CONSTRAINTS ON THE LEFT-RIGHT SYMMETRIC MODEL FROM
\( b \rightarrow s\gamma \) *

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ABSTRACT

The recent observation by the CLEO Collaboration of the inclusive decay \( b \rightarrow s\gamma \) with a branching fraction consistent with the expectations of the Standard Model is used to constrain the parameter space of the Left-Right Symmetric Model. Two scenarios are considered: (i) equal left- and right-handed Cabibbo-Kobayashi-Maskawa mixing matrices, \( V_L = V_R \) (or \( V_L^* \) and (ii) the Gronau-Wakaizumi model wherein B-decays proceed only via right-handed currents and \( V_L \) and \( V_R \) are quite distinct. In the later case the bounds from \( b \rightarrow s\gamma \) are combined with other constraints leaving a parameter range that is very highly restricted and which implies that this model may soon be completely ruled out by improving data.

Rare decay processes allow us to probe energy scales beyond those directly accessible at current \( e^+e^- \) and hadron colliders. The recent observation of the \( b \rightarrow s\gamma \) decay by CLEO with a branching fraction in the range \( 1 - 4 \cdot 10^{-4} \) at 95\% CL, coupled to the possible discovery of the the top quark, with a mass of approximately 175 GeV, by CDF, leads to many restrictions on new physics scenarios beyond the Standard Model(SM). In the analysis below, we consider the implications of these results for the Left-Right Symmetric Model(LRM), which is based on the gauge group \( SU(2)_L \times SU(2)_R \times U(1) \). The ‘classical’ constraints on this model arise from a number of sources including polarized \( \mu \) decay, the \( K_L - K_S \) mass difference, universality, and Tevatron direct \( Z', W' \) searches. However, the LRM is quite robust and possesses a large number of free parameters which play an interdependent role in the calculation of observables and in the constraints resulting from experiment. As far as \( b \rightarrow s\gamma \) and the subsequent discussion are concerned there are essentially 5 parameters of interest: (i) \( t_\phi = \tan \phi \), where \( \phi \) is the mixing angle between \( W_L \) and \( W_R \) which form the mass eigenstates \( W_{1,2} \), (ii) the ratio of masses, \( r = M_1^2/M_2^2 \), (with \( M_2 \approx M_R \)), (iii) the ratio of gauge couplings \( \kappa = g_R/g_L > 0.55 \), which is expected to be of order unity, (iv)...

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the masses of the right-handed(RH) neutrinos, and (v) the elements of the RH quark
mixing matrix, $V_R$. Our discussion below assumes that $W_R$ is the only new particle
occurring in the $b \rightarrow s\gamma$ penguin(e.g., charged Higgs may also contribute to these loops
in a highly model dependent way but they are neglected here) and ignores any additional
phases that may be present in the $W_L - W_R$ mixing matrix that may arise from complex
vev's.

We now outline our procedure which to leading order in the QCD corrections is
well known; for details see Ref.9. We first normalize $B(b \rightarrow s\gamma)$ to the semileptonic
SL decay rate using the quark level calculations including finite phase space and QCD
corrections, assuming $m_c/m_b = 0.3$ and $\alpha_s(M_Z) = 0.125$. In the LRM, the SL decay
rate is now a function of $t_\phi, r, \kappa$ and the appropriate $V_{L,R}$ factors. Apart from these
model parameters, $B$ is expressed in terms of the coefficients of the $C_{7L}$ and $C_{7R}$
electromagnetic dipole-moment operators evaluated at the scale $\mu = m_b$; $m_s$ is assumed
to be zero in the results quoted here. To obtain the numerical values of these operators
at the low mass scale we must know the two $10 \times 10$ anomalous dimension matrices for
the complete set of operators as well as all the operator coefficients at the weak scale.
To lowest order in $\alpha_s$, only 8 of these coefficients are non-zero:

