Revisiting the scalar leptoquark solution to the $R(D^{(*)})$ anomalies and its implications

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Nov. 4, 2016

HFCPV-2016 @ SJTU

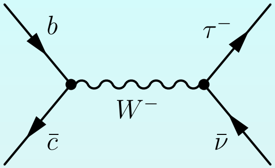
X. Q. Li, Y. D. Yang and X. Zhang, JHEP **08** (2016) 054

Outline

Motivation

$B \to D^{(*)}\tau\nu$

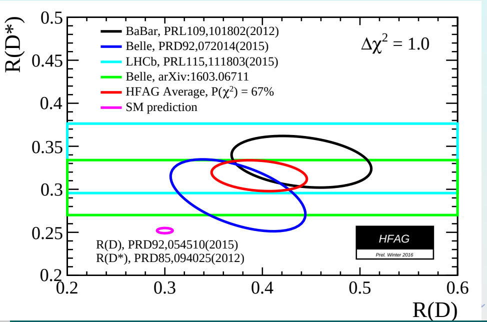
$$\mathcal{R}(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$$



$\mathcal{R}_{\rm exp}(D)$	$=0.397\pm0.049$	BaBar+Belle
$\mathcal{R}_{\rm SM}(D)$	$=0.300\pm0.008$	$2.0\sigma \to 1.9\sigma$
$\mathcal{R}_{\rm exp}(D^*)$	$=0.316\pm0.019$	BaBar+Belle+LHCb
$\mathcal{R}_{\rm SM}(D^*)$	$=0.252\pm0.003$	$2.7\sigma \to 3.3\sigma$

- combined excess: $3.4\sigma \to 4.0\sigma$
- the: V_{cb}, hadronic uncertainties canceled
- BSM: scalar leptoquark scenario
- exp: Belle II @ 50ab^{-1}
  $\sigma \approx 0.010$ for $R(D)$
  $\sigma \approx 0.005$ for $R(D^*)$

B. Golob *et al.*, Report No. BELLE2- NOTE-0021



Framework

The scalar leptoquark scenario

The scalar ϕ transforms as $(\mathbf{3},\mathbf{1},-\frac{1}{3})$ with couplings to fermions described by

$$\mathcal{L}_{\rm int}^{\phi} = \bar{Q}_L^c \boldsymbol{\lambda}^L i\tau_2 L\phi^* + \bar{u}_R^c \boldsymbol{\lambda}^R \ell_R \phi^* + \text{h.c.}\,,$$

M. Bauer and M. Neubert, Phys. Rev. Lett. 116 (2016), 141802

The ϕ mediates the $b\to c\tau^-\bar{\nu}_\tau$ at tree level, and gives rise to $\mathcal{H}_{\rm eff}$ including SM

$$\begin{aligned}\mathcal{H}_{\rm eff} =& \frac{4G_F V_{cb}}{\sqrt{2}}\Big[C_V(M_\phi)\,\bar{c}\gamma_\mu P_L b\,\bar{\tau}\gamma^\mu P_L \nu_\tau + C_S(M_\phi)\,\bar{c}P_L b\,\bar{\tau}P_L\nu_\tau \\ &- \frac{1}{4}C_T(M_\phi)\,\bar{c}\sigma_{\mu\nu}P_L b\,\bar{\tau}\sigma^{\mu\nu}P_L\nu_\tau\Big], \\ C_V(M_\phi) =& 1 + \frac{\lambda^L_{b\nu_\tau}\lambda^{L*}_{c\tau}}{4\sqrt{2}G_F V_{cb} M_\phi^2}\,, \\ C_{S,T}(M_\phi) =& -\frac{\lambda^L_{b\nu_\tau}\lambda^{R*}_{c\tau}}{4\sqrt{2}G_F V_{cb} M_\phi^2}\,.\end{aligned}$$

X.Q. Li *et.al*, JHEP 08 (2016) 054

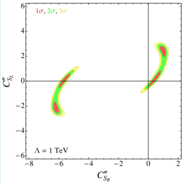
In order to re-sum potentially large logarithmic effects, the $C_{V,S,T}$ should be run down to $\mu_b \sim m_b$ scale. I. Doršner *et.al*, JHEP 11 (2013) 084

