Direct search for heavy gauge bosons at the LHC in the nonuniversal SU(2) model

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We study the phenomenology of heavy gauge bosons at the LHC in a nonuniversal gauge interaction model with the separate electroweak SU(2) gauge group for the third generation. Considered are the Drell-Yan processes into the final states of dilepton, dijet, $\tau^-\tau^+$, and $t\bar{t}$ for $Z'$ boson and those of lepton-neutrino for $W'$ boson. We find that the present LHC data provides lower bounds on the masses of the heavy gauge bosons, $m_{Z'}$, $m_{W'} > 2$ TeV, more stringent than indirect bounds, when $\sin^2\phi > 0.15$ for the mixing angle of two SU(2) gauge groups. We also note that the study of heavy resonances into the third generation fermions may provide some valuable information in the future.

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I. INTRODUCTION

The CERN Large Hadron Collider (LHC) has successfully completed the first stage of running with the discovery of a standard model (SM)-like Higgs boson. Still there is no evidence for the new physics beyond the SM at the LHC so far. We have to wait till the next stage of the LHC in order to find new results. However, we can read out valuable informations on the new physics scales from the present data. One of the most promising signal of new physics beyond the SM is the heavy resonances decaying into a pair of the SM particles. The CMS [1,5] and ATLAS [6–10] collaborations has reported the search results for the extra gauge bosons, $W'$ and $Z'$, with the data collected at the LHC in 2011 and in 2012. Recent search results at the LHC shows the absence of heavy mass resonances and present strong bounds on $m_{W'}$ and $m_{Z'}$ more than 2 TeV.

Many new physics models in the context of the gauge unification contain extended gauge symmetry and predict the existence of extra neutral and/or charged gauge bosons with heavy masses. It is very important to search for the extra gauge bosons directly and to study their phenomenology at the LHC in detail [11]. In this paper, we consider an extended model for the electroweak gauge group. The SM assumes the universality of the electroweak symmetry on all the fermion generations. If a separate SU(2) symmetry acts on the third generation, the nonuniversal nature of the electroweak symmetry as well as the additional gauge bosons presents various interesting phenomenology [12,13]. Such a gauge group might be vestiges of the family symmetry or a symmetry at an intermediate stage in the path of symmetry breaking of noncommuting extended technicolor models [14]. We assign the left-handed quarks and leptons for the first and second generations $(2, 1, 1/3), (2, 1, -1)$ and those for the third generation $(1, 2, 1/3), (1, 2, -1)$ under SU(2)$_l$×SU(2)$_h$×U(1)$_Y$. In the same manner the right-handed quarks and leptons transform as $(1, 1, 2Q)$ with the electric charge $Q = T_3 + T_3^3 + Y/2$. The separate SU(2) is mixed with the ordinary SU(2) in general and should be broken to the SM gauge group at a high energy scale $u$. It can be achieved by introducing an bidoublet scalar field $\Sigma$ $(2, 2, 0)$ with the vacuum expectation values (VEV) $\langle \Sigma \rangle = \text{Diag}(u, u)$. The electroweak symmetry breaking is performed by an additional scalar field at the scale $v$. The detailed discussion of the Higgs sector in this model can be found in Ref. [15]. The phenomenology of this model has been studied using the low-energy data [12,13,16,17]. The nonuniversality of this model derives the exotic flavor-violating terms in both neutral and charged current interactions. They give rise to the lepton flavor violations and the violation of unitarity of the CKM matrix, which lead to strong constraints on the model parameters [18,19].

Being introduced an additional SU(2) gauge symmetry, extra charged and neutral gauge bosons $W'$ and $Z'$ with heavy masses exist in this model. In this study, we study the phenomenology of $W'$ and $Z'$ with the data collected at the first run of the LHC. The direct bound on the $W'$ boson mass has been obtained from the early data of the LHC in the ref. [20]. Here we update the $W'$ data and perform the new analyses on the various channels of $Z'$ boson.

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The $W'$ and $Z'$ decays will be considered through the Drell-Yan mechanism which is the $s$–channel process mediated by $W'$ or $Z'$ into the fermion pairs. We obtain direct lower bounds on the $W'$ and $Z'$ masses and constraint on the mixing angle between two SU(2) groups from the lack of the signal of heavy gauge boson at the LHC. In the next section, we will briefly review the model and discuss the phenomenology of the heavy gauge bosons. The analysis of the LHC results in this model is presented in section III. Finally we conclude.

