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CP asymmetries in B_s decays and spontaneous CP violation

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Abstract

We study possible effects of new physics in CP asymmetries in two-body B_s decays in left-right models with spontaneous CP violation. Considering the contributions of new CP phases to the B_s mixing as well as to the penguin dominated decay amplitudes we show that, with the present constraints, large deviations from the standard model predictions in CP asymmetries are allowed in both cases. Detection of the new physics can be done by measuring non-zero asymmetries which are predicted to vanish in the standard model or by comparing two measurements which are predicted to be equal in the standard model. In particular, we show that the measurement of the CKM angle γ in electroweak penguin dominated processes $B_s^0 \to \rho^0\eta^{(\prime)}$, $\rho^0\phi$ can largely be affected by the new physics.

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I. INTRODUCTION

Although the establishment of CP violation goes back to more than thirty years ago, CP violation stills remains a mystery [1]. It has been observed so far only in the kaon system and our entire knowledge can be summarized by the single CP violating quantity ϵ_K. In the standard model (SM) the CP violation can be accommodated due to the single phase of the CKM matrix [2], whereas extended models, in general, contain extra sources of CP violation. Some of them explain the origin of CP violation due to spontaneous symmetry breaking [3]. These models include the two Higgs doublet models [4], aspon models [5], models with "real CP violation" [6] and left-right symmetric models [7] (LRSM). This possibility is particularly natural in the LRSM since parity is a spontaneously broken quantity in these theories. Because the SM has specific predictions on the size as well as on the pattern of CP violation in $B_{d,s}$ meson decays these predictions can be tested in the future B-factories and dedicated experiments HERA-b and LHC-b.

On the experimental side there might already exist some evidence for non-standard flavour physics in the quark sector. The large rate of $B \to \eta' X_s$ measured by CLEO seems to require enormously enhanced $b \to sg$ [8] if compared with the SM prediction. If new CP phases are incorporated in order to explain the enhancement of $b \to sg$, the CP asymmetries in $B_{d,s}$ decays would turn out to be largely affected. Such a situation may occur in models of supersymmetry [9], models with enhanced chromomagnetic operators [10] as well as in the LRSM [11], motivating also the present work.

In the SM the $B_{d,s}$ systems have been extensively studied [12]. There are also a number of studies of the new physics effects in B_d decays [13,14]. However, the B_s system has received somewhat less attention from new physics point of view [15,16]. Very fast oscillations of the B_s system require outstanding experimental sensitivity (not yet achieved) to measure time dependent asymmetries. However, due to large width difference $\Delta\Gamma^{(s)}$ the B_s system offers new possibilities for testing new physics which do not exist in the B_d system. Moreover, since many CP asymmetries in B_s decays are predicted to be vanishingly small in the SM the new physics effects may easily show up.

In this paper we study the possible new physics effects in CP asymmetries in two body B_s decays in the LRSM with spontaneous CP violation [17,18]. In this model there are new CP phases which are unsuppressed for the third family and thus may affect B_s system. Although the new phases of the right-handed sector can appear at tree level, these contributions are strongly suppressed by current phenomenology. So we look for new physics effects only in loops. We shall consider both new physics contribution to the $B_s^0 - \bar{B}_s^0$ mixing and to the penguin dominated decay modes and show that the new physics in both cases may be observable. While the former effect is suppressed by large right-handed gauge boson and flavour-changing Higgs bosons masses the latter is suppressed by the left-right mixing angle. This is because in the decay amplitudes the dominant new contribution arises due to new dipole operators induced by penguin diagrams with W_L in the loop which interacts via $(V+A)$ currents in one vertex. Thus the dipole operators contributions to the CP asymmetries in LRSM are enhanced by

(i) the large ratio $m_t(M_Z)/m_b(M_Z)$,

(ii) the larger values of the Inami-Lim type loop function if compared with the SM,

(iii) by *two independent* new phases $\sigma_{1,2}$ which values are unconstrained.

The new effect is dominated by the gluonic penguins. However, for the decays with vanishing QCD penguin contributions like $B_s \to \eta^{(\prime)}\pi$, $\phi\pi$, $\eta^{(\prime)}\rho$, $\phi\rho$, the electromagnetic dipole operators may play an important role. It has been proposed [19] to use these decay modes to measure the CKM angle γ. We shall show that in some of the decays these measurements can be dominated by the new phases occurring in dipole operators.

The paper is organized as follows. In the next Section we discuss the B_s system in the presence of new physics and study LRSM contributions to the B_s-$\bar{B}_s$ mixing. In Section III we study new physics contributions to the decay amplitudes. We conclude in Section IV.

II. CP ASYMMETRY IN THE B_S SYSTEM

The general expression of the time-dependent CP asymmetry for the decays that were tagged as pure B_q^0 or $\bar{B}_q^0$ (with $q=d,s$) into CP eigenstates,

$$a_{CP}^{(q)}(t) \equiv \frac{\Gamma(B_q^0(t)\to f) - \Gamma(\bar{B}_q^0(t)\to f)}{\Gamma(B_q^0(t)\to f) + \Gamma(\bar{B}_q^0(t)\to f)}\,, \tag{1}$$

is given explicitly by

$$a_{CP}^{(q)}(t) = -\frac{\left(|\lambda^{(q)}|^2-1\right)\cos(\Delta M^{(q)}t) - 2\mathrm{Im}\lambda^{(q)}\sin(\Delta M^{(q)}t)}{(1+|\lambda^{(q)}|^2)\cosh(\frac{1}{2}\Delta\Gamma^{(q)}t) - 2\mathrm{Re}\lambda^{(q)}\sinh(\frac{1}{2}\Delta\Gamma^{(q)}t)}\,, \tag{2}$$

where $\Delta\Gamma^{(q)} = \Gamma_H^{(q)} - \Gamma_L^{(q)}$ and $\Delta M^{(q)} = M_H^{(q)} - M_L^{(q)}$ are the differences in decay rates and masses between the physical eigenstates, respectively, whereas $\lambda^{(q)}$ is given by

$$\lambda^{(q)} = \left(\sqrt{\frac{M_{12}^{(q)*} - \frac{i}{2}\Gamma_{12}^{(q)*}}{M_{12}^{(q)} - \frac{i}{2}\Gamma_{12}^{(q)}}}\right)\frac{\bar{A}_q}{A_q} = e^{-2i\phi_M^q}\frac{\bar{A}_q}{A_q}\,. \tag{3}$$

Here A_q and $\bar{A}_q$ are the amplitudes of B_q^0 and $\bar{B}_q^0$ decay to a common CP eigenstate, respectively, and we have used $|\Gamma_{12}^{(q)}| \ll |M_{12}^{(q)}|$ to introduce the B_q^0-$\bar{B}_q^0$ mixing phase ϕ_M^q.

