Implications of new physics in $B \to K_1 \mu^+ \mu^-$ decay processes

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Abstract

In recent times, several discrepancies at the level of $(2 - 3)\sigma$ have been observed in the decay processes mediated by flavour changing neutral current (FCNC) transitions $b \to s \ell^+ \ell^-$, which may be considered as the smoking-gun signal of New Physics (NP). These intriguing hints of NP have attracted a lot of attention and many attempts are made to look for the possible NP signature in other related processes, which are mediated through the same quark-level transitions. In this work, we perform a comprehensive analysis of the FCNC decays of $B$ meson to axial vector mesons $K_1(1270)$ and $K_1(1400)$, which are admixture of the $1^3P_1$ and $1^1P_1$ states $K_{1A}$ and $K_{1B}$, in a model independent framework. Using the $B \to K_1$ form factors evaluated in the light cone sum rule approach, we investigate the rare exclusive semileptonic decays $B \to K_1(1270) \mu^+ \mu^-$ and $B \to K_1(1400) \mu^+ \mu^-$. Considering all the possible relevant operators for $b \to s \ell^+ \ell^-$ transitions, we study their effects on various observables such as branching fractions, lepton flavor universality violating ratio ($R_{K_1}$), forward-backward asymmetries, and lepton polarization asymmetries of these processes. These results will not only enhance the theoretical understanding of the mixing angle but also serve as a good tool for probing New Physics.

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I. INTRODUCTION

Understanding the nature of physics beyond the Standard Model (BSM) is of paramount importance today in the context of Particle Physics, Astrophysics, and Cosmology. Although it was very much anticipated that the LHC experiment would provide an unambiguous signature of new physics in the form of direct observation of some new particles, the null result so far inspires the community to look for alternative scenarios. As a consequence, much attention has been paid to indirect signals, where the experimentally measured values of the observables show few sigma deviations from their corresponding standard model (SM) expectations. In recent times, several such intriguing results are observed by LHCb, Belle and BaBar experiments, in the semileptonic decays of $B$ mesons both in the charged current $b \to c\ell\nu$ \[1\]-\[7] as well as neutral current $b \to s\ell^+\ell^-$ transitions \[8\]-\[16]. More specifically, hints of physics beyond the Standard Model have been observed in the semileptonic decays of $B$ mesons in the form of lepton flavor universality violating (LFUV) ratios. In the charged-current sector, these observables are defined as

$$R_D = \frac{\text{Br}(B \to D^(*)\tau\nu_\tau)}{\text{Br}(B \to D^(*)\ell\nu_\ell)},$$

where $(\ell = e, \mu)$, which show nearly $3\sigma$ deviation from their corresponding SM results, taking into account the correlation between $R_D$ and $R_{D^*}$ \[17\]. The analogous observable in the $B_c$ meson decay, i.e., $R_{J/\psi} = \frac{\text{Br}(B_c \to J/\psi\tau\bar{\nu}_\tau)}{\text{Br}(B_c \to J/\psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18$ \[18\] also exhibits $1.7\sigma$ deviation from its SM value $R_{j/\psi}^{\text{SM}} = 0.289 \pm 0.010$ \[19\]. To resolve these anomalies associated with the charged current transitions $b \to c\ell\nu_\ell$, it is usually assumed the presence of new physics in the semi-tauonic mode $b \to c\tau\nu_\tau$. In the neutral current sector, there are a plethora of observables which manifest deviations from their SM predictions at the level of $(2-4)\sigma$. Amongst them, the prime candidates are the LFUV observables $R_K$ and $R_{K^*}$, defined as

$$R_K = \frac{\text{Br}(B^+ \to K^+\mu^+\mu^-)}{\text{Br}(B^+ \to K^+e^+e^-)} , \quad R_{K^*} = \frac{\text{Br}(B \to K^*\mu^+\mu^-)}{\text{Br}(B \to K^*e^+e^-)} .\quad (1)$$

In 2014, the measurement on the LFUV ratio $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, in the low $q^2 \in [1,6]$ GeV$^2$ region by the LHCb experiment \[11\] attracted huge attention, as it manifested a discrepancy of $2.6\sigma$ from its SM prediction \[20\] (see also \[21\])

$$R_K^{\text{SM}} = 1.0003 \pm 0.0001 .\quad (2)$$
The updated LHCb measurement of $R_K$ in the $q^2 \in [1.1, 6]$ GeV$^2$ region by combining the Run 1 data with 2 fb$^{-1}$ of Run 2 data \cite{14}

$$R_{K}^{\text{LHCb}} = 0.846^{+0.060+0.016}_{-0.054-0.014},$$

also exhibits a discrepancy at the level of 2.5$\sigma$.

Recently, the LHCb Collaboration reported the updated result on $R_K$ in the dilepton mass-squared region $1.1 < q^2 < 6.0$ GeV$^2$, based on the data collected at the center-of-mass energy of 7, 8 and 13 TeV corresponding to an integrated luminosity of 9 fb$^{-1}$ \cite{22} as

$$R_{K}^{\text{LHCb}} = 0.846^{+0.044}_{-0.041},$$

which shows 3.1$\sigma$ deviation with the SM prediction.

In addition, the LHCb Collaboration has also measured the $R_{K^\ast}$ ratio in two bins of low-$q^2$ region \cite{13}

$$R_{K^\ast}^{\text{LHCb}} = \begin{cases} 
0.660^{+0.110}_{-0.070} \pm 0.024 & q^2 \in [0.045, 1.1] \text{ GeV}^2, \\
0.685^{+0.113}_{-0.069} \pm 0.047 & q^2 \in [1.1, 6.0] \text{ GeV}^2, 
\end{cases}$$

which also depict 2.2$\sigma$ and 2.4$\sigma$ deviations from their corresponding SM results \cite{23}

$$R_{K^\ast}^{\text{SM}} = \begin{cases} 
0.92 \pm 0.02 & q^2 \in [0.045, 1.1] \text{ GeV}^2, \\
1.00 \pm 0.01 & q^2 \in [1.1, 6.0] \text{ GeV}^2.
\end{cases}$$

These discrepancies associated with the flavor changing neutral current (FCNC) transition $b \to s\ell^+\ell^-$ are generally attributed to the presence of new physics (NP) in $b \to s\mu\mu$ decay channel. In addition to these LHCb results, the Belle experiment has recently announced new measurements on $R_K$ \cite{15} and $R_{K^\ast}$ \cite{16} in several other bins, which are though consistent with SM, but have large uncertainties.

There are also quite a few other deviations from the SM expectations in the measurement involving $b \to s\mu\mu$ transition, such as the branching fractions of $B_s \to \mu^+\mu^-$, $B \to K^{(s)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, the angular observable $P_{4,5}'$ in $B \to K^*\mu^+\mu^-$, etc \cite{24}. Additionally, LHCb Collaboration measured the lepton flavor universality observable in $\Lambda_b \to pK\ell^+\ell^-$ channel, using 7, 8 and 13 TeV data corresponding to integrated luminosity 4.7 fb$^{-1}$ in the $0.1 < q^2 < 6$ GeV$^2$ bin \cite{25}

$$R_{pK}^{-1} = \frac{\text{Br}(\Lambda_b \to pK e^+e^-)}{\text{Br}(\Lambda_b \to pK J/\psi(\to e^+e^-))} \bigg/ \frac{\text{Br}(\Lambda_b \to pK \mu^+\mu^-)}{\text{Br}(\Lambda_b \to pK J/\psi(\to \mu^+\mu^-))} = 1.17^{+0.18}_{-0.16} \pm 0.01.$$

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which is compatible with unity, i.e., the SM prediction, within 1\(\sigma\) deviation.

Hence, it is natural to address all these anomalies associated with the semileptonic FCNC transitions \(b \to s\ell^+\ell^-\) by assuming the presence of new physics only in the muon sector. It is thus quite reasonable to expect that if new physics is indeed responsible for the above mentioned anomalies, it might also leave its footprints in the other related decay modes mediated by \(b \to s\mu^+\mu^-\) transition. In this context, we would like to analyze the decay channels \(B \to (K_1(1270)/K_1(1400))\mu^+\mu^-\), where \(K_1(1270)\) and \(K_1(1400)\) are axial vector mesons, which are an admixture of \(1^3P_1\) and \(1^1P_1\) states \(K_{1A}\) and \(K_{1B}\) respectively,

\[
\begin{align*}
|K_1(1270)\rangle &= |K_{1A}\rangle \sin \theta + |K_{1B}\rangle \cos \theta, \\
|K_1(1400)\rangle &= |K_{1A}\rangle \cos \theta - |K_{1B}\rangle \sin \theta,
\end{align*}
\]

where \(\theta\) is the mixing angle, which is not yet determined precisely. Its value has been estimated to be \(-34 \pm 13\)^\circ from the decay of \(B \to K_1(1270)\gamma\) and \(\tau \to K_1(1270)\nu\) \cite{26}. However, it is experimentally challenging to separate the \(K_1(1270)\) and \(K_1(1400)\) states as these are broad resonances and have the common decay channel \(K_1 \to K\pi\pi\). The \(K_1(1270)\) state decays predominantly through intermediate \(K\rho\) state, while \(K_1(1400)\) decays almost exclusively via \(K^*\pi\) channel. Therefore, separating these two channels requires dedicated amplitude analysis. An unbinned maximum-likelihood Dalitz plot method can be used simultaneously fit the data in the three dimensional invariant mass-squared plane: \(M^2(K\pi\pi)\), \(M^2(K\pi)\) and \(M^2(\pi\pi)\) as done for the case of nonleptonic decays \(B \to J/\psi K_1(\to K\pi\pi)\) and \(B \to \psi' K_1(\to K\pi\pi)\) by Belle Collaboration \cite{27}. In the recent past, the \(B \to (K_1(1270)/K_1(1400))\ell^+\ell^-\), decay modes have been the subject of many theoretical discussions, both in the SM \cite{28–31} as well as in various new physics scenarios, such as supersymmetric model \cite{32}, extra dimension \cite{33, 34}, fourth generation model \cite{35}, nonuniversal \(Z'\) model \cite{36, 37}, two Higgs doublet model \cite{38} etc., and also in the model independent approach \cite{39}. The study of these semileptonic decays provide a complementary framework to corroborate the results of the observed anomalies associated with \(b \to s\mu^+\mu^-\) transitions, as a number of observables associated with these modes, such as branching fractions, forward-backward asymmetry, lepton polarization asymmetry, are quite sensitive to new physics. In this context, we would like to investigate these decay processes in a model independent framework, where the possible new physics effects are quantified by introducing additional new operators to the SM effective Hamiltonian.
It should be further emphasized that the differential branching ratio of \( B^+ \to K^+\pi^+\pi^-\mu^+\mu^- \) process has been reported in the LHCb paper using the 7 TeV and 8 TeV data set corresponding to an integrated luminosity of \( 3.0 \text{ fb}^{-1} \) \(^{[40]} \) as

\[
\text{Br}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = (4.36^{+0.29}_{-0.27}\text{(stat)} \pm 0.21\text{(syst)} \pm 0.18\text{(norm)}) \times 10^{-7}. \tag{9}
\]

