Resolving $R_D$ and $R_{D^*}$ anomalies

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Abstract The current world averages of the ratios $R_{D^{(*)}}$ are about $4\sigma$ away from their Standard Model prediction. These measurements indicate towards the violation of lepton flavor universality in $b \to c l \bar{\nu}$ decay. The different new physics operators, which can explain the $R_{D^{(*)}}$ measurements, have been identified previously. We show that a simultaneous measurement of the polarization fractions of $\tau$ and $D^*$ and the angular asymmetries $A_{FB}$ and $A_{LT}$ in $B \to D^* \tau \bar{\nu}$ decay can distinguish all the new physics amplitudes and hence uniquely identify the Lorentz structure of new physics.

1 Introduction

In recent years, the evidence for charged lepton universality violation is observed in the charge current process $b \to c \tau \bar{\nu}$. The experiments, BaBar, Belle and LHCb, made several measurements of the ratios

$$R_D = \frac{\Gamma(B \to D \tau \bar{\nu})}{\Gamma(B \to D \{e/\mu\} \bar{\nu})}, \quad R_{D^*} = \frac{\Gamma(B \to D^* \tau \bar{\nu})}{\Gamma(B \to D^* \{e/\mu\} \bar{\nu})}.$$ (1)

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The current world averages of these measurements are about $4\sigma$ away from the Standard Model (SM) predictions \cite{1}. All the meson decays in eq. (1) are driven by quark level transitions $b \to c \ell \nu$. These transitions occur at tree level in the SM. The discrepancy between the measured values of $R_D$ and $R_{D^*}$ and their respective SM predictions is an indication of presence of new physics (NP) in the $b \to c \tau \bar{\nu}$ transition. The possibility of NP in $b \to c \mu \bar{\nu}$ is excluded by other data \cite{2}. All possible NP four-Fermi operators for $b \to c \tau \bar{\nu}$ transition are listed in ref. \cite{3}. In ref \cite{2}, a fit was performed between all the $b \to c \tau \bar{\nu}$ data and each of the NP interaction term. The NP terms, which can account for the all $b \to c \tau \bar{\nu}$ data, are identified and their Wilson coefficients (WCs) are calculated. It was found that there are six allowed NP solutions. Among those six solutions, four solutions are distinct with a different Lorentz structure. In ref. \cite{4} it was found that the tensor NP solution could be distinguished from other possibilities provided $\langle f_L \rangle$, the $D^*$ polarization fraction can be measured with an absolute uncertainty of 0.1.

Here, we consider four angular observables, $P_L(D^*)$ ($\tau$ polarization fraction), $f_L$ ($D^*$ polarization fraction), $A_{FB}$ (the forward-backward asymmetry), $A_{LT}$ (longitudinal-transverse asymmetry) in the decay $B \to D^* \tau \bar{\nu}$. Note that these asymmetries can only be measured if the momentum of the $\tau$ lepton is reconstructed. We show that a measurement of these four quantities can uniquely identify the Lorentz structure of the NP operator responsible for the present discrepancy in $R_D$ and $R_{D^*}$ \cite{5}.

## 2 Distinguishing different new physics solutions

The most general effective Hamiltonian for $b \to c \tau \bar{\nu}$ transition can be written as

$$H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ O_{V_L} + \frac{\sqrt{2}}{4G_F V_{cb}} \right] \sum_i \left( C_i O_i + C_i' O_i' + C_i'' O_i'' \right) \right), \tag{2}$$

where $G_F$ is the Fermi coupling constant, $V_{cb}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element and the NP scale $\Lambda$ is assumed to be 1 TeV. We also assume that neutrino is always left chiral. The effective Hamiltonian for the SM contains only the $O_{V_L}$ operator. The explicit forms of the four-fermion operators $O_i$, $O_i'$ and $O_i''$ are given in ref \cite{3}. The NP effects are encoded in the NP WCs $C_i, C_i'$ and $C_i''$. Each primed and double primed operator can be expressed as a linear combination of unprimed operators through Feirz transformation.

The values of NP WCs which fit the data on the observables $R_D$, $R_{D^*}$, $R_{J/\psi}$, $P_L(D^*)$ and $\mathcal{B}(B_c \to \tau \bar{\nu})$, have been calculated previously \cite{2}. Here $R_{J/\psi}$ is the ratio of $\mathcal{B}(B_c \to J/\psi \tau \bar{\nu})$ to $\mathcal{B}(B_c \to J/\psi \mu \bar{\nu})$ \cite{6}. The results of these fits are listed in table \cite{1} This table also lists, for each of the NP solutions, the predicted values of the polarization fractions and the angular asymmetries in $B \to D^* \tau \bar{\nu}$ decay. Here we compute $A_{FB}(q^2)$ and $A_{LT}(q^2)$ in $B \to D^* \tau \bar{\nu}$ decay, as functions of $q^2 = (p_B - p_{D^*})^2$, where $p_B$ and $p_{D^*}$ are the four momenta of $B$ and $D^*$ respectively. The predictions
### Table 1

