

$\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ decay in the standard model and with new physics

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Recently hints of lepton flavor nonuniversality emerged when the *BABAR* collaboration observed deviations from the standard model predictions in $R(D^{(*)}) \equiv \mathcal{B}(\bar{B} \rightarrow D^{(*)+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^{(*)+} \ell^- \bar{\nu}_\ell)$ ($\ell = e, \mu$). Another test of this nonuniversality can be in the semileptonic $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ decay. In this paper we present predictions for this decay in the standard model and in the presence of new physics operators with different Lorentz structures. We present the most general fourfold angular distribution for this decay including new physics. For phenomenology, we focus on predictions for the decay rate and the differential distribution in the momentum transfer squared q^2 . In particular, we calculate $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$ where ℓ represents μ or e , and find the standard model prediction to be around 0.3 while the new physics operators can increase or slightly decrease this value.

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I. INTRODUCTION

A major part of particle physics research is focused on finding physics beyond the standard model (SM). In the flavor sector a key property of the SM gauge interactions is that they are lepton flavor universal. Evidence for violation of this property would be a clear sign of new physics (NP) beyond the SM. In the search for NP, the second and third generation quarks and leptons are quite special because they are comparatively heavier and are expected to be relatively more sensitive to NP. As an example, in certain versions of the two Higgs doublet models the couplings of the new Higgs bosons are proportional to the masses and so NP effects are more pronounced for the heavier generations. Moreover, the constraints on NP, especially involving the third generation leptons and quarks, are somewhat weaker allowing for larger NP effects.

Recently, the *BABAR* collaboration with their full data sample has reported the following measurements [1,2]:

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

where $\ell = e, \mu$. The SM predictions are $R(D) = 0.297 \pm 0.017$ and $R(D^*) = 0.252 \pm 0.003$ [1,3], which deviate from the *BABAR* measurements by 2σ and 2.7σ , respectively. [The *BABAR* collaboration itself reported a 3.4σ deviation from SM when the two measurements of Eq. (1)

are taken together.] This measurement of lepton flavor nonuniversality, referred to as the $R(D^{(*)})$ puzzles, may be providing a hint of the NP believed to exist beyond the SM. There have been numerous analyses examining NP explanations of the $R(D^{(*)})$ measurements [3–6].

The underlying quark level transition $b \rightarrow c \tau^- \bar{\nu}_\tau$ can be probed in both B and Λ_b decays. Note that in the presence of lepton nonuniversality the flavor of the neutrino does not have to match the flavor of the charged lepton [6]. Moreover the NP can affect all the lepton flavors. The main assumption here is that the NP effect is largest for the τ sector and for simplicity we neglect the smaller NP effects in the μ and e leptons. The Λ_b being a spin 1/2 baryon has a complex angular distribution for its decay products. As in B decays, we can construct several observables from the angular distribution of the Λ_b decay which can be used to find evidence of NP and to probe the structure of NP.

The decay $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ has not been measured experimentally though it might be possible to observe this decay at the LHCb. The full angular distribution of this decay is experimentally challenging and so in this paper, for the sake of phenomenology, we will focus on the rate as well as the q^2 differential distribution for this decay. Using constraints on the NP couplings obtained by using Eq. (1) we will make predictions for the effects of these couplings in $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ decay. Recently, in Ref. [7] this decay was discussed in the SM and with NP in Ref. [8].

The main uncertainty in the $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ decays are the hadronic form factors for the $\Lambda_b \rightarrow \Lambda_c$ transition. These form factors can also be studied systematically in a heavy m_b and m_c expansion [9]. However, unlike the B system the heavy baryon form factors have not been extensively studied. We will therefore construct ratios where the form factor uncertainties will mostly cancel leaving behind a smaller uncertainty for the theoretical predictions. We will

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then investigate if the NP effects are large enough to produce observable deviations from the SM predictions.

The paper is organized in the following manner. In Sec. II we introduce the effective Lagrangian to parametrize the NP operators, describe the formalism of the decay process and introduce the relevant observables. In Sec. III we present our results and in Sec. IV we present our conclusions.

II. FORMALISM

In the presence of NP, the effective Hamiltonian for the quark-level transition $b \rightarrow c l^- \bar{\nu}_l$ can be written in the form [10]

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

where $G_F = 1.1663787 \times 10^{-5} \text{ GeV}^{-2}$ is the Fermi coupling constant, V_{cb} is the Cabibbo-Kobayashi-Maskawa matrix element and we use $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. We have assumed the neutrinos to be always left chiral and to introduce nonuniversality the NP couplings are in general different for different lepton flavors. We assume the NP effect is mainly through the τ lepton and do not consider tensor operators in our analysis. Further, we do not assume any relation between $b \rightarrow ul^- \bar{\nu}_l$ and $b \rightarrow cl^- \bar{\nu}_l$ transitions and hence do not include constraints from $B \rightarrow \tau \nu_\tau$. The SM effective Hamiltonian corresponds to $g_L = g_R = g_S = g_P = 0$.

In Ref. [5] we had parametrized the NP in terms of the couplings $g_S, g_P, g_V = g_R + g_L$ and $g_A = g_R - g_L$ while in this paper we have traded g_V and g_A for $g_{L,R}$ to align our analysis closer to realistic models [6]. The couplings $g_{L,R,P}$ contribute to $R(D^*)$ while $g_{L,R,S}$ contribute to $R(D)$. We will consider one NP coupling at a time and provide constraints on these couplings from $R(D^{(*)})$.

