

R-parity violating supersymmetry, B_s mixing, and $D_s \rightarrow \ell\nu$

Anirban Kundu, Soumitra Nandi

Department of Physics, University of Calcutta, 92 A.P.C. Road, Kolkata - 700009, India

(Dated: November 12, 2018)

Recently, it was pointed out that the mixing phase in the $B_s - \overline{B}_s$ system is large, contrary to the expectations in the Standard Model as well as in minimal flavour violation models. The leptonic decay widths of the D_s meson are also found to be larger than expected. We show how a minimal set of four R-parity violating λ' -type couplings can explain both these anomalies. We also point out other phenomenological implications of such new physics.

PACS numbers: 12.60.Jv, 13.25.Ft, 14.40.Nd

I. EXPERIMENTAL DATA

A. $B_s - \overline{B}_s$ mixing

Recently, the UTfit collaboration has claimed that the phase coming from $B_s - \overline{B}_s$ box diagram, as found on averaging various data, is more than 3σ away from the SM expectation [1]. In the Standard Model (SM), β_s is defined as

$$\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*), \quad (1)$$

which is 0.018 ± 0.001 . If there were no new physics (NP), the angle ϕ_s is defined simply as $\phi_s \equiv -\beta_s$. If NP is present, ϕ_s , the phase coming from the $B_s - \overline{B}_s$ box, has both SM and NP contributions. UTfit has got two solutions for ϕ_s , and hence for the NP amplitude:

$$\begin{aligned} \phi_s(^{\circ}) &= -19.9 \pm 5.6 \quad [-30.45, -9.29] \\ &= -68.2 \pm 4.9 \quad [-78.45, -58.2] \\ \phi_s^{NP}(^{\circ}) &= -51 \pm 11 \quad [-69, -27] \\ &= -79 \pm 3 \quad [-84, -71] \\ A^{NP}/A^{SM} &= 0.73 \pm 0.35 \quad [0.24, 1.38] \\ &= 1.87 \pm 0.06 \quad [1.50, 2.47]. \end{aligned} \quad (2)$$

In each line, the first number stands for the 68% confidence limit (CL) and the second number stands for the 95% allowed range. The strong phase ambiguity affects the sign of $\cos \phi_s$ and hence $\Re(A^{NP}/A^{SM})$, which can either be -0.13 ± 0.31 or -1.82 ± 0.28 (both at 68% CL), while $\Im(A^{NP}/A^{SM}) = -0.74 \pm 0.26$ in any case. These two solutions are shown separately in eq. (2). Note that while the range of NP contribution for the second solution is more precise, this is more unlikely at the same time as NP amplitude is almost twice that of the SM one. Apart from SM, this result disfavors the minimal flavour violation models too.

However, the situation in the B_d system is markedly different. It has been established that the dominant CP-violation mechanism there is the CKM one, and any NP effect must be subdominant. One can, just to be conservative, discuss the case where there is no effect in the B_d system. We follow such an approach; the NP must be flavour-specific in nature.

B. $D_s \rightarrow \ell\nu$

The leptonic decay $D_s \rightarrow \ell\nu$, where $\ell = \mu, \tau$, has a branching fraction

$$B = \frac{1}{8\pi} m_{D_s} \tau_{D_s} f_{D_s}^2 |G_F V_{cs}^* m_\ell^2| \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right), \quad (3)$$

where τ_{D_s} is the lifetime of D_s and the decay constant f_{D_s} is defined through

$$\langle 0 | \bar{s} \gamma_\mu \gamma_5 c | D_s \rangle = i f_{D_s} p_\mu, \quad (4)$$

where p_μ is the 4-momentum of D_s . While lattice results predict [4]

$$f_{D_s} = 241 \pm 3 \text{ MeV}, \quad (5)$$

the experimental numbers are larger [2, 3]:

$$\begin{aligned} f_{D_s}(D_s \rightarrow \mu\nu) &= 273 \pm 11 \text{ MeV}, \\ f_{D_s}(D_s \rightarrow \tau\nu) &= 285 \pm 15 \text{ MeV}, \\ f_{D_s}(D_s \rightarrow \ell\nu) &= 277 \pm 9 \text{ MeV} \quad (\text{average}). \end{aligned} \quad (6)$$

This can be due to an improper estimate of lattice uncertainties. On the other hand, one can also say that f_{D_s} is indeed that of eq. (5) but the discrepancy is due to some NP contribution in the leptonic channels that enhance the branching fractions. The enhancement is about $13 \pm 6\%$ in the μ channel, $18 \pm 8\%$ in the τ channel, and $15 \pm 5\%$ on average.