When this asymmetry concerns the B_d system the terms $\Delta\Gamma^{(d)}$ in the denominator are neglected and the asymmetry takes a simple form (see, for instance, [20] for a review)

$$a_{CP}^{(d)}(t) = -\frac{\left(|\lambda^{(d)}|^2 - 1\right)\cos(\Delta M^{(d)}t) - 2\mathrm{Im}\lambda^{(d)}\sin(\Delta M^{(d)}t)}{(1+|\lambda^{(d)}|^2)}\,, \tag{4}$$

whereas in the B_s system this is not possible since $\Delta\Gamma^{(s)}/\Gamma^{(s)}$ is expected to be $\mathcal{O}(20\%)$ at leading order[1] in the SM [21]. This will affect the time dependent CP asymmetry already at $t \geq 2/\Delta\Gamma^{(s)}$.

The integrated asymmetry is now, including the $\Delta\Gamma^{(q)}$ terms:

$$A_{CP}^{(q)} = \frac{\left(-1+|\lambda^{(q)}|^2 - 2\mathrm{Im}\lambda^{(q)}x_q\right)(-4+y_q^2)}{4(1+x_q^2)\,(1+|\lambda^{(q)}|^2 - \mathrm{Re}\lambda^{(q)}y_q)}\,, \tag{5}$$

where $x_q = \Delta M^{(q)}/\Gamma^{(q)}$ and $y_q = \Delta\Gamma^{(q)}/\Gamma^{(q)}$. Notice that the previous expression reduces to the well known integrated asymmetry of the B_d system $A_{CP}^{(d)}$ in the limit $y_d \to 0$. Moreover if $\lambda^{(q)}$ reduces itself to a pure phase the contribution of the width difference factor outs, i.e.,

$$A_{CP}^{(s)}(\mathrm{Re}\lambda^{(s)}=0) = A_{CP}^{(s)}(y_s \to 0)(1 - y_s^2/4).$$

A first measurement of y_s comes out from Fermilab [23], $y_s = 0.34^{+0.31}_{-0.34}$, and they conclude that with the current statistics they are not sensitive to B_s lifetime differences, but they give an upper bound at a 95% confidence level of $y_s < 0.83$.

It is clear that the CP asymmetry in the B_s system is sensitive also to $\Delta\Gamma^{(s)}$. Then if some new physics affects it, it will also affect the asymmetry. Now, if this contribution is CP violating, it leads, as shown by Grossman in [15], to an unavoidably reduction of the width difference with respect to the SM prediction. In general, the width difference is given by

$$\Delta\Gamma^{(s)} = \frac{4Re(M_{12}^{(s)}\Gamma_{12}^{(s)*})}{\Delta M^{(s)}}\,. \tag{6}$$

The experimental lower bound $\Delta M^{(s)} > 9.5\,\mathrm{ps}^{-1}$ [24] implies that $\Delta M^{(s)} \gg \Delta\Gamma^{(s)}$ and consequently $\mid M_{12}^{(s)} \mid \gg \mid \Gamma_{12}^{(s)} \mid$. Therefore to a very good approximation

$$\Delta M^{(s)} = 2|M_{12}^{(s)}|\,, \tag{7}$$

and

[1]The recent next-to-leading order results [22], however, tend to reduce the central value of $\Delta\Gamma^{(s)}/\Gamma^{(s)}$.

$$\Delta\Gamma^{(s)} = 2|\Gamma_{12}^{(s)}||\cos 2\xi| \quad , \quad 2\xi \equiv arg(-M_{12}^{(s)}\Gamma_{12}^{(s)*})\,. \tag{8}$$

In the SM $\cos(2\xi) \sim 1$ whereas any type of new physics, regardless its origin, will imply $\cos(2\xi) < 1$ reducing the value of $\Delta\Gamma^{(s)}$ according to Eq. (8). Although $\Delta\Gamma^{(s)}$ is not by itself an indication of CP violation, such a reduction can come from new CP phases. As the large SM prediction for $\Delta\Gamma^{(s)}$ is based on the fact that the decay width into CP even final states is larger than into CP odd final states, the appearance of new phases in the mixing amplitude allows the mass eigenstates to differ significantly from the CP eigenstates. In this way both mass eigenstates are allowed to decay into the CP even final state and $\Delta\Gamma^{(s)}$ reduces accordingly.

At this point it is important recall the reader that for $|\Gamma_{12}^{(s)}|$ to be significatively enhanced, one needs a new decay mechanism which dominates over the W_1 mediated tree decay. This is most unlikely, there seems to be no viable model that suggest such a situation. Within the LRSM, the tree level exchange does not contribute to $\Gamma_{12}^{(s)}$ and all the contributions coming from the left-right boxes have either a $\beta = M_1^2/M_2^2$ or a β^2 suppression factor when compared to the SM result. Here M_1 is the mass of the normal left-handed gauge boson and $M_2 \gtrsim 1.6$ TeV [25] the mass of the new right-handed gauge boson. So, the left-right contribution is completely negligible. We have explicitly checked that it amounts, at most - being dreadfully optimistic-, a one per cent increase and we can therefore safely take $|\Gamma_{12}^{(s)}| = |\Gamma_{12}^{(s)\,SM}|$.

