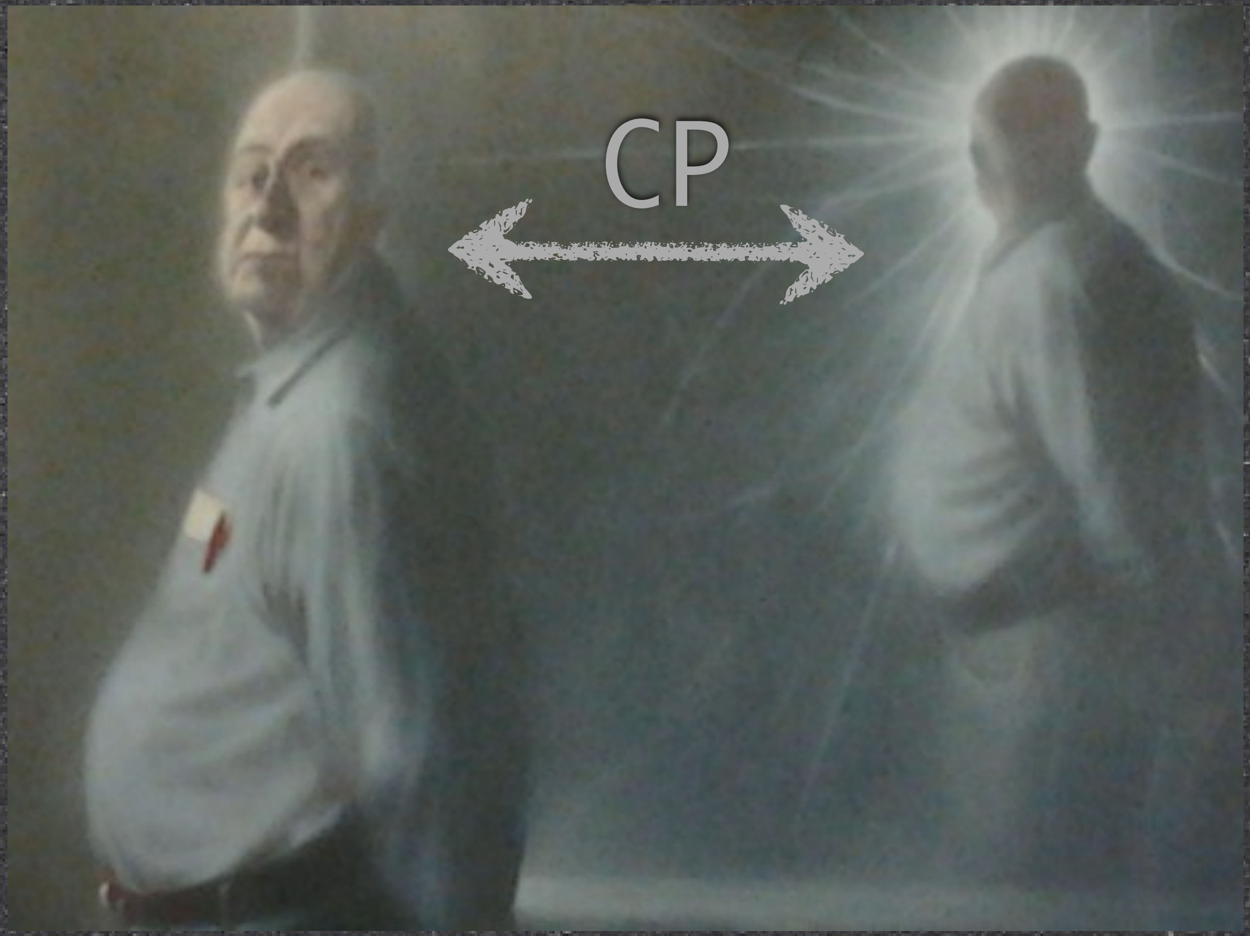
Adam Falkowski
LPT Orsay

CP Violation in 3-body Higgs Decays



Paris, 26 May 2014

Based on a paper with Yi Chen, Ian Low, Roberto Vega-Morales, 1405.xxxx

Plan

- CP violating Higgs couplings
- CP violating observables in Higgs physics
- New CP violating observable

Yi Chen, AA, Ian Low, Roberto Vega-Morales, 1405.xxxx

SM Higgs couplings

$$\mathcal{L}_{\rm SM} = D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 + \left(\frac{y_{ij}}{\sqrt{2}} H \bar{\psi}_i \psi_j + \text{h.c.} \right) + \dots$$

No Higgs

Couplings to EW gauge bosons

Self-Couplings

Couplings to fermions

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \dots \\ v + h + \dots \end{pmatrix}$$

$$\left(\frac{h}{v} + \frac{h^2}{2v^2} \right) (2 m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu)$$

$$-\frac{m_h^2}{2v} h^3 - \frac{m_h^2}{8v^2} h^4$$

$$-\frac{h}{v} \sum_f m_f \bar{f} f$$

Ensures unitarity of VV->hh scattering

Ensures unitarity of VV->VV scattering

Ensures unitarity of VV->VVVV... scattering

Ensures unitarity of VV->ff scattering

No CP violating couplings

$$\cancel{-\frac{h}{4v} \tilde{C}_{V_1 V_2} \epsilon^{\mu\nu\rho\sigma} \partial_\mu V_\nu^1 \partial_\rho V_\sigma^2}$$

$$\cancel{-i \tilde{y}_f h \bar{f} \gamma_5 f}$$

BSM Higgs couplings

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{v}\mathcal{L}_{D=5} + \frac{1}{v^2}\mathcal{L}_{D=6} + \ldots$$

Extending SM by higher dimensional operators modifies Higgs couplings existing in SM, and leads to new Higgs couplings with new tensor structures

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi \widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi \widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi \widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Grządkowski et al. 1008.4884

2499 ways to leave your lover Alonso,Jenkins,Manohar,Trott 1312.2014

BSM Higgs couplings

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{v}\mathcal{L}_{D=5} + \frac{1}{v^2}\mathcal{L}_{D=6} + \dots$$

Extending SM by higher dimensional operators modifies Higgs couplings existing in SM, and leads to new Higgs couplings with new tensor structures

Grządkowski et al. 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Some of these operators violate CP, either via CP violating tensor structures, or via CP violating complex couplings

