} \right),$$

where $\mathcal{H}_{\text{eff}}$ is the effective Hamiltonian including both standard and SUSY contributions, and $\mathcal{H}_{\text{SM}}$ only includes the effects of the standard model box diagrams.

With these definitions, CP violating asymmetries in B processes measure the angles as indicated in table 1. These processes have been discussed in the SM in [14]. The measurements of $\alpha - \theta_d$ and $\beta + \theta_d$ are somewhat influenced by penguin contributions, whose effects must be removed [15]. A subtle point is the presence of $\omega$ in $A_{CP}$ for $B^0_d \rightarrow \psi K_s$. This arises since we cannot assume the phase in $K\bar{K}$ mixing is given by the SM analysis [1]. However we do know, since $\epsilon_K$ is small, that the phase is nearly the same as that in $K$ decay, given by $\arg V_{ud}V_{us}^\ast$.

Provided that penguin contributions to the decays of table 1 can be removed, $\alpha, \beta, \theta_d, \omega$ and $\delta - \theta_s$ may be extracted from experiments [1] as indicated in figures 1 and 2. With the additional assumption of CKM unitarity, $\delta$ is quite small, and $\theta_s$ may be extracted separately [16].

We can estimate the sizes of these effects by comparing the superpartner contribution to $\Delta B = 2$ operators with the Standard Model. Effective Supersymmetry requires the squarks $\tilde{Q}_3$ and $\tilde{T}$ to have masses $\lesssim 1$ TeV. These mass eigenstates are mixtures of flavor eigenstates (where squark flavor, indicated by a lower case letter, is defined by the gluoino coupling to the corresponding quark) [17],

$$\tilde{Q}_3 \equiv \left( \begin{array}{c} \tilde{t} \\ \tilde{B} \end{array} \right) = Z_{\tilde{Q}}^T \left( \begin{array}{c} V_{tb} \tilde{b} + V_{ts} \tilde{s} + V_{td} \tilde{d} \\ V_{tb} \tilde{b} + V_{ts} \tilde{s} + V_{td} \tilde{d} \end{array} \right) + Z_{\tilde{Q}}^C \left( \begin{array}{c} \tilde{c} \\ \tilde{d} \end{array} \right) + Z_{\tilde{Q}}^U \left( \begin{array}{c} \tilde{u} \\ \tilde{u} \end{array} \right),$$

with $\tilde{T} = Z_{\tilde{T}}^t \tilde{t} + Z_{\tilde{T}}^c \tilde{c} + Z_{\tilde{T}}^u \tilde{u}$. Here $V$ is the CKM matrix, while the $Z$ factors arise from diagonalizing the squark mass matrix in the quark mass eigenstate basis (we neglect left-right squark mixing, which is small in realizations of Effective Supersymmetry which have been studied to date [20]). The $Z$ matrices satisfy $\sum_{i=u,c,t} |Z_{iT}^q|^2 = 1$, $\sum_{i=u,c,t} |Z_{IT}^q|^2 = 1$. Naturalness imposes order of magnitude constraints on the $Z$ factors: to avoid fine tuning in the Higgs sector, we require

$$|Z_{IT}^q|, |Z_{uT}^q|, |Z_{uT}^0|, |Z_{uT}^0| \lesssim \frac{1}{10 \text{ TeV}}.$$  \hspace{1cm} (5)

while naturalness of the squark mass matrix requires [17]:

$$|Z_{uT}^q| \lesssim \max \left\{ \frac{m_{\tilde{q}}}{M}, \frac{V_{ub}}{M} \right\};$$ \hspace{1cm} (6)

$$|Z_{uT}^0| \lesssim \max \left\{ \frac{m_{\tilde{q}}}{M}, \frac{V_{ub}}{M} \right\},$$

and similarly with $u$ replaced by $c$.

