Impact of D^* polarization measurement on solutions to R_D-R_{D^*} anomalies

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Updated Analysis of: JHEP 1809 (2018) 152 & Phys.Lett. B784 (2018) 16-20

Interpreting the LHC Run 2 Data and Beyond
ICTP Trieste

Outline

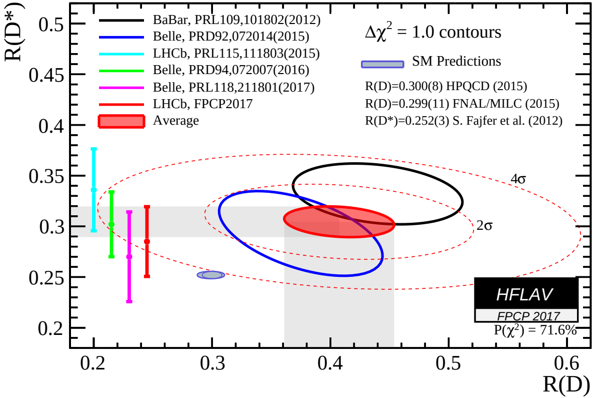
- Anomalies in $b \to c\tau\bar{\nu}$
- Global fit results
  1. Pre-Moriond'19 and Pre-D^* polarization measurement
  2. Post-Moriond'19 and Post-D^* polarization measurement
- Observables to distinguish new physics amplitudes
- Summary

$R_D - R_{D^*}$ Puzzle (**Pre-Moriond'19**)

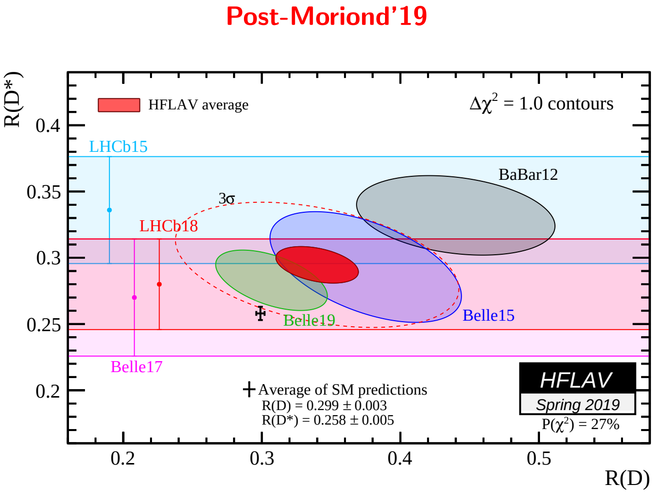
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\,\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\,l\,\bar{\nu})}, \quad (l = e,\, \mu)$$

$\Longrightarrow$ Discrepancy was at the level of $\sim 4\sigma$.

$\Longrightarrow$ Indication of Letpon Flavor Universaity (LFU) violation



$R_D - R_{D^*}$ World average 2019[1]



[1] https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

$R_{J/\psi}$ and $P_\tau(D^*)$ enter in 2017

In Sept. 2017 LHCb measured [LHCb PRL 120 (2018) no.12, 121801:

$$R_{J/\psi} = \frac{\mathcal{B}(B_c^- \to J/\psi\,\tau^-\,\bar{\nu})}{\mathcal{B}(B_c^- \to J/\psi\,\mu^-\,\bar{\nu})} = 0.71 \pm 0.17 \pm 0.18$$

$\Longrightarrow$ 1.7σ larger than the SM prediction of $R_{J/\psi}^{SM} = 0.29$.

Also a measurement of τ polarization in $B \to D^*\tau\bar{\nu}$ decay by Belle in 2016 [Belle PRL 118, no. 21, 211801 (2017)]

$$P_\tau(D^*) = \frac{\Gamma_{\lambda_\tau=1/2} - \Gamma_{\lambda_\tau=-1/2}}{\Gamma_{\lambda_\tau=1/2} + \Gamma_{\lambda_\tau=-1/2}} = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

Though it has large errors, it is consistant with SM prediction -0.497 ± 0.013.

$f_L(D^*)$ by Belle in 2019

The D^* longitudinal polarization fraction is measured by Belle [arXiv:1903.03102]

$$f_L(D^*) = \frac{\Gamma_{\lambda_{D^*}=0}}{\Gamma_{\lambda_{D^*}=0} + \Gamma_{\lambda_{D^*}=1} + \Gamma_{\lambda_{D^*}=-1}} = 0.60 \pm 0.08 \pm 0.04$$

$\Longrightarrow$ 1.7σ larger than the SM prediction of $f_L(D^*) = 0.45 \pm 0.04$. [Alok, Dinesh, SK, UmaSankar; PRD 95 (2017) no.11, 115038]

$\Longrightarrow$ All measurements indicate the mechanism of $b \to c\tau\bar{\nu}$ is not identical to that of $b \to c\{e/\mu\}\bar{\nu}$.
$\Longrightarrow$ New physics in $b \to c\{e/\mu\}\bar{\nu}$ transition is highly disfavoured by other measurements $R_D^{\mu/e}$ and $R_{D^*}^{e/\mu}$. [Alok, Dinesh, SK, UmaSankar; JHEP 1809 (2018) 152]
$\Longrightarrow$ Take new physics in $b \to c\tau\bar{\nu}$ transition !!

