

# Study of HZZ anomalous couplings by differential cross sections

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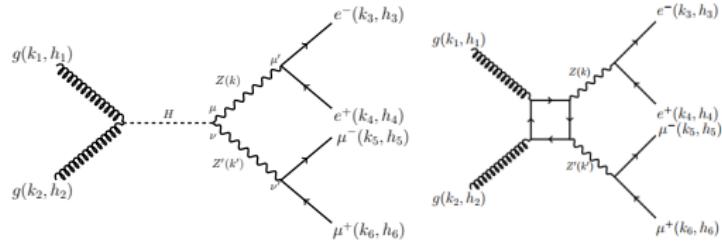
# Outline

- 1 Motivation
- 2 Theoretical calculation
- 3 Numerical calculation of the differential CS with  $HZZ$  anomalous couplings
- 4 Summary

# Motivation

- ① The Higgs boson discovered at the LHC is consistent with SM predictions.
- ② The anomalous HVV couplings can be related to matter-antimatter asymmetry & CP violation.
- ③ The channel of  $H \rightarrow ZZ$  can be fully reconstructed and has large S/B ratio.

- ① More physics information can be subtracted from differential cross section VS total cross section.
- ② Differential cross section involving contribution from interference of the signal and box background process.
- ③ Extend from Higgs on-shell to off-shell energy region.



# Theoretical calculation

## Effective couplings

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \mathcal{L}^{(8)} + \dots$$

$$\mathcal{L}^{(i)} = \sum_{j=1}^{N_i} \frac{C_j^{(i)}}{\Lambda^{i-4}} Q_j^{(i)}$$

Dim 6  $HZZ/HWW$  operators under Warsaw basis

$$\begin{aligned} Q_{\phi D}^6 &= (\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi), \\ Q_{\phi W}^6 &= \phi^\dagger \phi W_{\mu\nu}^I W^{I\mu\nu}, \quad Q_{\phi \widetilde{W}}^6 = \phi^\dagger \phi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}, \\ Q_{\phi B}^6 &= \phi^\dagger \phi B_{\mu\nu} B^{\mu\nu}, \quad Q_{\phi \widetilde{B}}^6 = \phi^\dagger \phi \widetilde{B}_{\mu\nu} B^{\mu\nu}, \\ Q_{\phi WB}^6 &= \phi^\dagger \tau^I \phi W_{\mu\nu}^I B^{\mu\nu}, \quad Q_{\phi \widetilde{W}B}^6 = \phi^\dagger \tau^I \phi \widetilde{W}_{\mu\nu}^I B^{\mu\nu}. \end{aligned}$$

# Theoretical calculation

After spontaneous symmetry breaking

$$\mathcal{L}_{HZZ} = \underbrace{\frac{a_1}{v} M_Z^2 \sigma Z^\mu Z_\mu}_{SM\ CP-even} - \underbrace{\frac{a_2}{v} \sigma Z^{\mu\nu} Z_{\mu\nu}}_{BSM\ CP-even} - \underbrace{\frac{a_3}{v} \sigma Z^{\mu\nu} \tilde{Z}_{\mu\nu}}_{BSM\ CP-odd}.$$

*HZZ effective couplings*

$$\Gamma_{HZZ}^{\mu\nu}(k, k') = 2i \frac{a_1}{v} M_Z^2 g^{\mu\nu} + 4i \frac{a_2}{v} (kk' g^{\mu\nu} - k^\nu k'^\mu) - 4i \frac{a_3}{v} \epsilon^{\mu\nu\rho\sigma} k_\rho k'_\sigma.$$

$$a_1 = 1 + \frac{v^2}{\Lambda^2} C_{\phi D}^6,$$

$$a_2 = -\frac{v^2}{\Lambda^2} \left( C_{\phi W}^6 \cos^2 \theta_W + C_{\phi B}^6 \sin^2 \theta_W + C_{\phi WB}^6 \cos \theta_W \sin \theta_W \right),$$

$$a_3 = -\frac{v^2}{\Lambda^2} \left( C_{\phi \widetilde{W}}^6 \cos^2 \theta_W + C_{\phi \widetilde{B}}^6 \sin^2 \theta_W + C_{\phi \widetilde{WB}}^6 \cos \theta_W \sin \theta_W \right).$$

$$Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu,$$

$$\tilde{Z}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} Z^{\rho\sigma}.$$

# Theoretical calculation

## Helicity amplitude method

In case of massless fermion, chirality  $\Leftrightarrow$  Helicity

$$u_{\pm}(k) = \frac{1}{2}(1 \pm \gamma_5)u(k), \quad v_{\mp}(k) = \frac{1}{2}(1 \pm \gamma_5)v(k).$$

$$\overline{u_{\pm}(k)} = \overline{u(k)} \frac{1}{2}(1 \mp \gamma_5), \quad \overline{v_{\pm}(k)} = \overline{v(k)} \frac{1}{2}(1 \pm \gamma_5).$$

