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# $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ Decay in the Standard Model and with New Physics

Shanmuka Shivashankara <sup>1</sup>, Wanwei Wu <sup>2</sup> and Alakabha Datta <sup>3</sup>

*Department of Physics and Astronomy, 108 Lewis Hall,  
University of Mississippi, Oxford, MS 38677-1848, USA*

## Abstract

Recently hints of lepton flavor non-universality 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 non-universality can be in the semileptonic  $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$  decay. In this work 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 four-fold 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  $\ell$  represents  $\mu$  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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<sup>1</sup>sshivash@go.olemiss.edu

<sup>2</sup>wwu1@go.olemiss.edu

<sup>3</sup>datta@phy.olemiss.edu

# 1 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 (2HDM) 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 new physics, especially involving the third generation leptons and quarks, are somewhat weaker allowing for larger new physics effects.

Recently, the BaBar Collaboration with their full data sample has reported the following measurements [1, 2]:

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

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  $2\sigma$  and  $2.7\sigma$ , respectively. (The BaBar Collaboration itself reported a  $3.4\sigma$  deviation from SM when the two measurements of Eq. (1) are taken together.) This measurement of lepton flavor non-universality, referred to as the  $R(D^{(*)})$  puzzles, may be providing a hint of the new physics (NP) believed to exist beyond the SM. There have been numerous analyses examining NP explanations of the  $R(D^{(*)})$  measurements [3, 4, 5, 6].

The underlying quark level transition  $b \rightarrow c \tau^- \bar{\nu}_\tau$  can be probed in both  $B$  and  $\Lambda_b$  decays. Note that in the presence of lepton non-universality 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  $\tau$  sector and for simplicity we neglect the smaller NP effects in the  $\mu$  and  $e$  leptons. The  $\Lambda_b$  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  $\Lambda_b$  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 new physics 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 standard model and with new physics 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 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.2 we introduce the effective Lagrangian to parametrize the NP operators, describe the formalism of the decay process and introduce the relevant observables. In sec.3 we present our results and in sec.4 we present our conclusions.

## 2 Formalism

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

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

where  $G_F = 1.1663787 \times 10^{-5} \text{ GeV}^{-2}$  is the Fermi coupling constant,  $V_{cb}$  is the Cabibbo-Kobayashi-Maskawa (CKM) 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 non-universality the NP couplings are in general different for different lepton flavors. We assume the NP effect is mainly through the  $\tau$  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 work 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  $R(D^{(*)})$ .

### 2.1 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

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

where the leptonic and hadronic currents are,

$$\begin{aligned} L^\mu &= \bar{u}_\tau(p_1) \gamma^\mu (1 - \gamma_5) v_{\nu_\tau}(p_2), \\ H_\mu &= \langle \Lambda_c | \bar{c} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle. \end{aligned} \quad (4)$$

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

$$\begin{aligned} \langle \Lambda_c | \bar{c} \gamma_\mu b | \Lambda_b \rangle &= \bar{u}_{\Lambda_c} (f_1 \gamma_\mu + i f_2 \sigma_{\mu\nu} q^\nu + f_3 q_\mu) u_{\Lambda_b}, \\ \langle \Lambda_c | \bar{c} \gamma_\mu \gamma_5 b | \Lambda_b \rangle &= \bar{u}_{\Lambda_c} (g_1 \gamma_\mu \gamma_5 + i g_2 \sigma_{\mu\nu} q^\nu \gamma_5 + g_3 q_\mu \gamma_5) u_{\Lambda_b}. \end{aligned} \quad (5)$$

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.

$$\begin{aligned} \langle \Lambda_c | \bar{c} b | \Lambda_b \rangle &= \bar{u}_{\Lambda_c} \left( f_1 \frac{\not{q}}{m_b - m_c} + f_3 \frac{q^2}{m_b - m_c} \right) u_{\Lambda_b}, \\ \langle \Lambda_c | \bar{c} \gamma_5 b | \Lambda_b \rangle &= \bar{u}_{\Lambda_c} \left( -g_1 \frac{\not{q} \gamma_5}{m_b + m_c} - g_3 \frac{q^2 \gamma_5}{m_b + m_c} \right) u_{\Lambda_b}. \end{aligned} \quad (6)$$

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

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

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

## 2.2 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  $\lambda_2, \lambda_W$  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.

