Non-resonant new physics search at the LHC for the $b \rightarrow c\tau\nu$ anomalies

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ABSTRACT: Motivated by the $b \rightarrow c\tau\nu$ anomalies, we study non-resonant searches for new physics at the large hadron collider (LHC) by considering final states with an energetic and hadronically decaying $\tau$ lepton, a $b$-jet and large missing transverse momentum ($pp \rightarrow \tau_b\bar{b} + E_T^{\text{miss}}$). Such searches can be useful to probe new physics contributions to $b \rightarrow c\tau\nu$. They are analyzed not only within the dimension-six effective field theory (EFT) but also in explicit leptoquark (LQ) models with the LQ non-decoupled. The former is realized by taking a limit of large LQ mass in the latter. It is clarified that the LHC sensitivity is sensitive to the LQ mass for $\mathcal{O}(1)$ TeV even in the search of $pp \rightarrow \tau_b\bar{b} + E_T^{\text{miss}}$. Although the LQ models provide a weaker sensitivity than the EFT limit, it is found that the non-resonant search of $pp \rightarrow \tau_b\bar{b} + E_T^{\text{miss}}$ can improve the sensitivity by $\approx 40\%$ versus a conventional mono-$\tau$ search ($pp \rightarrow \tau_b + E_T^{\text{miss}}$) in the whole LQ mass region. Consequently, it is expected that most of the parameter regions suggested by the $b \rightarrow c\tau\nu$ anomalies can be probed at the HL-LHC. Also, it is shown that $R_2$ LQ scenario is accessible entirely once the LHC Run 2 data are analyzed. In addition, we discuss a charge selection of $\tau_b$ to further suppress the standard-model background, and investigate the angular correlations among $b$, $\tau$ and the missing transverse momentum to discriminate the LQ scenarios.

KEYWORDS: Flavor physics, LHC, Beyond Standard Model, Effective Field Theories, Leptoquark
1 Introduction

Semi-leptonic $B$-meson decay processes have been investigated to test the Standard Model (SM) and to search for a hint for New Physics (NP). In the last decade, the BaBar [1, 2], Belle [3–7] and LHCb collaborations [8–10] have reported exiting anomalies in semi-leptonic decays of $B$ mesons, such as $R_{D^{(*)}} = \frac{\text{BR}(B \rightarrow D^{(*)} \tau \nu)}{\text{BR}(B \rightarrow D^{(*)} \ell \nu)}$, with $\ell = \mu$ for LHCb and an average of $e$ and $\mu$ for BaBar and Belle. Here, a ratio of the branching ratios is taken to reduce both experimental and theoretical (i.e., parametric and QCD) uncertainties significantly, so that $R_{D^{(*)}}$ is sensitive to NP that couples to quarks and leptons. Although the latest result released by Belle becomes closer to the SM values [6, 7], the world average of $R_{D^{(*)}}$ measurements still deviates from the SM predictions at the 3–4σ confidence level (CL) (see Ref. [11] for a recent summary of the SM predictions).
The $R_{D^{(*)}}$ discrepancy suggests violation of the lepton flavor universality (LFU) between $\tau$ and light leptons, and has prompted many attempts of the NP introducing new scalar and vector mediators (see, e.g., Ref. [12] for the very recent review). In terms of the low-energy effective Hamiltonian, their contributions are encoded as

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb} \left[ (1 + C_V)(\tau\gamma^\mu P_L b)(\bar{\tau}\nu_\mu P_L \nu_\tau) + C_V (\tau\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + C_{S_1}(\tau P_L b)(\bar{\tau} P_L \nu_\tau) + C_{S_2}(\tau P_L b)(\bar{\tau} P_L \nu_\tau) + C_{T}(\bar{\tau}\sigma^{\mu\nu} P_L b)(\tau\sigma_{\mu\nu} P_L \nu_\tau) \right] + \text{h.c.},$$

(1)

with $P_{L/R} = (1 \mp \gamma_5)/2$. Here, the Wilson coefficients (WCs), $C_X$, are normalized by the SM contribution, $\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb}(\tau\gamma^\mu P_L b)(\bar{\tau}\nu_\mu P_L \nu_\tau)$, corresponding to $C_X = 0$ for $X = V_{1,2}, S_{1,2}, T$. Note that the SM contribution is suppressed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{cb}$ [19, 20], where $V_{cb} = 0.041$ [21] is set throughout this paper. One can see that a scale of NP implied by the $R_{D^{(*)}}$ anomaly is restricted as $\lesssim O(10)$ TeV by the perturbative unitarity limit on NP interactions [22].

The large hadron collider (LHC) experiment has a great potential to test such NP contributions. They can be probed, e.g., by resonant searches for new particles such as charged Higgs, $W'$ (and related $Z'$), and leptoquark (LQ), and by non-resonant searches for the contact interactions of Eq. (1). In addition to various flavor measurements, e.g., $B_c \to \tau\bar{\nu}$, $B_d \to \Lambda_c\tau\bar{\nu}$, and polarization observables in $B \to D^{(*)}\tau\bar{\nu}$ in the near future, which have been studied to check those contributions, the collider searches provide independent information. Moreover, they are free from uncertainties of the flavor observables especially inherent in $B \to D^{(*)}$ hadronic form factors.

In this paper, we examine non-resonant searches in light of the $R_{D^{(*)}}$ anomaly. Even if new particles are heavier than the LHC beam collision energy, their contributions could be detected indirectly by exchanging these particles in $t$-channel propagators. The ATLAS and CMS collaborations have performed non-resonant searches especially to probe $W'$ boson (with assuming a decay $W' \to \tau\bar{\nu}$) in the sequential standard model. They have done a $\tau\bar{\nu}$ search, i.e., analyzed events with a hadronic $\tau$ jet and a large missing transverse momentum by using the Run 1 and 2 data [23–26]. The results are consistent with the SM background (BG) expectations, and one can use them to set upper bounds on the NP interactions relevant to the $R_{D^{(*)}}$ anomaly, or the operators in Eq. (1). References [27–30] have studied such an interplay, i.e., the relation between the high-$p_T$ tail of the $\tau\bar{\nu}$ events at the LHC and the $R_{D^{(*)}}$ anomaly in new physics models.

Recently, it has been pointed out that sensitivities to the NP may be improved versus the above non-resonant $\tau\bar{\nu}$ search by requiring an additional $b$-jet in the final state [31–33]. This can be understood from the fact that the genuine $\tau\bar{\nu} + b$ final state is achieved by $gq \to b\tau\bar{\nu}$ ($q = u, c$) within the SM. Since this contribution is suppressed by $|V_{ub}(cb)|^2 \sim O(10^{-5}(-3))$, the main SM background comes from $\tau\bar{\nu} + j$ events with mis-identifying a light-flavored jet as $b$ jet. This is in contrast to the $\tau\bar{\nu}$ search, whose SM contributions, e.g., $\bar{u}d \to \tau\bar{\nu}$, are not suppressed by the CKM factors or mis-identifications. In addition, the additional $b$ quark allows us to study

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The Wilson coefficients are also shown as $C_{V_1} = C_{V_2}^f$, $C_{S_1} = C_{S_2}^f$, and $C_{T} = C_{T}^f$ [13].

In this paper, right-handed neutrinos are not considered (or equivalently assumed to be heavier than the $B$ meson). See Refs. [14–18] for models with light right-handed neutrinos in the context of the $R_{D^{(*)}}$ anomaly.
angular correlations among the final state particles, which are potentially useful to distinguish the NP interactions. Such a channel has been studied in Ref. [34] for general NP contact interactions, including those relevant to the $R_{D^{(*)}}$ anomaly. They have argued that sensitivities to each WC searches can be improved by $\sim 30\%$ versus the $\tau\nu$ search. Moreover, it was argued that angular correlations between $b$ and $\tau$ or $\nu$ would be useful to distinguish possible NP scenarios working in the center of mass frame.

After the above analyses, there are significant developments within the context of the $\tau\nu$ search. In the previous studies, the effective field theory (EFT) approach (i.e., the contact-interaction approximation) had been taken to describe the NP contributions. However, as pointed out in Ref. [35], this prescription is not always appropriate to represent actual NP contributions when the LHC non-resonant search is studied. In fact, a transverse mass defined as

$$m_T = \sqrt{2p_T^e E_T^{\text{miss}} [1 - \cos \Delta \phi(p_T^e, \vec{p}_T^{\text{miss}})]},$$

(2)

is often introduced to analyze high-$p_T$ events, where $\Delta \phi$ is a relative angle ($0 \leq \Delta \phi \leq \pi$) and the missing transverse momentum is expressed by $\vec{p}_T^{\text{miss}}$ with magnitude $E_T^{\text{miss}}$. Since a new particle appearing in the $t$-channel propagator is likely to carry a large momentum transfer to produce a high-$p_T$ $\tau$ lepton and it produces an effective new particle mass (since $t < 0$),

$$M_{\text{LQ}} \approx \frac{g_{\text{LQ}}^2}{|t - M_{\text{LQ}}^2|} \approx \frac{g_{\text{LQ}}^2}{M_{\text{EFT}}^2},$$

(3)

the EFT description is no longer appropriate. We can see that sensitivities to the NP tend to become weaker than those in the EFT description, which is valid only for $M_{\text{LQ}} \gg m_T$. Although the study in Ref. [35] has been done for the non-resonant $\tau\nu$ search, a similar conclusion can hold for the $\tau\nu + b$ case. In this paper, it will be shown that the sensitivity to the WCs can be weakened by up to 50\% even for $\tau\nu + b$.

Moreover, it is pointed out that the NP sensitivity can be improved by choosing negative-charge mono-$\tau$ events [35]. This follows from the fact that the dominant SM background comes from $pp \rightarrow W^{\pm(*)} \rightarrow \tau^{\pm}\nu$, and then the imbalance of $N(W^+)/N(W^-) > 2$ is observed due to reflecting the proton charge [36, 37]. This is in contrast to the NP case: the interaction in Eq. (1) predicts $N(\tau^+)/N(\tau^-) = 1$ because the contribution is not generated from valence quarks. In fact, in order to distinguish the charge of the $\tau$ jet, one has to observe a sagitta of the charged pion from the $\tau$ decay. In the high-$p_T$ region such as $p_\tau^{\pm} = 1$ TeV, the sagitta in the CMS inner detector becomes $O(100) \mu$m. Since this is larger than the detector resolution, the charge of $\tau$ jet with $p_\tau^{\pm} = O(1)$ TeV could be distinguished with good accuracy. Therefore, it is important to study impacts of the charge selection.

In this paper, we perform a comprehensive analysis of the non-resonant $\tau\nu + b$ search as well as the $\tau\nu$ one with adopting the above developments. We also discuss directions of further improvements of the NP sensitivity especially to distinguish the NP interaction operators, e.g., by utilizing the charge asymmetry of $\tau^{\pm}$ and the angular correlations among the final states.

This paper is organized as follows. A model setup is explained in Sec. 2. A strategy to generate the background and signal events is explained in Sec. 3. Numerical results and future prospects are explored in Sec. 4. Impacts of their sensitivities on the NP interpretation for the notorious $R_{D^{(*)}}$ anomaly are also given in this section. Section 5 is devoted to conclusions and discussion.
2 New physics scenarios

In this paper, leptoquark (LQ) models are employed as an illustrative realization of the WCs of the effective Hamiltonian in Eq. (1). They form the WCs at the NP scale \( \Lambda \sim M_{LQ} \) as

\[
2\sqrt{2}G_F V_{cb} C_\chi(\Lambda) = N_\chi \frac{h_1 h_2}{M_{LQ}^{2}},
\]

with LQ mass \( M_{LQ} \) and LQ couplings to the SM fermions \( h_{1,2} \). The numerical factor \( N_\chi \) depends on the Lorenz structure of the EFT operator (\( X = V_{1,2}, S_{1,2}, T \)).

We are interested in NP scenarios that can explain the \( R_{D^{(*)}} \) anomaly. Solutions to the anomaly are given in terms of \( C_\chi \) in the literature, e.g., see Refs. [35, 38, 39]. A general consensus is, for instance, that scenarios with a single NP operator \( X = V_{1,2} \) work well, which can be realized in particular LQ models. Also, there are LQ models which contribute to multiple WCs.

Given the LQ mass \( M_{LQ} \), the high-\( p_T \) search puts an upper bound on the LQ couplings and the WCs in Eq. (1) at the \( \Lambda_{LHC} \) scale, which is encoded as \( C_\chi(\Lambda_{LHC}) \) in this paper. The LHC scale reflects the high-\( p_T \) region sensitive to the NP signal. Hence, in the following analysis, we take a typical size as \( \Lambda_{LHC} = 1 \) TeV, which is the same as Ref. [34]. In the flavor physics, the EFT limit \( q^2 \ll \Lambda^2 \) is a good approximation for \( \Lambda \gtrsim \mathcal{O}(100) \) GeV. However, as mentioned in the introduction, this is not the case for the high-\( p_T \) searches at the LHC, where \( p_T \) can be \( \mathcal{O}(1) \) TeV. Thus, we will investigate explicit \( M_{LQ} \) dependences of the sensitivities of \( C_\chi(\Lambda_{LHC}) \).

In the following subsections, we show explicit LQ models to setup the NP scenarios of our interest and also give a brief explanation for collider signatures.