A. 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

$$M_{\text{SM}} = \frac{G_F V_{cb}}{\sqrt{2}} L^\mu H_\mu, \quad (3)$$

where the leptonic and hadronic currents are

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

$$H_\mu = \langle \Lambda_c | \bar{c} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle. \quad (4)$$

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

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

$$\langle \Lambda_c | \bar{c} \gamma_\mu \gamma_5 b | \Lambda_b \rangle = \bar{u}_{\Lambda_c} (g_1 \gamma_\mu \gamma_5 + i g_2 \sigma_{\mu\nu} q^\nu \gamma_5 + g_3 q_\mu \gamma_5) u_{\Lambda_b}. \quad (5)$$

Here $q = p_{\Lambda_b} - p_{\Lambda_c}$ is the momentum transfer and the form factors are functions of q^2 . When considering NP operators we will use the following relations obtained by using the equations of motion:

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

$$\langle \Lambda_c | \bar{c} \gamma_5 b | \Lambda_b \rangle = \bar{u}_{\Lambda_c} \left(-g_1 \frac{q \gamma_5}{m_b + m_c} - g_3 \frac{q^2 \gamma_5}{m_b + m_c} \right) u_{\Lambda_b}. \quad (6)$$

We will define the following observable:

$$R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}. \quad (7)$$

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

$$B_{\Lambda_b}(q^2) = \frac{d\Gamma[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{d\Gamma[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}. \quad (8)$$

Our results will show that these observables are not very sensitive to variations in the hadronic form factors.

B. Helicity amplitudes and the full angular distribution

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 $\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda_s \pi) W^* (\rightarrow \tau \bar{\nu}_\tau)$. Following [11] one can analyze the decay in terms of helicity amplitudes which are given by

$$H_{\lambda_2 \lambda_W} = M_\mu(\lambda_2) \epsilon^{*\mu}(\lambda_W), \quad (9)$$

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 $\Lambda_b \rightarrow \Lambda_c$ transition. The helicity amplitudes can be expressed in terms of form factors and the NP couplings:

$$\begin{aligned}
 H_{\lambda_{\Lambda_c}, \lambda_w} &= H_{\lambda_{\Lambda_c}, \lambda_w}^V - H_{\lambda_{\Lambda_c}, \lambda_w}^A, \\
 H_{\frac{1}{2}0}^V &= (1 + g_L + g_R) \frac{\sqrt{Q_-}}{\sqrt{q^2}} ((M_1 + M_2)f_1 - q^2 f_2), \\
 H_{\frac{1}{2}0}^A &= (1 + g_L - g_R) \frac{\sqrt{Q_+}}{\sqrt{q^2}} ((M_1 - M_2)g_1 + q^2 g_2), \\
 H_{\frac{1}{2}1}^V &= (1 + g_L + g_R) \sqrt{2Q_-} (f_1 - (M_1 + M_2)f_2), \\
 H_{\frac{1}{2}1}^A &= (1 + g_L - g_R) \sqrt{2Q_+} (g_1 + (M_1 - M_2)g_2), \\
 H_{\frac{1}{2}2}^V &= (1 + g_L + g_R) \frac{\sqrt{Q_+}}{\sqrt{q^2}} ((M_1 - M_2)f_1 + q^2 f_3), \\
 H_{\frac{1}{2}2}^A &= (1 + g_L - g_R) \frac{\sqrt{Q_-}}{\sqrt{q^2}} ((M_1 + M_2)g_1 - q^2 g_3),
 \end{aligned} \tag{10}$$

where $Q_\pm = (M_1 \pm M_2)^2 - q^2$.

We also have

$$\begin{aligned}
 H_{\lambda_{\Lambda_c}, \lambda_w}^V &= H_{-\lambda_{\Lambda_c}, -\lambda_w}^V, \\
 H_{\lambda_{\Lambda_c}, \lambda_w}^A &= -H_{-\lambda_{\Lambda_c}, -\lambda_w}^A.
 \end{aligned} \tag{11}$$

The scalar and pseudoscalar helicities associated with the new physics scalar and pseudoscalar interactions are

$$\begin{aligned}
 H_{1/2,0}^{SP} &= H_{1/2,0}^P + H_{1/2,0}^S, \\
 H_{1/2,0}^S &= g_S \frac{\sqrt{Q_+}}{m_b - m_c} ((M_1 - M_2)f_1 + q^2 f_3), \\
 H_{1/2,0}^P &= -g_P \frac{\sqrt{Q_-}}{m_b + m_c} ((M_1 + M_2)g_1 - q^2 g_3).
 \end{aligned} \tag{12}$$

The parity related amplitudes are

$$\begin{aligned}
 H_{\lambda_{\Lambda_c}, \lambda_{NP}}^S &= H_{-\lambda_{\Lambda_c}, -\lambda_{NP}}^S, \\
 H_{\lambda_{\Lambda_c}, \lambda_{NP}}^P &= -H_{-\lambda_{\Lambda_c}, -\lambda_{NP}}^P.
 \end{aligned} \tag{13}$$

