PROCEEDINGS OF SCIENCE

Analysis of semileptonic $B \to a_1(1260)\ell^-\bar{\nu}_\ell$ process within SMEFT framework

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Motivated by the prospects of the ongoing B meson experiments, we study the exclusive $B \to a_1(1260)\ell^-\bar{\nu}_\ell$ process within the Standard model effective field theory formalism. The new physics parameters are constrained by using the experimental branching fractions of the (semi)leptonic $B \to \ell\bar{\nu}$ and $B \to (\pi, \rho, \omega)\ell\bar{\nu}$ processes (where $\ell = e, \mu, \tau$) which undergoes $b \to u\ell\bar{\nu}$ quark level transitions. We then study a comprehensive angular coefficient analysis of the exclusive $B \to a_1(1260)\ell^-\bar{\nu}_\ell$ process in the Standard model and in the presence of various new physics operators.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

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PoS(HQL2023)067

1. Introduction

The discrepancy between the SM prediction and the experimental measurement have been observed in various $b \to u\ell\nu$ quark level transition decays. The measurement of the branching ratio of the leptonic $B \to \tau\nu$ process, observed in Ref. [1] by Belle and BaBar collaborations [2], is not in good agreement with the SM values. An upper bound on the branching fraction of $B \to \pi\tau\nu$ was reported to be 2.5×10^{-4} by Belle collaboration[3]. Additionally, the branching ratios of the exclusive $B \to \mu\nu$ and $B \to (\pi, \rho, \omega)\mu\nu$ decays still show mild deviations from their SM results. Inspired by these differences of the measurement values from the SM expectations, we study the $B \to a_1\ell\nu$ mode in this work. The observations by BaBar and Belle collaborations [4] in the charmless hadronic $B^0 \to a_1(1260)\pi$ decay channel helps us to probe the detailed theoretical study in exclusive semileptonic $B \to a_1\ell\nu$ decay mode. In principle, the $B \to a_1\ell\nu$ decay mode can be easily access in B factory experiments in near future. In this work, our aim is to explore the consequences of a model independent effective theory formalism so called the Standard model effective field theory (SMEFT) approach on the exclusive semileptonic $B \to a_1\ell\nu$ decay mode. We mainly study the angular coefficient structure in the SM as well as in the presence of SMEFT NP operators.

2. Theoretical Framework

The SMEFT Lagrangian at dim - 6 level can be expressed as [5]:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}^{(4)}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i,$$

where $\mathcal{L}^{(4)}_{\rm SM}$ is the SM Lagrangian and Λ is the NP scale. The relevant SMEFT dimension - six operators contriutiong to $b \to u\ell\nu$ processes O_i can be obtained by integrating out the heavy NP particles. The EFT WCs in terms of the dim - 6 SMEFT operators, the above Wilson coefficients get modified and can be expressed as follows

$$C^{(\ell)}_{V_L} = -\frac{V_{ud}}{V_{ub}}\frac{v^2}{\Lambda^2}\left[\tilde{C}^{(3)}_{\ell q}\right]_{\ell\ell 13}, \qquad C^{(\ell)}_{V_R} = \frac{1}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[\tilde{C}_{\phi ud}\right]_{13}, \tag{1}$$

$$C^{(\ell)}_{S_L} = -\frac{1}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[\tilde{C}^{(1)}_{\ell equ}\right]^*_{\ell\ell 31}, \qquad C^{(\ell)}_{S_R} = -\frac{V_{ud}}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{\ell edq}\right]^*_{\ell\ell 31}, \tag{2}$$

$$C^{(\ell)}_{T} = -\frac{1}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[\tilde{C}^{(3)}_{\ell equ}\right]^*_{\ell\ell 31}. \tag{3}$$

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The four dimesional differential decay distribution amplitude is given as follows

$$\begin{aligned}
\frac{d^4\Gamma(\bar{B} \to a_1(\to \rho_{\|(\perp)}\pi)\ell^-\bar{\nu}_\ell)}{dq^2\, d\cos\theta\, d\phi\, d\cos\theta_V} &= \mathcal{N}_{a_1}^{\|(\perp)} |\vec{p}_{a_1}| \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \Big\{ I^{a_1}_{1s,\|(\perp)} \sin^2\theta_V + I^{a_1}_{1c,\|(\perp)} (3 + \cos 2\theta_V) \\
&+ \left(I^{a_1}_{2s,\|(\perp)} \sin^2\theta_V + I^{a_1}_{2c,\|(\perp)} (3 + \cos 2\theta_V) \right) \cos 2\theta \\
&+ I^{a_1}_{3,\|(\perp)} \sin^2\theta_V \sin^2\theta \cos 2\phi + I^{a_1}_{4,\|(\perp)} \sin 2\theta_V \sin 2\theta \cos\phi \\
&+ I^{a_1}_{5,\|(\perp)} \sin 2\theta_V \sin\theta \cos\phi \\
&+ \left(I^{a_1}_{6s,\|(\perp)} \sin^2\theta_V + I^{a_1}_{6c,\|(\perp)} (3 + \cos 2\theta_V) \right) \cos\theta \\
&+ I^{a_1}_{7,\|(\perp)} \sin 2\theta_V \sin\theta \sin\phi \Big\} \,.
\end{aligned} \tag{4}$$

The symbol $\perp$ and $\|$ refer to the transverse and longitudinal polarizations of ρ meson. The angular coefficient functions in the SM and NP can be obtained from Ref. [6].

