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Constraints on the masses of fourth generation quarks

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We study the one-loop contribution of the down-type quark of the standard model-like fourth generation (b') on the top quark electric dipole moment. Using the known limits on the top quark electric dipole moments, we place limits on the b' mass. Then, from the estimated ratio for the masses of the fourth generation of quarks from other studies and the achieved bound from top quark electric dipole moments on $m_{b'}$, we obtain a limit for the up-type quark of fourth generation (t') mass.

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I. INTRODUCTION

The standard model (SM) of particle physics is in very good agreement with present experimental data. Nonetheless, it is believed to leave many questions unanswered, and this belief has resulted in numerous theoretical and experimental attempts to discover a more fundamental underlying theory. Various types of experiments may expose the existence of physics beyond the SM, including the search for direct production of exotic particles at high energy colliders. A complementary approach in hunting for new physics is to examine its indirect effects in higher order processes.

As mentioned, the SM with three generations of quarks and leptons is in excellent agreement with the current experimental data. However, the SM does not explain the fermion mass hierarchy and it also is not able to explain why there are precisely three families. Several models have been proposed to solve the shortcomings of the SM through the introduction of new generations of quarks and leptons. Some models beyond the SM, such as grand unified theories (GUT), predict the new generations of quarks or leptons. The strong *CP* problem is solvable by requiring additional quarks. The weak *CP* violation may be accommodated through the Kobayashi-Maskawa mechanism, while the strong *CP* issue can be solved in a model with two additional flavors of quarks by spontaneous *CP* violation. Another motivation for the fourth generation is that in the literature it has been shown that a nonsupersymmetric model with four generations can have successful unification of gauge couplings at the unification scale. In the scenarios of gauge mediated supersymmetry breaking, additional generations of quarks and leptons arise automatically. More details can be found in [1–3], and references therein. It should be mentioned that the fourth generation of quarks and leptons can be a chiral doublet (SM-like fermion generation) or nonchiral doublet (also known as vectorlike). For example, in grand unified theories all types of additional fermions are possible, while in models which attempt to solve the strong *CP* problem, only nonchiral doublets of quarks are considered. There have already been many indirect and direct studies on the fourth generation of quarks. For example, the effects of a vectorlike fourth generation of quarks on the width of the Z boson and forward-backward asymmetry has been studied in [4]. Bounds on the mixing of the SM down-type quarks with new vectorlike singlet quarks were derived in [5]. In [6], the pair production of t' quarks at the Tevatron has been studied. It has been shown that the production cross section for $t'\bar{t}'$ at hadron colliders could be considerably higher than the QCD prediction if a gluon prime (a massive color octet vector boson) is present in the theory. In [7], using a data sample corresponding to 2.8 fb^{-1} of integrated luminosity recorded by the CDF experiment in proton antiproton collisions, a limit was set on the production cross section of $t'\bar{t}'$. From this limit a lower limit of 311 GeV/c^2 was derived for a new heavy toplike quark.

Since the top quark is far more massive than other SM fermions, its interactions may be quite sensitive to new physics originating at higher scales [8–10]. Hence, the study of interactions of the fourth generation of quarks with top quarks might give interesting results about the fourth generation.

In this article, our aim is to constrain the mass of the down-type quark of the fourth generation (b') using the one-loop contribution of b' in the electric dipole moment (EDM) of the top quark. In the analysis, we will use the estimated bounds on the EDM's of the top quark to constrain the mass of b'. In [2], it has been shown that for the chiral doublet of (t', b') the ratio of masses is 1.1 or less ($m_{t'}/m_{b'} \leq 1.1$). Using this value, the bound on $m_{t'}$ is also estimated.

