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Precocious signs of new physics: Are we eight now?

AMARJIT SONI
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
E-mail: soni@bnl.gov

Abstract. Although the CKM-paradigm seems to work to an accuracy of about 15–20%, we emphasize that there are by now several indications that suggest the need for a beyond the Standard Model CP-odd phase. The value of $\sin 2\beta$ measured via the gold-plated (tree) mode, $B \to \psi K_s$ is smaller than the value deduced by using improved lattice matrix elements. The value of $\sin 2\beta$ measured via 'penguin-dominated' (loop) decays tends to be even smaller still. There is also a rather large difference between the direct CP asymmetries in $\bar{B}^0 \to K^- \pi^+$ and $B^- \to K^- \pi^0$ that is rather difficult to understand. More recently, CDF and D0 are finding about a 2σ signal in CP asymmetry in the corresponding gold-plated mode $B_s \to \psi\phi$. If true, this would be consistent with the indications of new CP-phase in penguin $b \to s$ transitions seen at B-factories. After describing these possible signs of trouble for the SM-CKM paradigm, we give a brief discussion of some of the BSM scenarios that could be the underlying cause of these deviations. In particular, we find that the data are quite suggestive of a fourth family with m'_t in the range of 400–600 GeV as perhaps the simplest BSM candidate which 'naturally' explains the data.

Keywords. CP; warped; extra dimension; fourth family.

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1. Introduction

Due to the spectacular performance of the two asymmetric B-factories, we were able to reach an important milestone in our understanding of CP-violation phenomena. For the first time it was established that the observed CP-violation in the B and K systems was indeed accountable by the single, CP-odd, Kobayashi–Maskawa phase in the CKM matrix [1,2]. In particular, the time-dependent CP-asymmetry in the gold-plated $B^0 \to \psi K_s$ can be accounted for by the Standard Model (SM) CKM-paradigm to an accuracy of around 15% [3,4]. It has then become clear that the effects of a beyond the Standard Model (BSM) phase can only be a perturbation. However, in the past 3–4 years as more data were accumulated and also as the accuracy in some hadronic matrix element calculations on the lattice was improved it has become increasingly apparent that several of the experimental results are difficult to reconcile within the SM with three generations [SM3] [5–8] and are in fact indicative of the need for a BSM CP-odd phase. It is clearly important to follow these indications and try to identify the possible origin of these discrepancies

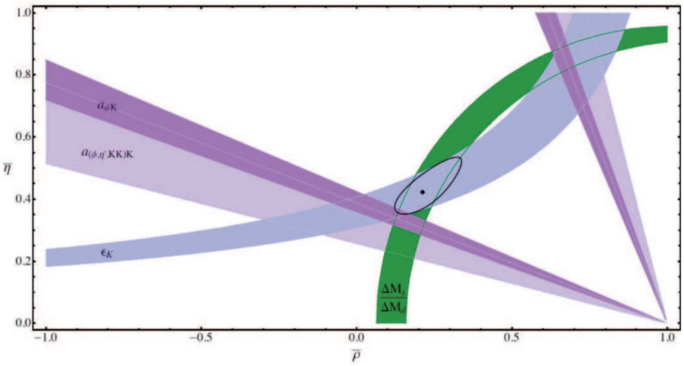

Figure 1. Unitarity triangle fit in the SM. All the constraints are imposed at the 68% CL. The solid contour is obtained using the constraints from ε_K and $\Delta M_{B_s}/\Delta M_{B_d}$. The regions allowed by $a_{\psi K}$ and $a_{(\phi+\eta'+K_sK_s)K_s}$ are superimposed (figure taken from [7]).

especially since they may provide experimental signals for the LHC which is to start almost any time now.

2. Signs of possible trouble for the SM-CKM paradigm

Let us briefly mention the experimental observations involving B-CP asymmetries that are indicative of possible difficulties for the CKM picture of CP-violation.

