Heavy Charged Gauge Bosons with General CP Violating Couplings

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Abstract

Heavy gauge bosons such as $W'$ are expected to exist in many extensions of the Standard Model. In this paper, it is shown that the most general Lagrangian for the interaction of $W'$ with top and bottom quarks which consists of V-A and V+A structure with in general complex couplings produces an Electric Dipole Moment (EDM) for the top quark at one loop level. We predict the allowed ranges for the mass and couplings of $W'$ by using the upper limit on the top quark EDM.

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1 Introduction

The Standard Model (SM) of the particles has been found to be in a good agreement with the present experimental data in many of its aspects. 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.

There are many different models which predicts the existence of new charged gauge bosons, $W'$. These scenarios include the Little Higgs model [1] [2], Grand Unified Theories [3], Universal Extra Dimension [4], Left-Right Symmetric Model [5] and some other models. One must note that the properties and interactions of $W'$ depend on the model. One of the simple extension of the SM is the Left-Right Symmetric Model. It is based on the $SU(2)_R \times SU(2)_L \times U(1)$ gauge group. The new $SU(2)_R$ symmetry leads to additional $W', Z'$ gauge bosons. For a detailed discussion of Left-Right Symmetric Model see for example [5],[6],[7]. The Left-Right Symmetric Model is constructed by placing the fermion right-handed singlets into doublets regarding $SU(2)_R$. This requires to introduce right-handed neutrinos. One the interesting aspects of this model is that the parity is broken spontaneously which causes to different masses for the $SU(2)_R$ and $SU(2)_L$ gauge bosons.

Although such charged massive bosons have not been found yet experimentally but it is widely believed that the experiments at the LHC are able to probe them in the coming years [8], [9], [10]. At the LHC, for an integrated luminosity of 10 fb$^{-1}$, $W'$ bosons can be discovered or excluded up to a mass of 5 TeV/$c^2$, from an analysis of the muonic decay mode. This result belongs to the model which makes the assumptions that the new gauge boson $W'$ has the same couplings as the Standard Model $W$ boson. The capability of LHC to explore the helicity of $W'$ is discussed in [9]. There are already direct and
indirect searches for the new gauge bosons. There is a severe limit obtained from $K_0 - \bar{K}_0$ mixing: $M_{W'} \geq 2.5 \text{ TeV}/c^2$ [11]. The direct searches for $W'$ can be found for example in [12], [13], [14].

In the framework of the SM top quark is the only quark which has a mass in the same order as the electroweak symmetry breaking scale, $v \sim 246 \text{ GeV}$, whereas all other observed fermions have masses which are a tiny fraction of this scale. This huge mass might be a hint that top quark plays an essential role in search for new physics originating from physics at higher scale [15]. Hence, the study of interaction of top quark with $W'$ might give useful information about $W'$. For example, the interference between $W'$ and $W$ in the production of single top quarks is important and could be useful in search for $W'$ which has been discussed in [10].

The aim of this article is to constrain the mass of $W'$ by considering its contribution to the electric dipole moment (EDM) of the top quark. In [16], the authors have estimated an upper limit of $10^{-20} \text{ e.cm.}$ on the top quark EDM from the experimental bound on the neutron EDM. Combination this limit with the contribution of the $W'$ to top EDM leads to valuable information on $M_{W'}$ and its couplings.

## 2 The Contribution of the $W'$ to the Top Quark EDM

Similar to the interaction of $Wtb$, the most general lowest order effective Lagrangian for the interaction of $W'$ with top and bottom quarks in the SM can be written in the following form [12], [13]:

\[
\mathcal{L} = \frac{g}{\sqrt{2}} \bar{t} \gamma^\mu (a_L P_L + a_R P_R) b W'_\mu
\]

where $P_L(P_R)$ are the left-handed (right-handed) projection operators. The $a_L, a_R$ coefficients are complex in general. This signifies the CP violating effects. In this notation, $a_L = 1$ and $a_R = 0$ for a so-called SM-like $W'$.

It is worth mentioning that in Eq. 1 if we replace $W'$ gauge boson by the Standard Model $W$ gauge boson, from the B decay processes the limits on $a_L, a_R$ are: $Re(a_R) \leq 4 \times 10^{-3}$,
Figure 1: Feynman diagrams contributing to the on shell $t\bar{t}\gamma$.

$\text{Im}(a_R) \leq 10^{-3}$ and $\text{Im}(a_L) \leq 3 \times 10^{-2}$ [17],[18],[19].

