Constraining the anomalous $HZZ$ couplings in off-shell Higgs region

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Abstract

We study the anomalous $HZZ$ couplings in the golden channel $gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell$ in both on-shell and off-shell Higgs regions. Especially, the interference between Higgs-mediated processes with anomalous $HZZ$ couplings and its continuum background $gg \rightarrow ZZ \rightarrow 4\ell$ is firstly calculated, which is indispensable for constraining the anomalous $HZZ$ couplings in off-shell Higgs region. The analytic formulas and numerical results are given.

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I. INTRODUCTION

Since the 125 GeV/c² Higgs boson was discovered at Large Hadron Collider (LHC) in 2012 [1, 2], its properties have been tested more and more precisely [3–5]. Even though no new physics beyond the Standard Model (SM) has been confirmed so far, it is still necessary and meaningful to search for new physics. There are at least two reasons to insist it. One reason is, in experiment there still left parameter spaces for heavy particles or weak anomalous interactions [6]. Another reason is, the SM has no satisfactory explanation about neutrino mass [7], dark matter [8], matter-antimatter asymmetry [9] and etc. . In this paper we study the anomalous HZZ couplings to search for new physics.

The anomalous HVV couplings could be probed through $V^* \rightarrow VH$ process and $H \rightarrow VV$ process at LHC, where $V$ represents $W, Z$ bosons. Among these processes with their subsequent decays to fermions, leptons or diphotons, the $gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell$ process is the most precise one at LHC, which is thus called golden channel and has been studied extensively in theoretical researches [10–45] and experiments at LHC [46–54]. The most stringent constraints on the anomalous HZZ couplings is thus from the newest measurement in this golden channel [51], where the anomalous HZZ couplings are added to the SM Lagrangian by higher dimensional operators and especially for precision two subtle effects are included. One is the interference between new processes and SM processes, the other is the cross section distributions in off-shell Higgs region. However, there is a deficit in this measurement. That is, while the interference between anomalous Higgs-mediated processes and SM Higgs-mediated process are included, the interference between the anomalous Higgs-mediated processes and the continuum background box process $gg \rightarrow ZZ \rightarrow 4\ell$ are not included. Actually the later kind of interference could not be neglected especially in the off-shell region [39, 48, 54–60]. To remedy this deficit, we study the interference for anomalous HZZ couplings in $gg \rightarrow 4\ell$ processes in both on-shell and off-shell Higgs regions. The analytic formulas and numerical results are given for comparison.

The rest of the paper is organized as follows. In Section II we describe the effective model, the helicity amplitudes with the anomalous couplings. In Section III we embed the helicity amplitudes into the MCFM8.0 package, make calculation for proton-proton collision and get the numerical results of cross sections. In Section IV the constraints on the HZZ anomalous couplings are estimated in off-shell Higgs region. Section V is the conclusion and
II. THEORETICAL CALCULATION

In this section firstly we introduce the $HZZ$ anomalous couplings in effective model, then we calculate the helicity amplitudes.

A. The effective model

The anomalous $HVV$ couplings have been discussed in effective Lagrangian abundantly [47, 51, 61–71]. Here we write the effective Lagrangian for the $HZZ$ coupling as

$$
\mathcal{L} = \frac{a_1}{v} M_Z^2 H Z^\mu Z_\mu - \frac{a_2}{v} H Z^{\mu\nu} Z_{\mu\nu} - \frac{a_3}{2v} H Z^{\mu\nu} \tilde{Z}_{\mu\nu},
$$

(1)

where $a_1, a_2, a_3$ are real numbers, the first term is a dimension-three operator allowed in SM at tree level, while the second term is a dimension-five $CP$-even operator and the third term is a dimension-five $CP$-odd operator. $Z_\mu$ is $Z$ boson field, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ is the field strength tensor of the $Z$ boson and $\tilde{Z}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} Z^{\rho\sigma}$ represents its dual field strength. When $a_1 = 1$ and $a_2 = a_3 = 0$, the Lagrangian would recover to the SM case. The $HZZ$ interaction vertex from this effective Lagrangian is

$$
\Gamma^{\mu\nu}(k, k') = i \frac{2}{v} \sum_{i=1}^{3} a_i \Gamma_i^{\mu\nu}(k, k') = i \frac{2}{v} [a_1 M_Z^2 g^{\mu\nu} + 2a_2 (k^{\nu} k'^{\mu} - k \cdot k' g^{\mu\nu}) + 2a_3 \epsilon^{\mu\nu\rho\sigma} k_\rho k'_\sigma],
$$

(2)

where $v = 246$ GeV is the electroweak vacuum expectation value, $k, k'$ are the momenta of two $Z$ bosons.

