New physics in baryonic $b \to c$ modes

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Outline of Talk

- One of the main goals in B physics experiments in to find new physics (NP) by observing deviations from the standard model (SM) predictions. Hints of deviation in $\bar{B} \to D^+ \tau^- \bar{\nu}_\tau$ and $\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau$.
- Implication of these deviations in $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ decays since the underlying transition in both baryon and meson decays is $b \to c \tau^- \bar{\nu}_\tau$. (arXiv:1502.07230 [New Physics], arXiv:1502.04864 [SM])
- Parametrization of new physics and discussion on models.
- Form factors and SM predictions in $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$.
- 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 :

$$\begin{aligned} R(D) &\equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)} = 0.440 \pm 0.058 \pm 0.042 \ , \\ R(D^*) &\equiv \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+} \ell^- \bar{\nu}_\ell)} = 0.332 \pm 0.024 \pm 0.018 \ . \end{aligned} \tag{1}$$

Belle and LHCb

$$\begin{aligned} R(D) &\equiv \ = 0.375 \pm 0.064 \pm 0.026 \ , \\ R(D^*) &\equiv \ = 0.293 \pm 0.038 \pm 0.015 \ , 0.336 \pm 0.027 \pm 0.030 \ . \end{aligned} \tag{2}$$

Average and Theory

$$\begin{aligned} R(D) &\equiv \ = 0.391 \pm 0.041 \pm 0.028 \ , 0.300 \pm 0.01, \\ R(D^*) &\equiv \ = 0.322 \pm 0.018 \pm 0.011 \ , 0.252 \pm 0.005 \ . \end{aligned} \tag{3}$$

$\frac{d\Gamma}{dq^2}$ is also measured.

Λ_b Rates

- Semileptonic Λ_b rates are of the same size as B semileptonic Decays.
- $\Lambda_b \to \Lambda_c l^- \bar{\nu}_l X$ is 10.7 ± 2.2 %, $B^0 \to X_c e^+ \nu = 10.1 \pm 0.4$ %.
- $\Lambda_b \to \Lambda_c l \bar{\nu}_l$ is $6.2^{+1.4}_{-1.2}$ %.
- Hadron machines can measure Λ_b Decays. Better measurements of $\Lambda_b \to \Lambda_c l \bar{\nu}_l$ and $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ with the differential distribution is desirable.
- Note effects in $R(D^{(*)})$ are large so effects in Λ_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 Λ_b decay be less than the SM value for some new physics?

Model independent NP analysis

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

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \Big[(1+g_L) [\bar{c}\gamma_\mu P_L b] [\bar{l}\gamma^\mu P_L \nu_l] + g_R [\bar{c}\gamma^\mu P_R b] [\bar{l}\gamma_\mu P_L \nu_l]$$
$$+ S_L [\bar{c} P_L b] [\bar{l} P_L \nu_l] + S_R [\bar{c} P_R b] [\bar{l} P_L \nu_l] + T_L [\bar{c}\sigma^{\mu\nu} P_L b] [\bar{l}\sigma_{\mu\nu} P_L \nu_l] \Big].$$

- Droping tensor interactions

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \Big[(1+g_L) [\bar{c}\gamma_\mu P_L b] [\bar{l}\gamma^\mu P_L \nu_l] + g_R [\bar{c}\gamma^\mu P_R b] [\bar{l}\gamma_\mu P_L \nu_l]$$
$$+ g_S [\bar{c} b] [\bar{l}(1-\gamma_5)\nu_l] + g_P [\bar{c}\gamma_5 b] [\bar{l}(1-\gamma_5)\nu_l] \Big].$$

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

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

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 $b \to c\ell\overline{\nu}$ process is (Tanaka:2012nw)

$$\begin{aligned} \mathcal{L}_2^{\rm LQ} &= \left(g_{2L}^{ij}\, \overline{u}_{iR} R_2^T L_{jL} + g_{2R}^{ij}\, \overline{Q}_{iL} i\sigma_2 \ell_{jR} R_2 \right), \\ \mathcal{L}_0^{\rm LQ} &= \left(g_{1L}^{ij}, \overline{Q}_{iL}^c i\sigma_2 L_{jL} + g_{1R}^{ij}, \overline{u}_{iR}^c \ell_{jR} \right) S_1, \end{aligned}$$

