Right Handed Weak W_R Bosons in $B - \bar{B}$ Mixing and CP Violation Experiments

Dennis Silverman
Department of Physics and Astronomy, University of California, Irvine, CA 92697
W. K. Sze and Herng Yao
Department of Physics, National Taiwan Normal University, Taipei, Taiwan 117

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1 Introduction

- To decide whether the B factories are significantly testing the standard CKM model SM of CP violation, and to determine the "reach" of the B_d and B_s CP violation asymmetries in ruling out "new physics" models, we need several alternate but full physical models for comparison.
- The Left-Right Symmetric Model (LRSM) of Electro-Weak Interactions with W_R bosons coupling to right handed currents, has forms that have not been ruled out by present experiments and is a well motivated model.
- In this poster, forms of the right handed quark mixing matrix are used which avoid present constraints and give new allowed regions to CP violating asymmetries up to W_R masses M_R of 8 TeV.
- The constraints are updated for $\sin 2\beta$ measurements, and new x_s bounds, and results presented in single variable form as a function of M_R.
- More detail is in our preprint hep-ph/0305013.
- A copy of this poster is at http://www.physics.uci.edu/∼silverma/fpcp.ps

2 The LR Symmetric Model: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(2)_R$ has two heavy charged $W_R^{\pm}$ and a Z_0'.

The charged weak current for one generation is

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

Three generations involve quark mixing with the left handed quark mixing matrix V^L being the CKM matrix of the standard model, although its experimental constraints are modified by right-handed contributions. V^R will denote the mixing matrix among the right handed quark currents.

3 The left handed CKM mixing matrix V^L

In Wolfenstein's parameterization

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

The CP violating phases are assigned to the smallest elements $V_{ub} \equiv |V_{ub}|e^{-i\gamma}$ and $V_{td} \equiv |V_{td}|e^{-i\beta}$, and therefore, the phase angles β and γ can be sizable in spite of the tiny intrinsic CP violation. The CP violating parameter can then be taken as the area of the (d-b) unitarity triangle, which is half of Jarlskog's parameter J.

The parameter $\lambda \equiv |V_{us}| = 0.221$ is quite accurately known, and we will disregard its small uncertainty in the analysis.

4 CP Violation in K Mesons in the LRSM

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

where $H(\Delta S = 2)$ is the Hamiltonian from the box diagrams mediated by two W_L, two W_R, or a W_L-W_R pair.

The H^{LL} contribution is

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

The H^{LR} contribution is

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

where $\lambda_i^{LR} = V_{id}^{L*}V_{is}^{R}$, $\beta_R = (M_L/m_R)^2$, and $x_i = m_i^2/M_L^2$. The contribution to ϵ_K from H^{LR} only comes from the surviving terms on $\lambda_i^{LR}\lambda j^{RL}$. The two W_R part H^{RR} gives no contribution due to the factors I_{ij} vanishing for both cases of V^R.

5 Avoiding ϵ_K for Lower W_R Mass

Langacker and Sankar have shown that the lower limit of the W_R mass of 1.6 TeV for manifest LR symmetry, $V^R \equiv V^L$, can be reduced by taking either of the following forms of V^R to avoid LR contributions to ϵ_K

$$V^R_{B_s} = \begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & ce^{i\tau} & se^{i\sigma} \\ 0 & -se^{i\phi} & ce^{i\chi} \end{pmatrix} \end{array}, \quad \text{(Case } B_s\text{)},$$

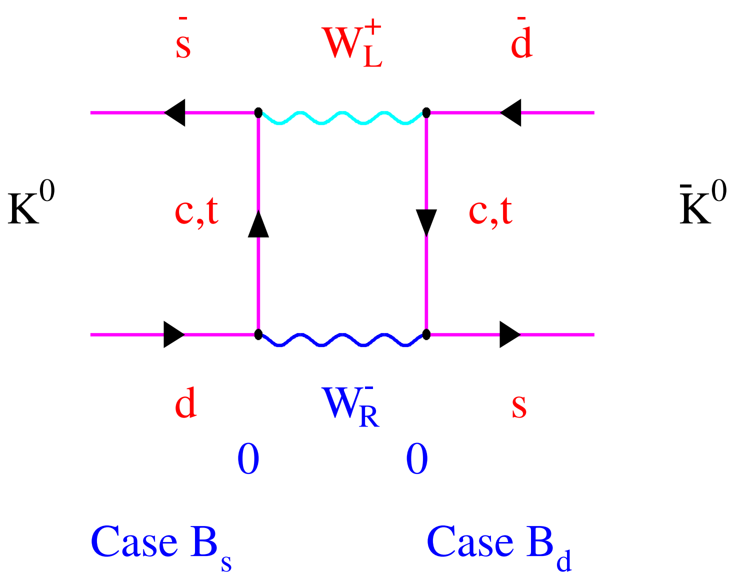
or

$$V^R_{B_d} = \begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 0 & 1 & 0 \\ ce^{i\tau} & 0 & se^{i\sigma} \\ -se^{i\phi} & 0 & ce^{i\chi} \end{pmatrix} \end{array}, \quad \text{(Case } B_d\text{)}.$$

Here $s = \sin\theta$ and $c = \cos\theta$ $(0 \leq \theta \leq 90^\circ)$, and the unitarity condition is

$$\tau - \sigma = \phi - \chi.$$

These regions of parameter space work because they introduce zeroes for couplings of W_R to c and t quarks to either d quarks (Case B_s or st coupling) or to s quarks (Case B_d or dt coupling).



