A simultaneous explanation of the large phase in $B_s - \overline{B}_s$ mixing and $B \to \pi\pi/\pi K$ puzzles in $R$-parity violating supersymmetry

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Abstract

Recent data on $B$ meson mixings and decays are, in general, in accord with the standard model expectations, except showing a few hiccups: (i) a large phase in $B_s$ mixing, (ii) a significant difference ($>3.5\sigma$) between CP-asymmetries in $B^\pm \to \pi^0 K^\pm$ and $B_d \to \pi^\mp K^\pm$ channels, and (iii) a larger than expected branching ratio in $B_d \to \pi^0 \pi^0$ channel. We show that selective baryon number violating Yukawa couplings in $R$-parity violating supersymmetry can reconcile all the measurements.

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Key Words: $B$ Meson mixings and decays, $R$-parity violation

Introduction: There is still a possibility that by the time we start analyzing the LHC data, some indirect evidence of new physics would pop up from $B$ meson mixings and decays. So far, most of the measurements in the $B$-factories are in reasonably good agreement with the standard model (SM). In some cases, they are not, but in most such cases the uncertainties plaguing the low energy hadronic phenomena prevent us from making any substantial claim for new physics (NP). But, rather than searching for individual solutions for these discrepancies taken separately, if we seek for a collective solution and observe that all or most of them can be reconciled by a single NP dynamics, then that indeed deserves attention. Here, we focus on three such anomalies, which we call puzzles, for each of which a departure from the SM expectation is noticed with a reasonable statistical significance:

(i) The $B_s$ mixing puzzle: A model-independent test of new physics contributing to $B_s$ mixing was performed with the following parametrization:

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_{s}^{SM} e^{-2i\beta_s} + A_{s}^{NP} e^{2i(\phi_{NP} - \beta_s)}}{A_{s}^{SM} e^{-2i\beta_s}},$$

where $\beta_s \equiv \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ has the value $0.018 \pm 0.001$ in the SM. UTfit has got two solutions [1]:

$$\phi_{B_s}^{(\text{deg})} = -19.9 \pm 5.6 \ , \ A_{s}^{NP}/A_{s}^{SM} = 0.73 \pm 0.35 ;$$

$$\phi_{B_s}^{(\text{deg})} = -68.2 \pm 4.9 \ , \ A_{s}^{NP}/A_{s}^{SM} = 1.87 \pm 0.06 .$$

The SM expectation of $\phi_{B_s}$ is zero. But the above numbers show that $\phi_{B_s}$ deviates from zero by more than $3.7\sigma$ for the first solution, while the second solution is significantly more distant from the
SM expectation\(^1\). It should be noted that here the theoretical uncertainty is small, so a statistically significant non-zero \(\phi_{B_s}\) would constitute an unambiguous NP signal. Combining the two UTfit solutions, the allowed range of the mixing-induced CP-asymmetry in the \(B_s\) system is given by \(S_{\psi\phi} \in [0.35, 0.89]\) at 95\% C.L. \(^2\), where \(S_{\psi\phi} = \sin(2(|\beta_s| - \phi_{B_s})).

(ii) The \(\pi K\) puzzle: The observed direct CP-asymmetries in the \(\pi K\) channel \(^3\),

\[
a_{\text{CP}}(B_d \to \pi^\pm K^\mp) = -0.097 \pm 0.012, \quad a_{\text{CP}}(B^\pm \to \pi^0 K^\mp) = 0.050 \pm 0.025,
\]

imply that \(\Delta a_{\text{CP}} = a_{\text{CP}}(B^\pm \to \pi^0 K^\mp) - a_{\text{CP}}(B_d \to \pi^\pm K^\mp) = 0.14 \pm 0.029\) differs from the naive SM expectation of zero at 4.7\(\sigma\) level. In the QCD factorization approach, \(\Delta a_{\text{CP}} = 0.025 \pm 0.015\), which differs from the experimental value by 3.5\(\sigma\). This is quite reliable as most of the model-dependent uncertainties cancel in the difference \(^4\).

