The fourth family: A simple explanation for the observed pattern of anomalies in $B$--$CP$ asymmetries

Amarjit Soni$^{a,*}$, Ashutosh Kumar Alok$^b$, Anjan Giri$^{c,d}$, Rukmani Mohanta$^e$, Soumitra Nandi$^{f,g}$

$^a$ Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
$^b$ Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
$^c$ Department of Physics, Punjabi University, Patiala-147002, India
$^d$ Physics Department, IIT Hyderabad, Andhra Pradesh-502205, India
$^e$ School of Physics, University of Hyderabad, Hyderabad-500046, India
$^f$ Harish Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad- 211 019, India
$^g$ Dipartimento di Fisica Teorica, Univ. di Torino and INFN, Sezione di Torino, I-10125 Torino, Italy

Abstract

We show that a fourth family of quarks with $m_t$ in the range of (400–600) GeV provides a rather simple explanation for the several indications of new physics that have been observed involving $CP$ asymmetries of the $b$-quark. The built-in hierarchy of the $4 \times 4$ mixing matrix is such that the $t'$ readily provides a needed perturbation ($\approx 15\%$) to $\sin 2\beta$ as measured in $B \to \psi K_s$ and simultaneously is the dominant source of $CP$ asymmetry in $B_s \to \psi \phi$. The correlation between $CP$ asymmetries in $B_s \to \psi \phi$ and $B_d \to \phi K_s$ suggests $m_t \approx (400–600)$ GeV. Such heavy masses point to the tantalizing possibility that the 4th family plays an important role in the electroweak symmetry breaking.

The spectacular performance of the two asymmetric $B$-factories allowed us 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. Nevertheless, in the past few years as more data were accumulated and also as the accuracy in some theoretical calculations was improved it has become increasingly apparent that several of the experimental results are difficult to reconcile within the SM with three generations [SM3] [5,6]. It is clearly important to follow these indications and to try to identify the possible origin of these discrepancies especially since they may provide experimental signals for the LHC which is set to start quite soon. While at this stage many extensions of the SM could be responsible, in this Letter, we will make the case that an addition of a fourth family of quarks [7–11] provides a rather simple explanation for the pattern of deviations that have been observed [12]. In fact we will show that the data suggests that the charge 2/3 quark of this family needs to have a mass in the range of (400–600) GeV [13].

We now 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 2–3 $\sigma$ larger than the directly measured values. Using only $\epsilon_b$ 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 $\xi_s \equiv \frac{\Delta M_s}{\Delta M_d}$, from the lattice, along with $V_{cb}$ yields a prediction, $\sin 2\beta_{\text{prediction}} = 0.87 \pm 0.09$ [6] in the SM. If along with that $\frac{\Delta M_s}{\Delta M_d}$ is also included as an input then one gets a somewhat smaller central value but with also appreciably reduced error: $\sin 2\beta_{\text{fullfit}} = 0.75 \pm 0.04$.

2. The celebrated measurement, via the “gold-plated” mode $B \to \psi K_s$, gives $\sin 2\beta_{\psi K_s} = 0.672 \pm 0.024$ which is smaller than either of the above predictions by $\approx 1.7$ to 2.1 $\sigma$ [6].

3. As is well-known penguin-dominated modes, such as $B \to (\phi, \eta', \pi^0, \omega, K_s, \ldots) K_s$ also allow an experimental determination of $\sin 2\beta$ in the SM [14,15]. This method is less clean as it has some hadronic uncertainty, which was naively estimated to be at the level of 5% [15,16]. Unfortunately, this uncertainty cannot be reliably determined in a model-independent manner. However, several different estimates [17] find that...
amongst these modes, ($\phi, \eta', K_1K_2) K_3$ are rather clean up to an error of only a few percent. In passing, we note also another intriguing feature of many such penguin-dominated modes is that the central value of $\sin 2\phi$ that they give seems to be below the two SM predicted values given above in #1 and in fact, in many cases, 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 $\Delta A_{CP} = A_{CP}(B^\to K^-\pi^0) - A_{CP}(\bar B^0 \to K^-\pi^+)$ [3]. Naively this difference is supposed to be zero. Using QCD factorization [18] in conjunction with any of the four scenarios for $1/m_t$ corrections that have been proposed [19] we were able to estimate $\Delta A_{CP} = (2.5 \pm 1.5)\%$ [5] which is several $\sigma$'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 serious [20]. However, given our limited understanding of hadronic decays it makes it difficult to draw compelling conclusions from this difficulty for the SM3.

