Neutrino mass and \((g - 2)_\mu\) with dark \(U(1)_D\) symmetry

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Abstract

We propose an extension of the Standard model (SM) for radiative neutrino mass by introducing a dark \(U(1)_D\) gauge symmetry. The kinetic mixing between the SM gauges and the dark \(U(1)_D\) gauge arises at 1-loop mediated by new inert scalar fields. We show that the tiny neutrino mass and dark matter candidates are naturally accommodated. Motivated by the recent measurement of \((g - 2)_\mu\) indicating 4.2 \(\sigma\) deviation from the SM prediction, we examine how the deviation \(\Delta a_\mu\) can be explained in this model.
I. INTRODUCTION

The recent measurement of the muon anomalous magnetic moment, \(a_\mu = (g - 2)_\mu/2\), by the E989 experiment at Fermilab \(^1\) shows a discrepancy with respect to the theoretical prediction of the Standard Model (SM) \(^2\)

\[
a_{\mu}^{\text{FNAL}} = 116592040(54) \times 10^{-11} \tag{1}
a_{\mu}^{\text{SM}} = 116591810(43) \times 10^{-11} \tag{2}
\]

which when combined with the previous Brookhaven determination \(^3\) of

\[
a_{\mu}^{\text{BNL}} = 116592089(63) \times 10^{-11} \tag{3}
\]

leads to a 4.2 \(\sigma\) observed excess of \(\Delta a_\mu = 251(59) \times 10^{-11}\). The status of the SM calculation of the muon anomalous magnetic moment \((g - 2)_\mu\) has been updated recently in \[^2,^4\] although the hadronic contributions are still challenging to reliably estimate \[^5\]. The apparent discrepancy with a 4.2 \(\sigma\) deviation between the SM prediction and the measured value of \((g - 2)_\mu\) is a long-standing puzzle which may point to new physics. Inspired by the latest Fermilab measurements, several literatures that explains the discrepancy with updating possible theoretical models \[^6–36\].

In this paper, we study how the recent measurement of \((g - 2)_\mu\) can be explained in a model for radiative generation of tiny neutrino masses. We extend the scotogenic model by introducing a dark \(U(1)_D\) gauge symmetry. The spontaneous symmetry breaking of dark \(U(1)_D\) for a massive a “dark photon” induces \(\mathbb{Z}_2\) symmetry, an essential ingredient in scotogenic scenarios for tiny neutrino masses through 1-loop contribution. The neutral component of a new inert scalar doublet is responsible for dark matter (DM). In this model, kinetic mixing between the SM neutral gauge bosons and the dark photon is naturally generated through 1-loop mediated by new scalar fields. The introduction of a few new particles can reconcile the discrepancy
between the recent measurement and the SM prediction. In this paper, we will 
examine the contributions of new scalars and dark photon to \((g - 2)_\mu\) and see how 
they can accommodate the 4.2 \(\sigma\) deviation of \((g - 2)_\mu\).

This paper is organized as follows. In section II, we present the setup and the 
content of new particles by assigning quantum numbers appropriately. In section 
III, we show how neutrino mass can arise from 1-loop and present the kinetic mixing 
between SM gauge bosons and the dark photon. The contributions of new scalars 
and the dark photon to \((g - 2)_\mu\) are explicitly shown. In section IV, numerical results 
and discussion are presented. We finally conclude in section V.

II. MODEL

To generate tiny neutrino masses radiatively and to have natural DM candidates, 
we take the framework of the scotogenic model where two scalar doublets \((\eta_1, \eta_2)\), two 
scalar singlets \((\phi, \chi)\) and two vector-like neutral fermions \(\Psi_{L,R}\) are introduced. The 
complete content of the new fields introduced and their quantum number assignments 
under \(SU(2)_L \otimes U(1)_Y \otimes U(1)_D\) gauge symmetry are shown in table I. We note that 
the model is anomaly free. The Lagrangian for the new fermions is given by

