Wino-Higgsino dark matter in MSSM from the $g - 2$ anomaly

Sho Iwamoto$^{(a)}$, Tsutomu T. Yanagida$^{(b,c)}$ and Norimi Yokozaki$^{(d)}$

$^{(a)}$ELTE Eötvös Loránd University, Pázmány Péter sétány 1/A, Budapest H-1117, Hungary
$^{(b)}$Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China
$^{(c)}$Kavli IPMU (WPI), UTIAS, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan
$^{(d)}$Zhejiang Institute of Modern Physics and Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China

Abstract

In this letter, we show that the wino-Higgsino dark matter (DM) is detectable in near future DM direct detection experiments for almost all consistent parameter space in the spontaneously broken supergravity (SUGRA) if the muon $g - 2$ anomaly is explained by the wino-Higgsino loop diagrams. We also point out that the present and future LHC experiments can exclude or confirm this SUGRA explanation of the observed muon $g - 2$ anomaly.
The new result on the muon $g-2$ measurement has been reported by the Fermilab group [1], which corresponds to a $4.2\sigma$-level discrepancy between the Standard Model prediction [2].

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (25.1 \pm 5.9) \times 10^{-10}.$$  \hspace{1cm} (1)

This new result is consistent with the previous Brookhaven result [3][4].

It is well known [6][8] that this anomaly can be easily explained in the minimal supersymmetric (SUSY) standard model (MSSM). However, this solution potentially has a problem of the flavor-changing neutral currents (FCNC), since sleptons are predicted below 1 TeV. To avoid too much FCNC, we assume the universality of the slepton masses at an ultraviolet (UV) scale such as the grand unified theory (GUT) scale or Planck scale. In this case, there are two well-known parameter regions consistent with the $g-2$ anomaly within the MSSM: one relies on the bino-slepton loop and the other utilizes the wino-Higgsino-slepton loop for the generation of the SUSY contribution $\Delta a_\mu^{\text{SUSY}}$ to the muon $g-2$ [7]. In the former case, the bino can be the dominant dark matter (DM), whose detection probability in the direct detection experiments is very low and we cannot expect the direct detection of the bino DM in near future [10]. \hspace{1cm} #1

In the latter case, the DM is a mixture of wino and Higgsino, i.e., “wino-Higgsino DM,” but its abundance is much smaller than the observed DM density [12].

In this short letter, we consider the latter case, where the wino and Higgsino soft masses are $\mathcal{O}(100)$ GeV and $\Delta a_\mu^{\text{SUSY}}$ mainly comes from the diagram in Fig. 1, and show that we can detect such a subdominant wino-Higgsino DM in near future direct detection experiments. We also discuss constraints and future prospects at collider experiments and provide benchmark points for LHC study. Note that, in this letter, we consider an almost generic model of supergravity (SUGRA) under the assumption that the FCNC problem is solved with universal masses for squarks and sleptons. All the SUSY breaking parameters are given at the UV scale (GUT scale). Because of this, our work is completely different from other related works such as Refs. [11][13][16], where the soft SUSY breaking mass parameters are given at the low-energy scale and effects of renormalization group running are negligible.

The model we consider is based on the spontaneously broken SUGRA and has ten free parameters, $m_0, m_{H_u}^2, m_{H_d}^2, A_u, A_d (= A_e), M_1, M_2, M_3, B_{\mu}/\mu$, and $\text{sign}(\mu)$, after

---

#1 See, e.g., Ref. [9] for other possibilities within the MSSM, such as those with $\text{sign}(\mu) = -1$.

#2 If we abandon the universality of the slepton masses, it is not the case [11].
imposing the EWSB conditions. Note that the FCNC problem is avoided because all the squarks and sleptons have the common soft mass, \( m_0 \), at the UV scale. We take \( \text{sign}(\mu) = +1 \) to obtain \( \Delta a_{\mu}^{\text{SUSY}} > 0 \). Furthermore, since the effects of \( m_0 \) can almost be absorbed into the bino mass \( M_1 \), we can take \( m_0 = 0 \) without a significant change in our conclusion. We also checked that the \( A_d \) dependence of the DM detection is very weak, for which we assume \( A_d = 0 \) at the GUT scale. Accordingly, we have seven parameters defined at the GUT scale, \( M_1, M_2, M_3, A_u, m_{\tilde{H}_u}^2, m_{\tilde{H}_d}^2 \) and \( B_\mu/\mu \). They are equivalent to the following parameter, which we choose as the model parameters in this work:

\[
M_1, M_2, M_3, A_u, \mu, m_A, \text{ and } \tan \beta,
\]

where \( M_{1,2,3} (A_u) \) are the gaugino soft mass (scalar cubic coupling) defined at the GUT scale, \( \mu \) is the Higgsino invariant mass at the low-energy scale (stop mass scale). \( m_A \) is the pole mass of the CP-odd Higgs boson, and \( \tan \beta \) is the ratio of Higgs vacuum expectation values.