Since the branching fraction of the rare decay \( B^+ \to K_1(1270)^+\mu^+\mu^- \) is expected to contribute significantly, it is strongly argued to perform the analysis for \( B^+ \to K^+\pi^+\pi^-\mu^+\mu^- \) process with 13 TeV data set as well as to look for \( B^+ \to K^+\pi^+\pi^-e^+e^- \) process so that the lepton flavour universality violation parameter

\[
R_{K\pi\pi} = \frac{B^+ \to K^+\pi^+\pi^-\mu^+\mu^-}{B^+ \to K^+\pi^+\pi^-e^+e^-} \tag{10}
\]

can also be tested independently in another semileptonic flavour changing neutral current process \( b \to s\ell^+\ell^- \) process, preferably in the low \( q^2 \) bin, i.e., \( q^2 \in [1.1, 6] \) GeV\(^2\).

The layout of the paper is as follows. In section II, we discuss the generalized effective Hamiltonian describing the semileptonic transition \( b \to s\ell^+\ell^- \), both in the SM and in the context of NP. We then proceed to constrain the NP parameters performing a two-dimensional fit to the existing \( b \to s\mu\mu \) observables, which show more than 1\( \sigma \) deviation from their corresponding SM predictions and relatively free from hadronic uncertainties. The discussion on differential decay distribution and other relevant observables is presented in Section III. The implications of new physics on various decay observables of \( B \to (K_1(1270)/K_1(1400))\mu^+\mu^- \) processes are presented in section IV followed by our conclusions and outlook in Section V.

\section{Theoretical Framework}

The SM effective Hamiltonian responsible for \( b \to s\ell^+\ell^- \) transition can be expressed as

\[
\mathcal{H}_{\text{eff}}^{\text{SM}} = -\frac{\alpha G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[ C_7^{\text{eff}} \left( \frac{\bar{s}\sigma^{\mu\nu}q_\nu(m_sP_L + m_bP_R)b}{q^2} (\bar{\ell}\gamma_\mu\ell) \right) + C_9^{\text{eff}} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\ell) + C_{10}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5\ell) \right], \tag{11}
\]

where \( \alpha \) is the fine structure constant, \( G_F \) is the Fermi coupling, \( V_{tb}, V_{ts} \) are the CKM matrix elements, and \( P_{L,R} = (1 \mp \gamma_5)/2 \) are the chiral projection operators, \( C_7^{\text{eff}}, C_9^{\text{eff}} \) and \( C_{10} \) are the Wilson coefficients, evaluated at the \( m_b \) scale. It should be noted that the
coefficient $C_{eff}^{9}$ contains both short-distance contributions from the 4-quark operators, away from the charmonium resonance domain, which are known to be calculated precisely in the perturbation theory and long distance part associated with real $c\bar{c}$ intermediate states, i.e., it can be expressed as: $C_{eff}^{9}(m_b, q^2) = C_9(m_b) + Y_{pert}(q^2) + Y_{LD}(m_b, q^2)$. The explicit forms of $Y_{pert}$ and $Y_{LD}$ are widely discussed in the literature [41–46] and their values are taken from [38]. The values of the Wilson coefficients $C_{1,...,6}$ at $m_b$ scale calculated in Next-to-next-to leading-logarithmic (NNLL) order by matching the full and effective theories at the electroweak scale and subsequently evolved down to the $b$ quark scale using renormalization group equations [47–49], while the values of $C_{eff}^{7}, C_9$ and $C_{10}$ are taken from [50], which are presented in Table-I.

\[
\begin{array}{cccccccc}
C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_{eff}^9 & C_9 & C_{10} \\
-0.257 & 1.009 & -0.005 & -0.078 & 0.000 & 0.001 & -0.292 & 4.08 & -4.31 \\
\end{array}
\]

TABLE I: Values of the SM Wilson coefficients evaluated at the $m_b$ scale.

Keeping in mind that, the new physics solutions, which can explain the observed anomalies in $b \rightarrow s\mu^+\mu^-$ transition are only in the form of vector and axial-vector operators, we consider only these additional operators to the SM Hamiltonian for both chiral quark currents. Thus, the total effective Hamiltonian describing the $b \rightarrow s\mu^+\mu^-$ transition processes can be represented as

\[
\mathcal{H}_{\text{eff}}^{\text{tot}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \mathcal{H}_{\text{eff}}^{\text{NP}},
\]

where $\mathcal{H}_{\text{eff}}^{\text{NP}}$ denotes the new physics effective Hamiltonian, which can be expressed as

\[
\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{\alpha G_F}{\sqrt{2\pi}} V_{tb} V_{ts}^* \left[ C_9^{NP} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma\mu\ell) + C_{10}^{NP} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma\mu\gamma_5\ell) \\
+ C_9'^{NP} (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma\mu\ell) + C_{10}'^{NP} (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma\mu\gamma_5\ell) \right],
\]

where $C_{9,10}^{NP}$ and $C_{9,10}'^{NP}$ are the new Wilson coefficients, and their values can be obtained from the global fit to the observed $b \rightarrow s\mu^+\mu^-$ data. A commonly acceptable presumption that emerged from the global fits performed by various groups, see e.g. [51], by considering one NP coefficient at a time is either (I) $C_9^{NP} = -1.09 \pm 0.18$ or (II) $C_9^{NP} = -C_{10}^{NP} = -0.53 \pm 0.09$ with pull values 6.24 and 6.40 respectively. Recently, a combined global fit is performed in
[50], to constrain the $C_{7,9,10}^{\text{NP}}$ Wilson coefficients, considering them as real, and the best-fit results obtained are given as $(C_{7}^{\text{NP}}, C_{9}^{\text{NP}}, C_{10}^{\text{NP}}) = (0.013, -1.03, 0.08)$, which are pretty well consistent with the scenario I, with only one NP coefficient at a time.

In this work, we perform a two-dimensional global fit, by taking two new operators at a time with the following possible combinations: $(C_{9}^{\text{NP}}, C_{9}^{\prime \text{NP}}), (C_{10}^{\text{NP}}, C_{10}^{\prime \text{NP}})$ and $(C_{9}^{\text{NP}}, C_{10}^{\text{NP}})$. In our fit, we include only those observables associated with $b \to s\mu^+\mu^-$ anomalies, which are relatively free from hadronic uncertainties and are listed below:

1. $R_K$ and $R_{K^*}$

The recently updated lepton flavour universality violating (LFUV) ratios $R_K$ [22] and $R_{K^*}$ [13], by LHCb measurement in the low $q^2$ bins:

$$R_K^{\text{LHCb}} = 0.846_{-0.041}^{+0.044}, \quad q^2 \in [1.1, 6] \text{ GeV}^2,$$

$$R_{K^*}^{\text{LHCb}} = \begin{cases} 
0.660_{-0.070}^{+0.110} \pm 0.024 & q^2 \in [0.045, 1.1] \text{ GeV}^2, \\
0.685_{-0.069}^{+0.113} \pm 0.047 & q^2 \in [1.1, 6.0] \text{ GeV}^2.
\end{cases}$$

(15)

Besides the LHCb results, the Belle experiment has recently announced new measurements on $R_K$ [15] and $R_{K^*}$ [16] in several other bins:

$$R_K^{\text{Belle}} = \begin{cases} 
1.01_{-0.25}^{+0.28} \pm 0.02 & q^2 \in [0.1, 4.0] \text{ GeV}^2, \\
0.85_{-0.24}^{+0.30} \pm 0.01 & q^2 \in [4.0, 8.12] \text{ GeV}^2, \\
1.03_{-0.24}^{+0.28} \pm 0.01 & q^2 \in [1.0, 6.0] \text{ GeV}^2, \\
1.97_{-0.89}^{+1.03} \pm 0.02 & q^2 \in [10.2, 12.8] \text{ GeV}^2, \\
1.16_{-0.27}^{+0.30} \pm 0.01 & q^2 > 14.18 \text{ GeV}^2.
\end{cases}$$

(16)

$$R_{K^*}^{\text{Belle}} = \begin{cases} 
0.52_{-0.26}^{+0.36} \pm 0.05 & q^2 \in [0.045, 1.1] \text{ GeV}^2, \\
0.96_{-0.29}^{+0.45} \pm 0.11 & q^2 \in [1.1, 6] \text{ GeV}^2, \\
0.90_{-0.21}^{+0.27} \pm 0.10 & q^2 \in [0.1, 8.0] \text{ GeV}^2, \\
1.18_{-0.32}^{+0.52} \pm 0.10 & q^2 \in [15, 19] \text{ GeV}^2.
\end{cases}$$

(17)

As the Belle results have relatively larger uncertainties, we do not include them in our fit.
2. $B_s \to \mu^+\mu^-$

The combined ATLAS, CMS and LHCb results on the branching fraction of $B_s \to \mu^+\mu^-$ process is \[52\]:

$$\text{Br}(B^0_s \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9},$$

which shows $2.4\sigma$ discrepancy with the SM prediction \[53\]

$$\text{Br}(B^0_s \to \mu^+\mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}.\quad(19)$$

3. Angular observables of $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ processes

- The angular observables of $B^0 \to K^{*0}\mu^+\mu^-$ decay process, such as the form factor independent (FFI) observables: $(P_{1,2,3}, P'_{4,5,6,8})$, longitudinal polarization asymmetry $(F_L)$, and the forward-backward asymmetry $(A_{FB})$ in the following $q^2$ bins: $(0.1 \to 0.98, 1.1 \to 2, 2 \to 3, 3 \to 4, 4 \to 5, 5 \to 6, 1 \to 6)$ taken from \[54\].