Framework

Parameters

M. Freytsis *et al.*, Phys. Rev. D92 (2015), 054018

$$(\lambda^{L}_{b\nu_\tau}\lambda^{L*}_{c\tau},\lambda^{L}_{b\nu_\tau}\lambda^{R*}_{c\tau})=\begin{cases}(\ \ 0.35, -0.03), & P_A \\ (\ \ 0.96, \ \ 2.41), & P_B \\ (-5.74, \ \ 0.03), & P_C \\ (-6.34, -2.39), & P_D\end{cases}$$



Only P_A is adopted by Bauer and Neubert.

M. Bauer and M. Neubert, Phys. Rev. Lett. 116 (2016), 141802

It would be worth investigating whether the four best-fit solutions could be discriminated from each other.

Our work

Purely leptonic decay $B_c^- \to \tau^- \bar{\nu}_\tau$

$$\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c}^3 \frac{m_\tau^2}{m_{B_c}^2} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| C_V - C_S \frac{m_{B_c}^2}{m_\tau [m_b(\mu_b) + m_c(\mu_b)]} \right|^2$$

	P_A	P_B	P_C	P_D
C_V	1.129	1.354	−1.117	−1.338
C_S	0.018	−1.465	−0.018	1.453

$$\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \begin{cases} 2.22\times 10^{-2}\,\Gamma_{B_c}, & \text{SM} \\ 2.45\times 10^{-2}\,\Gamma_{B_c}, & P_A \quad ☺ \\ 1.33\,\Gamma_{B_c}, & \not{P_B} \\ 2.39\times 10^{-2}\,\Gamma_{B_c}, & P_C \quad ☺ \\ 1.31\,\Gamma_{B_c}, & \not{P_D} \end{cases}$$

Comparison between P_A and P_C:

$$\mathcal{H}_{\rm fit}=\frac{4G_F}{\sqrt{2}}V_{cb}\Bigg\{\underbrace{\Bigg[1+\begin{pmatrix} 0.129 & P_A \\ -2.117 & P_C \end{pmatrix}\Bigg]}_{C_V^{\rm fit}}\bar{c}\gamma_\mu P_L b\,\bar{\tau}\gamma^\mu P_L\nu_\tau+\underbrace{\begin{pmatrix} 0.018 & P_A \\ -0.018 & P_C \end{pmatrix}}_{C_S^{\rm fit}}\bar{c}P_L b\,\bar{\tau}P_L\nu_\tau$$
$$+\underbrace{\begin{pmatrix} -0.002 & P_A \\ 0.002 & P_C \end{pmatrix}}_{C_T^{\rm fit}}\bar{c}\sigma_{\mu\nu}P_L b\,\bar{\tau}\sigma^{\mu\nu}P_L\nu_\tau\Bigg\}.$$

Figure: The leading order Feynman diagrams resulting from the $\mathcal{H}_{\rm eff}$.

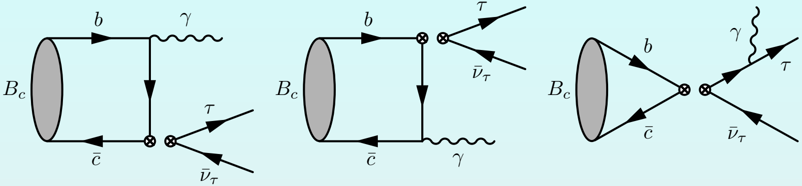
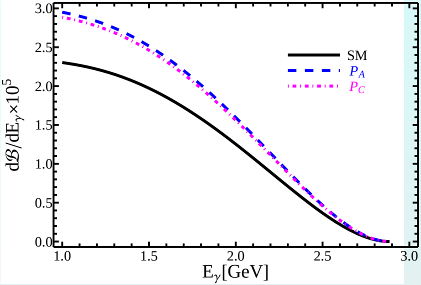


Table: Branching ratios within the SM and beyond with $E_\gamma \geq 1$ GeV.