Our SUGRA model, in which \( \Delta a_{\mu}^{\text{SUSY}} \) mainly comes from the wino-Higgsino loops (Fig. 1) and the DM is wino-Higgsino mixture, is characterized by sub-TeV \( \mu \) and \( M_2 \); Fig. 2–3 shows the consistent parameter region on the \( \mu-M_2 \) plane. The other parameters are chosen to be \( (M_1, M_3, A_u, m_A) = (2100, 2500, -1000, 2500) \text{GeV} \) and \( \tan \beta = 24 \). The SUSY mass spectra are calculated by SuSpect 2.43 [19] with modifications: the input scale of the model parameters (i.e. the GUT scale) is fixed to be \( 10^{16} \text{GeV} \) and iteration procedures are slightly changed (see Appendix). The

---

\#3 To ensure the universal mass, \( m_0 \), it is assumed that the couplings between the matter fields and a SUSY breaking fields are identical, leading to \( A_d = A_c \). The condition, \( A_d = A_c \), is not important, though.

\#4 As well-known examples to avoid the FCNC problem, a minimal Kahler potential or a sequestered Kahler potential [17][18] (for the matter fields) leads to the common soft mass, \( m_0 \) or zero.

\#5 With the choice of the model parameters, this SUGRA model is almost equivalent to a gaugino mediation model in Ref. [12], where the SUSY CP and flavor problems are solved, and the origin of the non-universal gaugino masses is naturally explained.
Figure 2: Summary of our benchmark parameter space, where the red contours show the SUSY contribution to the muon $g - 2$ ($\Delta a_\mu^\text{SUSY} \times 10^9$) and the lightest neutralino mass is displayed by the black contours ($m_{\tilde{\chi}_1^0}$/GeV). See text for details.

Higgs boson mass and $\Delta a_\mu^\text{SUSY}$ are computed by FeynHiggs 2.18.0 [20–27]. For the estimation of $\Delta a_\mu^\text{SUSY}$, we include tan $\beta$-enhanced corrections at the two-loop level [28]. We also use MicrOMEGAs 5.2.7.a [29,30] to obtain the relic density of the LSP, $\Omega_{\text{LSP}}$, and its spin-independent cross section to nucleons, $\sigma_{\text{SI}}$.

The results are summarized in Fig. 2 where $\Delta a_\mu^\text{SUSY}$ and the LSP mass are respectively shown by the red and black contours. The upper-right gray-shaded regions are excluded due to the stau LSP, while the left gray-shaded region is excluded by the LEP2 experiment [34]. The green-shaded region is excluded by the XENON1T experiment on DM direct detection. The remaining region is motivated by the muon $g - 2$ anomaly and we will discuss constraints on this benchmark space from DM direct detection and from LHC experiments.

Because of $M_1 \gg M_2 \sim \mu$, the lightest neutralino, being the LSP, is the mixture of wino and Higgsino and can be a subdominant component of the DM. Its relic density is shown by the black contours Fig. 3(a) in percentage terms, where the values are normalized by the total DM abundance, $\Omega_{\text{CDM}}h^2 \simeq 0.12$. Although it is only a few percent of the total DM, their spin-independent cross section to protons are sizable. As shown in Fig. 3(b), the effective spin-independent cross section of the DM direct detection, defined by $\sigma_{\text{SI}}^{\text{eff}} \equiv \Omega_{\text{LSP}}/\Omega_{\text{CDM}} \times \sigma_{\text{SI}}$, is as large as $10^{-46}$ cm$^2$.
Figure 3: The same as Fig. 2 but the black contours in the left figure show the relic abundance of the lightest neutralino $\tilde{\chi}_1^0$ normalized by the total DM density in percentage terms, while in the right figure they show the effective spin-independent cross section for the DM direct detection is given in units of $10^{-10}$ pb = $10^{-46}$ cm$^2$.

and the green-shaded region is excluded by the XENON1T experiment [35]. Most of the remaining region will be probed by future direct-detection experiments, such as DarkSide-20k [36], LZ [37], PandaX-4T [38], and XENONnT [39].