- For $B_s \to \phi\mu^+\mu^-$ process, we consider the longitudinal polarization asymmetry $(F_L)$ and CP averaged angular observables $(S_{3,4,7}, A_{5,6,8,9})$ of in three $q^2$ bins: $0.1 \to 2$, $2 \to 5$, and $1 \to 6$ \[12\].

The theoretical expressions for different observables of $B \to V\ell^+\ell^-$ processes where $V$ denotes the vector meson, are used from \[49\] and the form factors are calculated using the light cone sum rule approach \[55\]. Using these observables, the new Wilson coefficients are constrained by assuming the presence of two new real coefficients at a time. We consider three possible scenarios, i.e., the simultaneous presence of $(C^\text{NP}_9, C'^\text{NP}_9)$, $(C^\text{NP}_{10}, C'^\text{NP}_{10})$ and $(C^\text{NP}_9, C^\text{NP}_{10})$ new physics coefficients and perform a $\chi^2$ analysis. The expression for $\chi^2$ is delineated as

$$\chi^2(C^\text{NP}_i) = \sum_i \left(\frac{O^\text{th}_i(C^\text{NP}_i) - O^\text{exp}_i}{(\Delta O_i)^2}\right)^2,$$

where $O^\text{th}_i(C^\text{NP}_i)$ are the theoretical expectations for the observables used in our fit, $O^\text{exp}_i$ represent the measured central values of the observables and $(\Delta O_i)^2 = (\Delta O^\text{exp}_i)^2 + (\Delta O^\text{th}_i)^2$ encompasses the $1\sigma$ uncertainties from theory and experiment. In Fig.\[\text{[1]}\] we present the
allowed parameter space of the new Wilson coefficients in $C_{9}^{\text{NP}} - C_{9}^{\text{NP}}$ (top-left panel), $C_{10}^{\text{NP}} - C_{10}^{\text{NP}}$ (top-right panel) and $C_{9}^{\text{NP}} - C_{10}^{\text{NP}}$ (bottom panel) planes, where the red, blue and green colors represent the $1\sigma$, $2\sigma$ and $3\sigma$ contours and the black dots characterize the best-fit values. The best-fit values of the new coefficients along with the corresponding $\chi^2_{\text{min}}$/d.o.f and the pull $= \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{best-fit}}}$, for these three scenarios are presented in Table II.

TABLE II: The best-fit values of new coefficients, $\chi^2_{\text{min}}$/d.o.f and pull values for different scenarios.

| New Coefficients | Best-fit Values | $\chi^2_{\text{min}}$/d.o.f | Pull |
|------------------|-----------------|-----------------------------|------|
| $(C_{9}^{\text{NP}}, C_{9}^{\text{NP}})$ | $(-0.829, -0.463)$ | 1.04 | 4.8 |
| $(C_{10}^{\text{NP}}, C_{10}^{\text{NP}})$ | $(0.513, 0.125)$ | 1.3 | 3.0 |
| $(C_{9}^{\text{NP}}, C_{10}^{\text{NP}})$ | $(-0.526, 0.573)$ | 1.02 | 5.4 |

From Table II it should be noted that for $C_{10}^{\text{NP}} - C_{10}^{\text{NP}}$ case, the $\chi^2_{\text{min}}$/d.o.f is greater than 1, with a lower pull value, this scenario is not very robust, as also inferred in [56]. While for $C_{9}^{\text{NP}} - C_{9}^{\text{NP}}$ and $(C_{9}^{\text{NP}}, C_{10}^{\text{NP}})$ cases, the $\chi^2_{\text{min}}$/d.o.f $\simeq 1$, with a larger pull, hence these scenarios are acceptable. Therefore, in our analysis, we will consider the impact of three different classes of NP scenarios: the first scenario includes NP contributions only in operators which are non-zero in the SM, and the values of NP coefficients are taken from [50] as $(C_{7}^{\text{NP}}, C_{9}^{\text{NP}}, C_{10}^{\text{NP}}) = (0.013, -1.03, 0.08)$ (NP1), in the second case we will consider the presence of $C_{9}^{\text{NP}} - C_{9}^{\text{NP}}$ and use the extracted best-fit values of the NP coefficients: $(-0.829, -0.463)$ (NP2) and for the third case, we consider the new physics due to $(C_{9}^{\text{NP}}, C_{10}^{\text{NP}})$ Wilson coefficients as $(-0.526, 0.573)$ (NP3) on various observables. Since the effect due to the NP3 coefficients are similar to NP1 case, we have not shown explicitly the corresponding results in the plots and provided only the corresponding numerical results.

III. DIFFERENTIAL DECAY DISTRIBUTION AND OTHER RELEVANT OBSERVABLES

In this section, we discuss the differential decay distribution and other relevant angular observables like forward-backward asymmetries and lepton polarization asymmetries for the $B \to (K_{1}(1270)/K_{1}(1400)) \mu^+\mu^-$ processes. As mentioned before, the physical states
FIG. 1: Allowed parameter space in $C^\text{NP}_9 - C'^\text{NP}_9$ plane (top-left panel), $C^\text{NP}_10 - C'^\text{NP}_10$ plane (top-right panel) and $C^\text{NP}_9 - C^\text{NP}_10$ plane (bottom panel). Different colors represent the 1σ, 2σ and 3σ contours and the black points represent the best-fit values.

$K_1(1270)$ and $K_1(1400)$ are related to the flavour states $K_{1A}$ and $K_{1B}$ through the relation

$$
\begin{pmatrix}
|\bar{K}_1(1270)\rangle \\
|\bar{K}_1(1270)\rangle
\end{pmatrix}
= M
\begin{pmatrix}
|\bar{K}_{1A}\rangle \\
|\bar{K}_{1B}\rangle
\end{pmatrix},
$$

where $M = \begin{pmatrix} \sin \theta & \cos \theta \\
\cos \theta & -\sin \theta \end{pmatrix}$, (21)
is the mixing matrix with mixing angle $\theta = -(34 \pm 13)^\circ$ [26].

Now using the effective Hamiltonian given in Eqns. (11) and (13), the matrix elements for $B \to K_1 \ell^+ \ell^-$ process can be obtained using the relation $\mathcal{M} = \langle K_1 \ell^+ \ell^- | \hat{H}^{\text{SM}}_{\text{eff}} + \hat{H}^{\text{NP}}_{\text{eff}} | B \rangle$, which requires the knowledge of the $\bar{B} \to \bar{K}_1$ transition form factors. The required form
factors for both vector and axial vector current mediated transitions are defined as

\[
\langle \bar{K}_1(p_{K_1}, \varepsilon) | \bar{s} \gamma_\mu (1 \pm \gamma_5) b | B(p_B) \rangle = \pm i \frac{2}{m_B + m_{K_1}} \epsilon_{\mu \nu \rho \sigma} \varepsilon^{* \nu} p_B^{\rho} p_{K_1}^{\sigma} A_{K_1}^{K_1}(q^2)
\]

\[
- \left[ (m_B + m_{K_1}) \varepsilon_\mu^{*} V_{1}^{K_1}(q^2) - (p_B + p_{K_1})_\mu (\varepsilon^{*} \cdot p_B) \frac{V_{2}^{K_1}(q^2)}{m_B + m_{K_1}} \right]
\]

\[
+ 2m_{K_1} \frac{\varepsilon^{*} \cdot p_B}{q^2} \mu \left[ V_{3}^{K_1}(q^2) - V_{0}^{K_1}(q^2) \right],
\]

(22)

where \( \varepsilon \) is the polarization vector of \( K_1 \), \( V_i(q^2) \)'s are the vector form factors and \( A(q^2) \) is the axial-vector form factor, which depend on the square of momentum transfer \( q^2 \). Analogously, the tensor form factors are expressed as

\[
\langle \bar{K}_1(p_{K_1}, \varepsilon) | \bar{s} \sigma_{\mu \nu} q^\nu (1 \pm \gamma_5) b | B(p_B) \rangle = \pm 2 T_1^{K_1}(q^2) \epsilon_{\mu \nu \rho \sigma} \varepsilon^{* \nu} p_B^{\rho} p_{K_1}^{\sigma}
\]

\[
- i T_2^{K_1}(q^2) \left[ (m_B^2 - m_{K_1}^2) \varepsilon^{*}_\mu - (\varepsilon^{*} \cdot q)(p_B + p_{K_1})_\mu \right]
\]

\[
- i T_3^{K_1}(q^2)(\varepsilon^{*} \cdot q) \left[ \mu - \frac{q^2}{m_B^2 - m_{K_1}^2} (p_K + p_B)_\mu \right],
\]

(23)

with \( T_i(q^2) \) as the relevant tensorial form factors.

