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LHT model and Higgs boson production in association with a weak gauge boson at the LHC *

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Abstract Considering the process $pp \to VH+X (V=W \text{ or } Z)$ is a significant channel for searching for a light Higgs boson, we calculate the contributions of the littlest Higgs model with T-parity (called LHT model) to its production cross section. We find that, in most of the parameter space, the value of the relative correction parameter R is very small. However, with reasonable values of the free parameters, its value can be significantly larger.

Key words LHT model, light Higgs boson, production cross section

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1 Introduction

The Standard Model (SM) of particle physics is in agreement with most of the experimental measurements so far. However, the mechanism of electroweak symmetry breaking (EWSB) —— the Higgs mechanism, which is central to the SM, has not been tested yet. The discovery of the Higgs boson would provide experimental evidence of the Higgs mechanism. One of the primary goals of the Large Hadron Collider (LHC) at CERN is a thorough investigation of the EWSB mechanism, more specifically, the discovery of one or more Higgs bosons and the determination of their properties.

The Higgs boson has not been discovered yet. There are experimental bounds on its mass. A lower limit $m_H > 114.4$ GeV at 95% confidence level (C. L.) was put on the Higgs mass by the non-observation of the so-called "Higgs-strahlung" process $e^+e^- \to HZ$ at the LEP [1]. On the other hand, precision fits of electroweak observables, including data from the LEP and Tevatron colliders, provide an indirect estimation of the Higgs mass [2]. The latest fit results give $m_H = 84^{+34}_{-26}$ GeV or $m_H < 154$ GeV at 95% C. L. A very recent analysis, using a new fitting program, gives the more precise value $m_H = 116.4^{+18.3}_{-1.3}$ GeV [3].

At hadron colliders, the Higgs boson can be produced via four different production mechanisms [4]. The first production channel is the gluon-gluon fusion process $gg \to H$ mediated by the heavy quark loops. The second production channel is mediated by weak boson fusion, involving two forward jets with transverse momentum around $m_W/2$. The third production mechanism is Higgs boson production in association with top quarks, in which the Higgs boson is radiated off one of the two tops in the $q\bar{q}$, gg s-channel or off the top propagator in the qg t-channel at leading order (LO). Production of the Higgs boson H associated with a weak gauge boson W or Z is the fourth production mechanism for the Higgs boson, which proceeds via the partonic processes $qq \to W/ZH$ and $gg \to ZH$. At the LHC, mainly because of the large gluon luminosity, Higgs boson production is dominated by the first mechanism, followed by vector boson fusion. The associated WH, ZH and $t\bar{t}H$ production processes are significant channels for the search for a light Higgs boson.

Being large backgrounds, the WH and ZH production channels are generally considered less promising for the Higgs boson search at the LHC. However, Ref. [5] has recently shown that, at high transverse momentum, employing state-of-the-art jet reconstruc-

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tion and decomposition techniques, these two production channels can be recovered as promising search channels for the Higgs boson around 120 GeV in mass. Furthermore, these two production processes also provide unique information about the couplings of a light Higgs boson separately to W and Z bosons. The scale dependence of their production cross sections is very small, which makes these two processes the theoretically cleanest ones of all Higgs production processes [6]. Considering these factors and current electroweak fits favour a light Higgs boson (about 120 GeV) [7], in this paper, we will investigate these two processes in the context of the smallest Higgs model with T-parity (called LHT model) [8]. We expect this to be helpful in the search for a light Higgs boson at the LHC and for testing the LHT model.

After briefly reviewing the essential features of the LHT model, we will calculate its contributions to the production of Higgs boson H associated with a weak gauge boson W or Z at the LHC in the next section. Our conclusions are given in the last section.

