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ATLAS on-Z excess through vector-like quarks

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ABSTRACT

We investigate the possibility that the excess observed in the leptonic-Z + jets + $\not{E}_T$ ATLAS SUSY search is due to productions of vector-like quarks U, which decay to the first-generation quarks and Z bosons. We find that the excess can be explained within the 2σ (up to 1.4σ) level with satisfying the constraints from the other LHC searches. The mass and branching ratio are $610 < m_U < 760$ GeV and $\mathrm{Br}(U \to Zq) > 0.3$–$0.45$, respectively.

1. Introduction

After the LHC 8 TeV run, an excess has been reported in the leptonic-Z + jets + $\not{E}_T$ ("on-Z") channel by the ATLAS collaboration [1]. The observed number of the signal events is 16 and 13 for the final-state electrons and muons, respectively, whereas the standard model (SM) predicts 4.2 ± 1.6 and 6.4 ± 2.2. The discrepancy corresponds to the 3σ level, which stimulates many theoretical studies [2–14].[1]

The on-Z signal was investigated originally to search for the supersymmetry (SUSY) [1], and most of the theoretical works have been performed within the framework of SUSY. In this letter, we consider models with vector-like (VL) quarks as an alternative scenario. The VL particles are predicted in new physics models, e.g., the little Higgs models [18–22] and the composite Higgs models [23–29]. We assume that the VL quarks are pair-produced at the LHC via the QCD interactions.[2] Then, they decay into SM quarks and bosons through their mixings with the SM quarks, since otherwise they become stable and conflict with the cosmology and experiments [30–38]. The decay modes involve productions of the on-shell Z bosons, which contribute to the ATLAS signal. Since the branching ratios of the VL quark depend on details of the models, they are supposed to be free parameters in this letter, and we examine whether this scenario works as a candidate of the on-Z excess.

The models with the VL quarks may be distinguished from the SUSY ones if signal event distributions are measured precisely. In particular, the SUSY models tend to predict events with larger jet multiplicity, e.g., due to the gluino pair production, $pp \to \tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \to q\bar{q}Z\tilde{G}$ [1,2,5], where $\tilde{\chi}_1^0$ is the lightest neutralino, and $\tilde{G}$ is the gravitino.[3] In contrast, the VL quark U decays into less number of jets in $U \to qZ$. Although the current integrated luminosity at the LHC is not large enough to determine the distributions, the data may prefer a lower jet multiplicity. Thus, we also study the event distributions in the VL quark models.

2. Model

We extend the SM by introducing a VL quark. It is assumed to have the electric charge 2/3 and decay to the first-generation quarks. The following analysis does not change in the case when the VL quarks have the electric charge −1/3 or decay to the second-generation quarks.[4]

The interactions of the VL quark with gluons and photons are governed by the SM gauge symmetries. On the other hand, those to the weak gauge and Higgs bosons depend on models, and we take an effective-model approach. They are parameterized as [42]

$$\mathcal{L}_{\mathrm{eff}} = \eta \left(\kappa_W \frac{g}{\sqrt{2}} \bar{U}_L W_\mu^+ \gamma^\mu d_L + \kappa_Z \frac{g}{2c_W} \bar{U}_L Z_\mu \gamma^\mu u_L - \kappa_h \frac{M_U}{v} \bar{U}_R h u_L \right) + \text{h.c.}, \quad (1)$$

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[1] Although no excess has been observed by the CMS collaboration [15,16], the ATLAS collaboration has reported a new result based on the 13 TeV data recently [17], which shows the deviation at the 2.2σ level.

[2] Productions of VL quarks through extra gluon decays are studied in Refs. [3,14].

[3] Squark productions can predict lower jet multiplicity as $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to q\tilde{\chi}_i^0 \to qZ\tilde{\chi}_1^0$ [8,11], where $\tilde{\chi}_i^0$ is a heavier neutralino.

[4] In contrast, decays to the third-generation quarks are severely constrained by the LHC Run-I searches. For example, VL quarks of the mass less than 800 GeV have been already excluded [39–41].

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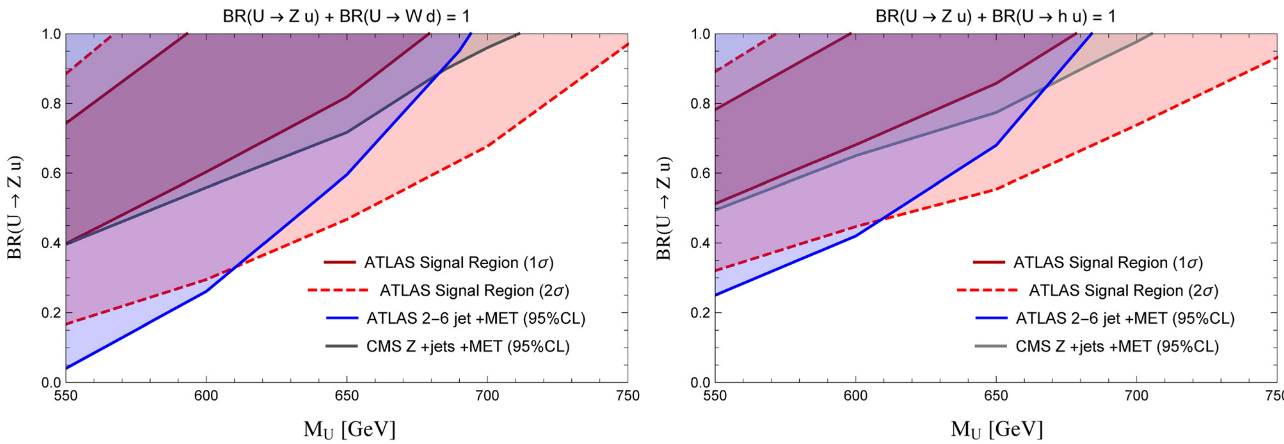