Figures 4–5 show the results (the LSP mass, the relic abundance and the SI cross section) for $(M_1, M_3, A_u, m_A) = (3800, 2500, -1000, 2000)$ GeV and $\tan \beta = 40$. The results are very similar to those shown in Fig. 2–3. The main difference is that the left-handed selectron and smuon can be as heavy as 740-760 GeV in the region consistent with the muon $g - 2$ at 1$\sigma$ level.

The LHC phenomenology of our scenario is rather complicated because of compressed spectra and the mixed nature of neutralinos. Therefore, we do not perform full analyses in this work, but instead introduce a few benchmark points (BPs) for future analyses and provide general brief discussion on the LHC phenomenology. The BPs are shown in Table 1; note that BP-WH4 is excluded by XENON1T as discussed above, but introduced for completeness. Colored SUSY particles are not displayed because they are heavy due to large $M_3$ and beyond the present LHC limits. We thus focus on non-colored SUSY particle production at LHC, which are of our interest because our scenario is motivated by the muon $g - 2$ anomaly and
wino-Higgsino partial dark matter.

Chargino searches based on disappearing-track signature are promising for the wino DM. Indeed, $\tilde{\chi}^\pm_1$ is almost wino-like in the upper-left corner of Fig. 2 and its lifetime, $\tau(\tilde{\chi}^\pm_1)$, is longer than $10^{-11}$s; a portion of that region is thus expected to be excluded by the results in Refs. [40,41]. However, those limits do not cover the region with $M_2 \simeq \mu$ because, due to the Higgsino component of $\tilde{\chi}^\pm_1$, the lifetime is shorter and the production cross section is smaller compared to wino-like chargino.

Although sleptons are as light as $\sim 400$ GeV, the slepton channel $pp \rightarrow \tilde{l}\tilde{l} \rightarrow 2l + p_T$ [42,43] does not provide significant limit, either. This is mainly because, unlike bino-LSP models studied in Refs. [14,44], the sleptons are allowed to decay into $\tilde{\chi}^\pm_1$ without emitting any hard charged leptons, as depicted in Table 1.

The region with $M_2 \simeq \mu$ are therefore to be searched for by the production of heavier electroweakinos, $\tilde{\chi}^\pm_2$ and $\tilde{\chi}^0_{2,3}$. In fact, as examined in Refs. [14], SUSY models with sizable $\Delta a^\mu_{\mu}^\text{SUSY}$ from wino-Higgsino loop (Fig. 1) are typically searched for by electroweakino pair-production, which yields signatures with two SM bosons ($W^\pm$, $h$, $Z$) with large missing transverse momentum. Unlike bino-LSP models studied in Refs. [13,14,44], the expected signature is diverse and involved because various production channels are expected and the electroweakinos are allowed to decay into all the SM bosons. Dedicated LHC analyses are called for and, thanks to

Figure 4: The same as Fig. 2 but the parameters are taken to be $(M_1, M_3, A_u, m_A) = (3800, 2500, -1000, 2000)$ GeV and $\tan \beta = 40$. 
Figure 5: The same as Fig. 3 but the parameters are taken to be \((M_1, M_3, A_u, m_A) = (3800, 2500, -1000, 2000)\) GeV and \(\tan \beta = 40\).

the sizable production cross section, they are expected to probe the whole parameter space that are motivated by the muon \(g - 2\) anomaly.

**Acknowledgments**

T. T. Y. is supported in part by the China Grant for Talent Scientific Start-Up Project and the JSPS Grant-in-Aid for Scientific Research No. 17H02878, and No. 19H05810, and by World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan.

