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ATLAS on-Z excess via gluino-Higgsino-singlino decay chains in the NMSSM

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Abstract: Recently the ATLAS experiment has reported 3.0 σ excess in an on-Z signal region in searches for supersymmetric particles. We find that the next-to-minimal supersymmetric standard model can explain this excess by the production of gluinos which mainly decay via $\tilde{g} \to g\tilde{\chi}^0_{2,3} \to gZ\tilde{\chi}^0_1$ where $\tilde{\chi}^0_{2,3}$ and $\tilde{\chi}^0_1$ are the Higgsino and the singlino-like neutralinos, respectively. We show that the observed dark matter density is explained by the thermal relic density of the singlino-like neutralino, simultaneously. We also discuss the searches for the Higgs sector of this scenario at the Large Hadron Collider.

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1 Introduction

The supersymmetric (SUSY) models are attractive candidates for physics beyond the standard model (SM) because the hierarchy problem can be solved and dark matter is naturally introduced when the R-parity is conserved. Among various possibilities, the minimal SUSY standard model (MSSM) has been the prime candidate for the realistic supersymmetric model. A drawback of the MSSM is, however, that it contains a dimensionful parameter μ, the mass term of the Higgs multiplets. This reintroduces an additional fine-tuning problem, the so-called μ problem [1]. The size of μ is required to be of the order of other soft SUSY breaking parameters for successful electroweak symmetry breaking whereas they are essentially unrelated with each other.

The simplest solution of the μ problem is to introduce an additional gauge-singlet superfield $\hat{S}$ [2] whose vacuum expectation value (VEV) is controlled by soft SUSY breaking parameters. By making an effective μ term generated by the VEV of $\hat{S}$, the size of μ is naturally interrelated to the size of the soft SUSY breaking parameters. The next-to-minimal SUSY standard model (NMSSM) is one of the simplest singlet extensions of the MSSM where a discrete $\mathbb{Z}_3$ symmetry is imposed [2–4].

Recently, the ATLAS experiment has reported excess events in the SUSY particle searches with dileptons, jets and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) in data of 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV [5]. They have observed 29 (16 for ee and 13 for $\mu\mu$) same-flavour opposite-sign dilepton pairs whose invariant masses are in the Z boson mass window, $81\,\mathrm{GeV} < m_{\ell\ell} < 101\,\mathrm{GeV}$ ("on-Z" signal region). The expected number of SM background events is 10.6 ± 3.2 pairs. The observed event number corresponds to excess of 3.0 σ local significance (3.0 σ for ee and 1.7 σ for $\mu\mu$, separately). In this paper, we call this excess "ATLAS on-Z excess". This excess seems to imply an existence of a gluino whose mass is lighter than 1.2 TeV or squarks lighter than 1.4 TeV [6]. The caveat is, though, that the CMS experiment has also analyzed the dileptons+jets+$E_{\mathrm{T}}^{\mathrm{miss}}$ final state using $\sqrt{s} = 8$ TeV data

in which the kinematical cut is different from the ATLAS one, and a significant excess has not been observed in the on-Z signal region [7].

After the report, many scenarios in the MSSM as well as in the NMSSM have been proposed to explain the ATLAS on-Z excess without conflicting with constraints from various SUSY searches including the CMS on-Z result [6, 8–20]. To have on-shell Z bosons in final states while escaping other SUSY search constraints, scenarios with a gravitino as the lightest SUSY particle (LSP) seems to be one of the simplest possibilities. The lightest neutralino decays into a pair of a Z boson and a gravitino, while the decay of colored SUSY particles into the gravitino with a large $E_{\rm T}^{\rm miss}$ are suppressed. Unfortunately, however, the simplified general gauge mediation model with the gravitino LSP cannot explain the ATLAS on-Z excess [9, 10], where the produced Z bosons are rather hard due to the lightness of the gravitino and are caught in the mesh of the SUSY searches with multi jets $+ E_{\rm T}^{\rm miss}$.

In ref. [16], it has been shown that this problem can be evaded by introducing a non-MSSM massive particle, a goldstini $\tilde{G}'$, into which the lightest neutralino mainly decays. Due to the massiveness of the goldstini, the Z bosons are emitted softly, and hence, the constraints from 0 lepton + multi jets $+ E_{\rm T}^{\rm miss}$ searches become weaker. In this scenario, similar to the gravitino LSP scenario, the couplings between the goldstini and the MSSM particles are suppressed. Besides, the sfermion masses are assumed to be rather larger than the gaugino masses and the lightest neutralino is assumed to be the Higgsino-like. With this setup, the ATLAS on-Z excess is successfully explained by the gluino production via a decay chain, $\tilde{g} \to g\tilde{\chi}^0_{1,2} \to gZ\tilde{G}'$, where $\tilde{\chi}^0_{1,2}$ are the Higgsino-like neutralinos.