B. Helicity amplitude of the process $gg \to H \to ZZ \to 2e2\mu$

The total helicity amplitude for the process $gg \to H \to ZZ \to 2e2\mu$ in Fig. 1 is composed of three individual amplitudes $A_{SM}^H, A_{CP-even}^H$ and $A_{CP-odd}^H$, which have same production process but different Higgs decay modes separately according to the three kinds of $HZZ$
The black dot represents an effective \( ggH \) coupling from loop contributions.

The specific formulas are

\[
\mathcal{A}_{gg\rightarrow H\rightarrow ZZ\rightarrow 2e2\mu} = \left[ a_1 \mathcal{A}_{gg\rightarrow H}^{SM} + a_2 \mathcal{A}_{gg\rightarrow H}^{H_{CP-even}} + a_3 \mathcal{A}_{gg\rightarrow H}^{H_{CP-odd}} \right] (1_g, 2_g, 3_e^-, 4_e^+, 5_{\mu^-}, 6_{\mu^+}) ,
\]

\[
= \mathcal{A}_{gg\rightarrow H}^{gg\rightarrow H \rightarrow ZZ\rightarrow 2e2\mu} (1_g, 2_g, 3_e^-, 4_e^+, 5_{\mu^-}, 6_{\mu^+}) ,
\]

where \( h_i (i = 1 \cdots 6) \) are helicity indicies of external particles, \( s_{ij} = (k_i + k_j)^2 \) and \( P_H(s) = \frac{s-M_H^2+iM_H\Gamma_H}{s-M_H^2+iM_H\Gamma_H} \) is the Higgs propagator. Then we discuss the production and decay parts.

The production part \( \mathcal{A}_{gg\rightarrow H}^{gg\rightarrow H \rightarrow ZZ\rightarrow 2e2\mu} \) is the helicity amplitude of gluon-gluon fusion to Higgs process, and \( h_1, h_2 \) represent the helicities of gluons with outgoing momenta. For all the other helicity amplitudes in this paper, we also keep the convention that the momentum of each external particle is outgoing. When writing the helicity amplitudes, we adopt the conventions used in [57, 72]:

\[
\langle ij \rangle = \bar{u}_-(p_i)u_+(p_j) , \quad [ij] = \bar{u}_+(p_i)u_-(p_j) ,
\]

\[
\langle ij \rangle [ji] = 2p_i \cdot p_j , \quad s_{ij} = (p_i + p_j)^2 ,
\]

and we have

\[
\mathcal{A}_{gg\rightarrow H}^{gg\rightarrow H \rightarrow ZZ\rightarrow 2e2\mu} (1_g, 2_g) = \frac{2c_g}{v} [12]^2 ,
\]

\[
\mathcal{A}_{gg\rightarrow H}^{gg\rightarrow H \rightarrow ZZ\rightarrow 2e2\mu} (1_g, 2_g) = \frac{2c_g}{v} (12)^2 .
\]

To keep the \( ggH \) coupling consistent with SM, we make

\[
\frac{c_g}{v} = \frac{1}{2} \sum_f \frac{\delta^{ab} \frac{i}{2}}{16\pi^2} g_s^2 4e \frac{m_f^2}{2M_Ws_W} \frac{1}{M_H^2} \left[ 2 + M_H^2(1-\tau_H)C_0^\gamma(m_f^2) \right] ,
\]
where \( a, b = 1, \ldots, 8 \) are SU(3)_c adjoint representation indices for the gluons, \( \tau_H = 4m_f^2/M_H^2 \), and \( C_{0}^{\gamma\gamma}(m^2) \) is the Passarino-Veltman three-point scalar function \([73]\). More details about Eq.s \((7)(8)\) could be found in Ref. \([74]\).

The decay part \( A^{H \rightarrow ZZ \rightarrow 2e2\mu}(3_{e^{-},4_{e^{+}},5_{\mu^{-}},6_{\mu^{+}}}) \) is the helicity amplitude of the process \( H \rightarrow ZZ \rightarrow e^{-}e^{+}\mu^{-}\mu^{+} \), which have three sources according to the three types of vertices as written in Eq. (2). Correspondingly we write it as

\[
A^{H \rightarrow ZZ \rightarrow 2e2\mu}(3_{e^{-},4_{e^{+}},5_{\mu^{-}},6_{\mu^{+}}}) = \sum_{i=1}^{3} a_i A_i^{H \rightarrow ZZ \rightarrow 2e2\mu}(3_{e^{-},4_{e^{+}},5_{\mu^{-}},6_{\mu^{+}}}) \tag{9}
\]