II. PHENOMENOLOGY OF HEAVY GAUGE BOSONS IN THE NONUNIVERSAL SU(2) MODEL

After the gauge symmetry in this model is broken to the SM gauge group and sequentially to the U(1) and SU(2)$_L$ and SU(2)$_H$. In this analysis, we assume the perturbativity of all of the gauge couplings, $g^2(1, 2)/4\pi < 1$, which is corresponding to $0.03 < \sin^2 \phi < 0.96$.

For simplicity of the analysis, we introduce a small parameter $\lambda \equiv v^2/u^2$. We define the physical state of gauge bosons $W'$ by

$$\left( \begin{array}{c} W^\pm_{\mu} \\ W'^\pm_{\mu} \end{array} \right) = \left( \begin{array}{cc} 1 & \lambda \sin^3 \phi \cos \phi \\ -\lambda \sin^3 \phi \cos \phi & 1 \end{array} \right) \left( \begin{array}{cc} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{array} \right) \left( \begin{array}{c} W^\pm_{\mu} \\ W'^\pm_{\mu} \end{array} \right),$$

and those of $Z'$ by

$$\left( \begin{array}{c} Z_{\mu} \\ Z'^{\mu}_{\mu} \\ A_{\mu} \end{array} \right) = \left( \begin{array}{ccc} 1 & \lambda \sin^3 \phi \cos \phi & 0 \\ -\lambda \sin^3 \phi \cos \phi & 1 & 0 \\ 0 & 0 & 1 \end{array} \right) \left( \begin{array}{ccc} \cos \phi & \cos \phi & \sin \phi \\ \sin \phi & \cos \phi & \cos \phi \\ \cos \phi & \sin \phi & \cos \phi \end{array} \right) \left( \begin{array}{c} W^3_{\mu} \\ W'^3_{\mu} \\ B_{\mu} \end{array} \right),$$

in the leading order of $\lambda$. Their masses are given by

$$m^2_{W'} = m^2_{Z'} = m^2_0 \frac{1}{\lambda \sin^2 \phi \cos^2 \phi} (1 + O(\lambda)),$$

where $m_0 = ev/(2 \sin \theta)$ is the ordinary $W$ boson mass at tree level. We note that the $W'$ and $Z'$ masses are degenerate in this model.

Two independent parameters $(\lambda, \sin^2 \phi)$ are introduced to describe the new physics effects in this model. We keep the linear order of the small parameter $\lambda$ in this paper. Presenting the results of phenomenological analyses, we will use the observable quantity $m_{Z'} (= m_{W'})$ instead of $\lambda$ as a model parameter.

We derive the neutral current interaction for $Z'$ boson such that

$$\mathcal{L}_{NC} = G'_{\mu} \tilde{f}_L \gamma_\mu Z'^{\mu} f_L + G'_{\mu} \tilde{f}_R \gamma_\mu Z'^{\mu} f_L + X'_{L} \tilde{f}_L \gamma_\mu Z'^{\mu} f_L,$$

where

$$G'_{L} = \frac{e}{\sin \theta} \tan \phi (T_{3L} + T_{3b}) + O(\lambda),$$

$$G'_{R} = O(\lambda),$$

$$X'_{L} = -\frac{e}{\sin \theta \sin \phi \cos \phi} T_{3b} + O(\lambda).$$

Note that $G'_{L}$ and $G'_{R}$ are universal couplings and $X'_{L}$ are the couplings only for the third generations. The charged current interactions for $W'$ boson are also given by

$$\mathcal{L}_{CC} = V_{UD} \bar{U}_L \gamma_\mu H'_{L} W'^{\mu} D_L + V_{UD} \bar{U}_L \gamma_\mu Y'_{L} W'^{\mu} D_L + \text{H. c.},$$

for quarks where $U_L = (u_L, c_L, t_L)^T$, $D_L = (d_L, s_L, b_L)^T$ and

$$H'_{L} = \frac{g}{\sqrt{2}} \tan \phi,$$

$$Y'_{L} = \frac{g}{\sqrt{2}} \sin 2 \phi \cos \phi \hat{Y}_3, \quad (8)$$
where $\hat{Y}_3$ is a $3 \times 3$ matrix with elements $\delta_{ij} \delta_{33}$. We note that the CKM matrix is also shifted by $\mathcal{O}(\lambda)$ terms, which is severely constrained by the precise test of the CKM matrix unitarity \cite{18}. We let the matrix elements $V_{UD}$ to be the SM values in this work to keep the decay rates in the leading order.

