$b \rightarrow c l \nu$ anomalies in light of vector and scalar interactions

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Charged current anomalies

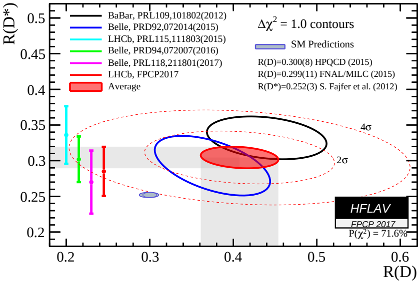
- In the precision era, flavour physics is the best probe for BSM NP. $\mathcal{R}(\mathcal{K}^{(*)})$:loop level. $\mathcal{R}(\mathcal{D}^{(*)})$, $\mathcal{R}(\mathcal{J}/\psi)$: tree level.
- Hints of Lepton flavour universality violating NP.
- Standard notation for charged current anomalies:

$$\mathcal{R}(X) = \int_{m_\tau^2}^{(m_{B_{(c)}}-m_X)^2} \frac{d\Gamma(B_{(c)} \to X\tau\nu)}{dq^2} \Big/ \int_{m_l^2}^{(m_{B_{(c)}}-m_X)^2} \frac{d\Gamma(B_{(c)} \to Xl\nu)}{dq^2}$$

- Ratio of decay widths to cancel out the form factor and CKM uncertainties.
- Model independent analyses followed by examples using models for further clarification.

Present Status: Theory and Experiment

	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	Correlation	$P_\tau(D^*)$	$\mathcal{R}(J/\psi)$
SM	0.304(3)	0.259(6)		−0.491(25)	0.249(42)(LFCQ) 0.289(28)(PQCD)
Babar	$0.440(58)_{st.}(42)_{sy.}$	$0.332(24)_{st.}(18)_{sy.}$	−0.27		
Belle (2015)	$0.375(64)_{st.}(26)_{sy.}$	$0.293(38)_{st.}(15)_{sy.}$	−0.49		
Belle (2016)-I	-	$0.302(30)_{st.}(11)_{sy.}$			
Belle (2016)-II	-	$0.270(35)_{st.}{}^{+0.028}_{-0.025}$	0.33	$-0.38(51)_{st.}{}^{+0.21}_{-0.16}$	
LHCb (2015)	-	$0.336(27)_{st.}(30)_{sy.}$			
LHCb (2017)	-	$0.286(19)_{st.}(25)_{sy.}(21)$			
World Avg.	$0.407(39)_{st.}(24)_{sy.}$	$0.304(13)_{st.}(7)_{sy.}$	0.20		$0.71(17)_{st.}(18)_{sy.}$



	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$P_\tau(D^*)$
$\mathcal{R}(D)$	1.	0.118	-0.023
$\mathcal{R}(D^*)$		1.	0.617
$P_\tau(D^*)$			1.

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Outline

$\mathcal{R}(\mathcal{D})$ and $\mathcal{R}(\mathcal{D}^*)$

- Differential decay rates for $B \to D^{(*)}\ell\nu_\ell$ (with $\ell = e$, μ or τ) with this new interaction are given by:

$$\frac{d\Gamma(\bar{B} \to D\ell\bar{\nu}_\ell)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{96\pi^3 m_B^2} q^2 p_D \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[\left|1 + C_{V_1}^l\right|^2 \left(1 + \frac{m_\ell^2}{2q^2}\right)^2 H_{V,0}^{s2} + \frac{3m_\ell^2}{2q^2} \left|1 + C_{V_1}^l + \frac{q^2}{m_\ell\,(m_b - m_c)} C_S^\ell\right|^2 H_{V,t}^{s2}\right],$$

$$\frac{d\Gamma(\bar{B} \to D^*\ell\bar{\nu}_\ell)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{96(\pi)^3 m_B^2} q^2 p_{D^*} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[(1 + \frac{m_\ell^2}{2q^2}) \left(H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2\right) \left|1 + C_{V_1}^l\right|^2 + \frac{3m_\ell^2}{2q^2} \left|1 + C_{V_1}^l + \frac{q^2}{m_\ell\,(m_b + m_c)} C_S^\ell\right|^2 H_{V,t}^2\right].$$

- FF's taken from Phys. Rev. D85 (2012) 094025.

$$\mathcal{R}_{D^{(*)}} = \left[\int_{m_\tau^2}^{q^2_{max}} \frac{d\Gamma\left(\overline{B} \to D^{(*)}\tau\overline{\nu}\right)}{dq^2} dq^2\right] \times \left[\int_{m_\ell^2}^{q^2_{max}} \frac{d\Gamma\left(\overline{B} \to D^{(*)}\ell\overline{\nu}\right)}{dq^2} dq^2\right]^{-1}.$$

