Polarization of top quark in vector-like quark decay

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Abstract

Vector-like quarks (VLQs) are attractive extensions to the Standard Model. They mix with the SM quarks and can lead to rich phenomenology. Determination of VLQ’s interaction structure with the SM is then an important issue, which can be inferred from the decay products of VLQs, such as top quark. We calculate the spin-analyzing powers for charged leptons from top quark in VLQ decay for various VLQ scenarios. We find that the top polarization effect will be helpful to distinguish different natures of the VLQ couplings with the SM.

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I. INTRODUCTION

Extra vector-like quarks (VLQ) are usually expected to be present in many beyond-SM models, such as little Higgs models, composite Higgs models and some extra-dimension models. For example, models are proposed to explain the lightness of the observed Higgs by assuming that it is a pseudo Goldstone boson and VLQs generally appear in these theories \cite{1-3}. In some supersymmetric models, the introduction of vector-like quarks can relax the restrictions imposed on the MSSM by the 125 GeV Higgs \cite{4-6}. As a popular extension to the SM, VLQs in a variety of models have been widely studied \cite{7-19}.

These new quarks are triplets under the $SU(3)_C$ gauge group just like the SM quarks, but have the same electroweak quantum numbers for both left- and right-handed components. That is, VLQs of different chiralities transform in the same representation of $SU(2)$. In a model-independent way, vector-like quarks can generally be introduced as $T$, $B$, $X$ and $Y$: $T$ and $B$ are quarks with electric charges of $+2/3$ and $-1/3$ respectively, while $X$ and $Y$ are ones of charge $+5/3$ and $-4/3$ respectively, which appear as different $SU(2)$ multiplets \cite{20, 21}. VLQs’ interaction in different multiplets have been studied systematically in \cite{22}. They are generally considered to mix with the SM quarks and thus can be involved in flavor-changing neutral currents (FCNC) at tree level \cite{23, 24}, which receives strong constraints from experiments.

At the LHC and other colliders, extra new quarks have long been searched for. The chirally coupled new quarks have already been excluded by recent searches and tests \cite{25, 26}, whereas the vector-like quarks survived. At a proton-proton collider, VLQs can be produced singly or in pairs and then decay to a SM quark and a gauge boson or a Higgs boson \cite{22}. Recent searches for the $+2/3$ charged $T$ quark and $-4/3$ charged $Y$ quark from 13 TeV pp collision data give a lower limit for their masses at 1.3 TeV at 95\%C.L. \cite{27}, while for the $-1/3$ charged $B$ quark, current analysis pushes the lower limit of $B$ mass up to 1.5 TeV from its single production at pp collision \cite{28,29}. As for the $5/3$ charged $X$ quark, pair-production searches based on 13 TeV pp collision set the mass limit at 1.02 TeV \cite{28, 30}. It should be noted that the VLQs once produced will decay into the SM quarks, which are generally polarized due to VLQs’ parity-violating couplings with the gauge bosons. Different from other SM quarks, top quarks decay before hadronization and hence the top polarization can be measured by the kinematics of its decay products. As a result, the final states from top
decay can in turn provide information about the parent VLQs’ gauge interaction, like the cases that have been studied in top decay or top-squark decay [31–48]. In this paper, we study, in a model-independent way, the polarization effects in the decay of VLQs in two scenarios:

\[
\text{Singlets : } T_{L,R}, \ B_{L,R}, \quad \text{Doublets : } (XT)_{L,R}, \ (TB)_{L,R}, \ (BY)_{L,R}.
\]

These polarization effects can be used to differentiate the \( SU(2) \) nature of these new quarks if ever discovered.

This paper is organized as follows. In section II we introduce the VLQ-related interactions in different scenarios mentioned above, which determine the decay modes of VLQs. Then we calculate the spin analyzing power of the final charged leptons from VLQ decays and analyze the polarization effects in different scenarios in section III. Section IV is our conclusion.

