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

Gautam Bhattacharyya,[1] Kalyan Brata Chatterjee,[1] and Soumitra Nandi[2,3]

[1]*Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700064, India*

[2]*Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 211019, India*

[3]*Dipartimento di Fisica Teorica, Universita di Torino and INFN, Sezione di Torino, I-10125 Torino, Italy*

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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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I. 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 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:

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP} - \beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}}, \qquad (1)$$

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

$$\begin{aligned} \phi_{B_s}(\text{deg}) &= -19.9 \pm 5.6, \\ A_s^{\rm NP}/A_s^{\rm SM} &= 0.73 \pm 0.35; \\ \phi_{B_s}(\text{deg}) &= -68.2 \pm 4.9, \\ A_s^{\rm NP}/A_s^{\rm SM} &= 1.87 \pm 0.06. \end{aligned} \qquad (2)$$

The SM expectation of ϕ_{B_s} is zero. But the above numbers show that ϕ_{B_s} deviates from zero by more than 3.7σ 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 nonzero ϕ_{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% confidence level (CL) [2], where $S_{\psi\phi} \equiv \sin 2(|\beta_s| - \phi_{B_s})$.

(ii) *The πK puzzle*: The observed direct CP-asymmetries in the πK channel [3],

$$\begin{aligned} a_{CP}(B_d \to \pi^\mp K^\pm) &= -0.097 \pm 0.012, \\ a_{CP}(B^\pm \to \pi^0 K^\pm) &= 0.050 \pm 0.025, \end{aligned} \qquad (3)$$

imply that $\Delta a_{CP} = a_{CP}(B^\pm \to \pi^0 K^\pm) - a_{CP}(B_d \to \pi^\mp K^\pm) = 0.14 \pm 0.029$ differs from the naive SM expectation of zero at the 4.7σ level. In the QCD factorization approach, $\Delta a_{CP} = 0.025 \pm 0.015$, which differs from the experimental value by 3.5σ. 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],

$$\begin{aligned} R_n &= \frac{1}{2} \frac{\mathcal{BR}[B_d^0 \to \pi^- K^+] + \mathcal{BR}[\overline{B_d^0} \to \pi^+ K^-]}{\mathcal{BR}[B_d^0 \to \pi^0 K^0] + [\overline{B_d^0} \to \pi^0 \overline{K^0}]} \\ &= 1.0 \pm 0.07, \end{aligned} \qquad (4)$$

[1]The UTfit Collaboration has presented an updated estimate: $\phi_{B_s} = (-19 \pm 7)^\circ \cup (-69 \pm 7)^\circ$, which shows a 2.6σ 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.

$$R_c = 2\frac{\mathcal{BR}[B^+ \to \pi^0 K^+] + \mathcal{BR}[B^- \to \pi^0 K^-]}{\mathcal{BR}[B^+ \to \pi^+ K^0] + [B^- \to \pi^- \bar{K}^0]} = 1.10 \pm 0.07, \quad (5)$$

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

$$R_{\pi\pi} = \frac{2\mathcal{BR}(B_d^0 \to \pi^0\pi^0)}{\mathcal{BR}(B_d^0 \to \pi^\pm\pi^\mp)} = 0.51 \pm 0.10, \quad (6)$$

is in conflict with the expected relation $\mathcal{BR}(B_d^0 \to \pi^\pm\pi^\mp) \gg \mathcal{BR}(B_d^0 \to \pi^0\pi^0)$. More specifically, what is expected, based on different theoretical models (naive factorization [5], perturbative QCD [6], QCD factorization [7]), is $\mathcal{BR}(B_d^0 \to \pi^0\pi^0) \simeq \mathcal{O}(\lambda^2)\mathcal{BR}(B_d^0 \to \pi^\pm\pi^\mp)$, while what is observed is $\mathcal{BR}(B_d^0 \to \pi^0\pi^0) \simeq \mathcal{O}(\lambda)\mathcal{BR}(B_d^0 \to \pi^\pm\pi^\mp)$. On the other hand,

$$R_a = \frac{\mathcal{BR}(B_d^0 \to \pi^-\pi^+)}{\mathcal{BR}(B^+ \to \pi^+\pi^0)} = 0.93 \pm 0.09, \quad (7)$$

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 πK 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 πK 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 πK data [10]. Again, the next-to-leading order contributions in QCD factorization approaches [7] might jack up the $B^0 \to \pi^0\pi^0$ branching ratio but then the $B^0 \to \rho^0\rho^0$ branching ratio goes out of control. Thus, a collective explanation for all anomalies is hard to obtain.

