Eur Phys J C **33**, s01, s346–s348 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2003-03-306-y

EPJ C direct
electronic only

Effects of new physics on CP violation in B decays

George W.S. Hou

Department of Physics, National Taiwan University, Taipei, Taiwan 10764

Received: 30 October 2003 / Accepted: 9 December 2003 /
Published Online: 12 December 2003 –

Abstract. We discuss two models with 1 extra CP phase in $b \leftrightarrow s$ transition. The CP phase $\arg(V_{t's}V_{t'b})$ with fourth generations, previously ignored, could impact on $b \to s\ell^+\ell^-$, Δm_{B_s} and $\sin 2\Phi_{B_s}$, but does not affect EM and strong penguins. With SUSY at TeV scale, a right-handed "$\widetilde{sb}_1$" squark can be driven light by flavor mixing. It does not affect $b \to s\ell^+\ell^-$, but can generate $S_{\phi K_S} < 0$ while giving $S_{\eta' K_S} \sim \sin 2\Phi_{B_d} \cong 0.74$. B_s mixing and $\sin 2\Phi_{B_s}$ would likely be large, and $S_{K_S\pi^0\gamma} \neq 0$ in $B^0 \to K^{*0}\gamma$ is promising.

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

1 Introduction

With $\sin 2\Phi_{B_d}$ agreeing with CKM fit, New Physics (NP) seems absent in B_d mixing, but $b \leftrightarrow s$ transitions seem fertile. The large $K\pi/\pi\pi$ ratio shows the importance of penguins. More intriguing [1] is the hint of $S_{\phi K_S} < 0$, although $S_{\eta' K_S} \sim \sin 2\Phi_{B_d}$. 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 $b \to s$ 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 $\sin 2\Phi_{B_s} \neq 0$, hopefully in the near future. Another clear sign for NP would be wrong helicity photons in $b \to s\gamma_L$, which can be tested via measuring $S_{B_s\to\phi\gamma}$, or by measuring Λ polarization in $\Lambda_b \to \Lambda\gamma$. However, there is now hope to reconstruct [1] B_d vertex from K_S at B factories, allowing one to measure $S_{B_d\to K_S\pi^0\gamma}$ where $K_S\pi^0$ comes from K^{*0}.

The present is already bright for NP search in $b \leftrightarrow s$ 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 $b \leftrightarrow s$. The first model is that of a 4th generation [3]. The second is large $\tilde{s}_R$-$\tilde{b}_R$ mixing [4,5] with SUSY.

2 4th generation

It is peculiar that, since the early [6] discussions of impact of 4th generation on $b \to s\ell\ell$, where $\lambda_{t'} \equiv V^*_{t's}V_{t'b} \equiv r_s\, e^{i\Phi_s}$ was taken as real for convenience, the literature that followed mostly ignored the possibility of $\Phi_s \neq 0$.

It is true that $\lambda_t \cong -\lambda_c - \lambda_{t'} \cong -0.04 - \lambda_{t'}$ for $r_s = |\lambda_{t'}| \gg |\lambda_u| \approx \lambda^5 \sim 0.0006$. For a typical operator $O_i(\mu)$, its coefficient is changed from $\lambda_t C_i^{\rm SM}(\mu) \to \lambda_t C_i^{\rm SM}(\mu) + \lambda_{t'} C_i^{\rm new}(\mu)$. By simple rearrangement one gets,

$$\lambda_t C_i^{\rm SM} + \lambda_{t'} C_i^{\rm new} = -\lambda_c C_i^{\rm SM} + \lambda_{t'}(C_i^{\rm new} - C_i^{SM}), \quad (1)$$

where *the first term is the usual SM contribution*. The second term is the genuine 4th generation effect. It vanishes for $m_{t'} \to m_t$ or $\lambda_{t'} \to 0$, as required by GIM. What has been popular, besides ignoring Φ_s, is to absorb $\lambda_{t'}$ into the definition of $C_i^{\rm new}$. This is rather bad practice.