CP violating Higgs couplings to EW bosons

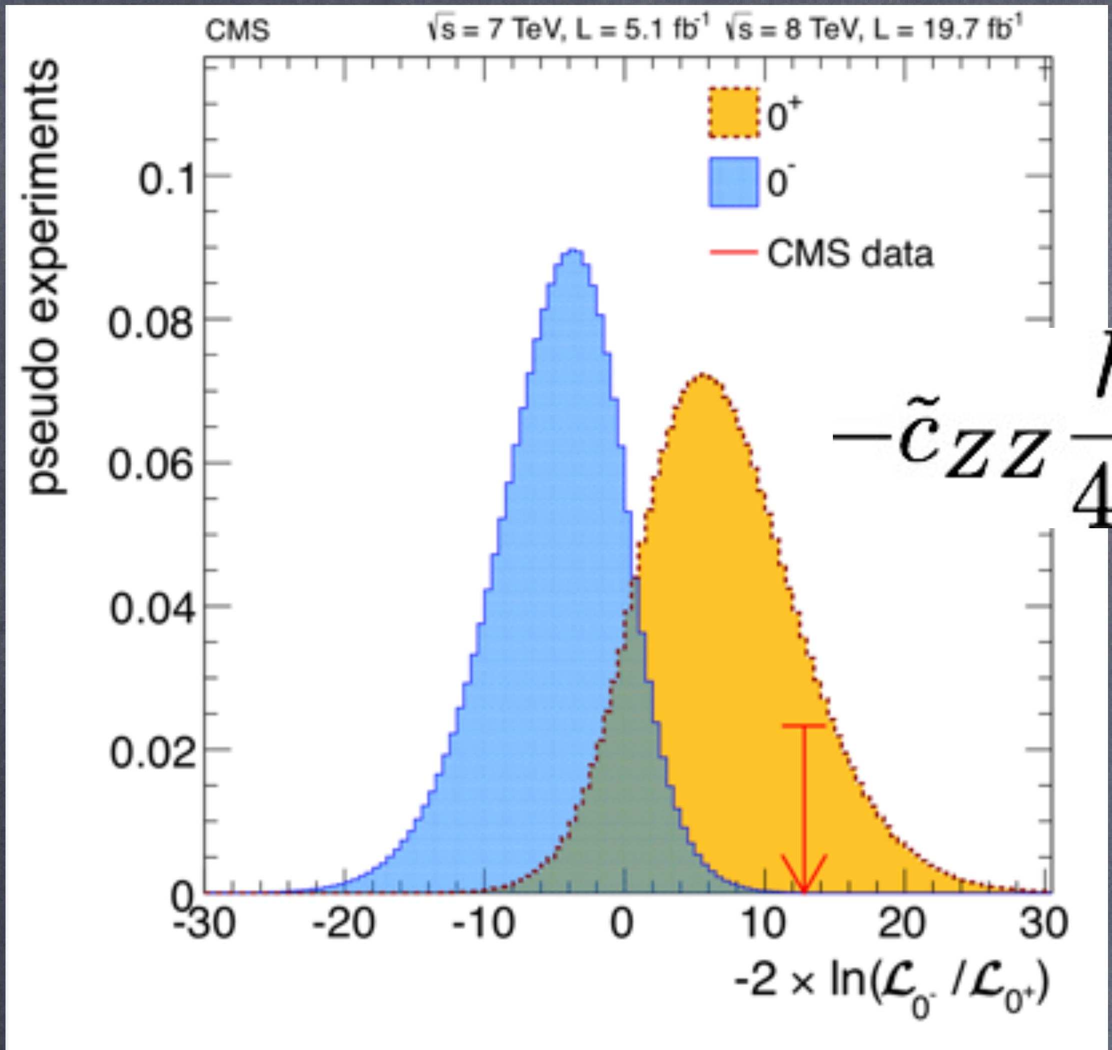
$$\mathcal{L}_{\rm CPV} \supset -\frac{h}{4v}\epsilon^{\mu\nu\rho\sigma}\left[\tilde{c}_{\gamma\gamma}\partial_\mu A_\nu \partial_\rho A_\sigma \right.$$
$$+2\tilde{c}_{Z\gamma}\partial_\mu Z_\nu \partial_\rho A_\sigma$$
$$\left. +\, \tilde{c}_{ZZ}\partial_\mu Z_\nu \partial_\rho Z_\sigma\right]$$

- Not present in SM at tree level; induced in effective action at 3-loop level, thus SM predicts they are zero for all practical purpose
- Very weak experimental constraints so far

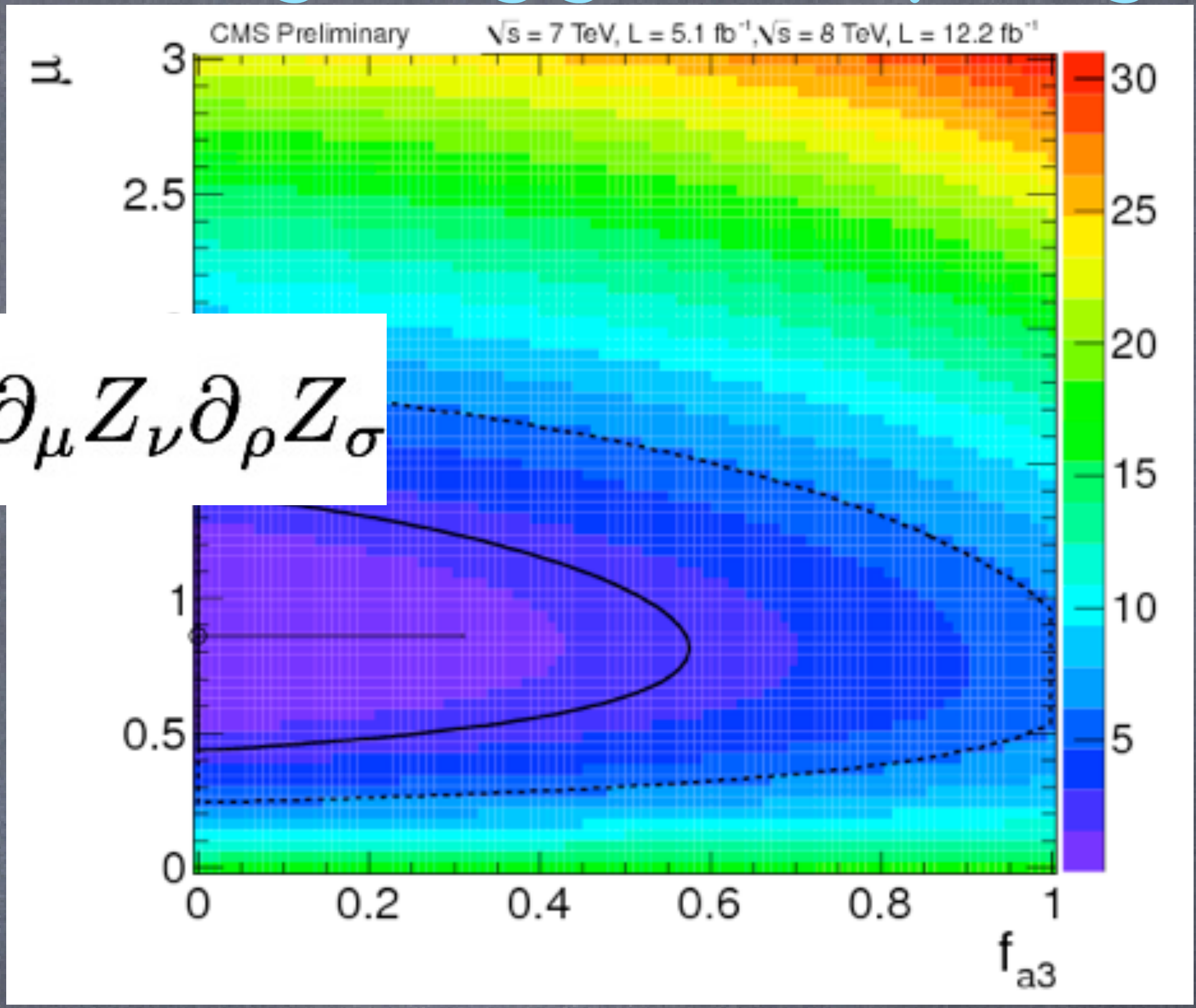
see e.g.
Belusca-Maito
1404.5343

- Higgs inclusive rates in given channel depends on squares of CP violating couplings, so corrections expected very small
- We should look at exclusive observables

LHC constraints on CP violating Higgs couplings



$$-\tilde{c}_{ZZ}\frac{h}{4v}\epsilon^{\mu\nu\rho\sigma}\partial_\mu Z_\nu \partial_\rho Z_\sigma$$

