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Implications of a small CP asymmetry in $B \to \psi K_S$

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Abstract: New measurements of the CP asymmetry in $B \to \psi K_S$, $a_{\psi K_S}$, by the BABAR and BELLE collaborations are consistent with the Standard Model prediction for $\sin 2\beta$. These measurements, however, leave open the possibility that $a_{\psi K_S}$ is well below the Standard Model prediction. We identify deviations from the "reasonable ranges" of hadronic parameters that can lead to low values of $\sin 2\beta$. New physics, mainly in $B^0 - \overline{B^0}$ mixing and/or $K^0 - \overline{K^0}$ mixing, can explain low values of $a_{\psi K_S}$ in two ways: either by allowing for values of $\sin 2\beta$ below the Standard Model prediction or by modifying the relation between $a_{\psi K_S}$ and $\sin 2\beta$.

Keywords: Standard Model, Beyond Standard Model, B-Physics, CP violation.

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Contents

1. Introduction

Recent studies of the time dependent $B \to \psi K_S$ decay rates by the BaBar [1] and BELLE [2] collaborations have provided highly interesting results concerning CP violation in B decays. When combined with a previous CDF result [3], the average measured CP asymmetry is

$$a_{\psi K_S} = 0.42 \pm 0.24\,, \tag{1.1}$$

where $a_{\psi K_S}$ is defined via

$$\frac{\Gamma[\overline{B^0}(t) \to \psi K_S] - \Gamma[B^0(t) \to \psi K_S]}{\Gamma[\overline{B^0}(t) \to \psi K_S] + \Gamma[B^0(t) \to \psi K_S]} = a_{\psi K_S} \sin(\Delta m_B t)\,. \tag{1.2}$$

(For previous measurements, see [4]–[6].) Within the Standard Model, $a_{\psi K_S}$ is related to the angle β of the unitarity triangle,

$$a_{\psi K_S} = \sin 2\beta\,, \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]. \tag{1.3}$$

Based on the detrmination of the CKM parameters through measurements of $|V_{ub}/V_{cb}|$, ε_K, Δm_B and Δm_{B_s}, the Standard Model (SM) prediction is

$$0.59 \lesssim \sin 2\beta \lesssim 0.82\,. \tag{1.4}$$

Thus, the measurement of $a_{\psi K_S}$ (1.1) is consistent with the SM prediction (1.4). This can be seen in figure 1 where the various bounds are given in the plane of the

