Effects of Anomalous Higgs Couplings in Higgs Boson Decays

Jian Jun liu

Center for High Energy Physics and Department of Physics,
Tsinghua University

Motivation

Present status of the Standard Model: Hierarchy, unclear Electroweak symmetry Breaking mechanism, ... which make us believe that SM is only an effective theory at some scale.One of the most important goal of future colliders(LHC) is searching for Higgs boson(s),and the SM Higgs is a light Higgs:

$$114.4GeV \leq m_H \leq 186GeV \tag{1}$$

S.Eidelmam et al.Phys.Lett.B 592(2004)1;C.Diacono,Int.J.Mod.Phys. A21 (2006) 1604
a SM Higgs boson can decay into fermions,massive gauge bosons, and there also are loop induced channels which Higgs decay into $\gamma\gamma$,γZ,gg...

The Decay of SM Higgs

New physics at TeV scale
A. Higgsless theory
B. New models with Higgs bosons
Even in models beyond the SM with a light Higgs(little Higgs, MSSM...), new physics can affect its property.

A. Linear realized effective Lagrangian
B. Non-linear realized effective Lagrangian

The Decay of SM Higgs

New physics at TeV scale
A. Higgsless theory
B. New models with Higgs bosons
Even in models beyond the SM with a light Higgs(little Higgs, MSSM...), new physics can affect its property.

A. Linear realized effective Lagrangian
B. Non-linear realized effective Lagrangian

Anomalous Couplings and Higgs Decay

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

When constructing such an extension of the SM, gauge invariance under $SU(2) \times U(1)$ is required and, in addition we assume that $\Lambda \gg v$, where $v \doteq 246\,\text{GeV}$ is the usual electroweak scale. This corresponds to the so-called “decoupling scenario”, in which the $SU(2) \times U(1)$ symmetry is realized linearly.t The unphysical Goldstone bosons enter via the standard complex $SU(2)$ doublet, along with the elementary Higgs boson field and, generally, the low-energy spectrum is supposed to be identical with that of SM.

Linear Effective Lagrangian

$$\mathcal{O}_{WWW} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_{\rho}^{\mu}],$$
$$\mathcal{O}_{WW} = \Phi^{\dagger}\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi,$$
$$\mathcal{O}_{BW} = \Phi^{\dagger}\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi,$$
$$\mathcal{O}_{DW} = \mathrm{Tr}\big([D_{\mu},\hat{W}_{\nu\rho}][D^{\mu},\hat{W}^{\nu\rho}]\big),$$
$$\mathcal{O}_{DB} = -\frac{g'^2}{2}\left(\partial_{\mu}B_{\nu\rho}\right)\left(\partial^{\mu}B^{\nu\rho}\right),$$
$$\mathcal{O}_{BB} = \Phi^{\dagger}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi,$$
$$\mathcal{O}_{W} = (D_{\mu}\Phi)^{\dagger}\hat{W}^{\mu\nu}(D_{\nu}\Phi),$$
$$\mathcal{O}_{B} = (D_{\mu}\Phi)^{\dagger}\hat{B}^{\mu\nu}(D_{\nu}\Phi),$$
$$\mathcal{O}_{\Phi,1} = (D_{\mu}\Phi)^{\dagger}\,\Phi^{\dagger}\Phi\,(D^{\mu}\Phi),$$

Linear Effective Lagrangian

$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu \left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right),$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3 .$$

$$\mathcal{O}_{8,1} = (\Phi^\dagger\tau^i\Phi)(\Phi^\dagger\tau^j\Phi)\hat{W}_{\nu\rho}\hat{W}^{\nu\rho},$$

$$\mathcal{O}_{8,3} = (\Phi^\dagger\Phi)^2 B_{\nu\rho}B^{\nu\rho},$$

$$\mathcal{O}_{t1} = (\Phi^\dagger\Phi)(\bar{q}_L t_R\widetilde{\Phi} + \bar{t}_R\widetilde{\Phi}^\dagger q_L) \quad ,$$

$$\mathcal{O}_{Dt} = (\bar{q}_L D_\mu t_R)D^\mu\widetilde{\Phi} + D^\mu\widetilde{\Phi}^\dagger((D_\mu\bar{t}_R)\, q_L) \quad ,$$