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

$$\begin{aligned}
 \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \tau^- \nu_\tau)}{dq^2 d(\cos\theta_l)} &= \frac{G_F^2 |V_{cb}|^2 q^2 |\mathbf{p}_{\Lambda_c}|}{512\pi^3 M_1^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \\
 &\times \left[A_1^{\text{SM}} + \frac{m_l^2}{q^2} A_2^{\text{SM}} + 2A_3^{\text{NP}} + \frac{4m_l}{\sqrt{q^2}} A_4^{\text{Int}} \right],
 \end{aligned} \tag{14}$$

where

$$\begin{aligned}
 A_1^{\text{SM}} &= 2\sin^2\theta_l (|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) + (1 - \cos\theta_l)^2 |H_{1/2,1}|^2 + (1 + \cos\theta_l)^2 |H_{-1/2,-1}|^2, \\
 A_2^{\text{SM}} &= 2\cos^2\theta_l (|H_{1/2,0}|^2 + |H_{-1/2,0}|^2) + \sin^2\theta_l (|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2) \\
 &\quad + 2(|H_{1/2,t}|^2 + |H_{-1/2,t}|^2) - 4\cos\theta_l \text{Re}[(H_{1/2,t}(H_{1/2,0})^* + H_{-1/2,t}(H_{-1/2,0})^*)], \\
 A_3^{\text{NP}} &= |H_{1/2,0}^{SP}|^2 + |H_{-1/2,0}^{SP}|^2, \\
 A_4^{\text{Int}} &= -\cos\theta_l \text{Re}[(H_{1/2,0}(H_{1/2,0}^{SP})^* + H_{-1/2,0}(H_{-1/2,0}^{SP})^*)] + \text{Re}[(H_{1/2,t}(H_{1/2,0}^{SP})^* + H_{-1/2,t}(H_{-1/2,0}^{SP})^*)].
 \end{aligned} \tag{15}$$

A_1^{SM} , A_2^{SM} , A_3^{NP} , and A_4^{Int} are the standard model non-spin-flip, standard model spin-flip, new physics, and interference terms, respectively apart from g_L and g_R . Note A_1^{SM} , A_2^{SM} have the same structure as the SM contributions but the helicity amplitudes in these quantities include the NP contributions from $g_{L,R}$. θ_l is the angle of the lepton in the W rest frame with respect to the W momentum.

After integrating out $\cos\theta_l$,

$$\begin{aligned}
 \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \tau^- \nu_\tau)}{dq^2} &= \frac{G_F^2 |V_{cb}|^2 q^2 |\mathbf{p}_{\Lambda_c}|}{192\pi^3 M_1^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \\
 &\times \left[B_1^{\text{SM}} + \frac{m_l^2}{2q^2} B_2^{\text{SM}} + \frac{3}{2} B_3^{\text{NP}} + \frac{3m_l}{\sqrt{q^2}} B_4^{\text{Int}} \right],
 \end{aligned} \tag{16}$$

where

$$\begin{aligned}
 B_1^{\text{SM}} &= |H_{1/2,0}|^2 + |H_{-1/2,0}|^2 + |H_{1/2,1}|^2 + |H_{-1/2,-1}|^2, \\
 B_2^{\text{SM}} &= |H_{1/2,0}|^2 + |H_{-1/2,0}|^2 + |H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 \\
 &\quad + 3(|H_{1/2,t}|^2 + |H_{-1/2,t}|^2), \\
 B_3^{\text{NP}} &= |H_{1/2,0}^{SP}|^2 + |H_{-1/2,0}^{SP}|^2, \\
 B_4^{\text{Int}} &= \text{Re}[(H_{1/2,t}(H_{1/2,0}^{SP})^* + H_{-1/2,t}(H_{-1/2,0}^{SP})^*)].
 \end{aligned} \tag{17}$$

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 apart from g_L and g_R . Again, B_1^{SM} , B_2^{SM} have the same structure as the SM contributions but the helicity amplitudes in these quantities include the NP contributions from $g_{L,R}$. The $g_{S,P}$ operators generate new terms in the angular distribution.

The angular distribution for the four body decay process ($\Lambda_b \rightarrow (\Lambda_s, \pi^+) \Lambda_c \tau^- \nu_\tau$) can be written as the following

where α is the parity parameter for the process $\Lambda_c \rightarrow \Lambda_s \pi^+$. θ_l is again the same leptonic angle. θ_s is the angle of Λ_s in the Λ_c rest frame with respect to the Λ_c momentum. χ is the dihedral angle between the decay planes of (τ^-, ν_τ) and (Λ_s, π^+) in the W and Λ_c rest frame, respectively,

$$\frac{d\Gamma(\Lambda_b \rightarrow (\Lambda_s, \pi^+) \Lambda_c \tau^- \nu_\tau)}{dq^2 d(\cos \theta_l) d\chi d(\cos \theta_s)} = \frac{G_F^2 |V_{cb}|^2 q^2 |\mathbf{p}_{\Lambda_c}|}{2^7 (2\pi)^4 M_1^2} \left(1 - \frac{m_l^2}{q^2}\right)^2 \left[C_1^{\text{SM}} + \frac{m_l^2}{q^2} C_2^{\text{SM}} + 2C_3^{\text{NP}} + \frac{4m_l}{\sqrt{q^2}} C_4^{\text{Int}} \right], \quad (18)$$