II. RELEVANT INTERACTIONS IN DIFFERENT VLQ SCENARIOS

As stated above, the vector-like quarks are studied in this paper in two different multiplets: singlet and doublet. We give in this section the relevant Lagrangian in terms of mass eigenstates of quarks with gauge bosons and the Higgs boson.

A. Singlets: \( T \) singlet and \( B \) singlet

1. \( T \) singlet

In this section and the rest of the paper, Greek indices \( \alpha, \beta = 1, 2, 3, 4 \) run over all quarks including the new vector-like quarks, while Latin indices \( i, j = 1, 2, 3 \) over three generations of the SM quarks. An introduction of a singlet VLQ \( T \) leads to the \( W-T \), \( Z-T \) and Higgs-\( T \) couplings as follows,

\[
\mathcal{L}_{W-\text{quark}} = -\frac{g}{\sqrt{2}} \bar{u}_{L \alpha} \gamma^\mu V_{\alpha i} d_{L i} W^+_{\mu} + \text{H.c.},
\]

\[
\mathcal{L}_{Z-\text{quark}} = -\frac{g}{2 \cos \theta_W} \left( \bar{u}_{L \alpha} \gamma^\mu X_{\alpha \beta} u_{L \beta} - 2 s_W^2 J_{\text{EM}}^\mu \right) Z_\mu,
\]

\[
\mathcal{L}_{H-\text{quark}} = -\frac{g}{2 m_W} \left( m_{u,\beta} \bar{u}_{L \alpha} X_{\alpha \beta} u_{R \beta} + m_{u,\alpha} \bar{u}_{R \alpha} X_{\alpha \beta} u_{L \beta} \right) H,
\]
in which $J_{\text{EM}}^\mu$ is the electromagnetic current and sums over all quarks. The CKM quark-mixing matrix $V$ is generalized to dimension $4 \times 3$ to include the new vector-like ones and $X = VV^\dagger$ is a $4 \times 4$ Hermitian matrix. $m_{u,\alpha}$ is mass of the up-type quark, $\theta_W$ is the Weinberg angle. In this $T$ singlet scenario, interactions given above lead to decays of $T$ quark into $W^+b$, $Zt$ and $Ht$. From (2)-(4), we can write explicitly the terms determining these decay processes

$$
\mathcal{L}_{T \to Wb} = -\frac{g}{\sqrt{2}} \bar{T} \gamma^\mu V_{Tb} P_L b W_\mu^+ + \text{H.c.}, \tag{5}
$$

$$
\mathcal{L}_{T \to Zt} = -\frac{g}{2 \cos \theta_W} \bar{t} \gamma^\mu X_{tt} P_L T Z_\mu + \text{H.c.}, \tag{6}
$$

$$
\mathcal{L}_{T \to Ht} = -\frac{g X_{tt}}{2m_W} \bar{t} (m_T P_R + m_T P_L) TH + \text{H.c.}. \tag{7}
$$

2. $B$ singlet

The coupling terms in the $B$ singlet scenario are similar to ones in the above $T$ singlet scenario.

$$
\mathcal{L}_{W-\text{quark}} = -\frac{g}{\sqrt{2}} \bar{u}_L j_{\mu} V_{j\alpha} d_{L\alpha} W_\mu^+ + \text{H.c.}, \tag{8}
$$

$$
\mathcal{L}_{Z-\text{quark}} = \frac{g}{2 \cos \theta_W} (\bar{d}_L \gamma^\mu X_{\alpha\beta} d_{L\beta} + 2 s_W J_{\text{EM}}^\mu) Z_\mu + \text{H.c.}, \tag{9}
$$

$$
\mathcal{L}_{H-\text{quark}} = -\frac{g}{2m_W} (m_{d,\beta} \bar{d}_L X_{\alpha\beta} d_{R\beta} + m_{d,\alpha} \bar{d}_R X_{\alpha\beta} d_{L\beta}) H + \text{H.c.}. \tag{10}
$$