On the other hand, the following CP-conserving observables, as ratios of branching ratios \(^3\)

\[
R_n = \frac{1}{2} \frac{\text{BR}[B^0_d \to \pi^- K^+] + \text{BR}[\bar{B}^0_d \to \pi^+ K^-]}{\text{BR}[B^0_d \to \pi^0 K^0] + \text{BR}[\bar{B}^0_d \to \pi^0 \bar{K}^0]} = 1.0 \pm 0.07, \\
R_c = \frac{2}{\text{BR}[B^+ \to \pi^0 K^+]} \frac{\text{BR}[B^- \to \pi^0 K^-]}{[B^- \to \pi^- K^0]} = 1.10 \pm 0.07,
\]

are both in excellent agreement with the SM in which each of them is expected to be unity. The ‘puzzle’ seems to lie in the asymmetries.

(iii) The \(\pi\pi\) puzzle: The ratio

\[
R_{\pi\pi} = \frac{2\text{BR}(B^0_d \to \pi^0 \pi^0)}{\text{BR}(B^0_d \to \pi^\pm \pi^\mp)} = 0.51 \pm 0.10,
\]

is in conflict with the expected relation \(\Delta \text{BR}(B^0_d \to \pi^\pm \pi^\mp) \gg \text{BR}(B^0_d \to \pi^0 \pi^0)\). More specifically, what is expected, based on different theoretical models (naive factorization \(^5\), PQCD \(^6\), QCDF \(^7\)), is \(\Delta \text{BR}(B^0_d \to \pi^0 \pi^0) \approx O(\lambda^2) \text{BR}(B^0_d \to \pi^\pm \pi^\mp)\), while what is observed is \(\Delta \text{BR}(B^0_d \to \pi^0 \pi^0) \approx O(\lambda) \text{BR}(B^0_d \to \pi^\pm \pi^\mp)\). On the other hand,

\[
R_a = \frac{\text{BR}(B^0_d \to \pi^- \pi^0)}{\text{BR}(B^+ \to \pi^+ \pi^0)} = 0.93 \pm 0.09,
\]

is in good agreement with the SM.

It was shown in \(^8\) that only a large color-suppressed tree amplitude, with other amplitudes as expected in the SM, can explain the \(\pi\pi\) and \(\pi K\) data, though such a large amplitude is hard to extract from short-distance dynamics. We also note that large electroweak penguin (EWP) effects can resolve the \(\pi\pi\) and \(\pi K\) puzzles \(^9\), but such large EWP contributions do not arise within the existing theoretical models. The option of suppressing the \(B^0 \to \pi^+ \pi^-\) and enhancing \(B^0 \to \pi^0 \pi^0\) branching ratios by pumping up the charming penguins faces a serious obstacle when confronted with the \(\pi K\) data \(^10\). Again, the next-to-leading order contributions in QCD factorization approaches \(^11\) might

\(^{1}\)The UTfit collaboration have presented an updated estimate at ICHEP2008 (talk by M. Pierini): \(\phi_{B_s} = (-19 \pm 7)^\circ \cup (-69 \pm 7)^\circ\), which shows a 2.6\(\sigma\) discrepancy with the SM expectation. In any case, as long as this deviation from the SM value remains sizable, the numerical exercise leading to our conclusion holds. We thank D. Tonelli of the CDF Collaboration for bringing this to our notice.
jack up $B^0 \rightarrow \pi^0\pi^0$ branching ratio but then $B^0 \rightarrow \rho^0\rho^0$ branching ratio goes out of control. Thus, a collective explanation for all anomalies is hard to obtain.

To account for the large phase in $b \rightarrow s$ transition, several new physics models have already been proposed \[^{[11]}\]. In this short paper, we show that some selective $R$-parity (more specifically, baryon-number) violating couplings cannot only provide a large phase encountered in $B_s\bar{B}_s$ mixing but can also explain the $\pi\pi$ and $\pi K$ riddles at the same time.