The above goldstini nature is also realized in the NMSSM with a singlino-like neutralino LSP, where the singlino is the fermionic component of the additional singlet superfield $\hat{S}$. Actually, some literature investigated this possibility with decay chains of $\tilde{g} \to q\bar{q}\tilde{\chi}^0_2 \to q\bar{q}Z\tilde{\chi}^0_1$ [9, 12], and $\tilde{q} \to q\tilde{\chi}^0_2 \to qZ\tilde{\chi}^0_1$ [17, 19], where in both cases $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ are the bino and singlino-like neutralinos, respectively.

In this paper, we discuss another possibility in the NMSSM and consider the gluino pair production whose decay chain is $\tilde{g} \to g\tilde{\chi}^0_{2,3} \to gZ\tilde{\chi}^0_1$, where $\tilde{\chi}^0_{2,3}$ and $\tilde{\chi}^0_1$ are the Higgsino-like and the singlino-like neutralinos, respectively (see figure 1). It should be noted that the two-body gluino decay modes $\tilde{g} \to g\tilde{\chi}^0_{2,3}$ at one-loop level are the dominant ones when the mass differences between the gluino and the Higgsinos are moderate and the squark masses are in the several TeV range [15, 21, 22]. Besides, as we will show, the radiative decay of the gluino reproduces the distribution of the jet multiplicity observed in the ATLAS results well.

We also investigate the properties of dark matter in the NMSSM, and find two distinct benchmark parameter sets. Eventually, we show that the ATLAS on-Z excess and the observed relic abundance of dark matter can be simultaneously explained in the NMSSM, without conflicting with other experimental constraints, including the CMS on-Z result.

We organize the rest of this paper as follows. In section 2, we briefly review the mass matrices of the Higgs-sector and neutralinos in the NMSSM. Next in section 3, we give an explanation of the ATLAS on-Z excess using the NMSSM with the singlino-like neutralino LSP. In section 4, the property of the dark matter around our benchmark points

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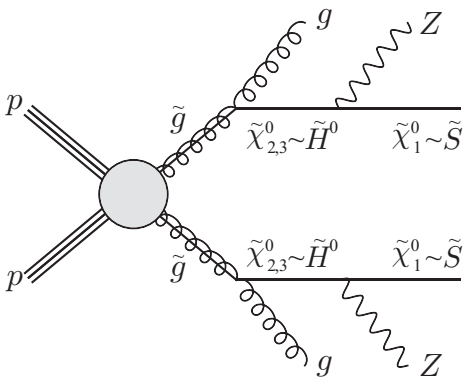

Figure 1. A typical diagram of the gluino decay in the scenario which we considered. See section 3 for details.

is discussed. In section 5, we discuss the searches for the Higgs sector at the LHC. The final section is devoted to conclusion.

2 NMSSM

In this paper, we investigate a possible explanation of the ATLAS on-Z excess in the NMSSM. Motivated by the study about the goldstini [16], we consider the case of the singlino-like neutralino LSP.

In this section, we quickly review the mass spectrum of the NMSSM by paying particular attention to the dependence on parameters. The detail of the NMSSM is given in ref. [23]. The superpotential and the scalar potential of the Higgs-sector in the NMSSM are given as

$$W = \lambda \hat{S}\hat{H}_2\hat{H}_1 + \frac{\kappa}{3}\hat{S}^3, \tag{2.1}$$

$$\begin{aligned} V =& (|\lambda S|^2 + m_1^2)|H_1|^2 + (|\lambda S|^2 + m_2^2)|H_2|^2 \\ &+ \frac{g^2}{2}|(H_1^\dagger H_2)|^2 + \frac{g^2+g'^2}{8}(|H_1|^2 - |H_2|^2)^2 \\ &+ |\lambda H_2 H_1 + \kappa S^2|^2 + m_s^2|S|^2 + \left(\lambda A_\lambda S H_2 H_1 + \frac{\kappa}{3}A_\kappa S^3 + \text{H.c.}\right), \end{aligned} \tag{2.2}$$

where fields with hats are superfields, and $\hat{S}$, $\hat{H}_{1,2}$ are the singlet and the down-type and up-type Higgs doublets, respectively. κ and λ are coupling constants in the superpotential, and g and g' are gauge coupling constants of the $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ gauge interactions. Due to the discrete $\mathbb{Z}_3$ symmetry under which $\hat{S}$ as well as $\hat{H}_{1,2}$ rotate with unit charges, the superpotential does not have dimensionful parameters. The dimensionful parameters in the scalar potential are the soft SUSY breaking parameters, i.e., $m^2_{1,2,s}$ and $A_{\lambda,\kappa}$.