3. Constraint on the new physics couplings

Using the data of the $B \to (\mu, \tau)\nu$, $B \to \pi(\mu, \tau)\nu$ and $B \to (\rho, \omega)(\mu, \tau)\nu$ decays, we perform a naive χ^2 analysis to constraint the NP SMEFT coefficient. We obtained the SMEFT new physics couplings where the input parameters are considered from the Ref. [1]. We study the presence of only the (vector+scalar± tensor) operator in this analysis. The SMEFT couplings are given below.

SMEFT couplings	Best fit (μ mode)
$[\tilde{C}^{(3)}_{\ell q}]_{\ell\ell 13}$, $([\tilde{C}^{(3)}_{\ell q}]_{\ell\ell 13}, [\tilde{C}^{(1)}_{\ell equ}]_{\ell\ell 31})$	0.013, (0.016, 0.001)
$[\tilde{C}^{(3)}_{\ell equ}]_{\ell\ell 31}$, $([\tilde{C}^{(3)}_{\ell q}]_{\ell\ell 13}, [\tilde{C}_{\ell edq}]_{\ell\ell 31})$	-0.0008, (0.015, 0.004)
$[\tilde{C}^{(1)}_{\ell equ}]_{\ell\ell 31}$, $([\tilde{C}^{(3)}_{\ell q}]_{\ell\ell 13}, [\tilde{C}^{(3)}_{\ell equ}]_{\ell\ell 31})$	-0.004, (0.113, 0.003)
$[\tilde{C}_{\ell edq}]_{\ell\ell 31}$, $([\tilde{C}^{(1)}_{\ell equ}]_{\ell\ell 31}, [\tilde{C}^{(3)}_{\ell equ}]_{\ell\ell 31})$	0.005, (-0.004, -0.001)
$([\tilde{C}_{\ell edq}]_{\ell\ell 31}, [\tilde{C}^{(3)}_{\ell equ}]_{\ell\ell 31})$	(0.006, -0.001)
$([\tilde{C}^{(1)}_{\ell equ}]_{\ell\ell 31}, [\tilde{C}_{\ell edq}]_{\ell\ell 31})$	(0.002, 0.0015)

Table 1: Best fit values of SMEFT coefficients at m_b scale, under the contraints from $b \to u\ell\nu$ modes.

4. Angular coefficients analysis: $B \to a_1(\to \rho_{||}\pi)\mu\bar{\nu}$

We focus on the longitudinal analysis of $B \to a_1(1260)\ell\bar{\nu}$ process. The coefficient functions $I^{a_1}_{(1s,||)}$, $I^{a_1}_{(2s,||)}$, $I^{a_1}_{(2c,||)}$, $I^{a_1}_{(3,||)}$, $I^{a_1}_{(4,||)}$, $I^{a_1}_{(6s,||)}$, and $I^{a_1}_{(1c,||)}$ are independent of the tensor coefficient $\tilde{C}_T$, providing the only the scalar and vector effects. The $I^{a_1}_{(6s,||)}$ displays a significant deviation in the presence of NP couplings whereas the others lies within 1σ of the SM contribution. The effect of scalar, vector and tensor couplings on $I^{a_1}_{(5,||)}$ are distinguished slightly at low q^2 region. However,

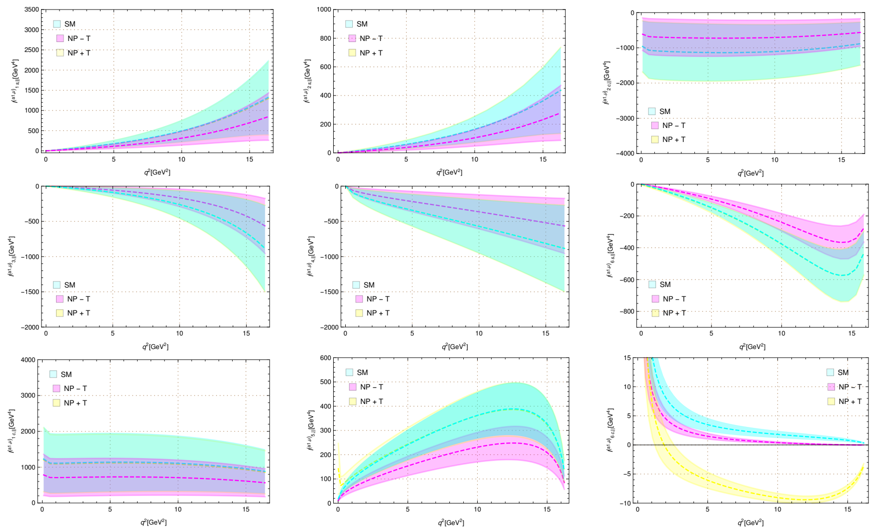

Figure 1: The q^2 dependency of the angular coefficients of $B \to a_1(\rho_{||}\pi)\mu\bar{\nu}$ decay mode in SM (cyan), scalar+vector (magenta) [NP-T] and scalar+vector + tensor contribution (yellow) [NP+T].

the impact without tensor are clearly remarked from the SM contribution though the central value aways from the 1σ bound of SM. In bottom-right panel of Fig. 1, the variation of $I^{a_1}_{(6s,||)}$ w.r.t q^2 with tensor coefficient provides a large deviation from the SM.

5. Conclusion

The theoretical study of $B \to a_1(1260)\ell\bar{\nu}$ process requires an assessment of the accuracy of hadronic uncertainties. The $B^0 \to a_1^{\pm}\pi^{\mp}$ mode observed by BABAR and Belle Collaboration indicates to study the semileptonic decays in future.

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