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An Analysis of B_s Decays in the Left-Right-Symmetric Model with Spontaneous CP Violation

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Abstract

Non-leptonic B_s decays into CP eigenstates that are caused by $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions, such as $B_s \to D_s^+ D_s^-$, $J/\psi\, \eta^{(\prime)}$ or $J/\psi\, \phi$, provide a powerful tool to search for "new physics", as the CP-violating effects in these modes are tiny in the Standard Model. We explore these effects for a particular scenario of new physics, the left-right-symmetric model with spontaneous CP violation. In our analysis, we take into account all presently available experimental constraints on the parameters of this model, i.e. those implied by K- and B-decay observables; we find that CP asymmetries as large as $\mathcal{O}(40\%)$ may arise in the B_s channels, whereas the left-right-symmetric model favours a small CP asymmetry in the "gold-plated" mode $B_d \to J/\psi\, K_S$. Such a pattern would be in favour of B-physics experiments at hadron machines, where the B_s modes are very accessible.

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1 Introduction

A particularly interesting tool to search for indications of "new physics" is provided by B_s-meson decays into final CP eigenstates $|f\rangle$ that originate from $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions [1]–[3]; important examples are given by $B_s \to D_s^+ D_s^-$, $J/\psi\,\eta^{(\prime)}$ or $J/\psi\,\phi$ decays. The interesting feature of these modes is that their decay amplitudes do not involve – to a very good approximation – a CP-violating weak phase in the Standard Model. Moreover, the weak B_s^0–$\overline{B_s^0}$ mixing phase, which governs "mixing-induced" CP violation, is negligibly small in the Standard Model. Consequently, these B_s decays exhibit tiny CP-violating effects within the Kobayashi–Maskawa picture of CP violation, thereby representing a sensitive probe for CP-violating contributions from physics beyond the Standard Model.

We analyse these effects for a particular scenario of new physics, the symmetrical $SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)$ model with spontaneous CP violation (SB–LR) [4, 5]. In a recent paper [6], the SB–LR model has been investigated in the light of current experimental constraints from K- and B-decay observables. In a large region of parameter space, the model mainly affects neutral-meson mixing, but does not introduce sizeable "direct" CP violation. The sensitive observables constraining the model are thus the meson mass differences ΔM_K, ΔM_{B_d}, ΔM_{B_s}, the "indirect" CP-violating parameter ϵ_K of the neutral kaon system, and the mixing-induced CP asymmetry $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S})$. In particular, it was found that, for a set of fixed CKM parameters and quark masses, the model predicts a small value for $|\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S})|$ below 10%, which is in agreement at the 2σ level with the CDF measurement $0.79^{+0.41}_{-0.44}$ [7], but at variance with the Standard-Model expectation 0.73 ± 0.21 [8].

The new point we want to make in this letter is that the SB–LR model predicts values also for the mixing-induced CP asymmetries of the B_s decays considered here, for example $B_s \to J/\psi\,\phi$, that largely deviate from the Standard-Model expectation of very small CP-violating effects. We show that mixing-induced CP asymmetries as large as $\mathcal{O}(40\%)$ may arise in these channels, whereas direct CP violation stays very small. We thus face the interesting possibility that, with all current experimental constraints being met, new physics may just lurk around the corner, and may be revealed by the pattern of CP violation exhibited by $B_d \to J/\psi\, K_{\rm S}$ and $B_s \to D_s^+ D_s^-$, $J/\psi\,\eta^{(\prime)}$ or $J/\psi\,\phi$. This scenario, with small CP-violating effects in the former decay and large effects in the latter ones, would be in favour of B-physics experiments at hadron machines, where the B_s modes are very accessible, in contrast to the situation at asymmetric e^+–e^- B-factories operating on the $\Upsilon(4S)$ resonance.

The outline of this paper is as follows: in Section 2, we have a brief look at the structure of the Standard-Model decay amplitudes of the B_s-meson decays considered here, and introduce the corresponding CP-violating observables. The basic features of the left-right-symmetric model with spontaneous CP violation are discussed in Section 3, and the numerical analysis is presented in Section 4. Finally, in Section 5 we summarize our conclusions.

2 Decay Amplitudes and CP-Violating Observables

Before we introduce the CP-violating observables, let us have a brief look at the structure of the Standard-Model transition amplitudes of B_s decays of the kind $B_s \to D_s^+ D_s^-$, $J/\psi\,\eta^{(\prime)}$ or $J/\psi\,\phi$. The new-physics contributions to the decay amplitudes of these channels arising within the left-right-symmetric model with spontaneous CP violation will be discussed in Section 3.

