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W_R effects on CP asymmetries in B meson decays

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Abstract: After we have limited elements of the right-handed CKM matrix to satisfy the bounds for CP violation ϵ_K in K meson systems, the right-handed charged current gauge boson W_R is shown to substantially affect CP asymmetries in B systems. A joint χ^2 analysis is applied to $B-\bar{B}$ mixing to constrain the right-handed CKM matrix elements. In $(\sin(2\alpha), \sin(2\beta))$, $(x_s, \sin(\gamma))$, (ρ, η), and $(x_s, \sin(2\phi_s))$ plots in the presence of the W_R boson, we find larger allowed experimental regions that can distinguish this model from the standard model.

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

Contents

1. Introduction

Within the standard model (SM), the flavour non-diagonal couplings in the weak charged-current interactions are described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. The SM has been considered as the complete description of the weak interactions. However, it is widely believed that there must be physics beyond the SM. The left-right symmetric model (LRSM) is one of the simplest extensions in new physics. Currently, B factories at SLAC and KEK have started to measure the CP violating asymmetries in the decays of B mesons and provide a test of the SM explanation of CP violation. The goal of this paper is to examine the possible effects of a right-handed boson W_R on the determinations of CP violating decay asymmetries.

2. Left-right symmetric models

The $V - A$ structure of the weak charged currents was established after the discovery of parity violation [2]. This is manifested in the standard model by having only the left-handed fermions transform under the SU(2) group. It is then natural to ask whether or not the right-handed fermions take part in charged-current weak interactions, and if they do, with what strength. Charged-current interactions for the right-handed fermions can easily be introduced by extending the gauge group [3]. The simplest example is the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times U(1)_{B-L}$ model, where the left-handed fermions transform as doublets under $\mathrm{SU}(2)_L$ and as singlet under $\mathrm{SU}(2)_R$, with the situation reversed for the right-handed fermions [4]. The addition of a new $\mathrm{SU}(2)_R$ to the gauge group implies the existence of three new weakly interacting gauge bosons: two are charged and one is neutral.

The charged right-handed gauge bosons (denoted by $W_R^{\pm}$) and a neutral gauge boson Z_2 acquire masses, which are proportional to a vacuum expectation value, and which become much heavier than those of the usual left-handed $W_L^{\pm}$ and Z_1 bosons. The charged current weak interactions can be written as (suppressing the generation mixing)

$$\begin{aligned} L = {} & \frac{g}{\sqrt{2}}(\bar{u}_L \gamma_\mu d_L + \bar{\nu}_L \gamma_\mu e_L) W_L^+ + \\ & + \frac{g}{\sqrt{2}}(\bar{u}_R \gamma_\mu d_R + \bar{\nu}_R \gamma_\mu e_R) W_R^+ + \mathrm{H.C.}\,, \end{aligned} \tag{2.1}$$

where the gauge coupling for left and right-handed currents is assumed to have the same strength g, and a $W_L - W_R$ mixing term is neglected since it is highly suppressed by the experimental data [5]. It is clear that for $m_{W_L} \ll m_{W_R}$, the charged current weak interactions will appear almost maximally parity-violating at low energies. Any deviation from the pure left-handed (or $V - A$) structure of the charged weak current will constitute evidence for a right-handed current and therefore a left-right symmetric structure of weak interactions.

Within the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)$ model, we denote the left- and right-handed quark mixing matrices by V^L and V^R, respectively. The form of V^L is parametrized by [6]

$$V^L = \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array} . \tag{2.2}$$

On the other hand, the choice of the manifest left-right symmetry, i.e. $V^R = V^L$, would yield a very strigent bound $m_{W_R} \geq 1.6\,\mathrm{TeV}$ from the constraint of the kaon mass difference [7]. The limits from Δm_K for arbitary V^R were first considered by Olness and Ebel [8] and followed by Langacker and Sankar [5]. They showed that the lower limit of the W_R mass could be reduced by taking either of the following two general forms of V^R

$$V_I^R = \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & ce^{i\xi} & se^{i\sigma} \\ 0 & se^{i\phi} & ce^{i\chi} \end{pmatrix} \end{array} , \qquad V_{II}^R = \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 0 & 1 & 0 \\ ce^{i\xi} & 0 & se^{i\sigma} \\ se^{i\phi} & 0 & ce^{i\chi} \end{pmatrix} \end{array} , \tag{2.3}$$

where $s = \sin\theta$ and $c = \cos\theta$ $(0 \leq \theta \leq 90^o)$, along with the unitarity condition $\xi - \sigma = \phi - \chi + \pi$. The former type will be called the case of st-coupling (V_I^R) and the latter that of dt-coupling (V_{II}^R) in the paper. There is the possibility of having an overall phase factor $e^{i\omega}$ multiplying both matrices, but in all relevant processes considered here, the W_R is not mixed but reabsorbed, so these phase factors are always cancelled by their complex conjugates and are not independent variables for statistical purposes. We therefore take ω to be zero for simplicity.

A general parametrization of V_R will involve six phases [9]. There is not enough data to constrain this many variables. As shown below, the contributions to ϵ_K from V^R from t and/or c quarks in the inner box could be a thousand times the standard model, unless products of V^R matrix elements were one part per thousand. Since the error on ϵ is only 10% to 15% from B_K, these matrix elements would have to be small and finely tuned to contribute. So it is more natural to assume that they are essentially zero for our calculations. This means that the c and t elements of the d or s columns are taken to vanish, as in the cases of st- and dt-coupling, respectively, in eq. (2.3).

For our purposes of showing the effects of LRSM in B physics CP violating experiments, we use the above cases as starting points. They will each be shown to bring in only one independent right-hand phase.

3. CP violation in K Meson systems

The CP violation parameter ϵ_K in K decays, which is proportional to the imaginary part of the box diagrams mediated by two W_L, or two W_R or a $W_L - W_R$ pair, is given as $\epsilon_K \approx \mathrm{Im}\,\langle K^0|H(\Delta S = 2)|\bar{K}^0\rangle/\sqrt{2}\Delta m_K$ where $H(\Delta S = 2) = H^{LL} + H^{RR} + H^{LR}$

is the hamiltonian from the box diagrams named above. The H^{LL} contribution gives [10]

$$\epsilon_K = \frac{G_F^2 f_K^2 B_K m_K m_{W_L}^2}{12\sqrt{2}\pi^2 \Delta m_K}[\eta_{cc} S(x_c) I_{cc} + \eta_{tt} S(x_t) I_{tt} + 2\eta_{ct} S(x_c, x_t) I_{ct}]\,, \tag{3.1}$$

where $I_{ij} = \mathrm{Im}(V_{id}^* V_{is} V_{jd}^* V_{js})$, and the Inami-Lim functions [7] are

$$\begin{aligned} S(x) &= x\left[\frac{1}{4} + \frac{9}{4(1-x)} - \frac{3}{2(1-x)^2}\right] - \frac{3}{2}\left(\frac{x}{1-x}\right)^3 \ln x\,, \\ S(x_c, x_t) &= x_c\left[\ln\frac{x_t}{x_c} - \frac{x_t}{4(1-x_t)}\left(1 + \frac{x_t}{1-x_t}\ln x_t\right)\right], \end{aligned} \tag{3.2}$$

with $x_i = m_i^2/m_{W_L}^2$. The factors $\eta_{cc} = 1.38, \eta_{tt} = 0.59$, and $\eta_{ct} = 0.47$ are QCD corrections [11].

