

Probe CP violation in $H\gamma\gamma$ coupling through interference



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EW and Flavor Physics @CEPC
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Outline

- Introduction

CP violation

Effective Field Theory (EFT)

Constraints of CP violation in Higgs couplings

- Probe CP violation in $H\gamma\gamma$ coupling

Interference between $gg \rightarrow H \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$

A new observable A_{int} in SM and CP violation cases

- Summary

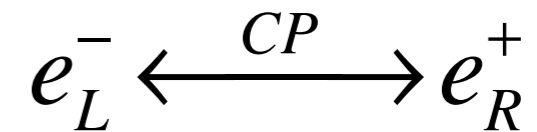
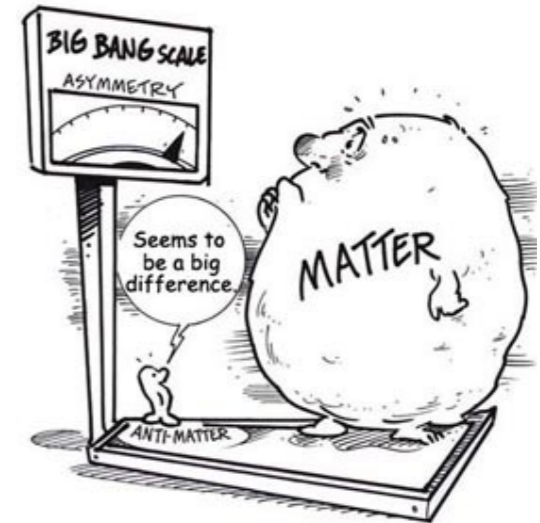
CP violation in Cosmology

- Matter-antimatter asymmetry.

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

- Sakharov's conditions:

1. **Baryon number violation.**
2. **C and CP violation.**
3. **Interactions out of thermal equilibrium.**



CP violation in SM

$$\frac{-g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu W_\mu^+ V_{\text{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.} \quad V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

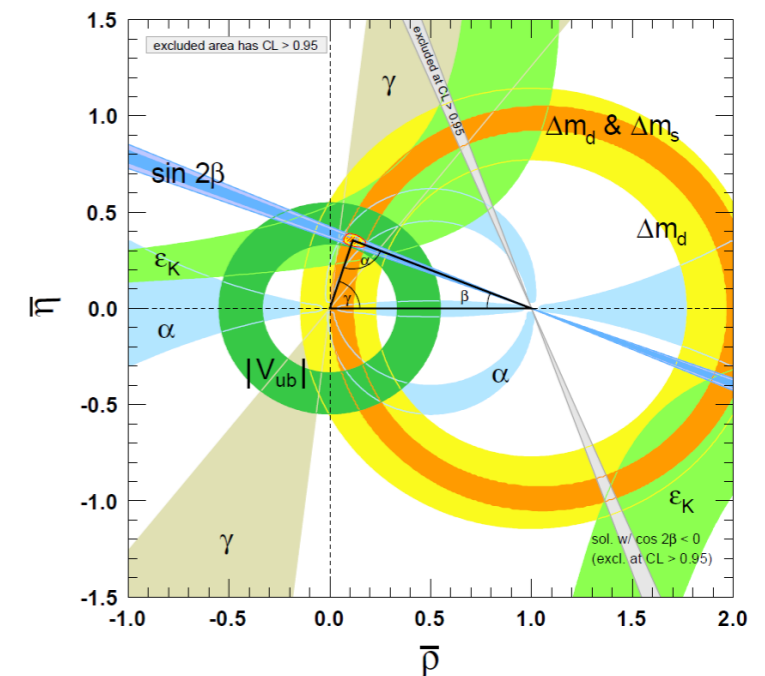
M. Kobayashi, T. Maskawa,
Prog.Theor.Phys. 49 (1973) 652

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta = (3.04_{-0.20}^{+0.21}) \times 10^{-5}.$$

C. Jarlskog, Z.Phys. C29 (1985) 491-497

$$\text{Baryon asymmetry} \sim 10^{-20} \ll \eta$$

M.E. Shaposhnikov, Nucl.Phys. B287 (1987) 757



CP violation from Higgs dynamics

- SM

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$V_{CKM} = U_u^\dagger U_d,$$

$$\lambda_u = U_u D_u W_u^\dagger, u_L^i \rightarrow U_u^{ij} u_L^j,$$

- For Example, 2HDM, SUSY

$$\Phi_i = \begin{pmatrix} \varphi_i^+ \\ (v_i + \eta_i + i\chi_i)/\sqrt{2} \end{pmatrix} \quad i=1,2$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ A \end{pmatrix}$$

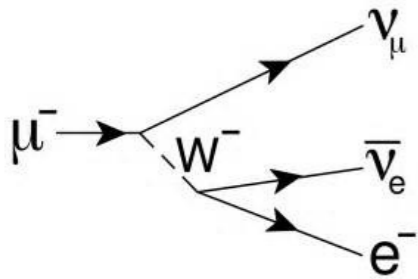
CP-even: η_1, η_2 .

CP-odd: $A = -\sin \beta \chi_1 + \cos \beta \chi_2$

Effective Field Theory

- Full theory (2HDM SUSY Little Higgs)

Howard Georgi,
Annu.Rev.Nucl.Part.
Sci.1993.43:209-52

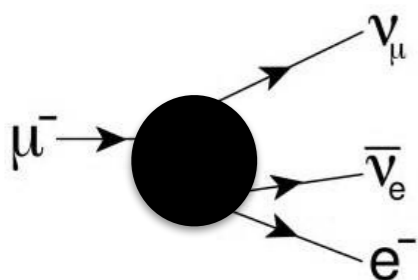


Large Scale
Heavy Particles
Light particles

Renormalization Group

$$\mu = M \text{ Matching}$$

Renormalization Group



Low Energy
Light particles

$$L(\psi_{li}, \psi_h)$$

ATLAS Exotics Searches* - 95% CL Exclusion
Status: August 2016

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	-	$\geq 1j$	Yes 3.2	M_0 6.58 TeV	$n = 2$ 1604.07773
	ADD non-resonant $\ell\ell$	$2 e, \mu$	-	-	M_0 4.7 TeV	$n = 3 \text{ HLZ}$ 1407.2410
	ADD OBH $\rightarrow \ell q$	$1 e, \mu$	$1j$	-	M_0 5.2 TeV	$n = 6$ 1311.2006
	ADD OBH	-	$\geq 2j$	-	M_0 15.7 TeV	$n = 6$ ATLAS-CONF-2016-069
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2j$	-	M_0 8.7 TeV	$n = 6, M_0 = 3 \text{ TeV, rot BH}$ 1606.02265
	ADD BH multijet	-	$\geq 3j$	-	M_0 9.55 TeV	$n = 6, M_0 = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	-	-	$G_{KK} \text{ mass}$ 2.68 TeV	$k/M_{Pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	$G_{KK} \text{ mass}$ 3.2 TeV	$k/M_{Pl} = 0.1$ 1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\bar{v}$	$1 e, \mu$	$1j$	Yes	$G_{KK} \text{ mass}$ 1.24 TeV	$k/M_{Pl} = 1.0$ ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	-	$4b$	-	$G_{KK} \text{ mass}$ 360-860 GeV	$k/M_{Pl} = 1.0$ ATLAS-CONF-2016-049
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	$G_{KK} \text{ mass}$ 2.2 TeV	BR = 0.925 1505.07018	
2UED / RPP	$1 e, \mu$	$\geq 2b, \geq 4j$	Yes	$KK \text{ mass}$ 1.46 TeV	Tier (1,1), $BR(A^{(1,1)} \rightarrow t\bar{t}) = 1$ ATLAS-CONF-2016-013	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	$Z' \text{ mass}$ 4.05 TeV	ATLAS-CONF-2016-045
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	$Z' \text{ mass}$ 2.02 TeV	1502.07177
	Leptophobic $Z' \rightarrow b\bar{b}$	-	$2b$	-	$Z' \text{ mass}$ 1.5 TeV	1603.08791
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	$W' \text{ mass}$ 4.74 TeV	ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	$0 e, \mu$	$1j$	Yes	$W' \text{ mass}$ 13.2 TeV	ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model B	$0 e, \mu$	$2j$	-	$W' \text{ mass}$ 3.0 TeV	ATLAS-CONF-2016-055
CI	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	$V' \text{ mass}$ 2.31 TeV	$g_V = 1$ 1607.05621
	LRSM $W'_2 \rightarrow t\bar{b}$	$1 e, \mu$	$2b, 0-1j$	Yes	$W' \text{ mass}$ 1.82 TeV	$g_V = 3$ 1410.4103
	LRSM $W'_2 \rightarrow t\bar{t}$	$0 e, \mu$	$\geq 1b, 1j$	-	$W' \text{ mass}$ 1.76 TeV	1408.0886
DM	CI qqq	-	$2j$	-	A 19.9 TeV	$\eta_{LL} = -1$ ATLAS-CONF-2016-069
	CI $\ell\ell q$	$2 e, \mu$	-	-	A 25.2 TeV	$\eta_{LL} = -1$ 1607.03669
	CI $uutt$	$2(SS) \geq 3 e, \mu$	$\geq 1b, \geq 1j$	Yes	A 4.9 TeV	$ C_{SM} = 1$ 1504.04605
LQ	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$\geq 1j$	Yes	m_A 1.0 TeV	$g_0 = 0.25, g_1 = 1.0, m(\chi) < 250 \text{ GeV}$ 1604.07773
	Axial-vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$1j$	Yes	m_A 710 GeV	$g_0 = 0.25, g_1 = 1.0, m(\chi) < 150 \text{ GeV}$ 1604.01306
	ZZ χ EFT (Dirac DM)	$0 e, \mu$	$1j, \leq 1j$	Yes	M_0 550 GeV	$m(\chi) < 150 \text{ GeV}$ ATLAS-CONF-2015-080
Heavy quarks	Scalar LQ 1^{st} gen	$2 e$	$\geq 2j$	-	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2^{nd} gen	2μ	$\geq 2j$	-	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 3^{rd} gen	$1 e, \mu$	$\geq 1b, \geq 3j$	Yes	LQ mass 640 GeV	$\beta = 0$ 1508.04735
	VLQ $TT \rightarrow Ht + X$	$1 e, \mu$	$\geq 2b, \geq 3j$	Yes	T mass 855 GeV	T in (T,B) doublet 1505.04306
	VLQ $YY \rightarrow Wb + X$	$1 e, \mu$	$\geq 1b, \geq 3j$	Yes	Y mass 770 GeV	Y in (B,Y) doublet 1505.04306
Excited fermions	VLQ $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2b, \geq 3j$	Yes	B mass 735 GeV	isospin singlet 1505.04306
	VLQ $BB \rightarrow Zb + X$	$2 \geq 3 e, \mu$	$\geq 2 \geq 1b$	-	B mass 755 GeV	B in (B,Y) doublet 1409.5500
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4j$	Yes	Q mass 690 GeV	1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	$2(SS) \geq 3 e, \mu$	$\geq 1b, \geq 1j$	Yes	$T_{5/3} \text{ mass}$ 990 GeV	ATLAS-CONF-2016-032
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$	-	$q^* \text{ mass}$ 4.4 TeV	only u' and d' , $\Lambda = m(q^*)$ 1512.05910
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	$q^* \text{ mass}$ 5.6 TeV	only u' and d' , $\Lambda = m(q^*)$ ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow b\gamma$	-	$1b, 1j$	-	$b^* \text{ mass}$ 2.3 TeV	ATLAS-CONF-2016-060
Other	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1b, 2-0j$	Yes	$b^* \text{ mass}$ 1.5 TeV	$f_u = f_b = f_t = 1$ 1510.02664
	Excited lepton ℓ^*	$3 e, \mu$	-	-	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
	LSTC $\tau\tau \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	$\tau\tau \text{ mass}$ 960 GeV	1407.8150
	LRSM Majorana ν	$2 e, \mu$	$2j$	-	$\nu\nu \text{ mass}$ 2.0 TeV	$m(W_2) = 2.4 \text{ TeV, no mixing}$ 1506.06020
Higgs triplet $H^{\pm\pm} \rightarrow ee$	$2 e$ (SS)	-	-	$H^{\pm\pm} \text{ mass}$ 570 GeV	DY production, $BR(H^{\pm\pm} \rightarrow ee) = 1$ ATLAS-CONF-2016-051	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\tau) = 1$ 1411.2921	
Monotop (non-res prod)	$1 e, \mu$	$1b$	Yes	spin-1 invisible particle mass 657 GeV	$\rho_{non-res} = 0.2$ 1410.5404	
Multi-charged particles	-	-	-	multi-charged particle mass 785 GeV	DY production, $ q = 5e$ 1504.04188	
Magnetic monopoles	-	-	-	monopole mass 1.34 TeV	DY production, $ g = 1g_D, \text{spin } 1/2$ 1509.08059	