**Appendix: SLHA Input**

Our benchmark parameter space corresponds to the following SLHA input for spectrum generators such as SuSpect [19] or SOFTSUSY [31 #6]

```
# BLOCK MODSEL
1 1 # mSUGRA

# BLOCK MINPAR
1 0.00000000E+00 # m0
2 1.00000000E+03 # M1/2
3 2.40000000E+01 # tan(beta)
4 1.00000000E+00 # sign(mu)
```

#6 “Number of loops in Higgs mass computation” should be set to 2.
To make the SUSY spectrum convergent during iteration processes, one may need to modify the spectrum generators. For instance, if one uses SuSpect 2.52, one needs to take $m_{H_u} = m_{H_d} = 0$ at the GUT scale for first few iterations; specifically, suspect2.52.f should be modified by the following patch:

```plaintext
@@ -231,4 +231,5 @@
c reinitialize various control parameters + other parameters:
  + myiter=0
  + do ierr=1,10
  + errmess(ierr)=0.d0
  + enddo
@@ -1099,2 +1100,7 @@
  if( myiter .lt .4) then
  + y(12)=0.
  + y(13)=0.
  + endif
  + myiter=myiter+1
```

References

[1] C. Polly, on behalf of Muon g-2 Collaboration, “First results from the Muon g-2 experiment at Fermilab,” 7 Apr. 2021. Seminar talk given at Fermilab.

[2] T. Aoyama et al., “The anomalous magnetic moment of the muon in the Standard Model,” Phys. Rept. 887 (2020) 1–166 [arXiv:2006.04822].

[3] Muon g-2 Collaboration, “Measurement of the positive muon anomalous magnetic moment to 0.7 ppm,” Phys. Rev. Lett. 89 (2002) 101804 [hep-ex/0208001]. [Erratum: Phys. Rev. Lett.89,129903(2002)].

[4] Muon g-2 Collaboration, “Measurement of the negative muon anomalous magnetic moment to 0.7 ppm,” Phys. Rev. Lett. 92 (2004) 161802 [hep-ex/0401008].
[5] Muon g-2 Collaboration, “Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL,” Phys. Rev. D73 (2006) 072003 [hep-ex/0602035].

[6] J. L. Lopez, D. V. Nanopoulos, and X. Wang, “Large (g-2)-mu in SU(5) x U(1) supergravity models,” Phys. Rev. D49 (1994) 366–372 [hep-ph/9308336].

[7] U. Chattopadhyay and P. Nath, “Probing supergravity grand unification in the Brookhaven g-2 experiment,” Phys. Rev. D53 (1996) 1648–1657 [hep-ph/9507386].

[8] T. Moroi, “The Muon anomalous magnetic dipole moment in the minimal supersymmetric standard model,” Phys. Rev. D53 (1996) 6565–6575 [hep-ph/9512396]. [Erratum: Phys. Rev.D56,4424(1997)].

[9] 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 (2017) 031 [arXiv:1704.05287].

[10] P. Cox, C. Han, T. T. Yanagida, and N. Yokozaki, “Gaugino mediation scenarios for muon g – 2 and dark matter,” JHEP 08 (2019) 097 [arXiv:1811.12699].

[11] P. Cox, C. Han, and T. T. Yanagida, “Muon g – 2 and dark matter in the minimal supersymmetric standard model,” Phys. Rev. D 98 (2018) 055015 [arXiv:1805.02802].

[12] K. Harigaya, T. T. Yanagida, and N. Yokozaki, “Higgs boson mass of 125 GeV and g – 2 of the muon in a gaugino mediation model,” Phys. Rev. D91 (2015) 075010 [arXiv:1501.07447].

[13] M. Endo, K. Hamaguchi, S. Iwamoto, and T. Yoshinaga, “Muon g-2 vs LHC in Supersymmetric Models,” JHEP 01 (2014) 123 [arXiv:1303.4256].

[14] M. Endo, K. Hamaguchi, S. Iwamoto, and T. Kitahara, “Muon g – 2 vs LHC Run 2 in supersymmetric models,” JHEP 04 (2020) 165 [arXiv:2001.11025].

[15] M. Chakraborti, S. Heinemeyer, and I. Saha, “Improved (g – 2)_µ Measurements and Supersymmetry,” Eur. Phys. J. C 80 (2020) 984 [arXiv:2006.15157].
[16] M. Chakraborti, S. Heinemeyer, and I. Saha, “Improved \((g - 2)_{\mu}\) Measurements and Wino/Higgsino Dark Matter.” arXiv:2103.13403.

[17] K. Inoue, M. Kawasaki, M. Yamaguchi, and T. Yanagida, “Vanishing squark and slepton masses in a class of supergravity models,” Phys. Rev. D 45 (1992) 328–337.

[18] L. Randall and R. Sundrum, “Out of this world supersymmetry breaking,” Nucl. Phys. B 557 (1999) 79–118 [hep-th/9810155].

[19] A. Djouadi, J.-L. Kneur, and G. Moultaka, “SuSpect: A Fortran code for the supersymmetric and Higgs particle spectrum in the MSSM,” Comput. Phys. Commun. 176 (2007) 426–455 [hep-ph/0211331].