1. The predicted value of $\sin 2\beta$ in the SM seems to be about 2–3σ larger than the directly measured values. Using only ε_K and $\Delta M_s/\Delta M_d$ from experiment along with the necessary hadronic matrix elements, namely kaon 'B-parameter' B_K and using $SU(3)$ breaking ratio $\xi_s \equiv \frac{f_{bs}\sqrt{B_{bs}}}{f_{bd}\sqrt{B_{bd}}}$, from the lattice, along with V_{cb} yields a prediction, $\sin 2\beta^{\text{prediction}}_{\text{no}V_{ub}} = 0.87 \pm 0.09$ [7] in the SM (see figure 1). If, along with that V_{ub}/V_{cb} is also included as an input then one gets a somewhat smaller central value but with also appreciably reduced error: $\sin 2\beta^{\text{prediction}}_{\text{fullfit}} = 0.75 \pm 0.04$ (see figure 2).
2. The celebrated measurement, via the 'gold-plated' mode $B \to \psi K_s$, gives $\sin 2\beta_{\psi K_s} = 0.681 \pm 0.025$ [3] which is smaller than either of the above predictions by $\approx$1.7 to 2.1σ [7].
3. Penguin-dominated modes, such as $B \to (\phi, \eta', \pi^0, \omega, K_sK_s, ...)K_s$ also allow an experimental determination of $\sin 2\beta$ in the SM [9,10]. This method is less clean as it has theory uncertainty which was naively estimated to be at the level of 5% [10,11]. Unfortunately, this uncertainty cannot be reliably determined in a model-independent manner. However, several different estimates [12,13] find that amongst these modes, $(\phi,\ \eta',\ K_sK_s)K_s$ are rather clean up to an error of only a few per cent. The average of these modes yields, $\sin 2\beta = 0.58 \pm 0.06$ which again deviates by about 2.5 to 2.7σ from the SM predictions. In passing, we note also another rather intriguing feature of many such penguin-dominated modes that the central value of $\sin 2\beta$ that they give

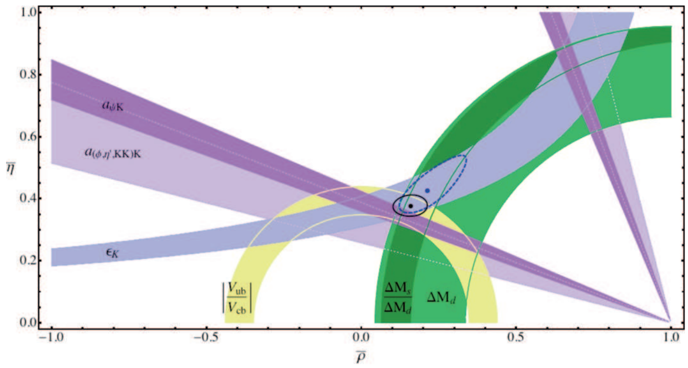

Figure 2. The solid contour is obtained using the constraints from ε_K, $\Delta M_{B_s}/\Delta M_{B_d}$ and $|V_{ub}/V_{cb}|$. The dashed contour shows the effect of excluding $|V_{ub}/V_{cb}|$ from the fit. The regions allowed by $a_{\psi K}$ and $a_{(\phi+\eta'+K_sK_s)K_s}$ are superimposed (figure taken from [7]).

seems to be systematically appreciably below the two SM predicted values given above in #1 and in fact even below the value measured via $B \to \psi K_s$ (given in #2).

4. Another apparent difficulty for the SM is understanding the rather large difference in the direct CP asymmetries $\Delta A_{\rm CP} \equiv A_{\rm CP}(B^- \to K^-\pi^0) - A_{\rm CP}(\bar{B}^0 \to K^-\pi^+) = (14.4 \pm 2.9)\%$ [3]. Naively this difference is supposed to be zero. Using QCD factorization [14] in conjunction with any of the four scenarios for $1/m_b$ corrections that have been proposed [15] we were able to estimate $\Delta A_{\rm CP} = (2.5 \pm 1.5)\%$ [5] which is several σ's away from the experimental observations. It is important to understand that by varying over those four scenarios one is actually spanning the space of a large class of final-state interactions; therefore the discrepancy with experiment is rather serious [16].
5. Finally, more recently the possibility of the need for a largish non-standard CP-phase has been raised [17] in the study of $B_s \to \psi\phi$ at the Fermilab by CDF [18] and D0 [19] experiments. Since the above items suggest the presence of a beyond the SM CP odd phase in $b \to s$ transitions as (for example) already emphasized in [5], such non-standard effects in B_s decays are rather natural and quite unavoidable.

3. Who's there?

We will now discuss a few BSM scenarios that could be responsible for these hints.