2.1 The Standard-Model Decay Amplitudes

Within the Standard Model, the amplitudes of B_s^0-meson decays caused by $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions can be expressed generically as follows [9]:

$$A(B_s^0 \to f) = \lambda_c^{(s)} \left(A_{\rm cc}^c + A_{\rm pen}^c \right) + \lambda_u^{(s)} A_{\rm pen}^u + \lambda_t^{(s)} A_{\rm pen}^t \,, \tag{1}$$

where $f \in \{D_s^+ D_s^-, J/\psi\, \eta^{(\prime)}, \ldots\}$ is a final-state configuration with $\bar{c}c\bar{s}s$ valence-quark content, $A_{\rm cc}^c$ denotes current–current contributions, i.e. "tree" processes, and the amplitudes $A_{\rm pen}^q$ describe the contributions from penguin topologies with internal q quarks ($q \in \{u, c, t\}$). These penguin amplitudes take into account both QCD and electroweak penguin contributions [9]. The $\lambda_q^{(s)} \equiv V_{qs} V_{qb}^*$ are the usual CKM factors. Making use of the unitarity of the CKM matrix and applying the Wolfenstein parametrization [10], generalized to include non-leading terms in λ [11], we obtain [12]

$$A(B_s^0 \to f) = \left(1 - \frac{\lambda^2}{2} \right) \mathcal{A} \left[1 + \left(\frac{\lambda^2}{1-\lambda^2} \right) a e^{i\theta} e^{i\gamma} \right], \tag{2}$$

where

$$\mathcal{A} \equiv \lambda^2 A \left(A_{\rm cc}^c + A_{\rm pen}^{ct} \right), \tag{3}$$

with $A_{\rm pen}^{ct} \equiv A_{\rm pen}^c - A_{\rm pen}^t$, and

$$a e^{i\theta} \equiv R_b \left(\frac{A_{\rm pen}^{ut}}{A_{\rm cc}^c + A_{\rm pen}^{ct}} \right). \tag{4}$$

The quantity $A_{\rm pen}^{ut}$ is defined in analogy to $A_{\rm pen}^{ct}$, and the relevant CKM factors are given by

$$\lambda \equiv |V_{us}| = 0.22 \,, \quad A \equiv \frac{1}{\lambda^2} |V_{cb}| = 0.81 \pm 0.06 \,, \quad R_b \equiv \left(1 - \frac{\lambda^2}{2} \right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| = 0.41 \pm 0.07 \,. \tag{5}$$

In Eq. (2), the CP-violating weak phase γ is the usual angle of the unitarity triangle of the CKM matrix, whereas θ denotes a CP-conserving strong phase.

2.2 The CP-Violating Observables

For a B_s decay into a final CP eigenstate $|f\rangle$, such as $B_s \to D_s^+ D_s^-$ or $J/\psi\, \eta^{(\prime)}$, B_s^0–$\overline{B_s^0}$ oscillations lead to the following time-dependent CP asymmetry:

$$a_{\rm CP}(t) \equiv \frac{\Gamma(B_s^0(t) \to f) - \Gamma(\overline{B_s^0}(t) \to f)}{\Gamma(B_s^0(t) \to f) + \Gamma(\overline{B_s^0}(t) \to f)}$$

$$= 2\, e^{-\Gamma_s t} \left[\frac{\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f) \cos(\Delta M_s t) + \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f) \sin(\Delta M_s t)}{e^{-\Gamma_{\rm H}^{(s)} t} + e^{-\Gamma_{\rm L}^{(s)} t} + \mathcal{A}_{\Delta\Gamma}(B_s \to f) \left(e^{-\Gamma_{\rm H}^{(s)} t} - e^{-\Gamma_{\rm L}^{(s)} t} \right)} \right], \tag{6}$$

where $\Delta M_s \equiv M_{\rm H}^{(s)} - M_{\rm L}^{(s)}$ denotes the mass difference between the B_s mass eigenstates $B_s^{\rm H}$ ("heavy") and $B_s^{\rm L}$ ("light"), the $\Gamma_{\rm H,L}^{(s)}$ are the corresponding decay widths, and Γ_s is defined as $\Gamma_s \equiv \left[\Gamma_{\rm H}^{(s)} + \Gamma_{\rm L}^{(s)}\right]/2$. In Eq. (6), we have separated the "direct" from the "mixing-induced" CP-violating contributions, which are described by $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f)$, respectively [9]. In contrast to the B_d system, the width difference

$$\Delta\Gamma_q \equiv \Gamma_{\rm H}^{(q)} - \Gamma_{\rm L}^{(q)} \tag{7}$$

may be sizeable in the B_s system [13], thereby providing the observable $\mathcal{A}_{\Delta\Gamma}(B_s \to f)$. This quantity is not independent from $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f)$, but satisfies the following relation:

$$\left[\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f)\right]^2 + \left[\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f)\right]^2 + \left[\mathcal{A}_{\Delta\Gamma}(B_s \to f)\right]^2 = 1. \tag{8}$$

