Distinguishing New Physics Models in $\bar{B} \to D^* \tau \bar{\nu}$

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Based on arXiv:1606.03164 with Ashutosh Alok, Dinesh Kumar and Suman Kumbhakar

Talk at Pheno-2017 at University of Pittsburgh

9 May 2017

R_{D^*} Puzzle

- It is assumed that New Physics (NP) mediated by scalars, couples more strongly to third generation particles compared to first or second generation.
- Hence the decays of B mesons to τ leptons are particularly interesting to study such scalar NP.
- The ratios of the semi-leptonic decay modes:

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

  were considered because a number of systematic effects (both theoretical and experimental) cancel in these ratios.
- The theoretical uncertainty in predicting these ratios in the SM is expected to be about $2-3\%$, much smaller than the form factor uncertainties. (arXiv:1503.07237 [hep-lat], arXiv:1505.03925 [hep-lat] and arXiv:1203.2654 [hep-lat]).

R_{D^*} Puzzle

- R_D and R_{D^*} were measured by BaBar (2007 - 2013) and Belle (2009 - 2016) Collaborations.
- They report

$$R_D = 0.391 \pm 0.041 \pm 0.028 \ (0.300 \pm 0.010)$$
$$R_{D^*} = 0.322 \pm 0.018 \pm 0.012 \ (0.252 \pm 0.005)$$

  Heavy Flavor Averaging Group (HFAG) Collaboration,
  http://www.sclac.stanford.edu/xorg/hfag/semi/eps15/eps15_dtaunu.htm

- These numbers are larger than the SM expectations by about 3.5 σ.
- This is called the R_D/R_{D^*} puzzle and it is known since 2012.
- In 2015, LHCb aslo has seen this discrepancy.
- In 2016, Belle used $\tau \to \pi \nu_\tau$ to tag τ. They do not see a discrepancy in this measurement. However, the uncertainty in this method is much larger than those of the previous measurements.

Effective Hamiltonian

- The most general New Physics (NP) effective Hamiltonian for $b \to c\tau\bar{\nu}_\tau$ transition is

$$H_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[O_{V_L} + \frac{\sqrt{2}}{4G_F V_{cb}} \frac{1}{\Lambda^2} \left\{ \sum_i \left(C_i O_i + C_i^{'} O_i^{'} + C_i^{''} O_i^{''} \right) \right\} \right], \quad (1)$$

  where Λ, the scale of NP is assumed to be 1 TeV. (arXiv:1506.08896 [hep-ph])

- In the above $H_{\rm eff}$, the operator O_{V_L} is the SM operator responsible for the quark level transition $b \to c\tau\nu_\tau$. It has the usual $(V - A) * (V - A)$ structure.

New Physics Operators

- The other operators O_i, $O_i^{'}$ and $O_i^{''}$ have, in general all other possible Lorentz structures.
- In general, they can be of three types: products of vectors/axial-vectors, products of scalar/pseudo-scalars or products of tensors.
- Unprimed operators couple a quark bilinear to a lepton bilinear.
- Primed operators couple a bilinear of form $\bar{\tau}\Gamma b$ to the bilinear $\bar{c}\Gamma\nu$.
- Double primed operators couple a bilinear of form $\bar{\tau}\Gamma c^c$ to $\bar{b}^c\Gamma\nu$.
- The primed and double primed operators arise from leptoquark models.

Complete list of New Physics Operators

	Operator		Fierz identity
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$		
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$		
$\mathcal{O}_{T}$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$		
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$\mathcal{O}_{V_L}$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$-2\mathcal{O}_{S_R}$
$\mathcal{O}'_{S_R}$	$(\bar{\tau} P_R b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{V_R}$
$\mathcal{O}'_{S_L}$	$(\bar{\tau} P_L b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$
$\mathcal{O}'_{T}$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow$	$-6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$-\mathcal{O}_{V_R}$
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$-2\mathcal{O}_{S_R}$
$\mathcal{O}''_{S_R}$	$(\bar{\tau} P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow$	$\frac{1}{2}\mathcal{O}_{V_L}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau} P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$
$\mathcal{O}''_{T}$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow$	$-6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$

New Physics Solutions to R_{D^*} Puzzle

The authors of arXiv:1506.08896, did a fit of NP couplings to data.