$$\mathcal{O}_{tW\Phi} = (\bar{q}_L\sigma^{\mu\nu}t_R)\widetilde{\Phi}\hat{W}_{\mu\nu} + \widetilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu}q_L)\hat{W}_{\mu\nu} \quad ,$$

$$\mathcal{O}_{tB\Phi} = (\bar{q}_L\sigma^{\mu\nu}t_R)\widetilde{\Phi}B_{\mu\nu} + \widetilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu}q_L)B_{\mu\nu} \quad ,$$

$$\mathcal{O}_{tG\Phi} = \left[(\bar{q}_L\sigma^{\mu\nu}\lambda^a t_R)\widetilde{\Phi} + \widetilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu}\lambda^a q_L)\right] G^a_{\mu\nu} \quad ,$$

Linear Effective Lagrangian

$$\hat{B}_{\mu\nu} = \frac{1}{2} i g' B_{\mu\nu}, \qquad \hat{W}_{\mu\nu} = i g \frac{\sigma^a}{2} W^a_{\mu\nu}, \tag{3}$$

with σ^a being the standard Pauli matrices and

$$B_\mu = -\sin\theta_W Z_\mu + \cos\theta_W A_\mu \tag{4}$$

$$W^\mp_\mu = \frac{1}{\sqrt{2}} (W^1_\mu \pm i W^2_\mu). \tag{5}$$

The covariant derivative acting on the isospin doublet Φ has the form

$$D_\mu = \partial_\mu + \frac{i}{2} g' B_\mu + i g \frac{\sigma^a}{2} W^a_\mu. \tag{6}$$

The Higgs boson field is introduced by means of the Φ in the usual way

Linear Effective Lagrangian

$$Htt = i\frac{\sqrt{2}}{\Lambda^2}v(f_{tW\Phi} + f_{tB\Phi})\sigma^{\mu\nu}(k_1 - k_2)_\nu,$$

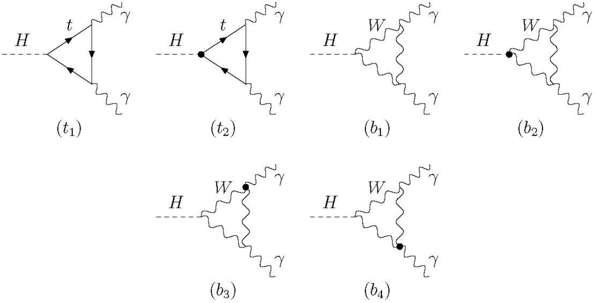
$$H\gamma\gamma = i\frac{gm_W}{\Lambda^2}2s^2(f_{BB} + f_{WW})[g^{\alpha\beta}(k_1 \cdot k_2) - k_1^\beta k_2^\alpha]$$

$$HW^+W^- = i\frac{gm_W}{\Lambda^2}\Big\{\frac{f_W}{2}[(k_1^\alpha k_1^\beta + k_2^\alpha k_2^\beta) - g^{\alpha\beta}(k_1^2 + k_2^2)]$$
$$+(f_W - 2f_{WW})[k_2^\alpha k_1^\beta - g^{\alpha\beta}(k_1 \cdot k_2)]\Big\}$$

Linear Effective Lagrangian

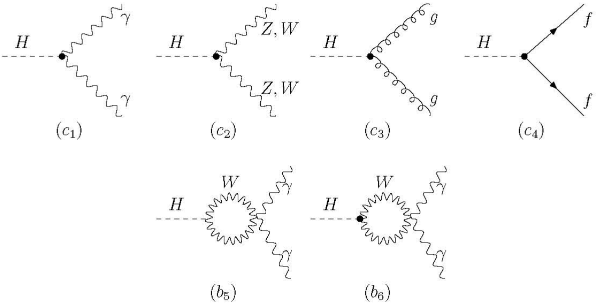
There already are some works in this framework:
tree level branching ratios, see M.C. Gonzalez-Garcia, Int.J.Mod.Phys. A14 (1999) 3121
fermions loop contributions to the partial width and Dim-8 contributions, J.M.Hernandez etal PRD51(1995)R2044
bosons loop contributions to the partial width, J.Horejsi, K.Kampf, Mod.Phys.Lett. A19 (2004) 1681
A comprehensive investigation of the branching ratios is very important.