The smoking gun in the left-right symmetric models comes from the additional terms to $B_s - \overline{B_s}$ mixing [18]. While the SM contribution to the off diagonal mixing matrix element, $M_{12}^{(s)}$, is dominated by the tt exchange, the left-right contribution gets its weight mainly from the $W_1 - W_2(S_2)$ boxes (being S_2 the Goldstone boson which becomes the longitudinal component of W_2) and the tree level flavour changing Higgs exchange (we denote its mass by M_H). The total off diagonal mixing matrix element $M_{12}^{(s)}$ can therefore be written as,

$$M_{12}^{(s)} = M_{12}^{(s)\,SM} + M_{12}^{(s)\,LR} = M_{12}^{(s)\,SM}\left(1 + \kappa e^{i\sigma_s}\right), \tag{9}$$

where

$$\kappa \equiv \left|\frac{M_{12}^{(s)\,LR}}{M_{12}^{(s)\,SM}}\right| \simeq \left[0.21 + 0.13\,\log\left(\frac{M_2}{1.6\text{TeV}}\right)\right]\left(\frac{1.6\text{TeV}}{M_2}\right)^2 + \left(\frac{12\text{TeV}}{M_H}\right)^2. \tag{10}$$

The new phase σ_s can be expressed as

$$\sigma_s = \text{Arg}\left(\frac{M_{12}^{(s)\,LR}}{M_{12}^{(s)\,SM}}\right), \tag{11}$$

with

$$\sin\sigma_s \simeq \pm r\sin\alpha\,(\mu_c/\mu_s + \mu_t/\mu_b)\,. \tag{12}$$

Here $\mu_i = \pm m_i$, r is the ratio of vevs occurring in the bidoublet and α is the spontaneous CP violating phase. The approach we follow in performing our calculations has been already discussed in [18] and we refer the interested reader to these papers for calculational details as well as for an explanation of the sign factors in the masses. It is worth pointing out that the most relevant effects we would find are related to the fact that despite r is bounded to be smaller that m_b/m_t in order to give to the quarks their masses appropriately, the enhancement factor m_t/m_b in Eq.(12) ensures that σ_s can take any value from 0 to 2π. Therefore the angle 2ξ given in terms of the above defined parameters by

$$2\xi = \mathrm{ArcTan}\left(\frac{\kappa \sin\sigma_s}{1+\kappa\cos\sigma_s}\right) \tag{13}$$

can depart significantly from its SM value.

This can be observed in figures 1 and 2 where we plot $\cos(2\xi)$ (for the B_s system) as a function of the spontaneous CP violating phase α for a fixed Higgs boson mass of 12 TeV and for various choices of the right-handed gauge boson mass (figure 1) and for a fixed value of the right-handed boson mass equal to 1.6 TeV and different Higgs boson masses (figure 2). According to the plots, the new physics can substantially affect the width difference for a wide range of the right-handed particle masses. It is worth to point out that the Higgs and box contributions add up constructively. The maxima observed in figures 1 and 2 correspond to the values of $\alpha = 0, \pi$ where $\sin\sigma_s$ vanishes, returning for $\cos\xi$ to the same value as in the SM. On the contrary, the minima in figure 1 correspond to the values of α, M_{W_2} and M_H such that the function $1+\kappa\cos\sigma_s$ vanishes. Comparing figure 1 and figure 2 one can see that the left-right contribution of the tree level Higgs exchange dominates over the left-right box diagrams. The largest possible departure from the SM value ($\cos(2\xi)\sim 1$) is governed by the values of the new Higgs mass close to its present lower bound, where $\kappa \sim 1$.

The above result, implies that within the left-right symmetric model, we still expect a large mixing parameter x_s as within the SM. This fact implies very rapid oscillations between B_s^0 and $\overline{B_s^0}$ and therefore for keeping track of the $(\Delta M^{(s)} t)$ terms an outstanding experimental sensitivity (not yet reached) is essential. Nevertheless as was pointed out in [12], this is not the end of the B_s saga. The untagged B_s rates, which are defined by

$$\Gamma(f) = \Gamma(B_q^0 \to f) + \Gamma(\bar{B}_q^0 \to f) \propto \exp\left[-\Gamma^{(s)} t\right] \cosh\left[\tfrac{\Delta\Gamma^{(s)} t}{2}\right], \tag{14}$$

can be a method to get an insight into the mechanism of CP violation. This possibility which does not exist in the B_d case, is given precisely by the sizeable width difference $\Delta\Gamma^{(s)}$.

III. NEW PHYSICS IN DECAY AMPLITUDES

Up to this point we have seen that non-standard model CP violating effects could be revealed by testing whether measurements agree with the SM allowed range. However, processes for which the SM contribution vanishes (or is negligibly small) offer an important complement for 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 CP asymmetries in the decay modes

$$\begin{aligned} b &\to c\bar{c}s \quad (\text{e.g. } B_s \to \psi\phi)\,, \\ b &\to c\bar{c}d \quad (\text{e.g. } B_s \to \psi K_s)\,, \\ b &\to c\bar{u}d \quad \Big(\text{e.g. } B_s \to D^0_{CP} K_s\Big)\,, \end{aligned} \tag{15}$$

is of great interest. (It is important to notice that CP asymmetries into final states that contain D_{CP} are not going to be affected by the new contribution in $D - \overline{D}$ mixing).

These CP asymmetries measure the same angle of the unitarity triangle, β' which is approximately equal to zero in the Standard Model. In the presence of new contributions to the $B^0 - \overline{B^0}$ mixing matrix, the CP asymmetries in these modes would no longer be measuring the CKM angle β'. However, they would all still measure the same angle $\beta' + \delta_m$, where δ_m is the new contribution to the $B^0 - \overline{B^0}$ mixing phase. In the LRSM with spontaneous CP violation, as we have already seen, $\delta_m = 2\xi$ and therefore large departures from the expected zero are possible. Specially interesting in this respect are the decays where the SM contribution is already tree level and therefore are very unlikely to be significantly affected by new physics in the decay. On the contrary, as we have seen, the mixing amplitude can be easily modified by new physics, providing this way an excellent testing ground for a measurement of $\sin 2\xi$. A particularly promising example, for future B-physics experiments to be performed at hadron machines, is $B_s \to \phi\psi$ where new physics in the mixing can be explored.