Denote the spinor as

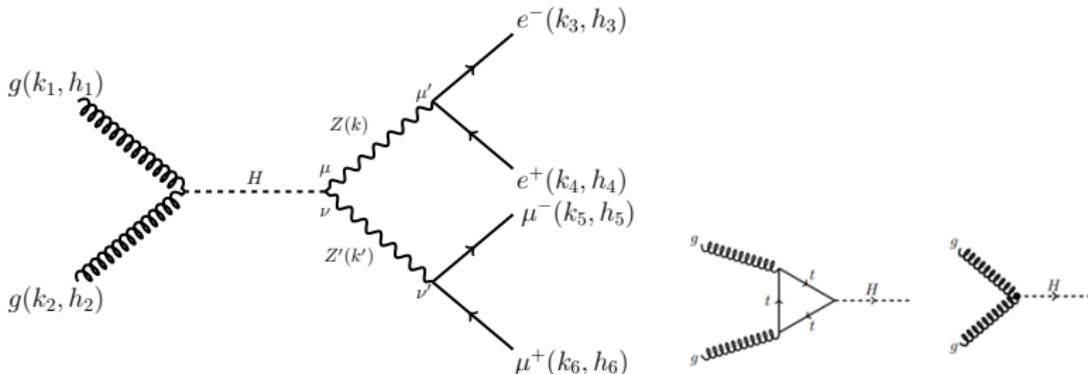
$$|i^{\pm}\rangle \equiv |k_i^{\pm}\rangle \equiv u_{\pm}(k_i) = v_{\mp}(k_i), \quad \langle i^{\pm}| \equiv \langle k_i^{\pm}| \equiv \overline{u_{\pm}(k_i)} = \overline{v_{\mp}(k_i)}.$$

Define spinor product

$$\langle ij \rangle \equiv \langle i^- | j^+ \rangle = \overline{u_-(k_i)} u_+(k_j), \quad [ij] \equiv \langle i^+ | j^- \rangle = \overline{u_+(k_i)} u_-(k_j).$$

# Theoretical calculation

Helicity amplitude for  $gg \rightarrow H \rightarrow ZZ \rightarrow 2e2\mu$



Helicity amplitude for Higgs production

$$iA^{gg \rightarrow H} (1_g^+, 2_g^+) = \frac{-e}{8\pi^2} \delta_{ab} g_s^2 \frac{\langle 12 \rangle}{\langle 12 \rangle} \left[ \frac{m^2}{2M_W \sin \theta} \left( 2 - s_{12} C_0(k_1, k_2, m, m, m) \left( 1 - \frac{4m^2}{s_{12}} \right) \right) \right],$$

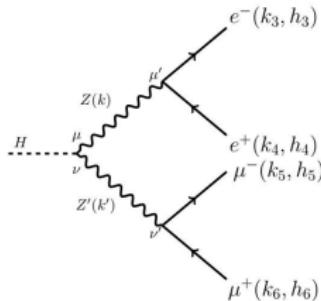
$$iA^{gg \rightarrow H} (1_g^-, 2_g^-) = \frac{-e}{8\pi^2} \delta_{ab} g_s^2 \frac{\langle 12 \rangle}{\langle 12 \rangle} \left[ \frac{m^2}{2M_W \sin \theta} \left( 2 - s_{12} C_0(k_1, k_2, m, m, m) \left( 1 - \frac{4m^2}{s_{12}} \right) \right) \right].$$

$$C_0(k_1, k_2, m_1, m_2, m_3) = \frac{1}{i\pi^2} \int d^4 l \frac{1}{d(l, m_1)d(l + k_1, m_2)d(l + k_1 + k_2, m_3)},$$

$$d(l, m) = (l^2 - m^2 + i\epsilon), \quad s_{12} = (k_1 + k_2)^2 = 2k_1 \cdot k_2$$

# Theoretical calculation

## Helicity amplitude of the Higgs decay



$$iA_{SM}^{H \rightarrow 2e2\mu}(3_{e^-}^-, 4_{e^+}^+, 5_{\mu^-}^-, 6_{\mu^+}^+) = \frac{-2ie^3 M_W}{\cos^2 \theta_W \sin \theta_W} \frac{P_Z(s_{34})}{s_{34}} \frac{P_{Z'}(s_{56})}{s_{56}} l_e^2 \langle 35 \rangle [46],$$

