Probing a pseudoscalar at the LHC in light of R(D(?))R(D(?))R(D^{(*)}) and muon g-2 excesses Postprint

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Preamble

Probing a Pseudoscalar at the LHC in Light of R(D(*)) and Muon g-2 Excesses

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Abstract

We study the excesses of R(D*()) and muon g-2 in the framework of a two-Higgs-doublet model with top quark flavor-changing neutral-current (FCNC) couplings. Considering the relevant theoretical and experimental constraints, we find that the R(D()*) and muon g-2 excesses can be simultaneously explained in a parameter space allowed by the constraints. In such a parameter space the pseudoscalar (A) has a mass between 20 GeV and 150 GeV so that it can be produced from the top quark FCNC decay $t \to Ac$. Focusing on its dominant decay $A \to \tau^+\tau^-$, we perform a detailed simulation on $pp \to jjbc\tau^+\tau^-$ and find that the 2 upper limits from a data set of 30 (100) fb ¹ at the 13 TeV LHC can mostly (entirely) exclude such a parameter space.

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Introduction

Recently, the BaBar [1, 2], Belle [3, 4] and LHCb [5] collaborations have reported anomalies in the ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)$ where $\ell = e, \mu$. The average values from the Heavy Flavor Average Group are [6] $R(D)_{\rm avg} = 0.397 \pm 0.057 \pm 0.028$ and $R(D^*)_{\rm avg} = 0.316 \pm 0.016 \pm 0.010$. Compared to the SM predictions $R(D)_{\rm SM} = 0.300 \pm 0.008$ and $R(D^*)_{\rm SM} = 0.252 \pm 0.003$, there is a discrepancy of 1.9 for $R(D)$ and 3.3 for $R(D^*)$. These anomalies have been studied in various new physics models [7–36], including the possibility of a charged Higgs boson [37–50].

On the other hand, the muon anomalous magnetic moment (g-2) is a very precisely measured observable. The muon g-2 anomaly has been a long-standing puzzle since the announcement by the E821 experiment in 2001 [51, 52]. There is an approximate 3 discrepancy between the experimental value and the SM prediction [53–55]. The muon g-2 anomaly can be simply explained in the two-Higgs-doublet model (2HDM) [56–72].

In this paper, we examine the $R(D^{(*)})$ and muon g-2 excesses in a 2HDM with top quark flavor-changing neutral-current (FCNC) couplings. We consider various theoretical and experimental constraints from precision electroweak data, B-meson decays, decays, as well as observables from top quark and Higgs searches. In this model, the lepton Yukawa couplings can simultaneously affect $R(D^{(*)})$, muon g-2 and lepton universality from decays, and thus these three observables have a strong correlation. The $R(D^{(*)})$ and muon g-2 excesses favor a light pseudoscalar with a large coupling to leptons and nonzero top FCNC couplings, which implies that the pseudoscalar can be produced from the top quark FCNC decay $t \to Ac$. We will perform a detailed simulation on the signal $pp \to WbAc$ and the corresponding backgrounds at the LHC, where the pseudoscalar dominantly decays in the mode $A \to \tau^+\tau^-$.

Our work is organized as follows. In Sec. II we recapitulate the 2HDM with top quark FCNC couplings. In Sec. III we perform numerical calculations. In Sec. IV, we discuss the $R(D^{(*)})$ and muon g-2 excesses after imposing the relevant theoretical and experimental constraints, and then perform simulations on $pp \to WbAc \to jjbc\tau^+\tau^-$. Finally, we give our conclusion in Sec. V.

II. Two-Higgs-Doublet Model with Top Quark FCNC Couplings

The general Higgs potential is written as [73]

$$V = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - \left[m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})\right] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi$$

We focus on the CP-conserving model in which all λ_i and m_{12}^2 are real. We assume λ_6 and λ_7 are zero, and thus the Higgs potential has a softly broken Z_2 symmetry. The two complex scalar doublets have hypercharge $Y = 1$:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix}$$

where the electroweak vacuum expectation values (VEVs) satisfy $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$, and the ratio of the two VEVs is defined as $\tan\beta = v_2/v_1$. After spontaneous electroweak symmetry breaking, there are five mass eigenstates: two neutral CP-even scalars h and H, one neutral pseudoscalar A, and two charged scalars $H^\pm$.

