

New physics and its interference effect

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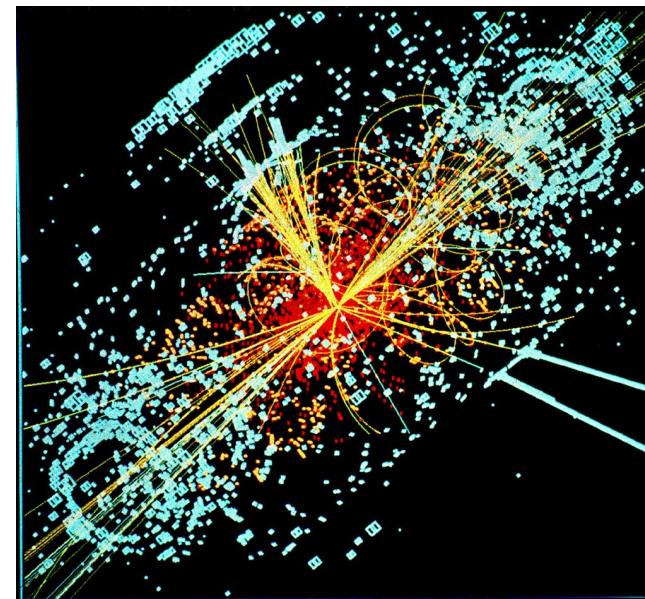
第十届全国会员代表大会暨学术年会



Outline

- Motivation of New Physics and its interference with Standard Model.
- The interference @LHC in channels of

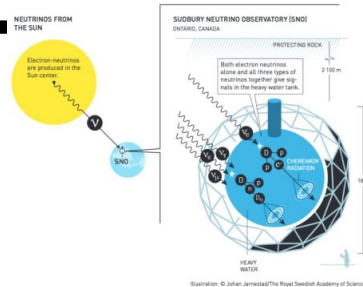
1. $H \rightarrow \gamma\gamma$
2. $H \rightarrow \gamma Z \rightarrow \gamma ll$
3. $H \rightarrow ZZ \rightarrow 4l$



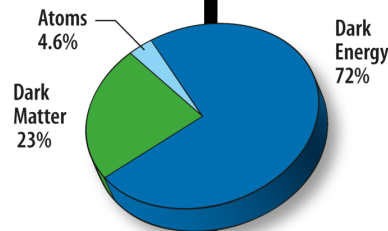
- Summary

New physics before LHC

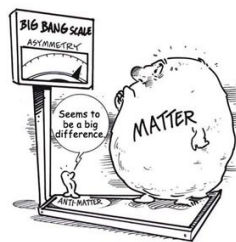
- Neutrino mass



- Dark matter, Dark energy



- Matter-antimatter asymmetry



- Gravity

-

- Higgs mass hierarchy

- Number of parameters

- Strong CP problem

-

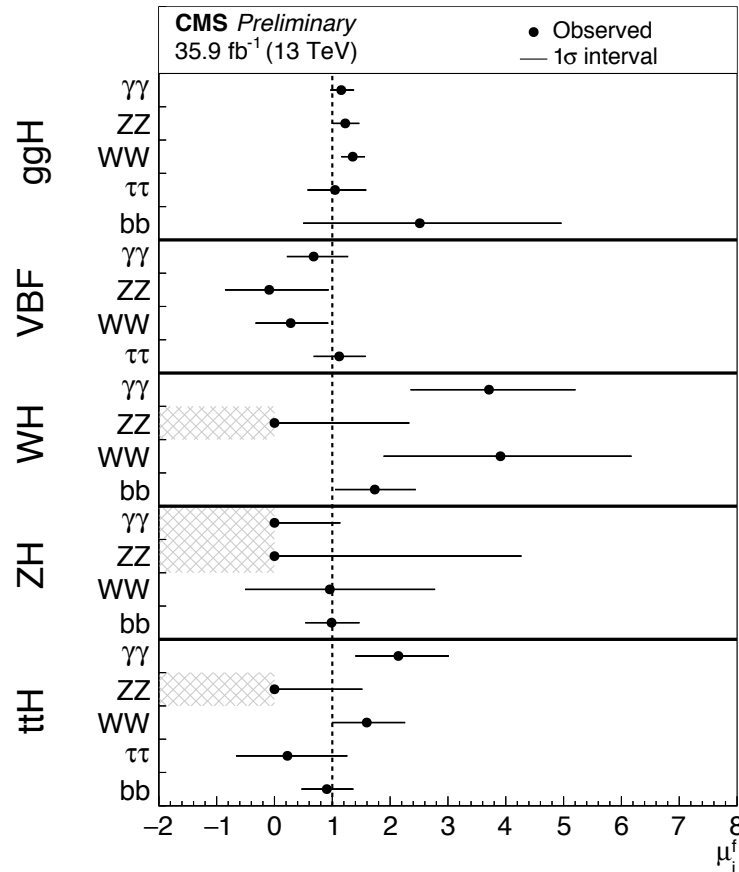
New Models: Supersymmetry Models, Extra dimension, GUT, String Theory,



Where is New physics @ LHC

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2017

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$



CMS-PAS-HIG-17-003

Model	ℓ, γ	Jets [†]	$E_{\text{T}}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	
	ADD QBH	-	2 j	-	37.0	M_{th} 8.9 TeV	$n = 6$	
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{th} 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$	
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass 4.1 TeV	$k/\bar{M}_{pl} = 0.1$	
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\bar{M}_{pl} = 1.0$	
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	36.1	Z' mass 4.5 TeV	
		SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass 2.4 TeV	
Leptophobic $Z' \rightarrow bb$		-	2 b	-	3.2	Z' mass 1.5 TeV		
Leptophobic $Z' \rightarrow tt$		1 e, μ	$\geq 1 b, \geq 1J/2j$	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	
SSM $W' \rightarrow \ell\nu$		1 e, μ	-	Yes	36.1	W' mass 5.1 TeV		
HVT $V' \rightarrow WV \rightarrow qq\bar{q}q$ model B		0 e, μ	2 J	-	36.7	W' mass 3.5 TeV	$g_V = 3$	
HVT $V' \rightarrow WH/ZH$ model B		multi-channel	-	-	36.1	V' mass 2.93 TeV	$g_V = 3$	
LRSM $W'_R \rightarrow tb$		1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		
LRSM $W'_R \rightarrow tb$		0 e, μ	$\geq 1 b, 1 J$	-	20.3	W' mass 1.76 TeV		
CI		CI $qq\bar{q}q$	-	2 j	-	37.0	Λ 21.8 TeV	η_{LL}
	CI $\ell\ell q\bar{q}$	2 e, μ	-	-	36.1	Λ 40.1 TeV	η_{LL}	
	CI $uutt$	2(SS)/ $\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	20.3	Λ 4.9 TeV	$ C_{RR} = 1$	
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	m_{med} 1.5 TeV	$g_q = 0.25, g_\ell = 1.0, m(\chi) < 400 \text{ GeV}$	
	Vector mediator (Dirac DM)	0 $e, \mu, 1 \gamma$	$\leq 1 j$	Yes	36.1	m_{med} 1.2 TeV	$g_q = 0.25, g_\ell = 1.0, m(\chi) < 480 \text{ GeV}$	
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, $\leq 1 j$	Yes	3.2	M_* 700 GeV	$m(\chi) < 150 \text{ GeV}$	
LQ	Scalar LQ 1 st gen	2 e	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$	
	Scalar LQ 2 nd gen	2 μ	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$	
	Scalar LQ 3 rd gen	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	
Heavy quarks	VLQ $TT \rightarrow Ht + X$	0 or 1 e, μ	$\geq 2 b, \geq 3 j$	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \rightarrow Ht) = 1$	
	VLQ $TT \rightarrow Zt + X$	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \rightarrow Zt) = 1$	
	VLQ $TT \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1J/2j$	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$	
	VLQ $BB \rightarrow Hb + X$	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$	
	VLQ $BB \rightarrow Zb + X$	2/ $\geq 3 e, \mu$	$\geq 2/\geq 1 b$	-	20.3	B mass 790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$	
	VLQ $BB \rightarrow Wt + X$	1 e, μ	$\geq 1 b, \geq 1J/2j$	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \rightarrow Wt) = 1$	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	37.0	q^* mass 6.0 TeV	only u^* and d^* , $\Lambda = m(q^*)$	
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$	
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	13.3	b^* mass 2.3 TeV		
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_\ell = f_R = 1$	
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	
Other	LRSM Majorana ν	2 e, μ	2 j	-	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q = 5e$	
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ g = 1g_D, \text{spin } 1/2$	

*Only a selection of the available mass limits on new states or phenomena is shown.

