Are the New Physics Contributions from the Left-Right Symmetric Model Important for the Indirect CP Violation in the Neutral B Mesons?

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Abstract
Several works analyzing the new physics contributions from the Left-Right Symmetric Model to the CP violation phenomena in the neutral B mesons can be found in the literature. These works exhibit interesting and experimentally sensible deviations from the Standard Model predictions but at the expense of considering a low right scale $\nu_R$ around 1 TeV. However, when we stick to the more conservative estimates for $\nu_R$ which say that it must be at least $10^7$ GeV, no experimentally sensible deviations from the Standard Model appear for indirect CP violation. This estimate for $\nu_R$ arises when the generation of neutrino masses is considered. In spite of the fact that this scenario is much less interesting and says nothing new about both the CP violation phenomenon and the structure of the Left-Right Symmetric Model, this possibility must be taken into account for the sake of completeness and when considering the see-saw mechanism that provides masses to the neutrino sector.

Keywords: Neutral B mesons; left-right models; indirect CP violation

1 Introduction
CP violation is one of the most intriguing puzzles in particle physics and a lot of work has been devoted to the search of its origin. The most accepted way to generate CP violation in the Standard Model (SM) is through the Cabibbo-Kobayashi-Maskawa (CKM) phase $\hat{\theta}$. This way has demonstrated to be very
accurate at describing the phenomenology of the neutral kaon system \[2, 3, 4\]. However, there are other ways which can give account of the CP violation effects on the neutral kaon system while exhibiting new interesting features. One of these ways consists of searching for a natural origin of the CP violating phase, for example, through complex vacuum expectation values. This can be achieved in the Left-Right Symmetric Model (LRSM) \[5, 6, 7, 8, 9\] where there is one genuine complex vacuum expectation value due to the presence of a scalar bidoublet, and that is responsible for the quark sector CP violating phase. There is also another genuine complex vacuum expectation value due to the presence of two scalar triplets that, together with the scalar bidoublet vacuum expectation value, are the responsible for the CP violation in the lepton sector. The main advantages of this model is that it explains both parity and CP as spontaneously broken symmetries, and identifies the hypercharge with the quantum number \(B − L\) giving it thus a physical meaning. Another property of this model is that it offers an explanation for the smallness of the neutrino masses, through the see-saw mechanism \[10\], as well as a framework for the study of CP violation in the lepton sector, which is not present in the SM and that is source of lots of present experimental and theoretical works \[11\].

As the SM explains successfully the effects of CP violation on the neutral kaon system, we expect that it can explain these effects on the B systems too. The dilepton asymmetry \(a_{ll} = \frac{N(l^+l^+) − N(l^−l^-)}{N(l^+l^+) + N(l^−l^-)}\) relates directly to the parameter of indirect CP violation \(\varepsilon_B\). The most recent measurement, made with dilepton events, shows that \(\text{Re}\varepsilon_B\), for the \(B_d\) system, lies in the range \([12] 1.2 \pm 2.9 \pm 3.6 \times 10^{-3}\) which has a central value different to zero but with a too long width\(^1\). Then, it is possible to have many different models which explain correctly the effects of CP violation on the neutral kaon system, giving a value for \(\text{Re}\varepsilon_B\) compatible with the experimental width but, in principle, different to the SM one. Many of these models are also able to give some insight in the understanding of CP violation in the lepton sector. Among these models of new physics is the LRSM.

Several authors have studied the predictions that the LRSM makes for the CP violation phenomena in the neutral B systems \[14, 15\], and have found interesting deviations from the SM predictions which could be tested in accelerator experiments. What they do is to assume an order of magnitude of 1 TeV for the right scale \(v_R\) of the model so that the new physics contributions are comparable with the usual SM ones. It is a nice feature to obtain comparable contributions since we can learn a lot about the underlying structure of the model by means of the comparison of the theoretical predictions and the experimental data. However, if we want to consider seriously the predictions of this scenario, we should ask ourselves where the order of magnitude \(v_R \sim 1\) TeV comes from.

The main goal of this article is to study the predictions of the LRSM about the parameter \(\text{Re}\varepsilon_B\) for both the \(B_d\) and \(B_s\) systems, by means of the calculation of the dilepton asymmetry \(a_{ll}\), and to compare them to both the predictions of the SM and the experimental results\(^2\). Unlike the other works mentioned be-

\(^1\)Instead, the quantity \(|q/p| = |1−\varepsilon_B|/|1+\varepsilon_B|\), measured by the BaBar collaboration from the fully reconstruction of a \(\Upsilon(4S)\) resonance decay \[13\], shows to have a much more narrow experimental width \(|q/p| = 1.029 \pm 0.013 \pm 0.011\). This is a good quantity to compare with the theoretical predictions but, unfortunately, it just gives information about the magnitude of \(\varepsilon_B\) leaving its argument unknown.