\[
\mathcal{L}_F \supset m_{H} H^\dagger H + m_{\phi} \phi^\dagger \phi + m_{\chi} \chi^\dagger \chi + m_{\eta_1} \eta_1^\dagger \eta_1 + m_{\eta_2} \eta_2^\dagger \eta_2 + \mu_2 \eta_1 \eta_2 \chi + \mu_1 \chi^* \phi \\
+ \lambda_H (H^\dagger H)^2 + \lambda_\phi (\phi^\dagger \phi)^2 + \lambda_\chi (\chi^\dagger \chi)^2 + \lambda_{\eta_1} (\eta_1^\dagger \eta_1)^2 + \lambda_{\eta_2} (\eta_2^\dagger \eta_2)^2 \\
+ \lambda_{\phi \eta_1} (\phi^\dagger \phi) (\eta_1^\dagger \eta_1) + \lambda_{\phi \eta_2} (\phi^\dagger \phi) (\eta_2^\dagger \eta_2) + \lambda_{\phi \chi} (\phi^\dagger \phi) (\chi^\dagger \chi) + \lambda_{\phi \eta_1} (\chi^\dagger \chi) (\eta_1^\dagger \eta_1) \\
+ \lambda_{\phi \eta_2} (\phi^\dagger \phi) (\eta_2^\dagger \eta_2) + \lambda_H \eta_1 \eta_1 \eta_2 \eta_2 + \lambda_H \eta_1 \eta_2 \eta_1 \eta_2^\dagger + \lambda_H \phi \chi \eta_1 \eta_1 + \lambda_H \phi \chi \eta_2 \eta_2 + \lambda_H \phi \chi \eta_1 \eta_2 + \lambda_H \phi \chi \eta_2 \eta_1 + \lambda_H \phi \chi \eta_1 \eta_2 + \lambda_H \phi \chi \eta_2 \eta_1, \tag{5}
\]

The Lagrangian for the entire scalar sector is given by

\[
\mathcal{L}_S \supset m_{H} H^\dagger H + m_{\phi} \phi^\dagger \phi + m_{\chi} \chi^\dagger \chi + m_{\eta_1} \eta_1^\dagger \eta_1 + m_{\eta_2} \eta_2^\dagger \eta_2 + \mu_2 \eta_1 \eta_2 \chi + \mu_1 \chi^* \phi \\
+ \lambda_H (H^\dagger H)^2 + \lambda_\phi (\phi^\dagger \phi)^2 + \lambda_\chi (\chi^\dagger \chi)^2 + \lambda_{\eta_1} (\eta_1^\dagger \eta_1)^2 + \lambda_{\eta_2} (\eta_2^\dagger \eta_2)^2 \\
+ \lambda_{\phi \eta_1} (\phi^\dagger \phi) (\eta_1^\dagger \eta_1) + \lambda_{\phi \eta_2} (\phi^\dagger \phi) (\eta_2^\dagger \eta_2) + \lambda_{\phi \chi} (\phi^\dagger \phi) (\chi^\dagger \chi) + \lambda_{\phi \eta_1} (\chi^\dagger \chi) (\eta_1^\dagger \eta_1) \\
+ \lambda_{\phi \eta_2} (\phi^\dagger \phi) (\eta_2^\dagger \eta_2) + \lambda_H \eta_1 \eta_1 \eta_2 \eta_2 + \lambda_H \eta_1 \eta_2 \eta_1 \eta_2^\dagger + \lambda_H \phi \chi \eta_1 \eta_1 + \lambda_H \phi \chi \eta_2 \eta_2 + \lambda_H \phi \chi \eta_1 \eta_2 + \lambda_H \phi \chi \eta_2 \eta_1 + \lambda_H \phi \chi \eta_1 \eta_2 + \lambda_H \phi \chi \eta_2 \eta_1, \tag{5}
\]
TABLE I: New particle content with quantum number assignment under an extended gauge symmetry.

| Field | SU(2)$_L$ | U(1)$_Y$ | U(1)$_D$ | 2S+1 |
|-------|-----------|----------|----------|-------|
| $\eta_1$ | 2  | $\frac{1}{2}$ | -1 | 1 |
| $\eta_2$ | 2  | $\frac{1}{2}$ | 1 | 1 |
| $\phi$   | 1  | 0 | 1 | 1 |
| $\chi$   | 1  | 0 | 2 | 1 |
| $\Psi_L$ | 1  | 0 | -1 | 2 |
| $\Psi_R$ | 1  | 0 | -1 | 2 |

where $H$ represents the SM Higgs scalar whose vacuum expectation value (VEV) is denoted by $v$. In addition the SM Higgs, $\chi$ gets the VEV, which spontaneously breaks $U(1)_D$, and then the scalar $\chi$ can be written as

$$\chi = v_\chi + h_\chi + i\xi_\chi,$$

where $v_\chi$ is VEV of $\chi$, and $h_\chi, \xi_\chi$ denote the real and imaginary components of the field, respectively. After Ew symmetry as well as $U(1)_D$ are spontaneously broken, we obtain the squared mass matrix for the scalars $H, \chi$ given as

$$M_{HH}^2 = \begin{pmatrix} \lambda_H v^2 & \lambda_H v v_\chi \\ \lambda_H v v_\chi & \lambda_\chi v_\chi^2 \end{pmatrix}.$$  \hspace{1cm} (7)

