New Physics solutions for $b \to c\tau\bar{\nu}$ anomalies before & after Moriond'19

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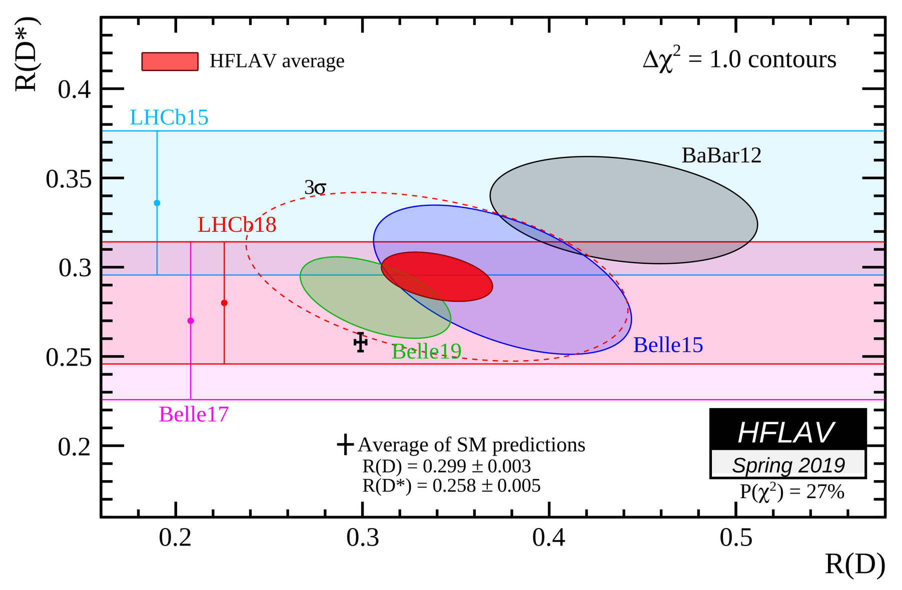
Measurements in $b \to c\tau\bar{\nu}$ sector

Lepton Flavor Universality Violation: The flavor ratios mediated by $b \to c\tau\bar{\nu}$ transitions are

- The ratios $R_{D^{(*)}} = \Gamma(B \to D^{(*)}\tau\bar{\nu})/\Gamma(B \to D^{(*)}\,l\bar{\nu})$, $(l = e,\,\mu)$ measured by BaBar, Belle and LHCb experiments [1] indicate evidence of lepton flavor non universality. These results disagree with the Standard Model (SM) prediction at 4.1σ level.
- In 2017, LHCb measured $R_{J/\psi} = \Gamma(B_c \to J/\psi\tau\bar{\nu})/\Gamma(B_c \to J/\psi\mu\bar{\nu})$ and found it to differ from the SM prediction by about $\sim 1.7\sigma$ [2].
- Belle presented updated results on R_D-R_{D^*} at Moriond 2019. Here, for the first time, they reconstructed the τ lepton. These results are consistent with the SM [3]. Combined with earlier results, the discrepancy with the SM reduces to 3.1σ which is still significant.



Angular observables: The following two angular observables are measured in $B \to D^*\tau\bar{\nu}$ decay:

- Belle collaboration has measured the τ polarization fraction $P_\tau(D^*) = \left(\Gamma_{\lambda_\tau=+1/2} - \Gamma_{\lambda_\tau=-1/2}\right) / \left(\Gamma_{\lambda_\tau=+1/2} + \Gamma_{\lambda_\tau=-1/2}\right)$ with a very large statistical error. This measurement is consistent with its SM prediction [4].
- Recently Belle has also measured the longitudinal D^* polarization fraction $f_L(D^*) = \Gamma_{\lambda_{D^*}=0} / \left(\Gamma_{\lambda_{D^*}=0} + \Gamma_{\lambda_{D^*}=1} + \Gamma_{\lambda_{D^*}=-1}\right)$. The measured value is $\sim 1.6\sigma$ higher than the SM prediction [5].

