Revisit to the b $\rightarrow$ c$\tau\nu$ transition: in and beyond the SM

Ruying Tang

Institute of High Energy Physics, CAS

In collaboration with Kingman Cheung, Zhuoran Huang, Huadong Li, Caidian Lü, Yingnan Mao

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Outline

- Introduction to $R(D(*))$
- Motivation
- Form factors
- Fit of the HQET parameters
- Analyses of New physics
- Summary and conclusions

Introduction to $R(D^{(*)})$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \qquad \text{with } \ell = \mu, e$$

- SM predictions (2012):

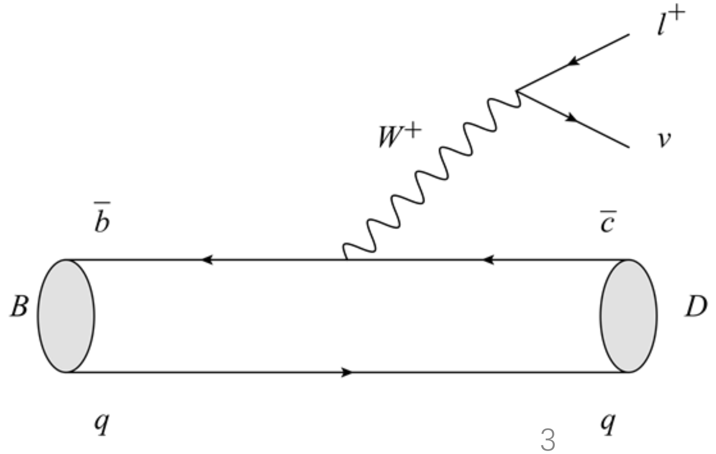
$R(D)=0.297\pm0.017$ | $R(D^*)=0.252\pm0.003$

- BABAR(2012):

$R(D)=0.440\pm0.058\pm0.042$ | $R(D^*)=0.332\pm0.024\pm0.018$

(3.4σ between SM predictions and BABAR measurements, for both)