The general Yukawa interactions in the physical basis are given by

$$\mathcal{L}_Y = Y_{u1}\bar{Q}_L\tilde{\Phi}_1 u_R + Y_{d1}\bar{Q}_L\Phi_1 d_R + Y_{\ell 1}\bar{L}_L\Phi_1 e_R + Y_{u2}\bar{Q}_L\tilde{\Phi}_2 u_R + Y_{d2}\bar{Q}_L\Phi_2 d_R + Y_{\ell 2}\bar{L}_L\Phi_2 e_R + \text{h.c.}$$

where $Q_L^T = (u_L, d_L)$, $L_L^T = (\nu_L, \ell_L)$, $\tilde{\Phi}_{1,2} = i\tau_2\Phi_{1,2}^*$, and $Y_{u1,2}$, $Y_{d1,2}$ and $Y_{\ell 1,2}$ are 3×3 matrices in family space.

To avoid tree-level FCNCs of down-type quarks and leptons, we take the two Higgs doublet fields to have aligned Yukawa coupling matrices [74, 75]:

$$Y_{\ell 1} = c_\ell \rho_\ell, \quad Y_{\ell 2} = s_\ell \rho_\ell, \quad Y_{d1} = c_d \rho_d, \quad Y_{d2} = s_d \rho_d$$

where $c_d = \cos\theta_d$, $s_d = \sin\theta_d$, $c_\ell = \cos\theta_\ell$, $s_\ell = \sin\theta_\ell$, and ρ_d (ρ_ℓ) is the 3×3 matrix.

For the Yukawa coupling matrices of up-type quarks, we take

$$X_{ii} = \frac{\sqrt{2}m_{u_i}}{v}(s_\beta + c_\beta \kappa_u), \quad X_{tc} = X_{ct} = \frac{\sqrt{2m_c m_t}}{v} c_\beta \lambda_{ct}$$

where $X = V_L Y_{u2} V_R^\dagger$, and V_L (V_R) is the unitary matrix which transforms the interaction eigenstates to the mass eigenstates for left-handed (right-handed) up-type quark fields. We adopt the Cheng-Sher ansatz for X_{ct} and X_{tc} [76], and other non-diagonal matrix elements of X are taken as zero.

The Yukawa couplings of the neutral Higgs bosons are given as

$$y_{hf_if_i} = \frac{\sqrt{2}m_{f_i}}{v}[\sin(\beta-\alpha) + \cos(\beta-\alpha)\kappa_f], \quad y_{Hf_if_i} = \frac{\sqrt{2}m_{f_i}}{v}[\cos(\beta-\alpha) - \sin(\beta-\alpha)\kappa_f]$$

$$y_{Af_if_i} = i\frac{\sqrt{2}m_{f_i}}{v}\kappa_f \quad (\text{for } u), \quad y_{Af_if_i} = i\frac{\sqrt{2}m_{f_i}}{v}\kappa_f \tan\beta \quad (\text{for } d, \ell)$$

$$y_{hct} = \cos(\beta-\alpha)\frac{\sqrt{2m_c m_t}}{v}\lambda_{ct}, \quad y_{Hct} = y_{Act} = \sin(\beta-\alpha)\frac{\sqrt{2m_c m_t}}{v}\lambda_{ct}$$

$$y_{htc} = y_{hct}, \quad y_{Htc} = y_{Hct}, \quad y_{Atc} = y_{Act}$$

where $\kappa_d = \tan(\beta - \theta_d)$ and $\kappa_\ell = \tan(\beta - \theta_\ell)$.

The Yukawa interactions of the charged Higgs are given as

$$\mathcal{L}_{H^\pm} = \frac{\sqrt{2}}{v}H^+\left\{\bar{u}_i[\kappa_d(V_{\text{CKM}})_{ij}m_{d_j}P_R - \kappa_u m_{u_i}(V_{\text{CKM}})_{ij}P_L]d_j + \kappa_\ell\bar{\nu}m_\ell P_R\ell\right\} + \left[\frac{\sqrt{2m_c m_t}}{v}\lambda_{ct}H^+(\bar{u}_m(V_{\text{CKM}})_{nj}P$$

where $i, j = 1, 2, 3$, and $m, n = 2, 3$ with $m \neq n$.

The neutral Higgs boson couplings with gauge bosons normalized to the SM are given by

$$g_{hVV} = \sin(\beta-\alpha), \quad g_{HVV} = \cos(\beta-\alpha)$$

where V denotes Z or W.

The non-diagonal matrix elements X_{ct} and X_{tc} lead to top quark FCNC couplings of h, H and A, and give additional contributions to the couplings of charged Higgs with top quark (charm quark), as shown in Eq. (14) and Eq. (15). In the exact alignment limit [77, 78], namely $\cos(\beta-\alpha) = 0$, from Eq. (14) and Eq. (16) we find that for h the couplings to fermions and gauge bosons are the same as in the SM, and the tree-level top quark FCNC couplings are absent. The heavy CP-even Higgs (H) has no couplings to gauge bosons.