New Physics operators for $b \to c\tau\bar{\nu}$

The most general effective Hamiltonian for $b \to c\tau\bar{\nu}$ transition at $\Lambda = 1$ TeV scale [Freytsis, Ligeti, Ruderman PRD92 (2015) no.5, 054018]

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

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

Fitting the data

- Take all data in $b \to c\tau\bar{\nu}$ sector: (a)R_D, (b) R_{D^*}, (c) $R_{J/\psi}$, (d) P_τ and (e) $f_L(D^*)$.
- Define χ^2 as a function of the NP WCs:

$$\chi^2(C_i) = \sum_{m,n=R_D,R_{D^*}} \left(O^{th}(C_i) - O^{exp}\right)_m \left(V^{exp} + V^{SM}\right)^{-1}_{mn} \left(O^{th}(C_i) - O^{exp}\right)_n + \sum_{R_{J/\psi},P_\tau,f_L(D^*)} \frac{\left(O^{th}(C_i) - O^{exp}\right)^2}{\sigma_O^2}.$$

- Use MINUIT library to minimize the χ^2 function and get the values of NP WCs. We choose one operator or two (dis-)similar operators at a time to get the strongest possible constarint.
- χ^2_{min} falls into two disjoint ranges $\lesssim 5$ and $\gtrsim 7.5$, whereas the $\chi^2_{SM} = 21.80$ (After Moriond'19).
- We choose the NP WCs as best fit solutions which fall in the range $\chi^2_{min} \lesssim 5$.

Constraint from $B_c \to \tau\bar{\nu}$

- Strong constraint from purely leptonic decay $B_c \to \tau\bar{\nu}$, especially on the scalar/pseudoscalar NP.
- The most general expression for the branching fraction of $B_c \to \tau\bar{\nu}$ is

$$
\begin{aligned}
Br(B_c \to \tau\bar{\nu}) \;&=\; \frac{|V_{cb}|^2 G_F^2 f_{B_c}^2 m_{B_c} m_\tau^2 \tau_{B_c}^{exp}}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \\
&\quad \times \left|1 + C_{V_L} - C_{V_R} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}(C_{S_R} - C_{S_L})\right|^2
\end{aligned}
$$

- The SM prediction is 2.15×10^{-2}. Particularly, LEP data imposes a constraint $Br(B_c \to \tau\bar{\nu}) < 0.1$. [Akeroyd and Chen, PRD 96, no. 7, 075011 (2017)]
- Keep only those NP WCs which predict $Br(B_c \to \tau\bar{\nu}) < 0.1$ and disard all others.

New Physics Solutions

- Pre-Moriond'19 & D^* polarization: [Alok, Dinesh, Jacky, SK, UmaSankar; JHEP 1809 (2018) 152]

Coefficient(s)	Best fit value(s)
C_{V_L}	0.149 ± 0.032
C_T	0.516 ± 0.015
C''_{S_L}	-0.526 ± 0.102
(C_{V_L}, C_{V_R})	$(-1.286, 1.512)$

- Post-Moriond'19 & D^* polarization: [Alok, Dinesh, SK, UmaSankar; arXiv:1903.10486]

NP type	Best fit value(s)
C_{V_L}	0.104 ± 0.024
C''_{S_L}	-0.338 ± 0.077
(C''_{S_L}, C''_{S_R})	$(0.265, 0.345)$
(C_{V_R}, C_{S_L})	$(-0.139, 0.249)$
(C_{V_R}, C_{S_R})	$(-0.108, 0.222)$

- Additional global fit analyses after Moriond'19: 1904.09311, 1904.10432, 1905.08498, 1905.08253 etc.

How to distinguish these solutions ?