On the other hand, new physics, in general independent from that influencing $B^0 - \overline{B^0}$ mixing, can enter also in the decay amplitudes of b quarks and cause deviations from the SM prediction even in the case of vanishing new physics contribution to the $B^0 - \overline{B^0}$ mixing. The decays (15) are dominated by tree level W exchange and the new physics contribution to them is negligible. However, pure QCD penguin decays like

$$\begin{aligned} b &\to s\bar{s}s \quad (\text{e.g. } B_s \to \phi\phi)\,, \\ b &\to s\bar{d}d \quad \Big(\text{e.g. } B_s \to \bar{K} K_s\Big)\,, \\ b &\to d\bar{s}s \quad (\text{e.g. } B_s \to \phi K_s)\,, \end{aligned} \tag{16}$$

or the electroweak penguin dominated decays

$$B_s \to \eta\pi,\ \eta'\pi,\ \eta\rho,\ \eta'\rho,\ \phi\pi,\ \phi\rho\,, \tag{17}$$

may receive considerable contribution from new physics. The SM CP asymmetries in $b \to s\bar{s}s$ and $b \to s\bar{d}d$ decays are vanishing while $b \to d\bar{s}s$ decays should measure the CKM angle β.

The decays (17) receive small contribution from tree level W processes which are sensitive to the CKM angle γ. It has therefore been proposed by Fleischer [19] to determine γ from the CP asymmetries in these decays. Since the CP asymmetries depend on the parameter λ in Eq. (3) it is clear that the new contributions to the b quark decay amplitudes would affect differently each of the modes in Eq. (16),(17) and therefore each of them would measure a different CP violating quantity. Therefore, new physics contribution to the decay amplitudes can be traced off not only for vanishing SM CP asymmetries but also by comparing the measurements of different B_d and B_s decay modes which should be equal within the SM. Complementary information on this new physics in the decay amplitudes can be extracted from the comparison of any of the penguin dominated diagrams (where the new physics in the decay amplitude can play an important role) with the ones only affected by new physics in the mixing, e.g., with $B_s \to \phi\psi$. Such a comparison would allow a clear separation between new physics coming from the decay and new physics in the mixing.

The flavor changing decays $b \to q\bar{q}'q'$ where $q, q' = s, d$ are induced by the QCD-, electroweak- and magnetic penguins (the latter are induced by the dipole operators as will be discussed below). In general both QCD and EW penguins are important. In some cases, e.g. for the decays (17) for which QCD penguins are absent, the EW penguins dominate. To demonstrate the source of dominant new physics contribution in LRSM we present as an example the Hamiltonian due to the gluon exchange describing the decay $b \to q\bar{q}'q'$ at the scale M_1

$$H^0_{eff} = -\frac{G_F}{\sqrt{2}}\frac{\alpha_s}{\pi}V_L^{tq*}V_L^{tb}\left(\bar{s}\left[\Gamma_\mu^{LL} + \Gamma_\mu^{LR}\right]T^a b\right)\left(\bar{s}\gamma^\mu T^a s\right), \tag{18}$$

where the colour indices are understood and

$$\begin{aligned} \Gamma_\mu^{LL} &= E_0(x)\gamma_\mu P_L + 2i\frac{m_b}{q^2}E_0'(x)\sigma_{\mu\nu}q^\nu P_R, \\ \Gamma_\mu^{LR} &= 2i\frac{m_b}{q^2}\tilde{E}_0'(x)[A^{tb}\sigma_{\mu\nu}q^\nu P_R + A^{tq*}\sigma_{\mu\nu}q^\nu P_L]. \end{aligned} \tag{19}$$

Here the Γ_μ^{LR} term describes the new dominant left-right contribution which is induced by W_1 exchange which interacts with right-handed currents via the mixing angle ξ in one vertex of the penguin diagram and

$$\begin{aligned} A^{tb} &= \xi\frac{m_t}{m_b}\frac{V_R^{tb}}{V_L^{tb}}e^{i\omega} \equiv \xi\frac{m_t}{m_b}e^{i\sigma_1}, \\ A^{tq} &= \xi\frac{m_t}{m_b}\frac{V_R^{tq}}{V_L^{tq}}e^{i\omega} \equiv \xi\frac{m_t}{m_b}e^{i\sigma_2}. \end{aligned} \tag{20}$$

Note that the phases $\sigma_{1,2}$ are independent and can take any value in the range $(0, 2\pi)$. The functions $E_0(x)$, $E_0'(x)$ and $\tilde{E}_0'(x)$ are Inami-Lim type functions [26] of $x = m_t^2/M_1^2$ and are given by

$$E_0(x) = -\frac{2}{3}\ln x + \frac{x(18-11x-x^2)}{(12(1-x)^3)} + \frac{x^2(15-16x+4x^2)}{(6(1-x)^4)}\ln x,$$
$$E_0'(x) = \frac{x(2+5x-x^2)}{(8(x-1)^3)} - \frac{3x^2}{(4(x-1)^4)}\ln x,$$
$$\tilde{E}_0'(x) = -\frac{(4+x+x^2)}{(4(x-1)^2)} + \frac{3x}{(2(x-1)^3)}\ln x. \qquad (21)$$

It follows from Eq. (20) that the new physics contribution to the CP asymmetries in B_s meson decays via Eq. (18), is suppressed by the bounds on the left-right mixing angle $\xi \lesssim 0.01$ [27], but enhanced due to

(i) the large ratio $m_t(M_Z)/m_b(M_Z) = 60$ for $m_t(M_Z) = 170$ GeV and $m_b(M_Z) = 2.8$ GeV [28]. This enhancement factor arises due to the presence of $(V+A)$ interactions since no helicity flip in external b quark line is needed in penguin contributions.

(ii) the large value of the loop function $\tilde{E}_0'(x)$ which is is numerically about factor of four larger than the SM function $E_0'(x)$.

(iii) the *two independent* new phases $\sigma_{1,2}$ whose values are unconstrained.