with

\[
A_1^{H \rightarrow ZZ \rightarrow 2e2\mu}(3_{e^{-},4_{e^{+}},5_{\mu^{-}},6_{\mu^{+}}}) = f \times l_e^2 \frac{M_W^2}{\cos^2 \theta_W} \langle 35 \rangle \langle 46 \rangle, \tag{10}
\]

\[
A_2^{H \rightarrow ZZ \rightarrow 2e2\mu}(3_{e^{-},4_{e^{+}},5_{\mu^{-}},6_{\mu^{+}}}) = f \times l_e^2 \times \left[ -2k \cdot k'(35) \langle 46 \rangle - \langle 35 \rangle \langle 45 \rangle + \langle 36 \rangle \langle 45 \rangle \langle 35 \rangle \langle 36 \rangle + \langle 35 \rangle \langle 36 \rangle \langle 45 \rangle \right], \tag{11}
\]

\[
A_3^{H \rightarrow ZZ \rightarrow 2e2\mu}(3_{e^{-},4_{e^{+}},5_{\mu^{-}},6_{\mu^{+}}}) = f \times l_e^2 \times \left[ 2(k \cdot k' + \langle 46 \rangle \langle 46 \rangle) \langle 35 \rangle \langle 46 \rangle + \langle 35 \rangle \langle 45 \rangle \langle 35 \rangle \langle 36 \rangle + \langle 35 \rangle \langle 36 \rangle \langle 45 \rangle \langle 46 \rangle \right] + \langle 36 \rangle \langle 46 \rangle \langle 35 \rangle \langle 36 \rangle - \langle 35 \rangle \langle 36 \rangle \langle 45 \rangle \langle 46 \rangle \right]. \tag{12}
\]

and

\[
f = -2ie^3 \frac{1}{M_W \sin \theta_W} \frac{P_Z(s_{34})}{s_{34}} \frac{P_Z(s_{56})}{s_{56}}, \tag{13}
\]

where \( M_W \) is the mass of the W boson, \( \theta_W \) is the Weinberg angle, \( l_e \) and \( r_e \) ( will appear for other helicity combinations) are the coupling factors of the Z boson to left-handed and right-handed leptons

\[
l_e = \frac{-1 + 2 \sin^2 \theta_W}{\sin(2\theta_W)} , \quad r_e = \frac{2 \sin^2 \theta_W}{\sin(2\theta_W)} . \tag{14}
\]

In Eq.s \((10)(11)(12)\), we only show the case that the helicities of four leptons \((h_3, h_4, h_5, h_6)\) are equal to \((-,+,-,+))\). As for the other three helicity combinations \((-,+,-,-)\), \((-,-,+,+), (,+,-,+,-)\), their helicity amplitudes are similar to Eq.s \((10)(11)(12)\), but with some exchanges like

\[
l_e \leftrightarrow r_e , \: 4 \leftrightarrow 6 , \: 3 \leftrightarrow 5 , \: \llbracket \leftrightarrow \rrbracket \right). \tag{15}
\]

Their specific formulas are shown in Appendix A.
\[ e^-(k_3, h_3) \]
\[ e^+(k_4, h_4) \]
\[ \mu^-(k_5, h_5) \]
\[ \mu^+(k_6, h_6) \]

FIG. 2: The Feynman diagram of the box process \( gg \rightarrow ZZ \rightarrow 2e2\mu \).

C. Helicity amplitude of the box process \( gg \rightarrow ZZ \rightarrow 2e2\mu \)

The process \( gg \rightarrow ZZ \rightarrow 2e2\mu \) is a continuum background of the Higgs mediated \( gg \rightarrow H \rightarrow 2e2\mu \) process. The interference between these two kinds of processes could have nonnegligible contribution in off-shell Higgs region. The Feynman diagram of the process \( gg \rightarrow ZZ \rightarrow 2e2\mu \) is a box diagram which is induced by fermion loops (see Fig. 2). The helicity amplitude \( A_{box}^{gg\rightarrow ZZ\rightarrow 2e2\mu} \) has been calculated analytically and coded in MCFM8.0 package [57, 75]. Another similar calculation that using a different method could be found in \( gg2VV \) code [76].

D. Helicity amplitude of the process \( gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell \)

The process \( gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell \) with identical \( 4e \) or \( 4\mu \) final states could also be used to probe the anomalous \( HZZ \) couplings. In SM the differential cross sections of the \( 4\ell \) (include both \( 4e \) and \( 4\mu \) ) and \( 2e2\mu \) processes are nearly same in both on-shell and off-shell Higgs regions [75], which indicates adding the \( 4e/4\mu \) process could almost double the total experimental statistics. This situation could probably be similar for the anomalous Higgs mediated processes. The \( 4e/4\mu \) Feynman diagrams consist of two different topology structures as shown in Fig. 3. Fig. 3(b) is different from Fig. 3(a) just by swapping the positive charged leptons \( (4\leftrightarrow 6) \). The helicity amplitude of each diagram is similar to the former \( 2e2\mu \) cases but need to be multiplied by a symmetry factor \( \frac{1}{2} \). While calculating the total cross section the interference term between Fig. 3(a) and (b) need an extra factor of -1 comparing to the self-conjugated terms because it connects all of the decayed leptons in one fermion loop while each self-conjugated term has two fermion loops. After considering
these details, the summed cross section of $4e$ and $4\mu$ processes is comparable to the $2e2\mu$ process. More details are shown in the following numerical results.

