Chapter 55
Effect of New Physics in $\bar{B} \to \rho \ell \bar{\nu}_\ell$ Decay Process

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Abstract Several anomalies have been observed in various lepton non universality (LNU) observables and other asymmetries associated with semileptonic B-meson decays mediated by $b \to (c, s)$ quark level transitions. In this context we perform a model independent analysis of $\bar{B} \to \rho \ell \bar{\nu}_\ell$ decay process mediated by $b \to u$ quark level transition. In this article, we calculate the branching fraction, lepton spin asymmetry and LNU parameter associated with this decay process and scrutinize whether there will be any deviation in these observables in presence of new Physics (NP).

55.1 Introduction

In B physics several anomalies have been observed in various observables associated with semileptonic decay processes mediated by $b \to (c, s)$ quark level transitions. These days the study of observed (2–4) σ discrepancies of several lepton non universality (LNU) observables are the center of attraction in B-physics. The list of various LNU observables, their theoretical predicted values and experimental values are presented in Table 55.1. As these observables are the ratio of two decay rates, the theoretical uncertainties arising from the form factors and CKM matrix elements cancel out to a great extent, reducing the overall uncertainty in the calculation of these parameters, hence they are considered as sensitive probe for new physics (NP). On the other hand, the decay processes involving τ lepton in the final state are more

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Table 55.1 List of various LNU observables along with their measured values and Standard model predictions and deviations from SM

LNU observable	Measured value	SM value	Deviation
$R_K = \frac{\text{Br}(B^+ \to K^+\mu^+\mu^-)}{\text{Br}(B^+ \to K^+e^+e^-)}\Big\vert_{q^2\in[1.1,6]\ \text{GeV}^2}$	$0.846^{+0.060+0.016}_{-0.054-0.014}$	1.0003 ± 0.0001	2.5σ
$R_{K^*} = \frac{\text{Br}(\bar{B} \to \bar{K}^*\mu^+\mu^-)}{\text{Br}(\bar{B} \to \bar{K}^*e^+e^-)}\Big\vert_{q^2\in[0.045,1.1]\ \text{GeV}^2}$	$0.660^{+0.110}_{-0.070} \pm 0.024$	0.92 ± 0.02	2.2σ
$R_{K^*}\Big\vert_{q^2\in[1.1,6]\ \text{GeV}^2}$	$0.685^{+0.113}_{-0.007} \pm 0.047$	1.00 ± 0.01	2.4σ
$R_D = \frac{\text{Br}(\bar{B} \to \bar{D}\tau\bar{\nu}_\tau)}{\text{Br}(\bar{B} \to \bar{D}l\bar{\nu}_l)}$	$0.340 \pm 0.027 \pm 0.013$	0.299 ± 0.003	1.9σ
$R_{D^*} = \frac{\text{Br}(\bar{B} \to \bar{D}^*\tau\bar{\nu}_\tau)}{\text{Br}(\bar{B} \to \bar{D}^*l\bar{\nu}_l)}$	$0.295 \pm 0.011 \pm 0.008$	0.258 ± 0.005	3.3σ
$R_{J/\psi} = \frac{\text{Br}(\bar{B} \to \bar{J}/\psi\tau\bar{\nu}_\tau)}{\text{Br}(\bar{B} \to \bar{J}/\psi\mu\bar{\nu}_\mu)}$	$0.71 \pm 0.17 \pm 0.184$	0.289 ± 0.01	2σ

effective for NP, as the third generation of leptons have comparatively larger mass than the other two generations. In this aspect we scrutinize the possibility of LNU and other asymmetries associated with $\bar{B} \to \rho\ell\bar{\nu}_\ell$ decay process mediated by $b \to u\ell\bar{\nu}_\ell$ transition considering the effective field theory approach.

The outline of our paper is follows. In Sect. 55.2, we present the general effective Lagrangian describing the processes $b \to u\ell\bar{\nu}_\ell$ in presence of new couplings in addition to the SM ones, and the theoretical framework for analysing $\bar{B} \to \rho\ell\bar{\nu}_\ell$ decay process. The constrained parameter space for the new couplings are presented in Sect. 55.3. In Sect. 55.4, we discuss the effect of NP on various parameters. Here we show the q^2 variation of branching fraction, lepton non-universality parameter and lepton spin asymmetry parameter of $\bar{B} \to \rho\ell\bar{\nu}_\ell$ processes in presence of individual new physics coefficients. We summarize our work in Sect. V.