The contribution to ϵ_K from H^{LR} only comes from the surviving terms including u quarks in $\lambda_i^{LR}\lambda j^{RL}$:

$$\begin{array}{lll} \text{Case } B_s & (\text{uc pair}): & -\lambda^2 c \sin\tau \\ & (\text{ut pair}): & -A\lambda^4[(1-\rho)^2+\eta^2]^{1/2} s \sin(\beta+\phi) \end{array}$$

$$\begin{array}{lll} \text{Case } B_d & (\text{uc pair}): & -c\sin\tau \\ & (\text{ut pair}): & -A\lambda^2 s\sin\phi. \end{array}$$

Limiting parameters:

Due to the smallness of $\epsilon_K = (2.28 \pm 0.02) \times 10^{-3}$, the parameters in the V^R cases can be further constrained so that no contribution to ϵ_K will come from H^{LR}. Since there turns out only to be one effective phase in all contributions to B physics, this is not a necessary step and does not further limit the model for larger M_R.

$$\begin{array}{lll} \text{Case } B_s: & \tau \approx 0, \pi & \phi \approx -\beta \bmod \pi \\ \text{Case } B_d: & \tau \approx 0, \pi & \phi \approx 0. \end{array}$$

χ is then fixed by the unitarity condition in terms of the others. There are thus two LR parameters in $V_{B_s}^R$: θ ($s = \sin\theta$) and σ.

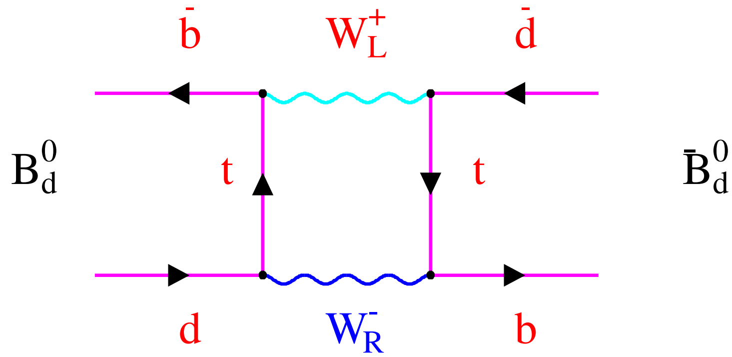
Case B_s:

$$V_{B_s}^R = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & c & se^{i\sigma} \\ 0 & -se^{-i\beta} & ce^{i(\sigma-\beta)} \end{pmatrix} \end{array}.$$

Case B_d:

$$V_{B_d}^R = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 0 & 1 & 0 \\ c & 0 & se^{i\sigma} \\ -s & 0 & ce^{i\sigma} \end{pmatrix} \end{array}.$$

6 $B^0 - \bar{B}^0$ Mixing in the LRSM



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

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 W_R-W_R contributions are

$$M_{q,12}^{RR} = \frac{G_F^2 M_L^2}{12\pi^2}(f_B^2 B_B) m_B \beta_R \eta_{tt} S(x_{tR})(V_{tq}^{R*} V_{tb}^R)^2, \tag{1}$$

where $x_{tR} = (m_t/M_R)^2$. In case B_s this vanishes in B_d mixing, but not in B_s mixing. In case B_d this contributes to B_d mixing, but not to B_s mixing.

