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Abstract

After we have fine-tuned 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. The joint χ^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 $(\sin(2\alpha), \sin(2\beta))$, $(x_s, \sin(\gamma))$, and (x_s, 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.

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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 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.

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 $W_R^{\pm}$) 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)

$$L = \frac{g}{\sqrt{2}}(\bar{u}_L\gamma_\mu d_L + \bar{\nu}_L\gamma_\mu e_L)W_L^+ + \frac{g}{\sqrt{2}}(\bar{u}_R\gamma_\mu d_R + \bar{\nu}_R\gamma_\mu e_R)W_R^+ + g^2\kappa\kappa' W_L^- W_R^+ + \text{H.C.} \tag{1}$$

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]

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

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

$$V_I^R = \begin{bmatrix} e^{i\omega} & 0 & 0 \\ 0 & ce^{i\xi} & se^{i\sigma} \\ 0 & se^{i\phi} & ce^{i\chi} \end{bmatrix}, \quad V_{II}^R = \begin{bmatrix} 0 & e^{i\omega} & 0 \\ ce^{i\xi} & 0 & se^{i\sigma} \\ se^{i\phi} & 0 & ce^{i\chi} \end{bmatrix}, \tag{3}$$

where $s = \sin\theta$ and $c = \cos\theta$ ($0 \le \theta \le 90^o$), 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 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 $\epsilon_K \approx \text{Im} < K^0|H(\Delta S = 2)|\bar{K}^0 > /\sqrt{2}\Delta m_K$ 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]

$$\epsilon_K = \frac{G_F^2 f_K^2 B_K m_K m_{W_L}^2}{12\sqrt{2}\pi^2 \Delta m_K}[\eta_{cc} S(x_c) I_{cc} + \eta_{tt} S(x_t) I_{tt} + 2\eta_{ct} S(x_c, x_t) I_{ct}], \tag{4}$$

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

$$S(x) = x\left[\frac{1}{4} + \frac{9}{4(1-x)} - \frac{3}{2(1-x)^2}\right] - \frac{3}{2}(\frac{x}{1-x})^3 \ln x, \tag{5}$$

$$S(x_c, x_t) = x_c\left[\ln\frac{x_t}{x_c} - \frac{x_t}{4(1-x_t)}(1 + \frac{x_t}{1-x_t}\ln x_t)\right], \tag{6}$$

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]

$$H^{LR} = \frac{2G_F^2}{\pi^2} m_{W_L}^2 \beta \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL}(\bar{d}_R s_L)(\bar{d}_L s_R)\frac{\sqrt{x_i x_j}}{4} \tag{7}$$
$$[(4\eta_{ij}^{(1)} + \eta_{ij}^{(2)} x_i x_j \beta) I_1(x_i, x_j, \beta) - (\eta_{ij}^{(3)} + \eta_{ij}^{(4)}\beta) I_2(x_i, x_j, \beta)],$$

where $\lambda_i^{LR} = V_{id}^{L*} V_{is}^R$, $\beta = (m_{W_L}/m_{W_R})^2$, and

$$I_1(x_i, x_j, \beta) = \frac{x_i \ln x_i}{(1-x_i)(1-x_i\beta)(x_i - x_j)} + (i \leftrightarrow j) - \frac{\beta \ln \beta}{(1-\beta)(1-x_i\beta)(1-x_j\beta)}, \tag{8}$$

$$I_2(x_i, x_j, \beta) = \frac{x_i^2 \ln x_i}{(1-x_i)(1-x_i\beta)(x_i - x_j)} + (i \leftrightarrow j) - \frac{\ln \beta}{(1-\beta)(1-x_i\beta)(1-x_j\beta)}. \tag{9}$$