2 The LHT model and production of the Higgs boson H associated with a weak gauge boson W or Z at the LHC

At leading order, the production of Higgs boson H in association with a weak gauge boson proceeds through a $q\bar{q}'$ annihilation process $q\bar{q}' \to V \to V+H$ ($V=W,Z$) at hadron colliders [9]. The next-to-leading order (NLO) QCD corrections coincide with those for the Drell-Yan process and increase the cross section by about 30% [10], which has been calculated at NNLO, giving a further enhancement of the cross section by about 5%–10% [11]. These corrections lead to a reduction in the scale dependence of the cross section from 10% at LO to 5% at NLO, to 2% when the NNLO result is included [6]. The $O(\alpha)$ electroweak corrections have also been derived and decrease the cross section by 5% to 10% [12]. For the ZH production channel, additional gluon-gluon fusion contributions appear at NNLO [13]. These contributions have been found to increase its production cross section at the LHC in the low mass region by about 10%. Thus these two processes can be seen as the theoretically cleanest of all Higgs production processes, which is an ideal tool for testing new physics at the coming LHC. The main aim of this section is to calculate the corrections of the LHT model to the WH and ZH production sections and to see whether its correction effects can be detected at the LHC.

The little Higgs theory [14] offers an alternative solution to the hierarchy problem of the SM, which is one of the interesting candidates of new physics. The LHT model is one of the attractive little Higgs models because it solves both the little hierarchy and the dark matter problems simultaneously [8, 15].

The LHT model is based on a $SU(5)/SO(5)$ global symmetry breaking pattern, which gives rise to fourteen Numbu-Goldstone (NG) bosons. Four of these GB bosons are eaten by the T-odd heavy gauge bosons $(B_H, Z_H, W_H^{\pm})$ associated with the gauge symmetry breaking $[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2 \to SU(2)_L \times U(1)_Y$ at the scale f. The remaining NG bosons decompose into a complex T-odd $SU(2)$ triplet Φ and a T-even doublet h considered to be the SM Higgs doublet, which is given by

$$h=\begin{pmatrix} -\mathrm{i}\dfrac{\pi^+}{\sqrt{2}} \\ \dfrac{\nu+H+\mathrm{i}\pi^0}{2} \end{pmatrix}. \tag{1}$$

Here, H is the physical Higgs boson and ν is the vacuum expectation value of the Higgs boson H in the LHT model. The NG bosons $\pi^{0,\pm}$ are absorbed by the weak gauge bosons Z and $W^{\pm}$ after EWSB. In the LHT model, the Higgs boson H is regarded as a pseudo NG boson.

To avoid severe constraints and simultaneously implement T-parity, one needs to double the SM fermion doublet spectrum [8, 15]. The T-even combination is associated with the SM $SU(2)_L$ doublet, while the T-odd combination is its T-parity partner, called the mirror fermions. Thus, in the LHT model, particles are divided into T-even and T-odd sectors under T-parity. The T-even sector consists of the SM particles (fermions, electroweak gauge bosons and a Higgs boson) and a heavy top partner T_+, while the T-odd sector contains heavy gauge bosons $(B_H, Z_H, W_H^{\pm})$, a scalar triplet Φ and the mirror fermions (U_H^i and D_H^i). At the order of ν^2/f^2, the masses of these new particles can be approximately expressed as

$$\begin{aligned} M_{B_H} &= \frac{g'f}{\sqrt{5}}\left[1-\frac{5\nu^2}{8f^2}\right], \\ M_{Z_H} &= M_{W_H} = gf\left[1-\frac{\nu^2}{8f^2}\right]; \end{aligned} \tag{2}$$

$$M_{U_H^i} \approx \sqrt{2}\kappa_i f\left(1-\frac{\nu^2}{8f^2}\right), \quad M_{D_H^i} = \sqrt{2}\kappa_i f; \tag{3}$$

$$M_{\mathrm{T}_+} = \frac{f}{\nu}\frac{m_{\mathrm{t}}}{\sqrt{x_{\mathrm{L}}(1-x_{\mathrm{L}})}}\left[1+\frac{\nu^2}{f^2}\left(\frac{1}{3}-x_{\mathrm{L}}\left(1-x_{\mathrm{L}}\right)\right)\right], \tag{4}$$