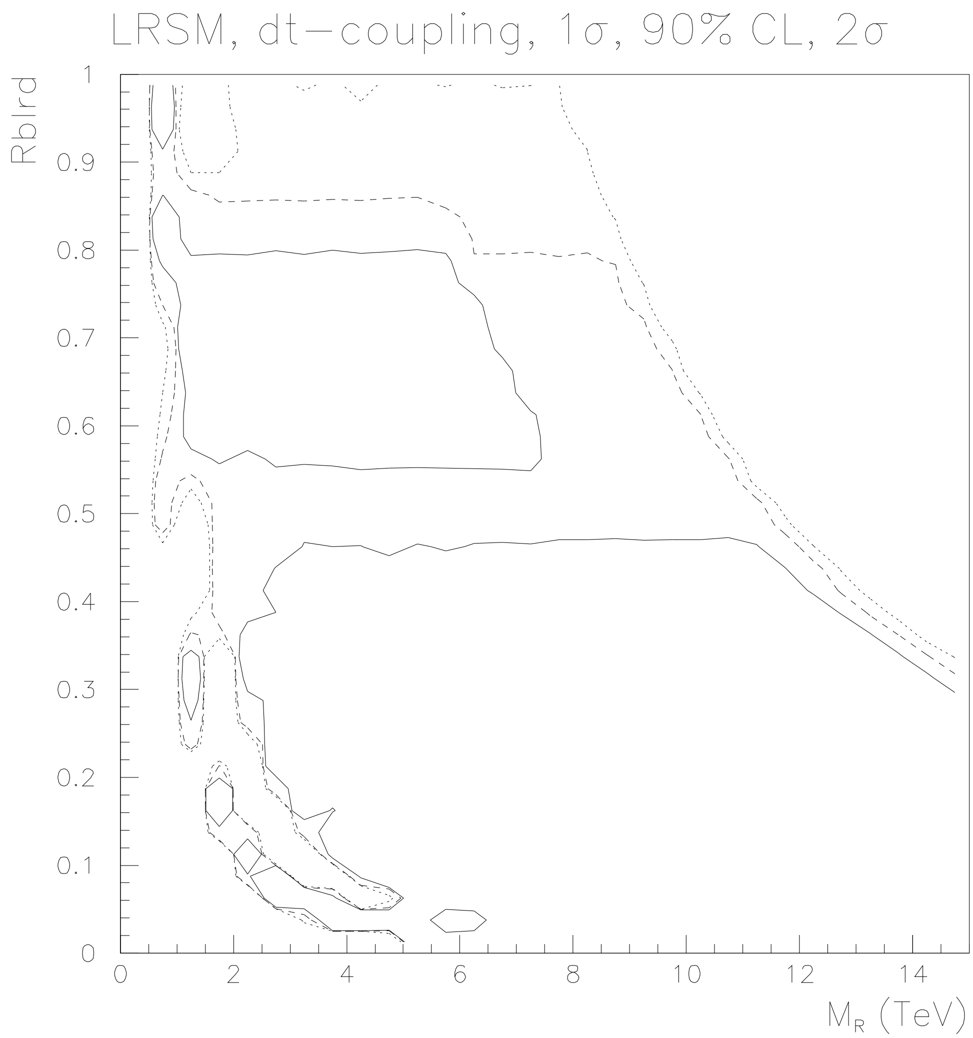
The W_L-W_R contributions are

$$\begin{aligned} M_{q,12}^{LR} \;&=\; \frac{G_F^2 M_L^2}{2\pi^2}(f_B^2 B_B)(\frac{m_B}{m_b})^2 m_B \beta_R \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL} \frac{\sqrt{x_i x_j}}{4} \\ &\quad [(4\eta_{ij}^{(1)} + \eta_{ij}^{(2)} x_i x_j \beta_R) I_1(x_i, x_j, \beta_R) - (\eta_{ij}^{(3)} + \eta_{ij}^{(4)} \beta) I_2(x_i, x_j, \beta_R)], \end{aligned}$$

where $\lambda_i^{LR} = V_{iq}^{L*} V_{ib}^R$ and $\lambda_i^{RL} = V_{iq}^{R*} V_{ib}^L$.

Dominant terms in the sum, quoted below, are largely determined by the quark mass factors $\sqrt{x_i x_j} = m_i m_j / M_L^2$. (t, c) pairs are suppressed by a factor of about $1/100$ compared to the leading (t, t) exchanges.

7 Numerical Results for $B_d - \bar{B}_d$ Mixing

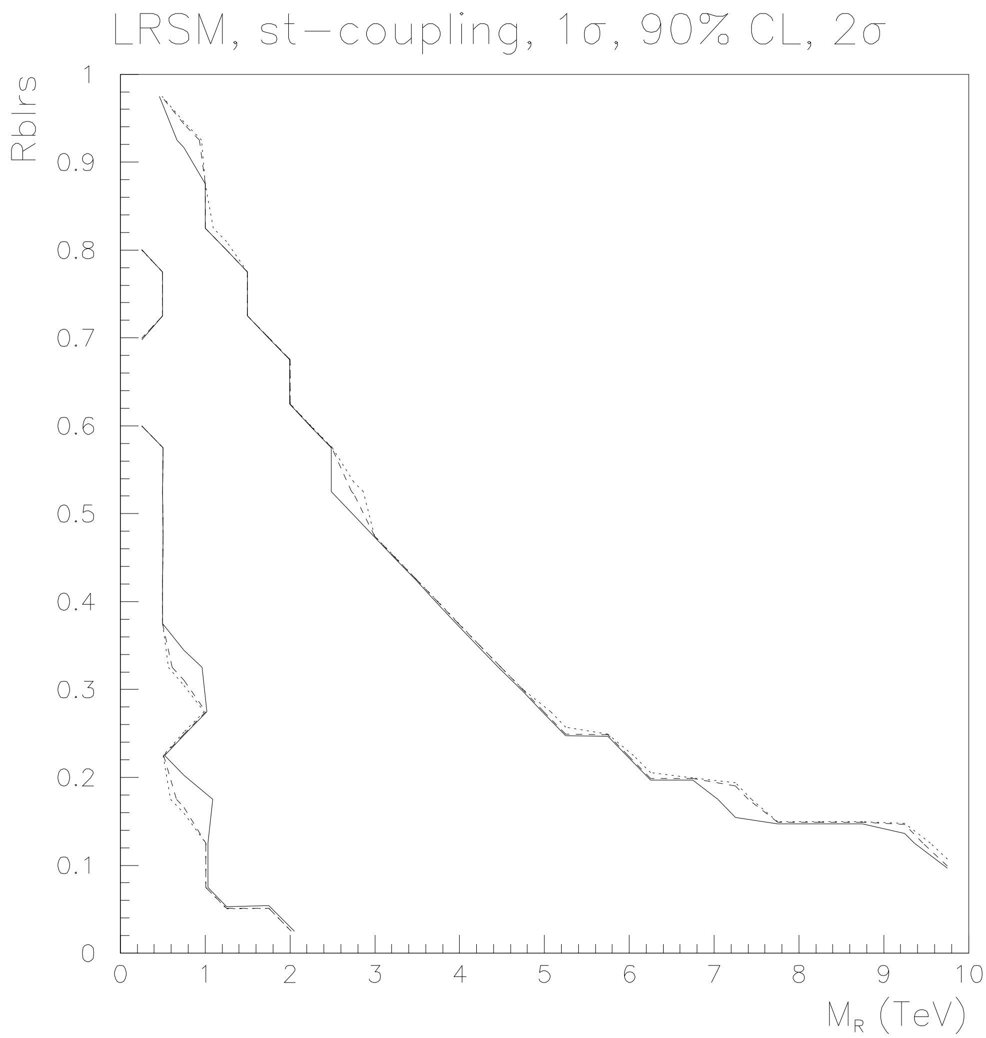


In case B_d (also called d-t coupling), the leading W_L-W_R box diagram has a pair of t quark exchanges. The LR to SM LL ratio is defined as