5. Finally, more recently the possibility of the need for a largish non-standard CP-violation in $K_S \to \pi^0\pi^0$ that we have used to constrain the SM4 parameter space; the error on $V_{ub}$ is increased to reflect the disagreement between the inclusive and exclusive methods.

\[ V_{td} = 0.72 \pm 0.05 \]
\[ f_{K^0} B_{K^0} = 0.281 \pm 0.021 \text{ GeV} \]
\[ M_{\Delta K} = 17.77 \pm 0.12 \text{ ps}^{-1} \]
\[ M_{\Delta K} = (0.507 \pm 0.005) \text{ ps}^{-1} \]
\[ \xi = 1.2 \pm 0.06 \]
\[ \gamma = (75.0 \pm 22.0)\% \]
\[ |\alpha| < 10^3 = 2.32 \pm 0.007 \]
\[ \sin 2\beta_{\phi K} = 0.672 \pm 0.024 \]
\[ B_{\Delta C}(K^+ \to \pi^+\pi^0) = (0.147^{+0.013}_{-0.014}) \times 10^{-9} \]
\[ B_{\Delta C}(B^- \to \chi_{CP}) = (10.61 \pm 0.17) \times 10^{-3} \]
\[ B_{\Delta C}(B^- \to \chi_{CP}) = (3.55 \pm 0.25) \times 10^{-4} \]
\[ B_{\Delta C}(B^- \to \chi_{CP}) = (0.44 \pm 0.12) \times 10^{-6} \]

Table 1. Inputs used to constrain the SM4 parameter space; the error on $V_{ub}$ is increased to reflect the disagreement between the inclusive and exclusive methods.

Table 2. Allowed ranges for the parameters, $\chi_{CP}$ ($\times 10^{-2}$) and phase $\phi'$ (in degree) for different masses $m_t$ (GeV), that has been obtained from the fitting with the inputs in Table 1.

Using the $4 \times 4$ CKM matrix unitarity relation, $\lambda_\phi + \lambda_\psi + \lambda_t + \lambda_{\phi'} = 0$ where $\lambda_\phi = V_{tb} V_{ts}^\ast$. The phase of $V_{tb}$ and $V_{ts}$ will also be obtained by using this unitarity relation. In this way we can reduce the number of unknown parameters by using information from known parameters.

With a sequential fourth generation, the effective Hamiltonian describing the $b \to s$ transitions becomes

\[ H_{eff} = \frac{G_F}{\sqrt{2}} \left[ \lambda_\phi \left( C_1^i O_1 + C_2^i O_2 + \sum_{i=3}^{10} C_i^i O_i \right) + \lambda_t \sum_{i=3}^{10} C_i^i O_i - \lambda_{\phi'} \sum_{i=3}^{10} \Delta C_i^i O_i \right]. \]

Table 1

| $m_t$ (GeV) | 400 | 500 | 600 |
|------------|-----|-----|-----|
| $\chi_{CP}$ ($\times 10^{-2}$) | 0.08–1.4 | 0.06–0.9 | 0.05–0.7 |
| $\phi'$ (degree) | $-80 \to 80$ | $-80 \to 80$ | $-80 \to 80$ |

where $C_i^i$'s are the Wilson coefficients, $\Delta C_i^i$'s are the effective ($t$ subtracted) $t'$ contributions and $O_i$ are the current–current operators. Using the above Hamiltonian, and following [5] we use the S4 scenario of QCD factorization approach [19] for the evaluation of hadronic matrix elements and the amplitudes for the decay modes $B \to \pi K$ and $B \to \phi K_S$ for $m_t = 400, 500$ and 600 GeV respectively.

Using the ranges of $\chi_{CP}$, $\phi'$, as obtained from the fit for different $m_t$ (Table 2), we studied the allowed regions in the $\Delta A_{CP} - \lambda_{\phi'}$ plane for different values of $m_t$. With the 4th family we see that there is some enhancement and $\Delta A_{CP}$ up to about 8% may be feasible which is still somewhat small compared to the observed value ($14.4 \pm 2.9\%$). Again, as mentioned this could be due to the inadequacy of the QCD factorization model we are using.

In Fig. 1 (left-panel) we have shown the allowed regions in the $S_{\phi'}\phi'$ plane for different values of $m_t$ and in the right-panel...
of Fig. 1 we have shown the correlation between CP asymmetries in $B \to \psi \phi$ and $B \to \phi K_s$. We follow the notation $S_{\psi \phi} = \sin(\phi_\psi - 2\beta_\psi) = \sin 2\beta_\psi^D$, where $\phi_\psi$ is the phase coming from mixing and $\beta_\psi = \arg\left(\frac{V_{ts}}{V_{tb}\sqrt{\beta}}\right) = 1.1^\circ \pm 0.3^\circ$, is the phase of $b \to c\bar{c}s$ decay amplitude [21,35]. The range for new $B_t$ mixing phase $\phi_\psi^A$ is given (@68% CL) by $\phi_\psi^A \in (-18 \pm 7)^\circ$ or $\phi_\psi^A \in (-70 \pm 7)^\circ$. The corresponding 2- and 1-σ ranges for $S_{\psi \phi}$ is given by $[-0.90, -0.17]$ and $[-0.78, -0.40]$ respectively. The large error on $S_{\phi K_s}$ and $S_{\psi \phi}$ does not allow at present to draw strong conclusions on $m_t$, nevertheless the present experimental bounds disfavor $m_t > 600$ GeV.

