Explanation of the ATLAS Z-peaked excess by squark pair production in the NMSSM (postprint)

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Preamble

Explanation of the ATLAS Z-peaked excess by squark pair production in the NMSSM

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The ATLAS collaboration recently reported a 3σ excess in the leptonic-Z + jets + E_T^{miss} channel. We interpret this excess through squark pair production in the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The decay chain we employ is $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\chi}_1^0 Z$, where $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ denote the lightest and next-to-lightest neutralinos with singlino and bino as their dominant components respectively. Our simulations indicate that after considering constraints from ATLAS searches for jets + E_T^{miss} signals, the central value of the excess can be obtained for $m_{\tilde{q}} \lesssim 1.2$ TeV, and if the constraint from the CMS on-Z search is further considered, more than 10 signal events remain attainable for $m_{\tilde{q}} \lesssim 750$ GeV. Compared with interpretations based on gluino pair production, the squark explanation allows for a significantly wider range of $m_{\tilde{q}}$ as well as a less compressed SUSY mass spectrum. We also show that the squark explanation will be readily tested at the initial stage of the 14 TeV LHC.

Abstract

Since the discovery of a Higgs-like particle by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) in 2012 [?], the primary focus of the LHC program has shifted to searches for new physics beyond the Standard Model (SM). These searches encompass a wide range of possible signatures, notably various combinations of jets (with or without b-tagging), missing transverse energy (E_T^{miss}), and/or leptons. In this context, the ATLAS collaboration recently reported an intriguing excess at 3σ significance in the leptonic-Z + jets + E_T^{miss} channel [?]. Based on the full 2012 dataset corresponding to approximately 20.3 fb^{-1} integrated luminosity at the 8 TeV LHC, the collaboration observed 29 events for the on-Z electron and muon pair channels, compared to an expected SM background of 10.6 ± 3.2, with no excess observed in any other signal region (SR) [?].

Several attempts have been made to explain this excess through the production of new physics particles that must decay with a sizable rate into jets as well as at least one Z boson and one invisible particle [?]. In the context of supersymmetric theories (SUSY), gluino pair production has typically been employed to provide sufficient events after the rather tight cuts used in [?] [?, ?, ?, ?]. The key aspect of this approach is to choose a lightest SUSY particle (LSP) with relatively suppressed couplings to squarks, so that the gluino preferentially decays first to a neutralino other than the LSP, with the neutralino subsequently decaying to the LSP plus a Z boson. In the Minimal Supersymmetric Standard Model (MSSM), a higgsino-dominated neutralino has very weak couplings to light-flavor squarks, so one can naturally consider a higgsino-dominated LSP and assume the decay chain $\tilde{g} \to q\bar{q}\tilde{\chi}_i^0$ (where q represents a light-flavor quark and $\tilde{\chi}_i^0$ denotes a gaugino-dominated neutralino) to interpret the excess.[1]

We note that for this scenario, the measured dark matter relic density is difficult to obtain if only the neutralino serves as the dark matter candidate (see, for example, Fig. 1 in [?]). In the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [?], however, a singlino-dominated neutralino also possesses this property, and simultaneously, if it acts as the LSP, the correct relic density can be achieved through multiple annihilation channels [?, ?]. Therefore, in this work we investigate the interpretation of the Z-excess in the NMSSM with a singlino-dominated LSP.

In the NMSSM framework with a singlino-dominated LSP, gluino pair production with the three-body decay $\tilde{g} \to q\bar{q}\tilde{\chi}_2^0 \to q\bar{q}Z\tilde{\chi}_1^0$ has been studied for the Z-excess in [?, ?]. These works indicated that the NMSSM can explain the excess quite well, even with simple assumptions on the relevant model parameters. Specifically, it was found that after considering constraints from ATLAS

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[1] In this case, the higgsino-dominated LSP plays the same role as the gravitino in the ATLAS report [?] for interpreting the excess.

searches for jets + E_T^{miss} signals, the NMSSM can reproduce the central value of the excess, and even if one further considers the constraint from the CMS search for the leptonic-Z + jets + E_T^{miss} channel (which observed no excess in any SRs), the event number in the ATLAS on-Z signal can still reach 11, approximately 1.2σ from the measured central value [**?**]. Moreover, as illustrated in [**?**], the gluino explanation can reproduce various distributions of the excess presented by the ATLAS collaboration quite well.

