The ZZH vertex and CP violation

Taller: Más allá del Modelo Estándar y Astropartículas

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Motivation

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nature physics

ARTICLES

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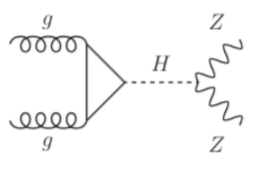
Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production

The CMS Collaboration*✉



The HZZ vertex and its anomalous couplings

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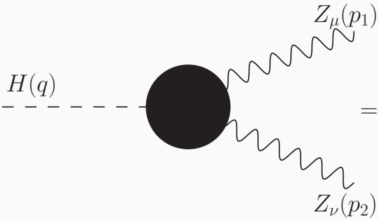


$$= i\frac{g}{c_W} m_Z \Gamma^{ZZH}_{\mu\nu}(p_1^2, p_2^2, q^2)$$

- The HZZ coupling can be induced by the Lagrangian

$$\mathcal{L} = \frac{g}{c_W} m_Z \Big[\frac{(1-a_Z)}{2} H Z_\mu Z^\mu + \frac{1}{2m_Z^2} \Big\{ \hat{b}_Z H Z_{\mu\nu} Z^{\mu\nu} + \hat{c}_Z H Z_\mu \partial_\nu Z^{\mu\nu} + \tilde{b}_Z H Z_{\mu\nu} \tilde{Z}^{\mu\nu} \Big\} \Big], \tag{1}$$

where $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ and $\tilde{Z}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} Z^{\alpha\beta}/2$.

The HZZ vertex and its anomalous couplings

- The vertex function for the general case where the three bosons are off-shell

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V(q^2,p_1^2,p_2^2)g_{\mu\nu} + \frac{h_2^V(q^2,p_1^2,p_2^2)}{m_Z^2}p_{1\nu}p_{2\mu} + \frac{h_3^V(q^2,p_1^2,p_2^2)}{m_Z^2}\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta. \quad (2)$$

- The relation between the form factors h_i and the parameters of Lagrangian (1) for the kinematics $H^* \to ZZ$ ($Z^* \to HZ$) are

$$h_1(q^2,p_1^2,p_2^2) = 1 + a_Z - \hat{b}_Z\frac{q^2-p_1^2-p_2^2}{m_Z^2} + \frac{\hat{c}_Z}{2}\frac{p_1^2+p_2^2}{m_Z^2}, \quad (3)$$

$$h_2(q^2,p_1^2,p_2^2) = \pm 2\hat{b}_Z, \quad (4)$$

$$h_3(q^2,p_1^2,p_2^2) = \pm 2\widetilde{b}_Z. \quad (5)$$

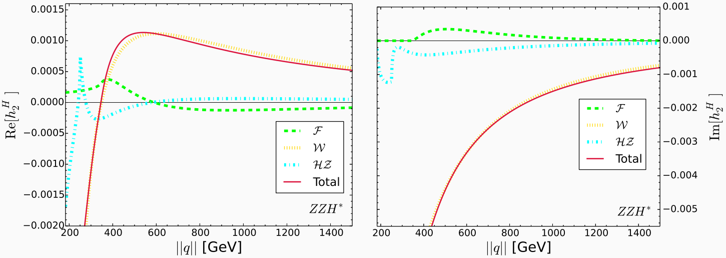
The HZZ vertex and its anomalous couplings

- The form factors h_1^V and h_2^V are CP-conserving, whereas h_3^V is related to CP violation.
- In the SM:
  - at tree level $h_1^V = 1$,
  - at one-loop level the anomalous coupling $\hat{b}_Z$ is induced,
  - and at three-loop[1] level $\widetilde{b}_Z \approx 10^{-11}$.
  - At one-loop there are more than 37 contributing Feynman diagrams.

[1] A. Soni and R. M. Xu, Probing CP violation via Higgs decays to four leptons, Phys. Rev. D 48, 5259 (1993).