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 case I

$$(\text{cu pair}) : \lambda^2 c \sin(\omega - \xi) \tag{10}$$

$$(\text{tu pair}) : A\lambda^4[(1-\rho)\sin(\phi - \omega) + \eta\cos(\phi - \omega)]; \tag{11}$$

and for case II

$$(\text{uc pair}) : (1 - \frac{\lambda^2}{2})^2 c \sin(\omega - \xi) \tag{12}$$

$$(\text{ut pair}) : As\lambda^2(1 - \frac{\lambda^2}{2})\sin(\omega - \phi). \tag{13}$$

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 ϵ_K will come from H^{LR}. This is accomplished by various conditions [10] in the two cases. For case I

$$\sin(\omega - \xi) = 0 \quad \text{and} \qquad \tan(\omega - \phi) = \frac{\eta}{(1-\rho)}. \tag{14}$$

In this case, using the unitarity relation also, we vary three V_I^R variables: s, ω, and σ. For case II

$$c = 0 \quad \text{and} \qquad \sin(\omega - \phi) = 0. \tag{15}$$

In this case we only vary two variable in V_{II}^R: ω and σ. 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

$$x_q \equiv \frac{(\Delta M)_{B_q}}{\Gamma} = 2\tau_{B_q}|M_{12}|, \tag{16}$$

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

$$M_{12} = M_{12}^{LL} + M_{12}^{RR} + M_{12}^{LR}, \tag{17}$$

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

$$M_{12}^{LL} = \frac{G_F^2}{12\pi^2} m_B m_{W_L}^2 (f_B^2 B_B) \eta_{tt} S(x_t) (V_{tq}^{L*} V_{tb}^L)^2 \tag{18}$$

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

$$f_{B_d} B_{B_d}^{1/2} = 200 \pm 40 \text{ MeV and } f_{B_s} B_{B_s}^{1/2} = 230 \pm 40 \text{ MeV} \tag{19}$$

from the scaling law and recent lattice calculations.

The element M_{12}^{RR} is given by

$$M_{12}^{RR} = \frac{G_F^2}{12\pi^2} m_B m_{W_L}^2 (f_B^2 B_B) \eta_{tt} S(x_t) \beta^2 (V_{tq}^{R*} V_{tb}^R)^2. \tag{20}$$

It disappears in $B_d - \bar{B}_d$ mixing due to either $V_{td}^R = 0$ 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

$$M_{12}^{LR} = \frac{G_F^2}{2\pi^2} m_B (f_B^2 B_B) (\frac{m_B}{m_b})^2 m_{W_L}^2 \beta \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL} \tag{21}$$
$$\left[\frac{\sqrt{x_i x_j}}{4} [(4\eta_{ij}^{(1)} + \eta_{ij}^{(2)} x_i x_j \beta) I_1(x_i, x_j, \beta) - (\eta_{ij}^{(3)} + \eta_{ij}^{(4)} \beta) I_2(x_i, x_j, \beta)] \right],$$

where $\lambda_i^{LR} = V_{iq}^{L*} V_{ib}^R$, $\lambda_j^{RL} = V_{jq}^{R*} V_{jb}^L$, 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, 4.6×10^{-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}.

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_{12}^{LR} in case II. One obtains $M_{12}^{LR} \sim M_{12}^{LL}$ if $m_{W_R} = 5$ TeV, and $M_{12}^{LR} \leq 10^{-2} M_{12}^{LL}$ if $m_{W_R} = 10$ TeV. The effect from W_R in $B_d - \bar{B}_d$ mixing appears in this case.

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

1. Case I

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 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 $M_{12}^{LR} \sim M_{12}^{LL}$ for $m_{W_R} = 5$ TeV, and $M_{12}^{LR} \ll M_{12}^{LL}$ 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_{12}^{LR} coming from the (c,u) pair in case II, 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.

V. JOINT χ^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 δ. These are those for the matrix elements V_{cb} and V_{ub}, for ϵ_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 therfore take λ 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_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 are close to those for the B factory from a single channel. Counting degrees of freedom, we have for case I df = 7 experiments - 3 SM angles - 3 LR angles = 1 df. For case II we have df = 7 experiments - 3 SM angles - 2 LR angles = 2 df.

