

Leptomeson contribution to the muon $g - 2$

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Many models on the market allow for particles carrying both lepton number and color, e.g., leptoquarks and leptogluons. Some of the models with this feature can also accommodate color-singlet leptohadrons. We have found that the long-standing discrepancy between the experimental result and the Standard Model prediction for the muon anomalous magnetic moment can be explained by the effect of leptomesons with masses of a few hundred GeV and couplings to the leptons and mesons either of $\mathcal{O}(10^{-2})$ (vector-meson case) or of $\mathcal{O}(1)$ (scalar case). These new particles are testable at the current run of the LHC.

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I. INTRODUCTION

Nowadays physics at small scales is established to the characteristic distances for the nucleons substructure of about 10^{-15} m. There are many interesting theories which explore physics at even smaller distances, e.g., theories of extra dimensions and string theories. Yet another type of models constitute so-called composite models [1–10]. The composite models—which contain colored preons—predict the possibility of leptoquarks and leptogluons. Leptoquarks are also present in many theories of grand unification [1,11,12], R -parity-violating supersymmetric models [13], and in the extended technicolor models [14]. Many theories containing particles that carry lepton number and color simultaneously predict color-singlet leptohadrons, in particular the bound states of leptoquark-antiquark pairs [15–17]. However, their experimental signatures are poorly addressed in the literature. In this paper we consider the possible phenomenology of a particle that interacts with a lepton and a meson and can be referred to as leptomeson (LM). Since LMs are colorless they can be lighter (and more accessible for collider probes) than the leptoquarks with their heavy color dressing.

At low energies the new heavy particles may reveal themselves in the tiny effects on the lepton intrinsic properties (magnetic moment, charge radius, etc.). Currently one of the tools most sensitive to the new physics is the precise measurement of the muon anomalous magnetic moment (AMM) $a_\mu = (g_\mu - 2)/2$, which reveals a $3\text{--}4\sigma$ discrepancy with its theoretical prediction within the Standard Model (SM) [18–20]. Among the possible new heavy composites in the theories of compositeness, leptogluons may contribute to the lepton AMM starting only from the two-loop level. However, one-loop contributions can be generated by the colorless excited leptons [21,22] and leptoquarks [23–26]. Leptomesons may effectively provide a new one-loop contribution to the muon AMM. A not too large size for this contribution can be achieved due to either large LM masses of $\mathcal{O}(100)$ GeV

(scalar LM case) or small LM couplings of $\mathcal{O}(10^{-2})$ (vector LM case), as shown below.

Many kinds of one-loop contributions to a_μ were classified [27,28] by the types of particles that propagate in the loop, which typically include light SM fermions (leptons and light quarks) and heavy vectors, scalars, and fermions (W , Z , H , t , and new heavy particles). In addition, there is a possibility of very light [with the masses of $\mathcal{O}(1)$ GeV] superweakly coupled new particles [29–33] propagating in the loop, which is hard to test in collider experiments. However, the discussed leptomeson contribution to a_μ is the new physics contribution that involves light vector and/or scalar particles (vector and scalar mesons), and can be tested at colliders.

In this paper we investigate the effects of LMs on the muon $g - 2$. To our knowledge, these effects have not been considered yet in the literature. In the next section we give analytical expressions for the characteristic LM contributions to a_μ . In Sec. III we present and discuss the numerical results, and we conclude in Sec. IV.

II. LEPTOMESONS IN MUON $g - 2$

The present discrepancy between the experimental data and the SM calculation for the muon AMM is [19]

$$\Delta a_\mu = 26.1(8.0) \times 10^{-10}, \quad (1)$$

which is 3.3σ . Recent progress in calculating the hadronic contribution increases this discrepancy up to 3.8σ [34]. A further essential increase is possible after more precise measurements of a_μ in the near-future experiments at Fermilab [35] and J-PARC [36]. We consider the possibilities of explaining this anomaly using LM contributions.