III. Numerical Calculations

In our analysis we take the light CP-even Higgs boson h as the SM-like Higgs with $m_h = 125$ GeV. To avoid constraints from searches for top quark FCNC of the SM-like Higgs, we take the exact alignment limit, namely $\sin(\beta-\alpha) = 1$. The muon g-2 favors a light pseudoscalar with a large coupling to leptons and a sizable mass splitting between H and A. The precision electroweak data favors a small mass splitting between H and $H^\pm$. Therefore, we take $m_H = 700$ GeV and $m_{H^\pm} = 200$ GeV.

To loosen constraints from searches for $pp \to A(H) \to \tau^+\tau^-$ and from observables of down-type quarks, we take $\kappa_u = \kappa_d = 1/\kappa_\ell$, which is similar to the Yukawa couplings of the lepton-specific 2HDM. For a very large κ_ℓ, this choice is equivalent to assuming κ_u and κ_d are negligible.

The other free parameters are randomly scanned in the following ranges: $0 < \lambda_{ct} < 30$, $(400\ \text{GeV})^2 < m_{12}^2 < (400\ \text{GeV})^2$, and $0.1 < \tan\beta < 50$. Note that the $R(D^{(*)})$ excess favors opposite signs between λ_{ct} and κ_ℓ [42].

In our scan, we consider the following observables and constraints:

(1) **Theoretical constraints and precision electroweak data.** We use 2HDMC [79, 80] to implement theoretical constraints from vacuum stability, unitarity and coupling-constant perturbativity, as well as constraints from oblique parameters (S, T, U) and $\delta\rho$.

(2) **Muon g-2.** At the one-loop level, the muon g-2 is corrected by [56, 81, 82]

$$\Delta a_\mu^1 = \sum_{\phi=h,H,A,H^\pm} \frac{y_{\phi\mu\mu}^2}{16\pi^2} \int_0^1 dx \frac{x^2(2-x)}{x^2+(1-x)r_{\phi\mu}}$$

where $y_{H^\pm\mu\mu} = y_{A\mu\mu}$. For $r_{\phi\mu} \equiv m_\mu^2/m_\phi^2 \ll 1$ we have

$$\Delta a_\mu^1 \simeq \sum_{\phi=h,H,A} \frac{y_{\phi\mu\mu}^2}{16\pi^2} f_\phi(r_{\phi\mu}) + \frac{y_{H^\pm\mu\mu}^2}{16\pi^2} f_{H^\pm}(r_{H^\pm\mu})$$

with $f_h(r) = f_H(r) = 7/6$, $f_A(r) = -\ln r + 11/6$, and $f_{H^\pm}(r) = 1/6$.

The muon g-2 can also be corrected by two-loop Barr-Zee diagrams with fermion loops and W loops. Using the well-known classical formulas [68, 83], the main contributions from two-loop Barr-Zee diagrams in the exact alignment limit are given by

$$\delta a_\mu^2 = \frac{1}{4\pi^3} \sum_{\phi=h,H,A;f=t,b,\tau} y_{\phi\mu\mu} y_{\phi ff} N_c^f Q_f^2 F_\phi(x_{f\phi}) + \frac{G_F m_\mu^2}{4\sqrt{2}\pi^3} \sum_{\phi=h,H,A} y_{\phi\mu\mu} g_{\phi WW} F_\phi(x_{W\phi})$$

where $x_{f\phi} = m_f^2/m_\phi^2$, $x_{W\phi} = m_W^2/m_\phi^2$, $g_{hWW} = 1$ and

$$F_h(y) = \frac{3}{2}F_h(y) - \frac{5}{6}, \quad F_A(y) = \frac{3}{2}F_A(y) - \frac{1}{6}, \quad G(y) = \frac{1}{2}F_h(y) - \frac{5}{6}$$

The difference between the SM value and the experimental value of muon g-2 is

$$\delta a_\mu = (26.2 \pm 8.0) \times 10^{-10}$$

(3) **Lepton universality from   decays.** The current experimental results for charged lepton universality from   decays are given by [84]

$$\frac{g_\mu}{g_e} = 1.0018 \pm 0.0014, \quad \frac{g_\tau}{g_\mu} = 1.0029 \pm 0.0015, \quad \frac{g_\tau}{g_e} = 1.0001 \pm 0.0014$$

where the first two values are from fits to leptonic   decays, and the third value is from fits to $\bar{\Gamma}(\tau \to h\nu)$ with $h = K, \pi$ and $\bar{\Gamma}$ denoting the partial width normalized to its SM value. The ratio g_τ/g_e favors a positive correction to the SM value, which imposes strong constraints on the 2HDM, as shown in [65]. Since only two of the ratios in Eq. (27) are independent, in principle we may take g_μ/g_e and g_τ/g_μ to constrain the model.