[20] S. Heinemeyer, W. Hollik, and G. Weiglein, “FeynHiggs: A Program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM,” Comput. Phys. Commun. 124 (2000) 76–89 [hep-ph/9812320].

[21] S. Heinemeyer, W. Hollik, and G. Weiglein, “The Masses of the neutral CP - even Higgs bosons in the MSSM: Accurate analysis at the two loop level,” Eur. Phys. J. C 9 (1999) 343–366 [hep-ph/9812472].

[22] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, and G. Weiglein, “Towards high precision predictions for the MSSM Higgs sector,” Eur. Phys. J. C 28 (2003) 133–143 [hep-ph/0212020].

[23] M. Frank, et al., “The Higgs Boson Masses and Mixings of the Complex MSSM in the Feynman-Diagrammatic Approach,” JHEP 02 (2007) 047 [hep-ph/0611326].

[24] T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, and G. Weiglein, “High-Precision Predictions for the Light CP -Even Higgs Boson Mass of the Minimal Supersymmetric Standard Model,” Phys. Rev. Lett. 112 (2014) 141801 [arXiv:1312.4937].

[25] H. Bahl and W. Hollik, “Precise prediction for the light MSSM Higgs boson mass combining effective field theory and fixed-order calculations,” Eur. Phys. J. C 76 (2016) 499 [arXiv:1608.01880].

[26] H. Bahl, S. Heinemeyer, W. Hollik, and G. Weiglein, “Reconciling EFT and hybrid calculations of the light MSSM Higgs-boson mass,” Eur. Phys. J. C 78 (2018) 57 [arXiv:1706.00346].

[27] H. Bahl, et al., “Precision calculations in the MSSM Higgs-boson sector with FeynHiggs 2.14,” Comput. Phys. Commun. 249 (2020) 107099 [arXiv:1811.09073].

[28] S. Marchetti, S. Mertens, U. Nierste, and D. Stockinger, “Tan(beta)-enhanced supersymmetric corrections to the anomalous magnetic moment of the muon,” Phys. Rev. D 79 (2009) 013010 [arXiv:0808.1530].

[29] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, “MicrOMEGAs: A Program for calculating the relic density in the MSSM,” Comput. Phys. Commun. 149 (2002) 103–120 [hep-ph/0112278].

[30] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, “micrOMEGAs: Version 1.3,” Comput. Phys. Commun. 174 (2006) 577–604 [hep-ph/0405253].

[31] B. C. Allanach, “SOFTSUSY: a program for calculating supersymmetric spectra,” Comput. Phys. Commun. 143 (2002) 305–331 [hep-ph/0104145].

[32] B. C. Allanach and T. Cridge, “The Calculation of Sparticle and Higgs Decays in the Minimal and Next-to-Minimal Supersymmetric Standard Models: SOFTSUSY4.0,” Comput. Phys. Commun. 220 (2017) 417–502 [arXiv:1703.09717].

[33] W. Beenakker, et al., “The Production of charginos / neutralinos and sleptons at hadron colliders,” Phys. Rev. Lett. 83 (1999) 3780–3783 [hep-ph/9906298]. [Erratum: Phys. Rev. Lett.100,029901(2008)].

[34] LEP2 SUSY Working Group (ALEPH, DELPHI, L3, OPAL), “Combined LEP Chargino Results, up to 208 GeV for large m0.” Notes LEPSUSYWG/01–03.1. 
http://lepsusy.web.cern.ch/lepsusy>Welcome.html

[35] XENON Collaboration, “Dark Matter Search Results from a One Ton-Year Exposure of XENON1T,” Phys. Rev. Lett. 121 (2018) 111302 [arXiv:1805.12562].

[36] DarkSide-20k Collaboration, “DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS,” Eur. Phys. J. Plus 133 (2018) 131 [arXiv:1707.08145].
[37] LUX-ZEPLIN Collaboration, “Projected WIMP sensitivity of the LUX-ZEPLIN dark matter experiment,” Phys. Rev. D101 (2020) 052002 [arXiv:1802.06039].

[38] PandaX Collaboration, “Dark matter direct search sensitivity of the PandaX-4T experiment,” Sci. China Phys. Mech. Astron. 62 (2019) 31011 [arXiv:1806.02229].