$$R_{\rm blrd} = \left|\frac{M_{d,12}^{LR}}{M_{d,12}^{LL}}\right|.$$

The upper 1σ, 90% CL, and 2σ contours show the region of LR contributions that still fit the six experimental constraints with five parameters and one degree of freedom with $\chi^2 = 1.0$, $\chi^2 = 2.71$, and $\chi^2 = 4.0$ for the respective contours.

8 Numerical Results for $B_s - \bar{B}_s$ Mixing



Here, for case B_s (also called s-t coupling), the (t,t) exchanges also dominate the W_L-W_R box diagram, and the LR ratio for contours is normalized to a maximum of 1

$$R_{\mathrm{blrs}} = \frac{|M_{s,12}^{LR}|}{(|M_{s,12}^{LL}| + |M_{s,12}^{LR}|)}.$$

9 χ^2 Plots for (ρ, η), $\sin(2\alpha)$, x_s, $\sin(\gamma)$) and $\sin 2\phi_s$ in the LRSM

- **CKM Experiments (6)**
  - **Decay Matrix Elements: (λ fixed)**

$$
\begin{aligned}
|V_{cb}| &= 0.041 \pm 0.002 \\
|V_{ub}/V_{cb}| &= 0.087 \pm 0.017
\end{aligned}
$$

  - **Mixing Experiments:**

    $x_d = 0.73 \pm 0.05$,

    $\sqrt{B_B} f_B = 0.228 \pm 0.032$ GeV

    $|\epsilon_K| = (2.282 \pm 0.017) \times 10^{-3}$

    x_s bounds from LEPBOSC

    $\sin(2\beta) = 0.735 \pm 0.056$

- **Left Right Symmetric Model:** (for various choices of W_R)

  Cases B_s and B_d: 6 experiments with 3 V^L parameters and 2 V^R parameters giving 1 degree of freedom.

  At 1σ, $\chi^2 = 1$, at 90% CL, $\chi^2 = 2.71$, and at 2σ, $\chi^2 = 4$.

- CP asymmetries and mixing predicted with $M_{q,12}$ including the LRSM

$$
\sin(2\beta) \equiv -\mathrm{Im}\left(\frac{M^*_{d,12}}{|M_{d,12}|}\frac{V^*_{cb}V_{cs}}{V_{cb}V^*_{cs}}\right), \qquad \sin(2\alpha) \equiv \mathrm{Im}\left(\frac{M^*_{d,12}}{|M_{d,12}|}\frac{V_{ub}V^*_{ud}}{V^*_{ub}V_{ud}}\right),
$$

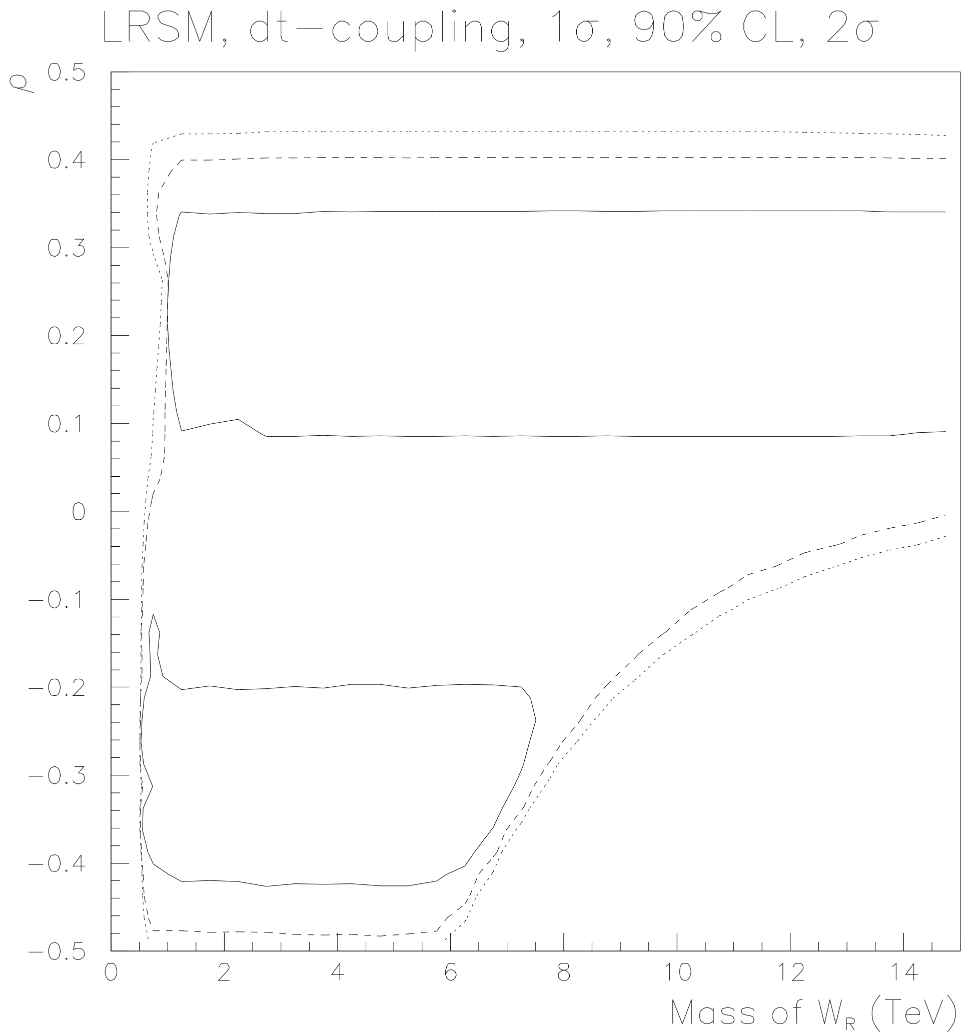
$$
\sin(\gamma) \equiv \mathrm{Im}\left(\frac{M_{s,12}}{|M_{s,12}|}\frac{V^*_{ub}V_{cs}}{|V_{ub}V_{cs}|}\right), \qquad \sin(2\phi_s) \equiv -\mathrm{Im}\left(\frac{M_{s,12}}{|M_{s,12}|}\frac{V^*_{cb}V_{cs}}{V_{cb}V^*_{cs}}\right),
$$

