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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 the Z' boson and those of the lepton-neutrino for the W' boson. We find that the present LHC data provides the most stringent lower bounds on the masses of the heavy gauge bosons, $m_{Z'} > 1.8$ TeV for $\sin^2\phi > 0.07$ and $m_{W'} > 2$ TeV for $\sin^2\phi > 0.15$, where ϕ is the mixing angle of two SU(2) gauge groups.

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I. INTRODUCTION

The CERN 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 until the next stage of the LHC in order to find new results. However, we can read out valuable information on the new physics scales from the present data. One of the most promising signals 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 have 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 show 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 predict the existence of extra neutral and/or charged gauge bosons with heavy masses and their phenomenology at the LHC have been studied [11]. In this paper, we consider an extended model for the electroweak gauge group with a separate SU(2) symmetry acting on the third generation. The nonuniversal nature of this model 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 $\mathrm{SU}(2)_l \times \mathrm{SU}(2)_h \times U(1)_Y$. In the same manner, the right-handed quarks and leptons transform as $(1,1,2Q)$ with the electric charge $Q = T_3^l + T_3^h + Y/2$. 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 a bidoublet scalar field Σ (2,2,0) with the vacuum expectation values $\langle\Sigma\rangle = \mathrm{Diag}(u,u)$. 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 gauge interactions derives exotic flavor-violating terms in both neutral and charged current interactions. We can find much non-SM phenomenology at colliders due to the nonuniversality in the literature [18] In this model, the flavor-violating terms give rise to the lepton-flavor violations and the violation of unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which lead to strong constraints on the model parameters [19,20].

With the introduction of an additional SU(2) gauge symmetry, extra charged and neutral gauge bosons W' and Z' with heavy masses exist in this model. In this work, we study the phenomenology of W' and Z' with the data collected at the first run of the LHC. 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. The direct bound on the W' boson mass of this model has been obtained from the early data of the LHC in Ref. [21]. Here, we update the W' analysis and perform the new analyses on the various channels of the Z' boson. 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 a 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 with the LHC data is presented in Sec. III. Finally, in Sec. IV, we conclude.

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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 sequently broken to the $U(1)_{EM}$, we parametrize the gauge coupling constants as

$$g_l = \frac{e}{\sin\theta\cos\phi}, \qquad g_h = \frac{e}{\sin\theta\sin\phi}, \qquad g' = \frac{e}{\cos\theta}, \tag{1}$$

in terms of the electromagnetic coupling e, the weak mixing angle θ, and the new mixing angle ϕ between $SU(2)_l$ and $SU(2)_h$. In this analysis, we assume the perturbativity of all of the gauge couplings, $g^2_{(l,h)}/4\pi < 1$, which corresponds to $0.03 < \sin^2\phi < 0.96$.

For simplicity of the analysis, we introduce a small parameter $\lambda \equiv v^2/u^2$ and describe the new physics effects in terms of two independent parameters $(\lambda, \sin^2\phi)$. We keep the linear order of the small parameter λ in this paper. The physical state of gauge bosons W' and Z' are found in Ref. [13].

Their masses are given by

$$m^2_{W'} = m^2_{Z'} = \frac{m_0^2}{\lambda\sin^2\phi\cos^2\phi}(1 + \mathcal{O}(\lambda)), \tag{2}$$

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.

Presenting the results of phenomenological analyses, we will use the observable quantity $m_{Z'}(= m_{W'})$ instead of λ as a model parameter.

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

$$\mathcal{L}_{NC} = G'_L \bar{f}_L\gamma_\mu Z'^\mu f_L + G'_R \bar{f}_R\gamma_\mu Z'^\mu f_R + X'_L \bar{f}_L\gamma_\mu Z'^\mu f_L, \tag{3}$$

where

$$\begin{aligned} G'_L &= \frac{e}{\sin\theta}\tan\phi(T_{3l} + T_{3h}) + \mathcal{O}(\lambda), \\ G'_R &= \mathcal{O}(\lambda), \\ X'_L &= -\frac{e}{\sin\theta}\frac{1}{\sin\phi\cos\phi}T_{3h} + \mathcal{O}(\lambda). \end{aligned} \tag{4}$$

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 the W' boson are also given by

$$\mathcal{L}_{CC} = V_{UD}\bar{U}_L\gamma_\mu H'_L W'^\mu D_L + V_{UD}\bar{U}_L\gamma_\mu Y'_L W'^\mu D_L + \text{H.c.}, \tag{5}$$

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

$$\begin{aligned} H'_L &= -\frac{g}{\sqrt{2}}\tan\phi, \\ Y'_L &= -\frac{g}{\sqrt{2}}\frac{1}{\sin 2\phi\cos\phi}\hat{Y}_3, \end{aligned} \tag{6}$$

where $\hat{Y}_3$ is a 3×3 matrix with elements $\delta_{i3}\delta_{j3}$. 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 [19]. We let the matrix elements V_{UD} be the SM values in this work to keep the decay rates in the leading order.

