Direct CP asymmetry of $b \to s\gamma$ and $b \to d\gamma$ in models beyond the Standard Model

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We study the direct CP asymmetry of the decays $b \to s\gamma$ and $b \to d\gamma$ in the context of two models: i) a supersymmetric (SUSY) model with unconstrained SUSY phases, and ii) a model with a single generation of vector quarks. In both the above models we show that $b \to d\gamma$ can sizeably influence the combined asymmetry (i.e. that of a sample containing both $b \to s\gamma$ and $b \to d\gamma$), and in case (ii) may in fact be the dominant contribution.

1. Introduction

Theoretical studies of rare decays of $b$ quarks have attracted increasing attention since the start of the physics programme at the $B$ factories at KEK and SLAC. Many rare decays will be observed for the first time over the next few years, and in this talk we summarize our work on the decays $b \to d\gamma$ and $b \to s\gamma$ in the context of two models: i) a supersymmetric (SUSY) model with unconstrained SUSY phases$^1$, and ii) a model with a single generation of vector quarks$^2$.

There is considerable motivation for measuring the BR and CP asymmetry ($A_{CP}$) of the inclusive channel $B \to X_d\gamma$. In particular we highlight the following:

(i) $b \to d\gamma$ transitions sizeably affect the measurements of $A_{CP}$ for $b \to s\gamma$$^3$. Therefore knowledge of $A_{CP}$ for $b \to d\gamma$ is essential, in order to compare experimental data with the theoretical prediction in a given model.

(ii) $A_{CP}$ for the combined signal of $B \to X_s\gamma$ and $B \to X_d\gamma$ is expected to be close to zero in the Standard Model (SM)$^4$$^5$$^6$, due the real Wilson coefficients and the unitarity of the CKM matrix. Both of these conditions can be relaxed in models beyond the SM.

2. The decays $b \to d\gamma$ and $b \to s\gamma$

There is much theoretical and experimental motivation to study the ratio

$$R = \frac{BR(B \to X_d\gamma)}{BR(B \to X_s\gamma)}$$

(1)

because it provides a clean handle on the ratio $|V_{td}/V_{ts}|^2$$^7$. In the context of the SM, $R$ is expected to be in the range $0.017 < R < 0.074$, corresponding to $BR(B \to X_d\gamma)$ of order $10^{-5}$. $R$ stays confined to this range in many popular models beyond the SM. This is because new particles such as charginos and charged Higgs bosons in SUSY models contribute to $b \to s(d)\gamma$ with the same CKM factors. Therefore $C_7$ is universal to both decays and cancels out in the ratio $R$. In a model with vector quarks this is not the case, and we shall see that $R$ can be suppressed or enhanced with respect to the SM.

$A_{CP}^{d\gamma(s\gamma)}$ is given by:

$$\frac{\Gamma(B \to X_d\gamma)}{\Gamma(B \to X_s\gamma)} = \frac{A_{CP}^{d\gamma(s\gamma)}}{\Gamma_{tot}^{d\gamma(s\gamma)}}$$

(2)

In the SM $A_{CP}^{d\gamma}$ is expected to lie in the range $-5\% \leq A_{CP}^{d\gamma} \leq -28\%$$^8$, where the uncertainty arises from varying the Wolfenstein parameters $\rho$ and $\eta$ in their allowed ranges. Therefore $A_{CP}^{d\gamma}$ is much larger than $A_{CP}^{s\gamma}$ ($\leq 0.6\%$).

If $b \to d\gamma$ and $b \to s\gamma$ cannot be properly separated, then only $A_{CP}$ of a combined sample can
be measured. It has been shown that $A_{\gamma}^{\gamma}$ and $A_{\gamma}^{d\gamma}$ approximately cancel each other in the SM, leading to a combined asymmetry close to zero.

A reliable prediction of $A_{\gamma}^{d\gamma}$ in a given model is necessary since it contributes to the measurement of $A_{CP}^{s\gamma}$. The CLEO result is sensitive to a weighted sum of CP asymmetries, given by:

$$A_{CP}^{s\gamma} = 0.965 A_{\gamma}^{s\gamma} + 0.02 A_{\gamma}^{d\gamma}$$  (3)

The latest measurement stands at $-27\% < A_{CP}^{s\gamma} < 10\%$ (90% C.L.). The small coefficient of $A_{CP}^{d\gamma}$ is caused by the smaller BR($B \to X_{\gamma}$) (assumed to be 1/20 that of BR($B \to X_s\gamma$)) and inferior detection efficiencies.