$$
x_s = 1.034 x_d \frac{|M_{s,12}|}{|M_{d,12}|}.
$$

  We have suppressed showing the W_R penguin decay terms (order β_R) in the above formulas just for simplicity.

  The α, β, γ, and ϕ_s are here defined by asymmetries and are different than those in the SM or from the left handed matrix V^L alone. They are each still phase angles, from their definitions.

10 LRSM ρ Plot for Case B_d



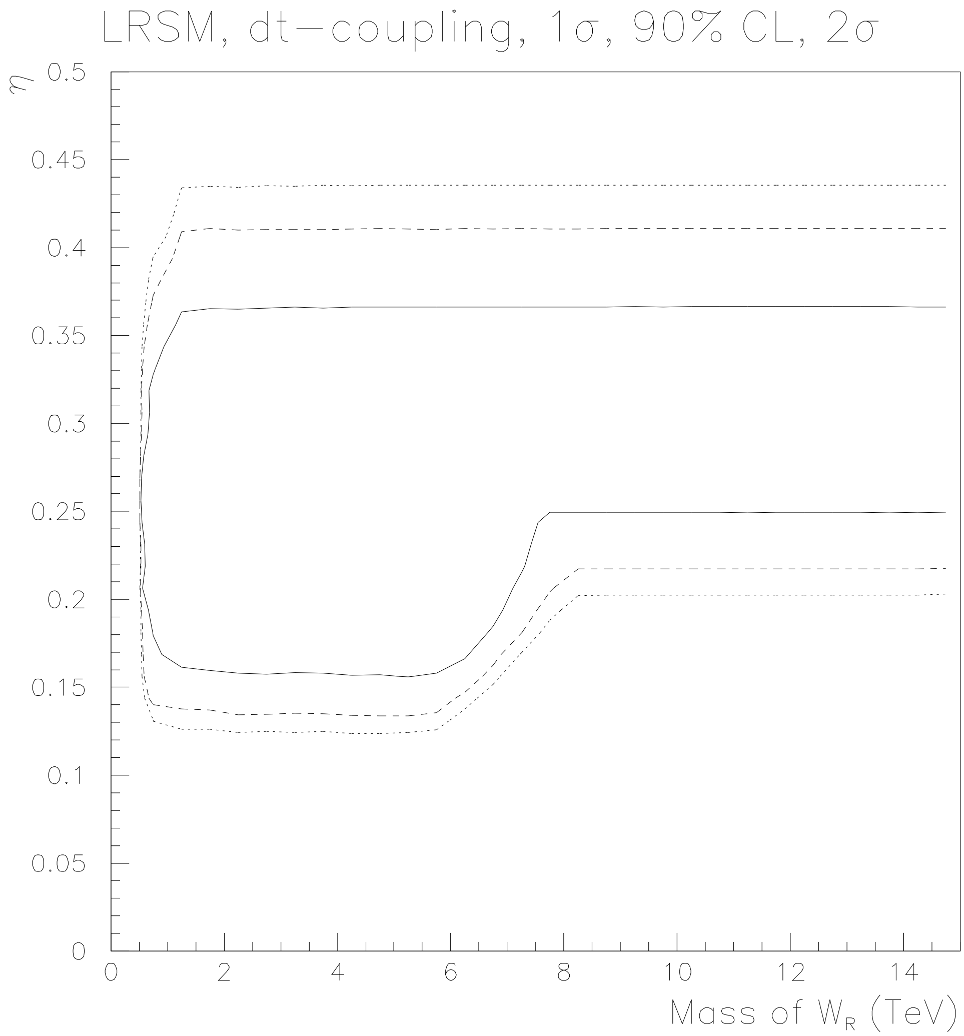
➤ ρ and η are defined as the coordinates of the apex in the scaled b-d unitarity triangle, which is equivalent to the Wolfenstein parametrization

$$\rho + i\eta \equiv \frac{V_{ub}^* V_{ud}}{|V_{cb}^* V_{cd}|}.$$

➤ There is a second region for ρ in addition to that for the SM, corresponding to a $130^\circ \leq \gamma \leq 160^\circ$ allowed region.

