

Wino LSP detection in the light of recent Higgs searches at the LHC

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ABSTRACT

Recent LHC data showed excesses of Higgs-like signals at the Higgs mass of around 125 GeV. This may indicate supersymmetric models with relatively heavy scalar fermions to enhance the Higgs mass. The desired mass spectrum is realized in the anomaly-mediated supersymmetry breaking model, in which the Wino can naturally be the lightest superparticle (LSP). We discuss possibilities for confirming such a scenario, particularly detecting signals from Wino LSP at direct detection experiments, indirect searches at neutrino telescopes and at the LHC.

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Higgs mass contains very important information about low-energy supersymmetry (SUSY) models, which is well motivated because it provides a viable candidate of dark matter (DM) and also because it realizes the gauge coupling unification. In particular, in the minimal SUSY standard model (MSSM), the lightest Higgs boson cannot be heavier than the Z-boson at the tree level, while a sizable radiative correction may enhance the Higgs mass [1]. The size of the radiative correction depends on the masses (and other parameters) of superparticles. The lightest Higgs mass becomes larger as superparticles (in particular, stops) become heavier. Thus, once the lightest Higgs mass is known, mass scale of superparticles is constrained.

Recently, the ATLAS Collaboration reported 3.6σ local excess of the standard model (SM) Higgs-like event at $m_h \simeq 126$ GeV [2]. In addition, the CMS Collaboration also showed more than 2σ local excess at $m_h \simeq 124$ GeV [3].¹ In order to achieve such a value of the lightest Higgs mass in the MSSM, relatively large values of the superparticle masses are required; the typical scale of the sfermion masses to realize $m_h \simeq 125$ GeV is 10 TeV– 10^3 TeV [4,5]. Then, if the masses of all the superparticles are of the same order, it is difficult to find experimental signals of low-energy SUSY and the existence of SUSY is hardly confirmed.

Although the sfermion masses are much larger than the electroweak scale, gauginos may be much lighter than sfermions and within the reach of collider and other experiments. One interesting possibility is the model in which the SUSY breaking scalar masses are from direct coupling to the SUSY breaking field while the gaugino masses are generated by the anomaly-mediation mech-

anism [6,7]; in this Letter, we call such a model as anomaly-mediated SUSY breaking (AMSB) model. Even in the AMSB model, however, if the pure anomaly-mediation relation holds among the gaugino masses, gluino mass is about 8 times larger than the mass of Wino. Thus, if the Wino mass is a few hundred GeV, which is the lower bound on it from astrophysical and cosmological considerations as will be reviewed later, the gluino mass becomes multi-TeV; with such a heavy gluino, the discovery of the SUSY signal at the LHC becomes challenging because we consider the case that all the squarks are extremely heavy.

Even so, there still exist possibilities of discovering signals of the AMSB scenario. In particular, in the present framework, the neutral Wino is the lightest superparticle (LSP) and may be DM. In such a case, pair annihilation cross section of the LSP and the scattering cross section of the LSP off the nuclei are both enhanced compared to the Bino LSP case, which has significant implications to direct and indirect detection of DM. Because the search of the superparticles at the LHC may be difficult, it is important to pursue these possibilities and explore how well we can study the AMSB scenario with these procedures.²

In this Letter, motivated by the recent Higgs searches at the LHC, we discuss the detectability of the signals of AMSB scenario. We pay particular attention to the case of the Wino LSP. We focus on direct/indirect detection of the Wino DM at underground laboratories and neutrino telescopes. We also comment on the LHC reach for the direct Wino production. Since superparticles except gauginos are heavy, standard methods for SUSY searches may not work. Even in this case, we will show that there are some windows for the confirmation of the SUSY.

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¹ The excesses based on global probabilities, which take account of the look-elsewhere effect, are 2.3σ (ATLAS) and 1.9σ (CMS).

² The heavy SUSY particle spectrum and their detectability were discussed in a different context in Ref. [8].