2.1 \( U_1 \) LQ

The \( SU(2)_L \) singlet vector LQ (\( U_1 \)) is one of the well-known candidates to explain several \( B \) anomalies [40–42]. Its interaction is written as

\[
\mathcal{L}_{U_1LQ} = h_L^i \left( \bar{u}_i \gamma_\mu p_L v_j + \bar{d}_i \gamma_\mu p_L \ell_j \right) U_1^\mu + h_R^j \left( \bar{d}_j \gamma_\mu p_R \ell_j \right) U_1^\mu + \text{h.c.} \tag{5}
\]

By integrating out the LQ, one can obtain two WCs as

\[
2\sqrt{2}G_F V_{cb} C_{V_i} = + \frac{(V_{CKM} h_R^i)^{23} h_L^{i,33}}{M_{LQ}^2}, \quad 2\sqrt{2}G_F V_{cb} C_{S_i} = - \frac{(V_{CKM} h_L^i)^{23} h_R^{i,33}}{M_{LQ}^2}. \tag{6}
\]

It is noticed that these WCs depend on different couplings, i.e., are independent with each other. The couplings irrelevant to \( b \to c \tau \bar{\nu} \) are assumed to be zero.

The scenario with \( C_{V_i} \neq 0 \) and \( C_{S_i} = 0 \), so-called the single \( C_{V_i} \) scenario, is realized by taking \( h_R^{i,33} = 0 \), which will be investigated later. Note that \( C_{V_i} \neq 0 \) can also be obtained by other LQ models such as the \( SU(2)_L \) triplet vector (\( U_3 \)), singlet scalar (\( S_1 \)), and triplet scalar (\( S_3 \)) LQs. However, these models confront a stringent constraint from \( b \to s \tau \bar{\nu} \) unavoidably in single LQ scenarios at the tree level, see Appendix B. For instance, \(|C_{V_i}| \lesssim 0.03 \) is obtained for the \( S_1 \) LQ scenario, which is not consistent with the \( R_{D^{(*)}} \) solution, \( C_{V_i} = 0.09 \pm 0.02 \). Hence, the \( U_1 \) LQ is the only possibility to realize this scenario (see Ref. [43] for alternative possibility by use of multiple LQs). Note that the constraints from \( \Delta M_s \) and \( \Delta M_d/\Delta M_q \) are UV-model dependent. For
U1 LQ models, additional vector-like leptons are often incorporated in the UV models. These constraints are weakened by incorporating light vector-like leptons contributions via a GIM-like mechanism [44, 45].

Another scenario has been discussed in the context of a U(2) flavor symmetry [46–53]. In this scenario, $h_L$ and $h_R$ are aligned, and the two WCs are related as

$$C_{S_1} = -2 \beta_R C_{V_1},$$

where $\beta_R = e^{i \phi_R}$ denotes a relative phase [53]. Assuming $C_{V_1}$ to be real, the result to explain the $R_{D^{(*)}}$ anomaly is given as $\phi_R \sim 0.4 \pi$ and $C_{V_1} \sim 0.09$. This scenario will also be investigated in this paper. Note that the LHC study is less sensitive to the phase.

### 2.2 R2 LQ

The $SU(2)_L$ doublet scalar LQ ($R_2$) also provides distinctive solutions to the $R_{D^{(*)}}$ anomaly [54]. A practical $R_2$ LQ model introduces two distinct LQ doublets, $R_{2,1} = (R_{2,1}^5, R_{2,1}^{2/3})$ and $R_{2,2} = (R_{2,2}^{2/3}, R_{2,2}^{1/3})$, in the SM gauge invariant form, for which a large mixing between $R_{2,1}^{2/3}$ and $R_{2,2}^{2/3}$ is induced via an electroweak symmetry breaking term; $R_{2,1}^{2/3} R_{2,2}^{-2/3} (H^0_0)^2$. Then, the interaction of the mass eigenstate $R_{2,1}^{2/3}$ is picked out as

$$\mathcal{L}_{R_{2,1}^{2/3}} = \left( h_L^{ij} \bar{u}_i P_L v_j + h_R^{ij} \bar{d}_i P_R \ell_j + \tilde{h}_L^{ij} \bar{d}_i P_L \ell_j \right) R_{2,1}^{2/3} + \text{h.c.}$$

Then three WCs are generated, two of which are related, as

$$2 \sqrt{2} G_F V_{cb} C_{S_2} = \frac{h_{L}^{23} h_{R}^{43}}{2 M_{LQ}^2}, \quad 2 \sqrt{2} G_F V_{cb} C_{S_2} = \frac{h_{L}^{23} h_{R}^{43}}{2 M_{LQ}^2}, \quad C_{S_2} = +4C_T. \quad (9)$$

Both two scenarios, namely the one with the single $C_{V_2}$ and another for the specific combination $C_{S_2} = +4C_T$, can solve the $R_{D^{(*)}}$ anomaly. Hence, collider studies will be performed for them in this paper.

Here, the coupling $\tilde{h}_L$ is generated from the mixing above the electroweak symmetry breaking scale. This implies that $C_{V_2}$ should have an additional suppression factor. See Ref. [55] for a UV completion of the $C_{V_2}$ scenario and its phenomenological bounds. It will be shown that there are still viable parameter regions. Nevertheless, our collider study provides a useful probe for the $C_{V_2}$ constraint as we will see in Sec. 4.3.

### 2.3 S1 LQ

The $SU(2)_L$ singlet scalar LQ ($S_1$) gives another solution to the $R_{D^{(*)}}$ anomaly. The relevant Yukawa interactions with the SM fermions are described by

$$\mathcal{L}_{S_{1,LQ}} = h_{L}^{ij} \bar{Q}^i H^0_L L_j + h_{R}^{ij} \bar{d}^i H^0_R \ell_j + \text{h.c.}$$

$$= \left( V_{CKM} h_{L}^{ij} \bar{u}^i H^0_L L_j - h_{L}^{ij} \bar{d}^i H^0_R \ell_j + h_{R}^{ij} \bar{u}^i H^0_R \ell_j \right) S_1 + \text{h.c.}. \quad (10)$$

The contribution to the relevant WCs are given by

$$2 \sqrt{2} G_F V_{cb} C_{V_i} = \frac{h_{L}^{33} (V_{CKM} h_{R}^{*})^{23}}{2 M_{LQ}^2}, \quad 2 \sqrt{2} G_F V_{cb} C_{S_2} = -\frac{h_{L}^{33} h_{R}^{23}}{2 M_{LQ}^2}, \quad C_{S_2} = -4C_T. \quad (11)$$

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There are two sets of the WCs which are controlled by the different Yukawa couplings. Although the single $C_V^1$ scenario looks promising, a stringent constraint from $b \to s \nu \nu$ is unavoidable at the tree level. We will discuss the relevant constraints in Sec. 4 and Appendix B.

3 Event generation

Monte Carlo (MC) event generators are used to simulate both NP signal and SM background processes with a hard $\tau$ lepton and a large missing transverse momentum with/without an additional $b$-jet in the final states at $\sqrt{s} = 13$ TeV. The NP models are implemented via F\textsc{FEYNRULES} v2.3.34 [56]. The model files are available in the arXiv web page. Event samples are generated by using \textsc{MadGraph5_aMC@NLO} v2.8.3.2 [57] interfaced with PYTHIA v8.303 [58] for hadronizations and decays of the partons. The MLM merging is adopted in the five-flavor scheme [59]. NNPDF2.3 in LHAPDF v6.3.0 [60] is used. Detector effects are simulated by using \textsc{Delphes} v3.4.2 [61]. Here, we modified a prescription of the identification of the hadronic $\tau$ jet, as will be described below. The jets are reconstructed by using anti-$k_T$ algorithm [62] with a radius parameter set to be $R = 0.5$. See Appendix A for some details.

To investigate the non-resonant $\tau \nu$ and $\tau \nu + b$ searches, and especially to evaluate an impact of the latter, the following two sets of kinematic cuts are compared:

**cut a**: Kinematic cuts to select the $\tau \nu$ events by following Ref. [34], originated from the CMS analysis [25]:

- 1. require exactly one $\tau$-tagged jet, satisfying the transverse momentum of $\tau$, $p_T^{\tau} \geq 200$ GeV, and the pseudo-rapidity of $\tau$, $|\eta_\tau| \leq 2.1$.
- 2. veto the event if it includes any isolated electron or muon with $p_{T}^{e,\mu} \geq 20$ GeV within $|\eta_e| \leq 2.5$ or $|\eta_\mu| \leq 2.4$, where the lepton isolation criteria are the same as Ref. [34],
- 3. require large missing transverse momentum, $E_T^{\text{miss}} \geq 200$ GeV, to suppress the $W^\pm$ resonant contribution,
- 4. require that the missing momentum is balanced with the $\tau$-tagged jet with the back-to-back configuration as $\Delta \phi(p_T^{\tau}, p_T^{\text{miss}}) \geq 2.4$ and $0.7 \leq p_T^{\tau}/E_T^{\text{miss}} \leq 1.3$ to further suppress the SM backgrounds.

**cut b**: Additional kinematic cuts to "cut a" for selecting the $\tau \nu + b$ events:

- 1. require exactly one $b$-tagged jet with $p_T^b \geq 20$ GeV and $|\eta^b| < 2.5$.
- 2. restrict the number of light-flavored jets, $N_j \leq 2$, to suppress the top-decay related backgrounds, where the jets satisfy $p_T^j \geq 20$ GeV and $|\eta^j| \leq 2.5$.

Energetic $\tau$ leptons can be emitted not only from the hard processes, but also from decays of energetic mesons, e.g., $B \to \tau X$ (at a branching ratio $\sim 3\%$) and $D_s \to \tau X$ ($\sim 5\%$). Quantitatively, these secondary $\tau$ gives mild contributions to cut a and cut b. In reality, it is likely to be accompanied by nearby jets and vetoed by $\tau$ isolation conditions adopted in the ATLAS/CMS analyses.
Since they do not use cut-based analyses, an implementation of their isolation procedure is complicated and beyond the scope of this paper. In our analysis, events with \( \tau \) whose parent particle is mesons or baryons are vetoed, for simplicity. Also, for a \( \tau \)-tagging efficiency, the “VLoose” working point is adopted for the hadronic decays; \( \varepsilon_{\tau \rightarrow \tau} = 0.7 \) \cite{63}. As the mis-tagging efficiencies, we apply \( p_T \)-dependent efficiency based on Ref. \cite{63}. For instance, \( \varepsilon_{j \rightarrow \tau} = 3.7 \times 10^{-3} \) for \( p_T^j = 100 \text{ GeV} \) and \( 7.2 \times 10^{-4} \) for \( p_T^j = 300 \text{ GeV} \) or larger. The mis-tagging rare \( \varepsilon_{c,b \rightarrow \tau} \) is assumed to be \( 7.2 \times 10^{-4} \) as a reference. When one imposes the condition requiring an additional \( b \)-jet in the final state, of crucial importance is which working point is chosen for the \( b \)-tagging efficiencies. For instance lower mis-tagging efficiencies can suppress backgrounds coming from fake \( b \)-jets. We adopt the following working point based on Table 4 of Ref. \cite{64},

\[
\begin{align*}
\varepsilon_{j \rightarrow b} &= 1/1300, \\
\varepsilon_{c \rightarrow b} &= 1/27, \\
\varepsilon_{b \rightarrow b} &= 0.6.
\end{align*}
\]  

Compared to the working point in Ref. \cite{34}\footnote{The reference \cite{34} adopted a different working point: \( \varepsilon_{j \rightarrow b} = 0.015, \varepsilon_{c \rightarrow b} = 0.3, \) and \( \varepsilon_{b \rightarrow b} = 0.7. \)} the mis-tagging rates, \( \varepsilon_{j \rightarrow b} \) and \( \varepsilon_{c \rightarrow b} \), are better by factors of 20 and 8, respectively, while the \( b \)-tagging rate \( \varepsilon_{b \rightarrow b} \) is slightly worse. Therefore, it is expected that the number of background events originated from fake \( b \)-jets is reduced in our analysis for the cut b category.

Note that the charge of the final-state \( \tau \) lepton is not distinguished in cut a or cut b, though it may be possible at the LHC as mentioned in Sec. 1 and will be discussed later. In order to stress this point, the searches are described with a script \( \pm \) as “the \( \tau^\pm \nu \) (\( \tau^\pm \nu + b \)) search” hereafter.

### 3.1 Background simulation

As for the SM background events generation, we basically trace the method explored in Ref. \cite{34}. Nonetheless, since this is crucial to derive NP sensitivities, we dare to present all the essential steps in some details, though most of them may be familiar to experts. The six categories of the background processes are considered:

**Wjj**

The event simulations in MadGraph5_aMC@NLO are performed up to QED=4, which includes contributions from vector boson fusions. The W boson is assumed to decay as \( W \rightarrow \tau V \), and the events are matched allowing up to two jets. The \( W jj \) contribution dominates the SM background in the cut a category, and also one of the main sources of the backgrounds for cut b because light-flavored jets are mis-tagged as \( b \) jets. The working point of \( b \)-tagging efficiencies is given in Eq. (12). It is checked that the number of events of \( W \) plus genuine \( b \)-jet is less than that of \( W jj \) by more than three orders of magnitude for cut b. Therefore, improving the discrimination efficiency of the light-flavored jets from the genuine \( b \) jets can result in suppressing the SM background effectively.

**Zjj**

The Z boson is assumed to decay as \( Z \rightarrow \nu \bar{\nu} \), contributing to missing transverse momentum. The events are matched allowing up to two jets. At least one fake \( \tau \)-jet is necessary to pass cut a. Namely, the final state should include associated QCD jets. This channel gives the subdominant
contribution both for cut a and cut b. Note that the ATLAS and CMS analyses categorize $Zjj$ into “QCD jet,” and estimate them with a data-driven technique, e.g., extrapolating from $Zjj$ with $Z \rightarrow \mu^+\mu^-$ events and requiring $p_T^T/E_T^{\text{miss}} \leq 0.7$.

