New physics in baryonic $b \rightarrow c$ modes

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One of the main goals in $B$ physics experiments is to find new physics (NP) by observing deviations from the standard model (SM) predictions. Hints of deviation in $\bar{B} \rightarrow D^+ \tau^- \bar{\nu}_\tau$ and $\bar{B} \rightarrow D^{\ast +} \tau^- \bar{\nu}_\tau$.

Implication of these deviations in $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ decays since the underlying transition in both baryon and meson decays is $b \rightarrow c \tau^- \bar{\nu}_\tau$. (arXiv:1502.07230 [New Physics], arXiv:1502.04864 [SM])

Parametrization of new physics and discussion on models.

Form factors and SM predictions in $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$.

Helicity amplitudes and angular distribution with new physics operators.

Results for rates and differential distributions.
Experiments

Recently, the BaBar, Belle and LHCb have reported the following measurements:

\[
R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)} = 0.440 \pm 0.058 \pm 0.042,
\]

\[
R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*-} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*-} \ell^- \bar{\nu}_\ell)} = 0.332 \pm 0.024 \pm 0.018. \tag{1}
\]

Belle and LHCb

\[
R(D) \equiv = 0.375 \pm 0.064 \pm 0.026,
\]

\[
R(D^*) \equiv = 0.293 \pm 0.038 \pm 0.015, 0.336 \pm 0.027 \pm 0.030. \tag{2}
\]

Average and Theory

\[
R(D) \equiv = 0.391 \pm 0.041 \pm 0.028, 0.300 \pm 0.01,
\]

\[
R(D^*) \equiv = 0.322 \pm 0.018 \pm 0.011, 0.252 \pm 0.005. \tag{3}
\]

\[
\frac{d\Gamma}{dq^2}
\] is also measured.
Semileptonic $\Lambda_b$ rates are of the same size as $B$ semileptonic Decays.

$\Lambda_b \rightarrow \Lambda_c l^- \bar{\nu}_l X$ is $10.7 \pm 2.2 \%$, $B^0 \rightarrow X_c e^+ \nu = 10.1 \pm 0.4 \%$.

$\Lambda_b \rightarrow \Lambda_c l \bar{\nu}_l$ is $6.2^{+1.4}_{-1.2} \%$.

Hadron machines can measure $\Lambda_b$ Decays. Better measurements of $\Lambda_b \rightarrow \Lambda_c l \bar{\nu}_l$ and $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ with the differential distribution is desirable.

Note effects in $R(D^{(*)})$ are large so effects in $\Lambda_b$ decays can be large enough and go beyond form factor uncertainties.

Measurement of $R(D^{(*)})$ is larger than the SM value. Can the corresponding ratio for $\Lambda_b$ decay be less than the SM value for some new physics?
Model independent NP analysis

- Effective Hamiltonian for $b \rightarrow c\tau^-\bar{\nu}_{\tau}$ with Non-SM couplings

\[
\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[ (1 + g_L) [\bar{c} \gamma_\mu P_L b] \, [\bar{\tau} \gamma_\mu P_L \nu_l] + g_R [\bar{c} \gamma_\mu P_R b] \, [\bar{\tau} \gamma_\mu P_L \nu_l] + S_L [\bar{c} P_L b] \, [\bar{\tau} P_L \nu_l] + S_R [\bar{c} P_R b] \, [\bar{\tau} P_L \nu_l] + T_L [\bar{c} \sigma^{\mu\nu} P_L b] \, [\bar{\tau} \sigma^{\mu\nu} P_L \nu_l] \right].
\]

- Dropping tensor interactions

\[
\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[ (1 + g_L) [\bar{c} \gamma_\mu P_L b] \, [\bar{\tau} \gamma_\mu P_L \nu_l] + g_R [\bar{c} \gamma_\mu P_R b] \, [\bar{\tau} \gamma_\mu P_L \nu_l] + g_S [\bar{c} b] \, [\bar{\tau} (1 - \gamma_5) \nu_l] + g_P [\bar{c} \gamma_5 b] \, [\bar{\tau} (1 - \gamma_5) \nu_l] \right].
\]
Models of NP, See for e.g. arXiv:1506.08896