II. THE CONTRIBUTION OF b' IN THE TOP QUARK EDM

In this work, we examine the properties of the masses of the fourth generation of quarks. Similar to the interaction

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of Wtb, a general effective Lagrangian for the interaction of Wtb' can be written in the following form:

$$\mathcal{L}_{Wtb'} = \frac{g}{\sqrt{2}}\bar{t}\gamma^{\mu}(g_L P_L + g_R P_R)b' W_{\mu} \tag{1}$$

where $P_L(P_R)$ are the left-handed (right-handed) projection operators. The g_L, g_R coefficients are complex, in general. This signifies the CP violating effects. These coefficients include the mixing factor between the fourth family and the top quark ($V_{tb'}$) in the generalized Cabibbo-Kobayashi-Maskawa matrix. For the interaction of Wtb, these factors have been estimated from different studies. For example, from the B decay processes the limits on g_L, g_R are $\mathrm{Re}(g_R) \leq 4\times 10^{-3}$, $\mathrm{Im}(g_R) \leq 10^{-3}$, and $\mathrm{Im}(g_L) \leq 3\times 10^{-2}$ [11–13].

The Lagrangian introduced in Eq. (1) induces an electric dipole moment for the top quark at the one-loop level via the Feynman diagrams shown in Fig. 1. After calculation of the one-loop corrections to the vertex of $\bar{t}t\gamma$ shown in Fig. 1, we find some terms with different structures. The coefficient of the structure of $\sigma_{\mu\nu}\gamma_5 q^{\nu}$ gives the top quark electric dipole moment where q^{ν} is the four-momentum of the photon [14]. It should be mentioned that this structure arises via radiative corrections and does not exist at tree level. After all calculations, the top EDM is found as follows:

$$\mathrm{Re}\,(d_{\mathrm{top}}) = -\frac{e}{m_W}\frac{3\alpha}{32\pi}\frac{m_{b'}}{m_W}\bigg(V_1(x_{b'}, x_W) + \frac{1}{3}V_2(x_{b'}, x_W)\bigg)\mathrm{Im}(g_L g_R^*), \tag{2}$$

where $x_a = m_a^2/m_t^2$. $V_{1,2}$ are the functions that stand for the contribution of the Feynman diagram where the photon emerges from the W boson and the b' quark line, respectively. They have the following forms:

$$\begin{aligned} V_1 &= -(4x_W - x_{b'} + 1)f(x_{b'}, x_W) - (x_{b'}^2 + 4x_W^2 \\ &\quad - 5x_{b'}x_W - 3x_W - 2x_{b'} + 1)g(x_{b'}, x_W), \\ V_2 &= -(4x_W - x_{b'} + 1)f(x_W, x_{b'}) + (x_{b'}^2 + 4x_W^2 \\ &\quad - 5x_{b'}x_W - 3x_W - 2x_{b'} + 1)g(x_W, x_{b'}), \end{aligned} \tag{3}$$

where the functions of f and g are as follows:

$$\begin{aligned} f(a,b) &= \bigg(\frac{1+a-b}{2}\bigg)\log\bigg(\frac{b}{a}\bigg) + \sqrt{(1-a-b)^2 - 4ab} \\ &\quad \times \mathrm{arcsech}\bigg(\frac{2\sqrt{ab}}{a+b-1}\bigg) + 2, \\ g(a,b) &= -\frac{1}{2}\log\bigg(\frac{b}{a}\bigg) - \frac{1+a-b}{\sqrt{(1-a-b)^2 - 4ab}} \\ &\quad \times \mathrm{arcsech}\bigg(\frac{2\sqrt{ab}}{a+b-1}\bigg). \end{aligned}$$

III. THE LIMITS ON $m_{t'}$, $m_{b'}$

In [15], the authors have predicted an upper bound for the top quark EDM. In that paper, a source of CP violation mediated by the $WW\gamma$ vertex has been analyzed using the effective Lagrangian technique and its implications on the CP-odd electromagnetic properties of the standard model particles have been studied. The contribution of the $WW\gamma$ vertex to the EDM of charged leptons and quarks has been calculated. Their estimate for the top quark EDM is 1.6×10^{-22} e.cm. In Eq. (2), a reasonable assumption is to set $\mathrm{Im}(g_L g_R^*)$ to a value around 10^{-3} [16]. Under this assumption and by using the bound of the top EDM, the lower limit of 268 $\mathrm{GeV/c^2}$ is achieved for the mass of the down-type quark in the fourth family of quarks. Figure 2 presents the dependence of the top quark electric dipole moment on $m_{b'}$ for $\mathrm{Im}(g_L g_R^*) = 10^{-3}$.

