Probing LHC Higgs Signals from Extended Electroweak Gauge Group

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We study the effects of the extended electroweak gauge sector on the signal strengths of the Higgs boson at the LHC. Extension of the Higgs sector associate with the extension of the electroweak gauge symmetry. In our setup, there are two neutral Higgs states ($h$, $H$) and three new gauge bosons ($W'\pm$, $Z'$). We assume the lightest scalar, $h$, is what LHC found and its mass is 125 GeV. We find the enhancement of $\mu(gg \to h \to \gamma\gamma)$. On the other hand, other decay processes are same as or smaller than the SM expectation.

I. INTRODUCTION

On July 2012, both ATLAS and CMS groups reported that they found a new particle whose mass is around 125 GeV \cite{2, 3}. This particle is expected to be the Higgs boson predicted in the standard model (SM). Although the data are consistent with this expectation, the signal strength of the diphoton decay mode has received attention. ATLAS experiment has detected larger signal strength than the SM expectation. Although the current deviations from the SM are still less than 2 sigma, it is intriguing to explore possible implications for new physics which can explain this excess. Since this process is induced via one-loop diagram, it is an ideal place where new physics can readily set in. Hence, the diphoton channel can provide an effective probe of possible heavy new states which hide in the loop and have not yet manifested in the direct productions.

In the SM, the $W$ boson loop diagrams give the dominant contributions to this process. Therefore, if we have one more $W$ boson, namely relatively light $W'$, then the diphoton signal might be enhanced. This idea is easily modelized by extending the electroweak gauge symmetry. The minimal extension is $SU(2) \times SU(2) \times U(1)$. This gauge structure contains $W'\pm$ and $Z'$ as well as the SM gauge bosons. It is also required to extend the Higgs sector for correct symmetry breaking pattern. In a simple realization of it, two CP-even scalars are predicted. One of these scalars is identified as the observed particle at the LHC.

In this talk, we focus on the signal strength of the lighter CP-even scalar. Other interesting phenomena in this model (such as the perturbative unitarity structure, phenomenology of heavier CP-even scalar) are discussed in \cite{1}.

II. MODEL

The gauge symmetry in this model is $SU(3)_c \times SU(2)_0 \times SU(2)_1 \times U(1)_2$, where $SU(3)_c$ is QCD part and others are electroweak sector. We introduce two Higgs fields, $H_1$ and $H_2$, for the electroweak symmetry breaking. The symmetry breaking patterns are $SU(2)_0 \times SU(2)_1 \rightarrow SU(2)_V$ by $H_1$, and $SU(2)_1 \times U(1)_2 \rightarrow U(1)_V$ by $H_2$, where the suffix $V$ stand for the diagonal part. After both symmetry breaking, the remnant symmetry is $U(1)_{QED}$, and the six of the gauge fields become massive. These massive gauge bosons are $W'\pm$, $Z$, $W_{1,2}^\pm$, and $Z'$. Each Higgs fields contain four real scalars, and six of them are eaten by the gauge bosons. Remaining two scalars, we call them as $h_1$ and $h_2$, are physical degrees of freedom. These two scalars are, however, not mass eigenstates which we define

$$h = \cos \alpha h_1 - \sin \alpha h_2, \quad (1)$$
$$H = \sin \alpha h_1 + \cos \alpha h_2. \quad (2)$$

We assume $h$ is 125 GeV and $H$ is heavier than $h$. As we will see in later, the phenomenology of $h$ is highly depending on this mixing angle, $\alpha$.

We introduce vector-like fermions as well as chiral fermions. The charge assignments are summarized in Table\textsuperscript{[1]} After the symmetry breaking, the vector-like and chiral fermions are mixed. Then the mass eigenstates

\* Speaker. This talk is based on the work done in \cite{1}.
TABLE I: Assignments for fermions under the gauge group of the present model. In the fourth and fifth columns, the $U(1)_c$ charges and $SU(3)_c$ representations are shown for the quarks (without parentheses) and leptons (in parentheses), respectively.

| Fermions  | $SU(2)_L$ | $SU(2)_R$ | $U(1)_Y$ | $SU(3)_c$ |
|-----------|-----------|-----------|----------|-----------|
| $\Psi_{0L}$ | 2         | 1         | $\frac{1}{3}$ (-$\frac{2}{3}$) | 3 (1)     |
| $\Psi_{1L}$ | 1         | 2         | $\frac{2}{3}$ (-$\frac{1}{3}$) | 3 (1)     |
| $\Psi_{1R}$ | 1         | 2         | $\frac{1}{3}$ (-$\frac{2}{3}$) | 3 (1)     |
| $\Psi_{2L}$ | 1         | 1         | $\frac{2}{3}$ (0)          | 3 (1)     |
| $\Psi_{2R}$ | 1         | 1         | $\frac{1}{3}$ (-1)        | 3 (1)     |

given by the mixture of the chiral and vector-like fermions. Due to this mixing, we can suppress potentially dangerous contributions to $S$ parameter at tree level without making $W'$ much heavy. In addition, the extra degrees of freedom in the fermion sector help to enhance $\sigma(gg \rightarrow h)$. We will see this cross section enhancement is crucial to explain the diphoton excess in this model.