$t\bar{t}$

The top quarks are assumed to decay as $t\bar{t} \rightarrow bW^+\bar{b}W^-$ with both $W$ bosons decaying to $\tau$ or one of them decaying to $\tau$. The former contribution is larger by a factor of four than the latter after cut a, while both are of similar size after cut b.

Single $t$

The single top productions are divided by the following five sub-categories, $t+j$, $tW (1)$, $tW (2)$, $tZ (1)$, and $tZ (2)$. The top quark decays into $bW$, and the number in the parentheses expresses how many gauge bosons decay leptonically, i.e., $W \rightarrow \tau\nu$ or $Z \rightarrow \nu\nu$. More explicitly $t+j \rightarrow b\nu\nu j$ is categorized as $t+j$, $tW \rightarrow b\nu\nu j j$ and $tW \rightarrow b\tau\tau\nu\nu$ are classified into $tW (1)$ and $tW (2)$ respectively. $tZ j \rightarrow b\nu\nu j j$, $tZ j \rightarrow b\tau\nu j j j$ and $tZ j \rightarrow b\tau\nu j j j$ are denoted as $tZ (1)$, and $tZ j \rightarrow b\tau\nu j j j$ are classified into $tZ (2)$.

$Z, \gamma$ Drell-Yan

A pair of $\tau$ leptons are produced via Drell-Yan processes mediated by $Z$ or $\gamma$ in accompany with up to two jets. Since the number of $\tau$ jets is required to be exactly one in cut a, another $\tau$ lepton needs to be missed in the detectors. Although the efficiency of $\tau$ mis-tagged as other particles is not so small, it is unlikely to achieve a large missing momentum because jets are rarely overlooked or their momenta are hardly mis-reconstructed so largely in the detectors. Thus, the contribution will be found to be negligibly small.

$VV$

Pair-productions of vector bosons are classified by the species as $WW$, $ZZ (\gamma)$, and $WZ (\gamma)$. The events for $WW$ are simulated with both $W$’s decaying to $\tau$ and allowing up to two additional jets or one of $W$’s decaying into $\tau$ and allowing up to one additional jet. The $ZZ (\gamma)$ events involve those with one of $Z$’s decaying as $Z \rightarrow \nu\nu$ or into $\tau^+\tau^-$. As for $WZ (\gamma)$, the events are generated from a tauonic $W$ decay along with $\gamma \rightarrow \tau^+\tau^-$ or $Z \rightarrow \tau^+\tau^-$, $\nu\nu$. It will be shown that the resultant contribution is subdominant in cut a and of $O(1)$% in cut b.

It is noted that pure QCD multi-jet backgrounds are not simulated in this paper. In order to pass cut a/b, one of energetic jets has to be mis-tagged as $\tau$. Moreover, although another jet is required to be overlooked to pass the condition of large missing momentum, this rarely happens in the calorimeters. Here we assume that the contributions are negligible, for simplicity, though one needs full detector simulations for further studies. In fact, the CMS collaboration has checked that the QCD multi-jet background is smaller than that from $Zjj$ in their simulation, and shown that the simulated result agrees with the data in a control region [25].
3.2 Signal simulation

Here, we show our setup with respect to the NP scenarios of interest for investigating the LHC sensitivities in the $\tau^\pm \nu (+b)$ search. Events of the NP signals are generated for each NP scenario by fixing the relevant LQ couplings and mass, and then matched by allowing up to two (five-flavored) jets. In turn, the couplings are encoded as in Eq. (4) to present our output. As the high-$p_T$ tail is concerned, NP–SM interferences are tiny enough, e.g., see Ref. [34] showing that the interference effect is a few percent level.\footnote{When one considers dimension-eight effective interactions, it is found that its NP–SM interference contribution is further smaller than the dimension-six NP–SM interference [65].} Note that a possible $s$-channel production is also suppressed by the requirement of the back-to-back condition between $\tau$ and $\nu$, see Appendix A. A set of process cards for the MadGraph event generation are available in the arXiv web page.

As already mentioned, we proceed with the LQ models that generate the effective four-fermion interactions at the EFT limit. Our approach has a benefit to clarify difference between EFT and a practical model of interest, especially for the case of the $C_{V_1}$ type interaction as explained below.

Motivated by the $R_{D^{(*)}}$ anomaly, NP contributions to $b\bar{c} \to \tau\nu$ have been studied in the EFT limit. However, one notices that there exist additional processes to be considered in realistic model setups. In fact, the $V_1$ operator is constructed from the U$_1$ LQ model, and $C_{V_1}$ depends on the LQ couplings $h_{L}^{23}$ and $h_{L}^{33}$, as seen in Eq. (6). Under the $SU(2)_L$ gauge invariance, the term, $\tilde{Q}_L^n \gamma_\mu L_\mu^U$, generates an interaction of $\bar{\tau} \tau - U_1$ as well as that of $\tau - \nu - U_1$ in presence of $h_{L}^{33}$. Therefore, additional production processes such as $s\bar{c} \to \tau\bar{\nu}$ should be taken into account even in the EFT limit. In this paper, this new process is considered via the following effective Lagrangian,

$$\mathcal{L}_{\text{eff}} \supset -2\sqrt{2} G_F V_{ib} \left[ (1 + C_{V_1}) (\tau^\mu P_\mu b) (\tau \gamma_\mu P_\mu \nu_\tau) + R_{s/b} C_{V_1} (\tau^\mu P_\mu b) (\tau \gamma_\mu P_\mu \nu_\tau) \right] + \text{h.c.} \quad (13)$$

The second term in the bracket corresponds to the new contribution, and $R_{s/b}$ is defined from Eq. (5) as

$$R_{s/b} \equiv \frac{|\text{coupling constant of } \bar{\tau} \tau - U_1|}{|\text{coupling constant of } b\bar{c} - U_1|} = \frac{h_{L}^{23}}{h_{L}^{33}}. \quad (14)$$

Hence, the U$_1$ LQ model possesses two parameters, $(C_{V_1}, R_{s/b})$, in the collider analysis, and the conventional EFT setup of $V_1$ is realized by taking $R_{s/b} \to 0$. Note that such an issue is not the case for the other operator scenarios. On the other hand, although the $\tau^\pm \nu + b$ search seems to be insensitive to it since the $b$ quark is required in the final state, it will be shown that the $\bar{\tau} \tau - U_1$ interaction can affect the result through $gs \to c\tau\nu$ with the final state $b$-jet mis-tagged from $c$-jet.

Single operator scenarios

Here, we list NP scenarios which can be responsible for the $R_{D^{(*)}}$ anomaly and whose collider signals will be investigated in this paper. First, from the view point of the EFT limit in Eq. (1), we consider LQ setups such that one of the WCs of $C_{V_1}, C_{V_2}, C_{S_1}, C_{S_2}$, and $C_T$ is non-vanishing. Let us call this setup as “the single $C_X$ scenario.” Note that $R_{s/b} = 0$ is taken in the $C_{V_1}$ scenario. The signal events are generated for the following LQ masses,

$$M_{LQ} = \{1.5, 2.5, 4.0, 6.5, 10, 15, 20\} \text{ TeV}. \quad (15)$$
According to Ref. [35] the EFT approximation becomes valid for \( M_{LQ} \gtrsim 10 \text{ TeV} \) in the \( \tau^\pm \nu \) search. In this paper, \( M_{LQ} \) is taken up to 20 TeV to check the decoupling behavior in the \( \tau^\pm \nu + b \) search. Then, we refer to the case of \( M_{LQ} = 20 \text{ TeV} \) as the EFT limit. It should be mentioned again that the LQ model which explains the \( R_{D(s)} \) anomaly is restricted as \( M_{LQ} < \mathcal{O}(10) \text{ TeV} \) due to the perturbative unitarity bound [22].

The above LQ masses satisfy the constraints from the LQ direct searches. The searches have been performed by studying LQ pair-production channels at the ATLAS [66] (CMS [67]) \( \int \mathcal{L} \, dt = 139 \text{ fb}^{-1} \) and provided limits on the LQ mass as \( M_{LQ} \gtrsim 1.2 (1.0) \text{ TeV} \) for a scalar LQ, and \( M_{LQ} \gtrsim 1.5 (1.3) \text{ TeV} \) for a gauged-vector LQ at the 95\% CL. \(^5\) On the other hand, single-production channels can provide alternative bounds. However, since they depend on LQ couplings irrelevant to the \( R_{D(s)} \) anomaly, we do not take them into account.

As we focus on the NP interactions responsible for the \( R_{D(s)} \) anomaly, the other LQ couplings, which are irrelevant for \( b \to c \tau \nu \), are set to be zero, and thus, the LQ production process comes only from the initial partons of \( cb, gc, gb, gg \).

**Single LQ scenarios**

We also perform the analysis which is based on the LQ model rather than the EFT operator. In particular, multiple WCs can become non-vanishing simultaneously, or \( R_{s/b} \) is not always zero. As aforementioned in Sec. 2, the following five scenarios can solve the \( R_{D(s)} \) anomaly by introducing a single LQ boson.

- The \( R_2 \) scalar LQ model induces the two independent WCs, \( C_{V_2} (M_{LQ}) \) and \( C_{S_2} (M_{LQ}) = +4 C_T (M_{LQ}) \), as given in Eq. (9). Thus, we study these two scenarios, called as single-\( R_2(C_{V_2}) \) and single-\( R_2(C_{S_2}) \) scenarios, respectively. Note that the former is identical to the \( C_{V_2} \) scenario (unlike \( C_{V_1} \) in the \( U_1 \) LQ scenario).

- The \( S_1 \) scalar LQ model induces the two independent WCs, \( C_{V_1} (M_{LQ}) \) and \( C_{S_2} (M_{LQ}) = -4 C_T (M_{LQ}) \), as seen in Eq. (11). In contrast to the \( R_2 \) LQ case, however, the single \( C_{S_2} = -4 C_T \) case cannot address the \( R_{D(s)} \) anomaly within 1\( \sigma \), though the tension can be relaxed. Thus, we investigate the scenario in a two-dimensional parameter space, \( (C_{V_1}, C_{S_2}) \), with assuming real WCs, simply called as \( S_1 \) LQ scenario.

- The \( U_1 \) vector LQ model possesses the two independent WCs, \( C_{V_1} (M_{LQ}) \) and \( C_{S_1} (M_{LQ}) \). In this paper, we investigate two scenarios in terms of the WCs of Eq. (6): the single \( C_{V_1} \) scenario assuming \( C_{S_1} = 0 \), and the scenario satisfying \( C_{S_1} = -2 e^{i \phi_R} C_{V_1} \) under the \( U(2) \) flavor symmetry, as introduced in Sec. 2.1. Hereafter, they are referred as single-\( U_1 \) and \( U(2)-U_1 \) scenarios, respectively. One can easily find that the relative phase \( \phi_R \) is almost irrelevant for the following collider analysis and taken to be zero. On the other hand, both two scenarios involve the aforementioned \( R_{s/b} \). In our analysis, the region of \( 1/16 \leq R_{s/b} \leq 16 \) is searched to see its effect in detail, in addition to the case of \( R_{s/b} = 0 \) that corresponds to the \( C_{V_1} \) scenario.

\(^5\) The lower bound for a strongly-coupled sector originated vector LQ is given as \( M_{LQ} \gtrsim 1.7 (1.6) \text{ TeV} \).
\begin{table}[h]
\centering
\begin{tabular}{|c|cccccc|}
\hline
BG (cut a) & $Wjj$ & $Zjj\ (Z \rightarrow \nu\nu)$ & $t\bar{t}$ & $Z, \gamma\text{DY}$ & $VV$ & single $t$ & total \\
\hline
$0.7 < m_T < 1$ TeV & 70.5 & 20.1 & 0.34 & 3.03 & 1.30 & 0.02 & 95.3 \\
1 TeV $< m_T$ & 16.9 & 5.1 & 0.06 & 0.56 & 0.32 & 0.02 & 23.0 \\
1 TeV $< m_T$ [25] & 22 ± 6.2 & 0.9 ± 0.5 & < 0.1 & < 0.1 & 0.7 ± 0.1 & < 0.1 & 23.4 ± 7.2 \\
1 TeV $< m_T$ [34] & 18 & 5.2 & 0.44 & 0.0025 & 1.7 & 0.1 & 25.4 \\
\hline
\end{tabular}
\caption{Expected number of SM background events after cut a (the \(\tau^\pm\nu\) search) for \(\int L dt = 35.9 \text{ fb}^{-1}\) and \(\sqrt{s} = 13\) TeV in each background category. The last two rows show the results obtained by Refs. [25] and [34]. Also shown are the total systematic uncertainties for the former. Detailed cut flows are shown in Table 9.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|cccccc|}
\hline
BG (cut b) & $Wjj$ & $Zjj\ (Z \rightarrow \nu\nu)$ & $t\bar{t}$ & $Z, \gamma\text{DY}$ & $VV$ & single $t$ & total \\
\hline
$0.7 < m_T < 1$ TeV & 0.58 & 0.37 & 0.056 & 0.28 & 0.018 & 0.029 & 1.33 \\
1 TeV $< m_T$ & 0.16 & 0.06 & 0.01 & 0.007 & 0.005 & 0.005 & 0.25 \\
1 TeV $< m_T$ [34] & 0.18(5) & 0.21(12) & 0.29(3) & 4.2(4) \times 10^{-5} & 0.35(5) & 0.067(7) & 1.10(14) \\
\hline
\end{tabular}
\caption{Expected number of SM background events after cut b (the \(\tau^\pm\nu + b\) search) for \(\int L dt = 35.9 \text{ fb}^{-1}\) and \(\sqrt{s} = 13\) TeV in each background category. The last row shows the result by Ref. [34], where a number in the parenthesis represents uncertainties. Note that their $b$-tagging efficiencies are different from ours (see the footnote #3). Detailed cut flows are shown in Table 10.}
\end{table}

In the analysis, the LQ mass region in Eq. (15) is studied. Besides, since we are interested only in the LQ couplings relevant to the $R_D(\ast)$ anomaly, the LQ production processes come from the initial partons of $cb, gc, gb, gg$ for $R_2$ and $S_1$ LQs, while the additional production from $cs$ is taken into account for $U_1$ LQ.