Note that (i) together with (ii) completely overcome the left-right suppression due to the smallness of ξ. Therefore large effects are anticipated in CP asymmetries due to (iii).

To calculate B_s meson decay rates at the energy scale $\mu = m_b$ in the leading logarithm (LL) approximation we adopt the procedure and results from Ref. [29]. Using the operator product expansion to integrate out the heavy fields, and to calculate the LL Wilson coefficients $C_i(\mu)$ we run them with the renormalization group equations from the scale of $\mu = W_1$ down to the scale $\mu = m_b$ (since the contributions of W_2 are negligible we start immediately from the W_1 scale). Because the new physics appears only in the magnetic dipole operators we can safely take over some well-known results from the SM studies. Therefore the the LRSM effective Hamiltonian should include only these new terms which mix with the gluon and photon dipole operators under QCD renormalization. We work with the effective Hamiltonian

$$H_{eff} = \frac{G_F}{\sqrt{2}}\Bigg[V_L^{uq*}V_L^{ub}\sum_{i=1,2}C_i(\mu)O_i^u(\mu) + V_L^{cq*}V_L^{cb}\sum_{i=1,2}C_i(\mu)O_i^c(\mu)$$
$$- V_L^{tq*}V_L^{tb}\left(\sum_{i=3}^{12}C_i(\mu)O_i(\mu) + C_7^\gamma(\mu)O_7^\gamma(\mu) + C_7^G(\mu)O_7^G(\mu)\right)\Bigg] + (C_iO_i \to C_i'O_i'), \qquad (22)$$

where $O_{1,2}$ are the standard current-current operators, O_3-O_6 and O_7-O_{10} are the standard QCD and EW penguin operators, respectively, and O_7^γ and O_8^G are the standard photonic and gluonic magnetic operators, respectively. They can be found in the literature (e.g. Ref.

[32–34]) and we do not present them here. The new operators to be added, $O_{11,12}$, are analogous to the current-current operators $O_{1,2}$ but with different chiral structure [29]

$$
\begin{aligned}
O_{11} &= \frac{m_b}{m_c}(\bar{s}_\alpha\gamma^\mu(1-\gamma_5)c_\beta)(\bar{c}_\beta\gamma_\mu(1+\gamma_5)b_\alpha), \\
O_{12} &= \frac{m_b}{m_c}(\bar{s}_\alpha\gamma^\mu(1-\gamma_5)c_\alpha)(\bar{c}_\beta\gamma_\mu(1+\gamma_5)b_\beta).
\end{aligned} \tag{23}
$$

Due to the left-right symmetry the operator basis is doubled by including operators O_i' which can be obtained from O_i by the replacements $P_L \leftrightarrow P_R$.

Because the new physics affects only the Wilson coefficients C_7^γ, C_8^G and C_7^γ, C_8^G it is sufficient to consider the basis $O_{1-6}, O_7^\gamma, O_8^G, O_{11,12} + (O \to O')$ for calculating them in the LL precision. Keeping only the top and bottom quark masses non-vanishing, the matching conditions at W_1 scale are given as

$$
\begin{aligned}
C_2(M_1) &= 1, & C_2'(M_1) &= 0, \\
C_7^\gamma(M_1) &= D_0'(x) + A^{tb}\tilde{D}_0'(x), & C_7'^\gamma(M_1) &= A^{ts*}\tilde{D}_0'(x), \\
C_8^G(M_1) &= E_0'(x) + A^{tb}\tilde{E}_0'(x), & C_8'^G(M_1) &= A^{ts*}\tilde{E}_0'(x),
\end{aligned} \tag{24}
$$

and the rest of the coefficients vanish. Here the SM function $D_0'(x)$ and its left-right analog $\tilde{D}_0'(x)$ are given by

$$
\begin{aligned}
D_0'(x) &= \frac{x(7-5x-8x^2)}{(24(x-1)^3)} - \frac{x^2(2-3x)}{(4(x-1)^4)}\ln x, \\
\tilde{D}_0'(x) &= \frac{(-20+31x-5x^2)}{(12(x-1)^2)} + \frac{x(2-3x)}{(2(x-1)^3)}\ln x\,.
\end{aligned} \tag{25}
$$

The 20×20 anomalous dimension matrix decomposes into two identical 10×10 sub-matrices. The SM 8×8 sub-matrix of the latter one can be found in Ref. [30] and the rest of the entries have been calculated by Cho and Misiak in Ref. [29]. In the LL approximation the low energy Wilson coefficients for five flavours are given by

$$
C_i(\mu = m_b) = \sum_{k,l}(S^{-1})_{ik}(\eta^{3\lambda_k/46})S_{kl}C_l(M_1), \tag{26}
$$

where the λ_k's in the exponent of $\eta = \alpha_s(M_1)/\alpha_s(m_b)$ are the eigenvalues of the anomalous dimension matrix over $g^2/16\pi^2$ and the matrix S contains the corresponding eigenvectors. One finds for photonic magnetic coefficients [29]

$$
\begin{aligned}
C_7^\gamma(m_b) &= C_7(m_b)_{SM} + A^{tb}\left[\eta^{\frac{16}{23}}\tilde{D}_0'(x) + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}\right)\tilde{E}_0'(x)\right], \\
C_7'^\gamma(m_b) &= A^{tq*}\left[\eta^{\frac{16}{23}}\tilde{D}_0'(x) + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}\right)\tilde{E}_0'(x)\right],
\end{aligned} \tag{27}
$$

where

$$C_7^\gamma(m_b)_{SM} = \eta^{\frac{16}{23}} D'_0(x) + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}\right) E'_0(x) + \sum_{i=1}^{8} h_i \eta^{p_i} , \tag{28}$$

where h_i = (2.2996, -1.0880, -0.4286, -0.0714, -0.6494, -0.0380, -0.0186, -0.0057) and p_i = (0.6087, 0.6957, 0.2609, -0.5217, 0.4086, -0.4230, -0.8994, 0.1456). Similarly one finds for the gluonic magnetic coefficients [11]