We produce the maximum likehood 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 χ^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 χ^2 in these plots corresponding to given confidence levels [13].

We also investigated the maximum likehood correlation plots for (ρ, η), and found that they are almost the same as the SM in both cases for V^R since ρ and η are SM or V^L paremeters.

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

$$\sin(2\beta) \equiv \mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{V_{cb}^* V_{cs}}{V_{cb} V_{cs}^*}\right), \quad \text{and} \quad \sin(2\alpha) \equiv \mathrm{Im}\left(\frac{M_{12}^*}{|M_{12}|}\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right). \tag{22}$$

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

1. Case I

$M_{12}^{LR} \ll M_{12}^{LL}$ for B_d mesons, which results in $M_{12} \simeq M_{12}^{LL}$. 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 χ^2 which correspond to confidence levels for 1σ, 2σ, and 3σ limits. We do not include the plot for $m_{W_R} = 1$ TeV because 1σ and 2σ 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 $M_{12}^{LR} \simeq M_{12}^{LL}$ 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 df = 7 - 3 = 4 rather than the 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 $B_s \to D_s K$ decays as [14]

$$\sin(\gamma) \equiv \mathrm{Im}\left(\frac{M_{12}^{B_s}}{|M_{12}^{B_s}|}\frac{V_{ub}^* V_{cs}}{|V_{ub}V_{cs}|}\right). \tag{23}$$

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

$$x_s = 1.3 x_d \frac{|M_{12}^{B_s}|}{|M_{12}^{B}|}. \tag{24}$$

1. Case I

Comparing to the range of x_s in the SM which is from 11 to 24 at 1σ, 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 $M_{12}^{B_s}$ 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} 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 asmmetry A_{B_s} for $B_s - \bar{B}_s$ mixing is defined by

$$A_{B_s} = \mathrm{Im}\left(\frac{M_{12}^{B_s}}{|M_{12}^{B_s}|}\frac{V_{cb}^* V_{cs}}{|V_{cb}V_{cs}|}\right). \tag{25}$$

It is almost zero (< 0.025) in the standard model due to the fact that both the decay process of $b \to c\bar{c}s$ 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 1σ 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.