We obtain the decay rates of $Z'$ and $W'$ bosons from the replacements of the ordinary couplings and masses by those of heavy gauge bosons in the SM decay rates of $Z$ and $W$ boson. We have

$$\Gamma(Z' \to f \bar{f}) = \frac{\Gamma_0^{Z'}}{m_Z} m_{Z'} \tan^2 \phi,$$

$$\Gamma(W' \to f \bar{f}') = \frac{\Gamma_0^{W'}}{m_W} m_{W'} \tan^2 \phi,$$

for the first and second generations and

$$\Gamma(Z' \to f \bar{f}) = \frac{\Gamma_0^{Z'}}{m_Z} m_{Z'} \tan^2 \phi \left(1 - \frac{1}{\sin^2 \phi}\right)^2,$$

$$\Gamma(W' \to f \bar{f}') = \frac{\Gamma_0^{W'}}{m_W} m_{W'} \tan^2 \phi \left(1 - \frac{1}{\sin^2 \phi}\right)^2,$$

for the third generation fermions where $\Gamma_0^{Z'}$ and $\Gamma_0^{W'}$ are corresponding $Z$ and $W$ decay rates into the same final states in the SM. You can see that even the top quark mass effects show just a very small splitting. Thus final state masses are ignored in this analysis.

Note that the triple gauge boson couplings involving $W'$ and $Z'$ arise in this model and $W'$ and $Z'$ can decay into a pair of gauge bosons through the triple gauge couplings. Generically their decay rates are suppressed by small mixing angles. Although the decays of the longitudinal modes of $W'$ and $Z'$ might becomes sizable by compensation of the factor of order $m_{W'}/m_W^4$, the branching ratio of $W_L' \to W_L Z_L$ is smaller than that of $W' \to e \nu$ by a numerical factor $\cos^4 \theta_W/4$ and just less than 2%. Moreover no direct search results are given for those channel yet and we do not involve the processes with the gauge boson final states in our analysis.

The branching ratios of $Z'$ and $W'$ boson are depicted in Fig. 1. They do not depend on the heavy gauge boson masses but only on $\phi$ when the final state masses are ignored. Only the $Z' \to t\bar{t}$ and $W' \to tb$ decays show a small splitting depending on $Z'$ and $W'$ masses due to the top quark mass effects. The decays into the third generation fermions dominate in the small $\phi$ region, while those rates are small in the large $\sin^2 \phi$ region. It is because $W'$ and $Z'$ bosons are almost $W_L$ and $W_3^L$ bosons in the small $\phi$ region and coupled to the third generations dominantly. When $\sin^2 \phi \to 1$, $W'$ and $Z'$ mostly consist of $W_L$ and $W_3^L$, respectively to decay into the first and second generations.

FIG. 1: Branching ratios of the $Z'$ and $W'$ boson with respect to $\sin^2 \phi$. 

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FIG. 2: The thick lines denote the upper limits on the production cross section times branching ratios into various final states for $Z'$ boson. Above regions are excluded by the absence of the heavy resonance signatures. The thin lines denote the theory predictions in this model. The top-left panel is for dilepton final states, the top-right for dijets, the middle panels for $t\bar{t}$, and the bottom panels for $\tau^-\tau^+$. All plots are for the combination of the 7 and 8 TeV data sets.

### III. DIRECT SEARCH AT THE LHC

In order to find new resonances at the LHC, the most promising channels are dilepton and dijet final states for $Z'$ and lepton-neutrino channels for $W'$. Processes involving the third generation fermions final states might be important for search for the new physics models violating universality. We consider the dilepton, the dijet, $\tau^-\tau^+$, $t\bar{t}$ final states for $Z'$ searches and $e\nu/\mu\nu$ final states for $W'$ searches. The CMS and the ATLAS groups have measured the upper limit on the production cross section times branching ratios for each channel. The thick lines of Fig. 2 and 3 denote the experimental limits from the data collected by the CMS and ATLAS collaborations in 2012 and in 2013 in part. We calculate the production cross sections for $Z'$ and $W'$ gauge bosons by using PYTHIA 6.4 [21]. The theoretical predictions of the cross sections times branching ratios are shown as thin lines in Fig. 2 and 3 together with the experimental limits from the LHC data. Each thin lines of the top panel in Fig. 2 denote the predictions with $\sin^2\theta = 0.1$ to 0.9 from the bottom to top. For the middle and bottom panels in Fig. 2, the thin lines denote
FIG. 3: Cross sections times branching ratios into lepton-neutrinos for $W'$ boson together with the updated experimental upper limits from the combined data at 7 and 8 TeV.