Scalar Type: Most discussed is the Two Higgs Doublet Model II:
In $\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau$ and $\bar{B} \to D^+ \tau^- \bar{\nu}_\tau$ the relevant interaction from charged Higgs is

$$\mathcal{A} \sim \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_H^2} \left[ \frac{m_c}{m_W} \cot \beta \bar{c} P_L b + \frac{m_b}{m_W} \tan \beta \bar{c} P_R b \right] \frac{m_\tau}{m_W} \tan \beta \bar{\nu}_\tau P_L \tau,$$

$$\sim \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_H^2} \left[ \frac{m_b m_\tau}{m_W^2} \tan^2 \beta \right] \bar{c} P_R b \bar{\nu}_\tau P_L \tau.$$

Only the RH quark interactions survive. This causes problems to explain the data.
Models of NP, Scalar- Tensor Type

Scalar and Tensor operators can be generated from scalar leptoquarks: The interaction Lagrangian that induces contributions to the $b \rightarrow c \ell \nu$ process is (Tanaka:2012nw)

$$\mathcal{L}_{2}^{LQ} = \left( g_{2L}^{ij} \bar{u}_{iR} R_{2}^{T} L_{jL} + g_{2R}^{ij} \bar{Q}_{iL} i\sigma_{2} \ell_{jR} R_{2} \right),$$
$$\mathcal{L}_{0}^{LQ} = \left( g_{1L}^{ij} \bar{Q}_{iL} i\sigma_{2} L_{jL} + g_{1R}^{ij} \bar{u}_{iR} \ell_{jR} \right) S_{1},$$

After performing the Fierz transformations, one finds the general Wilson coefficients at the leptoquark mass scale contributing to the $b \rightarrow c \tau \nu_{\ell}$ process:

$$S_{L} = \frac{1}{2\sqrt{2}G_{F}V_{cb}} \left[ -\frac{g_{1L}^{33} g_{1R}^{23^{*}}}{2M_{S_{1}}^{2}} - \frac{g_{2L}^{23} g_{2R}^{33^{*}}}{2M_{R_{2}}^{2}} \right],$$
$$T_{L} = \frac{1}{2\sqrt{2}G_{F}V_{cb}} \left[ \frac{g_{1L}^{33} g_{1R}^{23^{*}}}{8M_{S_{1}}^{2}} - \frac{g_{2L}^{23} g_{2R}^{33^{*}}}{8M_{R_{2}}^{2}} \right].$$
Models of NP, Vector Interactions

- In effective theory framework, we can write operators invariant under the SM gauge group.

\[
\mathcal{O}^{(1)}_{NP} = G_1 (\bar{Q}_L \gamma_\mu Q_L) (\bar{L}_L \gamma^\mu L_L),
\]

\[
\mathcal{O}^{(2)}_{NP} = G_2 (\bar{Q}_L \gamma_\mu \sigma^I Q_L) (\bar{L}_L \gamma^\mu \sigma^I L_L).
\]

These operators can come from a $Z'$ or $W'$ and just modify the SM interactions (\( g_L \)). (See e.g. e-Print: arXiv:1506.01705)

- Because of their structure, there are effects and constraints from other $b$ and $t$ decays.

- Prediction:

\[
\left[ \frac{R(D)}{R(D^*)} \right]_{\text{expt}} \quad (1.21) = \left[ \frac{R(D)}{R(D^*)} \right]_{SM} \quad (1.19).
\]
Models of NP, Vector Interactions

- The same modification to the SM interactions also comes from triplet leptoquarks:

\[ \mathcal{L}^{LQ} = h_{3i}^{ij} \bar{Q}_i \gamma^\mu \vec{\sigma} \cdot L_j \bar{U}_3 \mu + g_{3i}^{ij} \bar{Q}_i \sigma_2 \vec{\sigma} \cdot L_j \bar{S}_3. \]

- For \( b \rightarrow c \tau^- \bar{\nu}_\tau \) with vector triplet leptoquark:

\[ \mathcal{L}^{LQ}_{CC} = \frac{h_{3i}^{23} h_{3}^{33*}}{4 M_{U3}^2} [\bar{c} \gamma^\mu (1 - \gamma_5) b] [\bar{\tau} \gamma^\mu (1 - \gamma_5) \nu_\tau]. \]

