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CP Violating Lepton Asymmetries from B Decays and Their Implication for Supersymmetric Flavor Models

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Abstract

The lepton and dilepton charge asymmetries from B_d and B_s are predicted to be small in the standard model, whereas new physics could increase their values significantly. In this paper, we explore the use of the lepton asymmetries as a probe of the flavor structure of supersymmetric theories. In particular, we determine the sensitivity to parameters of various models. We find that in many interesting models which attempt to address the supersymmetric flavor problem, the mixing structure is such that it could be possible to detect new physics. The predictions are model dependent; with a measurement in both the B_s and B_d systems one can hope to constrain the flavor physics model, especially once squarks are detected and their masses measured. Thus, lepton charge asymmetries can be used as an alternative means of searching for new physics and distinguishing among potential solutions to the flavor problem. They are interesting precisely because they are small in the standard model and are therefore necessarily evidence of new physics.

1 Introduction

The next few years will be an exciting era for B physics, with the detailed investigation of B hadrons at b -factories. Particularly exciting is the potential for studying CP-violation in the B system, both within and beyond the standard model (SM). This affords the opportunity to look for new physics, and in fact might yield the first evidence for physics beyond the standard model. Hopefully this new physics will be further studied directly so that we will establish its origin. Whatever this new physics proves to be, a detection at b -factories should give new information which will not be accessible to high energy colliders. For example, should this new physics prove to be supersymmetry, detailed studies in the B system give a unique opportunity to probe the flavor structure of extensions of the SM.

Non-standard model CP-violating effects could be revealed by testing whether measurements agree with the SM allowed range. Processes for which the SM contribution vanishes (or is negligibly small) offer an important complement to these studies. In this case, any observation or non-observation of CP-violation can be interpreted directly as a constraint on physics beyond the SM. From this point of view, a measurement of the dilepton or of the lepton charge asymmetry is of great interest. The dilepton charge asymmetry is defined as¹ [1, 2, 3, 4, 5, 6]

$$A_{ll} \equiv \frac{l^{++} - l^{--}}{l^{++} + l^{--}}, \quad (1.1)$$

where l^{++} [l^{--}] denotes the numbers of l^+l^+ [l^-l^-] dilepton pairs observed. In the b -factories, they come from the mixing and decay of the $B\bar{B}$ pairs, while in the hadron colliders, the final hadronization states can be any combinations of B^+ , B_d , B_s , Λ_b and their conjugates. In the absence of CP-violation, this quantity clearly vanishes. In early studies of the dilepton charge asymmetry [7, 8], the KM angles and top quark mass were not sufficiently well determined to be certain that a measurement in excess of 10^{-3} would signal new physics. As we will see, this quantity is now determined to be small in the SM for both B_d and B_s , but can be significantly larger in non-standard flavor models.

Another useful quantity to look at [2, 3, 5, 6] is the total lepton charge asymmetry l^\pm , which is defined by

$$l^\pm = \frac{l^+ - l^-}{l^+ + l^-}. \quad (1.2)$$

Here $l^{+(-)} = N(B\bar{B} \rightarrow l^{+(-)})$ is the total number of positively (negatively) charged primary leptons coming from the decay of $b\bar{b}$ pairs. This quantity is smaller than A_{ll} , but should be measured with better statistics.

These lepton asymmetries are sensitive to the phase difference between Γ_{12} and M_{12} . In the SM, the dominant contribution to these quantities has the same phase, and is therefore suppressed. The dominant source of enhancement in non-standard physics is a new contribution to mass mixing, which would generally carry a different phase from the standard model contribution. In models for which the new source of mixing is comparable to that of the SM, one can expect a substantial change in the prediction of the lepton charge asymmetry. We

¹Here we use the convention that B contains a \bar{b} quark, thus decays into a l^+ if there is no mixing. This is opposite to the convention used in [2].

will show that there are many models for which one would expect up to an order of magnitude enhancement over the SM prediction for B_d and two orders of magnitude enhancement for B_s . In fact, because the predictions for asymmetries due to CP violation in the B_s and B_d systems is different, one can hope to use this measurement to help distinguish among potential solutions to the supersymmetric flavor problem. For this reason, we take an explicitly model-dependent approach to our results, and explore the predictions in various models already existing in the literature. They do not necessarily include the real world solutions to the flavor problems, but are nonetheless sufficiently general to illustrate the usefulness of the lepton asymmetry methods.

There are several ways to measure the lepton asymmetries. One can measure both the single lepton and dilepton asymmetries at the dedicated B factories. These will of course only be sensitive to new physics in the B_d sector. It would be extremely interesting to complement this measurement with the measurement of lepton asymmetries at a hadron collider, which will be sensitive to the asymmetries in both B_s and B_d . With all such measurements (or even some fraction of them) one should be able to distinguish new mixing contributions to either the B_s or B_d systems. We will see in particular that many supersymmetric flavor models yield a large deviation for at least one of the above systems.

Because the SM prediction for B_d is small, and even smaller for B_s (we discuss how small later), any lepton asymmetry measurement in excess of this value is a clear signal of new physics. Because of the suppression from $\Delta\Gamma/\Delta M$, a sensitivity of at least 10^{-2} is essential. So any asymmetry within this range will be an important signal of new physics. We emphasize that even without flavor tagging, a measurement of a CP-violating asymmetry in excess of the SM prediction will be an exciting signal of new physics, which ultimately complementary measurements should disentangle.

The importance of studying lepton asymmetries has been considered previously in [9] specifically in the context of B_s , and in [10] for B_d . $\text{Re}(\bar{\epsilon}_B)$ (which can be related to A_{ll} by $A_{ll} \sim 4\text{Re}(\bar{\epsilon}_B)$ [11]) in left-right symmetric models has also been discussed in [12]. However, no one has as yet done a detailed study of the potential significance of this measurement for distinguishing models for the supersymmetric soft masses or combined the information from both B_d and B_s . Of course, any non-standard model can be studied in the light of the measurement of the lepton charge asymmetry and thereby constrained. For specificity, and because of its likelihood as the source of a non-standard model CP-violating effect, we chose to study the specific case of contributions from soft scalar masses in some non-standard models of flavor physics that exist in the literature. We find that many squark mass models designed to address the flavor problem in supersymmetry will give rise to a significantly larger lepton asymmetry in either the B_d or B_s system for reasonable parameters. A simple order of magnitude estimate shows that the box diagrams would be comparable (assuming mixing similar to CKM mixing) for superpartner masses of order a few hundred GeV.

We begin in Sec. 2 by presenting the basic formulas relevant to $B\bar{B}$ mixing. We express the dilepton asymmetry in terms of $(\Delta\Gamma/\Delta M)_{\text{SM}}$, and the relative amplitude and phase difference between the supersymmetric and SM contributions. We then briefly review why supersymmetry gives new contributions to neutral B -meson mixing through non-trivial squark mass matrices. In Sec. 3, we give a brief review of three soft supersymmetry-breaking

scenarios which have been devised to address the flavor problem in supersymmetry models: alignment, non-abelian flavor symmetry, and heavy squark models. These suggestions solve or relax the Flavor-Changing Neutral-Current (FCNC) and CP-violation problems. In Sec. 4, we first present the model-independent lower limits on the phase difference between M_{12}^{SUSY} and M_{12}^{SM} and the $m_{\tilde{q}}$ range (linear with respect to the mixing angle), assuming the experimental sensitivity of measuring either dilepton asymmetry is 2×10^{-3} . For any particular ansatz for the squark mass matrices, this result can be interpreted as a sensitivity to $m_{\tilde{q}}$ and mixing angles. We show the parameter ranges of the models of Sec. 3, which can be probed with the measurement of the dilepton asymmetry. In Sec. 5, we conclude.

