Leptoquark and vectorlike quark extended models as the explanation of $(g - 2)_{\mu}$ anomaly

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In minimal leptoquark (LQ) models, the $R_2$ and $S_1$ can be the solution to the $(g - 2)_{\mu}$ anomaly because of the chiral enhancements. Here, we study the LQ and vectorlike quark (VLQ) extended models. In the one LQ and one VLQ extended models, the $(g - 2)_{\mu}$ can receive the contributions from top and top partner $T$ because of the $t - T$ mixing. Besides the traditional $R_2$ and $S_1$ representations, we find that the $S_3$ LQ can also explain the anomaly when including the $(X, T, B)_{L,R}$ triplet at the same time. Moreover, we find that the LQ has the new decay channel $T\mu$ in these models.
1. Introduction

The muon magnetic moment is well predicted in the standard model (SM) of elementary particle physics, and the most accurate calculation is $a^\mu_{SM} = 116591810(43) \times 10^{-11}$ [1]. Its deviation from the SM prediction can be a good probe to new physics. The $(g - 2)_\mu$ anomaly is first reported by the E821 experiment at BNL [2]. Last year, the FNAL muon $g - 2$ experiment announces the average result $a^\mu_{Exp} = 116592061(41) \times 10^{-11}$ after combining the BNL and FNAL data [3], which shows the $4.2\sigma$ discrepancy with $\Delta a_{\mu} \equiv a^\mu_{Exp} - a^\mu_{SM} = (251 \pm 59) \times 10^{-11}$. There are many interpretations on this anomaly regardless of theoretical and experimental uncertainties, or new physics. In our paper [4], we propose the simultaneous scalar LQ and VLQ extended models to explain this anomaly.

2. The LQ and VLQ extended models

For the mediator with mass scale $\Lambda$ above TeV, we have the rough estimation $m_\mu^2/(8\pi^2\Lambda^2) \lesssim 10^{-10}$. Thus, the chiral enhancements are required to explain the $(g - 2)_\mu$. In the minimal LQ models, only the $R_2$ and $S_1$ representations can lead to the left and right-handed (non-chiral) couplings to muons at the same time. In fact, the chiral enhancements are induced by the up-type quarks [5].

There are seven typical VLQs, while we are interested in the five types with top partner $T$ [6], namely, the singlet $T_{L,R}$, doublets $(X, T)_{L,R}/(T, B)_{L,R}$, and triplets $(X, T, B)_{L,R}/(T, B, Y)_{L,R}$. Here, the $X, T, B, Y$ quarks carry the electric charges, respectively. Although the five scalar LQs and five T VLQs can result in twenty-five combinations totally, only some combinations can lead to the up-type quark chiral enhancements. In the following, we will study these combinations, which are named as “LQ + VLQ” [1].

After the electroweak symmetry breaking, there are $t - T$ and $b - B$ mixings with the mixing angles denoted as $\theta^t_{L,R}$ (also $\theta^b_{L,R}$) and $\theta^b_{L,R}$. Hereafter, the $\sin \theta_{L,R}$ and $\cos \theta_{L,R}$ will be abbreviated as $s_{L,R}$ and $c_{L,R}$ (similar to the $b$). For the mentioned VLQs, there is only one independent mixing angle except for the $(T, B)_{L,R}$ with two independent mixing angles $\theta^t_{L,R}$ and $\theta^b_{L,R}$. In our paper [4], we list the relevant input parameters and mixing angle identities. For the singlet and triplet VLQs, the $\theta^t_{L,R}$ is chosen as the input mixing angle. For the doublet VLQs, the $\theta^b_{L,R}$ is chosen as the input mixing angle [6].

In Tab. 1, we parametrize the couplings in front of the $\tilde{\mu}_t(R^2_{2/3})^*, \tilde{\mu}_T(R^2_{2/3})^*, \tilde{\mu}^C(S_1)^*$, $\tilde{\mu}^T(S_1)^*$, $\tilde{\mu}^C(S_3^1)^*$, $\tilde{\mu}^T(S_3^1)^*$, and $\tilde{\mu}^B^C(S_3^4)^*$ interactions. In Tab. 2, we also list the couplings in front of the $\tilde{\mu}_b(R^2_{2/3})^*, \tilde{\mu}_B(R^2_{2/3})^*, \tilde{\mu}^B(S_3^4)^*$, and $\tilde{\mu}^B^C(S_3^4)^*$ interactions.