The two W_R exchange part, H^{RR}, gives no contribution due to the factor I_{ij} vanishing for both cases of V^R as shown in eq. (2.3).

The part from W_L and W_R exchange, H^{LR}, gives [12]

$$\begin{aligned} H^{LR} = {} & \frac{2G_F^2}{\pi^2} m_{W_L}^2 x_{LR} \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL} (\bar{d}_R s_L)(\bar{d}_L s_R) \frac{\sqrt{x_i x_j}}{4} \times \\ & \times \left[\left(4\eta_{ij}^{(1)} + \eta_{ij}^{(2)} x_i x_j x_{LR}\right) I_1(x_i, x_j, x_{LR}) - \left(\eta_{ij}^{(3)} + \eta_{ij}^{(4)} x_{LR}\right) I_2(x_i, x_j, x_{LR})\right], \end{aligned} \tag{3.3}$$

where $\lambda_i^{LR} = V_{id}^{L*} V_{is}^R$, the ratio of W masses squared is $x_{LR} = (m_{W_L}/m_{W_R})^2$,

$$\begin{aligned} I_1(x_i, x_j, x_{LR}) &= \frac{x_i \ln x_i}{(1-x_i)(1-x_i x_{LR})(x_i - x_j)} + (i \longleftrightarrow j) - \\ &\quad - \frac{x_{LR} \ln x_{LR}}{(1-x_{LR})(1-x_i x_{LR})(1-x_j x_{LR})}\,, \\ I_2(x_i, x_j, x_{LR}) &= \frac{x_i^2 \ln x_i}{(1-x_i)(1-x_i x_{LR})(x_i - x_j)} + (i \longleftrightarrow j) - \\ &\quad - \frac{\ln x_{LR}}{(1-x_{LR})(1-x_i x_{LR})(1-x_j x_{LR})}\,, \end{aligned} \tag{3.4}$$

and $\eta^{(1)-(4)}$ are the short-distance QCD correction factors, whose explicit forms are given in [12]. Their values are $(\eta_{cc}^{(1)}, \eta_{ct}^{(1)}, \eta_{tt}^{(1)}) = (0.61, 1.27, 1.98)$, $(\eta_{cc}^{(2)}, \eta_{ct}^{(2)}, \eta_{tt}^{(2)}) = (0.04, 0.27, 0.75)$, $(\eta_{cc}^{(3)}, \eta_{ct}^{(3)}, \eta_{tt}^{(3)}) = (0.55, 1.03, 1.93)$, and $(\eta_{cc}^{(4)}, \eta_{ct}^{(4)}, \eta_{tt}^{(4)}) = (0.45, 0.84, 1.58)$ for $m_{W_R} = 2.5\,\mathrm{TeV}$ and $m_t = 175\,\mathrm{GeV}$ at the scale $\mu = 4.5\,\mathrm{GeV}$.

The contribution to ϵ_K from H^{LR} only comes from the following combinations of quark mixing elements surviving in $\lambda_i^{LR} \lambda_j^{RL}$: for the case of st-coupling

$$\begin{aligned} &(\text{cu pair}): \quad \lambda^2 c \sin(-\xi)\,, \\ &(\text{tu pair}): \quad A\lambda^4[(1-\rho)\sin(\phi) + \eta\cos(\phi)]\,; \end{aligned} \tag{3.5}$$

and for the case of dt-coupling

$$\begin{aligned}
(\text{uc pair}): &\quad \left(1-\frac{\lambda^2}{2}\right)^2 c\sin(-\xi)\,,\\
(\text{ut pair}): &\quad As\lambda^2\left(1-\frac{\lambda^2}{2}\right)\sin(-\phi)\,.
\end{aligned} \tag{3.6}$$

Again, the contributions to ϵ_K would be of the same order as in the SM in the case of st-coupling, or 10 to 100 times as large in that of dt-coupling, unless some of the parameters were very small or if a cancelation occured. So we will adjust the parameters in V^R so that no contribution to ϵ_K will come from H^{LR}. This is accomplished by various conditions [14] in the two cases. For the case of st-coupling (V_I^R), the LRSM model needs effectively:

$$\sin(\xi)=0\,, \qquad \text{and} \qquad \tan(-\phi)=\frac{\eta}{(1-\rho)}\,. \tag{3.7}$$

From the geometry of the unitarity triangle in the ρ,η plane, we see that $\phi=-\beta$, where β is the unitarity triangle angle at $\rho=1$. In this case, using the unitarity relation also, we have remaining two V_I^R variables to vary: s and σ. For the case of dt-coupling (V_{II}^R) the LRSM model effectively needs

$$c=0\,, \qquad \text{and} \qquad \sin(\phi)=0\,. \tag{3.8}$$

In this case we have only the variable σ in V_{II}^R to vary. There are other solutions to suppress ϵ_K. However, we use the above cases since they give the most significant effects on CP violation in B decay by W_R. In summary then, the right-handed mixing matrices have become:

$$V_I^R=\begin{array}{c} \\ u\\ c\\ t\end{array}\!\!\begin{array}{c} \begin{array}{ccc} d & s & b\end{array}\\ \begin{pmatrix} 1 & 0 & 0\\ 0 & c & se^{i\sigma}\\ 0 & se^{-i\beta} & -ce^{i(\sigma-\beta)}\end{pmatrix}\end{array}\,, \qquad V_{II}^R=\begin{array}{c} \\ u\\ c\\ t\end{array}\!\!\begin{array}{c} \begin{array}{ccc} d & s & b\end{array}\\ \begin{pmatrix} 0 & 1 & 0\\ 0 & 0 & e^{i\sigma}\\ 1 & 0 & 0\end{pmatrix}\end{array}\,. \tag{3.9}$$

Just as in the left-handed CKM matrix where there is one somewhat sizeable parameter (λ) mixing the lightest generations, while the other matrix elements are rather small, a similar behavior is seen in the right-hand matrix. In the case of st-coupling (V_I^R), it is the heavier generations that mix more than the lightest one, and in the case of dt-coupling (V_{II}^R) it is the light s and d quarks whose mixing elements switch roles. Once the disappearance of the LR contribution to ϵ_K is arranged, which comes from the imaginary part of the M_{12}^{LR} matrix element, we also find that the contribution of the real part, which gives Δm_K, is also very small: there is no contribution in the case of dt-coupling, and in the case of st-coupling, the contributions are only from (t,u) and (c,u) intermediate quarks. These contributions have the same orders of λ as in the SM, but are suppressed by m_u/m_t and m_u/m_c, respectively.

Recently, some detailed analyses of W_R effects on ϵ_K have been made [9] in the LRSM models in which the third generation was not dominant. The large N_C expansion and chiral perturbation theory were applied to estimate the left-right hadronic matrix elements $\langle K^0|H^{LR}(\Delta S = 2)|\bar{K^0}\rangle$ and their uncertainties. The models considered here have dominant third generation effects and are complementary to the other models.