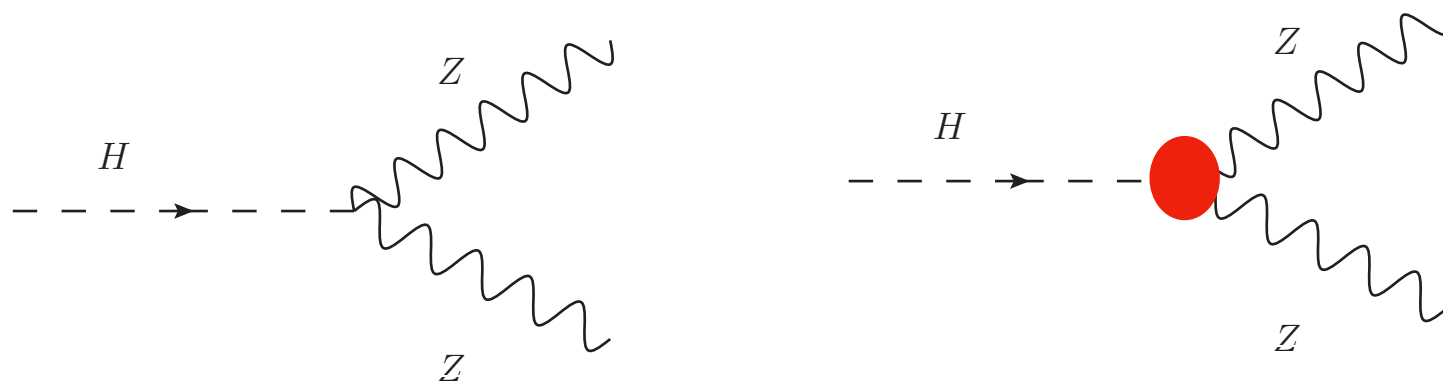
†Small-radius (large-radius) jets are denoted by the letter j (J).

Around 100GeV~1TeV, effectively new physics is highly suppressed !

Interference effect may become relatively large

$$|\mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{new}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + |\mathcal{M}_{\text{new}}|^2 + 2\text{Re}(\mathcal{M}_{\text{SM}}\mathcal{M}_{\text{new}}^*)$$

e.g.

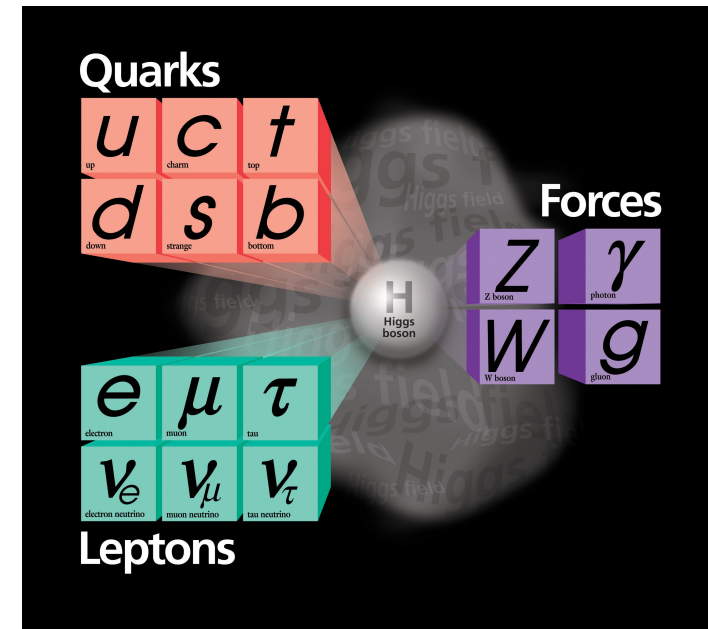
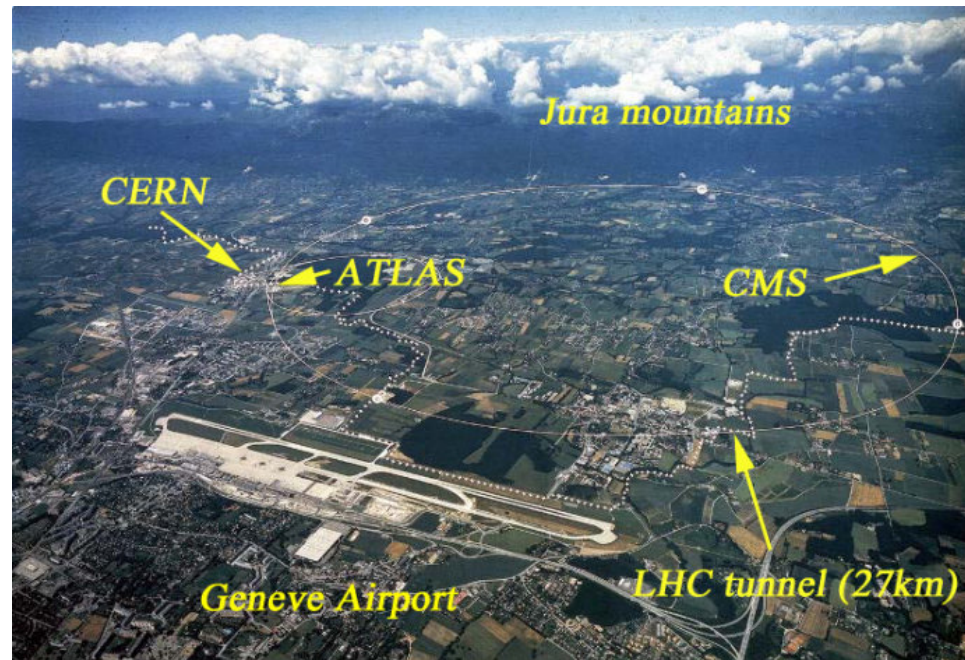


$$L(HZZ) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu + a_2 \frac{1}{2} H Z^{\mu\nu} Z_{\mu\nu}$$

$a_1=1, a_2=1$ $\sqrt{s}=13$ TeV, $gg \rightarrow H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$

σ_{SM}	σ_{new}	$\sigma_{\text{interference}}$
0.533fb	0.220fb	-0.599fb

Is there a new observable (method) from interference effect to probe new physics ?



1. $H \rightarrow \gamma\gamma$
2. $H \rightarrow \gamma Z \rightarrow \gamma ll$
3. $H \rightarrow ZZ \rightarrow 4l$