3. Contributions to the $(g - 2)_\mu$

In all of the mentioned models, there are top and $T$ quark contributions with chiral enhancements. In the $R_2 +$ VLQ models, there are also $b$ and $B$ quark contributions. In the $S_1 +$ VLQ models, there are no $b$ or $B$ quark contributions. In the $R_2/S_3 + (X, T, B)_{L,R}$ models, the $b$ and $B$ quark contributions are also chirally enhanced. For the models with $X$ quark, the $X$ quark only contributes in the $S_3 + (X, T, B)_{L,R}$ model but without the chiral enhancements. For the $R_2/S_1 + (T, B, Y)_{L,R}$ models, the $Y$ quark does not contribute to $(g - 2)_\mu$.

\[\text{In our paper [4], we also investigate the one LQ and two VLQ extended models.}\]
Table 1: The LQμ/T couplings in the LQ+VLQ models.

| LQ       | VLQ       | μRbL      | μRbR      | μRB     | μTB     |
|----------|-----------|-----------|-----------|---------|---------|
| T_L,R    | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_R, e_R |
| (X,T)_L,R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_R, e_R |
| (T,B)_L,R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_R, e_R |
| (X,T,B)_L,R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_L, e_L | y^μ_R μ_R, e_R | y^μ_R μ_R, e_R |

Table 2: The LQμb/B couplings in the LQ+VLQ models. The symbol “×” means no such interactions.

| LQ       | VLQ       | μR(μR)      | μR(B)      | μR(B)     | μR(B)     |
|----------|-----------|-------------|-------------|-----------|-----------|
| T_L,R    | 0          | 0           | 0           | 0         | 0         |
| (X,T)_L,R | 0          | 0           | 0           | 0         | 0         |
| (T,B)_L,R | 0          | 0           | 0           | 0         | 0         |
| (X,T,B)_L,R | 0          | 0           | 0           | 0         | 0         |

The complete contributions can be obtained from our paper [4]. Of course, they are dominated by the chirally enhanced contributions, because the non-chirally enhanced contributions are suppressed by the factor \( m_\mu / m_t (m_T) \) \( \lesssim 10^{-3} \). Considering \( m_b \ll m_t \ll m_T \approx m_B \), and \( s_{L,R} \ll 1 \), we show the approximate formulae of \( \Delta a_\mu \) in Tab. 3. In the \( R_2 + (X,T)_L,R/(T,B)_L,R \) and \( S_1 + (X,T)_L,R/(X,T,B)_L,R/(T,B,Y)_L,R \) models, the \( T \) contributions are highly suppressed by the factor \( m_s s_T^2 \). In the \( R_2 + T_L,R/(T,B)_L,R/(X,T,B)_L,R \) and \( S_1 + T_L,R/(T,B)_L,R \) models, the \( T \) contributions are suppressed by the mixing angle \( s_{L,R} \). In the \( S_3 + (X,T,B)_L,R \) model, the \( T \) and \( B \) quark contributions are dominated by the factor \( m_T / m_1 \).
To explain the $(g-2)_\mu$ anomaly, we consider the order of the multiplication of left and right-handed Leptoquark and vectorlike quark extended models. For the LQ mass, the direct search requires it to be above \[7\]. For the VLQ parameters, the main constraints are from direct search \[8, 9\] and electroweak LQ+VLQ models. Here, we will study the \[s_l\] and \[s_R\] approximate expressions of \[\Delta \mu\].

For the other LQs, the decay channels can be \[\rightarrow \mu L\] and \[\rightarrow \nu L\]. In the minimal \[\mu L\] models, the LQ decay final states are SM quark and lepton. In the four columns, we show the order of the multiplication of left and right-handed $T$ LQ Yukawa couplings with respect to the top quark. In the above, we redefine $\Delta \mu$ as \[m_\mu \Delta \mu / (4\pi^2 m_L^2)\].

4. Numerical analysis

We choose the input parameters as \[m_\mu = 105.66\text{MeV}, m_b = 4.2\text{GeV}, \text{and } m_t = 172.5\text{GeV}\ [7]. For the VLQ parameters, the main constraints are from direct search [8, 9] and electroweak precision observables [6, 10], which require the VLQ mass to be $O(\text{TeV})$ and the input mixing angle to be less than 0.1. For the LQ mass, the direct search requires it to be above TeV [11, 12]. Then, we adopt the mass parameters to be \[m_T = 1\text{TeV} = m_{LQ}\] by default. The input mixing angle is set as \[s_L = 0.05\] (singlet and triplet VLQs) and \[s_R = 0.05\] (doublet VLQs). In Fig. 1, we show the regions allowed at 1$\sigma$ (green) and 2$\sigma$ (yellow) CL, respectively.

5. LQ Phenomenology at hadron colliders

In the minimal \[R_2/S_1\] models, the LQ decay final states are SM quark and lepton. In the LQ+VLQ models, there are new LQ decay channels. Here, we will study the \[R_2 \rightarrow t/T\mu^+\] and \[S_1 \rightarrow t/T\mu^+\] decay channels. Considering \[m_T < m_T\] and \[s_{L,R} < 1\], we show the approximate expressions of $\Gamma(LQ \rightarrow T\mu)/(\Gamma(LQ \rightarrow t\mu))$ in Tab. 4. Then, we find that the $T\mu$ decay channel is important in the \[R_2 + T_{L,R}/(T, B)_{L,R}/(X, T, B)_{L,R}, S_1 + T_{L,R}/(T, B)_{L,R}, \text{and } S_{L,R} \rightarrow T\mu^+ \rho^+\].