In this scenario the CKM matrix $V$ is a $3 \times 4$ matrix and $X = V^\dagger V$. $m_{d,\alpha}$ is mass of the down-type quark. Interactions in this scenario lead to decays of $B$ quark into $W^-t$, $Zb$ and $Hb$, the Lagrangian of which can be specifically expressed as follows

$$
\mathcal{L}_{B \to Wt} = -\frac{g}{\sqrt{2}} \bar{t} \gamma^\mu V_{tb} P_L b W_\mu^+ + \text{H.c.}, \tag{11}
$$

$$
\mathcal{L}_{B \to Zb} = \frac{g}{2 \cos \theta_W} \bar{b} \gamma^\mu X_{bb} P_L b Z_\mu + \text{H.c.}, \tag{12}
$$

$$
\mathcal{L}_{B \to Hb} = -\frac{g X_{bb}}{2m_W} \bar{b} (m_B P_R + m_b P_L) BH + \text{H.c.}. \tag{13}
$$
B. Doublets: \((TB), (XT)\) and \((YB)\) doublet

1. \((TB)\) doublet

In the \((TB)\) doublet scenario, the relevant couplings written in mass eigenstates are

\[
\mathcal{L}_{W-\text{quark}} = -\frac{g}{\sqrt{2}} \left( \bar{u}_{Li} \gamma^\mu V_{Li,j} d_{Lj} + \bar{u}_{Ra} \gamma^\mu V_{R,a \beta} d_{R\beta} + \bar{T}_L \gamma^\mu B_L \right) W_{\mu}^+ + \text{H.c.},
\]

\[
\mathcal{L}_{Z-\text{quark}} = -\frac{g}{2\cos \theta_W} \left( \bar{u}_{La} \gamma^\mu u_{La} - \bar{d}_{La} \gamma^\mu d_{La} + \bar{u}_{Ra} \gamma^\mu X_{u,\alpha \beta} u_{R\beta} - \bar{d}_{Ra} \gamma^\mu X_{d,\alpha \beta} d_{R\beta} - 2 s_W^2 J_{\text{EM}}^\mu \right) Z_{\mu},
\]

\[
\mathcal{L}_{H-\text{quark}} = -\frac{g}{2m_W} \left[ m_{u,\alpha} \bar{u}_{La} (\delta_{\alpha \beta} - X_{u,\alpha \beta}) u_{R\beta} + m_{u,\beta} \bar{u}_{Ra} (\delta_{\alpha \beta} - X_{u,\alpha \beta}) u_{L\beta} + m_{d,\alpha} \bar{d}_{La} (\delta_{\alpha \beta} - X_{d,\alpha \beta}) d_{R\beta} + m_{d,\beta} \bar{d}_{Ra} (\delta_{\alpha \beta} - X_{d,\alpha \beta}) d_{L\beta} \right] H,
\]

where \(V_L\) is the \(3 \times 3\) CKM quark-mixing matrix and \(V_R\) is a \(4 \times 4\) generalized mixing matrix. \(X_u = V_R V_R^\dagger\) and \(X_d = V_R^\dagger V_R\) are Hermitian and non-diagonal leading to FCNC. The above interactions lead to \(T\) decays into \(W^+ b\), \(Zt\) and \(Ht\), while \(B\) decays into \(W^- t\), \(Zb\) and \(Hb\). These interactions can be expressed specifically

\[
\mathcal{L}_{T\rightarrow Wb,B\rightarrow Wt} = -\frac{g}{\sqrt{2}} \left( \bar{t} \gamma^\mu V_{R,b} P_R B + \bar{T} \gamma^\mu V_{R,t} P_T b \right) W_{\mu}^+ + \text{H.c.},
\]

\[
\mathcal{L}_{T\rightarrow Zb,Zt\rightarrow Zt} = \frac{g}{2\cos \theta_W} \left( \bar{b} \gamma^\mu X_{d,b} P_R B - \bar{t} \gamma^\mu X_{u,t} P_T T \right) Z_{\mu},
\]

\[
\mathcal{L}_{T\rightarrow Ht,B\rightarrow Hb} = -\frac{g}{2m_W} \left[ iX_{u,t} \left( m_t P_R + m_T P_L \right) T + \bar{b} X_{d,b} \left( m_b P_R + m_B P_L \right) B \right] H.
\]