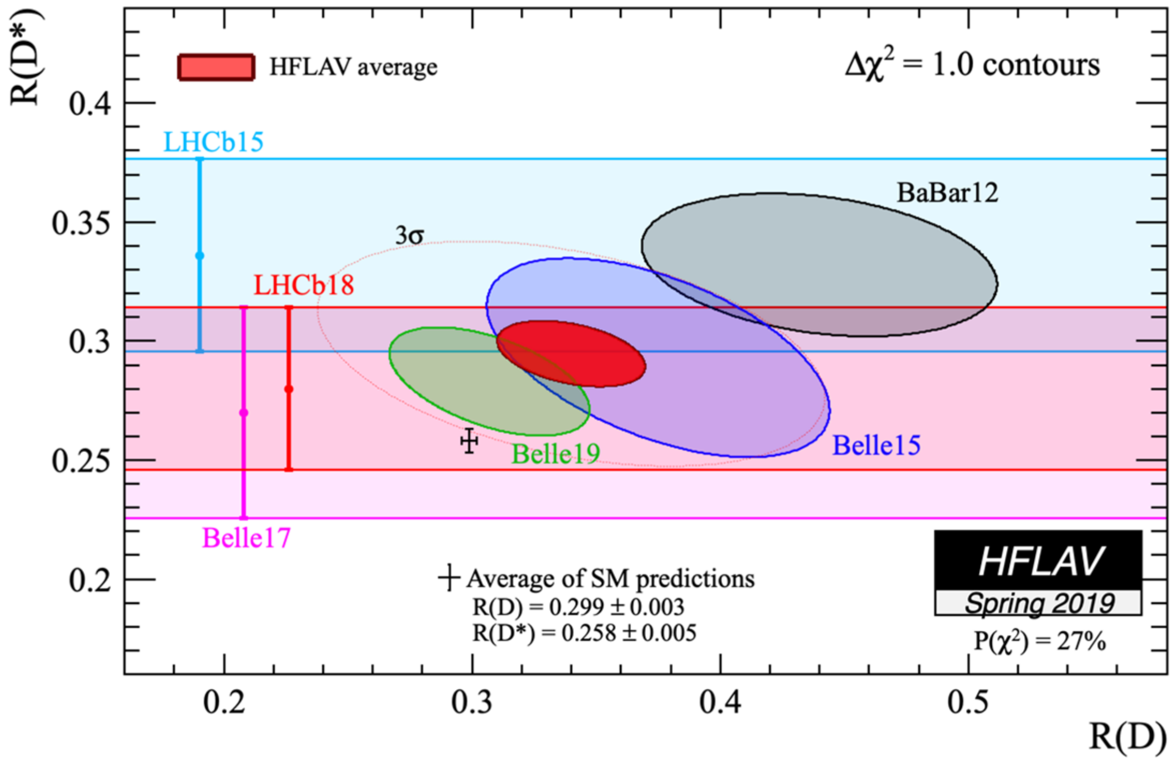
- Type II 2HDM is not compatible



S. Fajfer et al. , Phys.Rev.D 85 (2012) 094025
BaBar Collaboration, Phys.Rev.Lett. 109 (2012) 101802

Experimental Status

- The combined results of $R(D^{(*)})$ indicate about 3σ deviation from the SM predictions



$R(D)$=0.340±0.027±0.013

$R(D^*)$=0.295±0.011±0.008

- LHCb reported $R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi \tau \nu)}{\mathcal{B}(B_c \to J/\psi \mu \nu)}$ = 0.71±0.17±0.18, which deviate 2σ away from the SM prediction

https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/main.shtml

Motivation

- $R(D^{(*)})$ anomaly may imply New physics Effect.

- Study of form factors allow us to give more reliable predictions for $R(D^{(*)})$.

- In light of recent data of $R(D^{(*)})$ and the updated form factors, the analyses of New physics can be perform.

Form factors

Hadronic matrix element:

$$f_-(q^2) = \frac{m_B^2 - m_D^2}{q^2}\left(f_0(q^2) - f_+(q^2)\right)$$

$$\langle D(p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle = f_+(q^2)(p+p')^\mu + f_-(q^2)(p-p')^\mu$$

$$q = p - p'$$

In SM:

$$\frac{d\Gamma(B\to D\ell\nu)}{dq^2} = \frac{G_F^2|V_{cb}|^2\eta_{EW}^2}{192\pi^3 m_B^3}\frac{k}{(q^2)^{\frac{5}{2}}}(q^2-m_\ell^2)^2[4k^2q^2(2q^2+m_\ell^2)|f_+|^2 + 3m_\ell^2|f_0|^2]$$

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2} = \frac{G_F^2|V_{cb}|^2\eta_{EW}^2}{192\pi^3 m_B^3}\frac{k}{(q^2)^{\frac{5}{2}}}(q^2-m_\ell^2)^2\left\{(2q^2+m_\ell^2)[2q^2|f|^2 + |\mathcal{F}_1|^2 + 2k^2(q^2)^2|g|^2] + 3m_\ell^2k^2q^2|\mathcal{F}_2|^2\right\}$$

Where $k = \sqrt{\frac{[(m_B+m_{D^{(*)}})^2-q^2][(m_B+m_{D^{(*)}})^2-q^2]}{4q^2}}$

$$R(D^{(*)}) = \frac{\mathcal{B}(B\to D^{(*)}\tau\nu)}{\mathcal{B}(B\to D^{(*)}\ell\nu)}, \quad \text{with } \ell = \mu, e$$

C.G. Boyd, B. Grinstein and R.F. Lebed, Precision corrections to dispersive bounds on form-factors, Phys. Rev. D 56 (1997) 6895

Calculation of Form factors

- Small recoil(Near Max point of q^2):

  Lattice QCD

- Large recoil(Near $q^2 = 0$):

  Light Cone Sum Rule, Perturbative QCD

- Extrapolation of Form factors:

  Pole model ⊕ z expansion

  HQET

  Specific Parameterization:

  Boyd-Grinstein-Lebed (BGL)

  Bourrelly-Caprini-Lellouch (BCL)

  Caprini-Lellouch-Neubert (CLN)

C.G. Boyd, B. Grinstein and R.F. Lebed, Precision corrections to dispersive bounds on form-factors, Phys. Rev. D 56 (1997) 6895

Form factors in HQET

$$h_+ = \xi(w)(1 + \frac{\alpha_s}{\pi}(C_{V_1} + \frac{w+1}{2}(C_{V_2} + C_{V_3})) + (\varepsilon_c + \varepsilon_b)L_1(w) + \varepsilon_c^2\, \delta h_+)$$

$$h_- = \xi(w)(\frac{\alpha_s}{\pi}\frac{w+1}{2}(C_{V_2} - C_{V_3}) + (\varepsilon_c - \varepsilon_b)L_4(w))$$

$$f_+ = \frac{m_B + m_D}{2\sqrt{m_B m_D}}\left(h_+ - \frac{m_B - m_D}{m_B + m_D}h_-\right)$$

$$f_0 = \frac{\sqrt{m_B m_D}}{m_B + m_D}(1+w)\left(h_+ - \frac{m_B + m_D}{m_B - m_D}\frac{w-1}{w+1}h_-\right)$$

where $w = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2\, m_B\, m_{D^{(*)}}}$,

$$L_1 = -4(w-1)\chi_2 + 12\chi_3, \quad L_2 = -4\chi_3, \quad L_3 = 4\chi_2, \quad L_4 = 2\eta - 4, \quad L_5 = -1, \quad L_6 = -2\frac{1+\eta}{w+1}$$

