$W_R$ Effects on $CP$ Asymmetries in $B$ Meson Decays

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June 1997

Submitted to

*Physical Review D*
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This work was supported by U.S. Department of Energy under Contract Nos. DE-AC03-76SF00098 and DE-FG0391ER04679.
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Abstract

After we have fine-tuned the right-handed CKM matrix to satisfy the bounds for $CP$ violation $\epsilon_K$ in $K$ meson systems, the right-handed charged current gauge boson $W_R$ is shown to substantially affect $CP$ asymmetries in $B$ systems. The joint $\chi^2$ analysis is applied to CKM experiments and to $B - \bar{B}$ mixing to constrain the standard CKM and the right-handed CKM matrix elements. In $(\sin(2\alpha), \sin(2\beta))$, $(x_z, \sin(\gamma))$, and $(x_z, A_{B_s})$ plots in the presence of the $W_R$ boson, we find certain regions that can distinguish this model from the standard model.

PACS numbers: 12.15.Cc, 13.20.Jf, 14.80.Dq
I. 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 are under construction at SLAC and KEK. They will measure the $C\bar{P}$ violating asymmetries in the decays of $B$ mesons and provide a test of the SM explanation of $C\bar{P}$ violation. The goal of this paper is to examine the possible effects of a right handed boson $W_R$ on the determinations of $C\bar{P}$ violating decay asymmetries.

II. 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 $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, where the left-handed fermions transform as doublets under $SU(2)_L$ and as singlet under $SU(2)_R$, with the situation reversed for the right-handed fermions [4]. The addition of a new $SU(2)_R$ to the gauge group implies the existence of three new gauge bosons: two charged and one neutral.

The charged right-handed gauge bosons (denoted by $W^\pm_R$) 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 $W^\pm_L$ and $Z_1$ bosons. The charged current weak interactions can be written as (suppressing the generation mixing)
\[ L = \frac{g}{\sqrt{2}}(\bar{u}_L \gamma_\mu d_L + \bar{u}_L \gamma_\mu e_L)W_L^+ + \frac{g}{\sqrt{2}}(\bar{u}_R \gamma_\mu d_R + \bar{u}_R \gamma_\mu e_R)W_R^+ + g^2 \kappa \kappa' W_L^+ W_R^- + \text{H.C.} \]  

(1)

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 \( SU(2)_L \times SU(2)_R \times U(1) \) 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 [5]

\[
V^L = \begin{bmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{bmatrix}
\]

(2)

On the other hand, Langacker and Sankar have made a detailed analysis on \( W_R \) mass limits, and conclude that the lower limit of the \( W_R \) mass can be reduced by taking either of the following forms [6] of \( V^R \)

\[
V^R_I = \begin{bmatrix}
e^{i\omega} & 0 & 0 \\
0 & ce^{i\xi} & se^{i\sigma} \\
0 & se^{i\phi} & ce^{i\chi}
\end{bmatrix}, \quad V^R_{II} = \begin{bmatrix}
0 & e^{i\omega} & 0 \\
e^{i\xi} & 0 & se^{i\sigma} \\
se^{i\phi} & 0 & ce^{i\chi}
\end{bmatrix}, \quad (3)
\]

where \( s = \sin \theta \) and \( c = \cos \theta \) \((0 \leq \theta \leq 90^\circ)\), along with the unitarity condition \( \xi - \sigma = \phi - \chi + \pi \). The former type will be called case I and the latter case II in the following discussion.

**III. CP VIOLATION IN K MESON SYSTEMS**

The CP violation parameter \( \epsilon_K \) 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 

\[ \epsilon_K \approx \text{Im} < K^0 | H(\Delta S = 2) | \bar{K}^0 > / \sqrt{2} \Delta m_K \]  

where \( H(\Delta S = 2) = H^{LL} + H^{RR} + H^{LR} \) is the Hamiltonian from the box diagrams named above. The \( H^{LL} \) contribution is [7]
\[ \epsilon_K = \frac{G_F^2 f_K^2 B_k m_K m_{W_R}^2}{12\sqrt{2}\pi^2 \Delta m_K} \left[ \eta_{cc} S(x_c) I_{cc} + \eta_{tt} S(x_t) I_{tt} + 2\eta_{ct} S(x_c, x_t) I_{ct} \right], \]

where \( I_{ij} = \text{Im}(V_{id}^* V_{is} V_{jd}^* V_{js}) \), and the phase space factors are

\[ S(x) = x \left[ \frac{1}{4} + \frac{9}{4(1-x)} - \frac{3}{2(1-x)^2} \right] - \frac{3}{2} \left( \frac{x}{1-x} \right)^3 \ln x, \]

\[ S(x_c, x_t) = x_c \left[ \ln \frac{x_t}{x_c} - \frac{x_t}{4(1-x_t)} (1 + \frac{x_t}{1-x_t} \ln x_t) \right], \]

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 [8].