Outline

$\mathcal{R}(\mathcal{J}/\psi)$

- Differential decay rate for $\bar{B} \to J/\psi \ell \bar{\nu}_\ell$ (with $\ell = e$, μ or τ):

$$\frac{d\Gamma(\bar{B}_c \to J/\psi \ell \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2 |V_{cb}|^2}{96(\pi)^3 m_B^2} q^2 p_{J/\psi} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) \left(H_{J,+}^2 + H_{J,-}^2 + H_{J,0}^2\right) \left|1 + C_{V_1}^l\right|^2 + \frac{3m_\ell^2}{2q^2} \left|1 + C_{V_1}^l + \frac{q^2}{m_\ell (m_b + m_c)} C_S^\ell \right|^2 H_{J,t}^2 \right].$$

- Theoretical predictions heavily dependent on Form factors.
- Experiment: Phys. Rev. D79 (2009) 013008: fit results unavailable.
- PQCD:Chin. Phys. C37 (2013) 093102, constituent quark model:Phys. Lett. B452 (1999) 129-136, relativistic quark model:Phys. Rev. D68 (2003) 094020, non-relativistic quark model:Phys. Rev. D74 (2006) 074008, QCD sum rules:hep-ph/0211021, relativistic constituent quark model:Phys. Rev. D73 (2006) 054024 and LFCQ:Phys. Rev. D79 (2009) 054012.
- In this work we use PQCD (max value) and LFCQ (min. value)

Outline

$P_\tau(D^*)$

- Phys. Rev. Lett. 118 (2017) 211801: First ever measurement of the τ lepton polarization (BELLE)
- Imprecise, consistent with SM. Included due to correlation with $\mathcal{R}(D^*)$ in same work.

$$P_\tau(D^*) = \frac{\Gamma^{\lambda_\tau=1/2} - \Gamma^{\lambda_\tau=-1/2}}{\Gamma^{\lambda_\tau=1/2} + \Gamma^{\lambda_\tau=-1/2}}.$$

$$\frac{d\Gamma^{\lambda_\tau=+1/2}(\bar{B}\to D^*\tau\bar{\nu})}{dq^2} = \frac{G_F^2|V_{cb}|^2}{96(\pi)^3 m_B^2} q^2 p_{D^*}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \frac{m_\tau^2}{2q^2}\left[\frac{1}{2}\left|1+C_{V_1}^l\right|^2 \left(H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2\right) + 3(1+\frac{q^2}{m_\tau\left(m_b+m_c\right)}C_S^\tau)^2 H_{V,t}^2\right],$$

$$\frac{d\Gamma^{\lambda_\tau=-1/2}(\bar{B}\to D^*\tau\bar{\nu})}{dq^2} = \frac{G_F^2|V_{cb}|^2}{96(\pi)^3 m_B^2} q^2 p_{D^*}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \left|1+C_{V_1}^l\right|^2 \left[\left(H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2\right)\right].$$

Outline

$B_c \to \tau\nu_\tau$

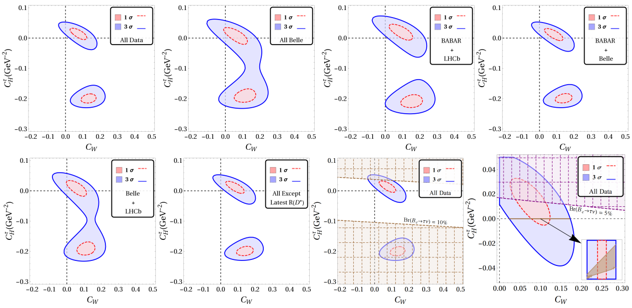
- Strong constraint for scalar type NP in $b \to c\tau\nu$ decays (Phys. Rev. Lett. 118 (2017) 081802).
- Branching fraction of $B_c \to \tau\nu$:

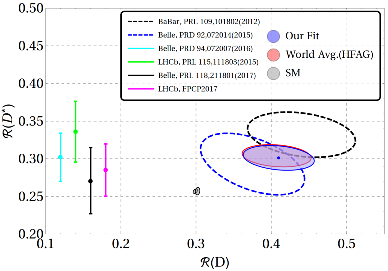
$$\mathcal{B}(B_c \to \tau\nu) = \tau_{B_c} \frac{m_{B_c} m_\tau^2 f_{B_c}^2 G_F^2 \left|V_{cb}\right|}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left|1 + C_{V_1}^l - \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} C_S^\tau\right|^2 , \quad (1)$$

