Muon Anomalous Magnetic Moment and Leptoquark Solutions

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The recent measurement on the muon anomalous magnetic moment $a_\mu$ shows a $2.6\sigma$ deviation from the standard model value. We show that it puts an interesting bound on the mass of the second generation leptoquarks. To account for the data the leptoquark must have both the left- and right-handed couplings to the muon. Assuming that the couplings have electromagnetic strength, the mass is restricted in the range $0.7 \text{ TeV} < M_{LQ} < 2.2 \text{ TeV}$ at 95% C.L. We also discuss constraints coming from other low energy and high energy experiments. If the first-second-generation universality is assumed, constraints come from the atomic parity violation and charged-current universality. We show that coexistence with other leptoquarks can satisfy these additional constraints and at the same time do not affect the $a_\mu$.

Many Grand-Unified theories predict the existence of leptoquarks, which are composite objects that carry both the lepton and quark numbers. The discovery of such particles certainly affects the planning for future experiments and guides the building of the theories. In fact, leptoquarks have been actively searched for in many collider experiments [1,2], and will still be in the future. Precision measurements are also very useful in testing leptoquark models and guides the building of the theories. In fact, leptoquarks have been actively searched for in many collider experiments.

In this Letter, we investigate the contributions of various leptoquarks to $a_\mu$. While we are completing this work, a paper [9] appears, which describes similar solutions to [1]. We limit to the second generation leptoquarks only without considering any generation mixing in order to avoid dangerous flavor changing neutral currents. Our main result is summarized as follows. To account for the $a_\mu$ data the solution requires a leptoquark that has both the left-handed and right-handed chiral couplings and the mass is required to be about $0.7 - 2.2 \text{ TeV}$ for an electromagnetic coupling strength. This solution is consistent with direct and indirect experimental search. The $a_\mu$ data disfavors, if not rule out, the leptoquarks that have only a left- or right-handed coupling. Also, coexistence with other leptoquarks can easily satisfy additional constraints, e.g., atomic-parity violation (APV) and charged-current (CC) universality, without affecting the $a_\mu$.

The recent measurement on the muon anomalous magnetic moment by the experiment E821 [11] at Brookhaven National Laboratory has reduced the error to a substantially smaller level. Combining with previous measurements the new world average is [6]

$$a_\mu^{\exp} = 116 592 023 (151) \times 10^{-11},$$

where the standard model (SM) prediction is

$$a_\mu^{\text{SM}} = 116 591 597 (67) \times 10^{-11},$$

in which the QED, hadronic, and electroweak contributions have been included. Thus, the deviation from the SM value is

$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{\text{SM}} = (42.6 \pm 16.5) \times 10^{-10}.$$ (3)

This $2.6\sigma$ deviation may be a hint to new physics because the deviation is beyond the uncertainties in QED, electroweak, and hadronic contributions.

Among various extensions of the SM, namely, supersymmetry [7], additional gauge bosons [8], leptoquarks [3,9,10], extra dimensions, muon substructure [12], they all contribute to $a_\mu$. However, not all of them can contribute in the right direction as indicated by the data. Thus, the $a_\mu^{\exp}$ measurement can differentiate among various models, and perhaps with other existing data can put very strong constraints on the model under consideration.

The interaction Lagrangians for the $F = 0$ and $F = -2$ ($F$ is the fermion number) scalar leptoquarks are [2]

$$\mathcal{L}_{F=0} = \lambda_L \bar{\ell}_L u_R S^L_{1/2} + \lambda_R \bar{q}_L c_R (i\tau_2 S^R_{1/2}) + \tilde{\lambda}_L \bar{L}_L d_R \tilde{S}^L_{1/2} + h.c.,$$