Obviously, this lower limit depends on the quantity of $\mathrm{Im}(g_L g_R^*)$. However, it is not highly dependent on $\mathrm{Im}(g_L g_R^*)$. When $\mathrm{Im}(g_L g_R^*)$ changes from 10^{-3} to 1, the lower limit on $m_{b'}$ varies only up to 3%. One of the recent estimated lower bounds on $m_{b'}$ is 199 $\mathrm{GeV/c^2}$ [17]. Hence, the constraint obtained in the current study is compatible

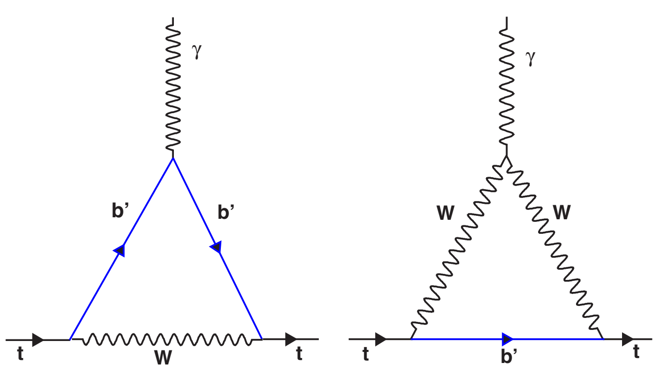

FIG. 1 (color online). Feynman diagrams contributing to the on-shell $\bar{t}t\gamma$ vertex.

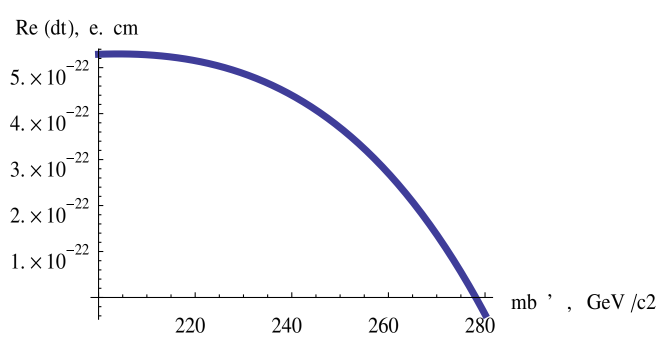

FIG. 2 (color online). The real part of the top electric dipole moment versus $m_{b'}$ when $\mathrm{Im}(g_L g_R^*) = 10^{-3}$.

with other studies and the lower bound on $m_{b'}$ is slightly increased.

For the chiral doublet of (t', b'), the electroweak precision measurements predict that $\frac{m_{t'}}{m_{b'}} \leq 1.1$. Combining this with the bound obtained from the top EDM on the mass of b' immediately gives the lower limit of 294.8 $\mathrm{GeV/c^2}$ on the mass of t'. This value also confirms the achieved constraint from other studies (311 $\mathrm{GeV/c^2}$) which was mentioned in the Introduction [7].

IV. CONCLUSION

In this paper, we tried to extract a limit on the mass of the down-type quark of the SM-like fourth generation (b') by employing a general Lagrangian for the interaction of $W - t - b'$ with complex left-handed and right-handed couplings. This general Lagrangian produces an electric dipole moment for the top quark at one-loop level which contains $m_{b'}$. From the estimated upper limit on the top quark EDM, a lower limit of 268 $\mathrm{GeV/c^2}$ was predicted for the mass of b'. From electroweak precision data, in other studies it has been shown that for the chiral doublet of (t', b') the ratio of masses is 1.1 or less. It turns out that the lower bound on the mass of t' is 294.8 $\mathrm{GeV/c^2}$. These results are regular and compatible with those obtained from other studies, and the bound on $m_{b'}$ is slightly increased.

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