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New physics contributions to $\bar{B}^0_{(s)} \to D^{(*)}_{(s)} K/\pi$

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Recently, the standard model predictions for the B-meson hadronic decays, $\bar{B}^0 \to D^{(*)+}K^-$ and $\bar{B}^0_s \to D^{(*)+}_s \pi^-$, have been updated based on the QCD factorization approach. This improvement sheds light on a novel puzzle of $4-5\sigma$ in the B-meson hadronic decays: there are universal tensions between data and the predicted branching ratios. Assuming the higher-order QCD corrections are not huge enough to solve the tension, several new physics interpretations of this puzzle is examined. It is found that the tension can be partially explained by a left-handed W' model which can be compatible with other flavor observables and collider bounds.

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1. Introduction

Precision measurements of meson decays, especially B-meson decays, have been considerably investigated to test the standard model (SM) and search for physics beyond the SM over the past 30 years. The both experimental and theoretical uncertainties has been surprisingly reduced in meantime. Theorists played an important role: Several approaches that can evaluate the QCD corrections have been invented, and the SM predictions have been sharpened.

Very recently, QCD factorization (QCDF) predictions of so called color allowed B-meson hadronic decays are improved by Ref. [2] (see also Refs. [3, 4]):

$$\mathcal{B}(\overline{B}^0 \to D^+ K^-)^{\rm exp}_{\rm SM} = \begin{cases} (1.86 \pm 0.20) \times 10^{-4}\,, \\ (3.03 \pm 0.15) \times 10^{-4}\,, \end{cases} \tag{1}$$

$$\mathcal{B}(\overline{B}^0 \to D^{*+} K^-)^{\rm exp}_{\rm SM} = \begin{cases} (2.12 \pm 0.15) \times 10^{-4}\,, \\ (3.27 \pm 0.16) \times 10^{-4}\,, \end{cases} \tag{2}$$

$$\mathcal{B}(\overline{B}^0_s \to D_s^+ \pi^-)^{\rm exp}_{\rm SM} = \begin{cases} (3.00 \pm 0.23) \times 10^{-3}\,, \\ (4.09 \pm 0.21) \times 10^{-3}\,, \end{cases} \tag{3}$$

$$\mathcal{B}(\overline{B}^0_s \to D_s^{*+} \pi^-)^{\rm exp}_{\rm SM} = \begin{cases} (2.0 \pm 0.5) \times 10^{-3}\,, \\ (4.46 \pm 0.22) \times 10^{-3}\,, \end{cases} \tag{4}$$

where the upper numbers are the PDG averages of the experimental data [5], while the lower ones are the SM expectation values. In the prediction, NNLO correction [6], V_{cb} and $B \to D^{(*)}$ form factors [7] are used. Consequently, the theoretical predictions deviate from the measured values by $4.7\,\sigma$, $5.3\,\sigma$, $3.5\,\sigma$ and $4.5\,\sigma$, respectively.

The above predictions are very clean theoretically. There is neither penguin nor annihilation contribution to these processes. As a result, there is no chirally-enhanced hard-scattering contributions at $O(\Lambda_{\rm QCD}/m_B)$. Moreover, power corrections at $O(\Lambda_{\rm QCD}/m_B)$, including twist-3 two-particle contributions of light-meson light-cone distribution amplitudes, a hard-collinear gluon exchange between b (or c) and the light meson, and a soft gluon exchange between the $B \to D$ system and the light meson, are expected to be less than a percent [3]. Besides, the QCD×QED factorization is studied recently in Ref. [8], where QED contributions to the color-allowed tree amplitudes are found to reduce the total amplitudes by the sub-percent level, though ultrasoft photons may correct the measured decay rates up to a few percent. The meson to meson rescattering contribution is also discussed but it is found that the puzzled situation remains [2].

The above situation could be resolved by introducing new physics contributions to $b \to c\bar{u}q$ transitions, where $q = d$ and s. In this work several new physics scenarios to explain this $b \to c\bar{u}q$ anomaly is investigated [9].