Corrections $\mathcal{O}(\alpha_s),\ \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_{b,c}}\right),\ \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{m_c^2}\right)$

$$\xi(w) = 1 - 8\rho^2\frac{\sqrt{1+w}-\sqrt{2}}{\sqrt{1+w}+\sqrt{2}} + (64c - 16\rho^2)\left(\frac{\sqrt{1+w}-\sqrt{2}}{\sqrt{1+w}+\sqrt{2}}\right)^2$$

$$\eta = \eta(1) + \eta'(1)(w-1)$$

$$\chi_2 = \chi_2(1) + \chi_2'(1)(w-1)$$

$$\chi_3 = \chi_3'(1)(w-1)$$

$\delta h_+, \delta h_{A_1}, \delta h_{T_1}$

I. Caprini, L. Lellouch and M. Neubert, Dispersive bounds on the shape of B → $D^{(*)}$ lepton anti-neutrino form-factors, Nucl. Phys. B 530 (1998) 153

Fit of the HQET parameters

- Data input:

Lattice QCD

H. Na, C. M. Bouchard, G. P. Lepage, C. Monahan, and J. Shigemitsu (HPQCD), Phys. Rev. D92, 054510 (2015)
J. A. Bailey et al. (MILC), Phys. Rev. D92, 034506 (2015)
S. Aoki et al., Eur. Phys. J. C77, 112 (2017)
J. Harrison, C. Davies, and M. Wingate (HPQCD), Phys. Rev. D97, 054502 (2018)

Light-cone sum rule

Y.-M. Wang, Y.-B. Wei, Y.-L. Shen, and C.-D. Lu, JHEP 06, 062 (2017)
N. Gubernari, A. Kokulu, and D. van Dyk, JHEP 01, 150 (2019)
S. Faller, A. Khodjamirian, C. Klein, and T. Mannel, Eur. Phys. J. C60, 603 (2009)

- Extrapolation method: HQET
- Unitarity bounds

Unitarity bound

Mapping $q^2 \mapsto z$

$$z = \frac{\sqrt{1+w} - \sqrt{2}}{\sqrt{1+w} + \sqrt{2}}$$

$$f_i = \frac{1}{P_i(z)\Phi_i(z)} \sum_{n=0}^{+\infty} a_n^i z^n$$

$$\mathrm{Im}\ \Pi_J^{T,L} = \frac{1}{2} \sum_X (2\pi)^4 \delta^4(q - p_X) \left|\langle 0 \left| J \right| X \rangle\right|^2$$

Dispersion relation

Crossing symmetry

$$\sum_{i=1}^{X} \sum_{n=0}^{+\infty} (a_n^i)^2 \leqslant 1$$

0^+	f_0, S_{0+}, S_{00}
0^-	$\mathcal{F}_2, \hat{\mathcal{F}}_2, P_{0+}$
1^-	$f_+, g, \hat{g}, V_{+0}, V_{++}, V_{0+}, V_{00}$
1^+	$f, \mathcal{F}_1, \hat{f}, \hat{\mathcal{F}}_1, A_{+0}, A_{++}, A_{0+}$

We choose that the max of n is 2

C.G. Boyd, B. Grinstein and R.F. Lebed, Precision corrections to dispersive bounds on form-factors, Phys. Rev. D 56 (1997) 6895

Fit of the HQET parameters

$$f_i = \frac{1}{P_i(z)\Phi_i(z)} \sum_{n=0}^{+\infty} a_n^i z^n = h_{i,HQET}(z)$$

$$a_{0,1,2}^{f_i}(\rho^2, c, \chi_2(1), \chi_2'(1), \chi_3'(1), \eta(1), \eta'(1), \delta h_+, \delta h_{A_1}, \delta h_{T_1})$$

$$\text{Fit constraint} \sum_{i=1}^{7}\sum_{n=0}^{2}(a_{1^-,n}^i)^2 \leq 1,\ \sum_{i=1}^{7}\sum_{n=0}^{2}(a_{1^+,n}^i)^2 \leqslant 1,\ \sum_{i=1}^{3}\sum_{n=0}^{2}(a_{0^-,n}^i)^2 \leqslant 1,\ \sum_{i=1}^{3}\sum_{n=0}^{2}(a_{0^+,n}^i)^2 \leqslant 1$$

