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Muon $g-2$ and coannihilating dark matter in the minimal supersymmetric standard model

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We demonstrate that the recent measurement of the anomalous magnetic moment of the muon and dark matter can be simultaneously explained within the minimal supersymmetric standard model. Dark matter is a mostly bino state, with the relic abundance obtained via coannihilations with either the sleptons or wino. The most interesting regions of parameter space will be tested by the next generation of dark matter direct detection experiments.

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I. INTRODUCTION

The recent measurement of the anomalous magnetic moment of the muon [1] represents an exciting hint for the existence of physics beyond the Standard Model. The combination of the new result and the Brookhaven (E821) measurement [2] is in tension with the Standard Model prediction¹ [8] at 4.2σ :

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.51 \pm 0.41_{(\text{exp})} \pm 0.43_{(\text{theory})}) \times 10^{-9}. \quad (1)$$

Supersymmetry is one of the leading candidates to explain this discrepancy. In this paper, and in light of the new measurement, we explore the possibility that the minimal supersymmetric standard model (MSSM) could be responsible for both the deviation in the muon $g-2$ and the dark matter (DM) of the universe.

The MSSM features a natural dark matter candidate in the form of the lightest neutralino. It is by now well understood that the most promising scenario to simultaneously explain the deviation in a_μ and obtain the observed relic abundance via thermal production involves binolike dark matter and coannihilations [9–13]. This conclusion is

primarily driven by the strong bounds from dark matter direct detection, combined with the fact that it is not possible to obtain a large enough contribution to a_μ for either pure Higgsino or wino dark matter.

There are two distinct scenarios to consider, depending on the identity of the coannihilating partner: *bino-slepton* and *bino-wino* coannihilation. As we shall demonstrate, both of these scenarios have regions of parameter space that can explain the result in Eq. (1) while simultaneously accounting for the dark matter relic abundance and evading all other constraints.

II. ANALYSIS FRAMEWORK AND ASSUMPTIONS

We begin by describing the details of our analysis. First, we assume that the squarks, gluinos and additional Higgs bosons are all decoupled, motivated by the strong bounds from collider searches. For concreteness we fix their masses to be ~ 3 TeV. This is also the renormalization scale at which all the parameters are specified. The trilinear coupling A_t is fixed to 5 TeV in order to obtain a Higgs mass of ≈ 125 GeV, and we assume that all other A -terms are negligible.

To simplify our analysis, we assume that the left and right-handed slepton soft masses are equal. We also take equal slepton soft masses for the first and second generations. We focus on the case where $\text{sgn}(M_{1,2\mu}) > 0$, since this ensures that the dominant contributions to a_μ have the correct sign to account for the difference in Eq. (1).

We use the spectrum generator `SuSpect-2.52` [14], while the dark matter relic abundance, DM-nucleon scattering cross-section, and one-loop SUSY contributions to a_μ are all calculated using `MicrOMEGAS-5.2.7` [15]. We also include the leading two-loop contributions to a_μ . These come from $\tan\beta$ -enhanced corrections to the muon

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¹This uses the R -ratio method [3–6] for the HVP contribution. A recent lattice determination [7] yields a different value which, if correct, would alleviate the tension in Eq. (1).

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Yukawa coupling [16,17] and the QED running down to the muon mass scale [18].

III. BINO-STAU COANNIHILATION

The first scenario we consider is bino-slepton coannihilation with universal slepton masses. The assumption of universal slepton masses is often imposed in order to avoid dangerous contributions to flavor changing neutral current (FCNC) processes. It can be motivated by certain supersymmetry breaking scenarios, such as gaugino mediation [19–21]. In this case, the NLSP and coannihilating partner is the lightest stau. Achieving the correct relic abundance then requires a mass-splitting $m_{\tilde{\tau}_1} - m_{\chi_1^0} \lesssim 15$ GeV.

The stau coannihilation region is shown in Fig. 1, where we have taken $M_2 = 1$ TeV. M_1 is adjusted across the parameter space in order to obtain the correct relic abundance. Consider first the left panel where we fix $\tan\beta = 50$. The green (blue) regions fit the a_μ measurement at 1σ (2σ). However, the 1σ region is already excluded by LHC searches for the first and second generation sleptons [22,23] (red line).