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

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

We also have,

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

The scalar and pseudo-scalar helicities associated with the new physics scalar and pseudo-scalar interactions are

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

The parity related amplitudes are,

$$\begin{aligned}
H^S_{\lambda_{\Lambda_c}, \lambda_{NP}} &= H^S_{-\lambda_{\Lambda_c}, -\lambda_{NP}}, \\
H^P_{\lambda_{\Lambda_c}, \lambda_{NP}} &= -H^P_{-\lambda_{\Lambda_c}, -\lambda_{NP}}. \tag{13}
\end{aligned}$$

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

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

where,

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

$A_1^{SM}$ ,  $A_2^{SM}$ ,  $A_3^{NP}$ , 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 new physics contributions from  $g_{L,R}$ .  $\theta_l$  is the angle of the lepton in the W rest frame with respect to the W momentum.

After integrating out  $\cos\theta_l$ ,

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

where,

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

$B_1^{SM}$ ,  $B_2^{SM}$ ,  $B_3^{NP}$ , 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 new physics 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  $\alpha$  is the parity parameter for the process  $\Lambda_c \rightarrow \Lambda_s \pi^+$ .  $\theta_l$  is again the same leptonic angle.  $\theta_s$  is the angle of  $\Lambda_s$  in the  $\Lambda_c$  rest frame with respect to the  $\Lambda_c$  momentum.  $\chi$  is the dihedral angle between the decay planes of  $(\tau^-, \nu_\tau)$  and  $(\Lambda_s, \pi^+)$  in the W and  $\Lambda_c$  rest frame, respectively.

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

where,

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



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

$$\begin{aligned}
C_3^{NP} &= (1 + \alpha \cos \theta_s) |H^{SP}_{1/2,0}|^2 + (1 - \alpha \cos \theta_s) |H^{SP}_{-1/2,0}|^2, \\
C_4^{Int} &= -\cos \theta_l \left( (1 + \alpha \cos \theta_s) \text{Re}[H_{1/2,0} (H^{SP}_{1/2,0})^*] \right. \\
& \quad \left. + (1 - \alpha \cos \theta_s) \text{Re}[H_{-1/2,0} (H^{SP}_{-1/2,0})^*] \right) \\
& \quad + (1 + \alpha \cos \theta_s) \text{Re}[H_{1/2,t} (H^{SP}_{1/2,0})^*] \\
& \quad + (1 - \alpha \cos \theta_s) \text{Re}[H_{-1/2,t} (H^{SP}_{-1/2,0})^*]. \tag{19}
\end{aligned}$$

$C_1^{SM}$ ,  $C_2^{SM}$ ,  $C_3^{NP}$ , 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 new physics 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 new physics. Note that the standard model portion of the twofold and fourfold distributions above, Eq. 14 and Eq. 18, are the same as in a recent paper[7] apart from a minus sign in  $C_2^{SM}$  above. <sup>4</sup>

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<sup>4</sup>In [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.