![Feynman diagrams](image)

**FIG. 3:** The Feynman diagrams of the process $gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell$, where $4\ell = 4e$ or $4\mu$. Note that diagram (b) is obtained by swapping the two positive charged leptons ($4e\leftrightarrow6$) in diagram (a).

### III. NUMERICAL RESULT

In this section we present the integrated cross sections and differential distributions in on-shell and off-shell Higgs regions, especially the interference between anomalous Higgs mediated processes and SM processes.

#### A. The cross sections

To compare the theoretical calculation with the experimental observation at LHC, we need to further calculate the cross sections at hadron level. From helicity amplitude to the cross section there need two more steps, firstly we should sum and square the amplitudes to get the differential cross section at parton level, then integrate the phase space and the parton distribution function (PDF) to get the cross section at hadron level. As following we show these two steps conceptually.

The differential cross section at parton level is

$$d\hat{\sigma}(s_{12}) \propto \left| A_{box}^{gg \rightarrow ZZ \rightarrow 4\ell} + A^{gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell} \right|^2,$$

$$\propto \left| A_{box}^{gg \rightarrow ZZ \rightarrow 4\ell} + a_1 A_{SM}^H + a_2 A_{CP-even}^H + a_3 A_{CP-odd}^H \right|^2.$$

(16) (17)
After expanding it, there left the self-conjugated terms and the interference terms that have different amplitude sources. As in the second step the integral of the phase space and PDF are same for each term, we note the integrated cross sections separately by the amplitude sources, which are

\[ \sigma_{k,l} \sim \begin{cases} 
|A_k|^2, & k = l; \\
2\text{Re}(A_k^* A_l), & k \neq l.
\end{cases} \]  

(18)

Where \( k, l = \{\text{box, SM, CP-even, CP-odd}\} \), the superscripts of \( A \) are left out for short.

**B. Numerical results for \( gg \rightarrow 2e2\mu \) processes**

We make the integral of phase space and PDF in \texttt{MCFM} 8.0 package [77, 78]. The simulation is performed for the proton-proton collision at the center-of-mass energy \( \sqrt{s} = 8 \) TeV. The Higgs mass is set as \( M_H = 125 \) GeV. The renormalization \( \mu_r \) and factorization scale \( \mu_f \) are set as the dynamic scale \( m_{4\ell}/2 \). For the PDF set we choose the leading order MSTW 2008 parton distribution functions MSTW08LO [79]. Some basic phase space cuts which are similar to the event selection cuts used in CMS experiment [80] are exerted as follows

\[ 
P_{T,\mu} > 5 \text{ GeV}, \ |\eta_\mu| < 2.4 ,
\]

\[ P_{T,e} > 7 \text{ GeV}, \ |\eta_e| < 2.5 , \]

\[ m_{\ell\ell} > 4 \text{ GeV}, \ m_{4\ell} > 100 \text{ GeV} . \]  

(19)

Besides, for \( 2e2\mu \) channel, the hardest (the second hardest) lepton should satisfy \( P_T > 20 \) (10) GeV; one pair of leptons with same flavour and opposite charge is required to have \( 40 \text{ GeV} < m_{\ell^+\ell^-} < 120 \text{ GeV} \) and the other pair needs to fulfil \( 12 \text{ GeV} < m_{\ell^+\ell^-} < 120 \text{ GeV} \). For the \( 4e \) or \( 4\mu \) channel, there exist four opposite charge lepton pairs as \( Z \) boson candidates. The selection strategy is firstly choosing one pair nearest to the \( Z \) boson mass as one \( Z \) boson, then considering the left two leptons as the other \( Z \) boson. Other requirements are similar to the \( 2e2\mu \) channel.