Thus, the matrix elements of \( B \to K_1(1270)/K_1(1400) \) processes can be parametrized in terms of \( B \to K_{1A}/K_{1B} \) form factors as [36]

\[
\begin{pmatrix}
\langle \bar{K}_1(1270) | \bar{s} \gamma_\mu (1 \pm \gamma_5) b | B \rangle \\
\langle \bar{K}_1(1400) | \bar{s} \gamma_\mu (1 \pm \gamma_5) b | B \rangle
\end{pmatrix}
= M
\begin{pmatrix}
\langle \bar{K}_{1A} | \bar{s} \gamma_\mu (1 \pm \gamma_5) b | B \rangle \\
\langle \bar{K}_{1B} | \bar{s} \gamma_\mu (1 \pm \gamma_5) b | B \rangle
\end{pmatrix},
\]

(24)

and analogously for tensor form factors. More explicitly the various form factors are related as

\[
\begin{pmatrix}
A_{K_1}^{K_1}(1270) / (m_B + m_{K_1}(1270)) \\
A_{K_1}^{K_1}(1400) / (m_B + m_{K_1}(1400))
\end{pmatrix}
= M
\begin{pmatrix}
A_{K_1}^{K_1A} / (m_B + m_{K_1A}) \\
A_{K_1}^{K_1B} / (m_B + m_{K_1B})
\end{pmatrix},
\]

\[
\begin{pmatrix}
(m_B + m_{K_1}(1270)) V_1^{K_1}(1270) \\
(m_B + m_{K_1}(1400)) V_1^{K_1}(1400)
\end{pmatrix}
= M
\begin{pmatrix}
(m_B + m_{K_1A}) V_1^{K_1A} \\
(m_B + m_{K_1B}) V_1^{K_1B}
\end{pmatrix},
\]

\[
\begin{pmatrix}
V_2^{K_1}(1270) / (m_B + m_{K_1}(1270)) \\
V_2^{K_1}(1400) / (m_B + m_{K_1}(1400))
\end{pmatrix}
= M
\begin{pmatrix}
V_2^{K_1A} / (m_B + m_{K_1A}) \\
V_2^{K_1B} / (m_B + m_{K_1B})
\end{pmatrix},
\]

\[
\begin{pmatrix}
m_{K_1}(1270) V_0^{K_1}(1270) \\
m_{K_1}(1400) V_0^{K_1}(1400)
\end{pmatrix}
= M
\begin{pmatrix}
m_{K_1A} V_0^{K_1A} \\
m_{K_1B} V_0^{K_1B}
\end{pmatrix},
\]

\[
\begin{pmatrix}
T_{K_1}(1270) \\
T_{K_1}(1400)
\end{pmatrix}
= M
\begin{pmatrix}
T_{K_1A}^{1,3} \\
T_{K_1B}^{1,3}
\end{pmatrix},
\]

(25)
\[
\left( m_B^2 - m_{K1(1270)}^2 \right) T_2^{K1(1270)} + \left( m_B^2 - m_{K1(1400)}^2 \right) T_2^{K1(1400)} = M \left( m_B^2 - m_{K1A}^2 \right) T_2^{K1A} + \left( m_B^2 - m_{K1B}^2 \right) T_2^{K1B}.
\]

Additionally, the form factors satisfy the following relations, which can be obtained using the equation of motion:

\[
\begin{align*}
V_3^{K1}(0) &= V_0^{K1}(0), \\
T_1^{K1}(0) &= T_2^{K1}(0), \\
V_3^{K1}(q^2) &= \frac{m_B + m_K}{2m_K} V_1^{K1}(q^2) - \frac{m_B - m_K}{2m_K} V_2^{K1}(q^2).
\end{align*}
\]  

(25)

The form factors are calculated in the light cone sum rule (LCSR) approach [57], and their \( q^2 \) dependence in the whole kinematical region is parametrized in the three parameter form as

\[
F(q^2) = \frac{F(0)}{1 - a(q^2/m_B^2) + b(q^2/m_B^2)^2}.
\]  

(26)

The values of different parameters involved in (26) are taken from [28] and are provided in Table III. Now we list below the various observables associated with \( B \rightarrow K_1\ell^+\ell^- \) processes.

| \( q^2 \) | \( a \) | \( b \) | \( q^2 \) | \( a \) | \( b \) |
|---|---|---|---|---|---|
| \( V_{1B}^{K1A} \) | 0.34 ± 0.07 | 0.635 | 0.211 | \( V_{1B}^{K1B} \) | -0.29 ± 0.08 | 0.729 | 0.074 |
| \( V_{2B}^{K1A} \) | 0.41 ± 0.08 | 1.51 | 1.18 | \( V_{2B}^{K1B} \) | -0.17 ± 0.05 | 0.919 | 0.855 |
| \( V_{0B}^{K1A} \) | 0.22 ± 0.04 | 2.40 | 1.78 | \( V_{0B}^{K1B} \) | -0.45 ± 0.12 | 1.34 | 0.690 |
| \( A_{B}^{K1A} \) | 0.45 ± 0.09 | 1.60 | 0.974 | \( A_{B}^{K1B} \) | -0.37 ± 0.10 | 1.72 | 0.912 |
| \( T_{1B}^{K1A} \) | 0.31 ± 0.09 | 2.01 | 1.50 | \( T_{1B}^{K1B} \) | -0.25 ± 0.06 | 1.59 | 0.790 |
| \( T_{2B}^{K1A} \) | 0.31 ± 0.09 | 0.629 | 0.387 | \( T_{2B}^{K1B} \) | -0.25 ± 0.06 | 0.378 | -0.755 |
| \( T_{3B}^{K1A} \) | 0.28 ± 0.08 | 1.36 | 0.720 | \( T_{3B}^{K1B} \) | -0.11 ± 0.02 | -1.61 | 10.2 |

A. Differential decay rate

The differential decay width with respect to the dilepton invariant mass (\( q^2 \equiv s \)) for the process \( \bar{B} \rightarrow \bar{K}_1\ell^+\ell^- \) is given as

\[
\frac{d\Gamma(\bar{B} \rightarrow \bar{K}_1\ell^+\ell^-)}{ds} = \frac{G_F^2\alpha^2m_B^5\tau_B}{2^{12}\pi^5}|V_{tb}V_{ts}|^2v\sqrt{s} \Delta(s),
\]

(27)
where \( v = \sqrt{1 - 4\hat{m}_\ell^2/\hat{s}} \), \( \lambda = 1 + \hat{m}_{K_1}^2 + \hat{s}^2 - 2\hat{s} - 2\hat{m}_{K_1} - 2\hat{m}_{K_1} \hat{s} \), with \( \hat{m}_{K_1} = m_{K_1}^2/m_B^2 \), \( \hat{m}_\ell = m_\ell/m_B \) and \( \hat{s} = q^2/m_B^2 \). The expression for \( \Delta(\hat{s}) \) is given as [38]

\[
\Delta(\hat{s}) = -\frac{4}{3} |\mathcal{F}_1|^2 (2\hat{m}_\ell^2 + \hat{s})\lambda + \frac{1}{3\hat{m}_{K_1}} |\mathcal{F}_2|^2 \left( -3 - 3\hat{m}_{K_1}^2 + 6\hat{m}_{K_1}(1 - 8\hat{m}_\ell^2 - 3\hat{s}) + 6\hat{s} - 3\hat{s}^2 + v^2\lambda \right) \\
- \frac{1}{3\hat{m}_{K_1}} |\mathcal{F}_3|^2 \lambda \left( 3 + 3\hat{m}_{K_1}^2 - 6\hat{s} + 3\hat{s}^2 - 6\hat{m}_{K_1}(1 + \hat{s}) - v^2\lambda \right) \\
+ |\mathcal{F}_5|^2 \left( 4\hat{m}_\ell^2\lambda - \hat{s}^3 \left( 3 + 3\hat{m}_{K_1}^2 - 6\hat{s} + 3\hat{s}^2 - 6\hat{m}_{K_1}(1 + \hat{s}) + v^2\lambda \right) \right) \\
+ \frac{1}{3\hat{m}_{K_1}} |\mathcal{F}_6|^2 \left( -3 - 3\hat{m}_{K_1}^2 + 6\hat{m}_{K_1}(1 + 16\hat{m}_\ell^2 - 3\hat{s}) + 6\hat{s} - 3\hat{s}^2 + v^2\lambda \right) \\
- \frac{1}{3\hat{m}_{K_1}} |\mathcal{F}_7|^2 \lambda \left( 3 + 3\hat{m}_{K_1}^2 + 12\hat{m}_\ell^2(2 + 2\hat{m}_{K_1} - \hat{s}) - 6\hat{s} + 3\hat{s}^2 - 6\hat{m}_{K_1}(1 + \hat{s}) - v^2\lambda \right) , \\
- \frac{4}{\hat{m}_{K_1}} |\mathcal{F}_8|^2 \hat{m}_\ell^2 \hat{s}(\hat{s}) + \frac{8}{\hat{m}_{K_1}} \text{Re}[\mathcal{F}_6 \mathcal{F}_8^*] \hat{m}_\ell^2 \lambda + \frac{8}{\hat{m}_{K_1}} \text{Re}[\mathcal{F}_7 \mathcal{F}_8^*] \hat{m}_\ell^2 \lambda (-1 + \hat{m}_{K_1}) \\
+ \frac{2}{3\hat{m}_{K_1}} \text{Re}[\mathcal{F}_6 \mathcal{F}_7^*](12\hat{m}_\ell^2 \lambda - (-1 + \hat{m}_{K_1} + \hat{s})(3 + 3\hat{m}_{K_1}^2 - 6\hat{s} + 3\hat{s}^2 - 6\hat{m}_{K_1}(1 + \hat{s}) - v^2\lambda)) \\
- \frac{2}{3\hat{m}_{K_1}} \text{Re}[\mathcal{F}_2 \mathcal{F}_3^*](-1 + \hat{m}_{K_1} + \hat{s})(3 + 3\hat{m}_{K_1}^2 - 6\hat{s} + 3\hat{s}^2 - 6\hat{m}_{K_1}(1 + \hat{s}) - v^2\lambda) . \tag{28}
\]

