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

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Based on arXiv:2011.05820v1

December 14, 2020
OUTLINE

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Several discrepancies at the level of \((2 - 3)\sigma\) have been observed in the decay processes mediated by FCNC transitions \(b \rightarrow s\ell^+\ell^-\) decays.

Analyze the decay channels \(B \rightarrow (K_1(1270/1400))\mu^+\mu^-\) where \(K_1(1270)\) and \(K_1(1400)\) are axial vector mesons.

**Admixture of \(1^3P_1\) and \(1^1P_1\) states \(K_{1A}\) and \(K_{1B}\) resp.**

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

\(\theta\) is the mixing angle, which is not yet determined precisely. Its value has been estimated to be \(-\nobreak (34 \pm 13)\degree\).
The SM effective Hamiltonian responsible for \( b \rightarrow s\ell^+\ell^- \) transition

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

- The NP 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.

The NP effective Hamiltonian responsible for \( b \rightarrow s\ell^+\ell^- \) transition

\[
\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{\alpha G_F}{\sqrt{2\pi}} V_{tb} V_{ts}^* \left[ C_9^{\text{NP}} (\bar{s}\gamma^\mu P_L b) (\bar{\ell}\gamma_\mu \ell) + C_{10}^{\text{NP}} (\bar{s}\gamma^\mu P_L b) (\bar{\ell}\gamma_\mu \gamma_5 \ell) + C_9'^{\text{NP}} (\bar{s}\gamma^\mu P_R b) (\bar{\ell}\gamma_\mu \ell) + C_{10}'^{\text{NP}} (\bar{s}\gamma^\mu P_R b) (\bar{\ell}\gamma_\mu \gamma_5 \ell) \right]
\]
We perform a two-dimensional global fit, by taking two new operators at a time with the following two possible combinations: \((C_{9}^{NP}, C_{9}^{NP'})\) and \((C_{10}^{NP}, C_{10}^{NP'})\).

The \(\chi^2\) is defined as

\[
\chi^2(C_i^{NP}) = \sum_i \left( \frac{\mathcal{O}_i^{th}(C_i^{NP}) - \mathcal{O}_i^{exp}}{(\Delta \mathcal{O}_i)^2} \right)^2
\]

\(\mathcal{O}_i^{th}(C_i^{NP})\) are the theoretical expectations for the observables used in our fit, \(\mathcal{O}_i^{exp}\) represent the measured central values of the observables and \((\Delta \mathcal{O}_i)^2 = (\Delta \mathcal{O}_i^{exp})^2 + (\Delta \mathcal{O}_i^{th})^2\) encompasses the 1\(\sigma\) uncertainties from theory and experiment.

Considering the impact of two different classes of NP scenarios:

(I) NP coefficients as \((C_{7}^{NP}, C_{9}^{NP}, C_{10}^{NP}) = (0.013, -1.03, 0.08)\) (NP1)

(II) Considering the presence of \(C_{9}^{NP} - C_{9}^{NP'}\) and use the extracted best-fit values of the NP coefficients: \((-1.315, -0.875)\) (NP2)
The best-fit values for $C_9^{NP} - C'_9^{NP}$ case are found to be $(-1.315, -0.875)$ with $\chi^2_{\text{min}} / \text{d.o.f} = 1.056 (\approx 1$ with a larger pull) and $\text{pull} = \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{best-fit}}} = 6.13$ (acceptable).

$C_{10}^{NP} - C'_{10}^{NP}$ case there are two degenerate solutions: $(0.618, 0.328)$ and $(3.415, 3.026)$ with $\chi^2_{\text{min}} / \text{d.o.f} = 1.262 (> 1$ with lower pull value) and $\text{pull} = 2.69$. (not very robust)
Differential Decay Rate

The differential decay width for the process $\bar{B} \to \bar{K}_1 \ell^+ \ell^-$ is given as

$$\frac{d\Gamma(\bar{B} \to \bar{K}_1 \ell^+ \ell^-)}{d\hat{s}} = \frac{G_F^2 \alpha^2 m_B^5 \tau_B}{2^{12} \pi^5} |V_{tb} V_{ts}^*|^2 v \sqrt{\lambda} \Delta(\hat{s})$$

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 $\hat{s} = q^2 / m_B^2$.

![Figure: Variation of differential branching ratio with $s$ for different values of the mixing angle $\theta$. Left panel is for $B \to K_1 (1270) \mu^+ \mu^-$ and Right panel is for $B \to K_1 (1400) \mu^+ \mu^-$ process.]
The expression for $\Delta(\hat{s})$ is given as

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

The unpolarized forward-backward asymmetry, defined as

\[ A_{FB}(\hat{s}) = \left( \int_{-1}^{0} d\cos\theta_\ell \frac{d^2\Gamma}{d\hat{s}d\cos\theta_\ell} - \int_{0}^{1} d\cos\theta_\ell \frac{d^2\Gamma}{d\hat{s}d\cos\theta_\ell} \right) \bigg/ \frac{d\Gamma}{d\hat{s}} \]

**Figure**: Variation of forward-backward asymmetry with \( s \) for different values of the mixing angle \( \theta \). Left panel is for \( B \rightarrow K_1(1270)\mu^+\mu^- \) and Right panel is for \( B \rightarrow K_1(1400)\mu^+\mu^- \) process.
**Lepton polarization asymmetry**

The single-lepton polarization asymmetry parameters in $B \rightarrow K_1 \ell^+ \ell^-$

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

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 $\ell^\pm$.

