Constrain HZZ anomalous couplings in off-shell Higgs regions

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contents

HZZ anomalous couplings

matrix element likelihood approach

$$L(\mathrm{HVV}) \sim a_1 \frac{m_Z^2}{2} \mathrm{H}Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H}Z_\mu \Box Z^\mu - \frac{1}{2} a_2 \mathrm{H}Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H}Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

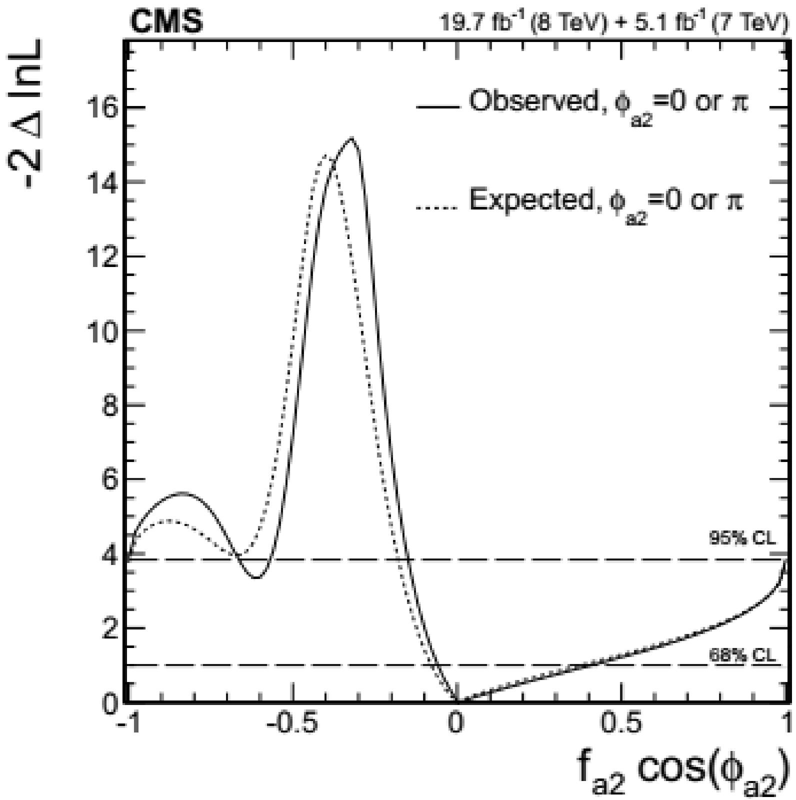
The effective fractional cross sections f_{ai} and phases ϕ_{ai}

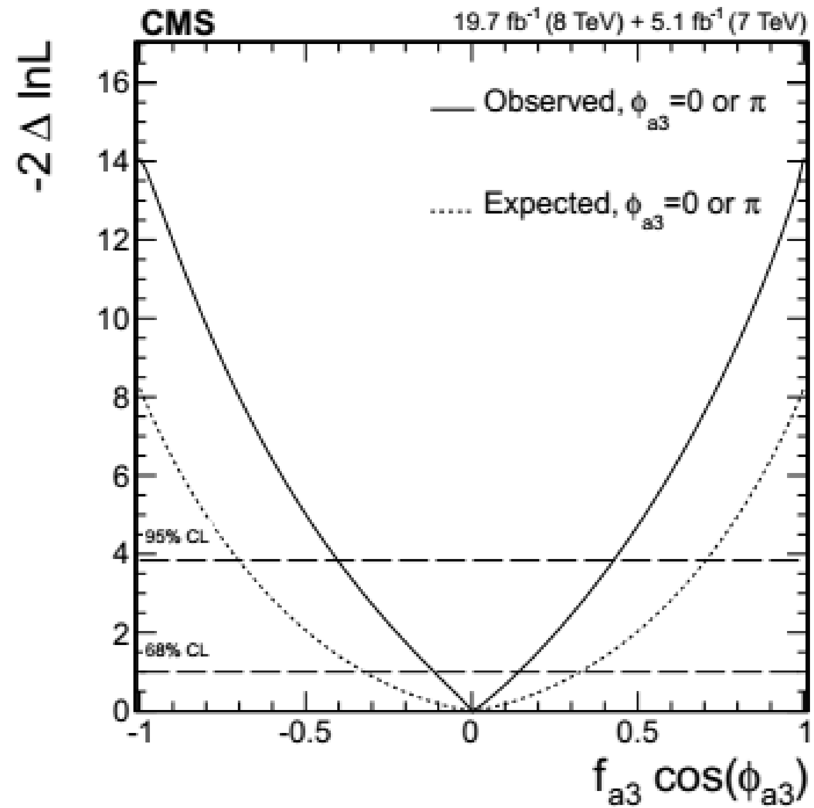
$$f_{ai} = |a_i|^2 \sigma_i \Big/ \sum |a_j|^2 \sigma_j, \text{ and } \phi_{ai} = \arg\left(a_i / a_1\right)$$

$$\left|\frac{a_i}{a_1}\right| = \sqrt{\frac{f_{ai}}{f_{a1}}} \sqrt{\frac{\sigma_1}{\sigma_i}}$$

$$Z_{\mu'\nu'} = \partial_{\mu'} Z_{\nu'} - \partial_{\nu'} Z_{\mu'} \qquad \tilde{Z}_{\mu'\nu'} = \tfrac{1}{2} \epsilon_{\mu'\nu'\rho\sigma} Z^{\rho\sigma}$$