- Lattice QCD results
- Light-cone sum rule results
- Masses of B_c given by experiment, Lattice QCD and model calculation

Fit of the HQET parameters

- Results:

$\chi_2(1)$	$\chi_2'(1)$	$\chi_3'(1)$	$\eta(1)$	$\eta'(1)$
0.132(23)	-0.150(19)	0.016(8)	0.366(28)	0.241(114)
ρ^2	c	$\delta_{h_{A_1}}$	δ_{h_+}	$\delta_{h_{T_1}}$
1.119(27)	0.930(212)	-1.340(285)	0.032(133)	-4.899(1974)

$R(D)=0.290\pm0.005$ $R(D^*)=0.237\pm0.008$

- HFLAV:

Theory:

$R(D)=0.299\pm0.003$ $R(D^*)=0.258\pm0.005$

Experiments:

$R(D)=0.340\pm0.027\pm0.013$ $R(D^*)=0.295\pm0.011\pm0.008$

χ^2 Fits of the Wilson Coefficients

	R_D	R_{D^*}	Correlation	$P_\tau(D^*)$
BaBar	$0.440(58)(42)$	$0.332(24)(18)$	-0.27	–
Belle	$0.375(64)(26)$	$0.293(38)(15)$	-0.49	–
Belle	–	$0.302(30)(11)$	–	–
Belle	–	$0.270(35)(^{+0.028}_{-0.025})$	0.33	$-0.38(51)(^{+0.21}_{-0.16})$
LHCb	–	$0.336(27)(30)$	–	–
LHCb	–	$0.291(19)(26)(13)$	–	–
Belle	$0.307(37)(16)$	$0.283(18)(14)$	-0.54	–

	$R_{J/\psi}$	$F_L^{D^*}$
LHCb	$0.71(17)(18)$	–
Belle	–	$0.60(8)(4)$

Experimental data used in the fits

$$\chi^2(C_X) = \sum_{m,n=1}^{\text{data}} (O^{th}(C_X) - O^{exp})_m (V^{exp} + V^{th})^{-1}_{mn} (O^{th}(C_X) - O^{exp})_n + \frac{(R^{th}_{J/\psi}(C_X) - R^{exp}_{J/\psi})^2}{\sigma^2_{R_{J/\psi}}} + \frac{(F_L^{D^*\,th}(C_X) - F_L^{D^*\,exp})^2}{\sigma^2_{F_L^{D^*}}}$$

