

Family Nonuniversal Z' and $b \rightarrow s\gamma$ decay

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Abstract

We have calculated the branching ratio and CP asymmetry of $B \rightarrow X_s\gamma$ decay within the family–nonuniversal Z' models. We have established certain bounds on the model parameters using the present experimental bounds. We also comment on the role of family–nonuniversality in the hadronic decay modes of the B meson.

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1 Introduction

The impressive agreement between the standard electroweak theory (SM) and experiment is not sufficient to make it the fundamental theory of nature up to very high energies. This follows mainly from the instability of its Higgs sector under radiative corrections. The supersymmetry (SUSY) is thus one of the remedies which can cure this hierarchy problem. However, the minimal supersymmetric model (MSSM) itself has a hierarchy problem concerning the natural scale of the Higgsino mass parameter (μ problem). This problem is solvable in various frameworks each of which introducing a certain SM singlets to dynamically generate the μ parameter. The Z' models form a viable candidate model to extend the MSSM in order to solve the μ problem [1]. The vacua that suppress the $Z - Z'$ mixing have been found in [2] with further improvements concerning the radiative effects [3]. The effects of such extra Z bosons on precision observables have been analyzed in detail in [4]. Moreover, several collider signatures have been analyzed for tree level Higgs sector [5].

Recently there have been a revived interest in the flavor changing neutral current phenomena [6] in such models [7, 8]. Given the recent indications for a light Z' boson [9], it is necessary to analyze certain rare phenomena within such models in order to test or at least determine the ballpark of model parameters. One such rare decay is the radiative decay of B mesons, $B \rightarrow X_s \gamma$ which is under intense experimental investigation at the present B factories.

The flavor mixing in the quark and lepton sectors will lead to flavor changing (nondiagonal) couplings of the heavy Z' . Since its topology is similar to the photon and gluon vertex, calculating the branching ratio (BR) and CP asymmetry (A_{CP}) of the process $B \rightarrow X_s \gamma$ can restrict the couplings ξ of the Z' . Although in SM CP asymmetry $A_{CP}(b \rightarrow s \gamma)$ is less than 1%, in the extension of the SM, due to CP violating couplings large CP asymmetries are possible [10]. In particular, large asymmetries arise naturally in models with enhanced chromomagnetic dipole operators. There is also flavor violating Z couplings if there is $Z-Z'$ mixing. This is another motivation to search for flavor changing neutral current (FCNC) effects.

The prediction for the $B \rightarrow X_s \gamma$ branching ratio is usually obtained by normalizing the result for the corresponding decay rate to that for the semileptonic decay rate, thereby eliminating a strong dependence on the b-quark mass [11].

The branching fraction is obtained from the CLEO experiment [12] as

$$BR(b \rightarrow s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4} \quad (1)$$

where the photon energy is $2.1 < E_\gamma < 2.7 \text{ GeV}$. Therefore the branching fraction is between

$$2.0 \times 10^{-4} < BR < 4.5 \times 10^{-4} \quad (2)$$

Direct CP violation can lead to a difference between the rates for $b \rightarrow s\gamma$ and $\bar{b} \rightarrow \bar{s}\gamma$ giving rise to a non-zero value for the CP asymmetry[13]

$$A_{CP} = \frac{\Gamma(b \rightarrow s\gamma) - \Gamma(\bar{b} \rightarrow \bar{s}\gamma)}{\Gamma(b \rightarrow s\gamma) + \Gamma(\bar{b} \rightarrow \bar{s}\gamma)}. \quad (3)$$

The SM predicts that this asymmetry is very small, less than 1%. Recent theoretical work suggests that non-SM physics may contribute significantly to a CP asymmetry, as large as 10-40%.

The signature for $b \rightarrow s\gamma$ is a photon with energy sufficiently high that it is unlikely to come from other B decay processes.

In Cleo's work the photon energy range is taken between 2.1-2.7 GeV, and in conclusion CP asymmetry A_{CP} in $b \rightarrow s\gamma$ plus $b \rightarrow d\gamma$ lies between the limits [13],

$$-0.27 < A < +0.10 \quad (4)$$

at 90% confidence level.