Despite these advantages, we believe it is necessary to seek alternative explanations because the gluino explanation restricts the gluino mass to a narrow range and simultaneously requires a rather compressed sparticle mass spectrum to evade constraints (see Fig. 2 of [**?**]). In this work, we consider squark pair production as an explanation for the excess. To compare with the gluino explanation, we make assumptions on the model parameters similar to those in [**?**]. We find that the squark explanation allows for a significantly extended range of $m_{\tilde{q}}$ compared to the gluino explanation, and furthermore, the relevant sparticle mass spectrum may be less compressed. We also find that, like the gluino explanation, the distributions of the excess can be well reproduced in the squark explanation.

This paper is organized as follows. In Section II, we briefly introduce our scenario for the excess. In Section III, we perform a comprehensive analysis of the relevant parameter space and present our simulation results for the Z-peaked excess. In Section IV, we select some representative parameter points and show their predictions for various distributions of the excess compared with the corresponding data provided by the ATLAS collaboration. In Section V, we briefly discuss future tests of our scenario at the 14 TeV LHC. Finally, we present our conclusions in Section VI.

II. Our Scenario for the Z-Excess

As one of the most economical extensions of the MSSM, the NMSSM includes one gauge singlet Higgs superfield $\hat{S}$ in its matter content. The superpotential of the general NMSSM is given by [**?**, **?**]:

$$W_{\mathrm{NMSSM}} = W_{\mathrm{MSSM}} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \xi_F \hat{S} + \mu' \hat{S}^2$$

where W_{MSSM} is the superpotential of the MSSM without the μ term, $\hat{H}_u$ and $\hat{H}_d$ are the $\mathrm{SU}(2)_L$ doublet superfields, κ and λ are dimensionless coefficients, ξ_F parameterizes the tadpole term, and μ' is a supersymmetric mass.

In this framework, the fermionic component field of $\hat{S}$, usually called the singlino $\tilde{S}$, mixes with the gauginos and higgsinos of the MSSM to form neutralinos. In the basis $(\psi_1 \equiv -i\tilde{B}, \psi_2 \equiv -i\tilde{W}^0, \psi_3 \equiv \tilde{H}_u^0, \psi_4 \equiv \tilde{H}_d^0, \psi_5 \equiv \tilde{S})$, the corresponding mass matrix is given by [**?**]:

$$M = \begin{pmatrix} M_1 & 0 & -ev_d/\sqrt{2} & ev_u/\sqrt{2} & 0 \\ 0 & M_2 & ev_d/\sqrt{2} & -ev_u/\sqrt{2} & 0 \\ -ev_d/\sqrt{2} & ev_d/\sqrt{2} & 0 & -\mu_{\text{eff}} & -\lambda v_d \\ ev_u/\sqrt{2} & -ev_u/\sqrt{2} & -\mu_{\text{eff}} & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa s + \mu' \end{pmatrix}$$