In this model,

$$\frac{g_\mu}{g_e} = 1 + \frac{m_\tau^2}{2m_{H^\pm}^2}\kappa_\ell^2$$

where the corrections come from tree-level diagrams mediated by the charged Higgs. Since the one-loop effect applies equally to both tau decays, it does not give correction to g_μ/g_e. Ignoring the electron mass, g_τ/g_μ is only corrected by the one-loop diagram mediated by the charged Higgs. The correction to g_τ/g_μ is given by [65]

$$\frac{g_\tau}{g_\mu} = 1 + 2\delta g$$

where

$$\delta g = \frac{1}{16\pi^2}\left[\frac{m_\tau^2}{m_{H^\pm}^2}\kappa_\ell^2 - \frac{m_\mu^2}{m_{H^\pm}^2}\kappa_\ell^2\right]$$

(4) **Measurements of $R(D^{(*)})$.** New four-fermion operators can be generated by exchanging the charged Higgs:

$$\mathcal{O}_{SRL} = (\bar{c}P_R b)(\bar{\tau}P_L\nu_\tau), \quad \mathcal{O}_{SLL} = (\bar{c}P_L b)(\bar{\tau}P_L\nu_\tau)$$

The corresponding tree-level Wilson coefficients are given by

$$C_{SLL}^c = \frac{2\sqrt{m_t m_c}\,m_\tau}{m_{H^\pm}^2 v^2}V_{tb}\lambda_{ct}\kappa_\ell, \quad C_{SRL}^c = \frac{2m_b m_\tau}{m_{H^\pm}^2 v^2}V_{cb}\kappa_d\kappa_\ell$$

which can give contributions to $R(D^{(*)})$ [37–39, 46]:

$$R(D) = R_{\text{SM}}(D) \left[1 + 1.5\text{Re} \left(\frac{C^c_{SRL} + C^c_{SLL}}{C^{c,\text{SM}}_{VLL}} \right) + 0.05 \left| \frac{C^c_{SRL} + C^c_{SLL}}{C^{c,\text{SM}}_{VLL}} \right|^2 \right]$$

$$R(D^*) = R_{\text{SM}}(D^*) \left[1 + 0.12\text{Re} \left(\frac{C^c_{SRL} - C^c_{SLL}}{C^{c,\text{SM}}_{VLL}} \right) + 1.0 \left| \frac{C^c_{SRL} - C^c_{SLL}}{C^{c,\text{SM}}_{VLL}} \right|^2 \right]$$

Here $C^{c,\text{SM}}_{VLL}$ is the Wilson coefficient in the SM:

$$C^{c,\text{SM}}_{VLL} = \frac{4G_F V_{cb}}{\sqrt{2}}$$

(5) **B-meson decays.** The non-diagonal matrix element X_{tc} can give additional contributions to the couplings of top quark and charged Higgs, which will correct Δm_{B_s}, Δm_{B_d} and $B \to X_s\gamma$ at one-loop level:

$$\mathcal{L}_{H^+\bar{t}s} = \frac{\sqrt{2m_t m_c}}{v} \lambda_{ct} H^+(\bar{t}P_R s), \quad \mathcal{L}_{H^+\bar{t}b} = \frac{\sqrt{2m_t m_c}}{v} \lambda_{ct} H^+(\bar{t}P_R b)$$

The Δm_{B_s}, Δm_{B_d} and $B \to X_s\gamma$ are calculated using the formulas in [85–87].

