ATLAS on-$Z$ Excess Through Vector-Like Quarks

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Abstract

We investigate the possibility that the excess observed in the leptonic-$Z + \text{jets} + \not{E}_T$ ATLAS SUSY search is due to pair productions of a vector-like quark $U$ decaying to the first-generation quarks and $Z$ boson. We find that the excess can be explained within the $2\sigma$ (up to $1.4\sigma$) level while evading the constraints from the other LHC searches. The preferred range of the mass and branching ratio are $610 < m_U < 760$ GeV and $\text{Br}(U \rightarrow Zq) > 0.3-0.45$, respectively.
Introduction

After the LHC 8 TeV run, an excess has been reported in the leptonic-
$Z$ + jets + $E_T$ ("on-$Z$") channel by the ATLAS collaboration [1]. The observed number of
the signal events are 16 and 13 for the final-state electrons and muons, respectively, whereas
the standard model (SM) predicts $4.2 \pm 1.6$ and $6.4 \pm 2.2$. The discrepancy corresponds to
the $3\sigma$ level, which stimulates many theoretical studies [2–14].

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 instead 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
directly at the LHC by the QCD interactions. 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 precisely measured. In particular, the SUSY models tend to predict events
with larger jet multiplicity, e.g., through the gluino pair production, $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_0^0 \rightarrow q\tilde{q}Z\tilde{G}$ [1, 2, 5], where $\tilde{\chi}_0^0$ is
the lightest neutralino, and $\tilde{G}$ is the gravitino. In contrast, the VL quark $U$ decays into less-multiple jets through, e.g., $U \rightarrow qZ$. 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.

Model

We extend the SM by introducing a VL quark which has the electric charge of
$\frac{2}{3}$ and only decays to the first-generation quarks. Discussions for VL quarks carrying the
electric charge of $-\frac{1}{3}$ or decaying also to the second-generation quarks go along the same
lines.

The interactions of the VL quark with gluons and photons are governed by the gauge
symmetries. On the other hand, the interactions to the weak gauge and Higgs bosons are
model dependent, and we employ an effective-model approach. The interaction of the VL
quark with the weak gauge and Higgs bosons are parameterized as [42]

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

#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 $2.2\sigma$ level.
#2 VL quark productions through a heavy-gluon decay are studied in Ref. [3, 14].
#3 Squark productions can predict lower jet multiplicity as $pp \rightarrow \tilde{q}\tilde{q}^*, \tilde{q} \rightarrow q\tilde{\chi}_i^0 \rightarrow qZ\tilde{\chi}_i^0$ [8, 11], where $\tilde{\chi}_i^0$
is a heavier neutralino.
#4 On the other hand, 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].
where \( g \) is the \( SU(2)_L \) gauge coupling constant, \( c_W \) 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

\[
\eta \equiv \sqrt{16\pi \frac{v^2}{M_U^2}} \Gamma_U
\]

with \( \Gamma_U \) being the total width of the VL quark. The VL couplings with the first-generation quarks are constrained to be less than \( \mathcal{O}(0.01) \). In order to avoid this constraint, \( \eta \) 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 that the VL quark couples to the left-handed light quarks. In the following discussion, we take the branching ratio of the VL quark, \( \text{Br}(U \rightarrow V q) \), as a free parameter by expressing the \( \kappa_V (V = W, Z, h) \) as

\[
\kappa_V = \frac{\text{Br}(U \rightarrow V q)}{\gamma_V},
\]

where \( q = u, d \) and

\[
\gamma_W = \left( 1 - \frac{m_W^2}{M_U^2} \right)^2 \left( 1 + \frac{m_W^2}{M_U^2} - 2 \frac{m_W^4}{M_U^4} \right) + \mathcal{O} \left( \frac{m_W^6}{M_U^6} \right),
\]

\[
\gamma_Z = \frac{1}{2} \left( 1 - \frac{m_Z^2}{M_U^2} \right)^2 \left( 1 + \frac{m_Z^2}{M_U^2} - 2 \frac{m_Z^4}{M_U^4} \right) + \mathcal{O} \left( \frac{m_z^6}{M_U^6} \right),
\]

\[
\gamma_h = \frac{1}{2} \left( 1 - \frac{m_h^2}{M_U^2} \right)^2 + \mathcal{O} \left( \frac{m_h^6}{M_U^6} \right).
\]

Note that the branching ratios are independent of \( \eta \).

**Analysis** We consider pair-production processes of the VL quark \( U \), decaying to the first-generation quarks along with \( Z, W \) or Higgs bosons at the 8 TeV LHC:

\[
pp \rightarrow U \bar{U}, \quad U \rightarrow Zu, W^{+}d, hu.
\]

Those processes are generated at the tree level using MadGraph5\_aMC@NLO v2.3. The model file of the VL quark is implemented via FeynRules v2.3. The generated events are passed to PYTHIA v6.428 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, 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 with Hathor v2.0. MSTW 2008 NNLO (68%CL) PDF is used with the factorization and renormalization scales set at the mass of the VL quark.

We then analyze the generated events following the LHC analyses below.
Figure 1: The ATLAS signal region and LHC constraints in the Br($U \rightarrow Zu$) 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 +$E_T$ search [15] and ATLAS 2-6 jet +$E_T$ search [52], respectively. The vector-like quark is assumed to decay with $Z$ or $W$ boson emission (left panel) and $Z$ or Higgs boson emission (right panel).