If the detection efficiencies for both decays were identical, this measured quantity would coincide with the weighted sum of the asymmetries

$$A_{CP}^{s\gamma+d\gamma} = \frac{BR^{s\gamma} A_{\gamma}^{s\gamma} + BR^{d\gamma} A_{\gamma}^{d\gamma}}{BR^{s\gamma} + BR^{d\gamma}}.$$  (4)

The two terms in eqs. (3) can be of equal or of opposite sign, i.e. they can contribute constructively or destructively to the combined asymmetry. The non-negligible contribution of $b \to d\gamma$ to this combined asymmetry should be verifiable at proposed future high luminosity runs of $B$ factories.

3. Results

We now show numerical results for the two models considered.

3.1. Effective SUSY model

In Fig. 1 we plot $A_{CP}^{d\gamma}$ against $m_{\tilde{t}_1}$, which clearly shows that a light $\tilde{t}_1$ may drive $A_{CP}^{d\gamma}$ positive, reaching maximal values close to +40%. For $\tilde{t}_1$ heavier than 250 GeV the $A_{CP}^{d\gamma}$ lies within the SM range, which is indicated by the two horizontal lines. In Fig. 2 we plot $A_{CP}^{s\gamma}$ against $A_{\gamma}^{s\gamma}$. One can see that both $A_{\gamma}^{s\gamma}$ and $A_{\gamma}^{d\gamma}$ may have either sign, resulting in constructive or destructive interference in eq. (3).

In Fig. 3 we plot the $A_{CP}^{d\gamma}$ (defined in eq. (3)) against $A_{CP}^{s\gamma}$. If the contribution from $A_{\gamma}^{d\gamma}$ were ignored in eq. (3), then Fig. 3 would be a straight line through the origin. The $A_{CP}^{s\gamma}$ contribution broadens the line to a thin band of width $\approx 1\%$, an effect which should be detectable at proposed higher luminosity runs of the $B$ factories.

3.2. Vector quark model

In Fig. 4 we plot $A_{CP}^{d\gamma}$ against $A_{CP}^{s\gamma}$. It can be seen that $A_{CP}^{s\gamma}$ does not substantially differ from its SM value, while $A_{CP}^{d\gamma}$ can vary over a much larger range. The correlation between $A_{CP}^{d\gamma}$ and BR($B \to X_{s\gamma}$) is studied in detail in Fig. 5, where it can be seen that $\lvert A_{CP}^{d\gamma} \rvert > 45\%$ occurs only for $\text{BR}(d\gamma < 10^{-6})$. Branching ratios of this magnitude would require $10^8 bb$ pairs to be detected which is beyond the discovery potential of current $B$ factories.

In Fig. 6 we plot the combined CP asymmetry as defined in eqn. (2) against the argument of $V_{us}V_{ub}^*$. Note that in our analysis BR($s\gamma$ and $A_{CP}^{s\gamma}$ are close to their SM values. The huge variations in $A_{CP}^{s\gamma+d\gamma}$ stem from the variation in BR($d\gamma$). In wide ranges of our parameter space, $b \to d\gamma$ actually dominates the combined asymmetry! Any large signal observed in $A_{CP}^{s\gamma+d\gamma}$ is a sign of physics beyond the SM, but although BR($s\gamma+d\gamma$) is strongly dominated by $b \to s\gamma$, a non–SM value for $A_{CP}^{s\gamma+d\gamma}$ can stem from both $b \to s\gamma$ and $b \to d\gamma$.

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Figure 1. $A_{CP}^{d_\gamma}$ against $m_{t_1}$

Figure 2. $A_{CP}^{d_\gamma}$ against $A_{CP}^{\gamma}$

Figure 3. CLEO $A_{CP}^{exp}$ against $A_{CP}^{\gamma}$

Figure 4. $A_{CP}^{d_\gamma}$ against $A_{CP}^{\gamma}$

Figure 5. $A_{CP}^{d_\gamma}$ against BR($b \to d \gamma$)

Figure 6. $A_{CP}^{\gamma+\ell_\gamma}$ against Arg $V_{Ud}^* V_{Ub}$