$$C_8^G(m_b) = \eta^{\frac{14}{23}}(E'_0(x) + A^{tb}\tilde{E}'_0(x)) + \sum_{i=1}^{5} h'_i \eta^{p'_i} , \tag{29}$$

$$C_8^{\prime G}(m_b) = \eta^{\frac{14}{23}} A^{ts*} \tilde{E}'_0(x) , \tag{30}$$

where h'_i = (0.8623, -0.9135, 0.0209, 0.0873, -0.0571) and p'_i = (14/23, 0.4086, 0.1456, -0.4230, -0.8994). Using $\Lambda_{\bar{MS}}^{(5)} = 225$ MeV and $\mu = \bar{m}_b(m_b) = 4.4$ GeV the LL Wilson coefficients take numerical values:

$$\begin{array}{lll} C_1 = 1.144, & C_2 = -0.308, & C_3 = 0.014, \\ C_4 = -0.030, & C_5 = 0.009, & C_6 = -0.038, \\ C_7 = 0.045\alpha, & C_8 = 0.048\alpha, & C_9 = -1.280\alpha, \\ C_{10} = 0.328\alpha, & C_7^{\prime\gamma} = -0.523A^{tq*}, & C_8^{\prime G} = -0.231A^{tq*}, \\ C_7^\gamma = -0.331 - 0.523A^{tb}, & C_8^G = -0.156 - 0.231A^{tb}. & \end{array} \tag{31}$$

To calculate hadronic matrix elements of various B_s decay modes we use the factorization approximation which has been recently extensively discussed in the literature [31–34]. Therefore we do not discuss it here but refer the reader to the original literature. However, we have to explain the assumptions which are involved in evaluating the hadronic matrix elements

$$\langle O_8^G \rangle = -\frac{2\alpha_s}{\pi}\frac{m_b}{q^2}\langle(\bar{q}_\alpha i\sigma_{\mu\nu}q^\mu P_R T^a_{\alpha\beta} b_\beta)(\bar{q}'_\gamma \gamma^\nu T^a_{\gamma\delta} q'_\delta)\rangle , \tag{32}$$

and similarly for $\langle O_8^{\prime G}\rangle$. Here q^μ is the momentum transfered by the gluon to the $(\bar{q}', q')$ pair. We are interested in two body decays of B_s mesons. In the factorization approach the two quarks $\bar{q}'$ and q' cannot go into the same decay product meson due to color. Following Ali and Greub [32] we therefore assume that the three momenta of $\bar{q}'$ and q' are equal in magnitude but opposite in direction, and in this case one may assume

$$q^\mu = \sqrt{\langle q^2 \rangle}\frac{p_b^\mu}{m_b} , \tag{33}$$

where $\langle q^2\rangle$ is an averaged value of q^2. Thus the parameter $\langle q^2\rangle$ introduces certain uncertainty into the calculation. In the literature its value is varied in the range $1/4 \lesssim \langle q^2\rangle/m_b^2 \lesssim 1/2$ [35]. In our numerical examples we use in the following $\langle q^2\rangle = 1/2 m_b^2$.

Combining Eq. (33) with Eq. (32) and using the equation of motion and some colour algebra relations one easily finds that

$$\langle O_8^G \rangle = -\frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left[\langle O_4 \rangle + \langle O_6 \rangle - \frac{1}{N_c} \left(\langle O_3 \rangle + \langle O_5 \rangle \right) \right] , \tag{34}$$

and similarly for $\langle O_8'^G \rangle$. An identical procedure gives for $\langle O_7^\gamma \rangle$

$$\langle O_7^\gamma \rangle = -\frac{\alpha}{3\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left[\langle O_7 \rangle + \langle O_9 \rangle \right] , \tag{35}$$

and similarly for $\langle O_7'^\gamma \rangle$.

In the factorization approximation one can easily relate the hadronic matrix elements of the operators O_i and O_i'. It is straightforward to show that for the decays of the types $B_s \to PP$, VV where P and V denote any pseudo-scalar and vector meson, respectively, one has $\langle O_i \rangle = -\langle O_i' \rangle$ while for the decays of the type $B_s \to PV$ one has $\langle O_i \rangle = \langle O_i' \rangle$. Therefore the magnetic penguin contributions can be absorbed into penguin contributions by redefinitions of the Wilson coefficients

$$\begin{aligned} C_3^{eff} &= C_3 + \frac{1}{N_c} \frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left(C_8^G + n C_8'^G \right) , & C_4^{eff} &= C_4 - \frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left(C_8^G + n C_8'^G \right) , \\ C_5^{eff} &= C_5 + \frac{1}{N_c} \frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left(C_8^G + n C_8'^G \right) , & C_6^{eff} &= C_6 - \frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left(C_8^G + n C_8'^G \right) , \\ C_7^{eff} &= C_7 - \frac{\alpha}{3\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left(C_7^\gamma + n C_7'^\gamma \right) , & C_9^{eff} &= C_9 - \frac{\alpha}{3\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left(C_7^\gamma + n C_7'^\gamma \right) , \end{aligned} \tag{36}$$

and for the remaining coefficients $C_i^{eff} = C_i$. Here $n = +1$ for the decays $B_s \to PV$, $n = -1$ for the decays $B_s \to PP$, VV and $N_c = 3$.