55.2 Theoretical Framework

In the effective field theory approach, the most general effective Lagrangian of $\bar{B} \to \rho\ell\bar{\nu}_\ell$ decay process mediated by $b \to u\ell\bar{\nu}_\ell$ transition can be expressed as [5],

$$
\begin{aligned}
L_{eff} = \frac{4G_F}{\sqrt{2}} V_{ub}\big[&(1 + V_L)(\bar{u}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) + V_R(\bar{u}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma^\mu\nu_L) \\
&+ S_L(\bar{u}_L b_R)(\bar{\tau}_R\nu_L) + S_R(\bar{u}_R b_L)(\bar{\tau}_R\nu_L) + T_L(\bar{b}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)\big], \quad (55.1)
\end{aligned}
$$

where G_F is the Fermi constant, V_{ub} is the CKM matrix element, V_L, V_R, S_L and S_R are new Wilson coefficients. In the SM V_L, V_R, S_L and S_R couplings are zero. Here we have assumed the neutrinos are left handed and the chiral quark and lepton fields are expressed as $(b, u, \ell)_{L,R} = P_{L,R}(b, u, \ell)$ with $P_{L,R} = (1 \mp \gamma^5)/2$.

The differential decay rate of $\bar{B} \to \rho\ell\bar{\nu}_\ell$ decay process mediated by $b \to u\ell\bar{\nu}_\ell$ transition in presence of additional Wilson coefficients can be written as,

$$\begin{aligned}\frac{d\Gamma}{dq^2} = &\frac{G_F^2|V_{ub}|^2}{192\pi^3 m_{\bar{B}}^3} q^2\sqrt{\lambda(q^2)}\left(1-\frac{m_\ell^2}{q^2}\right)\times \\ &\left[(|1+V_L|^2+|V_R|^2)\left\{\left(1+\frac{m_\ell^2}{q^2}\right)(H_{V_+}^2+H_{V_-}^2+H_{V_0}^2)+\frac{3}{2}\frac{m_\ell^2}{q^2}H_{V_t}^2\right\}\right. \\ &-2Re\{(1+V_L)V_R^*\}\{\left(1+\frac{m_l^2}{q^2}\right)(H_{V_0}^2+2H_{V_+}H_{V_-})+\frac{3}{2}\frac{m_\ell^2}{q^2}H_{V_t}^2\} \\ &+\frac{3}{2}|S_L-S_R|^2 H_S^2+8|T_L^2|\left(1+\frac{2m_\ell^2}{q^2}\right)(H_{T_+}^2+H_{T_-}^2+H_{T_0}^2) \\ &+3Re[(1+V_L-V_R)(S_L-S_R)]\frac{m_\ell^2}{\sqrt{q^2}}H_S H_{V_t} \\ &-12Re[(1+V_L)T_L^*]\frac{m_\ell^2}{\sqrt{q^2}}(H_{T_0}H_{V_0}+H_{T_+}H_{V_+}-H_{T_-}H_{V_-}) \\ &\left.+12Re[V_R T_L^*]\frac{m_\ell^2}{\sqrt{q^2}}(H_{T_0}H_{V_0}+H_{T_+}H_{T_-}-H_{T_-}H_{V_+})\right],\end{aligned} \tag{55.2}$$

where $H_{V_{+,-,0,t}}$, H_S, $H_{T_{+,-,0}}$ are the helicity amplitudes which are the function of form factors, $\lambda = ((m_B - m_\rho)^2 - q^2)((m_B + m_\rho)^2 - q^2)$, q^2 is the momentum transferred square.

The parameters sensitive to NP are,

- Lepton non-universality parameter:

$$R_\rho(q^2) = \frac{d\Gamma(\bar{B} \to \rho^+\tau^-\bar{\nu}_\tau)/dq^2}{d\Gamma(\bar{B} \to \rho^+ l^-\bar{\nu}_l)/dq^2}\ .$$

- Lepton-spin asymmetry:

$$A_\lambda^P(q^2) = \frac{d\Gamma(\lambda_l = -1/2)/dq^2 - d\Gamma(\lambda_l = 1/2)/dq^2}{d\Gamma(\lambda_l = -1/2)/dq^2 + d\Gamma(\lambda_l = 1/2)/dq^2}.$$