There is also a constraint from vacuum stability, due to the existence of charge-breaking minima in the scalar potential when $\mu \tan\beta$ becomes large [26]. We take the bound from Ref. [27]; the grey region is excluded at zero temperature, while a stronger bound (black line) is obtained by considering the finite temperature effective potential and requiring stability throughout the thermal history of the universe (note that this assumes a sufficiently high reheating temperature).

The right panel of Fig. 1 corresponds to $\tan\beta = 20$. The smaller value of $\tan\beta$ has the effect of compressing the

slepton spectrum, which relaxes the bounds from LHC slepton searches. There are then regions which can fit a_μ at 1σ , while evading the bounds from collider searches. These correspond to very small slepton masses, with the lightest stau close to the LEP lower bound.

It is clear from fig. 1 that bino-stau coannihilation with universal slepton masses, while still viable, is strongly constrained. One could consider decreasing M_2 in order to increase the chargino-sneutrino contribution to a_μ . This would move the best-fit region toward larger slepton masses and away from the collider bounds. However, M_2 cannot be decreased significantly without encountering bounds from chargino searches, particularly from slepton-mediated decays [22].

While LHC searches currently provide the strongest constraints on this scenario, dark matter direct detection will have an important role in the future. The entirety of the best-fit regions in both panels of Fig. 1 will be probed by the LZ experiment [28]. Indirect detection is not currently sensitive to any of the coannihilation scenarios, due to the small annihilation cross section today. In the future, the Cherenkov Telescope Array should have sensitivity to the bino-stau coannihilation scenario [29].

Finally, note that we are assuming universal slepton soft masses at low-scale. In a UV model this relation might be expected to hold at high scales, but the RG running tends to reduce the stau soft mass compared to the first and second generation sleptons. This may lead to slightly stronger bounds from slepton searches for small $\tan\beta$, but we do not expect this effect to significantly alter our conclusions (see also [30]).

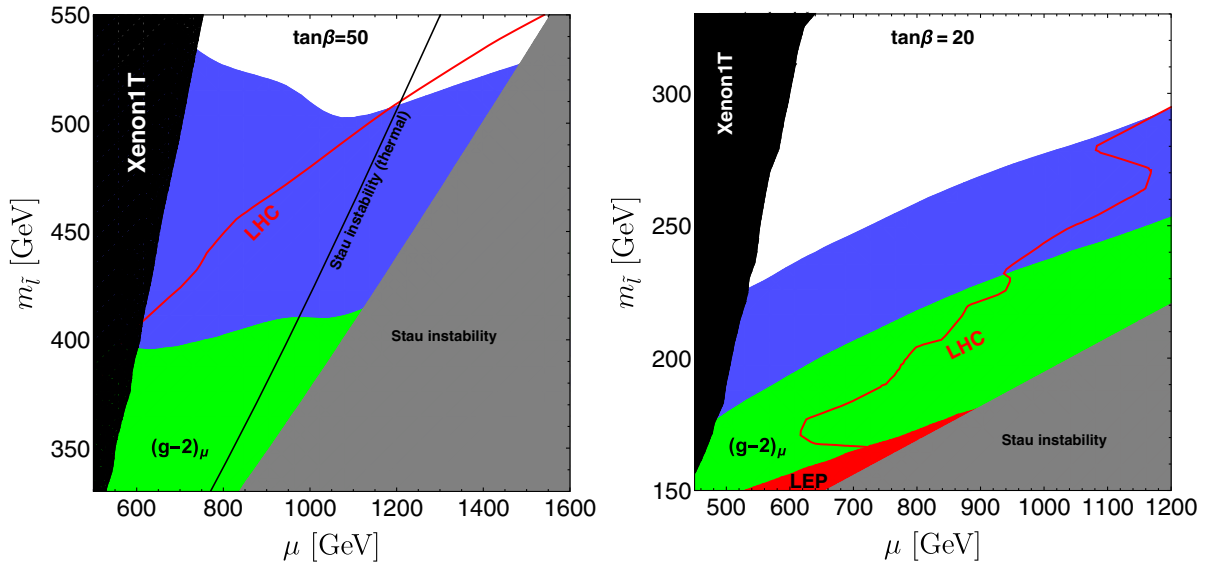


FIG. 1. Bino-stau coannihilation. M_1 has been adjusted to obtain the correct relic abundance, and we fix $M_2 = 1$ TeV. The green (blue) region is consistent with a_μ at 1σ (2σ). The black region is excluded by XENON1T [24]. The region to the right of the red line is excluded by the ATLAS slepton search with 139 fb^{-1} [22], and the red region is excluded by slepton searches at LEP [25]. The grey region is excluded by vacuum instability. Left: $\tan\beta = 50$. Right: $\tan\beta = 20$.