Angular observables in $B \to D^*\tau\bar{\nu}$

We consider four angular observables: (a) τ polarization P_τ, (b) D^* polarization fraction f_L, (c) forward-backward asymmetry A_{FB} and (d) longitudinal-transverse asymmetry A_{LT}.[Sakaki, Tanaka, Watanabe; PRD 2013]

$$
\begin{aligned}
P_\tau &= \frac{\Gamma_{\lambda_\tau=1/2} - \Gamma_{\lambda_\tau=-1/2}}{\Gamma_{\lambda_\tau=1/2} + \Gamma/_{\lambda_\tau=-1/2}}, \\
f_L &= \frac{\Gamma_{\lambda_{D^*}=0}}{\Gamma_{\lambda_{D^*}=0} + \Gamma_{\lambda_{D^*}=-1} + \Gamma_{\lambda_{D^*}=+1}}, \\
A_{FB} &= \frac{1}{\Gamma}\left[\int_0^1 - \int_{-1}^0\right] \frac{d^2\Gamma}{dq^2 d\cos\theta_\tau} d\cos\theta_\tau, \\
A_{LT} &= \frac{\int_{-\pi/2}^{\pi/2} d\phi \left(\int_0^1 - \int_{-1}^0\right) \frac{d^3\Gamma\, d\cos\theta_D}{dq^2 d\phi\, d\cos\theta_D}}{\int_{-\pi/2}^{\pi/2} d\phi \left(\int_0^1 + \int_{-1}^0\right) \frac{d^3\Gamma\, d\cos\theta_D}{dq^2 d\phi\, d\cos\theta_D}}.
\end{aligned}
$$

Predictions to distinguish NP WCs

Pre-Moriond and Pre-D^* polarization status

[Alok, Dinesh, SK, UmaSankar; PLB 784 (2018) 16-20]

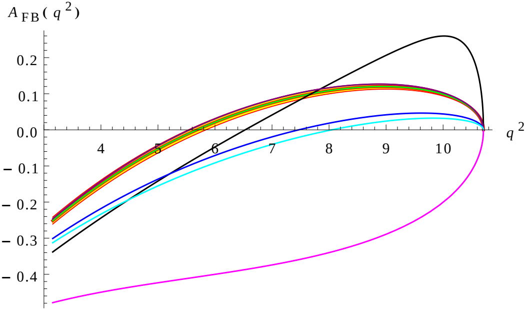
NP type	$\langle P_\tau \rangle$	$\langle f_L \rangle$	$\langle A_{FB} \rangle$	$\langle A_{LT} \rangle$
SM	-0.499 ± 0.004	0.45 ± 0.04	-0.011 ± 0.007	-0.245 ± 0.003
C_{V_L}	-0.499 ± 0.004	0.45 ± 0.04	-0.011 ± 0.007	-0.245 ± 0.003
C_T	$+0.115 \pm 0.013$	0.14 ± 0.03	-0.114 ± 0.009	$+0.110 \pm 0.009$
C''_{S_L}	-0.485 ± 0.003	0.46 ± 0.04	-0.087 ± 0.011	-0.211 ± 0.008
(C_{V_L}, C_{V_R})	-0.499 ± 0.004	0.45 ± 0.04	-0.371 ± 0.004	$+0.007 \pm 0.004$

- If P_τ or f_L can be measured with an absolute uncertainty of 0.1, then C_T is either confirmed or ruled out at 3σ level. [Alok, Dinesh, SK, UmaSankar; PRD 95 (2017) no.11, 115038]
- If A_{FB} or A_{LT} can be measured with an absolute uncertainty of 0.07, then (O_{V_L}, O_{V_R}) is either confirmed or ruled out at 3σ level.

Distinguishing power of A_{FB}

Pre-Moriond and Pre-D^* polarization status

[Alok, Dinesh, SK, UmaSankar; PLB 784 (2018) 16-20]



$\Longrightarrow$ $A_{FB}(q^2)$ for O_{V_L} solution (green curve)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''_{S_L} solution (blue curve).

$\Longrightarrow$ $\langle A_{FB} \rangle$ in the limited range 6 GeV$^2 < q^2 < q^2_{max}$ gives the result $+0.1$ for O_{V_L} and $+0.01$ for O''_{S_L}. 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 O_{V_L} and O''_{S_L} solutions.

Predictions of angular observables

Post-Moriond & Post-D^* polarization status

[Alok, Dinesh, SK, UmaSankar; arXiv:1903.10486]

