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The tiny ($g-2$) muon wobble from small- μ supersymmetry

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ABSTRACT: A new measurement of the muon anomalous magnetic moment, $g_\mu - 2$, has been reported by the Fermilab Muon $g-2$ collaboration and shows a 4.2σ departure from the most precise and reliable calculation of this quantity in the Standard Model. Assuming that this discrepancy is due to new physics, we concentrate on a simple supersymmetric model that also provides a dark matter explanation in a previously unexplored region of supersymmetric parameter space. Such interesting region can realize a Bino-like dark matter candidate compatible with all current direct detection constraints for small to moderate values of the Higgsino mass parameter $|\mu|$. This in turn would imply the existence of light additional Higgs bosons and Higgsino particles within reach of the high-luminosity LHC and future colliders. We provide benchmark scenarios that will be tested in the next generation of direct dark matter experiments and at the LHC.

KEYWORDS: Supersymmetry Phenomenology

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1 Introduction

The Standard Model (SM) of particle physics has built its reputation on decades of measurements at experiments around the world that testify to its validity. With the discovery of the Higgs boson almost a decade ago [1, 2] all SM particles have been observed and the mechanism that gives mass to the SM particles, with the possible exception of the neutrinos, has been established. Nonetheless, we know that physics beyond the SM (BSM) is required to explain the nature of dark matter (DM) and the source of the observed matter-antimatter asymmetry. Furthermore, an understanding of some features of the SM such as the hierarchy of the fermion masses or the stability of the electroweak vacuum is lacking.

The direct discovery of new particles pointing towards new forces or new symmetries in nature will be the most striking and conclusive evidence of BSM physics. However, it may well be the case that BSM particles lie beyond our present experimental reach in mass and/or interaction strength, and that clues for new physics may first come from results for precision observables that depart from their SM expectations. With that in mind, since the discovery of the Higgs boson, we are straining our resources and capabilities to measure the properties of the Higgs boson to higher and higher accuracy, and flavor and electroweak physics experiments at the LHC and elsewhere are pursuing a complementary broad program of precision measurements. Breakthroughs in our understanding of what lies beyond the SM could occur at any time.

Recently, new results of measurements involving muons have been reported. The LHCb experiment has reported new values of the decay rate of B -mesons to a kaon and a pair of muons compared to the decay into a kaon and electrons [3], providing evidence at the 3σ -level of the violation of lepton universality. This so-called R_K anomaly joins the ranks of previously reported anomalies involving heavy-flavor quarks such as the bottom quark forward-backward asymmetry at LEP [4, 5], and measurements of meson decays at the LHC and B -factories such as R_{K^*} [6–8] and $R_{D^{(*)}}$ [9–14]. The Fermilab Muon ($g-2$)

experiment has just reported a new measurement of the anomalous magnetic moment of the muon, $a_\mu \equiv (g_\mu - 2)/2$. The SM prediction of a_μ is known with the remarkable relative precision of 4×10^{-8} , $a_\mu^{\text{SM}} = 116\,591\,810(43) \times 10^{-11}$ [15–35]. From the new Fermilab Muon (g-2) experiment, the measured value is $a_\mu^{\text{exp, FNAL}} = 116\,592\,040(54) \times 10^{-11}$ [36], which combined with the previous E821 result $a_\mu^{\text{exp, E821}} = 116\,592\,089(63) \times 10^{-11}$ [37], yields a value $a_\mu^{\text{exp}} = 116\,592\,061(41) \times 10^{-11}$.

An important point when considering the tension between experimental results and the SM predictions are the current limitations on theoretical tools in computing the hadronic vacuum polarization (HVP) contribution to a_μ^{SM} , which is governed by the strong interaction and is particularly challenging to calculate from first principles. The most accurate result of the HVP contribution is based on a data-driven result, extracting its value from precise and reliable low-energy ($e^+e^- \rightarrow \text{hadrons}$) cross section measurements via dispersion theory. Assuming no contribution from new physics to the low energy processes and conservatively accounting for experimental errors, this yields a value $a_\mu^{\text{HVP}} = 685.4(4.0) \times 10^{-10}$ [15, 20–26], implying an uncertainty of 0.6% in this contribution.¹ The SM prediction for the anomalous magnetic moment of the muon and the measured value then differ by 4.2σ ,

$$\Delta a_\mu \equiv (a_\mu^{\text{exp}} - a_\mu^{\text{SM}}) = (251 \pm 59) \times 10^{-11}. \quad (1.1)$$

It is imperative to ask what these anomalies may imply for new physics. The most relevant questions that come to mind are: can the a_μ and $R_{K^{(*)}}$ anomalies be explained by the same BSM physics? Can they give guidance about the nature of DM? Are they related to cosmological discrepancies? How constrained are the possible solutions by other experimental searches? There are two broad classes of solutions to the $(g_\mu - 2)$ anomaly that may be considered in the light of the above:

- New relatively light particles with small couplings to muons, typically featuring particles with $\mathcal{O}(100)$ MeV masses and $\mathcal{O}(10^{-3})$ couplings to muons. Examples of such models are new (light) scalars [43–49] and new (light) (Z') vector bosons. A pseudoscalar particle may also lead to an explanation of Δa_μ , provided it couples not only to muons, but also to photons. The typical example are axion-like particles [50–53], although obtaining the proper Δa_μ requires a delicate interplay between the couplings to muons and to photons.² In the case of gauge bosons, a common explanation of both $R_{K^{(*)}}$ and a_μ is, however, strongly constrained by neutrino trident bounds on Z' bosons coupled to muons [55–57].³ In addition, bounds from BaBar [60] and CMS [61]

¹The HVP contribution has recently been computed in lattice QCD, yielding a higher value of $a_\mu^{\text{HVP}} = 708.7(5.3) \times 10^{-10}$ [38]. Given the high complexity of this calculation, independent lattice calculations with commiserate precision are needed before confronting this result with the well tested data-driven one. We stress that if a larger value of the HVP contribution were confirmed, which would (partially) explain the $(g_\mu - 2)$ anomaly, new physics contributions will be needed to bring theory and measurements of ($e^+e^- \rightarrow \text{hadrons}$) in agreement [39–42].

²A similar mechanism applies for ($g_e - 2$) in the case of the QCD axion; see, for instance, ref. [54].

