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Can electron and muon $g-2$ anomalies be jointly explained in SUSY?

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Abstract The FNAL+BNL measurements for muon $g-2$ is 4.2σ above the SM prediction, and the Berkeley ^{133}Cs measurement for the fine-structure constant $\alpha_{\rm em}$ leads to the SM prediction for electron $g-2$ which is 2.4σ above the experimental value. Hence, a joint explanation of both anomalies requires a positive contribution to muon $g-2$ and a negative contribution to electron $g-2$, which is rather challenging. In this work we explore the possibility of such a joint explanation in the minimal supersymmetric standard model (MSSM). Assuming no universality between smuon and selectron soft masses, we find out a part of parameter space for a joint explanation at 2σ level, i.e., $\mu M_1, \mu M_2 < 0$, $m_{L1}, m_{E2} < 200$ GeV, m_{L2} being much larger than the soft masses of other sleptons, $|M_1| < 125$ GeV and $\mu < 400$ GeV. This part of parameter space can survive LHC and LEP constraints, but gives an over-abundance for dark matter if the bino-like lightest neutralino is assumed to be the dark matter candidate. With the assumption that the dark matter candidate is a superWIMP (say a pseudo-goldstino in multi-sector SUSY breaking scenarios, whose mass can be as light as GeV and produced from the late-decay of the thermally freeze-out lightest neutralino), the dark matter problem can be avoided. So, we conclude that the MSSM may give a joint explanation for the muon and electron $g-2$ anomalies at 2σ level (the muon $g-2$ anomaly can be even ameliorated to 1σ).

1 Introduction

There has been a long-standing discrepancy between the standard model (SM) prediction and experiment for muon anomalous magnetic moment $a_\mu = (g-2)_\mu/2$. The combined result of the FNAL E989 experiment [1] and the BNL experiment gives a value which is 4.2σ above the SM prediction [2]:

$$\Delta a_\mu^{\rm Exp-SM} = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (2.51 \pm 0.59) \times 10^{-9}. \quad (1)$$

On the other hand, for electron anomalous magnetic moment a_e, the SM predicted value [3] derived from the measurement of the fine-structure constant $\alpha_{\rm em}$ using ^{133}Cs atoms at Berkeley [4] is 2.4σ above the electron $g-2$ experimental value [5]:

$$\Delta a_e^{\rm Exp-SM} = a_e^{\rm Exp} - a_e^{\rm SM}({\rm Cs}) = (-8.8 \pm 3.6) \times 10^{-13}. \quad (2)$$

However, another experimental result of $\alpha_{\rm em}$ measured with ^{87}Rb atoms at Laboratoire Kastler Brossel (LKB) [6] gives a value of a_e [7] which agrees with the electron $g-2$ experimental value [5]. So far, the cause of the discrepancy between the Berkeley and LKB results is not clear. Obviously, if the Berkeley result is correct, it may serve as a plausible hint for new physics; if the LKB result is correct, there will be no need for new physics to provide a contribution to $(g-2)_e$.

Actually, neither the Berkeley result for electron $g-2$ nor the FNAL + BNL result for muon $g-2$ can serve as a robust evidence for new physics beyond the SM. Whereas, while waiting for more forthcoming independent experiments to make confirmation, many theorists have chosen to keep open minds and intensively studied the implications of these anomalies for new physics. In this work, we keep open minds and study the implications of these anomalies for low energy supersymmetry.

The $g-2$ of a charged lepton relates to the new physics scale Λ as [8]

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$$\frac{\delta a_\ell}{a_\ell} \propto \left(\frac{m_\ell}{\Lambda}\right)^2, \tag{3}$$

where Λ is assumed to be much larger than the lepton mass m_ℓ. If the new physics is the same for different lepton flavors, we may expect

$$\frac{\delta a_e}{\delta a_\mu} \approx \left(\frac{m_e}{m_\mu}\right)^2 \approx \frac{1}{43000}. \tag{4}$$

But from Eqs. (1) and (2) we obtain

$$\frac{\Delta a_e^{\rm Exp-SM}}{\Delta a_\mu^{\rm Exp-SM}} \approx -15 \times \frac{1}{43000}, \tag{5}$$

which implies that the new physics should not be flavor blind [9]. This brings us a serious challenge for building new physics models. Intuitively, in order to jointly explain the electron and muon $g-2$ anomalies, new physics models must have different couplings for charged leptons of different flavors. This will suggest us to consider some new physics models with lepton flavor universality violation. However, in some models the manifest breaking of lepton flavor universality is not required [10–12].