The squared mass matrix is diagonalized by the mixing matrix defined as

$$\begin{pmatrix} H^0 \\ \chi \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix},$$

where the mixing angle $\theta$ is given as

$$\tan 2\theta = \frac{2\lambda_H v_\chi}{\lambda_\chi v_\chi^2 - \lambda_H v^2}. $$

$4$
FIG. 1: Feynman diagrams for the amplitudes generating the Kinetic mixing.

We take into account the kinetic mixing between the SM gauges and $U(1)_D$ gauge which arises via 1-loop. Then, the kinetic terms of the gauge fields containing the kinetic mixing are given by

$$\mathcal{L}_{\text{kin}} = -\frac{1}{4} \hat{F}^{\mu\nu} \hat{F}^{\mu\nu} - \frac{1}{4} \hat{Z}^{\mu\nu} \hat{Z}^{\mu\nu} - \frac{1}{4} \hat{V}^{\mu\nu} \hat{V}^{\mu\nu} - \frac{\epsilon Z}{2} \hat{F}^{\mu\nu} \hat{V}^{\mu\nu} - \frac{\epsilon ZV}{2} \hat{Z}^{\mu\nu} \hat{V}^{\mu\nu}, \quad (10)$$

where $\hat{F}^{\mu\nu}$, $\hat{Z}^{\mu\nu}$, and $\hat{V}^{\mu\nu}$ represent the gauge field strengths for $U(1)_Y$, $SU(2)_L$, and $U(1)_D$, respectively. The relevant piece of the covariant derivatives is given as

$$-ieQA_{\mu} - i \left[ \frac{g}{c_W} (T^2_L - s^2_W Q) - g_D s_{\theta_{2V}} Q_D \right] Z_{\mu} - i \left[ \epsilon eQ + g_D Q_D \right] Z'_{\mu} \quad (11)$$

where $Q$ and $Q_D$ are the charges of $U(1)_Y$ and $U(1)_D$, respectively. The kinetic terms are diagonalized by the field redefinition given as

$$\begin{pmatrix} \hat{A}_{\mu} \\ \hat{Z}_{\mu} \\ \hat{V}_{\mu} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{\epsilon}{D} \\ 0 & 1 & -\frac{\epsilon ZV}{D} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} A_{\mu} \\ Z_{\mu} \\ Z'_{\mu} \end{pmatrix}. \quad (12)$$

Following Ref. [37], the mixing parameter $\epsilon$ generated from the 1-loop diagram mediated by two scalars $\eta_1, \eta_2$ as shown in fig.1 and is given as

$$\epsilon = \frac{eg_D}{48\pi^2} \ln \left( \frac{M^2_{\eta_1}}{M^2_{\eta_2}} \right). \quad (13)$$

In this work, we ignore the term proportional to $\epsilon ZV$ which is in general much smaller than $\epsilon$. 5
III. RADIATIVE NEUTRINO MASS AND NEW CONTRIBUTIONS TO $(g - 2)_{\mu}$

Let us first study how the light neutrino mass can be radiatively generated. From the field redefinition of the neutral fermions whose mass terms are presented in Eq. (4) given as

$$
\begin{pmatrix}
\Psi_L \\
\Psi_R
\end{pmatrix}
= \begin{pmatrix}
\cos \theta_N & \sin \theta_N \\
-\sin \theta_N & \cos \theta_N
\end{pmatrix}
\begin{pmatrix}
N_1 \\
N_2
\end{pmatrix},
$$

we can obtain mass eigenvalues of the new neutral fermions after $\chi$ gets VEV given as

$$
M_{N_1(2)} = \frac{1}{2}[y_{\Psi L}v_\chi + y_{\Psi R}v_\chi \mp \sqrt{M_\Psi^2 - 4y_{\Psi L}y_{\Psi R}v_\chi^2}].
$$