where M_1 and M_2 are soft gaugino masses, $v_u = v \sin\beta$ and $v_d = v \cos\beta$ are the vacuum expectation values (vevs) of the Higgs fields H_u and H_d respectively, $\mu_{\text{eff}} = \mu + \lambda s$ with s denoting the vev of the singlet scalar field S, and $c_W = \cos\theta_W$. This matrix can be diagonalized by a 5×5 unitary matrix N, and consequently the neutralinos as mass eigenstates are defined by $\tilde{\chi}_i^0 = \sum_j N_{ij}\psi_j$, where the mass ordering $m_{\tilde{\chi}_1^0} < \cdots < m_{\tilde{\chi}_5^0}$ is assumed. Obviously, the matrix element N_{ij} measures the size of the ψ_j component in $\tilde{\chi}_i^0$ state, and for the singlino-dominated and bino-dominated neutralinos, their masses are mainly determined by the combination $2\kappa s + \mu'$ and M_1 respectively. Moreover, with the help of N_{ij} one can obtain the interactions of the neutralinos. As shown in [?], the $\bar{q}\tilde{\chi}_i^0\tilde{q}$ coupling (with q denoting a light-flavor quark) is determined by the gaugino components of $\tilde{\chi}_i^0$, while the $\tilde{\chi}_i^0\tilde{\chi}_j^0 Z$ coupling is determined by the higgsino components of the neutralinos. By contrast, the $\tilde{\chi}_i^0\tilde{\chi}_j^0 h$ coupling (with h denoting the SM-like Higgs boson) depends on all components of the neutralinos, and there may exist cancellations among different contributions. These characteristics are helpful for understanding our explanation of the Z-excess.

In the following, we interpret the ATLAS on-Z excess through squark pair production. To make our explanation as simple as possible, we adopt the following assumptions:

- Only the first and second generation squarks are responsible for the excess. In our analysis, we assume a common mass $m_{\tilde{q}}$ for the squarks, so the cross section for squark pair production depends only on $m_{\tilde{q}}$ and $m_{\tilde{g}}$. We calculate the cross section at NLO using the code Prospino [?], and show its dependence on $m_{\tilde{q}}$ at the 8 TeV LHC in Fig. 1.
- The leptonic-Z + jets + E_T^{miss} signal is generated by the cascade decay $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\chi}_1^0 Z$. To maximize this signal rate, we require both $\text{Br}(\tilde{q} \to q\tilde{\chi}_2^0)$ and $\text{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z)$ to be roughly 100%, where the former requirement can be satisfied if $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are singlino-dominated and bino-dominated respectively, and only these two particles in the neutralino and chargino sector are lighter than the squarks. The latter condition can be realized if $m_Z < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \le m_h$ or if the $\tilde{\chi}_i^0\tilde{\chi}_j^0 h$ interaction is significantly suppressed (see the discussion above and also our previous work [?]).
- With these assumptions, the parameters involved in our explanation are $m_{\tilde{q}}$, $m_{\tilde{g}}$, $\Delta m_1 \equiv m_{\tilde{q}} - m_{\tilde{\chi}_2^0}$, and $\Delta m_2 \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. In our discussion, we vary these parameters freely, but noting that the process $pp \to \tilde{q}\tilde{q} \to$

$\tilde{\chi}_1^0 Zq\tilde{\chi}_1^0 Zq$ can also generate multi-jet signals, we constrain these parameters using ATLAS searches for multi-jets + $E_T^{\rm miss}$ signals presented in [?, ?]. We also consider the CMS search for the leptonic-Z + jets + $E_T^{\rm miss}$ signal [?] as an alternative constraint on the parameters.

Regarding our scenario for the Z-excess, we have the following additional remarks:

- We ad hoc require that only $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ among the neutralinos are lighter than the squarks. This simplifies our analysis, but on the other hand, since the rate and various kinematic distributions of the process $pp \to \tilde{q}\tilde{q} \to \tilde{\chi}_1^0 Zq\tilde{\chi}_1^0 Zq$ are determined by few parameters, the capability of our scenario to interpret the excess is limited given that the scenario must satisfy the constraints mentioned above. In fact, as implied by the results of [?], allowing squarks to decay in multiple ways facilitates SUSY to balance the ATLAS signal and the constraints, thus enabling a better explanation of the excess. However, this requires an intensive scan over a higher-dimensional SUSY parameter space, and for each parameter point, simulations of various SUSY signals must be performed to compare with the corresponding experimental data. Such calculations are very time-consuming and beyond the capability of our cluster.
- Again for simplicity, we do not consider the effect of third-generation squarks in our analysis. These squarks have been tightly constrained by the SM-like Higgs boson mass and are preferred to be heavy [?]. For some optimized points in Fig. 2 for the Z-excess, we once included their contributions to the leptonic-Z + jets + $E_T^{\rm miss}$ and multi-jets + $E_T^{\rm miss}$ signals by assuming degeneracy of all squarks. However, we found no improvement in our explanation due to the constraints we considered.
- The assumptions on the properties of the LSP and NLSP in this work are the same as those in our previous work [?], where gluino pair production was used to explain the excess. This enables direct comparison between the two explanations.