For simplicity, we assume all parameters to be real in this paper. When the electroweak symmetry is broken, three neutral scalar bosons obtain VEVs and they are expanded around their VEVs as follows,

$$H_1^0 = v_1 + \frac{H_{1R} + iH_{1I}}{\sqrt{2}}, \quad H_2^0 = v_2 + \frac{H_{2R} + iH_{2I}}{\sqrt{2}}, \quad S = v_s + \frac{S_R + iS_I}{\sqrt{2}}, \tag{2.3}$$

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where $v^2 = v_1^2 + v_2^2 \simeq (174.1\ \text{GeV})^2$ and we use $\tan\beta \equiv v_2/v_1$ in the following. Then the effective μ term is generated,

$$\mu_{\text{eff}} = \lambda v_s. \tag{2.4}$$

Since the singlet VEV v_s is the same scale as the SUSY breaking dimensionful terms, the μ problem is solved.

In the NMSSM, the singlino is the one of the neutralino components. The neutralino mass matrix for the basis $\psi^0 = \left(\tilde{B},\ \tilde{W}^0,\ \tilde{H}_1^0,\ \tilde{H}_2^0,\ \tilde{S}\right)$ is given as

$$\mathcal{L} = -\frac{1}{2}(\psi^0)^T M_{\tilde{N}} \psi^0 + \text{H.c.}, \tag{2.5}$$

with

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -\frac{g'v_1}{\sqrt{2}} & \frac{g'v_2}{\sqrt{2}} & 0 \\ 0 & M_2 & \frac{gv_1}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} & 0 \\ -\frac{g'v_1}{\sqrt{2}} & \frac{gv_1}{\sqrt{2}} & 0 & -\mu_{\text{eff}} & -\lambda v_2 \\ \frac{g'v_2}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} & -\mu_{\text{eff}} & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa v_s \end{pmatrix}. \tag{2.6}$$

Typically, the mass of the singlino-like neutralino is given as $m_{\tilde{S}} \simeq |2\kappa v_s|$.

The Higgs mass matrices for the basis $(H',\ h',\ S_R)$ and $(A',\ S_I,\ G)$ (defined below) are given as

$$\begin{aligned} V = &\frac{1}{2}\begin{pmatrix} H' & h' & S_R \end{pmatrix} \begin{pmatrix} \tilde{\mathcal{M}}_{R11}^2 & \tilde{\mathcal{M}}_{R12}^2 & \tilde{\mathcal{M}}_{R13}^2 \\ \tilde{\mathcal{M}}_{R12}^2 & \tilde{\mathcal{M}}_{R22}^2 & \tilde{\mathcal{M}}_{R23}^2 \\ \tilde{\mathcal{M}}_{R13}^2 & \tilde{\mathcal{M}}_{R23}^2 & \tilde{\mathcal{M}}_{R33}^2 \end{pmatrix} \begin{pmatrix} H' \\ h' \\ S_R \end{pmatrix} \\ &+\frac{1}{2}\begin{pmatrix} A' & S_I & G \end{pmatrix} \begin{pmatrix} \tilde{\mathcal{M}}_{I11}^2 & \tilde{\mathcal{M}}_{I12}^2 & 0 \\ \tilde{\mathcal{M}}_{I12}^2 & \tilde{\mathcal{M}}_{I22}^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} A' \\ S_I \\ G \end{pmatrix}. \end{aligned} \tag{2.7}$$

with

$$\tilde{\mathcal{M}}_{R11}^2 = M_A^2 + M_Z^2 \sin^2 2\beta + \lambda^2 v^2 \cos^2 2\beta, \tag{2.8}$$

$$\tilde{\mathcal{M}}_{R22}^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \tag{2.9}$$

$$\tilde{\mathcal{M}}_{R33}^2 = \frac{\lambda A_\lambda v^2}{2v_s} \sin 2\beta + \kappa v_s (A_\kappa + 4\kappa v_s), \tag{2.10}$$

$$\tilde{\mathcal{M}}_{R12}^2 = M_Z^2 \sin 2\beta \cos 2\beta - \lambda^2 v^2 \sin 2\beta \cos 2\beta, \tag{2.11}$$

$$\tilde{\mathcal{M}}_{R13}^2 = \lambda v (2\kappa v_s + A_\lambda) \cos 2\beta, \tag{2.12}$$

$$\tilde{\mathcal{M}}_{R23}^2 = \lambda v \left(2\lambda v_s - (2\kappa v_s + A_\lambda) \sin 2\beta\right), \tag{2.13}$$

$$\tilde{\mathcal{M}}_{I11}^2 = M_A^2 + \lambda^2 v^2, \tag{2.14}$$

$$\tilde{\mathcal{M}}_{I22}^2 = \frac{\lambda A_\lambda v^2}{2v_s} \sin 2\beta + 2\lambda\kappa v^2 \sin 2\beta - 3\kappa A_\kappa v_s, \tag{2.15}$$

$$\tilde{\mathcal{M}}_{I12}^2 = \lambda v (-2\kappa v_s + A_\lambda), \tag{2.16}$$

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where

$$M_A^2 \equiv \frac{2\mu_{\rm eff}(A_\lambda + \kappa v_s)}{\sin 2\beta} - \lambda^2 v^2. \tag{2.17}$$