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.
†Small-radius (large-radius) jets are denoted by the letter j (J).

Appelquist-Carazzone
Decoupling theorem:

$$L = L_{SM}^4 + \sum_i \frac{C_i}{\Lambda^2} O_i,$$

Dimension-six operators

$$\mathcal{L}_{D=6} \equiv \sum_i \bar{c}_i \bar{O}_i = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{CP} + \dots$$

B. Grzadkowski, M. Iskrzynski, M. Misiak,
J. Rosiek, JHEP 1010 (2010) 085
R. Contino, M. Ghezzi, C. Grojean, M.
Muhlleitner, M. Spira, JHEP07(2013)035

$$\Delta\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{\bar{c}_T}{2v^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) \left(H^\dagger \overleftrightarrow{D}_\mu H \right) - \frac{\bar{c}_6 \lambda}{v^2} (H^\dagger H)^3$$

$$+ \left(\left(\frac{\bar{c}_u}{v^2} y_u H^\dagger H \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2} y_d H^\dagger H \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2} y_l H^\dagger H \bar{L}_L H l_R \right) + h.c. \right)$$

$$i \text{Im}(\bar{c}_f) y_f \bar{q} \gamma_5 q H$$

$$+ \frac{i\bar{c}_W g}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) (\partial^\nu B_{\mu\nu})$$

$$+ \frac{i\bar{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i\bar{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$+ \frac{\bar{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu},$$

$$\Delta\mathcal{L}_{CP} = \frac{i\tilde{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) \tilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$$

$$+ \frac{\tilde{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\tilde{c}_g g_S^2}{m_W^2} H^\dagger H G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

$$+ \frac{\tilde{c}_{3W} g^3}{m_W^2} \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} \tilde{W}_\rho^{k\mu} + \frac{\tilde{c}_{3G} g_S^3}{m_W^2} f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} \tilde{G}_\rho^{c\mu},$$

$$\bar{c}_f \sim \mathcal{O}(1)$$

$$\tilde{c}_{HW}, \tilde{c}_{HB} \sim \frac{1}{16\pi^2} \mathcal{O}(1)$$

$$\tilde{c}_\gamma, \tilde{c}_g \sim \frac{1}{16\pi^2} \mathcal{O}(1)$$

C. Arzt, M.B. Einhorn, J. Wudka
Nucl.Phys. B433 (1995) 41-66

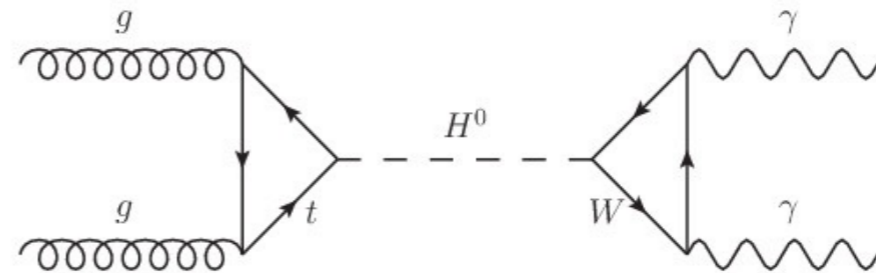
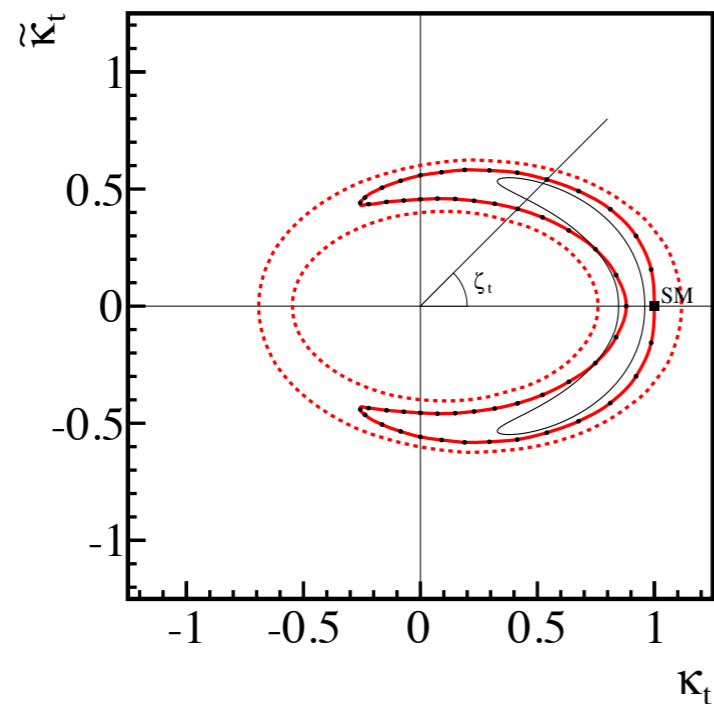
$$\tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}, \quad F = W, B, G.$$

Sensitivity to probe CP violation

	SM	CP-odd coupling	sensitivity
$H f \bar{f}$	tree	tree	✓
$H Z Z, H W W$	tree	loop	✗
$H \gamma \gamma, H g g$	loop	loop	✓

Experimental Constraints: $Ht\bar{t}$

$$\mathcal{L}_t = -\frac{m_t}{v} (\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t) H$$

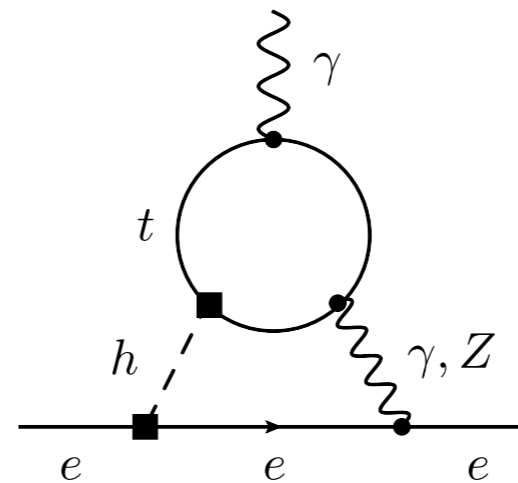
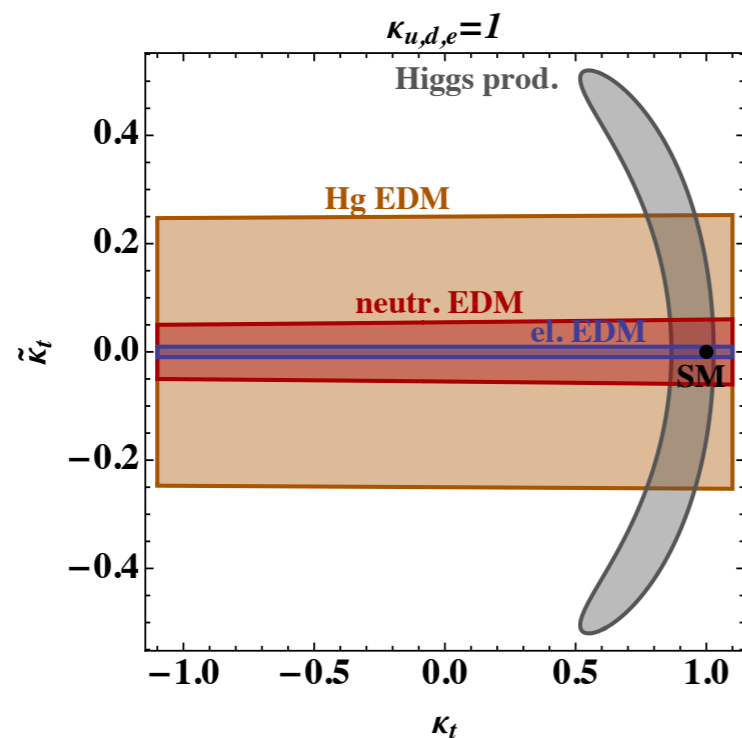


$$\mu_{gg} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t(\kappa_t - 1),$$

$$\mu_{\gamma\gamma} \simeq (1.28 - 0.28\kappa_t)^2 + (0.43\tilde{\kappa}_t)^2.$$