What we find here is that even with the mixing matrices V_R which in both cases avoid the ϵ_K and Δm_K constraints, the other experiments still give a lower bound of $m_{W_R} \geq 1.3\,\text{TeV}$ in the case of dt-coupling, at 95% CL. In this case, even though $V^R_{ud} = 0$ in W_R production, the experimental D0 limit from Fermilab [13] is $m_{W_R} \geq 505\,\text{GeV}$ at 95% CL (see [13, Figure 3].). In the case of st-coupling, with $V^R_{ud} = 1$, the Fermilab limit is $m_{W_R} \geq 720\,\text{GeV}$, and we present analyses for $m_{W_R} \geq 1\,\text{TeV}$. With only the set of experiments we have considered, the case of st-coupling does have solutions down to $m_{W_R} \geq 0.25\,\text{TeV}$.

4. $B^0 - \bar{B}^0$ mixing

The mixing parameter x_q in the $B^0_q - \bar{B}^0_q$ system is defined by

$$x_q \equiv \frac{(\Delta m)_{B_q}}{\Gamma} = 2\tau_{B_q}|M_{12}|\,, \tag{4.1}$$

where $q = d$ or s, and M_{12} is the dispersive part of the mixing matrix element, i.e. $M_{12} - \frac{i}{2}\Gamma_{12} = \langle B^0|H(\Delta B = 2)|\bar{B}^0\rangle$. In the standard model, the mixing is explained by the dominant contribution of the two t-quark box diagrams. In the LRSM, M_{12} contains three terms

$$M_{12} = M^{LL}_{12} + M^{RR}_{12} + M^{LR}_{12}\,, \tag{4.2}$$

corresponding to the contributions from box diagrams in which two W_L, two W_R and a $W_L - W_R$ pair are exchanged. The standard model matrix element M^{LL}_{12} is

$$M^{LL}_{12} = \frac{G_F^2}{12\pi^2} m_B m^2_{W_L} \left(f^2_B B_B\right) \eta_{tt} S(x_t) \left(V^{L*}_{tq} V^L_{tb}\right)^2\,, \tag{4.3}$$

where $S(x_t)$ is defined in eq. (3.2) and $\eta_{tt} = 0.59$ is the QCD correction factor. The evaluation of the hadronically uncertain $f^2_B B_B$ has been the subject of much work, which is summarized in [15]. We will use

$$f_{B_d} B^{1/2}_{B_d} = 210 \pm 40\,\text{MeV}\,, \qquad \text{and} \qquad f_{B_s} B^{1/2}_{B_s} = 230 \pm 45\,\text{MeV} \tag{4.4}$$

from the scaling law and recent lattice calculations.

The element M^{RR}_{12} is given by

$$M^{RR}_{12} = \frac{G_F^2}{12\pi^2} m_B m^2_{W_L} \left(f^2_B B_B\right) \eta_{tt} S(x_t) x^2_{LR} \left(V^{R*}_{tq} V^R_{tb}\right)^2\,. \tag{4.5}$$

It disappears in $B_d - \bar{B}_d$ mixing due to either $V^R_{td} = 0$ or $V^R_{tb} = 0$ for both cases in V^R, but it has a contribution for the case of st-coupling in $B_s - \bar{B}_s$ mixing due to the non-zero values of V^R_{ts} and V^R_{tb}.

The matrix element M^{LR}_{12} is

$$\begin{aligned} M^{LR}_{12} = {} & \frac{G_F^2}{2\pi^2} m_B \left(f_B^2 B_B\right) \left(\frac{m_B}{m_b}\right)^2 m^2_{W_L} x_{LR} \sum_{i,j=u,c,t} \lambda^{LR}_i \lambda^{RL}_j \times \\ & \times \left[\frac{\sqrt{x_i x_j}}{4} \left[\left(4\eta^{(1)}_{ij} + \eta^{(2)}_{ij} x_i x_j x_{LR}\right) I_1(x_i, x_j, x_{LR}) - \right.\right. \\ & \left.\left. - \left(\eta^{(3)}_{ij} + \eta^{(4)}_{ij} x_{LR}\right) I_2(x_i, x_j, x_{LR}) \right] \right], \end{aligned} \tag{4.6}$$

where $\lambda^{LR}_i = V^{L*}_{iq} V^R_{ib}$, $\lambda^{RL}_j = V^{R*}_{jq} V^L_{jb}$, $\eta^{(1)-(4)}$, and I_1 and I_2 are defined in eqs. (3.3) and (3.4). In order to obtain this formula, the following ratio of matrix elements of quark operators [12] has been applied

$$\begin{aligned} \frac{\left\langle B^0 \left| \left(\bar{d}_R b_L\right) \left(\bar{d}_L b_R\right) \right| \bar{B}^0 \right\rangle}{\left\langle B^0 \left| \left(\bar{d}_L \gamma_\mu b_L\right)^2 \right| \bar{B}^0 \right\rangle} &= \frac{\left\langle B^0 \left| \bar{d}_R b_L \right| 0 \right\rangle \left\langle 0 \left| \bar{d}_L b_R \right| \bar{B}^o \right\rangle}{\left\langle B^0 \left| \bar{d}_L \gamma_\mu b_L \right| 0 \right\rangle \left\langle \left| \bar{d}_L \gamma_\mu b_L \right| \bar{B}^0 \right\rangle} \\ &= \frac{3}{4} \frac{B'_B}{B_B} \left(\frac{m_B}{m_b}\right)^2, \end{aligned} \tag{4.7}$$

where the bag factors B'_B and B_B encompass all possible deviations from the vacuum saturation approximation. B'_B can be treated as approximately equal to B_B. Their slight difference is irrelevant compared to other uncertainties.

The contributions of the nine different combinations within eq. (4.6) are dominated by $(t,t), (t,c), (c,t)$ and (u,t) pairs, for which the values of the large square bracket at $m_{W_R} = 1\,\text{TeV}$ are 11.9, 4.6×10^{-2}, 5.0×10^{-2} and 0.80×10^{-2}, respectively, the ratios mainly due to the quark mass factors $\sqrt{x_i x_j}$. All of the remaining terms are less than 10^{-3}.

4.1 $B_d - \bar{B}_d$ mixing

4.1.1 st-coupling

In the matrix element M^{LR}_{12} of eq. (4.6) only two terms from (c,u) and (t,u) pairs will survive in the case of st-coupling because of the factor $\lambda^{LR}_i \lambda^{RL}_j$. One finds that $M^{LR}_{12} \ll M^{LL}_{12}$ by four orders of magnitude, no matter what the mass value m_{W_R} is. Therefore, we may neglect the W_R contribution to $B_d - \bar{B}_d$ mixing in this case.

4.1.2 dt-coupling

On the other hand, there is only one non-vanishing term from the (c,t) pair in M^{LR}_{12} in the case of dt-coupling. One obtains $M^{LR}_{12} \sim M^{LL}_{12}$ if $m_{W_R} = 2.5\,\text{TeV}$, $M^{LR}_{12} < M^{LL}_{12}$ if $m_{W_R} = 5\,\text{TeV}$, and $M^{LR}_{12} \leq 10^{-2} M^{LL}_{12}$ if $m_{W_R} = 10\,\text{TeV}$. The effect from W_R in $B_d - \bar{B}_d$ mixing appears in this case.