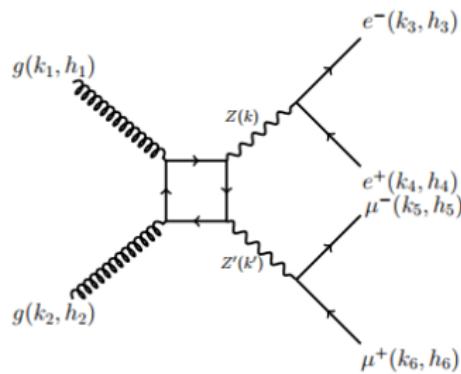
$$iA_{even}^{H \rightarrow 2e2\mu}(3_{e^-}^-, 4_{e^+}^+, 5_{\mu^-}^-, 6_{\mu^+}^+) = \frac{-2ie^3 M_W}{\cos^2 \theta_W \sin \theta_W} \frac{\cos^2 \theta_W}{M_W^2} \frac{P_Z(s_{34})}{s_{34}} \frac{P_{Z'}(s_{56})}{s_{56}} \\ l_e^2 \left[ 2kk' [46] \langle 35 \rangle + ([45] \langle 53 \rangle + [46] \langle 63 \rangle) ([36] \langle 53 \rangle + [46] \langle 54 \rangle) \right],$$

$$iA_{odd}^{H \rightarrow 2e2\mu}(3_{e^-}^-, 4_{e^+}^+, 5_{\mu^-}^-, 6_{\mu^+}^+) = \frac{-2ie^3 M_W}{\cos^2 \theta_W \sin \theta_W} \frac{i \cos^2 \theta_W}{M_W^2} \frac{P_Z(s_{34})}{s_{34}} \frac{P_{Z'}(s_{56})}{s_{56}} l_e^2 \\ \left[ (2kk' - 2\langle 46 \rangle [64]) \langle 53 \rangle [46] + \langle 54 \rangle [46] (\langle 63 \rangle [46] - \langle 53 \rangle [45]) - \langle 53 \rangle [36] (\langle 53 \rangle [45] + \langle 63 \rangle [46]) \right],$$

Amplitude for other helicity states can be obtained by  $[] \leftrightarrow \langle \rangle$ ,  $3 \leftrightarrow 4$ ,  $5 \leftrightarrow 6$ ,  $\square l_e \leftrightarrow \square r_e$ .

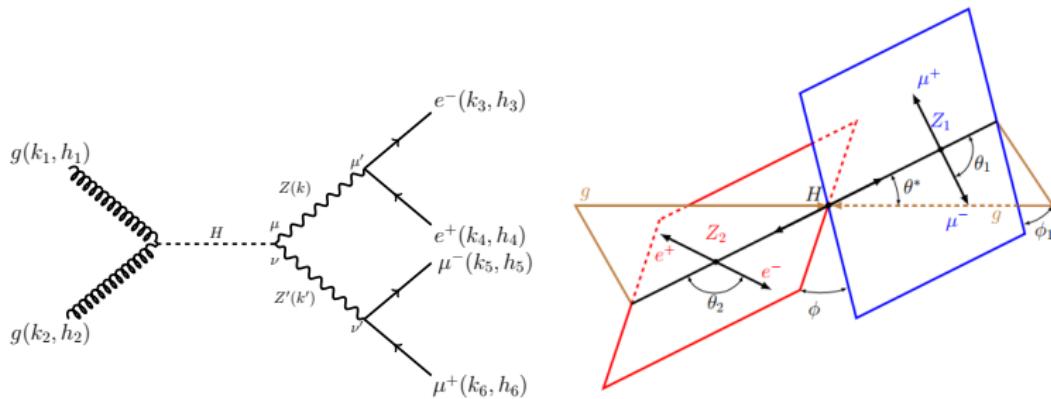
# Theoretical calculation

Background box process of  $gg \rightarrow ZZ \rightarrow 2e2\mu$



Helicity amplitude of the background box process has been written in MCFM8.0

# Impact of HZZ anomalous couplings on differential CS



## Definition of the decay angles

$$g(p_1)g(p_2) \rightarrow H(p_{12}) \rightarrow Z_1(p_{56})Z_2(p_{34}) \rightarrow \mu^-(p_5)\mu^+(p_6)e^-(p_3)e^+(p_4).$$

$$\theta_1 = \cos^{-1} \left( \frac{\vec{p}_{56} \cdot \vec{p}_5}{|\vec{p}_{56}| |\vec{p}_5|} \right), \theta_1 \in [0, \pi].$$

