Effects of New Physics on CP Violation in B Decays

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Abstract. We discuss two models with 1 extra CP phase in b → s transition. The CP phase arg(V_{ts}V_{tb}^*) with fourth generations, previously ignored, could impact on b → sℓ⁺ℓ⁻, Δm_{B_d} and sin 2Φ_{B_d}, but does not affect EM and strong penguins. With SUSY at TeV scale, a right-handed "s_1" squark can be driven light by flavor mixing. It does not affect b → sℓ⁺ℓ⁻, but can generate S_{φK_3} < 0 while giving S_{φ'K_3} sin 2Φ_{B_d} ≃ 0.74. B_s mixing and sin 2Φ_{B_s} would likely be large, and S_{K_3 s^o_γ} ≠ 0 in B^0 → K^{*0}γ is promising.

PACS. 11.30.Hv Flavor symmetries – 12.60.Jv Supersymmetric models – 13.25.Hw Decays of B mesons

1 Introduction

With sin 2Φ_{B_d} agreeing with CKM fit, New Physics (NP) seems absent in B_d mixing, but b → s transitions seem fertile. The large Kπ/ππ ratio shows the importance of penguins. More intriguing [1] is the hint of S_{φK_3} < 0, although S_{φ'K_3} sim 2Φ_{B_d}. Belle’s 2003 result [1,2] is 3.5σ from 0.74. Despite BaBar’s change in sign, this is still a strong indication for NP in b → s penguins.

B_s mixing has been “just around the corner” since the 1990s. It eliminates the second quadrant for φ_3 in the CKM fit, but this would no longer hold if NP lurks. The litmus test for NP would be to find sin 2Φ_{B_s} ≠ 0, hopefully in the near future. Another clear sign for NP would be wrong helicity photons in b → sγL, which can be tested via measuring S_{B_s→φγ}, or by measuring A polarization in B_s → Aγ. However, there is now hope to reconstruct [1] B_d vertex from K_3 at B factories, allowing one to measure S_{B_d→K_3 π^o γ} where K_3 π^o comes from K^{*0}.

The present is already bright for NP search in b → s transitions, and the future can only be brighter! To elucidate the possibilities lying ahead for us, we focus on models that bring in just 1 extra CP phase in b → s. The first model is that of a 4th generation [3]. The second is large s_R-b_R mixing [4,5] with SUSY.

2 4th Generation

It is peculiar that, since the early [6] discussions of impact of 4th generation on b → sℓℓ, where λ_{ν'} ≡ V_{ts}^* V_{tb} ≡ r_s e^{iθ_s} was taken as real for convenience, the literature that followed mostly ignored the possibility of Φ_s ≠ 0.

It is true that |λ_t| ≥ |λ_ν| ≥ |λ_γ| ≃ 0.0006. For a typical operator O_i(μ), its coefficient is changed from λ_{C^i_ν}(μ) to λ_{C^i_ν}(μ) + λ_{C^i_ν}(μ) by simple rearrangement one gets,

\[ \lambda_{C^i_ν} + \lambda_{C^i_ν} = -\lambda_{C^i_ν} + \lambda_{C^i_ν} \] (1)

where the first term is the usual SM contribution. The second term is the genuine 4th generation effect. It vanishes for m_{ν'} → m_ν or λ_{ν'} → 0, as required by GIM. What has been popular, besides ignoring Φ_s, is to absorb λ_{ν'} into the definition of C^i_ν. This is rather bad practice.

We have 3 new parameters, m_{ν'}, r_s and Φ_s, where we are most interested in the latter. The constraints from B^{exp}(B → X_s γ) = (3.3 ± 0.4) × 10^{-4}, which agrees with SM3, is rather weak. B_s mixing is strongly dependent on m_{ν'}.

Choosing SM parameters such that Δm_{B_s} = 17.0 ps^{-1}, the bound of 14.9 ps^{-1} disfavors 0 ≤ r_s ≤ 0.03 and cos Φ_s > 0, because t' effect is destructive. The allowed parameter space is larger for lower m_{ν'} , but the most forgiving zone is when Φ_s ~ π/2 or 3π/2, i.e. purely imaginary, when t' effects add in quadrature to SM3!