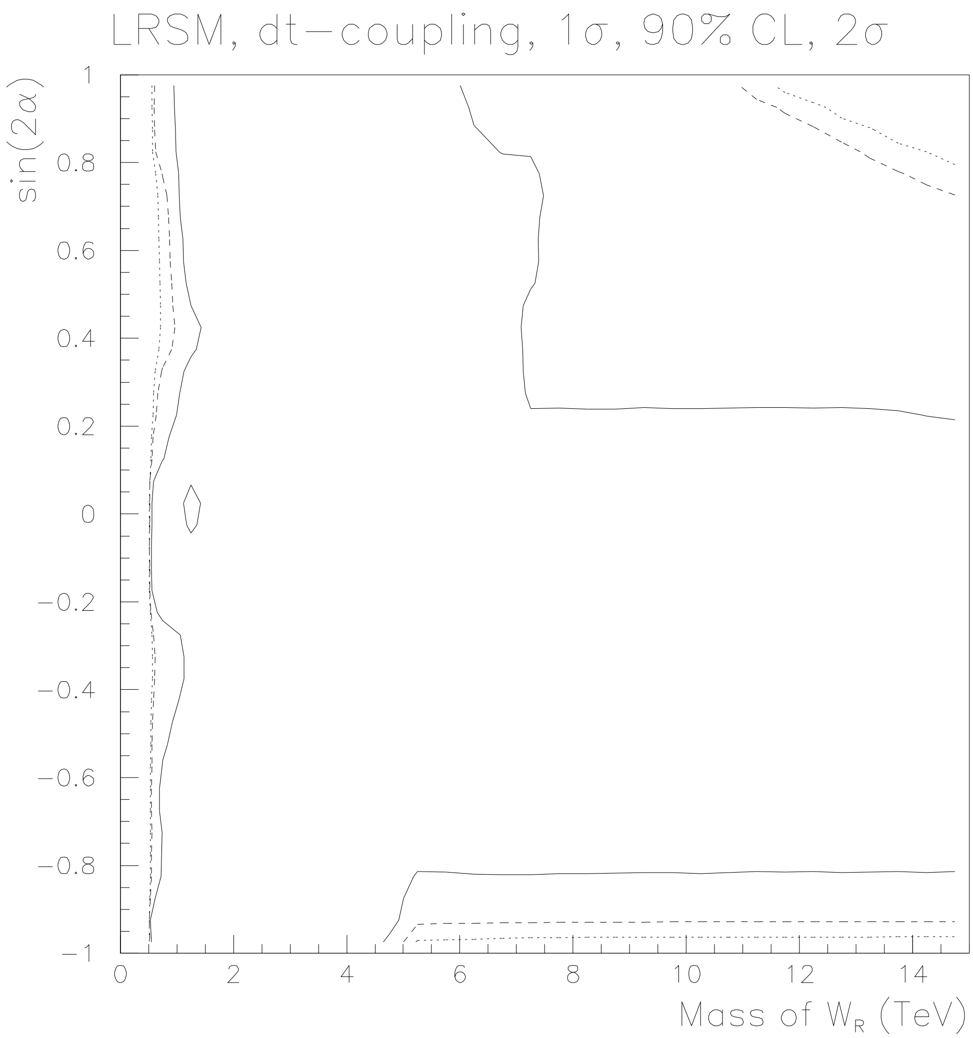
➤ The new ρ region is from -0.4 to -0.2 for $M_R \leq 7$ TeV.

11 LRSM η Plot for Case B_d



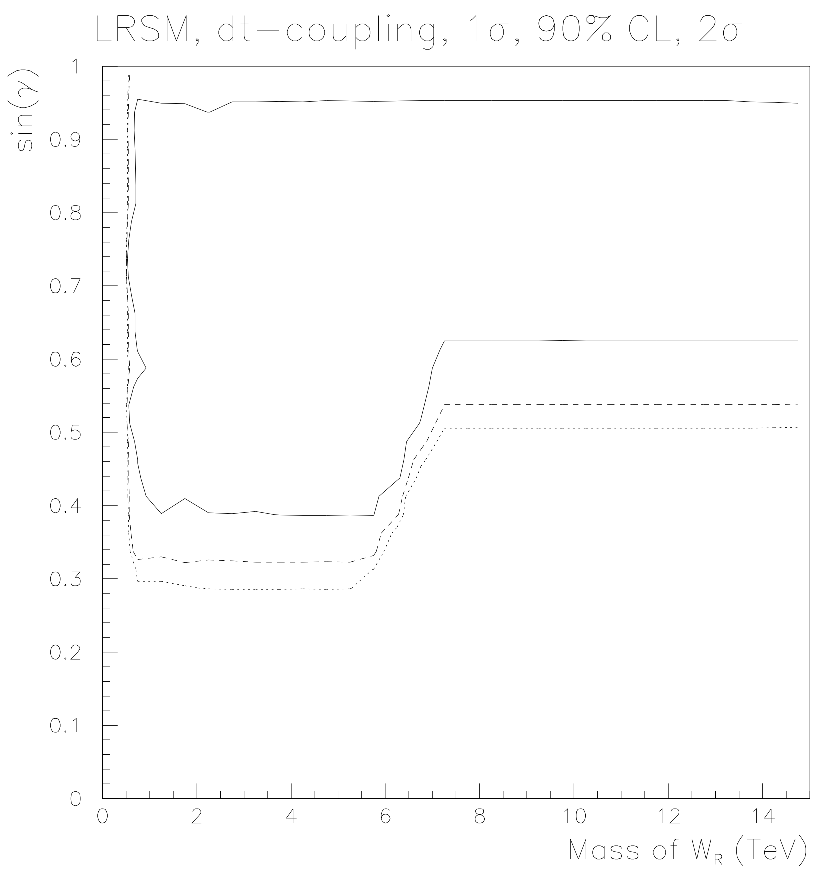
- The larger η range now extends to cover $0.15 \leq \eta \leq 0.25$ for $M_R \leq 7$ TeV.
- The higher γ region also shows up in extending $\sin\gamma$ from 0.4 to 0.6 at 1σ for $M_R \leq 7$ TeV.