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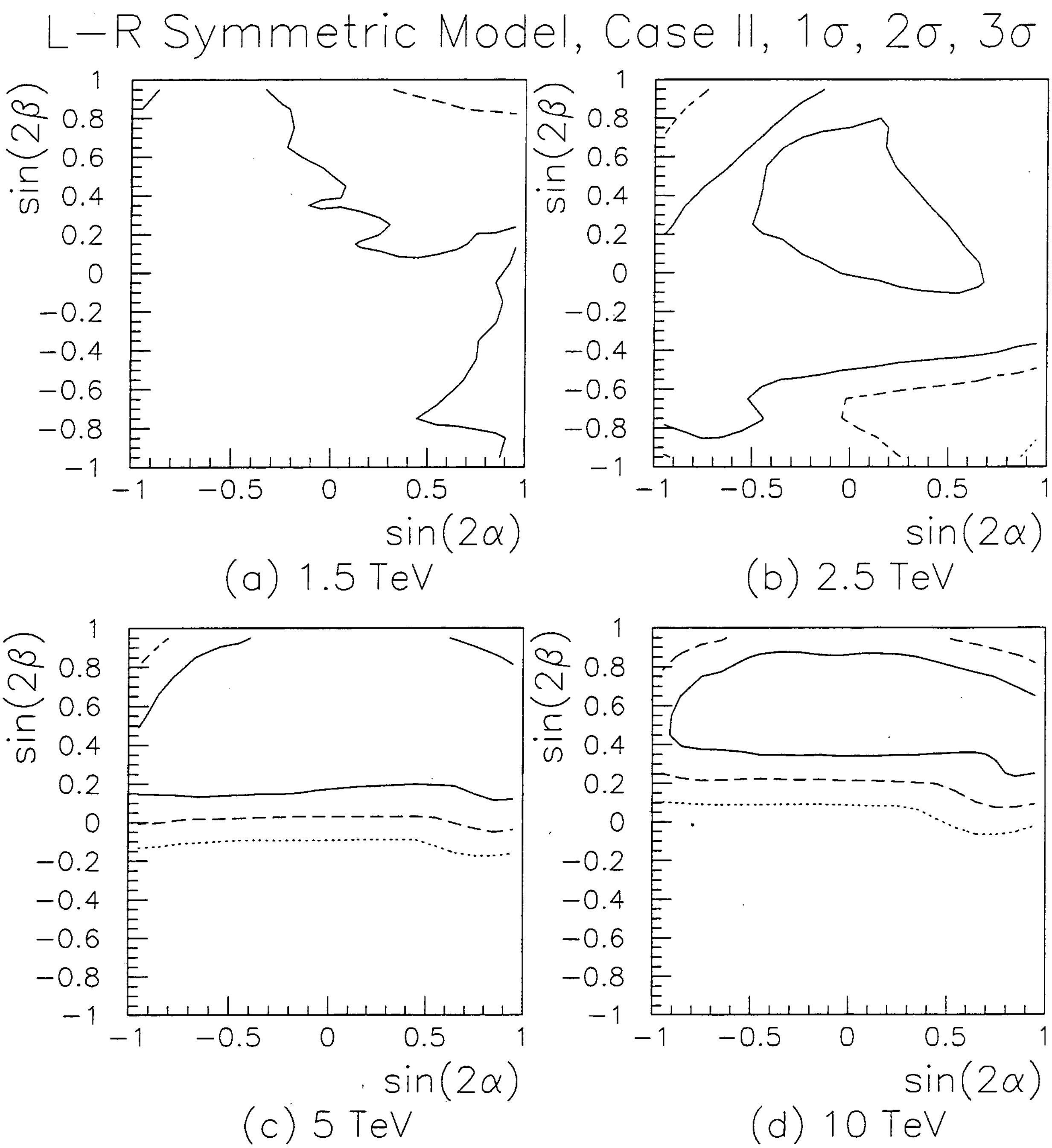
FIGURES