We obtain the decay rates of the 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 the Z and W bosons. We have

$$\Gamma(V' \to f\bar{f})_{1,2} = \Gamma_0^V \frac{m_{V'}}{m_V}\cdot\tan^2\phi \tag{7}$$

for the first and second generation fermions, where $V = Z, W$ and

$$\Gamma(V' \to f\bar{f})_3 = \Gamma(V' \to f\bar{f}')_{1,2}\left(1 - \frac{1}{\sin^2\phi}\right)^2 \tag{8}$$

for the third-generation fermions, where Γ_0^Z and Γ_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.

The triple gauge boson couplings $W'WZ$ and WWZ' arise in this model and W' and Z' can decay into a pair of gauge bosons. The decays of the longitudinal modes of W' and Z', $W'_L \to W_L Z_L$, are suppressed by the $W'W$ and $Z'Z$ mixings but enhanced by $m_{W'}$ and $m_{Z'}$, of which branching ratio is smaller than that of $W' \to e\nu$ by a numerical factor $\cos^4\theta_W/4$ and just less than 2% as shown in Fig. 1. Decays into final states involving the SM-like neutral Higgs boson, Wh and Zh, also exist through $W'Wh$ and $Z'Zh$ couplings in this model. They might becomes sizable by enhancement due to $m_{W'}$ and $m_{Z'}$ as the longitudinal mode decays. However, $W'Wh$ and $Z'Zh$ couplings are additionally suppressed by the neutral Higgs sector mixing angles which are undetermined yet. Thus we assume they are small enough to be ignored without loss of generality and we do not include the processes with Wh and Zh final states in our analysis.

The branching ratios of the Z' and W' bosons are depicted in Fig. 1. They do not depend on the heavy gauge boson masses but only on ϕ 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 ϕ region, while those rates are small in the large $\sin^2\phi$ region. It is because W' and Z' bosons are almost W_h and W_h^3 bosons in the small ϕ region and couple to the third generations dominantly. When

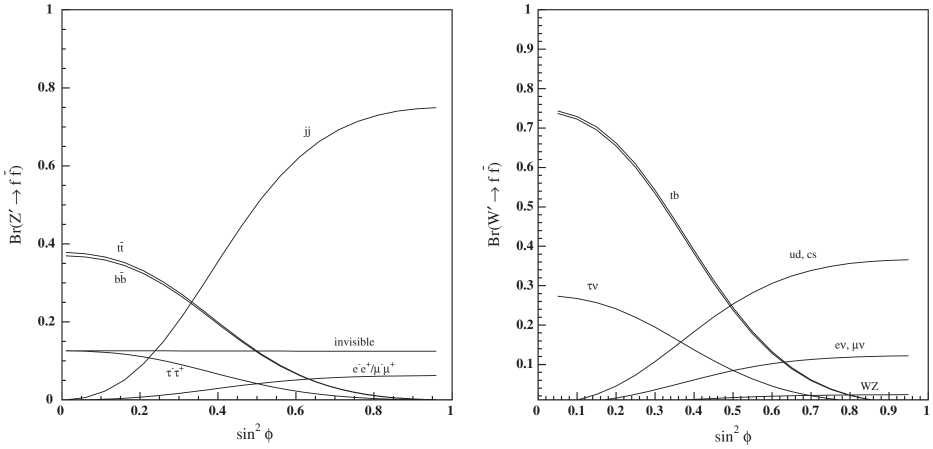

FIG. 1. Branching ratios of the Z' and W' bosons with respect to $\sin^2\phi$.

$\sin^2\phi \to 1$, W' and Z' mostly consist of W_l and W_l^3, respectively, to decay into the first and second generations.