\(^2\)We will also do the same for the quantity \(|q/p|\) although it just gives a piece of information:
fore [9, 11, 15] 10 17, we stick to the more conservative order of magnitude for the right scale $v_R \geq 10^7$ GeV which arises when the neutrino masses generation from the see-saw mechanism is considered [11, 19]. In this scenario the new physics sector of the LRSM decouples from the quark sector and, therefore, the new physics effects involving interactions with quarks are negligible. So, both the SM and the LRSM predict the same value for the parameter $Re \tau_B$ (and consequently for $|q/p|$) in the $B_{d,s}$ systems. This scenario becomes not so interesting as the expected new physics effects, useful to go deep into the structure of the model, do not appear. Nevertheless we think it is important to describe it for the sake of completeness, and to avoid enlarging even more the original LRSM. The latter would be required to lower the right scale without violating the constraints coming from the neutrino masses generation.

This paper is organized as follow: in the section 2 we study the phenomenology of CP violation for the neutral B systems. In the section 3 we describe the LRSM and the see-saw mechanism that provides masses to the neutrino sector. The parameters $Re \tau_B$ and $|q/p|$ for the $B_{d,s}$ systems are calculated in the section 4 in the frameworks of both the SM and the LRSM. We compare their predictions to the experimental data. The conclusions are presented in the section 5.

2 Phenomenology of CP Violation for the Neutral B Systems

There are two kinds of neutral B mesons: $B_L$ and $B_H$, which we can write as linear combinations of CP eigenstates and that at the same time are linear combinations of the flavor eigenstates $B^0$ and $\overline{B^0}$:

$$|B_L\rangle = \left( |B_1\rangle + \tau_B |B_2\rangle \right) / \sqrt{1 + |\tau_B|^2}, \quad (1)$$

$$|B_H\rangle = \left( |B_2\rangle + \tau_B |B_1\rangle \right) / \sqrt{1 + |\tau_B|^2}, \quad (2)$$

where $|B_1\rangle$ and $|B_2\rangle$ are the CP eigenstates, even and odd respectively:

$$|B_1\rangle = \left( |B^0\rangle + |\overline{B^0}\rangle \right) / \sqrt{2}, \quad (3)$$

$$|B_2\rangle = \left( |B^0\rangle - |\overline{B^0}\rangle \right) / \sqrt{2}. \quad (4)$$

We can see that $|B_L\rangle$ is almost the CP-even state $|B_1\rangle$ with a tiny admixture of the CP-odd state $|B_2\rangle$, and that $|B_H\rangle$ is almost the CP-odd state $|B_2\rangle$ with a tiny admixture of the CP-even state $|B_1\rangle$. The parameter $\tau_B$ represents the measure of the CP violation in the “mixed state”. The two states $|B_L\rangle$ and $|B_H\rangle$ have their own proper mass and lifetime [18].

One of the possible products in a $e^+e^-$ collision is a pair $B^0 - \overline{B^0}$. Working in the basis of flavor eigenstates, we can determine the evolution of this pair by [2]:

$$|B^0_{phys}(t)\rangle = f_+(t) |B^0\rangle + \frac{1 - \tau_B}{1 + \tau_B} f_-(t) |\overline{B^0}\rangle, \quad (5)$$

the magnitude of $\tau_B$. This is however helpful because of the experimental precision level reached in the measurement of $|q/p|_{1d}$. 

$\text{3}$
with
\[ f_{\pm} (t) = \frac{1}{2} \left\{ \exp \left[ -i \left( M_L - \frac{i}{2} \Gamma_L \right) t \right] + \exp \left[ -i \left( M_H - \frac{i}{2} \Gamma_H \right) t \right] \right\}, \]

where \( M_L(H) \) and \( \Gamma_L(H) \) are the mass and the inverse of the lifetime of \( B_L(H) \). For an event where both \( B \) mesons undergo semileptonic decay, we can define a charge asymmetry of such events as \([19]\):
\[ a_{ll} = \frac{N (l^+ l^+) - N (l^- l^-)}{N (l^+ l^+) + N (l^- l^-)}, \]

where \( N (l^\pm l^\pm) \) indicates the number of pairs \( l^\pm l^\pm \) produced in the decay. The numbers of leptonic pairs \( N (l^+ l^+) \) and \( N (l^- l^-) \) are related to \( \tau_B \) by:
\[
N (l^\pm l^\mp) = \int_0^\infty \left| \langle l^\pm l^\mp | (\mathcal{M}_L) X^\mp X^\mp | H \rangle | B_{phys}^0 \rangle \right|^2 dt
\]
\[ = \int_0^\infty \left| \langle l^+ l^+ | (\mathcal{M}_L) X^- X^- | H \rangle | B^0 \rangle \right| f_+ (t) f_- (t) \left( \frac{1 \pm \tau_B}{1 \pm \tau_B} \right)^2 dt. \]

Thus:
\[ a_{ll} \approx \frac{|1 + \tau_B|^4 - |1 - \tau_B|^4 |1 + \tau_B|^4 + |1 - \tau_B|^4} \approx 4 \text{ Re } \tau_B. \]

According to the last result, a dilepton asymmetry is directly related to a non vanishing value of \( \tau_B \) which measure the amount of indirect CP violation. This result is model independent and, therefore, it entitles us to calculate the dilepton asymmetry \( a_{ll} \) via the calculation of the parameter \( \tau_B \) for any kind of particle model.