The functions \( \mathcal{F}_{1,2,\ldots,8} \) are related to the form factors and the Wilson coefficients and are expressed as

\[
\mathcal{F}_{1}^{K_1}(\hat{s}) = \frac{2}{1 + \sqrt{\hat{m}_{K_1}}} \left( C_{9}^\text{eff} + C_{9}^{\text{NP}} + C_{9}^{\text{NP}} \right) A^{K_1}(\hat{s}) + \frac{4\hat{m}_b}{\hat{s}} C_{7}^\text{eff} T_{1}^{K_1}(\hat{s}) , \\
\mathcal{F}_{2}^{K_1}(\hat{s}) = 1 + \sqrt{\hat{m}_{K_1}} \left[ (C_{9}^\text{eff} + C_{9}^{\text{NP}} - C_{9}^{\text{NP}}) A^{K_1}(\hat{s}) + \frac{2\hat{m}_b}{\hat{s}} (1 - \sqrt{\hat{m}_{K_1}}) C_{7}^\text{eff} T_{2}^{K_1}(\hat{s}) \right] , \\
\mathcal{F}_{3}^{K_1}(\hat{s}) = \frac{1}{1 - \hat{m}_{K_1}} \left[ (1 - \sqrt{\hat{m}_{K_1}}) (C_{9}^\text{eff} + C_{9}^{\text{NP}} - C_{9}^{\text{NP}}) V_{2}^{K_1}(\hat{s}) \right. \\
\left. + \frac{2\hat{m}_b}{\hat{s}} C_{7}^\text{eff} \left( T_{3}^{K_1}(\hat{s}) + \frac{1 - \hat{m}_{K_1}}{\hat{s}} T_{2}^{K_1}(\hat{s}) \right) \right] , \\
\mathcal{F}_{4}^{K_1}(\hat{s}) = \frac{1}{\hat{s}} \left[ (C_{9}^\text{eff} + C_{9}^{\text{NP}} - C_{9}^{\text{NP}}) \left( (1 + \sqrt{\hat{m}_{K_1}}) V_{1}^{K_1}(\hat{s}) - (1 - \sqrt{\hat{m}_{K_1}}) V_{2}^{K_1}(\hat{s}) - 2\sqrt{\hat{m}_{K_1}} V_{0}^{K_1}(\hat{s}) \right) \right. \\
\left. - 2\hat{m}_b C_{7}^\text{eff} T_{3}^{K_1}(\hat{s}) \right] , \\
\mathcal{F}_{5}^{K_1}(\hat{s}) = \frac{2}{1 + \sqrt{\hat{m}_{K_1}}} \left( C_{10} + C_{10}^{\text{NP}} + C_{10}^{\text{NP}} \right) A^{K_1}(\hat{s}) , \\
\mathcal{F}_{6}^{K_1}(\hat{s}) = \left( 1 + \sqrt{\hat{m}_{K_1}} \right) \left( C_{10} + C_{10}^{\text{NP}} - C_{10}^{\text{NP}} \right) V_{1}^{K_1}(\hat{s}) , \\
\mathcal{F}_{7}^{K_1}(\hat{s}) = \frac{1}{1 + \sqrt{\hat{m}_{K_1}}} \left( C_{10} + C_{10}^{\text{NP}} - C_{10}^{\text{NP}} \right) V_{2}^{K_1}(\hat{s}) , \\
\mathcal{F}_{8}^{K_1}(\hat{s}) = \frac{1}{\hat{s}} \left( C_{10} + C_{10}^{\text{NP}} - C_{10}^{\text{NP}} \right) \left[ (1 + \sqrt{\hat{m}_{K_1}}) V_{1}^{K_1}(\hat{s}) - (1 - \sqrt{\hat{m}_{K_1}}) V_{2}^{K_1} - 2\sqrt{\hat{m}_{K_1}} V_{0}^{K_1}(\hat{s}) \right] . \tag{29}
\]
B. LFU violating observable

Analogous to $R_K$, the lepton flavor universality violating observable in $B \to K_1 \ell^+ \ell^-$ processes can be defined as

\begin{equation}
R_{K_1}(q^2) = \frac{d\text{Br}(B \to K_1 \mu^+ \mu^-)/dq^2}{d\text{Br}(B \to K_1 e^+ e^-)/dq^2}.
\end{equation}

(30)

C. $R_\mu$ observable

The observable $R_\mu$ is defined as

\begin{equation}
R_\mu(q^2) = \frac{d\text{Br}(B \to K_1(1400) \mu^+ \mu^-)/dq^2}{d\text{Br}(B \to K_1(1270) \mu^+ \mu^-)/dq^2}.
\end{equation}

(31)

Since the $K_1$ mesons depend on the mixing angle $\theta$, $R_\mu$ can be used for its determination.

D. Forward-backward asymmetries

The unpolarized forward-backward asymmetry, defined as

\begin{equation}
A_{FB}(\hat{s}) = \left( \int_{-1}^{0} d\cos \theta_\ell \frac{d^2 \Gamma}{d\hat{s} d\cos \theta_\ell} - \int_{0}^{1} d\cos \theta_\ell \frac{d^2 \Gamma}{d\hat{s} d\cos \theta_\ell} \right) / \frac{d\Gamma}{d\hat{s}},
\end{equation}

(32)

where $\theta_\ell$ represents the angle between the initial $B$ meson and final lepton $\ell^-$ in the C.o.M. frame of the outgoing lepton pair. In terms of the angular amplitudes, it can be expressed as

\begin{equation}
A_{FB}(\hat{s}) = \frac{2}{\Delta} \sqrt{\lambda \hat{s}} \left[ 2 \text{Re}(F_1 F_6^*) + \text{Re}(F_2 F_5^*) \right].
\end{equation}

(33)

Next, we focus on the differential forward-backward asymmetries, that are associated with the polarized leptons. In this regard, first we define two sets of orthogonal vectors belonging to the polarization of $\ell^-$ and $\ell^+$, which are denoted as $S_i$ and $W_i$, with $i = L, N$ and $T$, respectively.
corresponding to longitudinal, normal and transverse spin projections:

\[
S^\mu_L \equiv (0, e_L) = \left( 0, \frac{p_{\ell^-}}{|p_{\ell^-}|} \right), \quad
S^\mu_N \equiv (0, e_N) = \left( 0, \frac{p_{K_1} \times p_{\ell^-}}{|p_{K_1} \times p_{\ell^-}|} \right), \quad
S^\mu_T \equiv (0, e_T) = \left( 0, \frac{e_N \times e_L}{p_{\ell^-}} \right), \quad
W^\mu_L \equiv (0, w_L) = \left( 0, \frac{p_{\ell^+}}{|p_{\ell^+}|} \right), \quad
W^\mu_N \equiv (0, w_N) = \left( 0, \frac{p_{K_1} \times p_{\ell^+}}{|p_{K_1} \times p_{\ell^+}|} \right), \quad
W^\mu_T \equiv (0, w_T) = \left( 0, w_N \times w_L \right),
\]

(34)

where \( p_{\ell^\pm} \) and \( p_{K_1} \) represent the three-momenta of the outgoing particles \( \ell^\pm \), and \( K_1 \) respectively. It should be emphasized that the polarization vectors \( S^\mu_i \) (\( W^\mu_i \)) are defined in the \( \ell^- (\ell^+) \) rest frame. Thus, while Lorentz boost is applied to bring these vectors from the rest frame of \( \ell^- \) and \( \ell^+ \) to the C.o.M. frame of \( \ell^- \ell^+ \) system, only longitudinal component gets boosted, while the other two components remain unchanged. Hence, the longitudinal polarization four vectors have the form

\[
S^\mu_L = \left( \frac{|p_{\ell^-}|}{m_{\ell^-}}, \frac{E_{\ell^-} p_{\ell^-}}{|p_{\ell^-}|} \right), \quad
W^\mu_L = \left( \frac{|p_{\ell^+}|}{m_{\ell^+}}, \frac{E_{\ell^+} p_{\ell^+}}{|p_{\ell^+}|} \right).
\]

(35)

The polarized forward-backward asymmetry is defined as

\[
A_{FB}(s) = \left( \frac{d\Gamma}{d\hat{s}} \right)^{-1} \left\{ \int_0^1 d\cos \theta_\ell - \int_{-1}^0 d\cos \theta_\ell \right\} \left\{ \left[ \frac{d^2\Gamma(s^- = i, s^+ = j)}{d\hat{s} d\cos \theta_\ell} \right] - \frac{d^2\Gamma(s^- = -i, s^+ = -j)}{d\hat{s} d\cos \theta_\ell} \right\} \\
- \left[ \frac{d^2\Gamma(s^- = -i, s^+ = j)}{d\hat{s} d\cos \theta_\ell} \right] - \frac{d^2\Gamma(s^- = i, s^+ = -j)}{d\hat{s} d\cos \theta_\ell} \right\} \\
= A_{FB}(s^- = i, s^+ = j) - A_{FB}(s^- = i, s^+ = -j) - A_{FB}(s^- = -i, s^+ = j) \\
+ A_{FB}(s^- = -i, s^+ = -j),
\]

(36)
where $s^\pm$ are the spin projections of $\ell^\pm$ and $i,j = L,N,T$, are the unit vectors. Thus, the expressions for double polarized forward-backward asymmetries are given as:

$$A_{FB}^{LL} = \frac{2}{\Delta} v \sqrt{\hat{s}} \left[ 2 \text{Re}(F_1F_6^*) + \text{Re}(F_2F_5^*) \right],$$

$$A_{FB}^{LN} = \frac{4v\lambda}{3\hat{m}_K\sqrt{\hat{s}}\Delta} \text{Im} \left[ \hat{m}_\ell \lambda (F_3F_7^*) + \hat{m}_\ell (F_3F_6^* + F_2F_7^*) (-1 + \hat{m}_K + \hat{s}) + \hat{m}_\ell (F_2F_5^*) - \hat{m}_\ell \hat{s}\hat{m}_K (F_1F_5^*) \right],$$

$$A_{FB}^{LT} = \frac{4\lambda}{\hat{m}_K\sqrt{\hat{s}}\Delta} \text{Im} \left[ -2\hat{m}_\ell \lambda |F_3|^2 + 2\hat{m}_\ell \text{Re}[F_2F_3^*] (-1 + \hat{m}_K + \hat{s}) + \hat{m}_\ell |F_2|^2 - \hat{m}_\ell \hat{s}\hat{m}_K |F_1|^2 \right],$$

$$A_{FB}^{NT} = \frac{2\sqrt{\lambda}}{\hat{m}_K\sqrt{\hat{s}}\Delta} \text{Im} \left[ -2\hat{m}_\ell \lambda |F_3|^2 (1 - \hat{m}_K) + 2\hat{m}_\ell \lambda (F_3F_6^*) - 2\hat{m}_\ell (F_2F_6^*) (1 - \hat{m}_K - \hat{s}) + 2\hat{m}_\ell (F_2F_7^*) (1 - \hat{m}_K) (1 - \hat{m}_K - \hat{s}) - 2\hat{m}_\ell \hat{s}\lambda (F_3F_8^*) + 2\hat{m}_\ell \hat{s}(F_2F_8^*) (1 - \hat{m}_K - \hat{s}) \right],$$

along with the relations

$$A_{FB}^{LN} = A_{FB}^{NL}, \quad A_{FB}^{LT} = A_{FB}^{TL}, \quad A_{FB}^{TN} = -A_{FB}^{NT}.$$

It should be noted that $A_{FB}^{LL}$ has the same form as the unpolarized forward-backward asymmetry $A_{FB}$.