For each lepton flavor one can expect several neutral LMs ℓ_{Si}^0 (ℓ_{Vi}^0), which interact with the mesons of scalar (vector) type S (V) and decay into the lepton-meson pairs: $\ell^+ S^-$, $\ell^- S^+$, $\nu_\ell S^0$ ($\ell^+ V^-$, $\ell^- V^+$, $\nu_\ell V^0$). Concerning the charged LMs, we presume the singly charged $\ell_{S(V)}^\pm$ and the doubly charged $\ell_{S(V)}^{\pm\pm}$ states, which can decay into $\{\ell^\pm S^0, \nu_\ell S^\pm\}$

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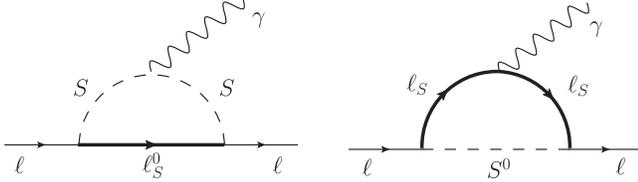


FIG. 1. Feynman diagrams for the one-loop contribution to $g_\ell - 2$ for the leptomesons: neutral ℓ_S^0 (left) and singly charged ℓ_S (right).

($\{\ell^\pm V^0, \nu_\ell V^\pm\}$) and $\ell^\pm S^\pm$ ($\ell^\pm V^\pm$), respectively.¹ Due to the large number of mesons and possible variety of LMs we restrict our consideration by typical scalar and vector meson-LM-lepton interactions, which may give significant corrections to the lepton AMM a_ℓ .

The lowest-dimension Lagrangian for the interactions of neutral, singly charged, and doubly charged LMs with the charged leptons and the mesons can be written as

$$\begin{aligned} \mathcal{L}_{\text{LM}} = & - \sum_{\alpha, \beta=L,R(\alpha \neq \beta)} \bar{\ell}_\beta (g_{\alpha S}^0 \ell_{\alpha S}^0 S^- + g_{\alpha S}^- \ell_{\alpha S}^- S^0 + g_{\alpha S}^- \ell_{\alpha S}^- S^+) \\ & - \sum_{\alpha=L,R} \bar{\ell}_\alpha \gamma^\mu (g_{\alpha V}^0 \ell_{\alpha V}^0 V_\mu^- + g_{\alpha V}^- \ell_{\alpha V}^- V_\mu^0 + g_{\alpha V}^- \ell_{\alpha V}^- V_\mu^+) \\ & + \text{H.c.}, \end{aligned} \quad (2)$$

where $\ell = e, \mu, \tau$ is the charged lepton, and $g_{\alpha S}$ and $g_{\alpha V}$ are the new dimensionless couplings with suppressed flavor indices. For simplicity we require real couplings (to avoid constraints from the electric dipole moment of the electron) and flavor conserving interactions in Eq. (2).

The leading contributions to the lepton AMM from the one-loop processes with neutral and singly charged scalar

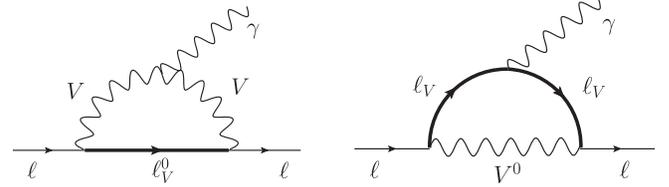


FIG. 2. Feynman diagrams for the one-loop contribution to $g_\ell - 2$ for the leptomesons: neutral ℓ_V^0 (left) and singly charged ℓ_V (right).

and vector LMs are represented in Figs. 1 and 2. Using the generic analytic formulas for the one-loop contributions to the lepton AMM [27,37] in the limit of large LM masses with respect to the lepton mass m_ℓ and the meson masses, these contributions can be written as

$$\Delta a_{\ell_S^0} = -\frac{(g_{\alpha S}^0)^2 m_\ell^2}{16\pi^2 M_0^2} f_{\text{SSF}} \left(\frac{m_{S^\pm}^2}{M_0^2} \right), \quad (3)$$

$$\Delta a_{\ell_S^\pm} = \frac{(g_{\alpha S}^-)^2 m_\ell^2}{16\pi^2 M^2} f_{\text{FFS}} \left(\frac{m_{S^0}^2}{M^2} \right), \quad (4)$$

$$\Delta a_{\ell_V^0} = \frac{(g_{\alpha V}^0)^2 m_\ell^2}{16\pi^2 m_{V^\pm}^2} f_{\text{VVF}} \left(\frac{m_{V^\pm}^2}{M_0^2} \right), \quad (5)$$

