UCB-PTH-15/04
DESY 15-105
UT-15-21

July 17, 2015

ATLAS Z Excess in Minimal Supersymmetric Standard Model

Xiaochuan Lu[(a)], **Satoshi Shirai**[(b)] and **Takahiro Terada**[(c, b)]

[(a)] *Berkeley Center for Theoretical Physics, Department of Physics, and Theoretical Physics Group, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA*

[(b)] *Deutsches Elektronen-Synchrotron (DESY), 22607 Hamburg, Germany*

[(c)] *Department of Physics, University of Tokyo, Tokyo 113-0033,Japan*

Abstract

Recently the ATLAS collaboration reported the 3σ excess in the search for the events containing a dilepton pair from a Z boson and large missing transverse energy. Although the excess is not sufficiently significant yet, it is quite tempting to explain this excess by a well-motivated model beyond the standard model. In this paper we study a possibility of the minimal supersymmetric standard model (MSSM) for this excess. Especially, we focus on the MSSM spectrum where the sfermions are heavier than the gauginos and Higgsinos. We show that the excess can be explained by the reasonable MSSM mass spectrum.

1 Introduction

The minimal supersymmetric (SUSY) standard model (MSSM) is one of the most attractive candidates of models beyond the standard model (SM). Especially the recent discovery of the Higgs boson h with a mass of around 125 GeV [1] seems to suggest the framework of the split SUSY [2, 3], where the SUSY fermions are around TeV scale and the SUSY scalars are heavier than TeV scale. This framework can overcome weak points of the weak-scale MSSM, such as SUSY flavor/CP and cosmological problems. Most importantly, the split SUSY is quite compatible with the observed Higgs mass [4, 5]. In the light of the Higgs discovery, this framework is intensively studied [6–9].

Recently the ATLAS collaboration reported the 3σ excess in the search for the events with a dilepton pair on Z boson mass peak and large missing transverse energy (MET), which is a typical signature of the MSSM [10]. The present excess is not so significant yet and might conflict with the constraints on similar channels by the CMS collaboration [11]. However it is quite tempting to investigate whether the well-motivated MSSM spectrum can explain the signal.

Several studies are devoted to the ATLAS Z excess in the context of the SUSY SMs. In Ref. [12], general requirements in the SUSY SMs to explain the excess are studied, and it is concluded that a particle lighter than about 1.2 TeV is needed whose production cross section is of order of those for colored particles and which produces at least one Z boson in its decay chain. In the MSSM with a neutralino as the lightest SUSY particle (LSP), it is found that generically Z bosons are not produced so much in the SUSY cascade decay chain. One can try to increase the production cross section with the light gluinos or squarks to enhance Z boson production, but the constraints from the jets and MET searches [13] get severer. To overcome this difficulty, the compressed spectrum or the spectrum with the light gravitino LSP, in which the neutralino next-to-LSP (NLSP) decays into a gravitino and a Z boson, is discussed. In Ref. [14], they discuss another spectrum in which the first and second generation squarks decay into Bino followed by the Bino decay into Higgsinos with W, Z, or h.

The spectrum with the light gravitino LSP is realized in the so-called general gauge mediation (GGM) [15, 16], where the branching fraction of neutralino NLSP into Z can be close to one. However, constraints from other SUSY searches such as jets+MET [13], stop search [17] or multilepton [18, 19] as well as CMS on-Z dilepton [11] are severe and such an explanation is not viable [20].

On the other hand, compressed spectra are utilized in other attempts to explain the excess [21–23]. When the mass difference between the neutralino LSP and the neutralino NLSP is less than the Higgs mass (125 GeV), the two-body decay of the NLSP into the LSP plus a Z boson can be efficient. An important requirement here is to ensure that the parent particle (gluino or squark) decays mainly into the NLSP so that the NLSP can produce Z in the next step of the decay chain. In the case of the GGM, this requirement is satisfied because the gravitino LSP is very weakly coupled. In the heavy LSP scenarios, the LSP is taken to be a Bino-like neutralino in the MSSM with light sbottom [22] or singlino-like in the next-to-MSSM (NMSSM) [21, 23]. Combining other constraints [11, 13, 24], the NMSSM scenario can reduce the significance of the excess only in a small region in the parameter space [23]. The light sbottom scenario [22] can also reduce the significance, but sbottom produces bottom quarks when it decays into Higgsino-like neutralinos. There is also a non-SUSY study [25] in the composite Higgs [26] / Randall-Sundrum [27] framework, but this also has bottom-rich signatures. Generally, these kinds of signals are severely constrained by b-jets searches [28].