### E. Lepton polarization Asymmetries

Next, we pay our attention to the single-lepton polarization asymmetry parameters in $B \to K_1\ell^+\ell^-$, defined as

$$P_i = \frac{d\Gamma(s^+ = i)/d\hat{s} - d\Gamma(s^+ = -i)/d\hat{s}}{d\Gamma(s^+ = i)/d\hat{s} + d\Gamma(s^+ = -i)/d\hat{s}},$$

where $i$ denotes the unit vector along longitudinal ($L$), normal ($N$) and transverse ($T$) polarization directions of the lepton and $s^\pm$ denote the spin direction of $\ell^\pm$. The polarized and unpolarized invariant dilepton mass spectra for the $B \to K_1\ell^+\ell^-$ processes are related as

$$\frac{d\Gamma(s^\pm)}{ds} = \frac{1}{2} \left( \frac{d\Gamma}{ds} \right) \left[ 1 + (P_L e_L + P_N e_N + P_T e_T) \cdot s^\pm \right].$$
Thus, by using the decay rate (27), one can obtain the expressions for the single polarization asymmetries as [31]:

\[
P_L = \frac{1}{3\hat{m}_K \Delta} \left[ 2 \text{Re}[\mathcal{F}_2^s \mathcal{F}_7^s]v(\hat{m}_K_1 + \hat{s} - 1)(3\hat{m}_K^2 - 6(\hat{s} + 1)\hat{m}_K + 3(\hat{s} - 1)^2 - \lambda) 
+ 2 \text{Re}[\mathcal{F}_3^s \mathcal{F}_6^s]v(\hat{m}_K_1 + \hat{s} - 1)(3\hat{m}_K^2 - 6(\hat{s} + 1)\hat{m}_K + 3(\hat{s} - 1)^2 - \lambda) 
+ 2 \text{Re}[\mathcal{F}_3^s \mathcal{F}_7^s]v\lambda(3\hat{m}_K^2 - 6(\hat{s} + 1)\hat{m}_K + 3(\hat{s} - 1)^2 - \lambda) 
+ 2\hat{m}_K_1 \text{Re}[\mathcal{F}_1^s \mathcal{F}_5^s]v\hat{s}(3\hat{m}_K^2 - 6(\hat{s} + 1)\hat{m}_K + 3(\hat{s} - 1)^2 + \lambda) 
- 2 \text{Re}[\mathcal{F}_2^s \mathcal{F}_6^s]v(\lambda - 3(\hat{m}_K^2 + (6\hat{s} - 2)\hat{m}_K + (\hat{s} - 1)^2)) \right].
\]

\[
P_T = \frac{\pi \hat{m}_t \sqrt{\lambda}}{\Delta} \left[ \frac{\text{Re}[\mathcal{F}_3^s \mathcal{F}_8^s] \sqrt{\hat{s}} \lambda}{\hat{m}_K_1} - \frac{\text{Re}[\mathcal{F}_3^s \mathcal{F}_6^s] \lambda}{\hat{m}_K_1 \sqrt{\hat{s}}} - \frac{\text{Re}[\mathcal{F}_3^s \mathcal{F}_7^s](\hat{m}_K_1 - 1)\lambda}{\hat{m}_K_1 \sqrt{\hat{s}}} 
+ \frac{\text{Re}[\mathcal{F}_2^s \mathcal{F}_7^s] \sqrt{\hat{s}(\hat{m}_K_1 + \hat{s} - 1)}}{\hat{m}_K_1} - \frac{\text{Re}[\mathcal{F}_2^s \mathcal{F}_8^s](\hat{m}_K_1 + \hat{s} - 1)}{\hat{m}_K_1 \sqrt{\hat{s}}} 
- \frac{\text{Re}[\mathcal{F}_2^s \mathcal{F}_7^s](\hat{m}_K_1 - 1)(\hat{m}_K_1 + \hat{s} - 1)}{\hat{m}_K_1 \sqrt{\hat{s}}} + 4\text{Re}[\mathcal{F}_1^s \mathcal{F}_2^s] \sqrt{\hat{s}} \right].
\]

\[
P_N = -\frac{\pi \hat{m}_t \sqrt{\lambda}}{\Delta} \left[ \frac{\text{Im}[\mathcal{F}_7^s \mathcal{F}_8^s] \sqrt{\hat{s}} \lambda}{\hat{m}_K_1} + \frac{\text{Re}[\mathcal{F}_6^s \mathcal{F}_7^s] \sqrt{\hat{s}}(-3\hat{m}_K_1 + \hat{s} - 1)}{\hat{m}_K_1} 
+ \frac{\text{Im}[\mathcal{F}_6^s \mathcal{F}_8^s] \sqrt{\hat{s}(\hat{m}_K_1 + \hat{s} - 1)}}{\hat{m}_K_1} - 2\text{Im}[\mathcal{F}_1^s \mathcal{F}_6^s] \sqrt{\hat{s}} - 2\text{Im}[\mathcal{F}_1^s \mathcal{F}_8^s] \sqrt{\hat{s}} \right].
\]

The averaged asymmetries can be obtained by using the formula

\[
\langle P_i \rangle = \frac{\int_{4m_K^2}^{s_{\text{max}}^2} P_i \frac{d \Gamma}{ds} ds}{\int_{4m_K^2}^{s_{\text{max}}^2} \frac{d \Gamma}{ds} ds}, \quad (44)
\]

where \(s_{\text{max}} = (m_B - m_K_1)^2\).

**IV. RESULTS AND DISCUSSION**

After gathering the required information about all the relevant observables, we now proceed for numerical estimation. The particle masses, the \(B\) meson lifetime and the values of CKM matrix elements are taken from [24]. The \(B \rightarrow K_1\) form factors used in this analysis are taken from [57], which are calculated in light cone sum rule (LCSR) approach. The \(q^2\) dependence of the form factors are parametrized in double pole form (26) and the necessary parameters are listed in Table [III]. Since the mixing angle \(\theta\) is not known precisely, to see its
FIG. 2: Variation of differential branching ratio, forward-backward asymmetry and longitudinal polarization fraction with $s$ for different values of the mixing angle $\theta$. The plots in the left panel are for $B \to K_1(1270)\mu^+\mu^-$ and those in the right panel are for $B \to K_1(1400)\mu^+\mu^-$ process.
FIG. 3: Three-dimensional representation of differential branching ratio (in units of $10^{-7}$), forward-backward asymmetry and longitudinal polarization with $s$ and the mixing angle $\theta$. The plots in the left panel are for $B \to K_1(1270)\mu^+\mu^-$ and those in the right panel are for $B \to K_1(1400)\mu^+\mu^-$ process.

of the contributions from $B \to K_{1A}$ and $B \to K_{1B}$ form factors. As expected, these observables are found to have their minimal values for $\theta = -47^\circ$, which is very close to the maximal mixing. For completeness, we show the $q^2$ variation of these observables for the one-sigma allowed range of the mixing angle $\theta$ in Fig. 3. Therefore, the measurement of various observables of $B \to K_1(1400)\mu^+\mu^-$ process will shed light on the determination of the mixing angle.

Next, we would like to see the impact of new physics on various observables, for which
FIG. 4: The $s$ variation of the differential branching fraction, lepton non-universality observable and the forward-backward asymmetry in the SM as well as the NP scenarios. The plots in left panel correspond to $B \to K_1(1270)\mu^+\mu^-$ process whereas the right panel plots are for $B \to K_1(1400)\mu^+\mu^-$ process.

we have fixed the value of the mixing angle at its central value $\theta = -34^\circ$. We consider three specific new physics scenarios, in the first case we consider the NP contributions only in operators which are non-zero in the SM, and the values of the NP coefficients as $C_7^{\text{NP}} = 0.013$, $C_9^{\text{NP}} = -1.03$, and $C_{10}^{\text{NP}} = 0.08$ \cite{50}. For the second scenario, we consider the case $C_9^{\text{NP}} = -0.829$ and $C_9^{\text{NP}} = -0.462$, and for the third case we use $C_9^{\text{NP}} = -0.526$ and $C_{10}^{\text{NP}} = 0.573$, which are obtained from the current data on $b \to s\mu^+\mu^-$ anomalies, that are relatively free from hadronic uncertainties. In Fig. 4 we show the $q^2$ variation of branching
FIG. 5: Lepton polarization asymmetries are shown in the SM as well as in the NP scenarios for $B \to K_1(1270)\mu^+\mu^-$ (left panel) and $B \to K_1(1400)\mu^+\mu^-$ (right panel) processes.

fraction, the lepton non-universality observable $R_{K_1}$ and the forward-backward asymmetry for $B \to K_1(1270)\mu^+\mu^-$ ($B \to K_1(1400)\mu^+\mu^-$) process in the left (right) panel, both in the SM and the two NP1 and NP2 scenarios. The plots for NP3 scenario are very similar and close to those of NP1, so we have not shown them explicitly. The branching fractions are shown in the top panel of the figure, where the dashed lines are due to the central values of the input parameters whereas the bands are due to the $1\sigma$ uncertainties. From the figure, it can be noticed that for $B \to K_1(1270)\mu\mu$ process, the branching fractions are lower than the SM values for both types of NP scenarios, whereas for $B \to K_1(1400)\mu^+\mu^-$, the branching ratio of NP scenario II (NP2) is higher than the SM while for scenario-I (NP1), it is lower than the SM prediction. In the middle panel the lepton flavour non universality
FIG. 6: Variation of polarized forward-backward asymmetry for $B \rightarrow K_1(1270)\mu^+\mu^-$ (left panel) and $B \rightarrow K_1(1400)\mu^+\mu^-$ (right panel) processes.

FIG. 7: The left (right) panel displays the variation of $R_\mu$ parameter with $s$ for SM and new physics scenario-I (scenario-II).
ratio is displayed, which is lower than the SM predicted value for both the NP scenarios for $B \to K_1(1270)\mu^+\mu^-$, while for $B \to K_1(1400)\mu^+\mu^-$, while it is lower than the SM for NP1 and higher than the SM value in the lower $q^2$ bin for NP2. The measurement of this observable in both the decay modes will help to distinguish between these two NP scenarios.