4.2 $B_s - \bar{B}_s$ mixing

4.2.1 st-coupling

The effect from two W_R exchanges appears here. $M_{12}^{RR} \ll M_{12}^{LL}$ with the ratio from 10^{-3} to 10^{-7} as m_{W_R} varies from 1 to 15 TeV. Nevertheless, there are four terms which appear in M_{12}^{LR} in the case of st-coupling, namely those from (c, c), (c, t), (t, c) and (t, t) pairs, and which are dominated by the (t, t) pair. This gives $M_{12}^{LR} \sim M_{12}^{LL}$ for $m_{W_R} = 2.5\,\mathrm{TeV}$, and $M_{12}^{LR} \ll M_{12}^{LL}$ by two orders of magnitude for $m_{W_R} = 10\,\mathrm{TeV}$. The W_R contribution to $B_s - \bar{B}_s$ mixing cannot be ignored since $m_{W_R} < 5\,\mathrm{TeV}$ in this case.

4.2.2 dt-coupling

There is also one non-vanishing term in M_{12}^{LR} coming from the (c, u) pair in the case of dt-coupling, but $M_{12}^{LR} \ll M_{12}^{LL}$ by five orders of magnitude. Here, W_R gives no contribution to $B_s - \bar{B}_s$ mixing.

5. Joint χ^2 analysis for CKM matrix elements

We use six present experiments for the determination of the CKM matrix elements angles s_{23}, s_{13}, and δ. These are results for the matrix elements $|V_{cb}| = 0.0404 \pm 0.0016$ and $|V_{ub}/V_{cb}| = 0.101 \pm 0.016$ [16], for ϵ_K in the neutral K system, for $B_d - \bar{B}_d$ mixing with $\Delta m_d = 0.476 \pm 0.016\,\mathrm{ps}^{-1}$, for the probability of each calculated Δm_s [17] , and $\sin(2\beta) = 0.79 \pm 0.19$ from Belle, BaBar and CDF [18]. Since W_R may also contribute to b-decay, we include the contraint on V_{cb} as $|V_{cb}^L|^2 + x_{LR}|V_{cb}^R|^2 = |V_{cb}|^2$, where the interfering term is neglected [19]. The V_{ub} value gives a $b - d$ unitarity triangle side of length 0.46 ± 0.07. Since some discrepancies for new physics will be very large, our conclusions are not dependent on which choice of V_{cb} or V_{ub} experiments are used.

For making projected experimental plots for pairs of experiments $(\sin(2\alpha), \sin(2\beta))$, $(x_s, \sin(\gamma))$, or $(x_s, \sin(2\phi_s))$, we add one of these pairs as two future experiments, and assign as their errors the bin widths, which are 5% of the total range in our 20×20 bin coverage. For $(\sin(2\alpha), \sin(2\beta))$, these errors are close to those achievable for the B factories. Counting degrees of freedom, we have for the case of st-coupling: df = 8 experiments - 3 SM angles - 2 LR angles = 3 df. For the case of dt-coupling we have: df = 8 experiments - 3 SM angles - 1 LR angles = 4 df.

We produce the maximum likehood correlation plots for $(\sin(2\alpha), \sin(2\beta))$, $(x_s, \sin(\gamma))$, and $(x_s, \sin(2\phi_s))$. For each possible bin with given values for these pairs, we search for the lowest χ^2 in the data sets of the four or five angles of V^L and V^R, depending upon which case in V^R we are dealing with. We then draw contours at a few values of χ^2 in these plots corresponding to given confidence levels [20] which match 1σ and 2σ limits.

6. CP asymmetries in B^0 decays

6.1 $(\sin(2\alpha), \sin(2\beta))$ plots

The first CP violating asymmetry in $B \to J/\psi K_S$ decays is related to the mixing matrix element M_{12} and the decay amplitudes as follows [21],

$$\sin(2\beta) \equiv -\,\mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{A\left(\bar{B} \longrightarrow \Psi K_s\right)}{A(B \longrightarrow \Psi K_s)}\right). \tag{6.1}$$

The second CP asymmetry is provided by the measurement of the asymmetry in $B \to \pi\pi$, namely [21]

$$\sin(2\alpha) \equiv \mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{A\left(\bar{B} \longrightarrow \pi\pi\right)}{A(B \longrightarrow \pi\pi)}\right). \tag{6.2}$$

Because of the non-SM contributions of the LRSM, the effective α and β as defined here no longer represent real angles in the unitarity triangle.

6.1.1 st-coupling

Penguin diagrams, dominated by internal top-loops, also contribute to $B \to J/\psi K_S$ decays in addition to the tree graphs. The phase of the W_R penguin amplitude, $V_{tb}^R V_{ts}^{R*} = cse^{i(\chi-\phi)}$, has exactly the same value but opposite sign to the phase of the W_R tree amplitude, $V_{cb}^R V_{cs}^{R*} = cse^{i(\sigma-\xi)}$, due to the unitarity condition on V_I^R: $\chi - \phi = \sigma - \xi + \pi$. Namely, $V_{tb}^R V_{ts}^{R*} = -V_{cb}^R V_{cs}^{R*}$. In the SM, the phase of the W_L penguin amplitude induced by an internal top-loop is also opposite to the phase of the W_L tree amplitude, since $V_{tb}^L V_{ts}^{L*} \simeq -A\lambda^2 \simeq -V_{cb}^L V_{cs}^{L*}$. Consequently, recalling that $x_{LR} = m_{W_L}^2/m_{W_R}^2$,

$$\begin{aligned}\frac{A\left(\bar{B} \longrightarrow J/\psi K_S\right)}{A(B \longrightarrow J/\psi K_S)} &= \frac{V_{cb}^L V_{cs}^{L*}(1-P)/m_{W_L}^2 + V_{cb}^R V_{cs}^{R*}(1-P')/m_{W_R}^2}{V_{cb}^{L*} V_{cs}^{L}(1-P)/m_{W_L}^2 + V_{cb}^{R*} V_{cs}^{R}(1-P')/m_{W_R}^2} \\ &= \frac{V_{cb}^L V_{cs}^{L*} + x_{LR} V_{cb}^R V_{cs}^{R*}}{V_{cb}^{L*} V_{cs}^{L} + x_{LR} V_{cb}^{R*} V_{cs}^{R}},\end{aligned} \tag{6.3}$$

where P and P' are the ratios of the W_L and W_R penguin contributions over the tree amplitudes, respectively, and the approximation [14] $P \cong P' \propto \alpha_s \ln(m_t^2/m_c^2)$ provides the simplification of $P = P'$. This gives

$$\sin(2\beta) = -\,\mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{V_{cb}^L V_{cs}^{L*} + x_{LR} V_{cb}^R V_{cs}^{R*}}{V_{cb}^{L*} V_{cs}^{L} + x_{LR} V_{cb}^{R*} V_{cs}^{R}}\right). \tag{6.4}$$

