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.

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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"[4].

After the electroweak symmetry breaking, there are $t - T$ and $b - B$ mixings with the mixing angles denoted as $\theta_{L,R}^t$ (also $\theta_{L,R}^b$) and $\theta_{L,R}^h$ 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 $\theta_{L,R}^b$ and $\theta_{L,R}^h$. In our paper [4], we list the relevant input parameters and mixing angle identities. For the singlet and triplet VLQs, the $\theta_L$ is chosen as the input mixing angle. For the doublet VLQs, the $\theta_{L,R}$ is chosen as the input mixing angle [6]. In Tab. 1, we parametrize the couplings in front of the $\bar{\mu} T (R_2^{5/3})^\ast$, $\bar{\mu} T (R_2^{5/3})^\ast$, $\bar{\mu} C (S_1)^\ast$, $\bar{\mu} T C (S_1)^\ast$, $\mu T C (S_1)^\ast$, and $\bar{\mu} T C (S_1)^\ast$ interactions. In Tab. 2, we also list the couplings in front of the $\bar{\mu} b (R_2^{5/3})^\ast$, $\bar{\mu} B (R_2^{5/3})^\ast$, $\bar{\mu} b C (S_3^{1/3})^\ast$, and $\bar{\mu} B C (S_3^{1/3})^\ast$ 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 chiral 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 $(g - 2)_\mu$.

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1 In our paper [4], we also investigate the one LQ and two VLQ extended models.
Table 1: The LQμ/T contributions are suppressed by the mixing angle θ.

| LQ | VLQ | \( \mu_R b_L \) | \( \mu_L b_R \) | \( \mu_R B_L \) | \( \mu_L B_R \) |
|----|-----|----------------|----------------|----------------|----------------|
| TR | L_R | 0 | 0 | 0 | 0 |
| R_L | 0 | 0 | 0 | 0 | 0 |
| S_1 | (T, B)_L_R | \( y_{L_R}^{\mu R} \) | \( y_{L_R}^{\mu L} \) | \( y_{L_R}^{\mu R} b_L \) | \( y_{L_R}^{\mu L} b_R \) |
| S_2 | (X, T)_L_R | 0 | 0 | 0 | 0 |

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

| LQ | VLQ | \( \mu_R b_R \) | \( \mu_L b_L \) | \( \mu_R B_R \) | \( \mu_L B_L \) |
|----|-----|----------------|----------------|----------------|----------------|
| 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 |
| S_3 | (X, T)_L_R | \( -y_{L_R}^{\mu R} \) | \( y_{L_R}^{\mu L} \) | \( \sqrt{2} y_{L_R}^{\mu R} b_R \) | \( \sqrt{2} y_{L_R}^{\mu L} b_L \) |

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 \( m_\mu / m_\tau (m_T) \lesssim 10^{-3} \). Considering \( m_\mu \ll m_\tau \ll m_T \approx m_B \), and \( s_{L,R} \ll 1 \), we show the approximate formulae of \( \Delta a_{\mu} \) in Tab. 3. In the \( R_2 + (X, T)_L_R + (T, B, Y)_L_R \) and \( S_1 + (X, T)_L_R + (T, B)_L_R \) models, the \( T \) contributions are highly suppressed by the factor \( m_\tau^2 s_{L,R}^2 / m_T \). In the \( R_2 + \mu_T \) model, the \( T \) and \( B \) quark contributions are dominated by the factor \( m_T / m_\mu \).
Table 3: In the third column, we show the approximate formulæ of the $\Delta\alpha_{\mu}$. In the fourth column, 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 $\Delta\alpha_{\mu}$ as $m_{\mu}m_{t}\Delta\alpha_{\mu}/(4\pi^{2}m_{LQ}^{2})$.

4. Numerical analysis

We choose the input parameters as $m_{\mu} = 105.66 \text{MeV}$, $m_{b} = 4.2 \text{GeV}$, 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 $\text{TeV}$ [11, 12]. Then, we adopt the mass parameters to be $m_{T} = 1 \text{TeV}$ and $m_{LQ} = 2 \text{TeV}$ 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 $R_{2}^{5/3} \rightarrow t/T\mu^{+}$ and $S_{1}/S_{3}^{1/3} \rightarrow t/T\mu^{+}$ decay channels. Considering $m_{t} \ll m_{T}$ and $s_{L,R} \ll 1$, we show the approximate expressions of $\Gamma(\text{LQ} \rightarrow T\mu)/\Gamma(\text{LQ} \rightarrow t\mu)$ in Tab. 4. Then, we find that the $T\mu$ decay channel is important in the $R_{2} + T_{L,R} / (T,B)_{L,R} / (X,T,B)_{L,R}$, $S_{1} + T_{L,R} / (T,B)_{L,R}$, and $S_{3}^{2/3} \rightarrow X\mu^{+}$.