The experimental measurements in Higgs on-shell region





Parameter	Observed	Expected
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda_1})$	$[-\infty, -119\,\text{GeV}] \cup [104\,\text{GeV}, \infty]$	$[-\infty, 50\,\text{GeV}] \cup [116\,\text{GeV}, \infty]$
a_2/a_1	$[-2.28, -1.88] \cup [-0.69, \infty]$	$[-0.77, \infty]$
a_3/a_1	$[-2.05, 2.19]$	$[-3.85, 3.85]$

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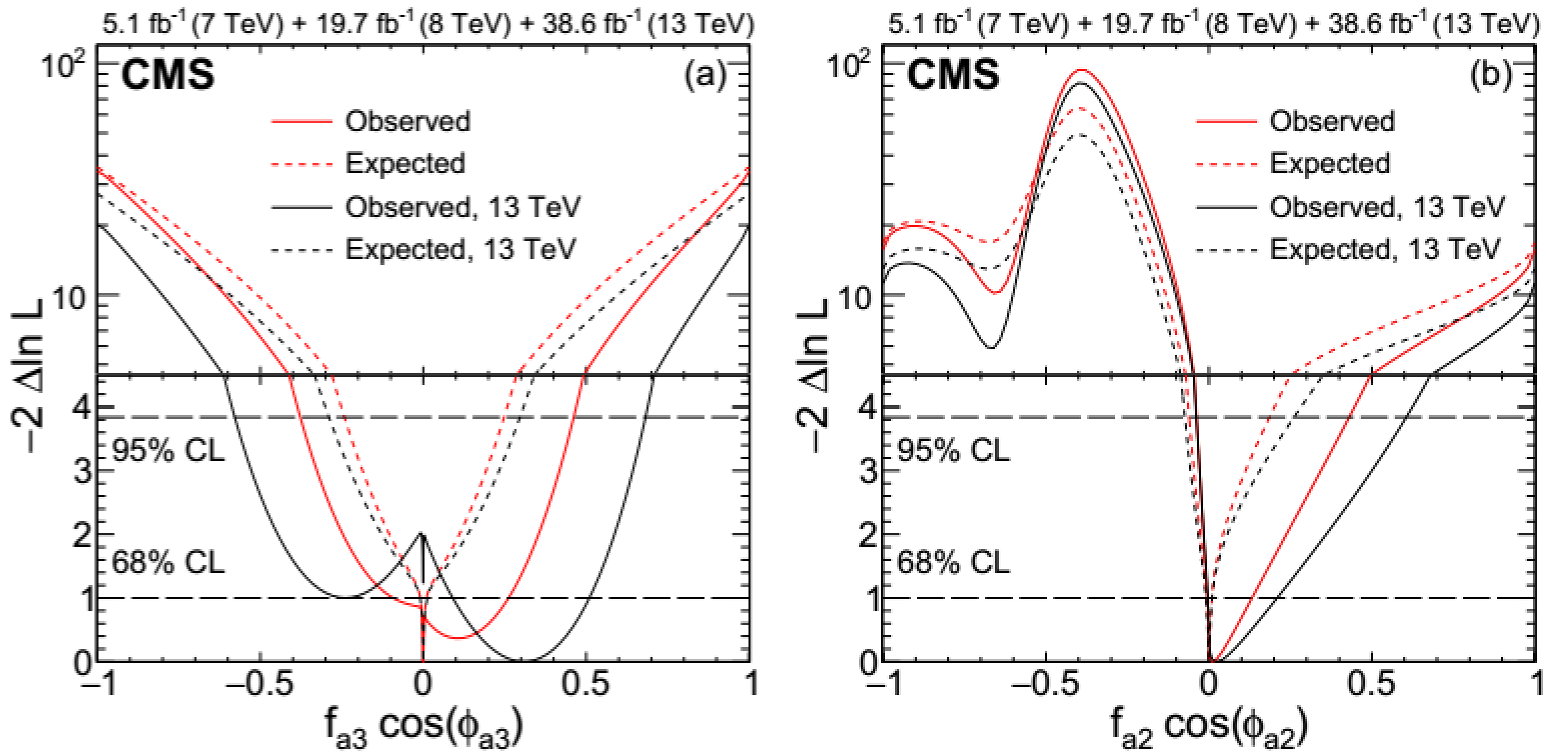
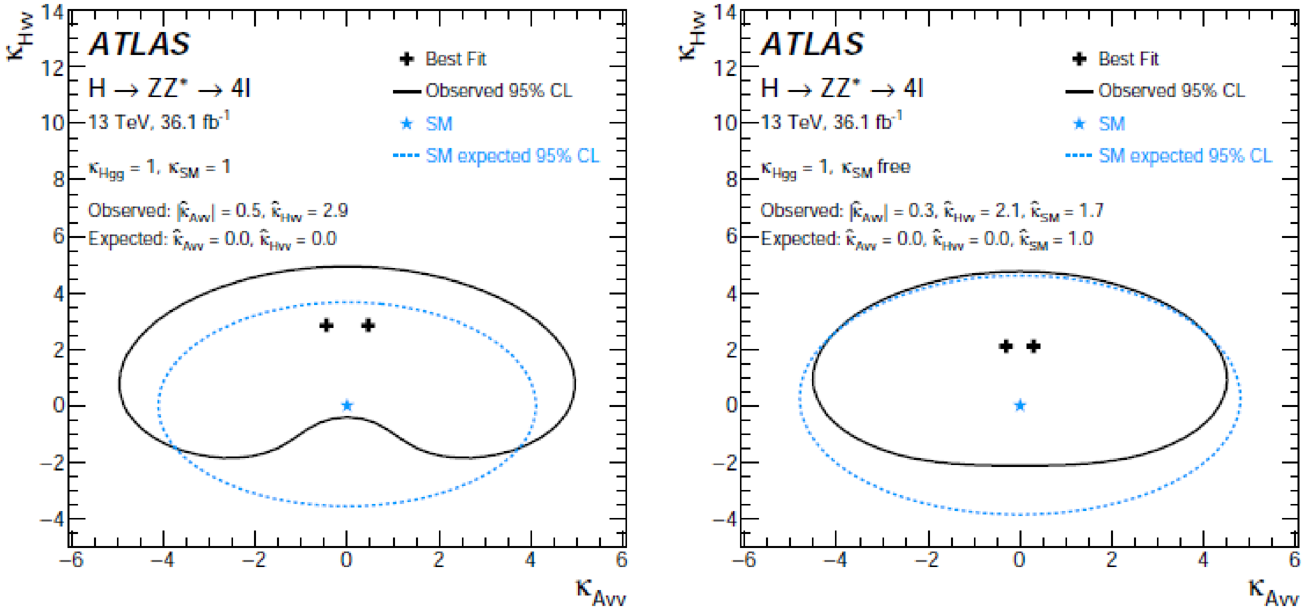


Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$

$$-0.34 \leq a_2 \leq 1.45, -2.0 \leq a_3 \leq 2.36,$$

Phys.Lett. B775 (2017) 1-24, 1707.00541

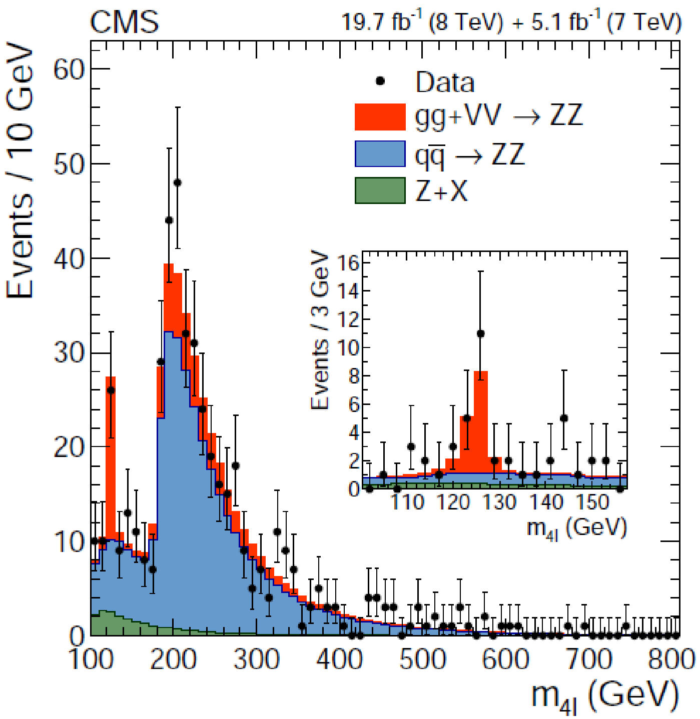
$$
\begin{aligned}
\mathcal{L}_0^V = \Bigg\{ & \kappa_{\mathrm{SM}} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \\
& - \frac{1}{4} \left[\kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \tan\alpha \, \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha \, \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \tan\alpha \, \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \Bigg\} X_0 .
\end{aligned}
$$



Higgs off-shell region physics

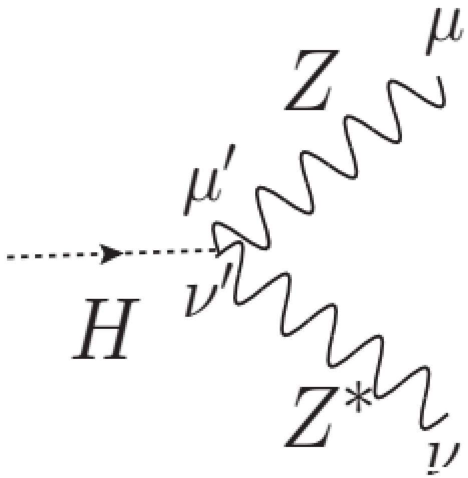
In gluon fusion production mode, the off-shell production cross section has been shown to be sizeable at high ZZ invariant mass

constraining the Higgs boson width from off-shell production and decay to ZZ(4l)



CMS PAS HIG-14-002 1307.4935

Effective Lagrangian

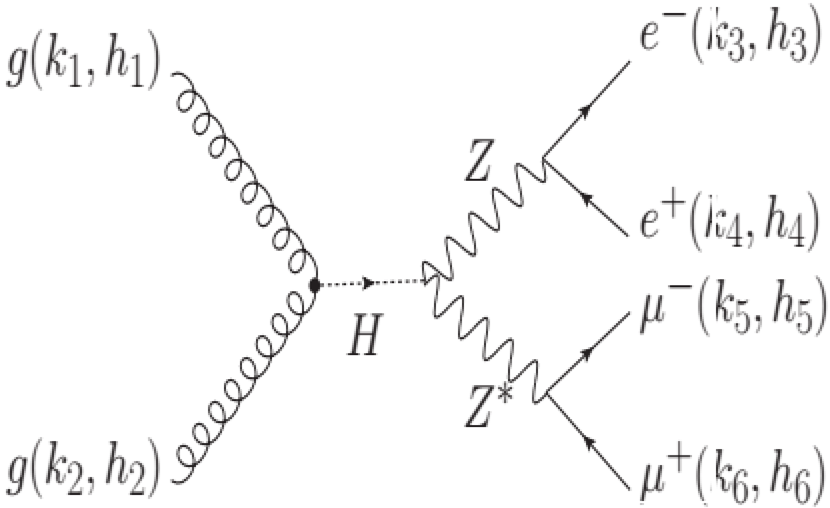


$$L \supset \frac{H}{4v}[2a_1 m_Z^2 Z^{\mu'} Z_{\mu'} - a_2 Z^{\mu'\nu'} Z_{\mu'\nu'} - a_3 Z^{\mu'\nu'} \tilde{Z}_{\mu'\nu'}]$$