(6) **Higgs search experiments:** (i) The non-observation of additional Higgs bosons. We employ HiggsBounds-4.3.1 [88, 89] to implement exclusion constraints from neutral and charged Higgs searches at LEP, Tevatron and LHC at 95% confidence level. Very recently, ATLAS reported searches for a heavy charged Higgs in single top quark associated production at the 13 TeV LHC with integrated luminosities of 14.7 fb ^{1} for $H^\pm \to \tau\nu$ [90] and 13.2 fb ^{1} for $H^\pm \to tb$ [91]. The upper bounds on production cross section times $\text{Br}(H^\pm \to \tau\nu)$ are in the range of 2.0 to 0.008 pb for $m_{H^\pm} = 200$–2000 GeV. The upper bounds on production cross section times $\text{Br}(H^\pm \to tb)$ are in the range of 1.37 to 0.18 pb for $m_{H^\pm} = 300$–1000 GeV. In this model, the top quark FCNC of the charged Higgs can give additional contributions to charged Higgs boson production in association with a top quark. Although the coupling of the charged Higgs to tau lepton is sizably enhanced, the decay $H^\pm \to AW^\pm$ is still an important mode. (ii) The global fit to the 125 GeV Higgs signal data. In the exact alignment limit, the SM-like Higgs couplings to SM particles at tree-level are the same as in the SM, which is favored by the 125 GeV Higgs signal data. For $m_A < 62.5$ GeV, the mode $h \to AA$ can open and enhance the total width of h sizably, which will be strongly constrained by the 125 GeV Higgs data. We perform the χ^2 calculation for signal strengths $\mu_{\text{ggF+ttH}}(Y)$ and $\mu_{\text{VBF+VH}}(Y)$ with Y denoting decay modes $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$ and $\bar{b}b$:

$$\chi^2(Y) = \begin{pmatrix} \mu_{\rm ggF+ttH}(Y) - \mu^{\rm data}_{\rm ggF+ttH}(Y) \\ \mu_{\rm VBF+VH}(Y) - \mu^{\rm data}_{\rm VBF+VH}(Y) \end{pmatrix}^T \begin{pmatrix} a_Y & b_Y \\ b_Y & c_Y \end{pmatrix} \begin{pmatrix} \mu_{\rm ggF+ttH}(Y) - \mu^{\rm data}_{\rm ggF+ttH}(Y) \\ \mu_{\rm VBF+VH}(Y) - \mu^{\rm data}_{\rm VBF+VH}(Y) \end{pmatrix}$$

where $\mu^{\rm data}_{\rm ggF+ttH}(Y)$ and $\mu^{\rm data}_{\rm VBF+VH}(Y)$ are the data best-fit values, and a_Y, b_Y and c_Y are parameters of the ellipse. These parameters are given by combined samples from ATLAS and CMS experiments [92]. We pay particular attention to surviving samples with $\chi^2 - \chi^2_{\rm min} \leq 6.18$, where $\chi^2_{\rm min}$ denotes the minimum of χ^2. These samples correspond to the 95.4% confidence level region in any two-dimensional plane of model parameters when explaining the Higgs data (corresponding to the 2 range).

(7) **Observables of the top quark:** (i) The total width of the top quark. There is no decay mode $t \to hc$ in the exact alignment limit. For $m_A < m_t$, the mode $t \to Ac$ opens and enhances the total width of the top quark. The measured value of the total top width is $\Gamma_t = 1.36 \pm 0.02^{+0.14}_{-0.11}$ GeV from the CMS collaboration [93]. (ii) Same-sign top pair production at the LHC. Same-sign top pairs can be produced at the LHC via the $cc \to tt$ process with t-channel exchange of A and H. From searches for same-sign dileptons and b-jets at the 8 TeV LHC with an integrated luminosity of 20.3 fb ¹ [94], ATLAS gave an upper bound of 62 fb.

Note that the observables of the top quark, B-meson decays and searches for heavy charged Higgs at the 13 TeV LHC are all sensitive to the FCNC of the top quark, namely the parameter λ_{ct}. For convenience, we use "Top-FCNC-Constraints" to denote these constraints in the following sections. We use MG5@NLO [95] to calculate the cross section of $pp \to tt$ at the 8 TeV LHC and $\sigma(pp \to tH^\pm){\rm Br}(H^\pm \to \tau\nu, tb)$ at the 13 TeV LHC. Our calculations show that searches for same-sign top pair production at the 8 TeV LHC and for charged Higgs at the 13 TeV LHC can hardly give further constraints on the model after imposing constraints from B-meson decays, top width, muon g-2, $R(D^{(*)})$,   decays, precision electroweak data and theoretical constraints.

IV. Results and Discussions

A. Explanation for $R(D^{(*)})$ and Muon g-2

In Fig. 1 [Figure 1: see original paper], we project the surviving samples on the planes of λ_{ct} versus $m_{H^\pm}$, κ_ℓ versus $m_{H^\pm}$ and κ_ℓ versus λ_{ct}. All points are allowed by constraints from muon g-2, $R(D^{(*)})$, theoretical constraints, precision electroweak data,   decays, exclusion limits of Higgs bosons and the 125 GeV Higgs data. The circles (green) and pluses (red) are respectively excluded and allowed by the "Top-FCNC-Constraints". Without the "Top-FCNC-Constraints", λ_{ct} and κ_ℓ increase with the charged Higgs mass, and κ_ℓ tends to decrease with increasing λ_{ct}. These features are mainly determined by $R(D^{(*)})$ since the product $\lambda_{ct}\kappa_\ell/m^2_{H^\pm}$ in the Wilson coefficient C^c_{SLL} can affect $R(D^{(*)})$ (see Eq. (33)

and Eq. (34)). In addition, observables of lepton universality from decays favor κ_ℓ to increase with the charged Higgs mass mainly due to the factor $\kappa_\ell^2/m_{H^\pm}^2$ in the correction terms of g_μ/g_e (see Eq. (28)).

