Higgs boson decays to a lepton pair and a $Z$ boson

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Abstract

The discovery of the Standard Model (SM) Higgs boson at the LHC completed the theory of electroweak and strong interactions. To determine the Higgs boson’s intrinsic properties, more measurements on its various decay channels are still necessary. In this paper, we investigate $H \rightarrow \ell \bar{\ell} Z$ and $H \rightarrow \nu \bar{\nu} \ell Z$ (with $\ell = e, \mu, \tau$) processes at the next-to-leading order electroweak accuracy. The total decay widths, and the differential decay rates with respect to various kinematic variables are obtained. For a typical choice of cut on the invariant mass of lepton pair, we find the branching ratios $\mathcal{B}(H \rightarrow \ell \bar{\ell} Z) = 7.5 \times 10^{-4}$ (with $\ell = e, \mu$), $\mathcal{B}(H \rightarrow \tau^- \tau^+ Z) = 7.3 \times 10^{-4}$, and $\mathcal{B}(H \rightarrow \nu \bar{\nu} \ell Z) = 1.5 \times 10^{-3}$ (with $\ell = e, \mu, \tau$), which are attainable in the LHC experiments.
I. INTRODUCTION

In the standard model (SM) of particle physics, the Higgs boson is inherently related to the mechanism of spontaneous symmetry breaking (SSB) [1–3]. The observation of Higgs boson in 2012 [4, 5] marked a key milestone in particle physics. Further measurements of its spin, parity and couplings have shown no significant deviation from the SM predictions. Nevertheless, it’s conceivable that much more detailed and precise investigations are required to verify the SSB mechanism and search for new physics beyond the SM.

The coupling of Higgs boson to SM particles is a major topic in Higgs physics. To date, the CMS and ATLAS Collaborations have studied the Higgs coupling to $W$ bosons [6–9], $Z$ bosons [9–13], $\tau$ leptons [14–16], $b$ quarks [17, 18], $t$ quarks [19, 20], and photons [21, 22]. Due to the small value of the mass, the Higgs direct coupling to the first two generation leptons is difficult to be measured. Hence more studies are focused on the rare decay processes $H \to \ell\ell\gamma$ (with $\ell = e, \mu$) [23–29], from which the indirect coupling of Higgs to $\ell\ell\gamma$ can be obtained.

In this paper we investigate the decays $H \to \ell\ell Z$ and $H \to \nu_\ell\bar{\nu}_\ell Z$ with $\ell = e, \mu, \tau$, at next-to-leading order (NLO) electroweak accuracy. Experimentally, the $Z$ boson may be reconstructed through its leptonic decay into electron or muon pair. Hence the final state signal is in fact four leptons. Although the Higgs to four leptons processes have been studied at NLO in Refs. [30–32], our investigation here is phenomenologically meaningful for following three reasons:

1. The $H \to \ell\ell Z$ process as an independent process is worthy of an independent calculation, from which we may obtain the informations about Higgs indirect coupling to $\ell\ell Z$.

2. In our evaluation all lepton masses are kept, whose effects are evident for $H \to \tau^-\tau^+ Z$ process, while the mass effects were neglected in previous studies Refs. [30–32].

3. $H \to \nu_\ell\bar{\nu}_\ell Z$ process may be employed to verify the number of active neutrinos, and hence the generations of fermions, which were found to be $2.984 \pm 0.008$ in the LEP experiment [33].

The rest of the paper is organized as follows. In Section II, we clear up the adopted convention and give explicit results for the tree-level amplitudes. In Section III, some tech-
nical details in the calculation of NLO corrections are given. In Section IV, the numerical evaluation for concerned processes is performed. The last section is remained for summary and conclusions.

II. CONVENTION AND LEADING-ORDER CALCULATION

In this section, we present the convention and primary formulas for the leading-order (LO) calculations of $H \rightarrow \ell \bar{\ell} Z$ processes. The LO formulas for $H \rightarrow \nu \ell \bar{\nu} Z$ can be obtained by taking the limit $m_\ell \rightarrow 0$, where $m_\ell$ denotes the mass of lepton $\ell$.