3 Description of the LRSM

3.1 The model

The LRSM is based on the group of symmetries \( SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes C \otimes P \) which assures both parity and CP conservation. According to this, it is possible to assign leptons and quarks the following quantum numbers:

\[ Q_L = \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \equiv (2, 1, 1/3), \quad Q_R = \left( \begin{array}{c} u_R \\ d_R \end{array} \right) \equiv (1, 1, 1/3), \]
\[ \psi_L = \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) \equiv (2, 1, -1), \quad \psi_R = \left( \begin{array}{c} \nu_R \\ e_R \end{array} \right) \equiv (1, 2, -1), \]

where the \( U(1) \) generator corresponds to the \( B - L \) quantum number of the multiplet \( u \ l \ e \). The gauge bosons consist of two triplets:
\[ W_{\mu L} = \left( \begin{array}{c} W_{\mu L}^+ \\ Z_{\mu L}^0 \\ W_{\mu L}^- \end{array} \right) \equiv (3, 1, 0), \quad W_{\mu R} = \left( \begin{array}{c} W_{\mu R}^+ \\ Z_{\mu R}^0 \\ W_{\mu R}^- \end{array} \right) \equiv (1, 3, 0), \]
and one singlet:

\[ B_\mu = B_\mu^0 \equiv (1, 1, 0). \] 

Due to the existence of a discrete parity symmetry, the model must be invariant under the transformations: \( \psi_L \leftrightarrow \psi_R, Q_L \leftrightarrow Q_R, \) and \( W_L \leftrightarrow W_R. \)

To break the symmetry, and give masses to bosons and fermions, it is necessary to introduce a bidoublet \( \Phi \) and two scalar triplets \( \Delta_L, \Delta_R \) which can be written in a convenient matrix representation \( 2 \times 2 \): 

\[ \Phi = \left( \begin{array}{c} \phi_L^0 \\ \phi_R^0 \\ \phi_L^+ \\ \phi_R^+ \end{array} \right) \equiv (2, 2, 0), \] 

\[ \Delta_L = \left( \begin{array}{cc} \delta_L^+ & \delta_L^+ \\ \sqrt{3} & \sqrt{3} \end{array} \right) \equiv (3, 1, 2) \quad \Delta_R = \left( \begin{array}{cc} \delta_R^+ & \delta_R^+ \\ \sqrt{3} & \sqrt{3} \end{array} \right) \equiv (1, 3, 2). \] 

We need to introduce these elements so that the new vectorial physical bosons \( W_R \) and \( Z' \) get heavy masses compatible with the experimental bounds.

With these scalar elements, the most general scalar potential \( V \) and Yukawa lagrangian for quarks \( (\mathcal{L}_q^Y) \) and leptons \( (\mathcal{L}_l^Y) \), which are invariants under the manifest discrete left-right symmetry \( \Phi \leftrightarrow \Phi^\dagger \) and \( \Delta_L \leftrightarrow \Delta_R \), can be written as:

\[ V = V_\Phi + V_\Delta + V_{\Phi\Delta}, \] 

where:

\[ V_\Phi = -\mu_1^2 \text{Tr} \left( \Phi^\dagger \Phi \right) - \mu_2^2 \left[ \text{Tr} \left( \Phi^\dagger \right) + \text{Tr} \left( \Phi \right) \right] \]

\[ + \lambda_1 \left[ \text{Tr} \left( \Phi^\dagger \right) \right]^2 + \lambda_2 \left[ \left( \text{Tr} \left( \Phi^\dagger \right) \right)^2 + \left( \text{Tr} \left( \Phi \right) \right)^2 \right] \]

\[ + \lambda_3 \left[ \text{Tr} \left( \Phi^\dagger \right) \text{Tr} \left( \Phi \right) \right] \]

\[ + \alpha_4 \left[ \text{Tr} \left( \Phi^\dagger \right) \left[ \text{Tr} \left( \Phi^\dagger \right) + \text{Tr} \left( \Phi \right) \right] \right], \] 

\[ V_\Delta = -\mu_3^2 \left[ \text{Tr} \left( \Delta_L \Delta_L^\dagger \right) + \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) \right] \]

\[ + \rho_1 \left[ \left( \text{Tr} \left( \Delta_L \Delta_L^\dagger \right) \right)^2 + \left( \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) \right)^2 \right] \]

\[ + \rho_2 \left[ \text{Tr} \left( \Delta_L \Delta_L \right) \text{Tr} \left( \Delta_L^\dagger \Delta_L^\dagger \right) + \text{Tr} \left( \Delta_R \Delta_R \right) \text{Tr} \left( \Delta_R^\dagger \Delta_R^\dagger \right) \right] \]

\[ + \rho_3 \left[ \text{Tr} \left( \Delta_L \Delta_L^\dagger \right) \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) \right] \]

\[ + \rho_4 \left[ \text{Tr} \left( \Delta_L \Delta_L \right) \text{Tr} \left( \Delta_L^\dagger \Delta_L^\dagger \right) + \text{Tr} \left( \Delta_R \Delta_R \right) \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) \right], \]

\[ V_{\Phi\Delta} = \alpha_1 \left[ \text{Tr} \left( \Phi^\dagger \Phi \right) \left[ \text{Tr} \left( \Delta_L \Delta_L^\dagger \right) + \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) \right] \right] \]