We have 3 new parameters, $m_{t'}$, r_s and Φ_s, where we are most interested in the latter. The constraints from $\mathcal{B}^{\rm expt}(B \to X_s\gamma) = (3.3 \pm 0.4) \times 10^{-4}$, which agrees with SM3, is rather weak. B_s mixing is strongly dependent on $m_{t'}$. Choosing SM parameters such that $\Delta m_{B_s}^{\rm SM3} = 17.0$ ps^{-1}, the bound of 14.9 ps^{-1} disfavors $0 \le r_s \le 0.03$ and $\cos\Phi_s > 0$, because t' effect is destructive. The allowed parameter space is larger for lower $m_{t'}$, but the most forgiving zone is when $\Phi_s \sim \pi/2$ or $3\pi/2$, i.e. purely imaginary, when t' effects add in quadrature to SM3!

One interesting test ground for SM4 is $b \to s\ell\ell$ [6], since the EW or Z penguin has strong $m_{t'}$ dependence like Δm_{B_s}. Unlike Δm_{B_s}, however, several modes are now measured. The first measurement of $B \to K\ell\ell$ was on the high side of SM3, which motivated our study of SM4 [3]. Now the number has come down, and both $B \to K\ell\ell$ and $K^*\ell\ell$ 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 $\mathcal{B}(B \to X_s\ell^+\ell^-) = (6.1 \pm 1.4^{+1.3}_{-1.1}) \times 10^{-6}$ is slightly higher than SM3 expectation of $\sim 4.2 \times 10^{-6}$, partly because NNLO result dropped by 40%. In Fig. 1 we plot $\mathcal{B}(B \to X_s\ell^+\ell^-)$ contours in Φ_s-r_s plane, for $m_{t'} = 250$ and 350 GeV. For $\cos\Phi_s > 0$, $B \to X_s l^+l^-$ is less than 4.2×10^{-6} hence less favored. The behavior for $\pi/2 < \Phi_s < 3\pi/2$ 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.

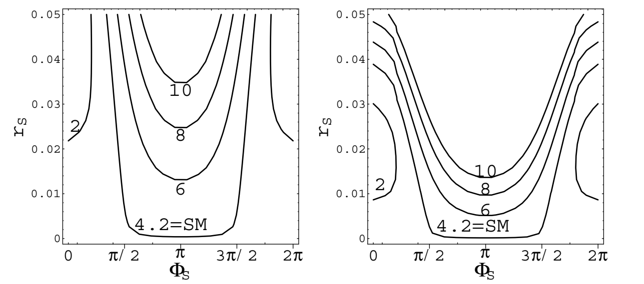

Fig. 1. $\mathcal{B}(B \to X_s \ell^+ \ell^-) \times 10^6$ for $m_{t'} =$ (a) 250, (b) 350 GeV

In a way, one may say that if NNLO result for SM3 remains low, if refined experiment still gives 5×10^{-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 $m_{\ell\ell}^2$ spectrum, and, constrained by the observed rate, $\mathcal{A}_{FB}$ is as in SM3.

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

$$M_{12} = |M_{12}| e^{2i\Phi_{B_s}} \approx r_s^2 e^{2i\Phi_s} A + r_s e^{i\Phi_s} B + C \qquad (2)$$

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. Φ_s in Fig. 2, which plots both Δm_{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 Δm_{B_s} this is slightly above experimental bound. Thus, only the Φ_s range where Δm_{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 Δm_{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, Δm_{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