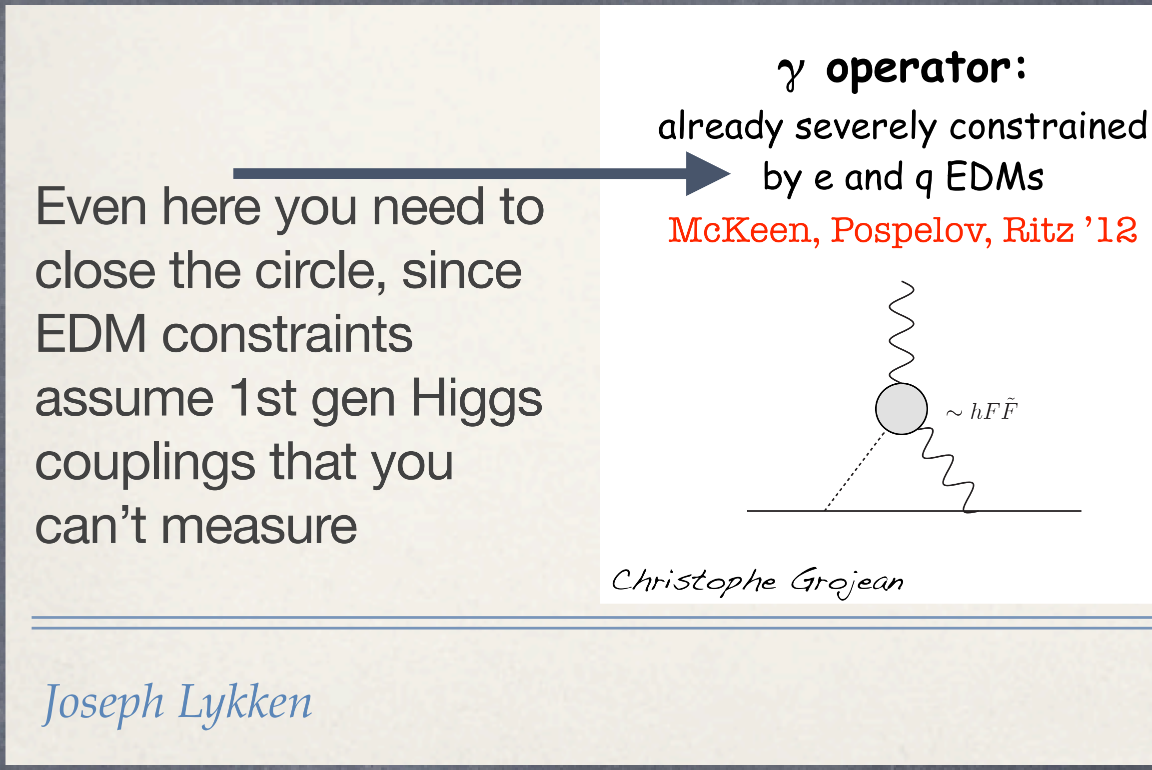


- Only tells that pure SM coupling to ZZ preferred over pure CP violating coupling to ZZ
- Useless at this point

- A step in the right direction
- Should be marginalized over other Higgs couplings to give a useful bound

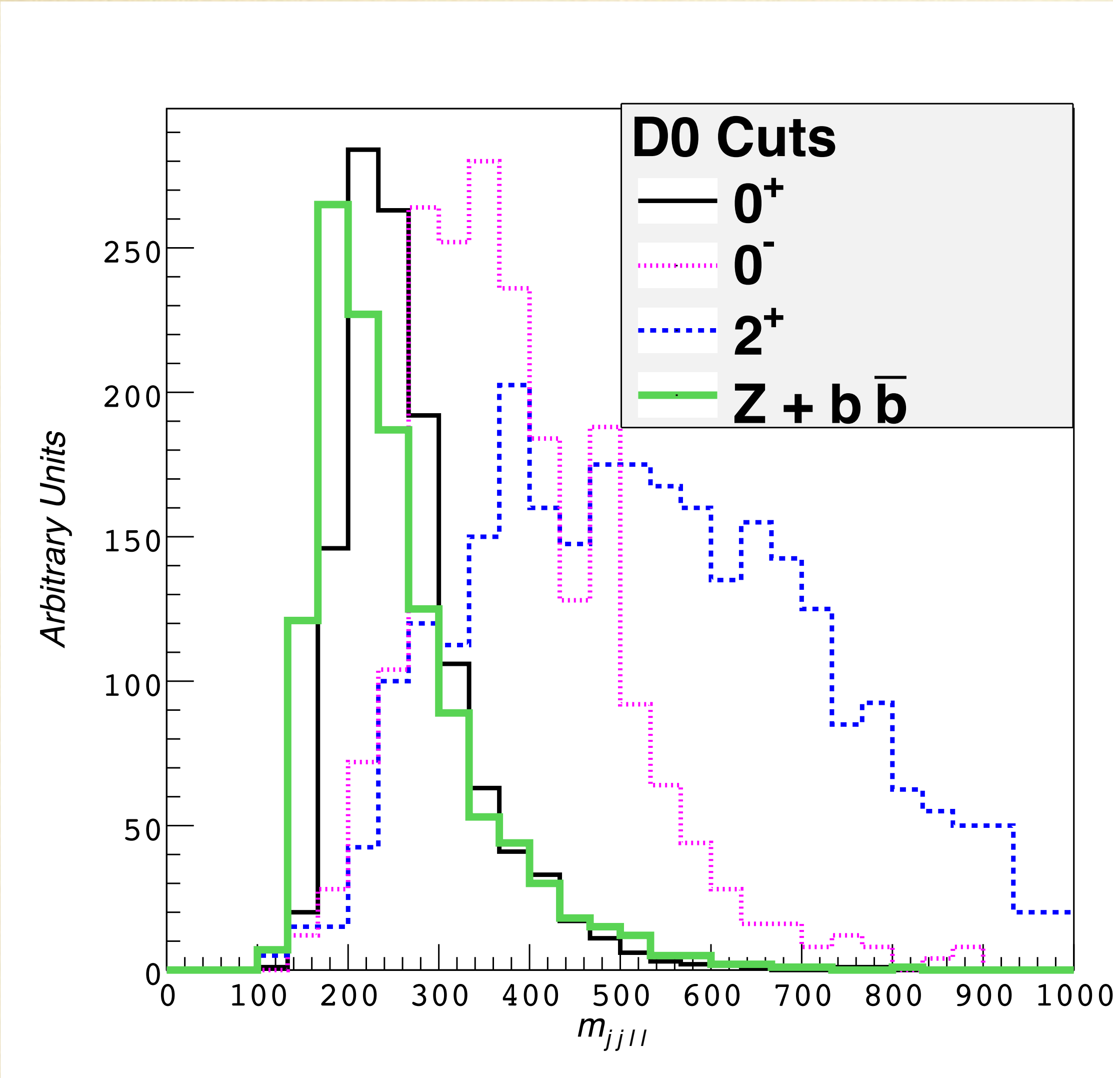
How to search for CP violating Higgs couplings

- Indirect: CP violating effects in low energy precision experiments
- Semi-direct: kinematic distributions sensitive to different momentum dependence of CP violating Higgs couplings
- Direct: genuinely CP violating observables in Higgs production and decay