\[ + \alpha_2 \left[ \text{Tr} \left( \Phi^\dagger \Phi \right) \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) + \text{Tr} \left( \Phi^\dagger \Phi \right) \text{Tr} \left( \Delta_L \Delta_L^\dagger \right) \right] \]

\[ + \text{Tr} \left( \Phi^\dagger \Phi \right) \text{Tr} \left( \Delta_R \Delta_R^\dagger \right) + \text{Tr} \left( \Phi^\dagger \Phi \right) \text{Tr} \left( \Delta_L \Delta_L^\dagger \right) \]

\[ + \alpha_3 \left[ \text{Tr} \left( \Phi^\dagger \Phi \Delta_L \Delta_L^\dagger \right) + \text{Tr} \left( \Phi^\dagger \Phi \Delta_R \Delta_R^\dagger \right) \right] \]
the right scale must be at least 
masses compatible with the experimental bounds \[9\]. In fact, as we will show, \(W\) in turn, assures that the right-weak bosons 
correct order of magnitude for the masses of the left-handed neutrinos. This, 
be very large in order to avoid flavor changing neutral currents and ensure the 
out a fine tuning of the coupling constants, the right scale of the model must 
condition 
where 
and, for the scalar triplets, by:

\[
- \mathcal{L}_Y^t = \sum_{i,j=1}^3 \left( h_{ij}^\ell \overline{\psi}_L \Phi \psi_R^i + \overline{\tilde{h}_{ij}^\ell} \overline{\psi}_L \tilde{\Phi} \psi_R^i \right) + h.c.,
\]

\[
- \mathcal{L}_Y' = \sum_{i,j=1}^3 \left( h_{ij}^\ell \overline{\psi}_L \Phi \psi_R^i + \overline{\tilde{h}_{ij}^\ell} \overline{\psi}_L \tilde{\Phi} \psi_R^i \right) + i f_{ij} \left[ \psi_L^T \Theta_2 \Delta_L \psi_R^j + (L \leftrightarrow R) \right] + h.c.,
\]

where \(\tilde{\Phi} = \tau_2 \Phi^* \tau_2\), \(h\), \(\overline{h}\), and \(f\) are the Yukawa coupling matrices, and \(C\) is the 
Dirac’s charge conjugation matrix. As a consequence of the discrete left-right 
symmetry all the terms in the potential are self-conjugate. We have chosen real 
coupling constants to avoid explicit CP violation.

The pattern of symmetry breaking, for the scalar bidoublet, is achieved by:

\[
\langle \Phi \rangle = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} k_1 e^{i\alpha} & 0 \\ 0 & k_2 \end{array} \right),
\]

and, for the scalar triplets, by:

\[
\langle \Delta_L \rangle = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} 0 & 0 \\ 0 & 0 \end{array} \right) \quad \langle \Delta_R \rangle = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} 0 & e^{i\theta} \\ v_R e^{i\theta} & 0 \end{array} \right),
\]

where \(k_1, k_2, v_L, v_R, \alpha,\) and \(\theta\) are real numbers. There are some constraints on 
the values that the vacuum expectation values \(k_1, k_2, v_L,\) and \(v_R\) may take: \(v_L\) 
must be much smaller than \(k_1\) and \(k_2\) \(^3\) to keep the well known experimental 
condition \(M_{W_L}^2 / M_{2L}^2 \simeq \cos^2 \theta_W\). \(^7\) In addition it has been showed that, 
without a fine tuning of the coupling constants, the right scale of the model must 
be very large in order to avoid flavor changing neutral currents and ensure the 
correct order of magnitude for the masses of the left-handed neutrinos. This, 
in turn, assures that the right-weak bosons \(W_R^+\), \(W_R^-\), and \(Z_R^0\) get really heavy 
masseS compatible with the experimental bounds \(^9\). In fact, as we will show, 
the right scale must be at least \(v_R \gtrsim 10^7\) GeV. This is a very important issue 
because most of the predictions at low energy of the LRSM will be equal to 
those of the SM.

A direct consequence of imposing CP as a spontaneously broken symmetry, 
together with the manifest left-right discrete symmetry \(\Phi \leftrightarrow \Phi^\dagger\), is that the 
Yukawa coupling matrices \(h\) and \(\overline{h}\) must be real and symmetric. This leads to 
a relationship between the left and right CKM matrices\(^4\):

\[
K_L = K_R^*.
\]

The only complex parameter in the quark mass matrices is the complex phase 
in \(\langle \Phi \rangle\). To break CP spontaneously, we have to search for a complex vev of the 
Higgs bosons. The vev \(\langle \Phi \rangle\) of the expression in Eq. \(23\) breaks the \(U(1)_{L-R}\) 
symmetry and is the only source of CP violation in the quark sector \(^9\).

\(^3\)\(v_L \simeq k_2^2 / v_R\) where \(k_1^2 = k_2^2 + k_3^2 \simeq (246 \text{ GeV})^2\).