To account for the large phase in $b \to s$ 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 can not only provide a large phase encountered in B_s-$\bar{B}_s$ mixing but can also explain the $\pi\pi$ and πK riddles at the same time.

II. 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 the explicitly broken B-violating part of R-parity violation (BRPV) only. These are contained in the superpotential

$$\mathcal{W} = \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (8)$$

where the antisymmetry in the last two indices implies $\lambda''_{ijk} = -\lambda''_{ikj}$. Our selection of BRPV 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 $\lambda''_{i13}\lambda''^*_{i12}$ and $\lambda''_{i23}\lambda''^*_{i21}$ respectively, where i corresponds to all the three singlet up-type flavors.

(ii) $\lambda''_{i13}\lambda''^*_{i12}$, for $i = 2$, contributes *at tree level* to $b \to c\bar{c}s$ ($B_d \to J/\Psi K_S$). This is a golden channel for $\sin 2\beta$ measurement, yielding $\sin 2\beta = 0.681 \pm 0.025$ [3], which is slightly lower than the SM fit $(\sin 2\beta)_{\rm fit} = 0.75 \pm 0.04$ [13].[2] Now, for any i, $\lambda''_{i23}\lambda''^*_{i21}$ does contaminate $\sin 2\beta$ extraction anyway by contributing to B_d-$\bar{B}_d$ mixing through one-loop box graphs. But, nevertheless, we refrain from using $\lambda''_{213}\lambda''^*_{212}$ to avoid any overwhelming tree level new physics imposition on the $\sin 2\beta$ golden channel.

(iii) For a simultaneous solution of the πK puzzle, we expect to generate a numerically meaningful contribution to $B^\pm \to K^\pm\pi^0$. The corresponding quark level process $b \to su\bar{u}$ is triggered by $\lambda''_{i13}\lambda''^*_{i12}$ for $i = 1$, but *not* for $i = 3$. For this reason, we consider $i = 1$ only as far the combination $\lambda''_{i13}\lambda''^*_{i12}$ is concerned. Regarding the other combination $\lambda''_{i23}\lambda''^*_{i21}$, again we select the $i = 1$ case as only this choice leads to $b \to du\bar{u}$ ($B \to \pi\pi$) at the tree level.

(iv) Thus we are left with two combinations: $\lambda''_{113}\lambda''^*_{112}$ and $\lambda''_{123}\lambda''^*_{121}$. These consist of three independent couplings: λ''_{113}, λ''_{112}, and λ''_{123}. The strongest constraint on λ''_{113} comes from $n - \bar{n}$ oscillation: $\lambda''_{113} <$ 0.002–0.1 for $m_{\tilde{q}} <$ 200–600 GeV [14]. On the other hand, double nucleon decay into two kaons puts the most stringent constraint $\lambda''_{112} < 10^{-15} R^{-5/2}$ with $R = \frac{\tilde{\Lambda}}{(M_{\tilde{g}} M_{\tilde{q}}^4)^{1/5}}$, the ratio between the hadronic and supersymmetry breaking scale. For $R \sim 10^{-3}$, the constraint is very strong: $\lambda''_{112} \sim 10^{-7}$; while for $R \sim 10^{-6}$, it gets pretty relaxed: $\lambda''_{112} \sim 1$. The upper bound on λ''_{123} is 1.25 arising from the requirement of perturbative unification.

[2] Using the recent lattice measurements of the hadronic matrix elements, B_K and ζ_s [see Eq. (13)], the authors of [13] have speculated a possible role of new physics to account for the difference between the fitted $\sin 2\beta = 0.87 \pm 0.09$ (without V_{ub} as input) and the measured value of $\sin 2\beta$, which is about 2.1σ lower than the fitted value.

III. BRPV 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

$$h(b \to s) \equiv \lambda''^{*}_{113}\lambda''_{112}, \qquad h(b \to d) \equiv \lambda''^{*}_{123}\lambda''_{121}. \quad (9)$$

