W^+W^+ Scattering as a Sensitive Test of the Anomalous Gauge Couplings
of the Higgs Boson at the LHC

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Abstract
We propose a sensitive way to test the anomalous HVV couplings (V = W^\pm, Z^0) of the Higgs boson (H), which can arise from either the dimension-3 effective operator in a non-linearly realized Higgs sector or the dimension-6 effective operators in a linearly realized Higgs sector, via studying the VV scattering processes at the CERN Large Hadron Collider (LHC). We show that, with an integrated luminosity of 300 fb^{-1} and sufficient kinematical cuts for suppressing the backgrounds, studying the process pp→W^+W^+jj→l^+\nu l^+\nu jj can probe the anomalous HWW couplings at a few tens of percent level for the non-linearly realized Higgs sector, and at the level of 0.01-0.08 TeV^{-1} for the linearly realized effective Lagrangian.

The electroweak symmetry breaking mechanism (EWSBM) is one of the most profound puzzles in particle physics. Since the Higgs sector of the standard model (SM) suffers the well-known problems of triviality and unnaturalness, there has to be new physics beyond the SM above certain high energy scale \(\Lambda\). If a light Higgs boson candidate (H) is found in future collider experiments, the next important task is to experimentally measure the gauge interactions of this Higgs scalar and explore the nature of the EWSBM. Let V = W^\pm, Z^0 be the electroweak (EW) gauge bosons. The detection of the anomalous HVV couplings (AHVVC) will point to new physics beyond the SM underlying the EWSBM.

Fig. 1: Illustration of Feynman diagrams for VV scatterings in the SM: (a) diagrams contributing to \(T(V,\gamma)\), (b) diagrams contributing to \(T(H)\).

Before knowing the correct new physics, the effect of new physics at energy below \(\Lambda\) can be parametrized as effective operators in an effective theory. This is a model-independent description. Testing the AHVVC relative to that of the SM can discriminate the EWSBM in the new physics model from

\(^*\)Contributed to Workshop on Physics at TeV Colliders, Les Houches, France, 26 May – 6 June 2003.
that of the SM. In Ref. [1], we propose a sensitive way of testing the AHVVC via $VV$ scatterings, especially the $W^+W^+$ scatterings, at the LHC [1]. This includes the test of either the dim-3 AHVVC in a nonlinearly realized Higgs model (NRHM) [2] or the dim-6 AHVVC in the linearly realized effective interactions (LREI) [3]. The reason for the sensitiveness is the following. The scattering amplitude contains two parts: (i) the amplitude $T(V, \gamma)$ related only to $V$ and $\gamma$ (Fig. 1(a)), and (ii) the amplitude $T(H)$ related to the Higgs boson (Fig. 1(b)). At high energies, both $T(V, \gamma)$ and $T(H)$ increase with the center-of-mass energy ($E$) as $E^2$ in the NRHM and as $E^4$ in the LREI. In the SM, though individual diagrams in Fig. 1(a) may behave as $E^4$, the sum of all diagrams in Fig. 1(a) can have at most $E^2$-dependent contribution. The $HVV$ coupling constant in the SM is just the non-Abelian gauge coupling constant. This causes the two $E^2$-dependent pieces to precisely cancel with each other in $T(V, \gamma) + T(H)$, resulting in the expected $E^0$-behavior for the total amplitude, as required by the unitarity of the $S$ matrix. If there is AHVVC due to new physics effect, $T(V, \gamma) + T(H)$ can grow as $E^2$ or $E^4$ in the high energy regime. Such deviations from the $E^0$ behavior of the SM amplitude can provide a rather sensitive test of the AHVVC in high energy $VV$ scattering experiments. This type of tests do not require the measurement of the $H$ decay branching ratios, and is thus of special interest, especially if the AHVVC are very large or very small [1].