III. Z-Peaked Excess in Our Scenario

From the ATLAS analysis of the leptonic-Z + jets + $E_T^{\rm miss}$ channel presented in [?], one can infer that the event number of the excess is 18.4 ± 6.3 after including statistical and systematic uncertainties [?]. This means that to explain the excess at 1σ and 2σ levels, the SUSY signal number after cuts should satisfy $12.1 \leq N_{ll} \leq 24.7$ and $5.8 \leq N_{ll} \leq 31$ respectively.

To find the parameter space that can produce the required event number, we fix $m_{\tilde{g}} = 4.5$ TeV (heavy gluino case) and $m_{\tilde{g}} = 1.5$ TeV (light gluino case) separately. For each case, we perform a grid scan over the parameters Δm_1 and Δm_2 by choosing a series of $m_{\tilde{q}}$ values. For each parameter point, we calculate the squark pair production rate at the 8 TeV LHC using the package Prospino [?], and generate parton-level events for the considered process with MG5_{aMC} [?], which includes Pythia [?] for parton showering and hadronization. We then use the package CheckMATE-1.2.0 [?], which contains the fine-tuned fast detector simulation code Delphes-3.0.10 [?], to repeat the analyses of various experiments. These experiments include the ATLAS on-Z search [?], the CMS on-Z search [?], and the ATLAS 2-6 jet + E_T^{miss} searches [?, ?], where the first is used to generate the excess signal and the others serve as constraints.

In [?], we encoded the cuts for these experiments in the package CheckMATE-1.2.0, and validation indicated that our calculations agree with the corresponding experimental analyses at the 20% level. When implementing the constraints from SUSY searches on the parameters, we define for each search the ratio $R = \max_i(N_{S,i}/S^{95\%}_{\text{obs},i})$, where $N_{S,i}$ is the event number of the SUSY signal in the ith SR of the search, $S^{95\%}_{\text{obs},i}$ is its 95% upper limit usually provided in the experimental report, and the maximum is taken over all SRs defined in the search. Obviously, only when $R < 1$ is the corresponding parameter point experimentally allowed at 95% C.L.

In Fig. 2 and Fig. 3, we present constant contours of the event number for the ATLAS on-Z analysis on the $\Delta m_1 - \Delta m_2$ plane for the heavy gluino and light gluino cases respectively. For each $m_{\tilde{q}}$, the region between the contour marked by 12.1 and that by 24.7 can explain the excess at 1σ level, and the region between the contours marked by 5.8 and 31 can account for the excess at 2σ level. The parameter spaces that satisfy various SUSY searches are also presented, which are bounded on the right by different types of lines (note that a compressed SUSY mass spectrum helps evade LHC constraints). The dotted and solid lines are the boundaries from the ATLAS preliminary and updated searches for 2-6 jets + E_T^{miss} signals respectively, and the dash-dotted line represents the CMS constraint. For the case $m_{\tilde{q}} = 700$ GeV, the constraint from the ATLAS preliminary search for 2-6 jets + E_T^{miss} signal is too weak to be drawn on the plane, and for $m_{\tilde{q}} = 970$ GeV, there are actually no boundaries on the plane.