As for the scalar doublet the mass matrix can be simplified by assuming the $\phi$ only mixes with the lightest doublet hence the mixing matrix takes the following form

$$
m_{R,I}^2 = \begin{pmatrix}
\mu^2_\eta & \lambda_{H\eta}\phi v_\chi \\
\lambda_{H\eta}\phi v_\chi & \mu^2_\phi \pm \mu_1 v_\chi
\end{pmatrix}.
$$

Consequently, the projection to the mass basis is given as

$$
\eta_{R,I} = \cos(\theta_{R,I})\xi_{1R,I} + \sin(\theta_{R,I})\xi_{2R,I}
$$

$$
\phi_{R,I} = -\sin(\theta_{R,I})\xi_{1R,I} + \cos(\theta_{R,I})\xi_{2R,I}
$$

The 1-loop Feynman diagram for the generation of neutrino mass is shown in Fig. 2. The neutrino mass is explicitly given by

$$
(M_\nu)_{\alpha\beta} = \sum_k y_{\alpha k}y_{\beta k}\Lambda_k
$$

$$
\Lambda_k = \frac{M_{N_k}}{16\pi^2} \left[ \cos^2(\theta_R)F(x_{1R}) + \sin^2(\theta_R)F(x_{2R}) - \cos^2(\theta_I)F(x_{1I}) - \sin^2(\theta_I)F(x_{2I}) \right],
$$
where $F(x_i, x_j)$ is defined as

$$F(x) = \frac{x}{x - 1} \ln[x],$$

with $x_i = \frac{m_i^2}{M_{h_i}^2}$. For the purpose of numerical calculation, we take Casas-Ibarra (CI) parametrisation [38] for the matrix of the Yukawa coupling satisfying the neutrino data given as

$$y_{i\alpha} = (UD_\nu^1 R^1 \Lambda^{1/2})_{i\alpha},$$

where $R, UD_\nu$ and $\Lambda$ are an arbitrary complex orthogonal matrix, the neutrino mixing matrix, diagonal light neutrino mass matrix, and diagonal loop factor given in eq.(19). For the sake of simplicity, we take $R$ to be identity. As for $U$ and $D_\nu$, we take experimental results for the case of normal hierarchy given in [4].

Now, let us consider the contributions of dark sector to $(g - 2)_\mu$. In our model, new particles are assumed to be heavy except for the dark photon $Z'$ and a light dark scalar $h_2$ whose masses are order of a few 100 MeV. Then, sizable corrections to $(g - 2)_\mu$ arises from the interactions

$$(e\bar{\nu})_\mu \gamma^{\mu} Z'_\mu,$$

$$(\sin \theta y_\mu) \bar{\nu}_\mu h_2$$

The $(g - 2)_\mu$ has new three main contributions which can be categorized as follows:

1. Mediated by dark scalar $\chi$ through SM Higgs Dark scalar mixing.

2. Mediated by the dark photon through kinetic mixing.

3. Mediated by the inert-double and the neutral fermion.
The 1-loop contribution mediated by the dark scalar $h_2$ to $(g - 2)_\mu$ is given by

$$\Delta a_\mu(h_2) = \frac{y_\mu^2 s_\theta^2 m_\mu^2}{4\pi^2 M_{h_2}^2} \int_0^1 dx \frac{x^2(2 - x)}{(1 - x)(1 - \xi_{h_2}^2, x) + \xi_{h_2}^2} \left[ \ln \left( \frac{M_{h_2}}{m_\mu} \right) - \frac{7}{12} \right],$$

(23)

where $\xi_{h_2} = m_\mu/M_{h_2}$. The 1-loop contribution mediated by the dark photon $Z'$ to $(g - 2)_\mu$ is given by

$$\Delta a_\mu(Z'_\mu) = \frac{e^2 e^2 m_\mu^2}{8\pi^2 M_{Z'}^2} \int_0^1 dx \frac{2x^2(1 - x)}{(1 - x)(1 - \xi_{Z'}^2, x) + \xi_{Z'}^2} x,$$

(24)

where $\xi_{Z'} = m_\mu/M_{Z'}$.