³There are also bounds from Coherent ν -Nucleus Scattering (CE ν NS), although these are not yet competitive with the bounds from neutrino trident processes [58, 59].

from $[e^+e^-/pp \rightarrow \mu^+\mu^- + (Z'/\phi \rightarrow \mu^+\mu^-)]$ rule out the values of the new gauge (or scalar) coupling which could explain the observed value of a_μ for $m_{Z'}(m_\phi) \geq 2m_\mu \simeq 210$ MeV. Explanations of the flavor anomalies require the gauge boson to decay into a pair of muons, preventing simultaneous explanations of $R_{K^{(*)}}$ and a_μ .

- New heavy fermions [62, 63] or scalars (possibly accompanied by additional new particles, like in the supersymmetric extensions of the SM discussed in detail below), as well as leptoquark particles [64–67], with larger couplings to muons. Leptoquarks provide one of the most interesting solutions to Δa_μ , since they can lead to a simultaneous explanation of the R_K anomaly. Note however that a careful choice of the leptoquark couplings is necessary to avoid flavor-changing neutral currents, which is perhaps the least attractive feature of such scenarios.

In section 2, we shall discuss a supersymmetric solution in the simplest supersymmetric model at hand, the Minimal Supersymmetric Standard Model (MSSM). We focus on a region of the parameter space of the MSSM where the $(g_\mu - 2)$ anomaly can be realized simultaneously with a viable DM candidate. We show that in the region of moderate $|\mu|$ and moderate-to-large values of $\tan \beta$, a Bino-like DM candidate can be realized in the proximity of *blind spots* (that require $\mu \times M_1 < 0$) for spin-independent direct detection (SIDD) experiments [68]. In this way, our MSSM scenario explores a different region of parameter space than the one considered in the study of refs. [69, 70], which considers regions of large μ as a way to accommodate current SIDD bounds. We summarize and conclude in section 3. In appendix A, we give details about the LHC constraints on these scenarios.

2 Tiny $(g_\mu - 2)$ muon wobble with small $|\mu|$ in the MSSM

Supersymmetric extensions of the SM remain among the most compelling BSM scenarios [71–73], not least because the stability of the Higgs mass parameter under quantum corrections can be ensured. In minimal supersymmetric extensions of the SM, the SM-like Higgs is naturally light [74–84] and the corrections to electroweak precision as well as flavor observables tend to be small, leading to good agreement with observations. Supersymmetric extensions can also lead to gauge coupling unification and provide a natural DM candidate, namely the lightest neutralino.

In this section, we propose simultaneous $(g_\mu - 2)$ and DM solutions in the Minimal Supersymmetric Standard Model (MSSM) [71–73] which have not been explored before. Related recent (but prior to the publication of the Fermilab Muon $(g-2)$ result) studies can, for example, be found in refs. [69, 70, 85–90]. One crucial difference between our study and the very recent work in refs. [69, 70] is that the spin-independent direct detection (SIDD) cross section is suppressed not by decoupling the Higgsino and heavy Higgs contributions, but by a partial cancellation between the amplitudes mediated by the two neutral CP-even Higgs boson mass eigenstates. This cancellation requires opposite signs of the Higgsino and the Bino mass parameters, $(\mu \times M_1) < 0$ [68]. Demonstrating that one can explain the a_μ anomaly in this region of parameter space is non-trivial, as this combination of the Higgsino and Bino mass parameters renders the contribution of the neutralino-smuon loop

to a_μ negative, while the experimentally observed value is *larger* than the SM prediction. Explaining the experimental measurement is only possible if the chargino-sneutrino contribution to a_μ is positive and has larger absolute magnitude than the neutralino-smuon contribution, and if the values of the individual contributions are such that the observed anomaly, $\Delta a_\mu = (20 - 30) \times 10^{-10}$, can be explained. Moreover, this can only be achieved for moderate (absolute) values of the Higgsino mass parameter $|\mu| \lesssim 500 \text{ GeV}$, and values of the heavy Higgs boson masses than are not far away from the current experimental limit coming from direct searches.

2.1 Δa_μ and direct dark matter detection constraints

The MSSM contributions to a_μ have been discussed extensively in the literature, see, for example, refs. [89, 91–97]. The most important contributions arise via chargino-sneutrino and neutralino-smuon loops, approximately described by [89]

$$a_\mu^{\tilde{\chi}^\pm - \tilde{\nu}_\mu} \simeq \frac{\alpha m_\mu^2 M_2 \tan \beta}{4\pi \sin^2 \theta_W m_{\tilde{\nu}_\mu}^2} \left[\frac{f_{\chi^\pm}(M_2^2/m_{\tilde{\nu}_\mu}^2) - f_{\chi^\pm}(\mu^2/m_{\tilde{\nu}_\mu}^2)}{M_2^2 - \mu^2} \right], \quad (2.1)$$

$$a_\mu^{\tilde{\chi}^0 - \tilde{\mu}} \simeq \frac{\alpha m_\mu^2 M_1 (\mu \tan \beta - A_\mu)}{4\pi \cos^2 \theta_W (m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2)} \left[\frac{f_{\chi^0}(M_1^2/m_{\tilde{\mu}_R}^2)}{m_{\tilde{\mu}_R}^2} - \frac{f_{\chi^0}(M_1^2/m_{\tilde{\mu}_L}^2)}{m_{\tilde{\mu}_L}^2} \right], \quad (2.2)$$

where M_2 is the Wino mass parameter and $m_{\tilde{f}}$ are the scalar particle $\tilde{f}$ masses, with the loop functions

$$f_{\chi^\pm}(x) = \frac{x^2 - 4x + 3 + 2\ln(x)}{(1-x)^3}, \quad (2.3)$$

$$f_{\chi^0}(x) = \frac{x^2 - 1 - 2x\ln(x)}{(1-x)^3}; \quad (2.4)$$

see refs. [94, 97] for the full (one-loop) expressions. It is interesting to note that these two contributions can be of the same order of magnitude: the chargino-sneutrino contribution is proportional to Higgsino-Wino mixing which can be sizeable, but suppressed by the smallness of the Higgsino-sneutrino-muon coupling which is proportional to the muon Yukawa coupling, $\propto m_\mu \tan \beta / v$, with the SM Higgs vacuum expectation value v . The neutralino-smuon contribution, on the other hand, arises via muon-smuon-neutralino vertices which are proportional to the gauge couplings, but is suppressed by the small smuon left-right mixing, $\propto m_\mu (\mu \tan \beta - A_\mu) / (m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2)$. Regarding corrections beyond one-loop [98, 99], the most relevant contribution is associated with corrections to the muon Yukawa coupling, Δa_μ . These corrections become relevant at large values of $\mu \tan \beta$ and can be re-summed at all orders of perturbation theory [100]. While these corrections lead to small modifications of a_μ , they do not change the overall dependence of Δa_μ on the masses of the supersymmetric particles.

