Associated production of Z boson and a pair of new quarks at the LHC

YANG Shuo

Key Laboratory of Frontiers in Theoretical Physics,
Institute of Theoretical Physics, Chinese Academy of Sciences,
P.O. Box 2735, Beijing 100190, China

Abstract

The associated production of Z boson and a pair of new quarks at the Large Hadron Collider (LHC) is studied. The cross sections for both sequential fermions and vector-like fermions are presented. It is found that for sequential fermions the cross sections can reach $1 \sim 10^2$ fb for heavy quark mass $m_Q$ from 1000 GeV to 200 GeV. For vector-like quarks, the cross sections are suppressed by mixing parameter $\sin \theta_L$. Focusing on process $pp \rightarrow b'b'$, we investigate the possibility of detecting the $6l + 2j$ signal. For a $b'$ with light mass and a large branching ratio of $b' \rightarrow bZ$, it is found that only several signal events (parton level) can be produced with 1000 fb$^{-1}$ integrated luminosity. Although the signal events are rare, all the final states are produced centrally and multi lepton final states are clear at hadron collider, which could be easily detected.

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*Electronic address: shuoyang@itp.ac.cn
I. INTRODUCTION

One of the main goals of LHC is searching for new physics beyond the Standard Model (SM). Many new physics models introduce new fermions to solve some problem or address some open question of SM. In some models, new fermions play an important role in electroweak symmetry breaking or CP violation, and their characters may be different from the presently known fermions. In little Higgs model \[1\], a pair of vector-like quarks are introduced in order to cancel the Higgs one-loop quadratic divergence caused by top quark. In another model \[2\], for understanding the Higgs, an extra vector-like generation of matter is introduced within the framework of supersymmetry. A heavy fourth generation might help in bringing the gauge couplings close to a unification point at order of \(10^{16}\) GeV \[3\]. Discovery of such new fermions would revolutionize our understanding of electroweak symmetry breaking and some other basic problems. In this paper, we study the associated production of Z boson and a pair of new heavy quarks. This process offer the possibilities to probe the electroweak couplings of new quarks.

This paper is organized as follows. In Sec. II, features of new quarks and phenomenological constraints on new quarks are briefly reviewed. In Sec. III, the associated production of Z boson and a pair of quarks for both sequential quarks and vector-like quarks are investigated. Finally, we give our conclusions in Sec. IV.

II. NEW QUARKS AND THEIR PHENOMENOLOGICAL CONSTRAINTS

In addition to three known generations of fermions, new fermions are introduced in various new physics models. They can be chiral or vector-like. In this section, we will start with a brief description of these two types of new quarks and then discuss the phenomenological bounds.

One can make a replica of a SM family to get the simplest fourth generation which is
the so-called sequential fermions [4]. The couplings of $Z$ to new sequential quarks are the same as those for known quarks. The new quarks can also be vector-like [5], where the left-handed and right-handed chiral components transform the same under electroweak gauge group $SU(2)_L \otimes U(1)_Y$. Both vector-like doublet quarks and vector-like singlet quarks are candidates. For simplicity and illustrative purpose, we only discuss SM with vector-like singlet extension in this paper. Introducing a vector-like pair $\tilde{b}, \tilde{b}'$ with quantum numbers $(3, 1, -2/3)$ and $(\bar{3}, 1, 2/3)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$, the mass terms of $b$ quark sector can be presented as

\[ L \supset y_{33} Q_3 \tau_2 \Phi^* b_3^c + f \tilde{b} \tilde{b}' + y_{34} Q_3 \tau_2 \Phi^* \tilde{b}^c + \text{h.c.,} \]  

where $y_{33}$ and $y_{34}$ denote Yukawa couplings, $\Phi$ is the Higgs doublet, $Q_3 = \begin{pmatrix} t_3 \\ b_3 \end{pmatrix}^T$ and $b_3^c$ are the third generation quark doublet and singlet, respectively. After diagonalizing the mass terms, one get the physical third generation quark $b$ and the new exotic heavy quark $b'_v$. 