$$\mathcal{L}_{F=-2} = g_L \bar{q}_L^{(i)} i\tau_2 \ell_L \bar{S}^L_0 + g_R \bar{u}_R^{(c)} e_R S^R_0 + g_R \bar{d}_R^{(c)} e_R \tilde{S}^R_0 + g_M \bar{q}_L^{(i)} i\tau_2 \tilde{\ell}_L \cdot \tilde{S}^L_1 + h.c.$$ (5)
where \( q_L, \ell_L \) denote the left-handed quark and lepton doublets, \( u_R, d_R, e_R \) denote the right-handed up-type quark, down-type quark, and lepton singlet, and \( q_L^{(c)}, u_R^{(c)}, d_R^{(c)} \) denote the charge-conjugated fields. The subscript on leptoquark fields denotes the weak-isospin of the leptoquark, while the superscript \((L, R)\) denotes the handedness of the lepton that the leptoquark couples to. The color indices of the quarks and leptoquarks are suppressed. The components of the \( F = 0 \) leptoquark fields are

\[
S_{1/2}^{L,R} = \begin{pmatrix} S_{L,R}^{L(-2/3)} \\ S_{L,R}^{L(-5/3)} \end{pmatrix}, \quad \tilde{S}_{1/2}^L = \begin{pmatrix} \tilde{S}_L^{L(1/3)} \\ -\tilde{S}_L^{L(-2/3)} \end{pmatrix},
\]

where the electric charge of the component fields is given in the parentheses, and the corresponding hypercharges are \( Y(S_{1/2}^{L}) = Y(S_{1/2}^{R}) = -7/3 \) and \( Y(\tilde{S}_{1/2}^{L}) = -1/3 \). The \( F = -2 \) leptoquarks \( S_0^L, S_0^R, \tilde{S}_0^L \) are isospin singlets with hypercharges 2/3, 2/3, 8/3, respectively, while \( S_1^L \) is a triplet with hypercharge 2/3:

\[
S_1^L = \begin{pmatrix} S_1^{L(4/3)} \\ S_1^{L(1/3)} \\ S_1^{L(-2/3)} \end{pmatrix}.
\]

The SU(2)\(_L\) \(\times\) U(1)\(_Y\) symmetry is assumed in the Lagrangians of Eqs. \( \text{[4]} \) and \( \text{[5]} \).

To calculate the contribution to \( a_\mu \) we start with the \( F = 0 \) leptoquark \( S_{1/2}^{L,R} \) that has both the left- and right-handed couplings. The other leptoquarks with either left- or right-handed couplings are simply special cases of it. The Lagrangian can be rewritten as

\[
\mathcal{L}_{S_{1/2}} = \bar{\mu}(\lambda_L P_R + \lambda_R P_L)c\tilde{S}_{1/2}^{(-5/3)} + h.c.,
\]

where \( P_{L,R} = (1 + \gamma^5)/2 \) and we explicitly write the second generation particles \( \mu \) and \( c \)-quark. The result can be easily obtained by some modifications on a \( c\gamma \) \([13]\) calculation, as follows (\( a_\mu \) is defined by \( \mathcal{L} = (e/4m_\mu)a_\mu\sigma_{\alpha\beta}\mu F^{\alpha\beta} \))

\[
\Delta a_\mu(S_{1/2}) = -\frac{N_c}{16\pi^2} \frac{m_\mu^2}{M_{S_{1/2}}^2} \left\{ (|\lambda_L|^2 + |\lambda_R|^2)(Q_c F_5(x) - Q_S F_2(x)) + \frac{m_c}{m_\mu} \text{Re}(\lambda_L \lambda_R^*)(Q_c F_6(x) - Q_S F_3(x)) \right\}, \tag{9}
\]

where

\[
\begin{align*}
F_2(x) &= \frac{1}{6(1-x)^4} (1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x), \\
F_3(x) &= \frac{1}{2(1-x)^2} (1 - x^2 + 2x \ln x), \\
F_5(x) &= \frac{1}{6(1-x)^4} (2 + 3x - 6x^2 + x^3 + 6x \ln x), \\
F_6(x) &= \frac{1}{(1-x)^3} (-3 + 4x - x^2 - 2\ln x).
\end{align*}
\]

In the above expression, \( N_c = 3, Q_c = 2/3, Q_S = -5/3 \), and \( x = m_\mu^2/M_{S_{1/2}}^2 \), and we have neglected terms proportional to \( m_\mu^2/M_{S_{1/2}}^2 \) in the parenthesis. Our expression agrees with that in Ref. \([4]\).