2. \((XT)\) doublet

In this case, \(+5/3\) charged quark \(X\) and \(+2/3\) charged quark \(T\) form a \(SU(2)\) doublet with a hypercharge \(7/6\). The relevant terms of Lagrangian are

\[
\mathcal{L}_{W-\text{quark}} = -\frac{g}{\sqrt{2}} \left( \bar{u}_{Li} \gamma^\mu V_{Li,j} d_{Lj} + \bar{X}_L \gamma^\mu T_L + \bar{X}_R \gamma^\mu V_{R,X,\beta} u_{R\beta} \right) W_{\mu}^+ + \text{H.c.},
\]

\[
\mathcal{L}_{Z-\text{quark}} = -\frac{g}{2\cos \theta_W} \left( \bar{u}_{Li} \gamma^\mu u_{Li} - \bar{X}_L \gamma^\mu X_{u,\alpha \beta} u_{R\beta} - \bar{X}_R \gamma^\mu T_L + \bar{X}_R \gamma^\mu X - 2 s_W^2 J_{\text{EM}}^\mu \right) Z_{\mu},
\]

\[
\mathcal{L}_{H-\text{quark}} = -\frac{g}{2m_W} \left[ m_{u,\alpha} \bar{u}_{La} (\delta_{\alpha \beta} - X_{u,\alpha \beta}) u_{R\beta} + m_{u,\beta} \bar{u}_{Ra} (\delta_{\alpha \beta} - X_{u,\alpha \beta}) u_{L\beta} \right] H,
\]

where \(V_R\) is a \(1 \times 4\) matrix and \(X = V_R^\dagger V_R\). In the \((XT)\) doublet scenario, \(T\) quark decays into \(Zt\) and \(Ht\), while \(X\) quark decays into \(W^+ t\), considering an almost degenerate mass.
spectrum \( m_X \sim m_T \). Coupling terms relevant to these processes are

\[
\mathcal{L}_{X \rightarrow W t} = - \frac{g}{\sqrt{2}} \bar{t} \gamma^\mu V_{R,Xt}^* P_R X W^-_\mu + \text{H.c.},
\]

\[
\mathcal{L}_{T \rightarrow Z t} = \frac{g X_{tT}}{2 \cos \theta_W} \bar{t} \gamma^\mu P_T Z_\mu,
\]

\[
\mathcal{L}_{T \rightarrow H t} = \frac{g X_{tT}}{2 m_W} \bar{t} (m_P + m_T P_L) T H .
\]

3. \((BY)\) doublet

Similarly extra \(-1/3\) charged quark \( B \) and \(-4/3\) charged quark \( Y \) can form a \( SU(2) \) doublet with a hypercharge \(-5/6\), we can write down in this case the relevant couplings

\[
\mathcal{L}_{W-\text{quark}} = - \frac{g}{\sqrt{2}} \left[ \bar{u}_L \gamma^\mu V_{L,ij} d_{Lj} + \bar{B}_L \gamma^\mu Y_L + \bar{d}_{Ra} \gamma^\mu V_{R,aY} Y_R \right] W^+_\mu + \text{H.c.},
\]

\[
\mathcal{L}_{Z-\text{quark}} = - \frac{g}{2 \cos \theta_W} \left[ - \bar{d}_{Lj} \gamma^\mu d_{Lj} + \bar{d}_{Ra} \gamma^\mu X_{\alpha\beta} d_{R\beta} + \bar{B}_L \gamma^\mu B_L - \bar{Y} \gamma^\mu Y - 2 s_W^2 J_{\text{EM}}^\mu \right] Z_\mu .
\]

\[
\mathcal{L}_{H-\text{quark}} = - \frac{g}{2 m_W} \left[ m_{d,\alpha} \bar{d}_{L\alpha} (\delta_{\alpha\beta} - X_{\alpha\beta}) d_{R\beta} + m_{d,\beta} \bar{d}_{R\alpha} (\delta_{\alpha\beta} - X_{\alpha\beta}) d_{L\beta} \right] H ,
\]