Feynmann Diagrams



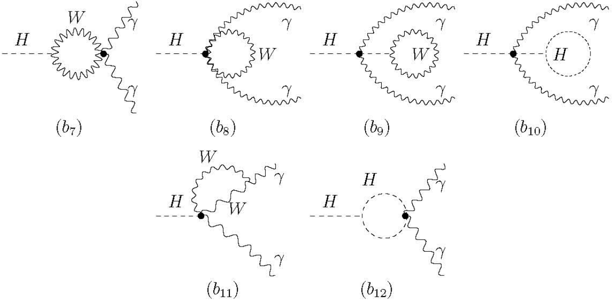
Effects of Anomalous Higgs Couplings in Higg

Feynmann Diagrams



Effects of Anomalous Higgs Couplings in Higg

Feynmann Diagrams



Linear Effective Lagrangian

$$\Gamma(H \to ZZ) = \frac{m_H^3}{32\pi}\sqrt{1-x_Z} \quad \left\{2\left[\frac{x_Z}{2v} + (x_Z - 2)g_{HZZ}^{(2)} - g_{HZZ}^{(1)}\right]^2 + \left[\frac{1}{v} - x_Z(\frac{1}{2v} + g_{HZZ}^{(2)}) - g_{HZZ}^{(1)}\right]^2\right\}, \tag{7}$$

$$\Gamma(H \to W^+W^-) = \frac{m_H^3}{16\pi}\sqrt{1-x_W} \quad \left\{2\left[\frac{x_W}{2v} + (\frac{x_W}{2} - 1)g_{HWW}^{(2)} - g_{HWW}^{(1)}\right]^2 + \left[\frac{1}{v} - \frac{x_W}{2}(\frac{1}{v} + g_{HWW}^{(2)}) - g_{HWW}^{(1)}\right]^2\right\}. \tag{8}$$

Linear Effective Lagrangian

where $x_Z = 4m_Z^2/m_H^2$ and $x_W = 4m_W^2/m_H^2$.

$$
\begin{aligned}
g_{HZZ}^{(1)} &= \left(\frac{gm_W}{\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \,, \\
g_{HZZ}^{(2)} &= -\left(\frac{gm_W}{\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \,, \\
g_{HWW}^{(1)} &= \left(\frac{gm_W}{\Lambda^2}\right)\frac{f_W}{2} \,, \\
g_{HWW}^{(2)} &= -\left(\frac{gm_W}{\Lambda^2}\right) f_{WW} \,.
\end{aligned}
$$

Linear Effective Lagrangian

For $H \to \gamma\gamma$,the dim-6 bosonic part have expressions like:

$$-8i\Big(f_B + f_W + 3g^2 f_{WWW})\Big) m_H^2 m_W^2 B_0(0, m_W^2, m_W^2)$$

$$- 3\ (f_{BB} + f_{WW}) m_H^4 B_0(m_H^2, m_H^2, m_H^2) + 2\Big\{ m_H^2 \Big((f_B + f_W) m_H^2 - 2(f_B + f_W$$
$$+ 12\ g^2 f_{WWW}) m_W^2 \Big) B_0(m_H^2, m_W^2, m_W^2) + 4 m_W^2 \Big[\Big(f_B + 3g^2 f_{WWW} \Big) m_H^2$$
$$- 24\ f_{WW} m_W^2 + 2\Big((f_W - 2 f_{WW}) m_H^4 - (f_B + 2(f_W - 7 f_{WW})$$
$$+ 3\ g^2 f_{WWW}) m_H^2 m_W^2 - 36 f_{WW} m_W^4 \Big) C_0(m_H^2, 0, 0; m_W^2)$$
$$+ 4\ f_{WW} m_W^2 \Big(-(m_H^2 + 6 m_W^2) C_0(m_H^2, m_H^2, 0; m_W^2)$$
$$- 2\ m_W^2(-m_H^2 + 6 m_W^2)(D_0(m_H^2; m_W^2) + 2 D_0(m_H^2, m_H^2; m_W^2))\Big) \Big] \Big\}. \quad (9)$$

The B_0, C_0 and D_0 denote the relevant Passarino-Veltman functions.

Linear Effective Lagrangian

In some new physics models, for example,in MSSM with large $tan\beta$, anomalous $H - b - \bar{b}$ coupling can influence the partial width significantly, A.Belyaev, A.Blum, R.S.Chivukula, E.H. Simmons have studied it in detail, see their paper PRD72 (2005) 055022.