2 Dilepton Charge Asymmetry

For the $B \bar{B}$ basis, one has the Hamiltonian

$$H = \begin{pmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{pmatrix} \quad (2.1)$$

The mass eigenstates are

$$B_{1,2} = \frac{1}{\sqrt{1 + |\eta|^2}} (|B\rangle \pm \eta |\bar{B}\rangle), \quad (2.2)$$

with eigenvalues

$$M_{1,2} - i\Gamma_{1,2}/2 = M - i\Gamma/2 \pm \Delta, \quad (2.3)$$

where

$$\eta = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}, \quad (2.4)$$

$$\Delta = \sqrt{(M_{12} - i\Gamma_{12}/2)(M_{12}^* - i\Gamma_{12}^*/2)}. \quad (2.5)$$

The quantities r, \bar{r} are defined as [2, 13]²

$$r \equiv \frac{P_{\bar{B} \rightarrow B}}{P_{\bar{B} \rightarrow \bar{B}}} = \frac{1}{|\eta|^2} \frac{x^2 + y^2}{2 + x^2 - y^2}, \quad (2.6)$$

$$\bar{r} \equiv \frac{P_{B \rightarrow \bar{B}}}{P_{B \rightarrow B}} = |\eta|^2 \frac{x^2 + y^2}{2 + x^2 - y^2}, \quad (2.7)$$

where $x = \Delta M/\Gamma$, $y = \Delta\Gamma/2\Gamma$, $\Delta M = M_1 - M_2 = 2\text{Re}\Delta$, $\Gamma = (\Gamma_1 + \Gamma_2)/2$ and $\Delta\Gamma = \Gamma_1 - \Gamma_2 = -4\text{Im}\Delta$.

When a $B\bar{B}$ pair is produced, it can mix and later decay into l^+l^+ or l^-l^- . Thus, we can replace the l^{++} and l^{--} in Eq. (1.1) by $N(BB)$ and $N(\bar{B}\bar{B})$, which is the number of BB

²The r, \bar{r} defined here is the interchange of r, \bar{r} defined in [2, 13] because of the opposite convention used in defining B .

($\bar{B}\bar{B}$) final states observed in a sample of events from a process where a $B\bar{B}$ pair is initially produced [2]. The dilepton asymmetry can then be written as [2, 3]

$$A_{ll} \equiv \frac{N(BB) - N(\bar{B}\bar{B})}{N(BB) + N(\bar{B}\bar{B})} = \frac{r - \bar{r}}{r + \bar{r}} = -\frac{|\eta|^4 - 1}{|\eta|^4 + 1} = \frac{\text{Im}(\Gamma_{12}/M_{12})}{1 + 1/4|\Gamma_{12}/M_{12}|^2} \approx \text{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right). \quad (2.8)$$

The last approximation holds if $|\Gamma_{12}/M_{12}| \ll 1$, which is the case for the $B\bar{B}$ systems even in the presence of new physics [14].

This formula is true whether or not $B\bar{B}$ is produced coherently. However at a hadron collider when a B_d is not necessarily produced in conjunction with a \bar{B}_d , one needs to account for all possible fragmentations. In this case we derive

$$A_{ll} = \frac{l^{++} - l^{--}}{l^{++} + l^{--}} = \frac{\left(\frac{r_d}{1+r_d}\lambda_d f_d + \frac{r_s}{1+r_s}\lambda_s f_s\right) A^{++} - \left(\frac{\bar{r}_d}{1+\bar{r}_d}\lambda_d f_d + \frac{\bar{r}_s}{1+\bar{r}_s}\lambda_s f_s\right) A^{--}}{\left(\frac{r_d}{1+r_d}\lambda_d f_d + \frac{r_s}{1+r_s}\lambda_s f_s\right) A^{++} + \left(\frac{\bar{r}_d}{1+\bar{r}_d}\lambda_d f_d + \frac{\bar{r}_s}{1+\bar{r}_s}\lambda_s f_s\right) A^{--}}, \quad (2.9)$$

where

$$A^{++} = \lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \frac{\lambda_d f_d}{1 + \bar{r}_d} + \frac{\lambda_s f_s}{1 + \bar{r}_s}, \quad (2.10)$$

and

$$A^{--} = \lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \frac{\lambda_d f_d}{1 + r_d} + \frac{\lambda_s f_s}{1 + r_s}. \quad (2.11)$$

Here f^i is the probability to hadronize as a state i and λ^i is the leptonic branching fraction. It is readily seen that when working to leading order in CP asymmetries, the formula (2.9) reduces to

$$(A_{ll})_{\text{total}} = (A_{ll})_d A_{d2} + (A_{ll})_s A_{s2}, \quad \text{with } (A_{ll})_{d,s} = \frac{r_{d,s} - \bar{r}_{d,s}}{r_{d,s} + \bar{r}_{d,s}}, \quad (2.12)$$

where

$$A_{d2} = \frac{\lambda_d f_d r_d}{(1 + r_d)^2} \frac{(\lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \lambda_d f_d + \lambda_s f_s)}{(\lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \frac{\lambda_d f_d}{1+r_d} + \frac{\lambda_s f_s}{1+r_s}) \left(\frac{\lambda_d f_d r_d}{1+r_d} + \frac{\lambda_s f_s r_s}{1+r_s}\right)}, \quad (2.13)$$

$$A_{s2} = \frac{\lambda_s f_s r_s}{(1 + r_s)^2} \frac{(\lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \lambda_d f_d + \lambda_s f_s)}{(\lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \frac{\lambda_d f_d}{1+r_d} + \frac{\lambda_s f_s}{1+r_s}) \left(\frac{\lambda_d f_d r_d}{1+r_d} + \frac{\lambda_s f_s r_s}{1+r_s}\right)}, \quad (2.14)$$

and we define A_2 to be the ratio between A_{s2} and A_{d2} , which gives

$$A_2 = \frac{A_{s2}}{A_{d2}} = \frac{\lambda_s f_s r_s (1 + r_d)^2}{\lambda_d f_d r_d (1 + r_s)^2}. \quad (2.15)$$

The most recent results for f^i and λ^i are $f^+ = 0.39 \pm 0.04 \pm 0.04$, $f^\Lambda = 0.096 \pm 0.017$, $f_d = 0.38 \pm 0.04 \pm 0.04$, $f_s = 0.13 \pm 0.03 \pm 0.01$ [15], $\lambda^+ = (10.3 \pm 0.9)\%$, $\lambda^\Lambda = (9.0_{-3.8}^{+3.1})\%$, $\lambda_d = (10.5 \pm 0.8)\%$ and $\lambda_s = (8.1 \pm 2.5)\%$ [16]. For the $B\bar{B}$ system, $|\eta|$ in Eqs. (2.6) and (2.7) is very close to 1, $y/x = \Delta\Gamma/2\Delta M$ is very close to 0, thus

$$r \approx \bar{r} \approx \frac{x^2}{2 + x^2}. \quad (2.16)$$

For B_s , x is large because of large mixing; thus B_s is almost 100% mixed and $r \rightarrow 1$. For B_d , $x = 0.734 \pm 0.035$ [16], which gives $r = 0.21 \pm 0.02$. Putting together these numbers,

we find that $A_{d2} = 0.53$, $A_{s2} = 0.25$, $A_2 = 0.46$; this means that, although B_s is 100% mixed, its contribution to the dilepton rate is less than B_d 's because the number of B_{ds} produced is about three times larger than B_s . In our analysis below, we will consider supersymmetric contributions to both B_d and B_s mixing. It should be borne in mind that a better measurement of A_{ll} is required to achieve the same sensitivity to the parameters relevant to B_s .

The total lepton charge asymmetry l^\pm has a different form when expressed in terms of r and \bar{r} in the case of a coherently or incoherently produced $B\bar{B}$ pair. When it is produced coherently, for example, in $\Upsilon(4S) \rightarrow B_d\bar{B}_d$, the total lepton asymmetry is given by [2, 3, 5, 6]

$$l^\pm = \frac{l^+ - l^-}{l^+ + l^-} = \frac{r - \bar{r}}{2 + r + \bar{r}}. \quad (2.17)$$

One can simplify the total lepton charge asymmetry l^\pm by observing

$$l^\pm = -\frac{|\eta|^4 - 1}{\frac{4+2x^2}{x^2}|\eta|^2 + |\eta|^4 + 1} \approx 0.17 (A_{ll})_d \text{ for } B_d, \quad (2.18)$$

here again we take $|\eta| \rightarrow 1$ in the denominator. In the b -factories, only $B_d\bar{B}_d$ is coherently produced.