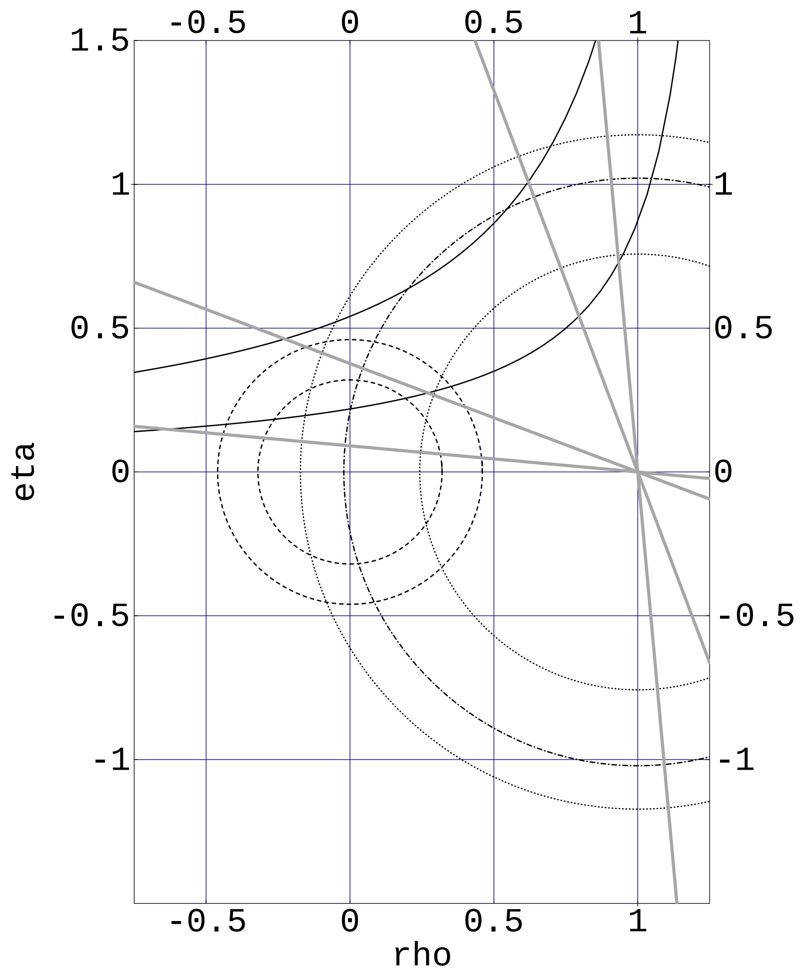

Figure 1: Present constraints on the apex $(\bar{\rho}, \bar{\eta})$ of the unitarity triangle: $|V_{ub}/V_{cb}|$ (dashed), Δm_{B_d} (dotted), $\Delta m_{B_d}/\Delta m_{B_s}$ (dash-dotted), ε_K (solid), and the average of the CDF, BELLE and BABAR measurements of $a_{\psi K_S}$ (thick grey lines).

two Wolfenstein parameters, $(\bar{\rho}, \bar{\eta})$. Yet, the allowed range in (1.1) leaves open the possibility that $a_{\psi K_S}$ is actually significantly smaller than the SM prediction. It is this possibility that we investigate in this work. For the sake of concreteness, we will assume that $a_{\psi K_S}$ lies indeed within the 1σ range of the BaBar measurement [1],

$$a_{\psi K_S} = 0.12 \pm 0.38 \,. \tag{1.5}$$

While negative values of $a_{\psi K_S}$ are unlikely in view of the other measurements, our main interest will be in the upper bound, $a_{\psi K_S} \lesssim 0.5$.

If, indeed, $a_{\psi K_S} \lesssim 0.5$, there are two ways in which the conflict with (1.4) might be resolved:

(i) The SM is valid but one or more of the hadronic parameters which play a role in the analysis that leads to (1.4) are outside their "reasonable range". We discuss this possibility in section 2.

(ii) New physics affects the CP asymmetry in $B \to \psi K_S$ and/or some of the measurements that lead to (1.4). We discuss this possibility in section 3.

We summarize our conclusions in section 4.

2. Hadronic uncertainties

The computations that relate experimental observables to CKM parameters suffer, in general, from theoretical uncertainties. In very few cases, the calculation is made entirely in the framework of a systematic expansion and it is possible to reliably estimate the error that is induced by truncating the expansion at a finite order. This is the case with the relation between the observable $a_{\psi K_S}$ and the CKM parameter $\sin 2\beta$: within the SM, the relation (1.3) holds to an accuracy of better than one percent (for a review, see [7]). Thus, if we assume that (1.5) holds, we have

$$-0.26 \lesssim \frac{2\bar{\eta}(1-\bar{\rho})}{\bar{\eta}^2 + (1-\bar{\rho})^2} \lesssim +0.50\,. \tag{2.1}$$

In most cases, however, the calculation involves models, ansatze or, on occasion, educated guesses and there is no easy way to estimate the errors that are involved. This is the case with almost all the observables that are involved in the prediction (1.4). We will follow the treatment of this issue of ref. [8]. We will quote "reasonable ranges" for the parameters that involve uncontrolled theoretical uncertainties, and compare them to the values that are required for consistency with (1.5).

We emphasize that we use rather conservative CKM constraints, similar to those of refs. [8]–[15]. In particular, these ranges arise when the BaBar method [8]–[11] or a flat distribution [12]–[15] are employed for theoretical errors. Studies that assume that theoretical errors have a gaussian distribution obtain stronger constraints. Our input parameters are taken from [12, 15] and the resulting constraints were calculated in [14].

The R_u parameter is determined from semileptonic charmless B decays:

$$R_u \equiv \sqrt{\bar{\rho}^2 + \bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|. \tag{2.2}$$

Using

$$\begin{aligned} |V_{ub}| &= (3.56 \pm 0.56) \times 10^{-3}\,, \\ |V_{cb}| &= (4.0 \pm 0.2) \times 10^{-2}\,, \end{aligned} \tag{2.3}$$

we obtain

$$\sqrt{\bar{\rho}^2 + \bar{\eta}^2} = 0.39 \pm 0.07\,. \tag{2.4}$$

Most of the uncertainty comes from hadronic modelling and therefore should be viewed as a "reasonable range" rather than a 1σ error.