A very appealing feature of the 4th family hypothesis is that it rather naturally explains the pattern of the observed anomalies. First of all the heavy $m_t^V$ 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 $m_t^2$ [7,36]. 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, $\Delta A_{CP}$ as it is really the $K^+\pi^0$ that is enhanced because of the color allowed coupling of the $Z$ to the $\pi^0$. A second important consequence of $t'$ is that $b \to s$ penguin has a new CP-odd phase carried by $V_{ts}^\prime V_{tb}^\star$. This is responsible for the fact that $\sin 2\beta$ measured in $B \to \psi K_s$ differs with that measured in penguin-dominated modes such as $B \to (\phi, \eta', K_{sbar}, \ldots) K_s$.

Note also that $\Delta B = 2$ box graph gets important new contributions from the $t'$ since these amplitudes as mentioned before are proportional to $m_t^2$. Furthermore, they are accompanied by new CP-odd phase which is not present in SM3. This phase is responsible for the fact that the $\sin 2\beta$ measured in $B \to \psi K_s$ is lower than the value(s) “predicted” in SM3 [6] given in item #1 on page 1.

Finally, we note briefly in passing how SM4 gives a very simple explanation for the size of the new CP-phase effects in $B_d$ versus $B_s$ mesons. In $B_d$ oscillations resulting in $B \to \psi K_s$, top quark plays the dominant role and we see that the measured value of $\sin 2\beta$ deviates by $\approx 15\%$ 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 $t$ get reversed. In $B_s$, mixing the top quark in SM3 has negligible CP-odd phase. Therein then the $t'$ has a pronounced effect. SM4 readily explains that just as $t$ is dominant in $\sin 2\beta$ and sub-

dominant in $\sin 2\beta_s$, the $t'$ is dominant in $\sin 2\beta_s$ and sub-

dominant in $\sin 2\beta$. We now briefly summarize some of the definitive signatures of the 4th family scenario in flavor observables [29]. The need for new CP phase(s) beyond the single KM phase [2] of course must continue to persist. This means that the three values of $\sin 2\beta$, the fitted one, the one measured via $\psi K_s$ and the one measured via penguin dominated modes (e.g. $\phi K_s$, $\eta' K_s$, etc.) should continue to differ from each other as more accurate analyses become available. Furthermore, $B_t$ mixing should also continue to show the presence of a non-standard phase (e.g. in $B_t \to \psi \phi$) as higher statistics are accumulated. For sure SM4 will have many more interesting applications in flavor physics which need to be explored. For the LHC, one definitive prediction of this analysis is a $t'$ with $m_t$ in the range of $\approx 400–600$ GeV and the detection of the $t'$, $b'$ and their leptonic counterparts deserves attention. EW precision constrains the mass-splitting between $t'$ and $b'$ to be small, around 50 GeV [37,38].

As far as the lepton sector is concerned, it is clear that the 4th family leptons have to be quite different from the previous three families in that the neutral leptons have to be rather massive, with masses $> m_Z/2$. This may also be a clue that the underlying nature of the 4th family may be quite different from the previous three families; for one thing it could be relevant to the dark matter issue [39]. It may also open up the possibility of unification with the SM gauge group [40]. KM [2] mechanism taught us the crucial role of the three families in endowing CP violation in SM3. It is conceivable that 4th family plays an important role [41–44] in yielding enough CP to generate baryogenesis which is difficult in SM3. Of course it also seems highly plausible that the heavy masses in the 4th family play a significant role in dynamical generation of electroweak symmetry breaking. In particular, the masses around 500 or 600 GeV that are being invoked in our study, point to a tantalizing possibility of dynamical electroweak symmetry breaking as the Pagels–Stokar relation in fact requires quarks of masses around 500 or 600 GeV for dynamical mass generation to take place [45–48]. Note also that for such heavy masses the values of Yukawa coupling will be large so that corrections to perturbation theory may not be negligible [49]. Finally, we want to emphasize that a fourth family of quarks does not violate electro-weak precision tests [50]. Clearly all this brief discussion is signaling is that there is a lot of physics involving the new family that needs to be explored and understood.
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