From Fig. 2 for the heavy gluino case, we learn the following:

- For all choices of $m_{\tilde{q}}$, the strongest constraint comes from the CMS dedicated on-Z counting experiment, while the weakest is the ATLAS preliminary search for 2-6 jets + E_T^{miss} signal.
- As the squark mass increases, Δm_1 is allowed to vary within a wider range. In this case, the improved cut efficiency due to the enlarged Δm_1 can compensate for the decrease in the squark pair production rate. Consequently, even for $m_{\tilde{q}} \lesssim 800$ GeV the central value of the excess (18.4 events) can still be obtained if only constraints from ATLAS searches for jets + E_T^{miss} signals are considered.
- In the CMS dedicated on-Z counting experiment, six signal regions dis-

criminated by jet number n_j and $E_T^{\rm miss}$ were considered (see Table 2 in [**?**]). We checked that for our scenario, the tightest constraint from this experiment comes from $n_j \geq 2$ SRs with $E_T^{\rm miss}$ either satisfying 200 GeV $\leq E_T^{\rm miss} \leq 300$ GeV (called SR-II hereafter) or satisfying $E_T^{\rm miss} > 300$ GeV (called SR-III hereafter).[2] In either case, the signal of the ATLAS on-Z search has a large overlap with that of the CMS on-Z search, so due to the tension between the two search results, the event number in the ATLAS experiment is always upper bounded by about 11 for $m_{\tilde{q}} \lesssim 750$ GeV after considering the CMS constraint. We also checked that with further increase of $m_{\tilde{q}}$ from about 750 GeV, the maximal reachable event number drops either because the tension between ATLAS and CMS data becomes stronger for moderately heavy $\tilde{q}$ or because the squark pair production rate is sufficiently suppressed for heavy $\tilde{q}$.

- The lower right panel of Fig. 2 indicates that there are actually no boundaries on the $\Delta m_1 - \Delta m_2$ plane for $m_{\tilde{q}} = 970$ GeV. In this case, the maximal reachable event number is 6.8, which is still within the 2σ range of the excess.

Next we turn to the light gluino case. From the event contours in Fig. 3, we obtain the following information:

- The dependence of the ATLAS event number on the parameters Δm_1 and Δm_2 is quite similar to that in the heavy gluino case, as are the dependencies of the constraints.
- For squarks lighter than about 1200 GeV, the tightest constraint comes from the CMS experiment, similar to the heavy gluino case; but as the squark mass increases, the strongest constraint may come from the ATLAS preliminary search for jets + $E_T^{\rm miss}$ signal, as shown in the lower right panel of Fig. 3. The underlying reason for this feature is that the capabilities of the SRs defined in the experiments to constrain SUSY depend on the configuration of the SUSY spectrum, and without specification of the spectrum, there is no definite conclusion about which is the strongest. To illustrate this, we take one point from each of the two lower panels in Fig. 3 as examples and show the details of the constraints in Table I. This table indicates that for points S1 and S2, the tightest constraints from the ATLAS preliminary search for jets + $E_T^{\rm miss}$ are the SRs CM and BM respectively, and those from the ATLAS updated search correspond to SRs 2jm and 2jt respectively. For point S1, the constraint from the former experimental analysis is weaker, while for point S2 the situation reverses.

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[2] In more detail, our calculations show that SR-II is more powerful than SR-III in limiting our scenario for the region defined by 100 GeV $\lesssim \Delta m_1 \lesssim 150$ GeV and 95 GeV $\lesssim \Delta m_2 \lesssim 150$ GeV, as well as that defined by 150 GeV $\lesssim \Delta m_1 \lesssim 200$ GeV and 95 GeV $\lesssim \Delta m_2 \lesssim 120$ GeV for all panels in Fig. 2. Consequently, the boundaries of the CMS experiment in the cases of $m_{\tilde{q}} = 650, 700$ GeV are mainly determined by SR-II, while in the case of $m_{\tilde{q}} \gtrsim 750$ GeV, they are determined by SR-III.

- We checked that the ATLAS excess can be explained at 2σ level by squarks with masses up to about 1.4 TeV. The wider mass range compared with the heavy gluino case is mainly due to the larger rate of squark pair production in the light gluino case. We also checked that the central value of the excess can be achieved for $m_{\tilde{q}} \lesssim 1.2$ TeV if only constraints from ATLAS searches for jets + E_T^{miss} signals are considered, and that if the constraint from the CMS experiment is further considered, the maximal event number is only 9.5. The latter fact implies that the heavy gluino case can provide a slightly better explanation.
- Note that for the lower right panel where $m_{\tilde{q}} = 1.36$ TeV and $m_{\tilde{g}} = 1.5$ TeV, the effect from squark-gluino associated production on the LHC searches is non-negligible. Discussion of such effects is beyond the scope of this work.