On the other hand, no tree or penguin W_R contributions exist in $B \to \pi\pi$ since $V_{ub}^R V_{ud}^{R*} = 0$ and $V_{tb}^R V_{td}^{R*} = 0$. There is a $\Delta I = 1/2$ penguin pollution for this decay mode in the SM, but it can be removed by isospin analysis [22]. Therefore, we have

$$\sin(2\alpha) = \mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{V_{ud}^{L*} V_{ub}^{L}}{V_{ud}^{L} V_{ub}^{L*}}\right). \tag{6.5}$$

Since $M_{12}^{LR} \ll M_{12}^{LL}$ for B_d mesons, the result is that $M_{12} \simeq M_{12}^{LL}$. For $m_{W_R} = 10\,\mathrm{TeV}$, with little W_R effect, the ranges at 1σ are $0.6 \leq \sin 2(\beta) \leq 0.8$ and $-0.4 \leq \sin(2\alpha) \leq 0.1$. However, for $m_{W_R} = 1.0\,\mathrm{TeV}$, the ranges are $-0.5 \leq \sin(2\alpha) \leq 0.4$ and $0.50 \leq \sin(2\beta) \leq 0.95$.

6.1.2 dt-coupling

There are no tree or penguin contributions by W_R in $B \to J/\psi K_S$ due to the fact that $V_{cb}^R V_{cs}^{R*} = 0$ and $V_{tb}^R V_{ts}^{R*} = 0$. Hence, one has

$$\sin(2\beta) = -\,\mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{V_{cb}^L V_{cs}^{L*}}{V_{cb}^{L*} V_{cs}^L}\right). \tag{6.6}$$

In the case of dt-coupling, eq. (6.5) still holds for the same reason, namely that the tree and penguin W_R contributions do not exist in this case. Figure 1 shows the $(\sin(2\alpha), \sin(2\beta))$ plots for the LRSM for values of $m_{W_R} = 2.5$, 5, 7.5 and 10 TeV, respectively, with contours at χ^2 which correspond to confidence levels for 1σ and 2σ limits. We do not include the plot for $m_{W_R} = 1\,\mathrm{TeV}$ because 1σ and 2σ contours do not appear in the graph with such a low value of m_{W_R}. The contributions for $m_{W_R} < 7.5\,\mathrm{TeV}$ are very different from those in the SM since $M_{12}^{LR} \simeq M_{12}^{LL}$ in this case. The contours at $m_{W_R} = 10\,\mathrm{TeV}$ should not be directly compared with SM fit contours, which are smaller, since the W_R has "decoupled" here along with its two angles. For the SM fits the $df = 8 - 3 = 5$ rather than the $df = 3$ used for the plots here when W_R is effective.

6.2 $(x_s, \sin(\gamma))$ plots

The third asymmetry angle in B meson systems is defined from $B_s \to D_s^+ K^-$ decays as [23]

$$\sin(\gamma) \equiv \mathrm{Im}\left(\frac{M_{12}^{B_s}}{\left|M_{12}^{B_s}\right|}\frac{A(B_s \longrightarrow D_s^+ K^-)}{A\left(\bar{B}_s \longrightarrow D_s^+ K^-\right)}\right). \tag{6.7}$$

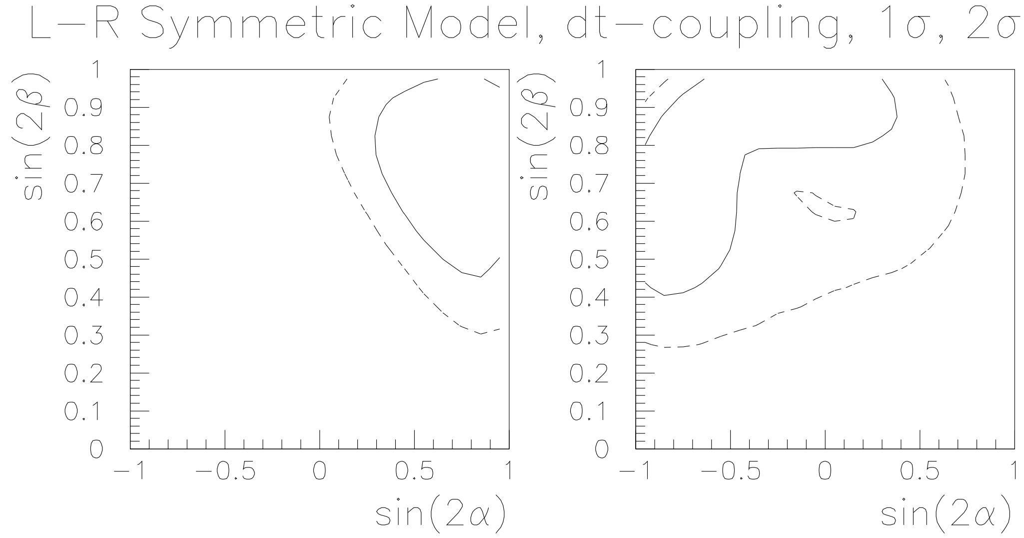
The penguin contribution is absent in both $B_s \to D_s^+ K^-$ and $\bar{B}_s \to D_s^+ K^-$ decays. Again, because of the LRSM contribution, γ as defined above is no longer an angle of the unitarity triangle. x_s is given here by

$$x_s = 1.034 x_d \frac{\left|M_{12}^{B_s}\right|}{\left|M_{12}^{B}\right|}. \tag{6.8}$$

6.2.1 st-coupling

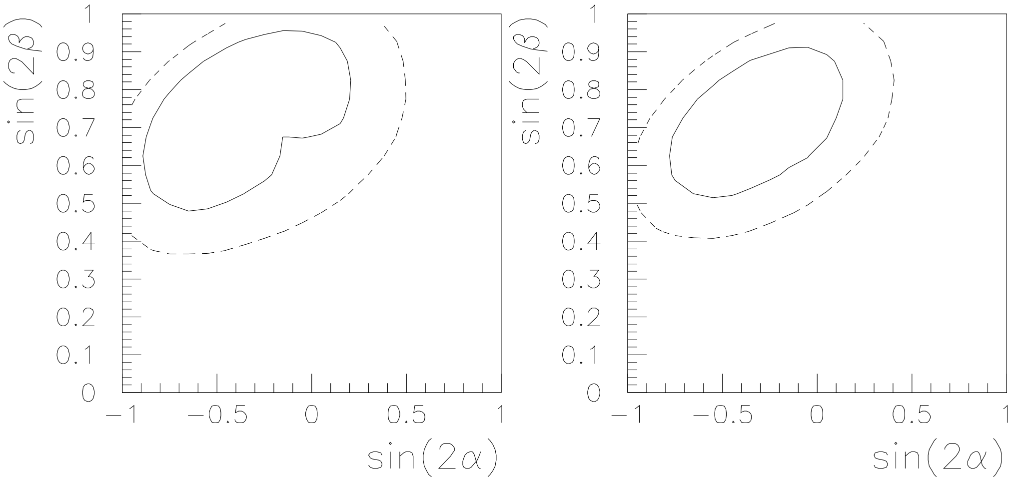
The contributions from W_R to both decay modes vanish since $V_{ub}^{R*} V_{cs}^R = 0$ and $V_{cb}^R V_{us}^{R*} = 0$. Therefore, the CP asymmetry for this decay mode can be simplified as

$$\sin(\gamma) = \mathrm{Im}\left(\frac{\frac{M_{12}^{B_s}}{\left|M_{12}^{B_s}\right|}\frac{V_{ub}^{L*} V_{cs}^L}{V_{cb}^L V_{us}^{L*}}}{\left|\frac{V_{ub}^{L*} V_{cs}^L}{V_{cb}^L V_{us}^{L*}}\right|}\right). \tag{6.9}$$