The HZZ vertex and its anomalous couplings

- ◇ Analytical results in terms of the Passarino-Veltman scalar functions for h_2^H can be found at `https://gitlab.com/fcfm-buap-rc-group/zzh-anomalous-couplings`.



(a) (b)

Figure 1: One loop contributions to the real (left plot) and absorptive (right plot) parts of the form factor h_2^H.

The HZZ vertex and its anomalous couplings

- Using the current LHC data and our results for h_2^H we can obtain bounds on the remaining anomalous couplings.

Table 1: Allowed intervals of the real and absorptive parts of the CP violating form factor of the HZZ coupling for a few values of the transfer momentum. We consider three different schemes: the LHC framework (a_3^{ZZ}), a general effective Lagrangian approach ($\tilde{b}_Z$) and the SMEFT ($\tilde{c}_{zz}$).

$\|\|q\|\|$	$\mathrm{Re}\left[a_3^{ZZ}\right]$	$\mathrm{Re}\left[\tilde{b}_Z\right]$	$\mathrm{Re}\left[\tilde{c}_{zz}\right]$
190	$[-0.024, 0.009]$	$[-0.0045, 0.012]$	$[-0.033, 0.088]$
285	$[-0.0029, 0.0011]$	$[-0.00055, 0.0014]$	$[-0.004, 0.01]$
400	$[-0.00053, 0.0014]$	$[-0.0007, 0.00026]$	$[-0.0051, 0.0019]$
800	$[-0.00069, 0.0018]$	$[-0.0009, 0.00034]$	$[-0.0066, 0.0025]$
1500	$[-0.00036, 0.00095]$	$[-0.00047, 0.00018]$	$[-0.0034, 0.0013]$

The HZZ vertex and its anomalous couplings

Table 2: Allowed intervals of the real and absorptive parts of the CP violating form factor of the HZZ coupling for a few values of the transfer momentum. We consider three different schemes: the LHC framework (a_3^{ZZ}), a general effective Lagrangian approach ($\tilde{b}_Z$) and the SMEFT ($\tilde{c}_{zz}$).

$\lVert q \rVert$	$\mathrm{Im}\left[a_3^{ZZ}\right]$	$\mathrm{Im}\left[\tilde{b}_Z\right]$	$\mathrm{Im}\left[\tilde{c}_{zz}\right]$
190	$\left[-0.026, 0.01\right]$	$\left[-0.005, 0.013\right]$	$\left[-0.037, 0.096\right]$
285	$\left[-0.018, 0.0069\right]$	$\left[-0.0034, 0.009\right]$	$\left[-0.025, 0.066\right]$
400	$\left[-0.012, 0.0044\right]$	$\left[-0.0022, 0.006\right]$	$\left[-0.016, 0.044\right]$
800	$\left[-0.0039, 0.0015\right]$	$\left[-0.00075, 0.0019\right]$	$\left[-0.0055, 0.014\right]$
1500	$\left[-0.0015, 0.00057\right]$	$\left[-0.00028, 0.00075\right]$	$\left[-0.002, 0.0055\right]$

The HZZ vertex and its anomalous couplings

Table 3: Allowed intervals for the real and absorptive parts of one of the CP conserving form factors of the HZZ coupling for a few values of the transfer momentum. We consider three different schemes: the LHC framework (κ_1^{ZZ}), a general effective Lagrangian approach ($\hat{c}_Z$) and the SMEFT ($\tilde{c}_{z\Box}$).