CP even SM | CP even BSM | CP odd BSM

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

Helicity amplitude calculation



Helicity amplitude for Higgs mediated process

$$A(1_g^{h_1}, 2_g^{h_2}, 3_{e^-}^{h_3}, 4_{e^+}^{h_4}, 5_{\mu^-}^{h_3}, 6_{\mu^+}^{h_6})$$

$$= A^{gg\to H}(1_g^{h_1}, 2_g^{h_2}) \times \frac{P_H(s_{12})}{s_{12}} \times A^{H\to Z(e^-,e^+)Z(\mu^-,\mu^+)}(3_{e^-}^{h_3}, 4_{e^+}^{h_4}, 5_{\mu^-}^{h_3}, 6_{\mu^+}^{h_6})$$

h=+,-

$$P_H(s) = \frac{s}{s - M_H^2 + iM_H\Gamma_H}$$

$$A^{H\to Z(e^-,e^+)Z(\mu^-,\mu^+)}(3^-_{e^-},4^+_{e^+},5^-_{\mu^-},6^+_{\mu^+}) = \sum_{i=1}^{3} a_i A_i$$

$$= \sum_{i=1}^{3} \overline{u}(k_3,h_3)\gamma^\mu(r_e P_R + l_e P_L)v(k_4,h_4)(g_{\mu\mu'} - \frac{k_\mu k_{\mu'}}{M_Z^2})\Gamma_i^{\mu'\nu'}(k_1,k_2)$$

$$(g_{\nu'\nu} - \frac{k'_{\nu'} k'_\nu}{M_Z^2})\overline{u}(k_5,h_5)\gamma^\nu(r_e P_R + l_e P_L)v(k_6,h_6)$$

$$s_{ij} = (k_i + k_j)^2,\ l_e = \frac{-1+2sin^2\theta_W}{sin(2\theta_W)}, r_e = \frac{2sin^2\theta_W}{sin(2\theta_W)}$$

k,k' are the momentum of Z boson

1. the CP even term under SM $a_1 = 1; a_i = 0 (i \neq 1)$

$$A^{H\to Z(e^-,e^+)Z(\mu^-,\mu^+)}(3^-_{e^-},4^+_{e^+},5^-_{\mu^-},6^+_{\mu^+}) = \frac{M_W^2}{cos^2\theta_W}\langle 35\rangle[46]l_e^2$$

1311.3588

$2.\quad$ *the CP-even term under BSM(A_2)* $\quad a_2 \neq 0; a_i = 0 (i \neq 2)$

$$A^{H\to Z(e^-,e^+)Z(\mu^-,\mu^+)}(3^-_{e^-}, 4^+_{e^+}, 5^-_{\mu^-}, 6^+_{\mu^+})$$

$$= a_2 l_e^2 [2k \cdot k' [46]\langle 53\rangle - ([45]\langle 53\rangle + [46]\langle 63\rangle)([36]\langle 53\rangle + [46]\langle 54\rangle)]$$

$3^-_{e^-}, 4^+_{e^+}, 5^+_{\mu^-}, 6^-_{\mu^+}$ when the term simultaneously emerges 5,6

5 $\longleftrightarrow$ 6

$3^+_{e^-}, 4^-_{e^+}, 5^-_{\mu^-}, 6^+_{\mu^+}$ when the term simultaneously emerges 3,4

3 $\longleftrightarrow$ 4

$3^+_{e^-}, 4^-_{e^+}, 5^+_{\mu^-}, 6^-_{\mu^+}$ [ ] $\longleftrightarrow$ <>

3. the CP-odd term under BSM(A_3) $a_3 \neq 0; a_i = 0 (i \neq 3)$

$$A^{H\to Z(e^-,e^+)Z(\mu^-,\mu^+)}(3^-_{e^-}, 4^+_{e^+}, 5^-_{\mu^-}, 6^+_{\mu^+})$$

$$= - a_3 i l_e^2 (2(k\cdot k' - [64]\langle 46\rangle)[46]\langle 53\rangle + [64]\langle 45\rangle([46]\langle 63\rangle - [45]\langle 53\rangle)$$

$$- [63]\langle 35\rangle([46]\langle 63\rangle) + [45]\langle 53\rangle))$$

$3^-_{e^-}, 4^+_{e^+}, 5^+_{\mu^-}, 6^-_{\mu^+}$ 5 ⟷ 6

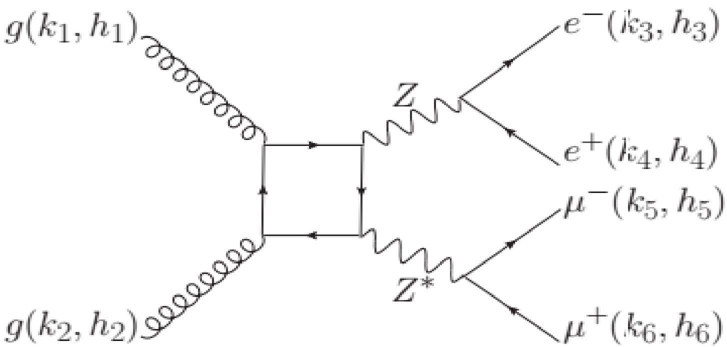
$3^+_{e^-}, 4^-_{e^+}, 5^-_{\mu^-}, 6^+_{\mu^+}$ 3 ⟷ 4