Coefficient(s)	Best fit value(s)	$\langle f_L(q^2) \rangle$
C_{V_L}	0.18 ± 0.04	0.46 ± 0.03
C_{V_L}	-2.88 ± 0.04	0.46 ± 0.03
C_T	0.52 ± 0.02,	0.16 ± 0.03
C_T	-0.07 ± 0.02 ,	0.45 ± 0.03
C''_{S_L}	-0.46 ± 0.09	0.46 ± 0.03
$(C_{S_R},\ C_{S_L})$	$(1.25, -1.02)$,	0.41 ± 0.03
$(C_{S_R},\ C_{S_L})$	$(-2.84, 3.08)$	0.76 ± 0.03
$(C'_{V_R},\ C'_{V_L})$	$(-0.01, 0.18)$	0.46 ± 0.03
$(C'_{V_R},\ C'_{V_L})$	$(0.01, -2.88)$	0.46 ± 0.03
$(C''_{S_R},\ C''_{S_L})$	$(0.35, -0.03)$	0.46 ± 0.03
$(C''_{S_R},\ C''_{S_L})$	$(0.96, 2.41)$	0.32 ± 0.03
$(C''_{S_R},\ C''_{S_L})$	$(-5.74, 0.03)$	0.46 ± 0.03
$(C''_{S_R},\ C''_{S_L})$	$(-6.34, -2.39)$	0.40 ± 0.03

Distinguishing between different Solutions

- The question now becomes: How to distinguish between different NP solutions?
- We consider the predictions of each NP mode to the related pure leptonic decay mode $B_c \to \tau\nu_\tau$.
- In the SM, this mode is helicity suppressed and the decay rate is quite small.
- If the NP operators of the form O_{V_L} or O_{V_R}, the helicity suppression is still operative and this leptonic mode will not be able to make any distinction.
- But, if the NP operators are scalar dominated, then helicity suppression is no longer operative and the NP operators lead to a large rate for this leptonic decay.
- Based on this argument, we can rule out the two solutions $(C''_{S_R}, C''_{S_L}) = (0.96, 2.41)$ and $(-6.34, -2.39)$, because they predict that the partial decay rate $\Gamma(B_c \to \tau\nu_\tau)$ is larger than the measured total decay rate of B_c.

Angular Observables in Vector Semi-leptonic Decays

- Various authors have done the full angular distribution calculation for the decay $B \to K^*(\to K\pi)l^+l^-$. We apply the same discussion to $B \to D^*\tau\nu_\tau$
- In the rest frame of $D^*(\to D\pi)$, one can define three angles:
  1. θ_τ, which is angle between p_B and p_τ,
  2. θ_D, which is the angle between p_B and p_D,
  3. ϕ, which is angle between the two planes defined by the momenta of $\tau - \nu_\tau$ and $D - \pi$.
- Since the τ momentum was not reconstructed so far, it is not possible to look at distributions in θ_τ and in ϕ but it is possible to look at the distribution in θ_D.

D^* Polarization as a discriminant

- The angular distribution in θ_D is given by

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = \frac{1}{4}\frac{d\Gamma}{dq^2}\left[2 f_L(q^2)\cos^2\theta_D + \right. \\ \left. + \{1 - f_L(q^2)\}\sin^2\theta_D\right],$$

  where

$$f_L(q^2) = \frac{A_L(q^2)}{A_L(q^2) + A_T(q^2)},$$

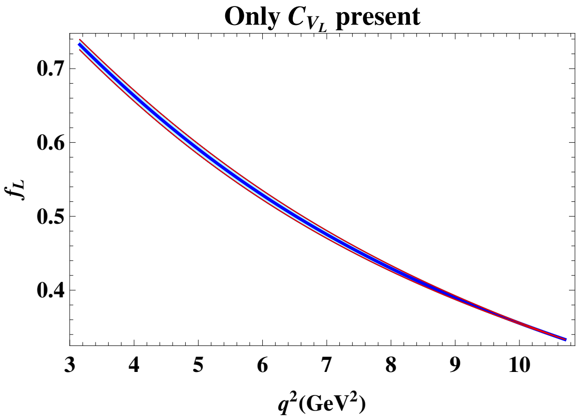
  is called the D^* polarization fraction.
- $A_L(q^2)$ and $A_T(q^2)$ are the amplitudes for the D^* meson to have longitudinal and transverse polarizations respectively.
- It was shown, in the case of $B \to K^* l^+ l^-$ that $f_L(q^2)$ has much weaker form factor dependence than the overall decay rate Γ and also the differential decay rate $d\Gamma/dq^2$.