2. Framework

We consider the following effective Lagrangian to investigate new physics contributions to $b \to c\bar{u}q$ processes:

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \sum_q V_{cb} V^*_{uq} \sum_{i=1,2} C^q_i(\mu) Q^q_i(\mu)\,, \tag{5}$$

with the left-handed current-current operators in the CMM basis [10, 11],

$$Q_1^q = (\bar{c}_L\gamma^\mu T^a b_L)(\bar{q}_L\gamma_\mu T^a u_L), \qquad Q_2^q = (\bar{c}_L\gamma^\mu b_L)(\bar{q}_L\gamma_\mu u_L), \tag{6}$$

where $q = d, s$. T^a is the SU(3)$_C$ generator, and V is the Cabibbo-Kobayashi-Maskawa matrix. In our analysis, we refrain from adding operators that are absent in the SM, e.g., $(\bar{c}_L b_R)(\bar{q}_L u_R)$ which can be induced by scalar mediators in a general two Higgs doublet model [12–15]. New physics contributions to the Wilson coefficients, $C_1^{q,\mathrm{NP}}$ and $C_2^{q,\mathrm{NP}}$, become involved at the new physics scale Λ. These values are modified by the renormalization-group (RG) evolution from Λ down to the hadronic scale m_b.

It is found that a universal destructive shift in the SM contributions is favored in the $b \to c\bar{u}q$ anomaly [3]. The preferred size is $\sim -17\%$, which corresponds to $C_2^{d,\mathrm{NP}} = C_2^{s,\mathrm{NP}} = C_2^{\mathrm{NP}}$ and

$$\frac{C_2^{\mathrm{NP}}(m_b)}{C_2^{\mathrm{SM}}(m_b)} = -0.17 \pm 0.03\,. \tag{7}$$

3. SU(2)×SU(2)×U(1) model

We consider an extended electroweak gauge group SU(2)$_1$×SU(2)$_2$×U(1)$_Y$ with heavy vector-like fermions produces heavy gauge bosons, $W'^{\pm}$ and Z', interacting with the left-handed SM fermions with a non-trivial flavor structure [9, 16]. These flavor structures are controlled by the number of generations of the vector-like fermions and mixings between the SM fermions and vector-like fermions.

The heavy gauge boson interactions are

$$\mathcal{L} \supset +\frac{g_{ij}}{2} Z'_\mu \bar{d}^i_L\gamma^\mu d^j_L - \frac{\left(VgV^\dagger\right)_{ij}}{2} Z'_\mu \bar{u}^i_L\gamma^\mu u^j_L - \frac{(Vg)_{ij}}{\sqrt{2}} W'^+_\mu \bar{u}^i_L\gamma^\mu d^j_L, \tag{8}$$

where u_L, d_L are the mass eigenstates, and a coupling g_{ij} is defined in the d_L basis corresponding to the so-called down basis. By integrating out $W'^{\pm}$, new physics contribution $C_2^{q,W'}$ is obtained as

$$C_2^{q,W'}(M_V) = \frac{1}{4\sqrt{2}G_F M_V^2}\frac{(Vg)_{23}(Vg)^*_{1q}}{V_{cb}V^*_{uq}}\,. \tag{9}$$

In order to generate a desired shift in both $b \to c\bar{u}d$ and $b \to c\bar{u}s$, a SM-like flavor structure in $(Vg)_{1q}$ is required, and hence g_{11} should be non zero. Also another non-zero entry of g_{33} or g_{23} is necessary to produce $C_2^{q,W'}$. Three scenarios is considered in order; (1) $g_{11} \times g_{33} \neq 0$ and $g_{23} = 0$, (2) $g_{11} \times g_{23} \neq 0$ and $g_{33} = 0$, (3) $g_{11} \times g_{23} \times g_{33} \neq 0$. The resultant parameter space and the relevant constraints are shown in Fig. 1 in each scenario.