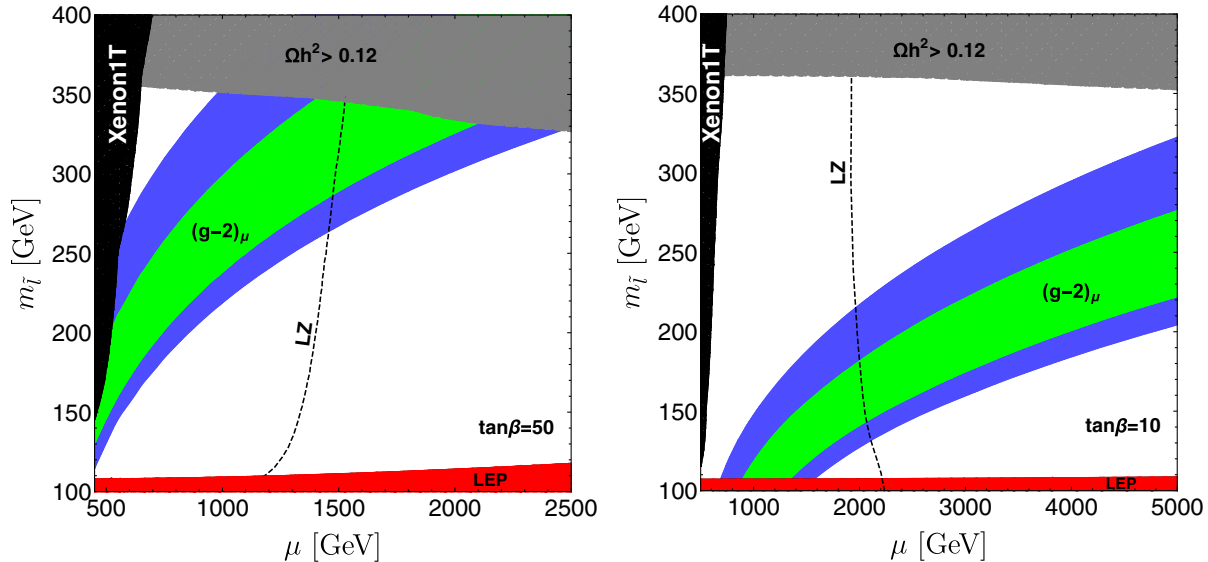


FIG. 2. Bino-slepton coannihilation. We have fixed $\tan\beta = 50$ (left) and $\tan\beta = 10$ (right). M_1 has been adjusted to obtain the correct relic abundance; for large slepton masses this becomes impossible as shown by the grey region. The green (blue) region is consistent with a_μ at 1σ (2σ). The black region is excluded by XENON1T [24], while the dashed line shows the future sensitivity of the LZ experiment [28]. The red shaded region is excluded by slepton searches at LEP [25].

IV. BINO-SLEPTON COANNIHILATION

Given the results of the previous section, we now relax the assumption of flavor universality for the slepton masses and assume that the staus are decoupled ($m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = 3$ TeV). As we shall see, this opens up significant regions of parameter space in which both the muon $g-2$ and dark matter can be accommodated. This type of spectrum can be realized, for example, in Gaugino + Higgs mediation [30],² without inducing large FCNCs [33].

