Phenomenology of Left-Right Twin Higgs Model

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Twin Higgs mechanism has recently been proposed to solve the “little Hierarchy” problem. We studied the implementation of twin Higgs mechanism in left-right models. We discussed the particle spectrum, and the collider phenomenology at the Large Hadron Collider.

PACS numbers: 12.60.Cn, 12.60.Fr, 13.85.-t

I. LEFT-RIGHT TWIN HIGGS MODEL

Naturalness requires the stabilization of the Higgs mass against large radiative corrections. The scale of new physics needs to be around the electroweak scale to avoid the fine-tuning of the Higgs potential. On the other hand, electroweak precision measurements push the new physics scale to be above a few TeV. This conflicts in the new physics energy scale is the so-called “little Hierarchy” problem.

Recently, twin Higgs mechanism has been proposed as a solution to the “little Hierarchy” problem \cite{1,2}. The Higgs is a pseudo-Goldstone boson of a spontaneously broken global symmetry. Gauge and Yukawa interactions that explicitly break the global symmetry give mass to the Higgs. Once a discrete symmetry is imposed, the leading quadratic divergent term respects the global symmetry, thus does not contribute to the Higgs mass. The resulting Higgs mass obtains logarithmic corrections. Its mass is around the electroweak scale when the cut off is around 5 – 10 TeV.

The twin Higgs mechanism could be implemented in different ways. In the mirror model \cite{1}, a complete copy of the Standard Model (SM) is introduced and the discrete symmetry is identified with mirror parity. The only collider signal for the mirror twin Higgs model is the invisible Higgs decay, which can be tested at the ILC.

The twin Higgs mechanism can also be implemented in left-right models with the dis-
crete symmetry being identified with left-right symmetry. There are new particles around the electroweak scale, which interact with SM particles. Such model has rich collider phenomenology, which will be discussed in this talk.

In the left-right twin Higgs model (LRTH), the global symmetry is SU(4), with a gauged SU(2)_L \times SU(2)_R \times U(1)_{B-L} subgroup. The Higgs field $H = (H_L, H_R)$ is in the fundamental representation of SU(4), with $H_L$ charged under SU(2)_L and $H_R$ charged under SU(2)_R. After the Higgs obtains a vacuum expectation value (vev) $\langle H \rangle = (0,0,0,f_1)$, the global symmetry SU(4) breaks down to SU(3), and SU(2)_R \times U(1)_{B-L} breaks down to the SM U(1)_Y. Three of the seven Goldstone bosons (GB) are eaten by the massive gauge bosons $Z_H$ and $W_H^\pm$, while the rest four contain the SM Higgs doublet.

The fermion sector of LRTH is similar to the SM, with the right handed quarks $(u_R, d_R)$ and leptons $(l_R, \nu_R)$ charged under the SU(2)_R. Notice that we have to introduce additional right handed neutrinos. Their masses are required to be larger than the proton mass to avoid the strong constraints on the heavy gauge boson masses from supernovae cooling.

To obtain order of one Yukawa coupling, additional vector pair of top quark singlet, $T_L$ and $T_R$, is introduced. The electroweak precision constraints push $f_1$ to be larger than 3 or 4 TeV, reintroducing the fine tuning of the Higgs potential.

To fix this, another Higgs field $\hat{H} = (\hat{H}_L, \hat{H}_R)$ is introduced, which only couples to the gauge sector if we impose a matter parity. It obtains a vev $\langle \hat{H} \rangle = (0,0,0,f_2)$ with $f_2 \gg f_1$. The heavy gauge boson gets a mass of the order of $g f_2$, which satisfies the precision constraints. The fine tuning in the Higgs potential is under control since the gauge sector contribution is suppressed by the small gauge coupling, while the top sector contribution is proportional to $f_1$, which can now be around a few hundred GeV.