\[ b = \cos \theta_L b_3 - \sin \theta_L \tilde{b}, \quad b^c = \cos \theta_R b_3^c - \sin \theta_R \tilde{b}^c, \]  
\[ b'_v = \sin \theta_L b_3 + \cos \theta_L \tilde{b}, \quad b'^c_v = \sin \theta_R b_3^c + \cos \theta_R \tilde{b}^c. \]  

Vector-like up-type quark extension is similar to this case. Replacing the weak eigenstates by the physical states, one can get the electroweak interactions of new quarks in vector-like singlet extended model. We summarize the $Z$-new quark-new quark interactions vertex for sequential quarks and exotic quarks in vector-like extended model in Table I. For convenience in discussion, we denote down-type new quark with the same quantum number as bottom quark by $b'$, sequential $b'$ quark by $b'_4$ and exotic $b'$ with large admixture of vector-like quark by $b'_v$. The similar notations are taken for up-type new quark $t'$. 

Now, we turn to the phenomenological constraints on the masses and mixings of new quarks. The most stringent constraints on sequential fermions are from "oblique parameters" $S$, $T$ and $U$ [6]. These constraints can be relaxed by allowing $T$ to vary or fourth
TABLE I: Z-new quark-new quark interactions for sequential quarks and exotic quarks. \( P_{L,R} = \frac{(1 \mp \gamma_5)}{2}, s_L = \sin \theta_L, c_L = \cos \theta_L. \)

generation masses are not degenerate \cite{7,8}. Recently, ref. \cite{8} has identified a region of particle masses and mixings for new sequential fermions which are in agreement with all experimental constraints and has minimal contributions to oblique parameters. Vector-like fermions do not contribute to ”oblique parameters” in the leading order, and thus these parameters do not constrain their masses.

As for direct search limits for new quarks, the strongest bound on \( t' \) is \( t' > 256 \text{ GeV} \) \cite{9}, which comes from CDF by searching for \( t'\bar{t}' \) with decay \( t' \rightarrow q + W \). Assuming the branching ratio \( BR(b' \rightarrow bZ) = 1 \), CDF obtains the bound \( m_{b'} > 268 \text{ GeV} \) \cite{10}. Note that if the decay branching ratio or lifetime of new quarks are affected by mixing parameters and mass difference between \( t' \) and \( b' \), the mass bounds can be softened. Detailed analysis of experimental constraints on masses of fourth generation quarks can be found in ref. \cite{11}. In this paper, we will consider a wide mass parameter space that the masses of new quarks are from 200 GeV to 1000 GeV.

CKM unitary and flavor physics also suppressed the mixing angles between the extra quarks and the ordinary three generation which suggest the mixing should be small. As for SM with vector-like fermions extension, GIM mechanism break down and therefore the most important consequences are the flavor changing neutral current ( FCNC ) and flavor diagonal neutral currents ( FDNC ) \cite{12}. \( R_b \) requires the mixing parameter \( \sin \theta_L \) between bottom quark and the new down-type quark should be small, roughly, \( \sin \theta_L < 0.1 \). For the mixing parameter between top and the new \( t' \) quark, the constraints are weaker.
III. ASSOCIATED PRODUCTION OF Z BOSON AND A PAIR OF NEW QUARKS

FIG. 1: Respective Feynman diagrams for associated production of Z boson and a pair of new quarks. The Feynman diagrams are drawn using FeynArts [13].