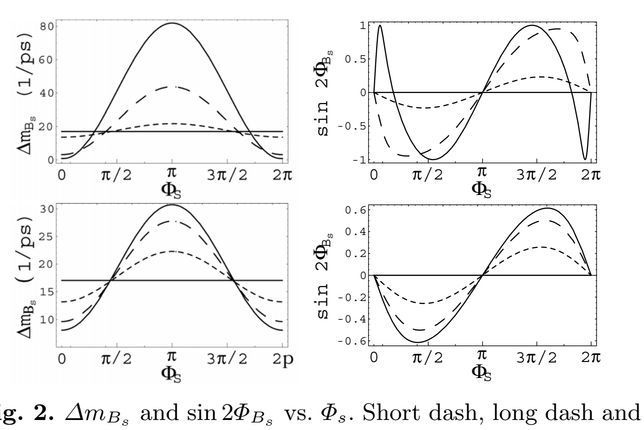

Fig. 2. Δm_{B_s} and $\sin 2\Phi_{B_s}$ vs. Φ_s. Short dash, long dash and solid lines for upper (lower) plots are for $r_s = 0.002$, 0.01, 0.02 (0.002, 0.004, 0.005) and for $m_{t'} = 250$ (350) GeV

to SM3 effects, *except* in the direct measure of CP phase, $\sin 2\Phi_{B_s}$. One has the ideal situation that Δm_{B_s} is most measurable, while $\sin 2\Phi_{B_s}$ can vary between ± 1.

3 Light $\widetilde{sb}_{1R}$ 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 $\widetilde{sb}_{1R}$ 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 ν_μ-ν_τ 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 $S_{\phi K_S} = -0.15 \pm 0.33$ is still 2.7σ 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 $S_{\eta' K_S} \sim \sin 2\Phi_{B_d}$, 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 s_R-b_R mixing, and SUSY makes this dynamical, and also activating one new CP phase in $\tilde{s}_R$-$\tilde{b}_R$ mixing.

Focusing only on the 2-3 down sector, the normalized d quark mass matrix has the elements $\hat{M}_{33}^{(d)} \simeq 1$, $\hat{M}_{22}^{(d)} \simeq \lambda^2$, while taking analogy with $V_{cb} \simeq \lambda^2$ gives $\hat{M}_{23}^{(d)} \simeq \lambda^2$. But $\hat{M}_{32}^{(d)}$ is unknown for lack of right-handed flavor dynamics. With effective AFS [9], however, the *Abelian* nature implies $\hat{M}_{23}^{(d)} \hat{M}_{32}^{(d)} \sim \hat{M}_{33}^{(d)} \hat{M}_{22}^{(d)}$, hence $\hat{M}_{32}^{(d)} \sim 1$ 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

$$\widetilde{M}_{RR}^{2(sb)} = \begin{bmatrix} \widetilde{m}_{22}^2 & \widetilde{m}_{23}^2 e^{-i\sigma} \\ \widetilde{m}_{23}^2 e^{i\sigma} & \widetilde{m}_{33}^2 \end{bmatrix} \equiv R \begin{bmatrix} \widetilde{m}_1^2 & 0 \\ 0 & \widetilde{m}_2^2 \end{bmatrix} R^\dagger, \qquad (3)$$

where $\widetilde{m}_{ij}^2 \simeq \widetilde{m}^2$, the common squark mass, and

$$R = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta e^{i\sigma} & \cos\theta e^{i\sigma} \end{bmatrix}. \qquad (4)$$

There is *just one* [4] CP phase σ, which is on equal footing with the KM phase δ as both are rooted in the quark mass matrix. Note that $\widetilde{M}_{LR}^2 = (\widetilde{M}_{RL}^2)^\dagger \sim \widetilde{m}M$ is suppressed by quark mass, while $\widetilde{M}_{LL}^2$ 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 (3) allows, by some fine tuning, one squark to be driven light by the large mixing. We denote this squark $\widetilde{sb}_{1R}$, and take its mass at 200 GeV for illustration (so $\widetilde{sb}_{2R}$ would