For the \( F = -2 \) leptoquarks only \( S_0^L \) has both the left- and right-handed couplings. The Lagrangian can be rewritten as

\[
\mathcal{L}_{S_0} = \bar{\mu}(g_L^L P_R + g_R^R P_L)\epsilon^{(c)} S_0^{(-1/3)} + h.c.,
\]

The contribution to \( a_\mu \) can be obtained from Eq. \( \text{[4]} \) with the following substitutions

\[
m_c \to -m_c, \quad Q_c \to Q_c^{(c)}, \quad \lambda_{L,R} \to g_{L,R}^c,
\]

where \( Q_c^{(c)} = -2/3 \) and \( Q_S = -1/3 \) for this leptoquark.

We note that our expression for \( F = -2 \) leptoquark agrees with Ref. \([4]\), but we have a different expression for \( F = 0 \) leptoquark. Ref. \([4]\) does not distinguish between these two types of leptoquarks.
Next, we use our expressions to fit to $\Delta a_\mu$. The range of $\Delta a_\mu$ at 95% C.L. ($\pm 1.96 \sigma$) is
\begin{equation}
10.3 \times 10^{-10} < \Delta a_\mu < 74.9 \times 10^{-10}.
\end{equation}
A rough estimate for the allowed range of $M_{LQ}$ can be obtained by realizing the dominant term in Eq. (3). In Eq. (10), the term with $Re(\lambda_L \lambda_R^*)$ dominates over the term with $|\lambda_L|^2 + |\lambda_R|^2$, because of the enhancement factor of $m_e/m_\mu$. This is valid as long as $\lambda_L \approx \lambda_R$. Also, the function $F_0(x) \rightarrow (-3 - 2 \ln x)$ and $F_3(x) \rightarrow 1$ when $x \rightarrow 0$. Therefore,
\begin{equation}
\Delta a_\mu(S_{1/2}) \approx -\frac{1}{8\pi^2} \frac{m_e m_\mu}{M^2 S_{1/2}} \Re(\lambda_L \lambda_R^*) (26),
\end{equation}
where the numerical factor of 26 is estimated by varying $M_{S_{1/2}}$ between 0.5 – 1.5 TeV. With the 95% C.L. bound on $\Delta a_\mu$ we obtain
\begin{equation}
2.6 \text{ TeV} < \frac{M_{S_{1/2}}}{\sqrt{-Re(\lambda_L \lambda_R^*)}} < 7.2 \text{ TeV}.
\end{equation}
Similarly, for the $F = -2$ leptoquark $S_0$ we obtain
\begin{equation}
2.5 \text{ TeV} < \frac{M_{S_0}}{\sqrt{-Re(g_L^* g_R)}} < 6.7 \text{ TeV}.
\end{equation}
If $\lambda_L = -\lambda_R = e$ and $g_L = -g_R = e$, where $e = \sqrt{4\pi e_{\text{em}}}$,
\begin{equation}
0.8 \text{ TeV} < M_{S_{1/2}} < 2.2 \text{ TeV} \quad \text{and} \quad 0.7 \text{ TeV} < M_{S_0} < 2.0 \text{ TeV}.
\end{equation}
We show in Fig. 4 the contributions to $\Delta a_\mu$ from the $F = 0$ and $F = -2$ leptoquarks $S_{1/2}$ and $S_0$ respectively, using the exact expression of Eq. (3). We have used $\lambda_L(g_L) = -\lambda_R(g_R) = e$. The shaded region is the 95% C.L. range allowed as in Eq. (12). One can see from the graph that the bounds on $M_{S_{1/2}}$ and $M_{S_0}$ are very close to the estimate in Eq. (14).