- $f_{B_c} = 0.434(15)$GeV and $\tau_{B_c} = 0.507(9)$ps.
- $\Gamma_{B_c} \lesssim 30\%$: Relaxed limit (Phys. Rev. Lett. 118 (2017) 081802).
- $\Gamma_{B_c} \lesssim 10\%$, LEP data at Z peak: Aggressive limit (Phys. Rev. D96 (2017) 075011). Even tighter bound considering full L3 data.
- Our analysis: Relaxed→Full B_c lifetime, Aggressive→ $\Gamma_{B_c} \lesssim 10\%$

Outline

Analysis:Vector and Scalar(Figures)



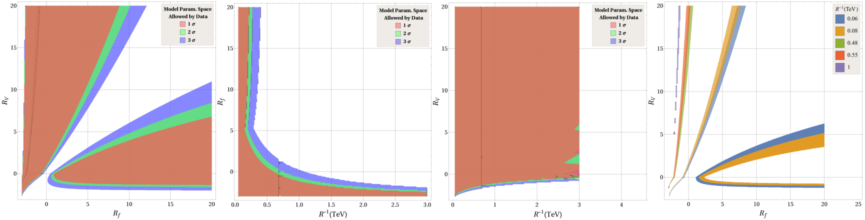


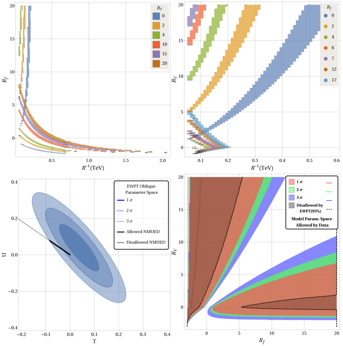
Analysis:Vector and Scalar(Table)

Data	χ^2_{min}	d.o.f	p-value	C_W	C_H^τ (in GeV^{-2})	Correlation
All Data	**2.935**	**6**	**81.694**	**0.076(32)**	**0.015(12)**	**-0.702**
All Belle	0.349	2	83.98	0.060(46)	0.010(18)	-0.715
Babar + LHCb	1.057	2	58.941	0.091(45)	0.022(17)	-0.687
Babar + Belle	2.652	4	61.77	0.084(36)	0.013(13)	-0.728
Belle + LHCb	0.398	4	98.264	0.057(39)	0.011(17)	-0.678
All Except Latest LHCb	2.662	5	75.191	0.084(36)	0.013(13)	-0.728

- Inclusion of BaBar Data: Fits worsen
- Best Result: Belle+LHCb
- Tension between BaBar and Belle & LHCb.

Example:NMUED

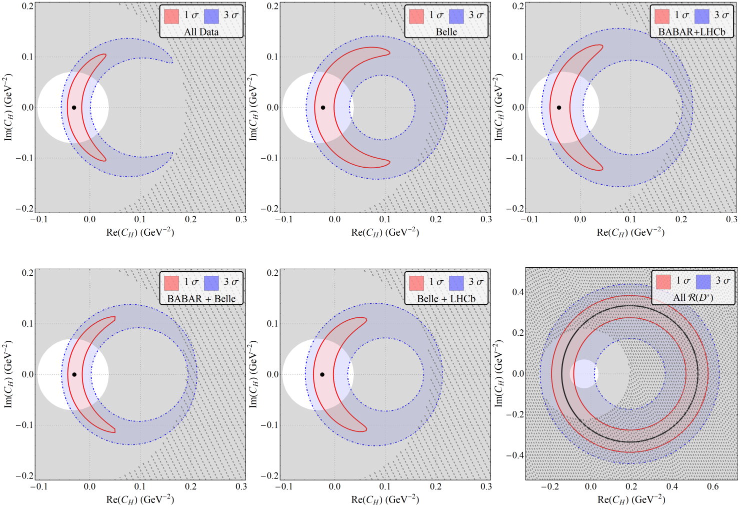




- $C_W = \sum_{n\geq 2} \frac{l_n^2 M_W^2}{M_{W(n)}^2}$, $C_S^l = m_b m_l C_H^l$
- $C_H^l = \sum_{n\geq 2} \frac{l_n^2 m_{V(n)}^2}{M_{W(n)}^4}$
  $\times [\cos(c(n)-l(n)) - \sin(c(n)+l(n))]$
- $l_n = \frac{\sqrt{2}\sqrt{1+\frac{R_V}{\pi R}}}{\left(1+\frac{R_f}{\pi R}\right)\sqrt{1+\frac{R_V^2 m_{V(n)}^2}{4}+\frac{R_V}{\pi R}}} \frac{(R_f - R_V)}{\pi R}$
- $\delta G_F = \sum_{n\geq 2} \frac{g_2^2 l_n^2}{4\sqrt{2} M_{W(n)}^2}$
- $S = 0,\ T = -\frac{1}{\alpha}\frac{\delta G_F}{G_F},\ U = \frac{4\sin^2\theta_W}{\alpha}\frac{\delta G_F}{G_F}$