In this paper, we revisit the possibility of explaining the excess in the MSSM, in particular in the

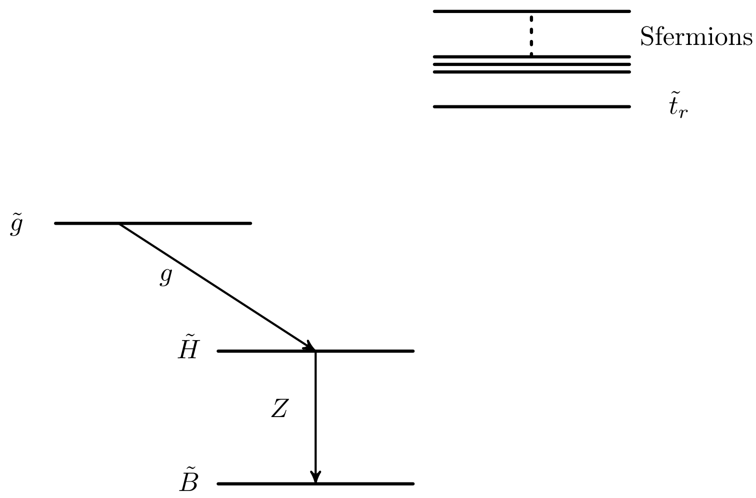


Figure 1: Schematic picture of the present MSSM spectrum.

well-motivated split SUSY-like spectrum. The present neutralino sector is similar to that of Ref. [22], but we take the scalar quarks heavier than the gluino. In Fig. 1, we show a schematic picture of the present MSSM mass spectrum. As we will see in the next Section, the gluino radiative decay into a Higgsino-like neutralino and a gluon becomes the dominant gluino decay channel, when the stop is heavy and the spectrum is sufficiently compressed. The neutralino decay is also summarized in the Section. In this section, we point out the above simple mass spectrum can efficiently produce the Z bosons from a gluino decay. We reduce essential features of the MSSM spectrum to a simplified model, and study LHC signals of the model and its constraints in Section 3. Summary and Discussion is given in Section 4.

2 SUSY Spectrum

2.1 Mass spectrum

We take the split SUSY-like spectrum, where the gauginos and Higgsinos are light whereas scalar superparticles are heavy, and we consider production of the relatively light gluino, which decays into neutralinos and charginos. The LSP is a Bino-like neutralino $\tilde{\chi}_1^0$, and there are nearly degenerate two Higgsino-like neutralinos $\tilde{\chi}_{2,3}^0$ and a Higgsino-like chargino $\tilde{\chi}_1^\pm$ as the NLSPs. For simplicity, we take the Wino heavier than the gluino.

Because of the renormalization group effects, the right-handed stop is expected to be typically lighter than the other squarks. If the right-handed stop is lighter among the squarks, gluino branching fraction shows an interesting feature: the dominant decay channel becomes the top-stop-loop-induced process into a Higgsino-like neutralino and a gluon for suitable mass splitting between gluino and the neutralinos [29–31] (see Fig. 2). This reduces the branching fraction of gluino three-body decay modes, and the gluino dominantly decays into a neutral Higgsino with a gluon.

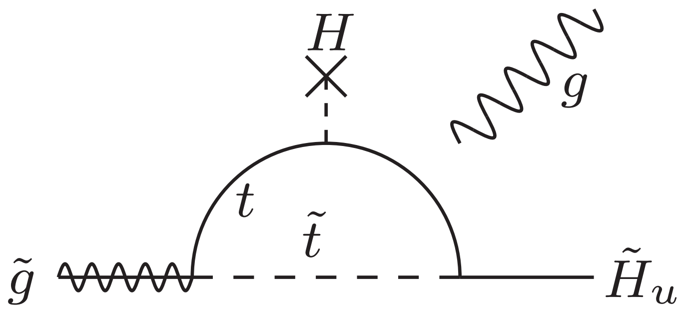


Figure 2: Diagrams of the gluino decay into a Higgsino and gluon.

2.2 Decay of neutralinos and gluino

We study neutralino and gluino decays in this Subsection to motivate the present split SUSY spectrum and a simplified model studied in the next Section.

Decay of neutralinos

First, we consider the neutralino decay. A neutralino may decay into a lighter neutralino emitting a Z or h boson, and into a chargino with a W boson if each channel is kinematically allowed. In the present mass spectrum, the lightest chargino $\tilde{\chi}_1^\pm$ is Higgsino-like, so it is approximately degenerate with Higgsino-like neutralinos $\tilde{\chi}_{2,3}^0$. This means that neutralinos cannot decay into the chargino with a W boson in the present spectrum. If the mass difference between $\tilde{\chi}_1^0$ and $\tilde{\chi}_{2,3}^0$ is greater than m_Z and less than m_h, $\mathrm{BF}(\tilde{\chi}_{2,3}^0 \to \tilde{\chi}_1^0 Z) \simeq 1$. Once the Higgs channel becomes kinematically available, the branching ratio of each Higgsino-like neutralino into Z or h varies substantially in the case of low $\tan\beta$ depending on the phases of parameters such as μ-term, but $\sum_{i=2,3} \mathrm{BF}(\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z)/2 \simeq \sum_{i=2,3} \mathrm{BF}(\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 h)/2 \simeq 0.5$ in the limit of large mass difference between $\tilde{\chi}_1^0$ and $\tilde{\chi}_{2,3}^0$. This can be understood in the Nambu-Goldstone picture: the longitudinal component of the Z boson is the complex partner of the Higgs, whereas the transverse components are unimportant in the limit. Taking the average is justified because gluino decays into the up-type Higgsino in our spectrum (see below), and it is approximately equally contained in the two mass eigenstates of Higgsino-like neutralinos. Therefore in order to produce the Z bosons in the gluino decay chain efficiently, $m_Z < m_{\tilde{\chi}_{2,3}^0} - m_{\tilde{\chi}_1^0} \lesssim m_h$ is required. In the following analysis, we assume $m_{\tilde{\chi}_{2,3}^0} - m_{\tilde{\chi}_1^0} \simeq 100$ GeV.