These limits rule out some extreme non-SM predictions, but are consistent with most, as well as with the SM.

By using the constrained couplings of Z' boson from this process, we may calculate other processes including Z' boson couplings.

2 Calculation

At the W-boson mass scale $Q=M_W$, the flavor changing radiative transition $b \rightarrow s\gamma$ is described by the following operator product expansion[14, 15, 16]

$$H_{eff} = -\frac{4G_F}{\sqrt{2}}K_{ts}^*K_{tb}\left\{C_2(M_W)O_2(M_W) + C_7(M_W)O_7(M_W) + C_8(M_W)O_8(M_W)\right\} \quad (5)$$

where $C_i(M_W)$ are the Wilson coefficients, and $O_i(M_W)$ are the local operators defined by

$$O_2(M_W) = (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma_\mu b_L), \quad (6)$$

$$O_7(M_W) = \frac{e(Q)}{16\pi^2}\bar{m}_b(M_W)(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}, \quad (7)$$

$$O_8(M_W) = \frac{g_s(Q)}{16\pi^2}\bar{m}_b(M_W)(\bar{s}_L\sigma^{\mu\nu}T^ab_R)G_{\mu\nu}^a. \quad (8)$$

Here $O_2(M_W)$ is a four-fermion operator and its coefficient satisfies $C_2(M_W) = 1$, that is, it is a constant independent of the looping particle species. However, the coefficients of the electric $O_7(M_W)$ and color $O_8(M_W)$ dipole operators can receive nonvanishing contributions from physics beyond the SM. In general

$$C_{7,8}(M_W) = C_{7,8}^{SM}(M_W) + C_{7,8}^{NP}(M_W) \quad (9)$$

where the last term is for the New Physics contributions, and the SM contributions $C_{7,8}^{SM}(M_W)$ are [17];

$$C_7^{SM}(M_W) = \frac{3x^3 - 2x^2}{4(x-1)^4} \ln x + \frac{-8x^3 - 5x^2 + 7x}{24(x-1)^3} \quad (10)$$

$$C_8^{SM}(M_W) = \frac{-3x^2}{4(x-1)^4} \ln x + \frac{-x^3 + 5x^2 + 2x}{8(x-1)^3}. \quad (11)$$

Here

$$x = \frac{m_{t,p}^2}{M_W^2} \left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)} \right)^{24/23} \left(1 - \frac{8}{3} \frac{\alpha_s(m_t)}{\pi} \right). \quad (12)$$

In the Langacker-Plümacher paper [7], we let $\xi_R^{sb} = \xi_L^{sb} \equiv \xi_{sb}$ for simplicity. Then the new physics contribution can be parametrized as

$$C_{7,8}^{NP}(M_W) = 2\sqrt{2} \frac{\xi_{sb}}{V_{ts}^* V_{tb}} \quad (13)$$

where we have used the fact that gluon and photon diagrams have the same topology as Z' boson which is neutral both electrically and chromoelectrically. Here ξ_{sb} is a complex number whose expression is [7]

$$\xi_{sb} = \frac{y}{m_b} (B^d m_d B^d)_{23} + w \epsilon_L(b) B_{23}^d \quad (14)$$

where m_d is the diagonal mass matrix of down quarks,

$$y = \left(\frac{g_2}{g_1} \right)^2 (\rho_1 \sin^2 \theta + \rho_2 \cos^2 \theta), \quad (15)$$

$$w = \frac{g_2}{g_1} \sin \theta \cos \theta (\rho_1 - \rho_2), \quad (16)$$

$$\rho_i = \frac{M_W^2}{M_i^2 \cos^2 \theta_W}. \quad (17)$$

M_i are the masses of the neutral gauge boson mass eigenstates, g_1 and g_2 are the coupling constants of the neutral gauge bosons Z and Z' respectively.