From eqs. (2.1)–(2.2) we can observe that the signs of the MSSM contributions to a_μ depend sensitively on the relative signs of the gaugino masses M_1 and M_2 and the

Higgsino mass parameter μ . As emphasized before, a DM candidate compatible with the current null-results from direct detection experiments can be realized for $|\mu| \lesssim 500$ GeV if M_1 and μ have opposite signs. For this combinations of signs, the contribution from the neutralino-smuon loop to a_μ will be negative, $a_\mu^{\tilde{\chi}_0^0 - \tilde{\mu}} < 0$. Since the measured value of a_μ is *larger* than the SM prediction by $\Delta a_\mu \simeq 25 \times 10^{-10}$, we require the chargino-sneutrino contribution to be positive and larger than the neutralino-smuon contribution. This can be realized if M_2 has the same sign as μ and if $|M_2|$ is of similar size as $|\mu|$ and the soft smuon masses. In the regime of moderate or large values of $\tan \beta$, and assuming all weakly interacting sparticles have masses of the same order, $\tilde{m}$, one obtains approximately

$$\Delta a_\mu \simeq 1.3 \times 10^{-9} \tan \beta \times \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2. \quad (2.5)$$

The factor 1.3 reduces to values closer to 1 if M_1 and M_2 have opposite signs. This implies that for values of $\tan \beta \simeq 10$, sparticles with masses $\tilde{m} \sim 200$ GeV can lead to an explanation of the observed Δa_μ anomaly, while for $\tan \beta = 60$, the characteristic scale of the weakly interacting particle masses may be as large as $\tilde{m} \sim 500$ GeV.

The range of $\tan \beta$ and of sparticle masses consistent with the observed Δa_μ has implications on the DM properties. We will concentrate on DM candidates with masses comparable to the weak scale, such that the thermal DM relic density reproduces the observed value. In the MSSM, DM candidates in this mass range can be realized if the lightest supersymmetric particle is an almost-pure Bino, $m_\chi \simeq |M_1|$.

For the moderate-to-large values of $\tan \beta$ required to explain the $(g_\mu - 2)$ anomaly, the SIDD amplitude for the scattering of DM with nuclei (N) is proportional to

$$\mathcal{M}_p^{\text{SI}} \propto \frac{v}{\mu^2} \left[2 \frac{(M_1 + \mu \sin 2\beta)}{m_h^2} - \frac{\mu \cos 2\beta}{m_H^2} \tan \beta \right], \quad (2.6)$$

where m_h and m_H are the masses of the SM-like and the new heavy neutral Higgs boson, respectively. We see that the SIDD amplitude depends in a crucial way on the sizes and signs of M_1 and μ . There are two options to lower the SIDD amplitude: for large values of $|\mu|$, the Higgsino components of the DM candidate become small and the SIDD amplitude is suppressed. Alternatively, the light and heavy CP-even Higgs contributions (first and second terms inside the brackets in eq. (2.6)) may interfere destructively, leading to a suppression of the SIDD amplitude. The latter option is particularly interesting since it allows $|\mu|$ to remain of the order of the electroweak scale; see, for example ref. [101] for a recent discussion of naturalness and the connection with direct detection bounds.

Regarding the first term in eq. (2.6), if $M_1 \simeq -\mu \sin 2\beta$, the contributions of the Higgsino-up and the Higgsino-down admixtures to the $(\chi\chi h)$ interaction cancel. The second term is the contribution to the $(\chi N \rightarrow \chi N)$ amplitude arising from the t -channel exchange of the non-SM-like heavy Higgs boson H . The *generalized blind spot* condition for the SIDD cross section of a Bino-like DM candidate is then [68]

$$\frac{2(M_1 + \mu \sin 2\beta)}{m_h^2} \approx \frac{\mu \tan \beta \cos 2\beta}{m_H^2}. \quad (2.7)$$

If the condition in eq. (2.7) is satisfied, the amplitudes mediated by h and by H exchange interfere destructively, suppressing the SIDD cross section; a property that also holds at the one-loop level [102]. In general, even if one is not in the proximity of the blind spot solution, if the neutralino is mostly Bino-like, for a given value of $|\mu|$ and M_1 , the cross section is suppressed (enhanced) if μ and M_1 have opposite (the same) sign.⁴

The mass of the heavy Higgs boson plays an important role in the blind-spot cancellation. In the presence of light electroweakinos, the current LHC bounds on m_H coming from searches for heavy Higgs bosons decaying into tau-leptons [103–106] can be approximated by

$$m_H \gtrsim 250 \text{ GeV} \times \sqrt{\tan \beta} \sim 2 m_h \sqrt{\tan \beta} . \quad (2.8)$$

For values of m_H close to this bound, the SIDD amplitude is proportional to

$$\mathcal{M}_p^{\text{SI}} \propto \frac{M_1 v}{\mu^2} \left[1 + \frac{\mu}{2M_1} \left(\frac{4}{\tan \beta} + \frac{1}{4} \right) \right] . \quad (2.9)$$

To exemplify the relevance of the relative sign and size of μ and M_1 , consider $\mathcal{M}_p^{\text{SI}}$ for $\tan \beta = 16$. As a reference value for the SIDD amplitude, let us set $\mu \simeq -M_1$. Keeping M_1 fixed, but increasing the value of $|\mu|$ to $\mu \simeq -2M_1$, the value of $\mathcal{M}_p^{\text{SI}}$ becomes a factor of $\approx 1/6$ smaller. Let us compare this to the situation for which μ and M_1 have the same sign. First, we can note that for $\mu = M_1$, the SIDD amplitude is almost a factor 2 larger than for $\mu = -M_1$. Furthermore, in order to obtain a reduction of $\mathcal{M}_p^{\text{SI}}$ by a factor of $1/6$, one would have to raise the value of $|\mu|$ from $\mu \sim M_1$ to $\mu \sim 4M_1$. This exemplifies that obtaining SIDD cross sections compatible with experimental limits either requires $(\mu M_1) < 0$ (blind spot solution) or, to compensate for a positive sign of this product, one must sufficiently enhance the ratio μ/M_1 (large- μ solution).

The spin dependent (SD) interactions are instead dominated by Z -exchange, and can only be suppressed by lowering the Higgsino component of the lightest neutralino. At moderate or large values of $\tan \beta$, the amplitude for SD interactions is proportional to [87]

$$\mathcal{M}^{\text{SD}} \propto \left(\frac{v}{\mu} \right)^2 \cos 2\beta . \quad (2.10)$$

Comparison with the results from direct detection experiments [107–110] leads to an approximate bound on μ ,

$$|\mu| \gtrsim 300 \text{ GeV} , \quad (2.11)$$

with a mild dependence on M_1 .