![Graphs showing variation of longitudinal polarization fraction with $s$ for different values of the mixing angle $\theta$. Left panel is for $B \rightarrow K_1(1270) \mu^+ \mu^-$ and Right panel is for $B \rightarrow K_1(1400) \mu^+ \mu^-$ process.](image-url)
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

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

The observable $R_\mu$ is defined as

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

Since the $K_1$ mesons depend on the mixing angle $\theta$, $R_\mu$ can be used for its determination.
Effect of NP on differential branching fraction

Figure: The $s$ variation of the differential branching fraction in the SM as well as the NP scenarios. The plot in left panel corresponds to $B \rightarrow K_1 (1270) \mu^+ \mu^-$ process whereas the right panel plot is for $B \rightarrow K_1 (1400) \mu^+ \mu^-$ process.
Effect of NP on $R_{K_1}$

**Figure:** The $s$ variation of the lepton non-universality observable in the SM as well as the NP scenarios. The plot in left panel corresponds to $B \to K_1(1270) \mu^+ \mu^-$ process whereas the right panel plot is for $B \to K_1(1400) \mu^+ \mu^-$ process.
Effect of NP on $A_{FB}$

**Figure:** The $s$ variation of the forward-backward asymmetry in the SM as well as the NP scenarios. The plot in left panel corresponds to $B \to K_1(1270)\mu^+\mu^-$ process whereas the right panel plot is for $B \to K_1(1400)\mu^+\mu^-$ process.
Effect of NP on Lepton polarization asymmetries

Figure: The $s$ variation of the lepton polarization asymmetries are shown in the SM as well as in the NP scenarios for $B \rightarrow K_1(1270)\mu^+\mu^-$ (above) and $B \rightarrow K_1(1400)\mu^+\mu^-$ (below).
Effect of NP on Polarized forward-backward asymmetries

Figure: The $s$ variation of the polarized forward-backward asymmetry for $B \rightarrow K_1 (1270) \mu^+ \mu^-$ (above) and $B \rightarrow K_1 (1400) \mu^+ \mu^-$ (below).
Effect of NP on $R_\mu$ parameter

**Figure:** The left (right) panel displays the variation of $R_\mu$ parameter with $s$ for SM and new physics scenario-I (scenario-II).

Implications of new physics in $B \rightarrow K \mu^+ \mu^-$ decay
Results

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

<table>
<thead>
<tr>
<th>Decay Process</th>
<th>SM Value</th>
<th>Value in NP scenario-I</th>
<th>Value in NP scenario-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K_1^0(1270)\mu\mu$</td>
<td>$(4.257 \pm 0.851) \times 10^{-7}$</td>
<td>$(3.433 \pm 0.687) \times 10^{-7}$</td>
<td>$(2.809 \pm 0.562) \times 10^{-7}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K_1^0(1400)\mu\mu$</td>
<td>$(8.548 \pm 1.71) \times 10^{-9}$</td>
<td>$(8.409 \pm 1.682) \times 10^{-9}$</td>
<td>$(1.989 \pm 0.398) \times 10^{-8}$</td>
</tr>
</tbody>
</table>

**Table:** The predicted values of the branching fractions in the whole $q^2$ range for the $B^0 \rightarrow K_1^0(1270)\mu^+\mu^-$ and $B^0 \rightarrow K_1^0(1400)\mu^+\mu^-$ processes, in the SM and in NP scenarios.

<table>
<thead>
<tr>
<th>Decay Process</th>
<th>SM Value</th>
<th>Value in NP scenario-I</th>
<th>Value in NP scenario-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K_1^0(1270)\mu\mu$</td>
<td>$(1.477 \pm 0.295) \times 10^{-6}$</td>
<td>$(1.184 \pm 0.237) \times 10^{-6}$</td>
<td>$(9.856 \pm 1.971) \times 10^{-7}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K_1^0(1400)\mu\mu$</td>
<td>$(4.084 \pm 0.817) \times 10^{-8}$</td>
<td>$(3.473 \pm 0.695) \times 10^{-8}$</td>
<td>$(5.036 \pm 1.007) \times 10^{-8}$</td>
</tr>
</tbody>
</table>
**Table:** The predicted values of the lepton nonuniversality ratio $R_{K_1}$, forward-backward asymmetry and lepton polarisation asymmetries in the low $q^2$ bin $q^2 \in [1, 6] \text{GeV}^2$ for the $B^0 \rightarrow K_1^0(1270) \mu^+ \mu^-$ and $B^0 \rightarrow K_1^0(1400) \mu^+ \mu^-$ processes in the SM as well as in NP scenarios.