- For \( b \rightarrow c \tau^- \bar{\nu}_\tau \) with scalar triplet leptoquark:

\[ \mathcal{L}^{LQ}_{CC} = \frac{g_{3i}^{23} g_{3}^{33*}}{4 M_{S3}^2} [\bar{c} \gamma^\mu (1 - \gamma_5) b] [\bar{\tau}_c \gamma^\mu (1 + \gamma_5) \tau_c]. \]
Formalism ◇ Decay Process

\[ \Lambda_b(p_{\Lambda_b}) \rightarrow \tau^-(p_1) + \bar{\nu}_\tau(p_2) + \Lambda_c(p_{\Lambda_c}) \]

SM

NP
The decay and helicity angles for $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ and $\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell$ are (See 1502.04864)

$$\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda \pi) W^*- (\rightarrow \ell^- \bar{\nu}_\ell)$$
Decay Process

The process under consideration is

\[ \Lambda_b(p\Lambda_b) \rightarrow \tau^- (p_1) + \bar{\nu}_\tau (p_2) + \Lambda_c(p\Lambda_c). \]

In the SM the amplitude for this process is

\[ M_{SM} = \frac{G_F V_{cb}}{\sqrt{2}} L^\mu H_\mu, \]

where the leptonic and hadronic currents are,

\[ L^\mu = \bar{u}_\tau (p_1) \gamma^\mu (1 - \gamma_5) v_{\nu_\tau} (p_2), \]

\[ H_\mu = \langle \Lambda_c | \bar{c} \gamma^\mu (1 - \gamma_5) b | \Lambda_b \rangle. \]

The hadronic current is expressed in terms of six form factors,

\[ \langle \Lambda_c | \bar{c} \gamma^\mu \gamma_5 b | \Lambda_b \rangle = \bar{u}_{\Lambda_c} (f_1 \gamma^\mu + i f_2 \sigma_{\mu\nu} q^\nu + f_3 q^\mu) u_{\Lambda_b}, \]

\[ \langle \Lambda_c | \bar{c} \gamma^\mu \gamma_5 b | \Lambda_b \rangle = \bar{u}_{\Lambda_c} (g_1 \gamma^\mu \gamma_5 + i g_2 \sigma_{\mu\nu} q^\nu \gamma_5 + g_3 q^\mu \gamma_5) u_{\Lambda_b}. \]

Here \( q = p_{\Lambda_b} - p_{\Lambda_c} \) is the momentum transfer and the form factors are functions of \( q^2 \).
In the heavy quark limit, $m_{b,c} \to \infty$ there is only one independent form factor.

$f_1 = g_1, f_2 = g_2 = f_3 = g_3 = 0$.

In the "light" charm case, $m_b \to \infty$ and $m_c$ finite there are only two independent form factors.

$g_1 = f_1, g_2 = f_2$ and $f_3 = g_3 = f_2$ (good at small recoil).

Time component helicity amplitudes are sensitive to lepton mass effects. In $B \to D(*) l \bar{\nu}_l$ decays these helicity amplitudes and the corresponding form factors cannot be measured. In the $\Lambda_b$ case, the measurement of form factors from $\Lambda_b \to \Lambda_c l \bar{\nu}_l$ is enough to construct the time component helicity amplitudes in the $m_b \to \infty$ but finite $m_c$ limit.

as these amplitudes depend on $f_1(g_1)$ and $f_3(g_3)$.
When considering NP operators we will use the following relations obtained by using the equations of motion.

\[
\langle \Lambda_c | \bar{c} b | \Lambda_b \rangle = \bar{u}_{\Lambda_c} \left( f_1 \frac{\hat{\phi}}{m_b - m_c} + f_3 \frac{q^2}{m_b - m_c} \right) u_{\Lambda_b},
\]

\[
\langle \Lambda_c | \bar{c} \gamma_5 b | \Lambda_b \rangle = \bar{u}_{\Lambda_c} \left( -g_1 \frac{\hat{\phi} \gamma_5}{m_b + m_c} - g_3 \frac{q^2 \gamma_5}{m_b + m_c} \right) u_{\Lambda_b}.
\]

We will define the following observable,

\[
R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}.
\]