Before concluding this section, we make four comments about our explanation. First, comparing Fig. 2 and Fig. 3 in this work with Fig. 2 in [?], where gluino pair production with the decay mode $\tilde{g} \to q\bar{q}\tilde{\chi}_2^0 \to q\bar{q}Z\tilde{\chi}_1^0$ was used to explain the excess, we conclude that the squark explanation allows for a significantly wider range of $m_{\tilde{q}}$ as well as a less compressed SUSY mass spectrum. One underlying reason is that the cut efficiency of the ATLAS on-Z search is usually larger for the squark explanation than for the gluino explanation, and consequently, moderately heavy squarks can still explain the excess. Second, we emphasize again that in our simple scenario, both the event number of the ATLAS signal and the constraints are determined by few SUSY parameters. Consequently, the capability of our scenario to interpret the excess is limited. As mentioned at the end of Sec. II, a more complex scenario with higher-dimensional SUSY parameters may improve this situation, but it requires tremendous computational effort to search for the relevant parameter space [?].

Third, we note that other simple SUSY scenarios to explain the excess have appeared, and studies of these scenarios indicated that they can explain the excess at 1σ level in certain narrow SUSY parameter spaces [?, ?]. This conclusion is slightly better than ours, where the best explanation is about 1.2σ away from the central value of the excess. Three factors may contribute to this difference:

- The difference in theoretical hypothesis about SUSY, which determines the kinematical distributions of the SUSY signals. For example, both [?] and [?] utilized the production $pp \to \tilde{g}\tilde{g}$ with the loop-induced decay $\tilde{g} \to g\tilde{\chi}_i^0 \to gZ\chi$ (where χ denotes the lightest neutralino in [?] and the gravitino in [?]) to explain the excess. Comparing their interpretations with ours, one can see that although all considered the two-body decay of a strongly produced SUSY particle, due to differences in the properties of the parent sparticles such as their spins and production channels, their kinematical distributions may differ greatly even when their predictions for the event number of the excess are the same. This point can be seen by comparing the E_T^{miss} distribution of the benchmark points P1 and P2 in this paper with that of the best point in [?], which are presented in Fig. 4 of this work and Fig. 6 of [?] respectively. As a result of this difference, there might exist SUSY points for which the ATLAS leptonic-Z signal is moderately enhanced while the CMS signal is appropriately suppressed.

- The uncertainties induced by related simulations. For all scenarios explaining the excess, simulations of the experimental searches for SUSY must be performed. As shown in the appendices of [?] and [?] where the validations of the simulations were explicitly presented, the uncertainties of the simulations are at the 20% level, and therefore, calculations performed by different groups may result in significant deviations. As far as our simulations are concerned, the computed efficiency for the ATLAS signal event is less than that presented by the ATLAS collaboration for the selected SUSY point by about 10%, while our efficiency for the CMS search is slightly larger than that in the CMS report.
- The treatment of the CMS constraint. From the CMS report presented in [?], one can only infer the approximate value of $S^{95\%}_{\rm obs}$ for SR-III. Confronted with such a situation, in our previous work [?] we calculated the $S^{95\%}_{\rm obs}$ values for all six SRs by the asymptotic CLs prescription [?] (see Table 2 of [?]). Furthermore, we pointed out that SR-II may provide a stronger constraint on the parameters than the other SRs when discussing Fig. 2 of this work. This conclusion indicates that calculating all $S^{95\%}_{\rm obs}$ values is necessary; but on the other hand, since the values of $S^{95\%}_{\rm obs}$ were not explicitly given in other previous literature and they depend on the calculation method, there might exist deviations among different authors when considering the CMS constraint.