As shown in Fig. 1, Z boson can be produced in association with a pair of new heavy quarks \((pp \to ZQQ)\) at the LHC \(\text{[1]}\), which provide a method to detect the electroweak couplings of new quarks. Probing electroweak top quark couplings via \(t\bar{t}\gamma\) and \(t\bar{t}Z\) production at hadron colliders has been studied [16]. In this paper, we calculate the cross section for process \(pp \to ZQQ\) at the LHC with \(\sqrt{s} = 14\) TeV where both chiral quarks (\(t'_4, b'_4\)) and vector-like quarks (\(t'_v, b'_v\)) are considered. The calculations in this paper were performed with MADGRAPH/MADEVENT [17]. CTEQ6L [18] parton distribution function with strong coupling constant \(\alpha_s(m_Z^2) = 0.118\), renormalization scale and factorization scale \(\mu_r = \mu_f = 2m_Q\) are taken. We plot the cross section for the associated production of Z and \(t'\) quarks at the LHC versus mass parameter \(m'_t\) in Fig. 2. Both of the cases for chiral quarks and vector-like quarks are shown for comparison. The cross sections decrease sharply as the

\[\text{[1]}\] There also exits the associated production of Z boson and a pair of new leptons (\(pp \to ZLL\)). It originates from lepton pair production via Drell-Yan mechanism [14] and gluon-gluon fusion mechanism [15] with the Z boson emitted from the lepton lines. However, the cross section for process \(pp \to ZLL\) is too small.
increase of mass parameter $m_Q$. For a sequential $t'$ with mass from 200 GeV to 1000 GeV, the cross section is variant from $10^2$ fb level to 1 fb level. For a typical $t'$ mass $m'_t = 300$ GeV, the cross sections are 86 fb for sequential $t'$ and 31 fb for vector-like $t'$, respectively. As for vector-like $t'$, the cross section is smaller because the coupling is suppressed by $\sin \theta_L$. Considering phenomenological constraints, we take $\sin \theta_L \leq 0.1$ and show the cross section for a typical value $\sin \theta_L = 0.1$ in Fig. 2. The results for vector-like fermion are not very sensitive to the mixing parameter $\sin \theta_L$ in this region. This is because the cross section is relevant to $g_v^2 + g_a^2$ where $g_v$ and $g_a$ are vector current coupling and axial current coupling, respectively. And the variation of $\sin \theta_L$ in the assumed parameter region doesn’t affect $g_v^2 + g_a^2$ apparently. So we don’t show the cross section for different value of $\sin \theta_L$ in Fig. 2.

We also plot the cross section for the associated production of $Z$ boson and $b'$ quarks in Fig. 3. The shape of the curves is similar to those shown in Fig 2. Roughly, the cross section for $ZQQ$ production is relevant to $g_v^2 + g_a^2$. For the same mass, the cross section for associated production of $Z$ boson and $b'$ quarks is larger than that for $t'$ quarks.

Now we further consider the signature of $ZQQ$ production at the LHC. The process $pp \rightarrow Zt'\bar{t}'$ followed by $t' \rightarrow Wq$ results in $ZWWqq$ states, which suffers large backgrounds from top pair relevant events and gauge bosons events. For process $pp \rightarrow Zb'b'$ with $b'$ decaying to $Z$ and $b$, if one $Z$ decays to neutrinos and another $Z$ decays to charge leptons, the signal will buried by large $t\bar{t}$ background or $ttZ$ background. If all the $Z$ bosons decay to hadrons, the signal also suffers large top pair background and it is hard to trigger at the LHC. So, we concentrate on the $6l + 2j$ signal for $Zb'b'$ production followed by $b' \rightarrow bZ$ where all the $Z$ bosons decay to charge leptons ($e$ or $\mu$). Although the branching ratio (BR) of $Z \rightarrow l^+l^-$ is smaller than the BRs for neutrino decay mode and hadronic decay mode, the charged leptons can provide efficient trigger and are easily identified at hadron collider. The process $ZZZjj$ with all $Z$ bosons decaying leptonically results in $6l + 2j$ final

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2 If using $b$ tagging, the $6l+2b$ signal are suppressed by $b$ tagging efficiency. Roughly, one $b$ tagging efficiency is $\epsilon \sim 50\% - 60\%$ at the LHC [19].
states. However, the cross section for $ZZZjj$ is too tiny and can be neglected. So there is nearly no background for the $6l + 2j$ signal.

