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Test of the $R(D^{(*)})$ anomaly at the LHC

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There are discrepancies between the experimental results and the Standard Model predictions, in the lepton flavor universality of the semileptonic B decays: $B \to D^{(*)}\ell\nu$. As the new physics interpretations, new charged vector and charged scalar fields, that dominantly couple to the second and third generations, have been widely discussed. In this work, we study the signals of the new particles at the LHC, and test the interpretations via the direct search for the new resonances. In particular, we see that the $\tau\nu$ resonance search at the LHC has already covered most of the parameter regions favored by the Belle and BaBar experiments. We find that the bound is already stronger than the one from the B_c decay depending on the mass of charged scalar.

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1. Introduction

Currently, there are large discrepancies in the lepton flavor universalities (LFUs) of the semileptonic B decays: $B \to D\ell\nu$ and $B \to D^*\ell\nu$ ($\ell = e, \mu, \tau$). The observables to measure the LFUs are defined as

$$R(D^{(*)}) = \mathrm{Br}(B \to D^{(*)}\tau\nu)/\mathrm{Br}(B \to D^{(*)}l\nu)\ (l = e, \mu), \tag{1.1}$$

and the experimental world average is $R(D) = 0.407 \pm 0.046$ and $R(D^*) = 0.306 \pm 0.015$ [1]. They are largely deviated from the Standard Model (SM) predictions: $R(D)_{SM} = 0.299 \pm 0.003$ and $R(D^*)_{SM} = 0.258 \pm 0.005$ [1]. Thus, it is expected that those excesses are the new physics signals and there are new particles that couple to the SM fermions flavor-dependently. One simple way to violate the LFU in the B decay is to introduce a field that couples to τ lepton, bottom and charm quarks. One good candidate for such a field is a charged scalar, $H_\pm$, that has Yukawa couplings with the heavy quarks and heavy leptons [2, 3, 4, 5, 6]. The Yukawa couplings are, in general, flavor-dependent, so that we can assume that a specific choice of the couplings. Then, the exchange of a charged scalar at the tree-level induces the violation of the LFU. Instead of the charged scalar, we can discuss a charged vector, $W'_\pm$, that dominantly couples to the second and third generations [7, 8, 9]. In order to introduce such a vector field, additional gauge symmetry is required. In addition, a non-trivial setup would be necessary to make the $W'_\pm$ couplings flavor-dependent.

In this work, we focus on those two new physics interpretations and discuss the consistency with the direct search for the new phenomena at the LHC in the each setup. In particular, it is recently claimed that the charged scalar explanation is in tension with the B_c decay [10, 11]. We study the $\tau\nu$ resonance search at the CMS [12] and see that the bound is stronger than the one from the B_c decay [13].

2. Models

In the SM, the processes: $B \to D^{(*)}\ell\nu$ are given by the tree-level diagrams. Then, relatively large new interaction is required to compensate the SM contribution. If there is a heavy charged particle that couples to quarks and leptons flavor-dependently, the following operators could be generated by the heavy particle exchange:

$$\begin{aligned}\mathscr{H}_{eff} = {} & (C^V_{SM} + C^V_L)(\overline{b_L}\gamma_\mu c_L)(\overline{\nu_{\tau L}}\gamma^\mu \tau_L) + C^V_R(\overline{b_R}\gamma_\mu c_R)(\overline{\nu_{\tau R}}\gamma^\mu \tau_R) \\ & + C^S_L(\overline{b_R}c_L)(\overline{\nu_{\tau L}}\tau_R) + C^S_R(\overline{b_L}c_R)(\overline{\nu_{\tau L}}\tau_R) + h.c.,\end{aligned} \tag{2.1}$$

here C^V_{SM} expresses a SM contribution, with $C^V_{SM} = 4G_F V^*_{cb}/\sqrt{2}$. The two terms in the fist (second) line can be generated by the W' ($H_\pm$) exchange. In this work, we focus on these two scenarios with the SU(3)$_c$-singlet mediators. In the following, we review the each new physics scenario briefly.

To begin with, we discuss a possibility that charged scalar, $H_\pm$, resides behind the $R(D^{(*)})$ anomalies. The charged scalar can be introduced by adding extra Higgs SU(2)$_L$ doublets. The Yukawa couplings between $H_\pm$ and the SM fermions depend on the setup, but in general the scalar couples to all of the SM fermions. Most of the Yukawa couplings are strongly constrained by the flavor physics, so that we have to assume a specific alignment of the couplings. In fact, we limit our Yukawa couplings to those between 2nd and 3rd generations as in [4]. Assuming such a specific

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parameter choice, we can focus on the $b \to c$ transition induced by the Yukawa coupling of charged scalar, i.e.,

$$\mathscr{L}_{H_\pm} = -H_- \left\{ Y_R(\overline{b_R} c_L) + Y_L(\overline{b_L} c_R) + Y_\tau(\overline{\tau_R}\nu_{\tau L}) \right\} + h.c.. \tag{2.2}$$