J. Ellis, etc. JHEP04(2014),001

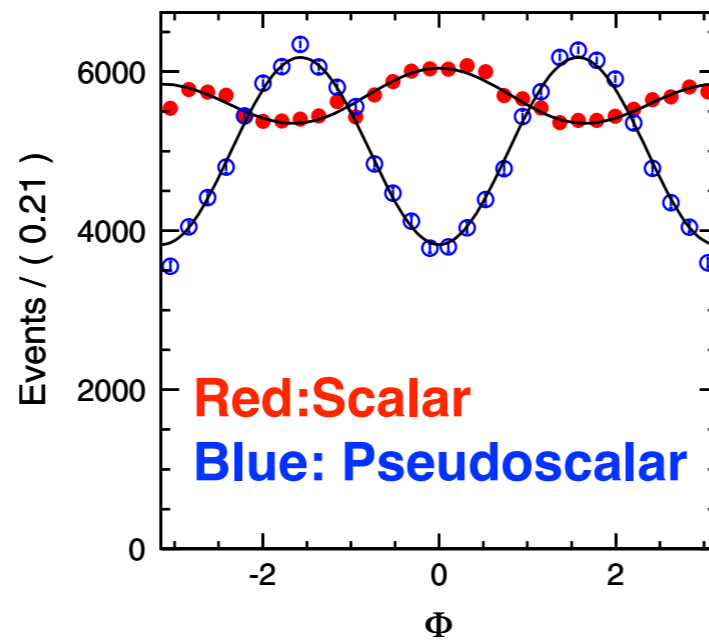
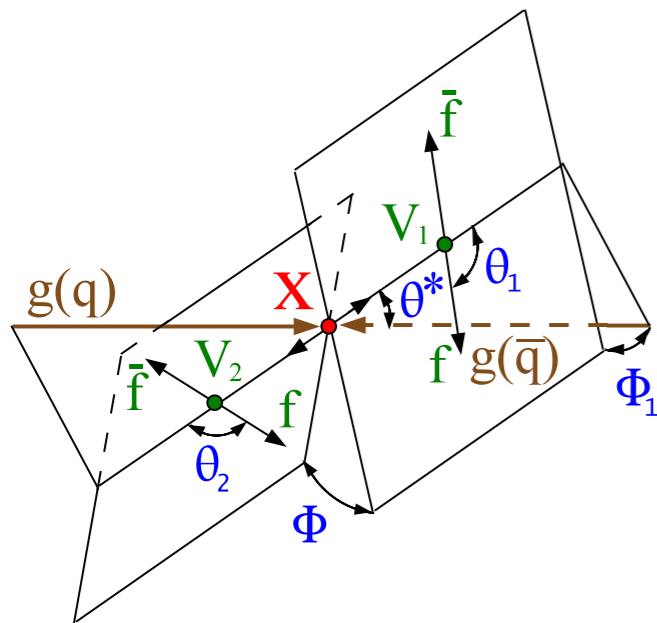
arxiv:1312.5736



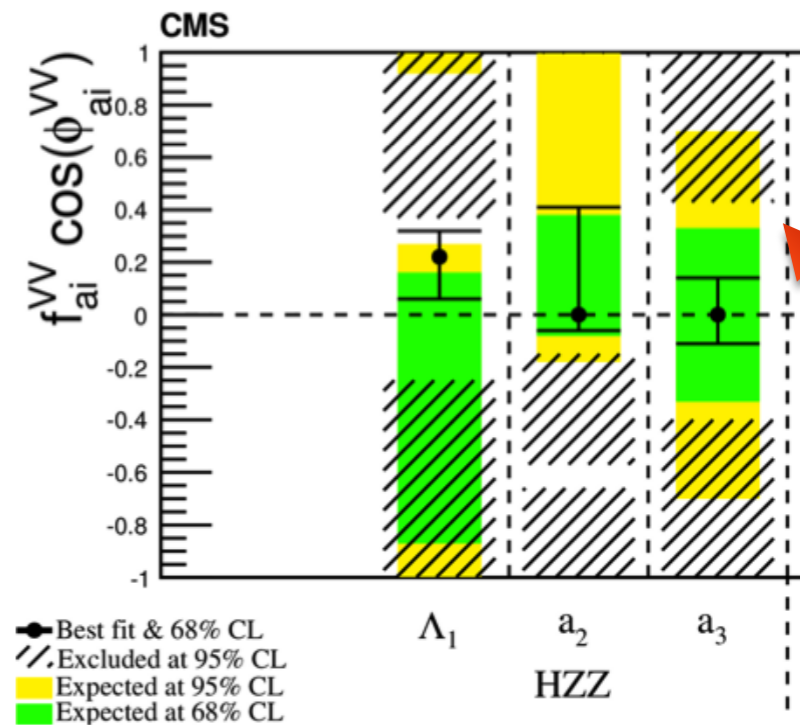
J. Brod, U. Haisch, J. Zupan
JHEP 1311 (2013) 180

Experimental Constraints: HZZ

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$



Y. Gao, etc PRD81, 075022



CMS, PRD92, 012004

$$\Phi = \frac{\mathbf{q}_1 \cdot (\hat{\mathbf{n}}_1 \times \hat{\mathbf{n}}_2)}{|\mathbf{q}_1 \cdot (\hat{\mathbf{n}}_1 \times \hat{\mathbf{n}}_2)|} \times \cos^{-1} (-\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2)$$

$$\hat{\mathbf{n}}_1 = \frac{\mathbf{q}_{11} \times \mathbf{q}_{12}}{|\mathbf{q}_{11} \times \mathbf{q}_{12}|}, \quad \hat{\mathbf{n}}_2 = \frac{\mathbf{q}_{21} \times \mathbf{q}_{22}}{|\mathbf{q}_{21} \times \mathbf{q}_{22}|}$$

$$c_{HZ} \sim \mathcal{O}(1)$$

$$\tilde{c}_{HZ} \sim \frac{1}{16\pi^2} \mathcal{O}(1)$$

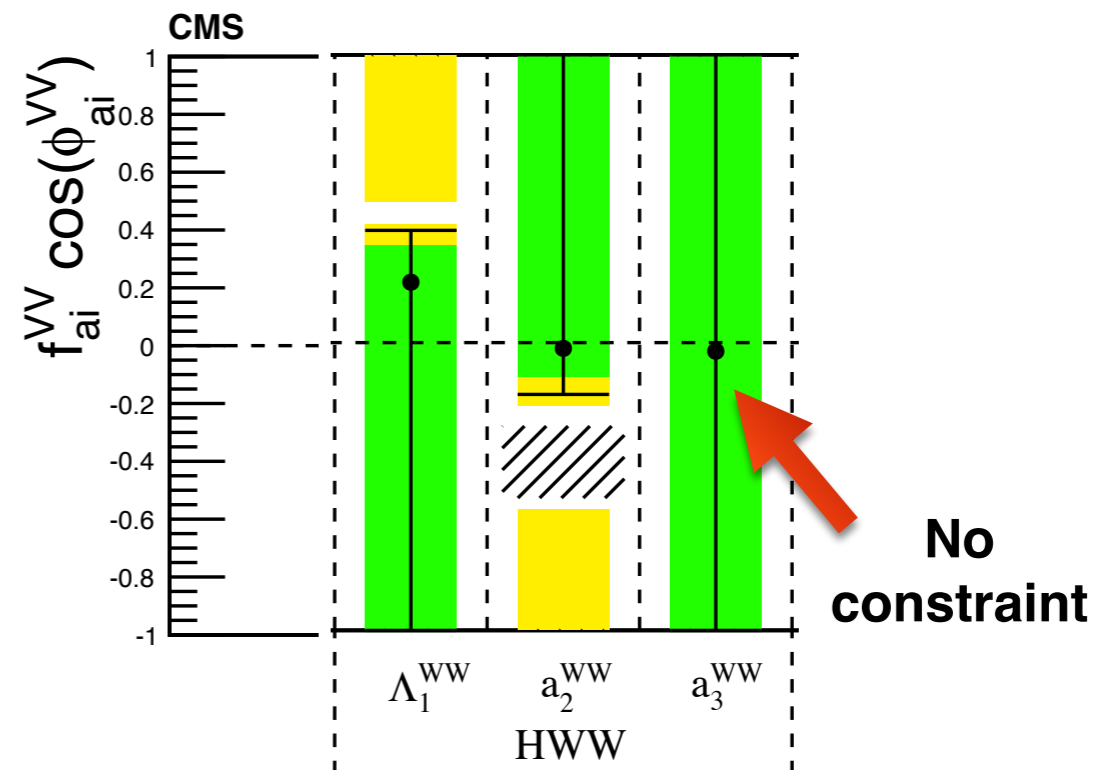
Experimental Constraints: HWW

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

HWW^*

$$m_T^2 = 2p_T^{ll} E_T^{\text{miss}} (1 - \cos \Delta\phi(ll, \vec{E}_T^{\text{miss}}))$$

$$\Delta\phi(ll, \vec{E}_T^{\text{miss}})$$

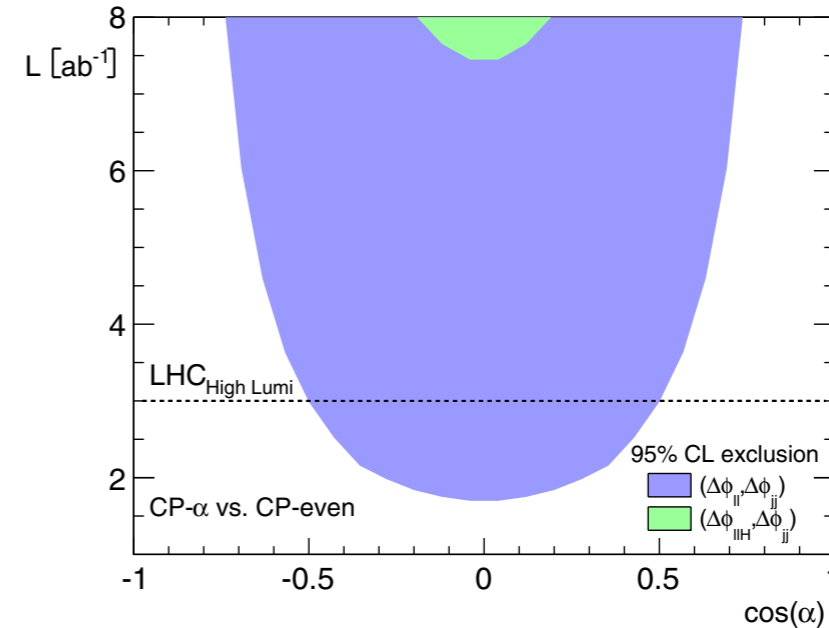
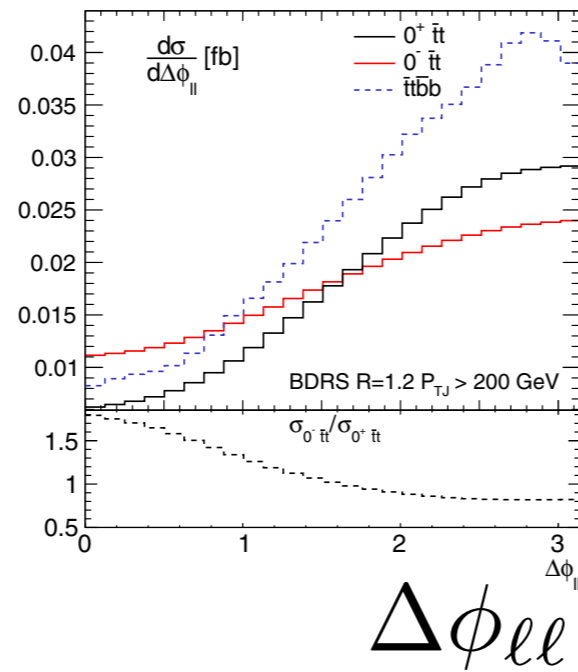