We take such enhanced $VV$ scatterings as the signals for testing the AHVVC. To avoid the large hadronic backgrounds at the LHC [5]. We choose the gold-plated pure leptonic decay modes of the final state $V$s as the tagging modes. Even so, there are still several kinds of backgrounds to be eliminated [5,7]. We take all the kinematic cuts given in Ref. [7] to suppress the backgrounds, and calculate the complete tree level contributions to the process

$$pp \rightarrow VVjj \rightarrow llll(\nu\nu)jj,$$

where $j$ is the forward jet that is tagged to suppress the large background rates. Our calculation shows that, for not too small AHVVC, all the backgrounds can be reasonably suppressed by such kinematic cuts. In the case of the SM, there are still considerably large remaining backgrounds contributed by the transverse component $V_T$. We shall call these the remaining SM backgrounds (RSMB) after taking the above treatment. Our calculation shows that the signals can be considerably larger than the RSMB even with not very large AHVVC.

We first consider the NRHM. The effective Lagrangian below $\Lambda$, up to dim-4 operators, respecting the EW gauge symmetry, charge conjugation, parity, and the custodial $SU(2)_c$ symmetry, is [2].

$$\mathcal{L} = -\frac{1}{4} \bar{W}_\mu^+ \cdot \bar{W}^\mu - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{4} \left(v^2 + 2k \nu H + \kappa' H^2\right) \text{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) + \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{m_H^2}{2} H^2 - \frac{\lambda_3 v}{3!} H^3 + \frac{\lambda_4}{4!} H^4,$$

where $\bar{W}_\mu^+$ and $B_{\mu\nu}$ are field strengths of the EW gauge fields, $v \approx 246$ GeV is the vacuum expectation value (VEV) breaking the EW gauge symmetry, $(\kappa, \lambda_3)$ and $(\kappa', \lambda_4)$ are, respectively, dimensionless coupling constants from the dim-3 and dim-4 operators, $\Sigma = \exp\{i \vec{w} \cdot \vec{\omega}/v\}$, and $D_\mu \Sigma = \partial_\mu \Sigma + ig \frac{\vec{w}}{v} \cdot \bar{W}_\mu \Sigma - ig' B_\mu \Sigma \frac{\omega_4}{v}$. The SM corresponds to $\kappa = \kappa' = 1$ and $\lambda_3 = \lambda_4 = \lambda = 3m_H^2/v^2$.

At the tree level, only the dim-3 operator $\frac{1}{2}k \nu H D_\mu \Sigma^\dagger D^\mu \Sigma$ contributes to the $VV$ scatterings in Fig. 1. Therefore, $VV$ scatterings can test $\kappa$, and $\Delta \kappa \equiv \kappa - 1$ measures the deviation from the SM value $\kappa = 1$.

In Ref. [1], the full tree level cross sections for all the processes in [1] are calculated for $15$ GeV $\leq m_H \leq 300$ GeV. The results show that the most sensitive channel is $pp \rightarrow W^+W^+jj \rightarrow l^+l^+\nu\nu jj$ [1]. With an integrated luminosity of $300$ fb$^{-1}$, there are more than 20 events for $\Delta \kappa \geq 0.2$ or $\Delta \kappa \leq -0.3$, while there are only about 15 RSMB events (see Ref. [1] for details). Considering only the statistical errors, the LHC can limit $\Delta \kappa$ to the range

$$-0.3 < \Delta \kappa < 0.2$$

(3)
at roughly the $(1 - 3)\sigma$ level if data is consistent with the SM prediction \cite{1}.

Other constraints on $\Delta\kappa$ from the precision EW data, the requirement of the unitarity of the $S$-matrix, etc. were studied in Ref. \cite{1}, which are either weaker than Eq. \cite{3} or of the similar level \cite{1}.

Next, we consider the LREI. In this theory, the leading AHVVC are from the effective operators of dim-6 \cite{3,4}. As is shown in Refs. \cite{3,4}, the $C$ and $P$ conserving effective Lagrangian up to dimension-6 operators containing a Higgs doublet $\Phi$ and the weak bosons $V^\alpha$ is given by

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n,$$

(4)

where $\mathcal{O}_n$'s are dim-6 operators composed of $\Phi$ and the EW gauge fields (cf. Ref. \cite{4}). $f_n/\Lambda^2$'s are the AHVVC.

