Probing the electroweak symmetry breaking with Higgs production at the LHC

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The electroweak symmetry breaking (EWSB) mechanism is still an undecided question in particle physics. We propose to utilize the single top quark and Higgs associated production (th), Zh production via gluon fusion at the LHC to probe the couplings between the Higgs and the gauge bosons and further to test the EWSB. We demonstrate that the th and gg → Zh productions are sensitive to the relative sign of couplings (htt, hWW) and (htt, hZZ), respectively. We find that the relative sign between hWW and hZZ couplings could be fully determined after combining the present measurements from gg → h, thh and the th, Zh channels, as well as tZj and Ztt production at the 13 TeV LHC, and this conclusion is not sensitive to the possible new physics contribution induced by Ztt couplings in the gg → Zh production.

Introduction: Verifying the electroweak symmetry breaking (EWSB) mechanism is one of the major tasks of particle physics at the Large Hadron Collider (LHC) after the discovery of the Higgs-like boson [1,2]. In the Standard Model (SM), the EWSB is triggered by the Brout-Englert-Higgs mechanism, in which the couplings of the Higgs to EW gauge bosons play a crucial role. Although their coupling strengths are predicted by the SM, many new physics (NP) models could have a different prediction. Observing a deviation in the gauge couplings from the SM prediction would shed light on various NP models and also the nature of EWSB.

Those gauge couplings are widely studied by both the theoretical [3–11] and experimental [12–16] groups within global analysis of Higgs data under the κ-scheme or the SM effective field theory (SMEFT) framework. Recently, both the ATLAS [14] and CMS [15,16] collaborations show a strong constraint for the gauge couplings through a combined analysis of Higgs production and decay signal strengths within κ-scheme at the 13 TeV LHC, i.e. \( \kappa_W = 1.10 \pm 0.08 \), \( \kappa_Z = 1.05 \pm 0.08 \) (ATLAS) and \( \kappa_W = 1.10 \pm 0.15 \), \( \kappa_Z = 0.99 \pm 0.11 \) (CMS) with an assumption \( \kappa_{W,Z} > 0 \). Here \( \kappa_{W,Z} \) are gauge coupling strength modifiers of Higgs to the W and Z bosons, i.e.

\[
\mathcal{L}_{hVV} = \kappa_W g_{hVV}^{SM} h W^+ W^- + \frac{\kappa_Z}{2} g_{hZZ}^{SM} h Z_\mu Z^\mu, \tag{1}
\]

where \( g_{hVV} = 2m_V^2/v \) with \( V = W, Z \) being the gauge couplings in the SM and \( v = 246 \) GeV. The modifier \( \kappa_V \) could be matched to the dimension-6 SMEFT operators after the EWSB [17–19], and should be a leading approximation of the SMEFT to parametrize the new physics in Higgs gauge couplings [20]. A global analysis to include Higgs, diboson and top quark measurements at the LHC in the framework of SMEFT with all possible dimension-6 operators could be found in Ref. [21]. With higher luminosity data being accumulated, one expects the accuracy on \( \kappa_V \) could be further improved, e.g. the uncertainty will be reduced to 2% at the high-luminosity LHC (HL-LHC) [22], which operates at the \( \sqrt{s} = 14 \) TeV with an integrated luminosity of 3 ab\(^{-1}\). However, the analysis based on the current Higgs signal strengths and the simulation of the future colliders can only constrain the magnitude of \( \kappa_V \), while not the relative sign between \( \kappa_W \) and \( \kappa_Z \). It has been shown in Ref. [23] that a negative ratio \( \lambda_{W,Z} \equiv \kappa_W / \kappa_Z \) is also possible in the NP models. It is crucial to determine both the sign and the magnitude of \( \kappa_V \) in order to further test the EWSB and search for the possible NP signals.