Let us first briefly discuss important properties of the AMSB scenario. We assume that the soft SUSY breaking scalar masses are generated by the direct coupling between the scalars and the SUSY breaking hidden sector field, while the gaugino masses are generated by the anomaly mediation mechanism. Adopting the pure AMSB relation, the gaugino masses are given by [6,7]

$$M_a^{(\text{AMSB})} = \frac{b_a}{16\pi^2} g_a^2 m_{3/2}, \quad (1)$$

where g_a ($a = 1-3$) are gauge coupling constants of the SM gauge groups, $m_{3/2}$ is the gravitino mass, and $(b_1, b_2, b_3) = (11, 1, -3)$. Then, the Wino becomes the lightest among the gauginos, and gaugino masses largely separate: $m_{\tilde{B}} : m_{\tilde{W}} : m_{\tilde{g}} \simeq 3 : 1 : 8$. Although the AMSB relation may be affected by Higgs and Higgsino loop diagrams [7,9], we adopt the pure AMSB mass relation. With the gaugino masses being of $O(100)$ GeV– $O(1)$ TeV, the gravitino mass becomes of $O(10)$ TeV– $O(100)$ TeV. The sfermion masses are expected to be of the same order of the gravitino mass, which is preferred from the point of view of realizing $m_h \simeq 125$ GeV. In particular, if the scalar masses are (almost) equal to the gravitino mass, $m_h \simeq 125$ GeV requires relatively small value of $\tan\beta \sim$ a few (where $\tan\beta$ is the ratio of the vacuum expectation values of up- and down-type Higgs bosons) [5].

Before discussing the detectability of the signals of AMSB model, we comment on the supersymmetric Higgs mass parameter (so-called μ -parameter). In the present setup, the soft SUSY breaking scalar mass parameters of up- and down-type Higgs bosons are expected to be of $O(10)$ TeV– $O(100)$ TeV. In order to have viable electroweak symmetry breaking, the μ -parameter (as well as heavy Higgs boson masses) is also expected to be of the same order; then, the Higgsinos become extremely heavy and the Wino becomes the LSP. Thus, we pay particular attention to the case of Wino LSP in the following. In some of our following analysis, however, we consider the case with $\mu \sim O(100)$ GeV– $O(1)$ TeV taking account of the possibility of an accidental tuning of the parameters. This is because detection rates of some of signals (in particular, the direct detection rates) strongly depend on the value of μ .

Taking account of the radiative correction due to the gauge boson loops, the neutral Wino becomes lighter than the charged one. Therefore, we focus on the case of neutral Wino LSP. In addition, we assume that the LSP (i.e., the neutral Wino) is the dominant component of DM. The Wino LSP accounts for the present DM density for $m_{\tilde{W}} \simeq 3$ TeV if it is produced only from thermal bath [10]. In the AMSB scenario, however, the Wino LSP can be non-thermally produced from the gravitino or moduli decay [7,11]. If the reheating temperature takes an appropriate value, for example, the decay of gravitino produces the Wino LSP with correct relic density [12], while thermal leptogenesis [13] works successfully [14]. Thus the Wino is a good DM candidate in the present setup. Hereafter, we assume that the right amount of Wino is somehow produced in the early universe to be DM.

We start with discussing direct detection experiments of DM. The scattering cross section of the Wino LSP off the nucleon significantly depends on μ . Since all scalars except for the lightest Higgs boson are expected to be heavy enough, it is only the lightest Higgs boson that mediates the spin-independent (SI) scattering. The DM–proton scattering cross section is given by [15]

$$\sigma = \frac{4}{\pi} \left(\frac{m_{\tilde{\chi}_0} m_N}{m_{\tilde{\chi}_0} + m_N} \right)^2 \times \left[(n_p f_p + n_n f_n)^2 + 4 \frac{J+1}{J} (a_p \langle s_p \rangle + a_n \langle s_n \rangle)^2 \right], \quad (2)$$

where the first and the second terms in the bracket are the contributions of SI and spin-dependent (SD) interaction, respectively. Here $m_{\tilde{\chi}_0}$ is the LSP mass, m_N is the mass of the target nucleus, $n_p(n_n)$ is the number of proton (neutron) in the target nucleus, J is the total nuclear spin, a_p and a_n are the effective DM–nucleon SD couplings, and $\langle s_{p(n)} \rangle$ are the expectation values of the spin content of the proton and neutron groups within the nucleus. We refer to Ref. [15] for definitions of these quantities. The effective DM–proton coupling, f_p , is given by

$$f_p = \sum_{q=u,d,s} \frac{f_q^H}{m_q} m_p f_{T_q}^{(p)} + \frac{2}{27} f_{T_C} \sum_{q=c,b,t} \frac{f_q^H}{m_q} m_p, \quad (3)$$