$$M_{\Phi} = \frac{\sqrt{2}m_{\mathrm{H}}}{\nu}f, \tag{5}$$

where f is the scale parameter of the gauge symmetry breaking of the LHT model. g' and g are the SM $U(1)_{\mathrm{Y}}$ and $SU(2)_{\mathrm{L}}$ gauge coupling constants, respectively. k_i are the eigenvalues of the mass matrix k and their values are generally dependent on the fermion species i. Being $f \geqslant 500$ GeV, it is clear from Eq. (3) that there is $M_{\mathrm{U}_{\mathrm{H}}^i} \approx M_{\mathrm{D}_{\mathrm{H}}^i} = M_{\mathrm{Q}}$, in which $i=1,2,3$ are the indexes of the fermion family. $x_{\mathrm{L}} = \lambda_1^2/(\lambda_1^2+\lambda_2^2)$ is the mixing parameter between the SM top quark t and the new top quark T_+, in which λ_1 and λ_2 are the Yukawa coupling parameters.

Compared with the VH associated production process $\mathrm{pp} \to \mathrm{VH+X(V=W,Z)}$ in the SM, this process in the LHT model receives additional contributions from new gauge bosons and new fermions. The Feynmen diagrams for the relevant partonic processes are depicted in Fig. 1 and Fig. 2. From Refs. [15–17], one can see that the Z axial-vector coupling to the T-odd quarks is equal to zero and the Higgs boson H cannot couple to the T-odd down-type quarks $\mathrm{D}_{\mathrm{H}}^i$. Thus, there is only the T-even heavy top quark T_+, which can contribute the partonic process $\mathrm{gg} \to \mathrm{ZH}$. The T-odd scalar triplet Φ can only contribute to this decay process at the order higher than ν^2/f^2. As numerical estimation, we will neglect its contributions. So the relevant Feynman diagrams have not been shown in Fig. 1 and Fig. 2.

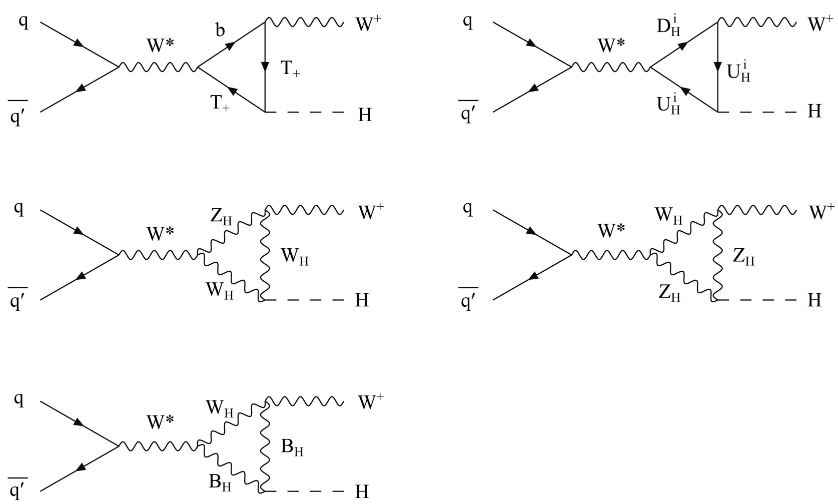

Fig. 1. In the LHT model, Feynman diagrams for the partonic processes $\mathrm{q\bar{q}'} \to \mathrm{W^+H}$ for $\mathrm{q=u,c}$ and $\mathrm{q'=d,s}$.