At tree level, the $S$ parameter is approximately given by

$$\alpha_{em}S \simeq -4 \sin^2 \theta_W \frac{m_W}{m_W'} \frac{g_{W'ff}}{m_{W'}^2} g_{Wff},$$

where $g_{Wff}$ and $g_{W'ff}$ are $W$ and $W'$ couplings to the SM fermions respectively. The later coupling is given by

$$g_{W'ff} \simeq -g_1 \left( \frac{1 + r^2}{r^2} \frac{m_W^2}{m_{W'}^2} - \sin^2 \theta_f \right),$$

where $r = \langle H_2 \rangle / \langle H_1 \rangle$, and $\theta_f$ is the mixing angle in the fermion sector [14]. We can realize $g_{W'ff} \simeq 0$ by choosing a proper configuration $\theta_f$ for the light fermion mass-eigenstates. Then $S$ parameter is suppressed even if $m_{W'}$ is lighter than 1 TeV [38]. If $m_{W'} \gg 1$ TeV, then we can not expect $W'$ affects to the diphoton excess because such a heavy $W'$ is decoupled from the SM sector. So, suppressed $g_{W'ff}$ is suitable in our purpose, and hereafter we take $g_{W'ff} = 0$ to mimic the ideal fermion delocalization [3][38]. Then we get another advantage: We can avoid direct detection bounds [9][13], because these bounds are derived under the assumptions that $W'$ is produced via Drell-Yan process, which never happen if $g_{W'ff} = 0$.

Since we impose $g_{W'ff} = 0$, the mixing angle in the fermion sector is determined by the parameters in the gauge sector. It is natural to assume $m_{W'} \gg m_W$, then the mixing angle is small as long as $r \sim 1$ [15], as we can see from Eq. (4). Hence, the main components of the SM fermions are the chiral fermions. On the other hand, the non-SM fermions are approximately the vector-like fermions.

In this setup, we find the $h$ couplings to the SM gauge bosons are suppressed as a consequence of the perturbative unitarity restoration mechanism in the longitudinally polarized gauge boson scattering processes. In the SM case, the amplitude of $W_L W_L \rightarrow W_L W_L$ process is proportional to $E^2$ if the Higgs boson contribution were absent. The Higgs boson exactly cancel this $E^2$ terms, and perturbative unitarity is restored, not violated at higher scale. This exact cancellation of $E^2$ terms is guaranteed by the relations among some couplings, so called unitarity sum rules;

$$4m_W^2 g_{WWWW} = 3m_Z^2 g_{WWZ} + g_{WWH}^2,$$

which is a consequence of gauge symmetry and renormalizability. In our model case, $W'/Z'$ and $H$ contribute to the process as well. We find the following sum rule for the $E^2$ term cancellation in $WW \rightarrow WW$ scattering amplitude:

$$4m_W^2 g_{WWWW} = 3m_Z^2 g_{WWZ} + 3m_Z^2 g_{WWZ'} + g_{WWH}^2 + g_{WWH}^2.$$
III. PRODUCTION CROSS SECTION AND SIGNAL STRENGTHS

In this section, we calculate the $h$ production cross section via gluon fusion process, and some signal strengths for $h$.

A. $\sigma(gg \rightarrow h)$

We start off by studying the $h$ production cross section via gluon fusion process. The cross section of this process can be enhanced because this is a loop induced process by colored particles and our model contains extra fermions as well as the SM fermions.

In Fig. 1, we show the ratio of $\sigma(gg \rightarrow h)$ in this model to the SM one. It highly depends on the parameters in the Higgs sector, especially $\alpha$. We find the cross section is enhanced in some region. This enhancement is due to the contributions from the extra fermions. This cross section also depends on $m_{W'}$, although the process seems independent from the gauge sector. This is due to the condition we take, $g_{W'ff} = 0$: This condition makes a connection among parameters in the fermion sector and the gauge sector, as we can see from Eq. (4).

Hence Fig. 1 shows the $m_{W'}$ dependence.