**$R$-parity violating couplings:** $R$-parity is a discrete symmetry defined as $R = (-1)^{3B+L+2S}$, where $B$, $L$, and $S$ are respectively the baryon number, lepton number and spin of a particle. $R$ equals 1 for all SM particles and $-1$ for all superparticles. Unlike in the SM, conservations of $B$ and $L$ in supersymmetric models are rather *ad hoc*, not motivated by any deep underlying principle. However, such couplings are highly constrained \[^{[12]}\]. Here, we concentrate on explicitly broken $B$-violating part of $R$-parity violation (B-RPV) only. These are contained in the superpotential,

$$W = \frac{1}{2} \lambda_{ijk}^\prime \tilde{u}_i^c \tilde{D}_j D_k^c, \quad (8)$$

where the antisymmetry in the last two indices implies $\lambda_{ijk}^\prime = -\lambda_{ikj}^\prime$. Our selection of B-RPV couplings is motivated through the following chain of arguments:

(i) First, we take only those product couplings which contribute to $B_s\bar{B}_s$ and $B_d\bar{B}_d$ mixings via one-loop box diagrams. These are $\lambda_{113}^\prime \lambda_{112}^\prime$ and $\lambda_{123}^\prime \lambda_{122}^\prime$ respectively, where $i$ corresponds to all the three singlet up-type flavors.

(ii) $\lambda_{113}^\prime \lambda_{112}^\prime$, for $i = 2$, contributes at tree level to $b \rightarrow c\bar{c}s$ ($B_d \rightarrow J/\Psi K_S$). This is a golden channel for $\sin 2\beta$ measurement, yielding $\sin 2\beta = 0.681 \pm 0.025$ \[^{[13]}\], which is slightly lower than the SM fit $\langle \sin 2\beta \rangle_{\text{fit}} = 0.75 \pm 0.04$ \[^{[15]}\]. Now, for any $i$, $\lambda_{123}^\prime \lambda_{122}^\prime$ does contaminate $\sin 2\beta$ extraction any way by contributing to $B_d\bar{B}_d$ mixing through one-loop box graphs. But, nevertheless, we refrain from using $\lambda_{213}^\prime \lambda_{212}^\prime$ to avoid any overwhelming tree level new physics imposition on the ‘$\sin 2\beta$ golden channel’.

(iii) For a simultaneous solution of the $\pi K$ puzzle, we expect to generate a numerically meaningful contribution to $B^\pm \rightarrow K^\mp \pi^0$. The corresponding quark level process $b \rightarrow u\bar{u}\pi$ is triggered by $\lambda_{113}^\prime \lambda_{112}^\prime$ for $i = 1$, but not for $i = 3$. For this reason, we consider $i = 1$ only as far the combination $\lambda_{113}^\prime \lambda_{112}^\prime$ is concerned. Regarding the other combination $\lambda_{123}^\prime \lambda_{122}^\prime$, again we select the $i = 1$ case as only this choice leads to $b \rightarrow d\bar{u}\pi$ ($B \rightarrow \pi\pi$) at the tree level.

(iv) Thus we are left with two combinations: $\lambda_{113}^\prime \lambda_{112}^\prime$ and $\lambda_{123}^\prime \lambda_{122}^\prime$. These consist of three independent couplings: $\lambda_{113}^\prime$, $\lambda_{112}^\prime$ and $\lambda_{123}^\prime$. The strongest constraint on $\lambda_{113}^\prime$ comes from $n - \bar{n}$ oscillation: $\lambda_{113}^\prime < 0.002 - 0.1$ for $m_q < 200-600 \text{ GeV}$ \[^{[14]}\]. On the other hand, double nucleon decay into two kaons puts the most stringent constraint: $\lambda_{112}^\prime < 10^{-15} R^{\frac{5}{2}}$ with $R = \frac{\lambda}{(M_3 M_4)^{\frac{5}{2}}}$, the ratio between the hadronic and supersymmetry breaking scale. For $R \sim 10^{-3}$, the constraint is very strong: $\lambda_{112}^\prime \sim 10^{-7}$; while for $R \sim 10^{-6}$, it gets pretty relaxed: $\lambda_{112}^\prime \sim 1$. The upper bound on $\lambda_{123}^\prime$ is 1.25 arising from the requirement of perturbative unification.

