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Full Text

ATLAS Z-Peaked Excess in the MSSM with a Light Sbottom or Stop

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Abstract. We attempt to explain the recent ATLAS 3 excess of dilepton events with an invariant mass near the Z peak through gluino-mediated sbottom production in a simplified scenario inspired by the Minimal Supersymmetric Standard Model (MSSM). The additional Z bosons can be produced through the cascade decay chain $\tilde{g} \to b\tilde{b}_1^\dagger$, in which $\tilde{b}_1$ is the right-handed sbottom, $\tilde{\chi}_{2,3}^0$ are two nearly degenerate higgsino-like next-to-LSPs (NLSPs), and $\tilde{\chi}_1^0$ is the bino-like lightest supersymmetric particle (LSP). Taking into account the constraint from the LHC search for gluino-mediated sbottom production in final states with missing transverse energy and at least three b-jets, we find that the ATLAS on-Z excess can only be marginally explained at the 2 level.

We also note that within the scenario where the gluino predominantly decays to the right-handed stop instead of the sbottom, the excess can hardly be explained, since the Z boson is not produced in the dominant stop decay channel $\tilde{t}_1 \to b\tilde{\chi}_1^+$.

INTRODUCTION

After the discovery of a 125 GeV SM-like Higgs boson [1, 2], the focus of the LHC program has shifted to searches for new particles beyond the Standard Model (SM). Among many promising new physics models, the MSSM has been extensively investigated by theorists and experimentalists. At the LHC, the typical signature for supersymmetry is multi-jet plus missing transverse energy in the final states. Other topologies involving leptons, photons, and heavy quarks have been explored in various simplified models as well. However, up to now, no significant excesses (5) beyond the SM have been observed at the LHC.

Recently, the ATLAS collaboration has reported a 3 excess in the on-Z region in the search for same-flavour opposite-sign dilepton pairs, jets, and large missing transverse energy [3]. Including both electron and muon pairs, the ATLAS collaboration observed 29 events after the selection cuts, while the expected SM background events are 10.6 ± 3.2. Although such an excess is currently not confirmed by the CMS analysis [4], it is interesting to study it in various new physics models.

In Ref. [5], the authors argued that the ATLAS on-Z excess can be explained in the general gauge-mediation (GGM) framework [6]. But later, in Ref. [6], it was claimed that such a model cannot explain the excess due to LHC constraints. In Ref. [7], considering the constraints from LHC searches for multi-jet plus missing transverse energy [8], the author proposed an explanation through gluino pair production in the Next-to-Minimal Supersymmetric Standard Model (NMSSM). Besides SUSY interpretations, a heavy gluon decaying to vector-like quarks in composite Higgs theories was suggested to explain the ATLAS on-Z excess [9].

In many popular supersymmetric grand unification models, the first-two generation squarks appear to be heavier than the third-generation squarks due to different renormalization effects related to Yukawa coupling contributions. In particular, a right-handed sbottom can be light in some models [10]. While a heavy stop sector is usually required by the observed 125 GeV Higgs boson in the MSSM, large mixing effects can also achieve the correct Higgs mass and lead to a relatively light stop. Therefore, if sufficiently light, third-generation squarks could be copiously produced through gluino decay. On the other hand, gluino-mediated third-generation squark production has been searched for at the LHC. The null results give strong bounds on the stop/sbottom and gluino masses [11, 12].

In this work, we focus on gluino-mediated sbottom production with $\tilde{b}_1 \to$

$b\tilde{\chi}^0_{2,3} \to bZ\tilde{\chi}^0_1$ in a simplified scenario inspired by the MSSM and examine its interpretation of the ATLAS Z-peaked excess under LHC constraints. We also study the feasibility of explaining the excess through gluino-mediated stop production. The structure of this paper is organized as follows. In Section II, we set up our calculations and present the numerical results. Finally, we draw our conclusions in Section III.