To summarize this discussion, we show the qualitative behavior of the direct detection cross sections in figures 1 and 2 in the M_1 – μ plane. We use approximate analytic expressions for the cross sections and set the masses of the heavy Higgs boson and $\tan \beta$ to characteristic values. The values of M_2 and the slepton masses have been chosen to lead to a compressed spectrum, alleviating constraints from slepton and chargino searches at the LHC, see, for example, refs. [112–123]. The regions shaded in the different colors denote

⁴Note that $\cos(2\beta) = (1 - \tan^2 \beta)/(1 + \tan^2 \beta) \simeq -1$ for moderate-to-large values of $\tan \beta$.

Figure 1. The colored shades show approximate regions in the μ - M_1 parameter plane allowed by current DM direct detection constraints on the spin-dependent WIMP-proton, spin-dependent WIMP-neutron, and spin-independent WIMP-nucleon cross section for $\tan\beta = 20$ and values of the slepton, Higgs and Wino mass parameters as indicated in the plot. In the gray areas bounded by the dashed black lines we find a MSSM contribution $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$, explaining the value observed by the Fermilab and Brookhaven Muon ($g-2$) experiments. The dash-dotted purple lines indicate constraints arising from tau-leptons +missing transverse energy(+jet) searches at the LHC, applicable if the mass of the lightest stau is approximately in the middle of the lightest chargino and neutralino masses [111].

the region allowed by current direct detection constraints on the SD-proton [107, 110], SD-neutron [108, 109], and SI [124–127] scattering cross section. We see that whereas the SD constraints provide an approximately symmetric lower bound on μ , due to the SIDD constraints, the values of $|\mu|$ need to be significantly larger for positive $\mu \times M_1$ than for negative $\mu \times M_1$. We show the region where the MSSM contribution explains the $(g_\mu - 2)$ anomaly in figures 1 and 2 with the gray shade bounded by the dashed black line. The shape of the region preferred by Δa_μ may be understood from the interplay between the Bino- and Wino-mediated contributions. For large values of $|\mu|$, the Bino contribution tends to be the most relevant one. If one considers positive values of $\mu \times M_1$, the Bino-smuon loop gives a positive contribution to Δa_μ which can account for the $(g_\mu - 2)$ anomaly for sufficiently large values of $\tan\beta$. However, for smaller values of $|\mu|$ and negative values of $\mu \times M_1$, as required by the blind spot solution, the Bino contribution tends to be subdominant and

Figure 2. Same as figure 1 but for $\tan \beta = 30$ and $m_H = 1500 \text{ GeV}$.

neither has the sign nor the magnitude to account for the $(g_\mu - 2)$ anomaly. If anything, depending on the sign of $M_1 \times M_2$, it will partially cancel the Wino contribution to Δa_μ . For smaller values of $|\mu|$, an explanation for the $(g_\mu - 2)$ anomaly requires a Wino-mediated contribution enabled by $\mu \times M_2 > 0$ and moderate values of M_2 .

For the LHC constraints indicated in figures 1 and 2 ($|M_1| \gtrsim 240 \text{ GeV}$, shown with the purple dash-dotted line) we have assumed that the lightest stau is the next-to-lightest supersymmetric particle, with a mass such that the proper relic density is obtained by co-annihilation of the lightest stau with the lightest neutralino. In such a case, the Wino-like chargino and neutralino have sizable branching ratios into staus, increasing the stau production rate. In order to estimate the LHC limits, we use a recent analysis [111] searching for tau-lepton final states, which assumed that the mass gap between the lightest chargino and neutralino is 50 GeV and the lightest stau mass lies in the middle of the lightest chargino and neutralino masses, which is close to the situation found under our assumptions. This shows that the LHC is already putting strong constraints on the realization of this scenario. Note that we chose the Wino- (M_2) and the first and second generation slepton ($M_L^{1,2}, M_R^{1,2}$) mass parameters to be approximately degenerate ($M_2 \approx M_L^{1,2} \approx M_R^{1,2} \approx |M_1| + 50 \text{ GeV}$) such that current LHC limits for direct slepton searches are avoided for slepton masses above $\sim 200 \text{ GeV}$ [112–123].

Additional constraints from LHC searches with charged leptons in the final states can arise from production of the Higgsino-like neutralino and chargino states. These states decay into gauge and Higgs bosons and lighter charginos and neutralinos. If μ is large compared to M_2 , Higgsino production and their decays can lead to relevant signals at the LHC despite Higgsinos having much smaller production cross section than Winos, because for such a choice of parameters, the Higgsino-decays lead to final states with much harder leptons than the leptons arising from Wino or slepton production. We have checked a number of example points from the preferred regions of figures 1 and 2 (i.e., where all direct detection constraints are satisfied, where $|M_1| \gtrsim 240$ GeV, avoiding the LHC constrain indicated in the figures, and where the Δa_μ contribution explains the observed value) using `checkmate2` to check that no additional LHC constraints arise from slepton and electroweakino (including Higgsino) production.

2.2 Benchmark points explaining Δa_μ , dark matter and avoiding LHC constraints

For a Bino-like DM candidate with mass in the few-hundred GeV range, the observed relic density can be realized via thermal production through different mechanisms, such as co-annihilation with sleptons or charginos [128–133], t -channel annihilation via light left-right mixed staus [134] or smuons [135], or resonant s -channel annihilation [131, 132]. In table 1 we present a few benchmark scenarios which simultaneously accommodate the $(g_\mu - 2)$ anomaly and a viable DM candidate. All of them are consistent with the observed relic density, the observed value of Δa_μ , and satisfy LHC constraints as well as constraints from direct detection. For all benchmark points, we set the parameters in the squark and gluino sectors such that experimental bounds are satisfied and that the observed mass of the SM-like Higgs boson is reproduced. In general, the supersymmetric partners of the color-charged particles must have masses of the order of a few TeV to satisfy current experimental bounds (see, for instance, refs. [136–139]). Note that in some of our benchmark scenarios, the hierarchy between the gluino and the weak gaugino masses is larger than the hierarchy induced by the running of the gaugino masses from (approximately) universal values at the Grand Unification scale. While a Grand Unified Theory (GUT) is theoretically attractive, we do not know if any GUT is realized in nature. The symmetries of the low energy theory do not impose any constraint on the hierarchy between the gluino and the weak gaugino masses. Furthermore, even in GUT models, higher order operators at the GUT scale can lead to departures from universal gaugino masses [140]. A somewhat related point is that the small- $|\mu|$ region we are interested in here tends to require particular choices for the soft supersymmetry breaking masses of the Higgs doublets. As is well known, the large stop masses required to reproduce a 125 GeV SM-like Higgs boson result in large radiative corrections to $m_{H_u}^2$. Starting from universal soft parameters $m_{H_u}^2 = m_{H_d}^2$ at high energy scales, $m_{H_u}^2$ is driven to large negative values at the electroweak scale, while $m_{H_d}^2$ receives much smaller radiative corrections. The correct electroweak symmetry breaking (and, in particular, the correct mass of the electroweak gauge bosons) is then achieved for $-m_{H_u}^2 \approx |\mu|^2 \gg m_{H_d}^2$ at the electroweak scale. We leave a dedicated investigation of the required values of the soft parameters to achieve the correct electroweak symmetry breaking pattern