55.3 Constraints on New Couplings

In our analysis, the new Wilson coefficients are considered as complex. we consider the contribution of one additional coefficient at a time while all other coefficients are considered to be zero. The constraints on new parameter space associated with $b \to u\ell\bar{\nu}_\ell$ transitions are computed by performing a χ^2 fit on experimentally measured

Table 55.2 Best-fit values and corresponding 1σ ranges of new complex coefficients associated with $b \to u\tau\bar{\nu}_\tau$ transition

New coefficients	Best-fit	1σ range	χ^2/d.o.f
(Re[V_L], Im[V_L])	(−0.8318, 1.098)	([−1.43, −0.43], [1.0, 1.2])	0.265
(Re[V_R], Im[V_R])	(−0.115, 0)	([−0.2, −0.025], [−0.45, 0.45])	0.1363
(Re[S_L], Im[S_L])	(−0.0236, 0)	([−0.042, −0.006], [−0.09, 0.09])	0.1906
(Re[S_R], Im[S_R])	(−0.439, 0)	([−0.46, −0.42], [−0.09, 0.09])	0.1906

values of R_π^ℓ, Br($B_u \to \tau\bar{\nu}_\tau$) and Br($B^0 \to \pi^+\tau^-\bar{\nu}_\tau$) observables [2]. The allowed range of new couplings we used in our analysis are presented in Table 55.2.

55.4 Effect of New Physics

We consider the effect of left-handed vector like new coupling (V_L) in addition to the SM and the contribution due to all other coefficients are taken to be zero. In presence of only V_L coefficient we calculate the branching ratio, LNU parameter and lepton spin asymmetry parameter of $\bar{B} \to \rho\ell\bar{\nu}_\ell$ decay process. Similarly we calculate all these parameters in presence of individual couplings V_R, S_L and S_R. The numerical values of branching fraction and LNU parameters in presence of various couplings are shown in Table. The q^2 deviation of all these parameters in presence individual couplings for their 1σ allowed range and best-fit values are shown in Fig. 55.1. The blue dashed line represents the SM variation whereas the orange, cyan, magenta and green bands represent the variation in presence of V_L, V_R, S_L, S_R coefficients respectively. The black line stands for the variation for the best-fit value of the corresponding Wilson coefficients. We also present the plots containing the variation of differential decay rate, LNU parameter and lepton spin asymmetry for the best-fit value of all the new coefficients in Fig. 55.2.

Numerical values	$\mathcal{B}(B \to \rho^+\tau^-\bar{\nu}_\tau)$	R_ρ
SM Value	2.58933×10^{-4}	1.00718
$S_L(Best-fit)$	2.57162×10^{-4}	1.00067
$S_L(1\sigma)$	$(2.53062 \to 2.55831) \times 10^{-4}$	0.85616→ 0.995773
$S_R(Best-fit)$	2.71036×10^{-4}	1.05222
$S_R(1\sigma)$	$(2.5996 \to 2.83176) \times 10^{-4}$	1.01114→1.09739
$V_L(Best-fit)$	4.01063×10^{-4}	1.54296
$V_L(1\sigma)$	$(1.56969 \to 16.7189) \times 10^{-4}$	0.597757→ 6.44812
$V_R(Best-fit)$	3.02434×10^{-4}	1.1804
$V_R(1\sigma)$	$(3.3915 \to 5.20621) \times 10^{-4}$	1.1804