The sign of \( \lambda_{W,Z} \) could be resolved through the Higgs golden decay channel \( h \rightarrow ZZ^* \rightarrow 4\ell \) with \( \ell = e, \mu \), due to the interference effects between the tree and loop level processes [24]. Alternatively, one can also use \( W^+ W^- h \) [25] and vector bosons fusion production of \( Vh \) processes [26] at \( e^+ e^- \) colliders to determine the sign of \( \lambda_{W,Z} \). In this work, we propose a novel method to pin down the sign of \( \lambda_{W,Z} \) through the measurements of a Higgs boson with a single top quark \( (th) \) and \( gg \rightarrow Zh \) production at the LHC; see Fig. 1. It is well known that the interference between the diagrams containing the \( htt \) vertex and those containing the \( hWW \) vertex in \( th \) production is destructive when \( \kappa_t \) and \( \kappa_W \) have the same sign due to the unitarity [27,28] (see Fig. 1(a)), where \( \kappa_t \) is the modifier of top quark Yukawa coupling,

\[
\mathcal{L}_{htt} = -\frac{m_t}{v} \kappa_t h \bar{t} t. \tag{2}
\]
We can therefore measure the sign of the $htt$ coupling respect to that of the $hWW$ coupling through $th$ production at the LHC [29–35]. Similarly the gluon-initiated $Zh$ production is sensitive to the relative sign between $htt$ and $hZZ$ couplings due to the cancelation between the box and triangle diagrams [32, 36–41]; see Fig. 1(b). Therefore, it would be promising to probe the sign of the $gg \rightarrow h$ production, $thh$ associated production and the two processes of we suggested, both the sign and magnitude of $\kappa_V$ could be well constrained.

**$th$ production:** The $th$ associated production can be classified into three channels: $t$-channel, $s$-channel and $tW$-channel. The higher order QCD and EW corrections under the SM and SMEFT have been discussed in Refs. [32, 42, 43]. The three channels share the same subprocess of $bW^\mu \rightarrow th$ and are related to each other by crossing symmetry. At high energy limit, the amplitude of $bW^\mu \rightarrow ht$ scattering will be dominated by the longitudinal polarized $W$ boson and it could be written as,

$$M \sim \frac{1}{m_W^2} \bar{u}(t) \left[ m_t (\kappa_t - \kappa_W) + \left( \frac{2m^2_W}{u} \kappa_W + \frac{m_t^2}{s} \kappa_t \right) P_L u(b) \right].$$ (3)

Here $s, t, u$ are the Mandelstam variables for describing the scattering of $bW \rightarrow th$. It clearly shows that there is a strong cancelation between $htt$ and $hWW$ anomalous couplings at high energy. As a result, the cross section of $th$ production can be significantly enhanced if the relative sign between $htt$ and $hWW$ is reversed. In order to compare $th$ cross section with non-standard $htt$ and $hWW$ couplings to the SM prediction, we define a ratio $R_{th}$ as,

$$R_{th} = \frac{\sigma(pp \rightarrow th)}{\sigma_{SM}(pp \rightarrow th)}. $$ (4)

Note that we include all three channels in $R_{th}$ definition.

Figure 2 displays the contours of $R_{th} = 1, 5$ and 10 in the plane of anomalous couplings $\kappa_t$ and $\kappa_W$ at the 13 TeV LHC.