Consider processes 

$$H(p_1) \rightarrow \ell(p_2) + \bar{\ell}(p_3) + Z(p_4),$$

where $\ell = e, \mu, \tau$, the external particles are all on their mass shell: $p_1^2 = m_H^2$, $p_2^2 = p_3^2 = m_\ell^2$, and $p_4^2 = m_Z^2$. The Mandelstam invariants are defined as $s = (p_2 + p_3)^2$, $t = (p_3 + p_4)^2$, $u = (p_2 + p_4)^2$, and $s + t + u = m_H^2 + 2m_\ell^2 + m_Z^2$. Throughout the calculation, the 't Hooft-Feynman gauge is adopted, and all lepton masses of are kept, hence their couplings to Higgs boson.

At the LO, there are four Feynman diagrams contributing to processes (1), which are shown in Fig. 1. With some simplification, the tree-level amplitude can be expressed as

$$M_{\text{tree}} = \frac{e^2}{4c_w s_w m_W} \left\{ - \left( \frac{p_3 \cdot \varepsilon}{m_\ell^2 - t} + \frac{p_2 \cdot \varepsilon}{m_\ell^2 - u} + \frac{2p_1 \cdot \varepsilon}{m_Z^2 - s} \right) m_\ell \bar{u}(p_2) \gamma_5 v(p_3) 
+ \left( \frac{m_\ell^2}{m_\ell^2 - t} + \frac{m_\ell^2}{m_\ell^2 - u} + \frac{m_Z^2}{m_Z^2 - s} \right) \bar{u}(p_2) \gamma_5 v(p_3) 
+ \left( \frac{1}{m_\ell^2 - t} - \frac{1}{m_\ell^2 - u} \right) \frac{m_\ell^2}{2} \bar{u}(p_2) \gamma_5 v(p_3) \right\} + e^2 (4s_w^2 - 1) \left\{ \left( \frac{p_3 \cdot \varepsilon}{m_\ell^2 - t} - \frac{p_2 \cdot \varepsilon}{m_\ell^2 - u} \right) m_\ell \bar{u}(p_2) v(p_3) 
+ \frac{m_Z^2}{m_Z^2 - s} \bar{u}(p_2) v(p_3) + \left( \frac{1}{m_\ell^2 - t} + \frac{1}{m_\ell^2 - u} \right) \frac{m_\ell^2}{2} \bar{u}(p_2) v(p_3) \right\}.$$

Here $e$ is the electromagnetic coupling constant; $c_w = \frac{m_W}{m_Z}$ and $s_w = \sqrt{1 - c_w^2}$ are the sine and cosine of weak mixing angle respectively; $\varepsilon$ denotes the polarization vector of $Z$ boson.

With the amplitude in Eq. (2), LO decay width can be readily obtained, i.e.

$$\Gamma_{\text{LO}} = \frac{1}{2m_H} \int d\Phi_3 \sum_{\text{pol}} |M_{\text{tree}}|^2,$$

(3)
FIG. 1: Tree-level Feynman diagrams for $H \rightarrow \ell \bar{\ell} Z$ processes, where $G^0$ represents Goldstone boson.

where $d\Phi_3$ is the three-body phase space, can be expressed as

$$\int d\Phi_3 = \frac{1}{128\pi^3m_H^2} \int_{4m_l^2}^{(m_H - m_Z)^2} ds \int_{t^-}^{t^+} dt ,$$

with

$$t^\pm = \frac{1}{2} \left\{ m_H^2 + 2m_l^2 + m_Z^2 - s \pm \sqrt{\left(1 - \frac{4m_l^2}{s}\right)\left[(m_H^2 + m_Z^2 - s)^2 - 4m_H^2m_Z^2]\right]} \right\}. \quad (5)$$

III. NLO CORRECTIONS

In this section, we elucidate some technical details in the NLO calculations of $H \rightarrow \ell \bar{\ell} Z$ processes. Since the NLO calculations of $H \rightarrow \nu \bar{\nu} \ell Z$ processes have no real corrections, they are similar and simpler.