XW, Youkai Wang, arXiv:1712.00267

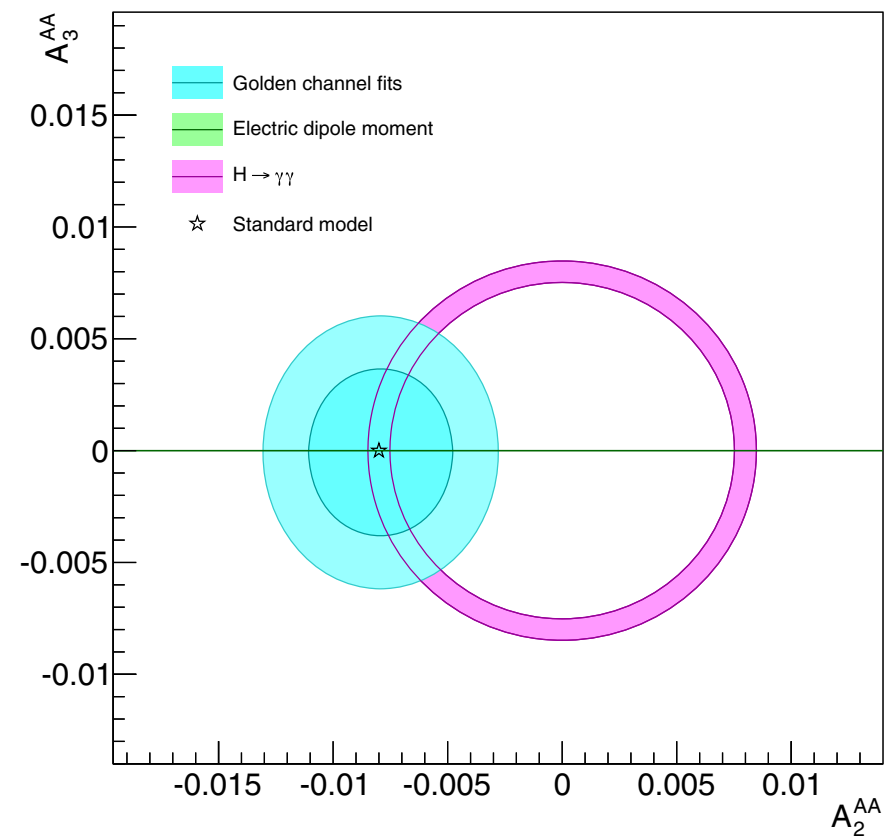
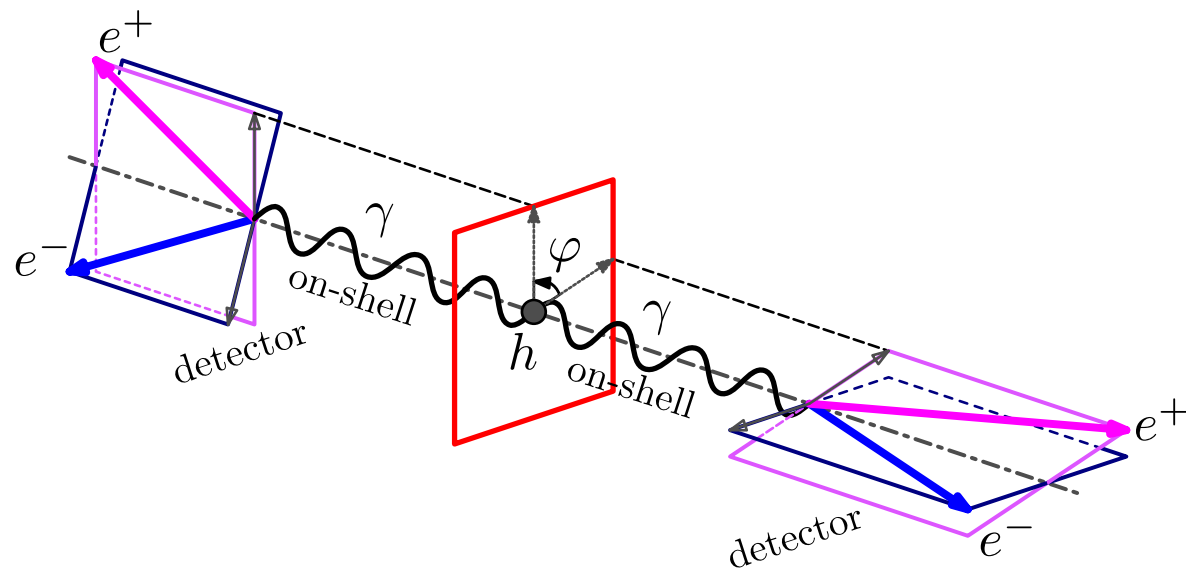
Xuan Chen, Gang Li, XW, PRD96, 055023 (2017)

Huarong He, XW, Youkai Wang in progress

1. CP violation in $H\gamma\gamma$

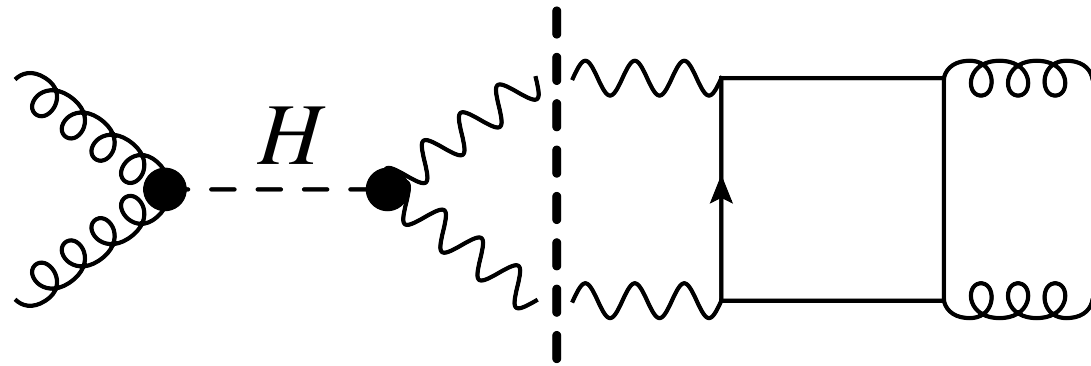
$$\mathcal{L}_h = \frac{c_\gamma \cos \xi_\gamma}{v} h F_{\mu\nu} F^{\mu\nu} + \frac{c_\gamma \sin \xi_\gamma}{2v} h F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{c_g}{v} h G_{\mu\nu}^a G^{a\mu\nu}$$

$$H \rightarrow \gamma^* \gamma^* \rightarrow 4\ell$$



F. Bishara, etc. JHEP04, 084 (2014)
Y. Chen, etc. PRL113, 191801 (2014)

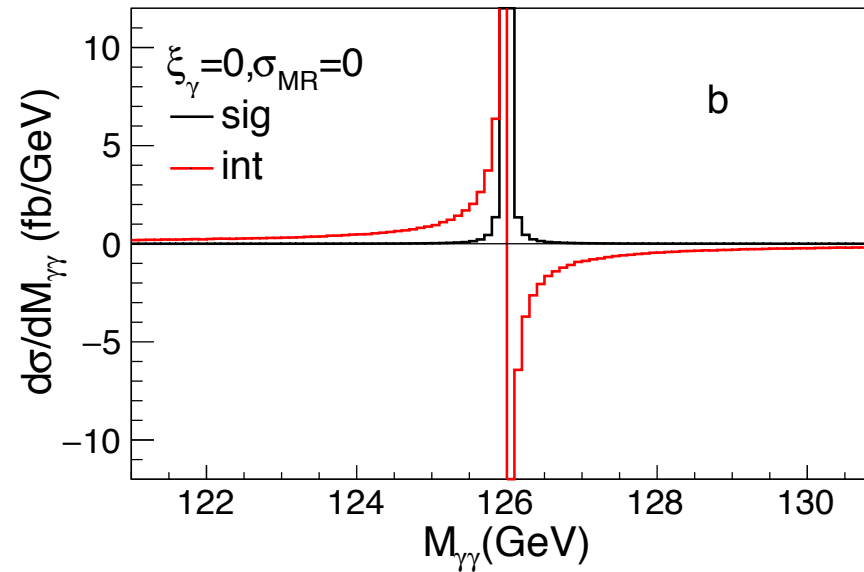
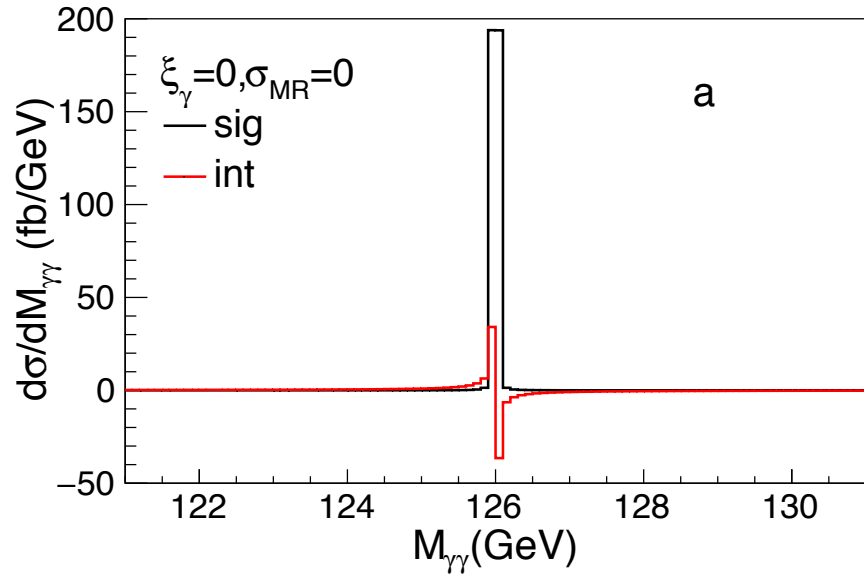
Interference



$$\mathcal{M} = -e^{-ih_3\xi_\gamma} \delta_{h_1 h_2} \delta_{h_3 h_4} \frac{M_{\gamma\gamma}^4}{v^2} \frac{4c_g c_\gamma}{M_{\gamma\gamma}^2 - M_H^2 + iM_H \Gamma_H} + 4\alpha\alpha_s \delta^{ab} \sum_{f=u,d,c,s,b} Q_f^2 \mathcal{A}_{box}^{h_1 h_2 h_3 h_4},$$