Table I show the cross sections \( \sigma_{k,l} \) with \( k, l = \{\text{box, SM, CP-even, CP-odd}\} \) while \( a_1, a_2, a_3 \) are all set to one. In the left and right panels the integral region of \( m_{4\ell} \) are separately set as \( m_{4\ell} < 130 \text{ GeV} \) and \( m_{4\ell} > 220 \text{ GeV} \), which correspond to the on-shell and off-shell Higgs regions. Next we focus on two kinds of interference effect: one is the
interference between each Higgs mediated process and continuum background, which is noted as \( \sigma_{\text{box},l} \) (or \( \sigma_{l,\text{box}} \)) with \( l \neq \text{box} \); the other is the interference between different Higgs mediated processes which is noted as \( \sigma_{k,l} \) with \( k,l \neq \text{box} \).

The interference terms between Higgs mediated processes and the continuum background \( \sigma_{\text{box},l} \) are all zeros in on-shell Higgs region, but relatively sizeble in the off-shell regions except for the cases with the \( CP \)-odd Higgs mediated process. There is an interesting reason for it. As from Eq. (4)(5)(18),

\[
\sigma_{\text{box},l} \sim 2 \operatorname{Re}(A_{\text{box}}^* A_l),
\]

\[
\sim 2 \operatorname{Re}(A_{\text{box}}^* A^{gg \rightarrow H} P_H(s_{12}) A_l),
\]

\[
\sim 2 (s_{12} - M_H^2) \operatorname{Re}(A_{\text{box}}^* A^{gg \rightarrow H} A_l) + M_H \Gamma_H \operatorname{Im}(A_{\text{box}}^* A^{gg \rightarrow H} A_l),
\]

\[
(s_{12} - M_H^2)^2 + M_H^2 \Gamma_H^2,
\]

which means the integrand of \( \sigma_{\text{box},l} \) consists of two parts, one is antisymmetric around \( M_H^2 \), the other is proportional to \( M_H \Gamma_H \operatorname{Im}(A_{\text{box}}^* A^{gg \rightarrow H} A_l) \). The first part could be largely suppressed almost to zero in the integral with an integral region symmetric around \( M_H \). The second part is also suppressed not only by the small factor of \( \Gamma_H/M_H \) but also by a small value of \( \operatorname{Im}(A_{\text{box}}^* A^{gg \rightarrow H} A_l) \) in the on-shell Higgs region. By contrary, in the off-shell Higgs region the integral regions are not symmetric around \( M_H \) but in one side larger than \( M_H \), which makes the first term have some non-zero contribution; both the first and the second terms could also be enhanced when \( \sqrt{s_{12}} \) is a little larger than twice of the top quark mass. That is because the \( gg \rightarrow H \) process is induced mainly by top quark loop, both the real part and the imaginary part of the amplitude (\( \operatorname{Re} A^{gg \rightarrow H} \) and \( \operatorname{Im} A^{gg \rightarrow H} \)) could be enhanced.

| \( \sigma_{k,l}(fb) \) | box | Higgs-med. | \( \sigma_{k,l}(fb) \) | box | Higgs-med. |
|------------------------|-----|-----------|------------------------|-----|-----------|
|                        |     | SM | \( CP \)-even | \( CP \)-odd |     | SM | \( CP \)-even | \( CP \)-odd |
| Higgs-med.             |     | 0  | 0          | 0  |     | 0  | 0          | 0  |
| \( CP \)-even          |     | 0  | -0.257    | 0  |     | 0.198 | -0.047     | 0  |
| \( CP \)-odd           |     | 0  | 0          | 0  |     | 0  | 0.035      |    |

**TABLE I:** The cross sections of \( gg \rightarrow 2e2\mu \) process in proton-proton collision at \( \sqrt{s} = 8 \text{ TeV} \).

8 TeV, \( m_{2e2\mu} < 130 \text{ GeV} \)

8 TeV, \( m_{2e2\mu} > 220 \text{ GeV} \)
when $\sqrt{s_{12}}$ is just beyond the $2M_t$ threshold (see Eq. (8)). Then $\text{Im} \left( A_{\text{box}}^* A^{gg\rightarrow H} A_i \right)$ could have a larger value, even though the relative contribution from the second term could be still suppressed by the smallness of the factor $\Gamma_H/M_H$. In conclusion mainly due to the nonsymmetric integral region and some enhancement of $A^{gg\rightarrow H}$, the interference contribution in the off-shell Higgs region becomes comparable with the self-conjugated contributions.

It is also worthwhile to point out there is no interference between the $CP$-odd Higgs-mediated process and other processes, which include not only the continuum background process but also other Higgs-mediated processes. It is because there is an antisymmetric tensor $\epsilon^{\mu\nu\rho\sigma}$ in its vertex (see Eq. (2)) while in the other three processes these four indices are symmetrically paired. Its difference is also indicated by an extra $i$ in the analytic amplitude in Eq. (12).