where $f_{T_C} = 1 - \sum_{u,d,s} f_{T_q}^{(p)}$, m_p and m_q denote the proton and quark masses, respectively, and f_q^H is the effective DM–quark coupling obtained by the exchange of the Higgs boson. Since the DM–Higgs coupling is proportional to the magnitude of Wino–Higgsino mixing,³ the cross section is enhanced if the Wino–Higgsino mixing is large. In Fig. 1 we plot the Wino–proton SI and SD scattering cross section. In this plot we have used the following values for the quark contents in the proton [17]: $f_{T_u}^{(p)} = 0.023$, $f_{T_d}^{(p)} = 0.034$, $f_{T_s}^{(p)} = 0.025$ and taken $\tan\beta = 3$ and $\tan\beta = 20$. The XENON100 experiment [18] most severely constrains the SI cross section. The sensitivity is improved by a few orders of magnitude for the next generation 1 ton scale detectors, and then broad parameter regions up to $m_{\tilde{W}} \sim \mu \sim 1$ TeV will be explored. The IceCube searches for neutrino events arising from the DM annihilation in the Sun. Since the efficiency for the DM trapping into the Sun depends on the DM–proton scattering cross section, the high-energy neutrino observations give limits on it. For the SD cross section, the IceCube gives the most stringent limit, and it will be further improved by about one order of magnitude with the DeepCore instrument [19].

We have also calculated the detection rate at the IceCube DeepCore, arising from high-energy neutrinos produced by the Wino annihilation at the galactic center (GC). We distinguish two event classes following Refs. [20–22]: contained muon events and shower events. The contained muons correspond to those emerge inside the instrumental volume through the high-energy neutrino interactions with nucleons. The shower events are caused by charged current interactions of electron and tau neutrinos, and neutral current interactions of all neutrino species. They leave electromagnetic/hadronic shower inside the instrumental volume. The event rate of the contained muons is given by

$$N_{\mu^+\mu^-} = \int dE_{\nu\mu} \int_{E_{\text{th}}}^{E_{\nu\mu}} dE_\mu \left[\frac{d\Phi_{\nu\mu}}{dE_{\nu\mu}} \left(\frac{d\sigma_{\nu\mu p}^{(\text{CC})}}{dE_\mu} n_p + \frac{d\sigma_{\nu\mu n}^{(\text{CC})}}{dE_\mu} n_n \right) + (\nu_\mu \leftrightarrow \bar{\nu}_\mu) \right] V_{\text{eff}}(E_\mu), \quad (4)$$

where $E_{\nu\mu}$ is the incident neutrino energy, E_μ is the muon energy resulting from the neutrino–proton (neutron) interactions, E_{th} is the threshold energy above which the muon can be detected, $d\Phi_{\nu\mu}/dE_{\nu\mu}$ is the neutrino flux at the Earth, $d\sigma_{\nu\mu p(n)}^{(\text{CC})}/dE_\mu$ denotes the neutrino–proton (neutron) charged current cross section for producing the muon energy with E_μ , $n_p(n_n)$ is the proton (neutron) number density in the detector material, and V_{eff} is the effective volume for the muon detection. The incident neutrino flux generated by DM annihilation from the GC within cone half angle of θ is given by

³ In the limit of pure Wino DM, the Wino–nucleon scattering cross section is too small to be detected [16].