The box diagrams with left handed light squarks and gluinos give [18]

$$\mathcal{H}_{\text{eff}} = \frac{g^2}{36m_B^2} (Z_{d_{1B}}^d Z_{b_{1B}}^q)^2 f_1(x_q) Q_1 \approx \left( \frac{6.4 \cdot 10^{-12}}{\text{GeV}^2} \right) \left( \frac{1000 \text{ GeV}}{m_B} \right)^2 \left( \frac{V_{td} + Z_{uT}^q}{0.05} \right)^2 Q_1,$$

where

$$Q_1 = \frac{b_\ell \gamma_\mu d_\alpha \bar{b}_L \gamma^\mu d_\beta L}{11 + 8x - 19x^2 + 26x \log(x) + 4x^2 \log(x)} (1 - x)^3,$$

and we have evaluated the function at $x_q = m_{\tilde{g}}^2/m_B^2 \approx 0.1$.

Unless gluinos are significantly heavier than squarks, charginos and neutralinos (which does not occur in any realization of effective supersymmetry discussed in the literature [21,23]), box diagrams from chargino and neutralino exchange produce a contribution suppressed by $O(\alpha_w/\alpha_s)^2 \approx 0.1$ when compared with the gluino boxes.
possible exceptions are the charged Higgsino and charged Higgs boxes which are proportional to $\lambda^4$. However these have the same phase as the standard model contribution.

From eq. [7] we see that even TeV mass squarks can produce an order one effect on $B_d\rightarrow \phi K_s$ mixing, detectable via a $\theta_d$ as large as $\pm \pi/2$, or via a ratio for $x_s/x_d$ (where $x_{s,d} \equiv \Delta m_{B_{s,d}}/\Gamma_{B_{s,d}}$) which is well outside the SM range. For $B_s\rightarrow \phi K_s$ mixing the effects of the superpartner box diagrams can only be comparable to the SM contribution for rather light ($\sim 200$ GeV) $b$ squarks and gluinos. A measurement of $\theta_s$ larger than 0.2 would suggest that gluinos and a squark are lighter than $\sim 400$ GeV.

In the SM $\epsilon_K$ significantly constrains the CKM matrix. However $\epsilon_K$ could be dominated by the contribution from supersymmetric particles, even if all superpartners are as heavy as 500 TeV. With $\sim 20$ TeV masses for the first two families of squarks and with susy mixing angles for the first two generations of squarks of order the Cabibbo angle, the CP violating susy phases in the down and strange squark couplings must be less than $\mathcal{O}(1/30)$ or the kaon CP violation parameter $\epsilon_K$ would be too large [3]. Note that suppressing this susy contribution to $\epsilon_K$ does not preclude observing new CP violating phases in B physics. However an interesting possibility is that an approximate CP symmetry renders all phases (including CKM phases) small. In this case the CP violating asymmetries in $B$ decays would all be too small to be easily measured.

In either the MSSM or in effective supersymmetry it is possible that $\Delta m_{B_d}$ could receive a significant supersymmetry contribution which has the same phase as the SM contribution. Thus the values of $\alpha, \beta$ determined by B physics could disagree with the values in the SM given by $V_{ub}, \Delta m_{B_s}$ and $\epsilon_K$, even if $\theta_{d,s}$ are too small to measure.

Supersymmetry may also have significant effects through $\Delta B = 1$ operators. Contributions to both the $b\rightarrow d$ and $b\rightarrow s$ penguins can be comparable to that of the SM but with different phases, provided gluino and third family squark masses are lighter than 200 GeV. The SM predictions for penguin operators, and methods for extracting their effects from CP asymmetries has been extensively discussed [3-5]. In the standard model there is a large uncertainty in the phase of the $b\rightarrow d$ penguin, however the uncertainty in the phase of the $b\rightarrow s$ penguins is of order $\delta$ if the three by three CKM matrix is unitary. Thus one can search for new CP violating phases in penguin contributions via, e.g., the CP asymmetry in $B_d(B_d)\rightarrow \phi K_s$.