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The R_t parameter is given by

$$R_t \equiv \sqrt{(1-\bar\rho)^2+\bar\eta^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|, \tag{2.5}$$

where V_{td} is determined from Δm_B [12],

$$\frac{|V_{td}|}{8.8\times 10^{-3}} = \frac{0.2\,\mathrm{GeV}}{\sqrt{B_{B_d}}f_{B_d}}\left(\frac{170\,\mathrm{GeV}}{m_t}\right)^{0.76}\left(\frac{\Delta m_B}{0.5\,\mathrm{ps}^{-1}}\right)^{1/2}\left(\frac{0.55}{\eta_B}\right)^{1/2}, \tag{2.6}$$

or from $\Delta m_{B_d}/\Delta m_{B_s}$:

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\left(\frac{m_{B_s}}{m_{B_d}}\right)^{1/2}\left(\frac{\Delta m_{B_d}}{\Delta m_{B_s}}\right)^{1/2}. \tag{2.7}$$

Using

$$\begin{aligned} \sqrt{B_{B_d}}f_{B_d} &= \ 0.20\pm 0.04\,\mathrm{GeV}\,, \qquad m_t = 165\pm 5\,\mathrm{GeV}\,,\\ \Delta m_B &= 0.471\pm 0.016\,\mathrm{ps}^{-1}\,, \qquad \Delta m_{B_s} \geq\ 14.6\,\mathrm{ps}^{-1}\,,\\ \xi &= 1.14\pm 0.08\,, \end{aligned} \tag{2.8}$$

we obtain

$$\sqrt{(1-\bar\rho)^2+\bar\eta^2} = 0.98^{+0.04}_{-0.22}\,. \tag{2.9}$$

There are two theoretical parameters in (2.8). The uncertainty in $\sqrt{B_{B_d}}f_{B_d}$ comes from systematic errors in lattice calculations and should be viewed as a "reasonable range". On the other hand, the deviation from $\xi = 1$ is a correction to the SU(3) limit and believed to be under much better control.

The ε_K constraint reads:

$$\bar\eta\left[(1-\bar\rho)A^2\eta_2 F_{tt} + P_c(\epsilon)\right]A^2\hat B_K = 0.226\,. \tag{2.10}$$

Using [12]

$$\begin{aligned} A &= 0.826\pm 0.041\,, \qquad \eta_2 = 0.57\pm 0.01\,, \\ F_{tt} &= 2.46\left(\frac{m_t}{170\,\mathrm{GeV}}\right)^{1.52}, \qquad P_c(\epsilon) = 0.31\pm 0.05\,, \qquad \hat B_K = 0.80\pm 0.15\,, \end{aligned} \tag{2.11}$$

we obtain:

$$\bar\eta\left[(1-\bar\rho)\left(0.91^{+0.16}_{-0.14}\right) + \left(0.31\pm 0.05\right)\right] = 0.41^{+0.15}_{-0.10}\,. \tag{2.12}$$

The main contribution to the uncertainty on the right hand side of eq. (2.12) comes from the theoretically calculated $\hat B_K$ and, again, represents a reasonable range.

The four constraints (2.1), (2.4), (2.9) and (2.12) are given in figure 2. There is no overlap between the four allowed ranges. The last three together form an allowed range in the $\bar\rho - \bar\eta$ plane which can be translated to the constraint on $\sin 2\beta$ given