The interference between $CP$-even Higgs-mediated process and SM Higgs-mediated process is nonnegligible both in on-shell and off-shell Higgs regions. In on-shell Higgs region, the contribution from interference terms is large than that from the self-conjugated terms. Furthermore, for $a_2 = 1$ choice, it has minus sign, which make the total contribution of $CP$-even Higgs-mediated process a destructive effect. In the off-shell region, the $CP$-even Higgs-mediated process have two interference terms, separately between SM Higgs-mediated process and the box process. These two interference terms have opposite sign, which means they cancel each other partly. Even though, the summed interference effect is still comparable to the self-conjugated contribution.

Fig. 4 shows the differential cross sections. The black histogram is from its main background process $q\bar{q} \rightarrow 2e2\mu$, which is a huge background but still controllable. The red dashed histogram is from the SM $gg \rightarrow 2e2\mu$ processes, include both the box process and SM Higgs-mediated process. The blue dotted histogram adds the $CP$-even Higgs mediated process to the SM processes, include the total interference terms. For a comparison, we show the magenta dashed-dotted histogram without interference terms, so the interference contribution could be calculated by the difference between blue and magenta histograms. In the on-shell region we could see the $CP$-even Higgs mediated process have a total destructive contribution (blue histogram) compare to the SM process, while the mageta histogram show the main destructive contribution is from the interference term. In the off-shell region, the interference contribution is obvious in $200 \text{ GeV} < m_{4\ell} < 600 \text{ GeV}$ region. There is a bump in blue and magenta histograms when $m_{4\ell} \approx 350 \text{ GeV}$, which is because the total cross
FIG. 4: The differential cross sections of the $gg \to 2e2\mu$ processes and $q\bar{q} \to 2e2\mu$ process in proton-proton collision at $\sqrt{s} = 8$ TeV.

section of the $CP$-even Higgs mediated process increase suddenly beyond the $2M_t$ (twice of the top quark mass) threshold. The differential cross section for the $CP$-odd Higgs mediated process is similar to the magenta histogram since it has no interference effect.

The numerical results at center-of-mass energy $\sqrt{s} = 13$ TeV are shown in Table II. By comparing them to the results at $\sqrt{s} = 8$ TeV in Table I, we could find that each cross section is increased by about one or two times and their relative ratios have some minor changes. That could be caused by both the PDF functions and kinematic distributions.

C. Numerical results for $gg \to 4e/4\mu$ processes

The cross sections of $gg \to 4e/4\mu$ processes are listed in Table III for a comparison and next use. Here $gg \to 4e/4\mu$ represents the sum of $gg \to 4e$ and $gg \to 4\mu$. Comparing Table III with Table I, the numbers in the right panels are similar, while the numbers in the left panels have relatively large differences. That is mainly because the different selection
13 TeV, \( m_{2e2\mu} < 130 \text{ GeV} \)

| \( \sigma_{k,l}(\text{fb}) \) | box | Higgs-med. | CP-even | CP-odd |
|---|---|---|---|---|
| box | 0.024 | 0 | 0 | 0 |
| SM | 0 | 0.503 | -0.558 | 0 |
| CP-even | 0 | -0.558 | 0.202 | 0 |
| CP-odd | 0 | 0 | 0 | 0.075 |

TABLE II: The cross sections of \( gg \to 2e2\mu \) processes in proton-proton collision at center-of-mass energy \( \sqrt{s} = 13 \text{ TeV} \).

13 TeV, \( m_{2e2\mu} > 220 \text{ GeV} \)

| \( \sigma_{k,l}(\text{fb}) \) | box | Higgs-med. | CP-even | CP-odd |
|---|---|---|---|---|
| box | 1.283 | -0.174 | 0.571 | 0 |
| SM | -0.174 | 0.100 | -0.137 | 0 |
| CP-even | 0.571 | -0.137 | 0.720 | 0 |
| CP-odd | 0 | 0 | 0 | 0.716 |

TABLE III: The cross sections of \( gg \to 4e/4\mu \) processes in proton-proton collision at center-of-mass energy \( \sqrt{s} = 8 \text{ TeV} \).

cuts [75]. If apply the \( 4e/4\mu \) selection cuts to the \( gg \to 2e2\mu \) process, \( \sigma_{\text{box, box}} \) in the left panels could become similar.

IV. CONSTRAINTS IN OFF-SHELL HIGGS REGION

In this section we show a simple example to constrain \( a_2 \) and \( a_3 \) by using the data in off-shell Higgs region. Firstly we estimate the expected number of events \( N^\text{exp}(a_2, a_3) \) in off-shell Higgs region, then compare it with the observed number of events \( N^\text{obs} \) in experiment. The expected number of events should be

\[
N^\text{theo}(a_2, a_3) = \sigma_{\text{tot}} \times L \times k \times \epsilon ,
\] (21)
where $L$ is the integrated luminosity, $\sigma_{\text{tot}}$ is the total cross section, $k$ represents the $k$-factor, $\epsilon$ is the total efficiency. For simplicity, we assume the $k$-factor and $\epsilon$ are same for all $gg \rightarrow 4\ell$ processes include the interference terms.