$$\Delta a_{\ell_V^\pm} = -\frac{(g_{\alpha V}^-)^2 m_\ell^2}{16\pi^2 m_{V^0}^2} f_{\text{FFV}} \left(\frac{m_{V^0}^2}{M^2} \right), \quad (6)$$

where m_S (m_V) is the scalar (vector) meson mass, M (M_0) is the mass of the charged (neutral) LM, and the loop functions are

$$\begin{aligned} f_{\text{SSF}}(x) &= \frac{1}{6(1-x)^4} [2 + 3x - 6x^2 + x^3 + 6x \ln x] \\ &\approx \frac{1}{3} + \frac{11}{6}x + x \ln x, \end{aligned} \quad (7)$$

$$\begin{aligned} f_{\text{FFS}}(x) &= \frac{1}{6(1-x)^4} [1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x] \\ &\approx \frac{1}{6} - \frac{x}{3}, \end{aligned} \quad (8)$$

$$\begin{aligned} f_{\text{VVF}}(x) &= \frac{1}{6(1-x)^4} [4 - 49x + 78x^2 - 43x^3 + 10x^4 - 18x \ln x] \\ &\approx \frac{2}{3} - \frac{11}{2}x - 3x \ln x, \end{aligned} \quad (9)$$

$$\begin{aligned} f_{\text{FFV}}(x) &= \frac{1}{6(1-x)^4} [5 - 14x + 39x^2 - 38x^3 + 8x^4 + 18x^2 \ln x] \\ &\approx \frac{5}{6} + x, \end{aligned} \quad (10)$$

¹To be definite we classify LMs by the type of their interaction with mesons (either scalar or vector). However, in general, one LM may have both scalar and vector type interactions.

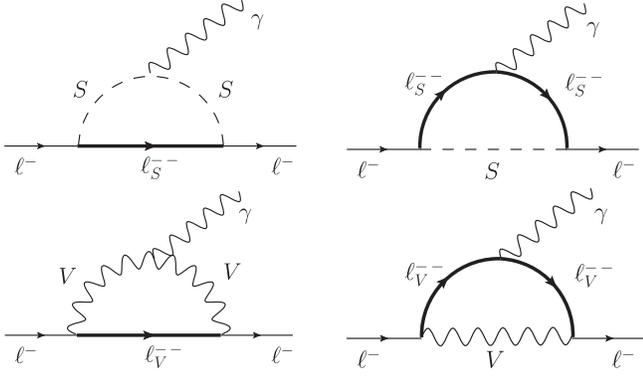


FIG. 3. Feynman diagrams for the one-loop contribution to the AMM of ℓ^- for the doubly charged leptomesons: ℓ_S^{--} (upper) and ℓ_V^{--} (lower).

where in the approximate expressions we neglected the terms of $\mathcal{O}(x^2)$. Clearly, these functions are positive for small x , and the contributions in Eqs. (3) and (5) are negative, while in Eqs. (4) and (6) they are positive. The relations to the loop functions given in Eq. (A.1) of Ref. [27] are as follows:

$$f_{\text{SSF}}(x) \equiv -\frac{1}{x} F_{\text{SSF}}\left(\frac{1}{x}\right) = F_{\text{FFS}}(x), \quad (11)$$

$$f_{\text{FFS}}(x) \equiv \frac{1}{x} F_{\text{FFS}}\left(\frac{1}{x}\right) = -F_{\text{SSF}}(x), \quad (12)$$

$$f_{\text{VVF}}(x) \equiv F_{\text{VVF}}\left(\frac{1}{x}\right), \quad (13)$$

$$f_{\text{FFV}}(x) \equiv -F_{\text{FFV}}\left(\frac{1}{x}\right). \quad (14)$$

The contributions of the scalar LMs in Eqs. (3) and (4) are suppressed by the second power of the meson-to-LM mass ratio. The case of vector LMs is special since their contributions in Eqs. (5) and (6) do not have this suppression. Hence smaller values of the couplings are required for the vector LM interactions to not to exceed the discrepancy in Eq. (1).

Notice that in the case of one-loop contributions to a_ℓ of a scalar S ($g_{LS} = g_{RS}$) and a pseudoscalar P ($g_{LS} = -g_{RS}$) the lepton mass m_ℓ receives large loop corrections unless the chirally symmetric limit $m_S = m_P$ is satisfied [38,39].