Decay of gluino

Next, let us move on to the gluino decay. As studied in Refs. [29–31], the partial decay rate of gluino into a gluon and an (up-type) Higgsino is relatively enhanced by a factor $(\log(m_{\tilde{t}}/m_t))^2$ compared to other channels: (i) gluon and Bino, (ii) neutralino, quark and antiquark, and (iii) chargino, quark and antiquark. Therefore, the gluino efficiently produces Higgsino-like neutralinos $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ in the case of the light gluino and heavy (but relatively lighter among the squarks) stop. This radiative decay of the gluino has some advantages to explain the ATLAS Z excess. The gluino decay into a Higgsino-like neutralino, followed by the decay of the neutralino into a Z boson, efficiently produces the Z boson. Thanks to the log enhancement, this decay mode dominates over the other channels for wide parameter space and the expectation value of the number of Z bosons per gluino decay is enhanced. In this case, the constraints from other SUSY searches, such as multi-jets and leptons signals, can be relaxed. Another advantage of this radiative decay is that we can suppress the branching fractions into heavy-flavor jets, which are severely constrained by LHC searches even for the compressed mass spectrum. These features of the gluino branching fractions are shown in Fig. 3a. In the Figure, the mass splittings between $\tilde{\chi}_1^0$ and $\tilde{\chi}_{2,3}^0$, $\tilde{\chi}_1^{\pm}$ are fixed to about 100 GeV by taking $\mu = M_1 + 100$ where $M_1(> 0)$ is the Bino mass. Also, we set the right-handed stop mass as 10 TeV and other squark masses three times larger than that. The renormalization effects are taken into account along the lines of Ref. [30].

In Fig. 3a, the black line represents the branching fraction of the gluino to the Higgsino-like neutralinos and gluon. It diminishes in the right side of the figure for the kinematical reason. As the mass splittings between the relevant neutralino or chargino and gluino increase (to the left of the Figure), the three-body decay channels emitting a quark-antiquark pair become non-negligible. The choice of the parameters in Fig. 3a is relatively inefficient for the gluon channel. The branching fraction of the gluino into $g\tilde{\chi}_{2,3}^0$ for other choices of parameters are shown in Fig. 3b. The branching fraction becomes large in particular when we take μ negative (we take M_1 positive). This is because the up-type Higgsino component in the LSP decreases by partial cancellation in the case of low $\tan\beta$ and $\mathrm{sgn}(\mu/M_1) = -1$.

In Fig. 3c, we show the dependence of the gluino branching fraction of $\tilde{g} \to g\tilde{\chi}_{2,3}^0$ on the squark masses. Here we assume $m_{\tilde{q}_{1,2/LR}} = m_{\tilde{q}_{3/L}} \equiv m_{\tilde{q}}$, $M_1 = 500$ GeV, $\mu = -600$ GeV and $\tan\beta = 2$. We show the cases that $m_{\tilde{q}}/m_{\tilde{t}_r} = 1, 1.5, 2$ and 3. If the $m_{\tilde{q}}/m_{\tilde{t}_r}$ is large enough, $m_{\tilde{t}_r} = O(1)$ TeV can realize the favoured gluino decay, which may leave the possibility that the relatively "natural" SUSY can account for the ATLAS Z excess. As seen in Fig. 3c, heavier stop can increase the $\mathrm{BF}(\tilde{g} \to g\tilde{\chi}_{2,3}^0)$, due to the large log enhancement. Note that, however, the gluino decay length gets larger as the stop mass increases:

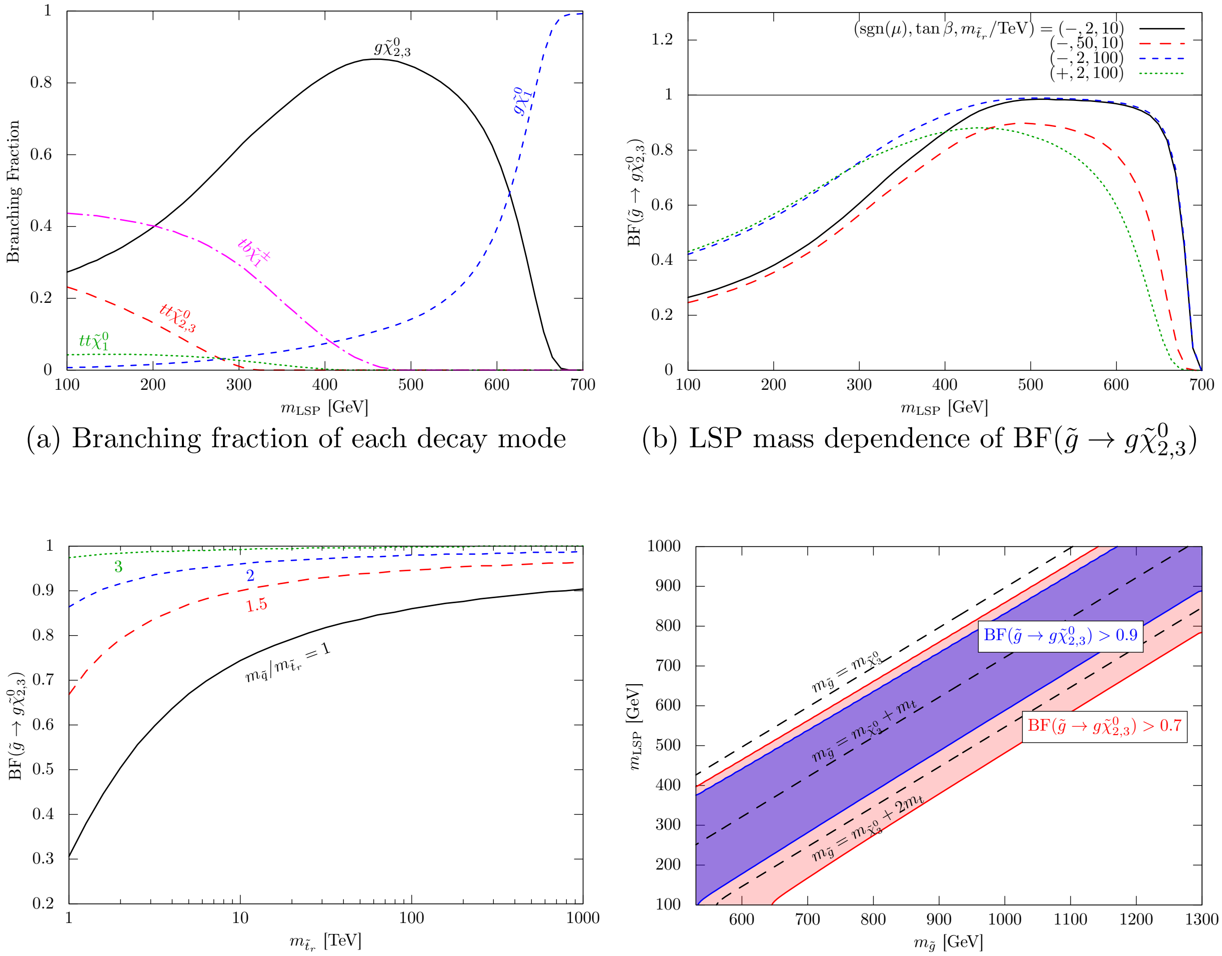
$$c\tau_{\tilde{g}} \sim O(10)\mu\mathrm{m} \left(\frac{m_{\tilde{g}} - m_{\mathrm{NLSP}}}{300\ \mathrm{GeV}}\right)^{-3} \left(\frac{m_{\tilde{t}_r}}{100\ \mathrm{TeV}}\right)^4 . \tag{1}$$

The standard tracking system assumes the gluino decay occurs within $O(1)$ mm from the primary vertex. Therefore the stop mass should be less than $O(100)$ TeV to produce the standard MET and/or jets and/or leptons signals. If the decay length is larger than $O(1)$ mm, severer constraints will be imposed even in the case of the compressed mass spectrum [32].

In Fig. 3d, we also vary the gluino mass as well as the LSP mass, showing the region where the branching fraction of the gluino into a Higgsino-like neutralino and a gluon is high. Here we set $(\mu/\mathrm{GeV}, \tan\beta, m_{\tilde{t}_r}/\mathrm{TeV}) = (-M_1 - 100, 2, 100)$, with M_1 being real and positive. We see, $m_{\tilde{g}} - m_{\tilde{\chi}_{2,3}^0} \lesssim 300$ GeV and $m_{\tilde{\chi}_{2,3}^0} - m_{\tilde{\chi}_1^0} \simeq 100$ GeV, can lead to efficient Z production, $\mathrm{BF}(\tilde{g} \to gZ\tilde{\chi}_1^0) \simeq 1$.