When the $B\bar{B}$ is produced incoherently, the total lepton asymmetry becomes [2]

$$l^\pm = \frac{r - \bar{r}}{1 + r + \bar{r} + r\bar{r}}, \quad (2.19)$$

which can also be simplified as

$$l^\pm = -\frac{|\eta|^4 - 1}{\left(\frac{2+x^2}{x^2} + \frac{x^2}{2+x^2}\right)|\eta|^2 + |\eta|^4 + 1} \approx \begin{cases} 0.29 (A_{ll})_d & \text{for } B_d, \\ 0.5 (A_{ll})_s & \text{for } B_s. \end{cases} \quad (2.20)$$

The single lepton asymmetry measures the same quantity, $\text{Im}(\Gamma_{12}/M_{12})$, as the dilepton asymmetry. The prediction for the dilepton asymmetry is bigger; however because both leptons must be tagged, the statistics are smaller. Yamamoto [6] has argued that the single lepton asymmetry will give a better measurement at a dedicated b -factory. At a hadron collider, the contribution from both B_d and B_s as well as other sources of single leptons must be accounted for:

$$(l^\pm)_{\text{total}} = l_d^\pm A_{d1} + l_s^\pm A_{s1}, \quad (2.21)$$

where

$$A_{d1} = \frac{\lambda_d f_d}{\lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \lambda_d f_d + \lambda_s f_s}, \quad A_{s1} = \frac{\lambda_s f_s}{\lambda^+ f^+ + \lambda^\Lambda f^\Lambda + \lambda_d f_d + \lambda_s f_s}, \quad (2.22)$$

and $l_{d,s}^\pm$ takes the form of Eq. (2.19). If the leptonic branching ratios were the same for all b -hadrons, $A_{d1,s1}$ would reduce to $f_{d,s}$. We define A_1 to be the ratio between A_{s1} and A_{d1} , which is

$$A_1 = \frac{A_{s1}}{A_{d1}} = \frac{\lambda_s f_s}{\lambda_d f_d}. \quad (2.23)$$

For the values of $f_{d,s}$ and $\lambda_{d,s}$ given before, we get $A_{d1} = 0.40$, $A_{s1} = 0.11$, $A_1 = 0.26$. However, to measure $\text{Im}\Gamma_{12}/M_{12}$ with the same sensitivity for B_d and B_s requires the same factor as with the dilepton asymmetry, in light of Eq. (2.20).

In the SM, the phases in Γ_{12} and M_{12} are approximately equal. Thus,

$$\Delta M_{\text{SM}} \approx 2|M_{12}^{\text{SM}}|, \quad \Delta\Gamma_{\text{SM}} \approx 2|\Gamma_{12}^{\text{SM}}|. \quad (2.24)$$

The SM contribution to the dilepton charge asymmetry is generally small [4, 5, 10, 17]

$$|A_{ll}| \sim \begin{cases} 10^{-3} & \text{for } B_d, \\ 10^{-4} & \text{for } B_s. \end{cases} \quad (2.25)$$

The current preferred solutions of the unitary fits to the CKM matrix yield: $\rho \simeq 0.12$ and $\eta \simeq 0.34$ [18], which gives $|A_{ll}| \simeq 4.2 \times 10^{-4}$ for B_d in the SM. When the mixing angles vary over their currently allowed range [19], the dilepton asymmetry can be as large as 1.9×10^{-3} for B_d . Until the angles are better known, a lepton asymmetry in excess of this number is required in order to test new physics, so in this paper this will be our benchmark. That is, we assume the experimental sensitivity is good enough to measure down to the largest possible standard model value. However, once these angles are better determined, even smaller values could indicate non-standard contributions. We will show that there are many interesting models that predict a contribution at this level. The current experimental bound on the dilepton asymmetry is $|A_{ll}| < 0.18$ [20, 21] at the 90% confidence level, far below the level of interest. We stress the importance of better measurements at Run II of the Tevatron and at b -factories, with the ultimate goal of at least this sensitivity.

One should bear in mind the reduced contribution of B_s relative to B_d (assuming equal $\text{Im}(\Gamma_{12}/M_{12})$) which means better experimental sensitivity is required to study B_s at the level assumed. This would require decoupling any possible standard model contribution which could be present.

Another caveat is that the small standard model rate is based on a quark calculation, and relies on a sensitive cancellation between intermediate states with light up-type quarks. Wolfenstein [22] has argued that the quark model calculations might not be reliable and predicts a much larger rate based on 100 % violation of duality. Even with a smaller violation of duality, of order 20 % for the $c \bar{c}$ intermediate state, we find the standard model prediction could be increased by a factor of 3 if the quark model rate is an overestimate. However, there is no evidence as yet [23] for this violation. It will be interesting to better test the assumption in the future by a better measurement of n_c , the average number of charm (or anticharm) quarks in the hadronic final state of a B decay.

As is well known, there can be large FCNCs in supersymmetric models because of the many new potentially flavor-violating parameters. In particular, the squark mass matrices introduce the possibility of new flavor-violating effects. These effects can be described through the mass matrices \tilde{M}_{LL}^2 , \tilde{M}_{RR}^2 , and \tilde{M}_{LR}^2 . Because of potential new contributions to $B\bar{B}$ mixing, the phase of Γ_{12} and M_{12} should be different. Assuming that supersymmetry does not substantially change Γ_{12} (since it only contributes at higher order) and defining

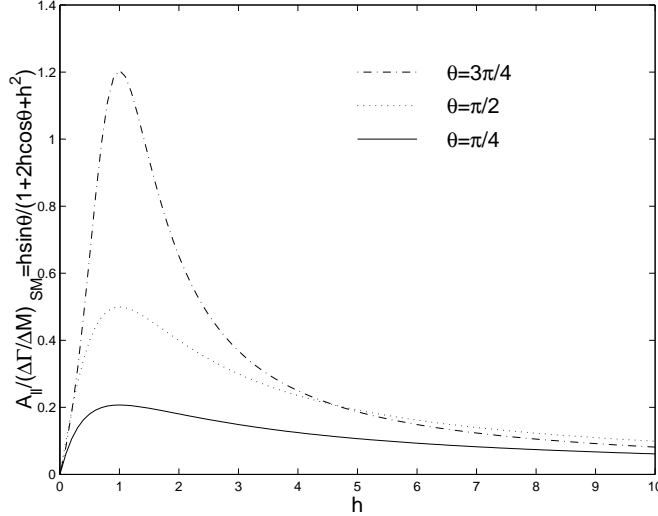


Figure 1: Plot of dependence of $A_{||}/(\Delta\Gamma/\Delta M)_{\text{SM}}$ on h , with $\theta = \pi/4, \pi/2, 3\pi/4$

$M_{12}^{\text{SUSY}}/M_{12}^{\text{SM}} = he^{-i\theta}$, the dilepton asymmetry A_{ll} is

$$A_{ll} = \text{Im} \left(\frac{\Gamma_{12}^{\text{SM}}}{M_{12}^{\text{SM}} + M_{12}^{\text{SUSY}}} \right) = \left(\frac{\Delta\Gamma}{\Delta M} \right)_{\text{SM}} \frac{h \sin \theta}{1 + 2h \cos \theta + h^2}, \quad (2.26)$$

which is similar to a formula that was also presented in Ref. [9]. In the SM, $(\Delta\Gamma/\Delta M)_{\text{SM}}$ is small [3, 5, 24, 25] :

$$\left(\frac{\Delta\Gamma}{\Delta M} \right)_{\text{SM}} = \begin{cases} (1.3 \pm 0.2) \times 10^{-2} & \text{for } B_d, \\ (5.6 \pm 2.6) \times 10^{-3} & \text{for } B_s. \end{cases} \quad (2.27)$$