For the other LQs, the decay channels can be $R_{2}^{2/3} \rightarrow b/B\mu^{+}$, $S_{1}^{4/3} \rightarrow b/B\mu^{+}$, and $S_{3}^{-2/3} \rightarrow X\mu^{+}$.
S3 + (X, T, B)_{L,R} models. For the LQ production, there are pair, single, and off-shell channels.

| LQ | VLQ | \( \Gamma'(\text{LQ} \to T \mu) / \Gamma(\text{LQ} \to t \mu) \) | suppress or not |
|----|-----|-----------------|---------------|
| \( R_2 \) | \( T_{L,R} \) | \( 1 - \frac{m_T^2}{m_{T_{L,R}}^2} |y_{R_2}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( (X, T)_{L,R} \) | \( (1 - \frac{m_T^2}{m_{T_{L,R}}^2} |y_{R_2}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( (T, B)_{L,R} \) | \( (1 - \frac{m_T^2}{m_{T_{L,R}}^2} |y_{R_2}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( (X, T, B)_{L,R} \) | \( (1 - \frac{m_T^2}{m_{T_{L,R}}^2} |y_{R_2}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( S_1 \) | \( T_{L,R} \) | \( 1 - \frac{m_T^2}{m_{S_1}^2} |y_{L}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( (X, T)_{L,R} \) | \( (1 - \frac{m_T^2}{m_{S_1}^2} |y_{L}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( (T, B)_{L,R} \) | \( (1 - \frac{m_T^2}{m_{S_1}^2} |y_{L}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |
| \( (X, T, B)_{L,R} \) | \( (1 - \frac{m_T^2}{m_{S_1}^2} |y_{L}^{\mu T} |^2/(|y_{L}^{\mu T} |^2 + |y_{R_2}^{\mu T} |^2) \) | \( s_L^2 \) |

Table 4: In the third column, we list the approximate formula of \( T_\mu \) partial decay width over \( t \mu \) in the LQ+VLQ models. In the fourth column, we show the order of \( \Gamma'(\text{LQ} \to T \mu) \) compared to \( \Gamma'(\text{LQ} \to t \mu) \).

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
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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References

[1] T. Aoyama et al. The anomalous magnetic moment of the muon in the Standard Model. Phys. Rept., 887:1–166, 2020.
[2] G. W. Bennett et al. Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL. Phys. Rev. D, 73:072003, 2006.
[3] B. Abi et al. Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm. Phys. Rev. Lett., 126(14):141801, 2021.
[4] Shi-Ping He. Leptoquark and vectorlike quark extended models as the explanation of the muon \( g - 2 \) anomaly. Phys. Rev. D, 105(3):035017, 2022. [Erratum: Phys. Rev. D 106, 039901 (2022)].
[5] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik, and N. Košnik. Physics of leptoquarks in precision experiments and at particle colliders. Phys. Rept., 641:1–68, 2016.
[6] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Pérez-Victoria. Handbook of vectorlike quarks: Mixing and single production. Phys. Rev. D, 88(9):094010, 2013.
[7] P. A. Zyla et al. Review of Particle Physics. PTEP, 2020(8):083C01, 2020.
[8] Albert M Sirunyan et al. Search for vector-like quarks in events with two oppositely charged leptons and jets in proton-proton collisions at \( \sqrt{s} = 13 \) TeV. Eur. Phys. J. C, 79(4):364, 2019.
[9] Morad Aaboud et al. Combination of the searches for pair-produced vector-like partners of the third-generation quarks at \( \sqrt{s} = 13 \) TeV with the ATLAS detector. Phys. Rev. Lett., 121(21):211801, 2018.
[10] Chien-Yi Chen, S. Dawson, and Elisabetta Furlan. Vectorlike fermions and Higgs effective field theory revisited. Phys. Rev. D, 96(1):015006, 2017.
[11] Albert M Sirunyan et al. Search for leptoquarks coupled to third-generation quarks in proton-proton collisions at \( \sqrt{s} = 13 \) TeV. Phys. Rev. Lett., 121(24):241802, 2018.
[12] Georges Aad et al. Search for pair production of scalar leptoquarks decaying into first- or second-generation leptons and top quarks in proton–proton collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector. Eur. Phys. J. C, 81(4):313, 2021.