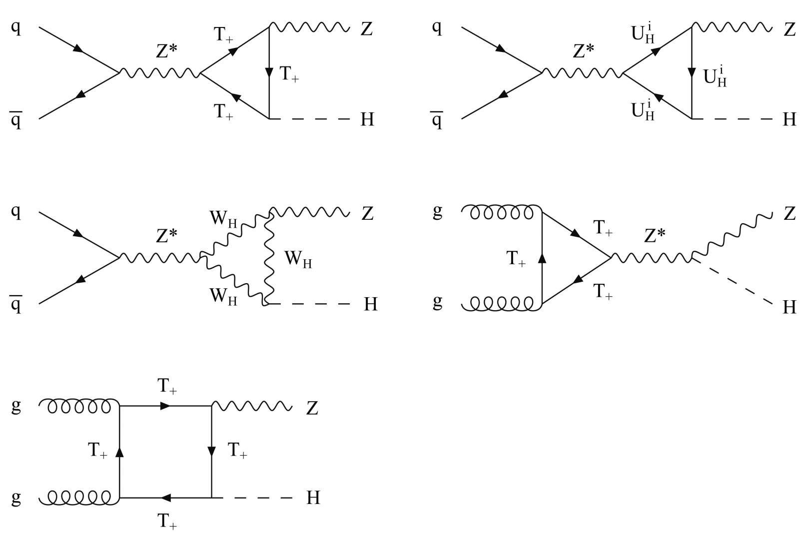

Fig. 2. In the LHT model, Feynman diagrams for the partonic processes $\mathrm{q\bar{q}} \to \mathrm{ZH}$ for $\mathrm{q=u,c,d,s}$.

The cross section $\sigma(\mathrm{VH})$ is dependant on the scale parameters f, the Higgs mass m_{H}, the T-odd fermion mass M_{Q} and the mixing parameter r (or x_{L}). To simplify our numerical calculation, we will take $r=1$, which means $\lambda_1=\lambda_2$ and $x_{\mathrm{L}}=1/2$. Since the process $\mathrm{pp}\rightarrow\mathrm{VH}+\mathrm{X}$ is a promising channel only for searching a light Higgs boson [5], we assume $m_{\mathrm{H}}=120$ GeV. The model dependant parameters f and M_{Q} are assumed in the ranges of 500–2000 GeV and 1000–2000 GeV, respectively.

The new particles predicted by the LHT model can contribute the process $\mathrm{pp}\rightarrow\mathrm{VH}+\mathrm{X}$ via the Feynman diagrams in Fig. 1 and Fig. 2. Each loop diagram is composed of some scalar loop functions, which are calculated by using LoopTools [18]. For the numerical analysis, we use the values $m_{\mathrm{W}}=80.425$ GeV, $m_{\mathrm{Z}}=91.187$ GeV and $m_{\mathrm{b}}=4.2$ GeV for the masses of the gauge bosons W, Z and the bottom quark [19], and we also use CTEQ6L parton distribution functions (PDFs) for the quark and gluon PDFs [20]. We identify the renormalization and factorization scales, $\mu=\mu_{\mathrm{R}}=\mu_{\mathrm{F}}=m_{\mathrm{H}}+m_{\mathrm{V}}$. The relative correction parameter R is defined as $R=[\sigma(\mathrm{SM+LH}T)-\sigma(\mathrm{SM})]/\sigma(\mathrm{SM})$, in which $\sigma(\mathrm{SM+LH}T)$ includes the contributions of the SM and those of the new particles predicted by the LHT model, $\sigma(\mathrm{SM})$ includes contributions calculated at NNLO [11]. For the process $\mathrm{pp}\rightarrow\mathrm{ZH}+\mathrm{X}$, $\sigma(\mathrm{SM})$ also includes the gluon-gluon fusion contributions [13]. Fig. 3 shows the scale parameter f dependence of the relative correction parameter R for the processes $\mathrm{pp}\rightarrow\mathrm{WH}+\mathrm{X}$ (left) and $\mathrm{pp}\rightarrow\mathrm{ZH}+\mathrm{X}$ (right), respectively. One can see from Fig. 3 that these new particles generate positive contributions to the cross section of the process $\mathrm{pp}\rightarrow\mathrm{VH}+\mathrm{X}$. The value of the relative correction parameter R is sensitive to the free parameters f and M_{Q}. The value of R for the process $\mathrm{pp}\rightarrow\mathrm{WH}+\mathrm{X}$ is generally larger than that for the process $\mathrm{pp}\rightarrow\mathrm{ZH}+\mathrm{X}$. For $f=500$ GeV and $M_{\mathrm{Q}}\geqslant 2$ TeV, the value of R for the process $\mathrm{pp}\rightarrow\mathrm{WH}+\mathrm{X}$ can be fairly large. For example, for 500 GeV$\leqslant f\leqslant$ 2000 GeV and M_{Q} =2000 GeV, the value of R is in the range of 36%–0.15%.