Here, the convenient basis $(H',\ h',\ S_R)$ and $(A',\ S_I,\ G)$ are defined by

$$\begin{pmatrix} H_{1R} \\ H_{2R} \\ S_R \end{pmatrix} \equiv \begin{pmatrix} \sin\beta & \cos\beta & 0 \\ -\cos\beta & \sin\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} H' \\ h' \\ S_R \end{pmatrix}, \tag{2.18}$$

$$\begin{pmatrix} H_{1I} \\ H_{2I} \\ S_I \end{pmatrix} \equiv \begin{pmatrix} \sin\beta & 0 & -\cos\beta \\ \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} A' \\ S_I \\ G \end{pmatrix}. \tag{2.19}$$

One of the NMSSM specific A terms A_λ plays two important roles in determining the properties of the singlet particles and the Higgs mass spectrum. First, the mass scale of the heavy Higgs in eq. (2.17) can be controlled by A_λ. Second, a singlet-doublet mixing for the SM-like Higgs boson can also be controlled by A_λ. Even if the mass of the singlet-like Higgs boson is heavy, the effect of the singlet-doublet mixing does not decouple. When the lightest CP even Higgs boson is the SM-like one and M_A is very large, the contribution of an off-diagonal mass term $\tilde{\mathcal{M}}^2_{R23}$ (eq. (2.13)) to the mass of the SM-like Higgs boson is roughly estimated as follows,[1]

$$\Delta m^2_{h_1} \sim -\frac{(\tilde{\mathcal{M}}^2_{R23})^2}{\tilde{\mathcal{M}}^2_{R33}} \sim -\mathcal{O}(v^2), \tag{2.20}$$

which leads to a too light SM-like Higgs boson mass. This undesirable negative contribution via the singlet-doublet mixing can be avoided if $\lambda \ll 1$ or when the following condition is satisfied,

$$A_\lambda = \frac{2\lambda v_s}{\sin 2\beta} - 2\kappa v_s \sim \frac{2m_{\tilde{H}}}{\sin 2\beta} - m_{\tilde{S}}. \tag{2.21}$$

These conditions also suppress the off-diagonal mass term $\tilde{\mathcal{M}}^2_{R23}$.

3 Explanation of the ATLAS on-Z excess

In this section, we give an explanation of the ATLAS Z+jets+$E_{\rm T}^{\rm miss}$ excess in the NMSSM. In order to explain the signals of the ATLAS on-Z excess by the gluino pair production, we consider the following mass spectrum,

$$\begin{aligned} m_{\tilde{g}} &\lesssim 1 \text{ TeV}, \\ m_{\text{Higgsino,NLSP}} &\gtrsim m_{\tilde{g}} - 300 \text{ GeV}, \\ m_{\text{singlino,LSP}} &\simeq m_{\text{Higgsino,NLSP}} - 100 \text{ GeV}. \end{aligned} \tag{3.1}$$

The reason to choose the above mass spectrum is described below.

[1] On the other hand, the contribution to the singlet component of the SM-like Higgs mass eigenstate is decoupled in proportion to $\tilde{\mathcal{M}}^2_{R23}/\tilde{\mathcal{M}}^2_{R33}$.

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In order to explain the ATLAS on-Z excess by the gluino production, the following items are required.

- The gluino mass is required to be lighter than about 1.2 TeV for a large enough production cross section to explain the number of the excess [6].

- In the dominant gluino decay chain, at least one Z boson emission like $\tilde{g} \to X +$ NLSP $\to X + Z +$ LSP is required, where X denotes SM colored particles.

- Since Z bosons dominantly decay hadronically, multi jets$+E_{\rm T}^{\rm miss}$ searches put severe constraints. In order to ameliorate these constraints, the Z boson is required to be emitted rather softly. In addition, the decay of the NLSP into the Higgs boson + LSP is required to be suppressed so that the Z boson production is enhanced. This requirement also helps to evade the multi-jets constraints caused by the Higgs boson decay.

- In order to shift the jet multiplicity distribution to smaller values as is favored by the ATLAS result, the loop-induced gluino two-body decay is required to become dominant channel. This requirement is also advantageous to evade the multi-jets constraints.

To satisfy the above conditions, we consider the following mass spectrum in the NMSSM. First, in order to enhance the soft Z boson production, we assume a slight degeneracy between the NLSP and the LSP; $m_Z < m_{\rm NLSP} - m_{\rm LSP} < m_h$.