CMS, PRD92, 012004

Some theoretical proposals

$H t \bar{t}$

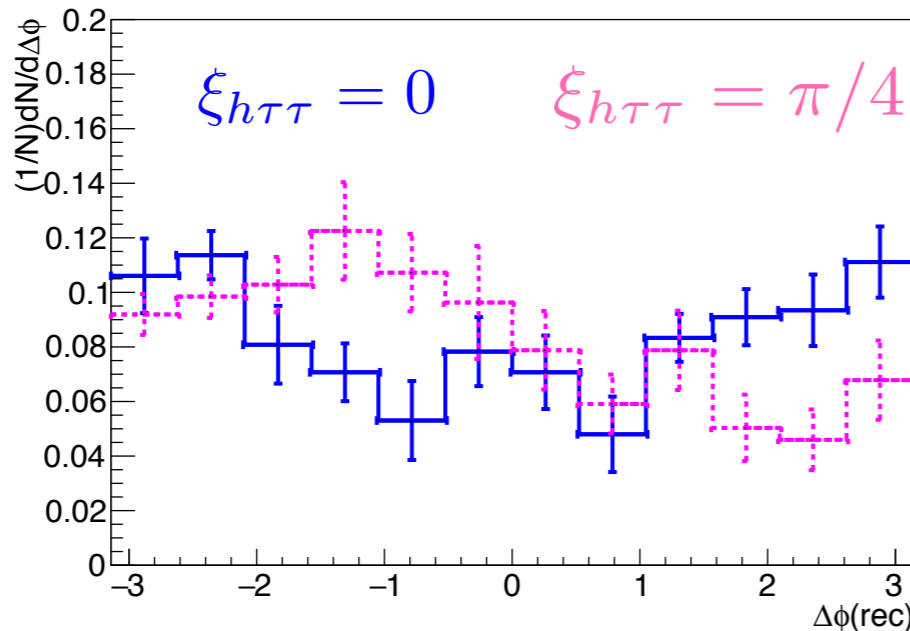
$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} (\cos \alpha + i \gamma_5 \sin \alpha) t H,$$



PRL116,091801(2016)
M. Buckley, etc.

$H \tau \tau$

$$\mathcal{L} = -g_{h\tau\tau} h (\cos \xi_{h\tau\tau} \bar{\tau} \tau + i \sin \xi_{h\tau\tau} \bar{\tau} \gamma^5 \tau)$$



$$\Delta \xi_{h\tau\tau} \approx 0.2$$

$$3 \text{ ab}^{-1} \text{ at } \sqrt{s} = 14 \text{ TeV}$$

PRL118,171802(2017)
K. Hagiwara, etc.

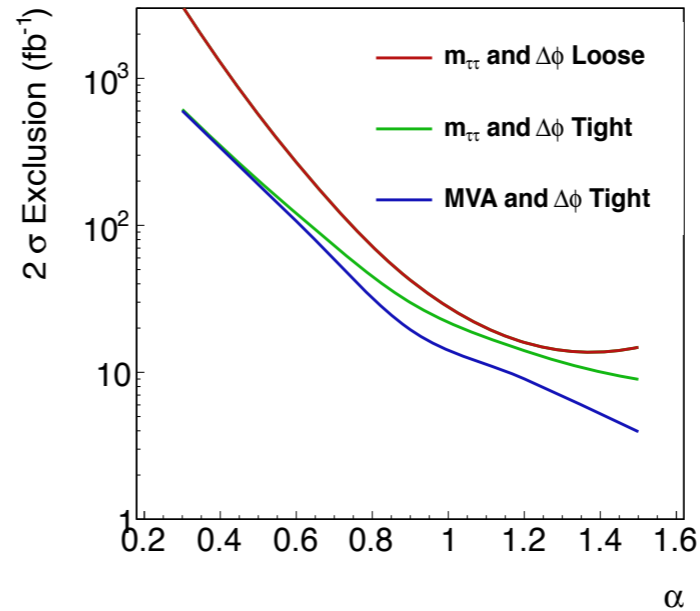
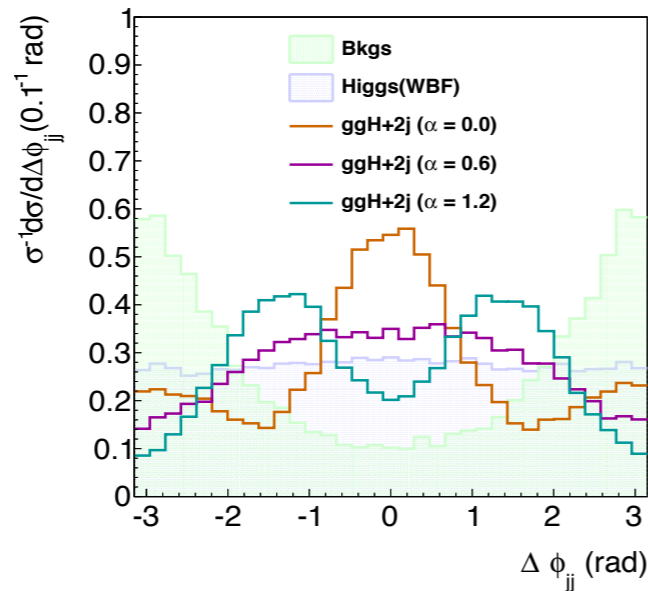
Some theoretical proposals

$$\mathcal{L}_{h\bar{f}f} = \cos \alpha y_f \bar{\psi}_f \psi_f h + \sin \alpha \tilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h$$

$$\mathcal{L}_{hgg} = \cos \alpha \frac{\alpha_S}{12\pi v} h G_{\mu\nu}^a G^{a,\mu\nu} + \sin \alpha \frac{\alpha_S}{4\pi v} h G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}$$

Hgg

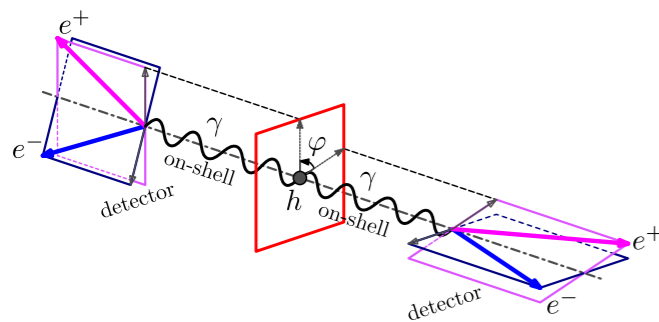
$gg \rightarrow Hjj, H \rightarrow \tau\tau$



PRD 90, 073008 (2014)
M.J. Dolan, etc.

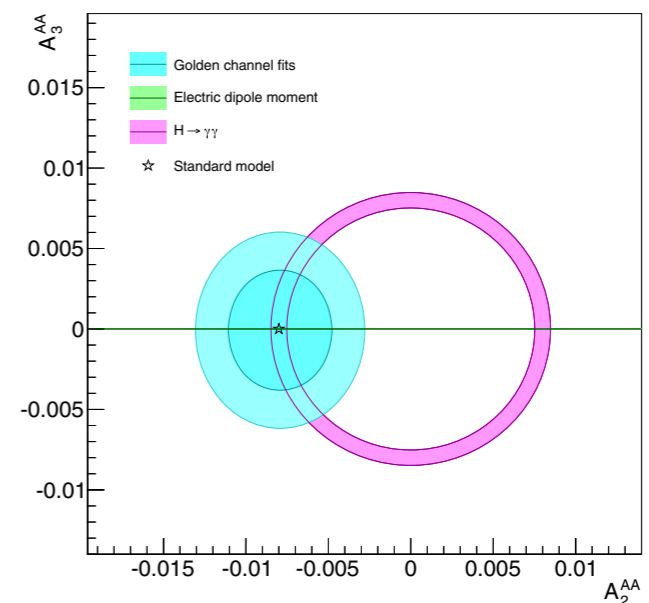
$H\gamma\gamma$

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



$$\mathcal{L} \supset \frac{h}{4v} (2A_1^{ZZ} m_Z^2 Z^\mu Z_\mu + A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu} \tilde{Z}_{\mu\nu} + 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu} \tilde{Z}_{\mu\nu} + A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu}),$$

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

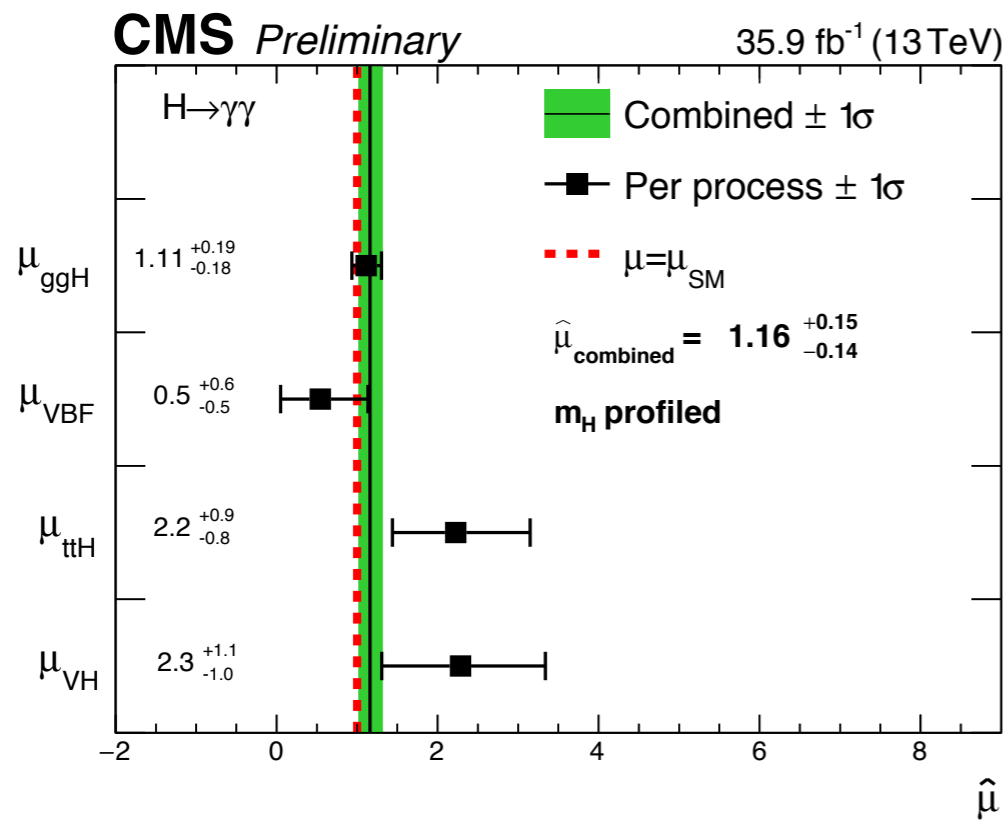


Methods and Feasibility

coupling	decay channel	sensitive observable	feasibility		feasibility @CEPC
			@LHC,	@HL-LHC	
HWW	$H \rightarrow WW \rightarrow 2\ell 2\nu$	$\Delta\phi_{\ell\ell}$			
$Ht\bar{t}$	$H \rightarrow t\bar{t} \rightarrow 2\ell 2\nu b\bar{b}$	$\Delta\phi_{\ell\ell}$			
$H\tau\tau$	$H \rightarrow \tau\tau \rightarrow \pi^+\pi^- 2\nu$	$\Delta\phi_{\pi^+\pi^-}$			
HZZ	$H \rightarrow ZZ \rightarrow 4\ell$	$\Delta\phi$			
Hgg	$gg \rightarrow Hjj$	$\Delta\phi_{jj}$			
$H\gamma\gamma$	$H \rightarrow \gamma\gamma \rightarrow 4\ell$	$\Delta\phi$			