The behaviour of forward-backward asymmetry is shown in the lower panel and it is found that the zero crossing points in the both types of NP scenarios differ from its SM value and shift towards higher value of $q^2$. In Fig. [5], the lepton polarization asymmetries are displayed. From the plots it is found that the behaviour of lepton polarization asymmetries in NP-II scenario is quite different from SM as well as NP-I cases. It is also inferred that the longitudinal polarization asymmetry receives the dominant contributions for both the decay modes. The polarized forward-backward asymmetries are presented in Fig [6]. In this case also the effect of NP2 is significantly different from SM as well as NP1 scenario, though its effect is more prominent in $B \to K_1(1400)\mu^+\mu^-$ process. Finally in Fig. [7] we show the $q^2$ variation of $R_\mu$ parameter for the case of NP1 (left panel) and NP2 (right panel) and it is found in the low $q^2$ regime, the impact of NP-II is relatively significant. The integrated values of the branching ratios in the low-$q^2$ bin well below the charmonium resonance region ($q^2 \in [1,6] \text{ GeV}^2$) are presented in Table [IV] both for the SM and the NP scenarios and the numerical values of all other observables are presented in Table [V]. The theoretical uncertainties arising from the hadronic form factors, CKM matrix elements and other input parameters are provided only for those observables for which SM predictions are more than a percent level. The value of $R_\mu$ ratio in the low-$q^2$ region ([1,6] GeV$^2$) is found to be 0.02 in the SM and 0.024/0.043/0.021 in the NP scenarios-1/2/3.

**TABLE IV:** The predicted values of the branching ratios in the low $q^2$ bin $q^2 \in [1,6]$ GeV$^2$ for the $B^0 \to K_1^0(1270)\mu^+\mu^-$ and $B^0 \to K_1^0(1400)\mu^+\mu^-$ processes, both in the SM and NP scenarios.

| Various in different scenarios | $\text{Br}(B^0 \to K_1(1270)\mu^+\mu^-)$ | $\text{Br}(B^0 \to K_1(1400)\mu^+\mu^-)$ |
|-------------------------------|------------------------------------------|------------------------------------------|
| Standard Model                | $(4.257 \pm 0.851) \times 10^{-7}$       | $(8.548 \pm 1.71) \times 10^{-9}$        |
| NP scenario-I                 | $(3.433 \pm 0.687) \times 10^{-7}$       | $(8.409 \pm 1.682) \times 10^{-9}$       |
| NP scenario-II                | $(3.057 \pm 0.611) \times 10^{-7}$       | $(1.307 \pm 0.261) \times 10^{-8}$       |
| NP scenario-III               | $(3.192 \pm 0.638) \times 10^{-7}$       | $(6.622 \pm 1.324) \times 10^{-9}$       |

We now proceed to calculate the branching fractions for $B \to K_1\mu^+\mu^-$ processes in
TABLE V: The predicted values of the the lepton nonuniversality ratio $R_{K_1}$, forward-backward asymmetry and lepton polarisation asymmetries in the low $q^2$ bin $q^2 \in [1, 6]$ GeV$^2$ for the $B^0 \rightarrow K^0_{1}(1270)\mu^+\mu^-$ and $B^0 \rightarrow K^0_{1}(1400)\mu^+\mu^-$ processes in the SM as well as in NP scenarios.

| Observables | $B^0 \rightarrow K_1(1270)\mu\mu$ | $B^0 \rightarrow K_1(1400)\mu\mu$ | Observables | $B^0 \rightarrow K_1(1270)\mu\mu$ | $B^0 \rightarrow K_1(1400)\mu\mu$ |
|-------------|-----------------|-----------------|-------------|-----------------|-----------------|
| $R_{K_1}^{\text{SM}}$ | 0.995 ± 0.05 | 0.987 ± 049 | $\langle A_{FB} \rangle^{\text{SM}}$ | 0.081 ± 0.004 | 0.149 ± 0.007 |
| $R_{K_1}^{\text{NP1}}$ | 0.803 ± 0.04 | 0.971 ± 0.048 | $\langle A_{FB} \rangle^{\text{NP1}}$ | 0.026 ± 0.001 | −(0.059 ± 0.003) |
| $R_{K_1}^{\text{NP2}}$ | 0.715 ± 0.036 | 1.51 ± 0.075 | $\langle A_{FB} \rangle^{\text{NP2}}$ | −(0.007 ± 0.003) | −(0.107 ± 0.005) |
| $R_{K_1}^{\text{NP3}}$ | 0.746 ± 0.037 | 0.765 ± 0.038 | $\langle A_{FB} \rangle^{\text{NP3}}$ | 0.053 ± 0.003 | 0.025 ± 0.001 |
| $\langle P_L \rangle^{\text{SM}}$ | −(0.8625 ± 0.043) | −(0.488 ± 0.024) | $\langle P_T \rangle^{\text{SM}}$ | −(0.095 ± 0.005) | −(0.019 ± 0.001) |
| $\langle P_L \rangle^{\text{NP1}}$ | −(0.713 ± 0.036) | −(0.137 ± 0.007) | $\langle P_T \rangle^{\text{NP1}}$ | −(0.085 ± 0.004) | −(0.009 ± 0.0004) |
| $\langle P_L \rangle^{\text{NP2}}$ | −(0.478 ± 0.024) | −(0.219 ± 0.011) | $\langle P_T \rangle^{\text{NP2}}$ | −(0.052 ± 0.003) | −(0.032 ± 0.002) |
| $\langle P_L \rangle^{\text{NP3}}$ | −(0.825 ± 0.041) | −(0.317 ± 0.016) | $\langle P_T \rangle^{\text{NP3}}$ | −(0.094 ± 0.005) | −(0.012 ± 0.006) |
| $\langle A_{LT} \rangle^{\text{SM}}$ | −0.37 ± 0.003 | −6.06 × 10$^{-3}$ | $\langle A_{LT} \rangle^{\text{SM}}$ | −0.357 × 10$^{-3}$ | −0.141 × 10$^{-3}$ |
| $\langle A_{LT} \rangle^{\text{NP1}}$ | −0.24 | 0.101 × 10$^{-3}$ | $\langle A_{LT} \rangle^{\text{NP1}}$ | −0.435 × 10$^{-3}$ | −0.140 × 10$^{-3}$ |
| $\langle A_{LT} \rangle^{\text{NP2}}$ | −0.008 | −0.038 | $\langle A_{LT} \rangle^{\text{NP2}}$ | −0.497 × 10$^{-3}$ | −0.92 × 10$^{-4}$ |
| $\langle A_{LT} \rangle^{\text{NP3}}$ | −0.037 | −3.35 × 10$^{-3}$ | $\langle A_{LT} \rangle^{\text{NP3}}$ | −0.413 × 10$^{-3}$ | −0.159 × 10$^{-3}$ |

the whole $q^2$ region, for which it is necessary to eliminate the backgrounds coming from the resonance regions. This can be done by using the following veto windows so that backgrounds coming from the dominant resonances $B \rightarrow K_1 J/\psi(\psi')$ with $J/\psi(\psi') \rightarrow \mu^+\mu^-$ can be eliminated,

$$(m_{J/\psi} - 0.02)^2 \text{ GeV}^2 \leq s \leq (m_{J/\psi} + 0.02)^2 \text{ GeV}^2,$$

and

$$(m_{\psi'} - 0.02)^2 \text{ GeV}^2 \leq s \leq (m_{\psi'} + 0.02)^2 \text{ GeV}^2,$$

which basically corresponds to the invariant mass of the muon pair to be within 20 MeV of the $J/\psi(\psi')$ mass. Using the above mentioned cuts, the predicted branching fractions for
the whole $q^2$ region are presented in Table VI.

| Various in different scenarios | $\text{Br}(B^0 \rightarrow K_1^0(1270)\mu^+\mu^-)$ | $\text{Br}(B^0 \rightarrow K_1^0(1400)\mu^+\mu^-)$ |
|--------------------------------|---------------------------------|---------------------------------|
| Standard Model                 | $(1.477 \pm 0.295) \times 10^{-6}$ | $(4.084 \pm 0.817) \times 10^{-8}$ |
| NP scenario-I                  | $(1.184 \pm 0.237) \times 10^{-6}$ | $(3.473 \pm 0.695) \times 10^{-8}$ |
| NP scenario-II                 | $(1.103 \pm 0.221) \times 10^{-6}$ | $(4.158 \pm 0.832) \times 10^{-8}$ |
| NP scenario-III                | $(1.122 \pm 0.224) \times 10^{-7}$ | $(3.236 \pm 0.647) \times 10^{-8}$ |

V. SUMMARY AND OUTLOOK

The recent results from LHCb experiment, show some level of discrepancies in the FCNC mediated transitions $b \rightarrow s\ell\ell$, e.g., the branching fractions of $B \rightarrow K^{(*)}\mu\mu$ and $B_s \rightarrow \phi\mu\mu$, angular observables of $B \rightarrow K^{*}\mu\mu$ process, such as $P_{4,5}'$, as well as the LFU violating ratios $R_{K^{(*)}}$ in $B \rightarrow K^{(*)}\ell\ell$ processes. All these discrepancies are generally attributed to the possible interplay of some kind of new physics in $b \rightarrow s\mu^+\mu^-$ channels. Hence, considerable interest has been paid to these decay processes in all possible ways to establish or rule out the role of NP. The general presumption is that, if indeed NP is responsible for the observed deviations in $b \rightarrow s\mu^+\mu^-$ processes, it must also show up in other modes having the same quark level transition. In this context, we have studied various observables of $B \rightarrow (K_1(1270)/K_1(1400))\mu^+\mu^-$ processes in depth. The main objective of our work is to understand the behaviour of these observables under the influence of new physics, associated with $b \rightarrow s\ell^+\ell^-$ anomalies. It should be emphasized that the existing $b \rightarrow s\mu\mu$ anomalies can be realized in a model independent approach, as new augmentation to the Wilson coefficient $C_{9\mu}$, along with some room for other Wilson coefficients. Even though such a contribution to $C_{9\mu}$ appears to be a reasonable way of elucidating a large set of discrepancies, theory predictions for some $b \rightarrow s\mu\mu$ observables may have better consistency with data, once additional contributions are incorporated in other WCs (such as $C_{9\mu}$ or $C_{10\mu}$). Recently a global fit has been performed in [50] considering the recent $b \rightarrow s\mu\mu$ data and it has been shown that, all the anomalies can be elucidated with the following set values for the NP
Wilson coefficients: \((C_{NP}^7, C_{NP}^9, C_{NP}^{10}) = (0.013, -1.03, 0.08)\).

