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New Physics in $b \to s\,\nu\,\bar{\nu}$ decays?

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Measurements of various lepton flavor universal observables in $b \to s\,l^+l^-$ transition decays continue to disagree with the standard model expectations. The recent update of R_K measurement from LHCb still indicates 3.1σ deviation from the standard model. Similarly, the measurements of other observables such as R_{K^*}, P_5' and $\mathcal{B}(B_s \to \phi\,\mu^+\,\mu^-)$ continue to show disagreement with standard model predictions. It is well known that there exists a very close relation between $b \to s\,l^+l^-$ and $b \to s\,\nu\bar{\nu}$ decays not only in standard model but also in beyond the standard model physics. In beyond the standard model physics these decay processes are related via $SU(2)_L$ gauge symmetry which relates neutrinos to the left handed charged leptons. Moreover, the B decays with $\nu\bar{\nu}$ final state are theoretically cleaner channels than the corresponding $b \to s\,l^+l^-$ neutral transitions as they do not suffer from hadronic uncertainties beyond the form factors such as the non-factorizable corrections and photonic penguin contributions. Hence, we explore $B_s \to (\phi\,,\eta\,,\eta')\,\nu\,\bar{\nu}$ decays mediated via $b \to s\,\nu\,\bar{\nu}$ transitions using the standard model effective field theory formalism, Z' and scalar and vector leptoquarks new physics models. We give predictions of branching ratio in standard model and in the presence of various new physics couplings.

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1. Introduction

The missing link to address the observed anomalies in B decays is very crucial as these anomalies have direct consequence in our understanding of the flavor structure in several flavor changing decay processes. So far till today the B factories have managed to provide the accurate measurements of the several rare semileptonic neutral decay observables which proceed via $b \to s\ell\ell$ quark level transitions. The experimental measurements of the ratio of branching ratios $R_{K^{(*)}}$, the angular coefficient P_5' in $B \to K^{(*)}\ell\ell$ decays and the measurement of the branching fraction of $B_s \to \phi\mu^+\mu^-$ decays encounter lack of consensus with respect to the theoretical predictions. From the theoretical point of view it is very challenging to understand the full kinematics of these rare decay process. In fact it is very crucial to calculate the relevant form factors associated to these decays as they are the main sources of theoretical uncertainties. Currently, the QCD motivated approaches such as the light cone sum rules and the lattice QCD methods have provided the precise form factors for $B \to K^{(*)}$ and $B_s \to \phi$ decays in the full kinematic range. If there is any NP present in $B \to K^{(*)}$ and $B_s \to \phi$ decays, it will be reflected in many other similar decays as well. Hence, studying new decay modes will help in providing the complementary information to the existing discrepancies.

In that sense, there exist another family of neutral rare decays with the neutral leptons in the final state such as $b \to s\,\nu\,\bar{\nu}$ decays which are considered to be theoretically cleaner decay channels. There are several advantages of studying these di-neutrino final state decays as they do not suffer from the various hadronic uncertainties beyond the form factors such as the non-factorizable corrections and photonic penguin contributions. In principle, it is important to study the implication of $b \to s\ell\ell$ anomalies on $b \to s\,\nu\,\bar{\nu}$ decays. In this context, we discuss the $B_s \to (\phi, \eta, \eta')\,\nu\,\bar{\nu}$ decays mediated via $b \to s\,\nu\,\bar{\nu}$ transitions in standard model and in the presence of model dependent and independent new physics scenarios.

2. Phenomenology

The effective Hamiltonian for $b \to s\,(l^+\,l^-, \nu\,\bar{\nu})$ decays [1],

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i\,O_i + h.c., \quad (1)$$

For $i = L, R$, the sum include the operators $O_{L,R}$ contributing to $b \to s\,\nu\,\bar{\nu}$ decays where,

$$O_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu), \qquad O_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu). \quad (2)$$

Here, $C_L = C_L^{SM} + C_L^{NP}$ with $C_L^{SM} = -6.38 \pm 0.06$ being the SM Wilson coefficient and $C_R = 0$ in SM. Similarly, for $i = 9, 10$ the sum include the operators $O_{9,10}^{(\prime)}$ contributing to $b \to s\,l^+\,l^-$ decays where,