where

$$\begin{aligned} C_1^{\text{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 \\ &\quad + (1 - \cos \theta_l)^2 (1 + \alpha \cos \theta_s) |H_{1/2,1}|^2 - \frac{4\alpha}{\sqrt{2}} \sin \theta_l \sin \theta_s \cos \chi \left((1 + \cos \theta_l) \text{Re}[H_{1/2,0}(H_{-1/2,-1})^*] \right. \\ &\quad \left. + (1 - \cos \theta_l) \text{Re}[H_{-1/2,0}(H_{1/2,1})^*] \right) - \frac{4\alpha}{\sqrt{2}} \sin \theta_l \sin \theta_s \sin \chi \left((1 + \cos \theta_l) \text{Im}[H_{1/2,0}(H_{-1/2,-1})^*] \right. \\ &\quad \left. - (1 - \cos \theta_l) \text{Im}[H_{-1/2,0}(H_{1/2,1})^*] \right). \\ C_2^{\text{SM}} &= 2\cos^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) + \sin^2\theta_l \left((1 + \alpha \cos \theta_s) |H_{1/2,1}|^2 \right. \\ &\quad \left. + (1 - \alpha \cos \theta_s) |H_{-1/2,-1}|^2 \right) + \frac{2\alpha}{\sqrt{2}} \sin 2\theta_l \sin \theta_s \cos \chi \left(\text{Re}[H_{1/2,0}(H_{-1/2,-1})^*] - \text{Re}[H_{-1/2,0}(H_{1/2,1})^*] \right) \\ &\quad + \frac{2\alpha}{\sqrt{2}} \sin 2\theta_l \sin \theta_s \sin \chi \left(\text{Im}[H_{1/2,0}(H_{-1/2,-1})^*] + \text{Im}[H_{-1/2,0}(H_{1/2,1})^*] \right) \\ &\quad - 4\cos \theta_l \left((1 + \alpha \cos \theta_s) \text{Re}[H_{1/2,t}(H_{1/2,0})^*] + (1 - \alpha \cos \theta_s) \text{Re}[H_{-1/2,t}(H_{-1/2,0})^*] \right) \\ &\quad - \frac{4\alpha}{\sqrt{2}} \sin \theta_l \sin \theta_s \cos \chi \left(\text{Re}[H_{1/2,t}(H_{-1/2,-1})^*] - \text{Re}[H_{-1/2,t}(H_{1/2,1})^*] \right) \\ &\quad - \frac{4\alpha}{\sqrt{2}} \sin \theta_l \sin \theta_s \sin \chi \left(\text{Im}[H_{1/2,t}(H_{-1/2,-1})^*] + \text{Im}[H_{-1/2,t}(H_{1/2,1})^*] \right) \\ &\quad + 2 \left((1 + \alpha \cos \theta_s) |H_{1/2,t}|^2 + (1 - \alpha \cos \theta_s) |H_{-1/2,t}|^2 \right). \\ C_3^{\text{NP}} &= (1 + \alpha \cos \theta_s) |H_{1/2,0}^{\text{SP}}|^2 + (1 - \alpha \cos \theta_s) |H_{-1/2,0}^{\text{SP}}|^2, \\ C_4^{\text{Int}} &= -\cos \theta_l \left((1 + \alpha \cos \theta_s) \text{Re}[H_{1/2,0}(H_{1/2,0}^{\text{SP}})^*] + (1 - \alpha \cos \theta_s) \text{Re}[H_{-1/2,0}(H_{-1/2,0}^{\text{SP}})^*] \right) \\ &\quad + (1 + \alpha \cos \theta_s) \text{Re}[H_{1/2,t}(H_{1/2,0}^{\text{SP}})^*] + (1 - \alpha \cos \theta_s) \text{Re}[H_{-1/2,t}(H_{-1/2,0}^{\text{SP}})^*]. \end{aligned} \quad (19)$$

C_1^{SM} , C_2^{SM} , C_3^{NP} , and C_4^{Int} are the standard model non-spin-flip, standard model spin-flip, new physics, and interference terms, respectively apart from g_L and g_R . C_1^{SM} and C_2^{SM} have the same structure as the SM contributions but the helicity amplitudes in these quantities include the NP contributions from $g_{L,R}$. Several additional observables can be constructed from the angular distributions, such as polarization asymmetries and CP violating triple product asymmetries [12] which can be sensitive probes of NP. Note that the SM portion of the twofold and fourfold distributions above, Eqs. (14) and (18), are the same as in a recent paper [7] apart from a minus sign in C_2^{SM} above.¹

¹In [7] Eq. (51), the minus sign is required in front of $\sin 2\theta$ on the second line in the spin-flip term as can be seen by the d -matrix elements.

III. NUMERICAL RESULTS

A. New physics couplings

We first present the constraints on the NP couplings from $R(D^*)$. The coupling g_S only contributes to $R(D)$, g_P only contributes to $R(D^*)$ while $g_{L,R}$ contributes to both $R(D)$ and $R(D^*)$. The details of the calculations for Fig. 1 can be found in Refs. [3,5].

B. Form factors

One of the main inputs in our calculations are the form factors. As first principle, lattice calculations of the form factors are not yet available. The form factors we use here are from QCD sum rules, which is a well-known approach to compute nonperturbative effects like form factors for systems with both light and heavy quarks [13,14].