In this scenario the NLSP is the lightest smuon. The results are shown in fig. 2 for $\tan\beta = 50(10)$ in the left (right) panels. M_1 has been adjusted to obtain the observed relic abundance, which requires a mass-splitting $m_{\tilde{\mu}_1} - m_{\tilde{\chi}_1^0} \lesssim 20$ GeV. The required mass-splitting decreases for larger slepton masses, and there is an upper bound on the slepton mass (grey region) above which it is no longer possible to obtain the correct relic density. When $\mu \tan\beta$ is small, the lightest selectron and smuon are almost degenerate and both act as coannihilation partners. As $\mu \tan\beta$ is increased, $\tilde{\mu}_1$ becomes lighter due to the left-right mixing and plays the dominant role in setting the relic abundance. This also leads to a decrease in the upper bound on the slepton mass.

Here, we have assumed that the wino is decoupled ($M_2 = 3$ TeV); the dominant contribution to a_μ therefore comes from the bino-smuon loop. This contribution is proportional to the left-right smuon mixing and is enhanced for large $\mu \tan\beta$. Hence, the best-fit region for a_μ moves

²This is achieved with large negative soft masses for the Higgs doublets at the GUT scale, and $\mu \sim \mathcal{O}(10)$ TeV [31,32].

toward higher slepton masses as μ is increased. For large $\tan\beta$, much of the best-fit region will be probed in the relatively near future by dark matter direct detection. Reducing $\tan\beta$ has the effect of moving the best-fit region for a_μ to lower slepton masses for a given μ . This is seen in the right panel of Fig. 2, where there is significant viable parameter space well beyond the reach of future direct detection experiments.

We now briefly discuss collider searches for the light sleptons. The compressed spectrum makes this scenario challenging to probe at hadron colliders. Nevertheless, there is a dedicated ATLAS search targeting bino-slepton coannihilation [34]. However, it does not currently constrain the parameter space in Fig. 2. Given the upper bound on the slepton mass from the relic abundance, the bino-slepton coannihilation scenario could, however, be fully tested at a future lepton collider with $\sqrt{s} > 700$ GeV (see Refs. [35,36]).

V. BINO-WINO COANNIHILATION

Last, we consider bino-wino coannihilation. In this scenario a slightly larger mass-splitting of 10–30 GeV is needed between the binolike LSP and winolike NLSP [37,38]. This situation is shown in Fig. 3 for $M_2 = 400$ GeV and $\tan\beta = 50$. We have fixed $M_2 - M_1 = 28$ GeV, which gives approximately the correct relic abundance across the parameter space (the precise mass-splitting needed has a mild μ -dependence). There are significant regions of parameter space that can explain both a_μ and the dark matter abundance. For large μ , the bino-smuon contribution to a_μ dominates, while for $\mu \lesssim 1.5$ TeV

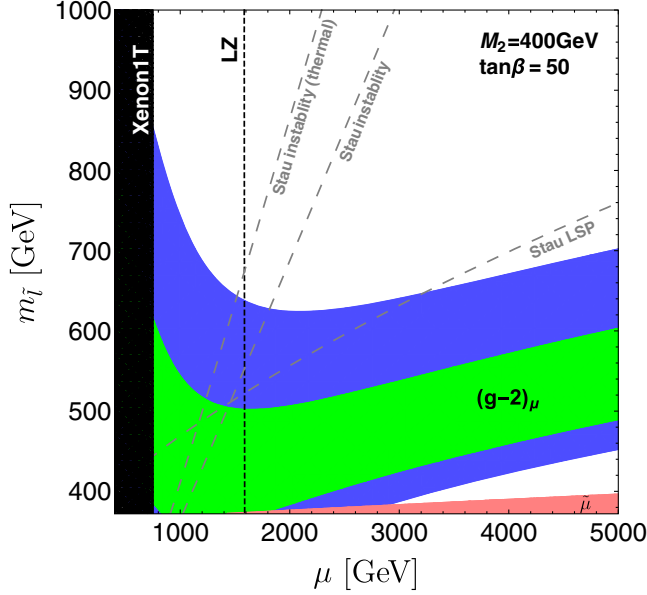


FIG. 3. Bino-wino coannihilation. We have fixed $\tan\beta = 50$ and $M_2 = 400$ GeV, with $M_2 - M_1 = 28$ GeV to obtain the correct relic abundance. The LSP mass is $m_{\tilde{\chi}_1^0} \approx 370$ GeV. The green (blue) region is consistent with a_μ at 1σ (2σ). The black region is excluded by XENON1T [24], while the black dashed line shows the future sensitivity of the LZ experiment [28]. In the pink region $\tilde{\mu}_1$ becomes the LSP. The grey dashed lines apply only for universal slepton masses, in which case the region to the right is excluded.

the chargino-sneutrino contribution becomes important and moves the $g - 2$ best-fit region to higher slepton masses. This latter region will be probed by future direct detection experiments.