$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu l), \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu\gamma_5 l). \quad (3)$$

The differential branching ratios for $b \to s\,\nu\,\bar{\nu}$ decays for pseudoscalar (P) and vector (V) meson final state are written as [1]

$$\frac{dBR(B \to P\,\nu\,\bar{\nu})}{dq^2} = \tau_{B_s}\, 3\,|N|^2\,|C_L|^2\,\rho_K(q^2),$$
$$\frac{dBR(B \to V\,\nu\,\bar{\nu})}{dq^2} = \tau_{B_s}\, 3\,|N|^2\,|C_L|^2\,\left[\rho_{A_1}(q^2) + \rho_{A_{12}}(q^2) + \rho_V(q^2)\right]. \quad (4)$$

where, N is the normalization term, τ_{B_s} is the B_s meson lifetime and $\rho_i(q^2)$ are the form factor dependent factors. For $B_s \to (\eta\,,\eta')$ we refer to the form factors obtained in light cone sum rule [2] and similarly, for $B_s \to \phi$ we have considered LCSR+LQCD form factors [3].

3. Result and discussion

3.1 Fit analysis

Among the various existing NP scenarios that are allowed by the $b \to s\ell\ell$ experimental data we choose to work in particular with the $C_9(NP) = -C_{10}(NP)$ new physics scenario. The advantage of this scenario was well explained in [4]. We obtain the best fits of the Z', LQ coupling strengths and the $\widetilde{c}_{ql}^{(3)}$ coefficient by fitting the latest experimental measurements of $R_{K^{(*)}}$, P_5', $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ using the naive χ^2 analysis.

3.2 Interpretation of $B_s \to (\phi,\eta,\eta')\nu\bar{\nu}$ decays in SM and beyond

We study $B \to K^{(*)}\nu\bar{\nu}$ and $B_s \to (\phi,\eta,\eta')\nu\bar{\nu}$ decays in SM and in the presence of SMEFT coupling $\widetilde{c}_{ql}^{(3)}$ and also in the presence of Z', LQ new physics models. We report the integrated values of the branching ratios in Table 1. Similarly, the q^2 dependent plots for $B_s \to (\phi,\eta,\eta\prime)\nu\bar{\nu}$ are displayed in Fig. 1. In SM, we obtain the branching ratio in the order of $O(10^{-6})$ for all the decay modes. For our NP analysis, in SMEFT platform the semileptonic WCs C_9 and C_{10} in $b \to s\ell\ell$ are expressed in terms of SMEFT coefficients c_i's [1]. Similarly, the respective WC C_L corresponding to $b \to s\,\nu\,\bar{\nu}$ intern receive the impact of $\widetilde{c}_{ql}^{(3)}$ under $C_9(NP) = -C_{10}(NP)$ condition as defined in Ref. [1]. Similarly, in Z' and LQ models the semileptonic WCs C_9 and C_{10} corresponding to $b \to s\ell\ell$ decays in principle fall under $C_9(NP) = -C_{10}(NP)$ NP scenario. The corresponding contribution of Z' and LQ (S3 and U3) to the respective WC C_L corresponding to $b \to s\,\nu\,\bar{\nu}$ are respectively different from one another. The additional information related to the effects of Z' and LQs on $b \to s\,\nu\,\bar{\nu}$ decays can be found in Refs. [4, 5]. Our observations in this context are as follows:

The impact of S3-LQ on the branching ratios of $B_s \to (\eta,\eta',\phi)\,\nu\,\bar{\nu}$ is quite similar to SM. The effect due to SMEFT coefficient $\widetilde{c}_{ql}^{(3)}$ do affect the branching ratios at more than 1σ level from the SM. Similarly, the impact of Z' is almost similar to the $\widetilde{c}_{ql}^{(3)}$ but lie not more than 1σ away from the SM central value. Very interestingly, the nature of curve corresponding to the vector U3-LQ have significant impact on the branching ratios at more than 2σ from the SM expectations. In addition, the important point to note here is that however, the contribution from Z' and LQs (U3 and S3) are indistinguishable in $b \to s\ell\ell$ sector but they are clearly distinguishable in $b \to s\,\nu\,\bar{\nu}$ sector.