In our calculations, we do not consider the anomalous $H - b - \bar{b}$ couplings

Couplings contribute to $\gamma\gamma$ mode are $f_W, f_{WW}, f_B, f_{WWW}, f_{BB}, f_{t1}, f_{Dt}, f_{tB\phi}, f_{tW\phi}$,in the contrary, only f_{WW}, f_{BB} contribute at the tree level, our results depend on these parameters in a very complicated way.

Couplings contribute to ZZ mode are f_W, f_{WW}, f_B, f_{BB}

Couplings contribute to W^+W^- mode are f_W, f_{WW}

Linear Effective Lagrangian

Constraints:
From the ΔS-ΔT bounds one obtains 95% C.L. constraints (in units of TeV^{-2}) for $m_H = 100$ GeV:

$$
\begin{aligned}
-6 &\leq f_{WWW}/\Lambda^2 \leq 3, \\
-6 &\leq f_{W}/\Lambda^2 \leq 5, \\
-4.2 &\leq f_{B}/\Lambda^2 \leq 2.0, \\
-5.0 &\leq f_{WW}/\Lambda^2 \leq 5.6, \\
-17 &\leq f_{BB}/\Lambda^2 \leq 20.
\end{aligned} \qquad (10)
$$

The triple gauge coupling data:

$$
\begin{aligned}
-31 &\leq (f_W + f_B)/\Lambda^2 \leq 68 \quad \text{for } f_{WWW} = 0, \\
-41 &\leq f_{WWW}/\Lambda^2 \leq 26 \quad \text{for } f_W + f_B = 0.
\end{aligned} \qquad (11)
$$

Linear Effective Lagrangian

Constraints:
From the ΔS-ΔT bounds one obtains 95% C.L. constraints (in units of TeV^{-2}) for $m_H = 100$ GeV:

$$\begin{aligned} -6 &\leq f_{WWW}/\Lambda^2 \leq 3, \\ -6 &\leq f_W/\Lambda^2 \leq 5, \\ -4.2 &\leq f_B/\Lambda^2 \leq 2.0, \\ -5.0 &\leq f_{WW}/\Lambda^2 \leq 5.6, \\ -17 &\leq f_{BB}/\Lambda^2 \leq 20. \end{aligned} \tag{10}$$

The triple gauge coupling data:

$$\begin{aligned} -31 \leq (f_W + f_B)/\Lambda^2 \leq 68 \quad &\text{for } f_{WWW} = 0, \\ -41 \leq f_{WWW}/\Lambda^2 \leq 26 \quad &\text{for } f_W + f_B = 0. \end{aligned} \tag{11}$$

Linear Effective Lagrangian

the Higgs searches data at the LEP2 and the Tevatron: for $m_H \leq 150$ GeV

$$-7.5 \leq \frac{f_{WW(BB)}}{\Lambda^2} \leq 18. \tag{12}$$

See B.Zhang,Y-P. Kuang,H-J. He,C.-P.Yuan Phys.Rev. D67 (2003) 114024 and references there in.

Effects of Anomalous Higgs Couplings in Higg

Linear Effective Lagrangian

the Higgs searches data at the LEP2 and the Tevatron: for $m_H \leq 150$ GeV

$$-7.5 \leq \frac{f_{WW(BB)}}{\Lambda^2} \leq 18. \tag{12}$$

See B.Zhang,Y-P. Kuang,H-J. He,C.-P.Yuan Phys.Rev. D67 (2003) 114024 and references there in.