\[^2\text{Using the recent lattice measurements of the hadronic matrix elements, } B_K \text{ and } \zeta_s \text{ (see Eq. (13)), the authors of [13] have speculated a possible role of new physics to account for the difference between the fitted } \sin 2\beta = 0.87 \pm 0.09 \text{ (without } V_{ub} \text{ as input) and the measured value of } \sin 2\beta, \text{ which is about } 2.1\sigma \text{ lower than the fitted value.} \]
**B-RPV contributions to observables:** The product coupling $\lambda''_{113}\lambda_{112}'$ triggers $b \to s$ transition, while $\lambda''_{123}\lambda_{121}'$ leads to $b \to d$ transition. We define:

$$h(b \to s) \equiv \lambda''_{113}\lambda_{112}', \quad h(b \to d) \equiv \lambda''_{123}\lambda_{121}' .$$

These combinations contribute to $B_q \to \bar{B}_q$ ($q = d, s$) mixing via two kinds of box diagrams, one with internal $d^c$ quark and $\tilde{u}^c$ squark and the other with $u^c$ quark and $\tilde{q}^c$ squark. They are given by

$$M_{12(q)}^{\text{B-RPV}} = \frac{h^2(b \to q)}{192\pi^2 M_Q^2} M_{B_q} \hat{\gamma} B_q f_{B_q}^2 B_{B_q} \left( \tilde{S}_0(x_u) + \tilde{S}_0(x_d) \right) ,$$

where

$$\tilde{S}_0(x) = \frac{1 + x}{(1 - x)^2} + \frac{2 x \log x}{(1 - x)^3} .$$

Above, we have assumed the relevant squarks, $\tilde{u}_R$ and $\tilde{q}_R$, to be mass degenerate, and we have denoted the common squark mass by $\tilde{m}$.

The product coupling $h(b \to s)$ also contributes at tree level to non-leptonic $B$ decays like $b \to d\bar{d}s$ and $b \to u\pi s$, like $B^+ \to K^0\pi^+, B^+ \to K^+\pi^0, B_d \to K^0\pi^0, B_d \to K^+\pi^-, B_s \to \phi\pi^0, B_s \to \pi^+\pi^-, B_s \to K^+\bar{K}^-$ and their CP conjugate decays. Similarly, $h(b \to d)$ provides new tree level contribution to different $B \to \pi\pi$ decay modes. Thus, different decay rates receive different amount of SM and B-RPV contributions, and the net amplitude in each case amounts to their coherent sum. The SM amplitude is calculated in the naive factorization model. Considering the uncertainties in any such calculation, we rely on observables which are either the ratio of branching ratios or CP-asymmetries (in $B \to \pi K$ modes). For the direct CP-asymmetries to proceed we need a sizable strong phase difference between the SM and the B-RPV amplitudes, which may be generated from final state interaction and rescattering. Indeed, the weak phases of the B-RPV couplings are free parameters. For simplicity, we have not considered the mixing between the B-RPV operators and the SM operators between the scale $M_W$ and $m_b$. The dominant effect, which is just a multiplicative renormalization of the B-RPV operator, can be taken into account by interpreting the B-RPV couplings to be valid at the $m_b$ scale and not at the $M_W$ scale (thus, one should be careful in using the constraints on the couplings and in comparing different limits, though the numerical differences are not expected to be significant).

**Numerical inputs:** Unless otherwise mentioned, all numbers are taken from Table 3. The measured values of the mass differences $<\Delta M_q>$ are

$$\Delta M_d = (0.507 \pm 0.005) \text{ ps}^{-1} , \quad \Delta M_s = (17.77 \pm 0.10\text{(stat)} \pm 0.07\text{(syst)}) \text{ ps}^{-1} .$$

We require $\sin 2\beta$ to lie between $0.75 \pm 0.04$ (the SM fit value with $V_{ub}$ as input) and $0.681 \pm 0.025$ (measured from the golden channel $B_d \to J/\Psi K_S$).
We also use the recent lattice values of the bag factors [19]

\[ f_{B_s} \sqrt{B_{B_s}} = 281 \pm 21 \text{ MeV}, \quad \zeta_s = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} = 1.20 \pm 0.06, \quad (13) \]

and the short distance factors

\[ \eta_{B_d} = \eta_{B_s} = 0.55, \quad S_0(x_t) = 2.327 \pm 0.044. \quad (14) \]

The relevant CKM elements are [20]

\[ |V_{td}| = 8.54(28) \times 10^{-3}, \quad |V_{ts}| = 40.96(61) \times 10^{-3}, \quad \gamma = (75 \pm 25)^\circ, \quad (15) \]

while the other elements are taken to be fixed at their central values.