$3^+_{e^-}, 4^-_{e^+}, 5^+_{\mu^-}, 6^-_{\mu^+}$ 3 ⟷ 4 5 ⟷ 6

the spinor producs emerged in above are defined as:

$$\langle ij\rangle = \overline{u}_-(p_i)u_+(p_j), \quad [ij] = \overline{u}_+(p_i)u_-(p_j), \quad \langle ij\rangle[ij] = 2p_i\cdot p_j$$

★ the amplititude for box process



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$$
\begin{aligned}
& A(1_g^{h_1}, 2_g^{h_2}, 3_e^-, 4_{\bar{e}}^+, 5_\mu^-, 6_{\bar{\mu}}^+) = \\
& A_{LL}(1_g^{h_1}, 2_g^{h_2}, 3_e^-, 4_{\bar{e}}^+, 5_\mu^-, 6_{\bar{\mu}}^+)\left(P^{L,L,-,-}(s_{34}, s_{56}) + P^{R,R,-,-}(s_{34}, s_{56})\right) \\
+ \; & A_{LR}(1_g^{h_1}, 2_g^{h_2}, 3_e^-, 4_{\bar{e}}^+, 5_\mu^-, 6_{\bar{\mu}}^+)\left(P^{L,R,-,-}(s_{34}, s_{56}) + P^{R,L,-,-}(s_{34}, s_{56})\right)
\end{aligned}
$$

$$
\begin{aligned}
P^{L,L,-,-}(s_{34}, s_{56}) &= (Q_i q_e + L_i l_e \mathcal{P}_Z(s_{34}))(Q_i q_e + L_i l_e \mathcal{P}_Z(s_{56})) \\
P^{L,R,-,-}(s_{34}, s_{56}) &= (Q_i q_e + L_i l_e \mathcal{P}_Z(s_{34}))(Q_i q_e + R_i l_e \mathcal{P}_Z(s_{56})) \\
P^{R,L,-,-}(s_{34}, s_{56}) &= (Q_i q_e + R_i l_e \mathcal{P}_Z(s_{34}))(Q_i q_e + L_i l_e \mathcal{P}_Z(s_{56})) \\
P^{R,R,-,-}(s_{34}, s_{56}) &= (Q_i q_e + R_i l_e \mathcal{P}_Z(s_{34}))(Q_i q_e + R_i l_e \mathcal{P}_Z(s_{56}))
\end{aligned}
$$

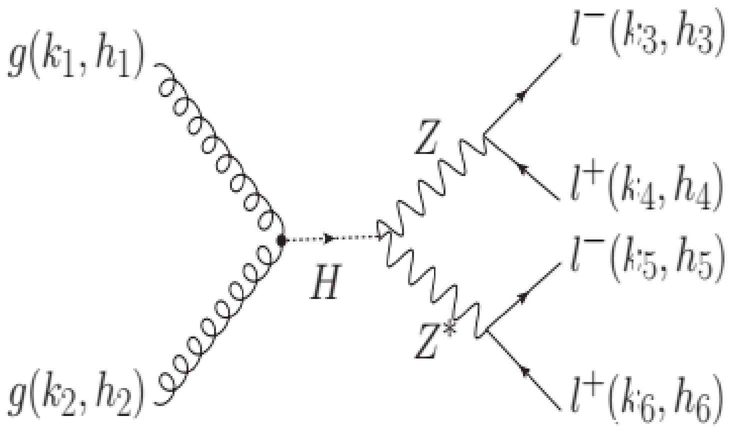
$$A_{LL}(1_g^{h_1}, 2_g^{h_2}, 3_e^-, 4_{\bar{e}}^+, 5_\mu^-, 6_{\bar{\mu}}^+) = \sum_{j=2}^{3} d_j^{d=6}(1^{h_1}, 2^{h_2})\, D_0^{d=6}(j) + \sum_{j=1}^{3} d_j(1^{h_1}, 2^{h_2})\, D_0(j)$$
$$+ \sum_{j=1}^{6} c_j(1^{h_1}, 2^{h_2})\, C_0(j) + \sum_{j=1}^{6} b_j(1^{h_1}, 2^{h_2})\, B_0(j) + R(1^{h_1}, 2^{h_2})$$