4 Numerical results

In this section, we present numerical results of the LHC simulations for the $\tau\nu(+b)$ processes. Also, it is argued how the requirement of an additional $b$-jet improves NP sensitivities and gives an impact on the NP solutions to the $R_D(\ast)$ anomaly.

4.1 Event numbers after selection cuts

The expected numbers of SM background events after the cuts, cut a and cut b, are shown in Tables 1 and 2, respectively. They correspond to the result at the integrated luminosity of 35.9 fb$^{-1}$ and $\sqrt{s} = 13$ TeV, which is equivalent to the CMS result [25]. Note that we imposed a pre-cut given in Eq. (21) of Appendix A at the generator level in the analysis to reduce the simulation cost. The cut can affect the event distributions for $m_T \lesssim 500$ GeV, while the result is insensitive to it for $m_T > 700$ GeV. Detailed cut flows of the SM background are shown in Tables 9 and 10 in Appendix A.

From Table 1, it is found that the main background of cut a (specified for the $\tau^\pm\nu$ search, i.e., without requiring $b$-jets in the final state) comes from the $Wjj$ channel. Our result is consistent with the CMS result [25].
those in Refs. [25] and [34] for $m_T > 1$ TeV, which may validate our analysis.

Let us comment on a preliminary result of the $\tau^+\nu$ search by the ATLAS collaboration with $\int \mathcal{L} dt = 139$ fb$^{-1}$ [26]. It has not observed any significant excess, and hence, constrained the $W'$ mass as $\gtrsim 5$ TeV. To be precise, the observed event number is smaller than the expected SM background, and thus, one can infer (much) stronger upper bounds on the EFT operators in Eq. (9) than the results based on the CMS analysis. Nevertheless, our result cannot be compared with it straightforwardly because the ATLAS has not provided enough information for this purpose and the tagging efficiency of hadronic $\tau$ is different from ours.

In Table 2, an additional $b$-jet is required, corresponding to cut b (specified for the $\tau^+\nu + b$ search). It is shown that the total number of the background is suppressed by about two orders of magnitude versus the result for cut a. In detail, the event number after the cut decreases in every channel, particularly in $Wjj$ and $Zjj$. Here, the range of reduction depends on whether the event involves genuine $b$-jets or not. Also, it is noticed from Table 10 that the condition on the number of $b$-jets is effective to suppress the background when it does not come from the top quarks, while the back-to-back condition reduces those via the top quarks. Our result is also compared with that given by Ref. [34], where the $b$-tagging efficiencies, especially those for fake $b$-jets, are different from ours (see the footnote #3). The total number of the background becomes smaller by $\sim 40\%$ than their result. The difference is prominent in $Zjj$, $t\bar{t}$ and $VV$, because a large number of events include fake $b$-jets.

The expected numbers of signal events after the selections, cut a and cut b, are shown in

| signal (cut a) | $C_{V1,1.5}$ | $C_{V1,EFT}$ | $C_{R_{b}=1}^{V1,1.5}$ | $C_{R_{b}=1}^{V1,EFT}$ | $U_{R_{b}=0}^{C_{V1,1.5}}$ | $U_{R_{b}=0}^{C_{V1,EFT}}$ | $U_{R_{b}=1}^{C_{V1,1.5}}$ | $U_{R_{b}=1}^{C_{V1,EFT}}$ | BG |
|---------------|--------------|----------------|----------------------|----------------------|-------------------|-------------------|-------------------|-------------------|-----|
| $0.7 < m_T < 1$ TeV | 90.0 | 139.4 | 225.9 | 351.4 | 361 | 582 | 502 | 809 | 95.3 |
| $1$ TeV $< m_T$ | 54.4 | 123.6 | 146.9 | 345.8 | 204 | 571 | 279 | 799 | 23.0 |

Table 3. Expected numbers of signal events after cut a (the $\tau^+\nu$ search) for $\int \mathcal{L} dt = 35.9$ fb$^{-1}$ and $\sqrt{s} = 13$ TeV in the single $C_{V1}$ scenario (from second to fifth columns) and the $U(2)$-$U_{1}$ scenario ($C_{S_{1}} = -2\beta_{R}C_{V1}$) (from sixth to ninth columns). In all cases, $C_{V1} = 1$ is fixed, while the LQ mass is $M_{LQ} = 1.5$ TeV or 20 TeV (the EFT limit). The s-quark contribution, parameterized by $R_{s/b}$, is also studied. The last column is the expected number of SM background (see Table 1). Detailed cut flows are shown in Tables 11 and 12.

| signal (cut b) | $C_{V1,1.5}$ | $C_{V1,EFT}$ | $C_{R_{b}=1}^{V1,1.5}$ | $C_{R_{b}=1}^{V1,EFT}$ | $U_{R_{b}=0}^{C_{V1,1.5}}$ | $U_{R_{b}=0}^{C_{V1,EFT}}$ | $U_{R_{b}=1}^{C_{V1,1.5}}$ | $U_{R_{b}=1}^{C_{V1,EFT}}$ | BG |
|---------------|--------------|----------------|----------------------|----------------------|-------------------|-------------------|-------------------|-------------------|-----|
| $0.7 < m_T < 1$ TeV | 11.6 | 16.6 | 13.9 | 21.7 | 53.9 | 86.4 | 55.8 | 92.0 | 1.33 |
| $1$ TeV $< m_T$ | 6.51 | 14.6 | 9.39 | 21.6 | 26.0 | 71.6 | 30.7 | 101 | 0.25 |

Table 4. Expected numbers of signal events after cut b (the $\tau^+\nu + b$ search) for $\int \mathcal{L} dt = 35.9$ fb$^{-1}$ and $\sqrt{s} = 13$ TeV. See the caption of Table 3 for further information. The last column is the expected number of SM background (see Table 2). Detailed cut flows are shown in Tables 13 and 14.

with those obtained by Refs. [25] and [34]. The next-to-leading contribution is provided by the $Zjj$ channel and consistent with Ref. [34], while it is larger by a factor of 5 than the CMS result. Note that the CMS $Zjj$ result is based on a data driven analysis. It should be mentioned that, although the background events are categorized by the channels, their criteria are not unique and not shown explicitly in the literature. Nevertheless, the total number of the SM background is consistent with those in Refs. [25] and [34] for $m_T > 1$ TeV, which may validate our analysis.
Tables 3 and 4, respectively. As a reference, the single $C_{V,1}$ scenario and the $U(2)$-$U_1$ scenario ($C_{S_1} = -2\beta_R C_{V,1}$) are evaluated at $\int \mathcal{L} dt = 35.9$ fb$^{-1}$ and $\sqrt{s} = 13$ TeV. Here, $C_{V,1} = 1$ is fixed, while the LQ mass is set to be $M_{LQ} = 1.5$ TeV and 20 TeV, where the latter corresponds to the EFT limit. By varying $R_{s/b}$, effects of the $s$-quark contribution are also studied. Detailed cut flows for those scenarios are given in Tables 11, 12, 13, and 14 of Appendix A.

From the tables, it is confirmed that the event number after the cut depends on the LQ mass for $M_{LQ} = \mathcal{O}(1)$ TeV. For instance, according to the results for $m_T > 1$ TeV the event number with $C_{V,1} = 1$ is less than a half of that in the EFT limit, $C_{V,EFT} = 1$. Such a feature is valid for both cut a and cut b.

Let us comment that the signal event numbers in our results are smaller than those in Ref. [34], e.g., 25.6 events are expected for $C_{V,EFT}$ ($m_T > 1$ TeV) in their analysis. This is mainly because the $b$ mis-tagging rate is different; $\epsilon_{c\rightarrow b} = 0.3$ in Ref. [34], while it is $1/27 \simeq 0.04$ in our case. With their set up, we checked that almost a half of the signal events come from this fake $b$-jet in the simulation.

Further systematic uncertainties can stem from a charm-quark PDF. We have checked that the PDF uncertainty including the scale variations and estimated by comparing different PDF sets is of order 20% in the number of signal events. This corresponds to $\sim 10\%$ uncertainty for the sensitivities to the NP model in terms of the WCs. Moreover, although the total number of background events in our analysis is consistent with the experimental result [25], the number of events in each category does not match perfectly (see Table 1). This might be due to a lack of sufficient information on the criteria of the categories. Nonetheless, if one adopted, for instance, the result of the $Z jj$ background in Ref. [25], which is based on the data-driven estimation, the total number of background events would be reduced by 20%. This would amplify the signal sensitivity. Besides, an uncertainty in the hadronic $\tau$-tagging efficiency could affect our results quantitatively. Therefore, dedicated studies especially with experimental information are required to improve the analysis.

### 4.2 Test of background-only hypothesis

In order to study sensitivities to the NP contributions, the background-only hypothesis is tested; under the hypothesis, the result is identified to be consistent with the SM if the total number of events, i.e., the sum of the signal and background event numbers (denoted as $N_{Sig}$ and $N_{BG}$, respectively), is smaller than an upper bound ($U_{tot}$). In this paper, the bound is determined as follows. Let us first turn off the systematic uncertainty to focus on the statistical one. Under the background-only hypothesis, $U_{tot}$ satisfies the relation,

$$
\sum_{n=0}^{N_{BG}} P(n; U_{tot}^{\text{stat}}) = p, \tag{16}
$$

where $P(n; \mu)$ is the probability function of the Poisson distribution for observing $n$ events with the mean value $\mu$, and $p = 0.05$ is taken, corresponding to 95% confidence level (CL). Here, $U_{tot}^{\text{stat}}$ is denoted with the superscript “stat,” since the systematic uncertainty is ignored. Then, the systematic uncertainty is taken into account. Although it is unknown, we assign 60% relative to the mean value at 95% CL for $\int \mathcal{L} dt = 35.9$ fb$^{-1}$ as inferred from the CMS result [25]. Furthermore, as shown in Table 1, the SM background is dominated by $W jj$. The CMS analysis obtains the total systematic uncertainty of 28% on this channel at 68% CL [25].
it is supposed to be scaled with $1/\sqrt{L}$ for the integrated luminosity $L$. Hence, the systematic uncertainty is assigned as $\sigma_{\text{sys}}^{95\%} = N_{BG} \times 60\% \times \sqrt{35.9 \, \text{fb}}/L \, \text{fb}$. In this paper, we combine the systematic uncertainty with the statistical one linearly, and then, $U_{\text{tot}}$ is obtained as $U_{\text{tot}} = U_{\text{tot}}^{\text{stat}} + \sigma_{\text{sys}}^{95\%}$. Finally, the upper bound on the NP signal event number $N_{\text{Sig}}$ is derived as $S^{95\%} = U_{\text{tot}} - N_{BG}$; the result is regarded as the SM consistent if $N_{\text{Sig}} < S^{95\%}$ is satisfied.

In the analysis, the expected number of events is not always integers, as shown in the tables of the previous subsection. Then, $N_{BG}$ in Eq. (16) is replaced with $|N_{BG}|$ corresponding to the mode for the Poisson distribution. Here, $[x]$ is the floor function, i.e., returns the maximum integer not exceeding $x$. The background event number for $\int L \, dt = 35.9 \, \text{fb}^{-1}$ is given in Tables 1 and 2. For higher luminosity, the event numbers are obtained by scaling the results in the tables with corresponding to the integrated luminosity. Note that, although the HL-LHC (LHC Run 4 and 5) will be operated at $\sqrt{s} = 14 \, \text{TeV}$, we ignore differences between the results at $\sqrt{s} = 13$ and $14 \, \text{TeV}$, for simplicity.

Before proceeding to the results, let us mention about the $m_T$ dependence of the NP sensitivities. From the tables it can be found that the category of $m_T > 1 \, \text{TeV}$ provides higher sensitivities to the NP contributions than the category of $0.7 < m_T < 1 \, \text{TeV}$. Similarly, among the three different $m_T$ bins in the CMS analysis, $m_T < 500 \, \text{GeV}$, $500 \, \text{GeV} < m_T < 1 \, \text{TeV}$ and $m_T > 1 \, \text{TeV}$, the last one provides the most stringent constraints. Hence, we will present the results obtained from $m_T > 1 \, \text{TeV}$ in the following.

### 4.3 Single operator scenarios

In Tables 5 and 6, the expected sensitivities to $|C_X(A_{\text{LHC}})|$ are shown for each single operator scenario in the $\tau^\pm \nu$ and $\tau^\pm \nu + b$ searches, respectively. They are determined from $S^{95\%}$ defined in the previous subsection. The number without (inside) the parenthesis is obtained in the EFT limit (at $M_{\text{LQ}} = 1.5 \, \text{TeV}$). The integrated luminosities are $\int L \, dt = 139 \, \text{fb}^{-1}$ (for the current sensitivity) and $1000/3000 \, \text{fb}^{-1}$ (for future). The results are provided at two scales; one is a scale of flavor experiments, $m_b = 4.2 \, \text{GeV}$, and another is that of the collider search, $A_{\text{LHC}}$, which is fixed to be $1 \, \text{TeV}$ in this paper. The WCs at the scale of $m_b = 4.2 \, \text{GeV}$ are derived by taking RG running corrections into account. For the $\tau^\pm \nu$ search, the current upper bounds on $|C_X(m_b)|$ are also listed in Table 5. They are obtained in Ref. [35] based on the CMS result with $\int L \, dt = 35.9 \, \text{fb}^{-1}$ [25]. Similar limits are provided in Refs. [30, 34]. It is noted that there are no experimental studies in the $\tau^\pm \nu + b$ search.