The Wilson coefficients mentioned so far are at the $Q = M_W$ scale. However, physically one must recalculate them at the $Q = m_b$ scale- the natural scale of the problem. Therefore, the Wilson coefficients above are now reduced to $Q = m_b$ scale via[11]

$$\begin{aligned}
C_2(m_b) &= \frac{1}{2}(\eta^{-\frac{12}{23}} + \eta^{\frac{6}{23}}), \\
C_7(m_b) &= \eta^{\frac{16}{23}}C_7(M_W) + \frac{8}{3}(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}})C_8(M_W) + C_2(M_W) \sum_{i=1}^8 h_i^{(72)} \eta^{a_i}, \\
C_8(m_b) &= \eta^{\frac{14}{23}}C_8(M_W) + C_2(M_W) \sum_{i=1}^8 h_i^{(82)} \eta^{a_i}, \tag{18}
\end{aligned}$$

where the magic numbers on the right are given by

$$\begin{aligned}
a_i &= \left(\frac{14}{23}, \frac{16}{23}, \frac{6}{23}, -\frac{12}{23}, 0.4086, -0.4230, -0.8994, 0.1456 \right), \\
h_i^{(72)} &= \left(\frac{626126}{272277}, -\frac{56281}{51730}, -\frac{3}{7}, -\frac{1}{14}, \right. \\
&\quad \left. -0.6494, -0.0380, -0.0186, -0.005 \right), \\
h_i^{(82)} &= \left(\frac{313063}{363036}, 0, 0, 0, -0.9135, 0.0873, -0.0571, 0.0209 \right). \tag{19}
\end{aligned}$$

In obtaining $C_7(m_b)$ we have made use of the leading order QCD renormalization group running from $Q = M_W$ down to $Q = m_b$ and so the renormalization factor $\eta = \alpha_s(M_W)/\alpha_s(m_b)$. Having $C_7(m_b)$ at hand, it is easy to calculate the branching ratio and CP asymmetry of the decay. Branching ratio is given by

$$BR(b \rightarrow s\gamma) = BR^{(\text{exp})}(b \rightarrow ce\bar{\nu}_e) \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6\alpha}{\pi f(z_c)} S(\delta) |C_7(m_b)|^2 \tag{20}$$

where $z_c = m_c^2/m_b^2$, $BR^{(\text{exp})}(B \rightarrow X_c e \bar{\nu}_e) \approx 10.5\%$, and $f(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln z$. Here $\delta = 0.9$ represents the energy of the emitted photon, and

$$S(\delta) = \exp \left[-\frac{2\alpha_s(m_b)}{3\pi} \left(\ln^2 \delta + \frac{7}{2} \ln \delta \right) \right]. \quad (21)$$

Similarly the CP asymmetry is given by

$$\begin{aligned} A_{CP}(b \rightarrow s\gamma) &= \frac{\alpha_s(m_b)}{|C_7(m_b)|^2} \left\{ \frac{40}{81} \text{Im} [C_2(m_b)C_7^*(m_b)] \right. \\ &\quad - \frac{8z_c}{9} [v(z_c) + b(z_c, \delta)] \text{Im} [(1 + \epsilon_s) C_2(m_b)C_7^*(m_b)] \\ &\quad \quad - \frac{4}{9} \text{Im} [C_8(m_b)C_7^*(m_b)] \\ &\quad \quad \left. + \frac{8z_c}{27} b(z_c, \delta) \text{Im} [(1 + \epsilon_s) C_2(m_b)C_8^*(m_b)] \right\} \end{aligned} \quad (22)$$

where ϵ_s represents the pure SM contribution

$$\epsilon_s \equiv \frac{V_{us}^* V_{ub}}{V_{ts}^* V_{tb}} \approx \lambda_c^2 (i\eta - \rho) = O(10^{-2}), \quad (23)$$

and the functions $v(z)$ and $b(z, \delta)$ are defined by

$$\begin{aligned} g(z, y) &= \theta(y - 4z) \{ (y^2 - 4yz + 6z^2) \ln \left(\sqrt{\frac{y}{4z}} + \sqrt{\frac{y}{4z} - 1} \right) \\ &\quad - \frac{3y(y - 2z)}{4} \sqrt{1 - \frac{4z}{y}} \}, \end{aligned} \quad (24)$$

$$\begin{aligned} v(z) &= \left(5 + \ln z + \ln^2 z - \frac{\pi^3}{3} \right) + (\ln^2 z - \frac{\pi^3}{3})z + \\ &\quad \left(\frac{28}{9} - \frac{4}{3} \ln z \right) z^2 + O(z^3), \end{aligned} \quad (25)$$

with $b(z, \delta) = g(z, 1) - g(z, 1 - \delta)$.