![Fig. 1: $\sigma(gg \rightarrow h)/SM$. We take $M_{W'} = 400$ GeV (in the panel (a)) and $M_{W'} = 600$ GeV (in the panel (b)). The variable in the horizontal axis is the mixing angle in the Higgs sector, and $r$ is the VEV ratio of the two Higgs fields, $\langle H_2 \rangle / \langle H_1 \rangle$. The actual physical space of mixing angle $\alpha$ is $\alpha = [0, \pi)$, only the half of the $[0, 2\pi)$ interval.](image)

B. $\mu(gg \rightarrow h \rightarrow \gamma\gamma, WW, ZZ)$

Next, we calculate signal strengths, $\mu = \sigma \cdot \text{Br}/(\sigma \cdot \text{Br})^{SM}$. Here we focus on three signal strengths, $\mu(gg \rightarrow h \rightarrow \gamma\gamma, WW, ZZ)$. In Fig. 2, we show these signal strengths as a function of $\alpha$, with $r = 1$. We find diphoton signal excess around $\alpha \sim 0.8\pi$. Therefore this model can explain the excess observed by both ATLAS and CMS. On the other hand, $\mu(gg \rightarrow h \rightarrow WW, ZZ)$ is suppressed. They are smaller than a half of the SM prediction. Since the central values of these processes are near the SM prediction, this result looks unattractive. These suppression in the WW and ZZ channels are originated from the suppression of the $h$ couplings to the SM gauge bosons, discussed around Eq. (6). Since the couplings depend on $r$, the situation can be moderated by the choice of $r$, and we find it is true. In Fig. 3, we show the same plot as in Fig. 2 but different choice of $r$. We take $r = 2$ ($1/2$) in the left (right) panel. In these plots, we fix $m_{W'} = 400$ GeV. We find $\mu(gg \rightarrow h \rightarrow WW, ZZ)$ can almost reach the SM prediction around $\alpha = 0.7\pi$ ($1.0\pi$) in the left (right) panel. In those region, we still see the diphoton excess. This is compatible with the LHC data.

C. $\mu(qq' \rightarrow Vh \rightarrow Vff')$ and $\mu(q_1q_2 \rightarrow hq_3q_4 \rightarrow f'q_3q_4)$

We study other important processes, $qq' \rightarrow V^* \rightarrow Vh \rightarrow Vff'$ and $q_1q_2 \rightarrow hq_3q_4 \rightarrow f'q_3q_4$, where $V$ stands for $W$ and $Z$. These processes are used for detecting $h \rightarrow bb, \tau\tau$ process. Since $g_{W'ff} = 0$ in our analysis, the
The only difference of these processes from the SM case is the $h$ couplings to the SM gauge bosons, namely

$$
\mu(qq' \to V h \to V f f') = \mu(q_1 q_2 \to h q_3 q_4 \to f f' q_3 q_4) = \left(\frac{g_{V V h}}{g_{V V h}^{\text{SM}}}\right)^2 < 1.
$$

The inequality in this equation is due to the suppression of the $h$ couplings to the SM gauge bosons as we discussed around Eq. (6), and hence this signal strength is always suppressed. This is a feature of this process in this model. We explicitly show this feature by plotting the signal strength in Fig. 4. These two plots make it apparent that this process is certainly suppressed compared to the SM prediction. This result is still consistent with the current LHC data due to large statistical error, but will become important to discriminate this model to other models in the future.

IV. SUMMARY

We study the model which has minimally extended electroweak gauge sector and vector-like fermions. The $W'$ coupling to the SM fermions can be suppressed thanks to the mixing between chiral and vector-like fermions. As a consequence, $W'$ can be lighter than 1 TeV without any conflict with the $S$ parameter constraint and direct search bounds.

In this set up, we study the diphoton signal strength of the lighter CP-even scalar. We find enhancement of $\mu(gg \to h \to \gamma\gamma)$, depending on the parameter choice. This enhancement is mainly due to the enhancement of $\sigma(gg \to h)$ by the extra fermions contributions. On the other hand, $\mu(gg \to h \to WW/ZZ)$ can be comparable with the SM prediction and be compatible with the LHC data, though they tend to be smaller than the SM predictions. This behavior is due to the suppression of the $h$ couplings to the SM gauge bosons. We also discuss the signal strength for other interesting processes, $\mu(qq' \to V h \to V f f')$ and $\mu(q_1 q_2 \to h q_3 q_4 \to f f' q_3 q_4)$. These processes are, for example, used to observe tau leptons as decay products from the Higgs boson. We find
FIG. 4: \(\mu (qq' \rightarrow Vh \rightarrow Vff')\). \(\mu (q_1 q_2 \rightarrow h q_3 q_4 \rightarrow ff' q_3 q_4)\) is also same. We take \(M_{W'} = 400\) GeV (in the panel (a)), \(M_{W'} = 600\) GeV (in the panel (b)). The actual physical space of mixing angle \(\alpha\) is \(\alpha = [0, \pi]\), only the half of the \([0, 2\pi]\) interval.

these signal strengths are always smaller than the SM prediction. This is also due to the suppression of the \(h\) couplings to the SM gauge bosons.

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[14] \(\sin \theta_f\) is determined by heavy fermion masses and Yukawa couplings. But its detail form is not important here.
[15] In \(r \gg 1\) and \(r \ll 1\) region, \(m_{W'}\) becomes heavier than a few TeV, and \(g_{W'ff}\) is not needed to be suppressed to satisfy both electroweak precision constraints and direct detection bounds. However, such heavy \(W'\) is almost decoupled from the SM sector and does not help to explain the diphoton excess. So we focus only in \(r \sim 1\) region in this talk.