Effective Hamiltonian with New Physics

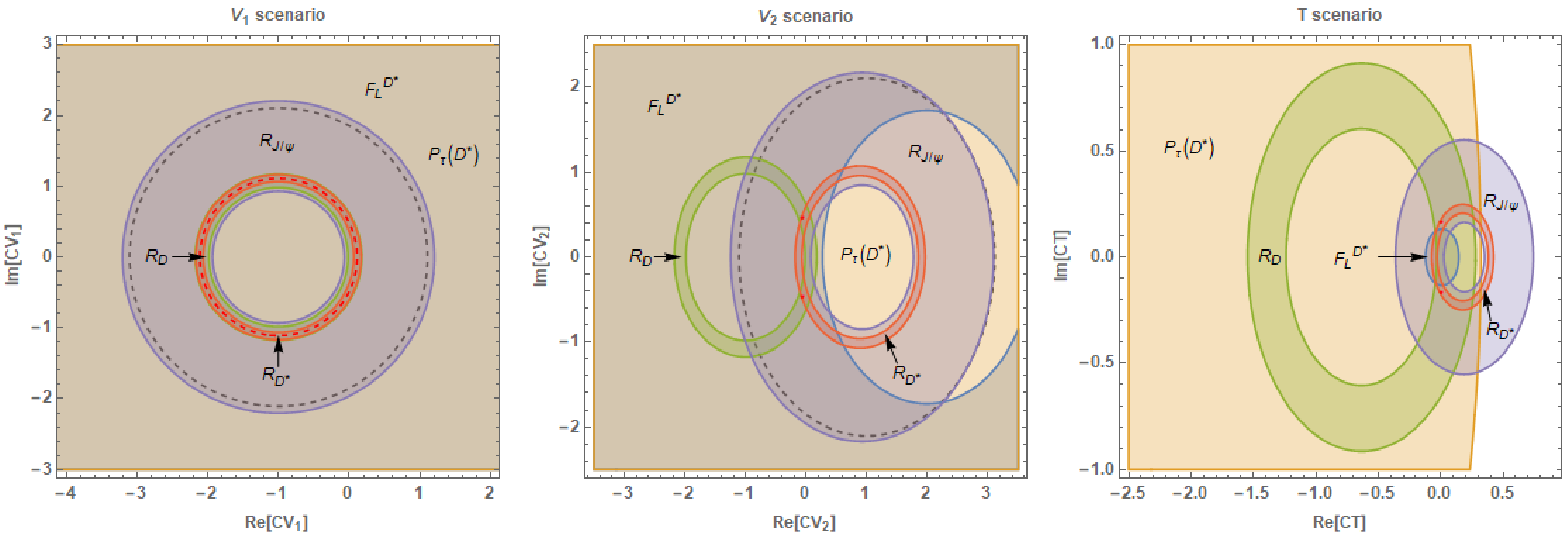
- Weak effective Hamiltonian

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

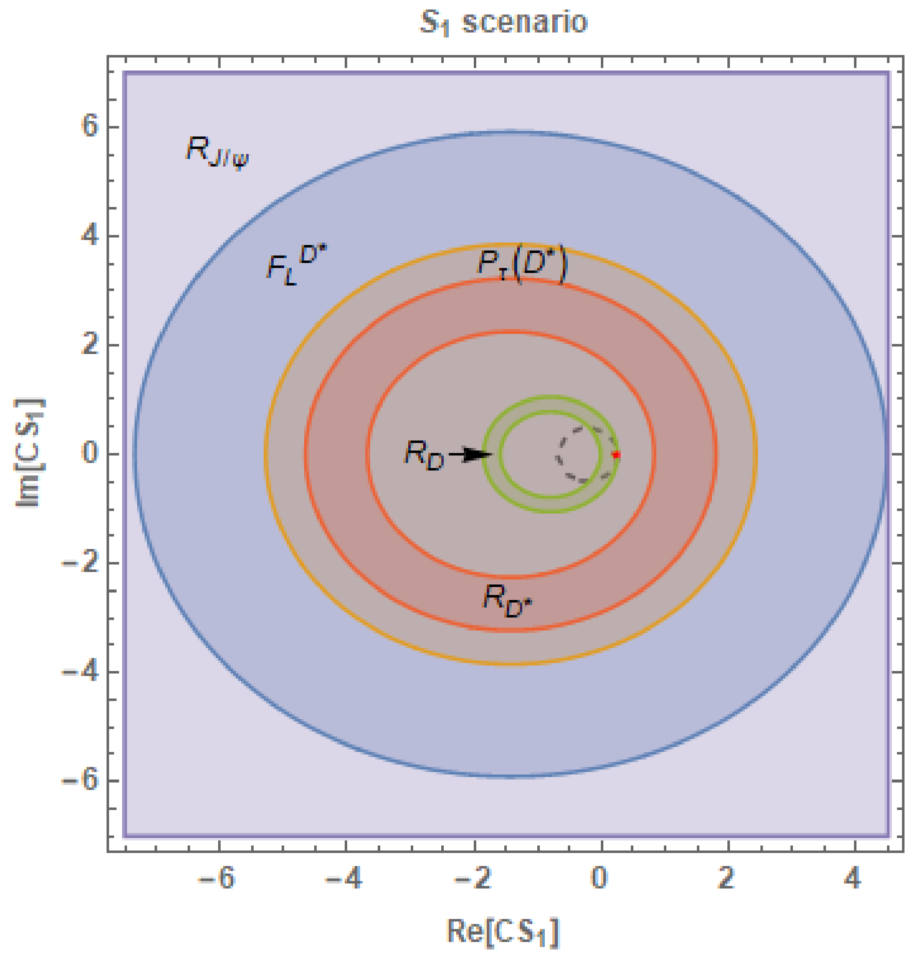
- For the b→c$\tau\nu$ transition, the four-fermion operator basis can be described as