\[\text{Table 3: In the third column, we show the approximate formulae of } \Delta \mu. \text{ In the fourth column, we show the order of the multiplication of left and right-handed } T \text{ LQ Yukawa couplings with respect to the top quark. In the above, we redefine } \Delta \mu \text{ as } m_\mu \Delta \mu / (4\pi^2 m_L^2).\]
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**Figure 1:** The allowed region in the plane of $\text{Re} \left[ y_{L/R}^{R_2 \mu T} (y_{L/R}^{R_2 \mu T})^* \right] - \text{Re} \left[ y_{L}^{S_1 \mu T} (y_{R}^{S_1 \mu T})^* \right]$ (left, $R_2 + \text{VLQ}$) and $\text{Re} \left[ y_{L/R}^{S_1 \mu T} (y_{L/R}^{S_1 \mu T})^* \right] - \text{Re} \left[ y_{L}^{S_1 \mu T} (y_{R}^{S_1 \mu T})^* \right]$ (middle, $S_1 + \text{VLQ}$). The right is for the $S_3 + (X, T, B)_{L,R}$ model.

$S_3 + (X, T, B)_{L,R}$ models. For the LQ production, there are pair, single, and off-shell channels.

| LQ          | VLQ          | the approximate expressions of $\Gamma (\text{LQ} \rightarrow T \mu)/\Gamma (\text{LQ} \rightarrow t \mu)$ | suppress or not |
|-------------|--------------|---------------------------------------------------------------------------------|-----------------|
| $R_2$       | $T_{L,R}$    | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L/R}^{R_2 \mu T} |^2 / ( y_{L}^{R_2 \mu T} |^2 + y_{R}^{R_2 \mu T} |^2)$ | No              |
|             | $(X, T)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L/R}^{R_2 \mu T} |^2 / ( y_{L}^{R_2 \mu T} |^2 + y_{R}^{R_2 \mu T} |^2)$ | $s_{L,R}$        |
|             | $(T, B)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L/R}^{R_2 \mu T} |^2 / ( y_{L}^{R_2 \mu T} |^2 + y_{R}^{R_2 \mu T} |^2)$ | No              |
|             | $(X, T, B)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L/R}^{R_2 \mu T} |^2 / ( y_{L}^{R_2 \mu T} |^2 + y_{R}^{R_2 \mu T} |^2)$ | No              |
| $S_1$       | $T_{L,R}$    | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L}^{S_1 \mu T} |^2 / ( y_{L}^{S_1 \mu T} |^2 + y_{R}^{S_1 \mu T} |^2)$ | No              |
|             | $(X, T)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L}^{S_1 \mu T} |^2 / ( y_{L}^{S_1 \mu T} |^2 + y_{R}^{S_1 \mu T} |^2)$ | $s_{L,R}$        |
|             | $(T, B)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L}^{S_1 \mu T} |^2 / ( y_{L}^{S_1 \mu T} |^2 + y_{R}^{S_1 \mu T} |^2)$ | No              |
|             | $(X, T, B)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L}^{S_1 \mu T} |^2 / ( y_{L}^{S_1 \mu T} |^2 + y_{R}^{S_1 \mu T} |^2)$ | $s_{L,R}$        |
| $S_3$       | $(X, T, B)_{L,R}$ | $(1 - \frac{m_T^2}{m_{S_3}^2})^2 y_{L}^{S_1 \mu T} |^2 / ( y_{L}^{S_1 \mu T} |^2 + y_{R}^{S_1 \mu T} |^2)$ | No              |

Table 4: In the third column, we list the approximate formulæ of $T \mu$ partial decay width over $t \mu$ in the LQ+VLQ models. In the fourth column, we show the order of $\Gamma (\text{LQ} \rightarrow T \mu)$ compared to the $\Gamma (\text{LQ} \rightarrow t \mu)$.

What is more, the $T$ quark can decay into the $bW, tZ, th$ final states further. Thus, it will lead to the characteristic multi-top and multi-muon signals at hadron colliders.

6. Summary and conclusions

We explain the $(g - 2)_\mu$ anomaly in the LQ and VLQ extended models. In the $R_2 + (X, T)_{L,R}/(T, B, Y)_{L,R}$ and $S_1 + (X, T)_{L,R}/(X, T, B)_{L,R}/(T, B, Y)_{L,R}$ models, it is dominated by the top quark contributions. In the $R_2 + T_{L,R}/(T, B)_{L,R}/(X, T, B)_{L,R}$ and $S_1 + T_{L,R}/(T, B)_{L,R}$ models, both the top and $T$ quark contributions are important. In the $S_3 + (X, T, B)_{L,R}$ model, it is dominated by the $T$ and $B$ quark contributions. In addition to the conventional $t \mu$ decay channel, the LQ can also
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decay into $T\mu$ final states, which can become important in the $R_2 + T_{L,R}/(T, B)_{L,R}/(X, T, B)_{L,R}$, $S_1 + T_{L,R}/(T, B)_{L,R}$ models, and $S_3 + (X, T, B)_{L,R}$ models.

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