The LQ mass dependence of the sensitivities are shown in Fig. 1 for the integrated luminosities of $\int L \, dt = 139$ (solid line) and $3000 \, \text{fb}^{-1}$ (dashed). The scale is set to be $A_{\text{LHC}}$. The blue (red) lines correspond to the $\tau^\pm \nu$ ($\tau^\pm \nu + b$) search. In the figure, the upper plot for each scenario shows a sensitivity to the WC based on cut a or cut b.

As mentioned above, the charge of the final-state $\tau$ lepton is not identified in cut a or cut b. If the event selections are performed with distinguishing the $\tau$-lepton charge, the sensitivities may be affected. The lower plot in each scenario displays $\delta C_X^{95\%}/C_X^{95\%}|_{\tau^\pm}$ for $\int L \, dt = 3000 \, \text{fb}^{-1}$ with $\delta C_X^{95\%} = C_X^{95\%}|_{\tau^\pm} - C_X^{95\%}|_{\tau^-}$, where $C_X^{95\%}|_{\tau^-}$ is the sensitivity to the WC with (without) selecting negative charged $\tau$ leptons, $\tau^-$. A positive value means that the sensitivities are improved by selecting $\tau^-$ versus the result collecting both $\tau^+$ and $\tau^-$. Let us summarize our observations from the figure and tables:
| $\tau^\pm \nu$ search | $C_{V_1}$ | $C_{V_2}$ | $C_{S_1}$ | $C_{S_2}$ | $C_T$ |
|----------------------|-----------|-----------|-----------|-----------|--------|
| current upper bound on EFT [35]: LHC 36 fb$^{-1}$ |           |           |           |           |        |
| $\mu = m_b$          | 0.32      | 0.33      | 0.55      | 0.55      | 0.17   |
| **sensitivity:** LHC 139 fb$^{-1}$ |           |           |           |           |        |
| $\mu = \Lambda_{LHC}$ | 0.30 (0.46) | 0.32 (0.68) | 0.32 (0.54) | 0.32 (0.59) | 0.18 (0.46) |
| $\mu = m_b$          | 0.30 (0.46) | 0.32 (0.68) | 0.55 (0.93) | 0.55 (1.02) | 0.15 (0.39) |
| **sensitivity:** HL-LHC 1000 fb$^{-1}$ |           |           |           |           |        |
| $\mu = \Lambda_{LHC}$ | 0.18 (0.28) | 0.20 (0.41) | 0.19 (0.33) | 0.19 (0.35) | 0.11 (0.28) |
| $\mu = m_b$          | 0.18 (0.28) | 0.20 (0.41) | 0.33 (0.56) | 0.33 (0.61) | 0.09 (0.24) |
| **sensitivity:** HL-LHC 3000 fb$^{-1}$ |           |           |           |           |        |
| $\mu = \Lambda_{LHC}$ | 0.14 (0.21) | 0.15 (0.31) | 0.15 (0.25) | 0.15 (0.27) | 0.08 (0.21) |
| $\mu = m_b$          | 0.14 (0.21) | 0.15 (0.31) | 0.25 (0.43) | 0.25 (0.47) | 0.07 (0.18) |

**Table 5.** Expected sensitivities to the absolute value of the WCs in the single-operator scenarios. They are evaluated at the scale of $\mu = \Lambda_{LHC}$ and $m_b$ based on cut a (the $\tau^\pm \nu$ search). The number without (inside) the parenthesis correspond to the EFT limit ($M_{LQ} = 1.5$ TeV). Also shown are the current upper bounds [35] based on the dataset of CMS 35.9 fb$^{-1}$ [25].

| $\tau^\pm \nu + b$ search | $C_{V_1}$ | $C_{V_2}$ | $C_{S_1}$ | $C_{S_2}$ | $C_T$ |
|-----------------------------|-----------|-----------|-----------|-----------|--------|
| **sensitivity:** LHC 139 fb$^{-1}$ |           |           |           |           |        |
| $\mu = \Lambda_{LHC}$      | 0.20 (0.31) | 0.20 (0.41) | 0.20 (0.33) | 0.18 (0.32) | 0.11 (0.22) |
| $\mu = m_b$                | 0.20 (0.31) | 0.20 (0.41) | 0.33 (0.57) | 0.31 (0.56) | 0.09 (0.19) |
| **sensitivity:** HL-LHC 1000 fb$^{-1}$ |           |           |           |           |        |
| $\mu = \Lambda_{LHC}$      | 0.12 (0.18) | 0.12 (0.24) | 0.11 (0.20) | 0.11 (0.19) | 0.06 (0.13) |
| $\mu = m_b$                | 0.12 (0.18) | 0.12 (0.24) | 0.20 (0.34) | 0.18 (0.33) | 0.05 (0.11) |
| **sensitivity:** HL-LHC 3000 fb$^{-1}$ |           |           |           |           |        |
| $\mu = \Lambda_{LHC}$      | 0.09 (0.14) | 0.09 (0.18) | 0.09 (0.15) | 0.08 (0.14) | 0.05 (0.10) |
| $\mu = m_b$                | 0.09 (0.14) | 0.09 (0.18) | 0.15 (0.26) | 0.14 (0.25) | 0.04 (0.08) |

**Table 6.** Same as Table 5 but for cut b (the $\tau^\pm \nu + b$ search).
Figure 1. Expected sensitivities to the absolute value of $C_X(\Lambda_{\text{LHC}})$ (upper in each scenario) with $\int L dt =$ 139 fb$^{-1}$ (solid) and 3000 fb$^{-1}$ (dashed) in the $\tau^+\nu$ (blue) and $\tau^+\nu + b$ (red) searches. In the lower plot of each scenario, $\delta C_X^{95\%}/C_X^{95\%}|_{\tau^\pm}$ is displayed for $\int L dt = 3000$ fb$^{-1}$ with $\delta C_X^{95\%} = C_X^{95\%}|_{\tau^\pm} - C_X^{95\%}|_{\tau^-}$, where $C_X^{95\%}|_{\tau^-}$ is the sensitivity to the WC with (without) selecting $\tau^-$. 
• In the $\tau^{\pm}\nu$ search, compared with the current bounds, some of the sensitivities are not improved even with the larger dataset of $\int L\,dt = 139$ fb$^{-1}$. This is mainly because the observed data at CMS in Ref. [25] are smaller than the expected SM background, probably due to unexpected (statistical) fluctuations.

• In the $\tau^{\pm}\nu$ search, the sensitivities to the WCs can be improved by a factor of two at $\int L\,dt = 3000$ fb$^{-1}$ compared with the current bounds (36 fb$^{-1}$) or sensitivities (139 fb$^{-1}$).

• By requiring an additional $b$-jet in the final states, the NP sensitivities can be improved by $\approx 40\%$ versus those in the $\tau^{\pm}\nu$ search. Note that this is beyond the statistical uncertainty of our MC; in the analysis, we generate 100K events for each NP model point, and the number of signal events after the cut could become $\lesssim 100$ for $\tau^-\nu+b$, leading to $\mathcal{O}(10)\%$ MC-uncertainty at most.

• The sensitivities depend on the LQ mass obviously; they become better as the mass increases. The dependence for $\tau^{\pm}v+b$ is similar to that for $\tau^{\pm}v$. It is found that the sensitivity from the $\tau^{\pm}v+b$ search is better than that from $\tau^{\pm}v$ in the whole mass region. (Note that the conclusion is valid for $R_{s/b} \lesssim 1$. See Fig. 5.)

• In the case of the $\tau^-\nu$ search, by selecting the negative-charged $\tau$ leptons, the sensitivities can be improved by $\approx 10\%$ compared with the result obtained without selecting $\tau^-$. However, the selection is not effective to improve the sensitivity for $\tau^-\nu+b$, especially because the number of events after the cut is not large enough even at $\int L\,dt = 3000$ fb$^{-1}$; the number of signal events is halved by the charge selection. Then, with the number of background events $N_{BG} = \mathcal{O}(10)$, the reduction of $N_{BG}$ due to the charge selection is not sufficient for improving $U_{tot}$. In other words, we found that larger $N_{BG}$ or better reduction is necessary to improve the sensitivity.

• In small LQ mass regions, the sensitivity for $C_{V1}$ is better than that for $C_{V2}$ at $\int L\,dt = 3000$ fb$^{-1}$, because of differences of $\tau$ angular distributions; the signal acceptance for the former is better than that for the latter (see Ref. [35]).

4.4 Single LQ scenarios

We discuss an impact of the LHC searches on the single LQ scenarios that can solve the $R_{D^{(*)}}$ anomaly. There are three single LQ fields, $U_1$, $R_2$, and $S_1$, introduced in Secs. 2.1, 2.2, and 2.3, respectively. For calculating the flavor observables such as $R_{D^{(*)}}$, we used the formulae of Ref. [39] with updating the form factors [11].

Let us first summarize the expected sensitivities based on the $\tau^{\pm}v$ and $\tau^{\pm}v+b$ searches in Tables 7 and 8, respectively. Here, the sensitivity to $C_{S2}$ is shown for $R_2$ and $S_1$, while that to $C_{S1}$ is given for the scenario of $U_1$ LQ with $U(2)$ flavor symmetry. The interplay with the $R_{D^{(*)}}$ anomaly is discussed in the following subsections.

In discussing the LHC search for the NP contributions and its interplay with the flavor observables, there are three renormalization scales: $\mu = m_b$, $\Lambda_{\text{LHC}}$, and $M_{LQ}$. The WCs in different energy scales should be evaluated by taking the RG corrections into account [13, 68, 69]. Although
all WCs are to be input at $\mu = M_{LQ}$, we show the results with discarding the RG corrections between $\Lambda_{\text{LHC}} = 1$ TeV and $M_{LQ} = \mathcal{O}(1)$ TeV, because they are found to be negligible (a few percent level for WCs). Nonetheless, the corrections are taken into account for $\mu = m_b$.

### 4.4.1 $R_2$ LQ scenarios

In the $R_2$ LQ model, two sets of WCs, $C_{V_2}(M_{LQ})$ and $C_{S_2}(M_{LQ}) = +4C_T(M_{LQ})$, are induced independently, as explained in Eq. (9). Thus, we study the following two scenarios; single-$R_2(C_{V_2})$ and single-$R_2(C_{S_2})$ scenarios separately. For each scenario, in order to solve the $R_D$ anomaly, we obtain that the WCs are favored to be

$$\text{single-}R_2(C_{V_2}) : C_{V_2}(\Lambda_{\text{LHC}}) = \pm i 0.42, \quad \text{single-}R_2(C_{S_2}) : C_{S_2}(\Lambda_{\text{LHC}}) = -0.07 \pm i 0.35,$$

where the measured values of $R_D$ and $R_{D^*}$ are fitted. Note that $\pm$ does not mean an uncertainty but represents two solutions. Since the LHC study is almost insensitive to the phase of WCs, it is set to be zero in the collider analysis.

Such large WCs are expected to be probed at the LHC. In the single-$R_2(C_{V_2})$ scenario, by comparing Tables 7 and 8 with the background results in Fig. 1, it is found that the LHC sensitivity of the $\tau^\pm \nu$ search is marginal at $\int L dt = 139$ fb$^{-1}$ to test the $R_D$ explanation depending on the LQ mass, whereas that of the $\tau^\pm \nu + b$ search is enough to probe the parameter region in all ranges of the LQ mass. We would like to stress that the scenario can be probed with use of the current data samples at the LHC (139 fb$^{-1}$) for $\tau^\pm \nu + b$. On the other hand, in the single-$R_2(C_{S_2})$ scenario, it is also shown that the $R_{D^*}$-favored value of $|C_{S_2}(\Lambda_{\text{LHC}})| \approx 0.36$ can be fully probed by the $\tau^\pm \nu + b$ search at 139 fb$^{-1}$, but not by $\tau^\pm \nu$. Therefore, it is concluded that requiring an additional $b$-jet is significant to test the LQ scenarios in light of the $R_{D^*}$ anomaly.

The combined summary plot for the LHC sensitivity and the allowed region from the flavor observables is shown in Fig. 2 for the case of the single-$R_2(C_{S_2})$ scenario with $M_{LQ} = 1.5$ TeV and 2.5 TeV. The sensitivity at $\int L dt = 139$ fb$^{-1}$ from the $\tau^\pm \nu$ and $\tau^\pm \nu + b$ channels are denoted by solid blue and red lines, respectively. Their HL-LHC prospects at $\int L dt = 3000$ fb$^{-1}$ are shown in dashed lines with the same color. The magenta lines are the current constraint from the CMS 36 fb$^{-1}$ data, taken from Ref. [35] assuming $M_{LQ} = 2$ TeV. The blue and green bands show the region favored by the measured $R_D$ and $R_{D^*}$, respectively. Then, the combined 1 $\sigma$ (2 $\sigma$) regions are shown in red (yellow). We also put the $B_c$ constraint as $\text{BR}(B_c \to \tau \nu) < 60\%$ ($30\%$) shown in (light) gray as references. Here, an updated study for the $B_c \to \tau \nu$ constraint is available in Refs. [70, 71]. We can clearly check from this figure that the $\tau^\pm \nu + b$ search fully (partially) covers the single-$R_2(C_{S_2})$ scenario with $M_{LQ} > 2.5$ TeV (1.5 TeV $< M_{LQ} < 2.5$ TeV) responsible for the $R_{D^*}$ anomaly.