The precision EW data and the requirement of the unitarity of the $S$-matrix give certain constraints on the $f_n$'s. The constraints on $f_{WW}/\Lambda^2$, $f_{WW}/\Lambda^2$, $f_{BB}/\Lambda^2$, $f_{BB}/\Lambda^2$, and $f_B/\Lambda^2$ from the presently available experimental data are rather weak \cite{1}. A better test of them is to study the $VV$ scatterings. In $\mathcal{L}_{\text{eff}}$, the operator $\mathcal{O}_{WWW}$ contributes to the triple and quartic $V$ boson self-interactions which may not be directly related to the EWBSM, we assume $f_{WW}/\Lambda^2$ is small in the analysis. and concentrate on the test of $f_{WW}/\Lambda^2$, $f_{BB}/\Lambda^2$, $f_{WW}/\Lambda^2$, and $f_{BB}/\Lambda^2$. They are related to the following AHVVC in terms of $H$, $W^\pm$, $Z$, and $\gamma$ \cite{4}:

$$\mathcal{L}_{\text{eff}}^H = g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{HZ\gamma} H A_{\mu\nu} Z^{\mu\nu} + g_{HZZ} H Z_{\mu\nu} Z^{\mu\nu} + g_{HWW} (W_{\mu\nu}^+ W_{\mu\nu}^- \gamma + \text{h.c.}) + g_{HWW}^2,$$

(5)

where

$$g_{H\gamma\gamma} = -\left(\frac{g_{WW}}{\Lambda^2}\right) s^2(f_{BB} + f_{WW})/2,$$

$$g_{HZ\gamma} = \left(\frac{g_{WW}}{\Lambda^2}\right) s^2 f_{BB} / c,$$

$$g_{HZZ} = \left(\frac{g_{WW}}{\Lambda^2}\right) c^2 f_{BB} / 2c,$$

$$g_{HWW} = \left(\frac{g_{WW}}{\Lambda^2}\right) f_{WW} / 2,$$

(6)

with $s \equiv \sin \theta_W$ and $c \equiv \cos \theta_W$.

The test of these AHVVC via $VV$ scatterings is quite different from that of $\Delta\kappa$. The relevant operators $\mathcal{O}_n$'s contain two derivatives. so, at high energies, the interaction vertices themselves behave as $E^2$, and thus the longitudinal $VV$ scattering amplitudes, $V_L V_L \rightarrow V_L V_L$, grows as $E^4$, and those containing $V_T$ grow as $E^2$. Hence the scattering processes containing $V_T$ actually behave as signals rather than backgrounds.

It is shown in Ref. \cite{1} that the most sensitive channel is still $pp \rightarrow W^+ W^+ j j \rightarrow l^+ \nu l^+ \nu j j$. Detailed calculations show that the contributions of $f_B$ and $f_{BB}$ are small even if they are of the same order of magnitude as $f_W$ and $f_{WW}$ \cite{1}. Hence, we take account of only $f_W/\Lambda^2$ and $f_{WW}/\Lambda^2$ in the analysis. If they are of the same order of magnitude, the interference between them may be significant, depending on their relative phase which undoubtedly complicates the analysis. Hence, we perform a single parameter analysis, i.e., assuming only one of them is dominant at a time. In the case that $f_W$ dominates, the obtained numbers of events in $pp \rightarrow W^+ W^+ j j \rightarrow l^+ \nu l^+ \nu j j$ with an integrated luminosity of 300 fb$^{-1}$ are more than 20 for $f_W/\Lambda^2 \geq 0.85$ TeV$^{-2}$ or $f_W/\Lambda^2 \leq -1.0$ TeV$^{-2}$, and the number of the RSMB events are still around 15 (see Ref. \cite{1} for details). If no AHVVC effect is found at the LHC, we can set the following bounds on $f_W/\Lambda^2$ (in units of TeV$^{-2}$) when taking into account of only the statistical error:

$$1\sigma : \quad -1.0 < f_W/\Lambda^2 < 0.85, \quad 2\sigma : \quad -1.4 < f_W/\Lambda^2 \leq 1.2.$$

(7)
In the case that \( f_{WW} \) dominates, the corresponding bounds are (in units of TeV\(^{-2}\)):

\[
1\sigma : \quad -1.6 \leq f_{WW}/\Lambda^2 < 1.6, \quad 2\sigma : \quad -2.2 \leq f_{WW}/\Lambda^2 < 2.2. \tag{8}
\]