Linear Effective Lagrangian

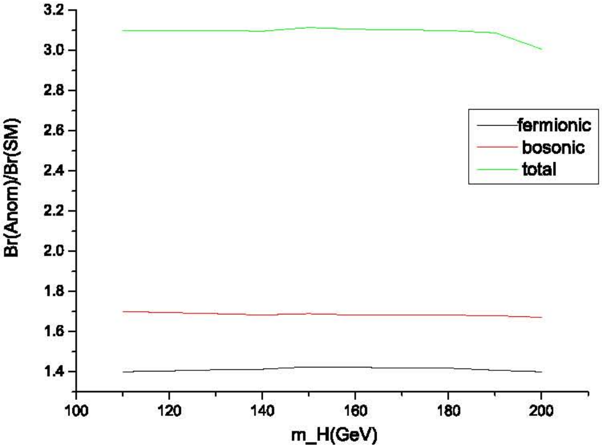
$$
\begin{aligned}
|C_{t1}| &\simeq \frac{16\pi}{3\sqrt{2}}\left(\frac{\Lambda}{v}\right), \\
C_{Dt} &\simeq 10.4 \text{ for } C_{Dt} > 0, \qquad C_{Dt} \simeq -6.4 \text{ for } C_{Dt} < 0, \\
|C_{tW\Phi}| &\simeq 2.5, \qquad |C_{tB\Phi}| \simeq 2.5 \,.
\end{aligned}
$$

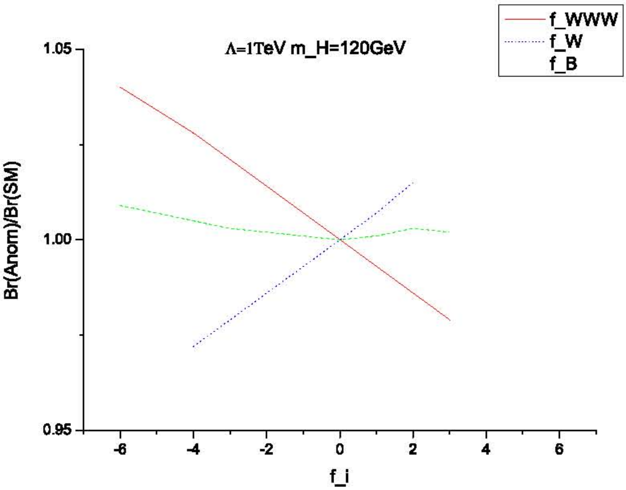
G. J. Gounaris, D. T. Papadamou, F. M. Renard, Z. Phys. **C76**, 333 (1997)

Linear Effective Lagrangian

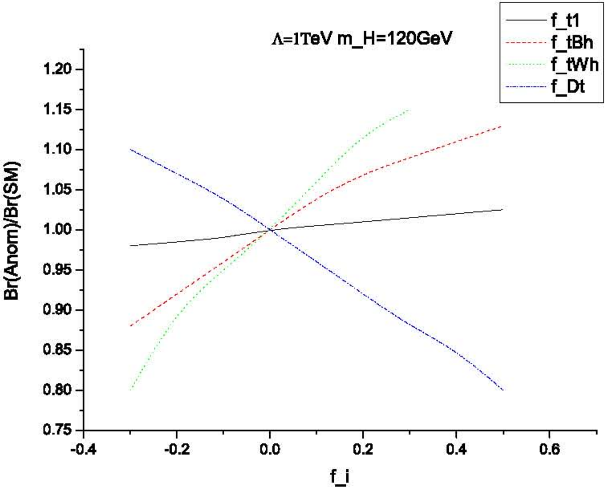
$$
\begin{aligned}
|C_{t1}| &\simeq \frac{16\pi}{3\sqrt{2}}\left(\frac{\Lambda}{v}\right), \\
C_{Dt} &\simeq 10.4 \text{ for } C_{Dt} > 0, \qquad C_{Dt} \simeq -6.4 \text{ for } C_{Dt} < 0, \\
|C_{tW\Phi}| &\simeq 2.5, \qquad |C_{tB\Phi}| \simeq 2.5\ .
\end{aligned}
$$

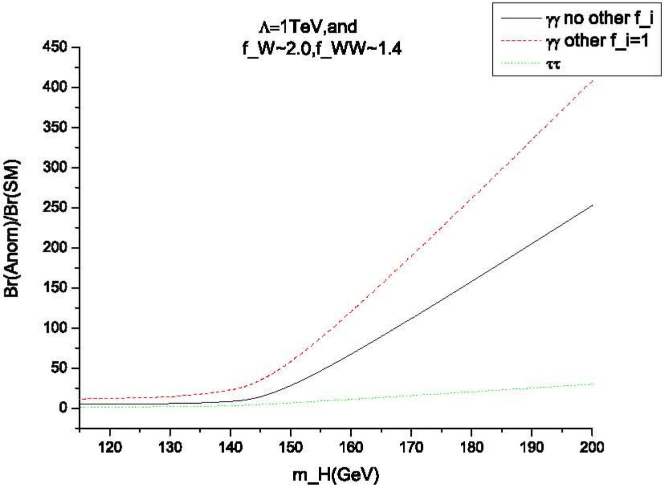
G. J. Gounaris, D. T. Papadamou, F. M. Renard, Z. Phys. **C76**, 333 (1997)