D^* Polarization as a discriminant

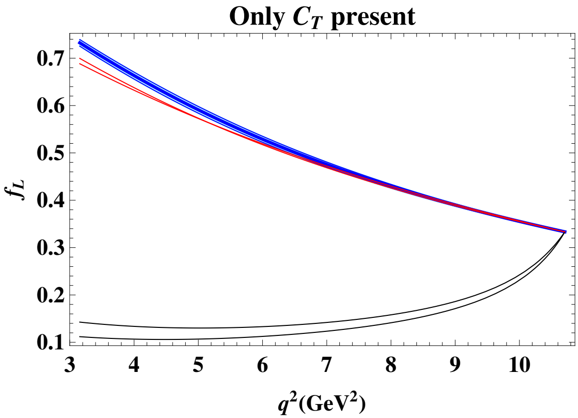
- We computed $f_L(q^2)$ and also $\langle f_L(q^2)\rangle$, for all the allowed NP couplings computed in arXiv:1506.08896.
- In the cases where the NP operators or their Fierz transformed forms have the same structure as the SM operators ($\mathcal{O}_{V_L}$), the plots for $f_L(q^2)$ are identical to those of the SM.
- But for the cases, where the NP couplings are of scalar or tensor form, both $f_L(q^2)$ as well as $\langle f_L(q^2)\rangle$ differ substantially from the SM values.

Coefficient(s)	Best fit value(s)	$\langle f_L(q^2)\rangle$
C_{V_L}	-2.88 ± 0.04	0.46 ± 0.03
C_T	0.52 ± 0.02,	0.16 ± 0.03
$(C_{S_R},\ C_{S_L})$	$(-2.84, 3.08)$	0.76 ± 0.03

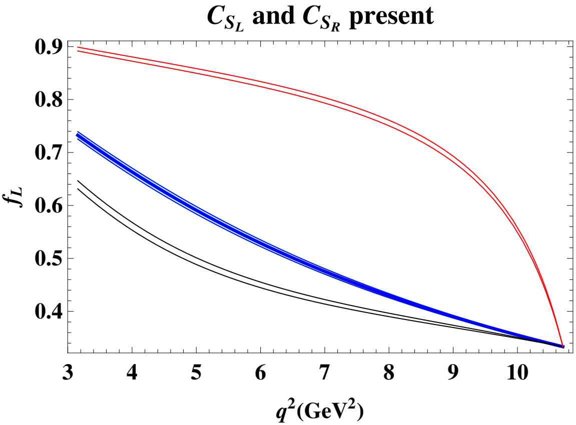
$f_L(q^2)$ with NP in the form of C_{V_L} Couplings



$f_L(q^2)$ with NP in the form of C_T Couplings



$f_L(q^2)$ with NP in the form of $C_{S_L} - C_{S_R}$ Couplings



Conclusions

- R_D and R_{D^*} (along with R_K and R_{K^*}) seem to point to lepton non-universality.
- Freytsis *et al* (arXiv:1506.08896 [hep-ph]) have done a fit of all NP operators which can explain the discrepancy and also give a fit to $d\Gamma/dq^2$.
- Solutions with pseudo-scalar NP operators are ruled out because they predict $\Gamma(B_c \to \tau\nu_\tau)$ to be greater than the measured total decay width of B_c.
- Solutions with tensor NP operatos predict a value 0.16 for $\langle f_L(q^2)\rangle$ compared to SM prediction 0.46.
- Belle Collaboration is in the process of measuring $\langle f_L(q^2)\rangle$. The expected uncertainty in the measurement is 0.1.
- Hence $\langle f_L(q^2)\rangle$ provides a good discrimination for solutions with NP operators of tensor form.