<table>
<thead>
<tr>
<th>Observables</th>
<th>$B^0 \rightarrow K_1(1270)\mu\mu$</th>
<th>$B^0 \rightarrow K_1(1400)\mu\mu$</th>
<th>Observables</th>
<th>$B^0 \rightarrow K_1(1270)\mu\mu$</th>
<th>$B^0 \rightarrow K_1(1400)\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{K_1}^{\text{SM}}$</td>
<td>0.995</td>
<td>0.987</td>
<td>$\langle A_{FB}\rangle^{\text{SM}}$</td>
<td>0.081</td>
<td>0.149</td>
</tr>
<tr>
<td>$R_{K_1}^{\text{NP1}}$</td>
<td>0.803</td>
<td>0.971</td>
<td>$\langle A_{FB}\rangle^{\text{NP1}}$</td>
<td>0.026</td>
<td>−0.059</td>
</tr>
<tr>
<td>$R_{K_1}^{\text{NP2}}$</td>
<td>0.657</td>
<td>2.297</td>
<td>$\langle A_{FB}\rangle^{\text{NP2}}$</td>
<td>−0.098</td>
<td>−0.165</td>
</tr>
<tr>
<td>$\langle P_L\rangle^{\text{SM}}$</td>
<td>−0.8625</td>
<td>−0.488</td>
<td>$\langle P_T\rangle^{\text{SM}}$</td>
<td>−0.095</td>
<td>−0.019</td>
</tr>
<tr>
<td>$\langle P_L\rangle^{\text{NP1}}$</td>
<td>−0.713</td>
<td>−0.137</td>
<td>$\langle P_T\rangle^{\text{NP1}}$</td>
<td>−0.085</td>
<td>−0.009</td>
</tr>
<tr>
<td>$\langle P_L\rangle^{\text{NP2}}$</td>
<td>0.072</td>
<td>−0.127</td>
<td>$\langle P_T\rangle^{\text{NP2}}$</td>
<td>0.010</td>
<td>−0.034</td>
</tr>
<tr>
<td>$\langle P_N\rangle^{\text{SM}}$</td>
<td>−1.387 $\times 10^{-3}$</td>
<td>−5.35 $\times 10^{-3}$</td>
<td>$\langle A_{LN}\rangle^{\text{SM}}$</td>
<td>4.863 $\times 10^{-3}$</td>
<td>0.023</td>
</tr>
<tr>
<td>$\langle P_N\rangle^{\text{NP1}}$</td>
<td>−1.69 $\times 10^{-3}$</td>
<td>−5.303 $\times 10^{-3}$</td>
<td>$\langle A_{LN}\rangle^{\text{NP1}}$</td>
<td>5.92 $\times 10^{-3}$</td>
<td>−0.023</td>
</tr>
<tr>
<td>$\langle P_N\rangle^{\text{NP2}}$</td>
<td>−2.107 $\times 10^{-3}$</td>
<td>−2.319 $\times 10^{-3}$</td>
<td>$\langle A_{LN}\rangle^{\text{NP2}}$</td>
<td>7.387 $\times 10^{-3}$</td>
<td>9.877 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$\langle A_{FB}\rangle^{\text{LT}}^{\text{SM}}$</td>
<td>−0.037</td>
<td>−6.065 $\times 10^{-3}$</td>
<td>$\langle A_{NT}\rangle^{\text{SM}}$</td>
<td>−0.357 $\times 10^{-3}$</td>
<td>−0.141 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$\langle A_{FB}\rangle^{\text{LT}}^{\text{NP1}}$</td>
<td>−0.024</td>
<td>0.101 $\times 10^{-3}$</td>
<td>$\langle A_{NT}\rangle^{\text{NP1}}$</td>
<td>−0.435 $\times 10^{-3}$</td>
<td>−0.140 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$\langle A_{FB}\rangle^{\text{LT}}^{\text{NP2}}$</td>
<td>4.08 $\times 10^{-3}$</td>
<td>−0.061</td>
<td>$\langle A_{NT}\rangle^{\text{NP2}}$</td>
<td>−0.542 $\times 10^{-3}$</td>
<td>−0.61 $\times 10^{-4}$</td>
</tr>
</tbody>
</table>
Summary

- For $\theta = -34^\circ, -21^\circ, -47^\circ$ we found that the observables of $B \to K_1(1400)\mu^+\mu^-$ processes are quite sensitive to the mixing angle whereas $B \to K_1(1270)\mu^+\mu^-$ process depend very mildly on it.

- In NP1, $C_{7,9,10}^{NP}$ structure is similar to the SM case whose values are extracted from the currently available data on $b \to s\mu\mu$ anomalies.

- In NP2, we considered $(C_9^{NP}, C_9'^{NP})$, i.e., in addition to the standard left-handed quark currents, we have also taken into account the right-handed current. We found various observables deviate significantly from their corresponding SM predictions whereas for NP scenario I, there are only marginal deviations from SM results.

- It should be emphasized that lepton flavour universal violating ratio $R_{K_1}$ deviates significantly for both type 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 it's true nature.
Conclusion

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.

Thank You!