The leading contributions to the lepton AMM from the one-loop processes with doubly charged scalar and vector LMs are shown in Fig. 3, and can be written as

$$\Delta a_{\ell_S^{--}} = -\frac{(g_{\alpha S}^-)^2}{16\pi^2} \frac{m_\ell^2}{M_{--}^2} f_{\text{SF}}\left(\frac{m_{S^\pm}^2}{M_{--}^2}\right), \quad (15)$$

$$\Delta a_{\ell_V^{--}} = -\frac{(g_{\alpha V}^-)^2}{16\pi^2} \frac{m_\ell^2}{m_{V^\pm}^2} f_{\text{VF}}\left(\frac{m_{V^\pm}^2}{M_{--}^2}\right), \quad (16)$$

where M_{--} is the mass of the doubly charged LM, and the loop functions are

$$\begin{aligned} f_{\text{SF}}(x) &= f_{\text{SSF}}(x) - 2f_{\text{FFS}}(x) \\ &= \frac{x}{2(1-x)^4} [5 - 4x - x^2 + (2+4x)\ln x] \\ &= \frac{5}{2}x + x\ln x + \mathcal{O}(x^2), \end{aligned} \quad (17)$$

$$\begin{aligned} f_{\text{VF}}(x) &= -f_{\text{VVF}}(x) + 2f_{\text{FFV}}(x) \\ &= \frac{1+2x}{2(1-x)^4} [2 + 3x - 6x^2 + x^3 + 6x\ln x] \\ &= 1 + \frac{15}{2}x + 3x\ln x + \mathcal{O}(x^2), \end{aligned} \quad (18)$$

where the factors of 2 in Eqs. (17) and (18) come from the fact that the electromagnetic interaction of the doubly charged LM is twice as strong as that of a singly charged particle. Both scalar and vector doubly charged LM contributions are negative.

We demonstrate in Sec. III that a single *mumeson* (muonic leptomeson)—which is either a charged scalar μ_S^0 or neutral vector μ_V^0 , and dominantly interacts with a specific meson—can provide the observed value of a_μ for the mass of a few hundred GeV with the couplings of $g_{\alpha S}^- = \mathcal{O}(1)$ and $g_{\alpha V}^0 = \mathcal{O}(10^{-2})$, respectively. The case with either several mumesons or one mumeson that has a significant interaction with several mesons, which essentially contribute to a_μ , is more involved and potentially has richer phenomenology. We discuss this case in several examples.

III. RESULTS AND DISCUSSION

The new particles in various theories can be generically constrained using the parameters S and T [40]. However, large contributions to the T parameter are excluded in the case of approximate mass degeneracy of the components of the new weak multiplets, while a significant change of the S parameter is avoided in case of vector-like couplings of new fermions to the gauge bosons (this simultaneously ensures the cancellation of axial-vector gauge anomalies) [27]. The existence of the three generations of the SM leptons supposes analogous generations of the leptohadrons. This allows one to accommodate the assumption of minimal flavor violation [41], which may help to avoid the constraints from the nonobservation of the flavor-violating processes (such as $\mu \rightarrow e\gamma$) and to protect the muon mass from large corrections induced by vector fermions [27]. The nonobservation of new fermions in e^+e^- collisions at the LEP collider at center-of-mass energies $\sqrt{s} \approx 200$ GeV yields a generic lower bound on the LM mass of $M \gtrsim 100$ GeV. Moreover, Z -pole precision measurements at LEP strongly constrain the vector LM mixings.