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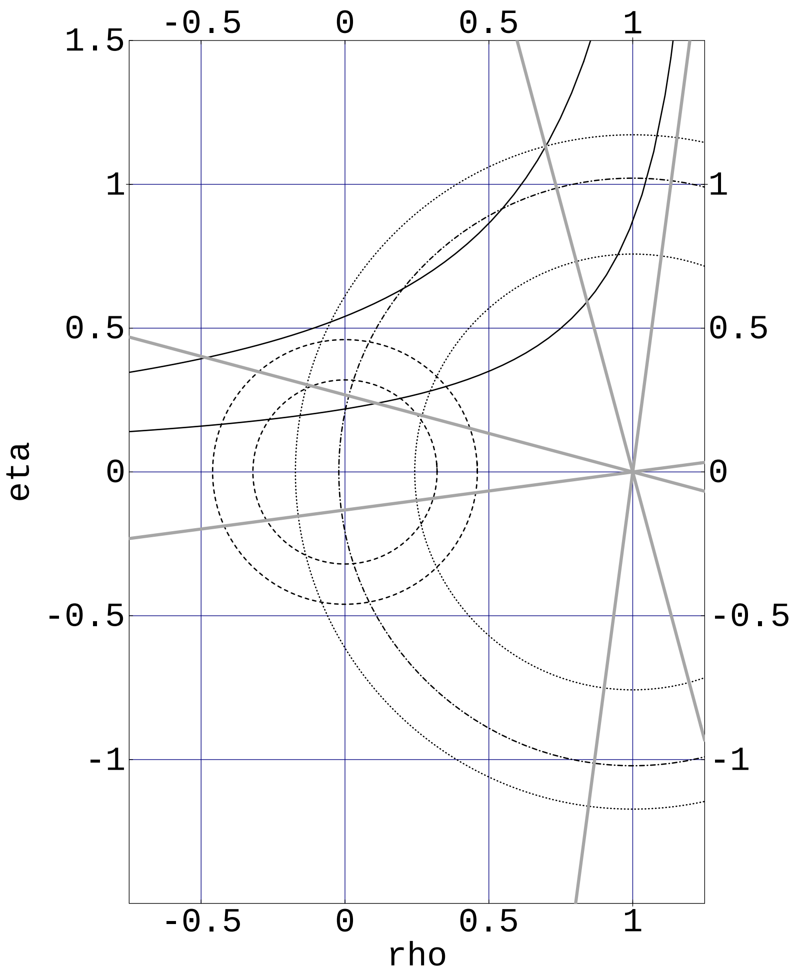

Figure 2: Present constraints on the apex $(\bar{\rho}, \bar{\eta})$ of the unitarity triangle: $|V_{ub}/V_{cb}|$ (dashed), Δm_{B_d} (dotted), $\Delta m_{B_d}/\Delta m_{B_s}$ (dash-dotted), ε_K (solid), and the BABAR measurement of $a_{\psi K_S}$ (thick grey lines).

in eq. (1.4). One lesson which should be clear from our discussion here is that there are several hadronic parameters that enter into this constraint. In particular, for R_u, $\sqrt{B_{B_d}} f_{B_d}$ and $\hat{B}_K$ we are only able to quote reasonable ranges. We now ask what values of these parameters will allow $\sin 2\beta \lesssim 0.5$, consistently with (1.5).

To answer this question, we study whether the discrepancy between (1.4) and (1.5) can be explained by a single theoretical parameter that is outside of its reasonable range.

(i) Let us assume that the R_t constraint (2.9) and the ε_K constraint (2.12) hold, but allow a failure of the R_u constraint (2.4). Indeed, under such assumptions, there is an allowed region around $(\bar{\rho}, \bar{\eta}) = (0.01, 0.26)$. It requires, however, that

$$R_u \lesssim 0.27\,, \tag{2.13}$$

which is below its reasonable range in (2.4). In other words, if the inconsistency comes from the hadronic modelling of charmless semileptonic B decays, the failure of these models should be such that $|V_{ub}|$ is about 30% lower than the presently most favorable value.

There is a second allowed region, around $(\bar{\rho}, \bar{\eta}) = (0.8, 0.8)$. Here, however, $R_u \gtrsim 1.1$ is required. This value is about three times larger than the best present estimate. We find such a situation very unlikely.

(ii) Let us assume that the R_u constraint (2.4) and the ε_K constraint (2.12) hold, but allow a failure of the R_t constraint (2.9). Under such assumptions, there is an allowed region around $(\bar{\rho}, \bar{\eta}) = (-0.3, 0.3)$. It requires, however, that

$$\xi \gtrsim 1.4\,, \tag{2.14}$$

which is well above the 1σ range in (2.8). Note, however, that $\sqrt{B_{B_d}} f_{B_d}$ could be within its reasonable range (close to the lower bound).