III. DIRECT SEARCH AT THE LHC

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'. 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 Figs. 2 and 3 denote the experimental limits from the data collected by the CMS and ATLAS

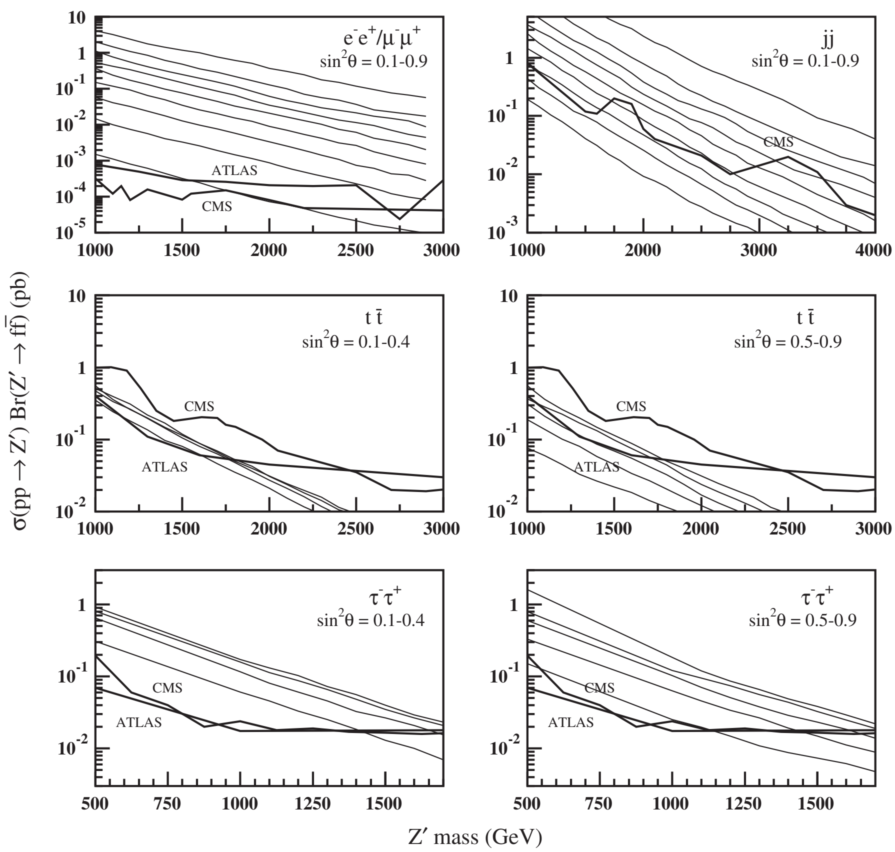

FIG. 2. The thick lines denote the upper limits on the production cross section times branching ratios into various final states for the Z' boson. The above regions are excluded by the absence of the heavy resonance signatures. The thin lines denote the theory predictions in this model. The top-left panel is for dilepton final states [1,6], the top-right for dijets [2,7], the middle panels for $t\bar{t}$ [3,8], and the bottom panels for $\tau^-\tau^+$ [4,9].

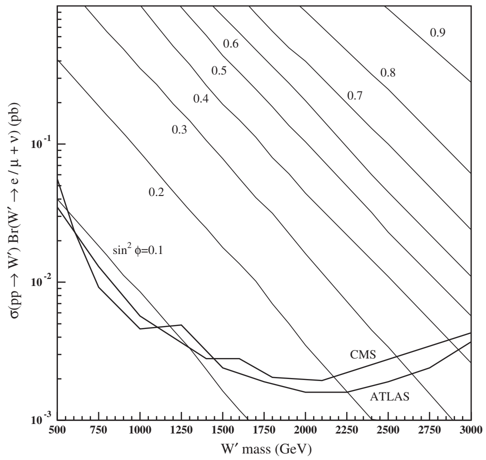

FIG. 3. Cross sections times branching ratios into lepton-neutrinos for the W' boson together with the updated experimental upper limits from the combined data at 7 and 8 TeV.

collaborations in 2012 and in 2013 in part. We obtain the production cross sections for Z' and W' gauge bosons with PYTHIA 6.4 [22]. The cross sections are calculated with the default values of PYTHIA that include the leading-order parton distribution function and the next-leading-order parton showers. The theoretical predictions of the cross sections times branching ratios are shown as thin lines in Figs. 2 and 3 together with the experimental limits from the LHC data. Each thin line of the top panel in Fig. 2 denotes the predictions with $\sin^2\phi = 0.1$ to 0.9 from the bottom to the top. For the middle and bottom panels in Fig. 2, the thin lines denote the predictions of $\sin^2\phi = 0.1$ to 0.4 from the bottom to the 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 $\sin^2\phi \sim 0.5$.