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\begin{align*}
C_{2L}(M_{W_1}) & = (1 + r t_\phi^2)(V_{cb} V_{cs}^*)_L, \\
C_{2R}(M_{W_1}) & = \kappa^2(r + t_\phi^2)(V_{cb} V_{cs}^*)_R, \\
C_{10L}(M_{W_1}) & = \kappa t_\phi(1 - r)\frac{m_t}{m_b} (V_{cb} V_{cs}^*)_L, \\
C_{10R}(M_{W_1}) & = C_{10L}(M_{W_1})(L \leftrightarrow R), \\
C_{7L}(M_{W_1}) & = (V_{tb} V_{ts}^*)_L[A_1(x_1) + r t_\phi A_1(x_2)] + \frac{m_t}{m_b} \kappa t_\phi (V_{tb}^R V_{ts}^L)[A_2(x_1) - r A_2(x_2)], \\
C_{7R}(M_{W_1}) & = \frac{m_t}{m_b} \kappa t_\phi (V_{tb}^L V_{ts}^R)[A_2(x_1) - r A_2(x_2)] + \kappa^2 (V_{tb} V_{ts}^*)_R [t_\phi^2 A_1(x_1) + r A_1(x_2)],
\end{align*}
\]

where $x_{1,2} = m_t^2/M_{W_{1,2}}^2$. The coefficients of the operators corresponding to the gluon
penguin, $C_{SL,R}(M_{W_1})$, can be expressed in a manner similar to $C_{7L,R}(M_{W_1})$ but with
$A_i \rightarrow B_i$; note that both $A_1$ and $B_1$ are the same functions found in the usual SM
calculation. The kinematic functions $A_i$ and $B_i$ are given in Ref.9. An important feature
in the expressions for $C_{7,8L}$ and $C_{7,8R}$ are terms proportional to $\kappa t_\phi m_t/m_b$ which arise
due to chirality flips and imply that $B$ will be highly sensitive to non-zero values of $t_\phi$
even when $r$ is quite small. This will be seen explicitly in our results below. The largest
new contribution to $b \rightarrow s\gamma$ in the LRM is thus due to the SM $W_L$ picking up a small
RH coupling via mixing and vice versa for the $W_R$.

To proceed further we need to make some assumptions about the LRM parameters.
The first case we consider, which one may think is the most natural, is when
$V_L = V_R$ or $V_L^*$ with heavy RH neutrinos and where we know that $M_R > 1.5$ TeV from
the $K_L - K_S$ mass difference. In Fig.1a we see the prediction for $B$ as a function of $t_\phi$
in this case for various values of $m_t$ assuming $\kappa = 1$ and $M_R = 1.6$ TeV. To satisfy the
CLEO data only a restricted range of $t_\phi$ is allowed; note the rather weak sensitivity to
$m_t$. Fixing $m_t = 175$ GeV and varying $M_R$ we see from Fig.1b that the $t_\phi$ constraints
are not sensitive to variations in the $W_R$ mass. If we vary $\kappa$ for $m_t$ and $M_R$ fixed we ob-
tain Fig. 1c which shows that the $t_\phi$ bounds are quite sensitive to $\kappa$. Note however that if we consider $B$ as a function of the combination $\kappa t_\phi$ (which enters directly into the expressions for the weak scale coefficients) there is very little additional $\kappa$ sensitivity. Thus we see that in this $V_L = V_R$ case the bounds we obtain on $t_\phi$ are more restrictive than those obtained from either $\mu$ decay or universality.

In principle, if we give up the assumption that $V_L = V_R$ ($V^*_R$) there is very little guidance as to what form $V_R$ might take and bizarre scenarios may in fact be realized. One possibility is the model of Gronau and Wakaizumi (GW) (and several of its clones). In this class of models, $B$ decays proceed only via RH-currents with the apparent smallness of $V_{cb}$ explained by the larger $W_R$ mass. The exact forms taken for $V_L, R$ are somewhat model dependent; in the original GW model, one has

$$V_L = \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$V_R = \begin{pmatrix} c^2 & -cs & s \\ \frac{s(1-c)}{\sqrt{2}} & c^2 + s^2 & \frac{c}{\sqrt{2}} \\ -\frac{s(1+c)}{\sqrt{2}} & \frac{-c s^2}{\sqrt{2}} & \frac{c}{\sqrt{2}} \end{pmatrix},$$

where $\lambda (\simeq 0.22)$ is the Cabibbo angle and $s \simeq 0.09$ and $c^2 = 1 - s^2$. Explicitly, to satisfy the $B$ lifetime constraint we must also have

$$M_{W_R} \leq 416.2 \kappa \left( \frac{|V^R_{cb}|}{\sqrt{2}} \right)^{1/2} \text{GeV} \simeq 415 \kappa \text{GeV},$$