The introduction of the extra Higgs field $\hat{H}$ enlarges the global symmetry to SU(4) \times SU(4). After spontaneous symmetry breaking, there are 14 GBs. Three of the six GBs that are charged under SU(2)_R are eaten by the heavy gauge bosons, while leaves three physical Higgses: $\phi^0$ and $\phi^\pm$. The remaining Higgses are the SM Higgs doublet $H_L$ and an extra Higgs doublet $\hat{H}_L = (\hat{H}_1^+, \hat{H}_2^0)$ that only couples to the gauge boson sector. A residue matter parity in the model renders the neutral Higgs $\hat{H}_2^0$ stable, and it could be a good
FIG. 1: The left plot shows (from top to bottom) the value of $f_2$ and masses of $Z_H, W_H, t_H$. The right plot shows (from top to bottom) the masses of $\tilde{H}_1^\pm (\tilde{H}_2^0)$, $\phi^\pm$, $h_{SM}$ and $\phi^0$. The other parameters are chosen as $\Lambda = 4\pi f_1$, $M = 150$ GeV, $\sqrt{B} = 50$ GeV and $\mu = f_1/2$.

dark matter candidate. After electroweak symmetry breaking, a physical Higgs boson $h_{SM}$ from $H_L$ is left, which plays the role of the SM Higgs particle.

The new particles in the LRTH are: heavy gauge bosons $Z_H, W_H^\pm$, heavy top quark $t_H$, neutral Higgs $\phi^0$, a pair of charged Higgses $\phi^\pm$, and a SU(2)$_L$ complex Higgs doublet: $\tilde{H}_1^\pm$, $\tilde{H}_2^0$. The model parameters are the vevs $f_1$, $f_2$, the cut off scale $\Lambda$, the top quark singlet mixing parameter $M$, a mass parameter $\sqrt{B}$ for $\phi^0$, and a mass parameter $\mu$ for $\tilde{H}_1^\pm$ and $\tilde{H}_2^0$. Once $f_1$ is fixed, the vev $f_2$ can be determined by fixing the SM Higgs vev to be 246 GeV. The remaining free parameters are: $(f_1, \Lambda, M, \sqrt{B}, \mu)$.

Fig. 1 shows the masses for the new particles as a function of $f_1$, for a typical set of choice for $(\Lambda, M, \sqrt{B}, \mu)$. The heavy top mass is between 500 GeV and 1.5 TeV. The heavy gauge boson masses are above 1 TeV. They are all within the reach of LHC. The mass of the Higgs $\phi^0$ is around 100 GeV for $\sqrt{B} = 50$ GeV, while the mass of the charged Higgs $\phi^\pm$ is between 200 to 400 GeV. The SM Higgs mass is around $150 - 170$ GeV, the LHC reach of these particles depends on their production processes and decay modes, which will be discussed below.
FIG. 2: Left plot shows the single and pair production for heavy top quark at LHC. The right plot shows the drell-yan production cross section for $W_H$ and $Z_H$ at LHC. The “x”s correspond to the value of $f_1$ being 100, 200, ..., 1000 GeV. The model parameters are chosen to be $M = 150$ GeV and $\Lambda = 4\pi f_1$.

II. COLLIDER PHENOMENOLOGY

The production cross section for heavy top at LHC is given in the left plot of Fig. 2. The dominant production mode for heavy top at LHC is single heavy top production in associated with a jet: $pp \rightarrow t_H j$. For a heavy top mass of $500 \sim 1500$ GeV, the cross section is in the range of $8 \times 10^3$ fb $\sim 10$ fb. The heavy top pair production via QCD process (dashed line in the left plot of Fig. 2) is about a factor of five smaller, due to the phase space suppression of the large heavy top mass.

More than 90% of heavy top decays via: $t_H \rightarrow \phi^+ + b$. Considering the subsequent decay of $\phi^+ \rightarrow t\bar{b}$, $t \rightarrow W^+b \rightarrow l^+\nu b$, the signal is three b-jets + one charged lepton + missing $E_T$. There is always an additional jet (most likely b-jet) that accompanies $t_H$. A detailed collider study of this process is under current investigation.

The heavy top can also decay into $t_{SM} h_{SM}$, $t_{SM} Z$ and $bW$, with branching ratios of the order of $10^{-2}$ for $M = 150$ GeV. Considering $t_H \rightarrow t_{SM} Z$ channel: the signal is one b-jet + tri-lepton + missing $E_T$, which is almost SM background free.