for future work, however, let us note that (radiative) electroweak symmetry breaking as well as the correct mass of the electroweak gauge bosons are straightforward to achieve regardless of the value of $|\mu|$ if one allows for different values of the soft supersymmetry breaking parameters $m_{H_u}^2$ and $m_{H_d}^2$ at high energy scales.

The constraints from Higgsino and Wino pair production depend on a careful consideration of the production cross sections and decay branching ratios [141, 142]. Here, we consider a compressed spectrum, for which the electroweakino and slepton constraints are weakened. The results for the spectrum, Δa_μ , the relic density, as well as the SI and SD cross sections have been obtained with `Micromegas 5.2.7.a` [143–145]. We use `SUSY-HIT 1.5` [146] to compute branching ratios relevant for checking the electroweakino and slepton constraints. One problem in the analysis of the LHC limits is that, in many cases, signals can be obtained from the chain decay of many different electroweak particles, and therefore it is difficult to directly apply the bounds from LHC analyses which are typically presented in terms of simplified models. In order to solve this problem, we use `checkmate2` [147–150], that uses Monte Carlo event generation to compare all production and decay channels for the neutralinos, charginos and sleptons with the current LHC analyses [151–214]. Although most of the relevant LHC analyses have been included in `checkmate2`, a few of the most recent analyses are not yet implemented in this code. In these cases, we check the compatibility of our points by using conservative estimates of the particle contributions to the different search signals, as explained in appendix A.

The scenarios presented below correspond to different origins of the observed DM relic density and should serve as a guidance for experimental probes of the supersymmetric explanation of the muon $(g - 2)$.

- **BMSM:** a DM production scenario closely related to the relatively low masses of the muon (neutrino) superpartners required to address the a_μ -anomaly is co-annihilation of the lightest neutralino with the light slepton states. The benchmark BMSM gives a representation of this possibility, where we set the masses of the tau-lepton superpartners to be larger than those of the first and second generation sleptons. Since multiple production channels contribute to final states containing leptons at the LHC, current searches strongly constrain the presence of light electroweak interacting particles in this scenario. In order to be compatible with Δa_μ , DM phenomenology and LHC searches, BMSM features the largest values of $|\mu|$ and $\tan \beta$ of the benchmark points presented in this article.
- **BMST:** a similar solution to BMSM is associated with the co-annihilation of a light stau with the lightest neutralino. For universal soft slepton masses, this happens naturally at large values of $\tan \beta$, where the lightest stau is pushed to masses lower than those of the sneutrinos. BMST gives a representative example of this possibility.
- **BMW:** the lightest neutralino may co-annihilate with the lightest chargino. The benchmark BMW represents such a possibility.
- **BMH:** the lightest neutralino can acquire the proper relic density via resonant s -channel annihilation via the SM-like Higgs boson. BMH represents such a possibility.

	BMSM	BMST	BMW	BMH
M_1 [GeV]	-352	-258	-274	63
M_2 [GeV]	400	310	310	700
μ [GeV]	690	475	500	470
$M_L^{1,2}$ [GeV]	360	320	350	750
M_L^3 [GeV]	500	320	350	750
$M_R^{1,2}$ [GeV]	360	320	350	750
M_R^3 [GeV]	500	320	350	750
M_A [GeV]	2000	1800	1600	3000
$\tan\beta$	60	40	35	65

	BMSM	BMST	BMW	BMH
m_χ [GeV]	350.2	255.3	271.4	61.0 (124.9)
$m_{\tilde{\tau}_1}$ [GeV]	414.4	264.2	305.3	709.5
$m_{\tilde{\mu}_1}$ [GeV]	362.7	323.0	352.8	751.3
$m_{\tilde{\nu}_\tau}$ [GeV]	496.0	313.7	344.2	747.3
$m_{\tilde{\nu}_\mu}$ [GeV]	354.4	313.7	344.2	747.3
$m_{\chi_\pm^\pm}$ [GeV]	392.3	296.2	297.9	469.6
Δa_μ [10^{-9}]	2.10	2.89	2.35	1.93
$\Omega_{\text{DM}} h^2$	0.121	0.116	0.124	0.121
σ_p^{SI} [10^{-10} pb]	0.645	1.58	1.42	0.315
σ_p^{SD} [10^{-6} pb]	1.03	5.11	4.23	3.01
σ_n^{SI} [10^{-10} pb]	0.632	1.57	1.41	0.330
σ_n^{SD} [10^{-6} pb]	0.882	4.10	3.42	2.34

Table 1. Values of the MSSM parameters, mass spectrum and quantities relevant for DM and ($g_\mu - 2$) for the case of Bino-like DM co-annihilating with light sleptons (BMSM), co-annihilating with a light stau (BMST), co-annihilating with a Wino (BMW) and resonant s -channel annihilation via the SM-like Higgs boson (BMH). For BMH we also provide the mass of the SM-like Higgs boson m_h between brackets.

Although the mechanisms controlling the relic density are different for the different benchmark points, they share many characteristics. They feature masses of weakly interacting sparticles masses lower than about 500 GeV and values of $\tan\beta$ of the order of a few 10's, leading to values of Δa_μ in the desired range. Apart from BMH, which we will discuss further below, all benchmark points in table 1 have negative values of $\mu \times M_1$ and positive values of $\mu \times M_2$.