II. CALCULATIONS AND DISCUSSIONS

In order to reduce SM background events, the following requirements are applied in the ATLAS searches for final states containing a same-flavour opposite-sign lepton pair, jets, and large missing transverse momentum:

- Events are required to have at least two same-flavour opposite-sign (SF-OS) leptons. If more than two signal leptons are present in an event, the two with the hardest p_T are selected. The leading lepton must have $p_T(\ell_1) > 25$ GeV and the sub-leading lepton $p_T(\ell_2)$ can be as low as 10 GeV. The invariant mass of these two leptons must be in the Z boson mass window $81 < m_{\ell^+\ell^-} < 101$ GeV.
- All events are further required to contain at least two hard jets with $p_T >$ 35 GeV and $|\eta| < 2.5$, to have missing transverse energy $E_T^{\text{miss}} > 225$ GeV and $H_T > 600$ GeV, where H_T is the scalar p_T sum over all jets with $p_T > 35$ GeV and $|\eta| < 2.5$ and the two leading leptons: $H_T = \sum_i p_T^{\text{jet},i} + p_T^{\text{lepton},1} + p_T^{\text{lepton},2}$.
- Besides, the azimuthal angle between each of the two leading jets and E_T^{miss} has to be larger than a specified threshold.

From these selection criteria, we can infer that a strong production process is more favored than an electroweak process to explain the ATLAS observed on-Z excess due to the requirement of jet multiplicity and a hard H_T cut [5]. Therefore, we focus on gluino production in the following.

FIG. 1 [Figure 1: see original paper]. The NLL+NLO cross section of gluino pair production for decoupled squarks at 8 TeV LHC. The purple band corresponds to 1 theoretical uncertainty.

In Fig. 1, we calculate the NLO+NLL cross section of gluino pair production at 8 TeV LHC using NLL-fast [13] with CTEQ6.6M PDFs [14]. We can see that the cross section of gluino pair $\sigma_{\tilde{g}\tilde{g}}$ can still reach tens of fb when the gluino mass $m_{\tilde{g}} \lesssim 1$ TeV.

If there is no branching ratio suppression in the gluino cascade decay chain, assuming $m_{\tilde{g}} = 1$ TeV and a signal event efficiency $\epsilon \sim 50\%$, one can obtain about 25 on-Z events at 8 TeV LHC with an integrated luminosity of $\mathcal{L} = 20.3$ fb^{-1}. Any reduction in the branching ratio or in the event efficiency will require the gluino to be lighter to enhance the total cross section. However, a light gluino (with mass less than 1 TeV) usually suffers from strong LHC constraints.

Thus, the most economical way to explain the ATLAS on-Z excess is to make the branching ratio of the gluino cascade decay with a Z boson in the final states as large as possible.

FIG. 2 [Figure 2: see original paper]. Gluino-mediated sbottom production contributing to the on-Z signal.

In Fig. 2, we show the diagram of the gluino decay chain that is relevant for our study. If $m_{\tilde{b}_1} < m_{\tilde{g}}$, the produced gluino will dominantly decay to the sbottom. However, the sbottom decay depends on the nature of the sbottom and the electroweakinos. The interaction between sbottom and neutralinos is given by [15]

$$\mathcal{L}_{\tilde{b}\bar{b}\tilde{\chi}^0} = \tilde{b}_L\bar{b}\left[y_b N_{i3} P_L + \frac{g'}{\sqrt{2}}\left(\frac{1}{3}N_{i1} - N_{i2}\right) P_R\right]\tilde{\chi}^0_i + \tilde{b}_R\bar{b}\left[\frac{2\sqrt{2}}{3}g' N_{i1} P_L + y_b N_{i3} P_R\right]\tilde{\chi}^0_i + \text{h.c.},$$

where $P_{L/R} = (1 \mp \gamma_5)/2$ and $y_b = 2m_b/(v\cos\beta)$. The mixing matrix N_{ij} of the neutralino sector is defined in [15]. For $\tilde{\chi}^0_{2,3}$ being higgsino-like neutralinos and $\tilde{\chi}^0_1$ being bino-like neutralino, we can see that the right-handed sbottom can have sizable decay branching ratios of $\tilde{b}_1 \to b\tilde{\chi}^0_{2,3}$ in comparison with the case of $\tilde{\chi}^0_{2,3}$ being wino-like neutralinos [16]. In particular, when $\tilde{b}_1 \to t\tilde{\chi}^-_1$ is not allowed by phase space, the decay $\tilde{b}_1 \to b\tilde{\chi}^0_{2,3}$ will be dominant. Then, the higgsino-like neutralinos $\tilde{\chi}^0_{2,3}$ can exclusively decay to the Z boson if $m_Z < m_{\tilde{\chi}^0_{2,3}} - m_{\tilde{\chi}^0_1} < m_h$. So we study a simplified scenario of the MSSM, which consists of a heavy gluino ($\tilde{g}$), a right-handed sbottom ($\tilde{b}_1$), a bino-like LSP ($\tilde{\chi}^0_1$), two neutral ($\tilde{\chi}^0_{2,3}$) nearly degenerate higgsino-like NLSPs, and one charged ($\tilde{\chi}^\pm_1$) higgsino-like NLSP. Other sparticles are assumed to be heavy and decoupled for simplicity.

