PROCEEDINGS OF SCIENCE

New physics sensitivity in $\Lambda_b \to \Lambda^{(*)}\mu^+\mu^-$ and $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ baryonic decays

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The flavor changing neutral b decays with di-leptons and di-neutrinos in the final state provide a great platform to explore physics beyond the standard model (SM). The recent measurements predicted by LHCb on R_K, R_{K_S}, R_{K*+}, $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ proceeding via $b \to s\ell^+\ell^-$ quark level transitions show a significant deviation from the standard model expectations. Very recently, Belle II collaboration reported a more precise upper bound of the branching fraction of $\mathcal{B}(B \to K^+\nu\bar{\nu}) < 4.1\times10^{-5}$ by employing a new inclusive tagging approach. The $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ decay channels are related in the SM as well as in beyond the SM physics. In the beyond SM physics, they are related via $SU(2)_L$ gauge symmetry and can be studied simultaneously in a model independent standard model effective field theory (SMEFT) approach. Moreover, $b \to s\nu\bar{\nu}$ decay channels are theoretically cleaner than the corresponding $b \to s\ell^+\ell^-$ decays due to the absence of non factorizable corrections and photonic penguin contributions. In this context, we perform a combined analysis of $\Lambda_b \to \Lambda^{(*)}\mu^+\mu^-$ and $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ decay modes and study the implication of $b \to s\ell^+\ell^-$ anomalies in a model independent SMEFT approach. We give predictions of several physical observables within SM and within several new physics scenarios.

41st International Conference on High Energy physics (ICHEP 2022),
6-13 July, 2022
Bologna, Italy

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PoS(ICHEP2022)1000

1. Introduction

In the standard model (SM), the gauge bosons couple to the leptons with equal strengths irrespective of their generations. Hence it is lepton flavor universal (LFU). However, recent experimental studies on the leptonic and semileptonic decays of b flavored mesons and baryons indicate the violation of lepton universality condition. Measurements of several observables in the neutral sector such as $R_{K^{(*)}}$ and P_5' in $B \to (K, K^*)\ell^+\ell^-$ decays, the branching fractions of $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ deviate from the SM predictions.

The neutral current transitions with neutral leptons in the final state proceeding via $b \to s\,\nu\,\bar{\nu}$ quark level transitions are also interesting probes to search for new physics (NP) signatures. These channels are theoretically cleaner as compared to $b \to s\ell\,\bar{\ell}$ processes as these decays are free from various hadronic uncertainties beyond form factors, such as non-factorizable corrections and photon penguin contributions. Despite the difficulties in capturing the missing energy in such decays, very recently, the Belle II collaboration reported an upper bound of the branching fraction 4.1×10^{-5} in $\mathcal{B}(B \to K^+\,\nu\,\bar{\nu})$ decay channel. Interestingly, One can relate $b \to s\,\ell^+\,\ell^-$ to $b \to s\,\nu\,\bar{\nu}$ transition in beyond the SM scenarios using standard model effective field theory (SMEFT) formalism. Motivated by this, we explore the consequences of $b \to s\,\ell^+\,\ell^-$ anomalies on $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))(\mu^+\mu^-, \nu\bar{\nu})$ decays in SMEFT formalism.

2. Theoretical Framework

The most general effective Hamiltonian governing both $b \to s\,(\ell^+\,\ell^-, \nu\,\bar{\nu})$ decays can be expressed as [1],

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

Here, C_i's are the Wilson coefficients and O_i's are the corresponding operators. The relevant operators that contribute to $b \to s\,\nu\,\bar{\nu}$ decays are $O_{L,R}$. In the SM $C_L^{SM} = -6.38 \pm 0.06$ and $C_R = 0$. Similarly, the relevant operators that contribute to $b \to s\,\ell^+\,\ell^-$ decays are $O_{9,10}^{(\prime)}$. We define all the operators as

$$\begin{aligned} O_L &= (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu), \qquad O_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu) \\ O_9^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu l), \qquad\qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu\gamma_5 l). \end{aligned} \tag{2}$$

In SMEFT framework, one can express $C_{9^{(\prime)},10^{(\prime)},L,R}$ in terms of various SMEFT coefficients as

$$\begin{aligned} C_9 &= C_9^{\rm SM} + \widetilde{c}_{qe} + \widetilde{c}_{ql}^{(1)} + \widetilde{c}_{ql}^{(3)} - \zeta\widetilde{c}_Z \qquad C_{10} = C_{10}^{\rm SM} + \widetilde{c}_{qe} - \widetilde{c}_{ql}^{(1)} - \widetilde{c}_{ql}^{(3)} + \widetilde{c}_Z \\ C_9' &= \widetilde{c}_{de} + \widetilde{c}_{dl} - \zeta\widetilde{c}_Z' \qquad\qquad\qquad\quad C_{10}' = \widetilde{c}_{de} - \widetilde{c}_{dl} + \widetilde{c}_Z' \\ C_L^\nu &= C_L^{\rm SM} + \widetilde{c}_{ql}^{(1)} - \widetilde{c}_{ql}^{(3)} + \widetilde{c}_Z \qquad\quad C_R^\nu = \widetilde{c}_{dl} + \widetilde{c}_Z' \end{aligned} \tag{3}$$

