Lepton Flavor Universality Anomalies in $B \to D^{(*)}$ Decay, Updated From Factor, and Leptoquark Explanations

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Warning:

- This is my first paper about B-physics, so I am not familiar with some details in my following talk;
- We failed to finish the paper before this conference, thus some results are preliminary, but they will not be modified a lot;
- My collaborators suggested not to talk about much details.

I. INTRODUCTION

- In SM, charged current processes $b \to c l^i (e, \mu, \tau)\nu$ are mediated by W-boson;

- $\mathcal{L} \supset \frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_i \bar{\nu}_L^i \gamma^\mu l_L^i + V_{cb} \bar{c}_L \gamma^\mu b_L\right) + \text{H.c.}$: independent on lepton flavor;

- Define the ratios $R_D \equiv \frac{\text{Br}(B\to D\tau\nu)}{\text{Br}(B\to D\ell\nu)}$, $R_{D^*} \equiv \frac{\text{Br}(B\to D^*\tau\nu)}{\text{Br}(B\to D^*\ell\nu)}$ with $\ell = e, \mu$, previous theoretical calculations showed $R_D \simeq (0.279 - 0.305)$ and $R_{D^*} \simeq (0.247 - 0.260)$: [S. Fajfer *et al.*, PRD85 (2012), 094025; M. Tanaka and R. Watanabe, PRD87 (2013), 034028; D. Bigi and P. Gambino, PRD94 (2016), 094008; S. Jaiswal *et al.*, JHEP12 (2017), 060; Z.-R. Huang *et al.*, PRD98 (2018), 095018; C. Murgui *et al.*, JHEP09 (2019), 103; etc.]

- Testing such observables is a possible way to test NP: if people discovered evidence away from the SM prediction, it means lepton flavor universality is broken.

Testings on R_{D,D^*} were performed since 2012:

Year	Group	R_D	R_{D^*}	Tagging	τ Decay	Reference
2012	BaBar	0.440(58)(42)	0.332(24)(18)	Hadronic	$\ell\nu\nu$	PRL109, 101802
2015	Belle	0.375(64)(26)	0.293(38)(15)	Hadronic	$\ell\nu\nu$	PRD92, 072014
2015	LHCb	-	0.336(27)(30)	-	$\ell\nu\nu$	PRL115, 111803
2016	Belle	-	0.302(30)(11)	Semi-leptonic	$\ell\nu\nu$	PRD94, 072007
2017	Belle	-	0.270(35)(27)	Hadronic	$(\pi,\rho)\nu$	PRL118, 211801
2018	LHCb	-	0.291(19)(29)	-	$3\pi+\nu$	PRL120, 171802
2019	Belle	0.307(37)(16)	0.283(18)(14)	Semi-leptonic	$\ell\nu\nu$	Belle-2019-18

Averaged: $R_D = 0.346(31)$, $(1-2)\sigma$ pull; $R_{D^*} = 0.300(12)$, $(3-4)\sigma$ pull.

Other observables:

- $R_{J/\psi} \equiv \frac{\mathrm{Br}(B_c \to J/\psi\tau\nu)}{\mathrm{Br}(B_c \to J/\psi\ell\nu)}$, $R^{\mathrm{exp}}_{J/\psi} = 0.71(17)(18)$ and $R^{\mathrm{SM}}_{J/\psi} \simeq (0.23 - 0.29)$: about 2σ pull. [LHCb Collaboration, PRL120 (2018), 121801; etc.]

- τ-polarization: $P_\tau \equiv \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$, where $\Gamma^\pm$ means the decay rate with τ having its helicity $\pm\frac{1}{2}$, $P_\tau = -0.38(51)\binom{21}{16}$. [Belle Collaboration, PRL118, 211801.]

- D^*-polarization: $F_L^{D^*} \equiv \frac{\Gamma_{D_L^*}}{\Gamma_{D_L^*} + \Gamma_{D_T^*}}$ is the ratio of longitudinal polarized D^* mode, $F_L^{D^*} = 0.60(8)(4)$, $(1.5 - 1.8)\sigma$ pull. [Belle Collaboration, BELLE-CONF-1805.]

- $\mathrm{Br}(B_c \to \tau\nu)$ has not been observed yet, currently the best estimation of its upper limit is about $\mathrm{Br}(B_c \to \tau\nu) \lesssim 10\%$ [A. G. Akeroyd and C.-H. Chen, PRD96 (2017), 075011], we also updated its estimation in this work.