Along with these there is another contribution coming from the neutral fermion and the charged scalar which is given as

$$\Delta a_\mu(\eta, N) = \sum_{ik} \frac{y_i^{\eta^*_k} y_k^{\eta^*}}{16\pi^2} \left[ \frac{1}{6(\alpha_{ik} - 1)^4} \left( -2\alpha_{ik}^3 + 3\alpha_{ik}^3 + 6\alpha_{ik} - 1 + 6\alpha_{ik}^2 \ln[\alpha_{ik}] \right) \right],$$

where $\alpha_{ik} = m_{N_k}^2/m_{\eta_i}^2$. It is worthwhile to note that the contribution mediated by the dark scalar is negligibly small because the yukawa coupling for the muon is already of the order $10^{-4}$ and small mixing between the dark scalar and the SM Higgs gives another suppression.
IV. NUMERICAL RESULT AND DISCUSSION

Ignoring the contributions from the light dark scalar, the total contribution of $\Delta a_\mu$ is given by the addition of the 1-loop contributions mediated by the dark photon, and by inert scalar bosons accompanied by neutral fermions as follows:

$$\Delta a_\mu = \Delta a_\mu(Z') + \Delta a_\mu(\eta, N).$$

We note that $\Delta a_\mu(\eta, N)$ has a overall minus sign which ends up contributing negatively and needs to be compensated by the contribution coming from the kinetic mixing $\Delta a_\mu(Z')$.

In our analysis, we assume that the mass of the dark photon is around 100 MeV, whereas the mass of the lightest inert neutral scalar is around $\geq O(500)$ GeV which is the favorable regime for the good dark matter candidate. For the yukawa coupling $y_\nu$, we take to be $O(1)$ so that we can achieve the tiny neutrino mass of order atmospheric mass scale by tuning the trilinear coupling $\mu_i$ small. But we keep the mass splitting between $\eta_{DMR}$ and $\eta_{DMI}$ to be above $O(keV)$ to circumvent the constraint coming from direct detection resulting from $Z-$ mediation. Under the assumptions above, we see that the contribution from the 1-loop mediated by the dark photon is dominant over the others.

To calculate $\Delta a_\mu$ we scan the ranges of the input parameter given as

$$1\text{GeV} \lesssim m_{\eta_1} \lesssim 1000\text{GeV},$$
$$0.1 \lesssim g_D \lesssim 1,$$
$$m_{\eta_2} = 4m_{\eta_1},$$
$$m_\phi = 5m_{\eta_1},$$
$$m_{N_i} = m_{\eta_1}.$$

Note that the parameter $\epsilon$ can be calculated from eq.(13). In Fig. 3 we present
| Parameters | BP1  | BP2  |
|-----------|------|------|
| $g_D$     | 0.92 | 0.98 |
| $v_{\chi}$ | 10 MeV | 50 MeV |
| $\mu_1$   | 1.14 (keV) | 460.8 (eV) |
| $m_{\eta_1}$ | 500 GeV | 800 GeV |
| $m_{\eta_2}$ | 2 TeV | 3.2 TeV |
| $m_{\phi}$ | 2.5 TeV | 3.6 TeV |
| $\lambda_{H\chi}$ | 0.01 | 0.01 |
| $\lambda_{\chi}$ | 0.001 | 0.001 |
| $\lambda_{H\eta_1\phi}$ | 0.4 | 0.4 |
| $\lambda_{H\eta_2\phi}$ | 0 | 0 |

TABLE II: Two benchmark points accommodating the tiny neutrino mass around atmospheric scale, dark matter relic density and the 4.2 $\sigma$ deviation of $(g - 2)_\mu$.

how $\Delta a_\mu$ is predicted in terms of model parameters. The upper left panel shows the predictions of $\Delta a_\mu(Z')$ in the parameter space $(m_{Z_D}/g_D, \epsilon)$, whereas the upper right panel shows the predictions of $\Delta a_\mu(\eta, N)$ in the parameter space $(m_\eta, y_\nu y_\nu^\dagger)$. The two red points correspond to the benchmark points presented in Table II. The lower panel shows how $\Delta a_\mu$ is composed of the two contributions. As can be seen, $\Delta a_\mu(Z')$ is dominant over $\Delta a_\mu(\eta, N)$ for the ranges of our parameter space we scan. The black curve in the plot corresponds to the 4.2 $\sigma$ deviation from the SM prediction. We have checked that the benchmark points present in the Table II can accommodate the tiny neutrino mass or order of atmospheric mass scale.
FIG. 3: Predictions of $\Delta a_\mu(Z')$ in terms of $(m_{Z'D}/g_D, \epsilon)$ (upper right) and those of $\Delta a_\mu(\eta, N)$ in terms of $(m_\eta, y'_\nu y_\nu)$ (upper left). Predictions of $\Delta a_\mu$ along with $\Delta a_\mu(Z')$ and $\Delta a_\mu(\eta, N)$. Two red points correspond to the two bench mark points presented in Table II and the black curve correspond to 4.2$\sigma$ deviation.