Dobrescu and Kronfeld [3] have attempted an explanation of the D_s leptonic anomaly with either charged Higgs bosons or leptoquarks. While they have not talked about the UTfit result, it can hopefully be shown that suitable leptoquark couplings with complex phases can explain both the discrepancies. Two facts, however, are obvious: first, the NP couplings should be large so that they can generate such large effects, and second, as we have just mentioned, these couplings *must be* flavour-dependent.

In this work, we will try to show that a simultaneous explanation can be found with a minimal set of four R-parity violating supersymmetric couplings.

II. R-PARITY VIOLATION

The discrete symmetry, R-parity, is defined as $(-1)^{3B+L+2S}$ where B, L and S are the baryon number, lepton number, and spin of the particle respectively. This is 1 for all particles and -1 for all sparticles. While one can demand the conservation of R-parity *ad hoc*, it is

$$\mathcal{L}_{LQD} = \lambda'_{ijk} [\tilde{\nu}_{iL} \bar{d}_{kR} d_{jL} + \tilde{d}_{jL} \bar{d}_{kR} \nu_{iL} + (\tilde{d}_{kR})^* \bar{\nu}_{iR}^c d_{jL} - \tilde{e}_{iL} \bar{d}_{kR} u_{jL} - \tilde{u}_{jL} \bar{d}_{kR} e_{iL} - (\tilde{d}_{kR})^* \bar{e}_{iR}^c u_{jL}] + h.c. \quad (7)$$

Let us consider four λ' -type couplings, λ'_{i12} and λ'_{i23} , where $i = 2, 3$, to be nonzero. This is a *minimal ansatz* that can explain the data while keeping all other experimental constraints intact. However, while such an ansatz can only be motivated from the data, let us also note that all the R-parity violating couplings are, to start with, free parameters of the model. At the same time, we keep all other RPV couplings to be zero at the weak scale. The nonzero couplings are assumed to be generated at the GUT scale in the quark mass basis, so that they are not further rotated and the constraints from neutrino masses would be weaker (the so-called ‘no-mixing’ scenario of [5]). If these GUT scale couplings are taken to be in the flavour basis, the running from M_{GUT} to M_Z would introduce nonzero values of other couplings in the mass basis because of the nontrivial mixing through the CKM elements. With a plethora of couplings at the weak scale, neutrino mass constraints would severely restrict the values of the input set, making them uninterestingly small.

In the ‘no-mixing’ scenario, the upper limit for all these couplings at the m_Z scale is about 0.39 [5]. However, the product $\lambda'_{i12} \lambda'^*_{i23}$ is constrained from $B_s - \bar{B}_s$ mixing [6]: the upper limit on its magnitude is 5.16×10^{-2} . If the coupling is complex, the real part can be as large as 7.56×10^{-2} . All the bounds are for 100 GeV sleptons, and scale as $\lambda' \lambda' / M^2$.

One can also take a bottom-up approach and consider a model where only these four λ' couplings are nonzero at M_Z , not caring about the physics at the GUT scale. In the scenarios where there is mixing either in the up-quark sector (the rotation matrices for the right- and left-chiral down quark fields are unity) or in the down-quark sector, such an arrangement at the weak scale will need considerable manipulation of the GUT scale couplings, and there is a high chance that the constraints coming from neutrino phenomenology will not be satisfied. For a detailed phenomenological analysis of such scenarios, we refer the reader to references [7, 8]. Here we stick, for a concrete realization, to the so-called ‘no-mixing’ scenario. Whether one can generate neutrino masses and mixing through two-loop effects of the said couplings is under investigation [9].