These combinations contribute to B_q-$\bar{B}_q$ ($q = d, s$) 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 ($x_f = m_f^2/\tilde{m}^2$) [15]

$$M_{12(q)}^{\text{B-RPV}} = \frac{h^2(b \to q)}{192\pi^2 M_{\tilde{q}_R}^2} M_{B_q}\hat{\eta}_{B_q} f_{B_q}^2 B_{B_q}(\tilde{S}_0(x_u) + \tilde{S}_0(x_d)), \quad (10)$$

where

$$\tilde{S}_0(x) = \frac{1+x}{(1-x)^2} + \frac{2x\log x}{(1-x)^3}. \quad (11)$$

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 nonleptonic B decays like $b \to d\bar{d}s$ and $b \to u\bar{u}s$, like $B^+ \to K^0\pi^+$, $B^+ \to K^+\pi^0$, $B_d \to K^0\pi^0$, $B_d \to K^+\pi^-$, $B_s \to \phi\pi^0$, $B_s \to \pi^+\pi^-$, $B_s \to K^+K^-$, and their CP conjugate decays.[3] Similarly, $h(b \to d)$ provides new *tree level* contribution to different $B \to \pi\pi$ decay modes.[4] Thus, different decay rates receive different amount of SM and BRPV contributions, and the net amplitude in each case amounts to their coherent sum.[5] The SM amplitude is calculated in the naive factorization model [5]. 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 BRPV amplitudes, which may be generated from final state interaction and rescattering. Indeed, the weak phases of the BRPV couplings are free parameters. For simplicity, we have not considered the mixing between the BRPV operators and the SM operators between the scale M_W and m_b. The dominant effect, which is just a multiplicative renormalization of the BRPV operator, can be taken into account by interpreting the BRPV 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).

[3]Contributions from lepton-number violating λ'-type couplings to CP-asymmetry in $B^+ \to \pi^+K$ channel have been studied in [16]. A similar study with λ' couplings affecting $B \to X_s\gamma$ channel has been performed in [17]. Note that the BRPV couplings we have considered in this paper would contribute to $B \to X_s\gamma$ too, but it can be kept under control.

[4]Interplay between B_d-$\bar{B}_d$ and $B_d \to \pi^+\pi^-$ with λ'-type couplings was studied in [18].

[5]It should be noted that for simplicity of our analysis we have neglected the contributions arising from R-parity conserving sector in all these cases. The leading contributions from this sector to nonleptonic B decays would come at one-loop order, whereas the BRPV contributions in those decays would proceed at tree level.

IV. NUMERICAL INPUTS

Unless otherwise mentioned, all numbers are taken from [3]. The measured values of the mass differences (ΔM_q) are

$$\Delta M_d = (0.507 \pm 0.005)\ \text{ps}^{-1}, \qquad \Delta M_s = (17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}))\ \text{ps}^{-1}. \quad (12)$$

We require $\sin 2\beta$ to lie between 0.75 ± 0.04 (the SM fit value with V_{ub} as input) and 0.681 ± 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]

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

and the short distance factors

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

The relevant Cabibbo-Kobayashi-Maskawa (CKM) elements are [20]

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

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

V. RESULTS

We proceed by making two assumptions or working conditions:

(i) The strong phase difference between the SM amplitude and the corresponding NP 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 nonleptonic decay modes we have followed a nave factorization approach and considered 10% uncertainty over the SM amplitudes to cover the different (model-dependent) nonfactorizable 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 [5].

There are five parameters which we like to constrain: the magnitude of two product couplings ($|\lambda''^{*}_{123}\lambda''_{121}|$ and $|\lambda''^{*}_{113}\lambda''_{112}|$), their weak phases [$\Phi_D \equiv \mathrm{Arg}(\lambda''^{*}_{123}\lambda''_{121})$ and $\Phi_S \equiv \mathrm{Arg}(\lambda''^{*}_{113}\lambda''_{112})$], and the common strong phase difference between the NP and the SM amplitude (δ_S). We vary all of them simultaneously, and constrain them by requiring consistency with the observables Δa_{CP}, R_n, R_c, $R_{\pi\pi}$, R_a, $\sin 2\beta$, ΔM_d, ΔM_s, and ϕ_{B_s}. We also use $R = \mathcal{BR}(B^0 \to \pi^+\pi^-)/\mathcal{BR}(B^0 \to \pi^+ K^-) = 0.259 \pm 0.023$ [3] to constrain those parameters. Our results are plotted in Figs. 1 and 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. 1(a) we projected the allowed region in a two-dimensional space of the magnitude ($|\lambda''^{*}_{113}\lambda''_{112}|$) and phase ($\Phi_S$) of $h(b \to s)$. The right-side patches in Fig. 1(a) are allowed solutions when all the five parameters pass through the filters of ΔM_d, $\sin 2\beta$, Δa_{CP}, R, R_n, and R_c; while the left-side patches are zones allowed by ΔM_s and ϕ_{B_s} only. There are *small* overlaps between the allowed regions from the two sets. The overlaps signify a common solution for all 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 BRPV interactions. In Fig. 1(b), we displayed the allowed zone in the plane of Φ_S and δ_S. We note at this stage that Φ_S has four sets of solutions, one in each quadrant, and for each such set there is an associated patch of δ_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 $\mathcal{BR}(B^0_d \to \pi^0\pi^0)$, only two sets of δ_S are allowed, one in the interval $(100 \to 165)^\circ$ and the other in $(195 \to 245)^\circ$. Since δ_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 Φ_S solutions in the second and the third quadrants. The finally allowed values of Φ_S lie in the range $(10 \to 60)^\circ$ and $(275 \to 340)^\circ$. Clearly, if we relax the assumption of *equality* of the strong phase difference (i.e. a *common* δ_S), Φ_S solutions in all the four regions will be allowed.