Integrating out $H_\pm$, we obtain

$$\mathscr{H}_{H_\pm} = -\frac{Y_L Y_\tau^*}{M_H^2}(\overline{b_L} c_R)(\overline{\nu_{\tau L}}\tau_R) - \frac{Y_R Y_\tau^*}{M_H^2}(\overline{b_R} c_L)(\overline{\nu_{\tau L}}\tau_R), \tag{2.3}$$

where M_H is the charged scalar mass. Then, we find that Y_R is also strongly constrained by the B_s-$\overline{B_s}$ mixing, taking into account the neutral Higgs exchange at the tree level [4]. As a result, Y_R is not useful to improve $R(D^{(*)})$. We forget $|Y_R|$ in our analysis below. If the charged scalar mass is less than a few TeV, these operators can largely contribute to the semileptonic B decay.

The numerical descriptions of $R(D)$ and $R(D^*)$ are given by [2]

$$R(D) \simeq R(D)_{SM}\left\{1 + 1.5\mathrm{Re}\left[C_L^{\prime S}\right] + |C_L^{\prime S}|^2\right\},\ R(D^*) \simeq R(D^*)_{SM}\left\{1 - 0.12\mathrm{Re}\left[C_L^{\prime S}\right] + 0.05|C_L^{\prime S}|^2\right\}, \tag{2.4}$$

where $C_L^{\prime S}$ is a normalized coefficient given as $C_L^{\prime S} = C_L^S / C_{SM}^V$, with $C_L^S = -Y_L Y_\tau^*/m_H^2$.

The explanation of $R(D^*)$ is, however, constrained indirectly by the B_c decay [10, 11]. The B_c meson decay is easily enhanced by the scalar-type operator. The enhancement of $R(D)$ while keeping the $R(D^*)$ consistent to the SM prediction can be achieved by tuning the phase of $Y_L Y_\tau^*$ [4].

We can discuss the possibility that the coefficients in Eq. (2.1) are induced by the heavy vector boson exchange. In the extended SM with extra non-abelian gauge symmetry, massive extra gauge bosons are predicted. If the SM quarks are charged under the extra gauge symmetry, an extra charged gauge boson, W', may couple to the third-generation quark and lepton as

$$\mathscr{L}_{W_I'} = W_{I\mu}' \left\{ g_I(\overline{b_I}\gamma^\mu c_I) + g_{I\tau}(\overline{\tau_I}\gamma^\mu \nu_{\tau I}) \right\} + h.c., \tag{2.5}$$

where, I denotes the chirality: $I = L, R$. The couplings g_I and $g_{I\tau}$ depend on the detail of the setup, and the other couplings involving light SM fermions may arise at the low energy. Assuming the third-generation couplings are dominant, we expect the following operators induced:

$$\mathscr{H}_{W'} = \frac{g_L g_{L\tau}^*}{M_{W_L'}^2}(\overline{b_L}\gamma_\mu c_L)(\overline{\nu_{\tau L}}\gamma^\mu \tau_L) + \frac{g_R g_{R\tau}^*}{M_{W_R'}^2}(\overline{b_R}\gamma_\mu c_R)(\overline{\nu_{\tau R}}\gamma^\mu \tau_R) \tag{2.6}$$

where $M_{W_I'}$ denotes the W_I' mass. $R(D)$ and $R(D^*)$ are numerically evaluated as [8]

$$R(D^{(*)}) \simeq R(D^{(*)})_{SM}\left\{ |1 + C_L^{\prime V}|^2 + |C_R^{\prime V}|^2 \right\}, \tag{2.7}$$

where $C_I^{\prime V}$ ($I = L, R$) is also given as $C_I^{\prime V} = C_I^V / C_{SM}^V$ with $C_L^V = g_L g_{L\tau}^*/m_{W_L'}^2$, $C_R^V = g_R g_{R\tau}^*/m_{W_R'}^2$.

3. Test of the new physics at the LHC

We study the signal of the each scenario at the LHC based on the above discussion. Working in 4 flavor scheme, the charged resonances ($V^+ = W_I^{\prime +}, H_+$) are produced in association with the third-generation quark and decay to $\tau\nu$ and bc as follows:

$$g\,c \to V^+ b \to \tau^+ \nu\, b. \tag{3.1}$$

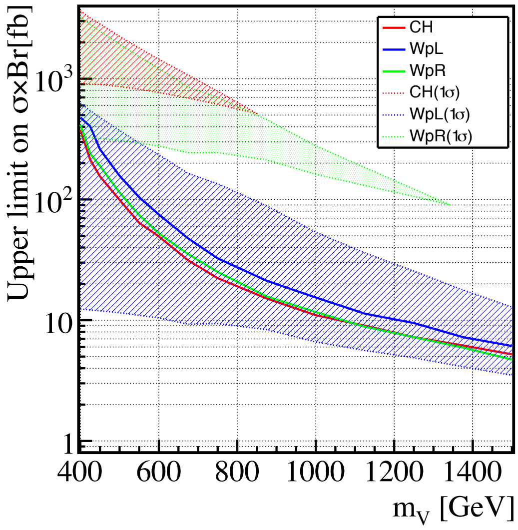

Figure 1: The upper bound on the cross section times branching ratio in the each model at 95% CL. See the main text for the description.