The observed relic density for a Bino-like DM candidate may also be obtained via resonant s -channel annihilation via the heavy Higgs boson A and H . However, for the values of $\tan\beta$ necessary to enhance Δa_μ , LHC bounds on the heavy Higgs bosons become very strong, implying a heavy spectrum. Using the bound on m_H provided in eq. (2.8), the approximate expression for Δa_μ in eq. (2.5), and assuming that all the weakly interacting sparticles have masses close to $m_H/2$, the maximal value for Δa_μ that may be obtained is

$$\Delta a_\mu \simeq 10^{-9} \tan\beta \frac{4}{m_H^2} (100 \text{ GeV})^2 \lesssim 7 \times 10^{-10}, \quad (2.12)$$

which is a factor of a few smaller than the observed anomaly. Therefore, we shall not discuss this particular solution further.

Resonant s -channel annihilation via the Z -boson presents similar characteristics to resonant annihilation mediated by the SM-like Higgs, h . Thus, we present only an example of the latter case here, BMH. For such small values of $M_1 \simeq m_h/2 = 62.5 \text{ GeV}$, values of $|\mu| \sim 500 \text{ GeV}$ may lead to the desired suppression of the SIDD cross section for either sign of μ . This follows, for instance, from eq. (2.6), where we also observe that for positive values of $\mu \times M_1$, values of m_H significantly larger than the current experimental bounds

are preferred. Note that, for BMH, we chose the sleptons and the Winos to be heavy to avoid the bounds from the LHC. Hence, obtaining the proper value of Δa_μ requires relatively large values of $\tan \beta$.

2.3 Future prospects

The benchmark points presented above are compatible with current experimental limits, but will be tested in the near future in several ways.

First, all four benchmark points will be probed by the next generation of direct detection experiments: the SIDD cross sections of all four benchmark points are within the projected sensitivities of the LZ and XENONnT experiments [215, 216]. More generally, for $\mu \times M_1 < 0$, and for fixed values of M_1 , μ and $\tan \beta$, the smallest possible value of the SIDD cross section is associated with the smallest allowed value of the heavy Higgs mass, see eq. (2.6). For masses $200 \text{ GeV} \lesssim |M_1| \lesssim 500 \text{ GeV}$, a hierarchy $1 \lesssim |\mu/M_1| \lesssim 3$, and $\tan \beta \gtrsim 20$, compatible with collider physics, muon ($g-2$), and Dark Matter relic density constraints, the smallest possible SIDD cross section is (see eq. (2.9))

$$\sigma_p^{\text{SI}} > \mathcal{O}(10^{-10}) \text{ pb} \times \left(\frac{M_1}{250 \text{ GeV}} \right)^2 \times \left(\frac{500 \text{ GeV}}{\mu} \right)^4. \quad (2.13)$$

The LZ and XENONnT experiments will probe cross sections as small as $\sigma_p^{\text{SI}} \sim \mathcal{O}(10^{-12}) \text{ pb}$ for $|M_1| \sim 40 \text{ GeV}$, growing to $\sigma_p^{\text{SI}} \sim \mathcal{O}(10^{-11}) \text{ pb}$ for $|M_1| \sim 500 \text{ GeV}$, implying full coverage of this representative region of parameters.

Furthermore, the spin-dependent WIMP-neutron cross sections can be probed by LZ and XENONnT, while the next generation of the PICO experiment will probe the spin-dependent WIMP-proton cross sections [217]. From eq. (2.10) we can see that the spin-dependent WIMP-nucleon cross sections are

$$\sigma_n^{\text{SD}} \sim \sigma_p^{\text{SD}} > \mathcal{O}(10^{-6}) \text{ pb} \times \left(\frac{500 \text{ GeV}}{\mu} \right)^4, \quad (2.14)$$

with a mild dependence on M_1 . The future sensitivities of LZ/XENONnT on σ_n^{SI} move from a few times 10^{-7} pb for $|M_1| \sim 100 \text{ GeV}$ to $\sim 10^{-6} \text{ pb}$ for $|M_1| \sim 500 \text{ GeV}$, while PICO-500 will probe $\sigma_p^{\text{SD}} \sim 10^{-6} \text{ pb}$ for $|M_1| \sim 100 \text{ GeV}$ and $\sigma_p^{\text{SD}} \sim 5 \times 10^{-6} \text{ pb}$ for $|M_1| \sim 500 \text{ GeV}$. Hence, these experiments will probe the region of parameter space where $|\mu| \lesssim 500 \text{ GeV}$. In particular, LZ, XENONnT and PICO-500 will probe the spin-dependent cross sections of the benchmark points BMST, BMW, BMH, while BSM has spin-dependent interactions smaller than the projected sensitivities of these experiments.

Second, for all benchmark points with $M_1 \times \mu < 0$ (BSM, BMST, and BMW), the SIDD cross section is suppressed below current experimental limits due to the destructive interference between the amplitudes mediated by the SM-like and the heavy Higgs bosons discussed above. For this suppression to be effective, the masses of the non-SM-like Higgs bosons must be low enough to within the reach (see, for example, ref. [218]) of future runs of the LHC: the high-luminosity LHC will be sensitive to Higgs bosons with masses of about a factor 1.5 larger than current exclusion limits (keeping all other parameters, in particular $\tan \beta$, fixed). From the expression of the SIDD cross section, eq. (2.6) we see that

increasing $m_H \rightarrow 1.5 m_H$ corresponds to a factor 2-3 increase of the SIDD cross section. Such SIDD cross sections would be in conflict with *current* experimental constraints, or conversely, values of the heavy Higgs mass allowed by current direct detection bounds will be efficiently probed by the high-luminosity LHC. For BMSH, on the other hand, the SIDD cross section is suppressed by a large hierarchy between the Higgsino and Bino mass parameters, $|\mu| \gg |M_1|$. Such “large $|\mu|$ ” solutions to suppressing the SIDD cross sections allow for heavy Higgs masses beyond the projected reach of the high-luminosity LHC.

Last but not least, our benchmark scenarios are also testable in searches for electroweakly interacting particles at future runs of the LHC, see, for example, refs. [219, 220]. We note that some of these projections have already been surpassed by innovative searches with current LHC data, like those presented in ref. [221], further bolstering the prospects of probing our benchmark points and similar scenarios in the upcoming runs of the LHC. The extrapolation of these conclusions to the whole region of parameters analyzed in this article should be the object of an independent dedicated study, that we plan to perform but is beyond the scope of the current article. Let us also emphasize that future lepton colliders play an important role to probe sleptons and charginos, especially for (semi-)compressed spectra, see refs. [222–234].

