Muon $g - 2$ at multi-TeV muon collider

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Abstract

The long-standing discrepancy of muon $g - 2$ is a hint of new physics beyond the standard model of particle theory. In this letter we show that heavy new physics contribution may be fully tested in a muon collider with center-of mass energy up to $\mathcal{O}(10)$ TeV. Even if there is no new particle in this energy range, one can measure the $g - 2$ directly via the channel to a Higgs boson and a monochromatic photon.
1 Introduction

The long-standing discrepancy of muon anomalous magnetic moment \((g - 2)\) is the leading candidate suggesting new physics that couples to the standard model (SM). The muon \(g - 2\) anomaly indicates the more than 3 \(\sigma\) level deviation of 

\[
\Delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = (27.4 \pm 7.3) \times 10^{-10},
\]

where \(a_\mu^{\text{SM}}\) is the SM prediction of the muon \(g - 2\) from the so-called R-ratio approach [1, 2] (see also [3, 4]) and \(a_\mu^{\text{EXP}}\) is its experimental result [5, 6]. The ongoing experiment E989 at Fermilab [7] and the upcoming one at J-PARC [8] may significantly increase the accuracy of the experimental value. On the other hand, the leading order vacuum polarization contribution was recently calculated by Borsanyi et al in the Lattice QCD [9] and was discussed to resolve the tension, although the result is still on debate [10, 11]. Therefore, in order to confirm the discrepancy, efforts are being made on both experimental and theory sides. In this Letter, on the contrary, we propose a high energy test of the \(g - 2\), which is not bothered by the QCD non-perturbative effect.

On the model-building side, if a UV theory generates the \(g - 2\) anomaly, the resulting low energy effective theory should have the muon \(g - 2\) operator given by 

\[
\Delta L_{\text{eff}} \supset e \Delta a_\mu \mu \sigma_{\mu\nu} F^{\mu\nu}
\]

Here \(m_\mu \simeq 0.11\) GeV is the muon mass, where \(\sigma_{\mu\nu} \equiv i[\gamma_\mu, \gamma_\nu]/2\), and \(F^{\mu\nu}\) is the field strength of photon. In this UV explanation, we may either have new states much heavier than \(m_\mu\) to generate (2), or have strongly-coupled theory at the high energy since (2) is a higher dimensional term. On the contrary, the \(g - 2\) may be also explained due to a weakly-coupled light particle, below or around the muon mass, i.e. IR explanation.

In this letter, we point out that the UV explanation scenarios may be fully tested in a muon collider [12, 13] (see also recent studies for BSM [14–16]) with center-of-mass energy up to \(\mathcal{O}(1 - 10)\) TeV. This is because the heavy new physics relevant to the discrepancy must couple to the muon and thus should play an important role in muon-antimuon collisions. The new particles in the reachable energy scales can be produced in the collider and thus the \(g - 2\) can be tested indirectly by searching for the new particles. If heavy particles are so heavy that they are not reachable, or if they do not exist with just various higher dimensional operators, the process \(\mu \bar{\mu} \rightarrow h\gamma\), where \(h\) is a Higgs boson and \(\gamma\) is a monochromatic photon, via a dimension six operator is a robust prediction, which has a suppressed SM background. Consequently, the muon \(g - 2\) can be measured in the muon collider by measuring this cross section.

2 Muon \(g - 2\) from GeV-TeV physics and muon collider

Let us consider a general UV theory, which is renormalizable. The \(g - 2\) operator (2) can be generated through loop diagrams including new states. At the 1-loop level\(^1\), the diagram can be either composed of the following set of particles:

\[
(X_1, P_i^{\text{SM}}) \text{ or } (X_1, X_2)
\]

where \(X_i\) and \(P_i^{\text{SM}}\) denotes new particles and SM particles, respectively. The sum of the electromagnetic charges of the two particles is \(-1\), which is the charge of a muon.

\(^1\)At higher loop generation, the production cross section in the muon collider should be even enhanced and the scenario is easier to be tested. The tree level process is not important in renormalizable UV theory.
2.1 General discussion in renormalizable theory

Before discussing in detail, let us make a general discussion. To test the former case, one may generally measure the cross section of the SM process, \( \mu \bar{\mu} \rightarrow P_{SM} \bar{P}_{SM} \), which is from a \( X_1 \) mediated diagram. (If \( P_{SM} \) is a neutrino, the discussion would be almost the same as the second case.) In the context of \( X_1 = Z' \), it was shown in Ref. [21] that the \( Z' \) mediated process would lead to a significant enhancement of the scattering cross section of \( \mu \bar{\mu} \rightarrow \mu \bar{\mu} \), and that the muon collider should be possible to discriminate the scenario from the SM.\(^2\)