which arises from recent determinations of $V_{cb}$ in the SM. With the assumed forms of $V_{L,R}$ in this model the usual $K_L - K_S$ constraint on the $W_R$ mass is easily circumvented. In addition, to satisfy the most stringent polarized $\mu$ decay data, the RH neutrino must be sufficiently massive ($\simeq 17 - 50$ MeV) but this has little effect on $B$ decay itself. (Note that some of the weaker $\mu$ decay constraints remain.) Of course, a $W_R$ satisfying the above constraint is relatively light and should have a significant production cross section at the Tevatron given the above form of $V_R$. We will assume $M_R = 400 \kappa$ GeV in what follows as we will want $M_R$ to be as large as possible. Figs. 1d and 1e show the predicted value of $B$ as a function of $t_\phi$ for $\kappa = 1.5$ and 2, respectively, for different values of $m_t$. In either case and for all $m_t$ values we see that agreement with the CLEO result demands that $t_\phi$ lie within either of two very narrow bands with a magnitude less than 0.001. These general results are maintained at the semi-quantitative level in the various clones of the GW model. Fixing $m_t = 175$ GeV, we see in Fig. 1f the overall behaviour of $B$ in the GW model as $\kappa$ is allowed to vary. As in the previous case, a plot of $B$ as a function of the combination $\kappa t_\phi$ shows little additional $\kappa$ sensitivity. Thus the CLEO result forces us to fine-tune $t_\phi$ to a narrow range of very small values in this model.

The GW model uses heavy RH $\nu$'s to avoid the bulk of the $\mu$ constraints. However, it cannot escape from $\tau$ decay in a similar manner, i.e., by making the RH $\nu_\tau$ heavy. Both ALEPH and L3 have measured the branching fraction for $B \rightarrow \tau \nu X$ and found it to be in agreement with the expectations of the SM. If the RH $\nu_\tau$ were heavy enough
to allow the GW model to escape the $\tau$ decay constraints, this branching fraction would be seriously compromised as is shown in Fig.2a. We see from the figure that the RH $\nu_\tau$ must have a mass less than about 0.3 GeV to maintain agreement with the ALEPH/L3 data implying that RH currents must be present in $\tau$ decay in the GW model. ALEPH and L3 have also recently updated the determinations of the Michel parameters for $\tau$ decay which are sensitive to such RH interactions and lead to new constraints on the GW model (taking $t_\phi \simeq 0$ as we learned from $b \to s \gamma$). These new constraints, together with those from $\mu$ decay, direct Tevatron searches, and the $B$ lifetime are combined in Fig.2b. We see that the GW model parameter space was comfortably large before the recent CDF $W'$ search and LEP $\tau$ Michel parameter results were announced. The new data highly compresses the model parameter space into the region near $M_R = 800$ GeV with $\kappa = 2$. Even this small region will soon become disallowed if the CDF limit scales logarithmically with increasing integrated luminosity (perhaps in a matter of months). Fig.2b shows the power of combining rare decay data, precision measurements, and direct searches to constrain the new physics in the GW version of the LRM.

As in the case of other new physics scenarios, $b \to s \gamma$ has been found to provide important constraints on the parameters of the LRM.

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Fig. 1: (a) \( B \) as a function of \( t_\phi \) assuming \( \kappa = 1 \), \( M_R = 1.6 \) TeV, and \( V_L = V_R \) for \( m_t = 140(160, 180, 200) \) GeV as represented by the dotted(dashed,dash-dotted, solid)curve. (b) Same as (a) but with \( m_t = 175 \) GeV and \( M_R \) varied between 1 and 3 TeV. (c) Same as (a) but with \( m_t = 175 \) GeV and \( \kappa = 0.6(0.8,1,1.2,1.4) \) corresponding to the dotted(dashed, dash-dotted, solid, square-dotted)curve. (d) Same as (a) but in the GW model with \( M_R = 600 \) GeV and \( \kappa = 1.5 \). (e) Same as (d) but with \( M_R = 800 \) GeV and \( \kappa = 2 \). (f) Same as (d) but with \( m_t = 175 \) GeV and \( M_R = 400\kappa \) GeV with \( \kappa \) varying between 1(outer curve) and 2(inner curve) in steps of 0.2.

Fig. 2: (a) Branching fraction for the decay \( \tau \nu_R X \) in the GW model as a function of the mass of the RH-neutrino. The combined ALEPH+L3 95\% CL lower bound is the horizontal dashed line. (b) Constraints on \( \kappa \) and \( M_R \) in the GW model: the solid line is the upper bound from Eq.3. The dash-dotted line is the lower bound from \( \tau \) and \( \mu \) decay data. The dotted(dashed) line is the CDF lower bound from the ’88-’89 run (run 1a). The currently allowed region lies in the upper right hand corner.
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