3.1 *Warped flavour dynamics*

Perhaps the most interesting BSM scenario is that of warped extra-dimensional models [20] as they offer a simultaneous resolution to EW-Planck hierarchy as well as flavour puzzle. While explicit flavour models are still evolving, potentially this class of models does have extra CP-violating phase(s) that can give smallish (i.e. O(20%)) deviations from the SM in B_d decays to penguin-dominated final states such as ϕK_s, $\eta' K_s$ etc. as well as the possibility of largish CP-odd phase in B_s mixing which then of course has manifestations in $B_s -> \psi\phi$; $X_s l^+ l^-$. etc. [21–23].

The most interesting RS-based flavour models provide a natural understanding of flavours by the notion of 'fermion geography' or localization along the warped (fifth) dimension [24,25]. Therein the light quarks are close to the UV-brane whereas in contrast the top quark tends to be close to the IR-brane. This automatically ensures that flavour changing neutral currents (FCNC) amongst the light quarks are severely suppressed whereas flavour changing processes involving the top-quark, e.g. $t \to cZ$ are significantly enhanced over the SM [26]. This also means that on general grounds one expects enhanced CP-conserving and CP-violating, non-standard effects in D^0 mixing and decays [22].

If these models are responsible for the above hints in B, B_s decays, then we should expect Kaluza–Klein particles such as extra gauge bosons [27–29] and indeed also graviton in the few TeV range [30–33]. However, unless the masses of some of these are below ≈2 TeV, which is unlikely as EW precision tests seem to allow only masses heavier than ≈3 TeV [34], their signatures at the LHC are likely to be very challenging.

3.2 *Two-Higgs doublet model for the top quark*

Another interesting BSM scenario that was studied in the context of such hints of new physics in B_d, B_s physics is that of a two-Higgs doublet model. Such classes of models are of course a very simple extension of the SM and in fact in SUSY they find a natural place as there the 2HDM's become a necessity. However, a specific such model, the two-Higgs doublet model for the top-quark (T2HDM) [35] is also of interest for a variety of reasons. It naturally accomodates $m_t \gg m_b$ by postulating that the second Higgs doublet, that couples only to the top quark, has a much larger VEV (v_2) compared to VEV (v_1) of the 'first' doublet that couples with all the fermions other than the top quark. This of course means that this model does not preserve 'natural flavour conservation' [36]; so, indeed it has tree-level flavour changing-Higgs couplings. However, these are restricted to the charge + 2/3 sector only. Thus the severe K-$\bar{K}$, $B_d\bar{B}_d$, $B_s\bar{B}_s$ constraints are respected but the model predicts enhanced $D^0 - \bar{D}^0$ mixing [37] and enhanced flavour changing decays of the types $Z \to b\bar{s}$, $t \to cZ$ etc. [38]. Furthermore, the model has additional CP violating phases that can have many interesting effects in flavour physics [5,39]

Specifically, the relevance of this model for some of the aforementioned anomalies in B decays, was examined in [5].

3.3 *Fourth family*

Another very simple and interesting extension of the SM is in fact adding a fourth generation [40,41], in short, SM4. Since no clear understanding of the rationale for the occurrence of families exists, it appears sensible to ask the possible role another family may play in explaining these anomalies.

Indeed the important role that b decays can play in the search for a fourth generation was already emphasized over 20 years ago [42]. Some work has also been done recently in identifying some of the interesting signals in B, B_s decays [43]. An important characteristic of this extension of SM3 is that it automatically endows enhanced EWP due to the intrinsic capability of evading the decoupling theorem as was already emphasized in those earlier works [42]. Another crucial feature of SM4 is that it brings in automatically two new CP-odd phases. Not only they can be important in explaining the deviations from SM3 mentioned above but also they can play a very important role in opening a much-needed new avenue for baryogenesis [44,45].

A very appealing feature of the fourth family hypothesis is that it rather naturally explains the pattern of the observed anomalies. First of all the heavy $m_{t'}$ generates a very important new source of electroweak penguin (EWP) contribution since, as is well known, these amplitudes are able to avoid the decoupling theorem and grow as $m_{t'}^2$ [42,46]. This helps to explain two of the anomalies in $b \to s$ transitions. The enhanced EWP contribution helps in explaining the difference in CP-asymmetries, $\Delta A_{\rm CP}$, as it is really $K^{\pm}\pi^0$ that is enhanced because of the colour allowed coupling of Z to π^0 [47]. The second important consequence of t' is that $b \to s$ penguin has a new, BSM3, i.e. beyond the 3-generation Standard Model, CP-odd phase carried by $V_{t'b}V_{t's}^*$. This is responsible for the fact that $\sin 2\beta$ measured in $B \to \psi K_s$ differs from that measured in penguin-dominated modes such as $B \to \phi K_s, \eta' K_s, K_s K_s K_s$.

