Muons g − 2 and Co-annihilating Dark Matter in the MSSM

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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 co-annihilations 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.

I. INTRODUCTION

The recent measurement of the anomalous magnetic moment of the muon \( \mu \) 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 prediction \([3]\) at 4.2σ:

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

Supersymmetry is one of the leading candidates to explain this discrepancy. In this letter, 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 \( a_{\mu} \) and obtain the observed relic abundance via thermal production involves bino-like dark matter and co-annihilations \([4,8]\). 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 \( a_{\mu} \) for either pure Higgsino or Wino dark matter.

There are two distinct scenarios to consider, depending on the identity of the co-annihilating partner: bino-slepton and bino-wino co-annihilation. 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 \( \sim 3 \) TeV. This is also the renormalisation 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 \( \approx 125 \) GeV, and we assume that all other A-terms are negligible.

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

We use the spectrum generator SuSpect \([9]\), while the dark matter relic abundance, DM-nucleon scattering cross-section, and one-loop SUSY contributions to \( a_{\mu} \) are all calculated using MicrOMEGAs-5.2.7 \([10]\). We also include the leading two-loop contributions to \( a_{\mu} \). These come from \( \tan \beta \)-enhanced corrections to the muon Yukawa coupling \([11,12]\) and the QED running down to the muon mass scale \([13]\).

III. BINO-STAU CO-ANNIHILATION

The first scenario we consider is bino-slepton co-annihilation with universal slepton masses. The assumption of universal slepton masses is often imposed in order to avoid dangerous contributions to flavour changing neutral current (FCNC) processes. It can be motivated by certain supersymmetry breaking scenarios, such as gaugino mediation \([18,20]\). In this case, the NLSP and co-annihilating partner is the lightest stau. Achieving the correct relic abundance then requires a mass splitting \( m_{\tilde{\chi}_{1}^{0}} \sim m_{\tilde{\tau}_{1}} \lesssim 15 \) GeV.

The stau co-annihilation 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 $a_\mu$ measurement at 1σ (2σ). However, most of the 1σ region is already excluded by LHC searches for the first and second generation sleptons [16, 21] (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 [22]. We take the bound from Ref. [23]; the dark 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 slepton searches. There are then regions which can fit $a_\mu$ 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.

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 [15].

It is clear from fig. 1 that bino-stau co-annihilation with universal slepton masses, while still viable, is strongly constrained. One could consider decreasing $M_2$ in order to further enhance the chargino-sneutrino contribution to $a_\mu$. However, $M_2$ cannot be decreased significantly without encountering bounds from chargino searches, particularly for slepton-mediated decays [16].

Finally, note that we are assuming universal slepton 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 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 [24]).

### IV. BINO–SLEPTON CO-ANNIHILATION

Given the results of the previous section, we now relax the assumption of flavour 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 realised, for example, in Gaugino+Higgs mediation without inducing large FCNCs [24].

In this scenario the NLSP and dominant co-annihilating partner(s) are either the lightest smuon or

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Footnote 1: This is achieved with large negative soft masses for the Higgs doublets at the GUT scale, and $\mu \sim \mathcal{O}(10)$ TeV.
the sneutrinos. These two cases can both be seen in the left panel of fig. 2, where we have fixed \( \tan \beta = 50 \). For \( \mu \lesssim 1 \text{ TeV} \) the NLSP is a sneutrino, while for larger \( \mu \) the smuon mixing ensures that \( \tilde{\mu}_1 \) is lighter. \( M_1 \) has been adjusted to obtain the observed relic abundance, which requires a mass splitting between the bino and NLSP of \( \lesssim 10 \text{ GeV} \) \cite{25}. 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.

Here, we have assumed that the wino is decoupled \((M_2 = 3 \text{ TeV})\); the dominant contribution to \( a_\mu \) 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 \( a_\mu \) moves towards higher slepton masses as \( \mu \) is increased. Most of this best-fit region will be probed in the relatively near future by dark matter direct detection.

The right panel of fig. 2 shows the same scenario but for \( \tan \beta = 10 \). This has the effect of moving the best-fit region for \( a_\mu \) to lower slepton masses for a given \( \mu \). As a result, there is significant viable parameter space well beyond the reach of future direct detection experiments. Here, the co-annihilation partners are always the sneutrinos.

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 co-annihilation \cite{26}. However, it does not currently constrain the best-fit region for \( a_\mu \). Given the upper bound on the slepton mass from the relic abundance, the bino-slepton co-annihilation scenario could, however, be fully tested at a future lepton collider with \( \sqrt{s} > 700 \text{ GeV} \).