How to search for CP violating Higgs couplings

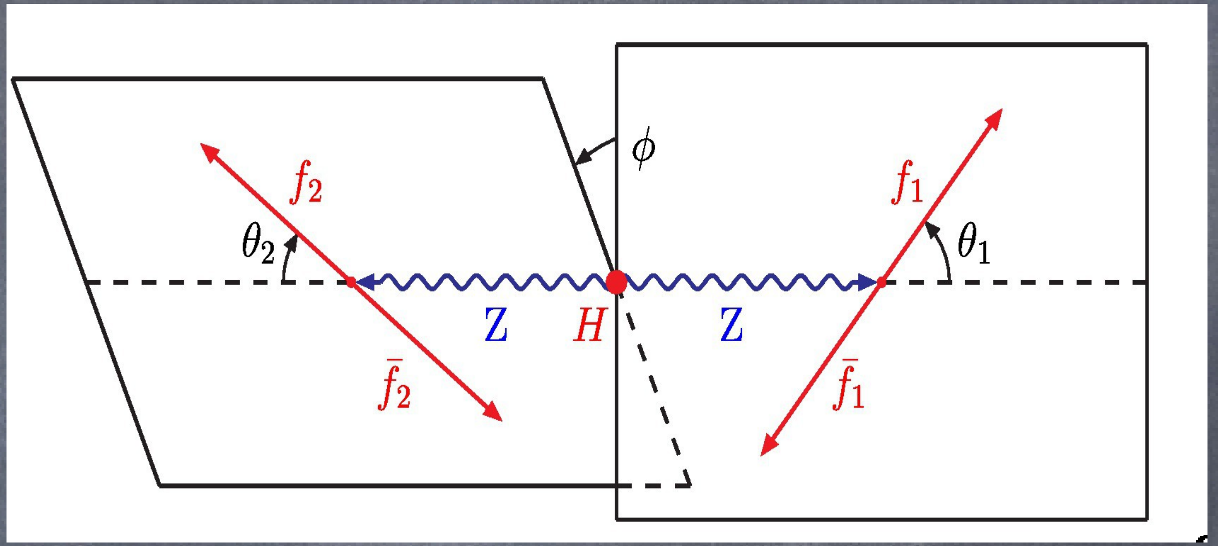
- Indirect: CP violating effects in low energy precision experiments
- Semi-direct: kinematic distributions sensitive to different momentum dependence of CP violating Higgs couplings
- Direct: genuinely CP violating observables in Higgs production and decay

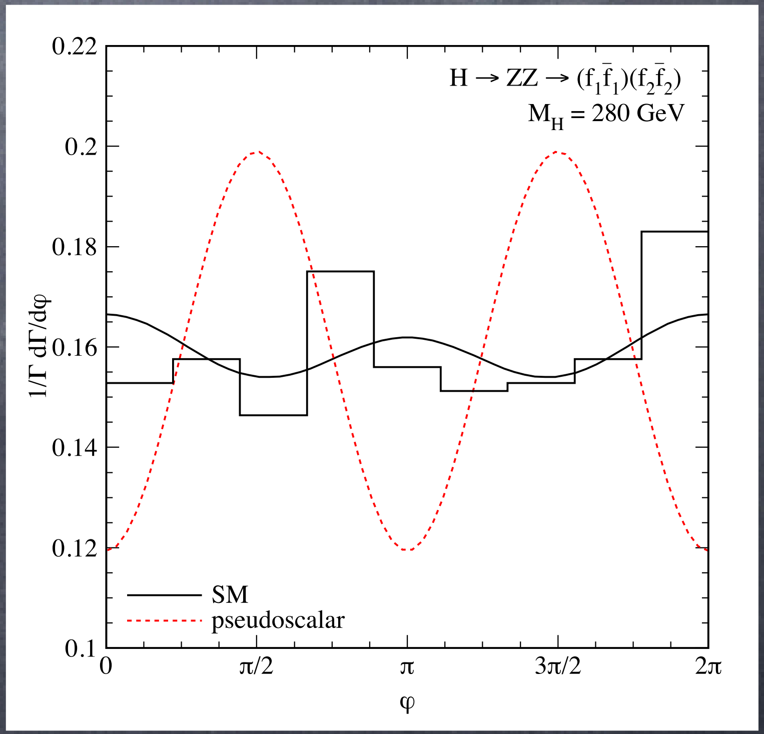


Ellis, Hwang, VS, You. 1208.6002

How to search for CP violating Higgs couplings

- Indirect: CP violating effects in low energy precision experiments
- Semi-direct: kinematic distributions sensitive to different momentum dependence of CP violating Higgs couplings
- Direct: genuinely CP violating observables in Higgs production and decay





Miller et al.
hep-ph/0210077

CP violation and strong phases

- For Higgs decay, simple asymmetry for decays into CP conjugate states F and Fbar requires interference of 2 amplitudes with different weak AND strong phases

$$\mathcal{M}_{h\to F} = |c_1|e^{i(\delta_1+\phi_1)} + |c_2|e^{i(\delta_2+\phi_2}$$
$$\mathcal{M}_{h\to \bar{F}} = |c_1|e^{i(\delta_1-\phi_1)} + |c_2|e^{i(\delta_2-\phi_2}$$

$$A_{\rm CP} = \frac{d\Gamma_{h\to F} - d\Gamma_{h\to \bar{F}}}{d\Gamma_{h\to F} + d\Gamma_{h\to \bar{F}}} \propto |c_1||c_2|\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)$$

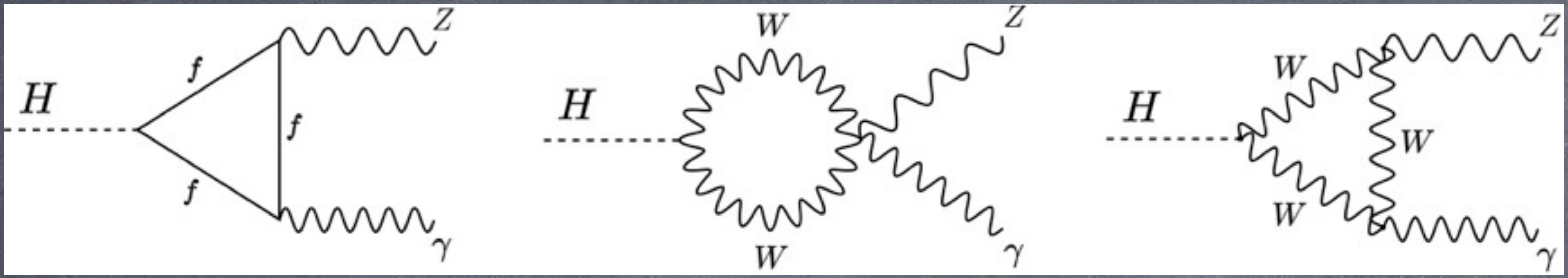
- In absence of strong phases, one needs to resort to triple product asymmetries, which require 4 visible momenta in final state

$$\cos\phi = \frac{(\vec{p}_1\times\vec{p}_2)\cdot(\vec{p}_3\times\vec{p}_4)}{|\vec{p}_1\times\vec{p}_2|\;|\vec{p}_3\times\vec{p}_4|},$$