### 4.4.2 $S_1$ LQ scenario

In the $S_1$ LQ model, two sets of WCs, $C_{V_1}(M_{LQ})$ and $C_{S_1}(M_{LQ}) = -4C_T(M_{LQ})$, are induced independently as given in Eq. (11). In the latter case, although the $R_{D^*}$ discrepancy can be reduced,

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\footnote{Interference with the SM part is preferred to be small by a fit for the $R_{D^*}$ anomaly in the $R_2$ LQ model. Therefore, resultant WCs have large imaginary components, and their absolute values tend to be large enough to be able to probed at the LHC.}
| \( \tau^\pm \nu \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: LHC 139 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.30 (0.58) | 0.29 (0.58) | 0.28 (0.47) | 0.24 (0.40) | 0.18 (0.28) |
| \( \mu = m_b \) | 0.51 (0.96) | 0.52 (1.04) | 0.48 (0.81) | 0.41 (0.69) | 0.18 (0.28) |

| \( \tau^\pm \nu + b \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: LHC 139 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.18 (0.35) | 0.17 (0.27) | 0.13 (0.22) | 0.11 (0.19) | 0.08 (0.13) |
| \( \mu = m_b \) | 0.31 (0.58) | 0.24 (0.48) | 0.22 (0.37) | 0.19 (0.32) | 0.08 (0.13) |

| \( \tau^\pm \nu + b \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: HL-LHC 1000 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.18 (0.35) | 0.17 (0.27) | 0.13 (0.22) | 0.11 (0.19) | 0.08 (0.13) |
| \( \mu = m_b \) | 0.31 (0.58) | 0.24 (0.48) | 0.22 (0.37) | 0.19 (0.32) | 0.08 (0.13) |

| \( \tau^\pm \nu + b \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: HL-LHC 3000 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.18 (0.35) | 0.17 (0.27) | 0.13 (0.22) | 0.11 (0.19) | 0.08 (0.13) |
| \( \mu = m_b \) | 0.31 (0.58) | 0.24 (0.48) | 0.22 (0.37) | 0.19 (0.32) | 0.08 (0.13) |

**Table 7.** Expected sensitivities of the absolute value of the WCs for cut a in the single LQ scenarios. The sensitivity to \( C_{S_2} \) is shown for \( R_2 \) and \( S_1 \), while that to \( C_{S_1} \) is given for the scenario of \( U_1 \) LQ with \( U(2) \) flavor symmetry. See Table 5 for details of the descriptions.

| \( \tau^\pm \nu + b \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: LHC 139 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.18 (0.35) | 0.16 (0.31) | 0.18 (0.30) | 0.16 (0.28) | 0.17 (0.25) |
| \( \mu = m_b \) | 0.30 (0.58) | 0.29 (0.56) | 0.32 (0.52) | 0.27 (0.48) | 0.17 (0.25) |

| \( \tau^\pm \nu + b \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: HL-LHC 1000 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.11 (0.20) | 0.10 (0.18) | 0.11 (0.18) | 0.09 (0.17) | 0.10 (0.15) |
| \( \mu = m_b \) | 0.18 (0.34) | 0.17 (0.33) | 0.19 (0.31) | 0.16 (0.28) | 0.10 (0.15) |

| \( \tau^\pm \nu + b \text{ search} \) | \( R_2(C_{S_2}) \) | \( S_1(C_{S_2}) \) | \( U_1^{R_{i/b}=0}(C_{S_1}) \) | \( U_1^{R_{i/b}=1}(C_{S_1}) \) | \( C_{V_{i}}^{R_{i/b}=1} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| sensitivity: HL-LHC 3000 fb\(^{-1} \) | \( \mu = \Lambda_{\text{LHC}} \) | 0.08 (0.15) | 0.07 (0.14) | 0.08 (0.14) | 0.07 (0.13) | 0.07 (0.11) |
| \( \mu = m_b \) | 0.13 (0.26) | 0.13 (0.25) | 0.14 (0.23) | 0.12 (0.21) | 0.07 (0.11) |

**Table 8.** Same as Table 7 but for cut b (the \( \tau^\pm \nu + b \) search).
Figure 2. The $R_2$ LQ scenario with $M_{LQ} = 1.5$ and 2.5 TeV. The regions outside the blue and red lines are probed by the $\tau^\pm \nu$ and $\tau^\pm \nu + b$ searches, respectively, where the solid (dashed) lines correspond to $\int \mathcal{L} dt = 139$ fb$^{-1}$ (3000 fb$^{-1}$). The magenta line shows the current bound from the experimental data with $\int \mathcal{L} dt = 36$ fb$^{-1}$ [35]. The (lighter) gray shaded regions are constrained by BR($B_c \to \tau \nu\nu$) $> 0.6 (~>0.3)$. The $R_D$ and $R_{D'}$ anomalies are explained at 1$\sigma$ in the blue and green shaded regions, respectively, while the combined fit at 1/2$\sigma$ is shown in orange/yellow.

In Fig. 3, the LHC sensitivity and the region favored by the $R_{D'}$ anomaly are shown for the $S_1$ LQ scenario on the plane of $(C_{V_1}, C_{S_2})$. Here, the imaginary components are fixed to be zero. See Fig. 2 for the color convention. As briefly mentioned in Sec. 2.3, unlike the cases for $R_2$ and $U_1$ LQs, the $S_1$ LQ scenario inevitably produces a tree-level contribution to $b \to s \nu \nu$ in addressing $R_{D'}$. Thus, the parameter space is constrained from precision measurements of $B \to K^{(*)}\nu \nu$, which is shown in the figure with the cyan-shaded region. Its evaluation formula is given in Appendix B. In addition, a more robust flavor bound comes from the $B_s - \bar{B}_s$ mixing ($\Delta M_s$). Based on the studies of Refs. [72, 73], the $\Delta M_s$ constraint is provided in the figure with the red-shaded region. This bound is comparable to or severer than $B \to K^{(*)}\nu \nu$ depending on the LQ mass. See again Appendix B for its detail. Although $\Delta M_d / \Delta M_s$ can give more stringent bound in general since QCD uncertainties are partially canceled, this constraint is avoidable if additional LQ contributions to $\Delta M_d$ are introduced properly.

From the figure, we see that the $S_1$ LQ mass larger than 4 TeV is disfavored by the $\Delta M_s$ and $B \to K^{(*)}\nu \nu$ constraints. Since this implies that the smaller LQ mass $M_{LQ} < 4$ TeV is viable for the $R_{D'}$ anomaly, the LQ mass dependence on the NP sensitivity of the present LHC searches is important. Then, one can see that the $\tau^\pm \nu + b$ search at $\int \mathcal{L} dt = 3000$ fb$^{-1}$ can reach the sensitivity to probe this scenario, while $\tau^\pm \nu$ cannot.
The $S_1$ LQ scenario with $M_{LQ} = 1.5$ TeV and $4.0$ TeV on the $(C_{V1}, C_{S1})$ plane. The color convention is the same as in Fig. 2. The magenta lines are the current bound from the experimental data with $\int L dt = 36$ fb$^{-1}$ by assuming $M_{LQ} = 2$ TeV (left panel) and the EFT limit (right panel) [35]. In addition, the cyan-shaded region is excluded by the $B \to K^* \nu \nu$ measurement at the 90% CL, and the red-shaded region is excluded by $\Delta M_s$.

**4.4.3 $U_1$ LQ scenarios**

The $U_1$ vector LQ model introduced in Sec. 2.1 is one of the most promising candidates to solve the $B$ anomalies. In fact, unlike the above two scalar LQ scenarios, flavor constraints can be suppressed or avoided. Therefore, the LHC search is significant to probe the model. In this paper, we investigate two scenarios in terms of the WCs of Eq. (6); the single $C_{V1}$ scenario (setting $C_{S1} = 0$), and the scenario satisfying $C_{S1} = -2e^{i\phi_R}C_{V1}$ with the $U(2)$ flavor symmetry, referred as the single-$U_1$ and $U(2)$-$U_1$ scenarios, respectively. By performing a parameter fit for these two scenarios to the $R_{D^{(*)}}$ measurement, we obtain the following WCs,

\[
\text{single-$U_1$ : } C_{V1} (\Lambda_{LHC}) \approx 0.09, \quad U(2)-U_1 : C_{V1} (\Lambda_{LHC}) \approx 0.09, \quad \phi_R \approx \pm 0.42 \pi.
\]  

Note again that $\pm$ does not mean an uncertainty. Also, the phase $\phi_R$ for $U(2)$-$U_1$ is almost irrelevant for the present LHC study.

In Fig. 4, the NP sensitivities are shown in the $\tau^\pm \nu$ ($\tau^\pm \nu + b$) search by the blue (red) lines. The solid (dashed) lines correspond to $\int L dt = 139$ fb$^{-1}$ (3000 fb$^{-1}$). The vertical axis is a product of the $U_1$ couplings, $h_L^{33} h_L^{23} \equiv h_{b\tau}h_{c\nu}$, and the horizontal one is the LQ mass, $M_{LQ}$. The region favored by $R_{D^{(*)}}$ at the 1 $\sigma$ (2 $\sigma$) level is also given in the green (yellow) color. Regarding the $U(2)$-$U_1$ scenario, the relative phase is fixed as $\phi_R = 0.42 \pi$.

In the figure, the results are shown for $R_{s/b} \to 0$ and $R_{s/b} = 1$ in the left and right panels, respectively. The former corresponds to the single $C_{V1}$ scenario, and hence, the NP sensitivity is exactly the same as that given in the previous section. On the other hand, since $h_L^{23} = h_{b\tau} = h_{c\nu}$
in the $U_1$ LQ model as aforementioned in Sec. 3.2, the latter indicates how $h_{\tau c} \neq 0$ contribution to the signal production affects the NP sensitivity. For $R_{s/b} = 1$, it is found that the $\tau^\pm \nu$ search can be competitive to that of $\tau^\pm \nu + b$. We also show the sensitivities for larger $R_{s/b}$ as $= 2, 4$ and $4$ in the single-$U_1$ and $U(2)$-$U_1$ scenarios, respectively, at $M_{LQ} = 4$ TeV for further comparison. It is concluded from the figures that both scenarios can be tested at HL-LHC with $\int L dt = 3000 \text{ fb}^{-1}$.

Regarding the $U(2)$-$U_1$ scenario, the present LHC data sample is large enough to probe the scenario...
if the $\tau^\pm \nu + b$ analysis is performed. Also, it should be mentioned that the result depends on $R_{s/b}$ significantly. It is shown that the sensitivities are enhanced by larger $R_{s/b}$ even in the EFT limit. Its contribution will be investigated in detail later.

Figure 5 shows a dependence of the LHC sensitivity on the LQ couplings, $h_{23}^L \equiv h_{s}^\tau = h_{cv}$ and $h_{33}^L \equiv h_{br}$ for $M_{LQ} = 2$ and 4 TeV. One can see that, for both scenarios, the result in the $\tau^\pm \nu + b$ search is sensitive to large $h_{br}$ and small $h_{s}^\tau$, namely small $R_{s/b}$, whereas that of $\tau^\pm \nu$ is sensitive to larger $R_{s/b}$. For the single-$U_1$ scenario, the region favored by $R_{D^{(*)}}$ can be tested at

![Figure 5](image-url)

**Figure 5.** Expected sensitivities to the $U_1$ LQ scenario as functions of the LQ couplings with the LQ mass of 2TeV (left) and 4TeV (right). The black dashed lines show the results with selecting $\tau^- \nu$. The gray horizontal lines correspond to the current LHC bound recast from the ATLAS $pp \to \tau^+ \tau^-$ search. See Fig. 4 for other color conventions.
\[ \int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1} \]

by the \( \tau^\pm \nu(\pm b) \) search only for \( h_{\tau} \simeq 0.8(1.1) \) with \( M_{LQ} = 2 \, \text{TeV} \), and for \( h_{\tau} \gtrsim 1.5(2.0) \) with \( M_{LQ} = 4 \, \text{TeV} \). As for \( U(2)-U_1 \), on the other hand, the \( R_{D^0(C)} \)-favored region is fully probed by \( \tau^\pm \nu + b \) at \( \int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1} \) for both \( M_{LQ} = 2, 4 \, \text{TeV} \).

In Ref. [74], the \( pp \rightarrow \tau^+ \tau^- \) search by the ATLAS [75] has been used to constrain the present two \( U_1 \) LQ scenarios. Their definition of the LQ couplings are related to ours as \( h_{\tau} \equiv g_U \beta_U^\tau \) and \( h_{\tau} \equiv f_U \beta_U^\tau \) by taking \( \beta_U^\tau = 1 \). Then, the upper limit on \( (g_U, M_{LQ}) \) has been recast from the ATLAS result at \( \int \mathcal{L} \, dt = 139 \, \text{fb}^{-1} \), where \( \beta_U^\tau \supset [0.10, 0.25] \) (or \([0.12, 0.26]\)) is fitted from relevant flavor observables for single-\( U_1 \) (\( U(2)-U_1 \)). Although it is unclear how to implement the sub-leading contributions from \( bs/\tau \tau \rightarrow \tau^+ \tau^- \) in their study, we naively translate their result into the \((h_{\tau}, h_{\nu})\) plane as shown in the figure with gray lines. It is found that the \( \tau^\pm \nu + b \) search is complementary to that of \( \tau^+ \tau^- \), though further discussions are needed on the analysis.