the predictions of $\sin^2 \phi = 0.1$ to 0.4 from the bottom to top for the left panels and of $\sin^2 \phi = 0.5$ to 0.9 from the top to bottom for the right panels. The middle and bottom panels are for the processes including the third generation fermions and the production and decay processes show reverse behaviors with respect to $\sin^2 \phi$. Thus their product has the maximum at $\sin^2 \phi = 0.5$ around. Figure 3 depicts the updated analysis of Ref. [20] on direct $W'$ search with the recent CMS and ATLAS data sets. Since the regions above the thick lines are excluded at 95% C.L., we determine the direct lower bounds on the $W'$ and $Z'$ masses with respect to $\sin^2 \phi$ for each channel.

We present the direct search limits on $m_{Z'}$ and $m_{W'}$ together with indirect limits of the previous analysis. Indirect studies of this model consists on search for new physics signals in the neutral current interactions including the LEP and SLC data and the atomic parity violation (APV) [12, 13, 17] and search for non-SM signatures due to nonuniversality of the SU(2) gauge interactions [18, 19]. The nonuniversality provides the stronger constraints on the model than the neutral current interactions data. We see the direct search limits of lepton final states give the most stringent bounds except for very small $\sin \phi$ region in Fig. 4. As discussed above, the decays into the third generation fermions are dominant in the small $\phi$ region, We note that the limit from $Z' \to \tau^- \tau^+$ channel is relatively stronger in Fig. 4 and expect that this process will play an important role with more data in the future run of the LHC.

The single top productions are electroweak processes involving charged current interactions and can be affected in this model. Generically three contributions to the single top production comes through $W$, $W'$ and $H^\pm$ exchanges in this model. The Higgs sector is not explicitly specified in this work and we can set the charged Higgs boson mass to be a free parameter without loss of generality. Then we can ignore the charged Higgs boson contribution by assuming that $m_{H^\pm}$ is large enough. The $W'$ exchange contribution is a $t$-channel process, which is given by

$$\sigma(b\bar{q} \to W' \to t\bar{q}' \to t\bar{q}'') \sim \sigma(b\bar{q} \to W \to t\bar{q}') \left( \frac{g_{W'tb}}{g_{W'tb}} \right)^2 \left( \frac{g_{W'ud}}{g_{W'ud}} \right)^2 \left( \frac{t - m_W^2}{m_{W'}^2} \right)^2. \quad (11)$$

The ratio $g_{W'tb}g_{W'ud}/g_{W'tb}g_{Wud} = O(1)$. Since this process is suppressed by the heavy $W'$ mass, we do not consider the constraints from the single top production data with errors more than 10% [22].

IV. CONCLUDING REMARKS

We obtain the lower bounds on the $W'$ and $Z'$ boson masses in the nonuniversal $SU(2)_l \times SU(2)_h \times U(1)_Y$ model with the direct search data from the first stage of the LHC run. We find that the direct bounds obtained from $Z' \to l^- l^+$ and $W' \to l\nu$ are the most stringent limit on $m_{Z'}$ and $m_{W'}$ for $\sin^2 \phi > 0.15$, and the extra gauge bosons should be heavier than 2 TeV.
FIG. 4: Allowed parameters on $(\sin^2 \phi, m_{Z'}\ (m_{W'})$ space with direct and indirect constraints. Regions below the plots are excluded at 95 % C.L.. The thick lines are the direct bounds from the LHC data and the thin lines the indirect bounds.

In the small $\sin^2 \phi$ region, the couplings of $Z'$ and $W'$ bosons to the light quarks and leptons decrease and the Drell-Yan processes, $pp \rightarrow q\bar{q}' \rightarrow Z'/W' \rightarrow f\bar{f}'$ are strongly suppressed. Thus all the constraints become weak in this region. Note that the constraints from the processes involving the third generation fermions are relatively stronger as you can compare the constraints from $Z \rightarrow l^-l^+$ and $Z \rightarrow \tau^-\tau^+$ in Fig. 4. With more data for the third generation fermions, we expect better results in this region.

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