TABLE I [TABLE:N]. A benchmark point for gluino-mediated sbottom production. Here the mass parameters $M_{1,2,3}$ (gaugino masses), μ (higgsino mass), $M_{\tilde{q}_{1,2}}$ (soft breaking masses for the first two generation squarks), m_A (CP-odd Higgs boson mass), $M_{\tilde{Q}_{3L},\tilde{t}_R,\tilde{b}_R}$ (soft breaking masses for the third generation squarks), and $A_{t,b}$ (third generation trilinear couplings) are in units of GeV. $\tan\beta$ is the ratio of the vacuum expectation values of the two-Higgs doublet fields in the MSSM. The gluino pair cross section is calculated up to NLL+NLO for LHC-8 TeV.

Parameter	Value
M_1	[value]
M_2	[value]
M_3	[value]
μ	[value]

Parameter	Value
$M_{\tilde{q}_{1,2}}$	[value]
m_A	[value]
$M_{\tilde{Q}_{3L}}$	[value]
$M_{\tilde{t}_R}$	[value]
$M_{\tilde{b}_R}$	[value]
A_t	[value]
A_b	[value]
$\tan\beta$	[value]
$m_{\tilde{g}}$	[value]
$m_{\tilde{b}_1}$	[value]
$m_{\tilde{\chi}_1^0}$	[value]
$m_{\tilde{\chi}_{2,3}^0}$	[value]
$m_{\tilde{\chi}_1^\pm}$	[value]
$\sigma(\tilde{g}\tilde{g})$	104 fb
$\mathrm{Br}(\tilde{g} \to \tilde{b}_1\bar{b})$	40.31%
$\mathrm{Br}(\tilde{g} \to \tilde{b}_1^\dagger b)$	34.81%
$\mathrm{Br}(\tilde{b}_1 \to b\tilde{\chi}_{2,3}^0)$	24.88%
$\mathrm{Br}(\tilde{\chi}_{2,3}^0 \to Z\tilde{\chi}_1^0)$	[value]

Next, we examine the LHC constraints on our scenario and investigate the ATLAS on-Z excess in the allowed parameter space region. In general, one can vary the mass splitting $m_{\tilde{b}_1} - m_{\tilde{\chi}_{2,3}^0}$ in the range of (m_b, m_t) and $m_{\tilde{\chi}_{2,3}^0} - m_{\tilde{\chi}_1^0}$ in the range of (m_Z, m_h), respectively. However, as the mass differences become smaller, fewer on-Z events are kept due to the requirement of a large H_T value in the ATLAS analysis. Thus, we assume $m_{\tilde{\chi}_{2,3}^0} - m_{\tilde{\chi}_1^0} = 100$ GeV and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_{2,3}^0} = 150$ GeV in the gluino decay chain. Finally, only the gluino mass and the right-handed sbottom mass are free parameters in our parameter space scan. Other irrelevant sparticles are assumed to be heavy, including sleptons, first-two generation squarks, stops, winos, heavy CP-even Higgs boson, and CP-odd Higgs boson.

To study LHC direct search constraints on our parameter space, we use CheckMATE-1.2.1 [19] to recast the ATLAS analysis of gluino-mediated sbottom production [11] and the search for multi-jet plus missing transverse energy events [8]. Additionally, we reinterpret the CMS search for multi-jet events [20] to examine its constraint on the parameter space using MadAnalysis 5-1.1.12 [21]. Both packages use FastJet [22], where the anti-k_t algorithm is chosen for jet clustering [23]. The validations of these analyses have been performed by the two groups. Parton-level signal events are generated by MadGraph5 [24] and showered/hadronized by PYTHIA [25]. Detector simulation effects are included with the tuned Delphes package [26], which is contained in CheckMATE-1.2.1 and MadAnalysis 5-1.1.12.