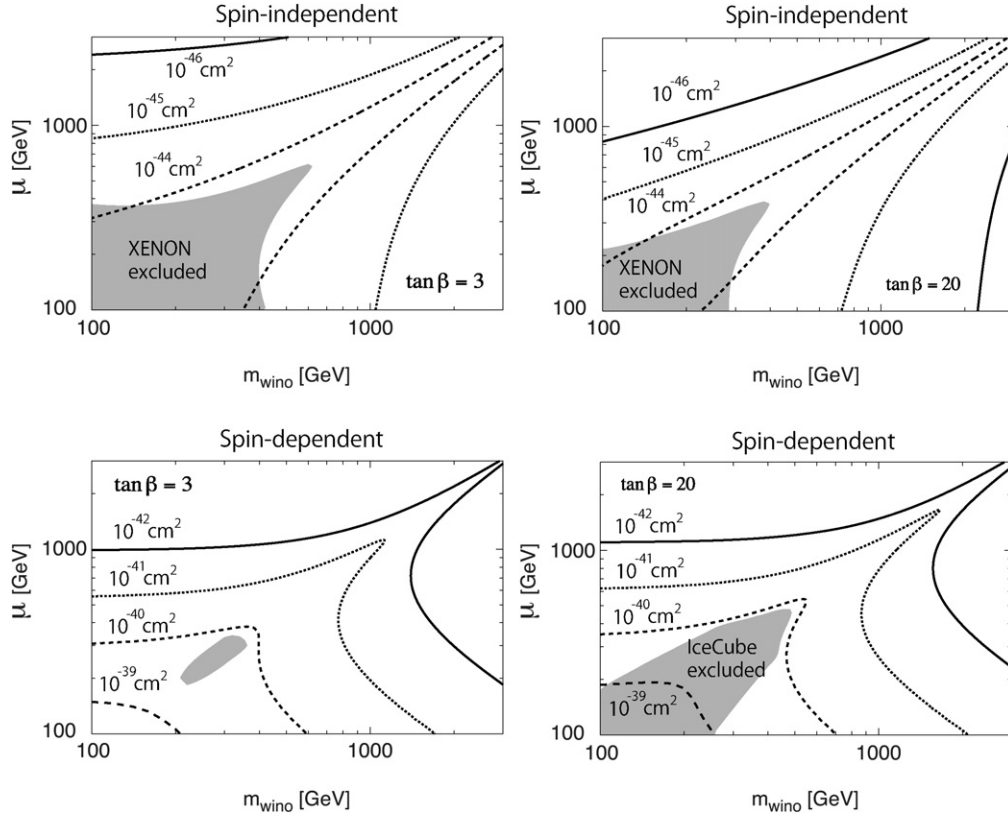


Fig. 1. Contours of spin-independent (SI) and spin-dependent (SD) Wino–proton scattering cross sections are plotted on the plane of m_{wino} and μ . Shaded regions are excluded by the XENON100 experiment for SI, and IceCube experiment for SD.

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{R_{\odot}\rho_{\odot}^2}{8\pi m_W^2} \left(\sum_{j=e,\mu,\tau} \langle\sigma v\rangle \frac{dN_{\nu_j}}{dE_{\nu_j}} P_{j\rightarrow i} \right) \langle J_2 \rangle_{\Omega} \Delta\Omega. \quad (5)$$

Here $R_{\odot} = 8.5$ kpc and $\rho_{\odot} = 0.3$ GeVcm $^{-3}$, $\langle\sigma v\rangle$ is the Wino self-annihilation cross section including the non-perturbative effect [23], and dN_{ν_j}/dE_{ν_j} is the energy spectrum of the neutrino produced by DM annihilation, which is calculated by the PYTHIA package for the WW final state [24], $P_{j\rightarrow i}$ is the probability that the ν_j at the production is converted to ν_i because of the neutrino oscillation effect, $\Delta\Omega = 2\pi(1 - \cos\theta)$, and $\langle J_2 \rangle_{\Omega}$ includes the information about the DM density profile in the Galaxy [25]. The shower event is evaluated in a similar way to the contained muon events (4), except that the charged current interactions from ν_e and ν_{τ} as well as the neutral current interactions for all neutrino flavors are included. The background event is evaluated by inserting the atmospheric neutrino flux into the expression (4).

Fig. 2 shows the signal-to-noise ratio at the IceCube DeepCore as a function of the Wino mass. Sensitivities for contained muon events (upper panel) and shower events (lower panel) with 1 year and 10 year observations are shown. We have adopted the NFW density profile and considered the neutrino flux from the cone half angle $\theta = 10^{\circ}$ and $\theta = 25^{\circ}$ around the GC. As noted in Ref. [22], the sensitivity is maximized for $\theta \simeq 10^{\circ}$. For this cone half angle, the flux dependence on the DM density profile is not large: it is within a factor of 2 [25]. The effective volume for the contained and shower events are set to be 0.04 km 3 and 0.02 km 3 , respectively [20]. The atmospheric background is taken from Ref. [26]. It is seen that the signal-to-noise ratio is at most of order one for the Wino mass of a few hundred GeV. We have also checked that the upward muon events expected at the KM3NeT detector [27], assuming the effective area of 1 km 2 and taking account

of the energy loss of muons [28], provide similar sensitivities to the DeepCore.