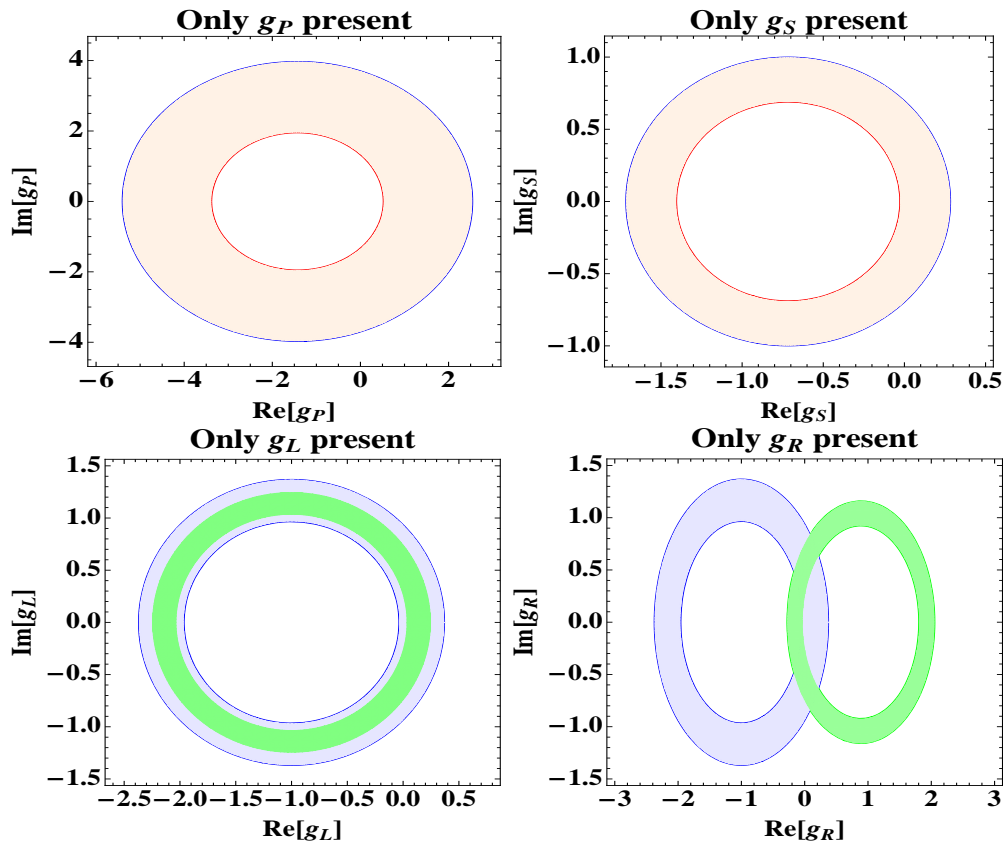


Figure 1: The figures show the constraints on the NP couplings taken one at a time at the 95% CL limit [3, 5]. When the couplings contribute to both  $R(D)$  and  $R(D^*)$  the green contour indicates constraint from  $R(D^*)$  and blue from  $R(D)$ .

### 3 Numerical Results

#### 3.1 New Physics Couplings

We first present the constraints on the NP couplings from  $R(D^{(*)})$ . The couplings  $g_S$  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 Ref. [3, 5].

#### 3.2 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 non-

perturbative effects like form factors for systems with both light and heavy quarks[13, 14].

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

continuum model	$\kappa$	$F_1^V(t) = f_1$	$F_2^V(t)(GeV^{-1}) = f_2$
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 1: Various choices of Form Factors.

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

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

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

continuum model	1	2	3	4	Average	Ref. [7]	Ref. [8]	Ref. [16]
$R_{\Lambda_b}(SM)$	0.31	0.29	0.28	0.28	$0.29 \pm .02$	0.29	0.31	$0.34 \pm .01$

Table 2: Values of  $R_{\Lambda_b}$  in the SM

We first present our prediction for  $R_{\Lambda_b}$  in the SM, in Table. 2, for the various choices of the form factors in Table.1. We also compare our results with other calculations of this quantity by other groups using different form factors. We find the average value for  $R_{\Lambda_b}$  in the SM,  $R_{\Lambda_b, SM} = 0.29 \pm .02$ . 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. [17], and Ref. [16] which uses the lattice QCD. This confirms our earlier assertion that the ratio  $R_{\Lambda_b}$  is largely free from form factor uncertainties making it an excellent probe to find new physics.

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

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

Therefore in this case  $R_{\Lambda_b} \geq R_{\Lambda_b}^{SM}$  and we find the range of  $R_{\Lambda_b}$  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,

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

In this case no clear relation between  $R_{\Lambda_b}$  and  $R_{\Lambda_b}^{SM}$  can be obtained. However, for the allowed  $g_R$  couplings we find  $R_{\Lambda_b}$  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 Eq. 16 and Eq. 12 we can write,

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

The quantities  $A_{S,P}$  and  $B_{S,P}$  depend on masses and form factors and they are positive. Hence for  $Re(g_P) \geq 0$  or  $Re(g_S) \geq 0$ ,  $R_{\Lambda_b}$  is always greater than or equal to  $R_{\Lambda_b}^{SM}$ . But, for  $Re(g_P) < 0$  or  $Re(g_S) < 0$ ,  $R_{\Lambda_b}$  can be less than the SM value. However, given the constraints on  $g_{S,P}$  we can make  $R_{\Lambda_b}$  only slightly less than the SM value. We find  $R_{\Lambda_b}$  is in the range  $0.37 - 0.28$  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. 3 we show the minimum and maximum values for the averaged  $R_{\Lambda_b}$  with the corresponding NP couplings.