(iii) Let us assume that the R_u constraint (2.4) and the R_t constraint (2.9) hold, but allow a failure of the ε_K constraint (2.12). There is a small viable region around $(\bar{\rho}, \bar{\eta}) = (0.25, 0.20)$. It requires, however, that

$$\hat{B}_K \gtrsim 1.3\,, \tag{2.15}$$

which is well above its reasonable range in (2.11).

To summarize: assuming that the CP asymmetry in $B \to \psi K_S$ is within the 1σ range of BaBar measurement, the SM could still be valid if some of the hadronic parameters are outside of their "reasonable" ranges. If the apparent discrepancy is related to an error in the theoretical estimate of just one parameter, then it requires either a small value of $|V_{ub}|$, or a large value of ξ or a large value of $\hat{B}_K$. The first of these, $|V_{ub}/V_{cb}| \lesssim 0.06$, is perhaps the least unlikely deviation from our "reasonable ranges".

3. New physics

New physics can explain an inconsistency of $a_{\psi K_S}$ measurement with the SM predictions. It can do so provided that it contributes significantly either to $B^0 - \overline{B^0}$ mixing or to the CP violating part of $K^0 - \overline{K^0}$ mixing or to both. In this section we examine each of these possibilities.

It is also possible, in principle, that the discrepancy is explained by a new contribution to $b \to u\ell\nu$ decays or to $b \to c\bar{c}s$ decays. We find it unlikely, however, that these SM tree level decays are significantly affected by new physics. In particular, we assume that the charmless semileptonic B decays provide a valid measurement of $|V_{ub}|$ and, consequently, (2.4) holds.

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3.1 $B^0 - \overline{B^0}$ mixing

The effects of new physics on $B^0 - \overline{B^0}$ mixing can be described by a positive dimensionless parameter r_d^2 and a phase $2\theta_d$ [16]–[20]:

$$M_{12} = r_d^2 e^{2i\theta_d} M_{12}^{\rm SM} \,. \tag{3.1}$$

Here M_{12} ($M_{12}^{\rm SM}$) is the full (SM) $B^0 - \overline{B^0}$ mixing amplitude.

If the new physics modifies the phase of the mixing amplitude, $2\theta_d \neq 0$, then the CP asymmetry in $B \to \psi K_S$ is modified. Instead of eq. (1.3) we now have:

$$a_{\psi K_S} = \sin 2(\beta + \theta_d) \,. \tag{3.2}$$

If the new physics modifies the magnitude of the mixing amplitude, $r_d^2 \neq 1$, then Δm_B is modified. In eq. (2.6), we should replace $|V_{td}|$ with $r_d|V_{td}|$. In addition, if the new physics modifies the $B_s - \overline{B_s}$ mixing amplitude, and we parametrize this modification with corresponding parameters r_s^2 and $2\theta_s$, then instead of eq. (2.7) we now have:

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi \, \frac{r_s}{r_d} \left(\frac{m_{B_s}}{m_{B_d}}\right)^{1/2} \left(\frac{\Delta m_{B_d}}{\Delta m_{B_s}}\right)^{1/2} \,. \tag{3.3}$$

If there is no new physics in the R_u and ε_K constraints, then the following bounds hold:

$$0.7 \lesssim R_t \lesssim 1.4 \,, \qquad 12^o \lesssim 2\beta \lesssim 55^o \,. \tag{3.4}$$

Furthermore, there are correlations between the allowed ranges. To achieve consistency with the measurements concerning $B^0 - \overline{B^0}$ mixing, it is required that either (i) $r_d/r_s \neq 1$, or (ii) $2\theta_d \neq 0$ or (iii) both.