In the remainder of this section, we mainly discuss the latter case of (3). Suppose the typical coupling of the new particle is \( g \) and the heaviest new particle in the loop is \( X_1 \), whose mass is \( M_X \). The muon \( g - 2 \) anomaly contribution can be denoted in the form

\[
\delta\alpha_\mu = \kappa \frac{m_\mu^2 g^2}{16\pi^2 M_X^2} \tag{4}
\]

where \( \kappa \) is a model-dependent function of parameters. When \( \kappa = \mathcal{O}(1) \), the UV contribution to the (15) is proportional to the muon Yukawa coupling, \( y_\mu \), which is satisfied in various models. \( \kappa \) may be larger than \( \mathcal{O}(1) \) which does not change our conclusion.

To explain the discrepancy,

\[
M_X = 340 \text{ GeV} \times g\sqrt{\kappa} \sqrt{\frac{2.7 \times 10^{-9}}{\delta\alpha_\mu}.} \tag{5}
\]

Therefore, even if \( g\sqrt{\kappa} = \sqrt{4\pi} \) which is around the perturbative unitarity bound if \( \kappa = \mathcal{O}(1) \), the mass of the new state is around 1 TeV, and thus is reachable in the muon collider of center-of-mass energy \( \mathcal{O}(1 - 10) \) TeV. The question is whether the heavy state can be significantly produced. In fact, by cutting the heavy state propagator in the loop for the muon \( g - 2 \), one gets the \( \mu + \bar{\mu} \rightarrow X_1 + \bar{X}_1 \) process. The corresponding cross section can be estimated as

\[
\sigma \simeq \kappa_2 \frac{g^2}{4\pi E_{cm}^2} \quad (\text{for } E_{cm} > 2M_X). \tag{6}
\]

Here \( \kappa_2 \) is another model-dependent function of momentum and parameters, and \( E_{cm} \) is the center-of-mass energy. By substituting (5), the lower band of the cross section can be obtained as

\[
\sigma \gtrsim 230 \text{ pb} \times \frac{\kappa_2}{\kappa^2} \left( \frac{M_X}{310 \text{ GeV}} \right)^4 \left( \frac{500 \text{ GeV}}{E_{cm}} \right)^2 \left( \frac{\delta\alpha_\mu}{2.7 \times 10^{-9}} \right). \tag{7}
\]

Here we take the inequality because there could be other processes like a Drell-Yan production of \( X_1, \bar{X}_1 \) pair if \( X_1 \) is charged. By assuming a year of the run and \( 10^7 \) s/year operation of a muon collider at the center-of-mass energy around \( M_X \) [13], the number of events for \( X_1, \bar{X}_1 \) pair production is

\[
N \simeq 2.3 \times 10^7 \left( \frac{\text{time}}{1 \text{ yrs}} \right) \left( \frac{\sigma}{27 \text{ pb}} \right) \left( \frac{\text{luminosity}}{10^{34} \text{cm}^2\text{s}^{-1}} \right). \tag{8}
\]

If \( X_1 \) does not carry any charge, \( X_1 \) soon decays to a muon and a charged new particle, which should be searched for analog to the dilepton search in the context of \( Z' \) [17,18].\(^3\) If \( X_1 \)

\(^2\)This is the case that \( Z' \) is heavy enough. In fact a light \( Z' \) can also explain the muon \( g - 2 \) anomaly with a small coupling, which is an IR scenario and is not our focus. This case may not be tested in the muon collider (See, on the other hand, the \( Z' \) search in DUNE, M\(^3\), and NA64 [22–24].)

\(^3\)Even if the \( X_1 \) decays to neutral particles dominantly, the scenario may be tested from the mono-photon search c.f. Ref. [16].
is charged, on the other hand, it may decay into a muon and a neutral state. So the event should be
\[
\mu + \bar{\mu} \rightarrow X_1 + \bar{X}_1 \rightarrow \mu + \bar{\mu} + X_2(\nu) + \bar{X}_2(\bar{\nu}),
\]
where \(X_2\) is assumed to be lighter than \(X_1\). The dominant background is
\[
\mu + \bar{\mu} \rightarrow W^+ + W^- \rightarrow \mu + \bar{\mu} + \nu_\mu + \bar{\nu}_\mu.
\]
Notice that in the muon collider, the center-of-mass colliding energy is given unlike the hadron collider. Thus, one may study the kinematics of the out-going muons to identify the masses of the new particles, e.g. for the background case, two out-going muons are almost back to back. This is in contrast with the new physics case: if \(X\) is massive, the produced muons is not so back to back. In any cases, the acoplanar dileptons in excess of expectations of \(WW\) and \(ZZ\) production may be the signal a la slepton searches in lepton colliders [19,20]. (For comparison the SM cross section of \(\mu\bar{\mu} \rightarrow \mu\bar{\mu} + \text{missing}\) is below a few fb with the center-of-mass energy \(\sim 10 \text{ TeV} [16]\).)