There have been many studies trying to explain electron and muon $g-2$ jointly: (i) using the two-Higgs-doublet model (2HDM) or its extended versions [13–19], among which the aligned 2HDM with right-handed neutrinos was used in [13], the 2-loop contribution in 2HDM with flavor conservation was considered in [14], while a neutral scalar H with mass satisfying $\mathcal{O}(1)\,\text{MeV} < m(H) < \mathcal{O}(1)\,\text{GeV}$ was used in [16]; (ii) using leptoquarks [17,20,21] and axion-like particles [21]; (iii) using flavor models [15,22] which attempted to solve the fermion mass hierarchy problem while provide a joint explanation for the muon/electron $g-2$ anomalies; (iv) using the inverse type-III seesaw model with a pair of vector-like leptons [23]; (v) using an abelian flavor symmetry [24] to make electron and muon decouple to circumvent the MEG bound of $\mathcal{B}(\mu^+ \to e^+\gamma)$ [25] (note that Z'-model cannot explain the muon/electron $g-2$ anomalies under the MEG bound, as shown in [26,27]); (vi) using a flavor-dependent global $U(1)$ symmetry and a discrete $\mathbb{Z}_2$ symmetry with some additional fermion and scalar fields [28].

As a leading candidate for new physics models, the MSSM (minimal supersymmetric standard model) was also considered [29] to interpret $\Delta a_{e,\mu}$ while escaping the $\mathcal{B}(\mu^+ \to e^+\gamma)$ constraint by assuming 1-3 flavor violation. Another attempt in the MSSM without assumption of flavor violation but with flavor non-universality was given in [30], where the authors decouple the right-hand smuon and choose a negative soft mass parameter M_1 to achieve the goal. Furthermore, one can explain $\Delta a_{e,\mu}$ jointly by using the SUSY threshold correction to change the selectron and smuon Yukawa couplings including size and sign [31]. In addition, the B-L SSM and an extended NMSSM (next-to-minimal supersymmetric standard model) was used for a joint explanation of muon/electron $g-2$ anomalies [32,33].

Anyway, it is rather challenging for the MSSM to simultaneously explain electron and muon $g-2$. Although previous studies found out a plausible part of parameter space in the MSSM, some relevant constraints were not considered (say from dark matter) or not fully considered (say from collider experiments). Given the popularity of the MSSM and the plausible new physics hints from the muon/electron $g-2$ anomalies, we in this work revisit the MSSM to give a more comprehensive study. We will explore the MSSM parameter space to figure out the possibility to accommodate the muon/electron $g-2$ anomalies under other relevant constraints from collider experiments and dark matter measurements.

This work is organized as follows. In Sect. 2, we describe the MSSM contributions to muon/electron $g-2$. In Sect. 3, we explore parameter space to accommodate the muon/electron $g-2$ anomalies. In Sect. 4, we show relevant constraints on the favored parameter space. Finally, we conclude in Sect. 5.

2 MSSM contributions to electron and muon $g-2$

The MSSM contributions to a charged lepton ℓ (electron or muon) $g-2$ mainly come from neutralino-slepton and chargino-sneutrino loops. The analytical expressions contributed by these two parts are given by [34]

$$\delta a_\ell^{\chi^0} = \frac{m_\ell}{16\pi^2}\sum_{i,m}\left\{-\frac{m_\ell}{12 m_{\tilde\ell_m}^2}(|n_{im}^L|^2+|n_{im}^R|^2)F_1^N(x_{im}) + \frac{m_{\chi_i^0}}{3m_{\tilde\ell_m}^2}\mathrm{Re}[n_{im}^L n_{im}^R]F_2^N(x_{im})\right\}, \tag{6}$$

$$\delta a_\ell^{\chi^\pm} = \frac{m_\ell}{16\pi^2}\sum_{k}\left\{\frac{m_\ell}{12 m_{\tilde\nu_\ell}^2}(|c_k^L|^2+|c_k^R|^2)F_1^C(x_k) + \frac{2m_{\chi_k^\pm}}{3m_{\tilde\nu_\ell}^2}\mathrm{Re}[c_k^L c_k^R]F_2^C(x_k)\right\}, \tag{7}$$

where $x_{im} = m_{\chi_i^0}^2/m_{\tilde l_m}^2$ and $x_k = m_{\chi_k^\pm}^2/m_{\tilde\nu_l}^2$. The definitions of $n^{L,R}$, $c^{L,R}$ and $F_{1,2}^{C,N}$ can be found in appendix.

In this work, we mainly use Eqs. (6) and (7) to calculate the muon/electron $g-2$ and some significant 2-loop corrections will also be included. After considering the 2-loop corrections, we have

$$\delta a_\ell^{\rm SUSY} = \left(1 - \frac{4\alpha}{\pi}\ln\frac{M_{\rm SUSY}}{m_\ell}\right) \times \left(\frac{1}{1+\Delta_\ell}\right)\delta a_\ell^{\rm SUSY,\,1L}, \tag{8}$$

where $\delta a_\ell^{\rm SUSY,\,1L}$ denotes one-loop SUSY contributions. The term in the first bracket arises from the leading-logarithmic QED correction [35]. This correction takes into account renormalization group evolution of effective operators from $M_{\rm SUSY}$ to m_ℓ scale, which can lead to a reduction of about 7% for δa_μ, and a reduction of about 11% for δa_e. The term in the second bracket of Eq. (8) arises from the $\tan\beta$-enhanced loop diagrams that can correct the Yukawa couplings of sleptons, and a resummation has been made [36,37]. Δ_ℓ is given by