Here \( \ell \) represents \( \mu \) or \( e \). We will also define the ratio of differential distributions,

\[
B_{\Lambda_b}(q^2) = \frac{d\Gamma[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{d\Gamma[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}.
\]
The decay $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ proceeds via $\Lambda_b \rightarrow \Lambda_c W^*$ (off-shell $W$) followed by $W^* \rightarrow \tau \bar{\nu}_\tau$. The full decay process is $\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda_s \pi) W^* (\rightarrow \tau \bar{\nu}_\tau)$. One can analyze the decay in terms of helicity amplitudes (hep-ph 9406359) which are given by

$$H_{\lambda_2 \lambda_W} = M_\mu(\lambda_2) \epsilon^{*\mu}(\lambda_W),$$

(4)

where $\lambda_2, \lambda_W$ are the polarizations of the daughter baryon and the $W$-boson respectively and $M_\mu$ is the hadronic current for $\Lambda_b \rightarrow \Lambda_c$ transition. The helicity amplitudes can be expressed in terms of form factors and the NP couplings.
\[ \begin{align*}
H_{\lambda\Lambda c,\lambda w} &= H^V_{\lambda\Lambda c,\lambda w} - H^A_{\lambda\Lambda c,\lambda w}, \\
H^V_{\frac{1}{2}0} &= (1 + g_L + g_R) \frac{\sqrt{Q_-}}{\sqrt{q^2}} \left( (M_1 + M_2) f_1 - q^2 f_2 \right), \\
H^A_{\frac{1}{2}0} &= (1 + g_L - g_R) \frac{\sqrt{Q_+}}{\sqrt{q^2}} \left( (M_1 - M_2) g_1 + q^2 g_2 \right), \\
H^V_{\frac{1}{2}1} &= (1 + g_L + g_R) \sqrt{2Q_-} \left( f_1 - (M_1 + M_2) f_2 \right), \\
H^A_{\frac{1}{2}1} &= (1 + g_L - g_R) \sqrt{2Q_+} \left( g_1 + (M_1 - M_2) g_2 \right), \\
H^V_{\frac{1}{2}t} &= (1 + g_L + g_R) \frac{\sqrt{Q_+}}{\sqrt{q^2}} \left( (M_1 - M_2) f_1 + q^2 f_3 \right), \\
H^A_{\frac{1}{2}t} &= (1 + g_L - g_R) \frac{\sqrt{Q_-}}{\sqrt{q^2}} \left( (M_1 + M_2) g_1 - q^2 g_3 \right),
\end{align*} \]

(5)

where \( Q_{\pm} = (M_1 \pm M_2)^2 - q^2 \).
The scalar and pseudo-scalar helicities associated with the new physics scalar and pseudo-scalar interactions are

\[ H^{SP}_{1/2,0} = H^P_{1/2,0} + H^S_{1/2,0}, \]
\[ H^S_{1/2,0} = g_S \frac{\sqrt{Q_+}}{m_b - m_c} \left( (M_1 - M_2)f_1 + q^2 f_3 \right), \]
\[ H^P_{1/2,0} = -g_P \frac{\sqrt{Q_-}}{m_b + m_c} \left( (M_1 + M_2)g_1 - q^2 g_3 \right). \]

The parity related amplitudes are,

\[ H^S_{\lambda_{\Lambda_c},\lambda_{NP}} = H^S_{-\lambda_{\Lambda_c},-\lambda_{NP}}, \]
\[ H^P_{\lambda_{\Lambda_c},\lambda_{NP}} = -H^P_{-\lambda_{\Lambda_c},-\lambda_{NP}}. \]
With the $W$ boson momentum defining the positive z-axis for the decay process ($\Lambda_b \rightarrow \Lambda_c \tau^- \nu_\tau$), the twofold angular distribution can be written as

$$
\frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \tau^- \nu_\tau)}{dq^2 d(\cos \theta_L)} = \frac{G_F^2 |V_{cb}|^2 q^2 |p_{\Lambda_c}|}{512\pi^3 M_1^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \left[ A_{1}^{SM} + \frac{m_l^2}{q^2} A_{2}^{SM} + 2A_{3}^{NP} + \frac{4m_l}{\sqrt{q^2}} A_{4}^{Int}\right]
$$