\(^4\)We have assumed that the diagonal entries of the quark squared mass diagonal matrices 
are all positive. For a complete review of the cases in which this does not happen see Ref. \(^{13}\).
3.2 The see-saw mechanism

In the LRSM neutrinos acquire masses via the see-saw mechanism, and the order of magnitude of these masses depends on the left and right scales of the model $\nu_L$ and $\nu_R$. Therefore it is interesting to check the bounds that are imposed on $\nu_R$ from the experimental constraints on the neutrino masses. As we will see, the right scale of the model must be at least $10^7$ GeV. This is a very strong constraint which makes the new physics contributions from the LRSM completely negligible compared with the SM ones. One way to avoid this issue is to search for another mechanism of neutrino masses generation, but this must be done at the expense of enlarging the content of the model. Assuming that it is possible to do this we could lower the bound on $\nu_R$ as much as 1 TeV, making the LRSM new physics contributions comparable with the SM ones, as it is done in most of the literature [6, 14, 15, 16, 17]. But, if we stick to the usual neutrino masses generation see-saw mechanism, we should keep the bound $\nu_R > 10^7$ GeV. This is something that seems not to have received enough attention before\textsuperscript{5}. Let’s have a look at the see-saw mechanism in the LRSM.

The Yukawa terms in the Lagrangian for the lepton sector are given by the expression (22):

$$-\mathcal{L}_Y = \frac{1}{\sqrt{2}} \sum_{i,j=1}^{3} \left( h_{ij} \bar{\psi}^L_i \Phi \psi^R_j + \tilde{h}_{ij} \bar{\psi}^L_i \tilde{\Phi} \psi^R_j \right) + if_{ij} \left[ \psi^R_j C \tau^2 \Delta_L \psi^L_i + (L \leftrightarrow R) \right] + h.c.,$$

(26)

where $h^l$ and $\tilde{h}^l$ must be hermitian. For convenience, we will work with a single generation, and ignore the spontaneous CP phases. Introducing the vacuum expectation values into the expression in Eq. (26), we obtain the following mass terms:

$$\frac{1}{\sqrt{2}} \left[ \left( h^l k_1 + \tilde{h}^l k_2 \right) v_L v_R + \left( h^l k_2 + \tilde{h}^l k_1 \right) v_L v_R + f \left( v_R v^\dagger_R + v_L v^\dagger_L \right) \right] + h.c..$$

(27)

Neutrino mass terms derive both from the $h^l$ and $\tilde{h}^l$ terms, which lead to a Dirac mass, and from the $f$ term, which leads to a Majorana mass. Defining, as usual, $\psi^c \equiv C (\psi)^T$, it is convenient to employ the self-conjugate spinors

$$\nu = \frac{1}{\sqrt{2}} (\nu_L + \nu^c_L), \quad N = \frac{1}{\sqrt{2}} (\nu_R + \nu^c_R).$$

(28)

Thus, the neutrino mass terms can be written as:

$$\begin{pmatrix} \nu^c \\ N \end{pmatrix} \begin{pmatrix} \sqrt{2} f v_L & h_D k_+ \\ h_D k_+ \sqrt{2} f v_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix},$$

(29)

where for simplicity we have defined

$$h_D = \frac{1}{\sqrt{2}} \frac{h^l k_1 + \tilde{h}^l k_2}{k_+}. \quad (30)$$

\textsuperscript{5}In Ref. [20], Ma remarks how important for leptogenesis it is to have a high right scale ($\nu_R \geq 10^{14}$ GeV). The difference with the model studied in our paper is that Ma uses a right doublet instead of a right triplet so that $m_N \sim 10^8$ GeV $\ll \nu_R$. 

7
Given the phenomenological condition $\nu_L \ll k_1, k_2 \ll \nu_R$, $\nu$ and $N$ are approximate mass eigenstates with masses

$$m_N \simeq \sqrt{2} f \nu_R,$$

$$m_\nu \simeq \sqrt{2} \left[ f \nu_L - \frac{h_D^2 k_1^2}{2 f \nu_R} \right],$$

(31, 32)

Additionally, the electron mass is given by

$$m_e = \frac{1}{\sqrt{2}} \left( h^1 k_2 + \bar{h}^1 k_1 \right) = h_D^2 k_+,$$

(33)

with

$$h_D^e = \frac{1}{\sqrt{2}} \frac{h^1 k_2 + \bar{h}^1 k_1}{k_+}.$$  (34)

Normally, we expect $h_D$ and $h_D^e$ to be similar in size. Then, substituting the expressions in Eqs. (31) and (33) into Eq. (32) and taking into account that $k_+^2 \approx \nu_L \nu_R$, we arrive at the following expression for $\nu_R$ in terms of $k_+$ and the masses of $\nu, N,$ and $e$:

$$\nu_R^2 \approx k_+^2 \frac{m_N^2}{m_\nu m_N + m_e^2}.$$  (35)

We can see from this expression that the minimum value that $\nu_R$ can take is determined by the lower bound on the mass of $N$ and the upper bound on the mass of $\nu$.