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

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

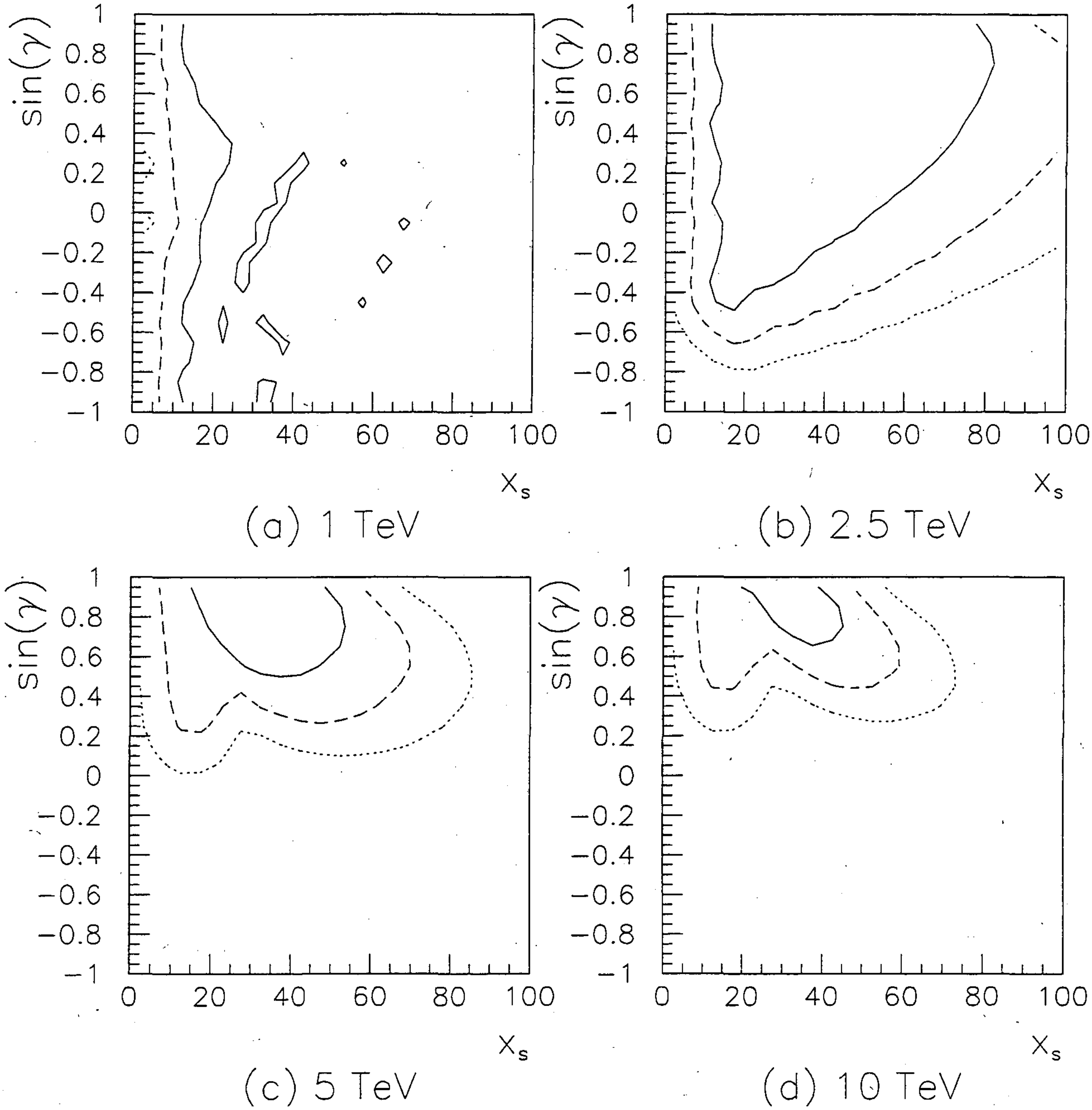
FIG. 3. The $(x_s, \sin(\gamma))$ plots for the left-right symmetric model in case II for values of (a) $m_{W_R} = 1.5$, (b) $m_{W_R} = 2.5$, (c) $m_{W_R} = 5$, and (d) $m_{W_R} = 10$ TeV, with contours at 1σ, 2σ and 3σ.