possible to write R-parity violating (RPV) terms in the superpotential. To forbid proton decay, one has to consider either baryon-number or lepton-number violating RPV couplings. For our case, we will consider lepton-number violating λ' -type couplings, since the interaction involves both quarks and leptons. The Lagrangian, in terms of component fields, is given by

Let us mention here that the minimal set is actually three and not four; one must have λ'_{223} and λ'_{323} to explain $D_s \rightarrow \mu\nu$ and $D_s \rightarrow \tau\nu$ respectively, and either λ'_{212} or λ'_{312} which, in conjunction with the λ' coupling with the same leptonic index, would contribute to the $B_s - \bar{B}_s$ mixing. However, to keep the couplings symmetric, we will consider both λ'_{212} and λ'_{312} to be present.

III. EXPLANATION OF D_s BRANCHING RATIO

Let us first consider the λ'_{i23} couplings. The leptonic index i can be 2 or 3. The relevant four-fermi interaction can be obtained by contracting the \tilde{b}_R field in the third and the sixth terms of eq. (7). Thus, both $\mu\nu_\mu$ and $\mu\nu_\tau$ can occur as final states. Only the former will interfere with the SM amplitude; the second one should be added incoherently. The product carries a minus sign. The $(S - P) \otimes (S + P)$ gives $-\frac{1}{2}(V - A) \otimes (V + A)$ under Fierz reordering. The two charge-conjugated spinors should be replaced by ordinary spinors; that involves another flip of position and the third minus sign (also, $V + A$ changes to $V - A$). Finally, the internal propagator is scalar and not a vector like SM; that brings in the fourth minus sign. Altogether, the SM and the NP come with same sign and the interference is positive, so the branching fraction should increase. However, note that we have to include both neutrino flavours. The product $|\lambda'_{223}|^2$ is always positive; $\lambda'_{223} \lambda'^*_{323}$ can come with a complex phase, but since this is incoherently added, the phase cancels out in the amplitude squared. The same applies for a $\tau\nu$ final state.

Note that λ'_{i22} type couplings are highly suppressed from neutrino mass ($\sim 10^{-5}$) [5], and λ'_{i21} does not resolve the $B_s - \bar{B}_s$ anomaly.

Since the neutrino flavour is not detected, we may replace $|G_F V_{cs}^*|^2$, for $D_s \rightarrow \mu\nu$, by

$$\left| G_F V_{cs}^* + \frac{1}{\sqrt{2} m_{b_R}^2} C_{A22}^\mu \right|^2 + \left| \frac{1}{\sqrt{2} m_{b_R}^2} C_{A23}^\mu \right|^2, \quad (8)$$

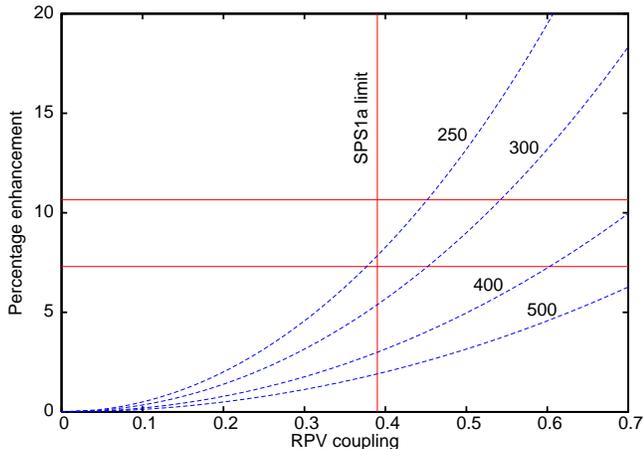


FIG. 1: The effect of the R-parity violating couplings λ'_{223} and λ'_{323} on $D_s \rightarrow \mu(\tau)\nu$. The upper (lower) horizontal line is the 1σ lower limit for the percentage enhancement of $D_s \rightarrow \tau\nu$ ($D_s \rightarrow \mu\nu$). The vertical line shows the SPS1a limit of 0.39 (see text). The curved lines are drawn for different values of $m_{\tilde{b}_R}$, as shown in the plot. We have assumed $\lambda'_{223} = \lambda'_{323}$, and both real.

where

$$C_{A22}^\mu = \frac{1}{4} |\lambda'_{223}|^2, \quad C_{A23}^\mu = \frac{1}{4} \lambda'_{223} \lambda'^*_{323}. \quad (9)$$

The leptonic indices 2 and 3 are to be interchanged for $D_s \rightarrow \tau\nu$ decay.