Interestingly, the observable $\mathcal{A}_{\Delta\Gamma}(B_s \to f)$ can be extracted from CP-violating effects in "untagged" B_s rates [14, 15]:

$$\Gamma[f(t)] \equiv \Gamma(B_s^0(t) \to f) + \Gamma(\overline{B_s^0}(t) \to f) \propto R_{\rm H}(B_s \to f)\, e^{-\Gamma_{\rm H}^{(s)} t} + R_{\rm L}(B_s \to f)\, e^{-\Gamma_{\rm L}^{(s)} t}, \tag{9}$$

where

$$R_{\rm H}(B_s \to f) = \frac{1}{2}\left[1 + \mathcal{A}_{\Delta\Gamma}(B_s \to f)\right], \quad R_{\rm L}(B_s \to f) = \frac{1}{2}\left[1 - \mathcal{A}_{\Delta\Gamma}(B_s \to f)\right], \tag{10}$$

and hence

$$\mathcal{A}_{\Delta\Gamma}(B_s \to f) = \frac{R_{\rm H}(B_s \to f) - R_{\rm L}(B_s \to f)}{R_{\rm H}(B_s \to f) + R_{\rm L}(B_s \to f)}\,. \tag{11}$$

Studies of such untagged rates, where there are no rapid oscillatory $\Delta M_s t$ terms present, are more promising than tagged rates in terms of efficiency, acceptance and purity.

Looking at (2), we observe that the weak phase factor $e^{i\gamma}$, which is associated with the "penguin parameter" $ae^{i\theta}$, is strongly Cabibbo-suppressed by λ^2. Consequently, there is no CP-violating weak phase present in this decay amplitude to an excellent approximation. In this very important special case, we obtain (for details, see [3, 9]):

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f) = 0\,, \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f) = \sin\phi_s\,, \quad \mathcal{A}_{\Delta\Gamma}(B_s \to f) = -\cos\phi_s\,, \tag{12}$$

where ϕ_s denotes a phase-convention-independent combination of the CP-violating weak B_s^0–$\overline{B_s^0}$ mixing and $\bar{b} \to \bar{c}c\bar{s}$ decay phases. In general, we have

$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}, \tag{13}$$

where the Standard-Model phase

$$\phi_s^{\rm SM} = 2\arg(-V_{ts}^* V_{tb}) + 2\arg(V_{cs} V_{cb}^*) = -2\lambda^2\eta \approx -0.03 \tag{14}$$

is negligibly small, and $\phi_s^{\rm NP}$ is due to new physics. Within the Standard Model, the CP-violating effects in the B_s decays considered here are thus very small. However, $\phi_s^{\rm NP}$ may be sizeable in our scenario for new physics, as we will see in Section 4, thereby leading to significant mixing-induced CP violation. A similar feature arises also in some other scenarios for physics beyond the Standard Model, for example in models allowing mixing to a new isosinglet down quark, as in E_6 [2]. Unfortunately, the new-physics effects reduce the magnitude of the B^0_s–$\overline{B^0_s}$ width difference as follows [16]:

$$\Delta\Gamma_s = \Delta\Gamma_s^{\rm SM}\cos\phi_s, \tag{15}$$

where $\Delta\Gamma_s^{\rm SM} = \mathcal{O}(-15\%)$ is the Standard-Model width difference [13]. Note that (7) implies a negative Standard-Model width difference. However, the sign of $\Delta\Gamma_s$ may change in the presence of new physics, as can be seen in (15).

The situation in the decay $B_s \to J/\psi\,\phi$, which is very promising for B-physics experiments at hadron machines because of its favourable experimental signature, is a bit more involved than in the case of the pseudoscalar–pseudoscalar modes $B_s \to D_s^+ D_s^-$ and $J/\psi\,\eta^{(\prime)}$, since the final state is an admixture of different CP eigenstates. In the case of decays into two vector mesons, such as $B_s \to J/\psi\,\phi$, it is convenient to introduce linear polarization amplitudes $A_0(t)$, $A_\parallel(t)$ and $A_\perp(t)$ [17]. Whereas $A_\perp(t)$ describes a CP-odd final-state configuration, both $A_0(t)$ and $A_\parallel(t)$ correspond to CP-even final-state configurations, i.e. to the CP eigenvalues -1 and $+1$, respectively. In order to disentangle them, one has to study angular distributions of the decay products of the decay chain $B_s \to J/\psi[\to l^+l^-]\,\phi[\to K^+K^-]$, which can be found in [18].[1] Let us here just give the following time-dependent CP asymmetry, under the same assumption as was made in (12), i.e. that there is no CP-violating weak phase present in the $B_s \to J/\psi\,\phi$ decay amplitude:

$$a_{\rm CP}(B_s(t)\to J/\psi\,\phi) \equiv \frac{\Gamma(t)-\overline{\Gamma}(t)}{\Gamma(t)+\overline{\Gamma}(t)} = \left[\frac{1-D}{F_+(t)+DF_-(t)}\right]\sin(\Delta M_s t)\,\sin\phi_s, \tag{16}$$

where $\Gamma(t)$ and $\overline{\Gamma}(t)$ denote the time-dependent rates for decays of initially, i.e. at $t=0$, present B^0_s- and $\overline{B^0_s}$-mesons into $J/\psi\,\phi$ final states, respectively. The remaining quantities are defined as

$$D \equiv \frac{|A_\perp(0)|^2}{|A_0(0)|^2+|A_\parallel(0)|^2}\,, \tag{17}$$

and

$$F_\pm(t) \equiv \frac{1}{2}\left[(1\pm\cos\phi_s)\,e^{+\Delta\Gamma_s t/2} + (1\mp\cos\phi_s)\,e^{-\Delta\Gamma_s t/2}\right]. \tag{18}$$