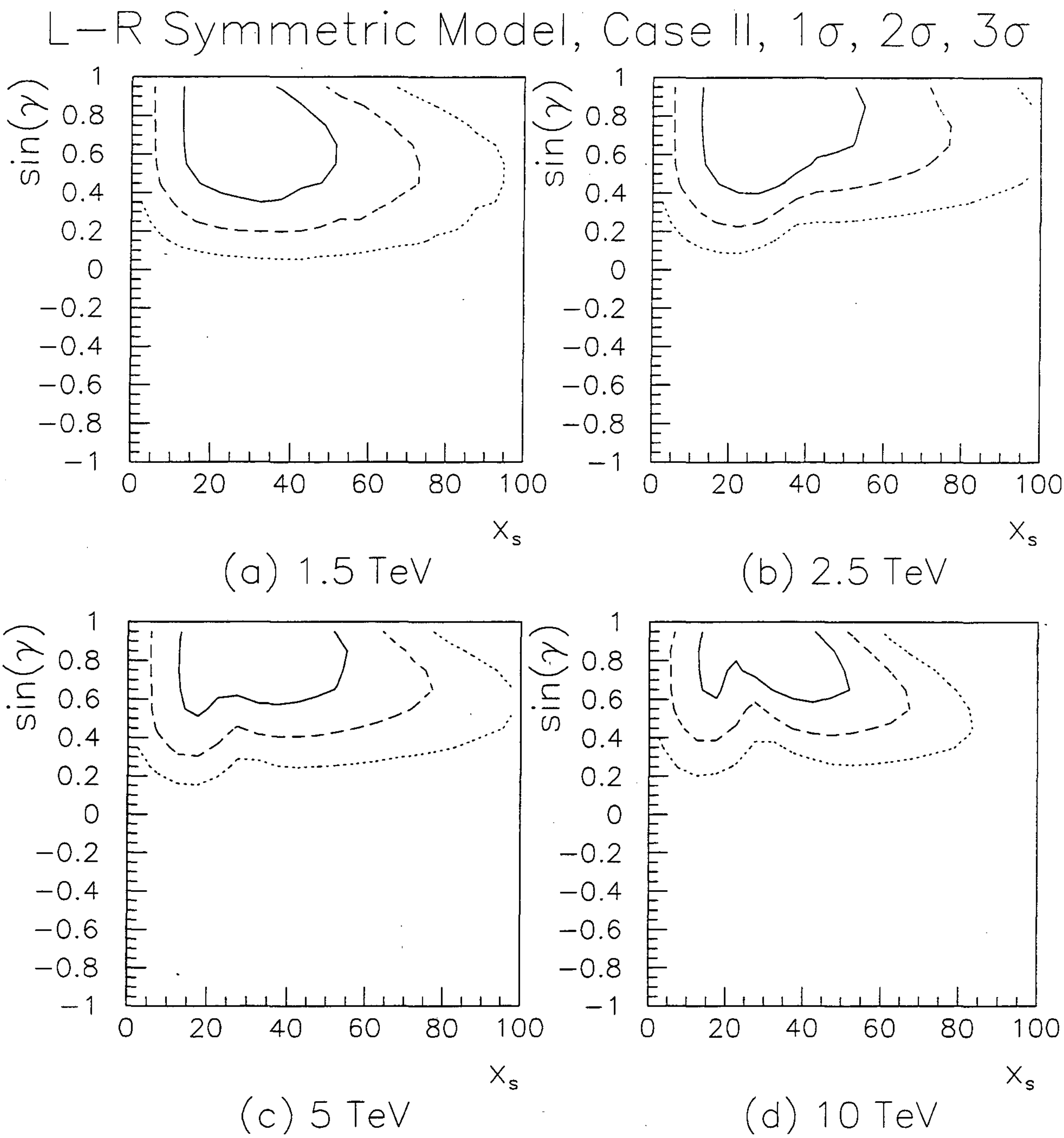
FIG. 4. The (x_s, A_{B_s}) plots for the B_s asymmetry A_{B_s} in the left-right symmetric model in case I for values of (a) $m_{W_R} = 1$, (b) $m_{W_R} = 2.5$, (c) $m_{W_R} = 5$, and (d) $m_{W_R} = 10$ TeV. Contours are at 1σ, 2σ and 3σ.