We numerically found the $\tau\nu$ resonances search by the CMS collaboration at the LHC Run II with 35.9 fb^{-1} [12] sets the most stringent bound on our models, where they focus on the W' heavier than 400 GeV with the universal couplings to quarks of all generations. Since the heavy resonances are only couples to the third generation in our models and the spin structures of the $H_\pm$ and the W' are different, we estimated the efficiency and the acceptance by the simulation [13] following the analysis in Ref. [12]. After the simulation, we plot the m_T distribution and performed the binned log-likelihood analysis using the background m_T distribution[12]. In Fig. 1, we show the resulting 95 % CL upper bound on the signal cross section times its branching ratio as a function of the resonance mass: m_V for each model. The difference of the spin structure provides different upper bounds, for charged scalar (red thick solid), W'_L (blue thick solid), and W'_R (green thick solid). For example, the harder m_T distribution give the more stringent bound on the charged scalar case. We also overlay the expected signal cross sections in the same plot for the three cases, in the red hatched region ($H_\pm$), in the blue hatched region (W'_L) and in the green hatched region (W'_R), assuming the couplings are compatible to accommodate the $R(D^{(*)})$ observation in 1σ level. In our models, we can parametrize the cross section with (M, g, g_τ), where g is the c-b-V coupling and can be taken real without loss of generality; e.g., $(M, g, g_\tau) = (M_H, Y_L, Y_\tau)$, and $(M, g, g_\tau) = (M_{W'_I}, g_I, g_{I\tau})$, respectively. The cross section for the above process is given as follows:

$$\sigma(pp \to V^{\pm}) \times Br(V^{\pm} \to \tau\nu) = \sigma_0(m_V) \times \frac{|g|^2|g_\tau|^2}{3|g|^2+|g_\tau|^2} = \sigma_0(m_V) \times \bar{g}^2 \frac{r}{3+r^2}. \tag{3.2}$$

Here, we define the variables, $\bar{g}^2 = |g\,g_\tau|$, which is related to the $R(D^{(*)})$ prediction, and $r = |g_\tau/g|$. Changing r, while keeping $\bar{g}$, varies the cross section. We find that basically, the signal cross section is maximized at $r = \sqrt{3}$ for a fixed $\bar{g}$. We also impose the perturbativity of the couplings, i.e. $|g|, |g_\tau| \leq 1$, and r would be constrained as well. We assume $\bar{g}^2 = a_V M_V^2$ to accommodate the $R(D^{(*)})$ observation at 1 σ, that is $a_{H_\pm} = 1.36 \times 10^{-6}\mathrm{GeV}^{-2}$, and $a_{W_L'} = 1.07 \times 10^{-7}\mathrm{GeV}^{-2}$. Compared with the required $a_{W_L'}$, $a_{H_\pm}$ needs to be large to accommodate the excess. Then, the more stringent bound can be obtained for a charged scalar scenario. Since we impose $\bar{g}^2 \leq 1$ due to the perturbativity, M_V exhibits an upper bound 850 GeV for $H_\pm$ and 3 TeV for W_L'. The upper boundary of the hatched region is given by $r = \sqrt{3}$ for $\bar{g}^2 \leq 1/\sqrt{3}$ or $r = 1/\bar{g}^2$ (g_τ=1) for $\bar{g}^2 > 1/\sqrt{3}$. The lower boundary of the region is given by $r = \bar{g}^2$ ($|g| = 1$).

4. Summary

The discrepancies of $R(D)$ and $R(D^*)$ may be the evidence of new physics behind the SM. Motivated by this issue, many new physics interpretations have been proposed, and we find that some of good candidates for the extra fields are charged scalar and charged vector fields.

In this work, we investigate one observable that does not depend on the detail of the setup, that is, the $\tau\nu$ resonance originated from the charged particle. We simply consider each minimal setup in the scalar case and in the vector case, and discuss the consistency between the explanation of $R(D^{(*)})$ and the latest experimental result at the LHC. Interestingly, we found that the $\tau\nu$ resonance search at the LHC has already covered most of the parameter regions favored by the experiments. We find that the bound is already stronger than the one from the B_c decay depending on the mass of charged scalar.

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