in which \( V_R \) is a \( 4 \times 1 \) matrix and \( X = V_R V_R^\dagger \). Allowed decays are \( Y \rightarrow W^- b \) and \( B \rightarrow Z b, H b \) considering an almost degenerate mass spectrum \( m_B \sim m_Y \). Coupling terms relevant to these processes are

\[
\mathcal{L}_{Y \rightarrow W b} = - \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{R,bY} P_R Y W^+_\mu + \text{H.c.},
\]

\[
\mathcal{L}_{B \rightarrow Z b} = - \frac{g X_{bB}}{2 \cos \theta_W} \bar{b} \gamma^\mu P_R Z_\mu,
\]

\[
\mathcal{L}_{B \rightarrow H b} = \frac{g X_{bB}}{2 m_W} \bar{b} (m_b P_R + m_B P_L) B H .
\]

III. TOP POLARIZATION IN VLQ DECAYS AND SPIN-ANALYZING POWER OF THE CHARGED LEPTON

As we have mentioned, top quarks from VLQ decays are polarized due to the parity-violating couplings and this polarization effect can be measured by the decay products of top quark due to its short lifetime. We calculate in different VLQ scenarios the spin-analyzing power for the final charged lepton in the decay chains of VLQ. The spin-analyzing power
is generally defined as follows: the angular distribution of a decay product \( f \) in the parent rest frame is given by,

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_f} = \frac{1}{2} (1 + \mathcal{P}_f \cos \theta_f),
\]

in which \( \theta_f \) is the angle between the momentum of particle \( f \) in the final state and the spin vector of the decaying particle in its rest frame, the coefficient \( \mathcal{P}_f \) is the spin analyzing power of final-state particle \( f \). In the following, we compute the angular distributions of the charged lepton from the decays of VLQs. An on-shell top quark narrow width approximation is assumed. Thus, we can have the spin-analyzing power \( P_{t}^{\text{VLQs}} \) for the decay chain of VLQs,

\[
P_{t}^{\text{VLQs}} = P_{t}^{\text{VLQs}} \cdot P_{l}^{t}
\]

Since the direction of the charged lepton momentum in the decay of \( t \to b l^+\nu \) is totally correlated with top quark polarization at leading order \cite{49}, \( P_{t}^{t} = 1 \) is used in our calculations.

**A. ** \( T \) singlet

In the \( T \) singlet scenario, we focus on the decay chains \( T \to Zt \to Z(b l^+\nu) \) and \( T \to Ht \to H(b l^+\nu) \). We first calculate the normalized differential decay width of \( T \) decay into \( Zt \)

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_t} = \frac{1}{2} \left[ 1 + \frac{\vec{p}(m_Z^2 + 2E_T E_Z - 2|\vec{p}|^2)}{2E_T E_Z^2 - 2E_Z|\vec{p}|^2 + m_Z^2 E_T} \cos \theta_t \right],
\]

where \( \theta_t \) is the angle between the momentum of top quark and the spin of \( T \) quark in the center-of-mass system. \( \vec{p} \) is the momentum of a final-state particle and \( E_{T/Z} \) the energy of \( T \) quark/Z in the C.M.S. which can be expressed simply using the parameter \( \lambda \)

\[
|\vec{p}| = \lambda^{1/2}(m_T^2, m_l^2, m_Z^2)
\]

\[
E_T = \frac{m_T^2 + m_l^2 - m_Z^2}{2m_l},
\]

\[
E_Z = \frac{m_T^2 - m_l^2 - m_Z^2}{2m_l},
\]

\[
\lambda(a, b, c) \equiv a^2 + b^2 + c^2 - 2ab - 2bc - 2ac.
\]