Next, in order for the gluino two-body decay to be a dominant channel, we assume that the gluino is lighter than the squarks, the bino, and the wino, while it is heavier than the Higgsinos and the singlino.[2] Besides, to suppress the decay of the gluino into $t\bar{t}(t\bar{b},\, b\bar{t}) +$ Higgsino kinematically, we assume a slight degeneracy between the gluino and the Higgsino; $m_{\tilde{g}} - m_{\rm Higgsino} \lesssim 300\,{\rm GeV}$. Finally, to suppress the decay of the gluino into $b\bar{b} +$ Higgsino, we take the squark masses to be of order of 10 TeV. Note that the loop-induced gluino two-body decay into the gluon + Higgsino is relatively enhanced by a factor $(\ln(m_{\tilde{t}}/m_t))^2$ [15, 21, 22].

With the above mass spectrum, the Z boson is produced by the decay of the NLSP Higgsino-like neutralino into the LSP singlino-like neutralino. In terms of the model parameters, the Higgsino mass is typically given by $|\lambda v_s|$ and the singlino mass is given by $|2\kappa v_s|$. Hence, $\lambda \sim 2\kappa$ to achieve the above mass spectrum.

Altogether, we consider the mass spectrum in eq. (3.1), in which the typical decay chain of the gluino is $\tilde{g} \to g\tilde{\chi}^0_{2,3} \to gZ\tilde{\chi}^0_1$, where $\tilde{\chi}^0_{2,3}$ and $\tilde{\chi}^0_1$ are the Higgsino and the singlino-like neutralinos, respectively. The diagram is drawn in figure 1. Note that due to small couplings between the singlino and the colored sector, the direct decay of the gluino into the singlino-like neutralino is suppressed. This is the advantage of the singlino-like

[2] This spectrum requires non-universal gaugino masses. We note that the doublet-triplet splitting of the Higgs is naturally achieved in grand unified theories with product gauge groups [24] (see ref. [25] and references therein for related discussions), which in general predict non-universal gaugino masses.

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LSP compared with the bino LSP scenario where the gluino decay mode into the bino LSP with jets can be comparable to the mode into the Higgsino NLSP depending on $\tan\beta$.

Keeping above arguments in mind, we find two distinct valid parameter regions where the ATLAS on-Z excess can be explained. One is a region with a small λ and the other is the one with a large λ. As we will discuss in the next section, these two regions have different dark matter properties. It should be noted that the NMSSM in the small λ region is almost the same with the MSSM plus an additional gauge singlet fermion whose couplings to the MSSM sector are suppressed as in the simplified goldstini model [16]. In this region, the analyses of ref. [16] would be applied. In table 1, we show the two benchmark parameter sets in the two distinct parameter regions which exemplify the small λ and the large λ regions, respectively. In our analysis, we use the spectrum calculator `NMSSMTools 4.7.0` [26, 27] and also use the decay width calculator `NMSDECAY` [28]. In the table, we also show the properties of the dark matter which are calculated using `MicrOMEGAs4.1.8` [29, 30] (see next section). Note that we take $M_1 = M_2 = 1.5\,\text{TeV}$ in both benchmark points, and the bino and winos are decoupled enough.

At the small λ benchmark point, the mass of the SM-like Higgs boson is given by the radiative correction from the stop loop diagrams, which requires a large $\tan\beta$. This large $\tan\beta$ leads to a large decay width of $\tilde{g} \to b\bar{b}(t\bar{b}, b\bar{t}) +$ Higgsino via an enhancement of the bottom Yukawa. Even for a rather large $\tan\beta$, however, we have confirmed that the dominant decay channel of the gluino is $\tilde{g} \to g +$ Higgsino (see table 1).

At the large λ benchmark point, the mass of the SM-like Higgs boson is given by both the radiative correction and an additional F-term contribution which requires a small $\tan\beta$ (see eq. (2.9)). Such a large λ also brings the undesirable negative contribution to the lightest CP-even Higgs mass in eq. (2.20). To avoid this problem, we choose A_λ that suppresses this negative contribution according to eq. (2.21).[3] Note that when one takes A_λ to be $\mathcal{O}(1)\,\text{TeV}$, this equation also suggests the small $\tan\beta$. The large λ also leads to a certain singlino-Higgsino mixing, so that the decay branch $\tilde{g} \to g +$ singlino-like neutralino exists. Even with such contributions, we have again confirmed that the dominant decay channel is $\tilde{g} \to g +$ Higgsino (see table 1).

To investigate the number of the SUSY events in the ATLAS on-Z search and to check the experimental constraints from the other SUSY searches at the ATLAS and CMS collaborations, we use `CheckMATE 1.2.1` [12, 31] which incorporates `DELPHES 3` [32] and `FastJet` [33, 34] internally. Signal events are generated by `MadGraph5 v2.2.3` [35, 36] connected to `Pythia 6.4` [37] where the MLM matching scheme is used with a matching scale at 150 GeV [38]. The parton distribution functions are `CTEQ6L1` [39]. We use the gluino production cross sections at the next-to-leading-logarithmic accuracy given in ref. [40] with `NLL-fast` [41–45].