BR $\times 10^{-6}$	SM	SMEFT ($\widetilde{c}_{ql}^{(3)}$)	Z′	LQ(U_3)	LQ(S_3)
$\mathcal{B}(B \to K\,\nu\,\bar{\nu})$	4.006 ± 0.261	4.891 ± 0.319	4.648 ± 0.302	5.586 ± 0.362	4.376 ± 0.285
$\mathcal{B}(B \to K^*\,\nu\,\bar{\nu})$	9.331 ± 0.744	11.394 ± 0.908	10.828 ± 0.861	13.012 ± 1.032	10.194 ± 0.811
$\mathcal{B}(B_s \to \eta\,\nu\,\bar{\nu})$	1.700 ± 0.187	2.075 ± 0.228	1.972 ± 0.217	2.370 ± 0.260	1.857 ± 0.204
$\mathcal{B}(B_s \to \eta'\,\nu\,\bar{\nu})$	1.673 ± 0.232	2.043 ± 0.283	1.942 ± 0.268	2.333 ± 0.322	1.828 ± 0.253
$\mathcal{B}(B_s \to \phi\,\nu\,\bar{\nu})$	9.762 ± 0.625	11.920 ± 0.763	11.329 ± 0.722	13.613 ± 0.863	10.665 ± 0.680

Table 1: The $B \to K^{(*)}\,\nu\,\bar{\nu}$, $B_s \to (\eta, \eta')\,\nu\,\bar{\nu}$ and $B_s \to \phi\nu\bar{\nu}$ BRs in SM, $\widetilde{c}_{ql}^{(3)}$, Z′ and LQs (U_3 & S_3).

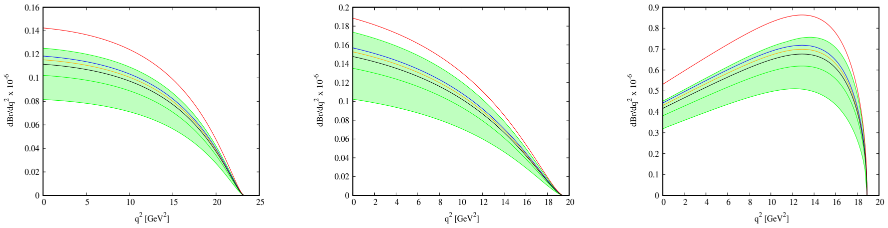

Figure 1: The differential branching ratios of $B_s \to (\eta, \eta')\,\nu\,\bar{\nu}$ and $B_s \to \phi\nu\bar{\nu}$ respectively in SM (green), model independent $\widetilde{c}_{ql}^{(3)}$ (orange), Z′ (blue) and LQ-U3 (red) and LQ-S3 (black)

4. Conclusion

The anomalies observed in $B \to K^{(*)}\ell\ell$ and $B_s \to \phi\mu^+\mu^-$ decays have motivated us to search for NP in the similar quark level transition decays. The decays which follow $b \to s\,\nu\,\bar{\nu}$ are in principle very interesting for several reasons. Hence in this context, we perform the NP analysis for $B \to K^{(*)}\,\nu\,\bar{\nu}$, $B_s \to (\eta, \eta')\,\nu\,\bar{\nu}$ and $B_s \to \phi\nu\bar{\nu}$ in SMEFT, Z' and LQ new physics models using the constraints coming from recent $b \to s\ell\ell$ data. We give predictions of the branching ratios for $B_s \to (\eta, \eta', \phi)\,\nu\,\bar{\nu}$ in SM and in the presence of SMEFT coefficient, Z' and LQ (S3 and U3) within the $C_9(NP) = -C_{10}(NP)$ NP scenario. We do observe very distinguishable contributions for all the NP models. Unlike $b \to s\ell\ell$ decays, the Z' and LQ (S3 and U3) models can be clearly distinguished from each other in $b \to s\,\nu\,\bar{\nu}$ decays. In principle, the study of $b \to s\,\nu\,\bar{\nu}$ are essential to deduce the complementary information to $b \to s\ell\ell$ decays and also to distinguish various NP models. In addition, the future measurements of $B_s \to (\eta, \eta', \phi)\,\nu\,\bar{\nu}$ will help to identify possible NP in $b \to s\,\nu\,\bar{\nu}$ decays.

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