(a) 2.5 TeV

(b) 5 TeV



(c) 7.5 TeV

(d) 10 TeV

Figure 1: The $(\sin(2\alpha), \sin(2\beta))$ plots for the left-right symmetric model in the case of dt-coupling for values of (a) $m_{W_R} = 2.5$, (b) $m_{W_R} = 5$, (c) $m_{W_R} = 7.5$, and (d) $m_{W_R} = 10\,\text{TeV}$. Contours are at 1σ and 2σ.

The $(x_s, \sin(\gamma))$ plots of the case of st-coupling are shown in figure 2. In the SM, with the same parameters that we used, $\sin(\gamma)$ has a range $0.6 \leq \sin(\gamma) \leq 0.9$ at 1σ, but in the LRSM at low m_{W_R}, $\sin(\gamma)$ can extend completely from -1 to 1 at 1 TeV, and from 0 to 1 at 2.5 TeV. Comparing to the range of x_s in the SM (with the parameters in this paper), which is from 20 to 40 at 1σ, x_s has a range of about 20 to 50 for $m_{W_R} = 2.5\,\text{TeV}$ and greater than 100 for $m_{W_R} = 1.0\,\text{TeV}$. This is because $M_{12}^{B_s}$ is almost double that in the SM, while M_{12}^{B} behaves similarly to that of the SM. This amplification is then reduced as $m_{W_R} \sim 5\,\text{TeV}$, and finally the ratio in x_s, eq. (6.8), approaches the SM result.

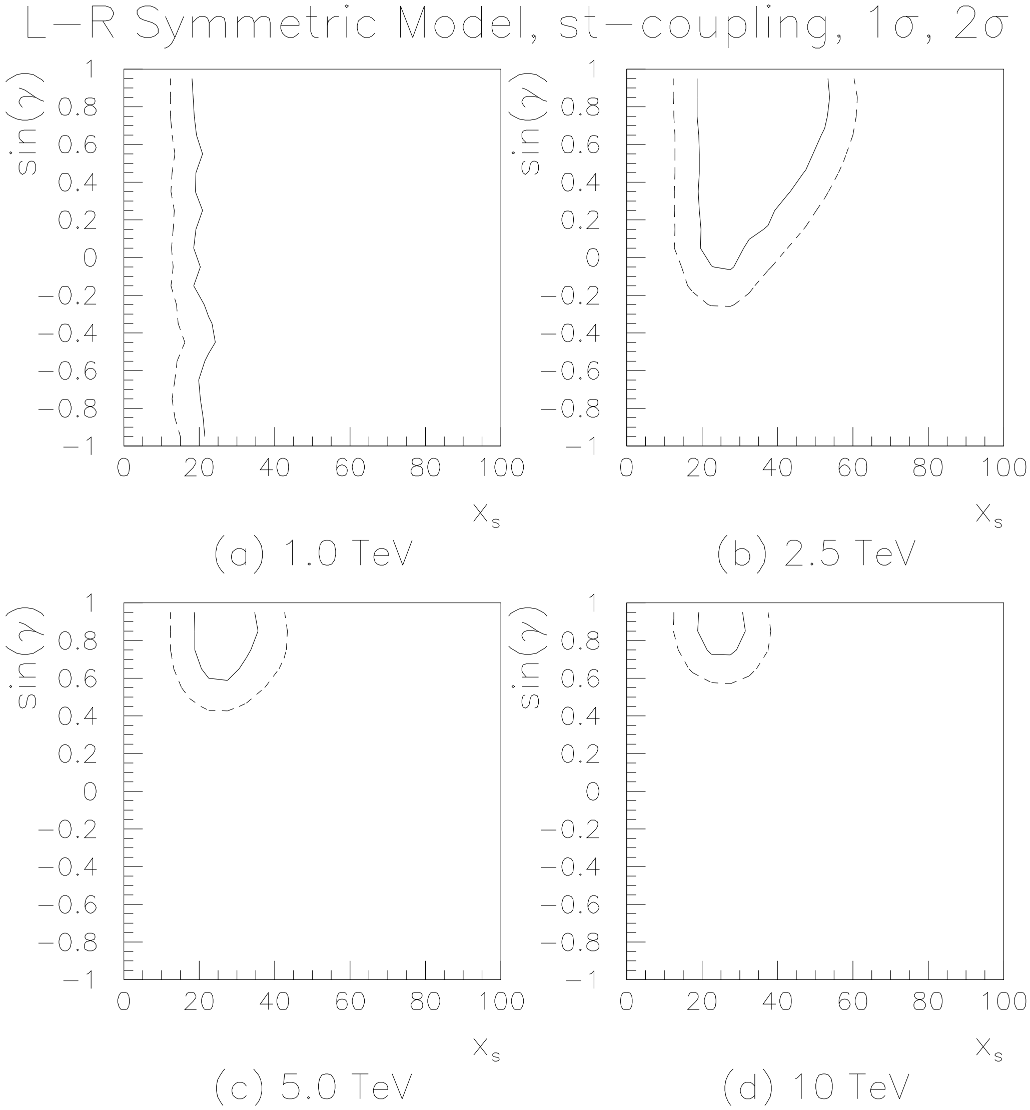


Figure 2: The $(x_s, \sin(\gamma))$ plots for the left-right symmetric model in the case of st-coupling for values of (a) $m_{W_R} = 1.0$, (b) $m_{W_R} = 2.5$, (c) $m_{W_R} = 5.0$, and (d) $m_{W_R} = 10\,\mathrm{TeV}$, with contours at 1σ and 2σ.

6.2.2 dt-coupling

Because W_R can contribute to $\bar{B}_s \to D_s^+ K^-$, in this case we have

$$\sin(\gamma) = \mathrm{Im}\left(\frac{\frac{M_{12}^{B_s}}{\left|M_{12}^{B_s}\right|} \frac{V_{ub}^{L*} V_{cs}^{L}}{V_{cb}^{L} V_{us}^{L*} + x_{LR} V_{cb}^{R} V_{us}^{R*}}}{\left| \frac{V_{ub}^{L*} V_{cs}^{L}}{V_{cb}^{L} V_{us}^{L*} + x_{LR} V_{cb}^{R} V_{us}^{R*}} \right|} \right). \tag{6.10}$$

In the $(x_s, \sin(\gamma))$ plot for the case of dt-coupling, x_s has about the same range as in the SM for $m_{W_R} \geq 2.5\,\mathrm{TeV}$.