Fig. 1. The ATLAS signal region and LHC constraints in the $\mathrm{Br}(U \to Zu)$ vs. M_U plane. In the dark-red (light-red) region, the ATLAS on-Z excess [1] is explained within the 1σ (2σ) level, while the gray- and blue-shaded regions are excluded at 95% C.L. by the CMS leptonic-Z + jets + $\not{E}_T$ search [15] and ATLAS 2–6 jet + $\not{E}_T$ search [53], respectively. The VL quark is assumed to decay into the Z or W boson (left panel) and Z or Higgs boson (right panel). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

where g is the $SU(2)_L$ gauge coupling constant, c_W the cosine of the Weinberg angle, $v \simeq 246\,\text{GeV}$ the vacuum expectation value of the Higgs field, M_U the mass of the VL quark, and

$$\eta \equiv \sqrt{16\pi \frac{v^2}{M_U^3}\Gamma_U} \tag{2}$$

with Γ_U being the total width of the VL quark. Since the VL couplings with the first-generation quarks are constrained [43,44], η is taken to be small. The following discussion does not depend on its detail as long as the VL quark decays promptly. For simplicity, we only consider the case when the VL quark couples to the left-handed quarks.[5] In the following discussion, we take the branching ratios of the VL quark, $\mathrm{Br}(U \to Vq)$, as free parameters by expressing κ_V ($V = W, Z, h$) as

$$\kappa_V = \sqrt{\frac{\mathrm{Br}(U \to Vq)}{\gamma_V}}, \tag{3}$$

where $q = u, d$ and

$$\gamma_W = \left(1 - \frac{m_W^2}{M_U^2}\right)^2 \left(1 + \frac{m_W^2}{M_U^2} - 2\frac{m_W^4}{M_U^4}\right) + \mathcal{O}\left(\frac{m_d^2}{M_U^2}\right), \tag{4a}$$

$$\gamma_Z = \frac{1}{2}\left(1 - \frac{m_Z^2}{M_U^2}\right)^2 \left(1 + \frac{m_Z^2}{M_U^2} - 2\frac{m_Z^4}{M_U^4}\right) + \mathcal{O}\left(\frac{m_u^2}{M_U^2}\right), \tag{4b}$$

$$\gamma_h = \frac{1}{2}\left(1 - \frac{m_h^2}{M_U^2}\right)^2 + \mathcal{O}\left(\frac{m_u^2}{M_U^2}\right). \tag{4c}$$

Note that the branching ratios are independent of η.

3. Analysis

We consider pair-production processes of the VL quark U, which decays to the first-generation quarks along with the Z, W or Higgs bosons, at the 8 TeV LHC:

$$pp \to U\bar{U}, \quad U \to Zu, W^+d, hu. \tag{5}$$

These are generated at the tree level by MadGraph5_aMC@NLO v2.3 [45]. The model file of the VL quark [42,46] is implemented via FeynRules v2.3 [47]. The generated events are passed to PYTHIA v6.428 [48] for decaying the Z, W and Higgs bosons as well as showering and hadronization, and then interfaced to the Delphes3-based detector simulator in CheckMATE v1.2.1 [49,50], which is tuned to reproduce the performance of the ATLAS detector. The cross sections of the VL-quark pair productions are estimated at the next-to-next-to-leading order (NNLO) accuracy by Hathor v2.0 [51]. MSTW 2008 NNLO (68%CL) PDF [52] is used, where the factorization and renormalization scales are set at the mass of the VL quark.

For the event analysis, we study the following LHC channels [7,49]:

- ATLAS search for leptonic-Z + jets + $\not{E}_T$ signal [1]
- ATLAS search for 2–6 jets + $\not{E}_T$ signal [53]
- CMS search for leptonic-Z + jets + $\not{E}_T$ signal (on-Z signal region) [15].

The event selection cuts are summarized in the appendix. The first analysis is used to determine the parameter regions where the ATLAS on-Z excess is reproduced. The other two analyses constrain the parameter space. We also checked that the other LHC searches implemented in CheckMATE v1.2.1 do not give severer constraints.

4. Results

In Fig. 1 we show the parameter regions where the ATLAS excess in the leptonic-Z + jets + $\not{E}_T$ channel [1] is reproduced within 1σ (dark-red shaded region) and 2σ (light-red shaded region), which correspond to the signal event number $12.1 \le N_{\mathrm{sig}} \le 24.7$ and $5.8 \le N_{\mathrm{sig}} \le 31$ [7], respectively. Here, we assumed that the VL quark decays to the Z or W boson (Z–W decay) in the left panel, while it decays to the Z or Higgs boson (Z–Higgs decay) in the right panel. As discussed below, a part of the parameter regions are excluded by the CMS search in the leptonic-Z + jets + $\not{E}_T$ final states [15] and/or the ATLAS search in the 2–6 jets + $\not{E}_T$ final states [53]. It is found that the VL quark model with a mass of $610 \lesssim M_U \lesssim 760\,\text{GeV}$ can explain the ATLAS on-Z excess within 2σ (up to 1.4σ) in both (the Z–W and Z–Higgs decay) cases.

The CMS search in the leptonic-Z + jets + $\not{E}_T$ final states excludes the parameter space of $m_U \lesssim 710\,\text{GeV}$ and $\mathrm{Br}(U \to Zu) \gtrsim 0.4$–$0.5$. Since the final-state particles are same as those of the ATLAS on-Z excess, the 95% C.L. exclusion lines are approximately parallel to the contours of the ATLAS signal region. Although the

[5] The following study does not depend on this assumption. The chirality structure may be identified by investigating angular correlations of the final-state particles.