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

$$\begin{aligned} S_L &= \frac{1}{2\sqrt{2}G_F V_{cb}} \left[-\frac{g_{1L}^{33} g_{1R}^{23*}}{2M_{S_1}^2} - \frac{g_{2L}^{23} g_{2R}^{33*}}{2M_{R_2}^2} \right], \\ T_L &= \frac{1}{2\sqrt{2}G_F V_{cb}} \left[\frac{g_{1L}^{33} g_{1R}^{23*}}{8M_{S_1}^2} - \frac{g_{2L}^{23} g_{2R}^{33*}}{8M_{R_2}^2} \right]. \end{aligned}$$

Models of NP, Vector Interactions

- In effective theory framework, we can write operators invariant under the SM gauge group.
  (e-Print: arXiv:1411.0565, e-Print: arXiv:1412.7164)

$$\begin{aligned}\mathcal{O}^{(1)}_{NP} &= G_1(\bar{Q}_L\gamma_\mu Q_L)(\bar{L}_L\gamma^\mu L_L) \ ,\\ \mathcal{O}^{(2)}_{NP} &= G_2(\bar{Q}_L\gamma_\mu\sigma^I Q_L)(\bar{L}_L\gamma^\mu\sigma^I L_L) \ .\end{aligned}$$

  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:

$$\left[\frac{R(D)}{R(D^*)}\right]_{expt}(1.21) = \left[\frac{R(D)}{R(D^*)}\right]_{SM}(1.19).$$

Models of NP, Vector Interactions

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

$$\mathcal{L}^{\rm LQ} = h_3^{ij}\,\bar{Q}_{iL}\gamma^\mu\vec{\sigma}\cdot L_{jL}\vec{U}_{3\mu} + g_3^{ij}\,\bar{Q}^c_{iL}i\sigma_2\vec{\sigma}\cdot L_{jL}\vec{S}_3.$$

- For $b \to c\tau^-\bar{\nu}_\tau$ with vector triplet leptoquark:

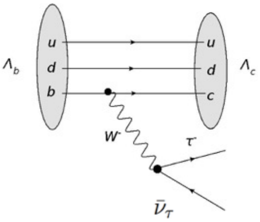
$$\mathcal{L}^{\rm LQ}_{CC} = \frac{h_3^{23}h_3^{33*}}{4M^2_{U_3}}\left[\bar{c}\gamma^\mu(1-\gamma_5)b\right]\left[\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau\right].$$

- For $b \to c\tau^-\bar{\nu}_\tau$ with scalar triplet leptoquark:

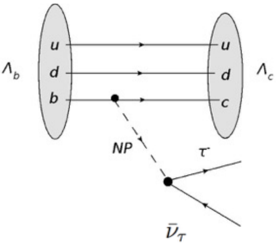
$$\mathcal{L}^{\rm LQ}_{CC} = \frac{g_3^{23}g_3^{33*}}{4M^2_{S_3}}\left[\bar{c}\gamma^\mu(1-\gamma_5)b\right]\left[\bar{\nu}^c_\tau\gamma_\mu(1+\gamma_5)\tau^c\right].$$

- **Formalism** ✧ *Decay Process*

Process: $$\Lambda_b(p_{\Lambda_b}) \to \tau^-(p_1) + \bar{\nu_\tau}(p_2) + \Lambda_c(p_{\Lambda_c})$$



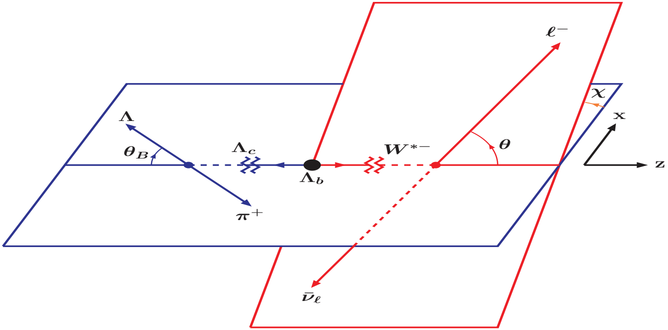
SM



NP

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

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



Decay Process

The process under consideration is

$$\Lambda_b(p_{\Lambda_b}) \to \tau^-(p_1) + \bar{\nu_\tau}(p_2) + \Lambda_c(p_{\Lambda_c}).$$