Note that we have $F_+(t) = F_-(t) = 1$ for a negligible width difference $\Delta\Gamma_s$. Obviously, the advantage of the "integrated" observable (16) is that it can be measured *without* performing an angular analysis. The disadvantage is of course that – in contrast to (12) – it also depends on the hadronic quantity D, which precludes a theoretically clean extraction of ϕ_s from (16). However, this feature does not limit the power of this CP asymmetry to search for indications of new physics, which would be provided by a measured sizeable value of (16). Model calculations of D, making use of the factorization hypothesis, typically give $D = 0.1\ldots0.5$ [18], which is also in agreement with a recent analysis of the $B_s \to J/\psi\,\phi$ polarization amplitudes performed by the CDF collaboration [19]. A recent calculation of the relevant hadronic form factors from QCD sum rules on the light-cone [20] yields $D = 0.33$ in the factorization approximation. Consequently, the CP-odd contributions proportional to $|A_\perp(0)|^2$ may have a significant impact on (16). In order to extract ϕ_s from CP-violating effects in the decay $B_s \to J/\psi\,\phi$ in a theoretically clean way, an angular analysis has to be performed, as is discussed in detail in [3].

[1] For a detailed discussion of new-physics effects in the corresponding observables, see [3].

3 The Left-Right-Symmetric Model with Spontaneous CP Violation

Before discussing its predictions for CP-violating phenomena, let us explain very shortly the essential features of the SB–LR model. It is based on the gauge group $SU(2)_{\rm R}\times SU(2)_{\rm L}\times U(1)$, which cascades down to the unbroken electromagnetic subgroup $U(1)_{\rm em}$ through the following simple symmetry-breaking pattern:

$$\underbrace{\underbrace{SU(2)_{\rm R} \times SU(2)_{\rm L}}_{SU(2)_{\rm L}} \times U(1)}_{U(1)_{\rm em}}$$

The scalar sector is highly model-dependent; for the generation of quark masses, there has to be at least one scalar bidoublet Φ, i.e. a doublet under both $SU(2)$, which, by spontaneous breakdown of $SU(2)_{\rm R}\times SU(2)_{\rm L}$, acquires the VEV

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v & 0 \\ 0 & w \end{pmatrix}. \tag{19}$$

In general, both v and w are complex, which is the (only) source of CP violation in the model. The particle content of Φ corresponds to four particles, one analogue of the Standard-Model Higgs, two flavour-changing neutral Higgs bosons, and one flavour-changing charged Higgs. The masses of these new Higgs particles can be assumed to be degenerate to good accuracy, and were found to lie in the range $10.2\,\mathrm{TeV} < M_H < 14.6\,\mathrm{TeV}$ [6].

LR symmetry implies that the left-handed quark sector of the Standard Model gets complemented by a right-handed one, with quark mixing matrices $V_{\rm L}$ and $V_{\rm R}$, respectively, and $|V_{\rm L}| = |V_{\rm R}|$. In the standard Maiani convention, $V_{\rm L}$ contains one, $V_{\rm R}$ five complex phases, which depend on the three generalized Cabibbo-type angles ("CKM angles"), the quark masses, and the VEV (19). The presence of such a large number of weak phases, calculable in terms of only one non-Standard-Model variable, is what makes the investigation of CP-violating phenomena in the SB–LR model that interesting. The left- and right-handed charged gauge bosons $W_{\rm L}$ and $W_{\rm R}$ mix with each other; the mass of the predominantly right-handed mass eigenstate W_2, M_2, is found to lie in the range $2.75\,\mathrm{TeV} < M_2 < 13\,\mathrm{TeV}$ [6]. The mixing angle ζ, defined as

$$\zeta = \frac{2|vw|}{|v|^2+|w|^2}\left(\frac{M_1}{M_2}\right)^2, \tag{20}$$

is rather small: as the ratio $|v|/|w|$ is smaller than 1,[2] one has $\zeta < (M_1/M_2)^2 = 8.5\times 10^{-4}$. There are, however, arguments, according to which a small ratio $|v|/|w| \sim \mathcal{O}(m_b/m_t)$ would naturally explain the observed smallness of the CKM angles [21]; in this case, $\zeta < 0.3\times 10^{-4}$. An experimental bound on ζ can in principle be obtained from the upper bound on the electromagnetic dipole moment of the neutron, which is due to L–R mixing; existing theoretical calculations are, however, very sensitive to the precise values of only poorly known nucleon matrix elements;[3] the present status of an experimental bound on ζ is thus not quite clear,

[2]Which can always be achieved by a redefinition of the Higgs bidoublet $\Phi \to \sigma_2\Phi^*\sigma_2$.