Then, we can have the spin-analyzing power \( P_{l}^{T\text{, singlet}} \) for the decay chain \( T \to Zt \to Z(b l^+\nu) \),

\[
P_{l, T \to Zt}^{T\text{, singlet}} = \frac{|\vec{p}|(m_Z^2 + 2E_T E_Z - 2|\vec{p}|^2)}{2E_T E_Z^2 - 2E_Z|\vec{p}|^2 + m_Z^2 E_T}.
\]
For the decay chain $T \to Ht \to H(b l^+ \nu)$ a similar calculation is performed and we have the spin-analyzing power of the charged lepton

$$P_{l,T \to Ht}^{T \text{ singlet}} = \frac{|\vec{p}|(m_T^2 - m_l^2)}{2m_tm_T^2 + E_T(m_T^2 + m_l^2)},$$

where $\vec{p}$ in this equation is the momentum of the final-state particle in the decay $T \to Ht$ in the C.M.S. $E_T$ is the energy of $T$ quark in this process.

B. $B$ singlet

In the $B$ singlet scenario, we calculate the spin-analyzing power of the final charged lepton for the process $B \to W^- t \to W^- (b l^+ \nu)$. A similar result is obtained with replacement of $m_W \to m_Z$ and $E_T \to E_B$ in (39),

$$P_{l,B \to Wt}^{B \text{ singlet}} = \frac{|\vec{p}|(m_W^2 + 2E_BE_W - 2|\vec{p}|^2)}{2E_BE_W^2 - 2E_W|\vec{p}|^2 + m_W^2E_B},$$

with $\vec{p}$ defined similarly as above.

C. $(TB)$ doublet

In the $(TB)$ doublet scenario, the spin-analyzing power is calculated for all of the above three processes $T \to Z/Ht \to Z/H(b l^+ \nu)$ and $B \to W^- t \to W^- (b l^+ \nu)$. As can be seen from the couplings we give in section II, the left-handed couplings in the $T/B$ singlet scenarios are turned to be right-handed in the $(TB)$ doublet scenario. Following the similar calculation in the singlet scenarios, we have the spin-analyzing power in the $(TB)$ doublet scenario

$$P_{l,T \to Zt}^{TB \text{ doublet}} = \frac{|\vec{p}|(2|\vec{p}|^2 - m_Z^2 - 2E_TE_Z)}{2E_TE_Z^2 - 2E_Z|\vec{p}|^2 + m_Z^2E_T} \quad \text{for } T \to Zt \to Z(b l^+ \nu),$$

$$P_{l,T \to Ht}^{TB \text{ doublet}} = \frac{|\vec{p}|(m_T^2 - m_l^2)}{2m_tm_T^2 + E_T(m_T^2 + m_l^2)} \quad \text{for } T \to Ht \to H(b l^+ \nu),$$

$$P_{l,B \to Wt}^{TB \text{ doublet}} = \frac{|\vec{p}|(2|\vec{p}|^2 - m_W^2 - 2E_BE_W)}{2E_BE_W^2 - 2E_W|\vec{p}|^2 + m_W^2E_B} \quad \text{for } B \to Wt \to W(b l^+ \nu).$$

From (39)-(44) we can see that spin-analyzing power of the final charged lepton in the doublet scenarios is turned opposite from one in the singlet scenario for the corresponding processes, since the VLQ-top couplings in the singlet and doublet scenarios have the opposite handedness.
D. (XT) doublet

In the (XT) doublet scenario, calculation is performed for three processes $X \rightarrow W^+ t \rightarrow W^+ (b l^+ \nu)$, $T \rightarrow Z t \rightarrow Z (b l^+ \nu)$ and $T \rightarrow H t \rightarrow H (b l^+ \nu)$. With replacement of $m_B \rightarrow m_X$ in (42)-(44) for the (TB) doublet scenario, we arrive at the results for the (XT) doublet scenario

$$P_{l, T \rightarrow Z t}^{XT \, \text{doublet}} = \frac{\bar{p} (2|\bar{p}|^2 - m_Z^2 - 2E_T E_Z)}{2E_T E_Z^2 - 2E_Z |\bar{p}|^2 + m_Z^2 E_T} \quad \text{for } T \rightarrow Z t \rightarrow Z (b l^+ \nu), \quad (45)$$