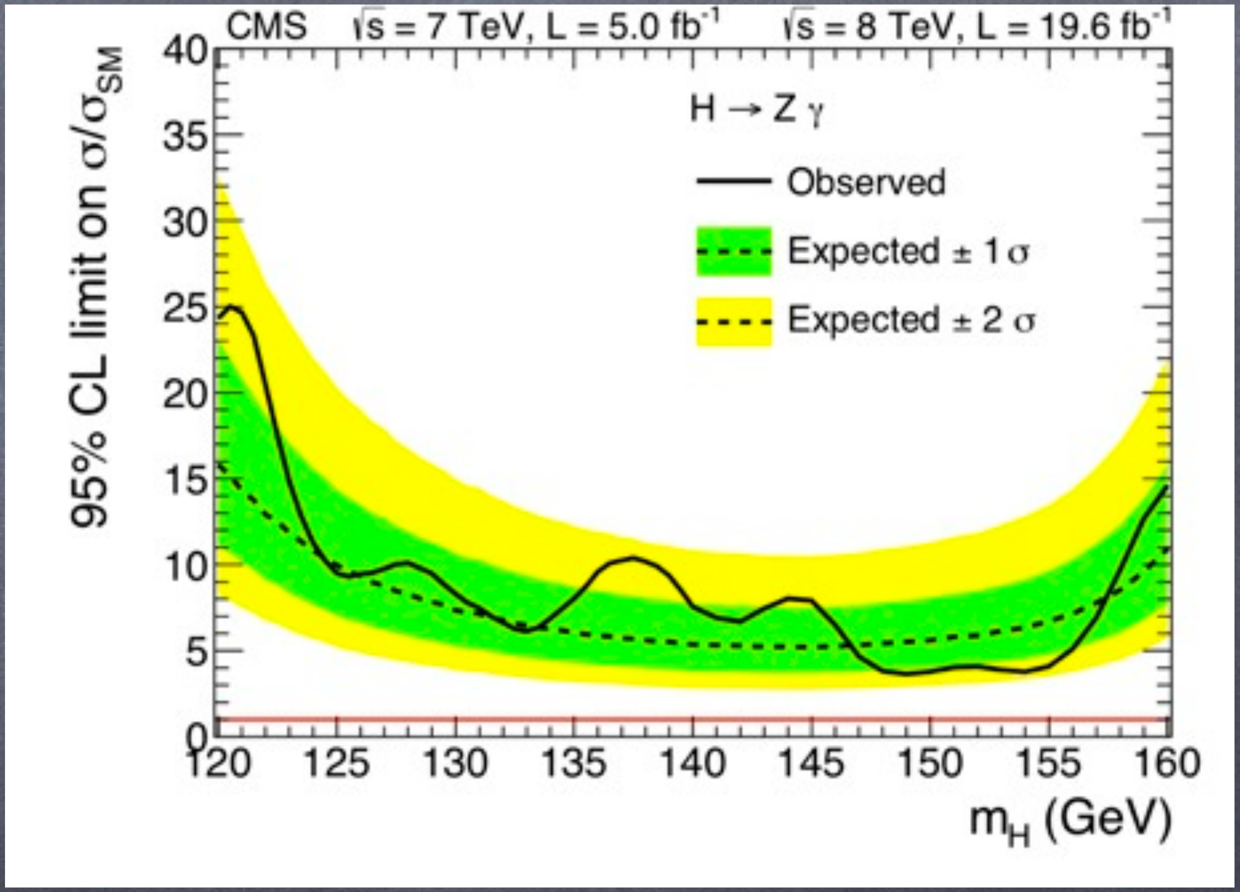
CP violation in 3-body Higgs decays

- New CP violating observable in certain 3-body Higgs decays that requires only 3 reconstructed momenta
- Analogous observables discussed to death in flavor physics, in context of BSM decay studied by Berger,Blanke,Grossman 1105.0672, but afaik no discussion in context of Higgs physics
- In Higgs decays, strong phase provided by the Breit-Wigner propagator of the Z boson, while weak phases may arise due to CP violating Higgs couplings
- Example: forward-backward asymmetry of lepton in $h \to (Z/\gamma)\gamma \to l^- l^+ \gamma$ decays

Higgs decays to Zγ in SM



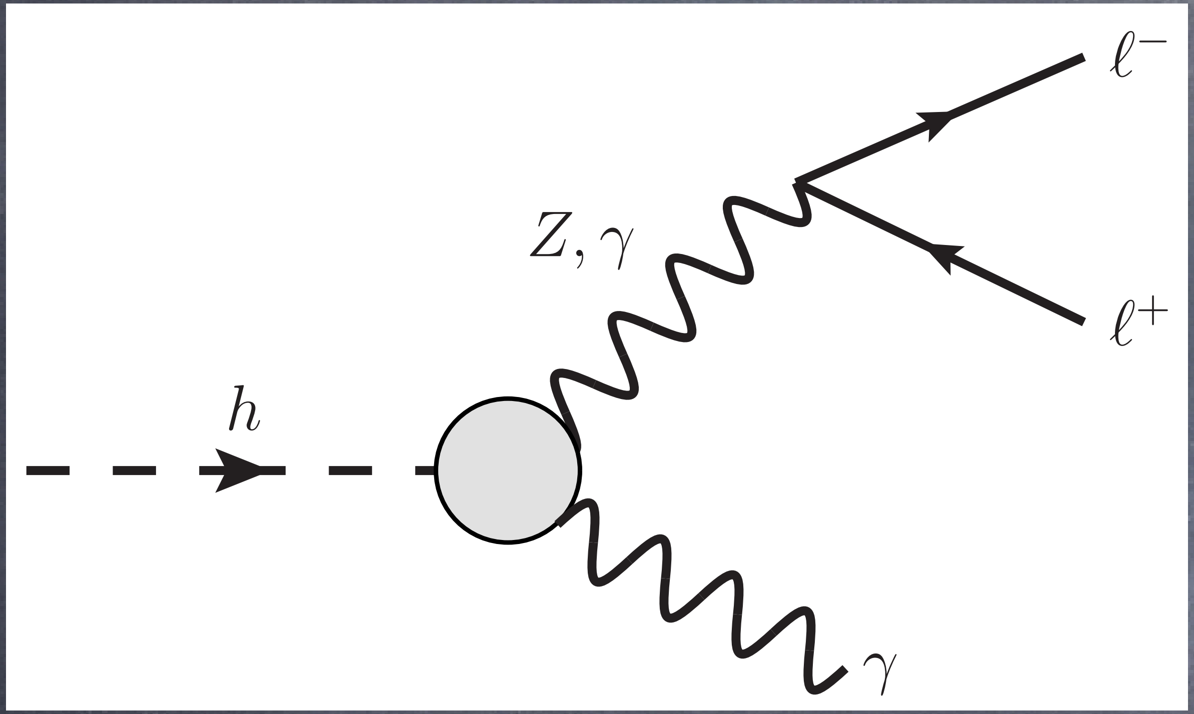
- In SM, loop level decays with branching fraction 0.16%
- Current limits order of magnitude larger
- Room for large CP violating Higgs coupling to Zγ from BSM

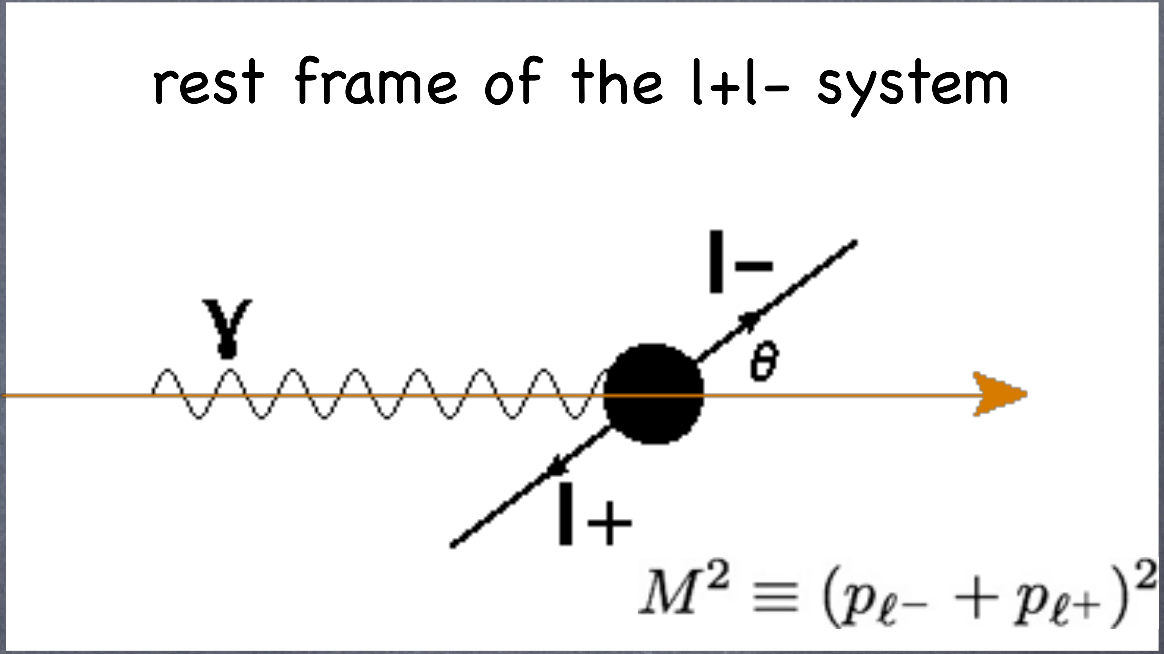


Higgs decays to Zγ in BSM

$$-\frac{h}{4v}\left(2c_{Z\gamma}A^{\mu\nu}Z_{\mu\nu}+2\tilde{c}_{Z\gamma}A^{\mu\nu}\widetilde{Z}_{\mu\nu}+c_{\gamma\gamma}A^{\mu\nu}A_{\mu\nu}+\tilde{c}_{\gamma\gamma}A^{\mu\nu}\widetilde{A}_{\mu\nu}\right)$$