The two \( W_R \) part \( H^{RR} \) gives no contribution due to the factor \( I_{ij} \) vanishing for both cases of \( V^R \) as shown in eq. (3).

The third part \( H^{LR} \) is [9]

\[ H^{LR} = \frac{2G_F^2 m_{W_L}^2}{\pi^2} \beta \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL} (\bar{d}_R s_L) (\bar{d}_L s_R) \frac{\sqrt{x_i x_j}}{4} \]

\[ [(4\eta_{i1}^{(1)} + \eta_{i2}^{(2)} x_i x_j \beta) I_1(x_i, x_j, \beta) - (\eta_{i1}^{(3)} + \eta_{i2}^{(4)} \beta) I_2(x_i, x_j, \beta)], \]

where \( i \leq j \).

\[ I_1(x_i, x_j, \beta) = \frac{x_i \ln x_i}{(1-x_i)(1-x_i \beta)} + (i \leftrightarrow j) - \frac{\beta \ln \beta}{(1-\beta)(1-x_i \beta)(1-x_j \beta)}, \]

\[ I_2(x_i, x_j, \beta) = \frac{x_i^2 \ln x_i}{(1-x_i)(1-x_i \beta)(x_i-x_j)} + (i \leftrightarrow j) - \frac{\ln \beta}{(1-\beta)(1-x_i \beta)(1-x_j \beta)}. \]

The contribution to \( \epsilon_K \) from \( H^{LR} \) only comes from the following combinations of quark mixing elements surviving in \( \lambda_i^{LR} \lambda_j^{RL} \): for case I

\( (cu \text{ pair}) : \lambda^2 c \sin(\omega - \xi) \)

\( (tu \text{ pair}) : A\lambda^4 [1 - \rho] \sin(\phi - \omega) + \eta \cos(\phi - \omega)]; \]

and for case II

\( (uc \text{ pair}) : (1 - \frac{\lambda^2}{2})^2 c \sin(\omega - \xi) \)

\( (ut \text{ pair}) : A\lambda^2 (1 - \frac{\lambda^2}{2}) \sin(\omega - \phi). \)
Since the experimental value of $\epsilon_K = (2.28 \pm 0.02) \times 10^{-3}$ is quite small, we will adjust the parameters in $V_R$ so that no contribution to $\epsilon_K$ will come from $H^{LR}$. This is accomplished by various conditions [10] in the two cases. For case I

$$\sin(\omega - \xi) = 0 \quad \text{and} \quad \tan(\omega - \phi) = \frac{\eta}{(1 - \rho)}.$$  

(14)

In this case, using the unitarity relation also, we vary three $V_f^R$ variables: $s$, $\omega$, and $\sigma$. For case II

$$c = 0 \quad \text{and} \quad \sin(\omega - \phi) = 0.$$  

(15)

In this case we only vary two variable in $V_f^R$: $\omega$ and $\sigma$. Having done this, we still see some extra effects of $W_R$ on $B - \bar{B}$ mixing and $CP$ violation asymmetries.

IV. $B^0 - \bar{B}^0$ MIXING

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

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

(16)

where $q = d$ or $s$, and $M_{12}$ is the dispersive part of the mixing matrix element, i.e., $M_{12} - \frac{i}{2} \Gamma_{12} = \langle B^0|H(\Delta B = 2)|\bar{B}^0 >$. 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

$$M_{12} = M_{12}^{LL} + M_{12}^{RR} + M_{12}^{LR},$$  

(17)

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 $M_{12}^{LL}$ is

$$M_{12}^{LL} = \frac{G_F^2}{12\pi^2} m_B m_{W_L}^2 (f_{B}^2 B_B) \eta_t S(x_t)(V_q^{L*}V_{tb}^{L})^2$$  

(18)

where $S(x_t)$ is defined in eq. (5). The evaluation of the hadronically uncertain $f_B^2 B_B$ has been the subject of much work, which is summarized in Ref. [11]. We will use
\[
\frac{f_{B_d} B_{B_d}^{1/2}}{2} = 200 \pm 40 \text{ MeV and } \frac{f_{B_s} B_{B_s}^{1/2}}{2} = 230 \pm 40 \text{ MeV}
\]

from the scaling law and recent lattice calculations.