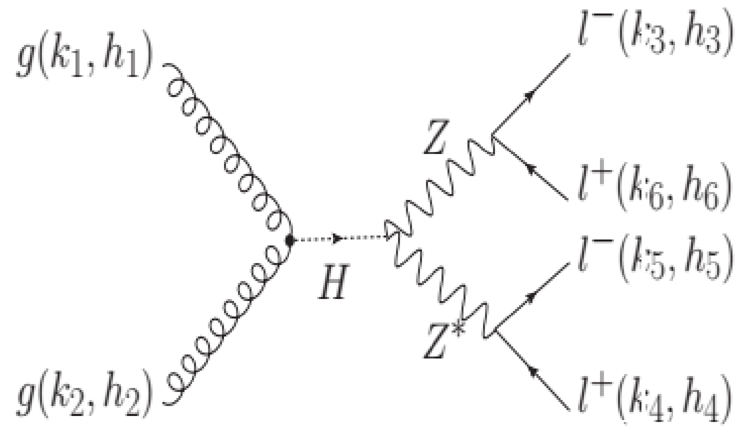
$$\epsilon_\mu^-(p_1)\epsilon_\nu^+(p_2)P_{LR}^{\mu\nu\rho\sigma} = \frac{1}{2}\frac{1}{s_{12}^2}\Big[-2g^{\rho\sigma}\frac{\langle 1|(3+4)|2]}{\langle 2|(3+4)|1]}s_{12}^2 A_2 - \langle 1|\gamma^\rho|2]\langle 1|\gamma^\sigma|2]s_{12}(A_3+A_4)$$
$$- \langle 1\,2\rangle[2|\gamma^\rho\gamma^\sigma|2]\langle 1|(3+4)|2]A_5 + \langle 1|\gamma^\rho\gamma^\sigma|1\rangle[1\,2]\langle 1|(3+4)|2]A_5\Big] \qquad \text{(B15)}$$

$$\frac{e^2}{s_{34}s_{56}}\langle 3|\gamma^\rho|4]\langle 5|\gamma^\sigma|6]$$

$$A(1_g^-, 2_g^+, 3_e^-, 4_{\bar{e}}^+, 5_\mu^-, 6_{\bar{\mu}}^+) = \frac{1}{s_{12}s_{34}s_{56}}\Big[\langle 3\,5\rangle[4\,6]\frac{\langle 1|(3+4)|2]}{\langle 2|(3+4)|1]}s_{12}\,A_2 - \langle 1\,3\rangle\langle 1\,5\rangle[2\,4][2\,6]\,(A_3+A_4)$$
$$+ \left(\frac{\langle 3\,5\rangle[2\,4][6\,2]}{[1\,2]} + \frac{\langle 1\,3\rangle\langle 1\,5\rangle[4\,6]}{\langle 1\,2\rangle}\right)\langle 1|(3+4)|2]\,A_5\Big], \qquad \text{(B19)}$$

★ the identical final state 4e/4μ





To increase statistics.

The calculation is similar as 2e2μ ,but there are two differences :

1、the cross section should times a symmetry factor 0.25

2、the interference term dictate a factor -1

Simulation by MCFM

Adding anomalous ($a_2, a_3 \neq 0$) Higgs mediated helicity amplitudes in MCFM program, considering its interference with gg->ZZ box diagram.

	SM	BSM
$gg \to H \to Z(e^+e^-)Z(\mu^-\mu^+)$	√	×
$gg \to H \to 4e/4\mu$	√	×
the interference term between Higgs mediated diagram and box diagram for 2e2\mu and for identical final states	√	×
$gg \to Z(e^+e^-)Z(\mu^-\mu^+)$	√	

CMS cuts for 2e2μ final states

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

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

$m_{ll} > 4\text{GeV}, \ \mathrm{m}_{4l} > 100\text{GeV}$

$P_{T,l}(hardest) > 20\text{GeV}$ $P_{T,l}(2nd, hardest) > 10\text{GeV}$

$40\text{GeV} < \mathrm{m}_{ll}(\text{near}) < 120\text{GeV}$ $12\text{GeV} < \mathrm{m}_{ll}(\text{other}) < 120\text{GeV}$

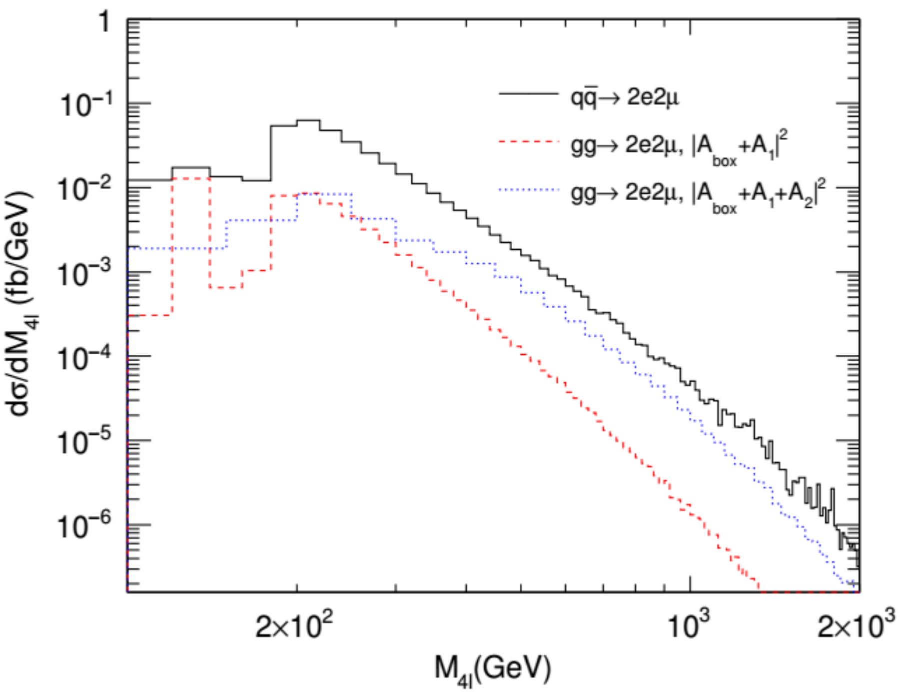
The cross section for the 2e2μ final state 8TeV LHC with unit in fb