What about the other leptoquarks that have only the left- or right-handed coupling? We can use Eq. (3) with only $\lambda_L$ or $\lambda_R$, then $\Delta a_\mu$ is given by
\begin{equation}
\Delta a_\mu = -\frac{N_c}{16\pi^2} \frac{m_e^2}{M^2_{LQ}} |\lambda_L|^2 (Q_c F_5(x) - Q_S F_2(x)).
\end{equation}
The factor in the parenthesis is only a fraction of unity. Thus, this $\Delta a_\mu$ is suppressed by about $10^{-3}$ relative to the contributions from $S_{1/2}$ or $S_0$. Hence, the mass limits are weakened by a factor of $\sqrt{10^{-3}} \approx 0.3$, which means the leptoquarks are to be lighter than 100 GeV in order to explain the $a_\mu^{\exp}$. It is obviously ruled out by the Tevatron direct search limit on the second-generation leptoquarks (see below).

We note that these two leptoquarks also give rise to an electric dipole moment (EDM) of muon, provided that $\Im(\lambda_L \lambda_R^*)$ is nonzero. The contribution to EDM is given by
\begin{equation}
d_\mu = \frac{e N_c}{32 \pi^2} \frac{m_e}{M^2_{LQ}} \Im(\lambda_L \lambda_R^*) (Q_c F_5(x) - Q_S F_3(x)),
\end{equation}
where $d_f$ is defined by $\mathcal{L} = (-i/2)d_f \bar{f} \sigma_{\mu\nu} \gamma_5 f F^{\mu\nu}$. Note that the same large numerical factor, scaling as $\ln(M^2_{LQ}/m_e^2)$, is in the parenthesis.

We also note that the self-energy diagram of the muon with the leptoquark and charm quark inside the loop gives a radiative correction to the muon mass. We calculated this diagram and found that it has an UV divergent piece and a finite piece. While the divergent piece is absorbed into the renormalization constant, the finite piece is given by $\delta m_\mu \sim (N_c \lambda^2/16\pi^2) m_\mu \ln(M^2_{LQ}/m_e^2)$. Numerically, $\delta m_\mu$ is less than the observed muon mass for $\lambda \simeq e$ and $M_{LQ} \simeq 1 – 2$ TeV, such that $\delta m_\mu$ can be included into the definition of the pole mass without any fine tuning problem, which gives the observed muon mass.

Summarizing, only the leptoquarks $S_{1/2}$ and $S_0$ that couple to both left- and right-handed muon can explain the data on $\Delta a_\mu$, while the other leptoquarks alone cannot explain the data. In fact, it is advantageous to have the
coexistence of other leptoquarks because they can satisfy constraints from other experiments and at the same time would not give any sizable contribution to $a_{μ}$.

The most obvious limits on leptoquarks are the direct search limits at the Tevatron $p\bar{p}$ collision and at the HERA $e^±p$ collision, based on two NLO calculations [3]. Both CDF and DØ searched for the first and second generation leptoquarks. Their limits are independent of the leptoquark couplings because the production is via the strong interaction. The lower limits on the first (LQ1) and second (LQ2) generation scalar leptoquarks are given by [4]

\[
\begin{align*}
M_{LQ1} &> 242 \, \text{GeV} \quad \text{for } \beta = 1 \quad \text{(CDF and DØ combined)}, \\
M_{LQ2} &> 202 (160) \, \text{GeV} \quad \text{for } \beta = 1(0.5) \quad \text{(CDF)}, \\
M_{LQ2} &> 200(180) \, \text{GeV} \quad \text{for } \beta = 1(0.5) \quad \text{(DØ)},
\end{align*}
\]

where $\beta = B (LQ \rightarrow ℓq)$. At HERA, the direct searches are limited to the first generation leptoquarks and depend on the leptoquark couplings. The best limits with $λ = e$ are [3]

\[
\begin{align*}
M_{LQ1} &> 280 \, \text{GeV} \quad \text{(ZEUS)}, \\
M_{LQ1} &> 275 \, \text{GeV} \quad \text{(H1)}.
\end{align*}
\]

The leptoquark solutions in Eq. (16) are safe with these limits.