**Results:** We proceed by making two assumptions or working conditions:

(i) The strong phase difference between the SM amplitude and the corresponding BSM amplitude is the same irrespective of whether it is \( b \to s \) or \( b \to d \) transition. This assumption relies on flavor SU(3) symmetry.

(ii) In order to calculate the amplitudes for different non-leptonic decay modes we have followed naive factorization approach and considered 10% uncertainty over the SM amplitudes to cover the different (model-dependent) non-factorizable corrections. For \( B_d \to \pi^0 \pi^0 \) mode we have taken this uncertainty to be 20%, since the SM branching ratio for this mode is \( N_c \) sensitive [3].

There are five parameters which we like to constrain: the magnitude of two product couplings (\( |\lambda''_{123}^s \lambda''_{121}^s| \) and \( |\lambda''_{113}^s \lambda''_{112}^s| \)), their weak phases (\( \Phi_D \equiv \text{Arg} (\lambda''_{123}^s \lambda''_{121}^s) \) and \( \Phi_S \equiv \text{Arg} (\lambda''_{113}^s \lambda''_{112}^s) \)), and the common strong phase difference between the NP and the SM amplitude (\( \delta_S \)). We vary all of them simultaneously, and constrain them by requiring consistency with the observables \( \Delta a_{\text{CP}}, R_n, R_c, R_{\pi \pi}, R_s, \sin 2\beta, \Delta M_d, \Delta M_s \) and \( \phi_{B_s} \). We also use \( R = B/R(B^0 \to \pi^+\pi^-)/R(B^0 \to \pi^+K^-) = 0.259 \pm 0.023 \) [3] to constrain those parameters. Our results are plotted in Fig. 1 and Fig. 2. Throughout our analysis we have taken \( \tilde{m} = 300 \) GeV; a few percent variation of it will not qualitatively alter our conclusions. Although we varied all the parameters simultaneously, in Fig. 1a we projected the allowed region in a two-dimensional space of the magnitude (\( |\lambda''_{113}^s \lambda''_{112}^s| \)) and phase (\( \Phi_S \)) of \( h(b \to s) \). The red (right-side) patches are allowed solutions when all the five parameters pass through the filters of \( \Delta M_d, \sin 2\beta, \Delta a_{\text{CP}}, R_n \) and \( R_c \); while the blue (left-side) patches are zones allowed by \( \Delta M_s \) and \( \phi_{B_s} \) only. There are small overlaps between the allowed regions from the two sets. The overlaps signify a common solution for all the three puzzles. With increasing statistics and with further reduction in theoretical uncertainties, the overlap may increase or decrease, i.e. it may or may not be possible to simultaneously address all the riddles with B-RPV interactions. In Fig. 1b, we displayed the allowed zone in the plane of \( \Phi_S \) and \( \delta_S \). We note at this stage that \( \Phi_S \) has four sets of solutions, one in each quadrant, and for each such set there is an associated patch of \( \delta_S \).