- ATLAS search for leptonic-$Z$ + jets + $E_T$ signal [1]
- ATLAS search for 2-6 jets + $E_T$ signal [52]
- CMS search for leptonic-$Z$ + jets + $E_T$ signal (on-$Z$ signal region) [15].

The first ATLAS analysis is used to search for parameter regions where the ATLAS excess is reproduced, and the other analyses are used to constrain the parameter space. We also checked that the other LHC searches implemented in CheckMATE v1.2.1 do not give severer constraints.

**Results** In Fig. 1 we show the parameter regions where the ATLAS excess in the leptonic-$Z$ + jets + $E_T$ channel [1] is reproduced within 1σ (dark-red shaded region) and 2σ (light-red shaded region), corresponding to the signal event number of 12.1 $\leq N_{\text{sig}}$ $\leq$ 24.7 and 5.8 $\leq N_{\text{sig}}$ $\leq$ 31 [17], respectively. The model parameter space is spanned by the mass of the VL quark and the branching ratio Br($U \rightarrow Zu$). In the figure we assume that the VL quark decays via $Z$ or $W$ boson emission ($Z$-$W$ decay in the left panel) or via $Z$ or Higgs boson emission ($Z$-Higgs decay in the right panel). The excluded regions from the other LHC analyses, i.e., the CMS search in the leptonic-$Z$ + jets + $E_T$ final states [15] and ATLAS search in the 2-6 jets +$E_T$ final states [52] are also shown as the gray- and blue-shaded regions, respectively. We see that the VL quark model with a mass of 610 $\lesssim M_U$ $\lesssim$ 760 GeV can explain the ATLAS excess within 2σ (up to 1.4σ) in both the $Z$-$W$ and $Z$-Higgs decay cases.
Figure 2: The distributions of the $E_T$, $H_T$ and jet multiplicity predicted by the VL quark model with $M_U = 680$ GeV and Br($U \to Zu$) = 0.8 (red boxes). The experimental data of the ATLAS on-Z excess with the expected SM backgrounds being subtracted are also shown (black dots with error bars). The highest bins contain overflow events.

The CMS search in the leptonic-$Z$ +jets +$E_T$ final states excludes the parameter space of $m_U \lesssim 710$ GeV and Br($U \to Zu$) $\gtrsim$ 0.4–0.5. Since the same final states as the ATLAS on-Z excess are investigated, the 95% C.L. exclusion lines are roughly parallel to the 1$\sigma$ and 2$\sigma$ ATLAS signal-region contours. The CMS exclusion region covers the whole 1$\sigma$ ATLAS signal region (dark-red shaded region) for $M_U > 550$ GeV, but still allowing the 2$\sigma$ signal region (light-red shaded region) for wide range of the VL quark mass due to the large uncertainty on the signal event number of the ATLAS on-Z excess.

On the other hand, the 2-6 jets +$E_T$ search is sensitive to a smaller $Z$-branching region and excludes the whole 1$\sigma$ ATLAS signal region as well as a part of the 2$\sigma$ signal region for $M_U \lesssim 680$ GeV. In the $Z$-$W$ decay case, the model parameter space of $M_U < 550$ GeV is almost excluded, while there remains an allowed region for Br($U \to Zu$) $\lesssim$ 0.2 in the $Z$-Higgs decay case. This is because the 2-6 jets +$E_T$ search is not so sensitive to the parameter space dominated by the Higgs-involving $U$ decays, which basically do not leave large $E_T$. The CMS constraint is stronger than the ATLAS 2-6 jets +$E_T$ search for Br($U \to Zu$) $\gtrsim$ 0.8.

Next we show the $E_T$, $H_T$ and jet-multiplicity distributions predicted by the VL quark model with $M_U = 680$ GeV and Br($U \to Zu$) = 0.8 for the $Z$-$W$ decay case (red boxes) in Fig. 2. This model point gives 8.3 signal events, which agrees with the ATLAS on-Z excess at 1.6$\sigma$. The black dots show the ATLAS data with the expected SM backgrounds being subtracted (taken from Ref. [11]). In the figure, all the model distributions show marginal agreements with the ATLAS ones. For the $E_T$, $H_T$ and jet-multiplicity distributions, $\chi^2$/d.o.f. = 7.7/9, 5.4/7 and 7.0/5, respectively. It is mentioned that the jet-multiplicity distribution of the VL quark model peaks around 2-3 number of jets, which may
be a distinguishable feature of the model. Future LHC Run-II data is expected to reveal the
detailed nature of the excess.

Conclusion. In this letter we have investigated the possibility that the excess observed in
the ATLAS SUSY search in the leptonic-$Z$ + jets + $E_T$ final states is due to pair productions
of the VL quark $U$, which only decays to the first-generation quarks. We find that the excess
can be explained within the 2$\sigma$ (up to 1.4$\sigma$) level while evading the constraints from the other
LHC searches such as the CMS leptonic-$Z$ + jets + $E_T$ and ATLAS 2-6 jets + $E_T$ searches. The
2$\sigma$ preferred range of the VL-quark mass and branching ratio of the $Z$-boson involving decay
are $610 \lesssim M_U \lesssim 760$ GeV and $\text{Br}(U \to Zu) \gtrsim 0.3$–4.5 (depending on the decay modes of
the VL quark), respectively. The $E_T$, $H_T$ and jet-multiplicity distributions predicted by the
VL-quark model show marginal agreements with those of the ATLAS excess. In conclusion,
there is room for VL quark models to explain the ATLAS on-$Z$ excess, and upcoming re-
results from the 13 TeV LHC would confirm or refute the VL quark interpretation of the excess.

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