We define the ratio $r = \max(N_{S,i}/S^{95\%}_{\text{obs},i})$ for each experimental search, where $N_{S,i}$ is the number of signal events for the i-th signal region and $S^{95\%}_{\text{obs},i}$ is the corresponding observed 95% C.L. upper limit. The maximum is taken over all signal regions for each search. If $r > 1$, we conclude that such a point is excluded at 95% C.L.

FIG. 3 [Figure 3: see original paper]. The on-Z signal events from gluino-mediated sbottom production. The blue triangles and pink bullets represent the number of on-Z signal events that can explain the ATLAS excess within and outside the 2 range, respectively. The cyan region is excluded by the ATLAS search for gluino production in final states with missing transverse energy and at least three b-jets [11].

In Fig. 3, we present the on-Z signal events from gluino-mediated sbottom production in the $m_{\tilde{b}_1}$ vs. $m_{\tilde{g}}$ plane. The blue triangles and pink bullets represent the number of on-Z events that can explain the ATLAS excess within and outside the 2 range, respectively. The cyan region is excluded by the ATLAS search for gluino-mediated sbottom production in final states with missing transverse energy and at least three b-jets [11], which is found to be the most stringent bound on our scenario. From Fig. 3, we can see that when $m_{\tilde{g}}$ is lighter than 800 GeV, the mass difference $m_{\tilde{g}} - m_{\tilde{b}_1}$ should be less than about 20 GeV to avoid the constraint. However, such a small splitting cannot produce the large H_T value required by the ATLAS analysis of the on-Z signal. If $m_{\tilde{g}}$ becomes heavy, the cross section for gluino pair production reduces rapidly. Therefore, we find that only a small parameter region with 800 GeV $\lesssim m_{\tilde{g}} \lesssim$ 860 GeV and 760 GeV $\lesssim m_{\tilde{b}_1} \lesssim$ 820 GeV can marginally explain the ATLAS on-Z excess at the 2 level.

We have also considered a similar scenario where the gluino dominantly decays to the right-handed stop with the sbottom decoupled. In this case, Z bosons can be produced through the decay chain $\tilde{t}_1 \to t\tilde{\chi}^0_{2,3} \to tZ\tilde{\chi}^0_1$. However, the branching ratios of $\tilde{t}_1 \to t\tilde{\chi}^0_{2,3}$ are usually less than 50% since $\tilde{t}_1 \to b\tilde{\chi}^+_1$ is the dominant decay mode of the right-handed stop [27]. Besides, such a scenario is strongly constrained by LHC searches for multi-jet events and gluino-mediated stop production. Therefore, it is hard to explain the ATLAS on-Z excess through gluino-mediated stop production.

In the above discussions, only the light right-handed sbottom or stop is involved in the gluino cascade decay process. If both are light enough, the gluino will decay to both $b\tilde{b}^\dagger_1$ and $t\tilde{t}^\dagger_1$. This leads to suppression of the branching ratios of $\tilde{g} \to \tilde{b}_1 \to b\tilde{\chi}^0_{2,3}$ and results in fewer on-Z signal events than in the two cases discussed above. We can conclude that such a light sbottom and stop scenario cannot provide a better explanation than our studied sbottom scenario.

Given that the current excess is only reported by ATLAS, with more data from LHC Run-2, both ATLAS and CMS analyses will be able to further confirm this excess if it is indeed a signal of new physics beyond the SM. On the other hand, regardless of whether this anomaly persists, a compressed gluino-mediated sbottom production scenario is an interesting topology to be explored at future LHC runs [28, 29].

III. CONCLUSION

In this work, we studied the possible explanation of the recent ATLAS 3 on-Z excess through gluino-mediated sbottom production in a simplified scenario inspired by the MSSM, where the spectrum consists of a gluino, a right-handed sbottom, two neutral and one charged nearly degenerate higgsino-like NLSPs, and a bino-like neutralino LSP. Under LHC constraints, particularly the ATLAS search for gluino-mediated sbottom production in final states with missing transverse energy and at least three b-jets, we find that the ATLAS on-Z excess can only be marginally explained at the 2 level in a narrow allowed parameter space region where the mass splittings between the gluino and sbottom are less than about 100 GeV. Additionally, we note that if the gluino decays to a right-handed stop instead of a sbottom, it is hard to explain the excess because the stop will predominantly decay to $b\tilde{\chi}_1^+$ without producing a Z boson.

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