3 LHC Signals

The experimental cuts of ATLAS Z + MET excess is briefly summarized below. There should be a same-flavor opposite-sign dilepton pair with its invariant mass in the Z mass range (81 GeV $< m_{ll} < 101$ GeV), two jets, and MET larger than 225 GeV. Additional cuts include the large scalar sum ($H_{\mathrm{T}} > 600$ GeV) of the transverse momenta of all signal jets and the two leading leptons, and large azimuthal angular separations ($\Delta\phi(\mathrm{jet}_{1,2}, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$) between each of the leading two jets and the MET direction. The observed events in the dielectron and dimuon channels are 16 and 13



(a) Branching fraction of each decay mode

(b) LSP mass dependence of $\mathrm{BF}(\tilde g \to g\tilde\chi^0_{2,3})$

(c) Squark mass dependence of $\mathrm{BF}(\tilde g \to g\tilde\chi^0_{2,3})$

(d) $\mathrm{BF}(\tilde g \to g\tilde\chi^0_{2,3})$ on $m_{\tilde g}$-$m_{\rm LSP}$ plane

Figure 3: Various dependencies of branching fractions of the gluino. (a): The branching fractions of the gluino decay as functions of the LSP mass $m_{\rm LSP} = m_{\tilde\chi^0_1}$. The solid black, long-dashed red, medium-dashed blue, short-dashed green, and dot-dashed pink lines show the branching fractions to $g\tilde\chi^0_{2,3}$, $tt\tilde\chi^0_{2,3}$, $g\tilde\chi^0_1$, $tt\tilde\chi^0_1$, and $tb\tilde\chi^\pm_1$, respectively. We take $m_{\tilde g} = 800$ GeV, and $(\mathrm{sgn}(\mu), \tan\beta, m_{\tilde t_r}/\mathrm{TeV}) = (+, 2, 10)$. (b): The branching fraction into $g\tilde\chi^0_{2,3}$ for various choices of parameters. The solid black, long-dashed red, medium-dashed blue, and short-dashed green lines correspond to $(\mathrm{sgn}(\mu), \tan\beta, m_{\tilde t_r}/\mathrm{TeV}) = (-, 2, 10), (-, 50, 10), (-, 2, 100)$, and $(+, 2, 100)$, respectively. (c): The branching fraction into $g\tilde\chi^0_{2,3}$ as a function of the stop mass $m_{\tilde t_r}$. The solid black, long-dashed red, short-dashed blue, and dotted green lines correspond to squarks masses 1, 1.5, 2, and 3 times larger than the lighter stop mass. We set $M_1 = 500$ GeV, $\mu = -600$ GeV, and $\tan\beta = 2$. (d): The branching fraction of $\tilde g \to g\tilde\chi^0_{2,3}$ on the $m_{\tilde g} - m_{\rm LSP}$ plane. We set $\tan\beta = 2$, $\mathrm{sgn}(\mu) = -$ and $m_{\tilde t_r} = 100$ TeV. It is greater than 0.7 and 0.9 in the red and blue regions, respectively.

whereas the expected numbers of background events are 4.2 ± 1.6 and 6.4 ± 2.2, combined to give 29 observed events compared to 10.6 ± 3.2 expected. This gives rise to the 3σ excess from the SM expectation.

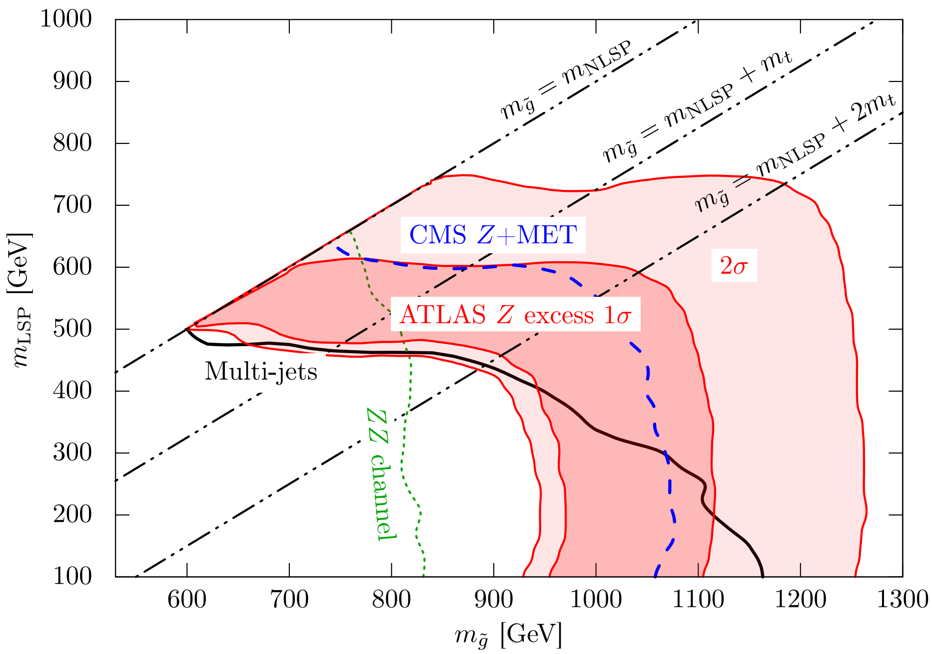


Figure 4: Constraints at the 95% CL of the simplified model. The black solid line shows the ATLAS multi-jets+MET constraints, the blue dashed lines shows the CMS Z+MET constraint, and green dotted ATLAS and CMS four leptons. The red regions show 1σ and 2σ regions to explain the excess of the Z channel.