- It is worthy to make better predictions on R_{D,D^*} together with other observables.

II. EFT FORMALISM SET-UP

Effective Lagrangian:

$$\mathcal{L} \supset -\frac{4G_F V_{cb}}{\sqrt{2}} \left[(1+C_{V_1})\mathcal{O}_{V_1} + C_{V_2}\mathcal{O}_{V_2} + C_{S_1}\mathcal{O}_{S_1} + C_{S_2}\mathcal{O}_{S_2} + C_T\mathcal{O}_T\right] + \text{H.c.}$$

- Operators: $\mathcal{O}_{V_1} \equiv (\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$, $\mathcal{O}_{V_2} \equiv (\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_L)$, $\mathcal{O}_{S_1} \equiv (\bar{c}_L b_R)(\bar{\tau}_R\nu_L)$, $\mathcal{O}_{S_2} \equiv (\bar{c}_R b_L)(\bar{\tau}_R\nu_L)$, $\mathcal{O}_T \equiv (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)$.

- We assume no NP appear in $bc\ell(e,\mu)\nu$ vertices, thus we only consider NP with τ;

- SM limit: if all coefficients $C_i \to 0$.

- If NP scale is Λ, $C_{V_1,S_1,S_2,T} \sim \mathcal{O}(v^2/\Lambda^2)$, $C_{V_2} \sim \mathcal{O}(v^4/\Lambda^4)$, reason: $\mathcal{O}_2$ cannot be a SM singlet and it can be generated at least from dim-8 EFT, while all the other four operators can be generated from dim-6 EFT.

III. UPDATED FORM FACTOR AND PREDICTIONS

Brief introduction to the method:

- Global fit using the data points from:

  ○ Lattice calculation at large q^2 (or small hadronic recoil) region [MILC collaboration, PRD92 (2015), 034506; HPQCD collaboration, PRD97 (2018) 054502; etc.]

  ○ Light-cone sum rule (LCSR) calculation at small q^2 (or large hadronic recoil) region [S. Faller *et al.*, EPJC60 (2009), 603; Y.-M. Wang *et al.*, JHEP06 (2017), 062; N. Gubernari *et al.*, JHEP01 (2019), 150.]

Predictions and Pulls:

	R_D	R_{D^*}	$P_\tau^{D^*}$	$F_L^{D^*}$
SM Prediction	0.312(7)	0.259(4)	−0.487(4)	0.483(6)
Pull	$+1.1\sigma$	$+3.2\sigma$	$< 1\sigma$	$+1.3\sigma$

IV. MODEL INDEPENDENT ANALYSIS

Before the analysis, we first turn to $B_c \to \tau\nu$ decay:

- Also $bc\tau\nu$ contact vertex: also receive the contributions from NP operators;
- Branching ratio dependence on the Wilson coefficients C_i:

$$\begin{aligned} \mathrm{Br}(B_c \to \tau\nu) &= \frac{\tau_{B_c} m_{B_c} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right) f_{B_c}^2 G_F^2 |V_{cb}|^2 \\ &\quad \times \left| 1 + C_{V_1} - C_{V_2} + \frac{m_{B_c}^2}{(m_b + m_c) m_\tau} (C_{S_1} - C_{S_2}) \right|^2 . \end{aligned}$$

- SM value: $\mathrm{Br}_{\mathrm{SM}}(B_c \to \tau\nu) \approx 2.4\%$;
- Independent on tensor operator, but very sensitive to scalar operators.

A. Re-estimation on the upper limit of Br$(B_c \to \tau\nu)$

- Currently the best estimation is Br$(B_c \to \tau\nu) \lesssim 10\%$ based on LEP data [A. G. Akeroyd and C.-H. Chen, PRD96 (2017), 075011].

- LEP data: $\mathrm{Br}_{\mathrm{eff}} \equiv \mathrm{Br}(B_u \to \tau\nu) + \frac{f_c}{f_u}\mathrm{Br}(B_c \to \tau\nu) < 5.7 \times 10^{-4}$ @ 90% C.L. [L3 Collaboration, PLB396 (1997), 327.]