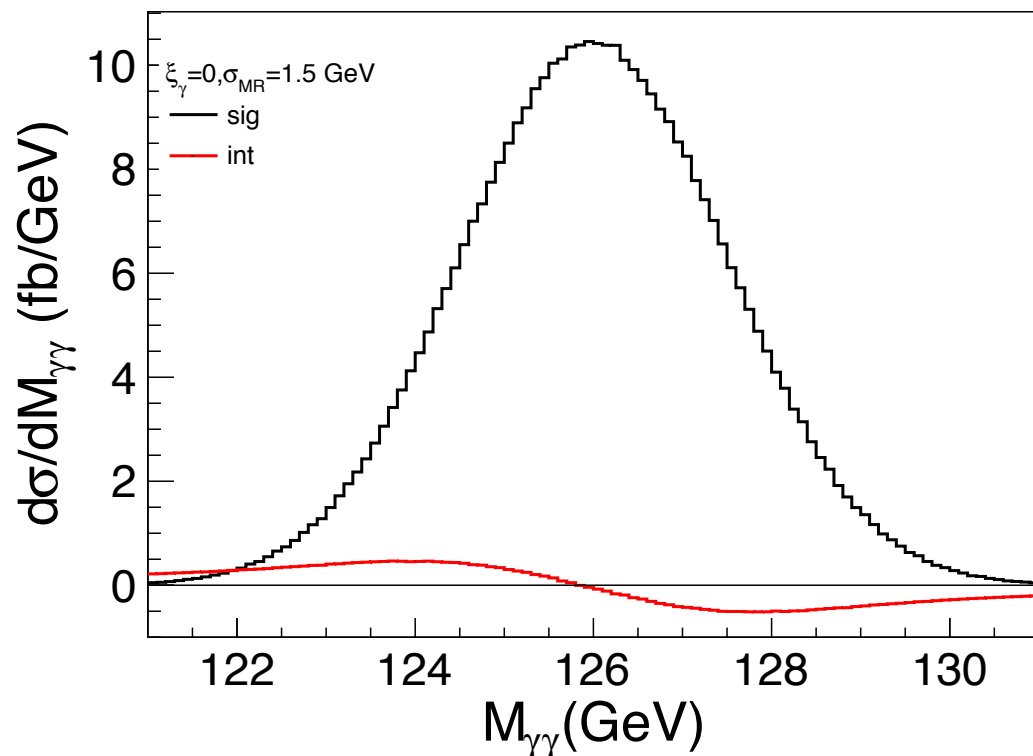
$$\frac{d\sigma_{int}}{dM_{\gamma\gamma}} \propto \frac{(M_{\gamma\gamma}^2 - M_H^2) \text{Re}(c_g c_\gamma) + M_H \Gamma_H \text{Im}(c_g c_\gamma)}{(M_{\gamma\gamma}^2 - M_H^2) + M_H^2 \Gamma_H^2} \times \int dz [\mathcal{A}_{box}^{++++} + \mathcal{A}_{box}^{++--}] \cos \xi_\gamma,$$

Interference in SM



$$A_{int}(\xi_\gamma) = \frac{\int dM_{\gamma\gamma} \frac{d\sigma_{int}}{dM_{\gamma\gamma}} \Theta(M_{\gamma\gamma} - M_H)}{\int dM_{\gamma\gamma} \frac{d\sigma_{sig}}{dM_{\gamma\gamma}}},$$

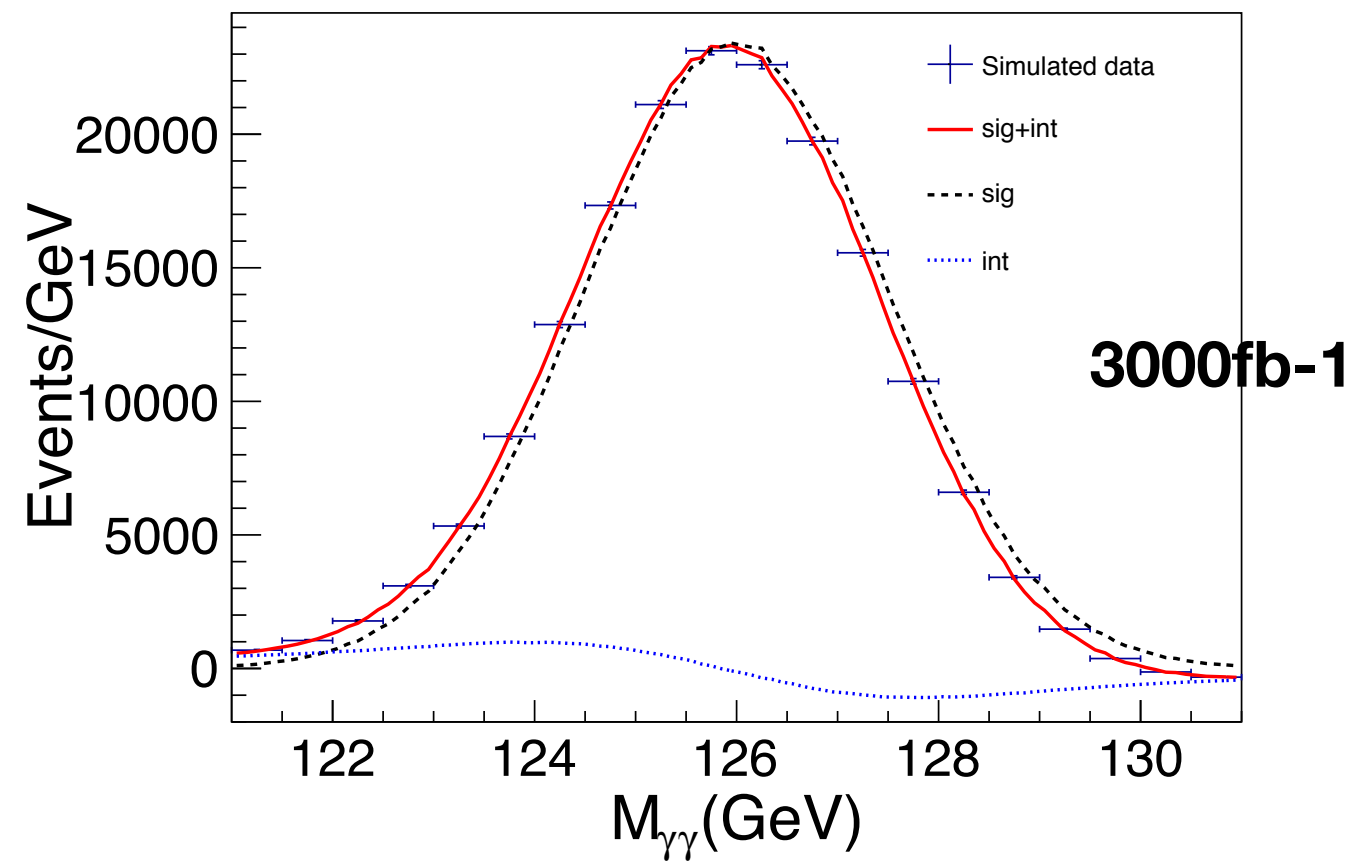
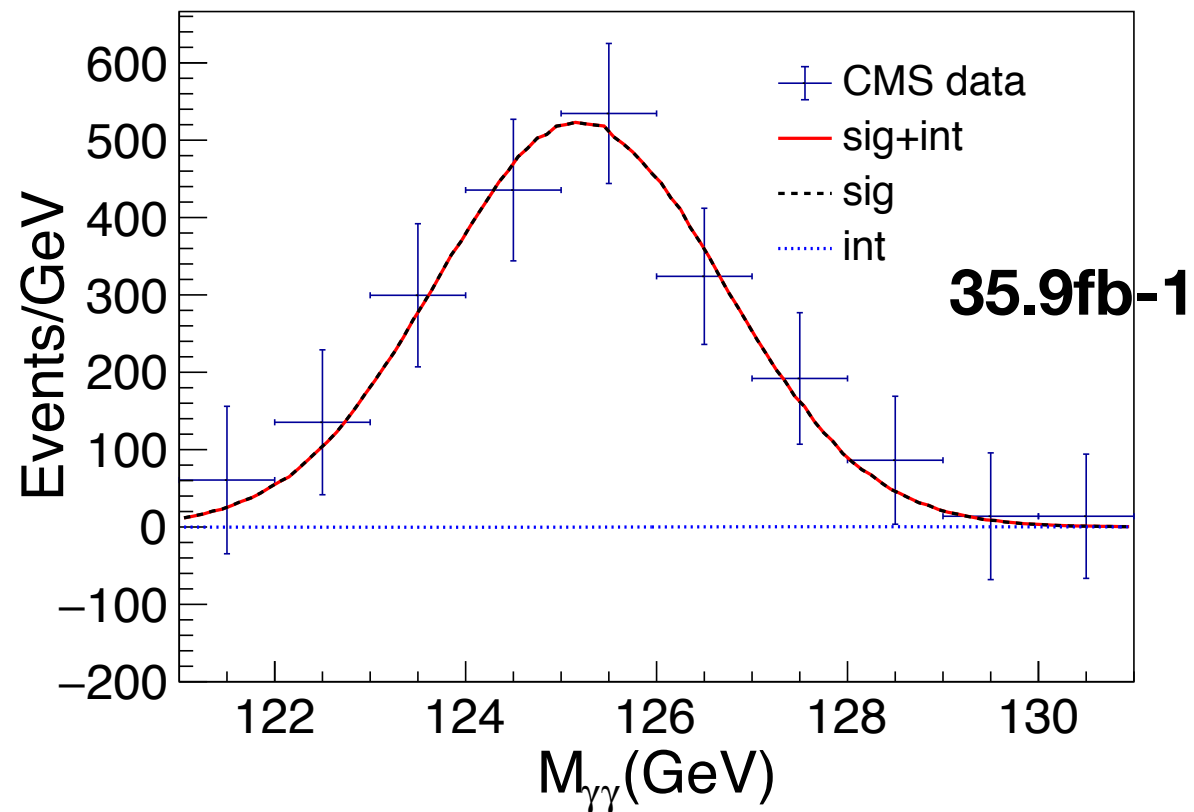
$$\Theta(x) \equiv \begin{cases} -1, & x < 0 \\ 1, & x > 0 \end{cases}$$