12 LRSM $\sin 2\alpha$ Plot for Case B_d



- $\sin 2\alpha$ is the asymmetry in $\boldsymbol{B_d^0 \longrightarrow \pi^+\pi^-}$.
- All $\sin 2\alpha$ is allowed for $M_R \leq 7$ TeV, after which the allowed region approximates the SM 1σ region of $-0.9 \leq \sin 2\alpha \leq 0.33$.
- The $\sin 2\beta$ range varies little from the input $0.68 \leq \sin 2\beta \leq 0.79$ at 1σ since it is used as one of the experimental constraints.

13 LRSM $\sin\gamma$ and x_s Plots for Case B_d

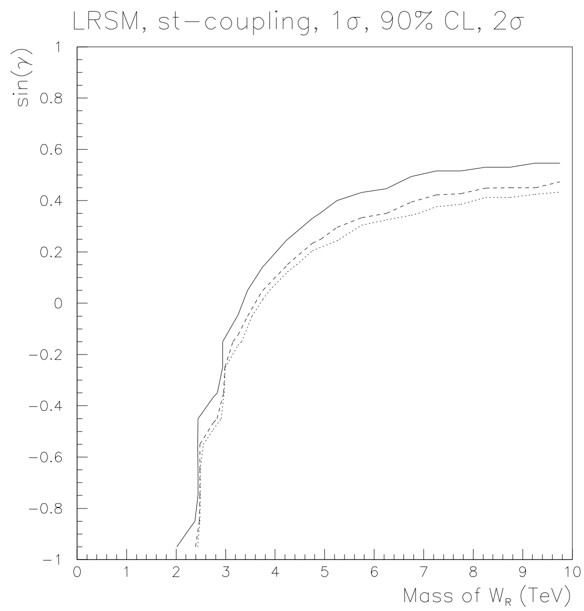


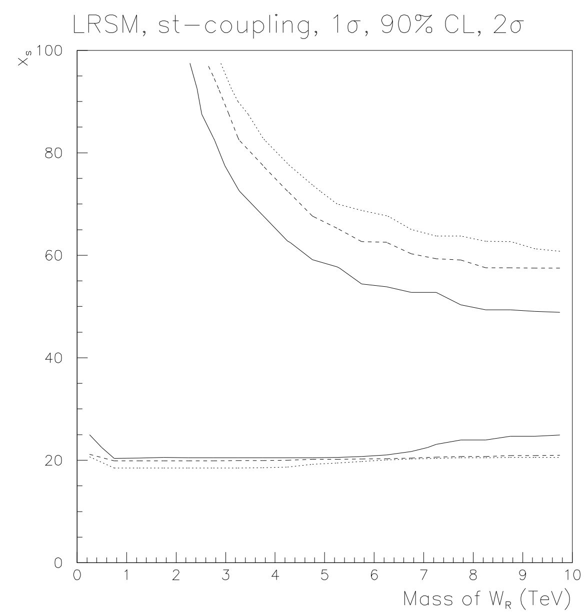
- $\sin\gamma$ occurs in $\bar{b} \to \bar{u} + c + \bar{s}$ decays, such as in the processes $B_s,\ \bar{B}_s \to D_s^{\pm}\ K^{\mp}$.
- For case B_d, there is a lower $\sin(\gamma)$ region from 0.4 to 0.6 for $M_R \leq 7$ TeV.
- For comparison, the SM range is $0.55 \leq \sin\gamma \leq 0.96$ at 1σ.
- For x_s, we exclude the theoretical uncertainty on $B_{B_s} f_{B_s}^2$, and take use the ratio of x_s to x_d, whose coefficient is better calculated.

$$x_s = 1.034\ x_d |M_{s,12}/M_{d,12}|.$$

- We include the amplitude method analysis of LEP and SLD to assign a $\Delta\chi^2$ for each x_s calculated in the parameter grid.
- The x_s range is similar to that of the SM range, $24 \leq x_s \leq 53$ at 1σ, but can rise to 85 at 2σ for $M_R \leq 10$ TeV.