(i) Consider models where there is a new contribution to both $B^0 - \overline{B^0}$ mixing and $B_s - \overline{B_s}$, but at least the first of these carries the same phase as the Standard Model contribution. With $2\theta_d = 0$, we need

$$0.5 \lesssim r_d \lesssim 1 \,, \qquad \frac{r_s}{r_d} \gtrsim 1.1 \,. \tag{3.5}$$

(ii) Consider the case where there is a new CP violating contribution to $B^0 - \overline{B^0}$ mixing which, however, keeps the magnitude of the mixing amplitude unchanged. We know of no mechanism that would predict such a scenario, which requires a relation between the magnitude and the phase of $M_{12}^{\rm NP}$, the new physics contribution to M_{12}. We view such a situation as a rather unlikely accident. For completeness, we quote the required θ_d range for $r_d^2 = r_s^2 = 1$:

$$2\theta_d \in \{95^o, 160^o\} \text{ or } \{290^o, 355^o\} \,. \tag{3.6}$$

(iii) With generic new contributions to $B^0 - \overline{B^0}$ and $B_s - \overline{B_s}$ mixing, we can accommodate the experimental measurements with

$$\begin{aligned} &0.5 \lesssim r_d \lesssim 1.7 \,, \qquad \frac{r_s}{r_d} \gtrsim 0.7 \,, \\ &2\theta_d \in \{0^o, 18^o\} \text{ or } \{95^o, 183^o\} \text{ or } \{290^o, 360^o\} \,. \end{aligned} \tag{3.7}$$

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Two points are in order:

1. If the new physics contribution carries no new phase, then it must be flavor violating in the sense that $r_s \neq r_d$. In other words, the flavor structure should be different from the CKM one.

2. The contribution of the new physics to the mixing amplitude cannot be much smaller than the Standard Model one. To be more quantitative on this point, it is convenient to replace the $(r_d^2, 2\theta_d)$ parametrization of eq. (3.1) with a different parametrization defined as follows:

$$M_{12}^{\rm NP} = h e^{i\sigma} M_{12}^{\rm SM} \,, \tag{3.8}$$

that is, $r_d^2 e^{2i\theta_d} = 1 + h e^{i\sigma}$. The h parameter gives the ratio between the size of the new physics contribution and the SM one. We numerically scanned the allowed region for h and σ. (We take in this scan $r_s = 1$, so that the new physics effects are restricted to $B^0 - \overline{B^0}$ mixing.) We find that

$$h \equiv \left| \frac{M_{12}^{\rm NP}}{M_{12}^{\rm SM}} \right| \gtrsim 0.1 \,. \tag{3.9}$$

3.2 $K^0 - \overline{K^0}$ mixing

A value of $a_{\psi K_S}$ below the SM prediction can arise even if there is no new physics in $B^0 - \overline{B^0}$ mixing and in $b \to c\bar{c}s$ decay, the two processes that are relevant to the CP asymmetry in $B \to \psi K_S$. The explanation must then be related to processes (other than Δm_B) that play a role in constraining the $\sin 2\beta$ range. The prime suspect is CP violation in the neutral kaon system, that is ε_K.

If ε_K is not fully explained by the SM, then the ε_K constraint, eq. (2.10), does not hold. On the other hand, with no significant new physics contributions to the mixing and the relevant decays of the B-mesons, the R_u, Δm_{B_q} and $a_{\psi K_S}$ constraints hold. As explained in the previous section, in such a case there is a small region around $(\bar\rho, \bar\eta) = (0.25, 0.20)$ that is marginally consistent with all of these constraints when the hadronic parameters reside within our "reasonable ranges". In this region, the new physics has to add up constructively to the SM contribution to ε_K, with

$$\frac{{\rm Im}\, M_{12}^{\rm NP}(K)}{{\rm Im}\, M_{12}^{\rm SM}(K)} \gtrsim 0.3 \,. \tag{3.10}$$

The situation that there is no new physics in $B^0 - \overline{B^0}$ mixing and $B_s - \overline{B_s}$ mixing has also interesting implications for ε'/ε. Within the SM, it is not easy to explain the measured value of ε'/ε, and various hadronic parameters have to assume values outside their reasonable ranges. In the scenario discussed in this section, the puzzle becomes even stronger. The combination of the constraints on $\sin 2\beta$ and on R_t implies that $\bar\eta$ is rather small. Even if we allow mild deviations from our range for either $|V_{ub}/V_{cb}|$ or $\sqrt{B_{B_d}} f_{B_d}$, the remaining $\Delta m_{B_s}/\Delta m_{B_d}$ and $a_{\psi K_S}$ constraints are enough to give $\bar{\eta} \lesssim 0.25$. Thus, even if the new physics contribution to ε_K can be rather small, it should also add up constructively to the SM contribution to ε'/ε.