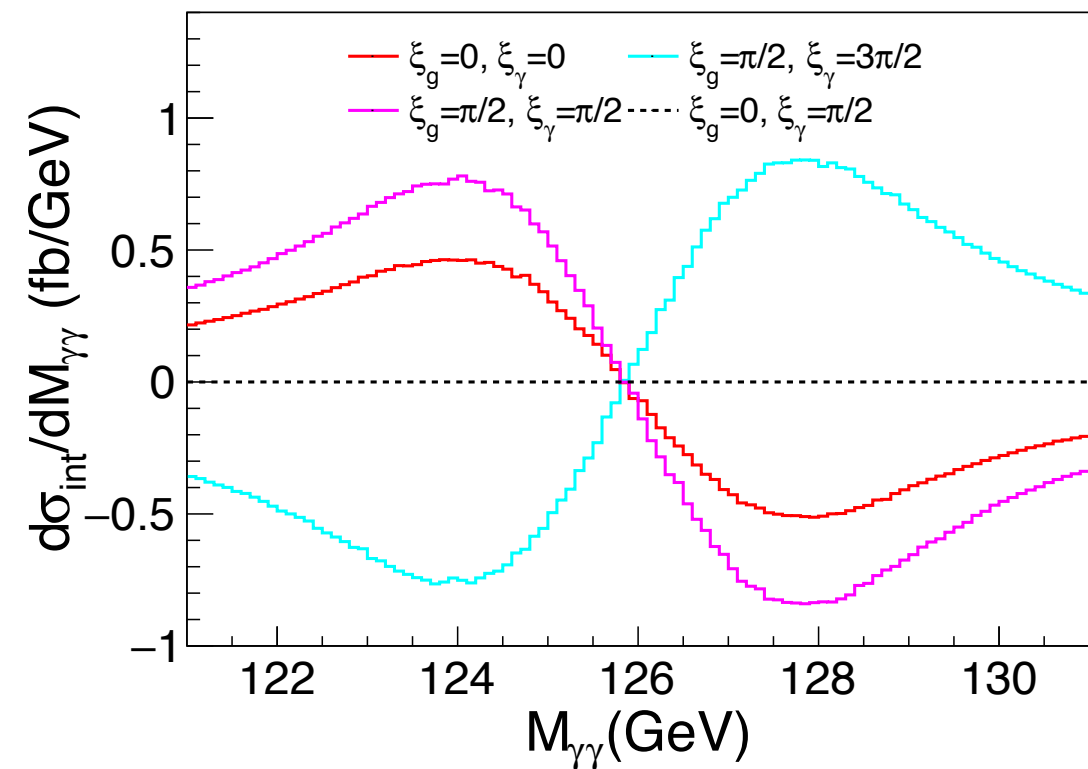
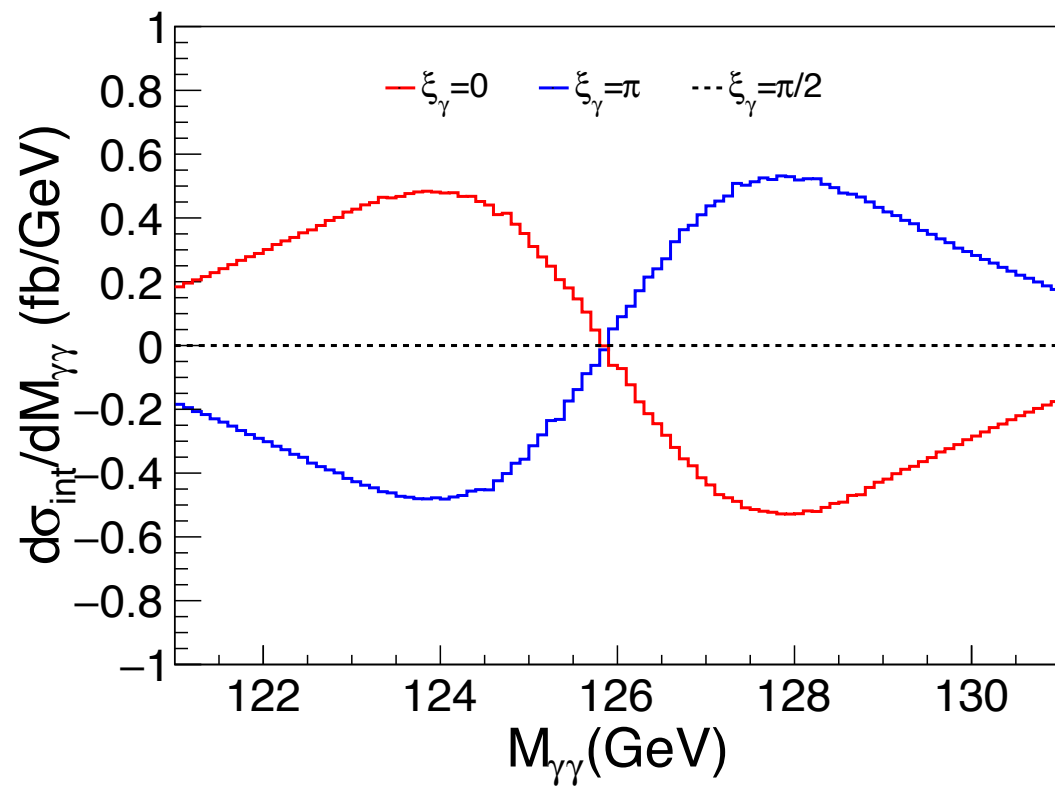
σ_{MR} (GeV)	A_{int}^{SM} denominator (fb)	A_{int}^{SM} numerator (fb)	A_{int}^{SM} (%)
0	39.3	14.3	36.3
1.1	39.3	4.0	10.2
1.3	39.3	3.7	9.4
1.5	39.3	3.4	8.6
1.7	39.3	3.1	7.9
1.9	39.3	2.8	7.2