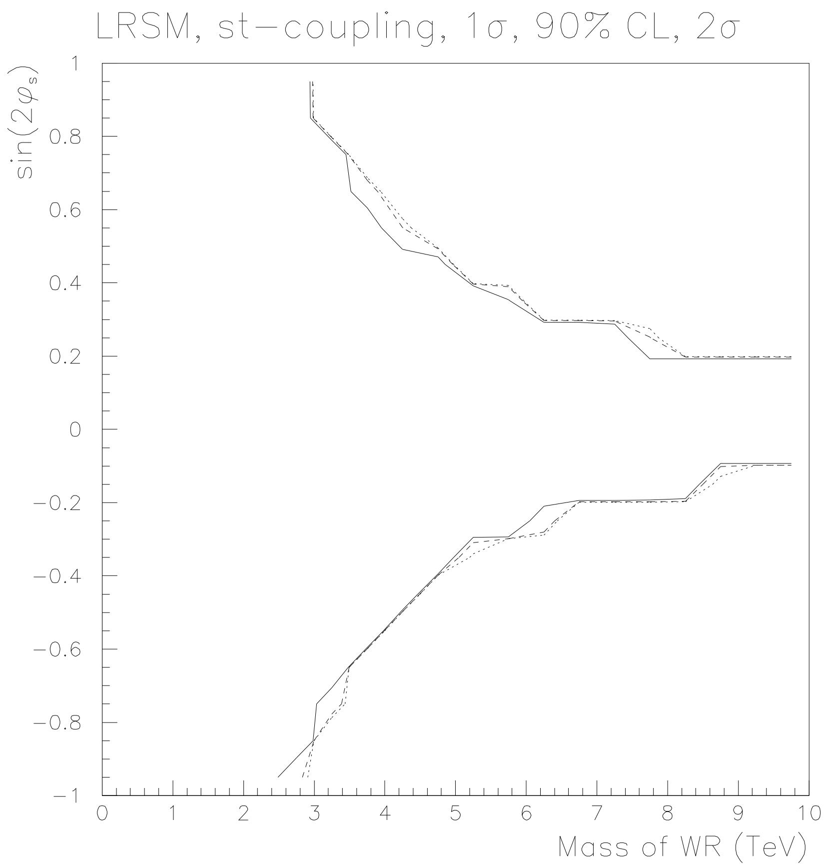
14 LRSM $\sin\gamma$ and x_s Plots for Case B_s





- In case B_s, $\sin\gamma$ has the complete -1 to 1 range form $M_R \leq 2.5$ TeV.
- $\sin\gamma$ approaches the SM range of $0.55 \leq \sin\gamma \leq 0.96$ by M_R equal to 6 TeV.
- In case B_s, x_s exceeds 100 for $M_R \leq 2$ TeV.
- x_s approaches the SM upper 1σ range of 53 at 6 TeV.

15 B_s Decay Asymmetry from B_s Mixing, $A_{B_s} = \sin 2\phi_s$



- ϕ_s is the small angle in the SM in the b-s unitarity triangle for the CKM opposite the $V_{ub}^* V_{us}$ side.

$$\sin(2\phi_s) \equiv -\mathrm{Im}\left(\frac{M_{s,12}}{|M_{s,12}|}\frac{V_{cb}^* V_{cs}}{V_{cb} V_{cs}^*}\right),$$

  here represents the asymmetry in $B_s - \bar{B}_s$ mixing followed by $\bar{b} \to \bar{c}c\bar{s}$ decay.

- $\sin 2\phi_s$ is very small but non-zero in the Standard Model:
  $0.025 \leq \sin 2\phi_s \leq 0.041$, for the same data.

- In case B_s, $\sin 2\phi_s$ can range from -1 to 1 for $M_R \leq 3$ TeV.

- In case B_s, the $\sin 2\phi_s$ range is much larger than the SM range out to 8 TeV.

- In case B_d (not shown), the range of $\sin 2\phi_s$ is still larger than the SM range, with $-0.2 \leq \sin 2\phi_s \leq 0.2$ up to 8 TeV.

16 Conclusions for LRSM

- The LRSM can contribute significantly to $B_d - \bar{B}_d$ mixing (in case B_d) and to $B_s - \bar{B}_s$ mixing (in case B_s), and give a new effective phase.
- In LRSM to SM ratios of mixing amplitudes $R_{\rm blrs}$ in case B_s (s-t coupling), and $R_{\rm blrd}$ in case B_d (d-t coupling), the LRSM give important contributions out to 12 TeV and 7 TeV, respectively.
- In case B_d, W_R shows its effects in (ρ, η), $\sin(2\alpha)$, and $\sin\gamma$ allowed regions, largely through an extra allowed region at large γ.
- In case B_d, there is a large $120^\circ \leq \gamma \leq 160^\circ$ region, which appears in $-0.4 \leq \rho \leq -0.2$, and in extending η down to the 0.16 to 0.25 region for $M_R \leq 8$ TeV.
- In case B_d, all $\sin(2\alpha)$ is allowed for $M_{W_R} \leq 7$ TeV.
- In case B_s, W_R greatly extends regions in $\sin\gamma$, $\sin 2\phi_s$ and x_s over those of the SM for $M_{W_R} \leq 8$ TeV.
- In case B_s, all $\sin 2\phi_s$ is allowed for $M_R \leq 3$ TeV, and the SM range is exceeded out to 8 TeV. x_s can greatly exceed the SM range for $M_R \leq 3$ TeV.
- $\sin\gamma$ can range from -1 to 1 for $M_R \leq 2.5$ TeV in case B_s. The $\sin\gamma$ range is from 0.55 to 0.96 in the SM at 1σ.
- Using the manifest symmetry assumption ($V^R \equiv V^L$) with the current data and ϵ_K, the lower bound on M_R is 1.5 TeV, similar to the Beall, Bander, and Soni bound from ΔM_K of 1.6 TeV.