The errors break down as follows: in B_d , ± 0.1 coming from $m_b = 4.8 \pm 0.2$ GeV; ± 0.1 coming from $m_t = 165 \pm 6$ GeV; ± 0.07 coming from the CKM matrix elements $|V_{ud}V_{ub}^*| = 0.003 \pm 0.0008$, $|V_{cd}V_{cb}^*| = 0.0086 \pm 0.0007$, $|V_{td}V_{tb}^*| = 0.0084 \pm 0.0018$ [16]; ± 0.02 coming from $\eta_{\text{QCD}} = 0.55 \pm 0.01$ [26]. In B_s , the dominant error comes from B_S/B . Here B_S and B are the “bag” parameters used to estimate the matrix element $Q_S = (\bar{b}_i s_i)_{S-P} (\bar{b}_j s_j)_{S-P}$ and $Q = (\bar{b}_i s_i)_{V-A} (\bar{b}_j s_j)_{V-A}$ respectively (see Ref. [24]). There are ± 2.3 from B_S/B varying between 0.7 and 1.3; ${}^{+1.1}_{-0.7}$ from varying μ between $m_b/2$ and $2m_b$; ± 0.4 from m_b and ± 0.4 from m_t .³ The dilepton charge asymmetry A_{ll} can be enhanced over the SM value by the second factor in Eq. (2.26). Notice that this factor reaches its maximum when $h = 1$, which gives

$$(A_{ll})_{\text{max}} = \left(\frac{\Delta\Gamma}{\Delta M} \right)_{\text{SM}} \frac{1}{2} \tan \frac{\theta}{2}. \quad (2.28)$$

This dilepton asymmetry is larger when θ is larger, especially when θ is close to π . We plot the dependence of $A_{ll}/(\Delta\Gamma/\Delta M)_{\text{SM}}$ on h by assuming the CP-violating phase difference θ to be $\pi/4, \pi/2, 3\pi/4$ in Fig. 1. Notice that A_{ll} is heavily suppressed if h is either very large or very small. This is because ΔM is large when h is large, while there is no significant new contribution to ΔM when h is small. For a given experimental sensitivity $(A_{ll})_{\text{min}}$,

³The m_t taken in Ref. [24] is $m_t = 176 \pm 9$ GeV. It is slightly different from the m_t we used in our calculation, which is the more recent experimental result [16].

there are corresponding h_{\min} and h_{\max} (or none if θ is too small) to which the measurement is sensitive. This in turn gives $(m_{\tilde{q}})_{\min}$ and $(m_{\tilde{q}})_{\max}$ by the formulas given in Sec. 4 for particular mixing angles. A measured dilepton asymmetry would constrain $m_{\tilde{q}}$ to be in a range between $(m_{\tilde{q}})_{\min}$ and $(m_{\tilde{q}})_{\max}$. The precise numerical results will be presented in Sec. 4.

In the literature, there are two different parametrizations of the effects of non-trivial squark matrices. One can diagonalize the $\tilde{g}q\tilde{q}$ coupling and quark mass matrices while keeping all the mixing effects in the \tilde{q} propagators. This is called the “mass insertion” method [27]. One can also work in the mass eigenstates of quarks and squarks with off-diagonal gluino couplings (we call this the “vertex mixing” method), and consider only the contribution from the lightest generation. The “mass insertion” works well when the squarks are near degenerate, that is, for $\tilde{m}_i^2 = \tilde{m}^2(1 + x_i)$, $i=1-6$ for \tilde{q}_L and \tilde{q}_R , $x_i \ll 1$. Here \tilde{m} is the average squark mass [28]. When the squark masses are not so degenerate but have the same order of magnitude, the mass insertion method can still be a good approximation if the average mass \tilde{m} is chosen appropriately. The “vertex mixing” is a better approximation when one generation is much lighter than the other two since the contributions from the heavy generations are suppressed by their masses. Notice that the mass insertion method assumes a GIM-like cancellation of the leading term, which is why the results using vertex mixing and mass insertion can be different. We will use both methods in our numerical calculation below, according to which is more appropriate.

In the flavor eigenstate basis of both quarks and squarks, the mass matrices for the up and down sector quark and squark are M^u , M^d , \tilde{M}^{u2} and \tilde{M}^{d2} , where the 6×6 squark mass matrix \tilde{M}^{d2} can be written in terms of 3×3 matrices \tilde{M}_{MN}^{d2} ($M, N = L, R$):

$$\tilde{M}^{d2} = \begin{pmatrix} \tilde{M}_{LL}^{d2} & \tilde{M}_{LR}^{d2} \\ \tilde{M}_{RL}^{d2} & \tilde{M}_{RR}^{d2} \end{pmatrix}. \quad (2.29)$$

The off diagonal \tilde{M}_{RL}^{d2} and \tilde{M}_{LR}^{d2} are usually very small due to the suppression by m_Z/\tilde{m} and quark masses (in particular for our purposes there is a λ_b suppression). In addition, the decay rate of $b \rightarrow s\gamma$ constrains $(\delta_{LR})_{23}$ (will be defined below) to be smaller than $1.6 \times 10^{-2}(m_{\tilde{q}}/500\text{GeV})^2$ [28]. We neglect \tilde{M}_{LR}^{d2} and diagonalize the squark mass matrices \tilde{M}_{LL}^{d2} and \tilde{M}_{RR}^{d2} in the mass basis of quarks and squarks, which defines the mixing angle V by

$$V_L^d M^d V_R^{d+} = \text{diag}(m_d, m_s, m_b), \quad (2.30)$$

$$V_L^u M^u V_R^{u+} = \text{diag}(m_u, m_c, m_t), \quad (2.31)$$

$$\tilde{V}_L^d \tilde{M}_{LL}^{d2} \tilde{V}_L^{d+} = \text{diag}(\tilde{m}_{dL}^2, \tilde{m}_{sL}^2, \tilde{m}_{bL}^2), \quad (2.32)$$

$$\tilde{V}_R^d \tilde{M}_{RR}^{d2} \tilde{V}_R^{d+} = \text{diag}(\tilde{m}_{dR}^2, \tilde{m}_{sR}^2, \tilde{m}_{bR}^2). \quad (2.33)$$

The $\tilde{g}q\tilde{q}$ vertices are in general not diagonal: the coupling mixing matrices (analogous to the standard CKM matrix) are

$$K_L^d = V_L^d \tilde{V}_L^{d+}, \quad K_R^d = V_R^d \tilde{V}_R^{d+}, \quad (2.34)$$

and similarly for the up system. This method of calculating flavor-changing effects is particularly useful when the mass eigenstates are very non-degenerate.

We can also work in the basis where the $\tilde{g}q\tilde{q}$ couplings and quark mass matrices are diagonal. All the mixing is now in the squark propagators, which can be expressed in terms of the dimensionless parameters $(\delta_{ij})_{MN}$

$$\delta_{MN} = \begin{pmatrix} \delta_{LL} & \delta_{LR} \\ \delta_{RL} & \delta_{RR} \end{pmatrix} = \frac{1}{\tilde{m}^2} \begin{pmatrix} V_L^d \tilde{M}_{LL}^{d2} V_L^{d+} & V_L^d \tilde{M}_{LR}^{d2} V_R^{d+} \\ V_R^d \tilde{M}_{RL}^{d2} V_L^{d+} & V_R^d \tilde{M}_{RR}^{d2} V_R^{d+} \end{pmatrix}. \quad (2.35)$$

The mass insertion method is valid if $(\delta_{ij})_{MN}$ ($i \neq j$) is small.