The element \(M_{12}^{RR}\) is given by

\[
M_{12}^{RR} = \frac{G_F^2}{12\pi^2} m_B m_W^2 \eta_{tt} X(x_t) \beta^2 (V_{tq}^R V_{tb}^R)^2.
\]

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

The matrix element \(M_{12}^{LR}\) is

\[
M_{12}^{LR} = \frac{G_F^2}{2\pi^2} m_B (f_B^2 f_B) \left( \frac{m_B}{m_b} \right)^2 m_W^2 \beta \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL}
\]

\[
\frac{\sqrt{x_i x_j}}{4} \left[ \left( 4 \eta_{ij}^{(1)} x_i x_j \beta I_1(x_i, x_j, \beta) - (\eta_{ij}^{(3)} + \eta_{ij}^{(4)} \beta) I_2(x_i, x_j, \beta) \right) \right],
\]

where \(\lambda_i^{LR} = V_{tq}^L \eta_{ib}^R, \lambda_j^{RL} = V_{tb}^L \eta_{ib}^R\), and \(I_1\) and \(I_2\) are defined in Eqs. (8) and (9).

The contributions of the nine different combinations within Eq. (21) are dominated by \((t, t), (t, c), (c, t)\) and \((u, t)\) pairs, for which the values of the large square bracket as \(m_{W_R} = 1\) TeV are \(11.9, 4.6 \times 10^{-2}, 5.0 \times 10^{-2}\) and \(0.80 \times 10^{-2}\), respectively, the ratios mainly due to the quark mass factors \(\sqrt{x_i x_j}\). All of the remaining terms are less than \(10^{-3}\).

### A. \(B_d - \bar{B}_d\) mixing

#### 1. Case I

In the matrix element \(M_{12}^{LR}\) of Eq. (21) only two terms from \((c, u)\) and \((t, u)\) pairs will survive in case I because of the factor \(\lambda_i^{LR} \lambda_j^{RL}\). One finds that \(M_{12}^{LR} \ll M_{12}^{LL}\) 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.
2. Case II

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

\[\text{B. } B_s - \bar{B}_s \text{ mixing}\]

1. Case I

The effect from two \(W_R\) exchanges appears here. \(M^{RR}_{12} \ll M^{LL}_{12}\) 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 \(M^{LR}_{12}\) in case I, namely those from \((c, c)\), \((c, t)\), \((t, c)\) and \((t, t)\) pairs, and which are dominated by the \((t, t)\) pair. This gives \(M^{LR}_{12} \sim M^{LL}_{12}\) for \(m_{W_R} = 5\) TeV, and \(M^{LR}_{12} \ll M^{LL}_{12}\) by two orders of magnitude for \(m_{W_R} = 10\) TeV. The \(W_R\) contribution to \(B_s - \bar{B}_s\) mixing cannot be ignored in this case.

2. Case II

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

V. JOINT \(\chi^2\) ANALYSIS FOR CKM MATRIX ELEMENTS

We use five present experiments for the determination of the CKM matrix elements angles \(s_{23}, s_{13}\), and \(\delta\). These are those for the matrix elements \(V_{cb}\) and \(V_{ub}\), for \(\epsilon_K\) in the neutral \(K\) system, for \(B_d - \bar{B}_d\) mixing \((x_d)\), and at LEP for the lower bound [12] on \(x_s\). The semi-leptonic decays only constrain the elements of \(V^L\) since we assume that the right handed neutrinos are heavier than the \(b\) quark. We therefore take \(\lambda\) as fixed, since the \(W_R\) do
not affect its determination, and since its small variation does not affect the other experiments. For making projected experimental plots for pairs of experiments \((\sin(2\alpha), \sin(2\beta))\), \((x_s, \sin(\gamma))\), or \((x_s, A_B)\), 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 \(20 \times 20\) bin coverage. For \((\sin(2\alpha), \sin(2\beta))\), these are close to those for the \(B\) factory from a single channel. Counting degrees of freedom, we have for case I \(\text{df} = 7\) experiments - 3 SM angles - 3 LR angles = 1 df. For case II we have \(\text{df} = 7\) experiments - 3 SM angles - 2 LR angles = 2 df.