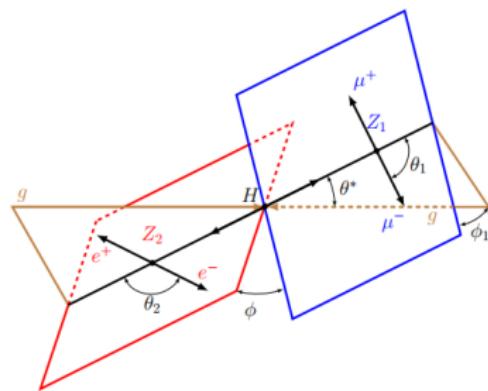
$$\theta_2 = \cos^{-1} \left( \frac{\vec{p}_{34} \cdot \vec{p}_3}{|\vec{p}_{34}| |\vec{p}_3|} \right), \theta_2 \in [0, \pi].$$

$$\theta^* = \cos^{-1} \left( \frac{\vec{p}_{56} \cdot \hat{n}_z}{|\vec{p}_{56}| |\hat{n}_z|} \right),$$

$$\hat{n}_z = (0, 0, 1), \theta^* \in [0, \pi].$$

# Impact of HZZ anomalous couplings on differential CS

$$g(p_1)g(p_2) \rightarrow H(p_{12}) \rightarrow Z_1(p_{56})Z_2(p_{34}) \rightarrow \mu^-(p_5)\mu^+(p_6)e^-(p_3)e^+(p_4).$$



$$\phi = [\cos^{-1} (\hat{n}_{decay1} \cdot \hat{n}_{decay2})] \\ \cdot \frac{(\hat{n}_{decay2} \times \hat{n}_{decay1}) \cdot \vec{p}_{56}}{|(\hat{n}_{decay2} \times \hat{n}_{decay1}) \cdot \vec{p}_{56}|}$$

$$\hat{n}_{decay1} = \frac{\vec{p}_5 \times \vec{p}_6}{|\vec{p}_5 \times \vec{p}_6|}, \quad \hat{n}_{decay2} = \frac{\vec{p}_3 \times \vec{p}_4}{|\vec{p}_3 \times \vec{p}_4|}.$$

$$\phi_1 = [\cos^{-1} (\hat{n}_{prod} \cdot \hat{n}_{decay1})] \\ \cdot \frac{(\hat{n}_{prod} \times \hat{n}_{decay1}) \cdot \vec{p}_{56}}{|(\hat{n}_{prod} \times \hat{n}_{decay1}) \cdot \vec{p}_{56}|}$$

$$\hat{n}_{prod} = \frac{\hat{n}_z \times \vec{p}_{56}}{|\hat{n}_z \times \vec{p}_{56}|}, \quad \hat{n}_z = (0, 0, 1).$$

$$\phi, \phi_1 \in [-\pi, \pi]$$

# Impact of HZZ anomalous couplings on differential CS

## Theoretical differential cross section by MCFM

### Parameters in the calculation

$$a_1 = a_2 = a_3 = 1,$$

$$\sqrt{s} = 13 \text{ TeV}, M_{Higgs} = 125 \text{ GeV},$$

PDF: MSTW08LO,

Renormalization factorization scale:  $m_{4I}/2$ ,

CMS cut criteria

$$P_t(\mu) > 5 \text{ GeV}, \quad |\eta_\mu| < 2.4,$$

$$P_t(e) > 7 \text{ GeV}, \quad |\eta_e| < 2.5,$$

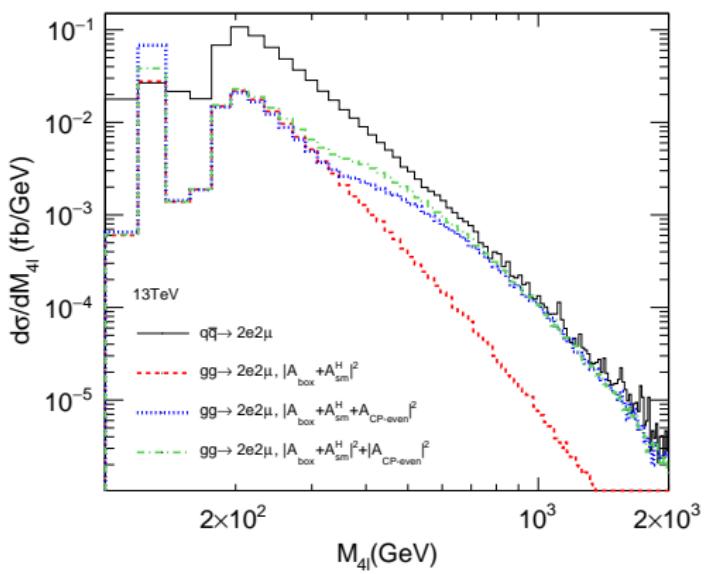
$$m_{4I} > 100 \text{ GeV}.$$

Draw the angular distribution diagrams by ROOT

- ① Higgs on-shell  $m_{2e2\mu} < 130 \text{ GeV}$  VS off-shell  $m_{2e2\mu} > 220 \text{ GeV}$  energy region.
- ② Contribution from interference between Higgs mediated process and background box process.
- ③ Which angular differential cross section is the most sensitive to a certain anomalous HZZ coupling?