3 Models of Soft Supersymmetry Breaking

As is well known, the many additional parameters in supersymmetric models can introduce large dangerous FCNC and CP-violating effects. The parameters must be such that the experimental bounds on ε_k , K , B , D mixing, the electric dipole moment (EDM) of electron (d_e) and the neutron (d_n) and branching ratio of $b \rightarrow s\gamma$ [28, 29, 30] are preserved. Different scenarios have been proposed to solve, or at least relax the FCNC and CP-violation problems [31]. It is possible that none of these are the true solution, but they serve as useful straw men. In this paper, we will discuss three of them: alignment [32, 33, 34, 35], non-abelian models [35, 36, 37, 38, 39, 40, 41, 42, 43] and heavy squark models [44, 45, 46]. This list of references is incomplete but incorporates the models we study. Any model can be interpreted as we do with these. Models with nearly exact universality, such as gauge-mediated models, are of course an intriguing possibility for solving FCNC problems; however, FCNC effects are generally suppressed, and we therefore do not discuss these here. In particular, the phase of Γ_{12} and M_{12} would still be correlated if universality were assumed as a boundary condition. Should the effects we describe be observed, gauge-mediated models would be excluded.

The idea of alignment [32, 33, 34] is that the squark mass matrices are aligned with the quark ones so that the $K_{L,R}$ in Eq. (2.34) are close to the identity; that is, the off-diagonal terms are small. Therefore, there are no large contributions to FCNC. Such models can be constructed with an abelian horizontal symmetry H and additional scalar fields S [47]. With the appropriate assignment of the horizontal quantum numbers to S , Higgs fields $\phi_{u,d}$ and matter fields Q, d, u , one can construct non-renormalizable terms in the Lagrangian

$$\frac{\lambda_{ij}^d}{M^{m_{ij}}} Q_i \phi_d S^{m_{ij}} \bar{d}_j + \frac{\lambda_{ij}^u}{M^{n_{ij}}} Q_i \phi_u S^{n_{ij}} \bar{u}_j + \text{h.c.}, \quad (3.1)$$

which can give masses to the fermions if S has a vacuum expectation value $\langle S \rangle$. Here m_{ij} and n_{ij} are determined by the H charge assignment, so that the terms are invariant under H , M is a higher energy scale that communicates the horizontal symmetry breaking to the light states, and $\lambda_{ij}^{d,u}$ are some coefficients of order 1. The horizontal symmetry is spontaneously broken when S gets a vacuum expectation value, which introduces a small number $\epsilon = \langle S \rangle / M$ (this is the Froggatt-Nielson mechanism [48]). Different powers of ϵ in the Yukawa coupling account for mixing angles and the hierarchy of fermion masses. In supersymmetric theories, squarks have the same H charges as the quarks of the same multiplet and will obtain masses by the same mechanism. An astute choice of charges can allow for the alignment of squark

mass matrices with quark mass matrices, thereby suppressing flavor-changing effects. Notice that more than one U(1) symmetry is generally needed in order to get feasible models consistent with the experimental bounds. In [34], the alignment model is associated with spontaneous CP-violation, which can predict small values of supersymmetric CP-violating phases so that the EDM bounds are satisfied. After diagonalizing both the quark and squark mass matrices, we found that the (12) and (13) mixing angles in the gluino coupling vertices (although the (12) mixing angle is too small for this to be relevant) and the (13) component of the CKM matrix can have a CP-violating phase $O(1)$, while the (23) mixing is almost real, so there will be no sizable contribution to the dilepton charge asymmetry for B_s .

The non-abelian models [35, 36, 37, 38, 39, 40, 41, 42, 43] are motivated by the large top mass and the different behavior of the third family with respect to the first two families. The maximum flavor symmetry group is $U(3)^5$ in the absence of Yukawa couplings. It can be assumed that there is a non-abelian flavor symmetry $G_f \subset U(3)^5$ where the first two families and the third family transform differently; G_f can be continuous or discrete, gauged or global. There are a variety of models based on different G_f : $G_f = U(2)$ [36, 37, 40], $G_f = SU(2)$ [35, 41], $G_f = (S_3)^3$ [38, 39], $G_f = U(1) \times O(2)/Z_2$ [42] and $G_f = \Delta(75)$ [43]. This symmetry is only approximate, and is broken by some small factor λ . Because the symmetry guarantees that the first two families are nearly degenerate, FCNC for the light generations are heavily suppressed. In some models where the degeneracy of the first two families does not fully resolve the FCNC constraints [36, 40, 41, 42], different scenarios are proposed to relax the constraints: the first two generations can be much heavier than the third generation $\tilde{m}_{1,2} \sim 10\tilde{m}_3$ (scenario (a) in [40]), or the CP-violation phase is very small $\varphi \sim 10^{-2}$ (scenario (b) in [40] and [42]).

The heavy squark models [44, 45, 46] provide another possible solution to the FCNC and CP-violation problems by allowing the maximal masses consistent with naturalness bounds. All those models permit the first two generations of squarks to be heavier, which is crucial for solving FCNC problems. In effective supersymmetry [46], a new gauge group G is introduced, which enlarges the accidental symmetry group and thus forbids the renormalizable B - and L -violating interactions. It also introduces a new mass scale $\tilde{M} \sim 5\text{--}20$ TeV, which sets the mass scale for the first two generations. In addition, the requirement of naturalness implies that some squarks (\tilde{t}_L, \tilde{b}_L) and most gauginos must have a mass below ~ 1 TeV. In [44], the first two families are charged under a gauged U(1) symmetry, while the third family is neutral. Thus, there is an extra contribution to squark masses of the first two families coming from the D-term, which generates the mass hierarchy. The constraints on the mixing angles come from the naturalness of the Higgs sector and the squark mass matrices [49]. We should emphasize that the heavy-squark models cannot fully satisfy the FCNC and CP constraints by themselves. They have to be combined with non-abelian symmetry (scenario (a) in [40]) or have some alignment for the squark mass matrices.

In the next section, we select specific models from the above-mentioned papers and present a detailed study of the dilepton asymmetry and how it can put constraints on the squark masses, mixing angles and CP-violation phases for these models. Of particular interest are those models that specified the squark and quark mass matrix textures (therefore we do not consider [43]) and have large mixing with the third generation (so we do not con-

	Model	(23) mixing			(13) mixing			
		LL	RR		LL	RR		
A	[32]	λ^2	λ^4	$LL \gg RR$	λ^3	λ^3	$LL = RR$	
	[33], [35] a	λ^2	1	$LL \ll RR$	Too small mixing			
	[34]	Small CP-violation angle			λ^3	λ^7	$LL \gg RR$	Mass
B	[35] b	λ^2	$\lambda^{1/2}$	$LL \ll RR$	λ^3	$\lambda^{3/2}$	$LL \ll RR$	insertion
	[37], [40] b	λ^2	λ^2	$LL = RR$	λ^3	λ^3	$LL = RR$	
	[38]	λ^3	λ^5	$LL \gg RR$	λ^2	λ^4	$LL \gg RR$	
	[42]	λ^2	λ^4	$LL \gg RR$	λ^3	λ^4	$LL \sim RR$	
B+C	[40] a	λ^2	λ^2	$LL = RR$	λ^3	λ^3	$LL = RR$	Vertex
C	[46]	λ^2		$LL \gg RR$	λ^3		$LL \gg RR$	mixing

Table 1: Selected models from the literature, which will be analysed in section 4. Here A — alignment, B — non-abelian, C — heavy squarks.

sider [39]). We also require that the models we consider satisfy the FCNC and CP-violation bounds set by the experimental value of ε_K , ΔM_K , ΔM_D , d_e and d_n . This excludes models in [36, 41], and bounds the squark masses in some other models. In [34], $m_{\tilde{q}} > 200$ GeV, so that the quark-squark alignment solution to Δm_K will not run into problems with Δm_D . In the scenario (a) of [40], m_{Q_3, D_3} should be heavier than 550 GeV if $m_{\tilde{q}} \sim m_{\tilde{g}}$, so that the supersymmetric contribution to ε_K is within the experimental bounds, but this constraint is relaxed if the CP-violation phase is small, so we do not impose this bound. In [46], there is 1 TeV upper bound which comes from the naturalness of the Higgs sector. For the models where the squarks of the first two generations are heavy (scenario (a) in [40] and [46]), $\tilde{m}_{1,2}$ are required to be heavier than $10\tilde{m}_3$.