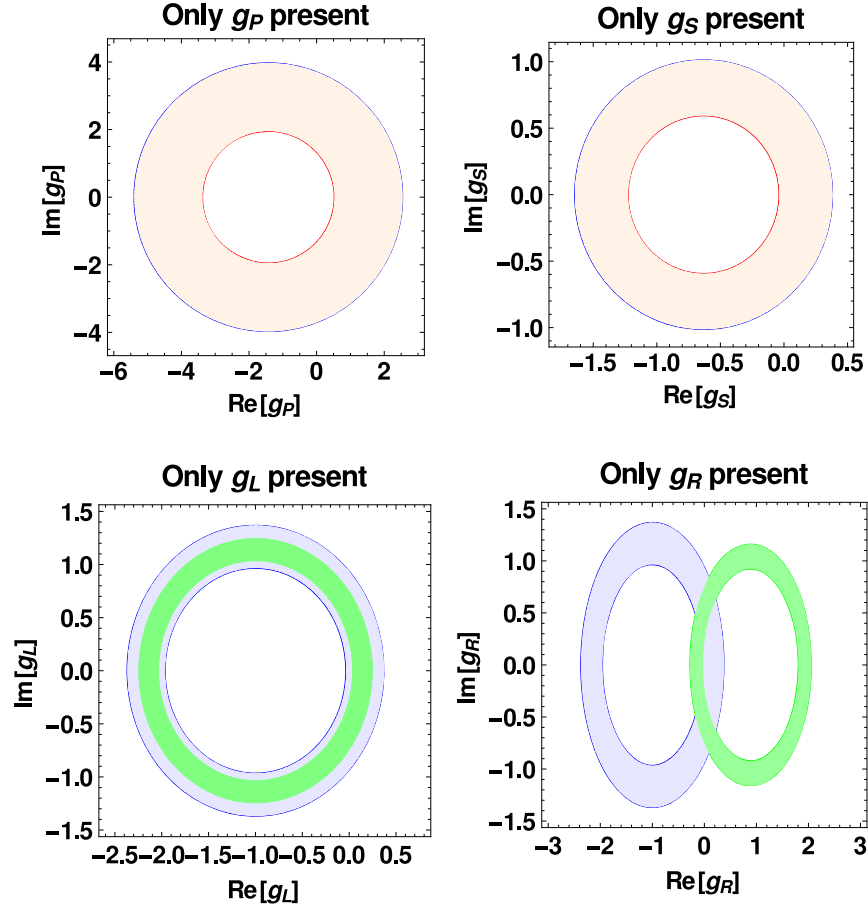


FIG. 1 (color online). The figures show the constraints on the NP couplings taken one at a time at the 95% C.L. limit [3,5]. When the couplings contribute to both $R(D)$ and $R(D^*)$ the green contour indicates constraint from $R(D^*)$ and blue from $R(D)$.

In Ref. [14], various parametrizations of the form factors are used. They are shown in Table I ($t = q^2$).

The form factors satisfy the heavy quark effective theory relations in the $m_b \rightarrow \infty$ limit:

$$f_1 = g_1 \quad f_2 = g_2 \quad f_3 = g_3 = 0. \quad (20)$$

C. Graphs and results

We have used the following masses in our calculations. The masses of the particles are $m_{\Lambda_b} = 5.6195$ GeV, $m_\tau = 1.77682$ GeV, $m_\mu = 0.10565837$ GeV, $m_{\Lambda_c} = 2.28646$ GeV, $m_b = 4.18$ GeV, $m_c = 1.275$ GeV and $V_{cb} = 0.0414$ [15].

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 I. For the differential distribution $\frac{d\Gamma}{dq^2}$ we present the average result over the form factors.

We first present our prediction for R_{Λ_b} in the SM, in Table II, for the various choices of the form factors in Table I. We also compare our results with other calculations

of this quantity by other groups using different form factors. We find the average value for R_{Λ_b} in the SM, $R_{\Lambda_b, \text{SM}} = 0.29 \pm .02$. This agrees very well with values for this quantity obtained in Ref. [7] which uses a covariant confined quark model for the form factors, Ref. [8] which uses the form factor model in Ref. [16], and Ref. [17] which uses the lattice QCD. This confirms our earlier assertion that the ratio R_{Λ_b} is largely free from form factor uncertainties making it an excellent probe to find NP.

We now discuss our results. From the structure of Eq. (16) we can make some general observations. 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 $(1 + g_L)$ [6]. Hence, if only g_L is present then

TABLE I. Various choices of form factors.

Continuum model	κ	$F_1^V(t) = f_1$	$F_2^V(t)(\text{GeV}^{-1}) = f_2$
Rectangular	1	$6.66/(20.27 - t)$	$-0.21/(15.15 - t)$
Rectangular	2	$8.13/(22.50 - t)$	$-0.22/(13.63 - t)$
Triangular	3	$13.74/(26.68 - t)$	$-0.41/(18.65 - t)$
Triangular	4	$16.17/(29.12 - t)$	$-0.45/(19.04 - t)$

TABLE II. Values of R_{Λ_b} in the SM.

Continuum model	1	2	3	4	Average	Ref. [7]	Ref. [8]	Ref. [17]
$R_{\Lambda_b}(\text{SM})$	0.31	0.29	0.28	0.28	$0.29 \pm .02$	0.29	0.31	$0.34 \pm .01$