where, $\widetilde{c}_Z = \frac{1}{2}(\widetilde{c}_{Hq}^{(1)} + \widetilde{c}_{Hq}^{(3)})$, $\widetilde{c}_Z' = \frac{1}{2}(\widetilde{c}_{Hd})$ and $\zeta \approx 0.08$ is the small vector coupling to charged leptons. The relevant form factors for $\Lambda_b \to \Lambda$ are taken from the recent lattice QCD results [2]. We make use of the full quark model wave function with the full relativistic form of the quark current. [3] to calculate the form factors in $\Lambda_b \to \Lambda^*$ channel.

3. Results and discussions

In SM, the branching fractions of $\Lambda_b \to \Lambda^*(\to pK^-)\mu^+\mu^-$ and $\Lambda_b \to \Lambda(\to p\pi)\mu^+\mu^-$ decays are found to be of the $O(10^{-9})$ and $O(10^{-7})$ respectively. Similarly, the branching fractions of $\Lambda_b \to \Lambda^*(\to pK^-)\nu\bar{\nu}$ and $\Lambda_b \to \Lambda(\to p\pi)\nu\bar{\nu}$ decays are found to be of the $O(10^{-6})$. For our new physics analysis, we choose to work with two SMEFT scenarios such as $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ = (-3.824, -4.905) and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ = (4.560, -3.938). We refer to Ref. [4] for the corresponding best fit values. These values are constrained by the latest experimental measurements of R_K, R_{K^*}, P'_5, $\mathcal{B}(B_s \to \phi\,\mu^+\,\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\,\mu^-)$. In Table 1, we report the central values and the corresponding 1σ uncertainties for the branching ratio (BR), the longitudinal polarization fraction (F_L) and the forward-backward asymmetry (A_{FB}) for $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))(\mu^+\mu^-, \nu\,\bar{\nu})$ decays.

Decay mode	q^2 bin	BR			F_L			A_{FB}		
		SM	$(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$	$(\widetilde{c}_Z, \widetilde{c}'_Z)$	SM	$(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$	$(\widetilde{c}_Z, \widetilde{c}'_Z)$	SM	$(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$	$(\widetilde{c}_Z, \widetilde{c}'_Z)$
$\Lambda_b \to \Lambda^*(\to pK^-)\,\mu^+\mu^-$	[1.1 - 6.0]	$(6.063 \pm 0.855) \times 10^{-9}$	10.775×10^{-9}	9.125×10^{-9}	0.781±0.011	0.760	0.764	-0.114±0.0013	-0.045	-0.064
	[16.0 - 16.8]	$(0.516 \pm 0.0715) \times 10^{-9}$	0.253×10^{-9}	0.254×10^{-9}	0.409±0.011	0.453	0.445	-0.108±0.009	-0.222	-0.226
$\Lambda_b \to \Lambda(\to p\pi)\,\mu^+\mu^-$	[1.1 - 6.0]	$(0.775 \pm 0.181) \times 10^{-7}$	0.895×10^{-7}	0.872×10^{-7}	0.829 ± 0.040	0.713	0.789	-0.028 ± 0.027	0.078	0.027
	[14.2 - 20.83]	$(4.246 \pm 0.263) \times 10^{-7}$	2.263×10^{-7}	3.005×10^{-7}	0.355 ± 0.013	0.352	0.326	$-0.305 \pm \pm 0.012$	0.055	0.017
$\Lambda_b \to \Lambda^*(\to pK^-)\,\nu\bar{\nu}$	$[0.0 - q^2_{max}]$	$(1.420 \pm 0.759)) \times 10^{-6}$	1.238×10^{-6}	0.785×10^{-6}	0.521 ± 0.033	0.717	0.716			
$\Lambda_b \to \Lambda(\to p\pi)\,\nu\bar{\nu}$	$[0.0 - q^2_{max}]$	$(1.798 \pm 0.133) \times 10^{-6}$	1.036×10^{-6}	0.651×10^{-6}	0.472 ± 0.028	0.589	0.578			

Table 1: The BR, F_L and A_{FB} in SM and in the presence of $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ SMEFT couplings.

In Fig 1 and Fig 2, we display the q^2 dependency of various physical observable for $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))(\mu^+\mu^-, \nu\,\bar{\nu})$ decays. In each figure, we report the SM central curve and corresponding 1σ error band in blue color. The main source of SM uncertainties are coming from the hadronic inputs such as form factors and the CKM matrix elements. The NP contributions coming from $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ are shown in black and red color respectively. The observations are as follows.