[3]In addition, the Higgs contributions to the dipole moment are usually not included.

although large values of $\zeta \sim \mathcal{O}(10^{-4})$ appear to be disfavoured (see also the discussion in [6]). The fact that the new boson masses are in the TeV range implies that the SB–LR model has no perceptible impact on Standard-Model tree-level amplitudes; rather, it manifests itself in

- $W_{\rm L}$–$W_{\rm R}$ mixing in top-dominated penguin diagrams, enhanced by large quark mass terms from spin-flips, $\zeta \to \zeta\, m_t/m_b$ (similar for penguins with charged Higgs particles),
- Standard-Model amplitudes that are forbidden or heavily suppressed (electric dipole moment of the neutron, for instance),
- mixing of neutral K- and B-mesons, where the suppression factor of $(M_1/M_2)^2$ is partially compensated by large Wilson coefficients or hadronic matrix elements (chiral enhancement in K mixing), and to which the flavour-changing Higgs bosons contribute at tree level.

We thus expect the SB–LR model to change the $B_s^0 \to f$ amplitude defined in (2) in the following way:

$$\mathcal{A} \to \mathcal{A}^{\rm LR} = \lambda^2 A \left(A_{cc}^c + A_{cc}^{c,{\rm LR}} + A_{\rm pen}^{ct} + A_{\rm pen}^{ct,{\rm LR}} \right), \tag{21}$$

with

$$A_{cc}^{c,{\rm LR}} \sim \mathcal{O}\left(\left[\frac{M_1}{M_2}\right]^2 A_{cc}^c \right), \quad A_{\rm pen}^{ct,{\rm LR}} \sim \mathcal{O}\left(\zeta \left[\frac{m_c}{m_b} A_{\rm pen}^c - \frac{m_t}{m_b} A_{\rm pen}^t \right] \right). \tag{22}$$

Numerically, $(M_1/M_2)^2 < 10^{-3}$ and $\zeta\, m_t/m_b < 0.05$ for maximum $|v|/|w| = 1$, and $\zeta\, m_t/m_b < 6 \times 10^{-3}$ for the more likely case of $|v|/|w| \sim \mathcal{O}(m_b/m_t)$. In any case, it is clear that the specific LR contributions to the decay amplitude, although they carry new weak phases, are heavily suppressed by powers of M_2 (and M_H for the corresponding charged Higgs penguins). Consequently, the new contributions of the SB–LR model to the amplitudes of the B decays considered in this letter are small and do not yield sizeable direct CP violation. The assumption used to calculate the CP-violating observables (12) and (16) is therefore also satisfied in the SB–LR model, so that we may use these expressions in the numerical analysis given in the following section.

4 Numerical Analysis

In the SB–LR model, the Standard-Model mixing matrix gets modified by $W_{\rm R}$ boxes and tree-level flavour-changing neutral Higgs exchange as

$$M_{12}^{B_q} = M_{12}^{\rm SM} + M_{12}^{\rm LR} \equiv M_{12}^{\rm SM}(1 + \kappa e^{i\sigma_q}) \tag{23}$$

with

$$\kappa \equiv \left| \frac{M_{12}^{\rm LR}}{M_{12}^{\rm SM}} \right|, \quad \sigma_q \equiv \arg \frac{M_{12}^{\rm LR}}{M_{12}^{\rm SM}} = \arg \left(-\frac{V_{tb}^R V_{tq}^{R*}}{V_{tb}^L V_{tq}^{L*}} \right), \tag{24}$$

such that the relevant observable phase ϕ_q becomes

$$\phi_q = \phi_q^{\rm SM} + \arg\left(1 + \kappa e^{i\sigma_q}\right), \tag{25}$$

where $q \in \{d, s\}$. The B_d counterpart ϕ_d to the phase ϕ_s can be determined in a theoretically clean way through mixing-induced CP violation in the "gold-plated" mode $B_d \to J/\psi\, K_S$ [22]:

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S}) = -\sin\phi_d\,. \tag{26}$$

To good accuracy, κ is independent on the flavour of the spectator quark q, and is given as [6]

$$\kappa = (1.2 \pm 0.2)\left[\left(\frac{7\,\text{TeV}}{M_H}\right)^2 + 1.7\left(\frac{1.6\,\text{TeV}}{M_2}\right)^2\left\{0.051 - 0.013\ln\left(\frac{1.6\,\text{TeV}}{M_2}\right)^2\right\}\right]. \tag{27}$$