There are also other existing constraints. Especially, if the first-second-generation universality is assumed for the leptoquarks, very strong constraints come from low energy and high energy experiments [15,16]. Among the constraints the APV and the CC universality are the most relevant to leptoquarks. First-second-generation universality

It is convenient to parameterize the effective interactions of leptoquarks in terms of contact parameters $η_{αβ}^{\ellq}$, where $α$ and $β$ denote the chirality of the lepton and the quark, respectively, when the mass of the leptoquarks are larger than the energy scale of the experiment. The contact parameters are defined by

\[
\mathcal{L}_A = \sum_{ℓ, q} \left\{ η_{LL}^{\ellq} \overline{ℓ}γ_μLγ_μLqL + η_{LR}^{\ellq} \overline{ℓ}γ_μLRγ_μLRqL + η_{RL}^{\ellq} \overline{ℓ}γ_μRLγ_μRLqL + η_{LR}^{\ellq} \overline{ℓ}γ_μLRγ_μLRqL \right\}.
\]

The APV is measured in terms of weak charge $Q_W$. The updated data with an improved atomic calculation [17,18] is about 1.0σ larger than the SM prediction, namely, $ΔQ_W = Q_W (Cs) - Q_W^{SM} (Cs) = 0.44 ± 0.44$. The contribution to $ΔQ_W$ from the contact parameters is given by [13,16]

\[
ΔQ_W = (-11.4 \, \text{TeV}^2) \left[ -η_{LL}^{\ellq} + η_{RR}^{\ellq} - η_{LR}^{\ellq} + η_{RL}^{\ellq} \right] + (-12.8 \, \text{TeV}^2) \left[ -η_{LL}^{\ellq} + η_{RR}^{\ellq} - η_{LR}^{\ellq} + η_{RL}^{\ellq} \right].
\]

Another important constraint is the CC universality. It is expressed as $η_{CC} = η_{LL}^{\ellq} - η_{RR}^{\ellq} = (0.051 ± 0.037) \, \text{TeV}^{-2}$. These $ΔQ_W$ and $η_{CC}$ are the two most important constraints relevant to leptoquarks. With the first-second-generation universality $η_{LL}^{\ellq} = η_{LR}^{\ellq}$ and $η_{RL}^{\ellq} = η_{RR}^{\ellq}$. We are going to analyze the leptoquark solutions that we found above with TeV mass leptoquarks [3].

For the $F = 0$ leptoquark $S_{1/2}$ with the interaction given in Eq. (8), the contributions to $η$ are

\[
η_{LR}^{μq} = -\frac{|λ_L|^2}{2M_{S_{1/2}}}, \quad η_{RL}^{μq} = -\frac{|λ_R|^2}{2M_{S_{1/2}}},
\]

which are equal to $-(0.01 - 0.07) \, \text{TeV}^{-2}$ for $λ = -λ_R = e$ and the mass range in Eq. (16). Similarly for the $F = -2$ leptoquark $S_0$ with the interaction given in Eq. (9), the contributions to $η$ are

\[
η_{LL}^{μq} = \frac{|g_L|^2}{2M_{S_0}} , \quad η_{LR}^{μq} = \frac{|g_R|^2}{2M_{S_0}},
\]

which are equal to $0.01 - 0.08 \, \text{TeV}^{-2}$ for $g_L = -g_R = e$ and the mass range in Eq. (16).