$$\begin{aligned}\Delta_\ell = &-\mu\tan\beta\,\frac{g_2^2 M_2}{16\pi^2}\left[I(m^2_{\chi_1^\pm}, m^2_{\chi_2^\pm}, m^2_{\tilde\nu_\ell}) + \frac{1}{2}I(m^2_{\chi_1^\pm}, m^2_{\chi_2^\pm}, m^2_{\tilde\ell_L})\right]\\ &-\mu\tan\beta\,\frac{g_1^2 M_1}{16\pi^2}\left[I(\mu^2, M_1^2, m^2_{\tilde\ell_R}) - \frac{1}{2}I(\mu^2, M_1^2, m^2_{\tilde\ell_L}) - I(M_1^2, m^2_{\tilde\ell_L}, m^2_{\tilde\ell_R})\right],\end{aligned} \tag{9}$$

where the loop function $I(a,b,c)$ is given by

$$I(a,b,c) = -\frac{ab\ln(a/b) + bc\ln(b/c) + ca\ln(c/a)}{(a-b)(b-c)(c-a)}. \tag{10}$$

We use some tricks to prevent enormous errors while avoid false singularities of $I(a,b,c)$. We note that $I(a,b,c)$ is fully symmetric to the three parameters, and therefore we assume $a \le b \le c$ and define $x = a/b$, $y = c/b$. Then we obtain

$$I(a,b,c) = \frac{1}{c-a}\left(y \times \frac{\ln y}{y-1} - x \times \frac{\ln x}{x-1}\right). \tag{11}$$

If $x \approx 1$ and $a \not\approx c$, one can perform Fourier expansion for $\ln x/(x-1)$ around $x = 1$ for the calculation. The practice is similar when $y \approx 1$ and $a \not\approx c$. If $a \approx c$, we demand the Fourier expansion of the binary function. Defining $\delta x = x - 1$ and $\delta y = y - 1$, then we have

$$I(a,b,c) = \frac{1}{2b}\left[1 - \frac{\delta x + \delta y}{3} + \frac{g(\delta x,\,\delta y,\,2)}{6} - \frac{g(\delta x,\,\delta y,\,3)}{10} + \frac{g(\delta x,\,\delta y,\,4)}{15} + \cdots\right], \tag{12}$$

where

$$g(\delta x,\,\delta y,\,n) = \sum_{i=0}^{n}\delta x^i\,\delta y^{n-i}. \tag{13}$$

From Eq. (9) we know that this correction can be enhanced by a large $\mu\tan\beta$. We calculate $\delta a_{e,\mu}^{\rm SUSY}$ using the above results. Our code is cross-checked with **CPsuperH 2.3** [38–40], and the difference between numerical results is less than 0.1% in magnitude.

In order to find out the parameter space that can jointly explain $\Delta a_{e,\mu}^{\rm Exp-SM}$, we classify the SUSY contributions approximately as [41,42]

$$\delta a_\ell(\tilde W, \tilde H, \tilde\nu_\ell) \simeq 15 \times 10^{-9} R\left(\frac{(100{\rm GeV})^2}{\mu\, M_2}\right), \tag{14}$$

$$\delta a_\ell(\tilde W, \tilde H, \tilde\ell_L) \simeq -2.5 \times 10^{-9} R\left(\frac{(100{\rm GeV})^2}{\mu\, M_2}\right), \tag{15}$$

$$\delta a_\ell(\tilde B, \tilde H, \tilde\ell_L) \simeq 0.76 \times 10^{-9} R\left(\frac{(100{\rm GeV})^2}{\mu\, M_1}\right), \tag{16}$$

$$\delta a_\ell(\tilde B, \tilde H, \tilde\ell_R) \simeq -1.5 \times 10^{-9} R\left(\frac{(100{\rm GeV})^2}{\mu\, M_1}\right), \tag{17}$$

$$\delta a_\ell(\tilde\ell_L, \tilde\ell_R, \tilde B) \simeq 1.5 \times 10^{-9} R\left(\frac{(100{\rm GeV})^2(\mu M_1)}{m^2_{\tilde\ell_L} m^2_{\tilde\ell_R}}\right), \tag{18}$$

where $\ell = e,\ \mu$, and $R = (m_\ell/m_\mu)^2(\tan\beta/10)$ for brevity. Equations (14–18) are obtained through simplification under certain conditions, focusing on the order of magnitude. δa_ℓ is derived from the loop correction. As the masses of the sleptons in the loops increase, the contribution of the loop diagrams becomes smaller. This dependency does not appear explicitly in Eqs. (14–17). We see that the MSSM contribution to $g-2$ of a charged lepton can be positive or negative. To have a negative $\delta a_e^{\rm SUSY}$ and a positive $\delta a_\mu^{\rm SUSY}$, we need to assume non-universality between smuon and selectron soft masses. We can find out two typical scenarios to have a negative $\delta a_e^{\rm SUSY}$ and a positive $\delta a_\mu^{\rm SUSY}$ for a joint explanation of muon/electron $g-2$ anomalies:

(i) Use the chargino-sneutrino loop in Eq. (14) to give a positive $\delta a_\mu^{\rm SUSY}$ assuming $\mu M_2 > 0$; use the bino-selectron loop in Eq. (18) to give a negative $\delta a_e^{\rm SUSY}$ assuming $\mu M_1 < 0$. This scenario was studied in [30] and will not be restudied in this work.