Observable	SM	P_A	P_C
$\mathcal{B}(B_c^- \to \gamma\tau^-\bar{\nu}_\tau) \times 10^5$	2.36	3.01	2.94

$\mathcal{B}(B_c^- \to \gamma\tau^-\bar{\nu}_\tau)$ are enhanced by $\sim 27\%$ in both P_A and P_C cases.

Figure: The dependence of the differential branching ratios on E_γ.



The enhancement is significant when $1\ \mathrm{GeV} < E_\gamma < 1.5\ \mathrm{GeV}$, but tiny near the end. P_A and P_C are almost indistinguishable.

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

- $R(D^{(*)})$ and $\mathcal{B}(\bar{B} \to D^{(*)}\tau\nu_\tau)$ (10^{-2})

Observable	SM	P_A	P_C	Exp
$R(D)$	0.298 ± 0.009	0.388 ± 0.012	0.380 ± 0.011	0.397 ± 0.049
$R(D^*)$	0.253 ± 0.002	0.325 ± 0.002	0.318 ± 0.002	0.316 ± 0.019
$\mathcal{B}(\bar{B} \to D\tau\nu)$	0.72 ± 0.06	0.94 ± 0.07	0.92 ± 0.07	1.07 ± 0.18
$\mathcal{B}(\bar{B} \to D^*\tau\nu)$	1.30 ± 0.04	1.67 ± 0.05	1.64 ± 0.04	1.64 ± 0.15

$$\begin{aligned}
V_1(w) =& V_1(1)[1 - 8\rho_D^2 z + (51\rho_D^2 - 10)z^2 - (252\rho_D^2 - 84)z^3]\,,\\
h_{A_1}(w) =& h_{A_1}(1)[1 - 8\rho_{D^*}^2 z + (53\rho_{D^*}^2 - 15)z^2 - (231\rho_{D^*}^2 - 91)z^3]\,,\\
R_1(w) =& R_1(1) - 0.12(w-1) + 0.05(w-1)^2\,,\\
R_2(w) =& R_2(1) + 0.11(w-1) - 0.06(w-1)^2\,,\\
R_3(w) =& 1.22 - 0.052(w-1) + 0.026(w-1)^2\,.
\end{aligned}$$

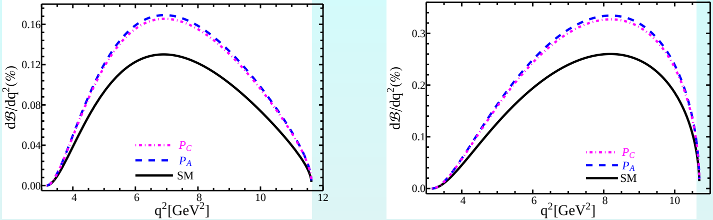
$$\begin{aligned}
\rho_D^2 =& 1.186 \pm 0.054\,,\\
\rho_{D^*}^2 =& 1.207 \pm 0.026\,,\\
R_1(1) =& 1.403 \pm 0.033\,,\\
R_2(1) =& 0.854 \pm 0.020\,,\\
V_1(1) =& 1.074 \pm 0.024\,,\\
h_{A_1}(1) =& 0.908 \pm 0.017\,.
\end{aligned}$$

I. Caprini *et al.*, Nucl.Phys. B530 (1998) 153, Lattice, Nucl.Phys.Proc.Suppl. 140 (2005) 461

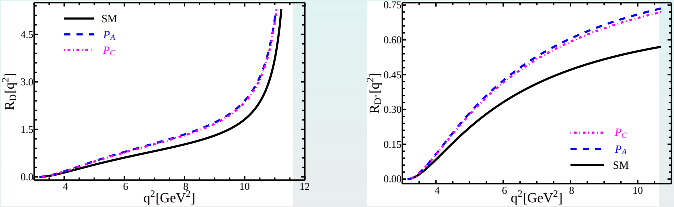
HFAG arXiv:1207.1158

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

- The q^2 distributions of $\mathrm{d}\mathcal{B}(\bar{B} \to D^{(*)}\tau\nu_\tau)/\mathrm{d}q^2$