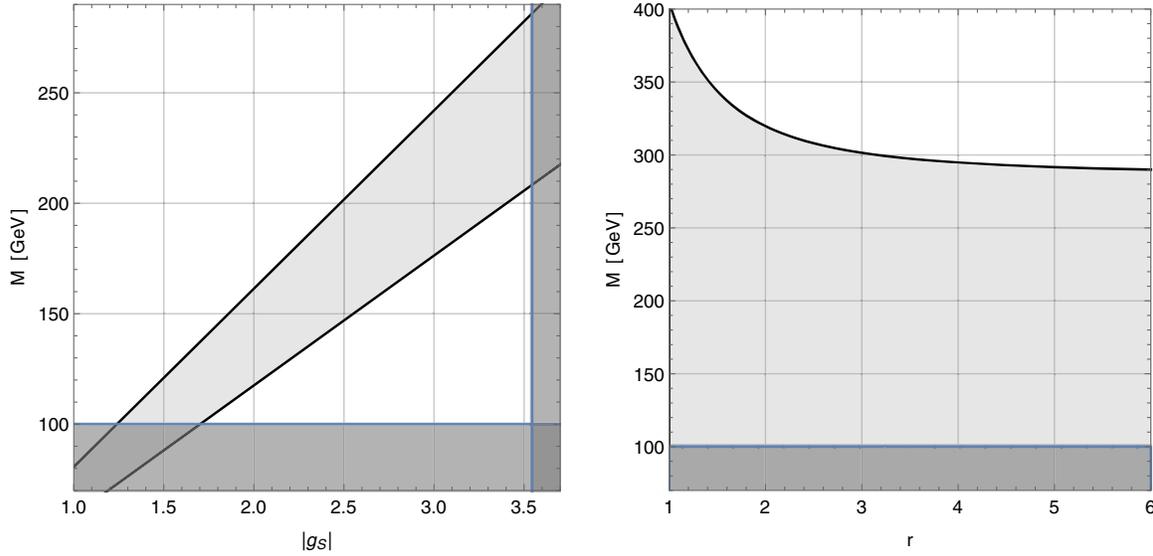


FIG. 4. Allowed regions for the charged mimeson(s) interacting with the scalar meson(s). Left: Mimeson mass M vs coupling $|g_S|$ for a single meson-mimeson-lepton interaction. The light grey region is allowed by the current $(g-2)_\mu$ data within the 1σ range. The dark grey regions represent the generic LEP mass bound of $M > 100$ GeV and the perturbativity bound of $|g_S| < \sqrt{4\pi}$. Right: Mass M vs ratio r in case of two mimeson contributions to a_μ . The light grey region is allowed by the current a_μ data (within 1σ) and the perturbativity bound of $|g_{Si}| < \sqrt{4\pi}$. The dark grey region is disfavored by the LEP data.

A. Scalar leptomeson contribution

For scalar mimesons the value of a_μ is insensitive to the meson masses of $\mathcal{O}(1)$ GeV. The proper value of a_μ can be provided for a single charged mimeson μ_S^- with a mass M below 280 GeV, as shown in Fig. 4 (left). In this figure we assume a significant effect on a_μ of only one coupling $g_S \equiv g_{\alpha S}$, where α is either R or L . It is clear that small values of the coupling $|g_S|$ below 1.2 are ruled out. Constraints from four-lepton contact interactions are absent if the meson S^0 is self-conjugate since the box diagram shown in Fig. 5 (left) is canceled by a second diagram with crossed fermion lines in the final state.

In the case of two significant scalar mimeson contributions to a_μ , the lightest mimeson mass M can be as large as 400 GeV, which is shown in Fig. 4 (right) for the charged mimesons. In this figure the ratio r is defined as

$$r = \frac{M_2 |g_{S1}|}{M_1 |g_{S2}|} < \frac{M_2 \sqrt{4\pi}}{M_1 |g_{S2}|}, \quad (19)$$

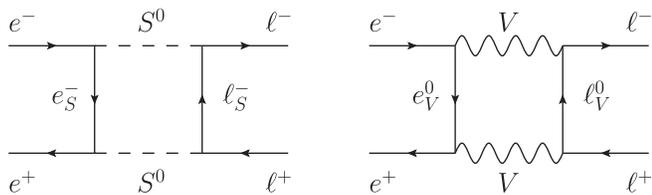


FIG. 5. One-loop leptomeson ℓ_S (left) and ℓ_V^0 (right) contributions to the effective four-lepton interactions $eell$.

where M_i ($i = 1, 2$; $M \equiv M_1 \leq M_2$) and $g_{Si} \equiv g_{\alpha Si}$ ($|g_{S1}| \geq |g_{S2}|$) are the mimeson masses and couplings, respectively. In particular, in the case of two scalar mimesons μ_{S1} and μ_{S2} that interact with a meson S^0 with the same coupling this ratio is reduced to $r = M_2/M_1$, while in the case of one scalar mimeson, which significantly interacts with two mesons S_1^0 and S_2^0 with different couplings $g_{S1} \neq g_{S2}$, the ratio is reduced to $r = |g_{S1}/g_{S2}| < 4\pi/|g_{S2}|$.