Box and electroweak penguin diagrams involving superpartners can affect the rates, polarizations, and lepton momentum distributions in $b\rightarrow (s,d)\ell^+\ell^-$, which can also be tested in B factories. In the MSSM with universality, the only potential discrepancies larger than 5% arise through changes in the coefficient $C_7$ [19] in the effective Lagrangian (we follow the notation of [19]). In Effective Supersymmetry with small left-right squark mixing and heavy charged Higgs the corrections to $C_7$ are small. With a bottom squark lighter than $\sim 100$ GeV and gluino lighter than $\sim 200$ GeV it is possible to change the size and/or phase of the coefficient $C_9$ by as much as 30%. If the bottom and/or top squarks, the weak gauginos and the tau charged slepton and/or tau sneutrino have masses $\sim 100$ GeV, it is possible for box diagrams to change the size and phase of $C_{9,10}$ (for the tau lepton only) by a maximum of $\mathcal{O}(10\%)$.

The B factories will also search for mixing and CP violation in the $D^0$ system, which are both predicted to be very small in the SM ($x_D \equiv \Delta m_{D^0}/\Gamma_{D^0} \sim 10^{-5}$, $y_D \equiv \Delta \Gamma_{D^0}/(2\Gamma_{D^0}) \sim 10^{-7}$, $\epsilon_D \sim 10^{-4}$). In Effective Supersymmetry there can be significant contributions to $x_D$ from both heavy squarks with masses $\sim M$ and from the lighter third family squarks, with comparable maximum possible size. For example the box diagrams with a right handed top squark and gluinos give a contribution

$$x_D = \frac{\alpha_D^2 M_D f_D^2}{54m_t^2 \Gamma_D} |(Z^u_{\tau T} Z^d_{\tau T})|^2 f_1(x_g)$$

$$\approx 5 \times 10^{-4} \left( \frac{1000 \text{ GeV}}{m_t^2} \right)^2 \left( \frac{f_D B_D}{200 \text{ MeV}} \right)^2 \left( \frac{Z^u_{\tau T} Z^d_{\tau T}}{0.0025} \right)^2$$

where again we have taken $x_g \approx 0.1$. The current experimental bound is $(x_D < 0.09)$ [20]. Charm decays will be dominated by the SM contribution and so there are no significant new contributions to $y_D$. We conclude that unless suppressed by flavor symmetries, $D^0 - \bar{D}^0$ mixing could be much larger than in the SM, although substantially smaller than the current experimental bounds. The superpartner contribution may also have a different phase than the SM contribution. If $\Delta m_{D^0}$ and $\Delta \Gamma/2$ turn out to be comparable, $\epsilon_D$ could be $\mathcal{O}(1)$, although $\epsilon_D$ is difficult to measure if $D^0 - \bar{D}^0$ mixing is very slow. In principle $D^0 - \bar{D}^0$ mixing affects the extraction of the CKM parameter $\gamma - \omega$ from $B \rightarrow D_{CP} K$ decays; however such effects are suppressed by $x_D, y_D$, and are negligible. However even if $\epsilon_D$ is small, $x_D$ may be as large as $\mathcal{O}(10^{-2})$, and then CP violation in interference between $D^0$ mixing and decays might be detectable [24].
In summary, Effective Supersymmetry, with naturalness and with $M \sim 20$ TeV, allows for interesting new physics for B factories. Observable possibilities which are precluded in other supersymmetric models (assuming R-parity conservation) include large values for the new physics parameters $\theta_d$ and $\theta_s$, 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. Note that observation of large $\theta_s$, non-standard phases in $b \to s$ penguins, or measurable deviation from the SM in $b \to (d,s) \ell^+ \ell^-$ would imply that gluinos and third family squarks are lighter than $\sim 200$ GeV, i.e. within near term experimental reach. Effective supersymmetry shares with other supersymmetric models the possibility of nonstandard contributions to $\epsilon_K$ and $B_{d} - B_{\bar{d}}$ mixing.

ACKNOWLEDGMENTS

A.C. was supported in part by the DOE under grant #DE-FG02-91ER40676. D.K. and F.L. were supported in part by the DOE under grant #DE-FG02-91ER40676, and NSF Presidential Young Investigator award PHY-9057153. A.N. was supported in part by the DOE under grant #DE-FG03-96ER40956. We thank Y. Nir for useful correspondence.

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