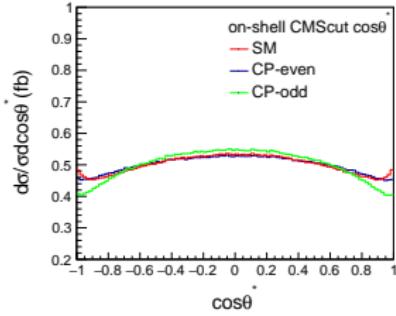
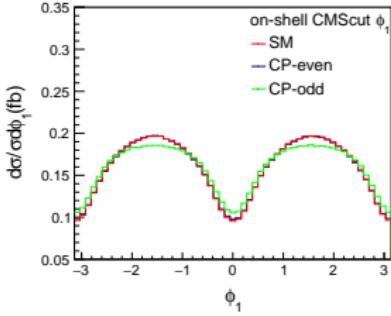
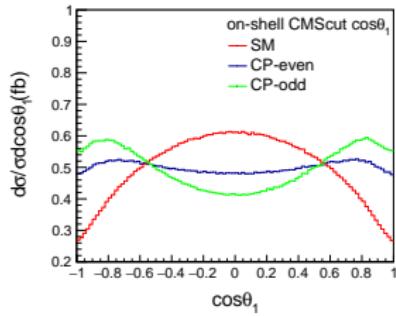
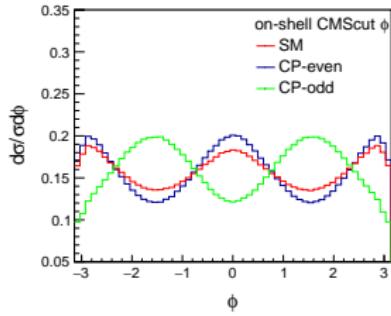
# Impact of HZZ anomalous couplings on differential CS

Differential cross sections of the processes  $gg \rightarrow 2e2\mu$  and  $q\bar{q} \rightarrow 2e2\mu$  process in proton – proton collision at  $\sqrt{s} = 13$  TeV with  $a_2 = 1, a_1 = a_3 = 0$ .



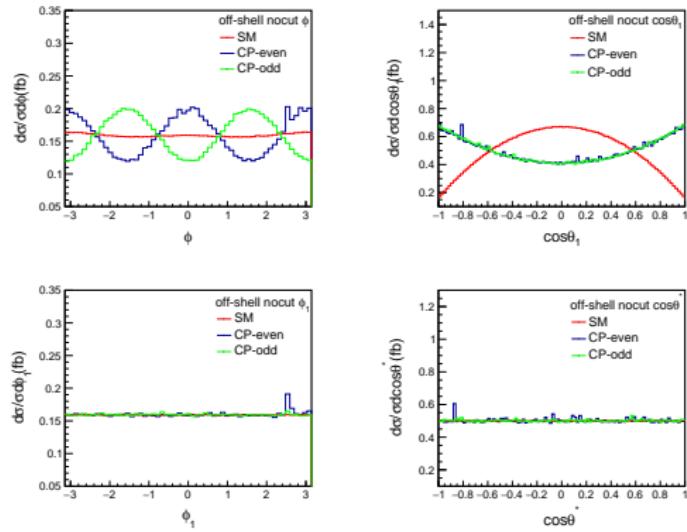
# Impact of HZZ anomalous couplings on differential CS

Angular differential CS for signal process ( $m_{2e2\mu} < 130$  GeV, Higgs on-shell, CMS cut)