The Wino DM annihilation may leave characteristic signatures on astrophysical observations. Gamma-ray observations by Fermi-LAT and HESS severely restrict the DM annihilation cross section (see, e.g., Refs. [29,30] for recent works). The non-observations of DM-induced gamma-rays from dwarf galaxies excludes the Wino mass below ~ 400 GeV [29].⁴ On the other hand, the cosmic-ray positron excess observed by PAMELA satellite [31] may be explained by the Wino DM annihilation with mass of 200 GeV [32, 33] although it may confront the constraints from gamma-rays and anti-protons. The observations of light element abundances also give stringent bound on the DM annihilation cross section so as not to destroy light elements during big-bang nucleosynthesis (BBN). It gives a lower bound on the Wino mass as $m_{\tilde{W}} \gtrsim 200$ GeV [34,32]. It may be encouraging that the cosmic lithium problem may be solved for the Wino mass of around this bound, which simultaneously may explain the PAMELA anomaly. DM annihilation also affects the recombination history of the Universe, which results in the modification on the cosmic microwave background (CMB) anisotropy [35–37]. The constraint is comparable to that from BBN. Taking these constraints into account, we conservatively consider that the Wino must be heavier than ~ 200 GeV if it is the dominant component of DM.

Finally, we comment on a possibility of discovering a signal of AMSB model at the LHC. If we adopt the AMSB mass relation among gauginos, gluino becomes relatively heavy. Then, colored

⁴ Ref. [29] derived this constraint by analyzing dwarf galaxies in a statistical way. The observations of each dwarf galaxy put a less severe limit on the cross section by a factor of ~ 2 compared with that derived by the statistical method.

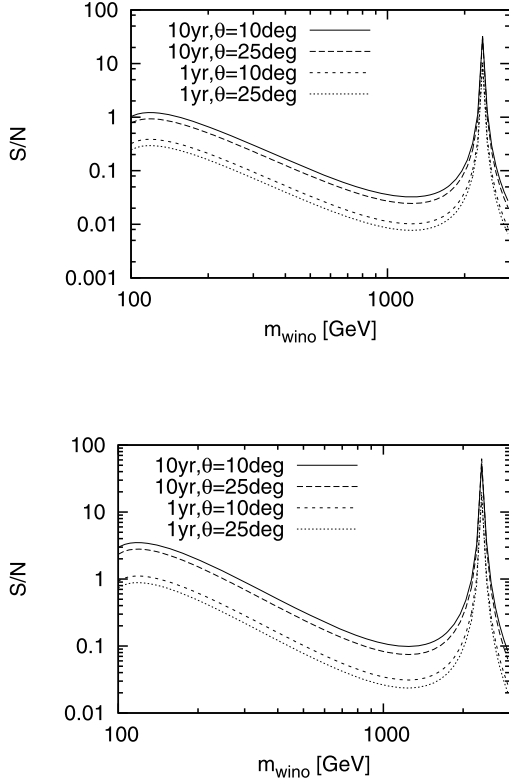


Fig. 2. Signal-to-noise ratio at the IceCube DeepCore as a function of the Wino mass. Sensitivities for contained muon events (upper panel) and shower events (lower panel) with 1 year and 10 year observations are shown. We have considered the neutrino flux from the cone half angle $\theta = 10^\circ$ and $\theta = 25^\circ$ around the GC.

superparticles are hardly produced at the LHC. Thus, we focus on the detection of a Wino signal.

If the neutral Wino \tilde{W}^0 is the LSP, we have a chance to observe the track of charged Wino \tilde{W}^\pm [38,39]. This is because the mass difference between charged and neutral Winos is so small (~ 160 MeV) that the decay length of \tilde{W}^\pm becomes macroscopic ($c\tau_{\tilde{W}^\pm} \simeq 5$ cm). Some of the produced charged Winos may travel through several layers of inner trackers and their track may be reconstructed. In the ATLAS experiment, for example, the charged Wino track can be reconstructed with almost 100% efficiency if \tilde{W}^\pm hits the third layer of the semiconductor tracker (SCT) before it decays [40]. Then, because of the smallness of $c\tau_{\tilde{W}^\pm}$ compared to the detector size, \tilde{W}^\pm decays before going through the whole detector. Such a charged Wino is identified as a high p_T track which disappears in the middle of the detector. Such a signal does not exist in the SM, and hence is a smoking gun evidence of the production of \tilde{W}^\pm .