Outline

Analysis:Scalar(Figures)



Analysis:Scalar(Table)

Datasets	Without $\mathcal{R}_{J/\psi}$		With $\mathcal{R}_{J/\psi}$				Fit Results	
			PQCD		LFCQ			
	χ^2_{min} /DoF	p-value (%)	χ^2_{min} /DoF	p-value (%)	χ^2_{min} /DoF	p-value (%)	Re(C_H) (GeV^{-2})	Im(C_H) (GeV^{-2})
All Data	9.22/8	23.72	11.86/9	15.76	12.38/9	13.51	-0.031(8)	0.000(73)
Belle	1.71/4	63.54	4.39/5	35.63	4.89/5	29.83	-0.023(11)	0.000(87)
Babar+LHCb	6.42/3	4.03	9.00/4	2.92	9.54/4	2.29	-0.042(11)	0.000(84)
Babar+ Belle	6.71/6	24.31	9.35/7	15.48	9.87/7	13.03	-0.030(8)	0.000(74)
Belle + LHCb	4.70/6	45.41	7.37/7	28.82	7.88/7	24.72	-0.025(11)	0.000(78)
All $\mathcal{R}_{D*}$	2.37/5	66.78	4.31/6	50.53	4.99/6	41.67	-	-
No $P_\tau(D^*)$	9.21/7	16.23	11.84/8	10.58	12.36/8	8.92	-0.031(8)	0.000(72)

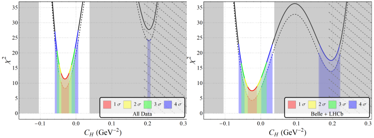
- $\mathcal{R}_{J/\psi}$ pull in opposite direction to $\mathcal{R}_{D^{(*)}}$
- PQCD fits better than LFCQ since the former lies close to experimental value.
- Illustrative case: All Data: $\chi^2_{\rm SM} = 22.82$, 2.87σ from best-fit point.

Example:GM and LQ

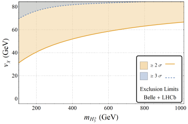
- GM Model:

$$C_S^{\ell} = -C_H\, m_b\, m_\ell = -\frac{\tan^2\theta_H}{m^2_{H_3^{\pm}}} m_b\, m_\ell,$$

$$\tan\theta_H = \frac{2\sqrt{2}\, v_\chi}{v_\phi}$$



Phys. Rev. D91 (2015) 015013



- LQ Model:

$$C^{l}_{S_1}(\mu_b) = \left[\frac{\alpha_s(m_t)}{\alpha_s(\mu_b)}\right]^{\frac{\gamma_S}{2\beta_0^{(5)}}} \left[\frac{\alpha_s(m_{\mathrm{LQ}})}{\alpha_s(m_t)}\right]^{\frac{\gamma_S}{2\beta_0^{(6)}}} C^{kl}_{S_1}(m_{\mathrm{LQ}})$$

$$= -\left[\frac{\alpha_s(m_t)}{\alpha_s(\mu_b)}\right]^{\frac{\gamma_S}{2\beta_0^{(5)}}} \left[\frac{\alpha_s(m_{\mathrm{LQ}})}{\alpha_s(m_t)}\right]^{\frac{\gamma_S}{2\beta_0^{(6)}}}$$

$$\frac{1}{2\sqrt{2} G_F V_{cb}} \sum_{k=1}^{3} V_{k3} \left[\frac{2 g^{kl}_{2L} g^{23*}_{2R}}{M^2_{V_2^{1/3}}}\right].$$

Data	$\mathrm{Re}\left(g^{33}_{2L} g^{23*}_{2R}\right)$	$\mathrm{Im}\left(g^{33}_{2L} g^{33*}_{2R}\right)$
All Data	−0.250(64)	0.0(6)
Belle	−0.186(90)	0.0(7)
Babar+LHCb	−0.338(89)	0.0(7)
Babar + Belle	−0.245(65)	0.0(6)
Belle + LHCb	−0.198(88)	0.0(6)
No P_τ (D^*)	−0.250(64)	0.0(6)

Summary and Conclusions

- Real vector and scalar WC: NMUED. Real scalar WC: GM. Complex scalar WC: LQ.
- Real vector+scalar and complex WC: allowed by the available data and constraints such as $\mathcal{B}(B_c \to \tau\nu)$.
- Preceding Wilson coefficient, if real, has to be positive to yield better fits to the data than the SM.
- However, models with extended Higgs sector: $\tan^2\theta_H/m^2_{H_3^\pm}$ with an overall negative sign.
- Present data for charged current anomalies disfavor all models with extended Higgs sector at $\sim 3\sigma$.
- Tension between BaBar and Belle, LHCb. More correlated R_D, R_{D^*} measurments welcome.

Thank You