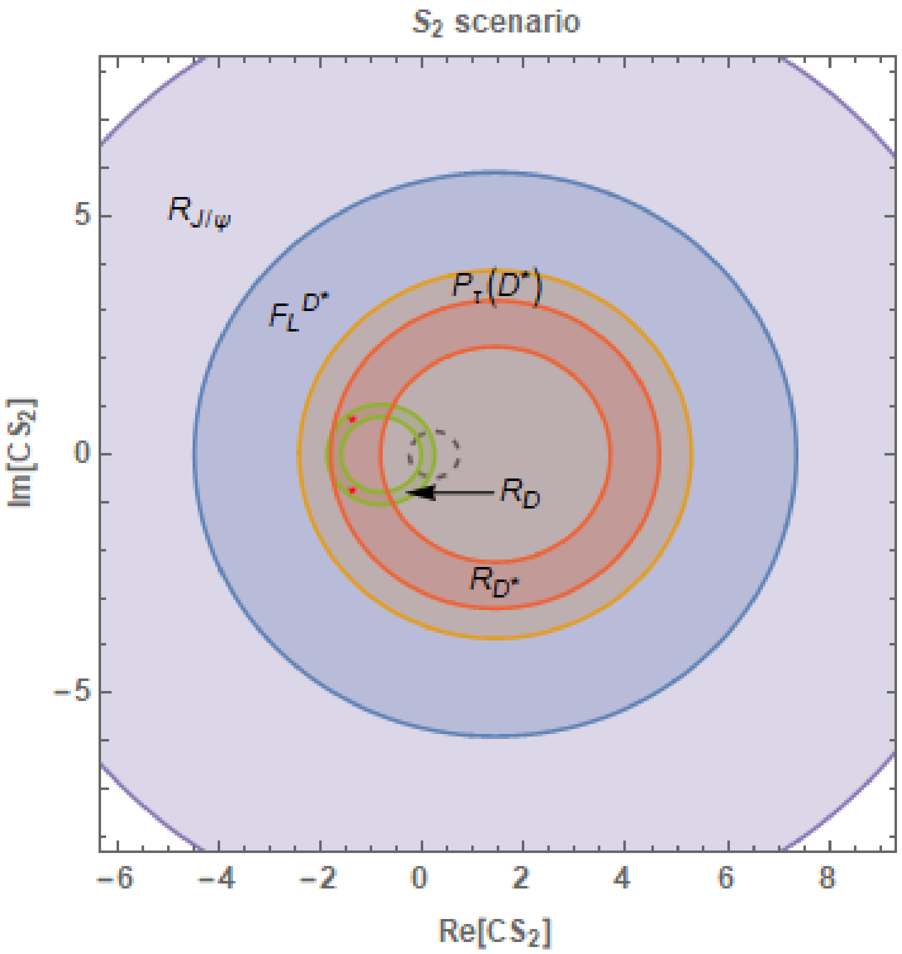
$$\mathcal{O}_{S_1} = (\overline{c}_L b_R)(\overline{\tau}_R \nu_L)\,, \quad \mathcal{O}_{S_2} = (\overline{c}_R b_L)(\overline{\tau}_R \nu_L)$$
$$\mathcal{O}_{V_1} = (\overline{c}_L \gamma^\mu b_L)(\overline{\tau}_L \gamma_\mu \nu_L)\,, \quad \mathcal{O}_{V_2} = (\overline{c}_R \gamma^\mu b_R)(\overline{\tau}_L \gamma_\mu \nu_L)$$
$$\mathcal{O}_T = (\overline{c}_R \sigma^{\mu\nu} b_L)(\overline{\tau}_R \sigma_{\mu\nu} \nu_L)$$

2σ Constraints on the NP Wilson coefficients



2σ Constraints on the NP Wilson coefficients





Exclusion of S_1 and S_2 scenario

NP scenario	value (with $\mathcal{B}(B_c \to \tau\nu) < 0.1$)	χ^2/dof	Correlation
V_1	$(1 + Re[C_{V_1}])^2 + (Im[C_{V_1}])^2 = 1.235(38)$	$13.72/11$	–
V_2	$-0.031(34) \pm 0.460(52)i$	$12.93/11$	± 0.59
S_1	$0.244(50) + 0.000(474)i$	$32.76/11$	–
S_2	$0.071 \pm 0.460i$	$39.06/11$	–
T	$0.011(62) \pm 0.164(60)i$	$16.79/11$	± 0.98

Predictions for the Observables

Exclusion:

Only Generate: S1,S2, (S1,S2)