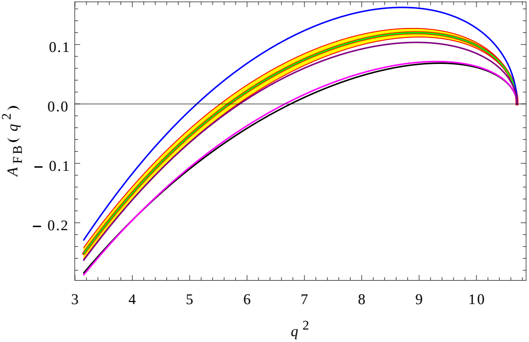
NP type	$\langle P_\tau \rangle$	$\langle f_L \rangle$	$\langle A_{FB} \rangle$	$\langle A_{LT} \rangle$	$\mathcal{B}(B_c \to \tau\bar{\nu})$
C_{V_L}	-0.499 ± 0.004	0.46 ± 0.04	-0.011 ± 0.007	-0.246 ± 0.003	2.50×10^{-2}
C''_{S_L}	-0.493 ± 0.003	0.44 ± 0.05	-0.062 ± 0.010	-0.223 ± 0.002	1.14×10^{-6}
(C''_{S_L}, C''_{S_R})	-0.494 ± 0.005	0.47 ± 0.04	0.027 ± 0.008	-0.260 ± 0.003	7.93×10^{-2}
(C_{V_R}, C_{S_L})	-0.526 ± 0.004	0.45 ± 0.04	-0.061 ± 0.006	-0.233 ± 0.002	2.23×10^{-3}
(C_{V_R}, C_{S_R})	-0.468 ± 0.005	0.47 ± 0.04	-0.023 ± 0.006	-0.225 ± 0.003	0.12

- Only (C''_{S_L}, C''_{S_R}) solution can be distinguished as $\langle A_{FB} \rangle$ is postive for the whole q^2 range.
- $\langle A_{FB} \rangle$ can not distinguish between C''_{S_L} and (C_{V_R}, C_{S_L}). Only possiblity is $\mathcal{B}(B_c \to \tau\bar{\nu})$. For C''_{S_L}, it is $\sim 10^{-6}$ and that for (C_{V_R}, C_{S_L}) is $\sim 10^{-3}$.
- (C_{V_R}, C_{S_R}) solution can be distinguished only by means of $\mathcal{B}(B_c \to \tau\bar{\nu}) \sim 10\%$

Capability of A_{FB}

Post-Moriond and Post-D^* polarization status

[Alok, Dinesh, SK, UmaSankar; arXiv:1903.10486]



- (C''_{S_L}, C''_{S_R}) solution (blue curve) has a zero crossing at 5 GeV^2.
- No other solutions can be distinguished by the q^2 dependence of A_{FB}.

Summary

- Pre-Moriond and Pre-D^* polarization: 4 NP solutions, each with different Lorentz structure.
- Post-Moriond and Post-D^* polarization: 5 NP solutions, The tensor solution is now ruled out at the level of 5σ by D^* polarization measurement.
- Discrimanting 5 solutions: Although A_{FB} and $\mathcal{B}(B_c \to \tau\bar{\nu})$ are useful to discriminate, but measuring these are challenging.
- Need to find other observables to distinguish all solutions uniquely.

Thank You !!

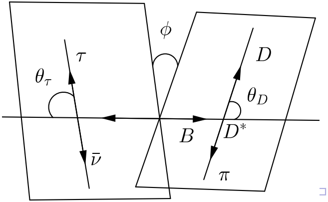
Backup Slides

$B \to D^* \tau \bar{\nu}$

We can describe the decay by defining 3 angles θ_τ, θ_D and ϕ in the D^* rest frame which are shown in figure

- θ_D the angle between B and D where D meson comes from D^* decay.
- θ_τ the angle between τ and B.
- ϕ the angle between D^* decay plane and plane defined by lepton momenta.

Out of these 3 angle it is possible to measure θ_D from the same data used by BaBar and Belle to determine R_{D^*}. Other 2 angles have not been measured because so far τ lepton has not been measured in any of the experiments which measure R_D/R_{D^*}.



4-Fold Distribution for $B \to D^* \tau \bar{\nu}$

The four-fold distribution for the decay can be obtained using helicity formalism i.e.

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\tau d\cos\theta_D d\phi} = N_F \times \Big[\cos^2\theta_D (I_1^0 + I_2^0 \cos 2\theta_\tau + I_3^0 \cos\theta_\tau) + \sin^2\theta_D (I_1^T + I_2^T \cos 2\theta_\tau + I_3^T \cos\theta_\tau + I_4^T \sin^2\theta_\tau \cos 2\phi + I_5^T \sin^2\theta_\tau \sin 2\phi) + \sin 2\theta_D (I_1^{0T} \sin 2\theta_\tau \cos\phi + I_2^{0T} \sin 2\theta_\tau \sin\phi + I_3^{0T} \sin\theta_\tau \sin\phi) \Big]$$

where the normalization factor $N_F = \frac{3 G_F^2 |p_{D^*}| |V_{cb}|^2 \beta_\tau}{2^{11} \pi^3 m_B^2} Br(D^* \to D\pi)$ Here $\beta_\mu = \left(1 - \frac{m_\tau^2}{q^2}\right)^2$ and $|p_{D^*}|$ is the D^* momentum in the B-meson rest frame, $|p_{D^*}| = \lambda^{1/2}\left(m_B^2, m_{D^*}^2, q^2\right)/2m_B$ with $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$. The twelve angular coefficients I's depend on couplings, kinematics variables and form factors.