(ii) Use the chargino-sneutrino loop in Eq. (14) to give a negative $\delta a_e^{\rm SUSY}$ assuming $\mu M_2 < 0$; use the bino-higgsino-smuon loop in Eq. (17) to give a positive $\delta a_\mu^{\rm SUSY}$ assuming $\mu M_1 < 0$. This scenarios will be studied in detail in this work.

We would like to comment on the virtues of the second scenario. Since the SUSY contributions to a_e are suppressed by $(m_e/m_\mu)^2$ compared with the contrubutions to a_μ, we need much larger SUSY loop effects for a_e. From the above formulas we see that the coefficient of the chargino-sneutrino loop in Eq. (14) is one order of magnitude higher than other four kinds of loops. Using it with assumption $\mu M_2 < 0$ to explain $\Delta a_e^{\text{Exp-SM}}$ in Eq. (5) is a wise choice. In this way, winos and higgsinos do not need to be very light. On the other hand, in order for $\delta a_\mu^{\text{SUSY}}$ not to get a sizable negative contribution from the chargino-sneutrino loop in Eq. (14), we assume the left-handed smuon $\tilde{\mu}_L$ to be very heavy (note that $\tilde{\nu}_\mu$ and $\tilde{\mu}_L$ are in a $SU(2)_L$ doublet and thus have the same soft mass). Therefore, in this scenario only the bino/higgsino-smuon loop in Eq. (17) is left to give a positive $\delta a_\mu^{\text{SUSY}}$ assuming $\mu M_1 < 0$. In this way, the right-handed smuon, bino and higgsinos are required to be light. As will be shown in the following, there is indeed a parameter space for a joint explanation of muon/electron $g-2$ anomalies, which can survive collider constraints. However, since the lightest neutralino is bino-like, its thermal freeze-out number density is large; thus it cannot be the dark matter candidate and must decay (to a lighter stable particle like a gravitino or speudo-goldstino as the dark matter particle) after thermal freeze-out.

3 MSSM parameter space for a joint explanation

According to previous discussions, we require $\mu M_1 < 0$ and $\mu M_2 < 0$. In this work we assume that the parameters are all real to avoid CP violation. We can freely choose $\mu > 0$, $M_1 < 0$ and $M_2 < 0$ (similar results can be obtained for the case of $\mu < 0$). For simplicity, we choose M_2 and μ as the scan variables, and

$$m_{L1} = m_{E2} = \min(|\mu|, |M_1|, |M_2|) + 30\,\text{GeV}, \tag{19}$$

where the 30 GeV increment is to ensure that the slepton masses are above the LEP bound [43] (in our scan the minimal value of $|\mu|$, $|M_1|$, $|M_2|$ is 80 GeV) and the difference from $m_{\chi_1^0}$ is larger than 30 GeV, which helps to avoid the LHC search constraints for the compressed slepton-neutralino spartciles (see Fig. 16 in [44]). The collider constraints will be discussed in the proceeding section. In order to suppress $\delta a_\mu^{\text{SUSY}}(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu)$, we take $m_{L2} = 10 m_{L1}$, with $L1$ and $L2$ denoting respectively the first and second generation left-handed sleptons (similarly $E2$ denotes the second generation righ-handed slepton, i.e., the righ-handed smuon). Because δa_e^{SUSY} is dominated by $\delta a_e^{\text{SUSY}}(\tilde{W}, \tilde{H}, \tilde{\nu}_e)$, the right-handed selectron mass m_{R1} will not observably affect this part as long as it does not make $\delta a_e^{\text{SUSY}}(\tilde{B}, \tilde{H}, \tilde{e}_R)$ too large. Hence we set $m_{R1} = 5 m_{L1}$.

The results from our exploration of parameter space are shown in Fig. 1. Because $\delta a_\mu^{\text{SUSY}}(\tilde{B}, \tilde{H}, \tilde{\mu}_R)$ is the dominant contribution to $\delta a_\mu^{\text{SUSY}}$, the value of $\delta a_\mu^{\text{SUSY}}$ (especially its 1σ range required by the explanation of $\Delta a_\mu^{\text{Exp-SM}}$) is sensitive to M_1. With respect to the case with $|M_1| = 80$ GeV, the 1σ range of $|M_1| = 120$ GeV moves down significantly. For $|M_1| > 120$ GeV, the value of $\delta a_\mu^{\text{SUSY}}$ will decrease rapidly, which is not shown in the figures. As for δa_e^{SUSY}, the dominant loop contribution is not sensitive to M_1. Hence even if $|M_1|$ is very large, δa_e^{SUSY} does not change drastically. Therefore, in order to satisfy the experimental value of a_μ, $|M_1|$ cannot be greater than $\sim$ 120 GeV. This makes the tree-level mass of χ_1^0 lower than 120 GeV.