A crucial consequence of the spontaneous breakdown of the CP symmetry is that the phases of the two quark mixing matrices, and hence also σ_q, can be calculated in terms of the quark masses, the three CKM angles and the VEV value of Φ, Eq. (19); they do not depend on M_2 or M_H. For the technicalities, we refer to Ref. [6]; here we only state that the dependence on $\langle\Phi\rangle$ can be lumped into a single variable, β, which is defined as [5]

$$\beta = \arctan\frac{2|wv|\sin[\arg(vw)]}{|v|^2 - |w|^2}\,. \tag{28}$$

From the requirement that diagonalization of the quark mass matrices be possible, β is bounded as follows [5]:

$$\tan\frac{\beta}{2} \le \frac{m_b}{m_t}.$$

The fact that quark mass signs are observable in the SB–LR model entails a 64-fold discrete ambiguity of the complex phases of $V_{\rm L}$ and $V_{\rm R}$. The dependence of the phases on the input parameters can be obtained in analytical form in a linear expansion in β, the so-called small-phase approximation [4], which is appropriate for studying the K system. For B decays, however, the approximation breaks down; the full functional dependence of σ_q on β can only be obtained numerically and has been calculated in [6].

Experimental observables sensitive to the new-physics contributions to the off-diagonal element M_{12} of the mixing matrix are, apart from $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S})$, in particular the meson mass differences ΔM_K, ΔM_{B_d} and ΔM_{B_s}, which are given by $\Delta M = 2|M_{12}|$. Other relevant observables are ϵ_K, which is sensitive to $\arg M_{12}^K$, the observable ${\rm Re}(\epsilon'_K/\epsilon_K)$ measuring direct CP violation in the neutral kaon system,[4] and the upper bound on the electromagnetic dipole moment of the neutron. Without going into details about the respective strength and viability of these constraints, we just quote the results of the comprehensive analysis of Ref. [6]: using the following set of Standard-Model input parameters,

$$\begin{aligned}
\overline{m}_t(\overline{m}_t) &= 170\,\text{GeV}, & \overline{m}_b(\overline{m}_b) &= 4.25\,\text{GeV},\\
\overline{m}_c(\overline{m}_c) &= 1.33\,\text{GeV}, & \overline{m}_s(2\,\text{GeV}) &= 110\,\text{MeV},\\
m_s/m_d &= 20.1, & m_u/m_d &= 0.56,\\
|V_{us}| = 0.2219, &\quad |V_{ub}| = 0.004, &\quad |V_{cb}| = 0.04, &
\end{aligned} \tag{29}$$

[4]Because of the large hadronic uncertainties affecting ${\rm Re}(\epsilon'_K/\epsilon_K)$, it has only been used that a positive value of this observable is implied by the most recent experimental data [23].

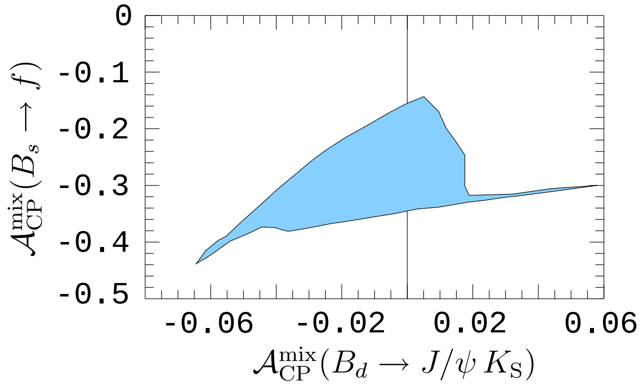

Figure 1: The allowed region in the space of $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S}) = -\sin\phi_d$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f) = \sin\phi_s$, with $f = D_s^+ D_s^-,\ J/\psi\, \eta^{(\prime)}$, in the SB–LR model.

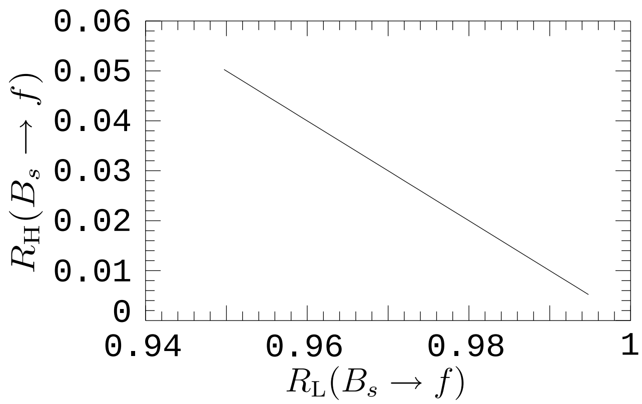

Figure 2: The correlation between the observables $R_{\rm L}(B_s \to f)$ and $R_{\rm H}(B_s \to f)$ of the untagged $B_s \to f$ rates, with $f = D_s^+ D_s^-,\ J/\psi\, \eta^{(\prime)}$, in the SB–LR model.

and neglecting their uncertainties, the 64-fold phase ambiguity gets completely resolved by requiring both $\sin[\arg M_{12}^K]$ and $\sin\phi_d$ to be positive, as implied by the measured values of ϵ_K and $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S})$. Choosing the SB–LR model parameters M_2, M_H and β such as to reproduce the experimental value of ϵ_K, one finds that the predicted value $-0.1 < \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_{\rm S}) < 0.1$ is rather small (see Fig. 9 in Ref. [6]) but still in agreement at the 2σ level with the CDF measurement $-0.79^{+0.44}_{-0.41}$ [7]. The parameter κ is found to lie in the interval [0.29,0.74]; σ_d assumes values in [0.12,1.81] rad and σ_s in [3.23,4.58] rad.