The simulation in CMS experiment [48] with an integrated luminosity of $L = 19.7 \text{ fb}^{-1}$ at $\sqrt{s} = 8$ TeV shows that for $gg + \text{VBF} \rightarrow 4\ell$ process, the expected numbers of events in off-shell Higgs region ($m_4 \ell > 220$ GeV) is $N_{\text{SM+box}}^{\text{theo}} = 29.6^{+2.8}_{-2.9}$ which includes the Higgs mediated process, the box process and their interference. Based on this number we could estimate

$$N_{\text{SM+box}}^{\text{theo}}(a_2, a_3) = N_{\text{SM+box}}^{\text{exp}} \times \left[ \sigma_{\text{SM+box}}^{\text{even}} + a_2^2 \sigma_{\text{CP-even}}^{\text{H}} + a_2 \sigma_{\text{int}}^{\text{CP-even}} + a_3^2 \sigma_{\text{CP-odd}}^{\text{H}} \right],$$

(22)

where $N_{\text{SM+box}}^{\text{exp}}(a_2, a_3)$ represents the expected number of events from $gg + \text{VBF} \rightarrow 4\ell$ process if we assume there is a linear proportional relation between $gg \rightarrow 4\ell$ and $gg + \text{VBF} \rightarrow 4\ell$ process and meanwhile neglect a small change caused by the anomalous $HZZ$ couplings in VBF Higgs production process; $\sigma_{\text{SM+box}}^{\text{SM+box}} = \sigma_{\text{SM+box}}^{\text{SM}} + \sigma_{\text{SM+box}}^{\text{box}}, \sigma_{\text{int}}^{\text{CP-even}} = \sigma_{\text{CP-even,SM+box}}^{\text{CP-even}} + \sigma_{\text{CP-odd,SM+box}}^{\text{CP-odd}}$. As the cross sections of $4\ell$ final states are the sum of the cross sections of $2\ell 2\mu$, $4e$ and $4\mu$ final states, we combine the cross sections from both Table. I and Table. III and get

$$N_{\text{SM+box}}^{\text{exp}}(a_2, a_3) = 29.6 + 14.8 \times a_2^2 + 9.8 \times a_2 + 14.1 \times a_3^2.$$  

(23)

The background is mainly from the $q \bar{q} \rightarrow 4\ell$ process, which is expected to have $N_{\text{bg}}^{\text{theo}} = 158.4 \pm 7.4$, the experimental observed number is $N_{\text{obs}}^{\text{exp}} = 183$ and the error for the total expected number is $\sigma_N = 7.9$. From these numbers of events, a $\chi^2$ variable is built to fit the $a_2, a_3$ coefficients, which is

$$\chi^2 = \left( \frac{N_{\text{SM+box}}^{\text{theo}}(a_2, a_3) + N_{\text{bg}}^{\text{theo}} - N_{\text{obs}}^{\text{exp}}}{\sigma_N} \right)^2.$$  

(24)

In principle, the $\chi^2$ is a sum of squares. However, the experiment only provide a single data point, and we can only make this rough estimation. The contour plot of $\chi^2$ is shown in Fig. 5. The yellow dashed line represents the $1\sigma$ bound, which means the $\chi^2 \leq \chi^2_{\text{min}} + 1$ bound. Similarly the green dotted line represents the $2\sigma$ bound, which means the $\chi^2 \leq \chi^2_{\text{min}} + 4$ bound. The black point represents the SM case ($a_2 = a_3 = 0$), which is inside the
FIG. 5: The contour plot of $\chi^2$. The yellow dashed and green dotted lines represent the 1σ and 2σ bounds respectively. The black point represents the SM case.

1σ bound. From this contour plot, the constraints at 95% confidence level are

$$a_2 \subset [-1.26, 0.60], \ a_3 \subset [-0.95, 0.95].$$

(25)

It is more stringent than the constraints in Ref. [47], which is based on an integrated luminosity of 5.1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and an integrated luminosity of 19.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. Nevertheless, in the newly updated CMS experiment [51], the constraints of $a_2, a_3$ have been much improved, which is about $a_2 \subset [-0.09, 0.19], a_3 \subset [-0.2, 0.18]$ based on an extra luminosity of 80.2 fb$^{-1}$ at $\sqrt{s} = 13$ TeV and also the $\sqrt{s} = 7, 8$ TeV data. The new measurement has adopted the data in off-shell Higgs region, but the interference effects between anomalous Higgs mediated process and the box process are not included. Thus the current experiment is not complete. It is suggested from our study that this kind of interference in the off-shell Higgs region should be added in next experimental measurements.