FIG. 2: Cross section for $t^\prime \bar{t}^\prime Z$ production as a function of mass parameter $m_{Q}$. (solid line for sequential $t^\prime$ and dash line for vector-like $t^\prime$)

Taking a typical mass of sequential $b^\prime$, $m_{Q} = 250$ GeV, and assuming the branching ratio $BR(b^\prime \rightarrow bZ) = 50\%$, we discuss further detecting probability of the signal. We present

FIG. 3: Cross section for $b^\prime \bar{b}^\prime Z$ production as a function of mass parameter $m_{Q}$. (solid line for sequential $b^\prime$ and dash line for vector-like $b^\prime$)
the pseudorapidity distribution and transverse momentum distribution of $b$ quark for signal events in Fig. 5 and Fig 6, respectively. The kinetic distributions of $\bar{b}$ are the same as those of $b$. As shown in Fig. 5, the $b$ quarks from $b'$ decay are produced centrally and tend to reside at high $P_T$ (peaks at $\sim 90$ GeV). The leptons from $Z$ bosons decay hold similar features. We also employ below cuts to simulate detector acceptance. Detector cuts:

\[ P_T(l) > 15 GeV, \ P_T(j) > 20 GeV, \ |\eta_j| < 5, \ |\eta_l| < 5, \ \Delta R(j, j) > 0.4, \ \Delta R(l, j) > 0.4. \]

FIG. 4: The pseudorapidity distribution of $b$ quark for process $pp \rightarrow Zb'\bar{b}' \rightarrow ZbZ\bar{b}Z$ at the LHC.

FIG. 5: The transverse momentum distribution of $b$ quark for process $pp \rightarrow Zb'\bar{b}' \rightarrow ZbZ\bar{b}Z$ at the LHC.

Because the BR of $Z \rightarrow l^+l^-$ ($l^- = e, \mu$) is small, the cross section of the signal is suppressed. After including detector acceptance, the signal events are rare. We give the...
cross section and event number for the signal in Table II. It is found that only 8 signal events (parton level) can be produced in the case we considered with 1000 fb$^{-1}$ integrated luminosity corresponding to ten years data collection of LHC at high luminosity $L = 10^{34} \text{cm}^{-2}\text{s}^{-1}$.

Although the signal events are rare, all the final states are produced centrally and multilepton final states are clear at hadron collider, which could be easily detected. For larger $m_Q$ and smaller $BR(b' \rightarrow bZ)$, it is not hopeful to detect the $6l + 2j$ signal for process $pp \rightarrow Zb'b'$. Further research is needed for other signal for process $pp \rightarrow ZQQ$.

IV. CONCLUSION

In this paper, we have considered the associated production of $Z$ boson and a pair of new heavy quarks ($pp \rightarrow ZQQ$) at the LHC with $\sqrt{s} = 14$ TeV. The cross sections for both sequential fermions ($t'_4$ and $b'_4$) and vector-like fermions ($t'_v$ and $b'_v$) are presented. For sequential fermions the cross sections can reach $1 \sim 10^2$ fb for heavy quark with mass $m_Q$ from 1000 GeV to 200 GeV. In the case of vector-like quarks, the cross sections are suppressed by mixing parameter $sinL$. Focusing on process $pp \rightarrow b'b'$, we investigate the detecting possibility for the $6l + 2j$ signal. With 1000 fb$^{-1}$ integrated luminosity corresponding to ten years run of LHC at high luminosity, only 8 signal events (parton level) can be produced in the case we considered ($m_Q = 250$ GeV and $BR(b' \rightarrow bZ) = 50\%$). Although the signal events are rare, all the final states are produced centrally and multilepton final states are
clear at hadron collider, which could be easily detected. And only a very narrow parameter space could be hopeful to detect the $6l + 2j$ signal for process $pp \rightarrow Zb\bar{b}'$. For other signal for process $pp \rightarrow ZQQ$, further research is needed.

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