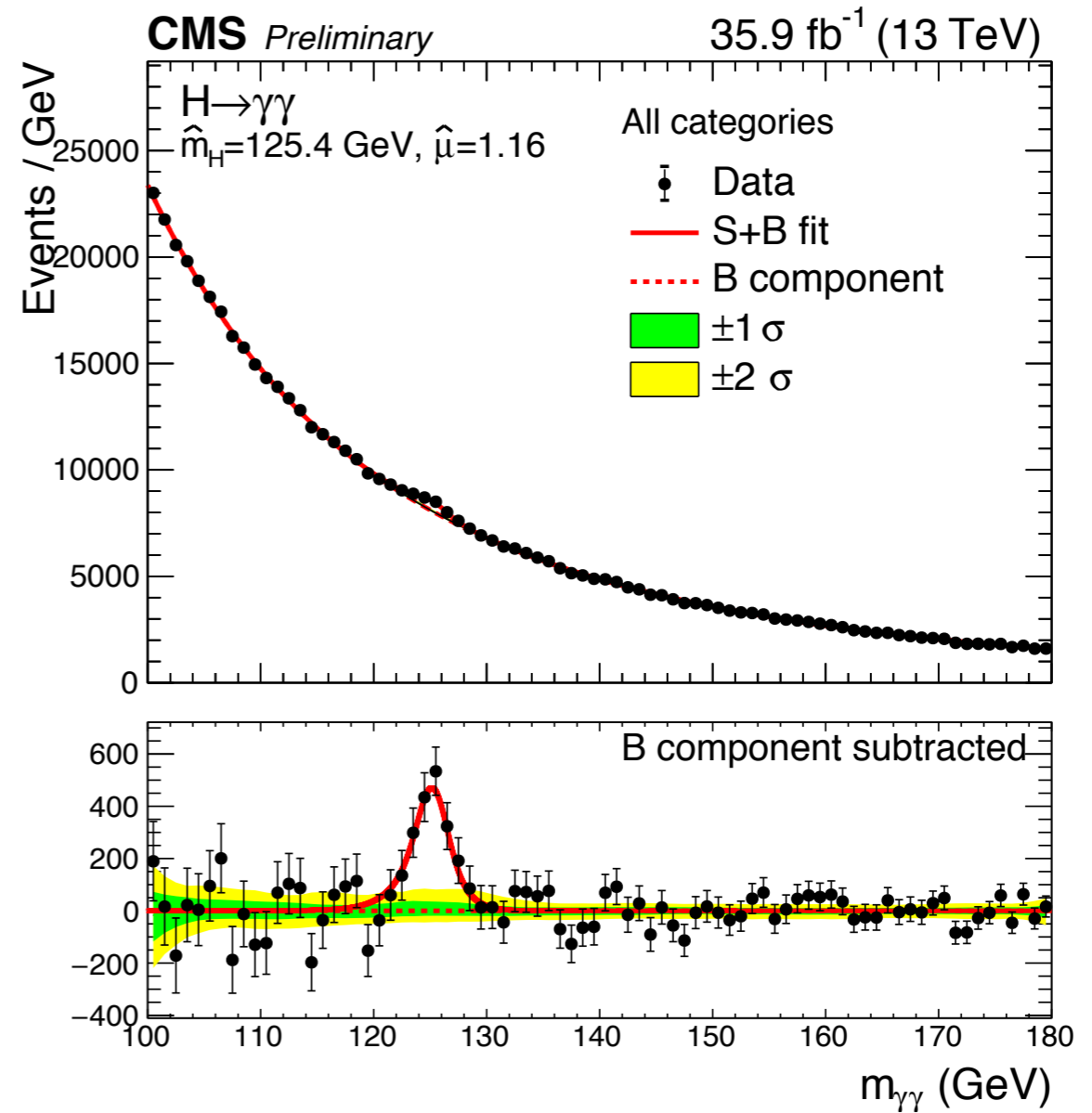
Precise measurement from $H \rightarrow \gamma\gamma$

- Include **Signal strength, Mass, Width, Spin,**



$$\hat{\mu} = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10} (\text{stat.})^{+0.09}_{-0.08} (\text{syst.})^{+0.06}_{-0.05} (\text{theo.})$$

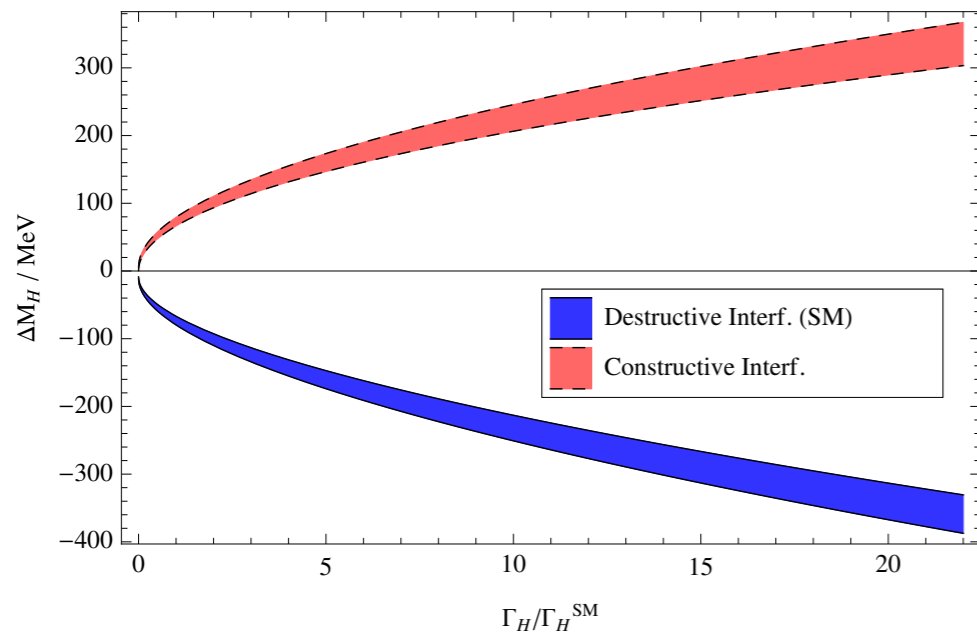
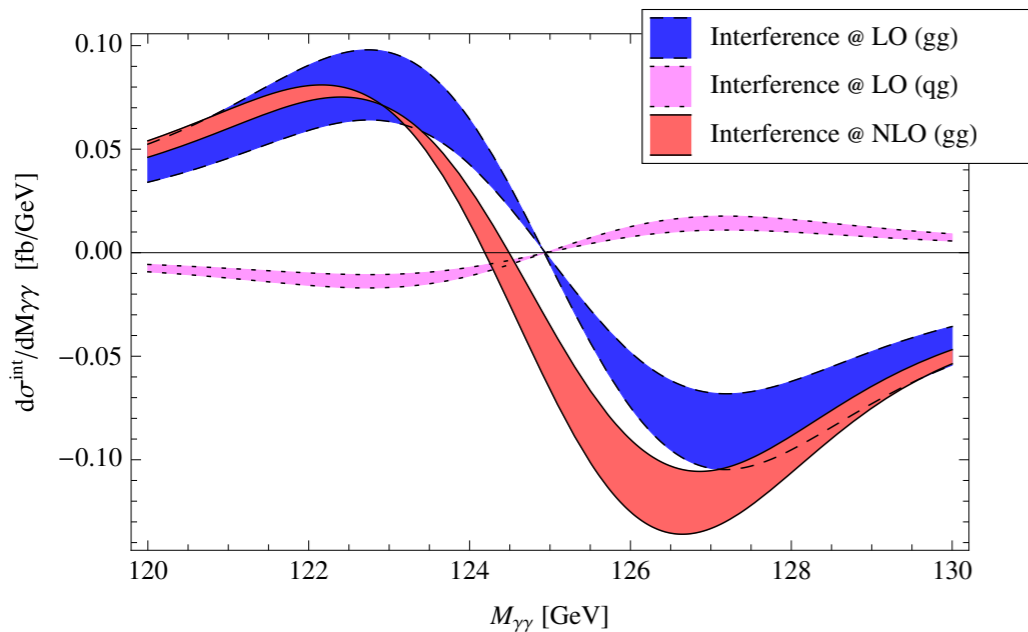
$$M_H = 125.4 \pm 0.15(\text{stat.}) \pm 0.2 \sim 0.3(\text{syst.}) \text{ GeV}$$