Figure 3 depicts the updated analysis of Ref. [21] on the 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. The K-factor from the order α_s correction may enhance the cross sections up to $\mathcal{O}(10)\%$ [23] and the lower bounds of Z' and W' masses might be changed by 100 or 200 GeV. But they do not cause significant modification in the Fig. 4.

We present the direct search limits on $m_{Z'}$ and $m_{W'}$ together with indirect limits of the previous analysis in Fig. 4. Indirect studies of this model have been performed with the search for new physics signals in the electroweak precision test by the large electron positron collider (LEP) and SLAC linear collider (SLC) data and the atomic parity violation data [12,13,17], in the unitarity test of the CKM matrix [19] and in the lepton-flavor violation [20]. The nonuniversality of the SU(2) gauge interactions leads to the lepton-flavor violation with the neutral currents interaction and the unitarity violation of the CKM matrix for quark mixings. The search for non-SM signatures due to nonuniversality provides the stronger constraints on the model than the electroweak precision data. We see the direct search limits of lepton final states at the LHC give the most stringent bounds except for a very small $\sin\phi$ region in Fig. 4. Since decays into the third-generation fermions are dominant in the small ϕ region as discussed above, the limit from the $Z' \to \tau^-\tau^+$ channel is relatively stronger in Fig. 4, and we expect that this process will play an important role with more data in the future run of the LHC. Since the gauge couplings are nonperturbative at $\sin^2\phi < 0.03$ and $0.96 < \sin^2\phi$, no constraints are given in these regions.

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 come through W, W', and $H^\pm$ exchanges in this model. The s-channel process into tb with the heavy

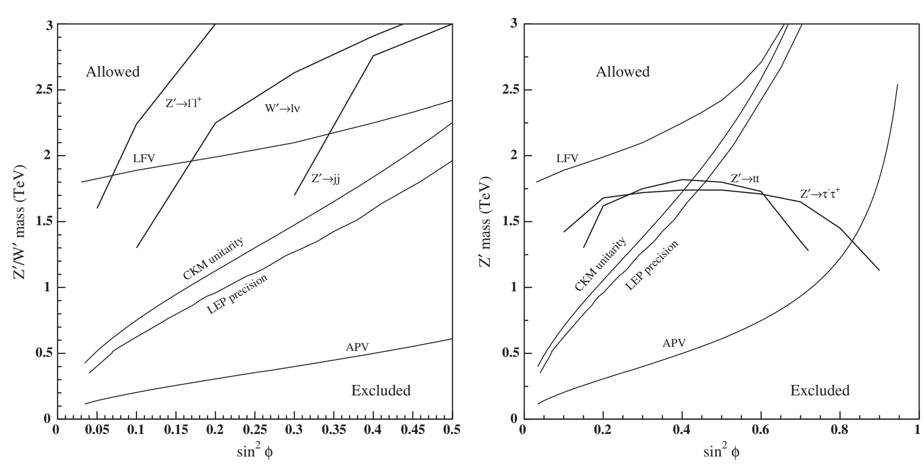

FIG. 4. Allowed parameters on $[\sin^2\phi, m_{Z'}(m_{W'})]$ space with direct and indirect constraints. Regions below the plots are excluded at 95% C.L. The thick lines are the direct bounds from the LHC data, and the thin lines are the indirect bounds.

resonance is the dominant process of W' production and is considered as shown in Fig. 1. The s channel other than tb final states is suppressed by the CKM matrix elements and is neglected here. The W' exchange contribution to the t-channel processes is suppressed by the heavy W' mass. The Higgs sector is not explicitly specified in this work, and we can ignore the charged Higgs boson exchange contributions by assuming that $m_{H^\pm}$ is large enough. Thus, we do not consider the constraints from the single top production data with errors more than 10% [24].

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 $Z' \to l^- l^+$ are the most stringent limit on $m_{Z'}$ in most regions of $\sin^2\phi$ and $W' \to l\nu$ gives the strongest bounds on $m_{W'}$ for $\sin^2\phi > 0.15$. We see that the extra gauge bosons should be heavier than 1.8 TeV for $\sin^2\phi > 0.07$.