# Impact of HZZ anomalous couplings on differential CS

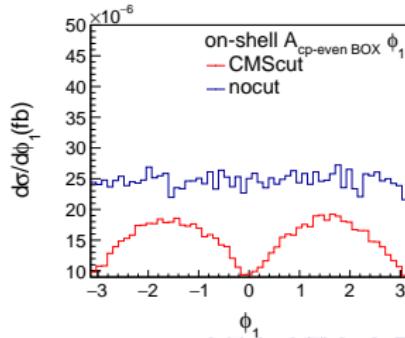
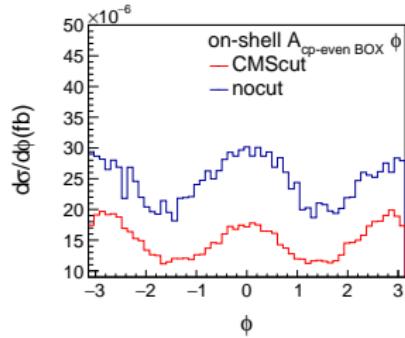
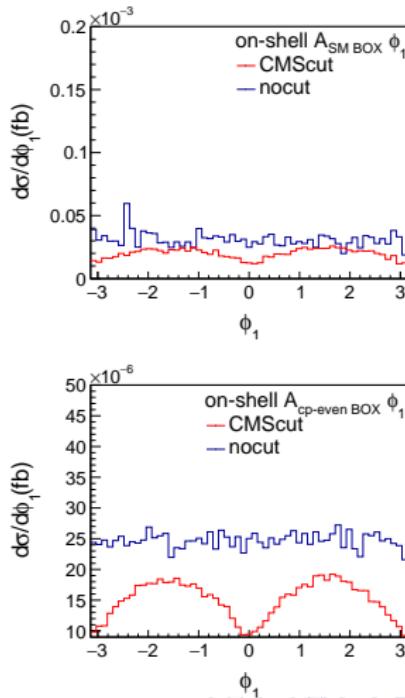
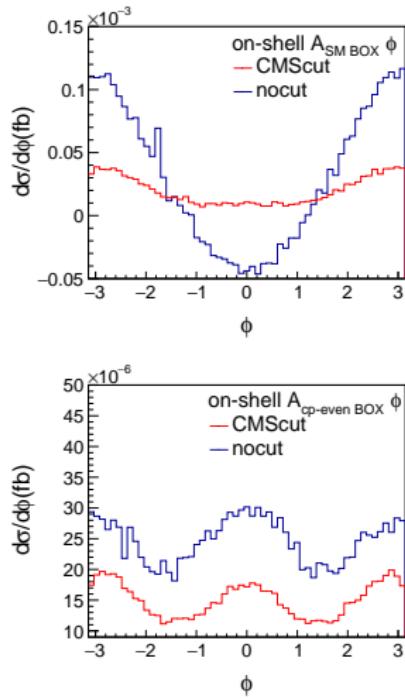
Angular differential CS for signal process ( $m_{2e2\mu} > 220$  GeV, Higgs off-shell, nocut)



纯信号过程, Higgs全区域,  $\phi$ 角分布对HZZ顶点CP敏感,  $\cos \theta_1$ 分布对BSM顶点结构敏感,  $\phi_1$  及  $\cos \theta^*$  分布受cut条件影响.

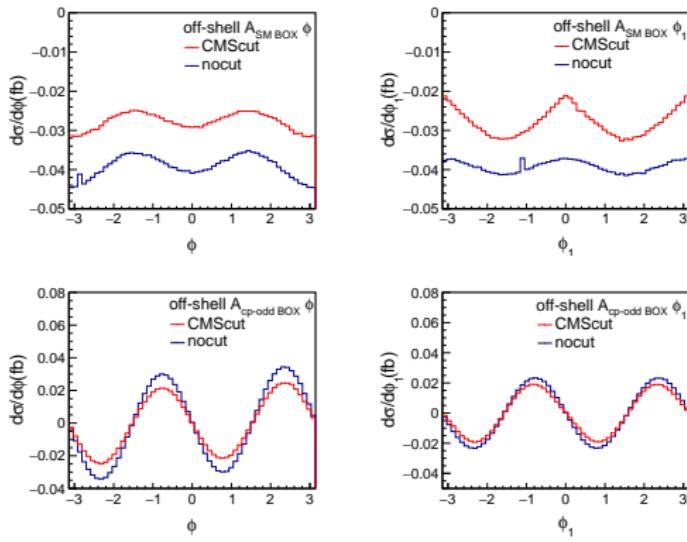
# Impact of $HZZ$ anomalous couplings on differential CS

Angular distribution of the CS for interference between signal and background box process ( $m_{2e2\mu} < 130$  GeV, Higgs on-shell )



# Impact of HZZ anomalous couplings on differential CS

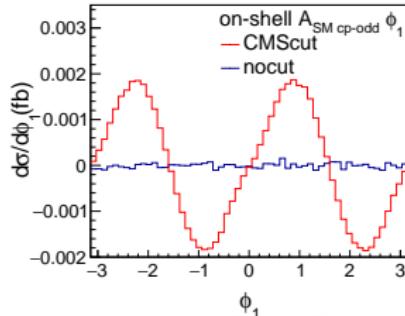
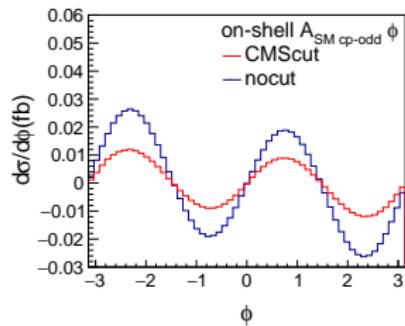
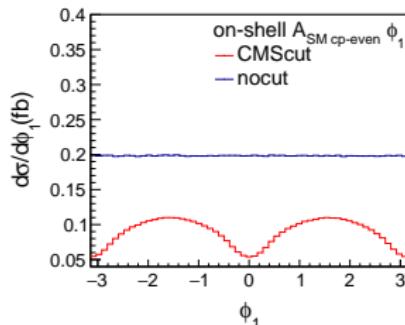
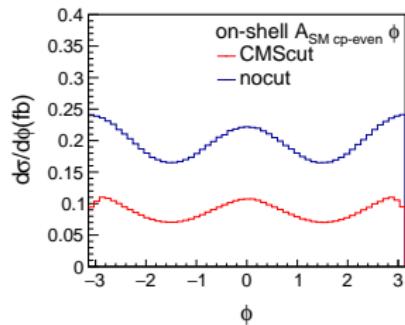
Angular distribution of the CS for interference between signal and background box process ( $m_{2e2\mu} > 220$  GeV, Higgs off-shell )