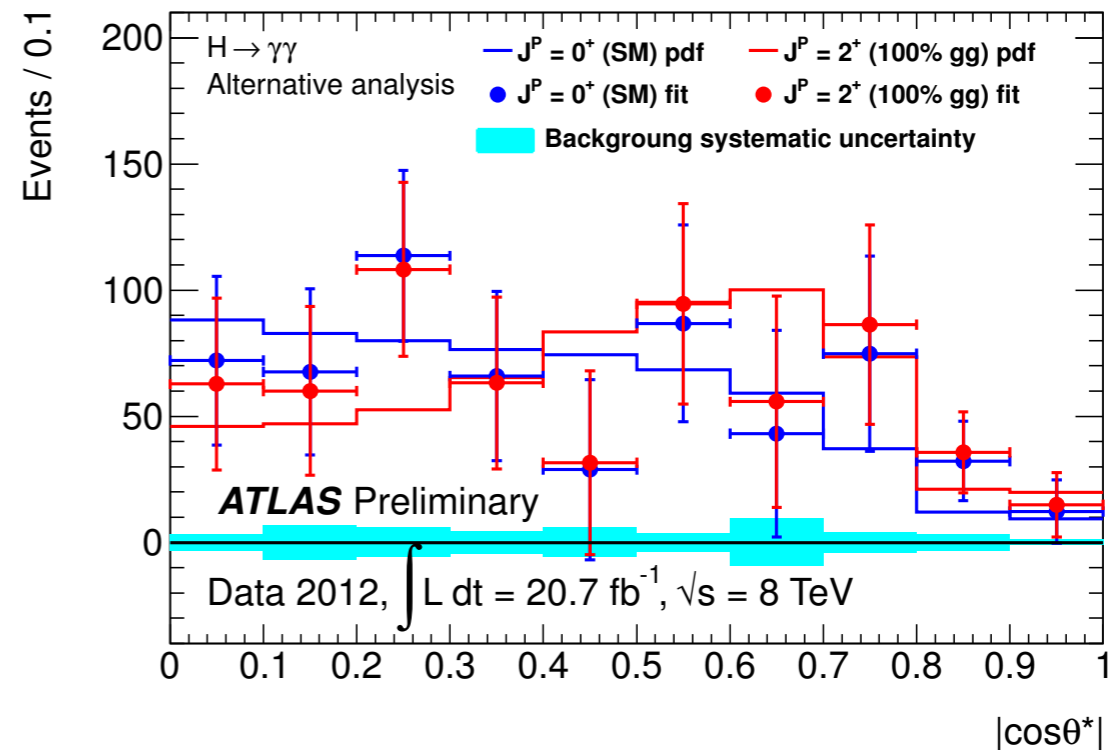
CMS-PAS-HIG-16-040

Precise measurement from $H \rightarrow \gamma\gamma$

- Include Signal strength, Mass, **Width, Spin**



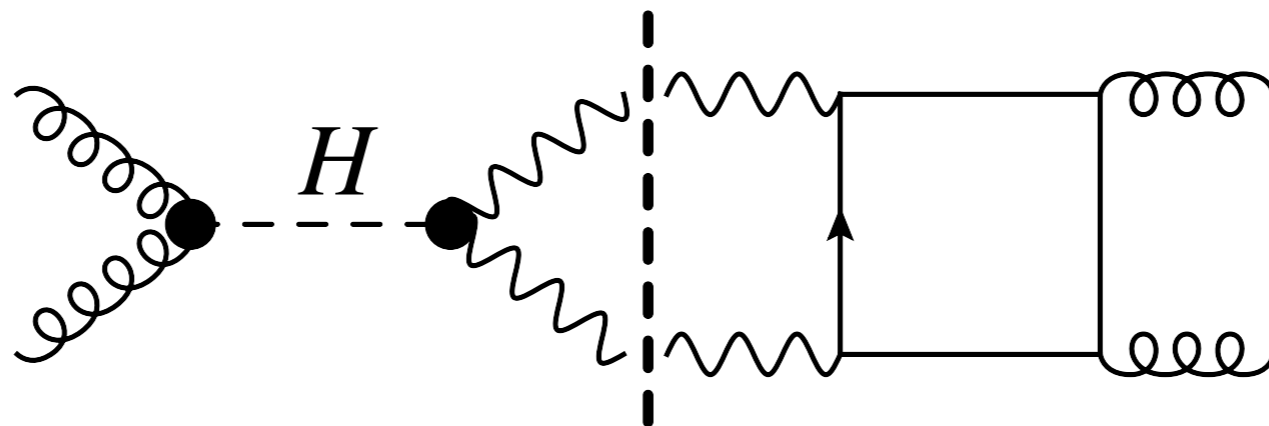
$$\Gamma_H < 15 \Gamma_H^{\text{SM}} \quad (14 \text{ TeV}, 3 \text{ ab}^{-1}, 95\% \text{ CL})$$



ATLAS-CONF-2013-029

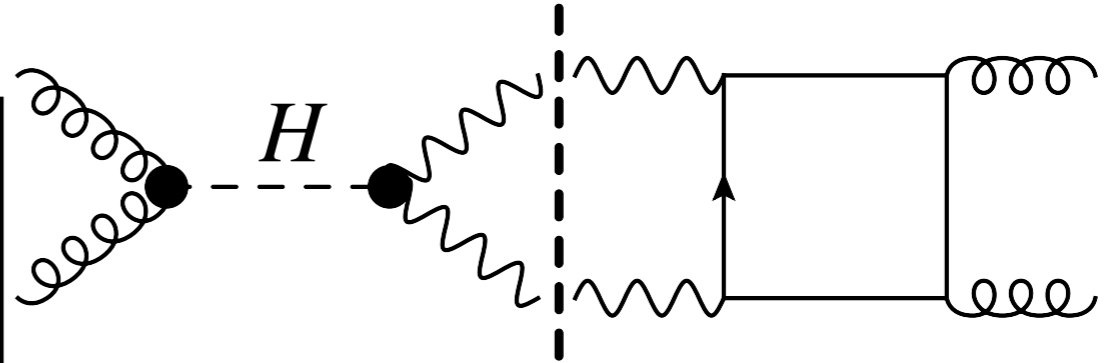
Spin-2 is excluded at 99.9% C.L.

Probe CP violation in $H\gamma\gamma$ coupling through interference



Interference

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



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

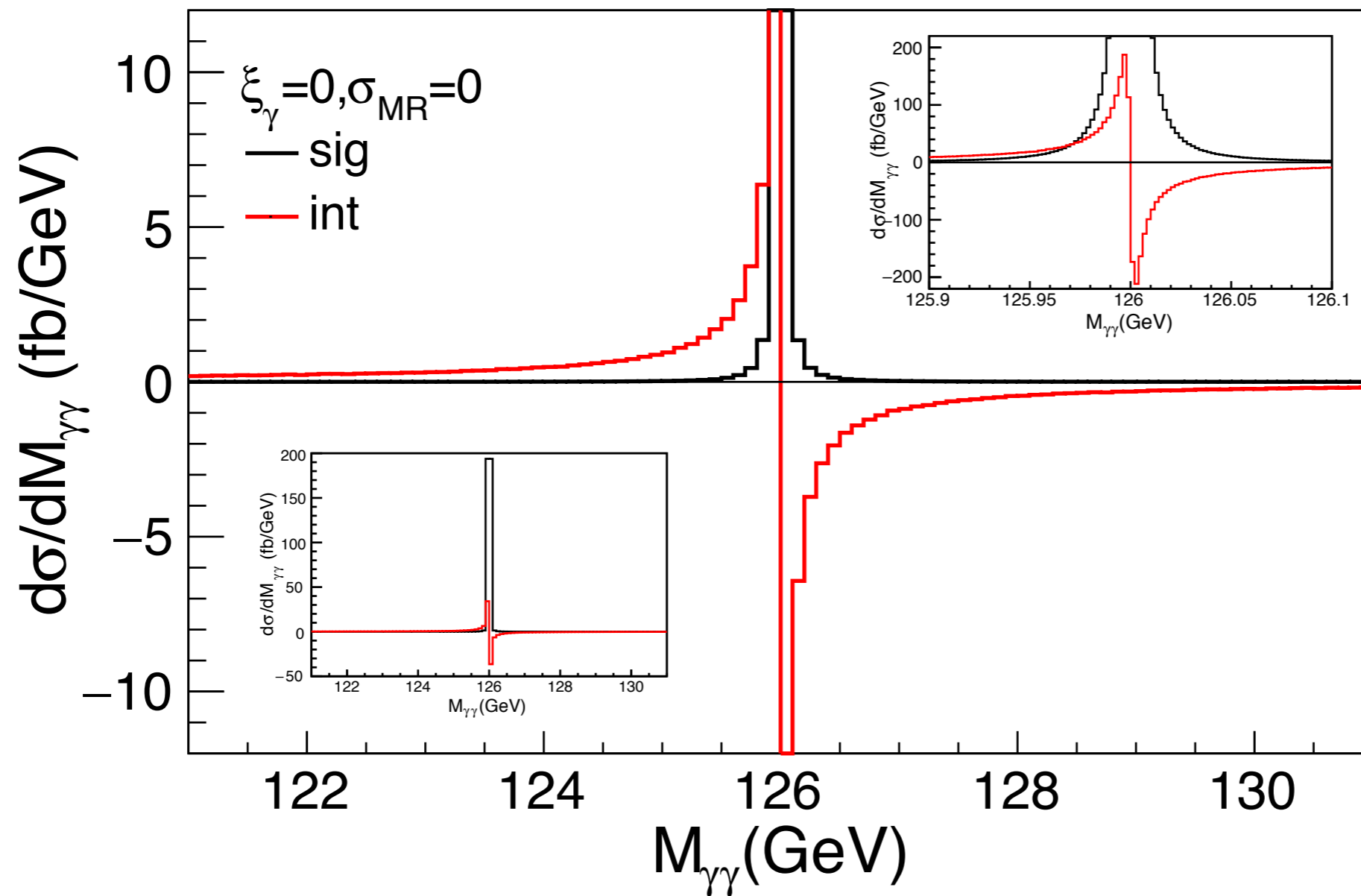
$$\mathcal{A}_{box}^{++++} = \mathcal{A}_{box}^{----} = 1$$

$$\mathcal{A}_{box}^{++--} = \mathcal{A}_{box}^{--++} = -1 + z \ln \left(\frac{1+z}{1-z} \right) - \frac{1+z^2}{4} \left[\ln^2 \left(\frac{1+z}{1-z} \right) + \pi^2 \right]$$

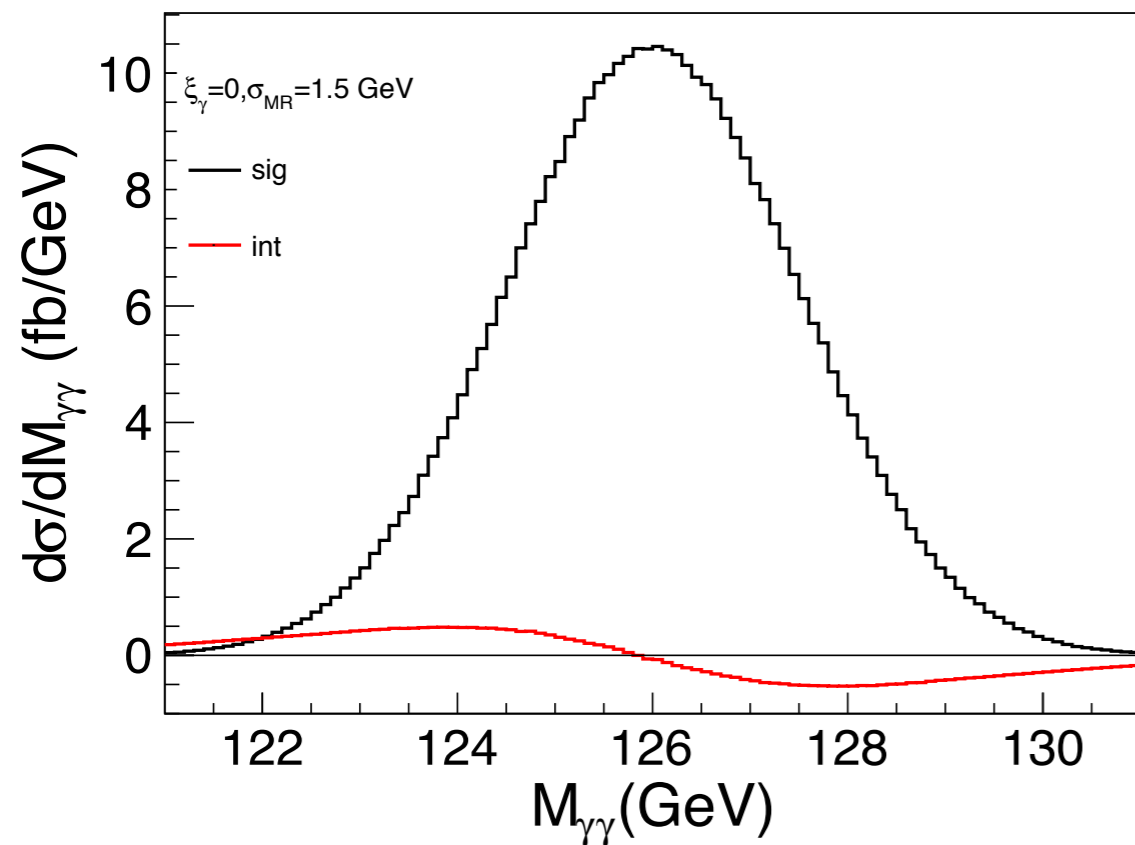
$$z = \cos \theta$$

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

Lineshape of Interference (SM)