3 Results

To get the numerical results from Eqs. 20. and 22. we use $\delta = 0.90$. We calculate the branching ratio from Eq. (20) as

$$BR(b \rightarrow s\gamma) = 0.00025 + 0.01232 * I^2 - 0.00352 * R + 0.01232 * R^2 \quad (26)$$

The branching ratio $BR(b \rightarrow s\gamma)$ is plotted in Fig. 1 as a function of R for different values of I .

Comparing the graph in Fig 1. with the experimental value [12], we get the following values with $\xi = R + i * I$

$$\begin{aligned} -0.03 < R < +0.02 \text{ for } I = 0.04, \\ -0.02 < R < +0.04 \text{ for } I = 0.08, \\ +0.01 < R < +0.11 \text{ for } I = 0.12 \end{aligned} \quad (27)$$

to get the following constraint

$$0.000222 < BR(b \rightarrow s\gamma) < 0.000408. \quad (28)$$

From the values obtained for R and I the coupling constant $\xi = R + i * I$ is between

$$0.05 \leq |\xi_{sb}| \leq 0.163. \quad (29)$$

We calculate the CP asymmetry $A_{CP}(b \rightarrow s\gamma)$ from Eq. (22) as

$$A_{CP}(b \rightarrow s\gamma) = \frac{-0.00648 Re[I]}{0.0963452 + 4.71401 I^2 - 1.34785 R + 4.71401 R^2} \quad (30)$$

The CP asymmetry $A_{CP}(b \rightarrow s\gamma)$ is plotted in Fig. 2 as a function of R for different values of I .

Similarly From Fig. 2, we obtain

$$-0.13 < R < +0.15 \text{ for } I = \pm 0.002 \quad (31)$$

to get the following experimental constraint

$$-0.27 < A_{CP}(b \rightarrow s\gamma) < +0.10, \quad (32)$$

from [13].

From the values obtained for R and I the coupling constant $\xi = R + i * I$ is between

$$0.132 \leq \xi_{sb} \leq 0.151. \quad (33)$$

4 Discussion and Conclusion

In summary we have analyzed the constraints on family non-universal Z' couplings from the branching ratio and the CP asymmetry of the decay $B \rightarrow X_s \gamma$. We have found that the parameter ξ_{sb} has non-vanishing real and imaginary parts, and the central value allowed is $|\xi_{sb}| \sim 0.1$. Although it is not possible to infer any further results about the parameters ξ_{sb} depends on, still one can infer that the parameter ξ_{sb} is complex and is required to be around 0.1 in magnitude.

As shown in Fig. 1 the dependence of the branching ratio on R is strong, and given the present 1σ bounds we conclude that only positive values of R are preferred. Similarly, the graph in Fig. 2 depicts the CP asymmetry of the decay, and it can be as large as 10% in the parameter region preferred by the branching ratio constraints.

Though we have restricted our analysis to $B \rightarrow X_s \gamma$ only, it is clear that such family-non-universal Z' bosons will contribute to various FCNC observables. Among others, the two hadronic decays $B \rightarrow J\psi K_s$ and $B \rightarrow \pi K_s$ are of prime importance. The CP violation in the former has already been measured constituting the present value of $\sin 2\beta$. The latter, however, is a pure

penguin process and it is still under investigation. Any measurable difference between the CP asymmetries of respective decay modes will be a violation of the SM expectation. This then can be taken as a signal of the new physics effects, among all possible candidates, the family non-universal Z' models are of particular importance since any difference between the couplings to charm and strange quarks will show up as shift from $\sin 2\beta$.

FIGURE CAPTIONS

Figure 1. Plot of branching ratio (BR) as a function of R for different values of I.

Figure 2. Plot of CP asymmetry A_{CP} as a function of R for different values of I.

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