Charged Higgs models are ruled out

Scenario	$R(D)$	$R(D^*)$	$P_\tau(D)$	$P_\tau(D^*)$
SM	0.290(5)(0)	0.237(8)(0)	0.328(3)(0)	−0.491(5)(0)
V_1	0.357(6)(11)	0.292(10)(9)	0.328(3)(0)	−0.491(5)(0))
V_2	0.333(5)(30)	0.300(10)(12)	0.328(3)(0)	−0.490(5)(1)
T	0.300(5)(26)	0.303(21)(34)	0.315(3)(48)	−0.358(25)(75)
(V_1, V_2)	0.333(5)(31)	0.300(10)(13)	0.328(3)(0)	-0.490(5)(1)
(V_1, S_1)	0.338(5)(30)	0.298(10)(12)	0.268(3)(87)	-0.502(4)(16)
(V_1, S_2)	0.332(5)(30)	0.300(10)(12)	0.263(3)(74)	-0.478(5)(14)
(V_1, T)	0.336(6)(30)	0.299(10)(15)	0.340(3)(15)	-0.479(4)(17)
(V_2, S_1)	0.318(5)(30)	0.297(10)(13)	0.523(3)(39)	−0.447(7)(10)
(V_2, S_2)	0.333(6)(32)	0.299(10)(12)	0.586(3)(43)	−0.535(4)(9)
(V_2, T)	0.328(5)(28)	0.300(21)(12)	0.396(2)(12)	−0.402(12)(23)
(S_1, T)	0.337(6)(29)	0.299(13)(12)	0.485(3)(41)	−0.428(5)(9)
(S_2, T)	0.333(6)(29)	0.300(15)(12)	0.487(3)(44)	−0.463(7)(13)

Predictions for the Observables

Scenario	$F_L^{D^*}$	$\mathcal{A}_{FB}(D)$	$\mathcal{A}_{FB}(D^*)$
SM	0.467(4)(0)	0.360(1)(0)	-0.057(6)(0)
V_1	0.467(4)(0)	0.360(1)(0)	-0.057(6)(0)
V_2	0.470(4)(3)	0.360(1)(0)	0.016(4)(10)
T	0.401(13)(40)	0.357(1)(25)	0.013(15)(20)
(V_1, V_2)	0.470(4)(3)	0.360(1)(0)	0.318(5)(9)/-0.048(4)(11)
(V_1, S_1)	0.463(4)(6)	0.365(1)(7)	-0.063(5)(9)
(V_1, S_2)	0.472(4)(5)	0.365(1)(5)	-0.050(4)(7)
(V_1, T)	0.462(4)(7)	0.352(1)(10)	-0.039(5)(25)
(V_2, S_1)	0.491(5)(4)	0.327(2)(9)	0.002(3)(9)
(V_2, S_2)	0.463(4)(3)	0.311(2)(12)	-0.032(4)(8)
(V_2, T)	0.422(7)(12)	0.310(2)(9)	0.011(9)(9)
(S_1, T)	0.458(6)(7)	0.313(2)(8)	0.012(6)(9)
(S_2, T)	0.440(5)(4)	0.309(2)(10)	-0.007(7)(12)