Both of these leptoquarks do not contribute to $ΔQ_W$ as the contributions get canceled. While $S_{1/2}$ does not contribute to $η_{CC}$, $S_0$ contributes to $η_{CC}$ but in the opposite direction. The lower mass range of $S_0$ is then ruled out by the $η_{CC}$ constraint.
As mentioned above, coexistence of other leptoquarks could satisfy the constraints on $\Delta Q_W$ and $\eta_{CC}$. The $\Delta Q_W$ constraint can be satisfied by the coexistence of either $S_{1/2}^R (-2/3)$ with interactions $-\lambda_R \overline{r} r d_L S_{1/2}^R (-2/3) + h.c.$, or $S_{1/2}^L$ with interactions $-g_{3L} (\overline{u}_L u_L \overline{e}_L e_L S_{1/2}^L (1/3) + \sqrt{2} d_L^* e_L S_{1/2}^L (4/3) + h.c.)$. The mass required to fit to $\Delta Q_W$ is $M_{S_{1/2}^R} = 1.2$ TeV or $M_{S_{1/2}^L} = 2.0$ TeV with electromagnetic coupling strength. For such heavy leptoquarks with only a left-handed or right-handed coupling, their contributions to $\Delta a_\mu$ are certainly negligible. At the same time $S_{1/2}^L$ contributes to $\eta_{CC}$ in the right direction, while $S_{1/2}^R (-2/3)$ does not.

Summarizing, we can have the following three viable combinations of leptoquarks.

1. $S_{1/2} (-5/3)$ and $S_{1/2}^L$. The former explains $\Delta a_\mu$ and the latter satisfies $\Delta Q_W$ and in the right direction as $\eta_{CC}$. This is the best scenario.

2. $S_{1/2} (-5/3)$ and $S_{1/2}^R (-2/3)$. The former explains $\Delta a_\mu$ and the latter satisfies $\Delta Q_W$. They both have no effect on $\eta_{CC}$, but it is fine.

3. $S_0$ and $S_{1/2}^L$. The former explains $\Delta a_\mu$ but violates $\eta_{CC}$. The latter can help pulling the leptoquark solution within a reasonable deviation in $\eta_{CC}$ and still partially explaining $\Delta Q_W$.

No first-second-generation universality

In this case, virtually no constraints exist on the second generation leptoquarks. The constraint of $D^+ \rightarrow \mu^+ \nu$ mentioned in Ref. [1] only applies to a very low leptoquark mass, which has already been ruled out by direct search [2]. There was a low-energy muon deep-inelastic scattering experiment on carbon [19]. An analysis [20] showed that this $\mu C$ experiment results in a constraint

\begin{align}
2\Delta C_{3u} - \Delta C_{3d} &= -1.505 \pm 4.92 \\
2\Delta C_{2u} - \Delta C_{2d} &= 1.74 \pm 6.31
\end{align}

where $\Delta C_{2q} = (\eta_{LL} - \eta_{LR} + \eta_{RL} - \eta_{RR})/(2\sqrt{2}G_F)$ and $\Delta C_{3q} = (-\eta_{LL} + \eta_{LR} + \eta_{RL} - \eta_{RR})/(2\sqrt{2}G_F)$. The leptoquark solutions of $S_{1/2}$ and $S_0$ give $\Delta C_{2q} = 0$ and $\Delta C_{3q} \sim -10^{-3}$. Therefore, the constraint from the $\mu C$ scattering is too weak to affect the leptoquark solutions.

We conclude that the $2.6\sigma$ deviation in the recent $a_\mu$ measurement places useful constraints on leptoquark models. To account for the $a_\mu$ data the leptoquark must have both the left- and right-handed couplings to the muon. Assuming that the couplings have electromagnetic strength, the mass is restricted to be about $0.7$ TeV < $M_{LQ} < 2.2$ TeV. If no first-second-generation universality is assumed, this mass range is well above the direct search limit at the Tevatron. On the hand, if the first-second-generation universality is assumed, constraints also come from other low energy and high energy experiments, among which the atomic-parity violation and charged-current universality are the most important. We have shown that coexistence with other leptoquarks can satisfy these additional constraints and at the same time do not affect the $a_\mu$. Leptoquarks in such a mass range should be produced at the LHC via the strong interaction.

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FIG. 1. Contributions to $\Delta a_\mu$ from the $F = 0$ leptoquark $S_{1/2}$ and the $F = -2$ leptoquark $S_0$. The shaded region is the 95% C.L. range of $\Delta a_\mu$ given in Eq. (12).