6.3 $(x_s, \sin(2\phi_s))$ plots

The asymmetry $\sin(2\phi_s)$ for $B_s - \bar{B}_s$ mixing is given by

$$\sin(2\phi_s) \equiv -\operatorname{Im}\left(\frac{M_{12}^{B_s}}{|M_{12}^{B_s}|}\frac{A\left(\bar{b} \longrightarrow \bar{c}c\bar{s}\right)}{A(b \longrightarrow c\bar{c}s)}\right), \tag{6.11}$$

where ϕ_s is also the small angle in the $b - s$ unitarity triangle in the SM. In the standard model, $\sin(2\phi_s)$ is almost zero (≈ 0.025) in due to the fact that neither the decay process of $\bar{b} \to \bar{c}c\bar{s}$ nor the mixing effect in B_s provides much phase to the asymmetry.

6.3.1 st-coupling

Both W_L and W_R can contribute to $\bar{b} \to \bar{c}c\bar{s}$ in this case. This implies

$$\sin(2\phi_s) = -\operatorname{Im}\left(\frac{M_{12}^{B_s}}{|M_{12}^{B_s}|}\frac{V_{cb}^{L*}V_{cs}^{L} + x_{LR}V_{cb}^{R*}V_{cs}^{R}}{V_{cb}^{L}V_{cs}^{L*} + x_{LR}V_{cb}^{R}V_{cs}^{R*}}\right). \tag{6.12}$$

$M_{12} \simeq M_{12}^{LL} + M_{12}^{LR} + M_{12}^{RR} \simeq M_{12}^{LL} + M_{12}^{LR}$ with $M_{12}^{LL} \simeq M_{12}^{LR}$ as $m_{W_R} \leq 2.5\,\text{TeV}$ for B_s mesons. M_{12}^{LR} is dominated by the (t, t) pair as shown in eq. (4.6), and this term can provide a non-vanishing phase to the asymmetry $\sin(2\phi_s)$. In this case, ϕ_s is no longer an angle in a unitarity triangle, although the measured asymmetry will be called $\sin(2\phi_s)$. The $(x_s, \sin(2\phi_s))$ plots for the case of st-coupling are shown in figure 3. $\sin(2\phi_s)$ can be zero or maximal at ± 1 at the 1σ level for $m_{W_R} \leq 2.5\,\text{TeV}$, and very large even for $5.0\,\text{TeV}$. This distinction from the small SM result at $m_{W_R} = 10\,\text{TeV}$ can provide a dramatic and clean test of new physics.

6.3.2 dt-coupling

There is no W_R contribution in $\bar{b} \to \bar{c}c\bar{s}$ decays. Thus,

$$\sin(2\phi_s) = -\operatorname{Im}\left(\frac{M_{12}^{B_s}}{|M_{12}^{B_s}|}\frac{V_{cb}^{L*}V_{cs}^{L}}{V_{cb}^{L}V_{cs}^{L*}}\right). \tag{6.13}$$

The fact that $M_{12}^{LR} < 10^{-3}M_{12}^{LL}$ makes $M_{12} \simeq M_{12}^{LL}$ for the B_s system. Hence, the asymmetry $\sin(2\phi_s)$ is almost zero and the same as that in the SM [20].

6.4 (ρ, η) plots

We define the (ρ, η) point from the V^L Wolfenstein form as

$$\rho + i\eta = \frac{V_{ub}^{L*}V_{ud}^{L}}{|V_{cb}^{L*}V_{cd}^{L}|}. \tag{6.14}$$

6.4.1 st-coupling

This case is explained in subsection 6.1.1, where for $m_{W_R} \geq 1.0\,\text{TeV}$, $M_{12} \simeq M_{12}^{LL}$, and the plots are about the same as in the SM and are independent of m_{W_R}.

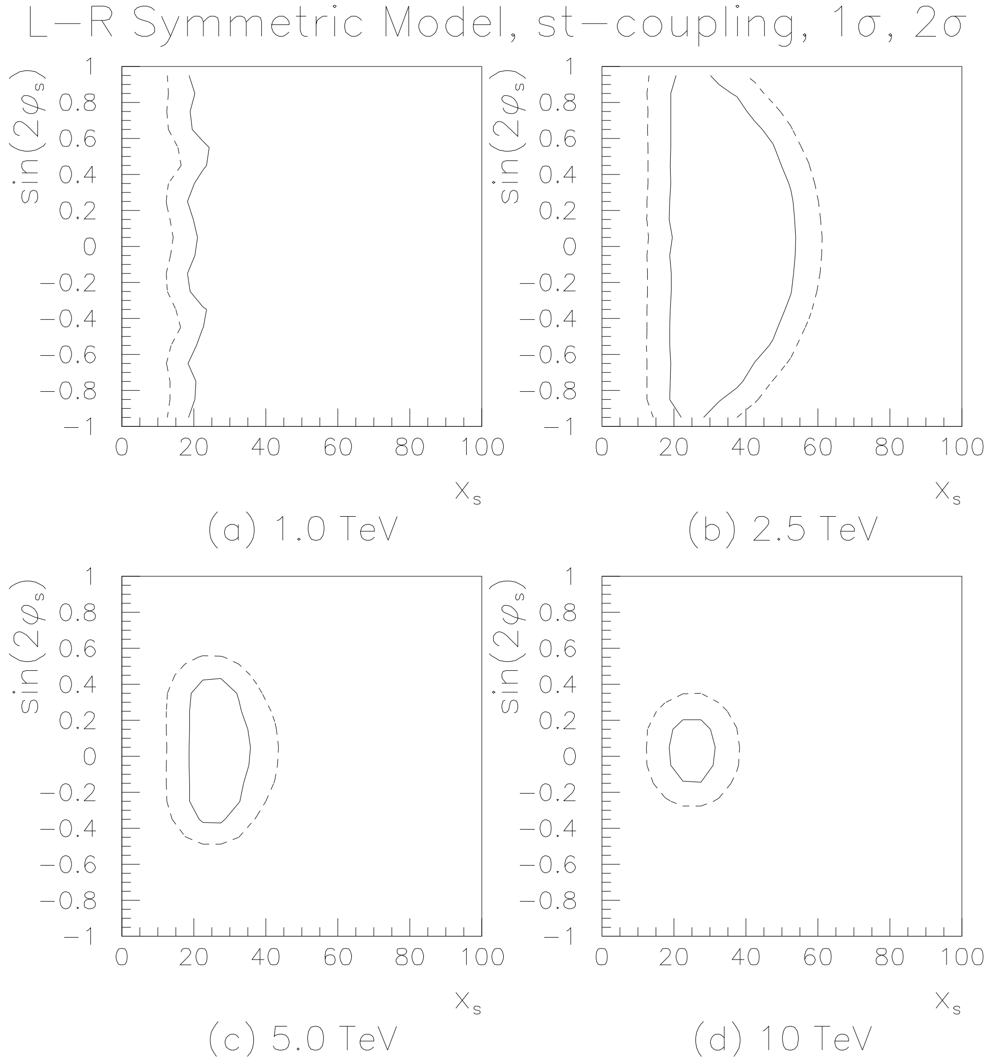


Figure 3: The $(x_s, \sin(2\phi_s))$ plots for the B_s asymmetry $\sin(2\phi_s)$ in the left-right symmetric model in the case of st-coupling for values of (a) $m_{W_R} = 1.0$, (b) $m_{W_R} = 2.5$, (c) $m_{W_R} = 5.0$, and (d) $m_{W_R} = 10\,\text{TeV}$. Contours are at 1σ and 2σ.