V. CONCLUSION AND DISCUSSION

After adding the anomalous $HZZ$ couplings into SM, we calculate the cross sections induced by these new couplings, and especial attentions are focused on the interference effects. In principle there are three kinds of interference, the first kind is the interference between $CP$-even Higgs mediated process and the continuum background box process, the second kind is the interference between $CP$-even Higgs mediated process and SM Higgs
mediated process, the third kind is the interference between \( CP \)-odd Higgs mediated process and all other processes. The numerical results of the integrated cross sections show that the first kind of interference could be neglected in the on-shell Higgs region but nonnegligible in the off-shell Higgs region, the second kind of interference is important both in on-shell and off-shell Higgs regions, and the third kind of interference are zero in all regions. So we emphasize that while studying the anomalous \( HZZ \) couplings in off-shell Higgs region, the interference between \( CP \)-even Higgs mediated process and continuum background is indispensable.

In this research we only show the numerical results of integrated cross sections, actually more information could be fetched from the differential cross sections. For example, the first kind of interference could have tiny but opposite values in on-shell Higgs region if checking the differential cross sections. Furthermore, the \( k \)-factors and total efficiencies should also be estimated separately according to different sources. Nevertheless, it is a first calculation of the interference between anomalous Higgs mediated process and continuum background. In the next step it could be embedded into the Monte Carlo simulation and improve the current experiment.

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**Appendix A: Helicity amplitudes for the process** \( H \to ZZ \to e^-e^+\mu^-\mu^+ \)

The helicity amplitudes \( A_1, A_2 \) and \( A_3 \) are shown separately. The common factor \( f \) is defined as

\[
f = -2ie^3 \frac{1}{M_W \sin \theta_W} \frac{P_Z(s_{34})}{s_{34}} \frac{P_Z(s_{56})}{s_{56}}.
\]
\begin{align}
A_1^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times l_e^2 \frac{M_W^2}{\cos^2 \theta_W} \langle 35 \rangle [46], \\
A_1^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times l_e r_e \frac{M_W^2}{\cos^2 \theta_W} \langle 36 \rangle [45], \\
A_1^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times l_e r_e \frac{M_W^2}{\cos^2 \theta_W} \langle 45 \rangle [36], \\
A_1^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times r_e^2 \frac{M_W^2}{\cos^2 \theta_W} \langle 46 \rangle [35].
\end{align}

(A1)

\begin{align}
A_2^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times l_e^2 \times \\
&\left[ -2k \cdot k' \langle 35 \rangle [46] - \langle 35 \rangle [45] + \langle 36 \rangle [46] \right] \\
A_2^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times l_e r_e \times \\
&\left[ -2k \cdot k' \langle 36 \rangle [45] - \langle 35 \rangle [45] + \langle 36 \rangle [46] \right] \\
A_2^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times r_e l_e \times \\
&\left[ -2k \cdot k' \langle 45 \rangle [36] - \langle 35 \rangle [35] + \langle 46 \rangle [36] \right] \\
A_2^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times r_e^2 \times \\
&\left[ -2k \cdot k' \langle 46 \rangle [35] - \langle 35 \rangle [35] + \langle 46 \rangle [36] \right].
\end{align}

(A2)

\begin{align}
A_3^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times i l_e^2 \times \\
&\left[ 2(k \cdot k' + \langle 46 \rangle [46]) \langle 35 \rangle [46] + \langle 35 \rangle [45] \langle 36 \rangle [36] + \langle 45 \rangle [46] \right] \\
A_3^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times i l_e r_e \times \\
&\left[ 2(k \cdot k' + \langle 45 \rangle [45]) \langle 36 \rangle [45] + \langle 36 \rangle [46] \langle 35 \rangle [35] + \langle 46 \rangle [45] \right] \\
A_3^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times i r_e l_e \times \\
&\left[ 2(k \cdot k' + \langle 36 \rangle [36]) \langle 45 \rangle [36] + \langle 45 \rangle [35] \langle 45 \rangle [46] + \langle 35 \rangle [36] \right] \\
A_3^{H \rightarrow ZZ \rightarrow 2e\mu} (3_{e^-}, 4_{e^+}, 5_{\mu^-}, 6_{\mu^+}) &= f \times i r_e^2 \times \\
&\left[ 2(k \cdot k' + \langle 35 \rangle [35]) \langle 46 \rangle [35] + \langle 46 \rangle [36] \langle 46 \rangle [45] + \langle 36 \rangle [35] \right].
\end{align}

(A3)
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