**$Zh$ production via gluon fusion:** We consider the $htt$, $hZZ$ and $Ztt$ couplings to the $gg \rightarrow Zh$ production. The couplings of top quark to $Z$ boson could be parametrized...
generically with,
\[
\mathcal{L}_{Ztt} = \frac{g_W}{2c_W} \bar{t} \gamma_\mu (\kappa_t^t v_t - \kappa_t^a a t) t Z_\mu ,
\]
(5)
where \(g_W\) is the EW gauge coupling and \(c_W\) is the cosine of the weak mixing angle \(\theta_W\). The vector and axial-vector couplings of \(Z\) boson to top quark in the SM are \(v_t = 1/2 - 4/3s_W^2\) and \(a_t = 1/2\). The helicity amplitudes of \(g(\lambda_i)g(\lambda_j) \to Z(\lambda_3)h\) with helicity \(\lambda_i = \pm 0\) for particle \(i\) have been calculated in Refs. [41, 51, 52]. It shows that the dominant amplitudes come from \((\pm, \pm 0)\) helicity configurations and the results with \(m_b = 0\) are [41],
\[
M_{\pm,0}^Z = 2 \sqrt{\lambda} \sum_{t,b} \kappa_t^a \kappa_a \frac{a t}{m_t^2} \left[ F_{\Delta} (s, m_t^2) + 2 \right] N, \tag{6}
\]
where
\[
\lambda = s^2 + m_\ell^4 + m_h^4 - 2 (m_\ell^2 m_h^2 + m_\ell^2 s),
\]
\[
N = \frac{\alpha g_W}{32 \pi c_W}. \tag{7}
\]
The symbols \(\Delta\) and \(\Box\) denote the contributions from triangle and box diagrams, respectively (see Fig. 1(b)). The parameter \(a_t = -1/2\) is the axial-vector coupling of \(Z\) boson to bottom quark and parameter \(\kappa_a^b = 1\). Note that the helicity amplitudes \(M_{\pm,0}^Z\) could be related to \(M_{\Delta,\Box}^Z\) by Bose symmetry [52]. The definition of the scalar functions \(F_\Delta\) and \(F_{\Box}^{\alpha+}\) in Eq. (6) could be found in Ref. [52]. We should note that only the axial-vector component \(\kappa_a^b\) of the \(Ztt\) couplings can contribute to the \(gg \to Zh\) production due to the charge conjugation invariance [41].

At high energy limit, only the top quark contributes to the \(gg \to Zh\) scattering and the total amplitude is,
\[
M_{\pm,0} \sim \frac{m_t^2}{m_Z^2} (\kappa_Z - \kappa_t) \log^2 \left( \frac{s}{m_t^2} \right),
\]
(8)

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\(th\) [45] & \(t\bar{t}h\) [45] & \(t\bar{t}h\) [46] & \(ggF (h \to WW^*)\) [16] & \(ggF (h \to ZZ^*)\) [16] & - \\
\hline
5.7 \pm 4.0 & 0.92^{+0.26}_{-0.23} & 1.43^{+0.39}_{-0.34} & 1.28^{+0.20}_{-0.19} & 0.98^{+0.12}_{-0.11} & - \\
\hline
Zh [47] & Zh [48] & Zh [49] & Zh [49] & Zh [50] & Zh [50] \\
\hline
0.92^{+0.26}_{-0.23} & 1.08^{+0.22}_{-0.23} & 0.34^{+0.70}_{-0.70} & 0.28^{+0.07}_{-0.83} & 1.6 \pm 0.89 & 1.2 \pm 0.34 \\
\hline
\end{tabular}
\caption{Signal strengths of Higgs production at the 13 TeV LHC.}
\end{table}

Figure 4 displays the contours of \(R_{Zh} = 1, 3\) and 7 in the plane of anomalous couplings \(\kappa_t\) and \(\kappa_Z\) at the 13 TeV LHC.