We are now in a position to calculate the correlation between the mixing-induced CP asymmetries in the decays $B_d \to J/\psi\, K_{\rm S}$ and $B_s \to D_s^+ D_s^-,\ J/\psi\, \eta^{(\prime)}$ within the SB–LR model. The result is given in Fig. 1, which nicely shows that large CP-violating asymmetries in $B_s \to D_s^+ D_s^-,\ J/\psi\, \eta^{(\prime)}$ are possible in the SB–LR model, whereas mixing-induced CP violation in $B_d \to J/\psi\, K_{\rm S}$ is predicted to be small. As we have already noted in Section 3, the corresponding direct CP asymmetries remain very small, since the new contributions of the SB–LR model to the decay amplitudes are strongly suppressed.

In Fig. 2, we show the correlation between the observables of the untagged $B_s \to f$ rates

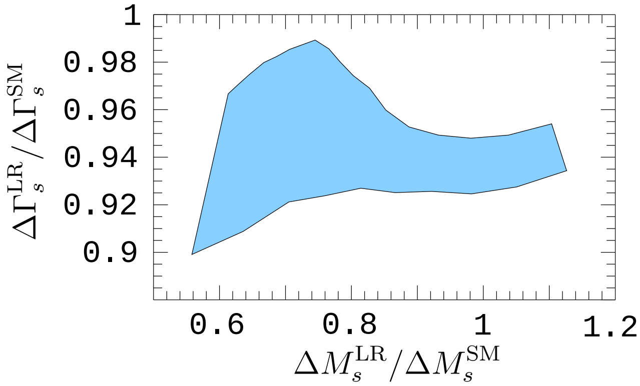

Figure 3: The correlation between the B_s^0–$\overline{B_s^0}$ mass and width differences, normalized to their Standard-Model values, in the SB–LR model.

($f = D_s^+D_s^-,\ J/\psi\,\eta^{(\prime)}$), which were introduced in (9), and are given by

$$R_{\rm L}(B_s \to f) = \frac{1}{2}\,(1+\cos\phi_s)\,, \quad R_{\rm H}(B_s \to f) = \frac{1}{2}\,(1-\cos\phi_s)\,. \tag{30}$$

As can be seen there, in the case of the SB–LR model, the component entering with $e^{-\Gamma_{\rm H}^{(s)}t}$ is at most 10% of that associated with $e^{-\Gamma_{\rm L}^{(s)}t}$. In order to extract $R_{\rm L}(B_s \to f)$ and $R_{\rm H}(B_s \to f)$, a sizeable value of $\Delta\Gamma_s$ is required, as we already noted in Section 2. In Fig. 3, we show the correlation between the B_s^0–$\overline{B_s^0}$ mass and width differences in the SB–LR model. The reduction of $\Delta\Gamma_s$ through new-physics effects, which is described by (15), is fortunately not very effective in this case, whereas the mass difference ΔM_s may be reduced significantly. Although, at first glance, values of ΔM_s as small as $0.55\Delta M_s^{\rm SM}$ may seem to be at variance with the experimental bound of $\Delta M_s > 14.3\,{\rm ps}^{-1}$ at 95% C.L. [24], this is actually not the case: with the hadronic parameters from [25] and $|V_{ts}| = 0.04$ with the generalized Cabibbo-angles fixed from (29), one has the theoretical prediction (see [6], e.g., for the full formula)

$$\Delta M_s^{\rm SM} = (14.5 \pm 6.3){\rm ps}^{-1}.$$

Combining this with the experimental bound, one has

$$\frac{\Delta M_s^{\rm LR}}{\Delta M_s^{\rm SM}} > \frac{14.3}{14.5 + 2\times 6.3} = 0.53.$$

A pattern of B_s mass and decay width differences like that emerging in the SB–LR model would be in favour of experimental studies of the B_s decays at hadron machines, where small values of ΔM_s and large values of $\Delta\Gamma_s$ would be desirable. Because of the small ratio of $R_{\rm H}(B_s \to f)/R_{\rm L}(B_s \to f) < 0.1$ of the "untagged" $B_s \to f$ observables, "tagged" studies, allowing us to extract the mixing-induced CP asymmetries $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f)$, appear more promising to search for indications of the SB–LR model. However, in other scenarios for new physics, the situation may be different.