## 4 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 non-

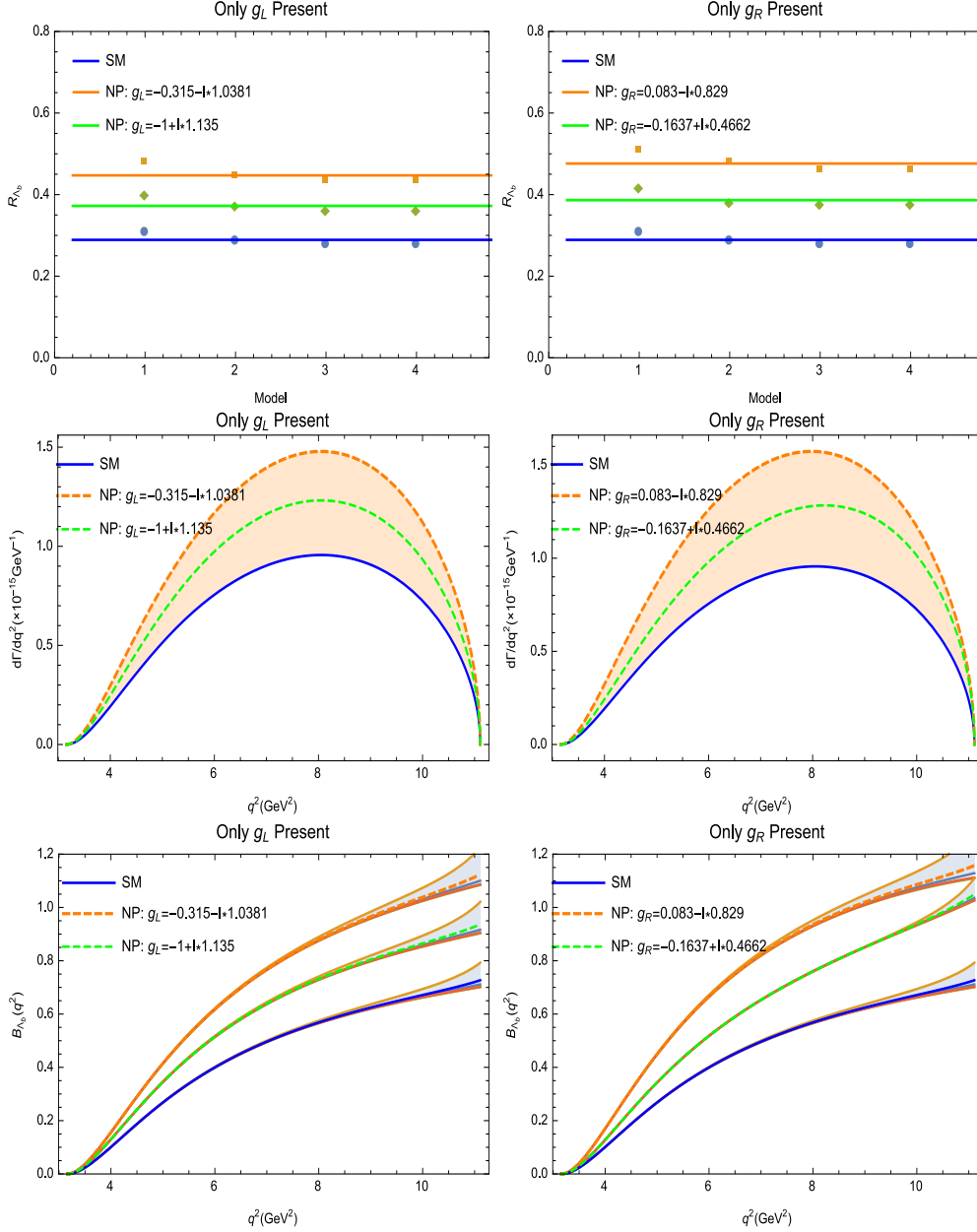


Figure 2: The graphs on the left-side (right-side) show the compared results between the standard model and new physics with only  $g_L$  ( $g_R$ ) present. The top and bottom row of graphs depict  $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$  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. 1. 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.

