SUSY Dark Matter Direct Detection Prospects Based on \((g - 2)_\mu\)

Manimala Chakraborti\(^1\)*, Sven Heinemeyer\(^2\)**, and Ipsita Saha\(^3\)***

\(^1\)Astrocent, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, 00-614 Poland

\(^2\)IFT (UAM/CSIC), Cantoblanco, 28049, Madrid, Spain

\(^3\)Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, Chiba, 277-8583 Japan

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Abstract—An electroweak (EW) sector of the minimal supersymmetric Standard Model (MSSM) with masses of a few hundred GeV can account for variety of experimental data, assuming the lightest neutralino to be the lightest supersymmetric (SUSY) particle: the non-observation at the LHC, searches owing to their small production cross sections, the results for the (upper limit of the) dark matter (DM) relic abundance and the DM direct detection (DD) limits. Such a light EW sector can in particular explain the reinforced \(4.2\sigma\) discrepancy between the experimental result for \((g - 2)_\mu\), and its Standard Model (SM) prediction. Using the improved limits on \((g - 2)_\mu\), we review the predictions for the future prospects of the DD experiments. This analysis is performed for several different realizations of DM in the MSSM: bino, bino/wino, wino, and higgsino DM. We find that higgsino, wino and one type of bino scenario can be covered by future DD experiments. Mixed bino/wino and another type of bino DM can reach DD cross sections below the neutrino floor. In these cases future collider experiments must cover the remaining parameter space.

Keywords: BSM physics, SUSY Dark Matter, muon g-2

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1. INTRODUCTION

Searches for dark matter (DM) is one of the main objectives in today’s particle and astroparticle physics. Searches at the LHC (or other collider experiments) are complementary to the searches in “direct detection” (DD) experiments. Among the beyond the Standard Model (BSM) theories that predict a viable DM particle the minimal supersymmetric Standard Model (MSSM) [1–4] is one of the leading candidates. Supersymmetry (SUSY) predicts two scalar partners for all Standard Model (SM) fermions as well as fermionic partners to all SM bosons. The MSSM requires two Higgs doublets, resulting in five physical Higgs bosons: the light and heavy \(CP\)-even Higgs bosons, \(h\) and \(H\), the \(CP\)-odd Higgs boson, \(A\), and the charged Higgs bosons, \(H^\pm\). The neutral SUSY partners of the (neutral) Higgs and electroweak (EW) gauge bosons give rise to the four neutralinos, \(\tilde{\chi}^0_{1,2,3,4}\). The corresponding charged SUSY partners are the charginos, \(\tilde{\chi}^\pm_{1,2}\). The SUSY partners of the SM leptons and quarks are the scalar leptons and quarks (sleptons, squarks), respectively. The lightest SUSY particle (LSP) is naturally the lightest neutralino, \(\tilde{\chi}^0_1\). It can make up the full DM content of the universe [5, 6], or, depending on its nature only a fraction of it. In the latter case, an additional DM component could be, e.g., a SUSY axion [7], which would then bring the total DM density into agreement with the experimental measurement.

In [8–11] we performed a comprehensive analysis of the EW sector of the MSSM, taking into account all relevant theoretical and experimental constraints. The experimental results comprised the direct searches at the LHC [12, 13], the DM relic abundance [14] the DM direct detection (DD) experiments [15–17] and in particular the deviation of the anomalous magnetic moment of the muon. Five different scenarios were analyzed, classified by the mechanism that brings the LSP relic density into agreement with the measured values. The scenarios differ by the next-to-LSP (NLSP), or equiv-
alently by the mass hierarchies between the mass scales determining the neutralino, chargino and slepton masses. These mass scales are the gaugino soft-SUSY breaking parameters $M_1$ and $M_2$, the Higgs mixing parameter $\mu$ and the slepton soft SUSY-breaking parameters $m_{\tilde{e}_L}$ and $m_{\tilde{e}_R}$, see [8–11] for a detailed description. The five scenarios can be summarized as follows,

(i) higgsino DM ($\mu < M_1, M_2, m_{\tilde{e}_L}, m_{\tilde{\nu}_\mu}$), DM relic density is only an upper bound (the null relic density implies $m_{\tilde{\chi}_1^0} \sim 1$ TeV and $(g - 2)_\mu$ cannot be fulfilled), $m_{\text{NLSP}} < 500$ GeV with $m_{\text{NLSP}} - m_{\text{LSP}} \sim 5$ GeV;

(ii) wino DM ($M_2 < M_1, \mu, m_{\tilde{e}_L}, m_{\tilde{\nu}_\mu}$), DM relic density is only an upper bound, (the null relic density implies $m_{\tilde{\chi}_1^0} \sim 3$ TeV and $(g - 2)_\mu$ cannot be fulfilled), $m_{\text{NLSP}} \lesssim 600$ GeV with $m_{\text{NLSP}} - m_{\text{LSP}} \sim 0.3$ GeV;