After imposing the "Top-FCNC-Constraints", a large part of parameter space is excluded, and λ_{ct} and $m_{H^\pm}$ are directly constrained. For a given $m_{H^\pm}$, λ_{ct} receives an upper bound from the "Top-FCNC-Constraints" and a lower bound from $R(D^{(*)})$. Once $m_{H^\pm}$ and the upper bound of λ_{ct} are given, $R(D^{(*)})$ imposes a lower bound on κ_ℓ. In addition, lepton universality from decays gives an upper bound on κ_ℓ. For example, $3.0 < \lambda_{ct} < 4.5$ and $90 < \kappa_\ell < 125$ for $m_{H^\pm} = 400$ GeV. After imposing "Top-FCNC-Constraints", λ_{ct} and κ_ℓ increase with the charged Higgs mass, and κ_ℓ tends to increase with λ_{ct}. For 200 GeV $< m_{H^\pm} <$ 620 GeV, λ_{ct} and κ_ℓ are respectively required to be in the ranges of 1.5–6.5 and 60–150.

In Fig. 2 [Figure 2: see original paper], we project the surviving samples on the planes of κ_ℓ versus m_A and λ_{ct} versus m_A. The left panel shows that κ_ℓ is sensitive to m_A and increases with m_A. These features are mainly determined by muon g-2, which receives dominantly positive contributions from the pseudoscalar via two-loop Barr-Zee diagrams. For $m_A > 150$ GeV, κ_ℓ is required to be larger than 150, which potentially leads to a problem with perturbativity of the lepton Yukawa coupling. For $m_A = 20$ GeV, κ_ℓ is required to be larger than 60 after imposing "Top-FCNC-Constraints". Compared to the region $m_A > 62.5$ GeV, there are relatively few surviving samples in the region $m_A < 62.5$ GeV. For m_A smaller than half the SM-like Higgs mass, the decay mode $h \to AA$ opens and enhances the total width of the SM-like Higgs. Therefore, the 125 GeV Higgs data give strong constraints on the parameter space.

The right panel of Fig. 2 shows that surviving samples favor a large λ_{ct} for a large m_A after imposing "Top-FCNC-Constraints". Since contributions from A and H to muon g-2 cancel, a large mass splitting between A and H is required to explain muon g-2. In addition, precision electroweak data favor a small mass splitting between H and $H^\pm$. Therefore, muon g-2 favors a large $m_{H^\pm}$ for a large m_A, and further a large $m_{H^\pm}$ tends to require a large λ_{ct} due to $R(D^{(*)})$ excess and "Top-FCNC-Constraints".

Note that flipping the signs of λ_{ct} and κ_ℓ does not change the results in this paper. As seen from Section III, muon g-2 and observables of lepton universality do not depend on the sign of κ_ℓ. $R(D^{(*)})$ depends on the sign of the product $\lambda_{ct}\kappa_\ell$. When flipping the signs of λ_{ct} and κ_ℓ, the sign of the charged Higgs coupling to the top quark will be flipped while the absolute value remains unchanged due to $\kappa_u = \kappa_d = 1/\kappa_\ell$, which does not change the results of B-meson decays.

B. Simulation on $pp \to WbAc \to jjbc\tau^+\tau^-$

As seen from the preceding section, after imposing relevant theoretical and experimental constraints, the muon g-2 and $R(D^{(*)})$ excesses can be simultaneously explained in the parameter space:

$$20\ \text{GeV} < m_A < 150\ \text{GeV}, \quad 200\ \text{GeV} < m_H(m_{H^\pm}) < 620\ \text{GeV},$$

$$150 < \kappa_\ell < 60, \quad \kappa_u = \kappa_d = 1/\kappa_\ell, \quad 1.5 < \lambda_{ct} < 6.5.$$

In such a parameter space, the pseudoscalar can be produced via the QCD process $pp \to t\bar{t}$ followed by the decay $t \to Ac$, and then dominantly decays into $\tau^+\tau^-$.