The dominant production channels for heavy gauge bosons at hadron colliders are the drell-yan processes: $pp \rightarrow W_H X$ and $pp \rightarrow Z_H X$, which are shown in the right plot of Fig. 2. The drell-yan cross section is large: varying from $4 \times 10^4$ fb for $W_H$ mass of about
1 TeV to 40 fb for $W_H$ mass of about 4 TeV.

For $W_H$, the dominant decay into two jets is not very useful due to the huge QCD jet background. $W_H$ could decay into $l\nu_R$ if the right handed neutrino mass is less than $m_{W_H}$. It leads to a clean signal of lepton plus missing energy. $W_H$ could also decay into $t_H b$, with a branching ratio of about 20%. Depending on the subsequent decays of the heavy top, we expect to see signals of 4 b + lepton + missing $E_T$ or 2 b + tri-lepton + missing $E_T$. About 3% $W_H$ decays into $\phi^0 \phi^{\pm}$, which is the dominant production mode for $\phi^0$.

Although the dominant decay mode of $Z_H$ is into di-jets, the discovery modes for $Z_H$ are $t_H\bar{t}_H$ (with a branching ratio of 2-6%), $t\bar{t}$ (with a branching ratio of 3-4%) and $l^+l^-$ (with a branching ratio of 2.5% for $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ individually). The di-lepton mode provides a clean signal. It can be separated from the SM background by studying the invariant di-lepton mass distribution.

The SM Higgs mass depends on $f_1$, $M$ and $\Lambda$, and is found to be in the range of $150 - 170$ GeV. It could be discovered via the gluon fusion process $gg \rightarrow H$ with Higgs decays into di-bosons.

Besides the SM Higgs, there are three additional Higgses that couple to both the SM fermions and gauge bosons: one neutral Higgs $\phi^0$ and a pair of charged Higgses $\phi^{\pm}$. $\phi^0$ decays into $b\bar{b}$ or $\tau^+\tau^-$, and $\phi^{\pm}$ dominantly decays into $tb$.

The gluon fusion production for $\phi^0$ is not so useful due to huge QCD background to the $b\bar{b}$ final states. It could, however, be produced in the decay of heavy particles in the model. The dominant production mode is through $W_H \rightarrow \phi^0\phi^{\pm}$, with a cross section of about 1 fb $- 10^3$ fb. For $\phi^{\pm}$, the dominant production mode is through heavy top decay, with a cross section in the range of 10 fb to $10^4$ fb.

The complex Higgses $\hat{H}^{\pm}_1$ and $\hat{H}^0_2$ couple to the gauge bosons only. Their masses are very degenerate; $\hat{H}^{\pm}_1$ is slightly heavier than $\hat{H}^0_2$ due to the small mass splitting introduced by the electromagnetic interactions. $\hat{H}^{\pm}_1$ can therefore decay into $\hat{H}^0_2$ plus soft jets or leptons. If the decay lifetime is long enough, we can see charged track in the detector with little hadronic activity. Otherwise, the soft jets and leptons can not be detected at colliders. The events appear as missing energy, which escape the detection.
All the above discussion is for a small but non-zero $M$. In the limit of $M = 0$, certain couplings go to zero, which changes the collider signatures significantly. In particular, $\phi^\pm tb$ coupling is now absent, and $\phi^\pm$ can no longer decays into $tb$ as in the non-zero $M$ case. The only possible decay channels are $\phi^\pm \rightarrow \phi^0 q\bar{q}'$ or $\phi^\pm \rightarrow H q\bar{q}'$. The former one suffers from huge QCD background, and the latter one suffers from small branching ratio. Similarly, the discovery for all the other new particles becomes very challenging. The only exceptions are $Z_H \rightarrow l^+ l^-$ and $W_H \rightarrow l\nu_R$, which remain unaffected.

In conclusion, the left-right Twin Higgs model provides an alternative mechanism to solve the “little Hierarchy” problem. The heavy gauge bosons and heavy top partner can be copiously produced at LHC and have rich collider phenomenology. The detailed collider analysis of this model is under current investigation.

Acknowledgments

We would like to thank Z. Chacko for useful discussions of the left-right Twin Higgs models. The current work is supported by DOE.