From Fig. 1 we can also see that μ and M_2 have an inverse relationship when δa_e^{SUSY} has a fixed value. This is easy to understand because of the appearance of μM_2 in Eq. (14). However, $\delta a_\mu^{\text{SUSY}}$ unexpectedly increases with the increase of $|M_2|$. This is because $\delta a_\mu^{\text{SUSY}}(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu)$ is not suppressed enough by assuming $m_{L2} = 10 m_{L1}$, which is getting suppressed by increasing $|\mu M_2|$. If we set the value of m_{L2} bigger than $10 m_{L1}$, we can further reduce the dependence of $\delta a_\mu^{\text{SUSY}}$ on M_2. In that way, the range of M_2 allowed by the experimental constraints will be extended.

From Fig. 1 we note that for $\tan\beta = 40$ the two 1σ-ranges for the explanations of $\Delta a_{e,\mu}^{\text{Exp-SM}}$ do not overlap. Therefore, a joint explanation of $\Delta a_{e,\mu}^{\text{Exp-SM}}$ at 1σ level needs a larger $\tan\beta$. For $\tan\beta = 60$ the two 1σ-ranges of $\Delta a_{e,\mu}^{\text{Exp-SM}}$ overlap, which, however, requires $\mu < 200$ GeV and $|M_2| < 300$ GeV. For a joint explanation of $\Delta a_{e,\mu}^{\text{Exp-SM}}$ at 2σ level, the ranges of the relevant parameters are relaxed significantly.

4 Dark matter and collider constraints

4.1 Dark matter constraints

We use **FlexibleSUSY 2.6.0** [45,46] to calculate the mass spectrum of supersymmetric particles, and then use **MicrOMEGAs 5.2.7** [47–50] to calculate the dark matter relic density Ωh^2 and the LSP-nucleon scattering cross section. For the parameters that are not directly related to $\delta a_{e,\mu}^{\text{SUSY}}$, we generally take 2 TeV. In addition, the mass parameters of stau are taken as $10 m_{L1}$ and the A-parameters that describe the trilinear soft-breaking terms are set to be 0.

We first assume the lightest neutralino χ_0^1 is the dark matter candidate and search for the parameter space that meets the following three requirements:

1. The SUSY contributions $\delta a_{e,\mu}^{\text{SUSY}}$ in the 2σ ranges of $\Delta a_{e,\mu}^{\text{Exp-SM}}$;

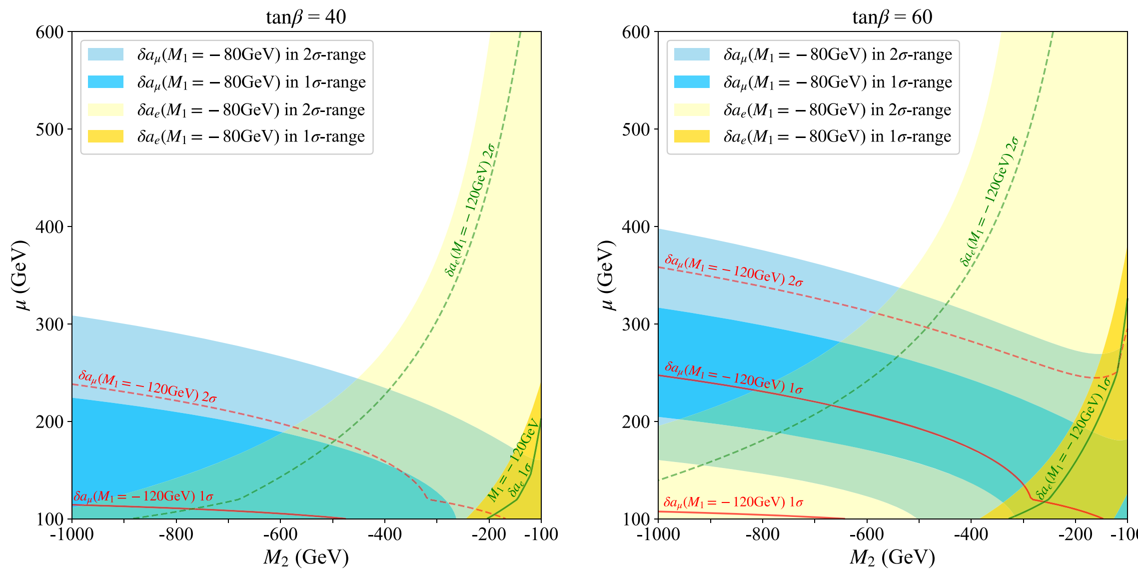

Fig. 1 Contours of $\delta a_e^{\rm SUSY}$ and $\delta a_\mu^{\rm SUSY}$ on the plane of μ versus M_2 for $\tan\beta = 40$ (left) and $\tan\beta = 60$ (right). The colored regions correspond to $M_1 = -80$ GeV while the colored curves correspond to $M_1 = -120$ GeV. The 1σ and 2σ mean to explain $\Delta a_{e,\mu}^{\rm Exp-SM}$ at 1σ and 2σ levels, respectively