The Wino pair can be produced by the Drell–Yan process at the LHC. However, there is no high p_T jet nor track in the final state in such an event, and hence the event cannot be recorded. In order to trigger on the Wino production events, one can use the event with high p_T jet; such a jet can be from the initial state radiation. Then, at the parton level, the Wino production processes relevant for the present study are the following:

$$\begin{aligned} q\bar{q} &\rightarrow \tilde{W}^+\tilde{W}^-g, & gq &\rightarrow \tilde{W}^+\tilde{W}^-q, & g\bar{q} &\rightarrow \tilde{W}^+\tilde{W}^-q, \\ q\bar{q}' &\rightarrow \tilde{W}^\pm\tilde{W}^0g, & gq &\rightarrow \tilde{W}^\pm\tilde{W}^0q', & g\bar{q} &\rightarrow \tilde{W}^\pm\tilde{W}^0q'. \end{aligned}$$

We calculate the cross section of the process $pp \rightarrow \tilde{W}\tilde{W}j$; we perform the parton level calculation, and we approximate the p_T of jet by that of final-state quark or gluon. In the calculation of the

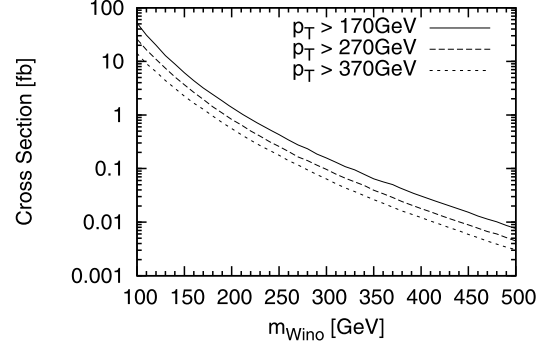


Fig. 3. Cross section for the process $pp \rightarrow \tilde{W}\tilde{W}j$ (with $j = q$ or g), for $\sqrt{s} = 14$ TeV. The transverse momentum of j is required to be larger than 170, 270, and 370 GeV from above.

cross section, the helicity amplitude package HELAS [41] and the CT10 parton distribution functions [42] are used. For the phase space integration, we use the BASES package [43]. In the calculation, we require that the transverse momentum of the jet be larger than 170, 270, and 370 GeV, and that at least one charged Wino travels more than 44.3 cm which is the distance to the third layer of SCT from the beam pipe in the ATLAS detector [44].

In Fig. 3, the cross section is plotted as a function of the Wino mass. In the high luminosity run with $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, for example, the so-called j370 trigger is planned to be available, which requires a jet with $p_T > 370$ GeV [44]. Then, requiring 10 events with $p_T > 370$ GeV for the discovery, for example, Wino mass smaller than 270 GeV (330 GeV) is covered by the LHC with the luminosity of $\mathcal{L} = 100 \text{ fb}^{-1}$ (300 fb^{-1}), where we have assumed that the background is negligible. Thus, in particular when μ is large, the LHC experiment still have a chance to cover the parameter region which has not been excluded yet by the current direct and indirect DM searches. If the p_T of the jet for the trigger can be reduced, the LHC can cover the region with larger Wino mass.

So far, we have assumed the pure AMSB relation among gaugino masses. However, as we have mentioned, such a relation may be largely affected by the Higgs and Higgsino loop diagrams. With such an effect, the gluino mass may become ~ 1 TeV even when the Wino mass is a few GeV. In such a case, the conventional procedures of the SUSY search using the missing energy distribution may work.

In summary, motivated by the recent report on the Higgs searches at the LHC, which indicated excesses of Higgs-like events at around $m_h \simeq 125$ GeV, we have investigated prospects for confirmation of the AMSB scenario, particularly the detection of Wino LSP. We have considered the situation that the scalars except for gauginos and Higgsinos are heavy enough so that they cannot be produced at colliders. Even in this unfortunate case, the Wino DM may be detected through direct/indirect detection experiments. Direct detection efficiency crucially depends on the Higgsino mass, and if the Wino and Higgsino masses happen to be close, future experiments may find their signals. The neutrino telescopes such as IceCube DeepCore and KM3NeT also have a potential to discover the Wino LSP through the observation muon and/or shower events induced by high-energy neutrinos from DM annihilation at GC.

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