$$\mathrm{SM}: \quad |c_{Z\gamma}|\sim 0.015, \quad |c_{\gamma\gamma}|\sim 0.0077, \quad \tilde{c}_{Z\gamma}\approx\tilde{c}_{\gamma\gamma}\approx 0$$





$$\frac{d\Gamma}{dM^2 d\cos\theta}=\left(1+\cos^2\theta\right)\frac{d\Gamma_{\mathrm{CPC}}}{dM^2}+\cos\theta\frac{d\Gamma_{\mathrm{CPV}}}{dM^2}$$

$$\frac{d\Gamma_{CPV}}{dM^2}=(c_{Z\gamma}\tilde{c}_{\gamma\gamma}-c_{\gamma\gamma}\tilde{c}_{Z\gamma})\times\frac{e(g_{Z,R}-g_{Z,L})m_Z\Gamma_Z(m_h^2-M^2)^3}{512\pi^3 m_h^3 v^2\left((M^2-m_Z^2)^2+m_Z^2\Gamma_Z^2\right)}$$

Asymmetric part manifestly CP odd

CP violation in h→l-l+γ decays

$$\frac{d\Gamma_{CPV}}{dM^2} = (c_{Z\gamma}\tilde{c}_{\gamma\gamma} - c_{\gamma\gamma}\tilde{c}_{Z\gamma}) \times \frac{e(g_{Z,R} - g_{Z,L}) m_Z \Gamma_Z (m_h^2 - M^2)^3}{512\pi^3 m_h^3 v^2 \left((M^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2\right)}$$

- CP violation is proportional to CP odd Higgs couplings to Zγ or γγ who provide weak phases
- CP violation is proportional to the width of Z who provides the strong phase
- It leads to forward-backward asymmetry of lepton direction in rest frame of l+l- system

$$A_{\mathrm{FB}}(M) = \frac{\left(\int_0^1 - \int_{-1}^0\right) d\cos\theta \frac{d\Gamma}{dM^2 d\cos\theta}}{\left(\int_0^1 + \int_{-1}^0\right) d\cos\theta \frac{d\Gamma}{dM^2 d\cos\theta}} = \frac{3}{8}\,\frac{d\Gamma_{\mathrm{CPV}}/dM^2}{d\Gamma_{\mathrm{CPC}}/dM^2}$$

CP violation in h→l-l+γ decays

$$L_{+1} = \mathcal{M}(+1, -1/2, -1/2) \quad \overset{C}{\longleftrightarrow} \quad R_{+1} = \mathcal{M}(+1, +1/2, +1/2)$$

θ→π-θ

CP θ→π-θ

P

θ→π-θ CP

C

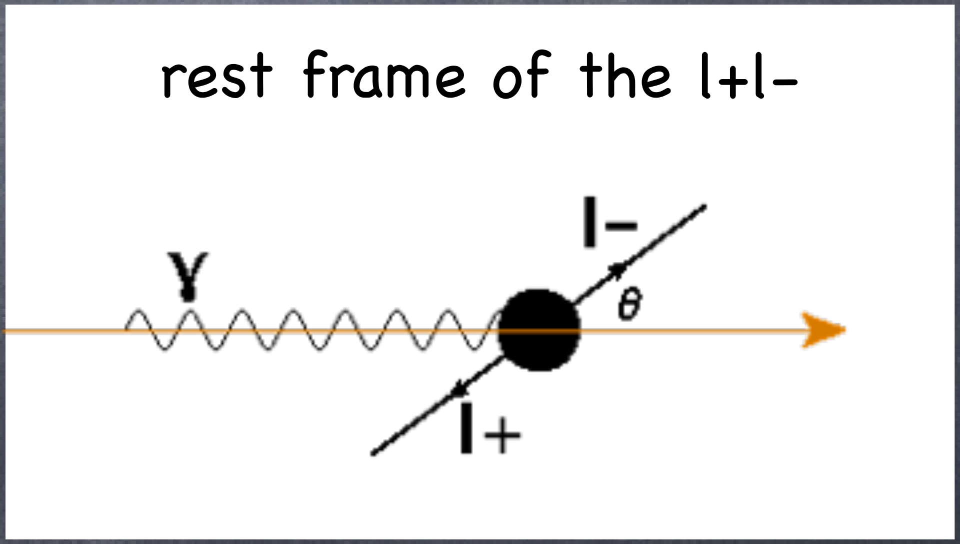
$$L_{-1} = \mathcal{M}(-1, -1/2, -1/2) \quad \longleftrightarrow \quad R_{-1} = \mathcal{M}(-1, +1/2, +1/2)$$

θ→π-θ

$$d\Gamma \sim |L_{+1}(\cos\theta)|^2 + |L_{-1}(\cos\theta)|^2 + |R_{+1}(\cos\theta)|^2 + |R_{-1}(\cos\theta)|^2$$

CP conserved ⇒

$$L_{+1}(\cos\theta) = L_{-1}(-\cos\theta)$$
$$R_{+1}(\cos\theta) = R_{-1}(-\cos\theta)$$



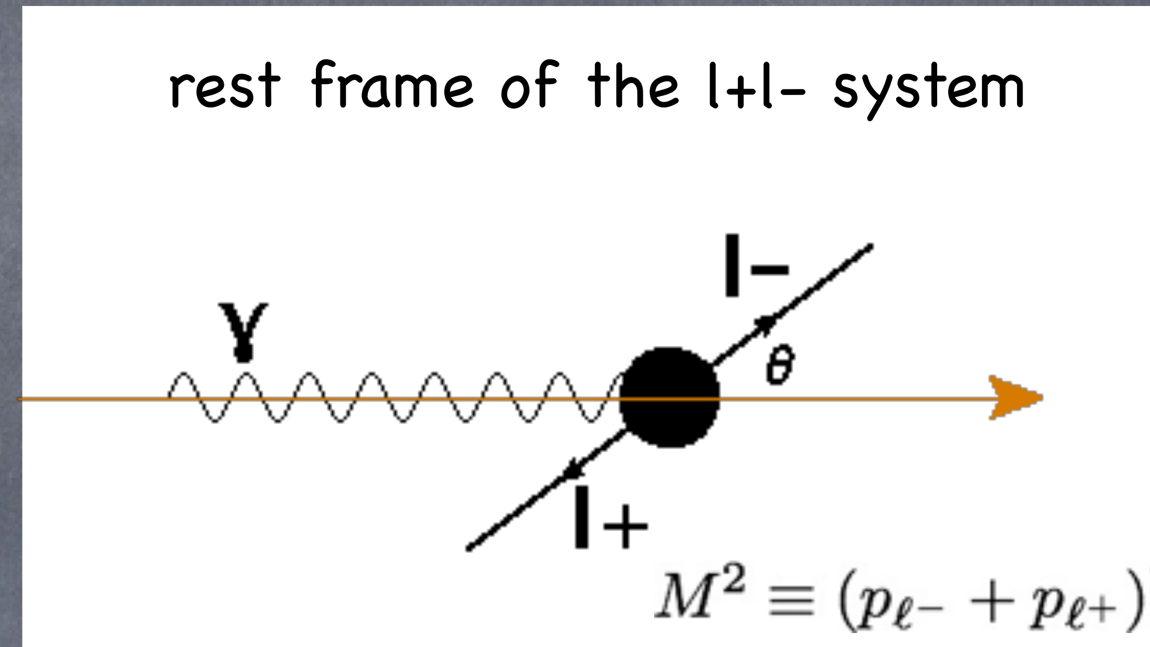
$$d\Gamma \sim |L_{+1}(\cos\theta)|^2 + |L_{+1}(-\cos\theta)|^2 + |R_{+1}(\cos\theta)|^2 + |R_{+1}(-\cos\theta)|^2$$