In scenario (1), even if the flavor violating coupling g_{23} is vanishing, there is W-W' contribution to ΔM. Also $b \to s\gamma$ and $K \to \pi\pi$ as well as LHC searches can constrain the model parameter space. More precisely, dijet, $t\bar{t}$ and single top searches set upper limit on the couplings as long as the particle width does not exceed the experimental assumptions. Currently the maximum width to mass ratio considered in dijet and $t\bar{t}$ are 55% and 30%. It is noted that the result of single top search is reported based on narrow width approximation (NWA). Once the particle width gets larger and

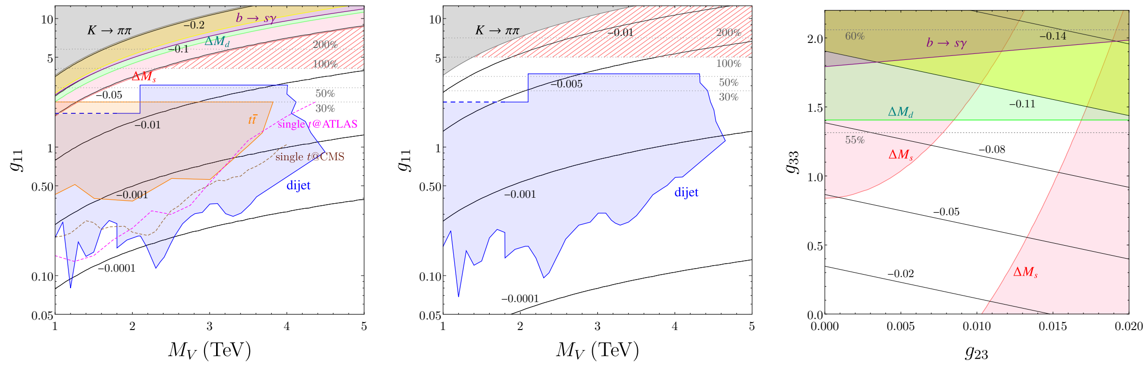

Figure 1: Contours of $C_2^{\rm NP}(m_b)/C_2^{\rm SM}(m_b)$ are presented in black. The puzzle can be explained at 2σ level in the yellow bands. The blue and orange shaded regions are excluded by the dijet and $t\bar{t}$ searches at 95% CL, respectively. The regions above the dashed lines are excluded by the single t searches in the NWA. Furthermore, the gray, red, green, and purple shaded regions are constrained by $K \to \pi\pi$, ΔM_s, ΔM_d, and $b \to s\gamma$, respectively. The dotted line indicates Γ_V/m_V and the red-hatched regions represent $\Gamma_V/m_V > 100\%$. **Left:** scenario (1). $g_{33} = -g_{11}$ is taken. **Middle:** scenario (2). $g_{23} = -0.01(M_V/\text{TeV})$ is taken. **Right:** scenario (3). $M_V = 1$ TeV and $g_{11} = -3.6$ is fixed which already results in $\Gamma_V/m_V \geq 52\%$.

exceeds the value that experimentally assumed, we can not apply the cross section limit directly and more dedicated analysis is necessary. It is found that if one allows the broad width regime $C_2^{\rm NP}(m_b)/C_2^{\rm SM}(m_b) \simeq -0.05$ is possible. Otherwise the allowed shift is less than sub percent. In scenario (2), non zero g_{23} induces ΔM_s at tree level. Also dijet resonance searches constrains the model. As a result, the possible deviation is $C_2^{\rm NP}(m_b)/C_2^{\rm SM}(m_b) \simeq -0.01$ even if one allows the broad width regime.

In scenario (3), we will demonstrate how large deviation could be possible within the broad width regime, otherwise it is obvious that the possible shift is less than 1%. Interestingly the cancellation between W' box and tree Z' contributions occurs and the stringent constraint from ΔM_s can be relaxed. Consequently $C_2^{\rm NP}(m_b)/C_2^{\rm SM}(m_b) \simeq -0.10$ is possible. It is noted again that the more dedicated collider analysis is necessary to check this parameter region. More specifically, imposing a kinematic cut based on the minimal m_{jj} would be helpful where m_{jj} is the invariant mass of a pair of the jets.