In the small $\sin^2\phi$ region, the Drell-Yan processes into light fermions are strongly suppressed due to decreasing couplings of Z' and W' bosons, and all the constraints become weak. On the other hand, the constraints from the processes involving the third-generation fermions are relatively stronger as you can compare the constraints from $Z \to l^- l^+$ and $Z \to \tau^- \tau^+$ in Fig. 4. With more data for the third-generation fermions, therefore, we expect better results in this region.

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[1] CMS Collaboration, EPJ Web Conf. **60**, 17013 (2013).
[2] CMS Collaboration, Phys. Rev. D **87**, 114015 (2013).
[3] CMS Collaboration, J. High Energy Phys. 09 (2012), 029.
[4] CMS Collaboration, Phys. Lett. B **716**, 82 (2012).
[5] CMS Collaboration, J. High Energy Phys. 08 (2012), 023.
[6] ATLAS Collaboration, Phys. Rev. D **90**, 052005 (2014).
[7] ATLAS Collaboration, J. High Energy Phys. 05 (2014), 059.
[8] ATLAS Collaboration, Phys. Rev. D **88**, 012004 (2013).
[9] ATLAS Collaboration, Phys. Lett. B **719**, 242 (2013).
[10] ATLAS Collaboration, Eur. Phys. J. C **72**, 2241 (2012).
[11] T. Jezo, M. Klasen, and I. Schienbein, Phys. Rev. D **86**, 035005 (2012); E. Accomando, D. Becciolini, S. De Curtis, D. Dominici, L. Fedeli, and C. Shepherd-Themistocleous, Phys. Rev. D **85**, 115017 (2012); M. Schmaltz and C. Spethmann, J. High Energy Phys. 07 (2011), 046; J. de Blas, J. M. Lizana, and M. Perez-Victoria, J. High Energy Phys. 01 (2013), 166; R. S. Chivukula, P. Ittisamai, and E. H. Simmons, arXiv:1406.2003; G. Arcadi, Y. Mambrini, M. H. G. Tytgat, and B. Zaldivar, J. High Energy Phys. 03 (2014), 134.
[12] E. Malkawi, T. Tait, and C.-P. Yuan, Phys. Lett. B **385**, 304 (1996); D. J. Muller and S. Nandi, Phys. Lett. B **383**, 345 (1996).
[13] J. C. Lee, K. Y. Lee, and J. K. Kim, Phys. Lett. B **424**, 133 (1998).
[14] R. S. Chivukula, E. H. Simmons, and J. Terning, Phys. Lett. B **331**, 383 (1994); Phys. Rev. D **53**, 5258 (1996).
[15] C.-W. Chiang, N. G. Deshpande, X.-G. He, and J. Jiang, Phys. Rev. D **81**, 015006 (2010).
[16] K. Y. Lee and J. C. Lee, Phys. Rev. D **58**, 115001 (1998).
[17] E. Malkawi and C.-P. Yuan, Phys. Rev. D **61**, 015007 (1999).
[18] I. Ahmed, Phys. Rev. D **89**, 014017 (2014); C.-W. Chiang, T. Nomura, and J. Tandean, Phys. Rev. D **87**, 075020 (2013); B. H. Li, C. S. Li, H. T. Li, Y. C. Zhan, Y. Zhang, and J. Wang, Phys. Rev. D **86**, 114027 (2012); J. L. Nisperuza and L. A. Sanchez, Phys. Rev. D **80**, 035003 (2009).
[19] K. Y. Lee, Phys. Rev. D **76**, 117702 (2007); **78**, 039904(E) (2008); **71**, 115008 (2005).
[20] K. Y. Lee, Phys. Rev. D **82**, 097701 (2010).
[21] Y. G. Kim and K. Y. Lee, Phys. Lett. B **706**, 367 (2012).
[22] T. Sjostrand, S. Mrenna, and P. Z. Skands, J. High Energy Phys. 05 (2006), 026.
[23] R. Hamberg, W. L. van Neerven, and T. Matsuura, Nucl. Phys. **B359**, 343 (1991); **B644**, 403(E) (2002).
[24] ATLAS and CMS Collaboration, Report No. CMS-PAS-TOP-12-002, Report No. ATLAS-COM-CONF-2013-061, Report No. ATLAS-CONF-2013-098; T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **103**, 092002 (2009); Phys. Rev. D **82**, 112005 (2010); V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **103**, 092001 (2009); arXiv:1105.2788.