Asymmetry in cosθ implies C and CP violation

CP violation in h→l-l+γ decays

Two interfering diagrams with intermediate Z or γ

$$\mathcal{M}(h \to \ell^- \ell^+ \gamma) = \mathcal{M}^Z + \mathcal{M}^\gamma$$



Each diagram has different strong and weak phase

$$L^V_{+1} = g_{V,L} \frac{(1+\cos\theta)(c_{V\gamma} + i\tilde{c}_{V\gamma})M(m_h^2 - M^2)}{2\sqrt{2}v(M^2 - m_V^2 + i m_V \Gamma_V)}$$

C

θ→π-θ

$$R^V_{+1} = g_{V,R} \frac{(1-\cos\theta)(c_{V\gamma} + i\tilde{c}_{V\gamma})M(m_h^2 - M^2)}{2\sqrt{2}v(M^2 - m_V^2 + i m_V \Gamma_V)}$$

CP θ→π-θ

P

θ→π-θ CP

C

θ→π-θ

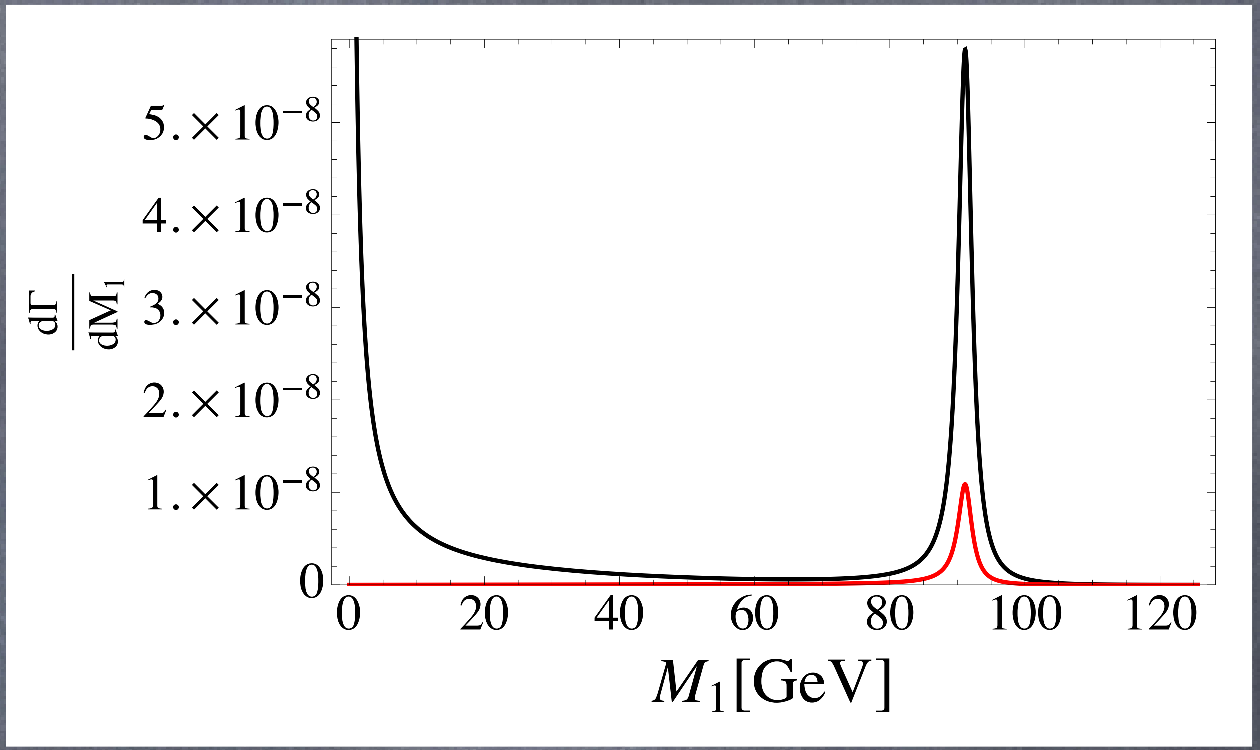
$$L^V_{-1} = g_{V,L} \frac{(1-\cos\theta)(c_{V\gamma} - i\tilde{c}_{V\gamma})M(m_h^2 - M^2)}{2\sqrt{2}v(M^2 - m_V^2 + i m_V \Gamma_V)}$$

$$R^V_{-1} = g_{V,R} \frac{(1+\cos\theta)(c_{V\gamma} - i\tilde{c}_{V\gamma})M(m_h^2 - M^2)}{2\sqrt{2}v(M^2 - m_V^2 + i m_V \Gamma_V)}$$

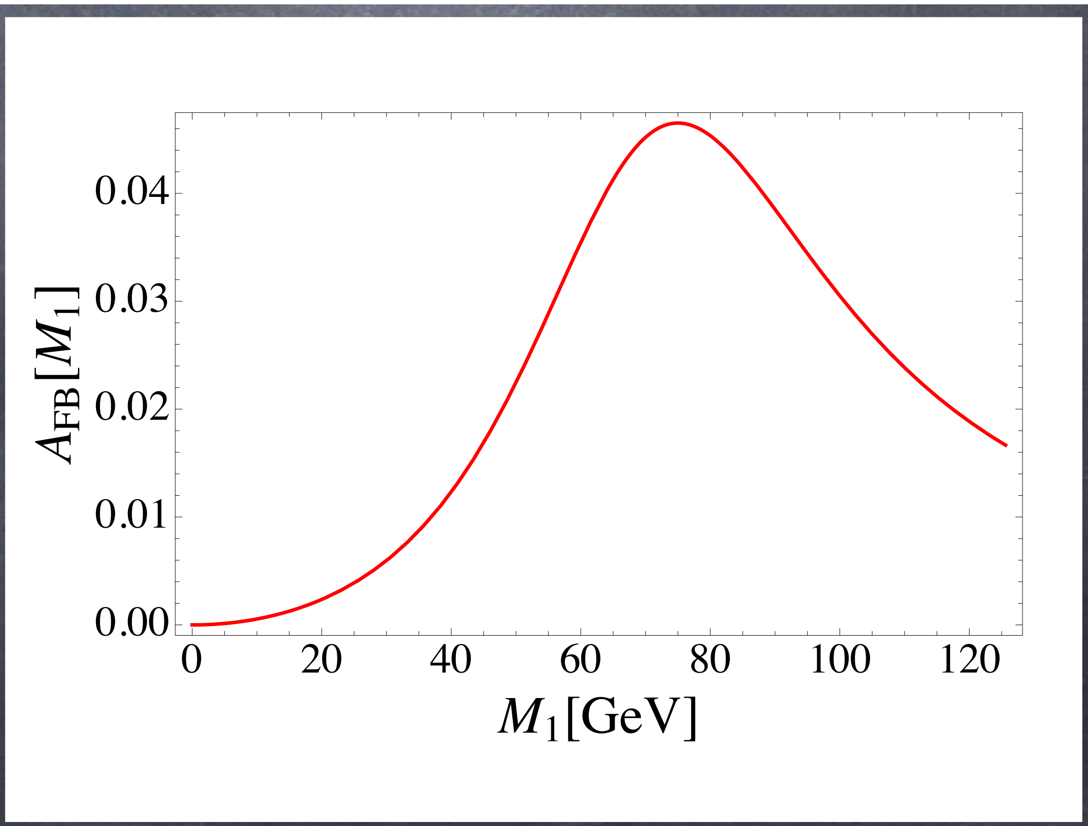
CP violation in h→l-l+γ decays

$$\frac{d\Gamma_{CPV}}{dM^2} = (c_{Z\gamma}\tilde{c}_{\gamma\gamma} - c_{\gamma\gamma}\tilde{c}_{Z\gamma}) \times \frac{e(g_{Z,R} - g_{Z,L}) m_Z \Gamma_Z (m_h^2 - M^2)^3}{512\pi^3 m_h^3 v^2 \left((M^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2\right)}$$