3 Summary and conclusions

A wide range of possible extensions of the Standard Model (SM) can lead to an explanation of the value of Δa_μ measured at the Fermilab and Brookhaven experiments. While arguably the simplest explanation is the addition of a scalar particle, one can also rely on new gauge bosons, vector-like fermions or leptoquark models. The leptoquark (or R-parity violating supersymmetry) solution seems to be interesting since it can accommodate not only the values of Δa_μ , but can also lead to an explanation of the flavor anomalies, although at the prize of a delicate choice of the couplings of the leptoquarks.

In this work, we explore a solution based on the (R-parity conserving) Minimal Supersymmetric extension of the SM, in which, although one cannot address the flavor anomalies, one can find solutions leading to a compelling DM explanation. In particular, we discuss the conditions that are required to be consistent with the observed Δa_μ , existing direct dark matter (DM) detection constraints, and the bounds from the LHC on new Higgs bosons and supersymmetric particles. We look for solution in which direct DM detection constraints are fulfilled by a partial cancellation of the light and heavy CP-even Higgs mediated contributions which significantly differ from previous studies relying on very heavy Higgs and Higgsino particles. This cancellation requires negative values of $\mu \times M_1$. Since the observed value of a_μ is *larger* than the SM prediction, the Bino contribution to a_μ , which is proportional to $\mu \times M_1$, must be subdominant. This can only be realized for small-to-moderate values of $|\mu|$. We present corresponding benchmark scenarios associated with different DM production mechanisms to achieve the observed relic density, including co-annihilation with sleptons, or resonant s -channel annihilation mediated by the SM-like Higgs or Z bosons.

The corresponding spectra have a number of interesting consequences: 1) The relatively small values of the Higgsino mass parameter lead to a more natural model, in terms of the

electroweak hierarchy problem. 2) The DM candidates have spin-independent and spin-dependent direct detection cross sections which can be probed in the next generation of direct detection experiments. 3) Explaining the anomalous magnetic moment of the muon for negative values of $\mu \times M_1$ requires light sleptons and electroweakinos, which should be probed at run 3 of the LHC, the HL-LHC, or, ultimately, at future lepton colliders. 4) The suppression of the direct detection cross section is only possible for relatively light non-SM-like Higgs bosons in the MSSM, which can be probed at run 3 of the LHC and the HL-LHC.

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A LHC constraints from chargino and slepton searches

In this appendix, we discuss the constraints from chargino and slepton searches on our benchmark points presented in table 1. The most severe chargino constraints tend to stem from production of the lightest chargino ($\tilde{\chi}_1^\pm$) and the next-to-lightest neutralino ($\tilde{\chi}_2^0$) at the LHC, $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$. Note that for all of our benchmark points, the lightest neutralino is Bino-like, while $\tilde{\chi}_2^0$ is Wino-like (for BSM, BMST and BMW) or Higgsino-like (for BMH) depending on the hierarchy of $|\mu|$ and $|M_2|$. Hence, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ will typically be mass degenerate. All the benchmark points presented in this article fulfill the current LHC constraints [151–214] implemented in `checkmate2` [147–150]. We also check compatibility with very recent LHC searches which are not yet implemented in `checkmate2` by using conservative estimates of the particle contribution to these search channels.

In order to gain a physical intuition of how the benchmark points avoid the LHC constraints, we provide a brief discussion of their properties.

BMSM. The lightest neutralino has a mass $m_{\tilde{\chi}_1^0} = 350$ GeV, and the Wino-like next-to-lightest neutralino and lightest chargino have masses $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 392$ GeV. We have computed the $\tilde{\chi}_2^0 + \tilde{\chi}_1^\pm$ production cross section at the 13 TeV LHC with `MadGraph5_v3.1.1` [148], finding $\sigma(pp \rightarrow \tilde{\chi}_2^0 + \tilde{\chi}_1^\pm) = 0.08$ pb. Comparing this to the upper limit from ref. [123] $\sigma(pp \rightarrow WZ + 2\tilde{\chi}_1^0) \lesssim 0.6$ pb at these masses (this search is not yet implemented in `checkmate2`; we have taken the limit from the supplementary material of ref. [123] accessible via HEPdata or the CERN Document Server), we see that this

benchmark point is not constrained by this search even before taking into account that the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ decay branching ratios into gauge bosons are small in this scenario. For this benchmark point, however, the Wino- and Higgsino-like neutralinos and charginos can undergo cascade decays involving the light sleptons, giving rise to potentially detectable signatures in searches for charged leptons and missing energy at the LHC. Due to BSM's mass spectrum, the production of the Wino-like $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ gives rise to relatively soft leptons. The most sensitive search corresponding to this final state currently implemented in `checkmate2` is ref. [196], for which we find a signal strength of $r \sim 0.8$. The signal strength here is defined as the ratio of the number of events predicted for the model point and the observed limits on the number of events in the most constraining signal region of any given LHC search. Production of the Higgsino-like $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, and $\tilde{\chi}_2^\pm$, on the other hand, leads to final states with much harder charged leptons and larger missing transverse energy. The most sensitive LHC search currently implemented in `checkmate2` for such signatures is ref. [214], for which we find a signal strength of $r \sim 0.8$. Regarding direct slepton searches, this benchmark point features approximately mass degenerate left- and right-handed selectrons and smuons with $m_{\tilde{\ell}^\pm} = 313$ GeV. Such compressed spectra with $m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}_1^0} = 10$ GeV are not constrained by current LHC searches for direct slepton production, see, for example, ref. [122].

BMST. The lightest neutralino has mass $m_{\tilde{\chi}_1^0} = 255$ GeV, and the Wino-like next-to-lightest neutralino and lightest chargino have masses $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 296$ GeV. Both the next-to-lightest neutralino and the lightest chargino decay into staus for this benchmark point, $\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1^\pm + \tau^\mp) = \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1^\pm + \nu_\tau) = 100\%$ from our `SUSY-HIT` results. The staus in turn decay into tau-leptons, $\text{BR}(\tilde{\tau}^\pm \rightarrow \tau^\pm + \tilde{\chi}_1^0) = 100\%$, leading to tau-leptons + missing transverse energy final states from $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ production at the LHC. Although the corresponding searches are quite challenging, studies with initial state radiation jets in a compressed region with chargino-neutralino mass gap $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \approx 50$ GeV and stau masses in the middle between the chargino and neutralino, $(m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2 = m_{\tilde{\tau}}$, constrain the chargino mass to $m_{\tilde{\chi}_1^\pm} \gtrsim 290$ GeV [111]. We have arranged the spectrum of BMST such that this bound is approximately applicable, and accordingly, we chose the masses of the Wino-like next-to-lightest neutralino and the lightest chargino to be larger than 290 GeV. Regarding the slepton searches, the selectrons and smuons have masses $m_{\tilde{\ell}^\pm} = 323$ GeV for BMST. Hence, $m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}_1^0} = 68$ GeV, which is below the mass gaps excluded by current LHC searches [122]. We note that out of the searches implemented in `checkmate2`, BMST has the largest signal strength ($r \sim 0.3$) for the search in ref. [197].