Now we are ready to estimate the new physics contribution to the B_s decay amplitudes. We first study the pure penguin induced decay $B_s \to \phi\phi$ ($b \to s\bar{s}s$) which is dominated by QCD penguins and receives also about 30% contribution from the EW penguins. The branching ratio of this decay mode is large, of the order $B(B_s \to \phi\phi) \sim \mathcal{O}(10^{-5})$ [34] which ensures detectability. The pollution from the other SM diagrams is estimated to be below 1% [13]. Since the CP asymmetries in this mode should vanish in the SM the decay $B_s \to \phi\phi$ should provide very sensitive tests of the SM. The amplitude of this decay takes a form [34,36]

$$A(B_s \to \phi\phi) = -\frac{G_F}{\sqrt{2}} V_L^{tb} V_L^{ts*} 2 \left[a_3 + a_4 + a_5 - \frac{1}{2} (a_7 + a_9 + a_{10}) \right] X^{(B_s\phi,\phi)} , \tag{37}$$

where $X^{(B_s\phi,\phi)}$ stands for the factorizable hadronic matrix element and

$$a_{2i-1} = C_{2i-1}^{eff} + \frac{1}{N_c} C_{2i}^{eff} , \qquad a_{2i} = C_{2i}^{eff} + \frac{1}{N_c} C_{2i-1}^{eff} . \tag{38}$$

The exact form of $X^{(B_s\phi,\phi)}$ can be found in Ref. [34]. Since it cancels out in CP asymmetries we do not present it here. Using $\sqrt{\langle q^2\rangle} = m_b/\sqrt{2}$, $\xi = 0.01$, $m_t/m_b = 60$ and the numerical values of LL coefficients in Eq. (31) we obtain

$$A(B_s \to \phi\phi) = -\frac{G_F}{\sqrt{2}} V_L^{tb} V_L^{ts*} 2 \left[-0.0164 + 0.0035 \left(e^{i\sigma_1} - e^{-i\sigma_2}\right)\right] X^{(B_s\phi,\phi)} . \tag{39}$$

This result implies large effects on CP asymmetries. The maximum deviation from the SM prediction $a_{CP} = 0$ is obtained if $\sigma_1 = \pi - \sigma_2 = \pi/2 + \delta_D$ implying $(\bar{A}/A)_{max} = e^{0.85i}$ and $|a_{CP}^{(s)\,max}| = 0.85$.

Next we consider the decays (17) which have the feature of having only one isospin channel describing a $\Delta I = 1$ transition. Consequently QCD penguins cannot contribute to the processes. Since the current-current operators contribution is CKM suppressed it has been shown [34] that the EW penguin contributions amount about 85% of all the decay rates which are estimated to be of order a few times 10^{-7}. The amplitudes of the decays $B_s \to P, P$ and $B_s \to V, P$ (i.e., pseudoscalar factorized out) receive a dominant contribution from the terms proportional to $(-a_7 + a_9)$. In the light of Eq. (36) it is clear that in this case the new physics contribution cancels out. However, the decays of type $B_s \to P, V$ and $B_s \to V, V$ depend on $(a_7 + a_9)$ and they should receive sizable new physics contributions. For definiteness let us work with the process $B_s^0 \to \eta\rho^0$ but the results apply also for the decays $B_s^0 \to \eta'\rho^0$, $\phi\rho^0$. The amplitude can be written as

$$\begin{aligned} A(B_s \to \eta\rho^0) &= \frac{G_F}{\sqrt{2}} \left[V_L^{ub} V_L^{us*} a_2 - V_L^{tb} V_L^{ts*} \left(\frac{3}{2}(a_7 + a_9)\right)\right] X_u^{(B_s\eta,\rho)} \\ &= \frac{G_F}{\sqrt{2}} |V_L^{ts}| \left[\lambda^2 R_b e^{-i\gamma} a_2 + \left(\frac{3}{2}(a_7 + a_9)\right)\right] X_u^{(B_s\eta,\rho)} , \end{aligned} \tag{40}$$

where γ is the CKM angle, $X_u^{(B_s\eta,\rho)}$ is the hadronic matrix element and $R_b = 1/\lambda |V_L^{ub}|/|V_L^{cb}|$. Because of the appearance of the CKM angle γ in the decay amplitude Fleischer has proposed to use this process for determining its value. In the SM one has $A(B_s \to \eta\rho^0) = A_{CC} e^{-i\gamma} + A_{EW}$, where A_{CC} and A_{EW} denote the current-current and EW penguin contributions, respectively. While $A_{CC} \ll A_{EW}$ the fact that A_{EW} is real still allows for clean determination of γ in the SM [19]. However, in the presence of new physics one has in general

$$A(B_s \to \eta\rho^0) = A_{CC} e^{-i\gamma} + A_{EW} + A_{NP} e^{-i\phi} , \tag{41}$$

where A_{NP} is the magnitude of new contribution and ϕ its phase. In such a case the CP asymmetry in the decay $B_s^0 \to \eta\rho^0$ takes a form

$$a_{CP}^{(s)} = \frac{2(y + \cos\gamma + z\cos\phi)(\sin\gamma + z\sin\phi)}{y^2 + 2y(\cos\gamma + z\cos\phi) + 1 + z^2 + 2z\cos(\gamma - \phi)} , \tag{42}$$

where $y = A_{EW}/A_{CC}$ and $z = A_{NP}/A_{CC}$. The corresponding SM expression is obtained by setting $z = 0$. For large $y \gg 1$ the CP asymmetry approaches $a_{CP} \to 2(\sin\gamma + z\sin\phi)/y$

and in the presence of sizable new physics contribution, $z \sim \mathcal{O}(1)$, the CP asymmetry does not measure γ any more.

In the LRSM the new contribution enters via the electromagnetic dipole operators. In the presence of QCD penguins this contribution is negligible because it is suppressed by $\alpha = 1/128$. However, in the present case QCD penguin contribution is exactly vanishing and A_{NP} should be compared with the sub-leading A_{CC}. Using $\lambda = 0.22$, $|V_L^{ub}|/|V_L^{cb}| = 0.08$ [37] and rest of the input as before we obtain numerically

$$A(B_s \to \eta\rho^0) = \frac{G_F}{\sqrt{2}}|V_L^{ts}| \left[-0.012 + 0.0013e^{-i\gamma} + 0.0011\left(e^{i\sigma_1} + e^{-i\sigma_2}\right)\right] X_u^{(B_s\eta,\rho)} \,. \quad (43)$$

Therefore z may be as large as $z \sim 2$ in the LRSM and comparison of $a_{CP}(B_s \to \eta\rho^0)(t)$ with other measurements determining CKM angle γ could reveal the presence of new physics.

At this point a remark regarding the branching ratios is in order. According to our results, modifications as large as 85% in the CP asymmetries can be expected in the decays where new physics modifies decay amplitudes. However, this cannot be directly translated to the branching ratios as, in this case, large cancellations take place. Even allowing maximum effects in the CP asymmetries the branching rations are modified not more than $\simeq 20\%$.