We produce the maximum likelihood correlation plots for \((\sin(2\alpha), \sin(2\beta))\), and for \((x_s, \sin(\gamma))\). For each possible bin with given values for these pairs, we search for the lowest \(\chi^2\) in the data sets of the five or six 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 \(\chi^2\) in these plots corresponding to given confidence levels [13].

We also investigated the maximum likelihood correlation plots for \((\rho, \eta)\), and found that they are almost the same as the SM in both cases for \(V^R\) since \(\rho\) and \(\eta\) are SM or \(V^L\) parameters.

VI. CP ASYMMETRIES IN B^0 DECAYS

A. \((\sin(2\alpha), \sin(2\beta))\) Plots

The \(CP\) violating asymmetries in \(B\) decays are defined as

\[
\sin(2\beta) \equiv \text{Im} \left( \frac{M^* \cdot V_{cb}^* V_{c2}}{|M_{12}|^2} \right), \quad \text{and} \quad \sin(2\alpha) \equiv \text{Im} \left( \frac{M^* \cdot V_{ud}^* V_{ub}}{|M_{12}|^2} \right). \tag{22}
\]

Because of the non-SM contributions of the LRSM, \(\alpha\) and \(\beta\) no longer represent real angles in the unitarity triangle.

1. Case I

\(M^L_{12} \ll M^L_{12}\) for \(B_d\) mesons, which results in \(M_{12} \simeq M^L_{12}\). This case has almost the same plots as that in standard model.
2. Case II

Fig. 1 shows the \((\sin(2\alpha), \sin(2\beta))\) plots for the LRSM for values of \(m_{W_R} = 1.5, 2.5, 5\) and 10 TeV, respectively, with contours at \(\chi^2\) which correspond to confidence levels for 1\(\sigma\), 2\(\sigma\), and 3\(\sigma\) limits. We do not include the plot for \(m_{W_R} = 1\) TeV because 1\(\sigma\) and 2\(\sigma\) contours do not appear in the graph with such a low value of \(m_{W_R}\). The contributions at \(m_{W_R} < 10\) TeV are very different from those in the SM since \(M^{LR}_{12} \approx M^{LL}_{12}\) in this case. The contours at \(m_{W_R} = 10\) TeV should not be directly compared with SM fit contours since the \(W_R\) has “decoupled” here along with its two angles. For the SM fits the \(\text{df} = 7 - 3 = 4\) rather than the \(\text{df} = 2\) used for the plots here when \(W_R\) is effective.

B. \((x_s, \sin(\gamma))\) Plots

The third asymmetry angle in \(B\) meson systems is defined from \(B_s \rightarrow D_s K\) decays as \cite{14}

\[
\sin(\gamma) \equiv \text{Im} \left( \frac{M^{B_s}_{12} V^{*}_{us} V_{cs}}{|M^{B_s}_{12}||V^{*}_{us} V_{cs}|} \right). \tag{23}
\]

Again, due to the LRSM contribution, \(\gamma\) is no longer an angle of the unitarity triangle. \(x_s\) is given here by

\[
x_s = 1.3 x_d \frac{|M^{B_s}_{12}|}{|M^{B_s}_{12}|}. \tag{24}
\]

1. Case I

Comparing to the range of \(x_s\) in the SM which is from 11 to 24 at 1\(\sigma\), \(x_s\) has a range of about twice those values and is larger than 25 for \(m_{W_R} = 1 \sim 5\) TeV. This is because \(M^{B_s}_{12}\) is almost double that in the SM, while \(M^{B}_{12}\) behaves similarly to that of the SM. This amplification is then reduced as \(m_{W_R}\) becomes larger, and finally the ratio for \(x_s\) approaches the SM result. The \((x_s, \sin(\gamma))\) plots of case I are shown in Fig. 2.
2. Case II

In Fig. 3 is shown the \((x_s, \sin(\gamma))\) plot for case II. \(x_s\) starts from around 5 for \(m_{W_R} = 1.5\) TeV, and finally also becomes similar to the SM for \(m_{W_R} = 10\) TeV. The reason is that \(M_{12}^{LR}\) is comparable to \(M_{12}^{LL}\) in \(B_d\) mesons for \(m_{W_R} \leq 5\) TeV and \(M_{12}^{B_s}\) has the same value as in the SM. This makes \(x_s\) smaller than that in the SM.