A. Virtual corrections

The NLO virtual corrections to processes (1) come from self-energy, triangle, box and counter-term diagrams, which are schematically shown in Fig. 2. The contribution from virtual corrections can be formulated as

$$\Gamma_{\text{virtual}} = \frac{1}{2m_H} \int d\Phi_3 \sum_{\text{pol}} 2\text{Re}(\mathcal{M}_{\text{virtual}}\mathcal{M}_{\text{tree}}^\ast) . \quad (6)$$

In the computation of $\text{Re}(\mathcal{M}_{\text{virtual}}\mathcal{M}_{\text{tree}}^\ast)$, the conventional dimensional regularization with $D = 4 - 2\epsilon$ is adopted to regularize the ultraviolet (UV) divergences, and an infinitesimal photon mass $m_\gamma$ is introduced to regularize the infrared (IR) divergences.
FIG. 2: Representative Feynman diagrams in virtual corrections.

According to the power counting rule, the UV divergences arise from self-energy and triangle diagrams, and are removed through renormalization procedure. Here we use the counter-term approach. Of the renormalization condition, we follow the implementation of Ref. [34]. After including counter-term diagrams, all UV singularities, which appear as $1/\epsilon$ pole, are canceled with each other.

The IR divergences arise from the structure where two external legs connected by photon, like Fig. 2(e)(g), or from self-energy corrections to external lines, which are embodied in on-shell renormalization constants. The IR singularities, appearing as $\ln(m_\gamma)$ terms, can be extracted from the corresponding Passarino-Veltman integrals:

$$C_0(m_\ell^2, m_\ell^2, s, m_\ell^2, m_\gamma^2, m_\ell^2) \sim \frac{\ln(y) + i\pi}{\sqrt{s(s-4m_\ell^2)}} \ln(m_\gamma^2),$$

$$D_0(m_H^2, m_\ell^2, m_\ell^2, m_Z^2, u, s, m_\ell^2, m_\ell^2, m_\gamma^2, m_\ell^2) \sim \frac{1}{m_\ell^2-u} \frac{\ln(y) + i\pi}{\sqrt{s(s-4m_\ell^2)}} \ln(m_\gamma^2),$$

$$D_0(m_H^2, m_\ell^2, m_\ell^2, m_Z^2, t, s, m_\ell^2, m_\ell^2, m_\gamma^2, m_\ell^2) \sim \frac{1}{m_\ell^2-t} \frac{\ln(y) + i\pi}{\sqrt{s(s-4m_\ell^2)}} \ln(m_\gamma^2),$$
\[
\frac{d}{ds} B_0(s, m_\gamma^2, m_\ell^2) \bigg|_{s=m_\ell^2} \sim -\frac{1}{2m_\ell^2} \ln(m_\gamma^2),
\] (10)
with
\[
y = \frac{\sqrt{s-\sqrt{s^2-4m_\ell^2}}}{\sqrt{s+\sqrt{s^2-4m_\ell^2}}},
\] (11)
Note, the imaginary parts of Eqs. (7) (8) (9) do not contribute to \( \text{Re}(M_{\text{virtual}}; M_{\text{tree}}^*) \), while the real parts should be canceled by their counterparts in real corrections.

B. Real corrections

The real corrections are induced by the processes\(^1\)
\[
H(p_1) \rightarrow \ell(p_2) + \bar{\ell}(p_3) + Z(p_4) + \gamma(p_5),
\] (12)
whose Feynman diagrams are representatively shown in Fig. 3. The independent Lorentz invariants are chosen as \((p_2 + p_5)^2 = s_1\), \((p_3 + p_5)^2 = s_2\), \((p_3 + p_4)^2 = s_3\), \((p_1 - p_2)^2 = t_1\), and \((p_1 - p_4)^2 = t_2\). The IR divergences in real corrections are also regularized by infinitesimal photon mass. To isolate the IR singular terms, we use the subtraction method which formulated in Ref. [35].

Following the implementation of Ref. [35], the contribution of real corrections can be separated into two parts:

\[
\Gamma_{\text{real}} = \Gamma_{\text{real}}^A + \Gamma_{\text{real}}^B
\] (13)
with
\[
\Gamma_{\text{real}}^A = \frac{1}{2m_H} \int d\Phi_4 \left( \sum_{\text{pol}} |M_{\text{real}}|^2 - |M_{\text{sub}}|^2 \right),
\] (14)
\(^1\) The IR divergence is absent in the calculation of \( H \rightarrow \nu_\ell \bar{\nu}_\ell Z \) processes.
Here \( |M_{\text{sub}}|^2 \) is an auxiliary subtraction function which possesses the same asymptotic behavior as \( \sum_{\text{pol}} |M_{\text{real}}|^2 \) in the singular limits, \( d\Phi_4 \) stands for the four-body phase space.