The models should have an $O(1)$ CP-violation phase difference in the (13) and (23) mixing angles between the SM and supersymmetric models, so that their contributions to the dilepton asymmetry is not negligible. Thus, in [34], we only consider (13) mixing since the (23) mixing CP-violation phase difference is small.

In Table 1, we list different models with the predicted LL and RR mixing (up to $O(1)$ uncertainties). As will be shown in the next section, M_{12} can get contributions from both LL and RR mixing. There are two different cases:

1. Either LL or RR mixing dominates.
2. LL mixing is comparable with RR mixing. For definiteness, we take $LL = RR$ in our calculation, except for model in ref. [42], where the (13) LL and RR mixing are λ^3 and λ^4 respectively, which is denoted by $LL \sim RR$ in Table 1. It is nonetheless important to take the RR term into account because the contribution to M_{12} from $(\delta_{31})_{LL}(\delta_{31})_{RR}$ is large.

We also show in the table whether the mass insertion (with mixing parameter $\delta_{LL,RR}$) or the vertex mixing (with mixing parameter $K_{L,R}$) method is used. We only use the vertex mixing in scenario (a) of [40] and in [46], where the first two generations are much heavier than the third one, while the mass insertion should be a good approximation in the other cases, though

it should be noted that in a detailed analysis one would account for the nondegeneracy of the squarks.

4 Numerical Results

We will assume the measurement of $\text{Im}(\Gamma_{12}/M_{12})$ for either B_d or B_s with a sensitivity 2×10^{-3} . This measurement can be obtained from either the single or dilepton asymmetries. For definiteness, since $A_{ll} \sim \text{Im}(\Gamma_{12}/M_{12})$, we refer to the dilepton asymmetry in this section.

From Eq. (2.26), we see that the dilepton asymmetry depends on $(\Delta\Gamma/\Delta M)_{\text{SM}}$, h and θ . $(\Delta\Gamma/\Delta M)_{\text{SM}}$ is given in Eq. (2.27) which has been calculated in the SM; θ is the phase difference between M_{12}^{SM} and M_{12}^{SUSY} , which can be in the range from 0 to 2π . Since $|A_{ll}|$ is symmetric with respect to π , we only consider θ to be in the range of 0 to π . The quantity h is the ratio between the amplitudes of M_{12}^{SUSY} and M_{12}^{SM} , which can be calculated through the $\Delta B = 2$ box diagrams with \tilde{q}, \tilde{g} or q, W running in the loop⁴; M_{12}^{SM} has already been calculated, including QCD corrections [2, 5, 25], and gives (we only include the top-quark contribution since this is the largest effects):

$$M_{12}^{\text{SM}} = \frac{G_F^2}{12\pi^2} m_t^2 B_{B_q} f_{B_q}^2 M_{B_q} (V_{tq} V_{tb}^*)^2 \frac{A(z_t)}{z_t} \eta_{\text{QCD}}, \quad (4.1)$$

where

$$\frac{A(z_t)}{z_t} = \frac{1}{4} + \frac{9}{4} \frac{1}{1-z_t} - \frac{3}{2} \frac{1}{(1-z_t)^2} - \frac{3}{2} \frac{z_t^2 \ln z_t}{(1-z_t)^3}, \quad z_t = \frac{m_t^2}{m_W^2}. \quad (4.2)$$

B_{B_q} is the "bag" parameter describing the uncertainty in evaluation of the hadronic matrix element, M_{B_q} and f_{B_q} are the B_q meson mass and decay constant respectively. Although $B_{B_q} f_{B_q}^2 M_{B_q}$ cancels in h , as will be shown below, we still need to know the value of B_{B_d} and f_{B_d} since we have to take into account the constraint from ΔM_{B_d} . The recent values of B_{B_d} and f_{B_d} are $B_{B_d} = 1.29 \pm 0.08 \pm 0.06$ [50], $f_{B_d} = 175 \pm 25$ MeV [51]. η_{QCD} is the QCD correction factor, which is taken to be 0.55 ± 0.01 [26] in our calculation. M_{12}^{SUSY} can be calculated either in the scenario of vertex mixing [30] or using mass insertion [28]. In the first case, M_{12}^{SUSY} is given in terms of $K_{L,R}^d$ (we take $(K_{L,R}^d)_{33} \sim 1$)⁵:

$$M_{12}^{\text{VM}} = -\frac{\alpha_s^2}{216 m_{\tilde{q}}^2} \frac{1}{3} B_{B_q} f_{B_q}^2 M_{B_q} \left\{ ((K_L^d)_{3i}^2 + (K_R^d)_{3i}^2) (66 \tilde{f}_4(x) + 24x f_4(x)) + \right. \\ \left. (K_L^d)_{3i} (K_R^d)_{3i} \left[\left(36 - 24 \left(\frac{M_{B_q}}{m_b + m_q} \right)^2 \right) \tilde{f}_4(x) + \left(72 + 384 \left(\frac{M_{B_q}}{m_b + m_q} \right)^2 \right) x f_4(x) \right] \right\}, \quad (4.3)$$

$$f_4(x) = \frac{2 - 2x + (1+x)\ln x}{(x-1)^3}, \quad \tilde{f}_4(x) = \frac{1 - x^2 + 2x\ln x}{(x-1)^3}, \quad x = m_{\tilde{g}}^2/m_{\tilde{q}}^2, \quad (4.4)$$

⁴Here we do not consider the contribution from box diagrams with \tilde{q} and chargino (or neutralino) running in the loop since it is suppressed by a factor $(g_2/g_s)^4$ with respect to the \tilde{q}, \tilde{g} box diagram contribution.

⁵There are mistakes in the formulas given by Ref. [30], which is pointed out by Ref. [28]. We use the corrected formulas here.

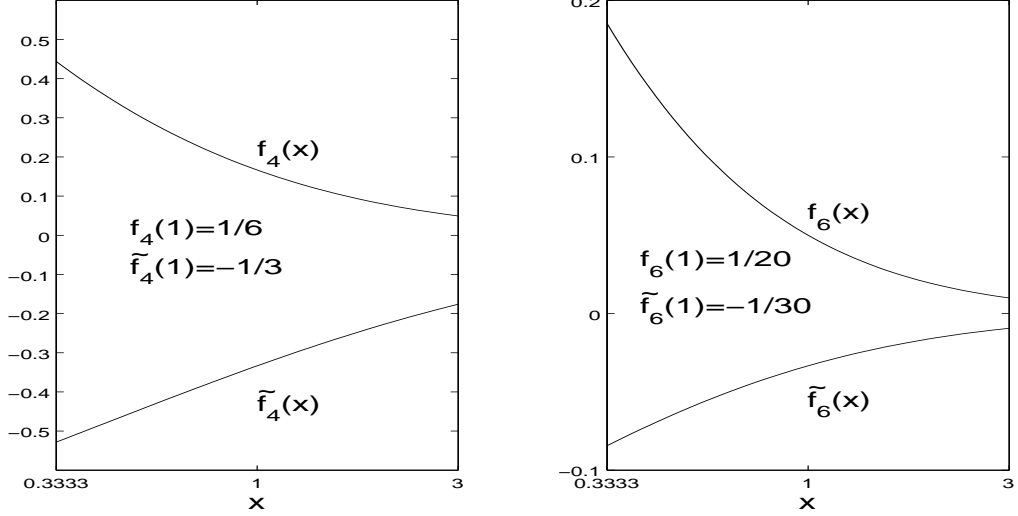


Figure 2: Plot of $f_4(x)$, $\tilde{f}_4(x)$, $f_6(x)$, $\tilde{f}_6(x)$ with x in the range of $1/3-3$.