The lower bound on the μ_S^\pm mass can be significantly increased through the searches for their pair production at the LHC. However, in this case the final state is composed of a dimuon and neutral meson-antimeson pair (the decay of which may give photons, leptons, π^\pm , etc.) instead of the final state of a dilepton plus either gluonic or quark jets, which was considered in the searches for leptoquarks [42,43] and leptogluons [44–46]. Other alternatives include searches for single μ_S^\pm productions, and $\mu^+\mu^-$ production in meson-meson fusion via t -channel exchange of μ_S^\pm .

B. Vector leptomeson contribution

For vector mimesons μ_V the value of a_μ is sensitive to the meson masses and almost insensitive to the mimeson masses. For one neutral mimeson interaction the allowed range of the mimeson mass values is $100 \text{ GeV} < M_0 \lesssim 180 \text{ GeV}$, which corresponds to the allowed area between the lower and upper dark grey bands in Fig. 6 (left). The three light grey areas in this figure correspond to the ranges

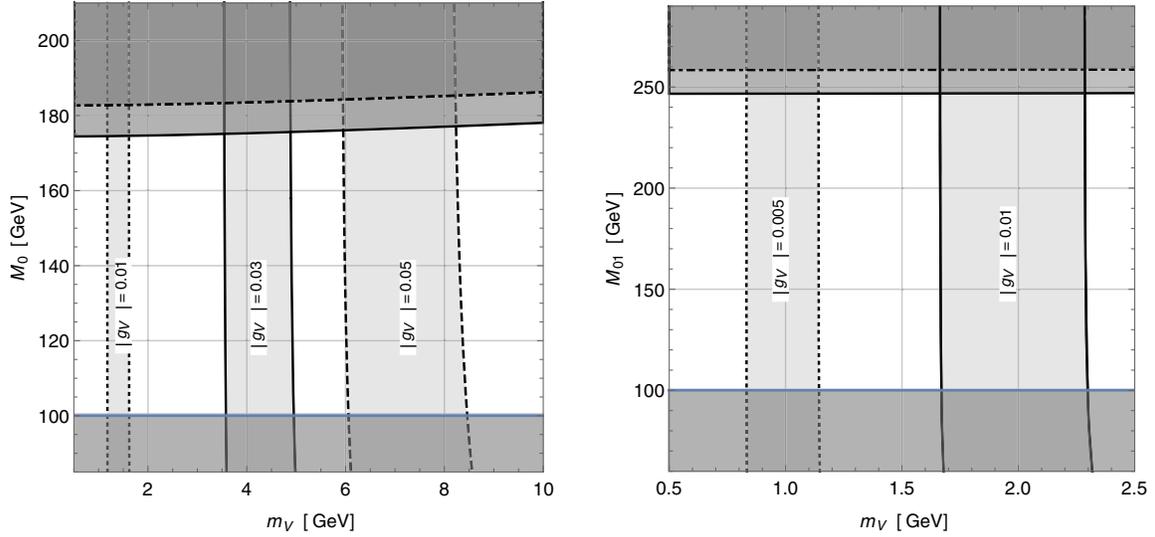


FIG. 6. Allowed regions in the vector meson-mimeson mass plane for the neutral mimeson(s) with flavor-universal LM interactions. The dark grey area in the bottom is disfavored by the generic mass bound of $M_0 > 100$ GeV. The top dark grey areas with solid and dot-dashed boundaries are disfavored by LEP constraints on $e\ell\ell$ contact interactions to explain a_μ (within the 1σ range) for the left-chiral and right-chiral case, respectively. Left: Case of a single mimeson μ_V^0 with the coupling g_V , where the light grey regions with dotted, solid, and dashed boundaries are allowed by the current a_μ data (within 1σ) for $|g_V| = 0.01, 0.03$, and 0.05 , respectively. Right: Case of two mimeson-meson-lepton couplings $g_{V1} = \pm g_{V2}$, where the light grey regions with dotted and solid boundaries are allowed by a_μ data (within 1σ) and correspond to $g_V \equiv g_{V1} = \pm 5 \times 10^{-3}$ and ± 0.01 , respectively.

allowed by the current a_μ data (within 1σ) for the chosen values of the coupling of $|g_V| = 0.01, 0.03$, and 0.05 , where $g_V \equiv g_{\alpha V}^0$ (α is either L or R). Clearly only small values of $|g_V| = \mathcal{O}(10^{-2})$ are allowed.