The \( |M_{\text{sub}}|^2 \) in \( \Gamma^A_{\text{real}} \) can be constructed as

\[
|M_{\text{sub}}|^2 = \frac{2e^2}{m_f^2 - s_1} \left( 1 - \frac{2m_f^2}{m_f^2 - s_1} + \frac{s_1 + s_2 - t_2}{m_f^2 - s_1 - s_2} \right) \left[ \frac{-t_2(4m_f^2 - t_2)}{m_f^2 - 2m_f^2(s_1 + t_2) + (s_1 - s_2)^2} \right]^{1/2} \times \sum_{\text{pol}} |M_{\text{tree}}(s', t')|^2 + \left\{ \begin{array}{l} s_1 \to s_2 \\ t_1 \to t_2 \\ \end{array} \right. 
\]

\[
\] (16)

Here the second term corresponds to the \( p_2 \leftrightarrow p_3 \) crossing transformation. The primes in the superscripts of \( s \) and \( t \) indicate the mapping of invariants \( 1 \to 3 \) and \( 1 \to 4 \):

\[
s' = t_2, \quad t' = \frac{1}{2} \left( m_f^2 + m_2^2 + m_Z^2 - t_2 \right) - \frac{1}{2} \left( m_f^2 (m_f^2 - s_1 + t_2) \\ - m_Z^2 (m_f^2 - s_1 - t_2) + t_2 (m_f^2 + s_1 - 2s_3 - t_2) \right) \left[ \frac{-t_2(4m_f^2 - t_2)}{m_f^2 - 2m_f^2(s_1 + t_2) + (s_1 - s_2)^2} \right]^{1/2} .
\]

(17)

With the subtraction function presented in Eq. (16), the phase-space integration of \( \Gamma^A_{\text{real}} \) is non-singular, and can be performed numerically without any regulator. In rest frame of Higgs boson, the four-body phase space can be chosen as

\[
\int d\Phi_4 = \frac{1}{4096 m_H^2 \pi^6} \int_{4m_f^2}^{(m_H - m_Z)^2} dM_2^2 \int_{m_f^2}^{(m_H - M_{23})^2} dM_3^2 \int_{t_2^+}^{t_2^-} dt_2 \int_{t_1^-}^{t_1^+} dt_1 \int_0^{2\pi} d\eta \frac{1}{\lambda} ,
\]

(18)

with

\[
\lambda = \left[ (m_f^2 - M_{23}^2 - M_{45}^2)^2 - 4M_{23}^2 M_{45}^2 \right]^{1/2},
\]

(19)

\[
t_2^\pm = M_{23} + \frac{1}{2} \left( 1 - \frac{m_f^2}{M_{45}} \right) (m_f^2 - M_{23}^2 - M_{45}^2 \pm \lambda),
\]

(20)

\[
t_1^\pm = \frac{1}{2} \left( m_f^2 - M_{23}^2 + M_{45}^2 + 2m_f^2 \pm \lambda \sqrt{1 - \frac{4m_f^2}{M_{23}^2}} \right).
\]

(21)

Here, \( M_{ij}^2 = (p_i + p_j)^2 \); \( \eta \) is defined as the azimuthal angle between \( \{ \vec{p}_2, \vec{p}_3 \} \) and \( \{ \vec{p}_4, \vec{p}_5 \} \) planes, with \( \vec{p}_2 + \vec{p}_3 \) being in the positive z-axis direction.