where $i = 1, 2$ for B_d and B_s respectively. In the mass insertion notation,

$$M_{12}^{\text{MI}} = -\frac{\alpha_s^2}{216m_{\tilde{q}}^2} \frac{1}{3} B_{B_q} f_{B_q}^2 M_{B_q} \left\{ ((\delta_{3i})_{LL}^2 + (\delta_{3i})_{RR}^2) (66\tilde{f}_6(x) + 24xf_6(x)) + \right. \\ \left. (\delta_{3i})_{LL}(\delta_{3i})_{RR} \left[\left(36 - 24 \left(\frac{M_{B_q}}{m_b + m_q} \right)^2 \right) \tilde{f}_6(x) + \left(72 + 384 \left(\frac{M_{B_q}}{m_b + m_q} \right)^2 \right) xf_6(x) \right] \right\}, \quad (4.5)$$

$$f_6(x) = \frac{6(1+3x)\ln x + x^3 - 9x^2 - 9x + 17}{6(x-1)^5}, \quad (4.6)$$

$$\tilde{f}_6(x) = \frac{6x(1+x)\ln x - x^3 - 9x^2 + 9x + 1}{3(x-1)^5}. \quad (4.7)$$

The mass parameters we used in our calculation below is $M_{B_d} = 5279.2 \pm 1.8$ MeV, $M_{B_s} = 5369.3 \pm 2.0$ MeV, $m_W = 80.41 \pm 0.10$ GeV [16]. From Eqs. (4.1), (4.3) and (4.5), we can see that h depends only on $m_{\tilde{q}}$, mixing parameters, and x . The x dependence comes from the functions $f_4(x)$, $\tilde{f}_4(x)$ or $f_6(x)$, $\tilde{f}_6(x)$. We plot the x dependence of these functions in Fig. 2 and also show their values when $x = 1$, which is the value of x we use in the calculation below. The supersymmetric contribution measured by h can dominate over the SM prediction for ΔM_{B_q} because of large mixing angles or small $m_{\tilde{q}}$. In Eq. (2.26), we see that A_{ll} is suppressed when h is either too large or too small; thus the limit on the value of A_{ll} that will be experimentally accessible translates into a range of h that can be probed, given a specific θ . This in turn determines the range of $m_{\tilde{q}}$ that can be probed in particular models, which specify (approximately) the mixing angles. Again we emphasize that in general for detectable values of θ we will find both an upper and lower bound on h which will be experimentally accessible. The upper bound corresponds to too large mixing whereas the lower bound corresponds to too small a supersymmetric contribution (so too small CP violation). The upper limit on h translates into a lower bound on the squark mass

θ	Vertex mixing		Mass insertion	
	LL (RR) dominates	$LL \sim RR$	LL (RR) dominates	$LL \sim RR$
$\pi/2$	$m_{\bar{q}} \sim 192\text{--}505$	$m_{\bar{q}} \sim 323\text{--}849$	$m_{\bar{q}} \sim 45\text{--}119$	$m_{\bar{q}} \sim 224\text{--}590$
$3\pi/4$	$m_{\bar{q}} \sim 192\text{--}485$	$m_{\bar{q}} \sim 323\text{--}814$	$m_{\bar{q}} \sim 45\text{--}114$	$m_{\bar{q}} \sim 224\text{--}566$

Table 2: $m_{\bar{q}}$ (GeV) range from B_d dilepton asymmetry with $A_{ll} = 2 \times 10^{-3}$, $x = m_{\bar{g}}^2/m_{\bar{q}}^2 = 1$ and the mixing angles are the same as the corresponding CKM entry.

θ	Vertex mixing		Mass insertion	
	LL (RR) dominates	$LL \sim RR$	LL (RR) dominates	$LL \sim RR$
$\pi/2$	$m_{\bar{q}} \sim 130\text{--}310$	$m_{\bar{q}} \sim 214\text{--}509$	$m_{\bar{q}} \sim 31\text{--}73$	$m_{\bar{q}} \sim 150\text{--}357$
$3\pi/4$	$m_{\bar{q}} \sim 115\text{--}352$	$m_{\bar{q}} \sim 188\text{--}578$	$m_{\bar{q}} \sim 27\text{--}83$	$m_{\bar{q}} \sim 132\text{--}405$

Table 3: $m_{\bar{q}}$ (GeV) range from B_s dilepton asymmetry with $A_{ll} = 2 \times 10^{-3}$, $x = m_{\bar{g}}^2/m_{\bar{q}}^2 = 1$ and the mixing angles are the same as the corresponding CKM entry.

(for definite mixing angles) whereas the lower bound translates into an upper bound on the mass.

For our results we take into account the constraint $\Delta M_{B_d} = 0.470 \pm 0.019 \text{ ps}^{-1}$ [16]. The supersymmetric contribution to ΔM_{B_d} cannot exceed this, which puts a severe bound on the (13) mixing and $m_{\bar{q}}$. The B_s mixing has no such constraint.

As explained in Sec. 2, B_d and B_s both contribute to the total dilepton rate. Assuming a measurement on the dilepton asymmetry with a sensitivity of 10^{-3} , we require at least 2×10^{-3} dilepton asymmetry from either B_d or B_s . This is also the current upper bound on the B_d standard model contribution, so it is clearly identifiable as new physics. Of course if better precision is possible a measurement of the B_s system with greater accuracy would be interesting since its standard model rate is much lower.

In Eq. (2.28), we see that the phase difference between M_{12}^{SUSY} and M_{12}^{SM} must be large enough so that the dilepton asymmetry can be measured. For the precision we choose, we find that

$$\theta \geq \begin{cases} 30^\circ - 40^\circ & \text{for } B_d, \\ 52^\circ - 106^\circ & \text{for } B_s. \end{cases} \quad (4.8)$$

Here the large range in the lower limit of θ comes from the large uncertainties in $(\Delta\Gamma/\Delta M)_{\text{SM}}$. Models with too small a CP-violation phase difference between the SM and supersymmetric models cannot be tested using the dilepton asymmetry.

For the results presented below, we take the SM CKM matrix elements [16, 55]:

$$|V_{td}V_{tb}^*| : \quad 0.0066 - 0.0102, \quad |V_{ts}V_{tb}^*| : \quad 0.026 - 0.060. \quad (4.9)$$

In Tables 2 and 3, we show the allowed ranges of $m_{\bar{q}}$ when the dilepton asymmetry of B_d or B_s is larger than 2×10^{-3} . Here we assume that the (13), (23) mixing angles are the same as the corresponding CKM entries. We notice that the vertex mixing results are larger than the mass insertion ones. This is because we only consider the contribution from the third generation in the vertex mixing case, while all the generations contribute in the mass

		(23) mixing				(13) mixing			
				$m_{\tilde{q}}$ (GeV)				$m_{\tilde{q}}$ (GeV)	
	Model	LL	RR	$\theta = \pi/2$	$\theta = 3\pi/4$	LL	RR	$\theta = \pi/2$	$\theta = 3\pi/4$
A	[32]	λ^2	λ^4	20–112	18–127	λ^3	λ^3	176–715	176–686
	[33], [35] a	λ^2	1	511–2807	450–3187			Too small mixing	
	[34]	Small CP-violation angle				λ^3	λ^7	36–144	36–139
B	[35] b	λ^2	$\lambda^{1/2}$	229–1255	201–1425	λ^3	$\lambda^{3/2}$	397–1614	397–1549
	[37], [40] b	λ^2	λ^2	100–549	88–624	λ^3	λ^3	176–715	175–686
	[38]	λ^3	λ^5	4–22	4–25	λ^2	λ^4	178–722	178–693
	[42]	λ^2	λ^4	20–112	18–127	λ^3	λ^4	73–298	73–286
B+C	[40] a	λ^2	λ^2	143–784	126–890	λ^3	λ^3	253–1029	253–987
C	[46]	λ^2		87–476	76–541	λ^3		151–613	151–588

Table 4: $m_{\tilde{q}}$ ranges for different models with $A_{ll} = 2 \times 10^{-3}$, $x = m_{\tilde{g}}^2/m_{\tilde{q}}^2 = 1$ and $\lambda = 0.2$ for B_s ((23) mixing) and B_d ((13) mixing) dilepton asymmetries. Notations are the same as in Table 1.

insertion method. In the latter case, the leading-order contribution cancels because of the GIM mechanism, which gives smaller M_{12}^{SUSY} . Thus, the squark masses obtained using the mass insertion method have to be smaller in order to compensate for this weakening effect. However without a detailed knowledge of the mixing angles and masses either method must be viewed as an approximation.