2.2 Muon-smuon-bino system

To be more concrete, one may consider
\[
\mathcal{L}_{\text{int}} = -g_1 \bar{\mu}_L \tilde{P}_L \phi_R \lambda - g_2 \bar{\mu}_R \tilde{P}_R \phi_L \lambda + \delta M^2 \phi_L^* \phi_R + h.c.
\]
where \(\lambda\) is a Majorana fermion with mass \(M_\lambda\) while \(\phi_{L,R}\) are complex scalars with mass squares \(m^2_{L,R}\); \(\mu_L\) and \(\mu_R\) represent the left and right-handed muon, respectively. This Lagrangian with restricted parameter relations can be identified as the one from the minimal supersymmetric SM (MSSM), in which \(\lambda\) and \(\phi_{L,R}\) are identified as bino and smuons, respectively. In the context of MSSM, the so-called Higgs mediation mechanism [26]\(^4\), which is proposed by the present authors, can lead to the sizable contribution to the muon \(g - 2\) with this effective Lagrangian. For scenarios involving the Higgs mediation in explaining the muon \(g - 2\) anomaly, see Refs. [26–30], and explaining both muon and electron \(g - 2\) anomaly [31,32].

The muon \(g - 2\) contribution is calculated as (c.f. Ref. [34])
\[
\delta a_\mu \simeq -\frac{g_1 g_2 m_\mu \delta M^2 M_\lambda}{8 \pi^2 m^2_L m^2_R} \left( \frac{m^2_L}{M^2_{\phi L}}, \frac{m^2_R}{M^2_{\phi R}} \right),
\]
where we have used the mass insertion approximation on the scalar mixings of \(\delta M^2\) and
\[
f(x, y) = xy \left( \frac{-3 + x + y + xy}{(x-1)^2(y-1)^2} + \frac{2x \log x}{(x-y)(x-1)^3} - \frac{2y \log y}{(x-y)(y-1)^3} \right),
\]
which satisfies \(0 < f(x, y) < 1\), and \(f(1, 1) = 1/6\). \(\delta M^2\) should satisfy that
\[
\delta M^2 \lesssim \min [m^2_L, m^2_R],
\]
Otherwise not only our approximation of mass insertion in (10) is invalid but also there are dangerous tachyonic scalars or vacuum instability (c.f. Ref [35]).

\(^4\)This is named in Ref. [27].
\(^5\)Also see Ref. [33] for the \(E_7/\text{SU}(5) \times \text{U}(1)^3\) unification of family. In the scenario the mass degeneracy between bino and wino is “predicted” to be within \(\mathcal{O}(1)\)%\(^5\). Thanks to the Higgs mediation, the bino can be the dominant dark matter with a bino-wino coannihilation, and, moreover, the bottom-tau Yukawa coupling unification can be achieved up to \(\mathcal{O}(1)\)%.
Let us check the minimal production cross section of the new particles in the muon collider. By fixing $g_1, g_2$, $\delta \alpha_\mu$ becomes the largest when $M_\lambda \sim m_L \sim m_R \sim \sqrt{|\delta M|^2}$. With the relation we obtain the maximum contribution as

$$|\delta a_\mu| \lesssim \frac{|g_1 g_2|}{8\pi^2} \frac{m_\mu}{M_\lambda} f_N \simeq 2.3 \times 10^{-9} \left( \frac{|g_1 g_2|}{0.01} \right) \left( \frac{1 \text{ TeV}}{M_\lambda} \right) \left( \frac{f_N}{1/6} \right). \quad (12)$$

We then get

$$\kappa \lesssim \frac{M_\lambda}{m_\mu}. \quad (13)$$

The upper limit corresponds to the smallest production cross section via the same coupling. In this scenario, the Drell-Yan production of charged leptons of $\phi_L$, or $\phi_R$, is significant. The cross-section purely mediated by a off-shell photon is given as

$$\sigma_{\text{Drell-Yan}}^{\mu\bar{\mu}\to\phi_{L,R}\phi^{*}_{L,R}} \simeq \frac{e^4}{24\pi E_{\text{cm}}^2} \sim 0.5 \text{ fb} \left( \frac{10 \text{ TeV}}{E_{\text{cm}}} \right)^2. \quad (14)$$

By taking into account the $Z$-boson contribution, the cross section can differ by $O(1)$ factor. Since the “sleptons” can be produced with $O(1)ab^{-1}$ with $E_{\text{cm}} \lesssim 100$ TeV, they may be easily detected due to the clean environment like the case of electron-positron collider (e.g. [19,20,35]).