Collider searches for the sleptons and wino can potentially provide powerful probes of this scenario, although do not currently constrain the parameter space shown in Fig. 3. Both ATLAS [34] and CMS [39] have dedicated chargino searches targeting the compressed spectra relevant for bino-wino coannihilation. Currently, the CMS search with 137 fb^{-1} obtains a bound of $m_{\tilde{\chi}_2^0/\tilde{\chi}_\pm^1} > 280$ GeV for $\Delta m = 10$ GeV, reducing to $m_{\tilde{\chi}_2^0/\tilde{\chi}_\pm^1} > 200$ GeV for $\Delta m = 30$ GeV. These limits assume that $\tilde{\chi}_2^0, \tilde{\chi}_\pm^1$ decay purely via off-shell gauge bosons. Here, there can also be decays to leptons mediated via the light sleptons, which strengthens the bounds slightly. At the HL-LHC these searches are projected to eventually be sensitive to $m_{\tilde{\chi}_2^0/\tilde{\chi}_\pm^1} \lesssim 430$ GeV [40].

Slepton searches can already probe masses up to 700 GeV [22,41], although the limits become weaker with increasing LSP mass and there is currently no bound for $m_{\tilde{\chi}_1^0} > 400$ GeV. For smaller values of M_2 than shown in Fig. 3, slepton searches do constrain the parameter space. However, care should be taken when imposing the limits. First, the naive limit is weakened by the fact that the $\text{BR}(\tilde{\ell}^\pm \rightarrow \tilde{\chi}_{1,2}^0 \ell^\pm) \approx 60\%$, since the decay mode $\tilde{\ell}^\pm \rightarrow \tilde{\chi}_1^\pm \nu$ is also accessible. Second, in addition to slepton pair

production, the processes $pp \rightarrow \tilde{\nu} \tilde{\ell}$ and $pp \rightarrow \tilde{\nu} \tilde{\nu}$, with $\tilde{\nu} \rightarrow \tilde{\chi}_1^\pm \ell^\mp$, may also pass the analysis cuts. This is because the additional soft leptons or jets from the subsequent chargino decay may not be reconstructed. This has the potential to strengthen the limit due to the large $\tilde{\nu} \tilde{\ell}$ production cross section, but requires a full recasting of the analysis.

In the future, slepton searches at the (HL-)LHC are expected to probe most of the 2σ region for a_μ , with two exceptions. The first is the fully compressed region where $M_1 \approx M_2 \approx m_{\tilde{\nu}}$. The second is when μ becomes extremely large, in which case a_μ can be explained with smuon masses exceeding 1 TeV [42].

So far in this section we have assumed that the staus are decoupled. Let us now briefly comment on the case of universal slepton masses. In this case the large- μ region is excluded due to the bound from vacuum stability or because the lightest stau becomes the LSP (grey dashed lines). The small surviving region that can explain a_μ will soon be tested by direct detection, although for smaller values of $\tan\beta$ this region moves beyond the reach of LZ.

VI. CONCLUSION

The discrepancy between the measurement of the anomalous magnetic moment of the muon and its Standard Model prediction now exceeds 4σ , providing a tantalising hint for physics beyond the Standard Model. In this letter, we have demonstrated that this result can easily be accommodated within the framework of the MSSM, with a binolike LSP simultaneously responsible for dark matter. The observed relic abundance is achieved through coannihilations with either the sleptons or a light wino.

We find that bino-stau coannihilation with universal slepton masses is now strongly constrained by LHC searches and will be thoroughly tested by the LZ experiment. On the other hand, with nonuniversal slepton masses the majority of the best-fit region for a_μ currently remains unconstrained for both the bino-slepton and bino-wino coannihilation scenarios.

In both scenarios, the regions with $\mu \lesssim 1.5$ TeV will be probed by the next generation of dark matter direct detection experiments in the near future. This is especially interesting, given that this region is also theoretically preferred by naturalness.

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