Note that the situation where the R_u, $\Delta m_{B_s}/\Delta m_{B_d}$ and $a_{\psi K_S}$ constraints are valid but the ε_K and Δm_{B_d} are not arises in models of new physics where all flavor violation and CP violation are described by the CKM matrix. This class of models was defined and analyzed in ref. [21]. We find that, if (1.5) holds, the new physics should probably play a role in both ε_K and ε'/ε.

3.3 Neutral meson mixing

In a large class of models, there could be significant contributions to both $B^0 - \overline{B^0}$ mixing and $K^0 - \overline{K^0}$ mixing. However, $b \to u\ell\nu$ decays are dominated by the W-mediated tree level decay. The implications of measurements of $a_{\psi K_S}$ in such a framework were recenty investigated in refs. [22, 23]. In such a framework, only the R_u constraint of eq. (2.4) holds. In particular, the upper bound $R_u \lesssim 0.46$ gives the following constraint on β:

$$|\sin 2\beta| \lesssim 0.82\,, \qquad \cos 2\beta \gtrsim 0.58\,. \tag{3.11}$$

The assumed value of $a_{\psi K_S}$ can be accommodated with $-0.940 \lesssim \sin 2\theta_d \lesssim +0.996$. (The bounds on r_d^2 are similar to [22].)

4. Conclusions

A low value of $a_{\psi K_S}$, say $a_{\psi K_S} \lesssim 0.5$, is well within the average of present measurements, $a_{\psi K_S} = 0.42 \pm 0.24$. It is outside however of the indirect constraint on $\sin 2\beta$ that holds within the Standard Model. We discussed two general scenarios in which the intriguing possibility of a low $a_{\psi K_S}$ can be accommodated:

1. The Standard Model is valid. The constraints on $\sin 2\beta$ are wrong because one or more of the relevant hadronic parameters are outside of the range that is considered in the literature. The possible explanations are as follows:

(i) $|V_{ub}|$ is smaller than its theoretically favored range.

(ii) ξ is larger than its theoretically favored range.

(iii) $\hat{B}_K$ is larger than its theoretically favored range.

(iv) At least two of the theoretical parameters are outside of the preferred ranges.

2. Present estimates of all hadronic parameters are correct. There is new flavor violating and/or CP violating physics. The possible scenarios of new physics are as follows:

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(i) There are significant new contributions to $B^0 - \overline{B^0}$ mixing and to $B_s - \overline{B_s}$ mixing. They can carry the SM phase but in such a case their flavor violation is different from the CKM one.

(ii) There is a significant new CP violating contribution to $B^0 - \overline{B^0}$ mixing.

(iii) There is a new CP violating contribution to $K^0 - \overline{K^0}$ mixing and very likely also to $K \to \pi\pi$ decays.

(iv) All of the above effects can simultaneously play a role in modifying both the relation between $a_{\psi K_S}$ and $\sin 2\beta$ and the SM predictions for $\sin 2\beta$.

(v) In addition, if there are extra quarks beyond the three generations of the SM, there are more ways in which the CKM constraints can be modified [23]. However, in such models, the dominant effect is always a new contribution to the mixing [24].

It is possibe now to consider specific models of new physics and examine whether they can lead to small values of $a_{\psi K_S}$. For example, within the supersymmetric framework, many models that do not have exact universality can significantly modify both $B^0 - \overline{B^0}$ mixing and $K^0 - \overline{K^0}$ mixing (for a review, see [25]), thus allowing for a small $a_{\psi K_S}$. On the other hand, in models of exact universality such effects are generically small [26]. Another interesting example is that of models with extra, SU(2)-singlet down quarks. Here, the new contribution to ε_K is small [27, 28] but the relation between $a_{\psi K_S}$ and $\sin 2\beta$ can be significantly modified [29, 30], allowing for low $a_{\psi K_S}$ values.

Finally, we would like to note that the allowed range for $a_{\psi K_S}$, eq. (1.1), is consistent with zero asymmetry at the 1.75σ level and certainly does not exclude the possibility that the asymmetry is small. This leaves viable a framework that is drastically different from the Standard Model where CP is an approximate symmetry of the full theory, that is, CP violating phases are all small [31]–[34].

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