In this section we have assumed that the new states relevant to the muon $g-2$ are reachable in the muon collider. If $|g_1 g_2| \gtrsim O(1)$ in Eq.(12), the new physics scale may be above 100 TeV. Then the new particles are difficult to reach in the muon collider. Nevertheless, one can test the muon $g-2$ by directly measuring the $g-2$ as shown soon.

### 3 Effective theory approach

Now let us assume the possibility that no new physics state is reachable in the muon collider. The $g-2$ operator is directly related with the coupling to the Higgs boson, $h$, as

$$\Delta L_{\text{eff}} \supset \frac{y_\mu}{M^2} \frac{h}{2\sqrt{2}} \bar{\mu} \sigma_{\mu\nu} F^{\mu\nu} \mu, \quad (15)$$

where we have used $m_\mu = y_\mu v$ with $v \simeq 174$ GeV being the expectation value of the Higgs field, $h$, and have replaced $v$ to be $v + h/\sqrt{2}$ from Eq.(2).\(^7\) Here, to explain the anomaly (1),

$$M \simeq 7.6 \text{ TeV} \left( \frac{2.7 \times 10^{-9}}{\Delta \alpha_\mu} \right)^{1/2}. \quad (16)$$

Notice that (15) is a dimension-six term which becomes stronger in the collisions of muon-antimuon at higher energy.

The robust prediction of the muon $g-2$ anomaly in the effective theory is the enhancement on the $h-\gamma$ production of

$$\mu + \bar{\mu} \rightarrow h + \gamma \quad (17)$$

\(^6\)In the symmetric phase, we may also have a vertex of muons, (charged) Higgs, and $Z$ ($W$) boson. This is more or less model-dependent, and we do not consider.

\(^7\)One may also consider dimension $>6$ terms to generate (2) with several Higgs fields. In this case, still we get a similar dimension 6 term with several Higgs field replaced by the vev, and the crosssection of $\mu\bar{\mu} \rightarrow h\gamma$ can be enhanced by $O(1-10)$. However we may get a much enhanced production cross-section of multiple Higgs boson and a photon at the high energy. That said, in a natural setup the contribution from the dimension six term should be the dominant.
Fig. 1: The cross section of $\mu\bar{\mu} \to h\gamma$ via the muon $g-2$ operator (15) by varying the center-of-mass energy. The red (blue) band corresponds to the $1\sigma$ ($2\sigma$) region of the muon $g-2$ anomaly.

at high energy. This provides a signal of a monochromatic photon with energy $\sim E_{cm}/2$ and two fermions or four fermions with the invariant mass of the Higgs boson. The production cross section of $h\gamma$ can be calculated as

$$\sigma_{\mu\bar{\mu} \to h\gamma} \approx \frac{y_\mu^2 E_{cm}^2}{48\pi M^4} \sim 0.1 \text{ab} \left(\frac{E_{cm}}{20 \text{ TeV}}\right)^2 \left(\frac{7.6 \text{ TeV}}{M}\right)^4$$

(18)

where we have neglected the masses of the initial and final states. The cross section at the tree-level is plotted in the Fig. 1. One finds that the cross section can be $\mathcal{O}(0.1-1) \text{ab} E_{cm} = \mathcal{O}(10) \text{ TeV}$. The process $\mu + \bar{\mu} \to h + \gamma$ is absent in the SM at the tree-level with neglecting the muon mass. At the loop level, for instance, the top-loop-induced contribution is

$$\sigma_{\mu\bar{\mu} \to h\gamma}^{\text{SM}} \sim \frac{y_t^2 e^6}{(4\pi)^5} \frac{1}{E_{cm}^2} \sim 0.002 \text{ab} \left(\frac{20 \text{ TeV}}{E_{cm}}\right)^2.$$ 

(19)

Thus this can be safely neglected at a multi-TeV muon collider. The background of $\mu\bar{\mu} \to Z\gamma$ or $\mu\bar{\mu} \to WW\gamma$ should not be very important, since the cross section decreases with larger $E_{cm}$ and the contribution should be suppressed with multi-TeV of $E_{cm}$ (c.f. Refs. [36–38]). Consequently, one can test the muon $g-2$ by directly measuring the $g-2$ operator (15).

4 Conclusions

We have shown that the muon $g-2$ anomaly explanation by integrating heavy new states or with dimension six operator can be fully tested in a muon collider with center-of-mass energy up to $\mathcal{O}(10) \text{ TeV}$ and integrated luminosity of several $\text{ab}^{-1}$. In our proposal the QCD non-perturbative effects are no more relevant, and our theoretical estimation is not bothered by them.

Note added: While preparing this paper, we found Ref. [39] which may overlap with the present work.
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