We can illustrate this point with an explicit example. During the revision of this manuscript, the paper [?] appeared interpreting the excess in an NMSSM extension with a Dirac gluino, and the authors presented details about their calculation of $S^{95\%}_{\rm obs}$. Briefly, the calculation in [?] differs from ours in at least two aspects: the authors of [?] used the standard Bayesian procedure in their calculation, while we used the asymptotic CLs method [?]; and the work [?] considered theoretical uncertainty in calculating the signal, while we ignored such effects. As a result, the $S^{95\%}_{\rm obs}$ values in [?] are usually larger than our predictions by about 15%, and consequently, the CMS constraint is significantly relaxed in [?].

Finally, we note that in our scenario the singlino-dominated LSP is usually heavier than about 450 GeV, and one may wonder how such heavy dark matter (DM) achieves its measured relic density. In this case, the possible annihilation final states of the DM include $f\bar{f}$, VV, $H_{iH}j$, $A_{iA}j$, and $H_{iA}j$, where $f(V)$ denotes any of the fermions (vector bosons) in the SM, and $H_i(A_j)$ denotes a CP-even (CP-odd) Higgs boson (see [?] and references therein). The easiest way to achieve the correct density is through s-channel annihilations mediated by a singlet-dominated Higgs boson, where, just like the light DM case discussed in

[?], the Higgs boson mass as well as the self-coupling coefficient κ for the singlet fields play an important role in tuning the annihilation rate.

IV. Distributions of the Excess

In this section, we investigate whether our explanation can reproduce the distributions of the excess reported by the ATLAS collaboration. For this purpose, we focus on three benchmark points P1, P2, and P3, with point P3 taken from our previous work [?]. Points P1 and P3 correspond to the best points after considering all constraints in the squark explanation and the gluino explanation respectively, and contribute 11 and 10.5 events to the excess. By contrast, point P2 only satisfies the constraints from ATLAS jets + E_T^{miss} searches, but it can reproduce the central value of the excess. Detailed information about these points is presented in Table II.

To compare our explanation with experimental data for various distributions, we generate the distributions of E_T^{miss}, H_T (the scalar sum of the p_T values for the leptons and signal jets), and the jet multiplicity n_j in the electron and muon combined channel for each parameter point. When obtaining the distributions of E_T^{miss} and H_T, we include overflow events in the last bin. The corresponding results are shown in Fig. 4, where the black solid circle with error bars represents the data obtained by the ATLAS experiment with the expected SM background subtracted [?], and the predictions of points P1, P2, and P3 are marked by triangles, squares, and asterisks respectively. To quantify the difference between the theoretical predictions and the corresponding experimental data, we define a χ^2 function for each distribution in a simple way:

$$\chi^2 = \sum_i \frac{(s_i - \hat{s}_i)^2}{(\delta s_i)^2}$$

where s_i is the theoretical prediction in the ith bin, $\hat{s}_i$ is the corresponding experimental datum, and δs_i is the error of the datum. In Table II, we show the χ^2 values for different distributions.

From Fig. 4 and Table II, we see that all points, especially P2, can reproduce the distributions excellently. The only significant difference between the squark explanation and the gluino explanation in generating the distributions comes from the jet multiplicity: for the former, the n_j distribution peaks at 3, while for the latter it peaks at 4. Due to the large errors in the current data, we cannot determine which explanation is preferred for accounting for the excess.

V. Test of Our Explanation at the 14 TeV LHC

Given that the squark pair production rate at the LHC-14 can be greatly enhanced compared to the LHC-8, one may expect that the squark explanation will be tested very soon at the LHC. We investigate this issue by considering the lepton-Z + jets + E_T^{miss} signal from production at the LHC-14. For simplicity, we assume the same cuts as those of the ATLAS on-Z search at the LHC-8, and estimate the SM background of the signal. In doing this, we suppose that the dominant background at the LHC-14 comes from the same processes as at the LHC-8, which include flavor-symmetric backgrounds, Z + jets, rare top, and diboson [?]. Since it is difficult to obtain accurate background events by directly simulating the processes at the LHC-14, we simulate each background process at the LHC-14 and LHC-8 separately to obtain the ratio of their rates after cuts, then we scale the background at the LHC-8, which was given in the ATLAS report [?], by this ratio. We realize that the results obtained in this way may deviate significantly from their true values, but without detailed information about the ATLAS detector at the LHC-14, our results may serve as a rough estimate of the background.