Fitting

$$f(m) = c_1 \times f_{sig}(m - \delta m) + c_2 \times f_{int}(m - \delta m),$$



Interference in BSM

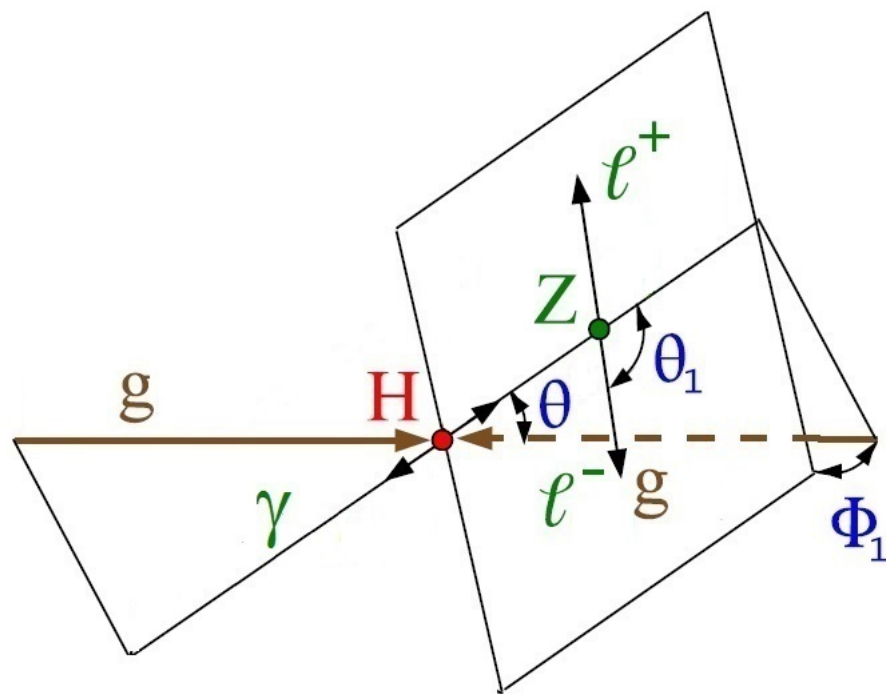


$$A_{int} \sim \pm 16\%$$

2. CP violation in $H\gamma Z$

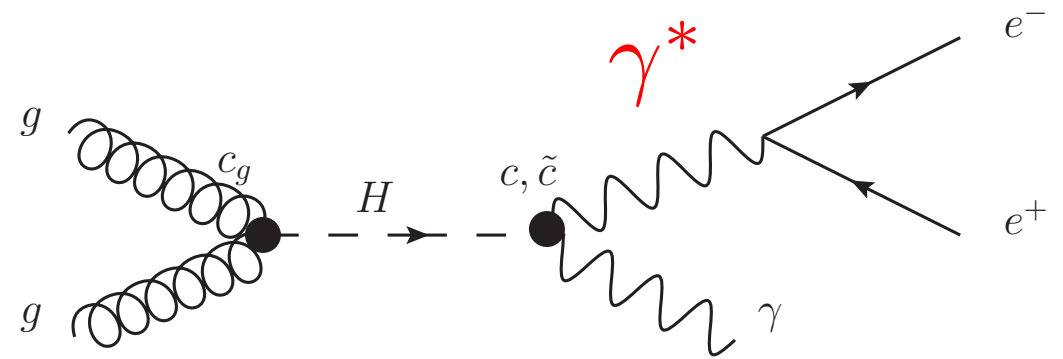
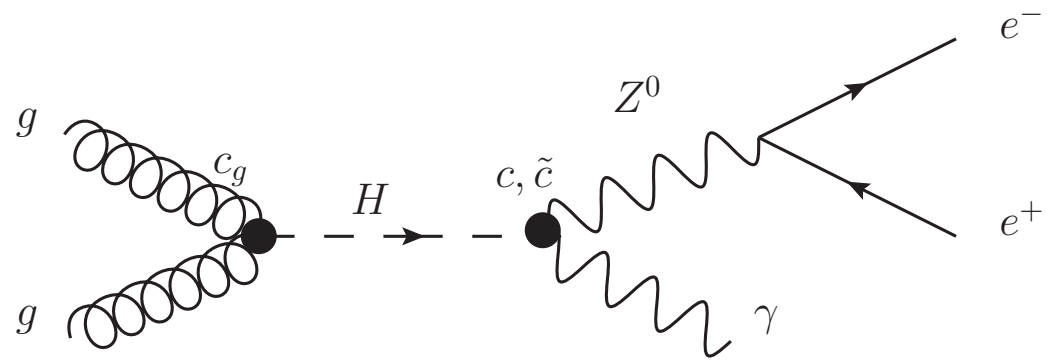
$$\mathcal{L}_h = \frac{c}{v} h F_{\mu\nu} Z^{\mu\nu} + \frac{\tilde{c}}{2v} h F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{c_g}{v} h G_{\mu\nu}^a G^{a\mu\nu}$$

$$\xi = \tan^{-1}(\tilde{c}/c)$$

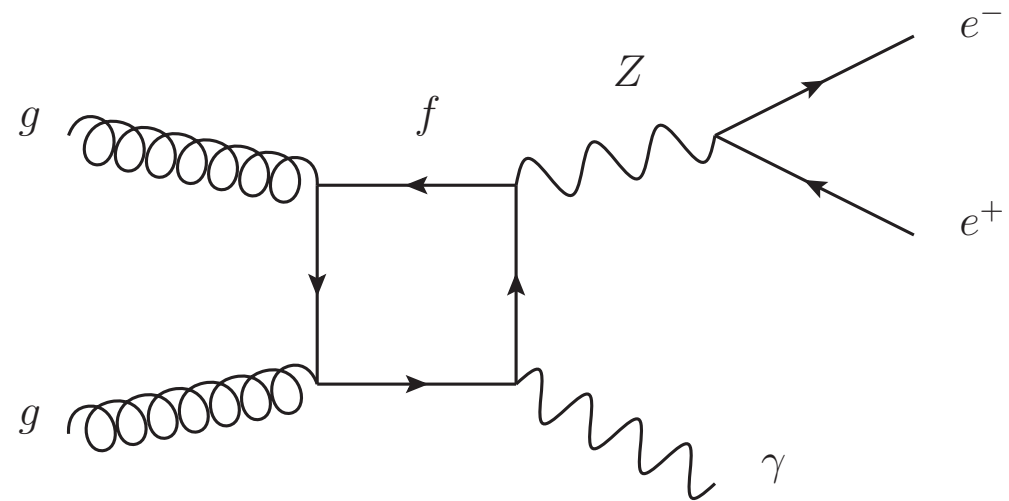


Kinematics has no sensitivity to ξ

Interference



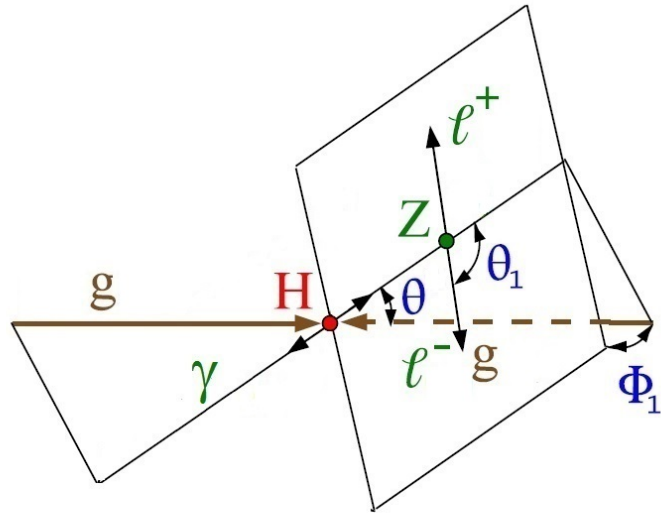
Yi Chen, etc PRD90, 113006 (2014)



Xuan Chen, Gang Li, Xia WAN PRD96, 055023 (2017)

Forward-backward Asymmetry

$$g(p_1)g(p_2) \rightarrow H(p_{12}) \rightarrow \gamma(p_3)Z(p_{45}) \rightarrow \gamma(p_3)\ell^-(p_4)\ell^+(p_5),$$

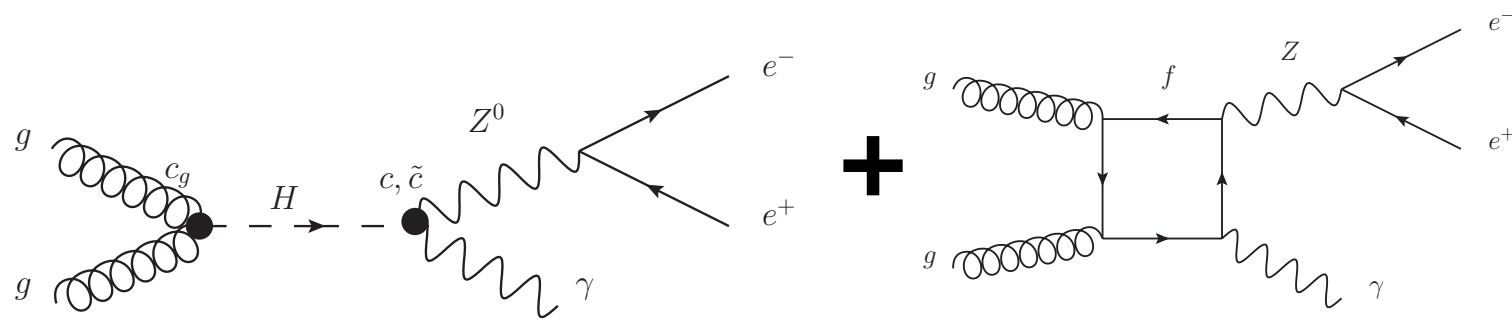


$$\theta_1 = \cos^{-1} \left(-\frac{\vec{p}_3 \cdot \vec{p}_4}{|\vec{p}_3||\vec{p}_4|} \right) \quad \begin{array}{l} \vec{p}_3 \text{ in } H \text{ rest frame,} \\ \vec{p}_4 \text{ in } Z \text{ rest frame.} \end{array}$$