Let us assume $\lambda'_{223} = \lambda'_{323}$, both being real. The contribution to D_s leptonic width depends on the mass of \tilde{b}_R . We have shown in figure 1 how the branching fraction gets enhanced for three values of $m_{\tilde{b}_R}$. To saturate the upper bound, the required value of $m_{\tilde{b}_R}$ is too small and is already ruled out by the Tevatron experiments.

One may argue that squarks lighter than 300 GeV are hardly allowed. We would like to point out that the propagator is a right-handed bottom squark, which may be light for large $\tan\beta$. Also, let us note how the bound of $|\lambda'_{i23}| < 0.39$ arose. The need to prevent tachyonic sneutrinos even at the GUT scale forces an inequality between λ'_{ijk} and the GUT scale input parameters M_0 , $M_{1/2}$, $\tan\beta$, and A_0 [10]. The maximum value at the GUT scale is driven by the input parameters; for the set known as SPS1a, this comes out to be about 0.13. When run down at the M_Z scale, the coupling increases three-fold and the bound becomes 0.39. One can easily relax this bound for other choices of the GUT scale input parameters; thus, even with a larger value of $m_{\tilde{b}_R}$ one can reach the 68% CL lower limit of $D_s \rightarrow \tau\nu$. This is shown in Fig. 1. It is nevertheless clear that one requires rather large values of λ'_{i23} to explain the present data; more precise lattice results are, therefore, eagerly awaited.

IV. EXPLANATION OF B_s MIXING PHASE

The product $\lambda'_{i23}\lambda'^*_{i12}$ contributes in the $B_s - \overline{B}_s$ box, with two i -type sleptons, a charm, and an up quark flow-

ing in the loop; it can also be leptons and squarks. Let us assume all sleptons degenerate at 100 GeV and all squarks degenerate at 300 GeV (the box amplitude is controlled by the slepton diagram, so the exact value of the squark mass is irrelevant). For simplicity (and without losing any generality), we will assume $\lambda'_{212}\lambda'_{223} = \lambda'_{312}\lambda'_{323}$, in both magnitude and the weak phase. One can consider the phase to be associated with the λ'_{i12} coupling. The relevant formulae can be obtained from [11].

We find that (i) A_{NP}/A_{SM} can at most go upto 38%, above that, the constraint $\Delta M_s = 17.77 \pm 0.12 \text{ ps}^{-1}$ [12] is violated; (ii) the phase coming from the box can lie in the 68% allowed range of UTfit, namely, $[-14.3^\circ, -25.5^\circ]$; (iii) there are two allowed regions where this can happen, *viz.*, $|\lambda'_{212}\lambda'_{223}| \in [0.002, 0.004], [0.014, 0.019]$.

Note that we have assumed both λ'_{212} and λ'_{312} to be nonzero (and equal). If only one of them is nonzero, the allowed range would have been enhanced by a factor of four (the two RPV amplitudes add coherently).

One might note that the charged Higgs H^+ , present in any supersymmetric model, can in principle affect the leptonic branching ratios of D_s [13]. However, we would consider the parameter space where such effects are minimal (since the effects go in the opposite direction, it would result in a more serious tension between theory and experiment, and hence one would need larger values of the R-parity violating couplings). This can happen, for example, in the low $\tan\beta$ region.

V. MORE FEATURES

Contracting the slepton index, we get the decay $b \rightarrow c\bar{u}s$. However, these couplings do not generate $b \rightarrow u\bar{c}s$. So only $B_s \rightarrow D_s^- K^+$ and not $B_s \rightarrow D_s^+ K^-$ will be affected. Thus, the method for the determination of the angle γ of the Unitarity Triangle (UT) based on the simultaneous study of $B_s(\overline{B}_s) \rightarrow D_s^\pm K^\mp$ will be affected. The same is true for the $B \rightarrow DK$ modes. On the other hand, γ determined from channels that are not affected by these RPV couplings will yield the true phase of V_{ub} . A signature for this hypothesis would then be to compare the measurements of γ from these channels.