Note that \( R_{\pi \pi} \) has been deliberately kept out of the above list of constraints. If we include it, then to accommodate large \( BR(B^0_d \to \pi^0\pi^0) \), only two sets of \( \delta_S \) are allowed, one in the interval (100 → 165)\(^\circ\) and the other in (195 → 245)\(^\circ\). Since \( \delta_S \) has been assumed to be the common strong phase difference, its limitations of the \( b \to d \) sector infiltrate into the \( b \to s \) sector as well, thus eliminating \( \Phi_S \) solutions in the second and the third quadrants. The finally allowed values of \( \Phi_S \) lie in the range (10 → 60)\(^\circ\) and (275 → 340)\(^\circ\). Clearly, if we relax the assumption of equality of the strong phase difference (i.e. a common \( \delta_S \)), \( \Phi_S \) solutions in all the four regions will be allowed.
Figure 1: (Left panel-1a): The allowed zone in the plane of the magnitude of $h(b \to s)$ and its weak phase ($\Phi_S$) is shown. The red patches (on the right side) are scatter plots of the allowed parameters obtained by using $\Delta M_d$, $\sin 2\beta$, $\Delta a_{CP}$, $R$, $R_n$, $R_c$ and $R_a$; while the blue patches (on the left side) correspond to the space allowed by $\Delta M_s$ and $\phi_B$, only. (Right panel-1b): The allowed patches in the plane of the strong phase difference ($\delta_S$) and $\Phi_S$ are displayed.

Fig. 2a is a zoomed version of Fig. 1a, except that in Fig. 2a we have included all possible constraints at the same time. For illustration, out of the two allowed sets of $\Phi_S$, the one within the range $(10 \to 60)^\circ$ has been shown. Fig. 2b is an equivalent description replacing the magnitude and weak phase of $h(b \to s)$ by those of $h(b \to d)$. Note that the constraint on $|h(b \to d)|$ is one order of magnitude tighter than $|h(b \to s)|$, primarily because the SM prediction of the $B_d$ mixing is relatively more precise.

Figure 2: (Left panel-2a): Zoomed version of Fig. 1a, only that all constraints are now used, and focused in the first quadrant solution of $\Phi_S$. (Right panel-2b): Similar to Fig. 2a, but in the space of the magnitude and phase of $h(b \to d)$.

Conclusions: In this paper, we wanted to solve three puzzles in $B$ physics, namely, the large phase in $B_s$ mixing, a more than $3.5 \sigma$ discrepancy between CP-asymmetries in charged and neutral $B$ decays in $\pi K$ modes, and a significantly larger than expected neutral $B$ decay in $\pi^0\pi^0$ channel. Here we make two remarks: (i) the theoretical uncertainty in the estimation of the $B_s$ mixing phase is small and hence a large non-zero phase would constitute a clinching signal for new physics; (ii) but, on account of large hadronic uncertainties associated with the $\pi K$ and $\pi\pi$ modes, the discrepancies observed in $\Delta a_{CP}$ and $R_{\pi\pi}$, though tantalizing, are not conclusive. In fact, to get rid of these theoretical uncertainties as much as possible, we considered the difference between CP-asymmetries and the
relative branching ratios. Yet, from a conservative point of view, instead of entering into a debate whether the discrepancies constitute ‘puzzles’ or ‘non-puzzles’, all that we wanted to emphasize in this paper is that if one can figure out a new dynamics beyond the SM that causes a simultaneous and systematic movement of all those theoretical estimates towards better consistency with experimental data, then that source of new physics calls for special attention. As an illustration, we advanced the case of explicit baryon-number violating part of supersymmetry, and we have used only two product couplings, constructed out of three individual ones, to explain all the data. One should keep track of it in the LHC data analysis, as such interactions would give lots of final state jets.

In fact, even within the $B$ physics context, it may be possible to infer our choices of $B$-RPV couplings (or, similar type diquark couplings) from the following observations: the coupling $h(\bar{b} \rightarrow s)$ will contaminate $B_s \rightarrow K^+K^-$ ($\bar{b} \rightarrow s\bar{u}u$ at the quark level) which is used to extract $\gamma = \mathrm{Arg} \left( V_{ub}^* \right)$ [21], but it would not affect $B_s \rightarrow D_sK$ ($\bar{b} \rightarrow s\bar{c}c$ at the quark level) which is also used to determine $\gamma$ [22]. Any statistically different measurement of $\gamma$ between these two methods will strengthen our hypothesis. Moreover, either of the two methods would yield $\gamma$ different from the value extracted from $B \rightarrow \pi K$. We stress again that the falsifiability of our hypothesis, under the assumptions spelt above, can be judged from Fig. 1a by noting that the common solution zone in the parameter space arising from the ‘$B_s$-set’ and the other data set may shrink or expand as more data accumulate. LHCb will definitely shed more light to these issues.

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