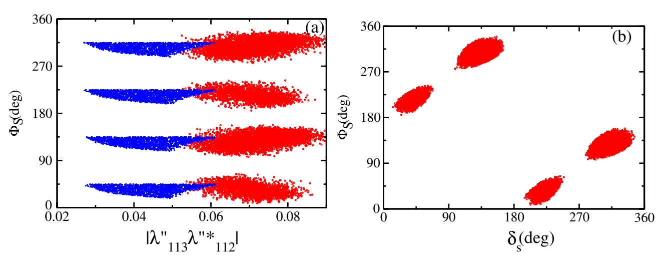

FIG. 1 (color online). (a) The allowed zone in the plane of the magnitude of $h(b \to s)$ and its weak phase (Φ_S) is shown. The patches on the right side are scatter plots of the allowed parameters obtained by using ΔM_d, $\sin 2\beta$, Δa_{CP}, R, R_n, R_c, and R_a; while the patches on the left side correspond to the space allowed by ΔM_s and ϕ_{B_s} only. (b) The allowed patches in the plane of the strong phase difference (δ_S) and Φ_S are displayed.

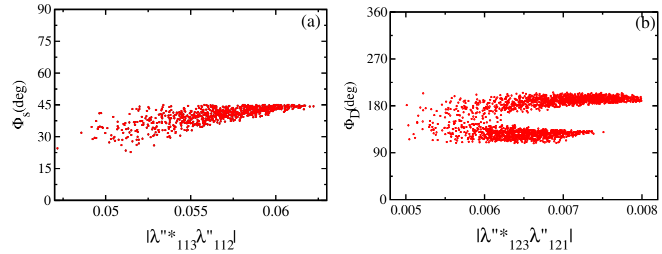

FIG. 2 (color online). (a) Zoomed version of Fig. 1(a), except that all constraints are now used, and focused in the first quadrant solution of Φ_S. (b) Similar to Fig. 2(a), but in the space of the magnitude and phase of $h(b \to d)$.

Figure 2(a) is a zoomed version of Fig. 1(a), except that in Fig. 2(a) we have included *all* possible constraints at the same time. For illustration, out of the two allowed sets of Φ_S, the one within the range $(10 \to 60)^\circ$ has been shown. Figure 2(b) 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 1 order of magnitude tighter than $|h(b \to s)|$, primarily because the SM prediction of the B_d mixing is relatively more precise.

VI. CONCLUSIONS

In this paper, we wanted to solve three puzzles in B physics, namely, the large phase in B_s mixing, a more than 3.5σ discrepancy between CP-asymmetries in charged and neutral B decays in πK 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 nonzero phase would constitute a clinching signal for new physics; (ii) but, on account of large hadronic uncertainties associated with the πK and $\pi\pi$ modes, the *discrepancies* observed in Δa_{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 nonpuzzles, 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 the 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 BRPV couplings (or, similar type diquark couplings) from the following observations: the coupling $h(b \to s)$ will contaminate $B_s \to K^+K^-$ ($b \to su\bar{u}$ at the quark level) which is used to extract $\gamma = \mathrm{Arg}(V_{ub}^*)$ [21], but it would not affect $B_s \to D_sK$ ($b \to sc\bar{u}$ at the quark level) which is also used to determine γ [22]. Any statistically different measurement of γ between these two methods will strengthen our hypothesis. Moreover, either of the two methods would yield γ different from the value extracted from $B \to \pi K$. We stress again that the falsifiability of our hypothesis, under the assumptions specified above, can be judged from Fig. 1(a) 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. The LHCb experiment will definitely shed more light to these issues.

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