In this work, we have considered a two-dimensional hypothesis with three specific scenarios for real NP Wilson coefficients: \((C_{NP}^9 - C_{NP}^{10})\), \((C_{NP}^{10} - C_{NP}^{10'})\) and \((C_{NP}^9 - C_{NP}^{10'})\), and extracted the values of these new coefficients from the existing data on \(b \to s\mu\mu\) anomalies, that are relatively free from hadronic uncertainties. We found that the combination \((C_{NP}^9 - C_{NP}^{10}) = (-0.829, -0.463)\) and \((C_{NP}^9 - C_{NP}^{10}) = (-0.526, 0.573)\) explain the anomalies preferably well.

We then studied the implications of these new physics scenarios on the semileptonic decay \(B \to (K_1(1270)/K_1(1400))\mu\mu\). The axial vector mesons \(K_1(1270)\) and \(K_1(1400)\) are admixture states of the \(1^1P_1\) and \(1^3P_1\) states with mixing angle \(\theta\), which is not yet known precisely. Its value extracted from the radiative decays \(B \to K_1^*\gamma\) is \(\theta = -(34 \pm 13)^\circ\). To see the impact of the mixing angle on various observables, we first looked into the SM branching ratio, forward-backward asymmetry and the longitudinal lepton polarization asymmetry of \(B \to K_1(1270)/K_1(1400)\mu^+\mu^-\) processes for three different values of \(\theta = -34^\circ, -21^\circ, -47^\circ\) and found that the observables of \(B \to K_1(1400)\mu^+\mu^-\) processes are quite sensitive to the mixing angle as the contributions from \(B \to K_{1A}\) and \(B \to K_{1B}\) come with a relative minus sign, whereas those associated with \(B \to K_1(1270)\mu^+\mu^-\) process depend very mildly on the mixing angle. Next we analysed these decay modes considering these new physics scenarios.

In the first case, we considered the structure of the NP which includes new contributions only in operators which are non-zero in the SM and the values of these new Wilson coefficients \(C_{NP}^{7,9,10}\) are extracted from the currently available data on \(b \to s\mu\mu\) anomalies \([50]\). In the second case we considered the NP contributions in terms of two new Wilson coefficients \((C_{NP}^9, C_{NP}^{9'})\), i.e., in addition to the standard left-handed quark currents, we have also taken into account the right-handed current and in the third case the new physics contributions are considered in terms of \((C_{NP}^9, C_{NP}^{10})\) coefficients. Since the effect due to the NP3 coefficients are similar to NP1 case, we have not shown explicitly the corresponding results in the plots and provided only the corresponding numerical results. We found that in the second category of NP scenario, various observables deviate significantly from their corresponding SM predictions whereas for NP scenarios 1 and 3, there are only marginal deviations from SM results. It should be emphasized that lepton flavour universal violating ratio \(R_{K_1}\) deviates significantly for all the three types of new physics scenarios. The measurement of these observables would be highly instrumental in exploiting the full potential of \(b \to s\mu\mu\) decays.
to look for new physics signal and ultimately uncover its true nature. To conclude, these decay processes offer an alternative probe to scrutinize the role of NP associated with the current $B$ anomalies in semileptonic transitions and could be accessible with the currently running LHCb and Belle II experiments.

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[1] J. P. Lees et al. (BaBar), Phys. Rev. Lett. 109, 101802 (2012), 1205.5442.
[2] J. P. Lees et al. (BaBar), Phys. Rev. D88, 072012 (2013), 1303.0571.
[3] R. Aaij et al. (LHCb), Phys. Rev. Lett. 115, 111803 (2015), [Erratum: Phys. Rev. Lett.115,no.15,159901(2015)], 1506.08614.
[4] M. Huschle et al. (Belle), Phys. Rev. D92, 072014 (2015), 1507.03233.
[5] S. Hirose et al. (Belle), Phys. Rev. Lett. 118, 211801 (2017), 1612.00529.
[6] R. Aaij et al. (LHCb), Phys. Rev. Lett. 120, 171802 (2018), 1708.08856.
[7] A. Abdesselam et al. (Belle) (2019), 1904.08794.
[8] R. Aaij et al. (LHCb), JHEP 07, 084 (2013), 1305.2168.
[9] R. Aaij et al. (LHCb), Phys. Rev. Lett. 111, 191801 (2013), 1308.1707.
[10] R. Aaij et al. (LHCb), JHEP 06, 133 (2014), 1403.8044.
[11] R. Aaij et al. (LHCb), Phys. Rev. Lett. 113, 151601 (2014), 1406.6482.
[12] R. Aaij et al. (LHCb), JHEP 09, 179 (2015), 1506.08777.
[13] R. Aaij et al. (LHCb), JHEP 08, 055 (2017), 1705.05802.
[14] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 191801 (2019), 1903.09252.
[15] A. Abdesselam et al. (Belle) (2019), 1908.01848.
[16] A. Abdesselam et al. (Belle) (2019), 1904.02440.
[17] Y. S. Amhis et al. (HFLAV) (2019), 1909.12524.
[18] R. Aaij et al. (LHCb), Phys. Rev. Lett. **120**, 121801 (2018), 1711.05623.
[19] R. Dutta and A. Bhol, Phys. Rev. **D96**, 076001 (2017), 1701.08598.
[20] C. Bobeth, G. Hiller, and G. Piranishvili, JHEP **12**, 040 (2007), 0709.4174.
[21] M. Bordone, G. Isidori, and A. Pattori, Eur. Phys. J. **C76**, 440 (2016), 1605.07633.
[22] R. Aaij et al. (LHCb) (2021), 2103.11769.
[23] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, JHEP **01**, 093 (2018), 1704.05340.
[24] M. Tanabashi et al. (Particle Data Group), Phys. Rev. **D98**, 030001 (2018).
[25] R. Aaij et al. (LHCb), JHEP **05**, 040 (2020), 1912.08139.
[26] H. Hatanaka and K.-C. Yang, Phys. Rev. **D77**, 094023 (2008), [Erratum: Phys. Rev.D78,059902(2008)], 0804.3198.
[27] H. Guler et al. (Belle), Phys. Rev. **D83**, 032005 (2011), 1009.5256.
[28] H. Hatanaka and K.-C. Yang, Phys. Rev. **D78**, 074007 (2008), 0808.3731.
[29] R.-H. Li, C.-D. Lu, and W. Wang, Phys. Rev. **D79**, 094024 (2009), 0902.3291.
[30] M. A. Paracha, I. Ahmed, and M. J. Aslam, Eur. Phys. J. **C52**, 967 (2007), 0707.0733.
[31] V. Bashiry, JHEP **06**, 062 (2009), 0902.2578.
[32] V. Bashiry and K. Azizi, JHEP **01**, 033 (2010), 0903.1505.
[33] I. Ahmed, M. A. Paracha, and M. J. Aslam, Eur. Phys. J. **C54**, 591 (2008), 0802.0740.
[34] A. Saddique, M. J. Aslam, and C.-D. Lu, Eur. Phys. J. **C56**, 267 (2008), 0803.0192.
[35] A. Ahmed, I. Ahmed, M. Ali Paracha, and A. Rehman, Phys. Rev. **D84**, 033010 (2011), 1105.3887.
[36] Y. Li, J. Hua, and K.-C. Yang, Eur. Phys. J. **C71**, 1775 (2011), 1107.0630.
[37] Z.-R. Huang, M. A. Paracha, I. Ahmed, and C.-D. Lu, Phys. Rev. **D100**, 055038 (2019), 1812.03491.
[38] F. Falahati and A. Zahedidareshouri, Phys. Rev. **D90**, 075002 (2014).
[39] I. Ahmed, M. Ali Paracha, and M. J. Aslam, Eur. Phys. J. **C71**, 1521 (2011), 1002.3860.
[40] R. Aaij et al. (LHCb), JHEP **10**, 064 (2014), 1408.1137.
[41] A. J. Buras and M. Munz, Phys. Rev. **D52**, 186 (1995), hep-ph/9501281.
[42] C. S. Lim, T. Morozumi, and A. I. Sanda, Phys. Lett. **B218**, 343 (1989).
[43] N. G. Deshpande, J. Trampetic, and K. Panose, Phys. Rev. **D39**, 1461 (1989).
[44] P. J. O’Donnell and H. K. K. Tung, Phys. Rev. **D43**, 2067 (1991).
[45] P. J. O’Donnell, M. Sutherland, and H. K. K. Tung, Phys. Rev. D 46, 4091 (1992).
[46] F. Kruger and L. M. Sehgal, Phys. Lett. B 380, 199 (1996), hep-ph/9603237.
[47] C. Bobeth, P. Gambino, M. Gorbahn, and U. Haisch, JHEP 04, 071 (2004), hep-ph/0312090.
[48] T. Huber, E. Lunghi, M. Misiak, and D. Wyler, Nucl. Phys. B 740, 105 (2006), hep-ph/0512066.
[49] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub, and M. Wick, JHEP 01, 019 (2009), 0811.1214.
[50] J. Bhom, M. Chrzaszcz, F. Mahmoudi, M. T. Prim, P. Scott, and M. White (2020), 2006.03489.
[51] A. K. Alok, A. Dighe, S. Gangal, and D. Kumar, JHEP 06, 089 (2019), 1903.09617.
[52] Combination of the ATLAS, CMS and LHCb results on the $B^0_{(s)} \rightarrow \mu^+\mu^-$ decays (ATLAS) (2020), ATLAS-CONF-2020-049.
[53] C. Bobeth, M. Gorbahn, T. Hermann, M. Misiak, E. Stamou, and M. Steinhauser, Phys. Rev. Lett. 112, 101801 (2014), 1311.0903.
[54] R. Aaij et al. (LHCb), JHEP 02, 104 (2016), 1512.04442.
[55] A. Bharucha, D. M. Straub, and R. Zwicky, JHEP 08, 098 (2016), 1503.05534.
[56] J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P. Stangl, and D. M. Straub, Eur. Phys. J. C 80, 252 (2020), 1903.10434.
[57] K.-C. Yang, Phys. Rev. D 78, 034018 (2008), 0807.1171.