One interesting test ground for SM4 is b → sℓℓ [6], since the EW or Z penguin has strong m_{ν'} dependence like Δm_{B_s}. Unlike Δm_{B_s}, however, several modes are now measured. The first measurement of B → Kℓℓ was on the high side of SM3, which motivated our study of SM4 [3]. Now the number has come down, and both B → Kℓℓ and K^*ℓℓ are not in disagreement with SM.

In any case, the exclusive rates have larger hadronic uncertainties, so let us focus on the inclusive, where the current Belle result of B(B → X_s l^+ l^-) = (6.1 ± 2.9) × 10^{-6} is slightly higher than SM3 expectation of ~ 4.2 × 10^{-6}, partly because NNLO result dropped by 40%. In Fig. 1 we plot B(B → X_s l^+ l^-) contours in Φ_s-r_s plane, for m_{ν'} = 250 and 350 GeV. For cos Φ_s > 0, B → X_s l^+ l^- is less than 4.2 × 10^{-6} hence less favored. The behavior for π/2 < Φ_s < 3π/2 is rather similar to Δm_{B_s}, but provides more stringent bounds since B_s mixing is not yet measured. Furthermore, it will more readily improve. In
a way, one may say that if NNLO result for SM3 remains low, if refined experiment still gives $5 \times 10^{-6}$, SM4 may be called for. Again we note that $\Phi_s \sim \pi/2$ or $3\pi/2$ is more accommodating, and allows for larger $r_s$. However, there is no further information in $m_{t R}^2$ spectrum, and, constrained by the observed rate, $A_{FB}$ is as in SM3.

The highlight for SM4, by considering CP phase $\Phi_s$, is prospect for sizable $\sin 2\Phi_s$, where any nonvanishing value would indicate NP. We define $\Delta m_{B_s} = 2|M_{12}|$ and $M_{12} = |M_{12}|^2 e^{i\Phi_{B_s}}$. As the box diagrams can contain none (SM3), one or two $t'$ legs, we have

$$M_{12} = |M_{12}|^2 e^{2i\Phi_{B_s}} \sim r_s^2 e^{2i\Phi_s} A + r_s e^{i\Phi_s} B + C$$  \hspace{1cm} (2)

where $A$ and $B$ are explicit functions of $m_t$ and $m_{t'}$ and $C$ is the usual SM3 contribution. This allows us to understand the change of “periodicity” of $\sin 2\Phi_{B_s}$ vs. $\Phi_s$ in Fig. 2, which plots both $\Delta m_{B_s}$ (left) and $\sin 2\Phi_{B_s}$ for $m_{t'} = 250$, $300$ GeV for several $r_s$ values. The straight lines are the SM3 expectations. For $\Delta m_{B_s}$ this is slightly above experimental bound. Thus, only the $\Phi_s$ range where $\Delta m_{B_s}$ falls a little below the straight line is ruled out.

We offer several observations on prospects for $\sin 2\Phi_{B_s}$ by inspection of Fig. 2: (1) Even small $r_s$ values can give sizable $\sin 2\Phi_{B_s}$; (2) Both signs are possible; (3) Largest if $\Delta m_{B_s}$ is “just around the corner”, i.e. to be measured soon. This last point makes SM4 very interesting at the Tevatron Run II. As discussed, $\Delta m_{B_s}$ hovers around SM3 expectation for $\Phi_s \sim \pi/2$ or $3\pi/2$, when all constraints are most accommodating because they add in quadrature to SM3 effects, except in the direct measure of CP phase, $\sin 2\Phi_{B_s}$. One has the ideal situation that $\Delta m_{B_s}$ is most measurable, while $\sin 2\Phi_{B_s}$ can vary between $\pm 1$.

### 3 Light $\tilde{s}b_{1R}$ Squark

The 4th generation is not effective on EM and strong penguins, because $t$ and $t'$ effects are very soft for such loops. Furthermore, the chirality is the same as SM3, i.e. left-handed, hence only the usual right-handed helicity photons appear in $b \to s\gamma$. The scenario of a light $\tilde{s}b_{1R}$ squark, however, can touch all these aspects as well as $B_s$ mixing, though it does not affect $b \to s\ell\ell$.