$\|\|q\|\|$	$\mathrm{Re}\left[k_1^{ZZ}\right]$ $\left(\mathrm{Re}\left[\hat{c}_Z\right]\right)$	$\mathrm{Re}\left[c_{z\Box}\right]$	$\mathrm{Im}\left[k_1^{ZZ}\right]$ $\left(\mathrm{Im}\left[\hat{c}_Z\right]\right)$	$\mathrm{Im}\left[c_{z\Box}\right]$
190	$[-0.0024, 0.0046]$	$[-0.0058, 0.011]$	$[-0.0026, 0.005]$	$[-0.0063, 0.012]$
285	$[-0.00028, 0.00055]$	$[-0.00068, 0.0013]$	$[-0.0018, 0.0035]$	$[-0.0043, 0.0085]$
400	$[-0.00027, 0.00014]$	$[-0.00065, 0.00034]$	$[-0.0012, 0.0023]$	$[-0.0029, 0.0055]$
800	$[-0.00034, 0.00017]$	$[-0.00082, 0.00041]$	$[-0.00038, 0.00075]$	$[-0.00092, 0.0018]$
1500	$[-0.00019, 0.0001]$	$[-0.00046, 0.00024]$	$[-0.00015, 0.00029]$	$[-0.00036, 0.0007]$

◇ Our limits are one or two orders of magnitude tighter than previous results.

The $H^* \to ZZ$ process

The $H^* \to ZZ$ process

- To study the role of the imaginary part of the anomalous couplings in the Z boson pair production, we consider the h_i^H form factors as complex quantities

$$h_i^H = \mathrm{Re}\left[h_i^H\right] + i\mathrm{Im}\left[h_i^H\right], \tag{6}$$

- and the amplitude for the $H^* \to ZZ$ process is

$$\mathcal{M}(\lambda_1, \lambda_2) = \frac{g}{c_W} m_Z \Big\{ g^{\mu\nu} \Big(\mathrm{Re}\left[h_1^H\right] + i\mathrm{Im}\left[h_1^H\right] \Big) + \frac{p_2^\mu p_1{}^\nu}{m_Z^2} \Big(\mathrm{Re}\left[h_2^H\right] + i\mathrm{Im}\left[h_2^H\right] \Big) + \frac{\epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta}}{m_Z^2} \Big(\mathrm{Re}\left[h_3^H\right] + i\mathrm{Im}\left[h_3^H\right] \Big) \Big\} \epsilon_\mu^*(p_1, \lambda_1) \epsilon_\nu^*(p_2, \lambda_2), \tag{7}$$

The $H^* \to ZZ$ process

- From the amplitude (7), the partial decay width in terms of the real and adsorptive parts of the h_i^H form factors can be obtained:

$$\Gamma_{H^* \to ZZ} = \frac{g^2\sqrt{q^2 - 4m_Z^2}}{512\pi q^2 c_W^2 m_Z^6}\mathcal{T}, \tag{8}$$

  where $\mathcal{T}$ is in terms of $\mathrm{Re}\left[h_i^H\right]$ and $\mathrm{Im}\left[h_i^H\right]$.

- Eq. (8) reduces to the SM tree-level result when $\mathrm{Re}\left[h_1^H\right] = 1$, $\mathrm{Re}\left[h_{2,3}^H\right] = \mathrm{Im}\left[h_{1,2,3}^H\right] = 0$:

$$\Gamma^{\text{Tree}}_{H^* \to ZZ} = \frac{g^2\sqrt{q^2 - 4m_Z^2}}{512\pi c_W^2 m_Z^6}\left(4q^2 m_Z^4 - 16m_Z^6 + 48\frac{m_Z^8}{q^2}\right). \tag{9}$$

The $H^* \to ZZ$ process

- To study the anomalous couplings contributions we define the ratio

$$\mathcal{R} = \frac{\Gamma_{H^* \to ZZ}}{\Gamma^{\text{Tree}}_{H^* \to ZZ}}. \tag{10}$$