In Fig. 6, the \( R_{D^0(C)} \)-favored region is compared with the LHC sensitivities and flavor constraints for \( M_{LQ} = 1.5 \, \text{TeV} \) (left) and 4 TeV (right) in the \( (C_{V_1}, \phi_R) \) plane. The region in the right-hand side of the vertical (solid/dashed) lines is probed or constrained by the LHC searches. The orange (yellow) region is favored by the measured \( R_{D^0(C)} \) at the 1 \( \sigma \) (2 \( \sigma \)) level. Note that the best fit is given at \( \phi_R \simeq \pm 0.42 \pi \), implying \( C_{S_1}/C_{V_1} \simeq -0.50 \mp 1.94 i \). Similar to the \( R_2 \) LQ model, imaginary component is favored to be large.\(^9\) From this figure, we found that the \( R_{D^0(C)} \)-favored region can be fully (mostly) probed by \( \tau^\pm \nu + b \) at \( \int \mathcal{L} \, dt = 3000 \, \text{fb}^{-1} \) for \( M_{LQ} > 4 \, \text{TeV} \) (< 4 TeV).

Similar to the \( S_1 \) LQ scenario, there is a strong bound from \( \Delta M_{s} \), as briefly mentioned in

\(^8\)References [42, 76, 77] also provide bounds on the LQ scenarios from the \( pp \rightarrow \tau^+ \tau^- \) search.
\(^9\)Phase degrees of freedom are not taken into account in the parameter fit in literature [74, 78].

\( \int \mathcal{L} \, dt = 36 \, \text{fb}^{-1} \) by assuming \( M_{LQ} = 2 \, \text{TeV} \) (left panel) and the EFT limit (right panel) [35].
Figure 7. Distribution of signal number density in $\eta_\tau$–$\eta_b$ plane for the single-U$_1$ ($C_{V_1}^{R_{s/b}=0}$) (left) and single-R$_2$ ($C_{S_2}$) (right). In both scenarios, the LQ mass is set to be 1.5 TeV. The warmer/reddish (colder/bluish) colors represent larger (smaller) number of signal events.

Sec. 2.1. In realistic model setups of the U$_1$ LQ scenario, vector-like leptons are introduced to realize a model flavor structure appropriately [44, 45, 78–80]. Their mass scale is comparable to the LQ one up to a factor depending on gauge and Yukawa couplings. Then, the GIM-like mechanism does work and the box contributions to $\Delta M_s$ are suppressed. Since the vector-like lepton mass determines an energy scale of the breakdown of the GIM-like cancellation, it cannot become too large, i.e., must be around the TeV scale at most. To summarize, model predictions of $\Delta M_s$ are quite model-dependent in the U$_1$ LQ scenarios, and dedicated studies are necessary. In Figs. 4 and 5, we do not draw the bounds from $\Delta M_s$, for simplicity.

4.5 Angular correlations

We investigate the angular distributions in the $\tau^\pm + b$ searches, which would be helpful to distinguish new physics scenarios and to further suppress the background. Requiring an additional $b$-jet not only amplifies sensitivity of new physics search, but also provides us information of the angular observables. Since the LQ models are characterized by the Lorentz structure of new physics interactions and the angular distributions of the final state are sensitive to them according to the analytic formulae of the scattering cross sections in Ref. [34], they are useful to discriminate the models.

Let us first demonstrate a correlation between the pseudorapidities of the bottom quark ($\eta_b$) and of the $\tau$ lepton ($\eta_\tau$). Figure 7 shows a pseudorapidity correlation in the single-U$_1$($C_{V_1}$) scenario with $R_{s/b} = 0$ (left) and the single-R$_2$($C_{S_2}$) scenario (right) for $M_{LQ} = 1.5$ TeV. Here, the LQ signal events passing cut $b$ with $m_T \geq 700$ GeV are exhibited. There are larger (smaller) number of signal events left after the cut in the reddish (blueish) points. As observed in the single-U$_1$($C_{V_1}$) scenario

#10In such a case, three-body decay branching ratios (mediated by U$_1$ LQ) of the vector-like leptons become dominant, and conventional searches [81, 82] are not applicable directly. The dedicated search for such a vector-like lepton at the LHC would be, therefore, important to probe a footprint of the LQ scenarios behind the B anomalies.
(left panel), their positive correlation indicates that $b$ and $\tau$ jets tend to be emitted in the same direction in the detector. On the other hand, the single-$R_2(C_{S_b})$ scenario (right panel) predicts a mild opposite correlation. Since the signal distribution on the $(\eta_\tau, \eta_b)$ plane depends on the NP scenarios, they could be distinguished by measuring the pseudorapidity correlation. It is noted that the same tendency is observed for $M_{LQ} = 20$ TeV. Moreover, it is found that distributions in a case of $R_{s/b} = 1$ are similar to those for $R_{s/b} = 0$. This is because a contribution from the $3-\tau-U_1$ interaction, which comes from the $b$-jet mis-tagged from $c$-jet, is negligible in the $\tau^{\pm}v + b$ events for $R_{s/b} \lesssim 1$ (see Fig. 4).

With having these observations, we propose the following quantities to probe the pseudorapidity correlation:

\[
\eta'_s = \text{sgn}(\eta_b) \times \eta_\tau, \quad \eta'_b = \text{sgn}(\eta_\tau) \times \eta_b.
\]  

(19)

For instance, the former is a modification of $\eta_\tau$ according to the $b$-jet direction. If a distribution of the $b$-jet is isotropic, a peak of $\eta'_s$ distribution must be placed at zero. However, events in the quadrants I and III of Fig. 7 provide a positive $\eta'_s$, while the others yield a negative $\eta'_s$. As a result, when there is the positive (negative) pseudorapidity correlation, a peak of $\eta'_s$ distribution shifts in a positive (negative) direction. Figure 8 shows the signal event distribution against $\eta'_s$ (left) and $\eta'_b$ (right) in the scenarios of single-$R_2(C_{S_b})$ (red), $S_1$ with $C_{V_1} = 0$ (black), single-$U_1$ ($C_{V_1}$) (blue), and $U(2)-U_1$ (light green). The event normalization for each histogram is taken to be arbitrary. As expected from Fig. 7, it is found that the single-$R_2(C_{S_b})$ and single-$U_1$ ($C_{V_1}$) scenarios have a peak in a positive and negative $\eta'_s$ (and also $\eta'_b$) region, respectively. In fact, the condition $m_T \geq 700$ GeV leads to large amount of events around $\eta_\tau = 0$, while $\eta_b$ tends to be isotropic. As a result, it is found that modification of the shape is clearer in the $\eta'_s$ plane than $\eta'_b$. It is also observed that for the $S_1$ and $U(2)-U_1$ scenarios predict larger numbers of signal events in the $\eta'_s > 0$ region compared to $\eta'_s(b) < 0$.

The azimuthal angle could also provide a tool to discriminate the UV models. We study the relative azimuthal angles among $\tau$, $v$ (missing transverse momentum) and $b$ to distinguish the NP scenarios. We show $\Delta \phi(\vec{p}_T^\tau, \vec{p}_T^b)$ (left) and $\Delta \phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^b)$ (right) in Fig. 9. Note that $\Delta \phi(\vec{p}_T^\tau, \vec{p}_T^{\text{miss}})$ distribution is already used in the cut as the back-to-back configuration: $\Delta \phi(\vec{p}_T^\tau, \vec{p}_T^{\text{miss}}) \geq 2.4$. The color convention is the same as the Fig. 8. It is observed that the single-$R_2(C_{S_b})$ scenario has more events in $0 \leq \Delta \phi(\vec{p}_T^\tau, \vec{p}_T^b) \leq \pi/2$ than the rest of that region, while the $S_1$ scenario has more in $\pi/2 \leq \Delta \phi(\vec{p}_T^\tau, \vec{p}_T^b) \leq \pi$. As for $\Delta \phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^b)$, it is found that the single-$R_2(C_{S_b})$ scenario has more events in $\pi/2 \leq \Delta \phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^b) \leq \pi$.

In conclusion, once signal events are measured, they would be helpful to discriminate the LQ models.

5 Conclusions and discussion

The $R_{D^{(*)}}$ anomaly is one of the hottest topics in the flavor physics from early in the last decade. Since the relevant $b \rightarrow c \tau \nu$ process is induced by exchanging the $W$ boson at the tree level within the SM and the observed deviation is $+O(10)\%$ at the amplitude level, the NP scale is indicated at around 1–10 TeV to solve the $R_{D^{(*)}}$ anomaly. Among the NP models, the LQ particles have attracted a lot of interests. Such particles have been searched for by studying direct pair-production
Figure 8. Distribution of signal event numbers against the modified pseudorapidity $\eta_{r}'$ (left) and $\eta_{b}'$ (right) defined by Eq. (19) in the scenarios of single-$R_2 (C_{S_2})$ (red), $S_1$ (black), single-$U_1 (C_{R_1}^{S_2,b=0})$ (blue), and $U'(2)$-$U_1^{R_1,b=0}$ (light green). Here, $M_{LQ} = 1.5$ TeV is taken, and the normalization of each histogram is arbitrary.

Figure 9. Distribution of signal event numbers against $\Delta \phi(\vec{p}_T^\tau, \vec{p}_T^b)$ (left) and $\Delta \phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^b)$ (right) in each LQ scenario. The color convention is the same as in Fig. 8. Here, $M_{LQ} = 1.5$ TeV is taken, and the normalization of each histogram is arbitrary.

channels at the ATLAS and CMS, and the LQ mass has been constrained to be > 1 – 1.5 TeV. Although the next run will start at the LHC, if the mass is larger than $\gtrsim 2$ TeV, it is unlikely to discover the LQ directly in the near future. Nonetheless, thanks to the crossing symmetry of scattering amplitudes, the NP contributions to $b \rightarrow c \tau \nu$ processes lead to $b\tau \rightarrow c\nu$ scattering at the LHC. Such a process was studied to probe the NP contributions indirectly even if the LQ is heavier.
than the LHC collision energy.

To amplify experimental sensitivities of such a non-resonant search, we examined the impact of requiring an additional $b$-jet in the final state, e.g., $g\tau \rightarrow b\tau\nu$. We evaluated the current and future LHC sensitivities based on both the EFT framework and the viable models of scalar- and vector-LQs: $S_1$, $R_2$, and $U_1$ with/without the $U(2)$ flavor symmetry. It was observed that the additional $b$-jet requirement and $\tau^-$ selection can improve the LHC sensitivity on the NP searches by $\approx 40\%$ and $\approx 10\%$ versus those in the $\tau^\pm\nu$ search, respectively. Furthermore, the LQ mass dependence of the sensitivities is explicitly shown in the LQ mass range of $M_{LQ} = \mathcal{O}(1)$ TeV for the $\tau^\pm\nu + b$ search as well as the $\tau^\pm\nu$ case. In particular, it was found that the sensitivity from the $\tau^\pm\nu + b$ search is better than that from $\tau^\pm\nu$ in the whole mass region for $R_{s/b} \lesssim 1$.

Based on those findings, the LHC sensitivities are compared with the parameter regions that can accommodate the $R_D(\ast)$ anomaly in several single LQ scenarios. There are three types of viable leptoquark models responsible for the anomaly; the $R_2$, $S_1$, and $U_1$ LQ scenarios. We observed the following results:

- For the single-$R_2(C_{S_2})$ LQ scenario, it is found that the current LHC data of $\int L dt = 139$ fb$^{-1}$ are enough to probe the $R_2$ LQ, although the LQ mass dependence is crucial to claim whether the LQ is fully detectable. For instance, the $\tau^\pm\nu + b$ search with $\int L dt = 139$ fb$^{-1}$ fully covers the single-$R_2(C_{S_2})$ scenario with $M_{LQ} > 2.5$ TeV responsible for the $R_{D(\ast)}$ anomaly, while the region of $1.5$ TeV $< M_{LQ} < 2.5$ TeV can be probed partially.

- For the $S_1$ LQ scenario, the parameter region is already severely constrained from $B \rightarrow K^*\nu\nu$ and $\Delta M_s$ measurements, and the current LHC data can not test the allowed region. Larger luminosity such as the HL-LHC with requiring an additional $b$-jet is needed to probe these parameter regions.

- For the $U_1$ LQ scenarios, there are several parameter regions that can accommodate the $R_{D(\ast)}$ anomaly depending on flavor structures of the LQ couplings and the LQ mass. It is found that the HL-LHC can probe the parameter regions in both the single-$U_1 (C_{V_1})$ and $U(2)$-$U_1$ scenarios by requiring an additional $b$-jet.

- As mentioned in Sec. 4.1, the ATLAS collaboration observed smaller number of events than the expected one in the $\tau^\pm\nu$ category at the data of $\int L dt = 139$ fb$^{-1}$, and provided stronger constraint than the expectation [26]. Therefore, an experimental analysis with requiring an additional $b$-jet is of great importance. Particularly, the single-$R_2$ LQ scenario could be probed immediately by using the data of $\int L dt = 139$ fb$^{-1}$.