The \( \int [dp_5] |M_{\text{sub}}|^2 \) in \( \Gamma^B_{\text{real}} \) can be expressed as

\[
\int [dp_5] |M_{\text{sub}}|^2 = \left\{ 3 + \frac{m_f^2}{(m_f^2 - s)^2} + 2 \ln \left( \frac{m_f^2 m_s (m_f^2 - s)^2}{s(2m_f^2 - s)^2} \right) - \frac{2m_f^2 - s}{\sqrt{s(4m_f^2 - s)}} \left[ 4\text{Li}_2(y) + 8\text{Li}_2(-y^{1/2}) - 8\text{Li}_2(-y^{3/2}) + 2 \ln(y) \ln \left( \frac{m_f^2 m_s^2}{s(4m_f^2 - s)} \right) - 3 \ln(y)^2 - \frac{2\pi^2}{3} \right] \right\} \frac{e^2}{8\pi^2} \sum_{\text{pol}} |M_{\text{tree}}|^2 .
\]

(22)
After summing up $\text{Re}(\mathcal{M}_{\text{virtual}}\mathcal{M}_{\text{tree}}^*)$ and $\int [dp_{5}][\mathcal{M}_{\text{sub}}]^2$, the $\ln(m^2_{\ell})$ terms cancel with each other as expected. In addition, the $\ln(m^2_{\ell})$ terms, which embodies the IR-collinear divergence in $m_{\ell} \to 0$ limit, are also canceled.

IV. NUMERICAL RESULTS

In numerical calculation, we use the following set of input parameters\cite{36},

\[
\begin{align*}
\alpha(m_Z) &= 1/133.2, \quad m_H = 125.1 \text{ GeV}, \quad m_W = 80.38 \text{ GeV}, \quad m_Z = 91.19 \text{ GeV}, \\
&\quad m_e = 0.5110 \text{ MeV}, \quad m_\mu = 105.6 \text{ MeV}, \quad m_\tau = 1.777 \text{ GeV}, \\
&\quad m_u = 2.16 \text{ MeV}, \quad m_d = 4.67 \text{ MeV}, \quad m_s = 93 \text{ MeV}, \\
&\quad m_c = 1.27 \text{ GeV}, \quad m_b = 4.18 \text{ GeV}, \quad m_t = 172.8 \text{ GeV}.
\end{align*}
\]

A kinematic cut on the invariant mass of lepton or neutrino pair is implemented, that is $M^2_{23} \geq M^2_{\text{cut}}$, with $M^2_{23} = (p_2 + p_3)^2$ and $M^2_{\text{cut}} = 0, 6, \text{ or } 12 \text{ GeV}$.

The LO and NLO decay widths of various channels are presented in Table I.\footnote{\ref{footnote}} We find that the total widths are about one order of magnitude larger than that of $H \to \ell\bar{\ell}\gamma$ and $H \to \nu\bar{\nu}\ell\bar{\ell}$ processes, respectively. The NLO corrections, which are about 9\% for $H \to \ell\bar{\ell}Z$ and 5\% for $H \to \nu\bar{\nu}\ell\bar{\ell}$, are more significant than that of $H \to 4 \text{ leptons}$ and $H \to \nu eW$ processes. With a total Higgs width of 4.1 MeV\cite{40}, we then have the branching fractions:

\[
\begin{align*}
\mathcal{B}(H \to \ell\bar{\ell}Z) &= 7.5 \times 10^{-4}, \quad (\ell = e, \mu), \\
\mathcal{B}(H \to \tau\bar{\tau}Z) &= 7.3 \times 10^{-4},
\end{align*}
\]

with $M^2_{\text{cut}} = 6 \text{ GeV}$, and

\[
\begin{align*}
\mathcal{B}(H \to \nu\bar{\nu}\ell\bar{\ell}) &= 1.5 \times 10^{-3}, \quad (\ell = e, \mu, \tau),
\end{align*}
\]

with $M^2_{\text{cut}} = 0$.

The differential decay rates of $H \to \ell\bar{\ell}Z$ processes with respect to $M_{23}$ are shown in Fig.\footnote{\ref{fig}} For comparison, we single out the gauge-invariant contribution via $H \to Z^*Z \to \ell\bar{\ell}Z$.