As a result, we find that the SUSY events can explain the ATLAS on-Z excess within $1\,\sigma$ without conflicting with any LHC constraints at 95% CL, including the CMS on-Z result for both benchmark points. In addition, the lightest CP-even Higgs boson mass is

[3] The singlet component of the lightest CP-even Higgs boson is suppressed by a large singlet scalar mass. Then the Higgs couplings are almost equivalent to the ones in the SM even if we do not choose such a A_λ.

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	small λ	large λ
λ	0.080	0.435
κ	0.033	0.185
$\tan\beta$	30	3
A_λ [GeV]	-146	1500
A_κ [GeV]	-50	-200
$\mu_{\rm eff}$ [GeV]	620	600
$m_{\tilde{q}}$ [TeV]	10	10
A_q [TeV]	6	0
$m_{\tilde{g}}$ [GeV]	900	925
$m_{\tilde{\chi}_3^0}$ [GeV]	641	625
$m_{\tilde{\chi}_2^0}$ [GeV]	636	624
$m_{\tilde{\chi}_1^0}$ [GeV]	527	519
$m_{\tilde{\chi}_1^\pm}$ [GeV]	637	615
m_{h_1} [GeV]	125	125
m_{h_2} [GeV]	500	453
m_{h_3} [GeV]	1061	1831
m_{a_1} [GeV]	195	439
m_{a_2} [GeV]	1061	1829
m_{H^+} [GeV]	1056	1822
$\mathrm{Br}(\tilde{g}\to g\tilde{\chi}_{2,3}^0)$	0.79	0.70
$\mathrm{Br}(\tilde{g}\to g\tilde{\chi}_1^0)$	0.008	0.12
$\mathrm{Br}(\tilde{g}\to \text{others})$	0.20 ($b\bar{b}\tilde{\chi}_{2,3}^0$)	0.18 ($tb\tilde{\chi}_1^\pm$)
$\mathrm{Br}(\tilde{\chi}_{2,3}^0\to Z\tilde{\chi}_1^0)$	1.00	1.00
SUSY events in ATLAS on-Z	14	14
$\Omega_{\tilde{\chi}}h^2$	0.118	0.121
$\sigma_{\rm SI}$ [cm^2]	4.0×10^{-47}	2.8×10^{-45}
Higgs coupling κ_V	0.997	0.9997
Higgs coupling κ_b	1.02	1.02

Table 1. Two benchmark parameter sets. In the line of $\mathrm{Br}(\tilde{g}\to\text{others})$, parentheses represent the dominant decay channel. In both benchmark points, the lightest neutralino $\tilde{\chi}_1^0$, the second lightest CP-even Higgs h_2, and the lightest CP-odd Higgs a_1 are the mass eigenstates dominated by singlet contributions.

125 GeV and the relic abundance of the singlino-like neutralino is also consistent with the observed values within $2\,\sigma$ [46].

Let us comment on the uncertainty in the calculation of the Higgs boson mass. In `NMSSMTools 4.7.0`, the Higgs boson masses are calculated at full one-loop plus two-loop $\mathcal{O}(\alpha_t\alpha_s+\alpha_b\alpha_s)$ level [47]. When the squark mass is about 10 TeV, a theoretical uncertainty of the SM-like Higgs boson mass from higher order corrections by the MSSM particles is about 5 GeV. Including the higher order corrections within the effective field theory approach, this uncertainty can be reduced to around 1 GeV with the similar central value

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in the case of the MSSM [48]. Thus, we simply use the result of `NMSSMTools 4.7.0`. Note that `FeynHiggs` [49] yields a larger Higgs mass by about 5 GeV. If this is the case, the required squark mass should be smaller by a factor of a few and the branching ratio of the radiative decay of the gluino becomes smaller. In the case of the large λ, we may change $\tan\beta$ as well as λ and obtain the similar LHC signal.

Before closing this section, let us comment on the distributions of the jet multiplicity, $E_{\rm T}^{\rm miss}$ and H_T in the on-Z signal region. In figure 2, we show the distributions of the jet multiplicity, $E_{\rm T}^{\rm miss}$ and H_T for the small λ and large λ benchmark points, respectively. Note that we combine the ee and $\mu\mu$ channels of the ATLAS results, although the efficiencies of the channels are different from each other. As shown in ref. [5], the jet multiplicity of the observed data is typically 2–5 jets while the multiplicity larger than 6 is disfavored. For both benchmark points, the jet multiplicity of the NMSSM contributions is peaked at around 4–5, which originates from two gluon jets in two gluino decays, two quarks from a Z-boson decay in one of the gluino decay chain, and an occasionally radiated jet. The predicted distributions of the jet multiplicity fit the ATLAS data very well, which confirms the advantage of the dominance of the gluino two body decay [16]. It can be seen that the distributions of $E_{\rm T}^{\rm miss}$ and H_T are also consistent with the data.