After mass resolution (SM)

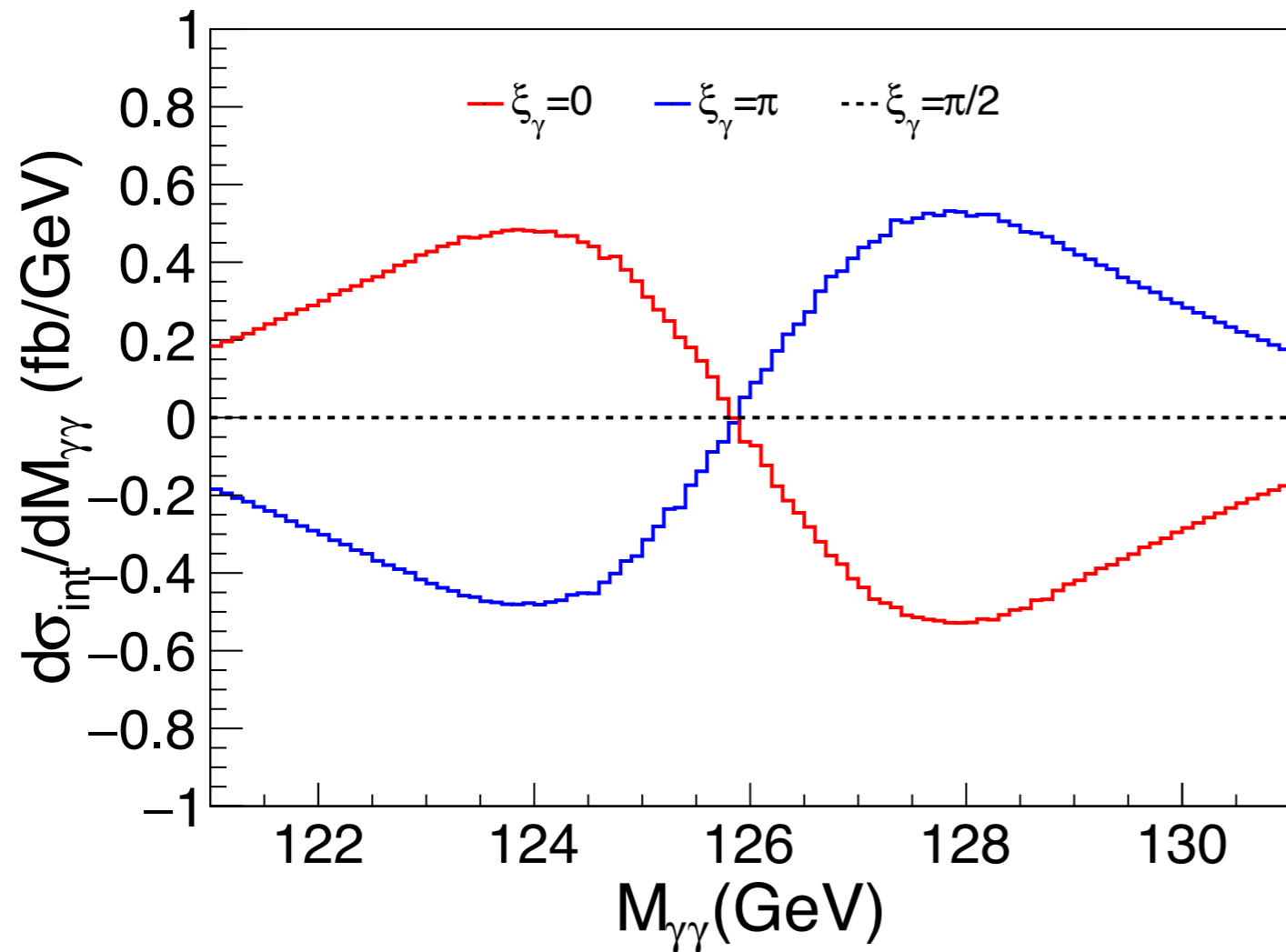


$$A_{int}(\xi_\gamma) = \frac{\int dM_{\gamma\gamma} \frac{d\sigma_{int}}{dM_{\gamma\gamma}} \Theta(M_{\gamma\gamma} - M_H)}{\int dM_{\gamma\gamma} \frac{d\sigma_{sig}}{dM_{\gamma\gamma}}},$$

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

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	4.1	10.4
1.3	39.3	3.8	9.6
1.5	39.3	3.5	8.8
1.7	39.3	3.2	8.2
1.9	39.3	3.0	7.5

Lineshape of CP -violating $H\gamma\gamma$ coupling



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

$$A_{int}(\xi_\gamma) = A_{int}^{SM} \times \cos \xi_\gamma$$

Significance

$$\text{Significance} = \frac{|A_{int} - A_{int}^{SM}|}{\sqrt{|\delta A_{int}|^2 + |\delta A_{int}^{SM}|^2}}$$

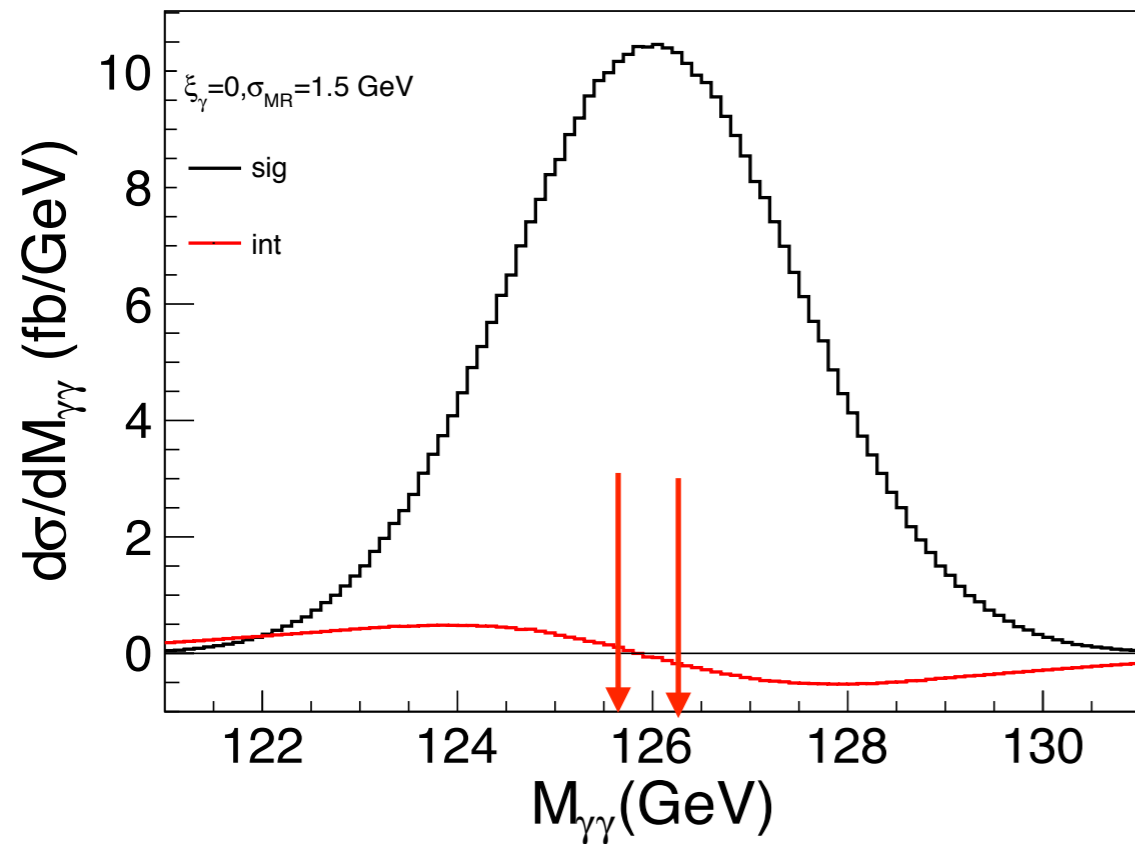
$$\delta A_{int} = A_{int} \times \frac{1}{\sqrt{L}} \sqrt{\frac{1}{|\sigma_{int}^I|} + \frac{1}{\sigma_{sig}^I}},$$

$$\sigma_{int}^I = \int^I dM \frac{d\sigma_{int}}{dM}, \quad \sigma_{sig}^I = \int^I dM \frac{d\sigma_{sig}}{dM},$$

ξ_γ	$A_{int}(\%)$	Significance($L = 30 fb^{-1}$)
0	8.8	-
π	-8.8	9
$\frac{\pi}{2}$	0	7

$\xi_\gamma \notin [\pi/2, 3\pi/2]$ at 99.9% C.L.