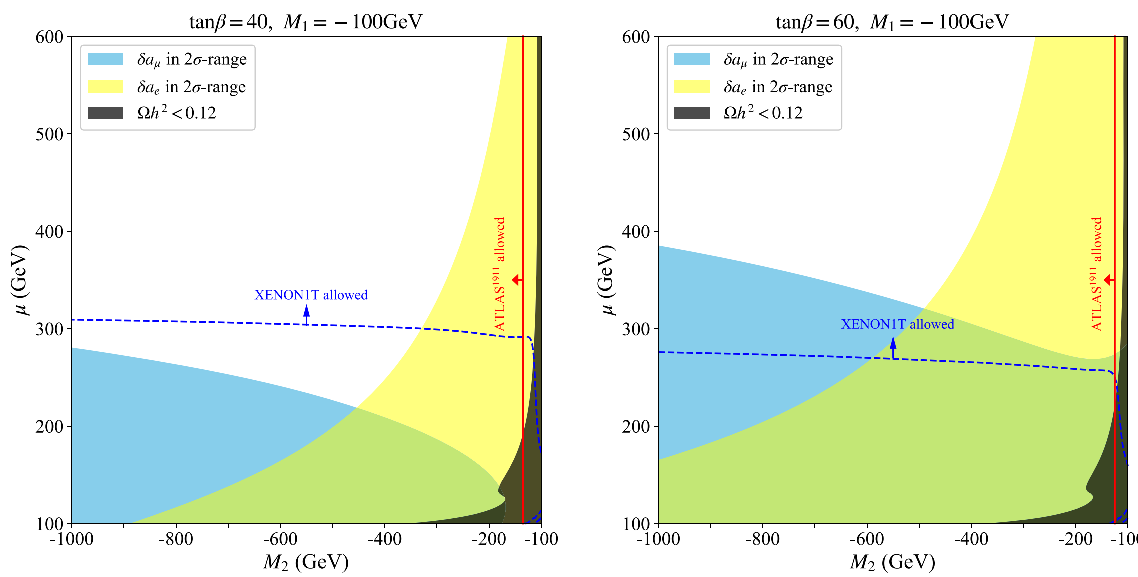

Fig. 2 The parameter regions survived the dark matter relic density constraint and the XENON1T exclusion limits on the plane of μ versus M_2 with $M_1 = -100$ GeV and $\tan\beta = 40, 60$. The 2σ regions for explaining the muon and electron $g-2$ anomalies are also shown. For the curves of limits, the regions indicated by the arrows are the allowed regions

2. The dark matter thermal freeze-out relic density under the upper bound, i.e., $\Omega_{\chi_1^0} h^2 < 0.12$ [51];
3. The XENON1T limits from the dark matter direct detection [52].

We scan over the parameter space and the results are shown in Fig. 2. In the regions shown in this figure, the dominant component of the lightest neutralino is bino, whose thermal freeze-out relic density can easily give an over-abundance. For the bino-like dark matter to give a correct relic density, higgsinos or wino must be mixed into it, which, however, will be not allowed by the XENON1T limits. As shown in this figure, only a very large $\tan\beta = 60$ can give a corner of parameter space to satisfy both the dark matter relic density and the XENON1T limits, which, however, is not allowed by the LHC constraints [44].

So we conclude that for the SUSY contributions $\delta a_{e,\,\mu}^{\rm SUSY}$ in the 2σ ranges of $\Delta a_{e,\,\mu}^{\rm Exp-SM}$, the assumption of the lightest neutralino as the dark matter candidate cannot satisfy the dark matter constraints under the LHC search bounds. Note that in the framework of SUSY, the lightest neutralino is not the only candidate for cosmic dark matter. Instead, the lightest super particle (LSP) as the dark matter candidate can be a super-WIMP (super-weakly interacting massive particle) like the gravitino [53,54] (its goldstino component has a relatively stronger interaction than gravity) or pseudo-goldstino [55] in multi-sector SUSY breaking with gauge mediation. As discussed in detail in [53], in such superWIMP dark matter scenarios, the superWIMPs produced thermally before inflation are diluted by inflation and the superWIMP dark matter is produced from the late decay of the lightest neutralinos which are produced from the thermal freeze-out after reheating (the reheating temperature is not high enough to thermally produce superWIMPs). Since the decay is one neutralino χ_0^1 to one superWIMP $\tilde{G}$, i.e., $\chi_0^1 \to \tilde{G} + X$ ($X = \gamma, Z, h$), the superWIMP dark matter inherits the number density of the parent neutralinos and hence its relic density is suppressed by a factor $m_{\tilde{G}}/m_{\chi_1^0}$, where $m_{\chi_1^0}$ is $\mathcal{O}(100)$ GeV and $m_{\tilde{G}}$ can be lighter than $\mathcal{O}(1)$ GeV [55,56]. So the relic density upper bound can be easily satisfied by such light superWIMP dark matter. Of course, a superWIMP scatters with a nucleon super-weakly and the direct detection limits can also be easily satisfied.