4 Dark matter property

In this section, we discuss the properties of dark matter in the small and large λ regions as exemplified in the above two benchmark points (see table 1). In the small λ region, the lightest neutralino is almost singlino-like. In most cases, such a singlino-like LSP results in overabundant dark matter in the universe because its annihilation cross section is too small. The overabundance is, however, avoided when the heavy Higgs masses are about twice of the mass of the singlino dark matter. Such a mass spectrum can be achieved by tuning the parameter A_λ [50]. With this tuning, the singlino-like neutralino annihilates resonantly via the s-channel heavy Higgs boson exchange, which significantly enhances the annihilation cross section.[4] In this way, the observed dark matter density is explained by the singlino-like neutralino at the small λ benchmark point in spite of the weakness of couplings. It should be noted that due to a suppressed coupling between the singlino and the SM-like Higgs boson, the spin-independent dark matter-nucleon elastic scattering cross section is much lower than the reaches in currently proposed direct dark mater searches.

In the large λ region, on the other hand, there is a certain singlino-Higgsino mixing. The Higgsino components in the LSP can enhance the annihilation cross section, so that the tuning of the heavy Higgs mass is not required. In addition, sizable κ can also enhance the annihilation cross section. It is because that contributions of diagrams of s-cannel a_s boson exchange into fermions [53] and t-channel $\tilde{\chi}_1^0$ exchange into $h_s + a_s$ [50] become efficient when κ is sizable, where both a_s and h_s are the singlet-like scalar bosons. In fact, at the large λ benchmark point, the contribution of a process $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$ to the annihilation cross section is 79 %, and $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_2 a_1$ is 15 %, where a dominant decay channel of a_1 is $t\bar{t}$.

[4]The other possibility is a resonant annihilation via the SM Higgs or Z boson [50–52]. However, due to a large mass difference between the NLSP and singlino, the emitted Z boson becomes energetic.

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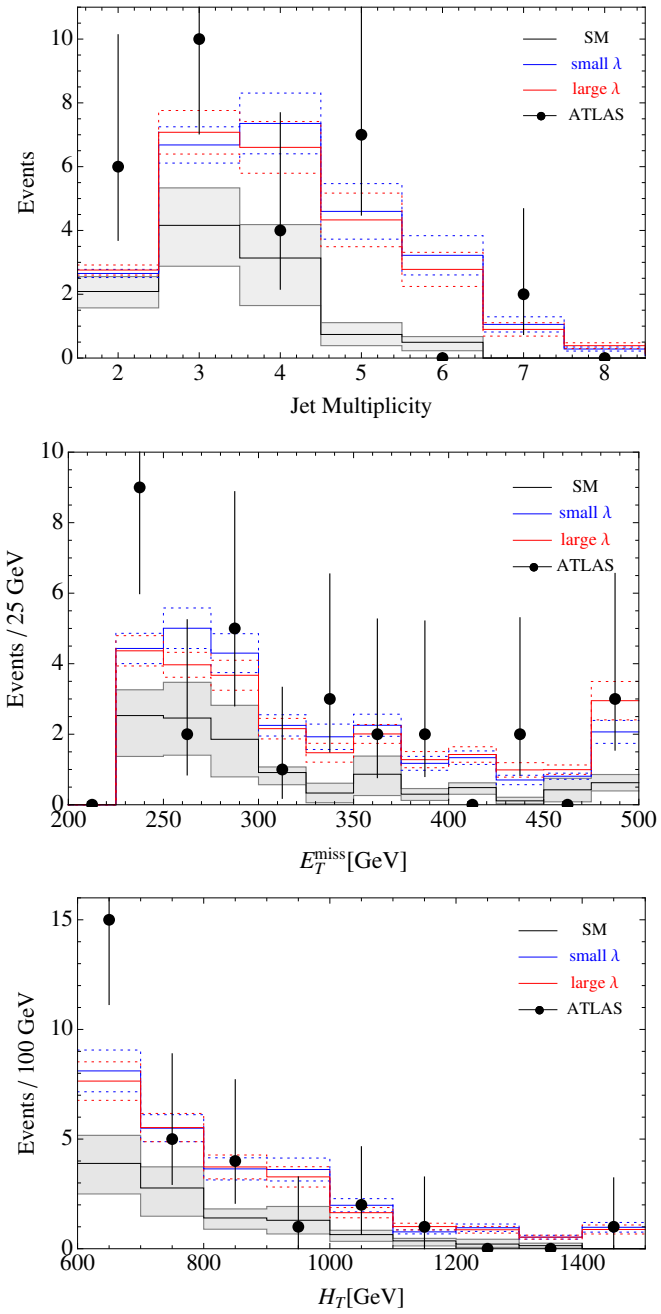

Figure 2. The distributions of the jet multiplicity (top), $E_{\mathrm{T}}^{\mathrm{miss}}$ (middle) and H_T (bottom) in the ATLAS on-Z signal region. The ATLAS data points are shown by black points with combined errors. The black line shows the Standard Model contributions whose errors are shown by gray shade. The expected distributions for the two benchmark points are shown by the blue (small λ) and the red (large λ) lines. The dotted lines represent the error of the NMSSM contributions which is dominated by the uncertainty of the gluino production cross section of about 30%. We ignore the uncertainty of the estimation of the efficiency in `CheckMATE 1.2.1`.