We need to take into account the current experimental lower bounds on the squark mass coming from the non-observation of any supersymmetry signals at either LEP [52] or the Tevatron [53, 54]. For the vertex mixing case, when the first two generation squarks are much heavier than the third generation ones, the $m_{\tilde{q}}$ bounds are on the lightest sbottom mass. The sbottom masses are all larger than 110 GeV, which have not been excluded by the experimental lower limit ($m_Z/2$) [52]. For the mass insertion case when the squark masses are almost degenerate, we impose the constraints from CDF and $D\bar{O}$ searches. While LL (or RR) dominates, the squark masses are smaller than 120 GeV, which has already been ruled out by the CDF ($m_{\tilde{q}} > 230$ GeV [53]) and the $D\bar{O}$ ($m_{\tilde{q}} > 260$ GeV [54]) limit; this means that if the soft supersymmetry-breaking models have the squark mixing angles in the SM ranges and LL (or RR) is dominating, then the dilepton asymmetry is too small to be measured experimentally. If $LL = RR$, the squark masses can be in the range of 130–600 GeV; most of the mass ranges have not been ruled out yet. Thus, the corresponding supersymmetric models can still be tested through a dilepton charge asymmetry measurement.

Also notice that the lower limits of $m_{\tilde{q}}$ in Table 2 (B_d case) are the same for different θ . This is because the upper bound on h (which corresponds to the lower bound on $m_{\tilde{q}}$) is set by the experimentally measured value of ΔM_{B_d} .

We now consider the implications of our results. In Table 4, we show the ranges of $m_{\tilde{q}}$ for different soft supersymmetry-breaking models. The lower mass limits coming from the constraints of FCNC have been imposed. We see that the models divide into several groups: those that show an effect in both, neither, or one of the B_d and B_s systems. It should of course be remembered that we used a definite value for the angle in these tables so there is an

order one fudge factor available in any model. Nonetheless, there are some clear tendencies indicated by these results.

For the models in [37, 40], both the $(\delta_{13,23})_{LL}$ and $(\delta_{13,23})_{RR}$ are of the order of λ^3 and λ^2 , respectively, which are comparable to the SM CKM mixing angles. This is the optimal situation in that for reasonable supersymmetric masses, the standard and nonstandard box contributions are competitive. The squark masses are below 1 TeV, which can be explored experimentally.

The models in [33, 35] predict quite different mixing angles from the SM. The RR mixing can be as large as 1 in (23) and $O(\lambda^{3/2})$ [35] in (13), which increases the squarks to heavy masses in order to keep the supersymmetric and SM box diagrams to be comparable to each other ($h \sim 1$). If the squark masses are indeed light, it is likely that there is a large supersymmetric contribution to flavor violation and that it will be completely undetected in the measurement of a lepton asymmetry! Since such large mixing angles will give rise to noticeable effects in other measurements, the lepton asymmetry provides a nice complement to such measurements and would provide a clear determination of a model with large mixing angles. However, it is possible that the squark masses are at the lighter end (which would be measured) and that there is visible evidence of a lepton asymmetry.

There are several models which should give a reasonable asymmetry for B_d but not for B_s . These include the models in [32, 38, 42], although the latter only has a small range of squark mass which has not already been excluded by the CDF and DØ limits. Actually for [34], the squark mass range which is accessible is already at the limit of what would be permitted once the 200 GeV lower bound arising from the Δm_D constraint is accounted for. We can see that the model of Ref. [34] which explicitly addresses the CP violation as well as the flavor structure gives no measurable effects in the lepton asymmetries.

We also find that the heavy squark models are very likely testable. However, we note that we assumed the mixing angles agreed with their CKM counterparts. Should they be bigger, the asymmetry could be too small to measure. For the effective supersymmetry model in [46], the upper limit increases with the mixing angles; it is 600 GeV for the mixing to be in the SM ranges. If the mixing is too large, this model predicts too small dilepton asymmetry because of the 1 TeV upper limit in squark masses coming from the naturalness constraints and thus cannot be tested.

In the analysis above, we assumed that the dilepton asymmetry of 2×10^{-3} is measured for either B_d or B_s . If we assume 4×10^{-3} sensitivity, then the lower limit on θ is $56^\circ - 72^\circ$ for B_d and $89^\circ - 139^\circ$ for B_s . For any given experimental sensitivity D , we define a θ -dependent scale factor $S_{d,s}(\theta, \frac{D}{2 \times 10^{-3}})$. The squark mass under this new sensitivity is then $(m_{\tilde{q}})_D = S_{d,s}(\theta, \frac{D}{2 \times 10^{-3}})(m_{\tilde{q}})_{2 \times 10^{-3}}$. If we take $\theta = 3\pi/4$ and $D = 4 \times 10^{-3}$ as an example, in B_d , the lower limit remains the same because it comes from the ΔM_{B_d} constraint, while for the upper limit $S_d(3\pi/4, 2)_{\text{upper}} = 0.765$. In B_s , the reduction in squark mass range follows from $S_s(3\pi/4, 2)_{\text{upper}} = 0.78$, $S_s(3\pi/4, 2)_{\text{down}} = 1.28$. In general, the factor D can be obtained from Eq. (2.26).

We conclude that models are certainly distinguishable from the lepton asymmetry measurements alone. With other complementary measures there is some hope to resolve the

flavor problem of supersymmetry. However, we have assumed a reasonably good sensitivity, which is essential for the measurement to be useful.

5 Conclusions

It is possible that the dilepton asymmetry could be one of the first indications of physics beyond the standard model. Once the source of new physics is ascertained through direct measurements, it can be used to impose further constraints. In particular, if the new physics is indeed low-energy supersymmetry, the dilepton charge asymmetry can be used to distinguish various soft supersymmetry-breaking models. The range of parameters which can be tested is such that there is often a good overlap with interesting flavor models. Unfortunately, there is not an unambiguous identification of the size of the signal with the category of model; nonetheless particular models with definite patterns for masses and mixings can be tested. We emphasize the importance of taking a model-dependent approach; although large mixing angles can give big effects in searches for physics beyond the standard model, existing constraints and the attempt to motivate flavor physics parameters through an underlying symmetry structure often disfavor this assumption.

We emphasize that there are uncertainties in the precise angles which can change the exact range of squark mass which is covered. In particular, all models we presented have order unity uncertainties for the angles which can change the range of mass which is probed. Furthermore nondegeneracy of the squark mass and gluino mass introduces another parameter which can affect the precise range of parameters which is covered. Finally, the mass insertion method is an approximation; it is generally only a good one if the mass parameter is appropriately interpreted. Nonetheless, the overall message is clear; it would be very interesting to do an accurate measurement of the single lepton and/or dilepton asymmetries.

In this paper, we have focussed on the lepton charge asymmetry as a means of searching for new physics, in particular for testing new models of flavor. These lepton asymmetries are sensitive to new sources of mixing in the B system. These new sources of mixing can be independently tested in other measurements [8, 14, 49, 56, 57]. Particularly interesting alternative tests for CP-violation in B_s are the study of $B_s \rightarrow D_s^+ D_s^-$, $B_s \rightarrow \psi\phi$, and related modes [17, 58, 59]; B_d , in particular modes such as $B_d \rightarrow \phi K_s$ and $B_d \rightarrow K_s \pi^0$ [57, 59, 60], where new physics effects might be large, and measurements of deviations in precisely predicted rates such as $B \rightarrow J/\psi K_s$. In particular, models with large mixing in the B_s sector (of order unity) should give large effects for these measurements. Even with these studies, it will be useful to have an alternative means of searching for new physics. Precisely because the rate is negligible in the standard model, the lepton asymmetry would be an extremely important measurement.

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