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,

$$\begin{aligned} L^\mu &= \bar{u}_\tau(p_1)\gamma^\mu(1-\gamma_5)v_{\nu_\tau}(p_2), \\ H_\mu &= \langle\Lambda_c|\,\bar{c}\gamma_\mu(1-\gamma_5)b\,|\Lambda_b\rangle\,. \end{aligned}$$

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

$$\begin{aligned} \langle\Lambda_c|\,\bar{c}\gamma_\mu b\,|\Lambda_b\rangle &= \bar{u}_{\Lambda_c}(f_1\gamma_\mu + if_2\sigma_{\mu\nu}q^\nu + f_3 q_\mu)u_{\Lambda_b}, \\ \langle\Lambda_c|\,\bar{c}\gamma_\mu\gamma_5 b|\,|\Lambda_b\rangle &= \bar{u}_{\Lambda_c}(g_1\gamma_\mu\gamma_5 + ig_2\sigma_{\mu\nu}q^\nu\gamma_5 + g_3 q_\mu\gamma_5)u_{\Lambda_b}. \end{aligned}$$

Here $q = p_{\Lambda_b} - p_{\Lambda_c}$ is the momentum transfer and the form factors are functions of q^2.

Heavy Quarks and form Factors

- 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 Λ_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.

$$\langle\Lambda_c|\,\bar{c}b\,|\Lambda_b\rangle = \bar{u}_{\Lambda_c}(f_1\frac{\not{q}}{m_b-m_c}+f_3\frac{q^2}{m_b-m_c})u_{\Lambda_b},$$

$$\langle\Lambda_c|\,\bar{c}\gamma_5 b\,|\Lambda_b\rangle = \bar{u}_{\Lambda_c}(-g_1\frac{\not{q}\gamma_5}{m_b+m_c}-g_3\frac{q^2\gamma_5}{m_b+m_c})u_{\Lambda_b}.$$

We will define the following observable,

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

Here ℓ represents μ or e. We will also define the ratio of differential distributions,

$$B_{\Lambda_b}(q^2) = \frac{\frac{d\Gamma[\Lambda_b\to\Lambda_c\tau\bar{\nu}_\tau]}{dq^2}}{\frac{d\Gamma[\Lambda_b\to\Lambda_c\ell\bar{\nu}_\ell]}{dq^2}}.$$

Helicity Amplitudes

The decay $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ proceeds via $\Lambda_b \to \Lambda_c W^*$(off-shell W) followed by $W^* \to \tau \bar{\nu}_\tau$. The full decay process is $\Lambda_b \to \Lambda_c(\to \Lambda_s \pi) W^*(\to \tau \bar{\nu}_\tau)$ One can analyze the decay in terms of helicity amplitudes (hep-ph 9406359) which are given by

$$H_{\lambda_2 \lambda_W} = M_\mu(\lambda_2) \epsilon^{*\mu}(\lambda_W), \tag{4}$$

where λ_2, λ_W are the polarizations of the daughter baryon and the W-boson respectively and M_μ is the hadronic current for $\Lambda_b \to \Lambda_c$ transition. The helicity amplitudes can be expressed in terms of form factors and the NP couplings.

$$
\begin{aligned}
H_{\lambda_{\Lambda_c},\lambda_w} &= H^V_{\lambda_{\Lambda_c},\lambda_w} - H^A_{\lambda_{\Lambda_c},\lambda_w}, \\
H^V_{\frac{1}{2}0} &= (1+g_L+g_R)\frac{\sqrt{Q_-}}{\sqrt{q^2}}\left((M_1+M_2)f_1 - q^2 f_2\right), \\
H^A_{\frac{1}{2}0} &= (1+g_L-g_R)\frac{\sqrt{Q_+}}{\sqrt{q^2}}\left((M_1-M_2)g_1 + q^2 g_2\right), \\
H^V_{\frac{1}{2}1} &= (1+g_L+g_R)\sqrt{2Q_-}\left(f_1 - (M_1+M_2)f_2\right), \\
H^A_{\frac{1}{2}1} &= (1+g_L-g_R)\sqrt{2Q_+}\left(g_1 + (M_1-M_2)g_2\right), \\
H^V_{\frac{1}{2}t} &= (1+g_L+g_R)\frac{\sqrt{Q_+}}{\sqrt{q^2}}\left((M_1-M_2)f_1 + q^2 f_3\right), \\
H^A_{\frac{1}{2}t} &= (1+g_L-g_R)\frac{\sqrt{Q_-}}{\sqrt{q^2}}\left((M_1+M_2)g_1 - q^2 g_3\right), \qquad (5)
\end{aligned}
$$