4. Conclusion

Motivated by a recent improvement of the QCDF predictions on so called allowed hadronic B meson decay and resultant coherent deviations from the measurement, we investigated the possible size of several new physics contributions to these processes. In spite of severe bounds from the other flavor observables and the LHC searches, it is found that a -10% shift in the $b \to c\bar{u}q$ amplitude is still not excluded by the left-handed W' model. Such a new physics contribution can reduce the tension in the $b \to c\bar{u}q$ processes.

References

[1] M. Beneke, G. Buchalla, M. Neubert and C. T. Sachrajda, Nucl. Phys. B **591**, 313-418 (2000) [arXiv:hep-ph/0006124 [hep-ph]].

[2] M. Endo, S. Iguro and S. Mishima, [arXiv:2109.10811 [hep-ph]].

[3] M. Bordone, N. Gubernari, T. Huber, M. Jung and D. van Dyk, Eur. Phys. J. C **80**, no.10, 951 (2020) [arXiv:2007.10338 [hep-ph]].

[4] F. M. Cai, W. J. Deng, X. Q. Li and Y. D. Yang, JHEP **10**, 235 (2021) [arXiv:2103.04138 [hep-ph]].

[5] P. A. Zyla *et al.* [Particle Data Group], PTEP **2020**, no.8, 083C01 (2020)

[6] T. Huber, S. Kränkl and X. Q. Li, JHEP **09**, 112 (2016) [arXiv:1606.02888 [hep-ph]].

[7] S. Iguro and R. Watanabe, JHEP **08**, no.08, 006 (2020) [arXiv:2004.10208 [hep-ph]].

[8] M. Beneke, P. Böer, G. Finauri and K. K. Vos, JHEP **10**, 223 (2021) [arXiv:2107.03819 [hep-ph]].

[9] S. Iguro and T. Kitahara, Phys. Rev. D **102**, no.7, 071701 (2020) [arXiv:2008.01086 [hep-ph]].

[10] K. G. Chetyrkin, M. Misiak and M. Munz, Phys. Lett. B **400**, 206-219 (1997) [erratum: Phys. Lett. B **425**, 414 (1998)] [arXiv:hep-ph/9612313 [hep-ph]].

[11] K. G. Chetyrkin, M. Misiak and M. Munz, Nucl. Phys. B **520**, 279-297 (1998) [arXiv:hep-ph/9711280 [hep-ph]].

[12] S. Iguro and K. Tobe, Nucl. Phys. B **925**, 560-606 (2017) [arXiv:1708.06176 [hep-ph]].

[13] S. Iguro and Y. Omura, JHEP **05**, 173 (2018) [arXiv:1802.01732 [hep-ph]].

[14] S. Iguro and Y. Omura, JHEP **08**, 098 (2019) [arXiv:1905.11778 [hep-ph]].

[15] S. Iguro, Y. Omura and M. Takeuchi, JHEP **11**, 130 (2019) [arXiv:1907.09845 [hep-ph]].

[16] S. M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente and J. Virto, JHEP **12**, 059 (2016) [arXiv:1608.01349 [hep-ph]].

[17] G. Aad *et al.* [ATLAS], JHEP **03**, 145 (2020) [arXiv:1910.08447 [hep-ex]].

[18] A. M. Sirunyan *et al.* [CMS], JHEP **05**, 033 (2020) [arXiv:1911.03947 [hep-ex]].

[19] A. M. Sirunyan *et al.* [CMS], JHEP **08**, 130 (2018) [arXiv:1806.00843 [hep-ex]].

[20] A. M. Sirunyan *et al.* [CMS], JHEP **04**, 031 (2019) [arXiv:1810.05905 [hep-ex]].

[21] G. Aad *et al.* [ATLAS], JHEP **10**, 061 (2020) [arXiv:2005.05138 [hep-ex]].

[22] A. M. Sirunyan *et al.* [CMS], Phys. Lett. B **777**, 39-63 (2018) [arXiv:1708.08539 [hep-ex]].

[23] M. Aaboud *et al.* [ATLAS], Phys. Lett. B **788**, 347-370 (2019) [arXiv:1807.10473 [hep-ex]].