Once we know the signal and total background after cuts, we can calculate the expected significance using the following formulae:

$$S = \frac{N_s}{\sqrt{N_b + (\epsilon N_b)^2}}$$

where N_s and N_b denote the event numbers for the signal and background respectively, and the coefficient ϵ parameterizes the effect induced by systematic errors. In our calculation, we set $\epsilon = 30\%$ for the 14 TeV LHC, which was adopted at the LHC-8 [?].

Assuming 10 fb^{-1} integrated luminosity at the LHC-14, we present in Table II the predictions of the points for the event numbers of the signal and background. This table indicates that the signals at the LHC-14 after cuts are enhanced by more than 9 times, while the background is enhanced by only about 2 times. As a result, either the squarks/gluino predicted by the points will be discovered, or in case of non-observation of the leptonic-Z + jets + E_T^{miss} signal, the points will be excluded. Moreover, comparing the squark explanation with the gluino explanation, we note that the former is more readily tested at the 14 TeV LHC.

VI. Conclusion

In this paper, we attempted to explain the 3σ excess recently reported by the ATLAS collaboration in the search for the leptonic-Z + jets + E_T^{miss} signal. For this purpose, we considered the pair production of the first two generations of squarks in the NMSSM with the decay chain $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\chi}_1^0 Z$. To maximize the signal rate and simplify our analysis, we considered a singlino-dominated $\tilde{\chi}_1^0$ and a bino-dominated $\tilde{\chi}_2^0$, and assumed $\mathrm{Br}(\tilde{q} \to q\tilde{\chi}_2^0)$ and $\mathrm{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z)$ to be roughly 100%. With these assumptions, the parameters relevant to our analysis include the common squark mass $m_{\tilde{q}}$, the gluino mass $m_{\tilde{g}}$, and the mass splittings $\Delta m_1 \equiv m_{\tilde{q}} - m_{\tilde{\chi}_2^0}$ and $\Delta m_2 \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$.

To find the parameter space that can explain the excess, we fixed $m_{\tilde{g}} = 4.5$ TeV and $m_{\tilde{g}} = 1.5$ TeV separately, and for each case performed a grid scan over the parameters Δm_1 and Δm_2 by choosing a series of $m_{\tilde{q}}$ values. For each parameter point encountered, we simulated the process $pp \to \tilde{q}\tilde{q} \to \tilde{\chi}_1^0 Zq\tilde{\chi}_1^0 Zq$ with the cuts adopted by the ATLAS on-Z search, the CMS on-Z search, and the ATLAS 2–6 jets + E_T^{miss} searches respectively. Based on our simulations, we reach the following conclusions:

- After considering constraints from ATLAS searches for jets + E_T^{miss} signals, the central value of the ATLAS Z-peaked excess can be obtained for $m_{\tilde{q}} \lesssim 1.2$ TeV.
- If the constraint from the CMS on-Z search is further considered, more than 10 signal events remain attainable for $m_{\tilde{q}} \lesssim 750$ GeV.
- For squarks as heavy as about 1.4 TeV, squark pair production can still account for the excess at 2σ level without conflicting with any constraints.
- Compared with explanations based on gluino pair production, the squark explanation allows for a significantly wider range of $m_{\tilde{q}}$ as well as a less compressed SUSY mass spectrum.

We also investigated whether squark pair production can reproduce the distributions of the excess reported by the ATLAS collaboration. We found that, quite similar to gluino pair production, squark pair production can fit the data quite well.

We also examined the prospects for probing the squark explanation at the 14 TeV LHC, and concluded that with only 10 fb^{-1} integrated luminosity, the squarks capable of explaining the excess will be either discovered or excluded.

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Note: Figure translations are in progress. See original paper for figures.