Large $\tilde{s}R$-$\tilde{b}R$ mixing can be related, in the context of SUSY-GUT, to [7] the observed near maximal $\nu_{\mu}$-$\nu_{\tau}$ mixing. While this is attractive in itself, we prefer not to assume the behavior at high scale, but to look at what data demands. The 2003 average for $S_{\nu_{\mu}\nu_{\tau}} = -0.15 \pm 0.33$ is still $2.7\sigma$ from SM expectation of 0.74. As this would be a large NP $b \to s$ CP violation effect, it would demand (i) large effective $s$-$b$ mixing, and the presence of a (ii) large new CP phase. Furthermore, to allow for $S_{\nu_{\mu}\nu_{\tau}} \sim \sin 2\Phi_{B_s}$, the (iii) new interaction should be right-handed [8]. We find it extremely interesting that all three aspects are brought about naturally by the synergies of Abelian flavor symmetry (AFS) and SUSY. We will see that AFS brings in large $sR$-$bR$ mixing, and SUSY makes this dynamical, and also activating one new CP phase in $sR$-$bR$ mixing.

Focusing only on the 2-3 down sector, the normalized $d$ quark mass matrix has the elements $\tilde{M}_{33}^{(d)} \approx 1$, $\tilde{M}_{22}^{(d)} \approx \lambda^2$, while taking analogy with $V_{cb} \approx \lambda^2$ gives $\tilde{M}_{23}^{(d)} \approx \lambda^2$. But $\tilde{M}_{32}^{(d)}$ is unknown for lack of right-handed flavor dynamics. With effective AFS [9], however, the Abelian nature implies $\tilde{M}_{23}^{(d)} \tilde{M}_{32}^{(d)} \sim \tilde{M}_{33}^{(d)} \tilde{M}_{22}^{(d)}$, hence $\tilde{M}_{32}^{(d)} \sim 1$ is deduced. This may be the largest off-diagonal term, but its effect is hidden within SM. With SUSY, the flavor mixing extends to $\tilde{s}R$-$\tilde{b}R$, which we parametrize as

$$\tilde{M}_{RR}^{(2)} = \begin{bmatrix} m_1^2 & m_2^2 e^{-i\sigma} & m_3^2 e^{-i\sigma} \\ m_2^2 e^{i\sigma} & m_3^2 & m_1^2 e^{-i\sigma} \\ m_3^2 e^{i\sigma} & m_1^2 e^{-i\sigma} & m_2^2 \\ \end{bmatrix} \equiv R \left[ \begin{bmatrix} \bar{m}_1^2 \\ 0 \\ 0 \end{bmatrix} \right] R^T \hspace{1cm} (3)$$

where $\bar{m}_{12} \approx \bar{m}_2$, the common squark mass, and

$$R = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \hspace{1cm} (4)$$

There is just one [4] CP phase $\sigma$, which is on equal footing with the KM phase $\delta$ as both are rooted in the quark mass matrix. Note that $\tilde{M}_{LL}^2 = (\tilde{M}_{RL}^2)^{\dagger} \sim \bar{m}M$ is suppressed by quark mass, while $\tilde{M}_{LL}^2$ is CKM suppressed.

The presence of large flavor violation in squark masses pushes SUSY scale to above TeV, even after one decouples $d$-flavor [4]. Interestingly, the near democratic nature of Eq. (3) allows, by some fine tuning, one squark to be driven light by the large mixing. We denote this squark $\tilde{s}b_{1R}$, and take its mass at 200 GeV for illustration (so $\tilde{s}b_{2R}$ would have mass $2\bar{m}_2$). The presence of right-handed
can in principle be brought up for \( \sigma < \) known that the standard gluonic dipole penguin (\( (e) \)) lines are for \( \left| s_{\ell K\pi} \right| \), for \( \widehat{m} = 200 \text{ GeV} \) and compared with experiment. Solid, dotdash (dash, dots) lines are for \( \widehat{m} = 2, 1 \text{ TeV} \), \( m_\theta = 0.8 (0.5) \text{ TeV} \).

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