The essential features of the present mass spectrum discussed in the last Section can be reduced into a simplified model with the decay chain: $\tilde{g} \to g\tilde{\chi}^0_2$ and $\tilde{\chi}^0_2 \to Z\tilde{\chi}^0_1$. We assume $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = 100$ GeV and take the branching fraction of each decay as 1 for simplicity.

As discussed before, this simplified model can produce sufficient amount of Z bosons, which we expect to be consistent with the ATLAS Z excess. On the other hand, similar channels by the CMS collaboration [11] should place severe constraints on it. In addition, this simplified model can easily produce up to six jets due to the gluons produced by the gluino decay and the hadronic decay modes of Z bosons. Therefore, constraints by multi-jets + MET channels could potentially be important. Dilepton + Dijet + MET and four-lepton + MET analyses could also be relevant due to the (semi-)leptonic decay modes of Z bosons. Single lepton + MET channels are expected to be less important due to the second lepton veto.

To study the fitting region and various constraints, we generate this simplified model with up to one extra parton in the matrix element using MADGRAPH 5 v2.1.2 [33] interfaced to Pythia 6.4 [34] and Delphes 3 [35] (which has FastJet incorporated [36]). The MLM matching [37] is applied with a scale parameter set to a quarter of the gluino mass. The parton distribution functions (PDFs) from CTEQ6L1 [38] are used. The gluino production cross sections are calculated at next-to-leading order (NLO) in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) by using NLL-fast v2.1 [39].

In Fig. 4, we show 1σ and 2σ regions to explain the ATLAS Z excess [10]. The exclusion curves at the 95% confidence level (CL) from CMS Z + MET data [11], ATLAS multi-jets (2-6 jets) + MET data [13], and combined constraints of four-lepton + MET data by ATLAS [18] and CMS

[19] and CMS Z + dijet + MET [40] are also shown. Other constraints such as ATLAS large jet multiplicities (7-10 jets) + MET [24] and ATLAS Z + dijet + MET [41] are found less important.

In Fig. 4, the relatively small mass splitting region ($m_{\tilde{g}} - m_{\rm NLSP} \lesssim 2m_t$) is of our true interest, because in this region the gluino decay branching fraction in the split MSSM can be very close to 1 (see Fig. 3), and hence which justifies our use of this simplified model. We see from the Figure that within the justified parameter region, there is a substantial parameter space that is consistent with ATLAS Z excess and not excluded by the various constraints, apart from the CMS Z + MET search. There is even a small parameter region consistent with both the ATLAS Z excess and the CMS exclusion limit by the similar search.

4 Summary and Discussion

In this paper, we study the possibility of explanation of the recent ATLAS Z excess in the MSSM spectrum. We study the gluino and neutralino decays in the case that sfermions are heavier than the gluino, assuming the Bino LSP and the Higgsino NLSP. We show that the small mass difference between the gluino and neutralinos and/or large stop mass can relatively enhance the radiative gluino decay $\tilde{g} \to g\tilde{H}_u^0$. In this model, while the LSP is Bino-like neutralino, the direct gluino decay into the LSP is relatively suppressed. Motivated by this feature, we explored the simplified model to explain the ATLAS Z+MET excess. We found that the gluino mass around 800-1000 GeV and $m_{\rm NLSP} \gtrsim m_{\tilde{g}} - 2m_t$ can well explain the ATLAS Z excess without conflicting with other SUSY searches, apart from the CMS Z+MET search. In such a region the gluino radiative decays into $\chi^0_{2,3}$ are dominated, as seen in Fig. 3, and the present simplified model well describes the realistic gluino decay chains. Therefore we can conclude the very simple MSSM spectrum may explain the ATLAS Z+MET excess.

Moreover the present MSSM mass spectrum has another advantage. As pointed out in Ref. [21], the compressed mass spectrum can well fit the observed distributions of MET $E_{\rm T}^{\rm miss}$ and the scalar sum of transverse momenta $H_{\rm T}$ in the signal region of the ATLAS Z+MET search. This feature is also the case for the present MSSM model. The mass spectrum of our interest, thus, can account for not only the number of the ATLAS Z excess without conflicting with the major SUSY searches but also the more detailed behaviours of the excess.