New Physics operators

The effective Hamiltonian for $b \to c\,\tau\,\bar{\nu}$ (assuming neutrinos are left-handed) at a scale $\Lambda = 1$ TeV is given by [6]

$$H_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[\mathcal{O}_{V_L} + \frac{\sqrt{2}}{4G_F V_{cb}\Lambda^2} \sum_i \left(C_i \mathcal{O}_i + C_i^{(\prime,\prime\prime)} \mathcal{O}_i^{(\prime,\prime\prime)}\right)\right]$$

	Operator	Fierz Transform
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$	
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$	
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$	
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$	
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L \nu)$	
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\mathcal{O}_{V_L}$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$-2\mathcal{O}_{S_R}$
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$	$-\frac{1}{2}\mathcal{O}_{V_R}$
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$	$-\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L b)\,(\bar{c}\sigma_{\mu\nu}P_L \nu)$	$-6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$-\mathcal{O}_{V_R}$
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$-2\mathcal{O}_{S_R}$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$	$\frac{1}{2}\mathcal{O}_{V_L}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$	$-\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu}P_L \nu)$	$-6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$

Methodology

We perform a χ^2 fit to the five observables R_D, R_{D^*}, $R_{J/\psi}$, $P_\tau(D^*)$ and $f_L(D^*)$. The fit is done by using the CERN minimization code MINUIT. The χ^2 is defined as

$$\chi^2(C_i) = \sum \left(O^{th}(C_i) - O^{exp}\right)^T \mathcal{C}^{-1} \left(O^{th}(C_i) - O^{exp}\right),$$

where $\mathcal{C}$ is the covariance matrix.

We perform three types of fits:

- Fit-A taking only one NP operator at a time.
- Fit-B taking two similar NP operators at a time.
- Fit-C taking two dissimilar NP operators at a time.

For each of the above fits, we allow only those NP solutions for which $\chi^2_{min} \lesssim 5$ as well as $\mathcal{B}(B_c \to \tau\bar{\nu}) < 0.1$ [7].

Fit results before Moriond'19

In this global fit [8], we take all the data which were available before the recent R_D-R_{D^*} results announced by Belle at Moriond'19.

NP type	Best fit value(s)	χ^2_{min}
SM	$C_i = 0$	24.70
C_{V_L}	0.15 ± 0.03	5.1
C''_{S_L}	-0.52 ± 0.10	5.2
(C_{V_L}, C_{V_R})	$(0.17, 0.05)$	4.5
(C'_{V_L}, C'_{V_R})	$(0.12, -0.06)$	4.2
(C''_{S_L}, C''_{S_R})	$(-0.26, 0.16)$	5.0
(C_{V_L}, C_{S_L})	$(0.14, 0.09)$	4.5
(C'_{V_L}, C'_{S_L})	$(0.17, -0.12)$	4.5
(C_{V_R}, C_{S_L})	$(-0.17, 0.42)$	4.6

NOTE: The tensor solution [9, 10] which was allowed before the measurement of D^* polarization fraction, is now **ruled out** at the level of 5σ [8].

Fit results after Moriond'19

After Moriond'19, the world averages of R_D-R^*_D are closer to SM. The NP solutions allowed by the present data are

NP type	Best fit value(s)	χ^2_{min}
SM	$C_i = 0$	21.80
C_{V_L}	0.10 ± 0.02	4.5
C''_{S_L}	-0.34 ± 0.08	5.7
(C''_{S_L}, C''_{S_R})	$(0.27, 0.35)$	4.3
(C_{V_R}, C_{S_L})	$(-0.14, 0.25)$	4.5
(C_{V_R}, C_{S_R})	$(-0.11, 0.22)$	3.9