Mass uncertainty



$$M_H = 125.4 \pm 0.15(stat.) \pm 0.2 \sim 0.3(syst.) GeV$$

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

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

Mass uncertainty of ~ 0.4 GeV doesn't affect much

A general framework

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

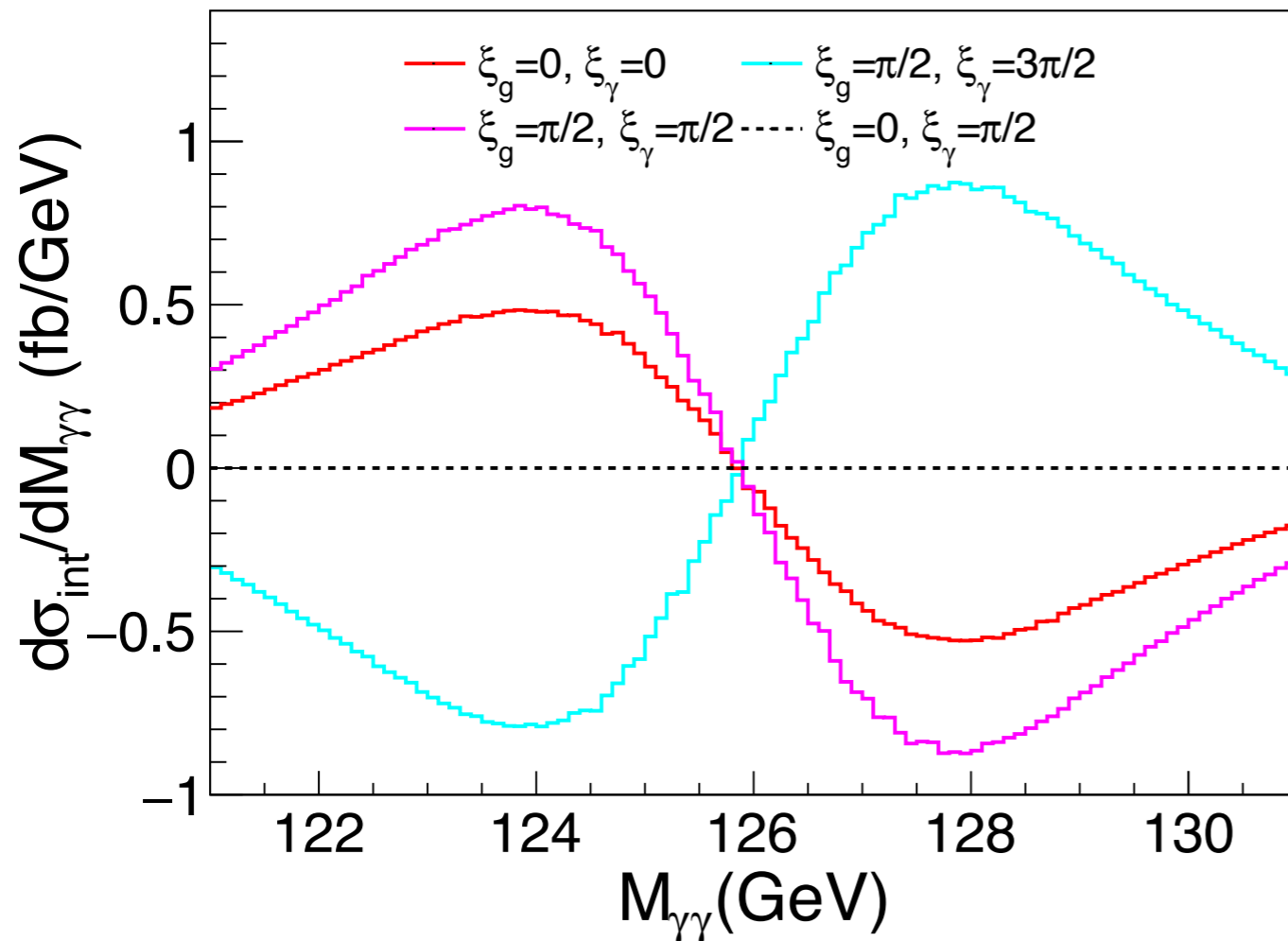
$$\mathcal{M} = -e^{-ih_1\xi_g} e^{-ih_3\xi_\gamma} \delta_{h_1 h_2} \delta_{h_3 h_4} \frac{M_{\gamma\gamma}^4}{v^2} \frac{4c_g c_\gamma}{M_{\gamma\gamma}^2 - M_H^2 + iM_H \Gamma_H} \\ + 4\alpha\alpha_s \delta^{ab} \sum_{f=u,d,c,s,b} Q_f^2 \mathcal{A}_{box}^{h_1 h_2 h_3 h_4}, \quad (17)$$

$$\frac{d\sigma_{int}}{dM_{\gamma\gamma}} \propto \frac{(M_{\gamma\gamma}^2 - M_H^2) \text{Re}(c_g c_\gamma) + M_H \Gamma_H \text{Im}(c_g c_\gamma)}{(M_{\gamma\gamma}^2 - M_H^2) + M_H^2 \Gamma_H^2} \\ \times \int dz [\cos(\xi_g + \xi_\gamma) \mathcal{A}_{box}^{++++} + \cos(\xi_g - \xi_\gamma) \mathcal{A}_{box}^{++--}] (18)$$

Lineshapes

$$A_{int}(\xi_g, \xi_\gamma) = A_{int}^{SM} \times \frac{\int dz [\cos(\xi_g + \xi_\gamma) \mathcal{A}_{box}^{++++} + \cos(\xi_g - \xi_\gamma) \mathcal{A}_{box}^{++--}]}{\int dz [\mathcal{A}_{box}^{++++} + \mathcal{A}_{box}^{++--}]}$$

$$\text{If } |\eta^\gamma| < 2.5, A_{int}(\xi_g, \xi_\gamma) \approx A_{int}^{SM} \times \frac{2 \cos(\xi_g + \xi_\gamma) - 9 \cos(\xi_g - \xi_\gamma)}{-7}$$



ξ_g	ξ_γ	$A_{int}(\%)$	Significance($L = 30 fb^{-1}$)
0	0	8.8	-
$\frac{\pi}{2}$	$\frac{\pi}{2}$	14.5	3
$\frac{\pi}{2}$	$\frac{3\pi}{2}$	-14.5	10
0	$\frac{\pi}{2}$	0	7

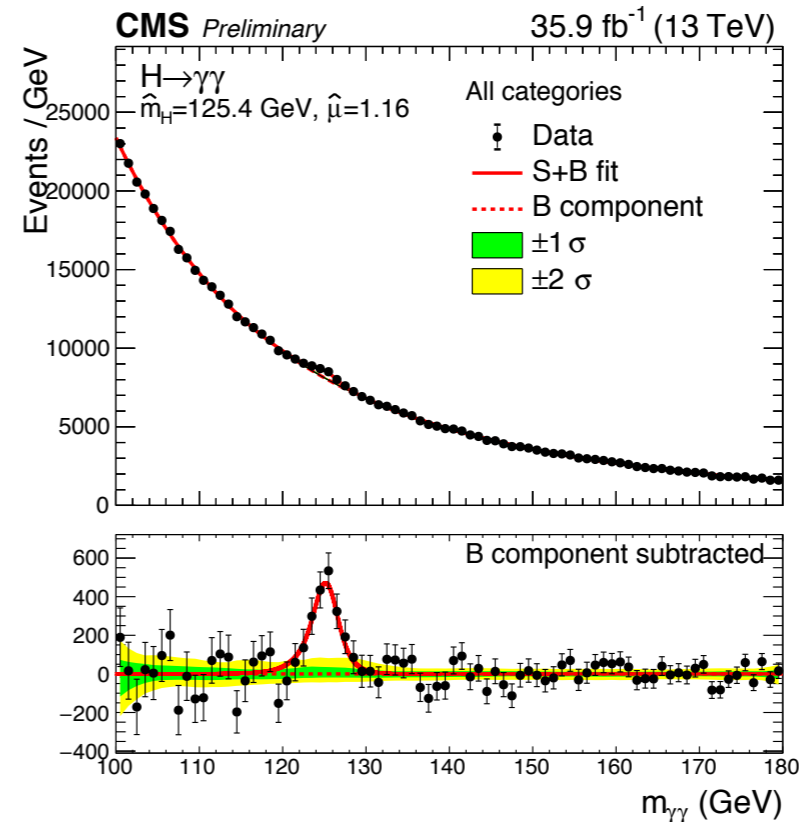
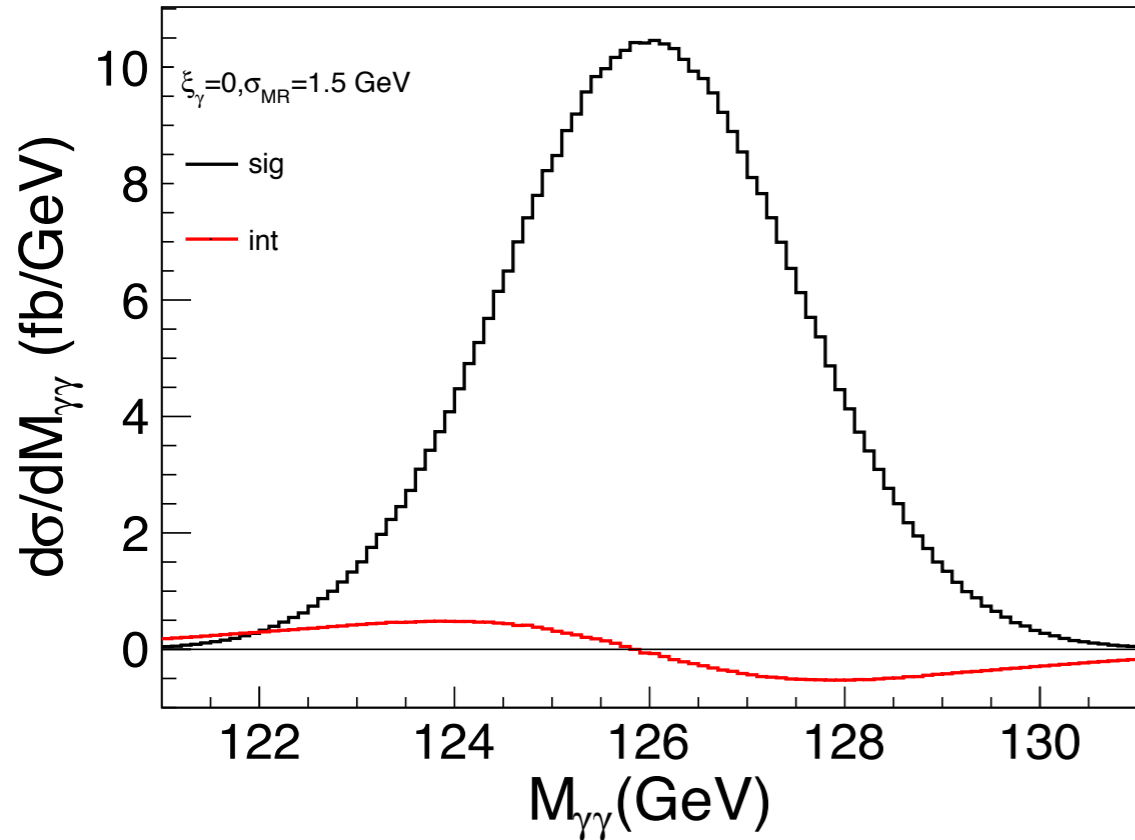
Summary

- CP violation have been studied variously in Higgs decays. For single channels with multiple final states such as $HZZ \rightarrow 4l$, $H \rightarrow t\bar{t} \rightarrow 2\ell 2\nu 2jet$, $\Delta\phi(\Delta\phi_{\ell\ell})$ is a sensitive observable. But it is not suitable for $H \rightarrow \gamma\gamma$.
- Interference between $gg \rightarrow H \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ is studied. Based on the antisymmetric line shape of interference at leading order, We propose an integral odd around M_H ($\int^{M_H} - \int_{M_H}$) to get the contribution of interference and divide it by the total cross section of Higgs signal, which makes a new observable A_{int} .
- A_{int} could reach about 10% in SM, and the significance of deviation caused by CP violation could be large as $5 \sim 10\sigma$, which could constrain the CP violation phase $\xi_\gamma \notin [\pi/2, 3\pi/2]$ at 99.9% confidence level.
- The A_{int} with both CP -violating $H\gamma\gamma$ and Hgg couplings are also studied, which could have larger deviation and significance.

Thanks for your attention!

Backups

How to separate lineshapes



$$\hat{\mu} = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10} \text{ (stat.) } ^{+0.09}_{-0.08} \text{ (syst.) } ^{+0.06}_{-0.05} \text{ (theo.)}$$

σ_{MR} (GeV)	A_{int}^{SM} denominator (fb)	A_{int}^{SM} numerator (fb)	A_{int}^{SM} (%)
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1.7	39.3	3.2	8.2
1.9	39.3	3.0	7.5

Separate lineshape of
signal and interference
is hopeful