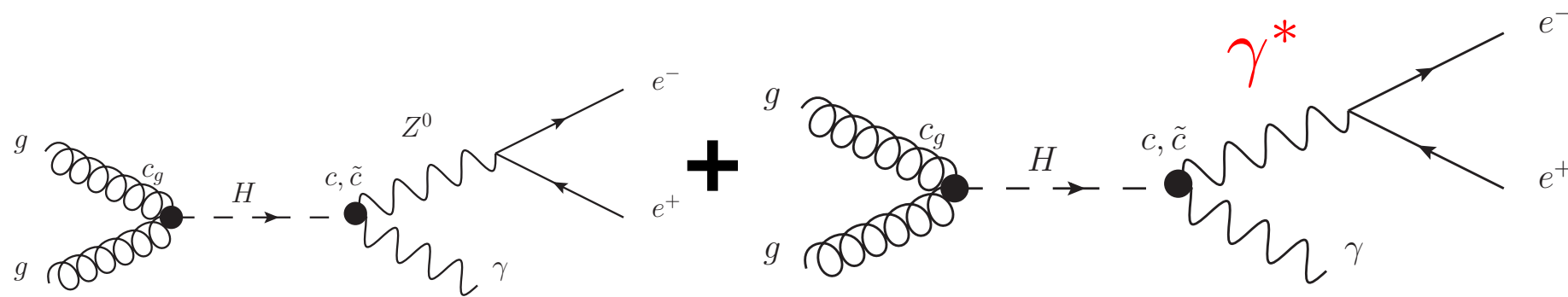
$$A_{FB}(s_{12}) = \frac{(\int_0^1 - \int_{-1}^0) d \cos \theta_1 \int_{-1}^1 d \cos \theta \int_{-\pi}^{\pi} d\phi_1 \frac{d\hat{\sigma}(s_{12}, \theta; \theta_1, \phi_1)}{d(\cos \theta)d(\cos \theta_1)d\phi_1}}{(\int_{-1}^1) d \cos \theta_1 \int_{-1}^1 d \cos \theta \int_{-\pi}^{\pi} d\phi_1 \frac{d\hat{\sigma}(s_{12}, \theta; \theta_1, \phi_1)}{d(\cos \theta)d(\cos \theta_1)d\phi_1}}$$

$$\propto 4 \operatorname{Im}[\tilde{\sigma}_{H,box}^{2 \rightarrow 2}]_{++} \sin \xi$$

A_{FB} value



A_{FB} < 1% for $\xi_{H\gamma Z} = \frac{\pi}{2}$

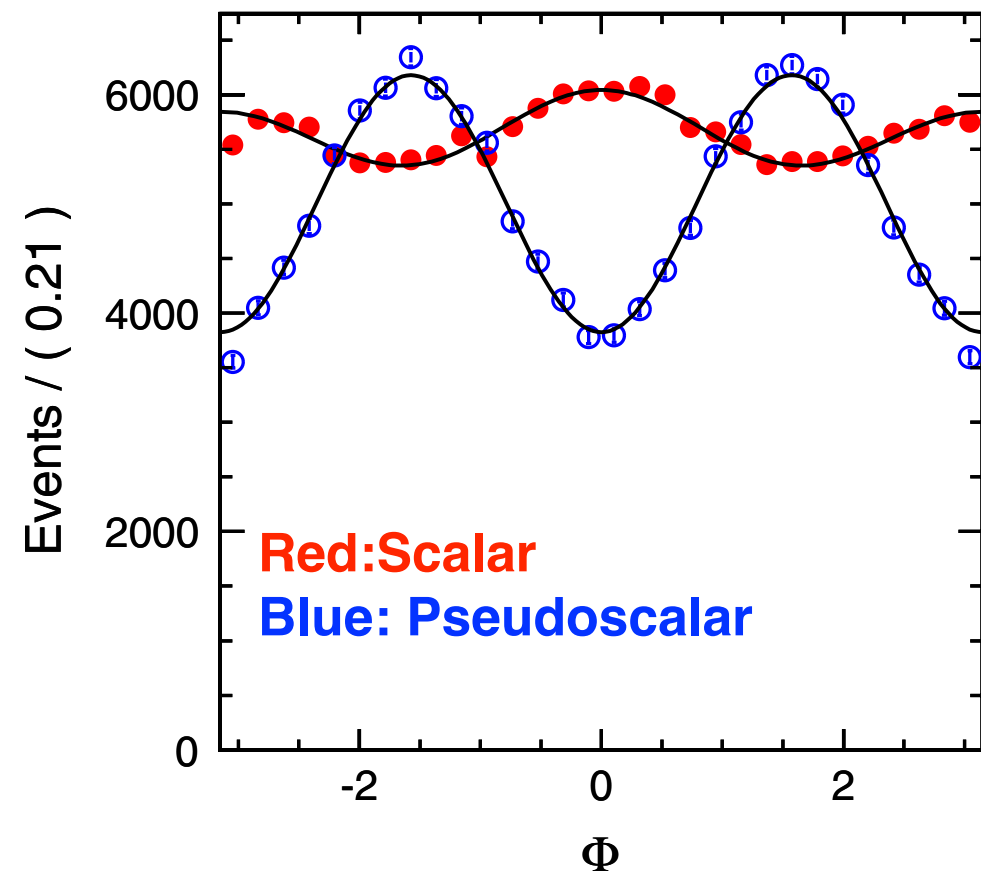
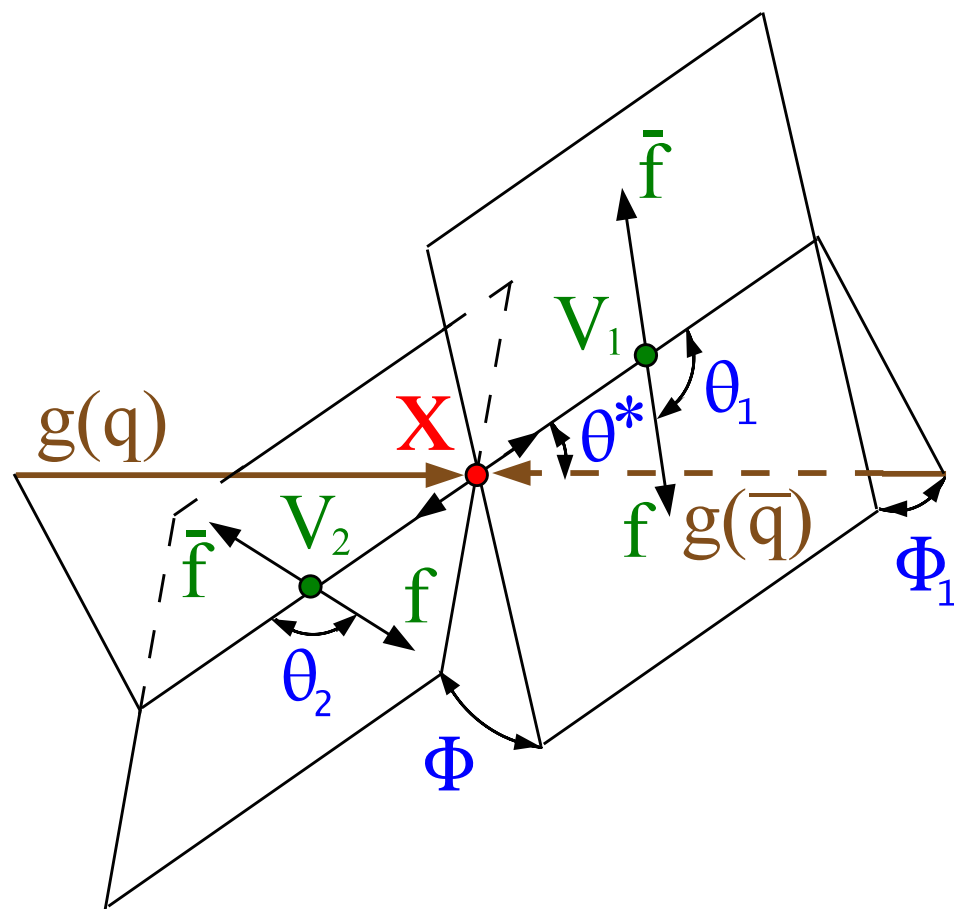