Taking the following central values from the Particle Data Group [18]:

$$m_e = 5.11 \times 10^{-4} \text{ GeV},$$

(36)

$$m_\nu < 3 \times 10^{-9} \text{ GeV},$$

(37)

$$m_N > 80.5 \text{ GeV},$$

(38)

we arrive at the lower bound for $\nu_R$:

$$\nu_R > 2.8 \times 10^7 \text{ GeV}.$$  (39)

### 4 Calculation of $\varepsilon_B$ for the $B_d$ and $B_s$ Systems

#### 4.1 $\varepsilon_B$ in the SM

We can calculate $\varepsilon_B$, by solving the Schrödinger’s equation for the $B^0 - \bar{B}^0$ system [2, 3]:

$$i \frac{d\Phi (t)}{dt} = H \Phi (t),$$

(40)

where

$$H = \begin{pmatrix} M_{11} - i \Gamma_{11}/2 & M_{12} - i \Gamma_{12}/2 \\ M_{12}^* - i \Gamma_{12}^*/2 & M_{11} - i \Gamma_{11}/2 \end{pmatrix},$$

(41)

and

$$\Phi (t) = a_B (t) \left| B^0 \right\rangle + a_{\bar{B}} (t) \left| \bar{B}^0 \right\rangle,$$

(42)

being $\left| B^0 \right\rangle$ and $\left| \bar{B}^0 \right\rangle$ the mutually orthogonal vectors $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$. 

8
The solution of this equation gives the following results \[2, 3, 14, 16, 17, 21, 22\]:

\[
\text{Re } \epsilon \approx \frac{M_{12}^R \Gamma_{12}^I - M_{12}^I \Gamma_{12}^R}{4 (M_{12}^R)^2 + (\Gamma_{12}^R)^2},
\]

\[
\text{Im } \epsilon \approx \frac{2 M_{12}^R M_{12}^I + \Gamma_{12}^R \Gamma_{12}^I}{4 (M_{12}^R)^2 + (\Gamma_{12}^R)^2},
\]

(43)

where the superscript indicates the real part (R) or the imaginary part (I).

Thus, to calculate the parameters \(\text{Re } \epsilon\) and \(\text{Im } \epsilon\), we have to calculate the matrix elements \(M_{12}\) and \(\Gamma_{12}\) through the box diagrams showed in Figs. 1, 2, 3, and 4 \[2, 3, 21, 22\], where \(W\) is the SM charged gauge boson and \(\phi\) is the corresponding charged Goldstone boson.

Following the well known standard techniques summarized in Ref. 23 we obtain

\[
M_{12} = \frac{G_F^2 f_B^2 B m_B m_W^2}{12 \pi^2} \sum_{i,j=c,t} \eta_{ij} \overline{E}(x_i, x_j) (\lambda_i \lambda_j),
\]

(45)

\[
\Gamma_{12} \approx -\frac{G_F^2 m_B^3}{8 \pi} f_B^2 B \left[ \lambda_u^2 P(uu) + \lambda_c^2 P(cc) + 2 \lambda_u \lambda_c P(uu) \right],
\]

(46)

where

\[
P(uu) \approx 1,
\]

(47)

\[
P(cc) \approx 1 - \frac{8}{3} \frac{m_c^2}{m_b^2},
\]

(48)

\[
P(uu) \approx 1 - \frac{4}{3} \frac{m_u^2}{m_b^2},
\]

(49)

and

\[
x_i = \left( \frac{m_i}{m_W} \right)^2,
\]

(50)

\[
\lambda_i = K_{ib} K_{id(s)}.
\]

(51)

Here \(G_F\) is the Fermi constant, \(B_B\) is the saturation factor for the B mesons, \(f_B\) is the B meson decay constant with \(f_B^2 B_B \approx 4.88 \times 10^{-2} \text{ GeV}^2\) for the \(B_d\) meson system and \(6.45 \times 10^{-2} \text{ GeV}^2\) for the \(B_s\) meson system \[24\], \(m_B\) and \(m_W\) are the B meson and W boson masses, \(\eta_{ij}\) are the QCD correction factors \[25\],

\[
\eta_{cc} \approx 1.38,
\]

(52)

\[
\eta_{ct} \approx 0.47,
\]

(53)

\[
\eta_{tt} \approx 0.59,
\]

(54)

and \(\overline{E}(x_i, x_j)\) are the box diagram functions showed below:

\[
\overline{E}(x_i, x_j) = x_i x_j \begin{cases} (x_j - x_i)^{-1} \left( \frac{1}{4} + \frac{3}{4} (1 - x_i)^{-1} - \frac{3}{4} (1 - x_i)^{-2} \right) \ln x_i \\ + (x_i \leftrightarrow x_j) + \frac{3}{4} [(1 - x_i) (1 - x_j)]^{-1} \end{cases},
\]

(55)

9
\[ E(x_i, x_i) = -x_i \left[ \frac{1}{4} + \frac{9}{4} (1 - x_i)^{-1} - \frac{3}{2} (1 - x_i)^{-2} \right] + \frac{3}{2} \left[ x_i / (1 - x_i) \right]^3 \ln x_i. \] (55)