A possible problem caused by such superWIMP dark matter produced from the late decay of the lightest neutralinos is that the decay may release much energy to affect BBN if the decay happens after BBN. Such a problem and its constraints have been discussed in detail in [53,57]. Recently, it was found [58] that late decay of the freeze-out neutralinos to very light gravitino dark matter can ameliorate the tension of Hubble constant. At a future lepton collider the decay of a bino-like neutralino to gravitino plus a photon may be tested [59].

4.2 LHC constraints

Now we consider constraints from colliders. We use **SPheno 4.0.4** [60,61] to calculate the decay branching ratios of the relevant super particles. We consider two cases:

$$\text{case 1} \begin{cases} M_1 = -100 \text{ GeV}, \quad \tan\beta = 40, \\ m_{L1} = m_{E2} = \dfrac{m_{E1}}{5} = \dfrac{m_{L2}}{10} = 130 \text{ GeV}; \end{cases} \tag{20}$$

$$\text{case 2} \begin{cases} M_1 = -100 \text{ GeV}, \quad \tan\beta = 60, \\ m_{L1} = m_{E2} = \dfrac{m_{E1}}{5} = \dfrac{m_{L2}}{10} = 145 \text{ GeV}; \end{cases} \tag{21}$$

where the 45 GeV increment of M_{L1} and M_{E2} in Eq. (21) is to avoid the decay $\chi_2^0 \to \ell\tilde{\ell}$ for escaping the CMS constraints [62]. At the same time, the 45 GeV increment of M_{L1} and M_{E2} will not make $\delta a_{e,\mu}^{\rm SUSY}$ too small.

For these two cases we plot $\delta a_{e,\mu}^{\rm SUSY}$ in Fig. 3. We see that a joint explanation of $\Delta a_{e,\mu}^{\rm Exp-SM}$ may need a relatively a compressed spectrum for the bino-like χ_1^0, the higgsino-like χ_2^0 and $\chi_1^{\pm}$. For such compressed electroweakinos, the LHC performed the searches and gave the bounds [44]. Together with other searches for electroweakinos and sleptons at the LHC because they give similar results or have been considered in our scan (for an extensive recasting of LHC constraints, see, e.g., [66]). For the ATLAS1911 limits, the regions indicated by the arrows are the allowed regions

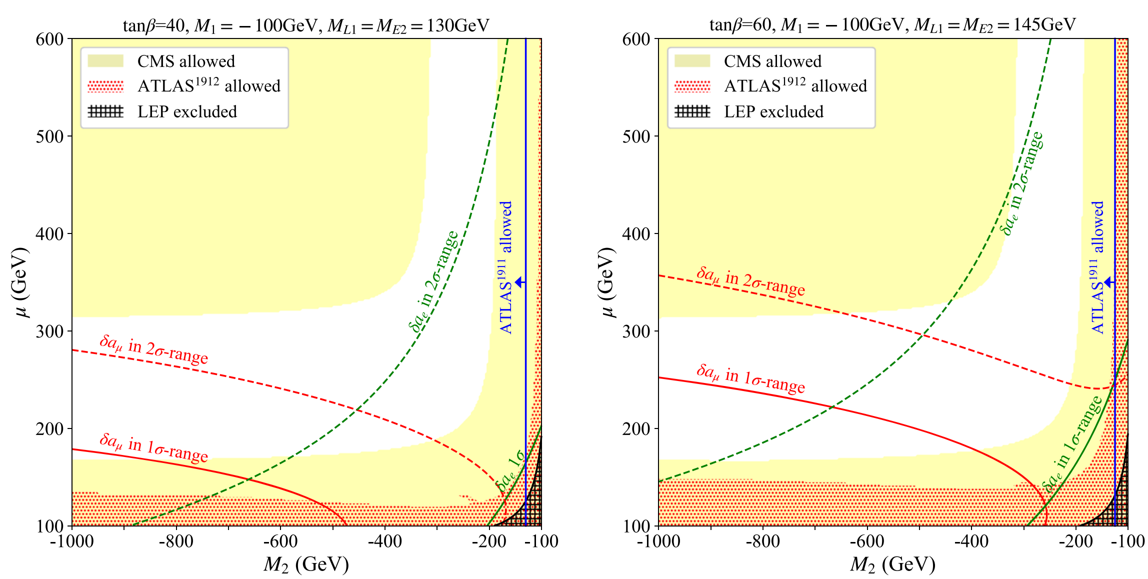

Fig. 3 The MSSM parameter space for a joint explanation of muon/electron $g-2$, showing the LHC and LEP constraints. The constraints are from ATLAS1912 [44], ATLAS1911 [63], CMS [62] and LEP [43]. Other constraints from the LHC [64,65] are not shown

[62,63] and LEP [43], the relevant experimental constraints are displayed in Fig. 3.

From Fig. 3 we see that in both cases the results of the CMS Collaboration give strong limits on μ: $\mu < 130$ GeV for $\tan\beta = 40$ and $\mu < 145$ GeV for $\tan\beta = 60$. For $\tan\beta = 40$, 470 GeV $< M_2 <$ 900 GeV is required for $\delta a_\mu^{\rm SUSY}$ within the 1σ range. However, the value of M_2 has a much wider range for $\tan\beta = 60$. Of course, the constraints plotted in Fig. 3 can be relaxed if the relevant decay branch ratios are not assumed to be 100%. So from Fig. 3 we see that there indeed exist a MSSM parameter space for a joint explanation of muon/electron $g-2$ anomalies.