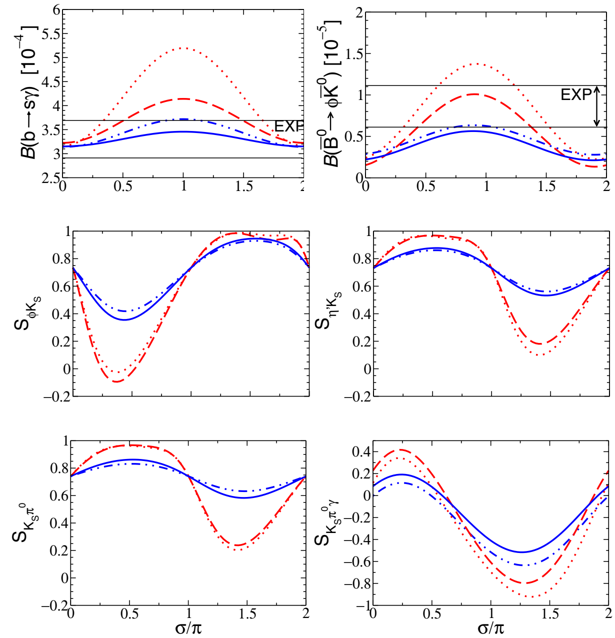

Fig. 3. a $\mathcal{B}(b \to s\gamma)$, **b** $\mathcal{B}(B^0 \to \phi K^0)$, **c** $S_{\phi K_S}$, **d** $S_{\eta' K_S}$, **e** $S_{K_S\pi^0}$ and **f** $S_{K_S\pi^0\gamma}(\bar{B}^0 \to \bar{K}^{*0}\gamma)$ vs σ for $\widetilde{m}_1 = 200$ GeV and compared with experiment. Solid, dotdash (dash, dots) lines are for $\widetilde{m} = 2$, 1 TeV, $m_{\tilde{g}} = 0.8$ (0.5) TeV

have mass $2\widetilde{m}^2$). The presence of right-handed $s_R\tilde{b}_R\tilde{g}$ couplings doubles the operators O_i by flipping chirality, to O'_i. We calculate coefficients c_i and c'_i in mass basis, and evaluate matrix elements in naive factorization. The most interesting effect occurs to photonic and gluonic dipole penguins, in particular c'_{11} and c'_{12}. Let us now just discuss the salient results, which are plotted in Fig. 3.

Figure 3(a) shows that $b \to s\gamma$ is rather accommodating. This is because the right-handed effect adds only in quadrature to $b \to s\gamma$ rate [4]. We cannot account for $B \to \eta' K$ rate, but Fig. 3(b) shows that $B \to \phi K_S$ rate can in principle be brought up for $\cos\sigma < 0$, while it is known that the standard gluonic dipole penguin (c_{12}) suppresses the rate. It is amusing that if one takes the two rates together as constraints, purely imaginary σ is preferred, which is further born out from CP measurables.

Figure 3(c) plots the enigmatic $S_{\phi K_S}$ vs. σ. It is interesting that the low $\widetilde{sb}_{1R}$ mass, together with a low $m_{\tilde{g}}$ mass of 500 GeV, can [7,8] bring $S_{\phi K_S}$ negative for $\sigma \sim \pi/2$. However, as seen from Fig. 3(d), $S_{\eta' K_S}$ stays above $\sin 2\Phi_{B_d} \cong 0.74$ hence is positive [8]. This is due to right-handed interactions. More specifically, one has

$$\mathcal{A}(\bar{B}^0 \to \phi\bar{K}^0) \propto \left\{\cdots + \frac{\alpha_s}{4\pi}\frac{m_b^2}{q^2}\,\tilde{S}_{\phi K}\,(c_{12} + c'_{12})\right\}, \quad (5)$$

where $\cdots$ are several terms $\propto a_i + a'_i$, and $\mathcal{A}(\bar{B}^0 \to \eta'\bar{K}^0)$ is even more complicated, but the crucial point is a sign change for the c'_{12} term. Pseudoscalar production picks up the sign of the axial current!