[39] XENON Collaboration, “Projected WIMP sensitivity of the XENONnT dark matter experiment,” JCAP 2011 (2020) 031 [arXiv:2007.08796].

[40] CMS Collaboration, “Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV,” Phys. Lett. B806 (2020) 135502 [arXiv:2004.05153].

[41] ATLAS Collaboration, “Search for long-lived charginos based on a disappearing-track signature using 136 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” ATLAS–CONF–2021–015, CERN, 2019.

[42] ATLAS Collaboration, “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. C80 (2020) 123 [arXiv:1908.08215].

[43] CMS Collaboration, “Search for supersymmetry in final states with two oppositely charged same-flavor leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV.” arXiv:2012.08600.

[44] M. Endo, K. Hamaguchi, S. Iwamoto, and T. Kitahara, “Supersymmetric Interpretation of the Muon $g - 2$ Anomaly.” arXiv:2104.03217.
Table 1: Benchmark points for the muon $g-2$ anomaly. The other UV parameters are fixed to $(M_1, M_3, A_u, m_A) = (2100, 2500, -1000, 2500)$ GeV and $\tan \beta = 24$ for BP-WH1 to BP-WH4, and $(M_1, M_3, A_u, m_A) = (3800, 2500, -1000, 2000)$ GeV and $\tan \beta = 40$ for BP-WH5. All the colored SUSY particles are heavier than 3 TeV and thus not collected here. Because $M_1 \gg M_2$, the heaviest neutralino $\tilde{\chi}_4^0$ is bino-like, while the other neutralinos are wino-Higgsino mixture. Lifetime is calculated by SOFTSUSY 4.1.10 [31, 32] and LHC production cross sections are by Prospino 2.1 [33].

|                  | BP-WH1  | BP-WH2  | BP-WH3  | BP-WH4 | BP-WH5 |
|------------------|---------|---------|---------|--------|--------|
| $M_2$/GeV        | 200     | 300     | 250     | 500    | 250    |
| $\mu$/GeV        | 300     | 450     | 250     | 200    | 250    |
| $m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm)$/GeV | (112, 112) | (201, 201) | (143, 145) | (188, 193) | (146, 147) |
| $m(\tilde{\chi}_2^0, \tilde{\chi}_2^\pm)/GeV$   | 314     | 464     | 263     | 211    | 263    |
| $m(\tilde{\chi}_3^0, \tilde{\chi}_3^\pm)/GeV$   | (322, 330) | (470, 476) | (284, 290) | (402, 402) | (284, 290) |
| $m(\tilde{\chi}_4^0)/GeV$ | 927     | 927     | 927     | 927    | 1457   |
| $m(\tilde{\mu}_L, \tilde{\mu}_R)/GeV$   | (459, 615) | (480, 615) | (469, 614) | (542, 609) | (736, 1314) |
| $m(\tilde{\tau}_1, \tilde{\tau}_2)/GeV$   | (286, 354) | (303, 365) | (298, 346) | (321, 407) | (292, 899) |
| $m_h$/GeV        | 124.0   | 123.5   | 123.6   | 123.6  | 124.2  |
| $\Delta a_{\mu}^{\text{SUSY}} \times 10^{10}$ | 28.0    | 19.9    | 29.2    | 19.3   | 25.5   |
| $\Omega_{\text{LSP}}/\Omega_{\text{CDM}}$ | 0.0033  | 0.010   | 0.006   | 0.040  | 0.007  |
| $\sigma_{\text{SI}}/10^{-10}$ pb          | 0.14    | 0.3     | 0.9     | 4.3    | 1.0    |
| $\tau(\tilde{\chi}_1^\pm)/s$               | $4 \times 10^{-12}$ | $2 \times 10^{-11}$ | $8 \times 10^{-14}$ | $7 \times 10^{-17}$ | $8 \times 10^{-14}$ |
| $\text{Br}(\tilde{\mu}_L \rightarrow \tilde{\chi}_1^- \nu)$ | 0.63    | 0.66    | 0.55    | 0.091  | 0.50   |
| $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm)/13$ fb | 144 fb  | 30 fb   | 263 fb  | 102 fb | 260 fb |

---

*a* Excluded by XENON1T experiment but prepared for collider studies.

$b$ $\text{Br}(\tilde{\mu}_L \rightarrow \tilde{\chi}_2^- \nu) = 0.56$.

$c$ For BP-WH1 to WH3 and WH5, $i$ is summed over 2–3, while BP-WH4 only includes $i = 3$. 

13