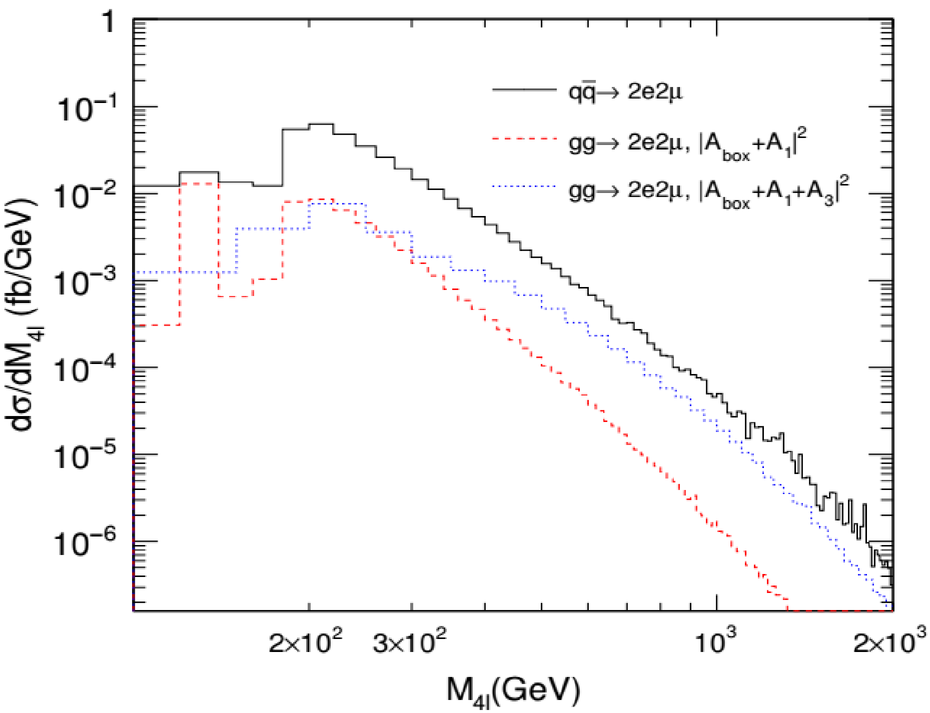
$m_{4l} < 130\text{GeV}$				
	box	A_1	A_2	A_3
box	0.011	0	0	0
A_1	0	0.245	-0.275	0
A_2	0	-0.275	0.101	0
A_3	0	0	0	0.038

$m_{4l} > 220\text{GeV}$				
	box	A_1	A_2	A_3
box	0.479	-0.056	0.199	0
A_1	-0.056	0.031	-0.047	0
A_2	0.199	-0.047	0.231	0
A_3	0	0	0	0.220

$m_{4l} > 330\text{GeV}$				
	box	A_1	A_2	A_3
box	0.091	-0.032	0.094	0
A_1	-0.032	0.023	-0.023	0
A_2	0.094	-0.023	0.168	0
A_3	0	0	0	0.168

8TeV LHC cross sections in off-shell Higgs regions can be used to constraint anomalous HZZ couplings ($A_2, A_3 \neq 0$)





★ Cuts for identical final state 4l

(1) $p_{T\mu(e)} > 7\text{GeV}$ and $|\eta_{\mu(e)}| < 2.4$

(2) Which lepton pair is close to Z mass and which is far away

The cross section for the 4e+4μ final state 8TeV LHC with unit in fb

$m_{4l} < 130\text{GeV}$				
	box	A_1	A_2	A_3
box	0.021	0	0	0
A_1	0	0.262	-0.280	0
A_2	0	-0.280	0.093	0
A_3	0	0	0	0.030

$m_{4l} > 220\text{GeV}$				
	box	A_1	A_2	A_3
box	0.485	-0.056	0.200	0
A_1	-0.056	0.031	-0.048	0
A_2	0.200	-0.048	0.229	0
A_3	0	0	0	0.218

$m_{4l} > 330\text{GeV}$				
	box	A_1	A_2	A_3
box	0.092	-0.032	0.094	0
A_1	-0.032	0.023	-0.023	0
A_2	0.094	-0.023	0.166	0
A_3	0	0	0	0.169

Advantages:

Relatively large interference cross section between box & A_2 in off-shell region

8TeV LHC real experimental measurements to constraint the anomalous coupling coefficients

CMS PAS HIG-14-002

		Full region	Signal-enriched region
	$gg + VBF \to 4\ell$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	$2.22^{+0.15}_{-0.17}$	$1.20^{+0.08}_{-0.09}$
	$gg + VBF \to 4\ell$ (background)	$31.1^{+3.0}_{-3.1}$	2.12 ± 0.21
(a)	$gg + VBF \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	$29.6^{+2.8}_{-2.9}$	$1.73^{+0.16}_{-0.17}$
	$gg + VBF \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 15$)	$51.8^{+4.9}_{-5.0}$	13.1 ± 1.1
(b)	$q\bar{q} \to 4\ell$	154.7 ± 7.4	8.6 ± 0.4
(c)	Reducible background	3.7 ± 0.6	0.44 ± 0.08
(a+b+c)	Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)	188.0 ± 7.9	10.8 ± 0.4
	Observed	183	8