To make the calculations we have used the central values for the elements in the CKM matrix as well as the central value for the CKM complex phase \[ \delta^6 \] [18, 22, 24]. In this way we obtain the following central values, for the \( B^0_{d,s} - \bar{B}^0_{d,s} \) systems, which we compare to the experimental results:

\[ Re \tau_{B_d} \approx 1.0 \times 10^{-3}, \] (57)

\[ Im \tau_{B_d} \approx 4.328 \times 10^{-1}, \] (58)

\[ \left| \frac{q}{p_d} \right| = \left| \frac{1 - \tau_{B_d}}{1 + \tau_{B_d}} \right| \approx 0.998, \] (59)

\[ \left( \left| \frac{q}{p_d} \right| \right)_{ex.} = 1.029 \pm 0.013 \pm 0.011, \] (60)

\[ \left( \left| \frac{q}{p_d} \right| \right)_{w.a.} = 0.999 \pm 0.006. \] (61)

\[ Re \tau_{B_s} \approx -1.2 \times 10^{-5}, \] (62)

\[ Im \tau_{B_s} \approx -1.725 \times 10^{-2}, \] (63)

\[ \left| \frac{q}{p_s} \right| - 1 \approx 2.425 \times 10^{-5}, \] (64)

\[ \left( \left| \frac{q}{p_s} \right| \right)_{ex.} \rightarrow \text{No experimental results yet.} \] (65)

What we see is that the SM prediction for the central value of the parameter \( Re \tau_{B_d} \) lies in the middle of the experimental width and its order of magnitude is the same as in the kaon system: \( 10^{-3} \). Moreover, the SM predicts a value for \( Re \tau_{B_s} \), two orders of magnitude below the prediction for \( Re \tau_{B_d} \) and with opposite sign. This is why there are no experimental results yet concerning CP violation in the \( B_s \) system. Future improvements on the measurement of the dilepton asymmetry will reduce the experimental width and let us constrain even more the possible candidate models of new physics.

The predicted value in the SM for the \( |q/p| \) parameter in the \( B^0_d - \bar{B}^0_d \) system is in agreement with the experimental results [13], especially with the world average [18, 27]. This is really good since these measurements are very precise. However they just give information about the magnitude of \( \tau_{B_d} \). Instead, the measurement of the the dilepton asymmetry [12], which is still very poor due to the huge experimental width, offers a way to know another piece of information: \( Re \tau_{B_d} \). This should be taken as a complementary information and a way to discriminate among different models that might predict the same value for \( |q/p|_d \), despite the present lack of experimental precision in the measurement of the dilepton asymmetry.

\[ \delta^6 \] is function of \( \alpha \) in the context of the LRSM, and matches its experimental value when \( \alpha \approx 0 \) [20].

\[ 6 \] Here the subscripts ex. and w.a. mean “experimental” (data extracted from Refs. [12, 13]) and “world average” (data extracted from Refs. [18, 27]).
4.2 \( \tau_B \) in the LRSM

According to the reference [9] there are four explored cases in the LRSM corresponding to combinations of maximum and no CP violation both in the quark and in the lepton sectors. Following this reference, the cases I and II corresponding to a maximal CP violation in the quark sector \((\alpha = \pi/2)\) are ruled out because they present flavor changing neutral currents at a level which is inconsistent with the current phenomenology. In contrast, the cases III and IV corresponding to no CP violation in the quark sector \((\alpha = 0)\) do not present any phenomenological inconsistency and are appropriated to calculate the matrix elements \(M_{12}\) and \(\Gamma_{12}\). To avoid an explicit origin for the CP violation in the quark sector, we have to adjust \(\alpha\) to be small enough so as not to change the main features and results found, and to lead to the correct experimental value for the CKM phase of the SM. Effectively, to obtain the correct value for the CKM phase of the SM, we need a value close to zero for the spontaneous CP phase \(\alpha\) [26].

The case III corresponds to no CP violation in the quark sector \((\alpha = 0)\), and maximum CP violation in the lepton sector \((\theta = \pi/2)\), and since the right scale of the model is very large \((\nu_R \geq 10^7 \text{ GeV})\) there is no any signal of new physics except for the presence of six additional physical scalar bosons at the electroweak scale: two neutral, two singly charged, and two doubly charged [9]. These new bosons, together with the SM-like scalar boson, are:

\[
\begin{align*}
\phi_0^D & = 0.50\phi_0^L - 0.32\phi_0^R, \\
\phi_0^E & = 0.45\phi_0^L + 0.89\phi_0^R, \\
\phi_0^F & = -0.71\phi_0^L - 0.71\phi_0^R, \\
\phi_B^\pm & = 0.71\phi_0^L + 0.71\phi_0^R, \\
\phi_{B}^{\pm\pm} & = \delta_{L}^{\pm},
\end{align*}
\]

where \(\phi_0^{i(i)}\) is the real (imaginary) part of

\[
\begin{align*}
\phi_+^0 & = \frac{1}{|k_+|}(-k_2\phi_1^0 + k_1 e^{i\alpha}\phi_2^0), \\
\phi_-^0 & = \frac{1}{|k_+|}(-k_1 e^{-i\alpha}\phi_1^0 + k_2\phi_2^0).
\end{align*}
\]

For the present calculation we need the SM box diagram version of Figs. [1] [2] [3] and [4] as well as the LRSM box diagram version including the new singly charged physical scalar bosons interacting with the quark sector. These bosons must be linear combinations of the singly charged fields \(\phi_1^\pm\) and \(\phi_2^\pm\) according to the Yukawa Lagrangian for the quarks in Eq. (21). However, as we can see in Eq. (67), the new light singly charged scalar bosons are linear combinations of the singly charged fields \(\delta_1^\pm\) and \(\delta_2^\pm\) in the scalar triplets, which do not interact with the quark sector, and, therefore, there is no new physics contribution to the matrix elements \(M_{12}\) and \(\Gamma_{12}\). Note that the neutral scalar fields do not.