- We also consider the following scenarios:
  - Scenario I: $\mathrm{Re}\left[\hat{c}_Z\right] = 0.0001$, $\mathrm{Im}\left[\hat{c}_Z\right] = 0.001$, $\mathrm{Re}\left[\tilde{b}_Z\right] = 0.0001$ and $\mathrm{Im}\left[\tilde{b}_Z\right] = 0.001$.
  - Scenario II: $\mathrm{Re}\left[\hat{c}_Z\right] = -0.001$, $\mathrm{Im}\left[\hat{c}_Z\right] = 0.001$, $\mathrm{Re}\left[\tilde{b}_Z\right] = -0.0001$ and $\mathrm{Im}\left[\tilde{b}_Z\right] = 0.001$.
  - Scenario III: $\mathrm{Re}\left[\hat{c}_Z\right] = 0.001$, $\mathrm{Im}\left[\hat{c}_Z\right] = -0.0001$, $\mathrm{Re}\left[\tilde{b}_Z\right] = 0.0001$ and $\mathrm{Im}\left[\tilde{b}_Z\right] = -0.001$.

THE $H^* \to ZZ$ PROCESS

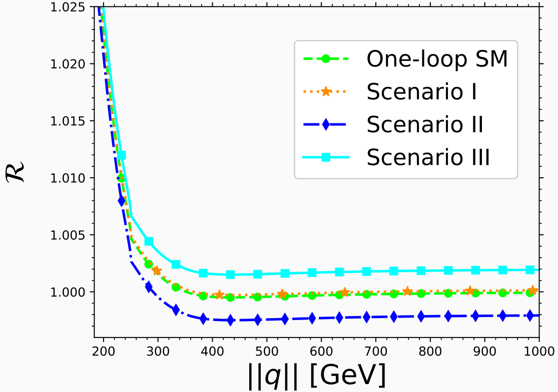


Figure 2: Behavior of the ratio $\mathcal{R}$ as function of the transfer momentum of the Higgs Boson $\|q\|$.

The $H^* \to ZZ$ process

- From the amplitude (7) it is also possible to obtain the partial decay width $\Gamma_{H^* \to ZZ}$ for polarized Z gauge bosons

$$\mathcal{M}^2 = \left(\frac{g}{c_W}\right)^2 m_Z^2 \left(\mathcal{M}_{LL}^2 + \mathcal{M}_{RR}^2 + \mathcal{M}_{00}^2\right), \tag{11}$$

- The polarized partial width can be defined as

$$\Gamma_{H^* \to Z_{\lambda_i} Z_{\lambda_i}} = \frac{g^2 m_Z^2 \sqrt{q^2 - 4m_Z^2}}{32\pi q^2 c_W^2} \mathcal{M}_{\lambda_i \lambda_i}^2. \tag{12}$$

The $H^* \to ZZ$ process

The transversal amplitudes are

$$\mathcal{M}_{LL}^2 = \frac{1}{4m_Z^4}\Big\{4m_Z^2\sqrt{q^4-4q^2m_Z^2}\Big(\mathrm{Re}\big[h_1^H\big]\mathrm{Im}\big[h_3^H\big]-\mathrm{Im}\big[h_1^H\big]\mathrm{Re}\big[h_3^H\big]\Big)$$
$$+q^2\left(q^2-4m_Z^2\right)\left(\mathrm{Re}\big[h_3^H\big]^2+\mathrm{Im}\big[h_3^H\big]^2\right)+4m_Z^4\Big(\mathrm{Re}\big[h_1^H\big]^2+\mathrm{Im}\big[h_1^H\big]^2\Big)\Big\}, \quad (13)$$

$$\mathcal{M}_{RR}^2 = \frac{1}{4m_Z^4}\Big\{-4m_Z^2\sqrt{q^4-4q^2m_Z^2}\Big(\mathrm{Re}\big[h_1^H\big]\mathrm{Im}\big[h_3^H\big]-\mathrm{Im}\big[h_1^H\big]\mathrm{Re}\big[h_3^H\big]\Big)$$
$$+q^2\left(q^2-4m_Z^2\right)\left(\mathrm{Re}\big[h_3^H\big]^2+\mathrm{Im}\big[h_3^H\big]^2\right)+4m_Z^4\Big(\mathrm{Re}\big[h_1^H\big]^2+\mathrm{Im}\big[h_1^H\big]^2\Big)\Big\}, \quad (14)$$