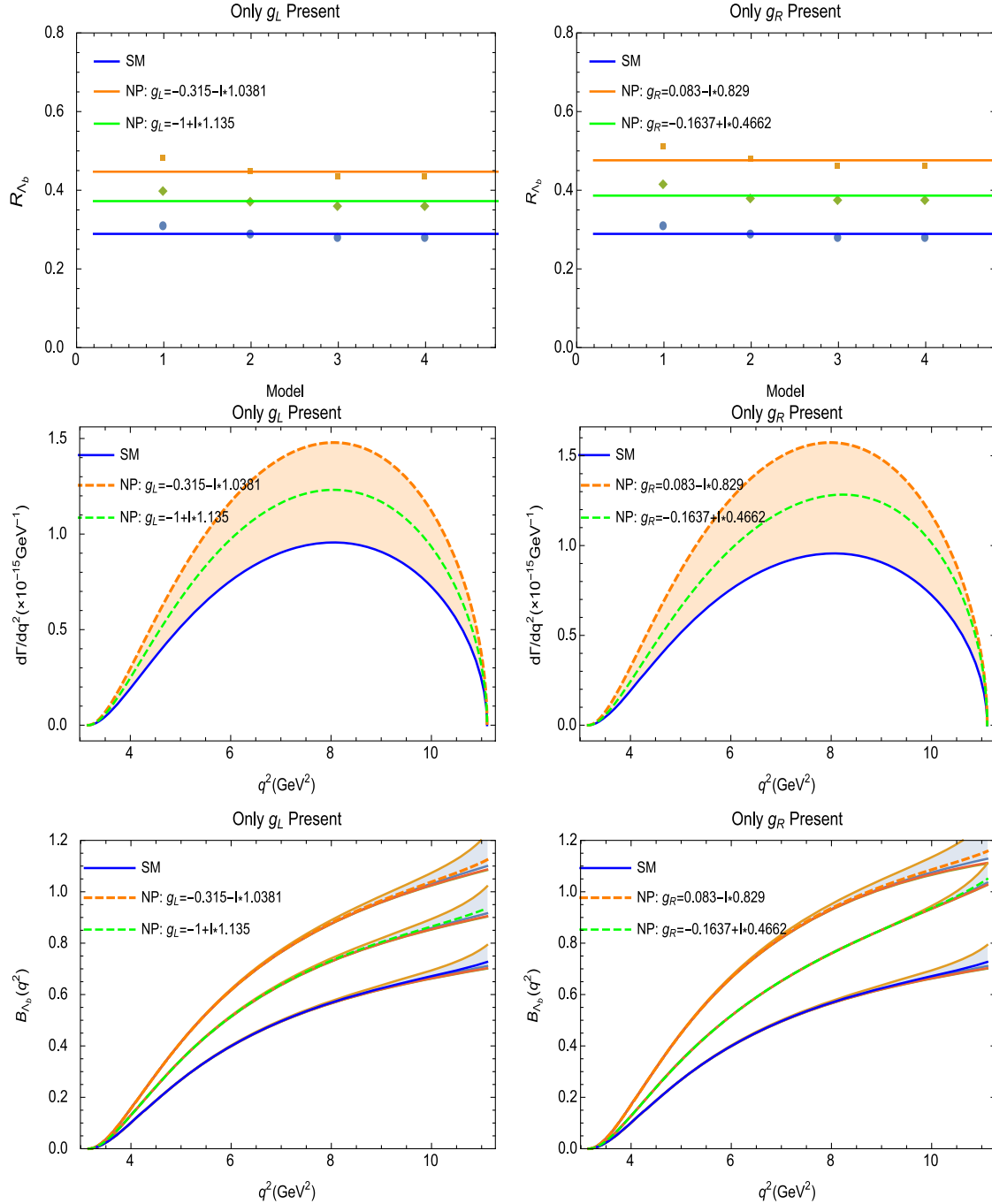


FIG. 2 (color online). The graphs on the left side (right side) show the compared results between the standard model and new physics with only g_L (g_R) present. The top and bottom row of graphs depict $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$ and the ratio of differential distributions $B_{\Lambda_b}(q^2) = \frac{\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau)}{\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell)}$ as a function of q^2 , respectively for the various form factors in Table I. The middle graphs depict the average differential decay rate with respect to q^2 for the process $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$. Some representative values of the couplings have been chosen.