- $f_q \equiv \sigma(B_q)/\sigma(b)$ which is the hadronization ratio of b-quark exclusively to B_q meson and $f_c \ll f_u = f_d$, $\mathrm{Br}(B_c \to \tau\nu) = \frac{f_u}{f_c}\left(\mathrm{Br}_{\mathrm{eff}} - \mathrm{Br}(B_u \to \tau\nu)\right)$.

- The key observable is f_c/f_u, which was recently measured by LHCb collaboration as [LHCb collaboration, LHCb-PAPER-2019-033]

$$\frac{f_c}{f_u + f_d}\mathrm{Br}(B_c \to J/\psi\mu\nu) = \begin{cases} 7.07 \pm 0.28, & (\sqrt{s} = 7\ \mathrm{TeV}); \\ 7.36 \pm 0.31, & (\sqrt{s} = 13\ \mathrm{TeV}). \end{cases}$$

- They are consistent with each other within 1σ which means the number depends weakly on the scale, thus it can be applied to Z-pole scale;

- Assuming no NP in $bc\ell(e,\mu)\nu$ vertices as above, thus $\mathrm{Br}(B_c \to J/\psi\mu\nu)$ should be its SM prediction $(1.95 \pm 0.46)\%$, see [LHCb collaboration, LHCb-PAPER-2019-033; and a lot of its references.]

- $\mathrm{Br}(B_u \to \tau\nu) = (1.06 \pm 0.19) \times 10^{-4}$ [HFLAV Collaboration, 1909.12524];

- Combine all the numerical results, we have the best limit till now:

$$\mathrm{Br}(B_c \to \tau\nu) < \begin{cases} 6.8\%, & (@\ 90\%\ \text{C.L.}) \\ 8.8\%, & (@\ 95\%\ \text{C.L.}) \end{cases}$$

B. Global-fit analysis

- We use all the measurements on $R_{D,D^*,J/\psi}$, P_τ, $F_L^{D^*}$ listed above to perform global χ^2-fit, and also consider the bound of $\mathrm{Br}(B_c \to \tau\nu)$ as a condition.

- For single scalar operator (S_1 or S_2) cases: $\chi^2_{\min}/\mathrm{d.o.f} > 19.7/11$, which means the scalar scenarios are excluded at 95% C.L., the main constraint comes from $B_c \to \tau\nu$ decay, because it is sensitive to scalar operators.

- For single vector and tensor operator (V_1, V_2, or T) cases: can explain the R_{D,D^*} anomalies without predicting other anomalies, but for single tensor operator scenario, it will predict small $F_L^{D^*}$ near 2σ exclusion boundary.

- Single V_2 scenario favor the case with large CP-violation: $C_{V_2} = -0.023(32) \pm 0.33(6)\mathrm{i}$.

V. IMPLICATIONS TO LEPTOQUARK MODEL

- Leptoquark (LQ) models are good candidates to explain the R_{D,D^*} anomalies;
- A LQ is a scalar or vector particle with both lepton and baryon numbers, and interact directly with a lepton and a quark.
- There are ten types of LQs if we consider only SM fermions.
- Three of which are expected to be able to explain R_{D,D^*} anomalies, which are named as R_2 (scalar), S_1 (scalar), and U_1 (vector).
- The LQs are listed in next page, where blue interactions can induce $bc\tau\nu$ vertices, and red ones can explain R_{D,D^*} anomalies.

LQ models ($F \equiv 3B + L$) [Particle Data, Group, PRD98 (2018), 030001]:

	SM quantum number [SU(3) × SU(2) × U(1)]	F	Spin	LQ Couplings
S_1	$(\bar{3}, 1, 1/3)$	-2	0	$(\bar{b}_L^c \nu_L, \bar{c}_L^c \tau_L, \bar{c}_R^c \tau_R) X_{1/3}$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	-2	0	$\bar{b}_R^c \tau_R X_{4/3}$
S_3	$(\bar{3}, 3, 1/3)$	-2	0	$(\bar{b}_L^c \nu_L, \bar{c}_L^c \tau_L) X_{1/3}$, $\bar{b}_L^c \tau_L X_{4/3}$, $\bar{c}_L^c \nu_L X_{-2/3}$
V_2	$(\bar{3}, 2, 5/6)$	-2	1	$(\bar{b}_R^c \gamma_\mu \nu_L, \bar{c}_L^c \gamma_\mu \tau_R) X^\mu_{1/3}$, $(\bar{b}_R^c \gamma_\mu \tau_L, \bar{b}_L^c \gamma_\mu \tau_R) X^\mu_{4/3}$
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$	-2	1	$\bar{c}_R^c \gamma_\mu \tau_L X^\mu_{1/3}$, $\bar{c}_R^c \gamma_\mu \nu_L X^\mu_{-2/3}$
R_2	$(3, 2, 7/6)$	0	0	$(\bar{c}_R \nu_L, \bar{b}_L \tau_R) X_{2/3}$, $(\bar{c}_R \tau_L, \bar{c}_L \tau_R) X_{5/3}$
$\tilde{R}_2$	$(3, 2, 1/6)$	0	0	$\bar{b}_R \tau_L X_{2/3}$, $\bar{b}_R \nu_L X_{-1/3}$
U_1	$(3, 1, 2/3)$	0	1	$(\bar{c}_L \gamma_\mu \nu_L, \bar{b}_L \gamma_\mu \tau_L, \bar{b}_R \gamma_\mu \tau_R) X^\mu_{2/3}$
$\tilde{U}_1$	$(3, 1, 5/3)$	0	1	$\bar{c}_R \gamma_\mu \tau_R X^\mu_{5/3}$
U_3	$(3, 3, 2/3)$	0	1	$(\bar{b}_L \gamma_\mu \tau_L, \bar{c}_L \gamma_\mu \nu_L) X^\mu_{2/3}$, $\bar{b}_L \gamma_\mu \nu_L X^\mu_{-1/3}$, $\bar{c}_L \gamma_\mu \tau_L X^\mu_{5/3}$

- Choose $m_{\rm LQ} = 1.5$ TeV as an example which is allowed at LHC;

- Lagrangian at $m_{\rm LQ}$ scale:

$$\mathcal{L} \supset \begin{cases} \left(y_R^{b\tau}\bar{b}_L\tau_R + y_L^{c\tau}\bar{c}_R\nu_L\right) X_{2/3} + \text{H.c.}, & (R_2\ \text{LQ}); \\ \left((V_{\rm CKM}^* y_L)^{c\tau}\bar{c}_L^c\tau_L - y_L^{b\tau}\bar{b}_L^c\nu_L + y_R^{c\tau}\bar{c}_R^c\tau_R\right) X_{1/3} + \text{H.c.}, & (S_1\ \text{LQ}); \\ \left((V_{\rm CKM}x_L)^{c\tau}\bar{c}_L\gamma_\mu\nu_L + x_L^{b\tau}\bar{b}_L\gamma_\mu\tau_L + x_R^{b\tau}\bar{b}_R\gamma_\mu\tau_R\right) X_{2/3}^\mu + \text{H.c.}, & (U_1\ \text{LQ}). \end{cases}$$

- Integrate LQs out, Wilson coefficients at $m_{\rm LQ}$ scale:

$$C_{S_2}(m_{\rm LQ}) = 4C_T(m_{\rm LQ}) = \frac{y_L^{c\tau}(y_R^{b\tau})^*}{4\sqrt{2}G_F V_{cb} m_{\rm LQ}^2}, \qquad (R_2\ \text{LQ});$$

$$C_{V_1}(m_{\rm LQ}) = \frac{y_L^{b\tau}(V_{\rm CKM}y_L^*)^{c\tau}}{4\sqrt{2}G_F V_{cb} m_{\rm LQ}^2}, \quad C_{S_2}(m_{\rm LQ}) = -4C_T(m_{\rm LQ}) = -\frac{y_L^{b\tau}(y_R^{c\tau})^*}{4\sqrt{2}G_F V_{cb} m_{\rm LQ}^2}, \quad (S_1\ \text{LQ});$$

$$C_{V_1}(m_{\rm LQ}) = \frac{(V_{\rm CKM}x_L)^{c\tau}(x_L^{b\tau})^*}{2\sqrt{2}G_F V_{cb}^2 m_{\rm LQ}^2}, \quad C_{S_1}(m_{\rm LQ}) = -\frac{(V_{\rm CKM}x_L)^{c\tau}(x_R^{b\tau})^*}{\sqrt{2}G_F V_{cb}^2 m_{\rm LQ}^2}, \qquad (U_1\ \text{LQ}).$$