The neutral leptomesons ℓ_V^0 generate four-lepton contact interactions $e\ell\ell$ through the box diagram shown in Fig. 5 (right). These interactions can be calculated and compared to the effective expression containing the contact interaction scale Λ as [27,47]

$$\begin{aligned} & \frac{(g_V^e)^2 (g_V^\ell)^2}{64\pi^2 m_{V^\pm}^2} F\left(\frac{M_0^2}{m_{V^\pm}^2}\right) (\bar{e}_\alpha \gamma_\mu e_\alpha) (\bar{\ell}_\alpha \gamma^\mu \ell_\alpha) \\ & \leq \frac{4\pi}{(1+\delta)\Lambda^2} (\bar{e}_\alpha \gamma_\mu e_\alpha) (\bar{\ell}_\alpha \gamma^\mu \ell_\alpha), \end{aligned} \quad (20)$$

where we restored the flavor index of the couplings $g_V^\ell \equiv g_{\alpha V}^{\ell}$ and assumed a common mass scale M_0 of the LMs ℓ_V^0 , the parameter $\delta = 1(0)$ for $\ell = e$ ($\ell \neq e$), and the loop function can be written as

$$\begin{aligned} F(y) = & \frac{1}{(y-1)^3} [y^4 - 16y^3 + 19y^2 \\ & + 2(3y^2 + 4y - 4)y \ln y - 4] > 0. \end{aligned} \quad (21)$$

For the flavor-universal couplings $g_V \equiv g_V^\ell$ the limit in Eq. (20) can be rewritten using Eq. (5) as

$$\pi (\Delta a_\mu^{\min})^2 \frac{m_{V^\pm}^2}{m_\mu^2} F\left(\frac{M_0^2}{m_{V^\pm}^2}\right) f_{\text{VVF}}^{-2}\left(\frac{m_{V^\pm}^2}{M_0^2}\right) \leq \frac{m_\mu^2}{(1+\delta)\Lambda^2}, \quad (22)$$

where Δa_μ^{\min} is the minimal allowed value of Δa_μ , e.g., within the 1σ range: $\Delta a_\mu^{\min} = 18.1 \times 10^{-10}$ from Eq. (1). In the considered case of constructive interference between the SM process and the contact interactions, the constraints from the LEP measurements of $e^+e^- \rightarrow \ell^+\ell^-$ processes correspond to the lower limits of $\Lambda = 12.7$ TeV for $\alpha = R$ and $\Lambda = 13.3$ TeV for $\alpha = L$ (for $\ell = \mu, \tau$, which gives stronger limits) [48], and exclude parts of the parameter space, which are labeled dark grey in the top of Fig. 6 (left).

In the case of two neutral vector-mimeson contributions to a_μ , which have the common LM and meson mass scales M_0 and m_V , the left-hand side of Eq. (22) gets an additional factor of

$$\frac{1+\rho^4}{(1+\rho^2)^2} \geq \frac{1}{2}, \quad (23)$$

where ρ is the ratio of the two couplings. The minimal value of $1/2$ of this factor is achieved for the equal couplings (up to the sign) and corresponds to the weakest constraint from the contact interactions. Figure 6 (right) illustrates the case of either two vector mimesons with approximately equal masses $M_{01} \approx M_{02}$ interacting with the same charged meson, or one mimeson with the mass $M_0 \equiv M_{01}$, which