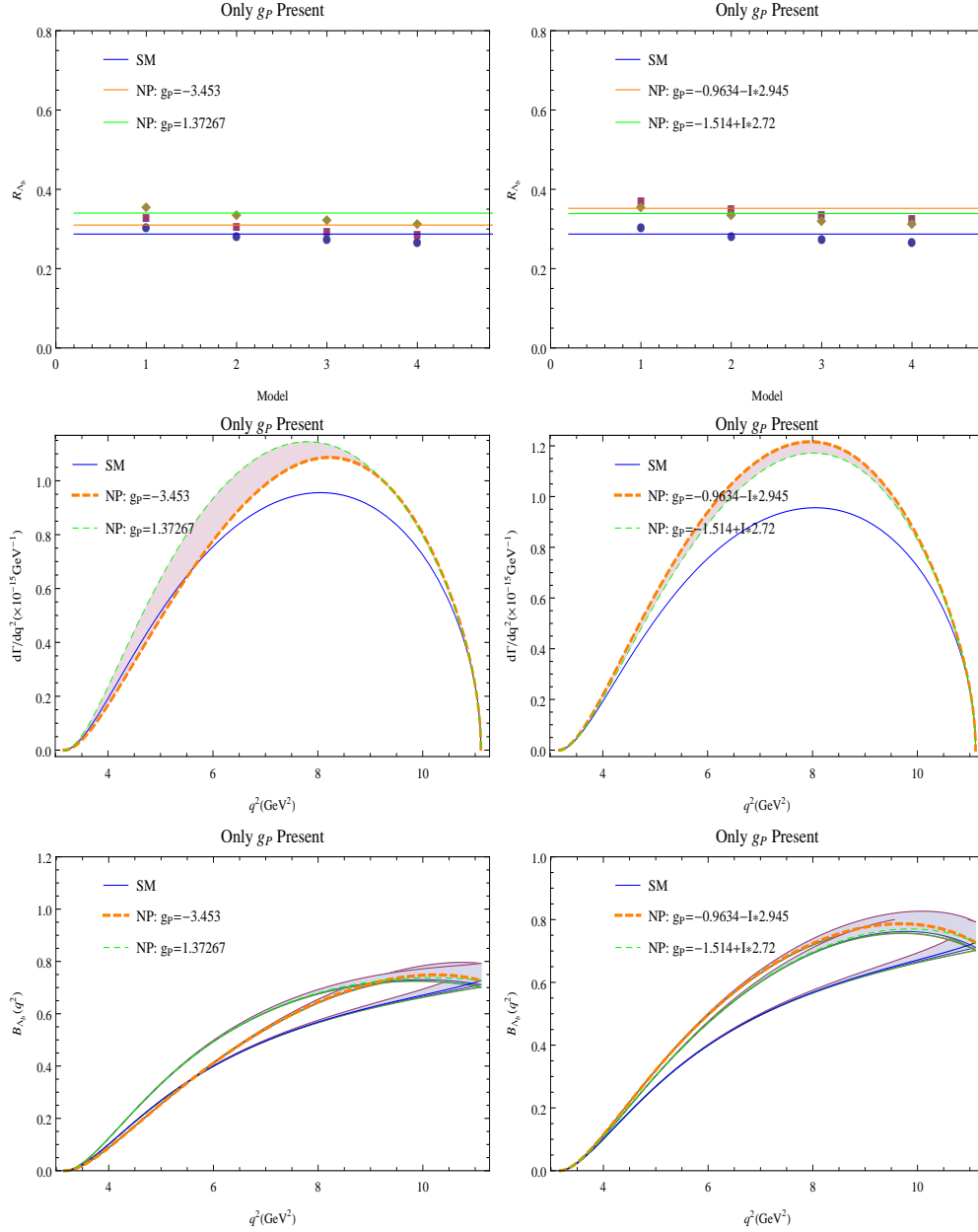


Figure 3: The figures show the compared results between the standard model and new physics with only  $g_P$  present. The top and bottom row of graphs depict  $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$  and 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. 1. 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.