Let us finally illustrate the CP-violating asymmetry (16) of the decay $B_s \to J/\psi\,\phi$. In Fig. 4, we plot this CP asymmetry as a function of t, for fixed values of $D = 0.3$, $\sin\phi_s = -0.38$,

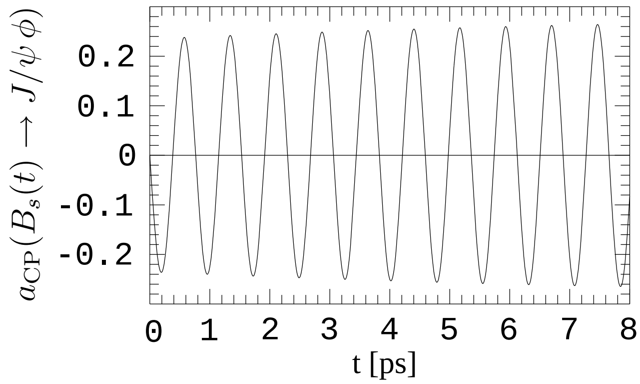

Figure 4: The time-dependent CP-asymmetry $a_{\rm CP}(B_s(t) \to J/\psi\,\phi)$ introduced in (16) for fixed values of $D = 0.3$, $\sin\phi_s = -0.38$, $\Delta\Gamma_s/\Gamma_s = -0.14$ and $\Delta M_s = 14.5\,\mathrm{ps}^{-1}$.

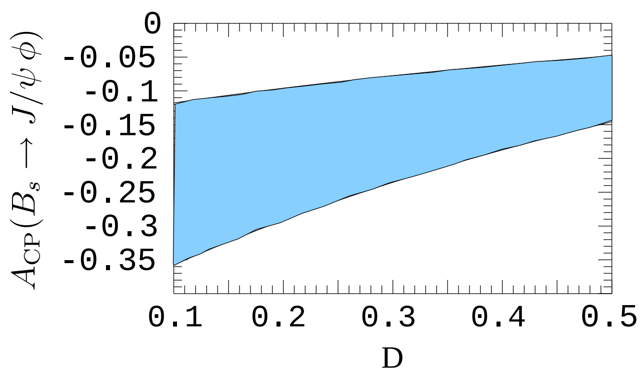

Figure 5: The prediction of the SB–LR model for the CP-violating observable $A_{\rm CP}(B_s \to J/\psi\,\phi)$ introduced in (31) as a function of the hadronic parameter D.

$\Delta\Gamma_s/\Gamma_s = -0.14$ and $\Delta M_s = 14.5\,\mathrm{ps}^{-1}$. Although the B^0_s–$\overline{B^0_s}$ oscillations are very rapid, as can be seen in this figure, it should be possible to resolve them experimentally, for example at the LHC. The first extremal value of (16), corresponding to $\Delta M_s t = \pi/2$, is given to a very good approximation by

$$A_{\rm CP}(B_s \to J/\psi\,\phi) = \left(\frac{1-D}{1+D}\right)\sin\phi_s, \tag{31}$$

which would also fix the magnitude of the $B_s \to J/\psi\,\phi$ CP asymmetry (16) in the case of a negligible width difference $\Delta\Gamma_s$. In Fig. 5, we show the prediction of the SB–LR model for (31) as a function of the hadronic parameter D. For a value of $D = 0.3$, the CP asymmetry may be as large as -25%. The dilution through the hadronic parameter D is not effective in the case of the CP-violating observables of the $B_s \to J/\psi[\to l^+l^-]\,\phi[\to K^+K^-]$ angular distribution, which allow us to probe $\sin\phi_s$ directly [3].

5 Conclusions

We have performed an analysis of mixing-induced CP-violating effects in $B_s \to D_s^+ D_s^-$, $J/\psi\,\eta^{(\prime)}$, $J/\psi\,\phi$ decays in the SB–LR model with spontaneous CP violation, taking into account all presently available experimental constraints on the parameters of this model, and have demonstrated that the corresponding CP asymmetries may be as large as $\mathcal{O}(40\%)$, whereas the Standard Model predicts vanishingly small values. Since the decay amplitudes of these modes are not significantly affected in the SB–LR model, direct CP violation remains negligible, as in the Standard Model. From an experimental point of view, $B_s \to J/\psi\,\phi$ is a particularly promising mode, which is very accessible at B-physics experiments at hadron machines. We have proposed a simple strategy to search for indications of new physics in this transition, which does not require an angular analysis of the $J/\psi[\to l^+l^-]$ and $\phi[\to K^+K^-]$ decay products. In contrast to the large mixing-induced CP asymmetries in the B_s channels, the SB–LR model predicts a small value for $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\,K_{\rm S})$ below 10%. Since the B_s decays cannot be explored at the asymmetric e^+–e^- B-factories operating at the $\Upsilon(4S)$ resonance, such a pattern would be in favour of hadronic B experiments. We look forward to experimental data to check whether this scenario is actually realized by Nature.

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