\begin{align*}
A_{1}^{SM} &= 2\sin^2 \theta_L(|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) + (1 - \cos \theta_L)^2 |H_{1/2,1}|^2 \\
&\quad + (1 + \cos \theta_L)^2 |H_{-1/2,-1}|^2, \\
A_{2}^{SM} &= 2\cos^2 \theta_L(|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) + \sin^2 \theta_L(|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2) \\
&\quad + 2(|H_{1/2,t}|^2 + |H_{-1/2,t}|^2) - 4\cos \theta_L \text{Re}[H_{1/2,t} (H_{1/2,0})^* + H_{-1/2,t} (H_{-1/2,0})^*] \\
A_{3}^{NP} &= |H^{SP}_{1/2,0}|^2 + |H^{SP}_{-1/2,0}|^2, \\
A_{4}^{Int} &= -\cos \theta_L \text{Re}[H_{1/2,0} (H^{SP}_{1/2,0})^* + H_{-1/2,0} (H^{SP}_{-1/2,0})^*] \\
&\quad + \text{Re}[H_{1/2,t} (H^{SP}_{1/2,0})^* + H_{-1/2,t} (H^{SP}_{-1/2,0})^*].
\end{align*}

$\theta_L$ is the angle of the lepton in the $W^*$ rest frame.
After integrating out $\cos \theta_I$, 

$$
\frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \tau^- \nu_\tau)}{dq^2} = \frac{G_F^2 |V_{cb}|^2 q^2 |p\Lambda_c|}{192\pi^3 M_1^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \left[B_1^{SM} + \frac{m_l^2}{2q^2} B_2^{SM} + \frac{3}{2} B_3^{NP} + \frac{3m_l}{\sqrt{q^2}} B_4^{Int}\right]
$$

where,

$$
B_1^{SM} = |H_{1/2,0}|^2 + |H_{-1/2,0}|^2 + |H_{1/2,1}|^2 + |H_{-1/2,-1}|^2,
$$

$$
B_2^{SM} = |H_{1/2,0}|^2 + |H_{-1/2,0}|^2 + |H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 + 3(|H_{1/2,t}|^2 + |H_{-1/2,t}|^2),
$$

$$
B_3^{NP} = |H_{1/2,0}^{SP}|^2 + |H_{-1/2,0}^{SP}|^2,
$$

$$
B_4^{Int} = \text{Re}[(H_{1/2,t} (H_{1/2,0}^{SP})^* + H_{-1/2,t} (H_{-1/2,0}^{SP})^*)].
$$

$B_1^{SM}, B_2^{SM}, B_3^{NP}$, and $B_4^{Int}$ are the standard model non-spin-flip, standard model spin-flip, new physics, and interference terms, respectively.
The four fold angular distribution contains CP violating terms proportional to \( \sin \chi \).

\[
C_{1}^{SM} = 2 \sin^2 \theta_l \left( (1 + \alpha \cos \theta_s) |H_{1/2,0}|^2 + (1 - \alpha \cos \theta_s) |H_{-1/2,0}|^2 \right) \\
+ (1 + \cos \theta_l)^2 (1 - \alpha \cos \theta_s) |H_{-1/2,-1}|^2 + (1 - \cos \theta_l)^2 (1 + \alpha \cos \theta_s) \\
- \frac{4\alpha}{\sqrt{2}} \sin \theta_l \sin \theta_s \cos \chi \left( (1 + \cos \theta_l) \Re[H_{1/2,0} (H_{-1/2,-1})^*] \right) \\
+ (1 - \cos \theta_l) \Re[H_{-1/2,0} (H_{1/2,1})^*] \\
- \frac{4\alpha}{\sqrt{2}} \sin \theta_l \sin \theta_s \sin \chi \left( (1 + \cos \theta_l) \Im[H_{1/2,0} (H_{-1/2,-1})^*] \right) \\
- (1 - \cos \theta_l) \Im[H_{-1/2,0} (H_{1/2,1})^*].
\]

In the SM helicity amplitudes \( H_i \propto V_{cb} \) and so \( \Im(H_i H_j^*) = 0 \). Hence non zero such terms indicate new physics independent of form factor uncertainties. (Datta and Duraisamy, JHEP 1309 (2013) 059)
Results BaBar only

We first present the constraints on the NP couplings from $R(D^{(*)})$.