The above discussion shows that the $B_s - \overline{B}_s$ mixing box will have an absorptive part. As has been discussed in [14], such new absorptive parts bypass the Grossman theorem [15] of reduction of $\Delta\Gamma$, the width difference of two B_s mass eigenstates, in the presence of new physics. Unfortunately, we find that the effect is too small to be detected over the SM uncertainty in $\Delta\Gamma_s$ [16], so the result is consistent with the experimental number [17].

If we contract the sneutrino instead of the charged slepton, the decay process is $b \rightarrow s\bar{d}s$. Such $\Delta B = 1, \Delta S = 2$ decays are extremely suppressed in the SM. However, this can now occur with a branching ratio that should be in the range of LHC-B. One can have, for example, the decay $B^+ \rightarrow K^{*0} K^+$ and then $K^{*0} \rightarrow K^+ \pi^-$.

A. Collider signals

It has been noted in [7] that large values of λ'_{i23} at the GUT scale can generate, through RG evolution, neutrino masses compatible with experiment. The neutralino, in these cases, will decay to μcb or $\nu_\mu sb$ channel (for $i = 3$, replace μ by τ). The gaugino signal would be one b jet (plus other jets) and an isolated hard lepton. Thus, an increase in $2j + 2\mu$ (or $2j + 2\tau$) channel would be an

encouraging signal for this hypothesis.

VI. ACKNOWLEDGEMENTS

The authors thank Biswarup Mukhopadhyaya for helpful discussions and comments. AK is supported by the projects SR/S2/HEP-15/2003 of DST, Govt. of India, and 2007/37/9/BRNS of DAE, Govt. of India.

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- [1] M. Bona *et al.* [UTfit Collaboration], arXiv:0803.0659 [hep-ph].
- [2] W.M. Yao *et al.* [Particle Data Group Collaboration], J. Phys. G **33**, 1 (2006) and <http://pdg.lbl.gov> for 2007 partial update; B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **98**, 141801 (2007); T.K. Pedlar *et al.* [CLEO Collaboration], Phys. Rev. D **76**, 072002 (2007); K. Abe *et al.* [Belle Collaboration], arXiv:0709.1340 [hep-ex]; K.M. Ecklund *et al.* [CLEO Collaboration], Phys. Rev. Lett. **100**, 161801 (2008).
- [3] B.A. Dobrescu and A.S. Kronfeld, arXiv:0803.0512 [hep-ph].
- [4] E. Follana *et al.* [HPQCD and UKQCD Collaboration], Phys. Rev. Lett. **100**, 062002 (2008).
- [5] B.C. Allanach, A. Dedes, and H.K. Dreiner, Phys. Rev. D **60**, 075014 (1999), Phys. Rev. D **69**, 115002 (2004).
- [6] S. Nandi and J.P. Saha, Phys. Rev. D **74**, 095007 (2006).
- [7] A. Datta *et al.*, Phys. Rev. D **72**, 055007 (2005).
- [8] B.C. Allanach and C.H. Kom, J. High Energy Physics **0804**, 081 (2008).
- [9] P. Dey, A. Kundu, B. Mukhopadhyaya, and S. Nandi, in preparation.
- [10] B. de Carlos and P.L. White, Phys. Rev. D **55**, 4222 (1997).
- [11] J.P. Saha and A. Kundu, Phys. Rev. D **70**, 096002 (2004).
- [12] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 242003 (2006).
- [13] A.G. Akeroyd and C.H. Chen, Phys. Rev. D **75**, 075004 (2007).
- [14] A. Dighe, A. Kundu, and S. Nandi, Phys. Rev. D **76**, 054005 (2007).
- [15] Y. Grossman, Phys. Lett. **B380**, 99 (1996).
- [16] A. Lenz and U. Nierste, J. High Energy Physics **0706**, 072 (2007).
- [17] V.M. Abazov *et al.* [D0 Collaboration], arXiv:0802.2255 [hep-ex].