Note also that $\Delta B = 2$ box graph gets important new contributions from t' since these amplitudes as mentioned before are proportional to $m_{t'}^2$. Furthermore, they are again accompanied by the same new CP-odd phase, $V_{t'b}V_{t's}^*$, which is not present in SM3. This phase is also responsible for the fact that $\sin 2\beta$ measured in $B \to \psi K_s$ is lower than the value(s) 'predicted' in SM3 [7] given in 1 in §2.

Finally, we note briefly in passing how SM4 gives a very natural explanation for the size of the new CP-phase effects in B_d vs. B_s mesons. In B_d oscillations resulting in $B \to \psi K_s$, the top quark plays the dominant role and we see that the measured value of $\sin 2\beta$ deviates by ≈15% from predictions of SM3. It is then the usual hierarchical structure of the mixing matrix (now in SM4) that guarantees that on $\sin 2\beta$, t' will only have a subdominant effect. However, when we consider B_s oscillations then the role of t' and t gets reversed. In B_s mixing the top quark in SM3 has negligible CP-odd phase originating from $V_{tb}V_{ts}^*$. Therein then the new BSM3 t', which carries the BSM3 new CP-odd phase, $V_{tb}V_{ts}^*$ can have important observable effects. SM4 readily explains that just as t is dominant in $\sin 2\beta$ and subdominant in $\sin 2\beta_s$, t' is dominant in $\sin 2\beta_s$ and subdominant in $\sin 2\beta$.

Figure 3 shows the correlation bewteen $S_{\phi K_s}$ and $S_{\psi\phi}$ for $m_t' = 400$ GeV (red), 600 GeV (green), 800 GeV (pink) and 1 TeV (blue) [41]. It should be clear from this figure that once experimentally precise determinations of these two asymmetries are available that should help in pinning the mass of m_t'. For now, the data from the B-factories (on $S_{\phi K_s}$) and from CDF/D0 on ($S_{\psi\phi}$) tend to suggest m_t' in the range of 400–600 GeV.

Since a fourth family necessarily involves rather heavy quarks, we find that $m_t' >$ 400 GeV is needed [41]. It is very likely that it will have an important role in

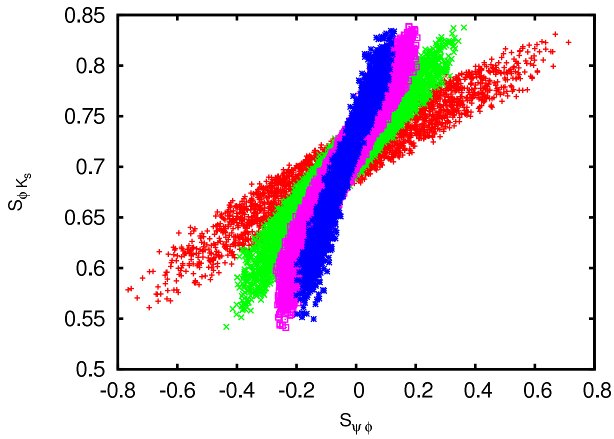

Figure 3. The correlation bewteen $S_{\phi K_s}$ and $S_{\psi\phi}$ for $m_t' = 400$ GeV (red), 600 GeV (green), 800 GeV (pink) and 1 TeV (blue) (taken from [41]).

dynamical EW symmetry breaking. So in this sense it may become also relevant to our understanding of the EW-Planck hierarchy. Thus given its potential roles in important issues such as dynamical EW symmetry breaking and/or in baryogenesis, it need not be just another boring addition. It should also be clear that this family cannot just be another one like the first three, since we know that neutral leptons with this family have to be quite massive with masses $>m_Z/2$. Possible role of this family for the important issue of dark matter has also been suggested [48]. Note also that recent studies show that a fourth family does not necessarily run into conflict with EW precision tests but may require a heavy Higgs particle [49].

If the fourth family hypothesis is true, the LHC could become a gold mine for studies of the heavy quarks and leptons of this family. These collider studies need to be complemented, though, with precision studies at high luminosity super-flavour-factories. Flavour studies will continue to remain important in the LHC era.

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