However there is a subtlety when we consider the Z+MET search by the CMS, which seems to exclude a large portion of the best-fit region for the ATLAS Z+MET signals. There is a tiny region where the ATLAS excess can be explained and the CMS constraint is evaded, although the CMS exclusion limit and the ATLAS best fit region is very close, and it is hard to conclude the both searches can be consistent within this model. The LHC Run II will clarify it.

It will be worth noting that this mass spectrum may provide a good Bino-like dark matter candidate. The abundance and detection of the dark matter is quite sensitive to the other parameters, such as the Wino mass, CP phases and $\tan\beta$, and its detailed study is beyond the scope of the present paper.

In this study, we assume the split SUSY-like spectrum in which the scalar tops play a dominant role in the gluino decay, and the Bino and Higgsino are the LSP and NLSP, respectively. Although this assumption is well motivated, it is interesting to investigate more generic types of MSSM spectra, and it will be done elsewhere.

Acknowledgments

The work of T.T. is supported by a Grant-in-Aid for JSPS Fellows, and a JSPS Grant-in-Aid for Scientific Research No. 26·10619.

References

[1] G. Aad *et al.* (ATLAS), Phys.Lett. **B716**, 1 (2012), arXiv:1207.7214 [hep-ex]; S. Chatrchyan *et al.* (CMS), Phys.Lett. **B716**, 30 (2012), arXiv:1207.7235 [hep-ex].

[2] J. D. Wells, (2003), arXiv:hep-ph/0306127 [hep-ph]; J. D. Wells, Phys.Rev. **D71**, 015013 (2005), arXiv:hep-ph/0411041 [hep-ph].

[3] N. Arkani-Hamed and S. Dimopoulos, JHEP **0506**, 073 (2005), arXiv:hep-th/0405159 [hep-th]; G. Giudice and A. Romanino, Nucl.Phys. **B699**, 65 (2004), arXiv:hep-ph/0406088 [hep-ph]; N. Arkani-Hamed, S. Dimopoulos, G. Giudice, and A. Romanino, Nucl.Phys. **B709**, 3 (2005), arXiv:hep-ph/0409232 [hep-ph]; N. Arkani-Hamed, S. Dimopoulos, and S. Kachru, (2005), arXiv:hep-th/0501082 [hep-th].

[4] Y. Okada, M. Yamaguchi, and T. Yanagida, Prog.Theor.Phys. **85**, 1 (1991); Y. Okada, M. Yamaguchi, and T. Yanagida, Phys.Lett. **B262**, 54 (1991); J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys.Lett. **B257**, 83 (1991); H. E. Haber and R. Hempfling, Phys.Rev.Lett. **66**, 1815 (1991); J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys.Lett. **B262**, 477 (1991).

[5] G. F. Giudice and A. Strumia, Nucl.Phys. **B858**, 63 (2012), arXiv:1108.6077 [hep-ph].

[6] L. J. Hall and Y. Nomura, JHEP **1201**, 082 (2012), arXiv:1111.4519 [hep-ph]; L. J. Hall, Y. Nomura, and S. Shirai, JHEP **1301**, 036 (2013), arXiv:1210.2395 [hep-ph]; Y. Nomura and S. Shirai, Phys.Rev.Lett. **113**, 111801 (2014), arXiv:1407.3785 [hep-ph].

[7] M. Ibe and T. T. Yanagida, Phys.Lett. **B709**, 374 (2012), arXiv:1112.2462 [hep-ph]; M. Ibe, S. Matsumoto, and T. T. Yanagida, Phys.Rev. **D85**, 095011 (2012), arXiv:1202.2253 [hep-ph].

[8] A. Arvanitaki, N. Craig, S. Dimopoulos, and G. Villadoro, JHEP **1302**, 126 (2013), arXiv:1210.0555 [hep-ph].

[9] N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, and T. Zorawski, (2012), arXiv:1212.6971 [hep-ph].

[10] G. Aad *et al.* (ATLAS), (2015), arXiv:1503.03290 [hep-ex].

[11] V. Khachatryan *et al.* (CMS), JHEP **1504**, 124 (2015), arXiv:1502.06031 [hep-ex].

[12] G. Barenboim, J. Bernabeu, V. Mitsou, E. Romero, E. Torro, *et al.*, (2015), arXiv:1503.04184 [hep-ph].

[13] G. Aad *et al.* (ATLAS), JHEP **1409**, 176 (2014), arXiv:1405.7875 [hep-ex].

[14] M. Cahill-Rowley, J. Hewett, A. Ismail, and T. Rizzo, (2015), arXiv:1506.05799 [hep-ph].

[15] P. Meade, N. Seiberg, and D. Shih, Prog.Theor.Phys.Suppl. **177**, 143 (2009), arXiv:0801.3278 [hep-ph].

[16] M. Buican, P. Meade, N. Seiberg, and D. Shih, JHEP **0903**, 016 (2009), arXiv:0812.3668 [hep-ph].