The $H^* \to ZZ$ process

The left-right asymmetry can be written as

$$\mathcal{A}_{LR} = \frac{\Gamma_{H^*\to Z_L Z_L} - \Gamma_{H^*\to Z_R Z_R}}{\Gamma_{H^*\to Z_L Z_L} + \Gamma_{H^*\to Z_R Z_R}}, \quad (15)$$

which can be expressed in terms of the real and imaginary parts of the form factors via Eqs. (13) and (14):

$$\mathcal{A}_{LR} = \frac{4m_Z^2 \|q\| \sqrt{q^2 - 4m_Z^2} \left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2 - 4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2\right) + 4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2\right)}. \quad (16)$$

- It is worth noting that the size of this asymmetry is dominated by the CP-violating form factor h_3^H.

The $H^* \to ZZ$ process

◇ In the SM

$$\mathcal{A}_{LR}^{SM} \approx 10^{-8} - 10^{-9}, \tag{17}$$

◇ To assess the importance of the CP-violating form factor, together with the complete anomalous couplings contributions and their allowed values obtained, we fix $\mathrm{Re}\left[\hat{c}_Z\right] = \mathrm{Im}\left[\hat{c}_Z\right] = 0.001$ and consider the following four scenarios:

- Scenario i: $\mathrm{Re}\left[\tilde{b}_Z\right] = 0.001$ and $\mathrm{Im}\left[\tilde{b}_Z\right] = 0.01$.
- Scenario ii: $\mathrm{Re}\left[\tilde{b}_Z\right] = 0.001$ and $\mathrm{Im}\left[\tilde{b}_Z\right] = -0.01$.
- Scenario iii: $\mathrm{Re}\left[\tilde{b}_Z\right] = 0.0001$ and $\mathrm{Im}\left[\tilde{b}_Z\right] = 0.001$.
- Scenario iv: $\mathrm{Re}\left[\tilde{b}_Z\right] = \mathrm{Im}\left[\tilde{b}_Z\right] = 0.0001$.

THE $H^* \to ZZ$ PROCESS

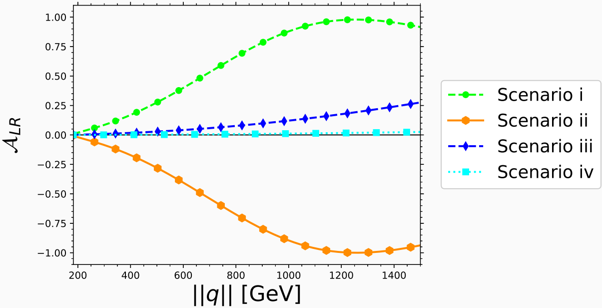


Figure 3: $\mathcal{A}_{LR}$ asymmetry as a function of the transfer momentum of the Higgs boson $||q||$ for the four scenarios.

Final remarks

Final remarks

- We presented for the first time the imaginary one-loop contributions to the anomalous couplings ($\hat{b}_Z$) of H^*ZZ vertex in the SM.
- New bounds on $\hat{c}_Z$ and $\tilde{b}_Z$ were obtained considering the Higgs virtuality dependence. They are smaller than previous results.
- The imaginary parts of the anomalous couplings and the CP-violating form factor ($\tilde{b}_Z$) play a relevant role in the production of polarized Z bosons.
- A new Left-Right asymmetry ($\mathcal{A}_{LR}$) in the process $H^* \to ZZ$ is reported for the firs time, which is more relevant at high energies.

For more details see:

`https://arxiv.org/pdf/2301.13127.pdf`

PERSPECTIVES

- We are interested in the implications of the asymmetry ($\mathcal{A}_{LR}$), imaginary parts of the anomalous couplings in the process

$$H^* \to ZZ \to 2\ell_1^\pm 2\ell_2^\pm. \tag{18}$$

- Then,

$$gg \to H^* \to ZZ \to 2\ell_1^\pm 2\ell_2^\pm \tag{19}$$

- The implementation of our results in MC generators.