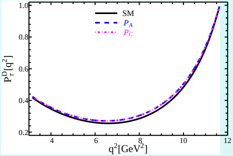


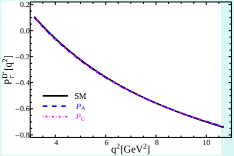
- The q^2 distributions of the ratios $R_{D^{(*)}}(q^2)$

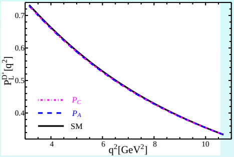


$\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$

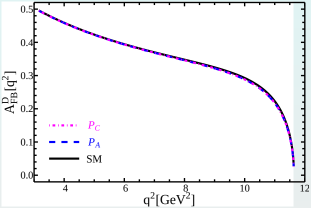
- $P_\tau(q^2) = \frac{d\Gamma^{\lambda_\tau=1/2}/dq^2 - d\Gamma^{\lambda_\tau=-1/2}/dq^2}{d\Gamma/dq^2}$, $\quad P_L^{D^*}(q^2) = \frac{d\Gamma^{\lambda_{D^*}=0}/dq^2}{d\Gamma/dq^2}$

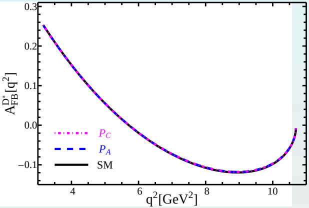






- $A_{FB}(q^2) = \frac{\int_0^1 d\cos\theta(d^2\Gamma/dq^2 d\cos\theta) - \int_{-1}^0 d\cos\theta(d^2\Gamma/dq^2 d\cos\theta)}{d\Gamma/dq^2}$





$B \to X_c \tau^- \bar{\nu}_\tau$

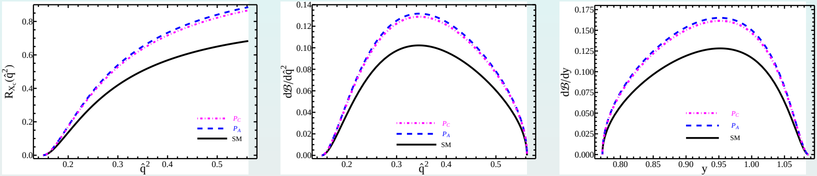
$R(X_c) = \frac{\mathcal{B}(\bar{B} \to X_c \tau \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu}_\ell)}$, calculated with OPE, with $\mathcal{B}(B^- \to X_c e \bar{\nu}_e) = (10.92 \pm 0.16)\%$

F. U. Bernlochner *et al.* Phys. Rev. D85 (2012) 094033

Observable	SM	P_A	P_C
$R(X_c)$	0.230	0.297	0.290
$\mathcal{B}(B^- \to X_c \tau^- \bar{\nu}_\tau)$	2.51%	3.24%	3.17%

Our SM value of $R(X_c)$ is roughly consistent with $R(X_c) = 0.223 \pm 0.004$.

Z. Ligeti *et al.*, Phys. Rev. D90 (2014) 034021



Conclusion

- The scalar leptoquark can solve the $R(D^{(*)}), R_K$ and $(g-2)_\mu$ anomalies simultaneously with four best-fit solutions obtained.
- The two solutions $P_{B,D}$ are excluded by the decay $B_c^- \to \tau^- \bar{\nu}_\tau$.
- $P_{A,C}$ lead to different sign of $\mathcal{H}_{\text{fit}}$ with just 1.2% difference in $|C_V^{\text{fit}}|$, which is much larger than $|C_S^{\text{fit}}|$ and $|C_T^{\text{fit}}|$.
- The scalar ϕ could give sizeable enhancements to almost all the observables except for $P_L^\tau, P_L^{D^*}$ and A_{FB}.
- With future measurement at LHCb or at Belle-II, one could further decipher various NPs.

Thanks for your attention !!