A_{FB} ~ 4% for $\xi_{H\gamma Z} = \frac{\pi}{2}, \xi_{H\gamma\gamma} = 0$

Yi Chen, etc, PRD90,113006

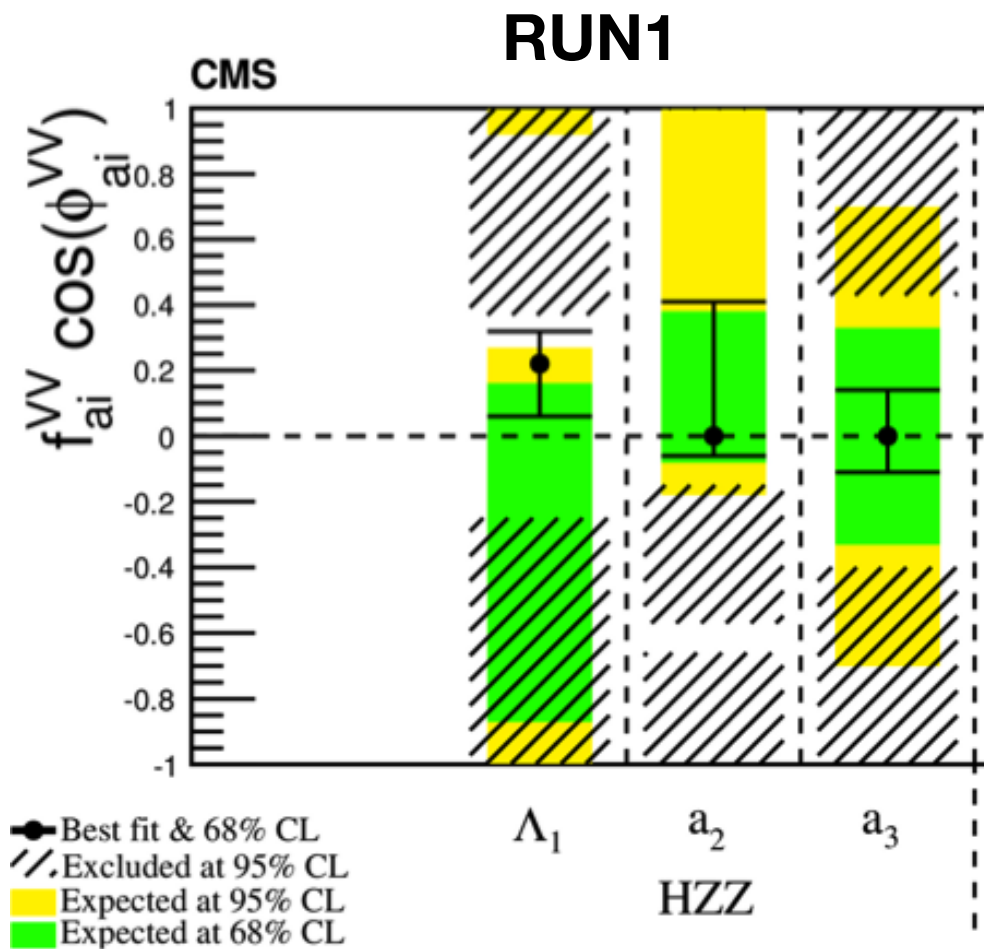
3. Anomalous couplings in HZZ

$$L(HZZ) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu + a_2 \frac{1}{2} H Z^{\mu\nu} Z_{\mu\nu} + a_3 \frac{1}{2} H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$



Y. Gao, etc PRD81, 075022

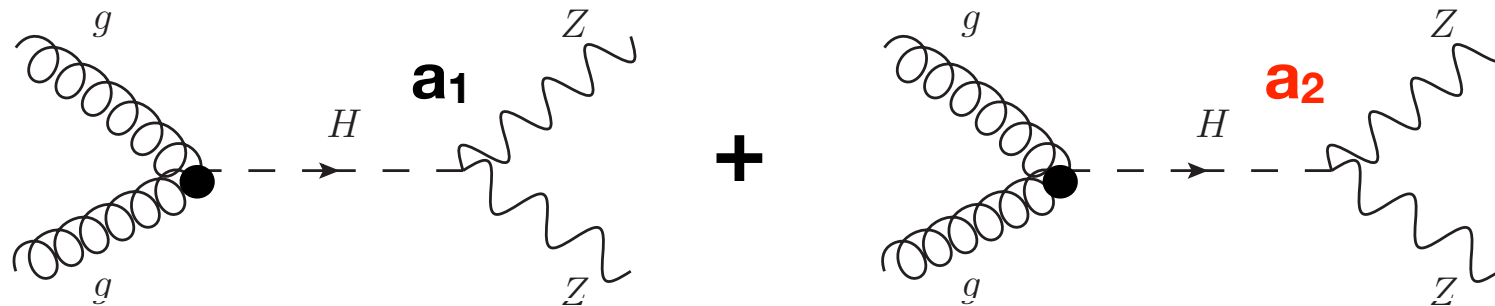
Constraints from experiments



CMS, PRD92, 012004 (2014)

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

Interference in on-shell region



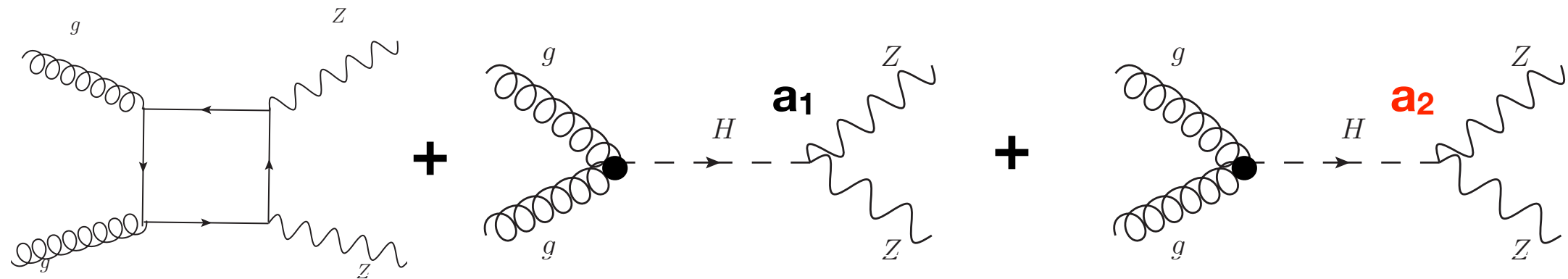
$\sqrt{s}=8$ TeV, $gg \rightarrow H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$, $M(4\ell) < 130$ GeV

$a_1=1, a_2=1$

σ_{SM}	σ_{new}	$\sigma_{\text{interference}}$
0.245fb	0.101fb	-0.275fb

Interference in off-shell region

SM



$\sqrt{s}=8$ TeV, $gg(\rightarrow H^*) \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-, M(4\ell) > 220$ GeV

$a_1=1, a_2=1$

σ_{SM}	σ_{new}	$\sigma_{\text{interference}}$
0.45fb	0.23fb	0.15fb

Constraints in off-shell region

CMS data for off-shell region

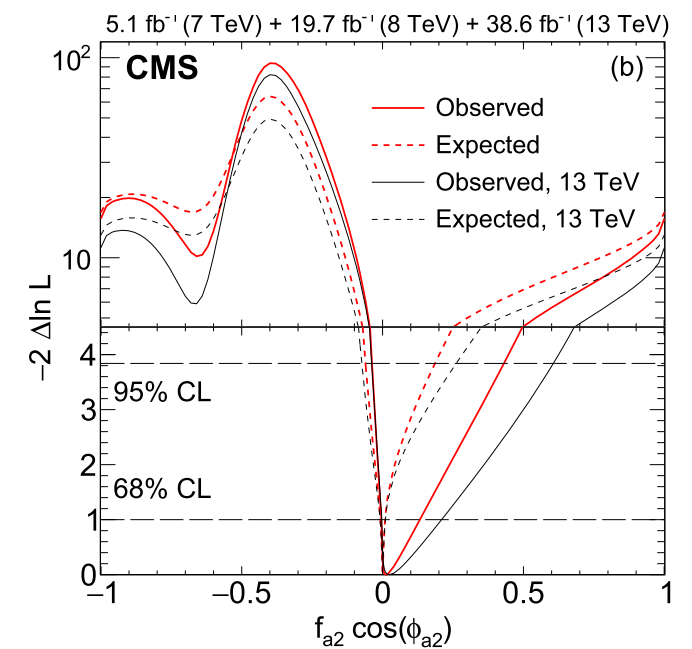
CMS PAS Higg-14-002

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

$$a_2 \subset [-2.0, 1.4]$$

$$a_3 \subset [-1.7, 1.7]$$

run2, on-shell



$$a_2 \subset [-0.34, 1.5]$$

$$a_3 \subset [-2.0, 2.4]$$

Summary

The interference effect of new physics are studied in three Higgs processes at LHC.

- The antisymmetric lineshape in $H \rightarrow \gamma\gamma$ could be extracted to probe CP -violating $H\gamma\gamma$ coupling.
- The forward-backward symmetry of the lepton in Z rest frame could totally reach as large as $\sim 4\%$ for a maximal CP violation in $H\gamma Z$ coupling.
- Constraints of anomalous HZZ couplings in Higgs off-shell region could be good complement for the experimental measurements in on-shell region.

Thanks!