[17] G. Aad *et al.* (ATLAS), JHEP **1406**, 124 (2014), arXiv:1403.4853 [hep-ex].

[18] G. Aad *et al.* (ATLAS), Phys.Rev. **D90**, 052001 (2014), arXiv:1405.5086 [hep-ex].

[19] S. Chatrchyan *et al.* (CMS), Phys.Rev. **D90**, 032006 (2014), arXiv:1404.5801 [hep-ex].

[20] B. Allanach, A. Raklev, and A. Kvellestad, Phys.Rev. **D91**, 095016 (2015), arXiv:1504.02752 [hep-ph].

[21] U. Ellwanger, (2015), arXiv:1504.02244 [hep-ph].

[22] A. Kobakhidze, A. Saavedra, L. Wu, and J. M. Yang, (2015), arXiv:1504.04390 [hep-ph].

[23] J. Cao, L. Shang, J. M. Yang, and Y. Zhang, (2015), arXiv:1504.07869 [hep-ph].

[24] G. Aad *et al.* (ATLAS), JHEP **1310**, 130 (2013), arXiv:1308.1841 [hep-ex].

[25] N. Vignaroli, Phys.Rev. **D91**, 115009 (2015), arXiv:1504.01768 [hep-ph].

[26] D. B. Kaplan and H. Georgi, Phys.Lett. **B136**, 183 (1984).

[27] L. Randall and R. Sundrum, Phys.Rev.Lett. **83**, 3370 (1999), arXiv:hep-ph/9905221 [hep-ph].

[28] G. Aad *et al.* (ATLAS), JHEP **1410**, 24 (2014), arXiv:1407.0600 [hep-ex].

[29] M. Toharia and J. D. Wells, JHEP **0602**, 015 (2006), arXiv:hep-ph/0503175 [hep-ph].

[30] P. Gambino, G. Giudice, and P. Slavich, Nucl.Phys. **B726**, 35 (2005), arXiv:hep-ph/0506214 [hep-ph].

[31] R. Sato, S. Shirai, and K. Tobioka, JHEP **1211**, 041 (2012), arXiv:1207.3608 [hep-ph]; R. Sato, S. Shirai, and K. Tobioka, JHEP **1310**, 157 (2013), arXiv:1307.7144 [hep-ph].

[32] N. Nagata, H. Otono, and S. Shirai, Phys. Lett. **B748**, 24 (2015), arXiv:1504.00504 [hep-ph].

[33] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, *et al.*, JHEP **1407**, 079 (2014), arXiv:1405.0301 [hep-ph]; J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, JHEP **1106**, 128 (2011), arXiv:1106.0522 [hep-ph].

[34] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP **0605**, 026 (2006), arXiv:hep-ph/0603175 [hep-ph].

[35] J. de Favereau *et al.* (DELPHES 3), JHEP **1402**, 057 (2014), arXiv:1307.6346 [hep-ex].

[36] M. Cacciari, G. P. Salam, and G. Soyez, Eur.Phys.J. **C72**, 1896 (2012), arXiv:1111.6097 [hep-ph]; M. Cacciari and G. P. Salam, Phys.Lett. **B641**, 57 (2006), arXiv:hep-ph/0512210 [hep-ph].

[37] J. Alwall, S. Hoche, F. Krauss, N. Lavesson, L. Lonnblad, *et al.*, Eur.Phys.J. **C53**, 473 (2008), arXiv:0706.2569 [hep-ph].

[38] J. Pumplin, D. Stump, J. Huston, H. Lai, P. M. Nadolsky, *et al.*, JHEP **0207**, 012 (2002), arXiv:hep-ph/0201195 [hep-ph].

[39] W. Beenakker, R. Hopker, M. Spira, and P. Zerwas, Nucl.Phys. **B492**, 51 (1997), arXiv:hep-ph/9610490 [hep-ph]; A. Kulesza and L. Motyka, Phys.Rev.Lett. **102**, 111802 (2009), arXiv:0807.2405 [hep-ph]; A. Kulesza and L. Motyka, Phys.Rev. **D80**, 095004 (2009), arXiv:0905.4749 [hep-ph]; W. Beenakker, S. Brensing, M. Kramer, A. Kulesza, E. Laenen, *et al.*, JHEP **0912**, 041 (2009), arXiv:0909.4418 [hep-ph]; W. Beenakker, S. Brensing, M. Kramer, A. Kulesza, E. Laenen, *et al.*, Int.J.Mod.Phys. **A26**, 2637 (2011), arXiv:1105.1110 [hep-ph].

[40] V. Khachatryan *et al.* (CMS), Eur.Phys.J. **C74**, 3036 (2014), arXiv:1405.7570 [hep-ex].

[41] G. Aad *et al.* (ATLAS), JHEP **1405**, 071 (2014), arXiv:1403.5294 [hep-ex].