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

$$\begin{aligned} {H^{SP}}_{1/2,0} &= {H^P}_{1/2,0} + {H^S}_{1/2,0}, \\ {H^S}_{1/2,0} &= g_S \frac{\sqrt{Q_+}}{m_b - m_c}\Big((M_1 - M_2)f_1 + q^2 f_3\Big), \\ {H^P}_{1/2,0} &= -g_P \frac{\sqrt{Q_-}}{m_b + m_c}\Big((M_1 + M_2)g_1 - q^2 g_3\Big). \end{aligned}$$

The parity related amplitudes are,

$$\begin{aligned} {H^S}_{\lambda_{\Lambda_c},\lambda_{NP}} &= {H^S}_{-\lambda_{\Lambda_c},-\lambda_{NP}}, \\ {H^P}_{\lambda_{\Lambda_c},\lambda_{NP}} &= -{H^P}_{-\lambda_{\Lambda_c},-\lambda_{NP}}. \end{aligned}$$

With the W boson momentum defining the positive z-axis for the decay process ($\Lambda_b \to \Lambda_c \tau^- \nu_\tau$), the twofold angular distribution can be written as

$$\frac{d\Gamma(\Lambda_b \to \Lambda_c \tau^- \nu_\tau)}{dq^2 d(\cos\theta_l)} = \frac{{G_F}^2 |V_{cb}|^2 q^2 |\mathbf{p}_{\Lambda_c}|}{512\pi^3 {M_1}^2} \left(1 - \frac{{m_l}^2}{q^2}\right)^2 \left[A_1^{SM} + \frac{{m_l}^2}{q^2} A_2^{SM} + 2A_3^{NP} + \frac{4m_l}{\sqrt{q^2}} A_4^{Int}\right]$$

$$\begin{aligned}
A_1^{SM} &= 2\sin^2\theta_l(|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) + (1-\cos\theta_l)^2 |H_{1/2,1}|^2 \\
&\quad + (1+\cos\theta_l)^2 |H_{-1/2,-1}|^2, \\
A_2^{SM} &= 2\cos^2\theta_l(|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) + \sin^2\theta_l(|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2) \\
&\quad + 2(|H_{1/2,t}|^2 + |H_{-1/2,t}|^2) - 4\cos\theta_l Re[(H_{1/2,t}\ (H_{1/2,0})^* + H_{-1/2,t} \\
A_3^{NP} &= |{H^{SP}}_{1/2,0}|^2 + |{H^{SP}}_{-1/2,0}|^2, \\
A_4^{Int} &= -\cos\theta_l Re[(H_{1/2,0}\ ({H^{SP}}_{1/2,0})^* + H_{-1/2,0}\ ({H^{SP}}_{-1/2,0})^*)] \\
&\quad + Re[(H_{1/2,t}\ ({H^{SP}}_{1/2,0})^* + H_{-1/2,t}\ ({H^{SP}}_{-1/2,0})^*)].
\end{aligned}$$

θ_l is the angle of the lepton in the W^* rest frame.

After integrating out $cos\theta_l$,

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

where,

$$\begin{aligned}
B_1^{SM} &= |H_{1/2,0}|^2 + |H_{-1/2,0}|^2 + |H_{1/2,1}|^2 + |H_{-1/2,-1}|^2, \\
B_2^{SM} &= |H_{1/2,0}|^2 + |H_{-1/2,0}|^2 + |H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 \\
&\quad +3(|H_{1/2,t}|^2 + |H_{-1/2,t}|^2), \\
B_3^{NP} &= |H^{SP}_{1/2,0}|^2 + |H^{SP}_{-1/2,0}|^2, \\
B_4^{Int} &= Re[(H_{1/2,t}\ ({H^{SP}}_{1/2,0})^* + H_{-1/2,t}\ ({H^{SP}}_{-1/2,0})^*)]. \qquad (8)
\end{aligned}$$