- The k factor are set to be equal for signal, background and interference.
- Assume the efficiency is also the same

$$\epsilon = \frac{N_{4l}^{H}}{\sigma_{4l}^{H} \times f \times k \times L}$$

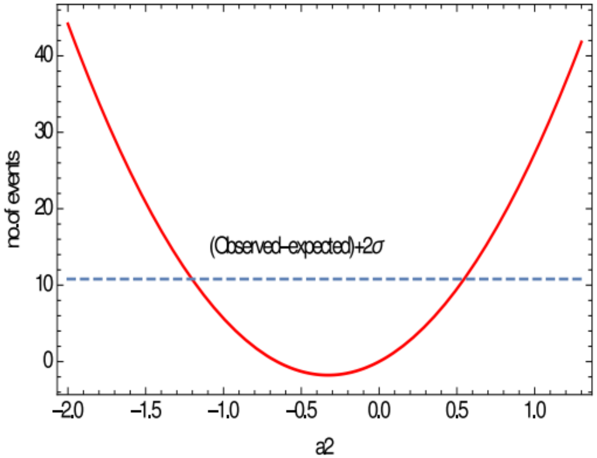
$$\frac{N_{4l}^{H_1}}{\sigma_{4l}^{1}}(a_2^2\sigma_{4l}^{2,2} + a_2\sigma_{4l}^{1,2} + a_2\sigma_{4l}^{2,box}) + N_{exp}^{SM} = N_{exp}^{4l}$$

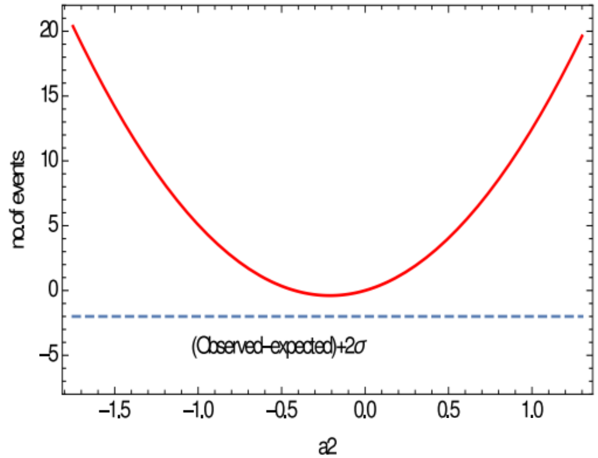
$$N_{exp}^{4l}(m_{4l} > 220\text{GeV}) = 16.44\text{a}_2^2 + 10.79\text{a}_2 + 188 \pm 7.9$$

$$N_{exp}^{4l}(m_{4l} > 330\text{GeV}) = 8.77\text{a}_2^2 + 3.7\text{a}_2 + 10.8 \pm 0.4$$

$$N_{exp}^{4l}(m_{4l} > 220\text{GeV}) = 15.56\text{a}_3^2 + 188 \pm 7.9$$

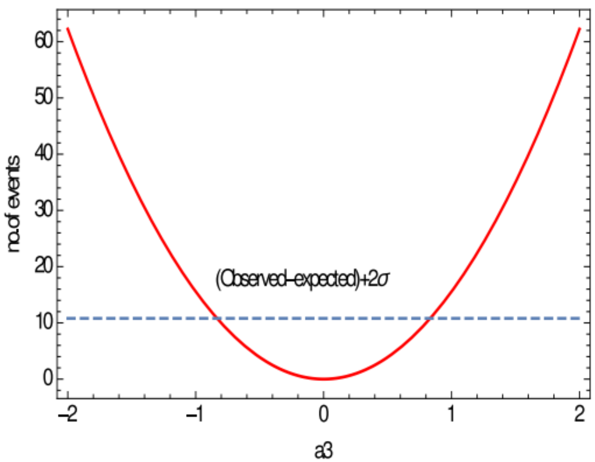
$$N_{exp}^{4l}(m_{4l} > 330\text{GeV}) = 8.82\text{a}_3^2 + 10.8 \pm 0.4$$

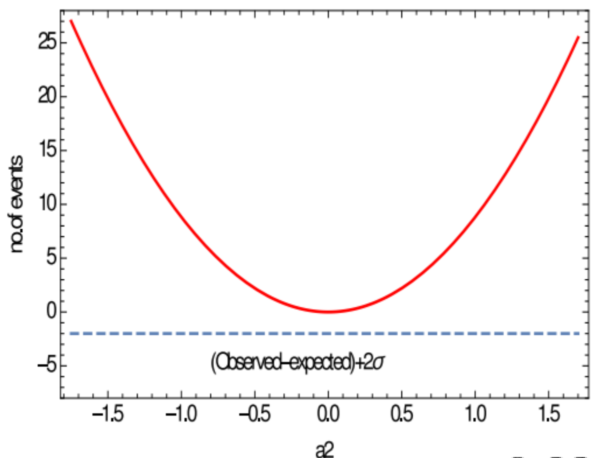




$$-1.20 < a_2 < 0.546 \ (m_{4l} > 220\text{GeV})$$

$$a_2 \in null \ (m_{4l} > 330\text{GeV})$$





$$-0.833 < a_3 < 0.833 \ (m_{4l} > 220\text{GeV})$$

$$a_3 \in null \ (m_{4l} > 330\text{GeV})$$

More accurate constraints on HZZ anomalous coupling coefficients obtained here, comparing to $-0.34 \le a_2 \le 1.45, -2.0 \le a_3 \le 2.36.$

Summary

- CP properties can be studied in HZZ decay.
- Existed experimental results constraint HZZ anomalous coefficients in Higgs on-shell region.
- We calculate Helicity amplitudes of HZZ anomalous decay, implemented it in MCFM.
- HZZ anomalous coefficients are constrained in Higgs off-shell region, with considering the interference with gg->4l box diagram.
- More accurate anomalous HZZ coefficients are obtained in Higgs off-shell region, comparing to that in on-shell region.