\[\text{We have chosen a universal value for the free dimensionless parameters of the scalar potential equal to 0.7 (see Ref. [9]).}\]

\[\text{Our point of view agrees with Cocolicchio and Fogli’s [16] concerning the lack of new important CP violation phenomena, in the neutral kaon system, with respect to the standard left-left computation when there is no valuable } W_L - W_R \text{ mixing.}\]
contribute to the calculation since the flavor changing neutral currents are well suppressed. The doubly charged scalar fields do not contribute either because it is impossible to construct one-loop diagrams for the $B^0 - \bar{B}^0$ oscillation which include internal doubly charged bosons.

As we had said before, most of the predictions found in the literature \cite{6, 14, 15, 16, 17} assume an order of magnitude for $\nu_R$ of 1 TeV, leading to a low mass spectrum of scalar particles that contribute appreciably to the box diagrams with one or two internal singly charged scalar fields and that are linear combinations of $\phi_1^\pm$ and $\phi_2^\pm$. In this case the gauge boson $W_R$ also contributes appreciably to the box diagrams with one or two internal gauge fields and must be considered. This scheme, which ignores the strong constraint on $\nu_R$, must be accompanied by a new mechanism of neutrino masses generation due to an enlargement of the original LRSM.

The case IV, corresponding to no CP violation both in the quark sector ($\alpha = 0$) and in the lepton sector ($\theta = 0$), is the easiest of all the cases because it reduces to the SM in the limit where $\nu_R$ goes to the infinity and $\alpha \approx 0$ \cite{7, 9}. Therefore we just need to use the SM box diagrams of Figs. 1, 2, 3, and 4 and at the end the predictions of both the LRSM and the SM on the parameters $Re \tau_B$ and $|q/p|$ are equal.

5 Conclusions

The study of CP violation in the B mesons systems is a very strong source of developments in particle physics. In particular, the improvements in the measurement of the dilepton asymmetry will let us understand more about the origin of CP violation and the possible models of new physics we can propose to explain it. Given the present experimental uncertainty in the value of $Re \tau_{B_d}$ we have shown that the SM prediction agrees with the experiment and its order of magnitude is the same as in the kaon system: $10^{-3}$. We have also shown that the SM predicts a value for $Re \tau_{B_s}$ two orders of magnitude below the prediction for $Re \tau_{B_d}$ and with opposite sign. In addition, the parameter $|q/p|$ is shown to be 0.998 for the $B_d$ system and $1 + 2.425 \times 10^{-5}$ for the $B_s$ one.

Lots of models may be proposed to explain the origin of the CP violation phenomenon. Among these models is the LRSM which gives us a natural explanation for the parity and CP violation as well as a physical meaning for the hypercharge quantum number. Additionally, this model explains the smallness of the neutrino masses, gives us a framework to study CP violation in the lepton sector, which has not been observed yet but that we will surely be able to observe in the foreseeable future, and exhibits new scalar bosons at the electroweak scale which are the focus of most current and future experimental work \cite{28}. However, since the right scale of the model is very large ($\nu_R \geq 10^7$ GeV), the new physics sector decouples from the quark sector and, therefore, most of the predictions at low energy of the LRSM will be equal to those of the SM, in particular those corresponding to the parameters $Re \tau_{B_{d,s}}$ and $|q/p|_{d,s}$.

There are several papers in the literature \cite{14, 15} which analyze the LRSM contributions to the CP violation phenomena in the B mesons. They are very interesting because the LRSM contributions are comparable to the SM ones and, therefore, they lead to some potentially observable signatures. The right scale in these papers is chosen to be around 1 TeV and that is why the new
physics contributions are sizable. The conclusion of our work is that we must view these papers with caution because they avoid the strong constraint on $\nu_R$ coming from the see-saw neutrino masses generation. If we want to lower the right scale of the model to 1 TeV and use the results found in these papers, we must enlarge the content of the model and look for a different neutrino masses generation mechanism.

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Figure 1: Box diagrams with two internal charged gauge bosons, used to calculate the non diagonal matrix elements $M_{12}$ and $\Gamma_{12}$. $Q$ is the quark $d$ for the $B_d$ system and the quark $s$ for the $B_s$ system.
Figure 2: Box diagrams with two internal charged bosons: one gauge and the other scalar, used to calculate the non diagonal matrix elements $M_{12}$ and $\Gamma_{12}$. $Q$ is the quark $d$ for the $B_d$ system and the quark $s$ for the $B_s$ system.
Figure 3: Box diagrams with two internal charged bosons: one gauge and the other scalar, used to calculate the non diagonal matrix elements $M_{12}$ and $\Gamma_{12}$. $Q$ is the quark $d$ for the $B_d$ system and the quark $s$ for the $B_s$ system.
Figure 4: Box diagrams with two internal charged scalar bosons, used to calculate the non diagonal matrix elements $M_{12}$ and $\Gamma_{12}$. $Q$ is the quark $d$ for the $B_d$ system and the quark $s$ for the $B_s$ system.