${B_1}^{SM}$, ${B_2}^{SM}$, ${B_3}^{NP}$, 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 $\sin\chi$.

$$\begin{aligned} C_1^{SM} &= 2\sin^2\theta_l\Big((1+\alpha\cos\theta_s)|H_{1/2,0}|^2+(1-\alpha\cos\theta_s)|H_{-1/2,0}|^2\Big) \\ &+(1+\cos\theta_l)^2(1-\alpha\cos\theta_s)|H_{-1/2,-1}|^2+(1-\cos\theta_l)^2(1+\alpha\cos\theta \\ &-\frac{4\alpha}{\sqrt{2}}\sin\theta_l\sin\theta_s\cos\chi\Big((1+\cos\theta_l)Re[H_{1/2,0}\ (H_{-1/2,-1})^*] \\ &+(1-\cos\theta_l)Re[H_{-1/2,0}\ (H_{1/2,1})^*]\Big) \\ &-\frac{4\alpha}{\sqrt{2}}\sin\theta_l\sin\theta_s\sin\chi\Big((1+\cos\theta_l)Im[H_{1/2,0}\ (H_{-1/2,-1})^*] \\ &-(1-\cos\theta_l)Im[H_{-1/2,0}\ (H_{1/2,1})^*]\Big). \end{aligned}$$

In the SM helicity amplitudes $H_i \propto V_{cb}$ and so $Im(H_iH_j^*)=0$. 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 $R(D^{(*)})$.

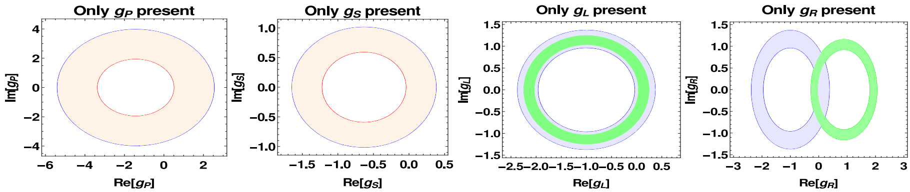


Figure: The figures show the constraints on the NP couplings taken one at a time at the 95% CL limit. When the couplings contribute to both $R(D)$ and $R(D^*)$ the green contour indicates constraint from $R(D^*)$ and blue from $R(D)$.

Results, Updated

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

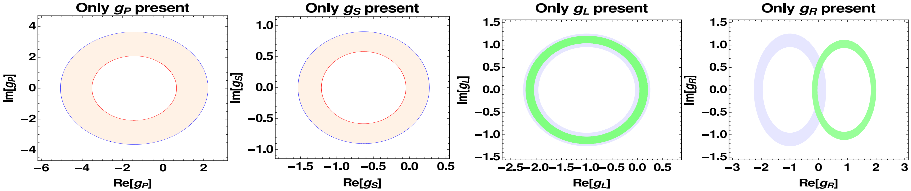


Figure: The figures show the constraints on the NP couplings taken one at a time at the 95% CL limit. When the couplings contribute to both $R(D)$ and $R(D^*)$ the green contour indicates constraint from $R(D^*)$ and blue from $R(D)$.

Results

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.

QCD sum rules(hep/ph 9903326)	1	2	3	4	Average
$R_{\Lambda_b}(SM)$	0.31	0.29	0.28	0.28	$0.29 \pm .02$

Table: Values of R_{Λ_b} in the SM

Model	Gutsche, T et.al.	Woloshyn, R	Lattice, 1503.01421
$R_{\Lambda_b}(SM)$	0.29	0.31	$0.33 \pm .01$

Table: Values of R_{Λ_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

$$\begin{aligned} H^V_{\lambda_{\Lambda_c},\lambda_w} &= (1 + g_R) \left[H^V_{\lambda_{\Lambda_c},\lambda_w} \right]_{SM} , \\ H^A_{\lambda_{\Lambda_c},\lambda_w} &= (1 - g_R) \left[H^A_{\lambda_{\Lambda_c},\lambda_w} \right]_{SM} . \end{aligned}$$

For the allowed g_R couplings we find R_{Λ_b} is greater than the SM value. The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ is similar to the SM.