In the parameter space shown in Eq. (39), the decay modes $A \to HZ$, $A \to H^\pm W^\mp$ and $A \to hZ$ are kinematically forbidden, and $A \to hZ$ is also absent in the exact alignment limit. The pseudoscalar will dominantly decay into $\tau^+\tau^-$ with $\text{Br}(A \to \tau^+\tau^-) \approx 99.65\%$ and $\text{Br}(A \to t\bar{t}) \approx 0.35\%$, which are not sensitive to κ_ℓ in the range of 60–150. Therefore, the cross section $\sigma(pp \to t\bar{t}) \times \text{Br}(t \to Ac)$ is only sensitive to m_A and λ_{ct}. Besides, since the $At\bar{t}$ couplings are sizably suppressed by κ_u^2, the $pp \to t\bar{t}$ production process becomes more important.

Now we perform detailed simulations on the signal and backgrounds at the 13 TeV LHC. We consider top quark pair production where one decays to $(W \to jj) + b$ and the other decays to $(A \to \tau^+\tau^-) + c$. The major SM background processes to this signal are $t\bar{t}$, $tW+$ jets, $tZ+$ jets and $Zb\bar{b}+$ jets. Other backgrounds, such as multi-jets, can be significantly reduced by requiring one b-tagged jet and two -tagged jets.

The model file of the 2HDM is generated by FeynRules [96]. Both signal and background processes are generated with MG5@NLO [95], using PYTHIA for showering and hadronization [97] and TAUOLA for lepton decay [98]. Fast simulations of the detector and trigger are performed by Delphes3.3.0 [99], including Fastjet3 for jet clustering [100].

We identify lepton candidates by requiring $p_T > 15$ GeV and $|\eta| < 2.5$. The anti-k_T algorithm is employed to reconstruct jets with radius parameter $R = 0.4$ [101], and jets are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. We assume an average b-tagging efficiency of 70% for real b-jets, with misidentification efficiencies of 10%, 4% and 0.2% for c-jets, -jets and jets initiated by light quarks or gluons respectively. We use medium hadronic identification criteria with efficiency of about 55% [102]. To suppress multi-jet backgrounds, we also require that jets separated by $\Delta R < 0.2$ from -tagged jets are removed.

According to the signal topology, we consider a final state with more than six jets including exactly two tau-tagged jets, one or two b-tagged jets, with missing transverse momentum $E_T^{\text{miss}} > 20$ GeV. Events with electrons or muons are vetoed. For event selection we require the E_T^{miss} centrality C_{miss} to be greater than zero [103]:

$$C_{\mathrm{miss}} = \frac{x+y}{\sqrt{x^2+y^2}}, \quad x = \sin(\phi_{\mathrm{miss}} - \phi_{\tau_1})\sin(\phi_{\tau_2} - \phi_{\tau_1}), \quad y = \sin(\phi_{\mathrm{miss}} - \phi_{\tau_2})\sin(\phi_{\tau_1} - \phi_{\tau_2})$$

where ϕ_{miss} is the azimuthal angle of E_T^{miss} and $\phi_{\tau_1,2}$ are the azimuthal angles of the two tau-tagged jets in the transverse plane.

To suppress backgrounds, we reconstruct the kinematics of the top quarks from the corresponding decay particles. First, because of neutrinos in hadronic decays, we use the collinear approximation technique to determine the 4-momenta of neutrinos [104], based on two assumptions: neutrinos from each are collinear with the corresponding visible decay products, and E_T^{miss} is only due to neutrinos. For our signal events, there is no other E_T^{miss} contribution and the leptons come from the cascade decay of the top quark which can be boosted depending on m_A. The invisible momentum of neutrinos in each decay is determined by

$$E_T^{\mathrm{miss}} \cos\phi_{\mathrm{miss}} = p^1_{\mathrm{mis}} \sin\theta^1_{\mathrm{vis}} \cos\phi^1_{\mathrm{vis}} + p^2_{\mathrm{mis}} \sin\theta^2_{\mathrm{vis}} \cos\phi^2_{\mathrm{vis}},$$

$$E_T^{\mathrm{miss}} \sin\phi_{\mathrm{miss}} = p^1_{\mathrm{mis}} \sin\theta^1_{\mathrm{vis}} \sin\phi^1_{\mathrm{vis}} + p^2_{\mathrm{mis}} \sin\theta^2_{\mathrm{vis}} \sin\phi^2_{\mathrm{vis}}.$$

where ϕ_{miss} is the azimuthal angle of E_T^{miss}, $\theta^{1,2}_{\mathrm{vis}}$ and $\phi^{1,2}_{\mathrm{vis}}$ are the polar and azimuthal angles of the jets, and p^1_{mis} and p^2_{mis} are the invisible momenta from decays. Then one can obtain the invariant mass of the two leptons $M_{\tau\tau}$ and compare with the mass of the pseudoscalar A. In the left panel of Fig. 3 [Figure 3: see original paper], we show example distributions of $M_{\tau\tau}$ for signal events with $M_A = 40$ GeV, 90 GeV and 140 GeV. This technique is more effective for small m_A.