6.4.2 dt-coupling

Figure 4 shows the (ρ, η) plots for $m_{W_R} = 2.5, 5.0, 7.5$ and $10.0\,\text{TeV}$. For the lowest value, $m_{W_R} = 2.5\,\text{TeV}$, we see in addition to the SM oval, a second oval region to the left of the SM region at 2σ.

7. Conclusions

In order to provide a reasonable lower limit for the W_R mass within the $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)$ model, the right-handed quark mixing matrices can be parametrized into two forms or cases [5] as shown in eq. (2.3). We suppress the large contributions

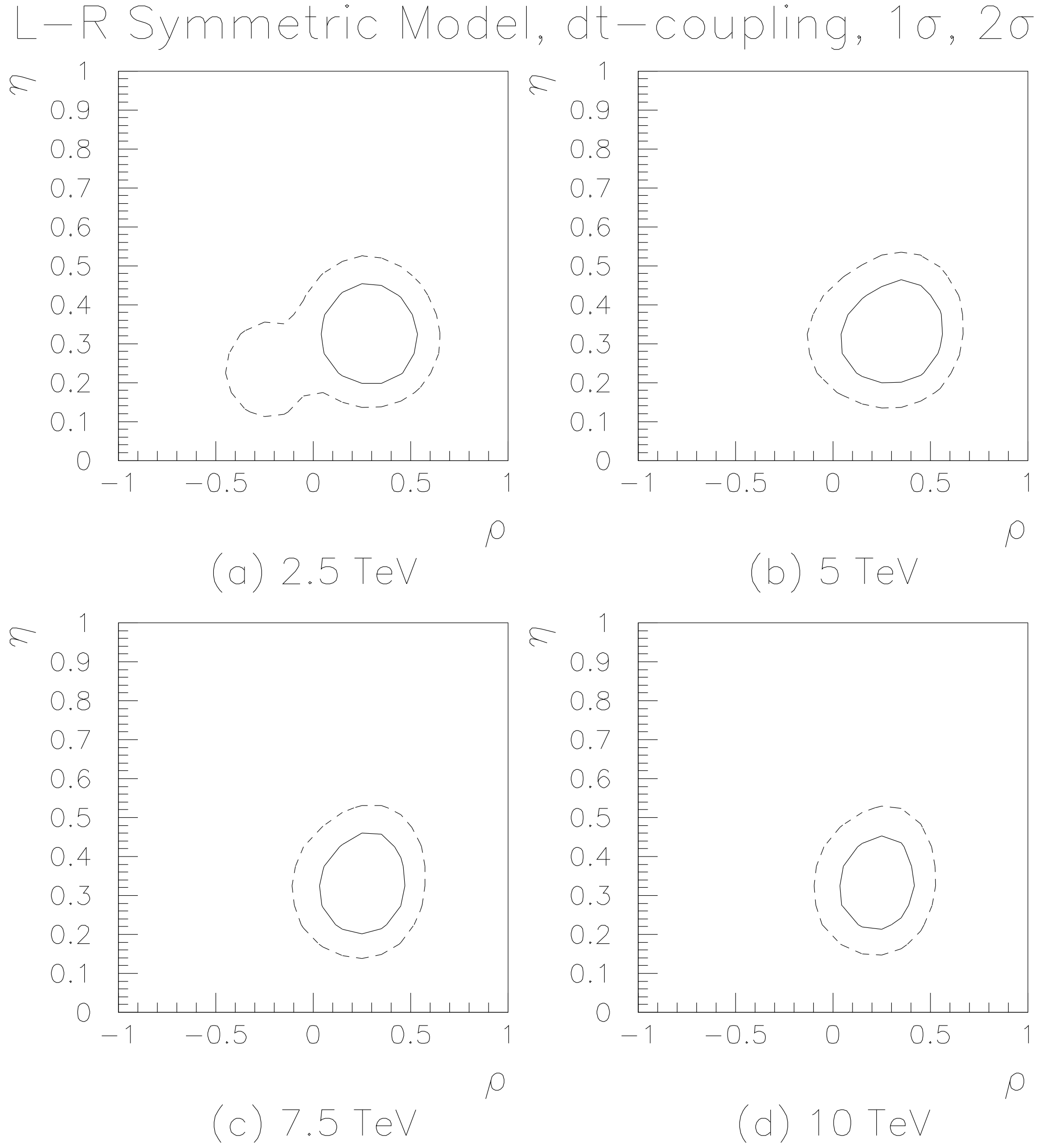


Figure 4: The (ρ, η) plots for the left-right symmetric model in the case of dt-coupling for values of (a) $m_{W_R} = 2.5$, (b) $m_{W_R} = 5$, (c) $m_{W_R} = 7.5$, and (d) $m_{W_R} = 10\,\text{TeV}$, with contours at 1σ and 2σ.

to ϵ_K from the $W_L - W_R$ box diagram by effectively taking some parameters of V^R to vanish, as depicted in eqs. (3.7) and (3.8), so that the quite small experimental value of ϵ_K can be satisfied and W_R can give the most significant effects on CP asymmetries in B decays [14].

The LRSM can contribute importantly to $B_d - \bar{B}_d$ mixing in the case of dt-coupling and to $B_s - \bar{B}_s$ mixing in the case of st-coupling, and give new phases, for $m_{W_R} < 10\,\text{TeV}$. Hence, W_R shows its effects on $(\sin 2\alpha, \sin 2\beta)$ in the case of dt-coupling and on $(x_s, \sin\gamma)$ in the case of st-coupling, for $m_{W_R} < 10\,\text{TeV}$. The CP asymmetries in the LRSM for $m_{W_R} < 10\,\mathrm{TeV}$ that are different from those in the SM are: (i) $\sin(2\phi_s)$ can be maximal at ±1 in the case of st-coupling; (ii) the range for x_s is from 20 to ≥ 100 at the 1σ level in the case of st-coupling; (iii) $\sin\gamma$ has a much larger range in the case of st-coupling; and (iv) $0.3 \leq \sin(2\alpha) \leq 1$ in the case of dt-coupling at $m_{W_R} = 2.5\,\mathrm{TeV}$. If the experimental results are consistent with the SM at 1σ in $(\sin(2\alpha), \sin(2\beta))$ and in $(x_s, \sin(\gamma))$, the LRSM cannot be ruled out, but the limit $m_{W_R} \geq 10\,\mathrm{TeV}$ will be established. What is striking is that the asymmetry $\sin(2\phi_s)$ for $B_s - \bar{B}_s$ mixing is clearly far from zero at the 1σ level even for $m_{W_R} \simeq 10\,\mathrm{TeV}$ in the case of st-coupling, as shown in figure 3. This difference from the SM can provide a clean test of new physics.

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