The angular correlations among $\tau^-$, $b$-jets and missing transverse momentum were also studied. It was shown that the correlation between $\tau^-$ and $b$-jets in the pseudorapidity plane could be useful to discriminate the LQ scenarios. Besides, it was found that the azimuthal angle distributions would also be helpful. However, further studies especially with experimental information are needed for improving the analysis. In this paper, models with light right-handed (sterile) neutrinos are not discussed. In those scenarios, WCs are likely to be large to explain the $R_{D(\ast)}$ anomaly, because there is no interference with the SM amplitude. For instance, the effective Hamiltonian
analogous to that of $C_{V_1}$ is given as

$$H_{eff} = 2\sqrt{2} G_F V_{cb} C_1' \tau \gamma^\mu P_L b (\tau \gamma_\mu P_R v_\tau) + \text{h.c.},$$  \hspace{1cm} (20)

and $C_1' \approx 0.4 \pm 0.05$ can explain the $R_{D^{(*)}}$ anomaly. Since the LHC searches are expected to be insensitive to the neutrino chirality, we can apply the bound/sensitivity obtained for $C_{V_1}$ to the right-handed neutrino scenario. It was shown that the current data of $\int L dt = 139 \text{ fb}^{-1}$ are enough to probe $C_{V_1} \gtrsim 0.2 \ (0.3)$ in the EFT limit (for $M_{LQ} = 1.5 \text{ TeV}$) in the $\tau^\pm v_R + b$ search, see Table 6. Thus, the parameter region of $C_{V_1}$ favored by the $R_{D^{(*)}}$ anomaly can be tested immediately. Further improvements could be possible if larger amount of data is accumulated. In this work, we studied events in the region of $m_T > 1 \text{ TeV}$ to derive the NP sensitivities. With larger data, one could push the $m_T$ condition to a larger side, e.g., $m_T > 2 \text{ TeV}$. Then, the sensitivity would be improved by further suppression of the SM backgrounds. Moreover, further suppression of $\varepsilon_{f \rightarrow b}$ is expected to improve the sensitivity, since a large amount of the SM background events coming from fake $b$-jets can be reduced.

In the aspect of the flavor physics, $q^2$ distribution, $D^*$ polarization and $\tau$ polarization in $\bar{B} \rightarrow D^{(*)}\tau \bar{\nu}$ as well as the other $b \rightarrow c \tau \bar{\nu}$ processes, e.g., $B_c \rightarrow J/\psi \tau \bar{\nu}$, $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}$, and $B_s \rightarrow D_s \tau \bar{\nu}$ will be important to cross check the NP scenarios in the next decade. It would be exciting to see how the data evolves once we are moving to the higher precision. Since the LHC and Belle II experiments enjoy the high statistic era in this and next decades, the interplay between the flavor physics and collider physics would become more significant.

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**A Simulation details**

Here, we present some details of our MC setup and the signal and background cut flows, whose final results are summarized in Sec. 4.1.
Event generations and hadronizations are done as described in Sec. 3 with the following details; as for a jet matching scale, qCut = 45 GeV is used to obtain the merged cross section; regarding the SM background, a model of “sm-no_b_mass” in MADGRAPH5 is used, which sets the bottom quark mass to be 0 while keeping the Yukawa coupling non-vanishing. For the NP signal, the bottom mass is set to be 0.

In the MC simulation, the following pre-cuts are imposed at the run_card level to reduce the computation cost:

\[ p_T^\tau \geq 200 \text{ GeV}, \quad E_T^{\text{miss}} \geq 200 \text{ GeV}, \quad |\eta_\tau| \leq 5, \quad \text{maxjetflavor} = 5, \quad \text{(21)} \]

and JetMatching:nJetMax=-1 (default number) is set. The number of generated background events are 5M for W jj, 40M for Z jj, 5M for t\bar{t} with both W bosons decaying to \tau, 5M for t\bar{t} with one of the W bosons decaying to \tau, 5M for t+j, 6M for tW(1), 1M for tW(2), 0.5M for tZ(1), 5M for Z, γ DY, and 3M for each WW, ZZ(γ), and WZ(γ) categories. For the signal simulations, 100K events are generated in each model point of the NP signals. We have checked that the mT distributions after the cut a and cut b are well smooth for each SM background category and the LQ signal. For the analysis of angular distributions discussed in Sec. 4.5, we increased the generated event numbers by factors to suppress the MC-statistical uncertainty appropriately.

Tables 9 and 10 are detailed cut flows of the SM background for the cut a and cut b, respectively. As a comparison with literature, we show the results of Refs. [25] and [34] for cut a and Ref. [34] for cut b. It should be noted that some details in the analysis procedures are different from ours; particularly, the b-tagging efficiencies (different from Ref. [34] for cut b), the jet cone size (different from Ref. [25] for cut a and cut b), hadronic \tau tagging method (not explained in Ref. [34] explicitly, and different from Ref. [25], for cut a and cut b), and so on. As for cut a the differences are expected to hardly affect the results, and we found that our result is consistent with those in Refs. [25] and [34].

On the other hand, our result for cut b is well suppressed versus those in Ref. [34]. This is mainly because we used a working point with smaller b mis-tagging rates.

Tables 11, 12, 13, and 14 are detailed cut flows of the LQ signal for cut a and cut b. See the caption of Table 3 for the details.

B Flavor observables

In this appendix, the S1 LQ contributions to B \to K^{(*)}\nu\nu and B_s-B_s mixing are discussed.

A ratios between the measured branching fractions of B \to K^{(*)}\nu\nu and the SM predictions is represented by \( \mathcal{R}_K^{\nu\nu} \) [83]. For a case of the minimal coupling of the S1 LQ scenario, we obtain [84]

\[ \mathcal{R}_K^{\nu\nu} = \frac{2}{3} + \frac{1}{3} \left| \frac{C_{L,33}^{\text{SM}} + C_{L,33}^{\text{NP}}}{C_{L,33}^{\text{SM}}} \right|^2, \quad \text{(22)} \]

with

\[ C_{L,33}^{\text{NP}} \simeq +2 \frac{\pi}{\alpha} C_{V_1}, \quad C_{L,33}^{\text{SM}} \simeq -\frac{1.47}{\sin^2 \theta_W}, \quad \text{(23)} \]
### Table 9
Cut flows of the SM background events in the \textbf{cut a} category (the $\tau\pm\nu$ search). The expected number of events corresponding to $\int \mathcal{L} dt = 35.9 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$ are shown. The last two rows show the results by Refs. [25] and [34]. See, the main text for the detail.

| BG (\textbf{cut a}) | $Wjj$ | $Zjj$ ($Z \rightarrow \nu\bar{\nu}$) | $t\bar{t}$ | $Z, \gamma\text{DY}$ | $VV$ | single $t$ |
|---------------------|-------|--------------------------------|-----------|-----------------|------|----------|
| $\tau$ cut (a-1)    | 4613.3 | 562.0                      | 241.8     | 1236.4          | 72.2 | 52.4     |
| lepton cut (a-2)    | 4609.1 | 561.9                      | 230.3     | 744.1           | 65.5 | 50.1     |
| MET cut (a-3)       | 2933.0 | 471.9                      | 190.8     | 83.9            | 42.8 | 42.6     |
| back-to-back (a-4)  | 777.0  | 184.6                      | 9.85      | 52.5            | 12.1 | 1.09     |
| $0.7 < m_T < 1 \text{ TeV}$ | 70.5  | 20.1                       | 0.34      | 3.03            | 1.30 | 0.02     |
| $1 \text{ TeV} < m_T$ | 16.9 | 5.1                       | 0.06      | 0.56            | 0.32 | 0.02     |
| $1 \text{ TeV} < m_T$ [25] | 22 ± 6.2 | 0.9 ± 0.5                  | < 0.1     | < 0.1           | 0.7 ± 0.1 | < 0.1     |
| $1 \text{ TeV} < m_T$ [34] | 18  | 5.2                       | 0.44      | 0.0025          | 1.7  | 0.1      |

### Table 10
Same as Table 9 but for \textbf{cut b} (the $\tau\pm\nu+b$ search). The last row shows the results by Ref. [34]. Note that their $b$-tagging efficiencies are different from ours (see, the footnote #3).

| BG (\textbf{cut b}) | $Wjj$ | $Zjj$ ($Z \rightarrow \nu\bar{\nu}$) | $t\bar{t}$ | $Z, \gamma\text{DY}$ | $VV$ | single $t$ |
|---------------------|-------|--------------------------------|-----------|-----------------|------|----------|
| number of jets       | 6693.4 | 235099                      | 346.7     | 1813.2          | 125.8 | 151.8   |
| number of $\tau$     | 3173.5 | 5617.1                      | 73.9      | 894.9           | 59.7  | 34.0    |
| number of $b$        | 90.6   | 305.5                       | 35.9      | 163.9           | 5.28  | 18.8    |
| isolated lepton      | 90.5   | 305.5                       | 29.7      | 10.4            | 1.38  | 17.0    |
| $\tau$ kinematics    | 78.8   | 20.8                        | 23.6      | 9.19            | 1.13  | 14.0    |
| MET cut              | 71.2   | 4.62                        | 20.9      | 2.52            | 0.98  | 12.7    |
| back-to-back         | 7.84   | 3.61                        | 1.67      | 0.57            | 0.18  | 0.54    |
| $0.7 < m_T < 1 \text{ TeV}$ | 0.58 | 0.37                       | 0.056     | 0.28            | 0.018 | 0.029   |
| $1 \text{ TeV} < m_T$ | 0.16 | 0.06                       | 0.01      | 0.007           | 0.005 | 0.005   |
| $1 \text{ TeV} < m_T$ [34] | 0.18(5) | 0.21(12)                   | 0.29(3)   | 4.2(4)×10⁻⁵     | 0.35(5) | 0.067(7) |

\begin{equation}
\mathcal{H}_{\text{eff}}^{VV} = -\frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{ts}^* C_{L, sb}^f (\gamma P_L b) (\gamma P_L (1 - \gamma s) v_i) + \text{h.c.}, \tag{24}
\end{equation}
where there are no QCD corrections from the RG evolution. Note that the WC, $C_{V_1}$, is defined by the effective Hamiltonian in Eq. (1). The Belle collaboration has provided a severe upper bound on $B \to K^* \nu \nu$ as $R_{K^*}^{\nu \nu} < 2.7$ at the 90% C.L. [85]. From these numbers, we obtain

$$-0.011 < C_{V_1} < 0.027,$$

for the $S_1$ LQ scenario. It is clearly seen that the $S_1$ LQ scenario is severely constrained (see Fig. 3). It is known, however, that adding $SU(2)_L$ triplet scalar LQ $S_3$ can alleviate the constraints from the $b \to s \nu \nu$ processes due to a destructive interference [43, 72, 86].

Next, the $S_1$ LQ contribution to $\Delta M_s$ (via LQ–$\nu_\tau$ box) is given as [72, 73]

$$\frac{\Delta M_s}{\Delta M_s^{\text{SM}}} = \left| 1 + \frac{C_1^{\text{NP}}}{C_1^{\text{SM}}} \right|,$$

(26)

Such a singlet-triplet LQ model can also explain the $b \to s \ell^+ \ell^-$ anomaly [87, 88] and the muon $g - 2$ anomaly [89], simultaneously [72].
Table 13. Same as Table 11 but in the cut \( b \) category. See the caption of Table 4 for the details.

|                     | \( C_{V_1, 1.5 \text{ TeV}} \) | \( C_{V_1, \text{EFT}} \) | \( C_{R_{i/b} = 1, 1.5 \text{ TeV}} \) | \( C_{R_{i/b} = 1, \text{EFT}} \) | BG    |
|---------------------|-----------------------|----------------------|-----------------------|----------------------|-------|
| number of jets      | 1529                  | 1873                 | 3290                  | 4283                 | 244230|
| number of \( \tau \) | 693                   | 907                  | 1576                  | 2114                 | 9853  |
| number of \( b \)   | 144                   | 182                  | 178                   | 237                  | 620.0 |
| isolated lepton     | 142                   | 180                  | 177                   | 234                  | 454.5 |
| \( \tau \) kinematics | 128                  | 165                  | 156                   | 210                  | 147.5 |
| MET cut             | 99.5                  | 131                  | 125                   | 169                  | 112.9 |
| back-to-back        | 48.5                  | 84.3                 | 76.0                  | 111                  | 14.4  |

0.7 < \( m_T \) < 1 TeV

\[
\begin{array}{cccccc}
\text{number of jets} & 11.6 & 16.6 & 13.9 & 21.7 & 1.33 \\
\text{number of } \tau & 6.51 & 14.6 & 9.39 & 21.6 & 0.25 \\
\end{array}
\]

Table 14. Same as Table 13 but for the \( U_1 \) LQ scenario with the \( U(2) \) flavor symmetry, where \( C_{V_1} = 1 \) and \( \int \mathcal{L} dt = 35.9 \text{ fb}^{-1} \).

with

\[
C_{1}^{\text{NP}} \simeq \left( \alpha_{s}(M_{LQ}) / \alpha_{s}(M_{W}) \right)^{2} \frac{(V_{cb}G_{F}M_{LQ})^{2}}{4\pi^{2}} C_{V_1}, \quad C_{1}^{\text{SM}} = 2.35 \frac{(V_{tb}V_{ts}^{*}G_{F}M_{W})^{2}}{4\pi^{2}}.
\]
and

$$\mathcal{H}_{\text{eff}} = C_1 (\bar{\tau} \gamma^\mu P_L b) (\bar{\tau} \gamma_\mu P_L b).$$

(28)

Here, the WC, $C_1$, is given at the electroweak scale, and the prefactor $[\alpha_s(M_{LQ})/\alpha_s(M_W)]^{\gamma_s}$ is the leading QCD correction from the RG evolution [90]. Using the experimental data $\Delta M_{\tau}^{\exp} = (17.741 \pm 0.020) \text{ps}^{-1}$ [21] and the SM prediction is $\Delta M_{\tau}^{\text{SM}} = (18.4_{-0.3}^{+0.7}) \text{ps}^{-1}$ [91], one obtains the upper bound, $\Delta M_{\tau}/\Delta M_{\tau}^{\text{SM}} < 1.11$, at 2 $\sigma$ level.

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