| NP WCs | Fit values | $\langle P_2(D^*)\rangle$ | $\langle f_L \rangle$ | $\langle A_{FB} \rangle$ | $\langle A_{LT} \rangle$ |
|--------|------------|---------------------------|------------------|-----------------|------------------|
| SM     | $c_1 = 0$  | $-0.499 \pm 0.004$        | $0.45 \pm 0.04$   | $-0.011 \pm 0.007$ | $-0.245 \pm 0.003$ |
| $C_{V_{1}}$ | $0.149 \pm 0.032$ | $-0.499 \pm 0.004$ | $0.45 \pm 0.04$ | $-0.011 \pm 0.007$ | $-0.245 \pm 0.003$ |
| $C_{T}$     | $0.516 \pm 0.015$ | $-0.115 \pm 0.013$ | $0.14 \pm 0.03$ | $-0.114 \pm 0.009$ | $+0.110 \pm 0.009$ |
| $C_{S_{L}}$  | $-0.526 \pm 0.102$ | $-0.485 \pm 0.003$ | $0.46 \pm 0.04$ | $-0.087 \pm 0.011$ | $-0.211 \pm 0.008$ |
| $(C_{L}, C_{Y})$ | $(-1.286, 1.512)$ | $-0.499 \pm 0.004$ | $0.45 \pm 0.04$ | $-0.371 \pm 0.004$ | $+0.07 \pm 0.004$ |
| $(C_{V_{1}}, C_{V_{2}})$ | $(0.124, -0.058)$ | $-0.484 \pm 0.005$ | $0.45 \pm 0.04$ | $-0.003 \pm 0.007$ | $-0.243 \pm 0.003$ |
| $(C_{Y_{L}}, C_{Y_{R}})$ | $(-0.643, -0.076)$ | $-0.477 \pm 0.003$ | $0.46 \pm 0.04$ | $-0.104 \pm 0.005$ | $-0.202 \pm 0.002$ |

### 3 Results and Discussions

The average values of $P_2(D^*)$ and $f_L$ for all six NP solutions are given in Table 1. Not surprisingly, there is a large difference between the predicted values for $O_T$ solution and those for other NP solutions. If either of these observables is measured with an
absolute uncertainty of 0.1, then the $O_T$ solution is either confirmed or ruled out at 3$\sigma$ level.

We now show that the angular asymmetries $A_{FB}$ and $A_{LT}$ have a good discrimination capability between the three remaining NP WCs. The plots for $A_{FB}$ and $A_{LT}$ as a function of $q^2$ are shown in the bottom row of fig. 1 and their average values are listed in table 1. We see that the plots of both $A_{FB}(q^2)$ and $A_{LT}(q^2)$, for $(O_{VL}, O_{VR})$ solution, differ significantly from the plots of all other NP solutions as do the average values. If either of these asymmetries is measured with an absolute uncertainty of 0.07, then the $(O_{VL}, O_{VR})$ solution is either confirmed or ruled out at 3$\sigma$ level.

So far we have identified observables which can clearly identify the $O_T$ and the $(O_{VL}, O_{VR})$ solutions. As we can see from table 1, one needs to measure $\langle A_{FB} \rangle$ with an absolute uncertainty of 0.03 or better to obtain a 3$\sigma$ distinction between $O_{VL}$ and $O''_{SL}$ solutions. However, this ability to make the distinction can be improved by observing $q^2$ dependence of $A_{FB}$ for these solutions. We note that $A_{FB}(q^2)$ for $O_{VL}$ solution has a zero crossing at $q^2 = 5.6$ GeV$^2$ whereas this crossing point occurs at $q^2 = 7.5$ GeV$^2$ for $O''_{SL}$ solution. A calculation of $\langle A_{FB} \rangle$ in the limited range 6 GeV$^2 < q^2 < q^2_{\text{max}}$ gives the result $+0.1$ for $O_{VL}$ and $+0.01$ for $O''_{SL}$. Hence, determining the sign of $\langle A_{FB} \rangle$, for the full $q^2$ range and for the limited higher $q^2$ range, provides a very useful tool for discrimination between these two solutions.

Hence, we find that a clear distinction can be made between the four different NP solutions to the $R_D/R_{D^*}$ puzzle by means of polarization fractions and angular asymmetries. Note that only the observables ($P_\tau(D^*)$ and $f_L$) isolating $O_T$ do not require the reconstruction of $\tau$ momentum. The reconstruction of $\tau$ momentum is crucial to measure the asymmetries which can distinguish between the other three NP solutions.

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