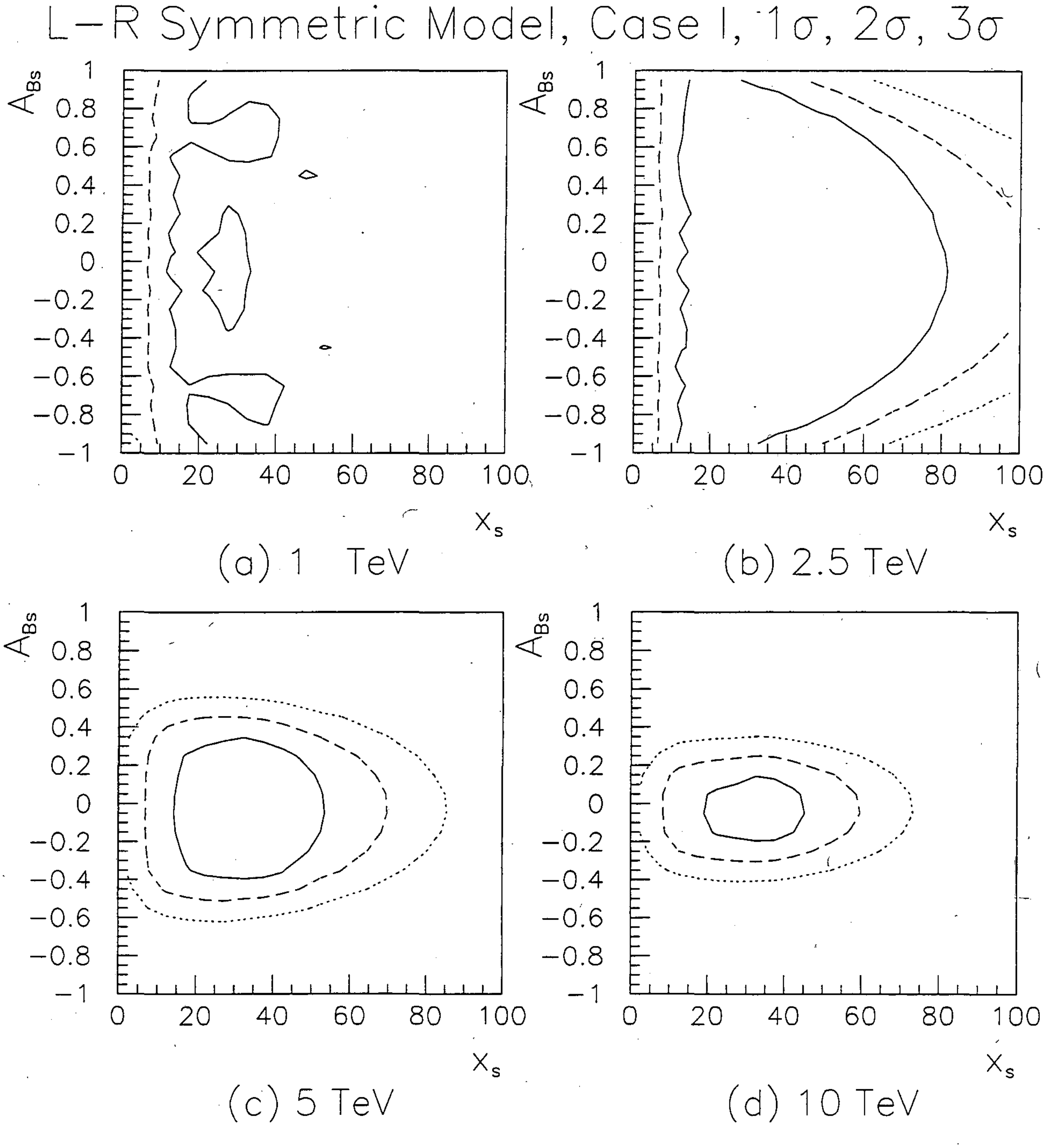


L−R Symmetric Model, Case II, 1σ, 2σ, 3σ
sin(2β)
sin(2α)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−0.5
0.5
(a) 1.5 TeV
(b) 2.5 TeV
(c) 5 TeV
(d) 10 TeV

L−R Symmetric Model, Case I, 1σ, 2σ, 3σ




L–R Symmetric Model, Case II, 1σ, 2σ, 3σ
sin(γ)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
20
40
60
80
100
x_s
(a) 1.5 TeV
(b) 2.5 TeV
(c) 5 TeV
(d) 10 TeV


L−R Symmetric Model, Case I, 1σ, 2σ, 3σ
A_Bs
x_s
(a) 1 TeV
(b) 2.5 TeV
(c) 5 TeV
(d) 10 TeV

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