IV. CONCLUSIONS

In this work we have analyzed the possible effects of new physics in CP asymmetries in two body decays in left-right models with spontaneous CP violation. This model possesses the attractive feature that, quite independently of phenomenological considerations, all the CP violating quantities (when the spontaneous CP violation is achieved, as in our case, with the minimal content of the Higgs sector) depend on a single phase, α, and not on unconstrained quantities such as Yukawa couplings or additional phases. This makes the model particularly predictive.

We have shown that the width difference in left-right models can be drastically modified, in fact, reduced from its Standard Model value. This reduction itself can be an indication indication of CP violation. As the large Standard Model prediction for $\Delta\Gamma^{(s)}$ is a consequence that the decay width into CP even final states is larger that that on to CP odd final states; the appearance of a new phase in the mixing amplitude can make the CP eigenstates very different from the mass eigenstates and therefore both mass eigenstates can then be allowed to decay into CP even final states.

Considering the new contributions to the B_s mixing, with its own phases which in general differ from the SM one, as well as the new contribution to the penguin dominated decay amplitudes, we have found that large deviations from the SM predictions are possible with the present constraints on the masses of new gauge and Higgs bosons and on the left-right mixing angle. It is important to emphasize that these types of contributions can be clearly differentiated by comparing the tree level W-mediated diagrams (new physics enters here only in the mixing) with the penguin dominated ones (both contributions are present).

Due to the new physics contribution to the B_s mixing non-zero CP asymmetries as large as $|a_{CP}| = 1$ can appear even if the SM predictions for them are negligible. Even more promising is, perhaps, the fact that due to the new physics contributions to the decay amplitudes their effect can be probed by comparing two experiments that measure the same phase in the SM. CP asymmetries af all QCD penguin dominated decays may largely be affected by the new physics as we explicitly demonstrate in the case of $B_s^0 \to \phi\phi$. The EW penguin dominated decays $B_s^0 \to \eta^{(\prime)}\rho^0$, $\phi\rho^0$ may also receive sizable new contributions which dominate the CP asymmetry measurements.

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FIGURES

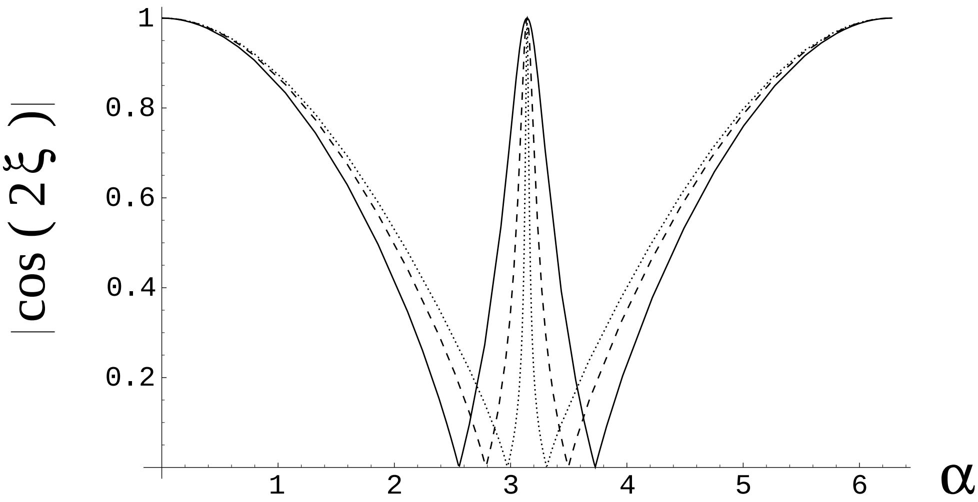

FIG. 1. Absolute value of $\cos(2\xi)$ (for the B_s system) as a function of the spontaneous symmetry breaking phase α for the fixed value of the flavour changing Higgs mass $M_H = 12$ TeV and for the right handed gauge boson masses $M_2 = 1.6$ TeV (solid line), 5 TeV (dashed line) and 9 TeV (dotted line).

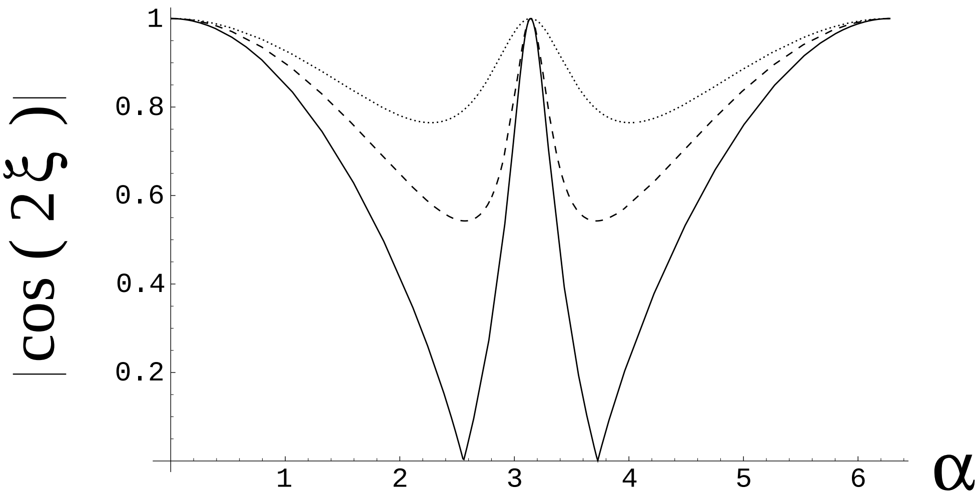

FIG. 2. Absolute value of $\cos(2\xi)$ (for the B_s system) as a function of the spontaneous symmetry breaking phase α for the fixed value of the right-handed gauge boson mass $M_2 = 1.6$ TeV and for the flavour changing Higgs boson masses $M_H = 12$ TeV (solid line), 18 TeV (dashed line) and 25 TeV (dotted line).