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The singlino-Higgsino mixing also contributes to the spin-independent dark matter-nucleon elastic scattering cross section at the large λ benchmark point. We found that the typical scattering cross section around the benchmark point is a little smaller than a current experimental bound by LUX [54], and proposed future experiments for the direct dark matter search can probe around this benchmark point [55–58].

5 Higgs sector searches at the LHC

In this section, we discuss the searches for the Higgs sector at the LHC. First, we consider the heavy doublet-like Higgses h_3 and a_2. Successful parameter points in the small λ region always predict that the heavy doublet-like Higgses have masses around 1 TeV so that the singlino-like neutralino annihilates resonantly via the s-channel heavy Higgses exchanges. Interestingly, the 14 TeV LHC with a luminosity of $300\,\text{fb}^{-1}$ can probe such a charged Higgs directly by the channel of $pp \to tbH^+ \to tbtb$ due to a $\tan\beta$ enhancement of the bottom Yukawa [59].[5] In the large λ region, although the production cross section of the heavy doublet-like Higgses is small, a high-luminosity LHC can probe them through the top Yukawa via the same channel [59].

Next, we consider the singlet-like scalars h_2 and a_1. The masses of the singlet-like scalars tend to be within the TeV range in our scenario. This is because typical masses of the singlet scalars are controlled by κv_s, which also determines the singlino mass and is taken as about 500 GeV in our scenario.

The singlet-like CP-even Higgs boson h_2 mainly decays into WW and ZZ due to an enhancement of the longitudinally polarized gauge bosons when the decay width into double Higgs, h_1h_1, is suppressed. In our benchmark points, we find that the gluon-gluon (vector boson) fusion cross sections of $pp \to h_2(jj) \to WW(jj)$ are 8 fb (1 fb) at the small λ benchmark point, and 0.2–20 fb (0.2–4 fb) at the large λ benchmark point for $\sqrt{s} = 14$ TeV, where we vary A_λ in the range of 1500–1100 GeV in the large λ benchmark point. Within this range of A_λ, the reduction of the SM-like Higgs boson mass (see eq. (2.20)) can be compensated by taking a large trilinear coupling between the up-type Higgs doublet and stops. For a smaller A_λ, h_2 contains more doublet components and hence the production cross section is larger. The current experimental upper bounds for the gluon-gluon (vector boson) fusion cross sections are 200 (100) fb for $m_{h_2} = 500$ GeV at $\sqrt{s} = 8$ TeV [62].

On the other hand, the singlet-like CP-odd Higgs boson a_1 mainly decays into $t\bar{t}$. The cross section of $pp \to a_1 \to t\bar{t}$ is 1 fb at $\sqrt{s} = 14$ TeV at the large λ benchmark point.[6] The current upper bound is 2 pb for $m_{a_1} = 500$ GeV at $\sqrt{s} = 8$ TeV [63]. Therefore, the direct search for such the singlet-like Higgses would be challenging. It is recently shown that the precision measurement of the double Higgs production can probe the singlet-like Higgs bosons through the interference effect between a resonance production of the

[5] In the small λ region, another promising channel for the heavy doublet-like Higgs searches is $pp \to h_3/a_2 \to \tau\tau$ [60, 61].

[6] In the small λ benchmark point, $a_1 \to t\bar{t}$ is forbidden by the kinematics, and mainly decays into $b\bar{b}$. However, $pp \to a_1 \to b\bar{b}$ cannot be probed due to enormous background.

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singlet-like Higgs and SM processes [64–68]. This resonance signal, however, would become narrower than results in the literature due to the small singlet-doublet mixing in our benchmark points.

6 Conclusion

In this paper, we have studied a possible explanation of the ATLAS on-Z excess in the NMSSM by the gluino production via typical decay chains, $\tilde{g} \to g\tilde{\chi}^0_{2,3} \to gZ\tilde{\chi}^0_1$, with $\tilde{\chi}^0_{2,3}$ and $\tilde{\chi}^0_1$ being the Higgsino and the singlino-like neutralinos, respectively. We found two distinct benchmark parameter sets. At the benchmark points, the observed dark matter density is also explained by the thermal relic abundance of the singlino-like neutralino. In addition, it is found that the expected distributions of the jet multiplicity, $E_{\rm T}^{\rm miss}$ and H_T for our benchmark points are consistent with the ATLAS data.

In the small λ region, we find that the 14 TeV LHC with a luminosity of 300 fb^{-1} can probe the 1 TeV charged Higgs directly by the channel of $pp \to tbH^+ \to tbtb$. On the other hand, in the large λ region, we find that proposed future experiments for the direct dark matter search can probe our scenario at around the benchmark point.

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