Since the mass of the pseudoscalar A is unknown, we use the reconstructed mass of the top quark $m_{jc\tau\tau}$ instead of $M_{\tau\tau}$. Together with reconstructed masses from the SM top quark decay and the W boson, $m_{jbj_1j_2}$ and $m_{j_1j_2}$, we define a χ^2 function as

$$\chi^2 = \frac{(m_{jc\tau\tau} - m_t^{\mathrm{FCNC}})^2}{\sigma^2_{\mathrm{FCNC}}} + \frac{(m_{jbj_1j_2} - m_t^{\mathrm{SM}})^2}{\sigma^2_{\mathrm{SM}}} + \frac{(m_{j_1j_2} - m_W)^2}{\sigma^2_W}$$

where $m_t^{\mathrm{FCNC}} = 153$ GeV, $m_t^{\mathrm{SM}} = 173$ GeV, $\sigma_{\mathrm{FCNC}} = 20$ GeV, $\sigma_{\mathrm{SM}} = 20$ GeV, $m_W = 82$ GeV and $\sigma_W = 15$ GeV taken from [103, 105]. As we keep events containing two b-tagged jets where one is misidentified as the charm quark from $t \to Ac$, the assignment of each jet to the reconstructed masses depends on the number of b-tagged jets. For events with two b-tagged jets, any b-tagged jet can be assigned to j_c and j_b, while j_1 and j_2 correspond to the leading two light-flavor jets. For events with one b-tagged jet, the b-tagged jet is taken as j_b, j_c is chosen from the leading three light-flavor jets, and the other two jets in the leading three act as j_1, j_2. From all combinations, the one with minimum $\chi^2_{\min}$ is chosen, and we require $\chi^2_{\min} < 6$ according to the distributions of $\chi^2_{\min}$ for signal and background events shown in Fig. 3.

After imposing these selection conditions, the cross section of $t\bar{t}$ at the 13 TeV LHC is reduced to 61.3 fb, while $Z + b\bar{b}/c\bar{c}$ and tZ are reduced to 0.12 fb and 0.03 fb respectively. We calculate the signal significance with the simplified definition

$$\mathcal{S} = \frac{n_s}{\sqrt{n_b + (\epsilon n_b)^2}}$$

where n_s and n_b are the expected numbers of signal and background events, and ϵ is the relative systematic uncertainty which we conservatively take as 20% and 10% for data sets of 30 fb ^{1} and 100 fb ^{1} at the 13 TeV LHC respectively. In Fig. 4 [Figure 4: see original paper] we show the results in the plane of m_A and Br$(t \to Ac)$. All samples in Fig. 4 satisfy the relevant constraints and can simultaneously explain the muon g-2 and $R(D^{(*)})$ excesses. Depending on m_A, the branching ratio of $t \to Ac$ is required to be above 1% and below 16%. The 2 upper limits from a data set of 30 fb ^{1} at the 13 TeV LHC can exclude almost all samples, with only a few surviving when m_A approaches 150 GeV or 20 GeV. However, the 2 upper limits from a data set of 100 fb ^{1} at 13 TeV LHC can exclude all samples.

V. Conclusion

In the framework of a two-Higgs-doublet model with top quark FCNC couplings, we examined the excesses of $R(D^{(*)})$ and muon g-2 by imposing relevant theoretical and experimental constraints from precision electroweak data, B-meson decays, decays, and observables from top quark and Higgs searches. In this model the coupling κ_ℓ can simultaneously affect $R(D^{(*)})$, muon g-2 and lepton universality from decays, and thus these three observables have a strong correlation.

We found that the $R(D^{(*)})$ and muon g-2 excesses can be simultaneously explained in the parameter space allowed by the relevant constraints. In such a parameter space, the pseudoscalar mass is between 20 GeV and 150 GeV so that it can be produced from the top quark FCNC decay $t \to Ac$ and then dominantly decays into $\tau^+\tau^-$. We performed a detailed simulation on the signal $pp \to WbAc \to jjbc\tau^+\tau^-$ and the corresponding backgrounds, and found that the 2 upper limits from a data set of 30 (100) fb ^{1} at the 13 TeV LHC can mostly (totally) exclude such a parameter space.

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