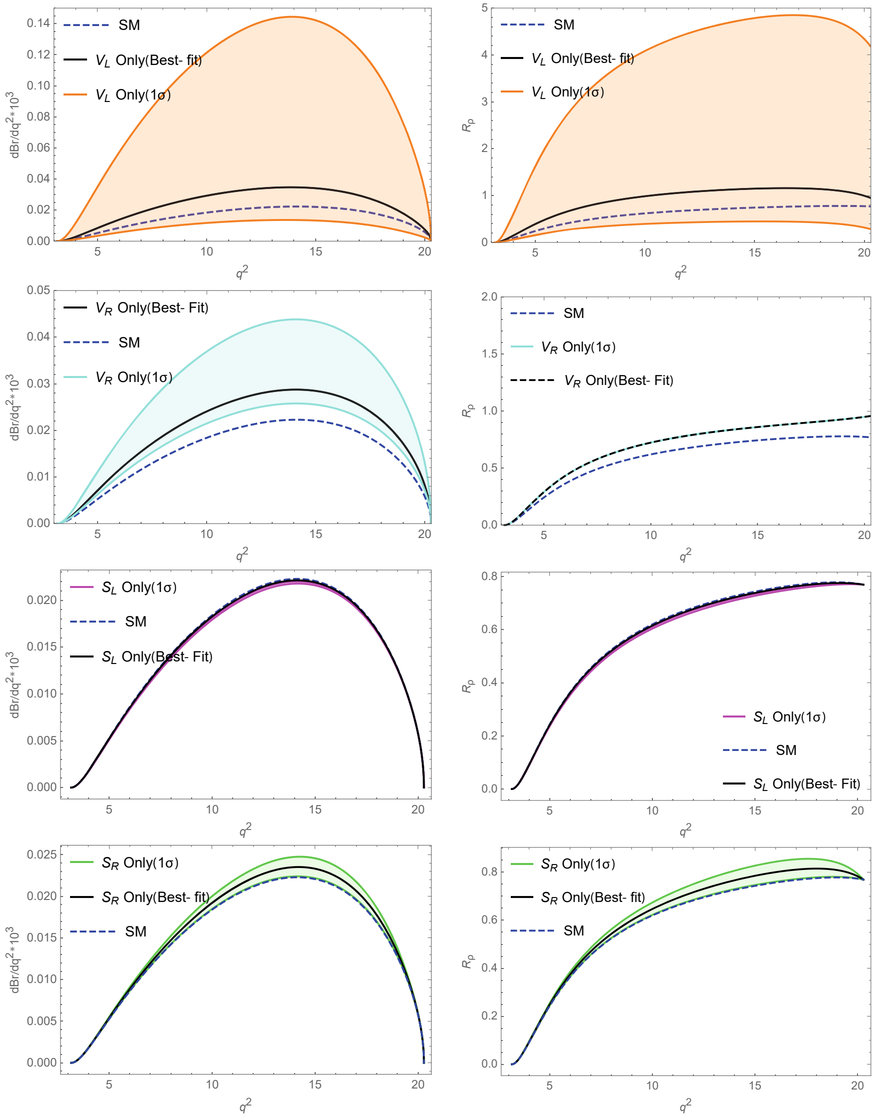

Fig. 55.1 The q^2 variation of the differential Branching ratio (left panel), LNU parameter (right panel) of $\bar{B} \to \rho \tau \bar{\nu}_\tau$ decay process in presence of individual NP coefficients

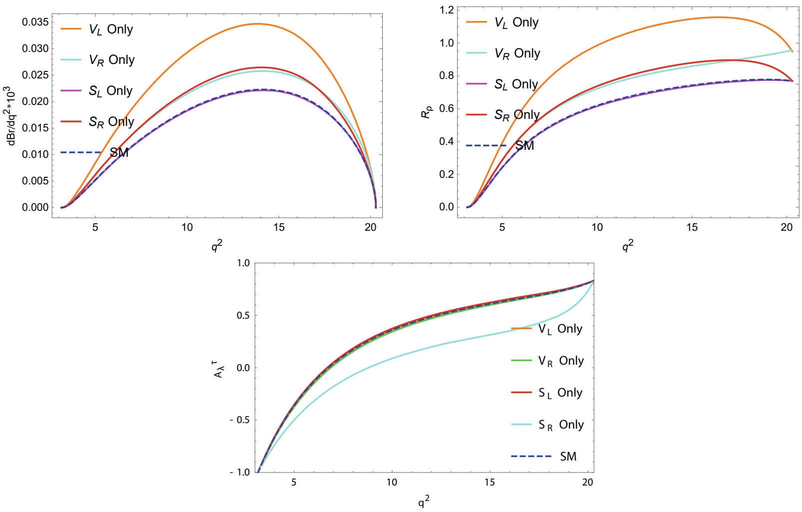

Fig. 55.2 The q^2 variation of differential branching ratio (top-left panel), Lepton non universality Parameter (top-right panel) and lepton spin asymmetry (bottom panel) for the best-fit values of NP coefficients. Blue dashed line represents the variation in SM whereas the orange, cyan, magenta and red lines represent the variation for the best-fit value of V_L, V_R, S_L and S_R coefficients respectively

55.5 Conclusion

In this analysis we have performed a model independent study of $\bar{B} \to \rho \ell \bar{\nu}_\ell$ decay process. We consider the new Wilson coefficients as complex quantities and calculated the branching ratio, LNU parameter and lepton spin asymmetry parameter in presence of individual couplings. We also show the q^2 variation of all these parameters in presence of all these new coefficients.

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