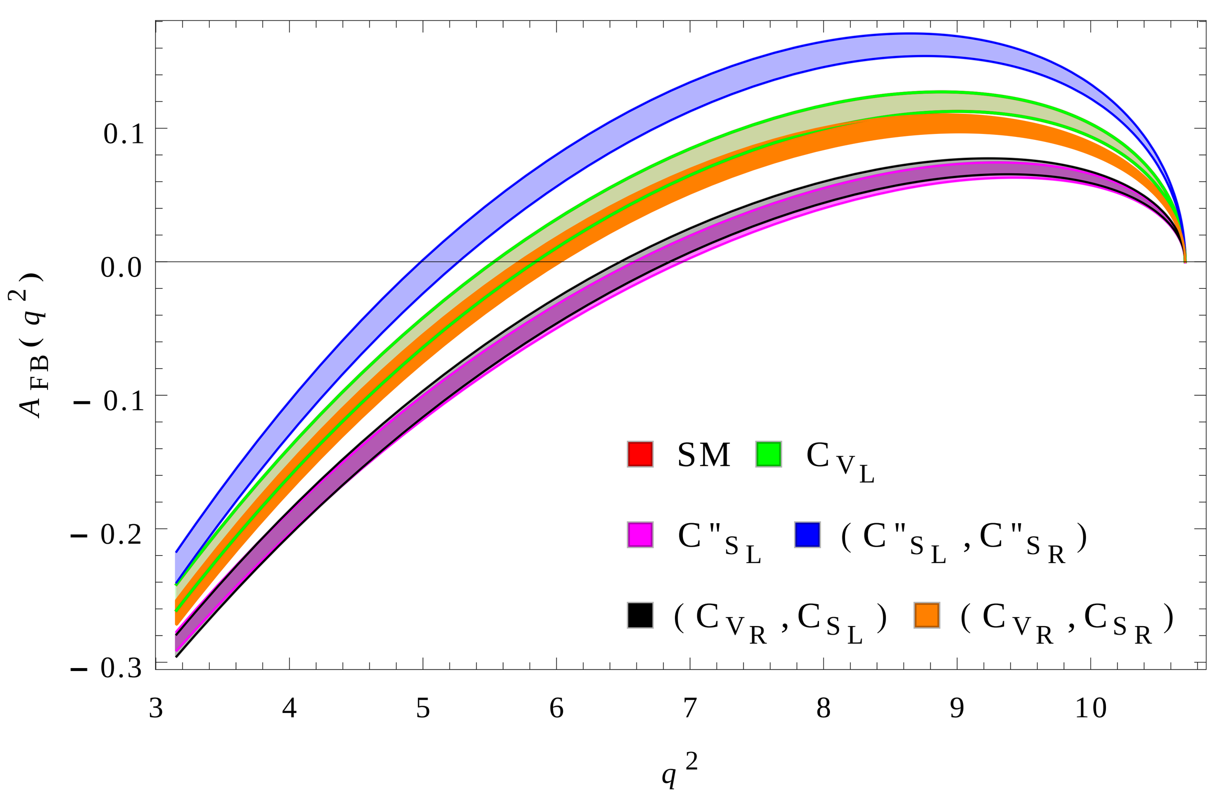
NOTE: 1. The 3rd, 4th, 6th and 7th solutions, in previous table, are still viable. However, the values of C_{V_R}, C'_{V_R}, C_{S_L} and C'_{S_L} in these solutions are close to zero. Also $\mathcal{O}'_{V_L} = \mathcal{O}_{V_L}$. Hence these four solutions are now essentially equivalent to C_{V_L}.
2. We get an additional solution (C_{V_R}, C_{S_R}). Though it "just violates" $\mathcal{B}(B_c \to \tau\bar{\nu})$, we have included it.
3. We got a small tensor $(C_T = -0.06)$ solution with a $\chi^2_{min} = 8.0$ which is disfavored in view of goodness of fit.

Methods to discriminate the NP operators

Angular observables are the standard and powerful tools to discriminate between the NP operators [11].

NP type	$P_\tau(D^*)$	$f_L(D^*)$	$A_{FB}(D^*)$	$q^2[A_{FB}(q^2) = 0]$ GeV^2	$\mathcal{B}(B_c \to \tau\bar{\nu})$
SM	-0.499 ± 0.004	0.45 ± 0.04	-0.011 ± 0.007	5.7	2.15×10^{-2}
C_{V_L}	-0.499 ± 0.004	0.46 ± 0.04	-0.011 ± 0.007	5.7	2.50×10^{-2}
C''_{S_L}	-0.493 ± 0.003	0.44 ± 0.05	-0.062 ± 0.010	6.8	1.14×10^{-6}
(C''_{S_L}, C''_{S_R})	-0.494 ± 0.005	0.47 ± 0.04	0.027 ± 0.008	5.0	7.93×10^{-2}
(C_{V_R}, C_{S_L})	-0.526 ± 0.004	0.45 ± 0.04	-0.061 ± 0.006	6.7	2.23×10^{-3}
(C_{V_R}, C_{S_R})	-0.468 ± 0.005	0.47 ± 0.04	-0.023 ± 0.006	5.8	0.12