We note that both the inclusive cross section and transverse momentum distribution of \(Z\) boson in the \(pp \to Zh\) production at the 13 TeV LHC have been measured by the ATLAS and CMS collaborations with integrated luminosities \(79.8 \sim 139 \, \text{fb}^{-1}\) [16, 47–50]. We show the limits from the present measurements to the plane of anomalous couplings \(\kappa_t\) and \(\kappa_Z\) with assumption \(\kappa_W = \kappa_a^t = 1\) at 2\(\sigma\) level in Fig. 5. The light blue region denotes the constraint from the measurements of the \(pp \to Zh\) production, in which both \(q\bar{q}\) and \(gg\) initial states are considered. A constant \(k\)-factor has been used to mimic the higher order QCD correction effects for both \(q\bar{q} \to Zh\) and \(gg \to Zh\) production in the analysis, i.e. \(k_{qq} = 1.3\) and \(k_{gg} = 2.7\) [53, 54]. It is worthwhile discussing how much our result will be influenced by the QCD corrections. The NNLO QCD corrections to the \(Zh\) production with the anomalous couplings have been discussed in Ref. [55] and it shows a constant \(k\)-factor should be a reasonable assumption in this work [55]. Furthermore, the scale uncertainty is around 1\% \sim 2\%, as a result, the high order QCD effects should not alter the conclusion in this section. The orange and green bounds show the constraints imposed by the measurements of \(t\bar{t}h\) [45, 46].
and $gg \to h \to ZZ^*$ production [16]; (see tabel I for the detail of the signal strengths.) It clearly shows that the current measurements of the $Zh$ cross sections at the LHC has resolved the ambiguity of the relative sign between $\kappa_t$ and $\kappa_Z$, i.e. $\kappa_t \kappa_Z > 0$ is allowed. Again, we emphasize that the sign $\kappa_t \kappa_Z$ should not be sensitive to the assumption of $\kappa_W = 1$ due to $\kappa_W$ can not change the cross section of $Zh$ scattering.

Next we consider the impact of the non-standard $Zt\bar{t}$ coupling to determine the relative sign between $\kappa_t$ and $\kappa_Z$. The $Zt\bar{t}$ couplings have been well constrained by the measurements of $tZj$ [56, 57] and $Zt\bar{t}$ [58, 59] productions at the 13 TeV LHC. The limits could be potentially improved after we combining the measurement from $gg \to ZZ$ production [60]. As a conservative estimation of the impact from the $Zt\bar{t}$ coupling, we choose two benchmark points of $\kappa_t = 0.7,1.3$ in the analysis, and show the allowed parameter space of $\kappa_t$ and $\kappa_Z$ at 2$\sigma$ level with above value of $\kappa_t$ in Fig. 6. Although the value of $\kappa_t$ will change the allowed parameter space of the $\kappa_t$ and $\kappa_Z$ from the $Zh$ measurements, the relative sign between them is still fixed, i.e. $\kappa_t \kappa_Z > 0$.

**Summary and discussion:** Now equipped with the constraints for the Higgs couplings $h\bar{t}h$ and $hWW$ (see Fig. 3), $h\bar{t}t$ and $hZZ$ (see Fig. 5) at the 13 TeV LHC, we are ready to estimate the potential of pinning down the sign of $\lambda_{WZ}$ through the global analysis of the $gg \to h$, $t\bar{t}h$ production and $th$, $Zh$ scattering with present measurements. From the above discussion one sees that current data favors same sign for both the $(ht\bar{t}, hWW)$ and $(htt, hZZ)$ couplings, as a result, the $hht$ coupling could be a good reference to determine the relative sign between Higgs gauge couplings. In Fig. 7, we show the constraints on the plane of $\kappa_Z$ and $\kappa_W$ with $\kappa_t = 0.9,1,1.1$ and $\kappa_t = 1$ from the current measurements with (blue) and without $Zh$ data (orange) at 2$\sigma$ level. Although the $Zh$ data itself can not improve the accuracy of the $\kappa_W$, the $\lambda_{WZ} < 0$ region could be excluded almost at 2$\sigma$ level by $Zh$ measurements, and this conclusion is not sensitive to possible new physics contribution induced by $Zt\bar{t}$ coupling in the $gg \to Zh$ production (see Fig. 6). At the HL-LHC, all the experimental measurements could be much improved compared to the current data, and as a result, we expect that the gauge couplings of Higgs to $W$ and $Z$ bosons could be well constrained and the nature of EWSB will surface at that time.

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FIG. 7. Present constraints on the anomalous couplings $\kappa_Z$ and $\kappa_W$ at the 13 TeV LHC with $\kappa_t = 0.9, 1.1, 1.1$ and $\kappa_d = 1$. The blue region comes from the limits after we include all the data, while the orange band denotes the impact after we removing the $Zh$ data (both the inclusive cross section and transverse momentum distribution of $Z$ boson in $pp \rightarrow Zh$ production).
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