V. CONCLUSION

We have considered a dark $U(1)_D$ extension of the SM gauge symmetry to achieve the tiny neutrino mass and to have dark matter candidate. In this model, the
kinetic mixing between the SM gauges and the $U(1)_D$ gauge naturally arises at 1-loop mediated by new inert scalar fields. The light neutral inert scalar boson can be a good dark matter candidate. Motivated by the recent measurement of $(g - 2)_\mu$ indicating $4.2 \sigma$ deviation from the SM prediction, we have studied how the deviation $\Delta a_\mu$ can be explained in this model. The 1-loop mediated by dark photon with mass of order 100 MeV as well as inert scalar fields accompanied by the neutral fermions can accommodate the recent measurement of $(g - 2)_\mu$ at Fermilab.

[1] B. Abi et al. Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm. Phys. Rev. Lett., 126(14):141801, 2021.
[2] T. Aoyama et al. The anomalous magnetic moment of the muon in the Standard Model. Phys. Rept., 887:1–166, 2020.
[3] G. W. Bennett et al. Measurement of the negative muon anomalous magnetic moment to 0.7 ppm. Phys. Rev. Lett., 92:161802, 2004.
[4] P. A. Zyla et al. Review of Particle Physics. PTEP, 2020(8):083C01, 2020.
[5] Thomas Blum, Achim Denig, Ivan Logashenko, Eduardo de Rafael, B. Lee Roberts, Thomas Teubner, and Graziano Venanzoni. The Muon $(g-2)$ Theory Value: Present and Future. 11 2013.
[6] Giorgio Arcadi, Lorenzo Calibbi, Marco Fedele, and Federico Mescia. Muon $g - 2$ and $B$-anomalies from Dark Matter. 4 2021.
[7] Bin Zhu and Xuewen Liu. Probing light dark matter with scalar mediator: muon $(g - 2)$ deviation, the proton radius puzzle. 4 2021.
[8] Xiao-Fang Han, Tianjun Li, Hong-Xin Wang, Lei Wang, and Yang Zhang. Lepton-specific inert two-Higgs-doublet model confronted with the new results for muon and electron $g-2$ anomalies and multi-lepton searches at the LHC. 4 2021.
[9] Sebastian Baum, Marcela Carena, Nausheen R. Shah, and Carlos E. M. Wagner. The Tiny (g-2) Muon Wobble from Small-µ Supersymmetry. 4 2021.
[10] Yang Bai and Joshua Berger. Muon g-2 in Lepton Portal Dark Matter. 4 2021.
[11] Pritam Das, Mrinal Kumar Das, and Najimuddin Khan. The FIMP-WIMP dark matter and Muon g-2 in the extended singlet scalar model. 4 2021.
[12] Shao-Feng Ge, Xiao-Dong Ma, and Pedro Pasquini. Probing the Dark Axion Portal with Muon Anomalous Magnetic Moment. 4 2021.
[13] Vedran Brdar, Sudip Jana, Jisuke Kubo, and Manfred Lindner. Semi-secretly interacting ALP as an explanation of Fermilab muon $g - 2$ measurement. 4 2021.
[14] Manuel A. Buen-Abad, Jiji Fan, Matthew Reece, and Chen Sun. Challenges for an axion explanation of the muon $g - 2$ measurement. 4 2021.
[15] Lei Zu, Xu Pan, Lei Feng, Qiang Yuan, and Yi-Zhong Fan. Constraining $U(1)_{L_\mu-L_\tau}$ charged dark matter model for muon $g - 2$ anomaly with AMS-02 electron and positron data. 4 2021.
[16] D. W. P. Amaral, D. G. Cerdeño, A. Cheek, and P. Foldenauer. Distinguishing $U(1)_{L_\mu-L_\tau}$ from $U(1)_{L_\mu}$ as a solution for $(g - 2)_\mu$ with neutrinos. 4 2021.
[17] Waqas Ahmed, Intiaz Khan, Jinmian Li, Tianjun Li, Shabbar Raza, and Wenxing Zhang. The Natural Explanation of the Muon Anomalous Magnetic Moment via the Electroweak Supersymmetry from the GmSUGRA in the MSSM. 4 2021.
[18] Murat Abdughani, Yi-Zhong Fan, Lei Feng, Yue-Lin Sming Tsai, Lei Wu, and Qiang Yuan. A common origin of muon g-2 anomaly, Galaxy Center GeV excess and AMS-02 anti-proton excess in the NMSSM. 4 2021.
[19] Melissa Van Beekveld, Wim Beenakker, Marrit Schutten, and Jeremy De Wit. Dark matter, fine-tuning and $(g - 2)_\mu$ in the pMSSM. 4 2021.
[20] Peter Cox, Chengcheng Han, and Tsutomu T. Yanagida. Muon $g - 2$ and Co-annihilating Dark Matter in the MSSM. 4 2021.
[21] Fei Wang, Lei Wu, Yang Xiao, Jin Min Yang, and Yang Zhang. GUT-scale constrained 
SUSY in light of E989 muon g-2 measurement. 4 2021.