信号与背景箱图干涉.Higgs在壳,可忽略干涉影响.Higgs离壳,应考虑干涉影响,尤其是CP-odd与box干涉.

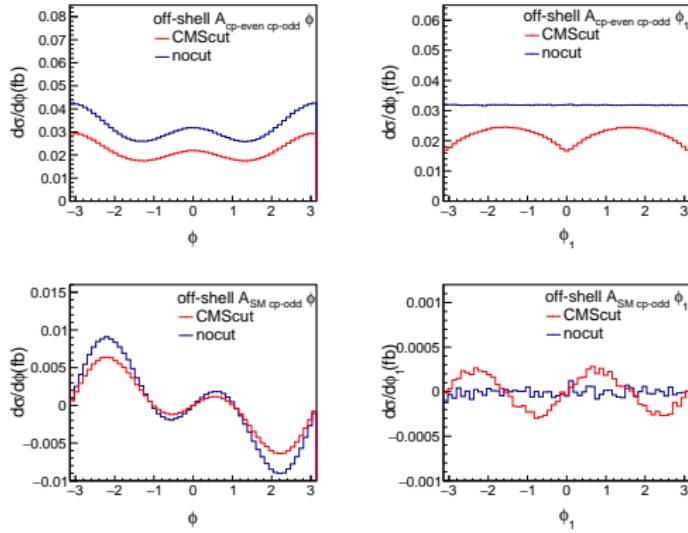
# Impact of $HZZ$ anomalous couplings on differential CS

Angular distribution of the CS for interference between different signal processes ( $m_{2e2\mu} < 130$  GeV, Higgs on-shell )



# Impact of HZZ anomalous couplings on differential CS

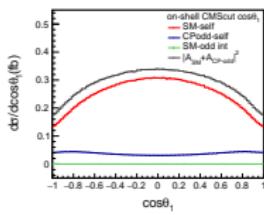
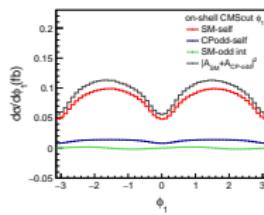
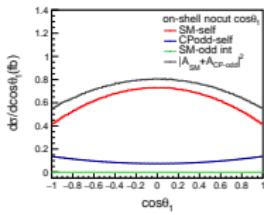
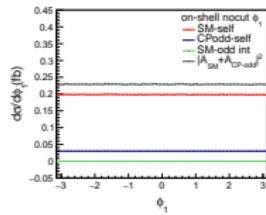
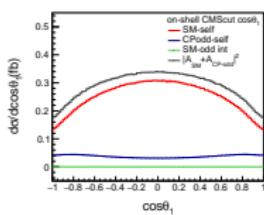
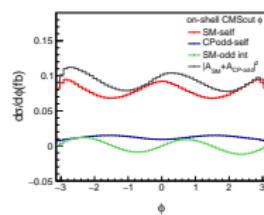
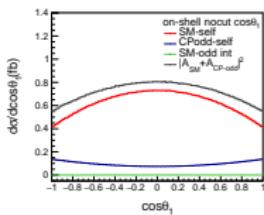
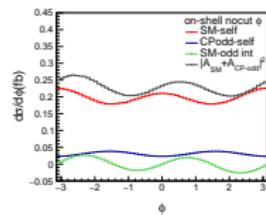
Angular distribution of the CS for interference between different signal processes ( $m_{2e2\mu} > 220$  GeV, Higgs off-shell )



不同信号间的干涉, Higgs在壳及离壳, SM与CP-odd的干涉均会对总体 $\phi$ 角分布产生影响.