Figure: The figures show the constraints on the NP couplings taken one at a time at the 95% CL limit. When the couplings contribute to both $R(D)$ and $R(D^*)$ the green contour indicates constraint from $R(D^*)$ and blue from $R(D)$. 
We first present the constraints on the NP couplings from $R(D^{(*)})$.

**Figure:** The figures show the constraints on the NP couplings taken one at a time at the 95% CL limit. When the couplings contribute to both $R(D)$ and $R(D^*)$ the green contour indicates constraint from $R(D^*)$ and blue from $R(D)$. 
In the following we present the results for $R_{\Lambda_b}$, $\frac{d\Gamma}{dq^2}$ and $B_{\Lambda_b}(q^2)$. For the first and third observables we use different models of the form factors given in Table. For the differential distribution $\frac{d\Gamma}{dq^2}$ we present the average result over the form factors.

<table>
<thead>
<tr>
<th>QCD sum rules(hep/ph 9903326)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\Lambda_b}(SM)$</td>
<td>0.31</td>
<td>0.29</td>
<td>0.28</td>
<td>0.28</td>
<td>0.29 ± .02</td>
</tr>
</tbody>
</table>

**Table:** Values of $R_{\Lambda_b}$ in the SM

<table>
<thead>
<tr>
<th>Model</th>
<th>Gutsche, T et.al.</th>
<th>Woloshyn, R</th>
<th>Lattice, 1503.01421</th>
</tr>
</thead>
<tbody>
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<td>$R_{\Lambda_b}(SM)$</td>
<td>0.29</td>
<td>0.31</td>
<td>0.33 ± .01</td>
</tr>
</tbody>
</table>

**Table:** Values of $R_{\Lambda_b}$ in the SM
Results, Vector Operators

We start with the case where only $g_L$ is present. In this case the NP has the same structure as the SM and the SM amplitude gets modified by the factor $(1 + g_L)$. Hence, if only $g_L$ is present then

$$R_{\Lambda b} = R_{\Lambda b}^{SM} |1 + g_L|^2.$$ 

The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ is the same as the SM. If only $g_R$ is present then

$$H_{\lambda \Lambda c, \lambda w}^V = (1 + g_R) \left[ H_{\lambda \Lambda c, \lambda w}^V \right]_{SM},$$

$$H_{\lambda \Lambda c, \lambda w}^A = (1 - g_R) \left[ H_{\lambda \Lambda c, \lambda w}^A \right]_{SM}.$$ 

For the allowed $g_R$ couplings we find $R_{\Lambda b}$ is greater than the SM value. The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ is similar to the SM.
We now move to the case when only $g_{S,P}$ are present.

\[ R_{\Lambda_b} = R_{\Lambda_b}^{SM} + \left| g_P \right|^2 A_P + 2 \text{Re}(g_P) B_P, \]
\[ R_{\Lambda_b} = R_{\Lambda_b}^{SM} + \left| g_S \right|^2 A_S + 2 \text{Re}(g_S) B_S. \]

The quantities $A_{S,P}$ and $B_{S,P}$ depend on masses and form factors and they are positive. However, given the constraints on $g_{S,P}$ we can make $R_{\Lambda_b}$ only slightly less than the SM value.

The shape of the differential distribution $\frac{dR}{dq^2}$ can be different from the SM.
Max and Min deviations from SM, BaBar

<table>
<thead>
<tr>
<th>NP</th>
<th>( R_{\Lambda_b,\text{min}} )</th>
<th>( R_{\Lambda_b,\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only ( g_L )</td>
<td>0.31, ( g_L = -0.502 + 0.909 i )</td>
<td>0.44, ( g_L = -0.315 - 1.0381 i )</td>
</tr>
<tr>
<td>Only ( g_R )</td>
<td>0.30, ( g_R = -0.035 - 0.104 i )</td>
<td>0.47, ( g_R = 0.0827 + 0.829 i )</td>
</tr>
<tr>
<td>Only ( g_S )</td>
<td>0.28, ( g_S = -0.0227 )</td>
<td>0.36, ( g_S = -1.66 )</td>
</tr>
<tr>
<td>Only ( g_P )</td>
<td>0.30, ( g_P = 0.539 )</td>
<td>0.42, ( g_P = -5.385 )</td>
</tr>
</tbody>
</table>