NOTE: Neither the τ nor the D^* polarization fraction has any capability to distinguish between the allowed solutions listed above. The zero crossing point of the forward-backward asymmetry $A_{FB}(q^2)$ and the branching ratio $\mathcal{B}(B_c \to \tau\bar{\nu})$ together can uniquely identify each NP operator.



- The A_{FB} is defined as $A_{FB}(q^2) = \frac{1}{d\Gamma/dq^2}\left[\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_\tau} d\cos\theta_\tau - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_\tau} d\cos\theta_\tau\right]$.
- The bands of $A_{FB}(q^2)$ for the SM and $\mathcal{O}_{V_L}$ solution are exactly overlaped with each other.
- The zero crossing points of $A_{FB}(q^2)$ are:
  1. ~ 5 GeV^2 for (C''_{S_L}, C''_{S_R}) solution,
  2. ~ 5.8 GeV^2 for C_{V_L} and (C_{V_R}, C_{S_R}) solutions,
  3. ~ 6.8 GeV^2 for C''_{S_L} and (C_{V_R}, C_{S_L}) solutions.
- $\mathcal{B}(B_c \to \tau\bar{\nu}) \sim 2\%$ for C_{V_L} solution whereas it is $> 10\%$ for (C_{V_R}, C_{S_R}) solution.
- It is more difficult to distinguish between C''_{S_L} and (C_{V_R}, C_{S_L}) solutions. It requires the measurement of $\mathcal{B}(B_c \to \tau\bar{\nu})$ at the level of 10^{-3}.

Summary

- Present data in $b \to c\tau\bar{\nu}$ sector implies that five distinct NP solutions with different Lorentz structures are allowed.
- As the tension in R_D-R_{D^*} has been come down to 3.1σ, the coefficient of $\mathcal{O}_{V_L}$ solution is now reduced by $\sim 33\%$.
- The operator $\mathcal{O}_{V_L}$ has the same Lorentz structure as the SM. Therefore, its predictions for all the angular observables are the same as those of the SM.
- The zero crossing point of $A_{FB}(q^2)$ and $\mathcal{B}(B_c \to \tau\bar{\nu})$ are powerful tools to distinguish between the five solutions.
- To measure A_{FB}, the reconstruction of τ momentum is necessary. This is difficult but this challenge should be taken up.
- Also $B_c \to \tau\bar{\nu}$ is quite sensitive to NP. In present and future experiments, it should be tested with a good accuracy.

References

[1] Heavy Flavor Averaging Group, https://hflav.web.cern.ch.
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **120** (2018) no.12, 121801
[3] A. Abdesselam *et al.* [Belle Collaboration], arXiv:1904.08794
[4] S. Hirose *et al.* [Belle Collaboration], Phys. Rev. Lett. **118** (2017) no.21, 211801
[5] K. Adamczyk [Belle and Belle-II Collaborations], arXiv:1901.06380 [hep-ex].
[6] M. Freytsis, Z. Ligeti and J. T. Ruderman, Phys. Rev. D **92** (2015) no.5, 054018
[7] A. G. Akeroyd and C. H. Chen, Phys. Rev. D **96** (2017) no.7, 075011
[8] A. K. Alok, D. Kumar, S. Kumbhakar and S. Uma Sankar, arXiv:1903.10486 [hep-ph].
[9] A. K. Alok, D. Kumar, S. Kumbhakar and S. Uma Sankar, Phys. Rev. D **95** (2017) no.11, 115038
[10] A. K. Alok, D. Kumar, J. Kumar, S. Kumbhakar and S. Uma Sankar, JHEP **1809** (2018) 152
[11] A. K. Alok, D. Kumar, S. Kumbhakar and S. Uma Sankar, Phys. Lett. B **784** (2018) 16