These are somewhat weaker than those in Eq. (7). From Eqs. (7) and (8) we obtain the corresponding bounds on \( g_{HV V}^{(i)} \), \( i = 1, 2 \) (in units of TeV\(^{-1}\)):

\[
1\sigma : \quad -0.026 < g_{HW W}^{(1)} < 0.022, \quad -0.026 < g_{HZ Z}^{(1)} < 0.022, \quad -0.014 < g_{HZ Z}^{(1)} < 0.012, \\
-0.083 \leq g_{HW W}^{(2)} < 0.083, \quad 0.032 \leq g_{HZ Z}^{(2)} < 0.032, \quad -0.018 \leq g_{HZ Z}^{(2)} < 0.018, \tag{9}
\]

\[
2\sigma : \quad -0.036 < g_{HW W}^{(1)} \leq 0.031, \quad 0.036 < g_{HZ Z}^{(1)} \leq 0.031, \quad 0.020 < g_{HZ Z}^{(1)} \leq 0.017, \\
-0.11 \leq g_{HW W}^{(2)} < 0.11, \quad -0.044 \leq g_{HZ Z}^{(2)} < 0.044, \quad -0.024 \leq g_{HZ Z}^{(2)} < 0.024. \tag{10}
\]

These bounds are to be compared with the 1\( \sigma \) bound on \( g_{HW W}^{(2)} \) obtained from studying the on-shell Higgs boson production via weak boson fusion at the LHC given in Ref. [8], where \( g_{HW W}^{(2)} \) is parametrized as \( g_{HW W}^{(2)} = 1/\Lambda_5 = g^2 v/\Lambda^2 \). The obtained 1\( \sigma \) bound on \( \Lambda_5 \) for an integrated luminosity of 100 fb\(^{-1}\) is about \( \Lambda_5 \geq 1 \) TeV [8], which corresponds to \( g_{HW W}^{(2)} = 1/\Lambda_5 \leq 0.1 \) TeV\(^{-1}\). We see that the 1\( \sigma \) bounds in Eq. (9) are all stronger than the above bound given in Ref. [8]. For an integrated luminosity of 300 fb\(^{-1}\), the bound in Ref. [8] corresponds roughly to a 1.7\( \sigma \) level accuracy. Comparing it with the results in Eq. (10), we conclude that our 2\( \sigma \) bound on \( g_{HW W}^{(2)} \) is at about the same level of accuracy, while our 2\( \sigma \) bounds on the other five \( g_{HV V}^{(i)} \) \( (i = 1, 2) \) are all stronger than those given in Ref. [8].

It has been shown in Ref. [9] that the anomalous \( H ZZ \) coupling constants \( g_{HZ Z}^{(1)} \) and \( g_{HZ Z}^{(2)} \) can be tested rather sensitively at the Linear Collider (LC) via the Higgs-strahlung process \( e^+ e^- \rightarrow Z^* \rightarrow Z + H \) with \( Z \rightarrow f \bar{f} \). The obtained limits are \( g_{HZ Z}^{(1)} \sim g_{HZ Z}^{(2)} \sim O(10^{-3} - 10^{-2}) \) TeV\(^{-1}\) [9]. Although the bounds shown in Eqs. (9) and (10) are weaker than these LC bounds, \( W^+ W^+ \) scattering at the LHC can provide the bounds on \( g_{HW W}^{(i)} \), \( i = 1, 2 \) which are not easily accessible at the LC. So that the two experiments are complementary to each other.

Further discrimination of the effect of the AHVVC from that of a strongly interacting EW symmetry breaking sector with no light resonance will eventually demand a multichannel analysis at the LHC by searching for the light Higgs resonance through all possible on-shell production channels including gluon-gluon fusion. Once the light Higgs resonance is confirmed, \( VV \) scatterings, especially the \( W^+ W^+ \) channel, can provide rather sensitive tests of various AHVVC for probing the EWSB mechanism. So \( VV \) scatterings are not only important for probing the strongly interacting EWSBM when there is no light Higgs boson, but can also provide sensitive test of the AHVVC (especially the anomalous \( HW W \) couplings) at the LHC for discriminating new physics from the SM when there is a light Higgs boson.

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