Results, Scalar Operators

We now move to the case when only $g_{S,P}$ are present.

$$
\begin{aligned}
R_{\Lambda_b} &= R_{\Lambda_b}^{SM} + |g_P|^2 A_P + 2Re(g_P) B_P, \\
R_{\Lambda_b} &= R_{\Lambda_b}^{SM} + |g_S|^2 A_S + 2Re(g_S) B_S.
\end{aligned}
$$

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_{Λ_b} only slightly less than the SM value.

The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ can be different from the SM.

Max and Min deviations from SM, BaBar

NP	$R_{\Lambda_b,min}$	$R_{\Lambda_b,max}$
Only g_L	$0.31,\ g_L = -0.502 + 0.909\ i$	$0.44,\ g_L = -0.315 - 1.0381\ i$
Only g_R	$0.30,\ g_R = -0.035 - 0.104\ i$	$0.47,\ g_R = 0.0827 + 0.829\ i$
Only g_S	$0.28,\ g_S = -0.0227$	$0.36,\ g_S = -1.66$
Only g_P	$0.30,\ g_P = 0.539$	$0.42,\ g_P = -5.385$

Table: Minimum and Maximum values for the averaged R_{Λ_b}.

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

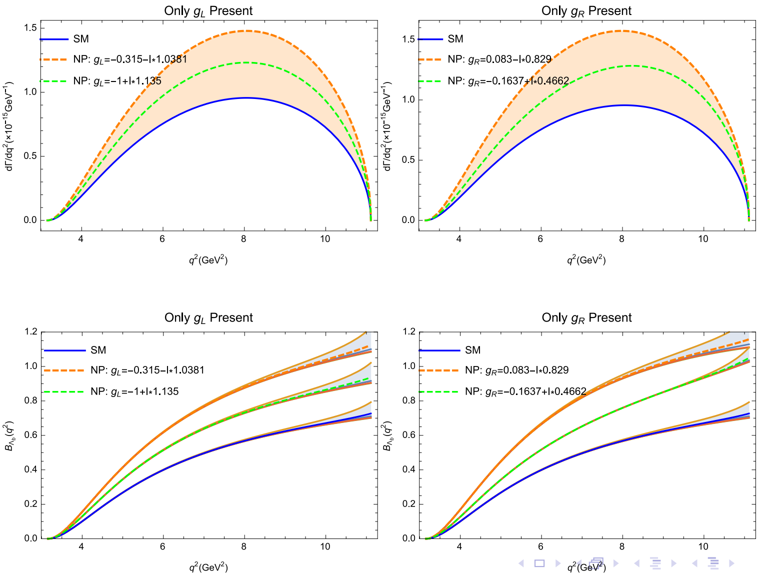
Max and Min deviations from SM, Updated

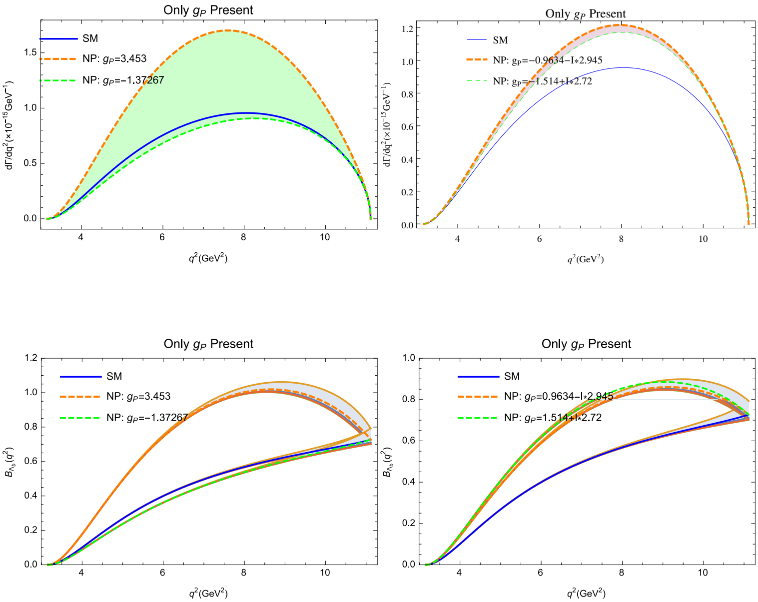
NP	$R_{\Lambda_b,min}$	$R_{\Lambda_b,max}$
Only g_L	$0.32,\ g_L = .0476$	$0.41,\ g_L = 0.202$
Only g_R	$0.30,\ g_R = -.0453 - 0.122\ i$	$0.43,\ g_R = 0.0313 - 0.707\ i$
Only g_S	$0.28,\ g_S = -1.22$	$0.34,\ g_S = 0.265$
Only g_P	$0.31,\ g_P = 0.684$	$0.39,\ g_P = 2.19$