2 Although we keep the lepton mass precisely, the difference between $\Gamma_{eeZ}$ and $\Gamma_{\mu\mu Z}$, as well as the differences between $\Gamma_{\nu_e\bar{\nu}_eZ}$, $\Gamma_{\nu_\mu\bar{\nu}_\muZ}$ and $\Gamma_{\nu_\tau\bar{\nu}_\tauZ}$ are invisible under the numerical accuracy.
TABLE I: The NLO decay widths (with LO results in parentheses) for various decay channels and cuts on $M_{23}^{\text{cut}}$.

| $M_{23}^{\text{cut}}$ (GeV) | $\Gamma_{\ell\ell Z}$ (keV) with $\ell = e, \mu$ | $\Gamma_{\tau\tau Z}$ (keV) | $\Gamma_{\nu\nu Z}$ (keV) with $\ell = e, \mu, \tau$ |
|--------------------------|-----------------|-----------------|-----------------|
| 0                        | 3.167 (2.896)   | 3.041 (2.780)   | 6.019 (5.726)   |
| 6                        | 3.077 (2.812)   | 2.996 (2.738)   | 5.845 (5.560)   |
| 12                       | 2.791 (2.548)   | 2.722 (2.486)   | 5.299 (5.039)   |

mechanism, which includes both $Z^* \rightarrow \ell\bar{\ell}$ and $G^0 \rightarrow \ell\bar{\ell}$ structures. We find that at LO the $H \rightarrow Z^*Z \rightarrow \ell\bar{\ell}Z$ mechanism may occupy 99.9% of the full result, and it decreases to 98% with NLO corrections.

FIG. 4: Differential decay rates with respect to the invariant mass of lepton pair, where (a) for $H \rightarrow \ell\bar{\ell}Z$ with $\ell = e, \mu$; (b) for $H \rightarrow \tau^-\tau^+Z$.

The differential decay rates with respect to $\theta$ are shown in Fig. 5, where $\theta$ is the angle between $\ell$ lepton and $Z$ boson in the rest frame of Higgs. By defining the forward-backward asymmetry as

$$A = \frac{\int_{0}^{\pi/2} (d\Gamma/d\theta) d\theta - \int_{\pi/2}^{\pi} (d\Gamma/d\theta) d\theta}{\int_{0}^{\pi/2} (d\Gamma/d\theta) d\theta + \int_{\pi/2}^{\pi} (d\Gamma/d\theta) d\theta}$$

we have

$$A^{(e,\mu)} = 0.690, \quad A^{(\tau)} = 0.695,$$

with $M_{23}^{\text{cut}} = 6$ GeV. Here the NLO corrections are found less than 0.1%.
FIG. 5: Differential decay rates vs the angle between $\ell$ and $Z$ with $M_{23}^{\text{cut}} = 6$ GeV, where (a) for $H \to \ell\ell Z$ with $\ell = e, \mu$; (b) for $H \to \tau^-\tau^+Z$.

FIG. 6: Differential decay rate of $H \to \nu_l\bar{\nu}_lZ$ processes vs the energy of $Z$ with no cut on $M_{23}$.

For $H \to \nu_l\bar{\nu}_lZ$ processes, the final state neutrinos are invisible in LHC experiments. The differential decay rates with respect to $E_4$ are shown in Fig. [8] where $E_4$ is the energy of $Z$ boson in the rest frame of Higgs. By confronting $N_\nu d\Gamma/dE_4$ to the experimental measurement, one may obtain the number of active neutrinos $N_\nu$, which is assumed to be 3 in the SM in account of the measurement $2.984 \pm 0.008$ in LEP experiment [33].

V. SUMMARY

In this work, we investigate the Higgs decays to a lepton pair and a $Z$ boson processes at the NLO electroweak accuracy. The total decay width, as well as the differential decay rates with respect to various kinematic variables are presented. Numerical results show that the impacts of NLO corrections are about 9% for $H \to \ell\ell Z$ processes, and 5% for
$H \rightarrow \nu \bar{\nu} \ell Z$ processes. For a typical choice of cut on invariant mass of lepton pair, we find the branching ratios $B(H \rightarrow \ell \bar{\ell} Z) = 7.5 \times 10^{-4}$ (with $\ell = e, \mu$), $B(H \rightarrow \tau \bar{\tau} Z) = 7.3 \times 10^{-4}$, and $B(H \rightarrow \nu \bar{\nu} \ell Z) = 1.5 \times 10^{-3}$ (with $\ell = e, \mu, \tau$). Our results indicate that the processes concerned are attainable in the LHC experiments, and the quest for fermion generation issue, one of the great mysteries of nature, at hadron collider LHC is tempting.

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