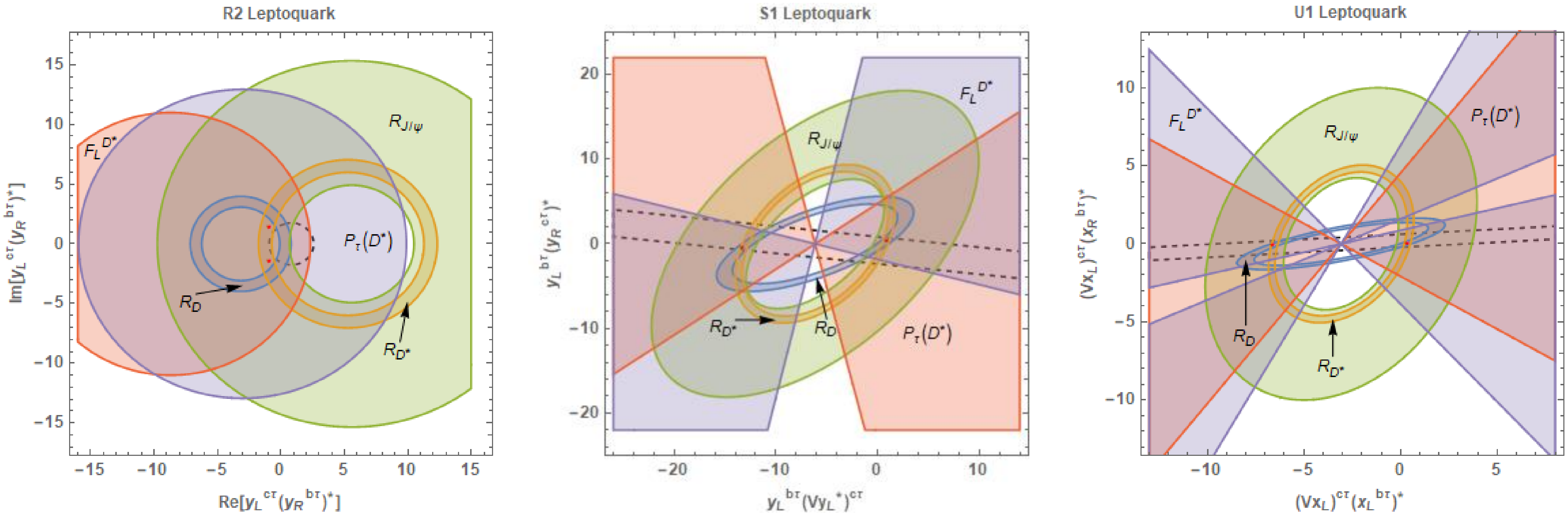
Leptoquark model

- Lagrangian of Leptoquark

$$\mathcal{L}_{R_2} = \left(y_R^{b\tau}\bar{b}_L\tau_R + y_L^{c\tau}\bar{c}_R\nu_L\right) Y_{2/3} + \text{H.c.}$$
$$\mathcal{L}_{S_1} = \left((V_{\text{CKM}}^* y_L)^{c\tau}\bar{c}_L^c\tau_L - y_L^{b\tau}\bar{b}_L^c\nu_L + y_R^{c\tau}\bar{c}_R^c\tau_R\right) Y_{1/3} + \text{H.c.}$$
$$\mathcal{L}_{U_1} = \left((V_{\text{CKM}} x_L)^{c\tau}\bar{c}_L\gamma_\mu\nu_L + x_L^{b\tau}\bar{b}_L\gamma_\mu\tau_L + x_R^{b\tau}\bar{b}_R\gamma_\mu\tau_R\right) X_{2/3}^\mu + \text{H.c.}$$

	SM quantum number $[\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)]$	Spin	Fermions coupled to
R_2	$(3, 2, 7/6)$	0	$\bar{c}_R\nu_L, \bar{b}_L\tau_R$
S_1	$(\bar{3}, 1, 1/3)$	0	$\bar{b}_L^c\nu_L, \bar{c}_L^c\tau_L, \bar{c}_R^c\tau_R$
U_1	$(3, 1, 2/3)$	1	$\bar{c}_L\gamma_\mu\nu_L, \bar{b}_L\gamma_\mu\tau_L, \bar{b}_R\gamma_\mu\tau_R$

2σ Constraints on the Leptoquark couplings



Predictions for the Observables with LQ model

LQ Type	value (with $\mathcal{B}(B_c \to \tau\nu) < 0.1$)	χ^2/dof	corr
R_2	$(-0.165(395), \pm 1.445(117))$	$22.82/11$	± 0.28
S_1	$(0.936(270), 0.478(509))$	$12.70/11$	0.92
S_1	$(-13.224(270), -0.478(509))$	$12.70/11$	0.92
U_1	$(0.391(85), 0.061(86))$	$13.18/11$	0.78
U_1	$(-6.535(85), -0.061(86))$	$13.18/11$	0.78

LQ type	$R(D)$	$R(D^*)$	$P_\tau(D)$	$P_\tau(D^*)$
S_1	$0.330(5)(29)$	$0.301(10)(13)$	$0.192(5)(145)$	$-0.474(7)(20)$
U_1	$0.338(5)(30)$	$0.298(10)(12)$	$0.268(3)(87)$	$-0.502(4)(16)$

LQ type	$F_L^{D^*}$	$\mathcal{A}_{FB}(D)$	$\mathcal{A}_{FB}(D^*)$
S_1	$0.479(4)(13)$	$0.375(1)(12)$	-0.062(6)(5)
U_1	$0.463(4)(6)$	$0.365(1)(7)$	-0.063(5)(9)

Summary and Conclusions

- Fit the parameters in the HQET parametrization including the $\mathcal{O}(\alpha_s, \Lambda_{\rm QCD}/m_{b,c})$ corrections and part of $\mathcal{O}(\varepsilon_c^2)$ correlations
- Our calculations of $R(D^{(*)})$ in SM are smaller than the predictions of HFLAV and still have 3-4σ deviation from the experiments
- The NP models that generate only scalar operators are ruled out, such as the charged Higgs models
- The R_2 Leptoquark model is disfavored to explain the $R(D^{(*)})$ anomalies
- Our calculations of $R(D^{(*)})$ in new physics scenario can well explain the experiments

Thank you!