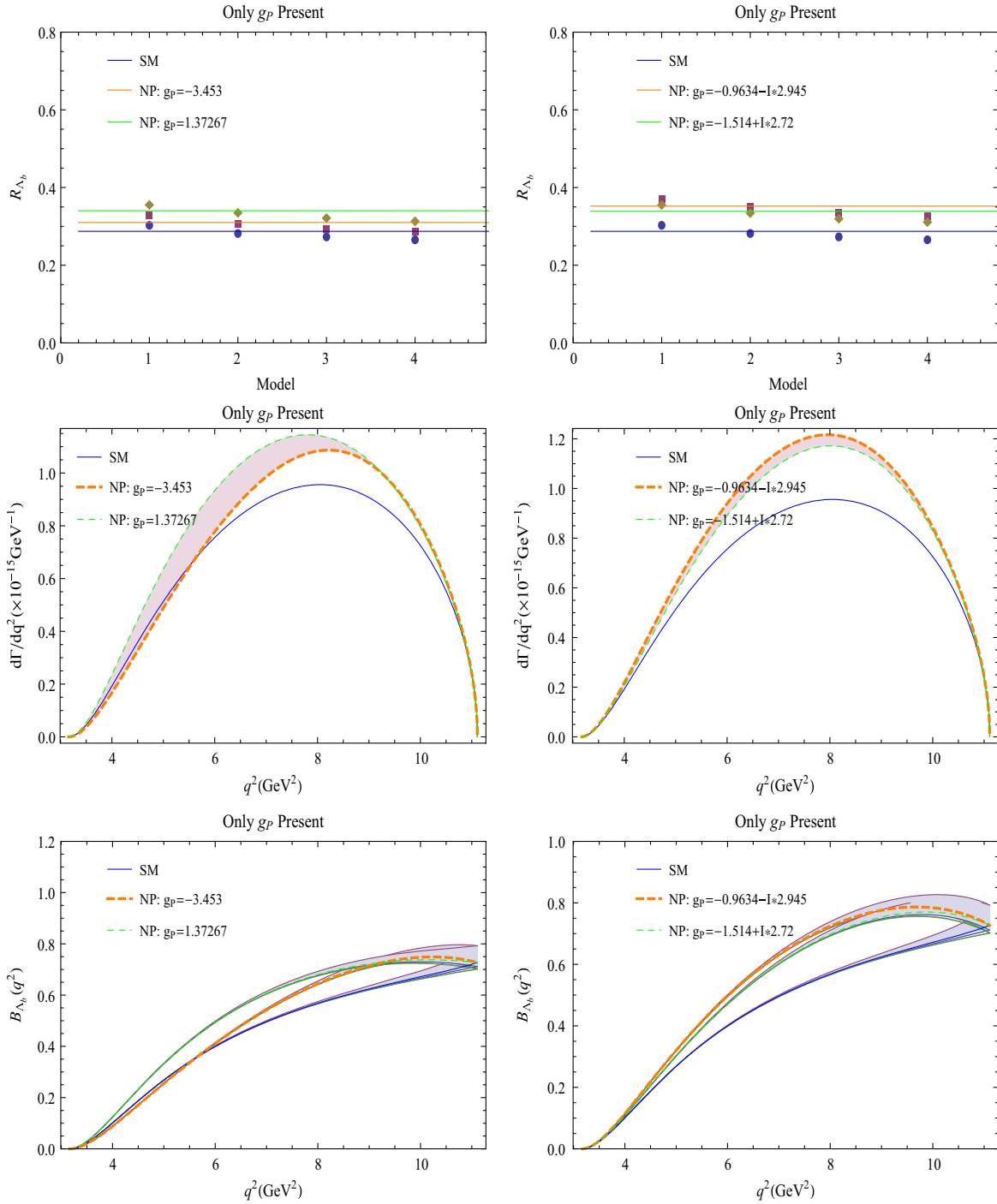


FIG. 3 (color online). The figures show the compared results between the standard model and new physics with only g_P present. The top and bottom row of graphs depict $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$ and the ratio of differential distributions $B_{\Lambda_b}(q^2) = \frac{\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau)}{\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell)}$ as a function of q^2 , respectively for the various form factors in Table I. The middle graphs depict the average differential decay rate with respect to q^2 for the process $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$. Some representative values of the couplings have been chosen.