(iii) bino/wino DM with $\tilde{\chi}_1^0$-coannihilation ($M_1 \lesssim M_2$), DM relic density can be fulfilled, $m_{\text{NLSP}} \lesssim 650(700)$ GeV;

(iv) bino DM with $\tilde{\chi}_1^\pm$-coannihilation case-L ($M_1 \lesssim m_{\tilde{e}_L}$), DM relic density can be fulfilled, $m_{\text{NLSP}} \lesssim 650(700)$ GeV;

(v) bino DM with $\tilde{\chi}_1^\pm$-coannihilation case-R ($M_1 \lesssim m_{\tilde{\nu}_\mu}$), DM relic density can be fulfilled, $m_{\text{NLSP}} \lesssim 650(700)$ GeV.

Recently the “MUON G-2” collaboration published the results of their Run 1 data [18], which is within 0.8$\sigma$ in agreement with the older BNL result on $(g - 2)_\mu$ [19]. The combined measurement yields a deviation from the SM prediction of $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$, corresponding to 4.2$\sigma$. Imposing this limit on the MSSM parameter space allows to set upper limits on the EW sector. A list of works that explain the $(g - 2)_\mu$ result with in SUSY can be found in [11].

Here we review the results in the five scenarios as obtained in [11] for the expectations of the future DD experiments. We take into account the projections for the exclusion reach of XENON-nT [20] and of the LZ experiment [21] (which effectively agree with each other). We also include the projections of the DarkSide [22] and Argo [23] experiments, which can go down to even lower cross sections, as well as the neutrino floor (NF) [24].

2. RELEVANT CONSTRAINTS

The SM prediction of $a_\mu$ is given by [25]. The comparison with the combined experimental new world average, based on [18, 19] yields a deviation of $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$, corresponding to 4.2$\sigma$. The prediction of $(g - 2)_\mu$ in the MSSM is calculated using G2Calc [26], implementing two-loop corrections from [27–29] (see also [30, 31]). Vacuum stability constraints are taken into account with the public code Evade [32, 33]. All relevant SUSY searches for EW particles are taken into account, mostly via CheckMATE [34–36] (see [8] for details on many analyses newly implemented by our group). For the DM relic density constraints we use the latest result from Planck [14], either as a direct measurement, or as an upper bound. The relic density in the MSSM is evaluated with MicrOMEGAs [37–40]. For the DD DM constraints, we use the results for the spin-independent DM scattering cross-section $\sigma_p^\text{SI}$ from XENON-1T [15] experiment. The theoretical predictions are evaluated using the public code MicrOMEGAs. Details about the parameter scan performed in the five scenarios can be found in [8–11].

3. RESULTS

In this section we review our results for the DM DD prospects in the five scenarios [11]. They are summarized in Fig. 1, where we show the $m_{\tilde{\chi}_1^0} - \sigma_p^\text{SI}$ planes for higgsino DM (upper left), wino DM (upper right), bino DM case-L (middle left) and case-R (middle right) and bino/wino DM with $\tilde{\chi}_1^\pm$-coannihilation (lower plot). The color code indicates the DM relic density, where the red points are in full agreement with the Planck measurement. The black dashed, blue dashed, blue dot-dashed and black dot-dashed lines indicate the prospects for LZ/Xenon-nT, DarkSide, Argo and the NF, respectively.

One can observe that in for higgsino and wino DM all points will be covered by the next round of DD experiments, LZ and/or Xenon-nT are sufficient to cover the whole parameter space. The situation is different for bino DM case-L/R and bino/wino DM. In these three cases cases a large part of the allowed points cannot be probed by LZ/Xenon-nT. The Argon-based experiments can cover a substantially larger part of the allowed parameter space, where he parameter points giving the full DM relic density are mostly covered by LZ/Xenon-nT, but DarkSide/Argo might be needed in the case of $\tilde{\chi}_1^\pm$-coannihilation, as can be seen in the lower plot.

However, in all three scenarios some parameter points are allowed even below the NF, which makes
them unaccessible to current DD techniques (see [11] for a short discussion on future directional detection techniques). The allowed parameter spaces below the NF are relatively restricted in the LSP mass, which is bound to be $m_{\tilde{\chi}^0_1} \lesssim 400$ GeV. This makes them relatively easily accessible to possible future $e^+e^-$ colliders. As was demonstrated in [11], all points below the NF can indeed be covered by an $e^+e^-$ collider with $\sqrt{s} \lesssim 1$ TeV. On the other hand, at the HL–LHC these points may still remain elusive due to the small mass splitting between the NLSP and the LSP.

![Fig. 1. The results of our parameter scan in the five DM scenarios in the $m_{\tilde{\chi}^0_1}$ plane. The color code indicates the DM relic density. Red points are in full agreement with the Planck measurement.](image-url)
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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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