**Table:** Minimum and Maximum values for the averaged \( R_{\Lambda_b} \).

For the lattice form factors, the range of allowed values is larger. Large effects are possible, beyond the form factor uncertainties. (Remember \( R_{\Lambda_b} = 0.29 \) (our model), \( 0.33 \pm 0.01 \) (lattice).)
Max and Min deviations from SM, Updated

<table>
<thead>
<tr>
<th>NP</th>
<th>$R_{\Lambda_b,min}$</th>
<th>$R_{\Lambda_b,max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only $g_L$</td>
<td>$0.32, g_L = 0.0476$</td>
<td>$0.41, g_L = 0.202$</td>
</tr>
<tr>
<td>Only $g_R$</td>
<td>$0.30, g_R = -0.0453 - 0.122 i$</td>
<td>$0.43, g_R = 0.0313 - 0.707 i$</td>
</tr>
<tr>
<td>Only $g_S$</td>
<td>$0.28, g_S = -1.22$</td>
<td>$0.34, g_S = 0.265$</td>
</tr>
<tr>
<td>Only $g_P$</td>
<td>$0.31, g_P = 0.684$</td>
<td>$0.39, g_P = 2.19$</td>
</tr>
</tbody>
</table>

Table: Minimum and Maximum values for the averaged $R_{\Lambda_b}$.

For the lattice form factors, the range of allowed values is larger. Large effects are possible, beyond the form factor uncertainties. (Remember $R_{\Lambda_b} = 0.29$ (our model), $0.33 \pm 0.01$ (lattice).)
Differential Distribution

Only $g_L$ Present

- SM
- NP: $g_L = -0.315 - i1.0381$
- NP: $g_L = 1 + i1.135$

Only $g_R$ Present

- SM
- NP: $g_R = 0.083 - i0.829$
- NP: $g_R = -0.1637 + i0.4662$

New physics in baryonic $b \rightarrow c$ modes

November 4, 2015
Only $g_P$ Present

$\frac{d^2\Gamma}{dq^2}(\times 10^{-6}$ GeV$^{-1}$)

$g_P$ Present

$\frac{d^2\Gamma}{dq^2}(\times 10^{-6}$ GeV$^{-1}$)

Only $g_P$ Present

$\beta_0(q^2)$

Only $g_P$ Present

$\beta_0(q^2)$
Only $g_S$ Present

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November 4, 2015
Other Observables

We can use the other helicity angles to construct additional observables:

- Using the leptonic angle we can define:

\[
A_{FB\Lambda_b}(q^2) = \frac{\left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_l \frac{d\Gamma}{dq^2}}{\int d\Gamma}\frac{d\Gamma}{dq^2}.
\]

- We can observe the \(\tau\) polarization:

\[
P^*_L(\tau)(q^2) = \frac{\frac{d\Gamma[\lambda_{\tau}=-1/2]}{dq^2} - \frac{d\Gamma[\lambda_{\tau}=1/2]}{dq^2}}{\int d\Gamma}.\]

- We can look at the azimuthal distribution and the \(\Lambda_c\) polarization:

\[
\frac{d^2\Gamma^{(2)}}{dq^2 d\chi} \frac{d^2\Gamma^{(2)}}{dq^2 d\cos\theta_B}.
\]
Conclusions and Outlook

- Hints of new physics in $\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^{+}\tau^-\bar{\nu}_\tau$.

- Another mode to look for these effects are in $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ decays as the quark level transition is the same.

- Large deviations from the SM are possible in $R_{\Lambda_b} = \frac{BR[\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell]}$ and $B_{\Lambda_b}(q^2) = \frac{\frac{d\Gamma[\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau]}{dq^2}}{\frac{d\Gamma[\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell]}{dq^2}}$. Effects are beyond form factor uncertainties.

- Additional observables including the additional helicity angles can be constructed to probe new physics.

- Azimuthal distributions can probe new sources of CP violation cleanly.

- Experimental measurements of the rates and differential distribution for $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ and $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ are desirable.