Note that here we used the constraints from the LHC searches in which the LSP is assumed to be the lightest neutralino. If the LSP is a superWIMP, the signals of the searched processes could be different, depending on the lifetime of the lightest neutralino. If the lightest neutralino has a relatively long lifetime and decays outside the detector [53], the above LHC search constraints are applicable. If the lightest neutralino has a relatively short lifetime and decays inside the detector [67,68], the signals of the relevant processes will be different. In the latter case, the signals may be more difficult to detect, for example, if the decay is dominated by $\chi_1^0 \to \tilde{G} + h$ rather than by $\chi_1^0 \to \tilde{G} + Z/\gamma$ [67,68].

Finally we should remark that in SUSY only the low energy effective MSSM has enough free parameters to possibly allow for a joint explanation of muon/electron $g-2$ anomalies (we do not go beyond the minimal framework of SUSY, albeit some extensions like NMSSM has the virtue of smaller fine-tuning extent confronting with the requirement of a 125 GeV Higgs boson, see, e.g., [69], which can explain muon $g-2$ plus the AMS-02 anti-proton excess [70]). The GUT-constrained models like mSUGRA cannot even explain the single anomaly of muon $g-2$ (the MSSM can readily explain the single anomaly of the muon $g-2$, see, e.g., [71–75]). For this end, some extensions have been proposed for these models, e.g., in [76–84].

5 Conclusions

Given the FNAL+BNL measurements for muon $g-2$ and the Berkeley ^{133}Cs measurement for electron $g-2$, we explored the parameter space for a joint explanation, which requires a positive contribution to muon $g-2$ and a negative contribution to electron $g-2$. Assuming no universality between smuon and selectron soft masses, we found out a part of parameter space for such a joint explanation at 2σ level, i.e., $\mu M_1, \mu M_2 < 0$, the masses of left selectron and right smuon below 200 GeV, m_{L2} much larger than the soft masses of other sleptons, $|M_1| < 125$ GeV and $\mu < 400$ GeV ($|M_2|$ is not subject to strict restrictions). This part of parameter space can survive the LHC and LEP constraints, but gives an over-abundance for the dark matter if the bino-like lightest neutralino is assumed to be the dark matter candidate. Then with the assumption that the dark matter candidate is a superWIMP (such as a pseudo-goldstino in multi-sector SUSY breaking scenarios, whose mass can be as light as GeV and produced from the late-decay of the thermally freeze-out lightest neutralinos), the dark matter problem can be avoided. So, we conclude that the MSSM may give a joint explanation for the muon and electron $g-2$ anomalies at 2σ level (the muon $g-2$ anomaly can be ameliorated to 1σ).

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Appendix

The definitions of $n^{L,R}$, $c^{L,R}$ and the kinematic loop functions $F_{1,2}^{C,N}$ used in Eqs. (6) and (7) are given by [34]

$$n_{im}^R = \sqrt{2} g_1 N_{i1} X_{m2}^{(\ell)} + y_\ell N_{i3} X_{m1}^{(\ell)}, \tag{22}$$

$$n_{im}^L = \frac{1}{\sqrt{2}} (g_2 N_{i2} + g_1 N_{i1}) X_{m1}^{(\ell)*} - y_\ell N_{i3} X_{m2}^{(\ell)*}, \tag{23}$$

$$c_k^R = y_\ell U_{k2}, \tag{24}$$

$$c_k^L = -g_2 V_{k1}, \tag{25}$$

$$F_1^N(x) = \frac{2}{(1-x)^4} \left(1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x\right), \tag{26}$$

$$F_2^N(x) = \frac{3}{(1-x)^3} \left(1 - x^2 + 2x \ln x\right), \tag{27}$$

$$F_1^C(x) = \frac{2}{(1-x)^4}\left(2 + 3x - 6x^2 + x^3 + 6x \ln x\right), \quad (28)$$

$$F_2^C(x) = -\frac{3}{2(1-x)^3}\left(3 - 4x + x^2 + 2 \ln x\right), \quad (29)$$

where $y_\ell = g_2 m_\ell/(\sqrt{2} m_W \cos\beta)$. N, (U, V) and $X^{(\ell)}$ are the mixing matrices for the neutralinos, charginos and sleptons, respectively. In other words, these matrices satisfy

$$N^* M_{\chi^0} N^\dagger = \mathrm{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0}), \quad (30)$$

$$U^* M_{\chi^\pm} V^\dagger = \mathrm{diag}(m_{\chi_1^\pm}, m_{\chi_2^\pm}), \quad (31)$$

$$X^{(\ell)} M_{\tilde{\ell}}^2 X^{(\ell)\dagger} = \mathrm{diag}(m_{\tilde{\ell}_1}^2, m_{\tilde{\ell}_2}^2). \quad (32)$$

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