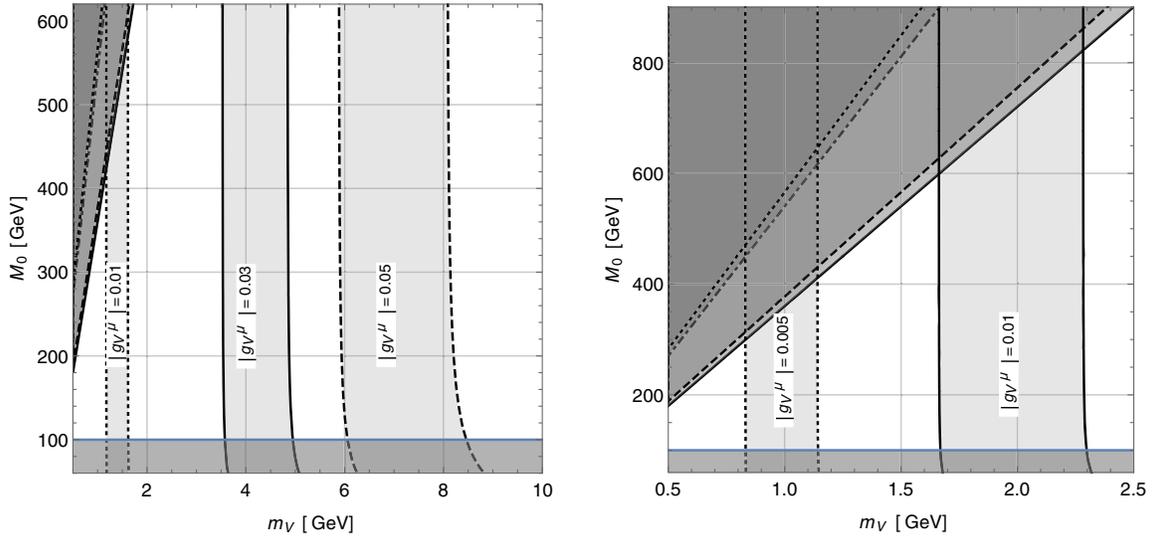


FIG. 7. Same as Fig. 6 but for the flavor-nonuniversal LM interactions. The dark grey regions with solid and dashed (dot-dashed and dotted) boundaries are disfavored by LEP constraints on the $ee\mu\mu$ contact interaction to explain a_μ within the 1σ range for the left-chiral and right-chiral case, respectively, taking $|g_V^e| = 3 \times 10^{-3}$ ($|g_V^e| = 2 \times 10^{-3}$).

significantly interacts with the two mesons with close masses $m_{V_1^\pm} \approx m_{V_2^\pm}$. In this figure we assumed equal meson-mumeson-lepton couplings $|g_{V1}| = |g_{V2}|$, where $g_{Vi} \equiv g_{\alpha Vi}^0$ with fixed α . The allowed range for the values of the mumeson mass of $100 \text{ GeV} < M_{01} \lesssim 250 \text{ GeV}$ corresponds to the space between the lower and upper dark grey bands.

For flavor-nonuniversal couplings $g_V^e \neq g_V^\mu$ the limit in Eq. (20) can be rewritten as

$$\frac{(g_V^e)^2}{16\pi} \Delta a_\mu^{\text{min}} F\left(\frac{M_0^2}{m_{V^\pm}^2}\right) f_{\text{VVF}}^{-1}\left(\frac{m_{V^\pm}^2}{M_0^2}\right) \leq \frac{m_\mu^2}{\Lambda^2}, \quad (24)$$

which is also valid for the two neutral vector-mumeson contributions to a_μ with the common LM and meson mass scales. Figure 7 shows that in this flavor-nonuniversal case the limits from the contact interaction $ee\mu\mu$ can be relaxed by a small value of the coupling g_V^e .

Concerning the LHC searches for μ_V^0 , in the case of a SM gauge singlet, Drell-Yan production of singlet pairs may be not possible. Then cascade decays from heavier charged particles can be considered [27].

Notice that in the case of long-lived neutral LMs, which can escape the detector, the generic LEP lower bound of 100 GeV may be weakened for their masses.²

²Some questions of models with very light leptoquarks with masses of $\mathcal{O}(1)$ MeV (which we do not consider in this paper) were discussed in Refs. [49,50].

IV. CONCLUSION

We have found the regions for LM model parameters which are allowed by the muon $g-2$ data and the LEP data. We considered various minimal models and have shown that the scenarios with one (two) scalar meson-LM-lepton interactions limit the value of the lightest charged LM mass from above by 280 (400) GeV. However, the case of vector meson-LM-lepton interactions is, in general, less predictive.

This is very useful to investigate further collider restrictions on LM model parameters. In particular, the charged scalar LM interactions can potentially be either strongly bounded or even ruled out through the searches for their Drell-Yan production at the LHC. Future collider experiments such as the ILC and the FCC have great potential to probe a significant part of the LM model parameter space, which is still allowed.³

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³In the case of discovery of LMs the question of the utility of lepton-meson and meson-meson colliders will be opened.

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