Besides elucidating how $S_{\phi K_S} < 0$ while $S_{\eta' K_S} \sim \sin 2\Phi_{B_d}$ can be maintained, (5) also shows the elements in enhancing the effect of c'_{12}. Lowering squark and gluino masses enhances c'_{12}, but we also have the hadronic parameters $\tilde{S}_{\phi K}/q^2$. We resort to these for further enhancement rather than lowering $m_{\tilde{g}}$ further.

Having zoomed into $\sigma \sim 65°$ as "preferred", we were surprised to find, contrary to our earlier thought [4], that the lighter gluino makes $\Delta m_{B_s} \gtrsim 70$ ps^{-1} rather difficult to avoid [5], even though $\sin 2\Phi_{B_s}$ could vary through 0 to 1. Reminded by the sluggish start of Tevatron Run II, it seems that $\Delta m_{B_s} \gtrsim 70$ ps^{-1} would have to await LHCb or BTeV. What is worse, even with Δm_{B_s} measured some years from now, the very fast B_s oscillations would make, with the exception of perhaps $\sin 2\Phi_{B_s}$ itself, much of the CP program in B_s decay rather difficult.

We are, however, intrigued by a very recent development. BaBar has made a first attempt [1] at measuring $S_{K_S\pi^0}$, "reconstructing" the B^0 vertex by extrapolating K_S momentum onto the boost, i.e. B direction, a knowledge that is unique to B factories. They find $S_{K_S\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.10$, which is in agreement with our results shown in Fig. 3(e). The features are similar to $S_{\eta' K_S}$ of Fig. 3(d), since both are PP final states. What excites us is the prospect for measuring mixing dependent CP in $B \to K^{*0}\gamma$, formerly thought impossible, but now hopeful with this "K_S vertexing" technique. We note that

$$S_{M^0\gamma} = \frac{2|c_{11}c'_{11}|}{|c_{11}|^2 + |c'_{11}|^2}\,\xi\,\sin\left(2\phi_{B_d} - \varphi_{11} - \varphi'_{11}\right), \quad (6)$$

where ξ is the CP of reconstructed M^0 final state, and $\phi_{B_d} = \phi_1$, $\varphi_{11}^{(\prime)}$ are the phases of B_d mixing and $c_{11}^{(\prime)}$, respectively. For $B \to K^{*0}\gamma$ with K^{*0} decaying to CP eigenstate $K_S\pi^0$, (6) can be completely calculated, with little hadronic uncertainty, which we plot in Fig. 3(f).

The finiteness of this single measurable justifies the luminosity upgrades of B factories, currently being contemplated, because it provides a clean measure and confirmation of the type of NP. The measurables such as $S_{\phi K_S}$, $S_{\eta' K_S}$ and $S_{K_S\pi^0}$, tantalizing as they might be, are plagued by hadronic parameters such as $\tilde{S}_{\phi K}/q^2$. We note, finally, that $S_{K_S\pi^0\gamma}(\bar{B}^0 \to \bar{K}^{*0}\gamma)$ is close to impossible to measure at hadronic machines, for not knowing B direction, and having too many photons.

SuperB upgrades should invest on a large Silicon Vertex Detector.

References

1. Plenary talk by T. Browder at Lepton Photon Symposium, August 2003, Fermilab, USA
2. K. Abe et al. (Belle Collab.): hep-ex/0308035
3. A. Arhrib and W.S. Hou: Eur. Phys. J. C **27**, 555 (2003)
4. A. Arhrib, C.K. Chua, and W.S. Hou: Phys. Rev. D **65**, (2002) 017701
5. C.K. Chua, W.S. Hou, and M. Nagashima: hep-ph/0308298
6. W.S. Hou, R.S. Willey, and A. Soni: Phys. Rev. Lett. **58**, 1608 (1987)
7. R. Harnik, D.T. Larson, H. Murayama, and A. Pierce: hep-ph/0212180
8. S. Khalil and E. Kou: hep-ph/0303214
9. Y. Nir and N. Seiberg: Phys. Lett. B **309**, 337 (1993)