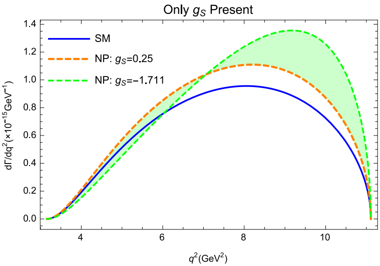
Table: Minimum and Maximum values for the averaged R_{Λ_b}.

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

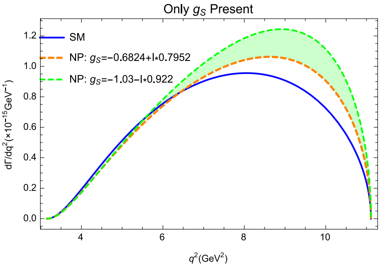
Differential Distribution



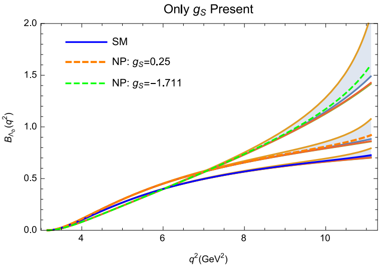

Only g_P Present
SM
NP: g_P=3.453
NP: g_P=−1.37267
$d\Gamma/dq^2(\times10^{-15}\mathrm{GeV}^{-1})$
$q^2(\mathrm{GeV}^2)$
Only g_P Present
SM
NP: g_P=−0.9634−I∗2.945
NP: g_P=−1.514+I∗2.72
$d\Gamma/dq^2(\times10^{-15}\mathrm{GeV}^{-1})$
$q^2(\mathrm{GeV}^2)$
Only g_P Present
SM
NP: g_P=3.453
NP: g_P=−1.37267
$B_{\Lambda_b}(q^2)$
$q^2(\mathrm{GeV}^2)$
Only g_P Present
SM
NP: g_P=0.9634−I∗2.945
NP: g_P=1.514+I∗2.72
$B_{\Lambda_b}(q^2)$
$q^2(\mathrm{GeV}^2)$



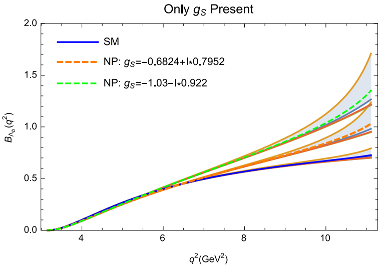
Only g_S Present
SM
NP: g_S=0.25
NP: g_S=−1.711
$d\Gamma/dq^2(\times10^{-15}\mathrm{GeV}^{-1})$
$q^2(\mathrm{GeV}^2)$



Only g_S Present
SM
NP: g_S=−0.6824+I∗0.7952
NP: g_S=−1.03−I∗0.922
$d\Gamma/dq^2(\times10^{-15}\mathrm{GeV}^{-1})$
$q^2(\mathrm{GeV}^2)$



Only g_S Present
SM
NP: g_S=0.25
NP: g_S=−1.711
$B_{\Lambda_b}(q^2)$
$q^2(\mathrm{GeV}^2)$



Only g_S Present
SM
NP: g_S=−0.6824+I∗0.7952
NP: g_S=−1.03−I∗0.922
$B_{\Lambda_b}(q^2)$
$q^2(\mathrm{GeV}^2)$

Other Observables

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

- Using the leptonic angle we can define:

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

- We can observe the τ polarization:

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

- We can look at the azimuthal distribution and the Λ_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.