BMW. The lightest neutralino has mass $m_{\tilde{\chi}_1^0} = 271$ GeV, and the Wino-like next-to-lightest neutralino and lightest chargino have masses $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 298$ GeV. For the $\tilde{\chi}_2^0 + \tilde{\chi}_1^\pm$ production cross section, we find $\sigma(pp \rightarrow \tilde{\chi}_2^0 + \tilde{\chi}_1^\pm) = 0.26$ pb. While this point is not constrained by any of the analyses included in `checkmate2`, it may be constrained by the recent bounds coming from the multi-lepton final state analyses in ref. [123], which is not yet implemented in `checkmate2`. Note that the dominant production mechanism of charged lepton final states from the charginos and neutralinos in BMS is via tau-leptons. In

ref. [123], however, the limits are obtained assuming decays of the charginos and neutralinos into gauge bosons and the lightest neutralinos and hence the limits are not directly applicable to this case. In order to make a conservative comparison to the upper limit $\sigma(pp \rightarrow WZ + 2\tilde{\chi}_1^0) \lesssim 0.9 \text{ pb}$ [123] at these masses, we can note that, including the dominant contribution coming from τ lepton decays, the total leptonic branching ratio from $\tilde{\chi}_2^0 + \tilde{\chi}_1^\pm$ production⁵ for this benchmark points is 4.5 %, while ref. [123] assumed $\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z) = \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm) = 100 \%$, corresponding to a total leptonic branching ratio of 1.9 %, leading to an estimate of the signal strength of $r = (0.26 \text{ pb}/0.9 \text{ pb}) \times (4.5 \%/1.9 \%) \sim 0.7$. Note that the true signal strength is most likely significantly lower since leptons coming from tau-lepton decays are softer than those coming from direct lepton production.

Regarding direct slepton searches, the lightest charged sleptons for this benchmark point are the staus, $m_{\tilde{\tau}_1} = 305 \text{ GeV}$, followed by the selectrons and smuons with $m_{\tilde{\ell}^\pm} = 353 \text{ GeV}$. Such mass gaps, $m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}_1^0} = 82 \text{ GeV}$, are not constrained by current LHC bounds even under the assumption of $\text{BR}(\tilde{\ell}^\pm \rightarrow \ell^\pm + \tilde{\chi}_1^0) = 100 \%$ for all four of the left- and right-handed selectron and smuon states, with stau bounds being even weaker. For this benchmark point, the left-handed charged sleptons decay preferentially into charginos, $\text{BR}(\tilde{\ell}_L^\pm \rightarrow \nu_\ell + \tilde{\chi}_1^\pm) = 53 \%$, and have sizeable branching ratios into the next-to-lightest (Wino-like) neutralino, $\text{BR}(\tilde{\ell}_L^\pm \rightarrow \ell^\pm + \tilde{\chi}_2^0) = 28 \%$. The reduced decay branching ratios into the lightest neutralino implies softer spectra of visible decay products at the LHC and hence even weaker bounds. Moreover, due to the compressed chargino and neutralino spectrum, no relevant additional constraints emerge from the decay of the sleptons into the Wino-like states.

We note that out of the searches implemented in `checkmate2`, BMW has the largest signal strength ($r \sim 0.4$) for the search in ref. [197].

BMH. The lightest neutralino has mass $m_{\tilde{\chi}_1^0} = 61 \text{ GeV}$, and the next-to-lightest neutralino and lightest chargino have masses $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 470 \text{ GeV}$. Unlike for all of the other benchmark points, $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^\pm}$ are Higgsino-like, leading to a relatively small $\tilde{\chi}_2^0 + \tilde{\chi}_1^\pm$ production cross section of $\sigma(pp \rightarrow \tilde{\chi}_2^0 + \tilde{\chi}_1^\pm) = 0.013 \text{ pb}$ at the 13 TeV LHC. This is significantly below the upper limit from ref. [123] at these masses, $\sigma(pp \rightarrow WZ + 2\tilde{\chi}_1^0) \lesssim 0.02 \text{ pb}$, even before taking the branching ratios of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ into account [$\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h) = 62 \%$ and $\text{BR}(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 + h) = 34 \%$ for this point]. The masses of the Wino-like state are $m_{\tilde{\chi}_4^0} = m_{\tilde{\chi}_2^\pm} = 745 \text{ GeV}$, beyond the current limit on these states [121, 190, 235], even before accounting for the decay patterns of the heavy Winos. The Wino-like states dominantly decay into the intermediate Higgsino-like states, $\tilde{\chi}_4^0/\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_3^0/\tilde{\chi}_2^0/\tilde{\chi}_1^\pm + W^\pm/Z/h$. Thus, production of Wino-like states at the LHC will mostly lead to cascade decays with softer visible final states than if the Wino-like states would directly decay into the lightest neutralino, $\tilde{\chi}_4^0/\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^0 + W^\pm/Z/h$, complicating experimental searches. Furthermore, let us stress that the bounds on Wino production presented by the experimental collaborations assume that the squarks are decoupled, and accordingly ignore the important t -channel squark-mediated contributions to the Wino

⁵Here, we define the leptonic branching ratio as the sum of the branching ratios of $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$ involving $Z/W^\pm$ -bosons multiplied by their leptonic branching ratios and the (stau-mediated) decays into tau-lepton(s) multiplied with the leptonic branching ratio of the taus.

production cross section which can lower the cross section by order one factors depending on the exact squark masses [142]. These arguments apply to very recent searches for Winos in hadronic final states [221, 236] that would rule out this scenario in the absence of cascade decays and the t -channel squark contributions. Nonetheless, these impressive searches clearly show the potential of the experimental collaborations to test the regions of parameters represented by our scenarios in future runs of the LHC. Regarding the slepton searches, the lightest charged sleptons for this benchmark point are the staus, $m_{\tilde{\tau}_1} = 710$ GeV, and the selectrons and smuons have masses $m_{\tilde{\ell}^\pm} = 751$ GeV, beyond the reach of current LHC searches [122]. We note that out of the searches implemented in **checkmate2**, BMH has the largest signal strength ($r \sim 0.4$) for the search in ref. [197].

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