C. \((x_s, A_{B_s})\) Plots

The asymmetry \(A_{B_s}\) for \(B_s - \bar{B}_s\) mixing is defined by

\[
A_{B_s} = \text{Im} \left( \frac{M_{12}^{B_s} V_{cb}^* V_{cs}}{|M_{12}^{B_s}| |V_{cb} V_{cs}|} \right) \tag{25}
\]

It is almost zero (< 0.025) in the standard model due to the fact that both the decay process of \(b \rightarrow c\bar{c}s\) and the mixing effect in \(B_s\) do not provide any phase to \(A_{B_s}\).

1. Case I

\(M_{12} \simeq M_{12}^{LL} + M_{12}^{LR} + M_{12}^{RR} \simeq M_{12}^{LL} + M_{12}^{LR}\) with \(M_{12}^{LL} \simeq M_{12}^{LR}\) for \(B_s\) mesons. \(M_{12}^{LR}\) is dominated by the \((t,t)\) pair as shown in Eq. (21), and this term can provide a non-vanishing phase to the asymmetry \(A_{B_s}\). The \((x_s, A_{B_s})\) plots for case I are shown in Fig. 4. \(A_{B_s}\) is clearly far from zero at the 1\(\sigma\) level. This distinction from the SM can provide a clean test of new physics.

2. Case II

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 \(A_{B_s}\) is almost zero and the same as that in the SM.
ACKNOWLEDGMENTS

H.Y. is grateful for the generous supports from the National Science Council of the Republic of China, and the hospitality of LBL and UC Irvine. This research was supported in part by the U. S. Department of Energy under Contract No. DE-FG0391ER40679.
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FIGURES

FIG. 1. The \((\sin(2\alpha), \sin(2\beta))\) plots for the left-right symmetric model in case II for values of (a) \(m_{WR} = 1.5\), (b) \(m_{WR} = 2.5\), (c) \(m_{WR} = 5\), and (d) \(m_{WR} = 10\) TeV. Contours are at 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\).

FIG. 2. The \((x_5, \sin(\gamma))\) plots for the left-right symmetric model in case I for values of (a) \(m_{WR} = 1\), (b) \(m_{WR} = 2.5\), (c) \(m_{WR} = 5\), and (d) \(m_{WR} = 10\) TeV, with contours at 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\).

FIG. 3. The \((x_5, \sin(\gamma))\) plots for the left-right symmetric model in case II for values of (a) \(m_{WR} = 1.5\), (b) \(m_{WR} = 2.5\), (c) \(m_{WR} = 5\), and (d) \(m_{WR} = 10\) TeV, with contours at 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\).

FIG. 4. The \((x_5, A_{B_s})\) plots for the \(B_s\) asymmetry \(A_{B_s}\) in the left-right symmetric model in case I for values of (a) \(m_{WR} = 1\), (b) \(m_{WR} = 2.5\), (c) \(m_{WR} = 5\), and (d) \(m_{WR} = 10\) TeV. Contours are at 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\).
L–R Symmetric Model, Case II, 1σ, 2σ, 3σ

(a) 1.5 TeV

(b) 2.5 TeV

(c) 5 TeV

(d) 10 TeV

\( \sin(2\beta) \)

\( \sin(2\alpha) \)
L–R Symmetric Model, Case I, 1σ, 2σ, 3σ

(a) 1 TeV

(b) 2.5 TeV

(c) 5 TeV

(d) 10 TeV
L–R Symmetric Model, Case II, $1\sigma$, $2\sigma$, $3\sigma$

(a) 1.5 TeV

(b) 2.5 TeV

(c) 5 TeV

(d) 10 TeV
L–R Symmetric Model, Case I, $1\sigma$, $2\sigma$, $3\sigma$

(a) 1 TeV

(b) 2.5 TeV

(c) 5 TeV

(d) 10 TeV