- For simplify, denote

$$y^{R_2}_{LR} \equiv y^{c\tau}_L (y^{b\tau}_R)^*, y^{S_1}_{LL} \equiv y^{b\tau}_L (V_{\rm CKM} y^*_L)^{c\tau}, y^{S_1}_{LR} \equiv y^{b\tau}_L (y^{c\tau}_R)^*, x^{U_1}_{LL(LR)} \equiv (V_{\rm CKM} x_L)^{c\tau} (x^{b\tau}_{L(R)})^*.$$

- Consider the RGE running (3-loop QCD+1-loop EW) from $m_{\rm LQ}$ to m_b scale [S. Iguro *et al.*, JHEP02 (2019), 194; M. Gonzalez-Alonso *et al.*, PLB772 (2017), 777]:

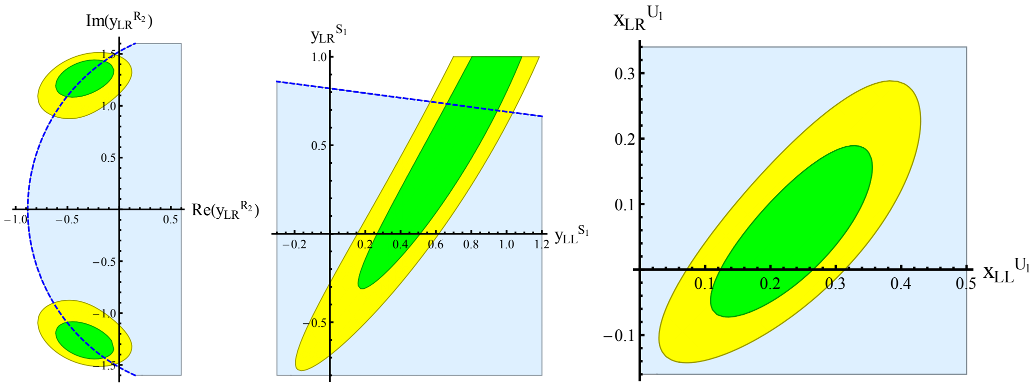
$$\begin{pmatrix} C_{S_1}(m_b) \\ C_{S_2}(m_b) \\ C_T(m_b) \end{pmatrix} = \begin{pmatrix} 1.788 & & \\ & 1.789 & -0.340 \\ & -4.43 \times 10^{-3} & 0.837 \end{pmatrix} \begin{pmatrix} C_{S_1}(m_{\rm LQ}) \\ C_{S_2}(m_{\rm LQ}) \\ C_T(m_{\rm LQ}) \end{pmatrix};$$

$$C_{V_{1,2}}(m_b) = C_{V_{1,2}}(m_{\rm LQ}).$$

- In the following global fits, we fix coefficients in S_1 and U_1 models real, but allow the coefficient for R_2 model complex.

- For all the three LQ models, $\chi^2_{\text{min}} \simeq 13/11$ and best fit points locate in the region $\text{Br}(B_c \to \tau\nu) \lesssim 9\%$, which means all three LQs can explain the anomalies.

- We show the 68% C.L. (green) and 95% C.L. (yellow) allowed regions for the coefficients, and the light blue regions are shown for $\text{Br}(B_c \to \tau\nu) \lesssim 9\%$:



- For R_2 LQ, the fitting result implies large CP-violation: $y^{R_2}_{LR} = -0.33(19) \pm 1.30(11)\text{i}$.

VI. SUMMARY

- We updated the $B \to D^{(*)}$ form factors and hence the updated predictions on R_{D,D^*}, $F_L^{D^*}$, P_τ, etc.: still over 3σ tension in R_{D^*}.
- We updated the limit estimation $\mathrm{Br}(B_c \to \tau\nu) \lesssim 9\%$ at 95% C.L.
- We updated model-independent analysis for each operator, scalar cases are excluded at 95% C.L., because of strict constraint from $B_c \to \tau\nu$ decay.
- Though single tensor scenario is not excluded by global-fit yet, it predicts small $F_L^{D^*} \sim 0.37(7)$, which is close to the 2σ exclusion boundary.
- Implication to LQ models: three usual models R_2, S_1, and U_1 can still explain the anomalies, in which the fitting result of R_2 model implies large CP-violation.


The end,
thank you!
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