V. BINO–WINO CO-ANNIHILATION

Last, we consider bino-wino co-annihilation. In this scenario a slightly larger mass-splitting of \( 10 – 30 \text{ GeV} \) is needed between the bino-like LSP and wino-like NLSP \cite{27, 28}. This situation is shown in fig. 3 for \( M_2 = 400 \text{ GeV} \) and \( \tan \beta = 50 \). We have fixed \( M_2 – M_1 = 28 \text{ GeV} \), which gives approximately the correct relic abundance across the parameter space (the precise mass splitting needed has a mild \( \mu \)-dependence). There are significant regions of parameter space that can explain both \( a_\mu \) and the dark matter abundance. For large \( \mu \), the bino-smuon contribution to \( a_\mu \) dominates, while for \( \mu \lesssim 1.5 \text{ TeV} \) 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 \cite{26} and CMS \cite{29} have dedicated chargino searches targeting the compressed spectra relevant for bino-wino co-annihilation. Currently, the CMS search with \( 137 \text{ fb}^{-1} \) obtains a bound of \( m_{\chi_2^0/\chi_1^\pm} > 280 \text{ GeV} \) for \( \Delta m = 10 \text{ GeV} \), reducing to

\[\Omega h^2 > 0.12\]

FIG. 2. Bino–slepton co-annihilation. 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 \( a_\mu \) at 1\( \sigma \) (2\( \sigma \)). The black region is excluded by XENON1T \cite{14}, while the dashed line shows the future sensitivity of the LZ experiment \cite{15}. The red region is excluded by slepton searches at LEP \cite{17}. 

\[\mu \text{ [GeV]}\]

\[\tan \beta = 50\]

\[\Omega h^2 > 0.12\]

\[\mu \text{ [GeV]}\]

\[\tan \beta = 10\]
with ν has the potential to strengthen the limit due to the large because the additional soft leptons or jets from the sub-

that the BR 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 decay mode ℓ± → ν is also accessible. Second, in addition to slepton pair production, the processes pp → ℓ and pp → ν, with ν → ℓ, 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 ℓ 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 aµ, with two exceptions. The first is the fully compressed region where M2 ≈ M ≈ m. The second is when µ becomes extremely large, in which case aµ can be explained with sneutrino masses exceeding 1 TeV [52].

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 aµ will soon be tested by direct detection, although for smaller values of tan β this region will move 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 bino-like LSP simultaneously responsible for dark matter. The observed relic abundance is achieved through co-annihilations with either the sleptons or a light wino.

We find that bino-stau co-annihilation 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 non-universal slepton masses the majority of the best-fit region for aµ currently remains unconstrained for both the bino-slepton and bino-wino co-annihilation scenarios.

In both scenarios, the regions with µ < 1.5 GeV 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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[1] B. Abi et al. (Muon g – 2 Collaboration), Measurement of the positive muon anomalous magnetic moment to 0.46 ppm, Phys. Rev. Lett. 126, 141801 (2021)
[2] G. W. Bennett et al. (Muon g-2), Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL, Phys. Rev. D 73, 072003 (2006) arXiv:hep-ex/0602035

[3] T. Aoyama et al., The anomalous magnetic moment of the muon in the Standard Model, Phys. Rept. 887, 1 (2020) arXiv:2006.04822 [hep-ph]

[4] M. Endo, K. Hamaguchi, S. Iwamoto, and K. Yanagi, Probing minimal SUSY scenarios in the light of muon g − 2 and dark matter, JHEP 06, 031 arXiv:1704.05287

[5] G. Bélanger, A. Mjallal, and A. Pukhov, Recasting direct

[6] G. Degrassi and G. F. Giudice, QED logarithms in the

[7] E. Aprile et al., The anomalous magnetic moment of the muon, Phys. Rept. 887, 1 (2020) arXiv:1710.11091 [hep-ph]

[8] M. Chakraborti, S. Heinemeyer, and I. Saha, Improved

[9] A. Djouadi, J.-L. Kneur, and G. Moultaka, SuSpect: A

[10] T. Aoyama et al.

[11] J. Zhao, Testing electroweak SUSY for muon

[12] K. Inoue, M. Kawasaki, M. Yamaguchi, and T. Yanagida, Vanishing squark and slepton masses in a class of supergravity models, Phys. Rev. D 45, 328 (1992)

[13] D. E. Kaplan, G. D. Kribs, and M. Schmaltz, Supersymmetry breaking through transparent extra dimensions, Phys. Rev. D 62, 035010 (2000) arXiv:hep-ph/9911293

[14] Z. Chacko, M. A. Luty, A. E. Nelson, and E. Ponton, Gaugino mediated supersymmetry breaking, JHEP 01, 003 arXiv:hep-ph/9911233

[15] Search for electroweak production of charginos and neutralinos in proton-proton collisions at sqrt(s)=13 TeV, Tech. Rep. CMS-PAS-SUS-19-012 (CERN, Geneva, 2021).

[16] G. Aad et al. (ATLAS), Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in sqrt(s) = 13 TeV pp collisions using the ATLAS detector, Eur. Phys. J. C 80, 123 (2020) arXiv:1908.08215 [hep-ex]