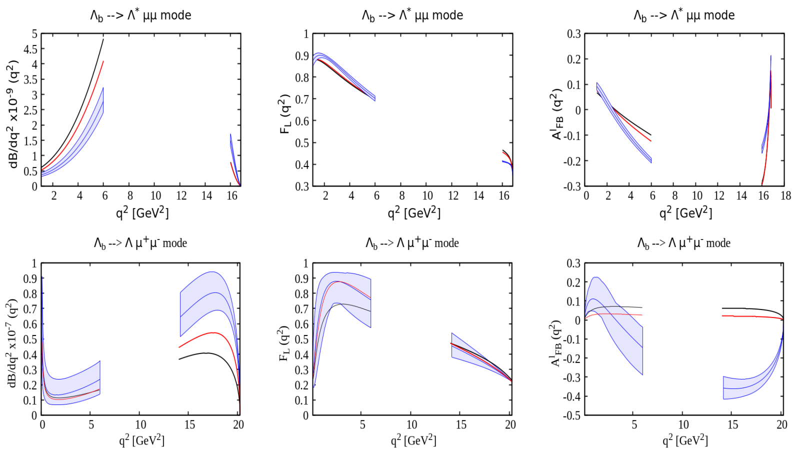

Figure 1: q^2 distribution for $\Lambda_b \to (\Lambda(\to p\pi), \Lambda^*(\to pK^-))\mu^+\mu^-$ in SM (blue), $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ (black) and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ (red) couplings.

- BR: The NP contribution from both scenarios are significant in all decay modes, which are, distinguishable beyond the SM uncertainty. For $\Lambda_b \to \Lambda^*(\to pK^-)\mu^+\mu^-$ decays, the contributions coming from $(\widetilde{c}_Z, \widetilde{c}'_Z)$ and $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ stand more than 9σ away from the SM at

$q^2 \in (1.1, 6.0)$. At $q^2 \in (16.0, 16.8)$, the BR lies more than 3σ away from the SM in the presence of both $(\widetilde{c}_Z, \widetilde{c}'_Z)$ and $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ couplings. Similarly, for $\Lambda_b \to \Lambda(\to p\pi)\mu^+\mu^-$ decays, both scenarios stand more than 5σ away from the SM particularly at $q^2 \in (14.2, 20.83)$. In case of $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))\nu\bar{\nu}$ decays, both scenarios exhibit considerable deviation from the SM expectation.

- F_L: In the case of di-neutrino modes, the contribution from $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ are distinguishable from SM since they include right-handed couplings. No interesting deviation is observed in the case of di-leptons decay channels.

- A_{FB}: In case of $\Lambda_b \to \Lambda^*(\to pK^-)\mu^+\mu^-$ decay, we obtain two zero crossing points at low and high q^2 regions. At low q^2 region, the SM zero crossing is obtained at $q^2 \approx 2.45 \pm 0.13$ GeV^2, while at at high q^2 region, it is obtained at $q^2 \approx 16.63 \pm 0.18$ GeV^2. The zero crossing is found to be shifted 1σ away from the SM in the presence of both $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ couplings. Similarly, for the $\Lambda_b \to \Lambda(\to p\pi)\mu^+\mu^-$ decay channel, the SM zero crossing is obtained at $q^2 = 3.25 \pm 1.65$. However, interestingly no zero crossing is found for $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ SMEFT couplings.

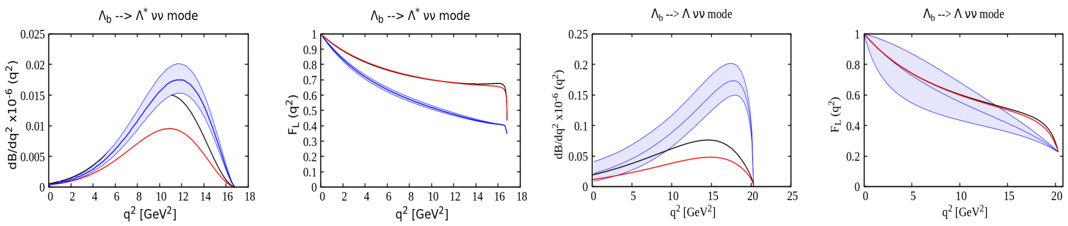

Figure 2: q^2 plots for $\Lambda_b \to (\Lambda(\to p\pi), \Lambda^*(\to pK^-))\nu\bar{\nu}$ in SM (blue), $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ (black) and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ (red) couplings.

4. Conclusion

In this analysis, we studied the consequences of $b \to s\,\mu^+\mu^-$ experimental data on $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))(\ell^+\ell^-, \nu\,\bar{\nu})$ baryonic decays. In the presence of $(\widetilde{c}^{(3)}_{ql}, \widetilde{c}'_Z)$ and $(\widetilde{c}_Z, \widetilde{c}'_Z)$ SMEFT couplings BR shows prominent deviation at low q^2 region in case of $(\Lambda_b \to \Lambda^*(\to pK^-)\mu^+\mu^-$ decay. Similarly, BR shows significant deviation at high q^2 region in $(\Lambda_b \to \Lambda^*(\to p\pi)\mu^+\mu^-$ decay. Study of $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))(\mu^+\mu^-, \nu\,\bar{\nu})$ both theoretically and experimentally will help to identify possible NP in $b \to s\ell^+\ell^-$ decays.

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