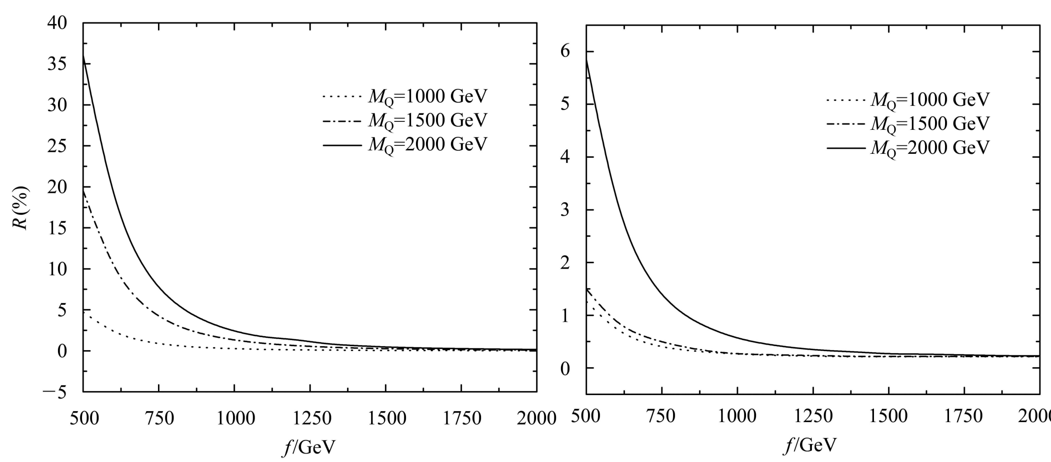

Fig. 3. The scale parameter f dependence of the relative correction parameter R for the processes $\mathrm{pp}\rightarrow\mathrm{WH}+\mathrm{X}$ (left) and for processes $\mathrm{pp}\rightarrow\mathrm{ZH}+\mathrm{X}$ (right).

3 Conclusions

One of the main tasks for the LHC is to discover one or more Higgs bosons. Studying Higgs boson production at the LHC is very interesting, and will help to test the SM and search for new physics. Although the process $\mathrm{pp}\rightarrow\mathrm{VH}+\mathrm{X}$ (V=W or Z) is not the dominant production channel of the Higgs boson H, it is a significant channel for searching for a light Higgs boson [5]. So, in this paper, we consider the contributions of the LHT model to this process.

In this paper, we consider the correction effects of the new particles predicted by the LHT model on the production cross section of the process $\mathrm{pp}\rightarrow\mathrm{VH}+\mathrm{X}$. Our numerical results show that the LHT model can give positive contributions to this process. The value of the relative correction parameter R is very sensitive to the free parameters f and M_{Q} and, in most of the parameter space, its value is very small. However, with reasonable values of the free parameters, the correction values can reach 35% and 5% for the processes $\mathrm{pp}\rightarrow\mathrm{WH}+\mathrm{X}$ and ZH+X, respectively.

The search for the Higgs boson is a primary goal of the LHC, which has a huge discovery potential for the SM Higgs boson. If the Higgs mechanism is realized in nature, the corresponding Higgs boson should not escape detection at the LHC. The full mass range can be explored and Higgs couplings can be extracted with typical errors around 20%–40% using an integrated luminosity of 30 fb^{-1} and properly simulating all errors involved [21]. Thus, we expect that our numerical results will be useful to test the LHT model at the LHC via the processes $\text{pp} \rightarrow \text{WH}+\text{X}$ and $\text{pp} \rightarrow \text{ZH}+\text{X}$.

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