The introduced Lagrangian 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. One should note that all the particles are taken on-shell. After calculation of the one loop corrections to the vertex of $t\bar{t}\gamma$ shown in Fig.1, we find some terms with different structures. The coefficient of the structure of $\sigma^{\mu\nu}q^\nu$ gives the top quark electric dipole moment where $q^\nu$ is the four momentum of photon [20],[21]. It should be noted that this structure arises via radiative corrections and does not exist at tree level.

After all calculation, the top EDM is found as:

$$d_t = -\frac{e}{m_{W'}} \frac{3\alpha}{32\pi} \frac{m_b}{m_{W'}} \left( V_1(x_b, x_{W'}) + \frac{1}{3} V_2(x_b, x_{W'}) \right) \text{Im}(a_L a_R^*) ,$$  \hspace{1cm} (2)

where $x_a = m_a^2/m_t^2$. The $V_{1,2}$ are the functions 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:

$$V_1 = -(4x_{W'} - x_b + 1) f(x_b, x_{W'}) - (x_b^2 + 4x_{W'}^2 - 5x_bx_{W'} - 3x_{W'} - 2x_b + 1) g(x_b, x_{W'})$$

$$V_2 = -(4x_{W'} - x_b + 1) f(x_{W'}, x_b) + (x_b^2 + 4x_{W'}^2 - 5x_bx_{W'} - 3x_{W'} - 2x_b + 1) g(x_{W'}, x_b) \hspace{1cm} (3)$$
where the functions of $f$ and $g$ are as follows:

$$f(a, b) = \left(1 + a - b\right) \log \left(\frac{b}{a}\right) + \sqrt{(1 - a - b)^2 - 4ab} \times \text{ArcSech} \left(\frac{2\sqrt{ab}}{a + b - 1}\right) + 2$$

$$g(a, b) = -\frac{1}{2} \log \left(\frac{b}{a}\right) - \frac{1 + a - b}{\sqrt{(1 - a - b)^2 - 4ab}} \times \text{ArcSech} \left(\frac{2\sqrt{ab}}{a + b - 1}\right)$$

3 Results

In [16], the authors have predicted an upper bound for the top quark EDM using the experimental limit on the neutron EDM. Their estimate for the top quark EDM is $10^{-20}$ e.cm. In Eq.2, if we assume $\text{Im}(a_La^*_R) \sim 10^{-1}$ and by using the bound of the top EDM, the upper limit of 190 GeV/c$^2$ is achieved for the mass of $W'$ and if $\text{Im}(a_La^*_R) \sim 10^{-3}$ we have $M_{W'} \leq 1470$ GeV/c$^2$. The shaded region in Fig.2 is the excluded region in the plane of $M_{W'}$ and $\text{Im}(a_La^*_R)$. Fig.2 obviously presents the the strong dependence of the upper bound of the mass of $W'$ on the $\text{Im}(a_La^*_R)$.

The predicted lower limit for the $W'$ mass from other studies ($K_0 - \bar{K}_0$ mixing) which mentioned in the introduction can be used to estimate the allowed range for $\text{Im}(a_La^*_R)$. In Eq.2 if we put $d_t < 10^{-20}$ and $M_{W'} \geq 2.5$ TeV/c$^2$ the upper bound of $3.18 \times 10^{-4}$ is derived for $\text{Im}(a_La^*_R)$.

In [13] a search has been performed for $W'$ bosons which decay to $t + b$, using 0.9 fb$^{-1}$ of data recorded by D0 detector in proton anti-proton collisions. A 95% C.L. upper limit on $\sigma(p\bar{p} \rightarrow W') \times BR(W' \rightarrow tb)$ has been set. This excludes the gauge couplings ($a_L, a_R$) above $\sim 0.7$ for $W'$ bosons with a mass of 600 GeV/c$^2$. From the current analysis, for the $W'$ bosons with a mass of 600 GeV/c$^2$, $\text{Im}(a_La^*_R)$ above $\sim 0.007$ is excluded.

4 Conclusion

In this paper we focus our attention on the contribution of the $W'$ gauge boson to the electric dipole moment (EDM) of the top quark. The most general Lagrangian for the
interaction of $W'$ with top and bottom quarks which consists of V-A and V+A structure with in general complex couplings ($a_L, a_R$) produces an EDM for the top quark at level of one loop. The top EDM is proportional to $\text{Im}(a_L a_R^*)$. Using the upper limit on the top EDM, we exclude the region shown in Fig. 2 in the plane of $M_{W'}$ and $\text{Im}(a_L a_R^*)$. For example, for $\text{Im}(a_L a_R^*) \sim 0.001$, the $W'$ boson mass above 1470 GeV/$c^2$ is excluded. The upper bound of $3.18 \times 10^{-4}$ is derived for $\text{Im}(a_L a_R^*)$ by considering the lower limit on the $M_{W'}$ from $K_0 - \bar{K}_0$ mixing studies.

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