[22] Yuchao Gu, Ning Liu, Liangliang Su, and Daohan Wang. Heavy Bino and Slepton for 
Muon g-2 Anomaly. 4 2021.

[23] Junjie Cao, Jingwei Lian, Yusi Pan, Di Zhang, and Pengxuan Zhu. Improved \((g - 2)_\mu\) 
Measurement and Singlino dark matter in the general NMSSM. 4 2021.

[24] Wen Yin. Muon \(g - 2\) Anomaly in Anomaly Mediation. 4 2021.

[25] Chengcheng Han. Muon g-2 and CP violation in MSSM. 4 2021.

[26] Amin Aboubrahim, Michael Klasen, and Pran Nath. What Fermilab \((g - 2)_\mu\) experiment 
tells us about discovering SUSY at HL-LHC and HE-LHC. 4 2021.

[27] Jin-Lei Yang, Hai-Bin Zhang, Chang-Xin Liu, Xing-Xing Dong, and Tai-Fu Feng. 
Muon \((g - 2)\) in the B-LSSM. 4 2021.

[28] P. M. Ferreira, B. L. Gonçalves, F. R. Joaquim, and Marc Sher. \((g - 2)_\mu\) in the 2HDM 
and slightly beyond – an updated view. 4 2021.

[29] Hong-Xin Wang, Lei Wang, and Yang Zhang. muon \(g - 2\) anomaly and \(\mu-\tau\)-philic 
Higgs doublet with a light CP-even component. 4 2021.

[30] Tianjun Li, Junle Pei, and Wenxing Zhang. Muon Anomalous Magnetic Moment and 
Higgs Potential Stability in the 331 Model from \(E_6\). 4 2021.

[31] M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, and E. Picciau. Muon and electron 
g-2, proton and cesium weak charges implications on dark \(Z_4\) models. 4 2021.

[32] Lorenzo Calibbi, M. L. López-Ibáñez, Aurora Melis, and Oscar Vives. Implications of 
the Muon g-2 result on the flavour structure of the lepton mass matrix. 4 2021.

[33] Junmou Chen, Qiaoyi Wen, Fanrong Xu, and Mengchao Zhang. Flavor Anomalies 
Accommodated in A Flavor Gauged Two Higgs Doublet Model. 4 2021.

[34] Pablo Escribano, Jorge Terol-Calvo, and Avelino Vicente. \((g - 2)_{e,\mu}\) in an extended 
inverse type-III seesaw. 4 2021.
[35] Eung Jin Chun and Tanmoy Mondal. Leptophilic bosons and muon g-2 at lepton colliders. 4 2021.

[36] Peter Athron, Csaba Balázs, Douglas Hj Jacob, Wojciech Kotlarski, Dominik Stöckinger, and Hyejung Stöckinger-Kim. New physics explanations of $a_\mu$ in light of the FNAL muon $g - 2$ measurement. 4 2021.

[37] Thomas D. Rueter and Thomas G. Rizzo. Building Kinetic Mixing From Scalar Portal Matter. 11 2020.

[38] J. A. Casas and A. Ibarra. Oscillating neutrinos and $\mu \rightarrow e, \gamma$. Nucl. Phys. B, 618:171–204, 2001.

[39] Farinaldo S. Queiroz and William Shepherd. New Physics Contributions to the Muon Anomalous Magnetic Moment: A Numerical Code. Phys. Rev. D, 89(9):095024, 2014.