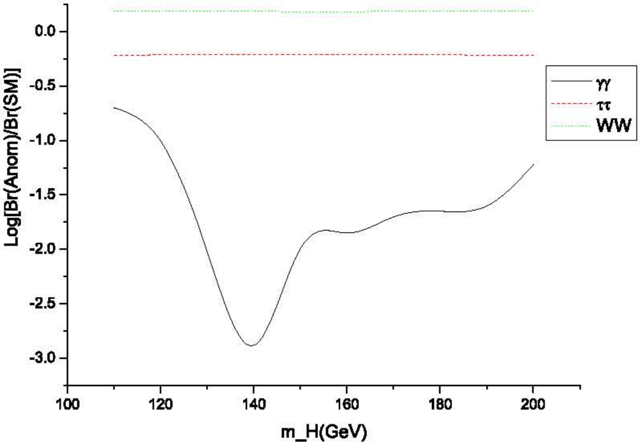

3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
Br(Anom)/Br(SM)
100
120
140
160
180
200
m_H(GeV)
fermionic
bosonic
total



Λ=1TeV m_H=120GeV
f_WWW
f_W
f_B
Br(Anom)/Br(SM)
1.05
1.00
0.95
-6
-4
-2
0
2
4
6
f_i


Λ=1TeV m_H=120GeV
f_t1
f_tBh
f_tWh
f_Dt
Br(Anom)/Br(SM)
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
-0.4
-0.2
0.0
0.2
0.4
0.6
f_i


Λ=1TeV,and
f_W~2.0,f_WW~1.4
γγ no other f_i
γγ other f_i=1
ττ
Br(Anom)/Br(SM)
m_H(GeV)
0
50
100
150
200
250
300
350
400
450
120
130
140
150
160
170
180
190
200



0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Log[Br(Anom)/Br(SM)]
100
120
140
160
180
200
m_H(GeV)
γγ
ττ
WW

Conclusions

a light Higgs boson can be very different with the SM one.

Fermion operators and dim-6 boson operators have similar contributions in magnitude.

Within the constraints of the anomalous couplings, the branching ratios of $H\gamma\gamma$ can be enhanced by 2 magnitude of order, which means such a light Higgs can be detected in this channel more easier.

The branching ratios of $H\gamma\gamma$ also can be decreased by several magnitude of order, as the WW channel partial widths are not effected by the related couplings, so the branching ratios of HWW and $H\tau\tau$ are not changed significantly, but deserve to study its influences to the light Higgs boson search, We can not rule out a light Higgs only through $H\gamma\gamma$ channel.

Conclusions

a light Higgs boson can be very different with the SM one.

Fermion operators and dim-6 boson operators have similar contributions in magnitude.

Within the constraints of the anomalous couplings, the branching ratios of $H\gamma\gamma$ can be enhanced by 2 magnitude of order, which means such a light Higgs can be detected in this channel more easier.

The branching ratios of $H\gamma\gamma$ also can be decreased by several magnitude of order, as the WW channel partial widths are not effected by the related couplings, so the branching ratios of HWW and $H\tau\tau$ are not changed significantly, but deserve to study its influences to the light Higgs boson search, We can not rule out a light Higgs only through $H\gamma\gamma$ channel.

Conclusions

a light Higgs boson can be very different with the SM one.

Fermion operators and dim-6 boson operators have similar contributions in magnitude.

Within the constraints of the anomalous couplings, the branching ratios of $H\gamma\gamma$ can be enhanced by 2 magnitude of order, which means such a light Higgs can be detected in this channel more easier.

The branching ratios of $H\gamma\gamma$ also can be decreased by several magnitude of order, as the WW channel partial widths are not effected by the related couplings, so the branching ratios of HWW and $H\tau\tau$ are not changed significantly, but deserve to study its influences to the light Higgs boson search, We can not rule out a light Higgs only through $H\gamma\gamma$ channel.