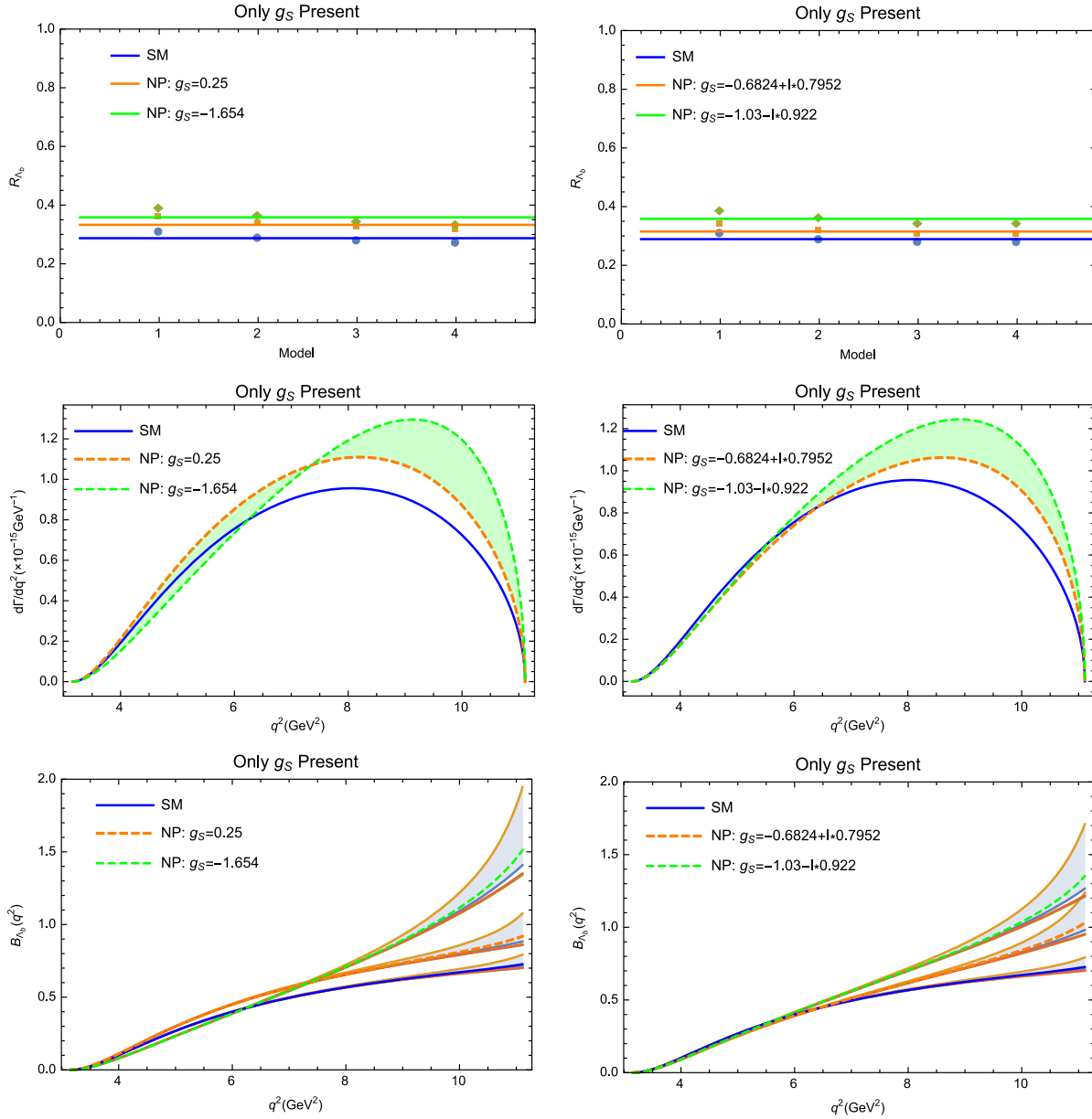


FIG. 4 (color online). The figures show the compared results between the standard model and new physics with only g_S present. The top and bottom row of graphs depict $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$ and the ratio of differential distributions $B_{\Lambda_b}(q^2) = \frac{\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau)}{\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell)}$ as a function of q^2 , respectively for the various form factors in Table I. The middle graphs depict the average differential decay rate with respect to q^2 for the process $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$. Some representative values of the couplings have been chosen.

TABLE III. Minimum and maximum values for the averaged R_{Λ_b} .

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

$$R_{\Lambda_b} = R_{\Lambda_b}^{\text{SM}} |1 + g_L|^2. \quad (21)$$

Therefore in this case $R_{\Lambda_b} \geq R_{\Lambda_b}^{\text{SM}}$ and we find the range of R_{Λ_b} to be 0.44–0.31. The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ is the same as the SM. In the left-side figures of Fig. 2 we show the plots for $R_{\Lambda_b, \frac{d\Gamma}{dq^2}}$ and $B_{\Lambda_b}(q^2)$ when only g_L is present. We then consider the case where only g_R is present. If only g_R is present then from Eq. (10),

$$\begin{aligned} H_{\lambda_{\Lambda_c}, \lambda_w}^V &= (1 + g_R) [H_{\lambda_{\Lambda_c}, \lambda_w}^V]_{\text{SM}}, \\ H_{\lambda_{\Lambda_c}, \lambda_w}^A &= (1 - g_R) [H_{\lambda_{\Lambda_c}, \lambda_w}^A]_{\text{SM}}. \end{aligned} \quad (22)$$

In this case no clear relation between R_{Λ_b} and $R_{\Lambda_b}^{\text{SM}}$ can be obtained. However, for the allowed g_R couplings we find R_{Λ_b} is greater than the SM value and is in the range 0.47–0.30. The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ is the same as the SM. In the right-side figures of Fig. 2 we show the plots for $R_{\Lambda_b, \frac{d\Gamma}{dq^2}}$ and $B_{\Lambda_b}(q^2)$ when only g_R is present.

We now move to the case when only $g_{S,P}$ are present. Using Eqs. (16) and (12) we can write

$$\begin{aligned} R_{\Lambda_b} &= R_{\Lambda_b}^{\text{SM}} + |g_P|^2 A_P + 2\text{Re}(g_P) B_P, \\ R_{\Lambda_b} &= R_{\Lambda_b}^{\text{SM}} + |g_S|^2 A_S + 2\text{Re}(g_S) B_S. \end{aligned} \quad (23)$$

The quantities $A_{S,P}$ and $B_{S,P}$ depend on masses and form factors and they are positive. Hence for $\text{Re}(g_P) \geq 0$ or $\text{Re}(g_S) \geq 0$, R_{Λ_b} is always greater than or equal to $R_{\Lambda_b}^{\text{SM}}$. But, for $\text{Re}(g_P) < 0$ or $\text{Re}(g_S) < 0$, R_{Λ_b} can be less than the SM value. However, given the constraints on $g_{S,P}$ we can make R_{Λ_b} only slightly less than the SM value. We find R_{Λ_b} is in the range 0.36–0.28 when only g_S is present and in the range 0.42–0.30 when only g_P is present.

In Fig. 3 we show the plots for $R_{\Lambda_b, \frac{d\Gamma}{dq^2}}$ and $B_{\Lambda_b}(q^2)$ when only g_P is present. The shape of the differential distribution $\frac{d\Gamma}{dq^2}$ can be different from the SM. In Fig. 4 we show the plots for $R_{\Lambda_b, \frac{d\Gamma}{dq^2}}$ and $B_{\Lambda_b}(q^2)$ when only g_S is present. In this case also the shape of the differential distribution $\frac{d\Gamma}{dq^2}$ can be different from the SM.

In Table III we show the minimum and maximum values for the averaged R_{Λ_b} with the corresponding NP couplings.

IV. CONCLUSION

In this paper we calculated the SM and NP predictions for the decay $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$. Motivation to study this decay comes from the recent hints of lepton flavor nonuniversality observed by the *BABAR* collaboration in $R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)+} \tau \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)+} \ell \bar{\nu}_\ell)}$ ($\ell = e, \mu$). We used a general parametrization of the NP operators and fixed the NP couplings from the experimental measurements of $R(D)$ and $R(D^*)$. We then made predictions for R_{Λ_b} [Eq. (7)], $\frac{d\Gamma}{dq^2}$, and $B_{\Lambda_b}(q^2)$ [Eq. (8)] for the various NP couplings taken one at a time. We found the interesting result that $g_{L,R}$ couplings gave predictions larger than the SM values for all the three observables. We found the g_P couplings to produce larger effects than the g_S couplings. We also provided the general formula for the various angular distributions in the presence of NP operators.

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