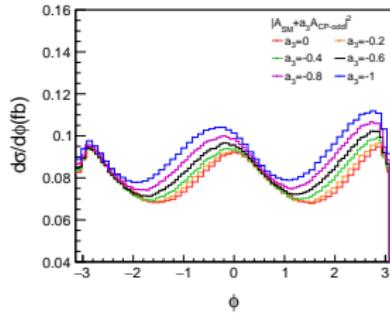
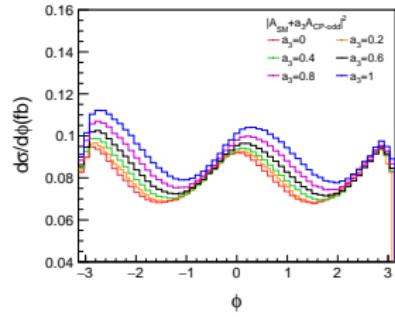
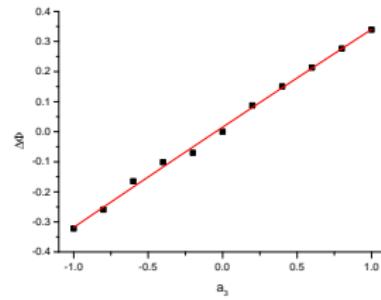
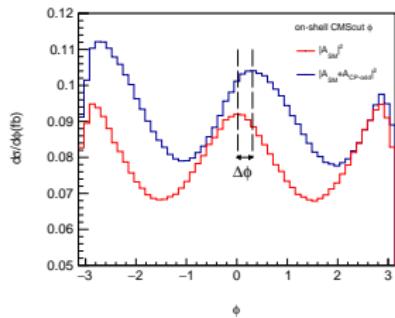
# Impact of $HZZ$ anomalous couplings on differential CS

Angular distribution of the CS including all contributions ( $m_{2e2\mu} < 130$  GeV, Higgs on-shell)



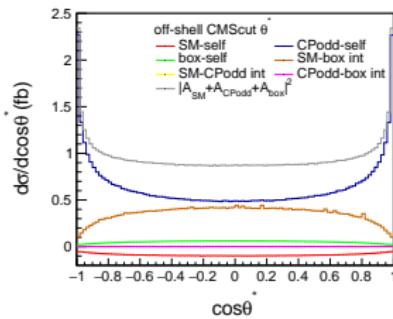
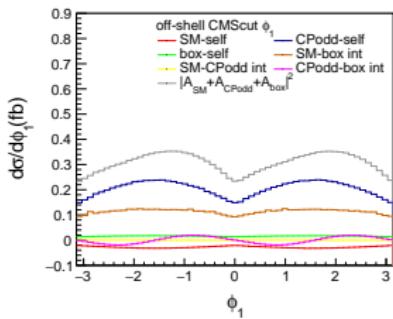
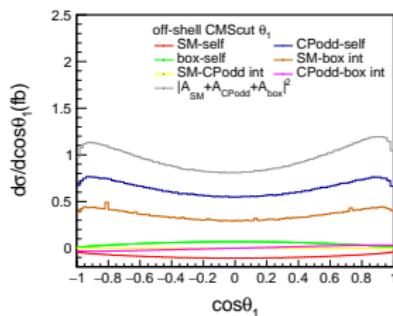
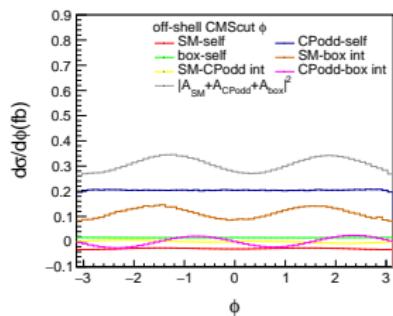
# Impact of HZZ anomalous couplings on differential CS

## Linear relationship between $\Delta\phi$ and $a_3$



# Impact of $HZZ$ anomalous couplings on differential CS

Angular distribution of the CS including all contributions ( $m_{2e2\mu} > 220$  GeV, Higgs off-shell, CMScut)



# Summary

- ① 计算了包含BSM  $HVV$ 反常耦合顶点的  $gg \rightarrow H \rightarrow ZZ \rightarrow 2e2\mu$  过程中 Higgs 衰变过程的振幅, 通过 MCFM 数值计算得到微分截面角分布.
- ② 在 Higgs 离壳以及在壳区域模拟过程的角分布, 考虑了事例筛选条件对于角分布的影响, 以及背景箱图的影响.

- ① 在 Higgs 在壳区域, 信号与背景箱图的干涉对于角分布的影响是可以忽略的, 而 SM 与 CP-odd 的干涉应该被考虑, 干涉的存在会使得总体  $\phi$  角分布发生偏移, 这样的偏移与反常耦合系数  $a_3$  存在近似的线性关系.
- ② 在 Higgs 离壳区域, 信号与背景箱图的干涉对角分布有明显的影响. SM 与 CP-odd 的干涉以及 CP-odd 与背景箱图的干涉均会对总体角分布产生影响.

谢谢