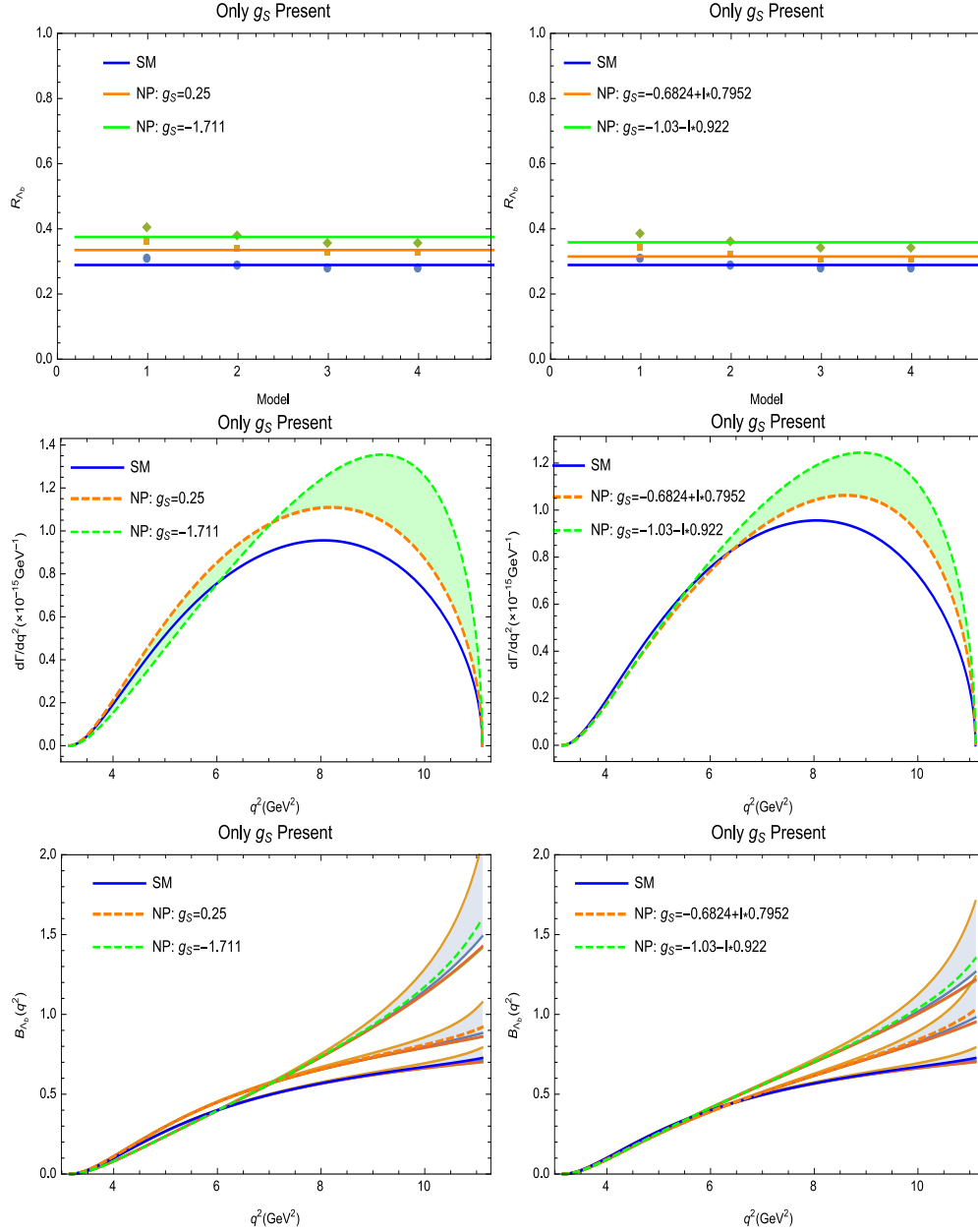


Figure 4: The figures show the compared results between the standard model and new physics with only  $g_S$  present. The top and bottom row of graphs depict  $R_{\Lambda_b} = \frac{BR[\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau]}{BR[\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell]}$  and 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. 1. 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.

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, $g_S = -0.0227$	0.37, $g_S = -1.71$
Only $g_P$	0.30, $g_P = 0.539$	0.42, $g_P = -5.385$

Table 3: Minimum and Maximum values for the averaged  $R_{\Lambda_b}$ .

universality 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 new physics couplings from the experimental measurements of  $R(D)$  and  $R(D^*)$ . We then made predictions for  $R_{\Lambda_b}$  ( 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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