$$P_{l, T \rightarrow H t}^{XT \, \text{doublet}} = \frac{\bar{p} (m_t^2 - m_T^2)}{2m_t m_T^2 + E_T (m_T^2 + m_T^2)} \quad \text{for } T \rightarrow H t \rightarrow H (b l^+ \nu), \quad (46)$$

$$P_{l, X \rightarrow W t}^{XT \, \text{doublet}} = \frac{\bar{p} (2|\bar{p}|^2 - m_W^2 - 2E_X E_W)}{2E_X E_W^2 - 2E_W |\bar{p}|^2 + m_W^2 E_X} \quad \text{for } X \rightarrow W t \rightarrow W (b l^+ \nu). \quad (47)$$

As for the (BY) doublet scenario there are no allowed decay processes from VLQ to top quark, so this scenario is not discussed here. To have an intuitive understanding on the polarization effect of top quark from VLQ decay, we plot the calculated spin-analyzing powers as functions of the VLQ masses. In FIG. 1 we show $P_l$’s for $T$ decay in different scenarios as a function of the mass of $T$ quark. And in FIG. 2 we show $P_l$’s for $B/X$ decay in different scenarios as a function of the mass of $B/X$ quark. Actually due to the closeness of $m_Z$ and $m_W$, the distribution of spin-analyzing power corresponding to $T \rightarrow Z t \rightarrow Z (b l^+ \nu)$ in $T$ singlet scenario and the one corresponding to $B \rightarrow W^- t \rightarrow W^- (b l^+ \nu)$ in $B$ singlet
scenario are pretty close to each other, which may not be obvious if we compare the above two figures. And similarly the curve corresponding to $T \rightarrow Zt \rightarrow Z(bl^+\nu)$ in $(TB)/(XT)$ doublet is quite close to the one corresponding to $B \rightarrow Wt \rightarrow W^-(bl^+\nu)$ in the same scenarios.

From Lagrangians given in section II.A, one can see that top quark from VLQ decay in the singlet scenarios is always left-handed. While in the doublet scenarios, top quark form VLQ decay is always right-handed due to the right-handed couplings given in section II.B. In $T \rightarrow Zt$ or $B/X \rightarrow W^+t$ decays, the top quark’s spin state is determined by the helicity of vector bosons: for a longitudinally polarized $Z/W$, the directions of top spin and $T/B/X$ spin are parallel; while for a left-handed $Z/W$, top spin and $T/B/X$ spin directions are anti-parallel. In the $T \rightarrow Ht$ decay, top spin can be either parallel or anti-parallel to the $T$ spin since their coupling structure is a mixture of left- and right-handedness. In all of the cases, as the mass of the VLQ increases, curves of spin-analyzing power approach to 1 (or $-1$). And this is what one expects since the more massive the VLQ is, the more the top is boosted and the top decay, as mentioned above, has the maximal spin-analyzing power ($\sim 1$) for the charged lepton. It should also be noted that, spin-analyzing power for the charged lepton from $T \rightarrow Ht \rightarrow H(bl^+\nu)$ grows much slower than the one from gauge boson mediated decay in both singlet and doublet scenarios, which is due to the fact that
the VLQ-gauge couplings are purely chiral whereas the VLQ-Higgs couplings contain both left- and right-handed components. In summary, in case VLQ decay processes are probed at colliders, the polarization effects of the top quark can serve to determine its coupling structure with the VLQ.

IV. CONCLUSION

In this paper, we calculate the spin-analyzing power for the charged lepton from top quark in the VLQ decay in singlet and doublet VLQ scenarios. We find that the top polarization effect is helpful to differentiate various VLQ couplings with the SM particles. The spin-analyzing power for the final charged lepton is positive for the singlet VLQ scenarios, while for the doublet VLQ scenarios it is negative. Calculation also shows that spin-analyzing power for charged lepton from Higgs mediated VLQ decay grows slower than the one from gauge boson mediated VLQ decay, as a result of the difference between the chiral structures of their interactions.

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