- Both symmetric and anti-symmetric peak at the Z pole -> one can use narrow width approximation for both



- Dependence on axial coupling to Z is because C needs to be violated as well



CP violation in h→l-l+γ decays

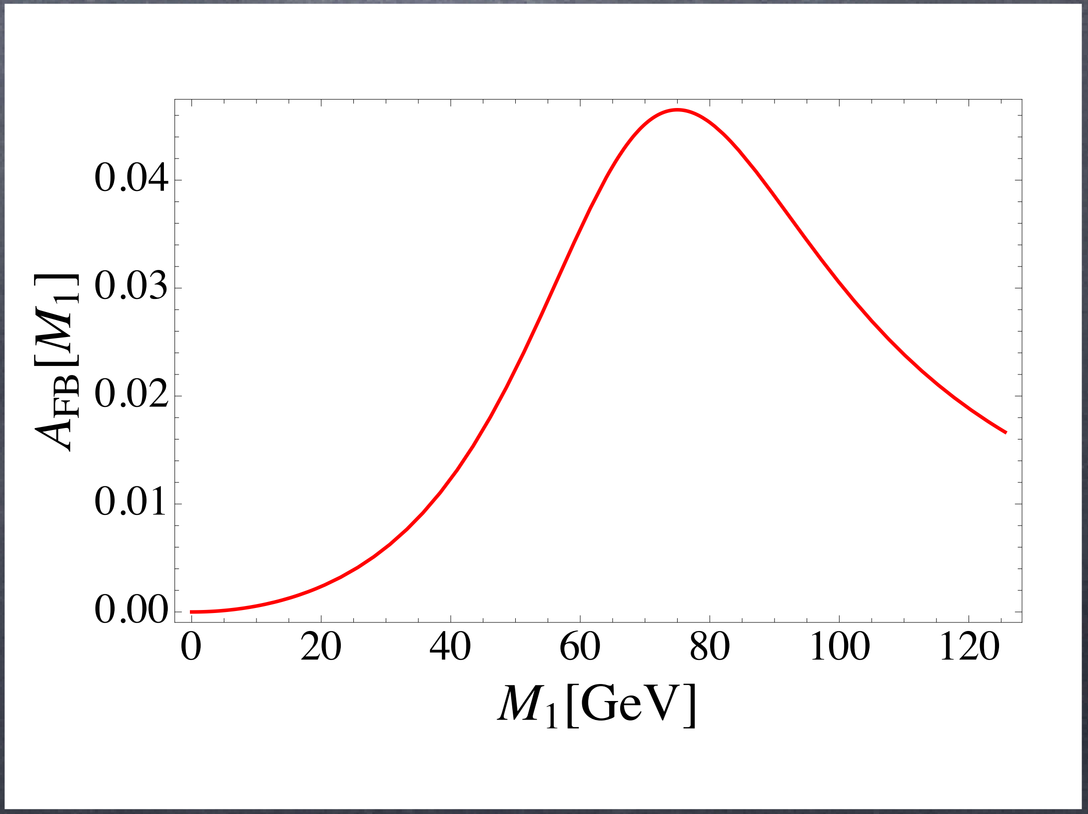
- Integrated asymmetry suppressed by Γz/mZ, but otherwise no parametric suppression

$$\bar{A}_{\rm FB} \sim \frac{\Gamma_Z}{m_Z}\frac{c_{Z\gamma}\tilde{c}_{\gamma\gamma} - c_{\gamma\gamma}\tilde{c}_{Z\gamma}}{c_{Z\gamma}^2 + \tilde{c}_{Z\gamma}^2}$$

- 5% asymmetry possible if CP violating Higgs couplings of the same order as conserving ones

$$\bar{A}_{\rm FB} \approx 0.07\frac{c_{Z\gamma}\tilde{c}_{\gamma\gamma} - c_{\gamma\gamma}\tilde{c}_{Z\gamma}}{c_{Z\gamma}^2 + \tilde{c}_{Z\gamma}^2}$$

- Larger asymmetry possible if effective Higgs coupling to Zγ smaller than in SM



CP violation in $h \to l^- l^+ \gamma$ decays in LHC

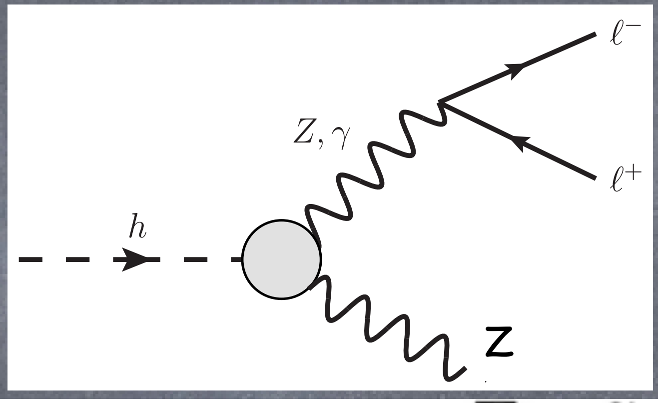
- $h \to Z\gamma$ with leptonic Z decay routinely searched for
- For CP violation, one has to fight not only symmetric Higgs background, but also symmetric non-Higgs SM background
- Standard cut-based analysis in $h \to Z\gamma$ channel has signal to background of order 1/100. Then sensitivity estimated as

$$\frac{S}{\sqrt{B}} \sim \left(\frac{A_{\mathrm{FB}}}{0.1}\right)\sqrt{\frac{L}{3000\ \mathrm{fb}^{-1}}}$$

Better signal to background using matrix element methods implies better sensitivity

Chen, Vega-Morales; work in progress

Related CP violating Higgs processes



- $h \to l^- l^+ Z$: asymmetry more suppressed because of symmetric part profiting from tree-level hZZ coupling cV

$$A_{\rm FB}(h \to \ell^-\ell^+ Z) \sim \frac{\Gamma_Z}{m_Z}\frac{\tilde{c}_{Z\gamma}}{c_V} \lesssim 10^{-3}$$

- $e^-e^+ \to h\,Z$: asymmetry more suppressed in by additional mZ/E

$$\bar{A}_{\rm FB}(e^-e^+ \to hZ) \sim \frac{\Gamma_Z m_Z}{s}\frac{\tilde{c}_{Z\gamma}}{c_V} \lesssim 10^{-4}$$

- $e^-e^+ \to h\,\gamma$: large asymmetry but small rate

$$\bar{A}_{\rm FB}(f\bar{f} \to h\gamma) \sim \frac{\Gamma_Z}{m_Z}\frac{c_{Z\gamma}\tilde{c}_{\gamma\gamma} - c_{\gamma\gamma}\tilde{c}_{Z\gamma}}{c_{Z\gamma}^2 + \tilde{c}_{Z\gamma}^2} \lesssim 10^{-1}$$

To take out

- A new class of CP violating observables in Higgs physics not relying on triple product asymmetries
- Can be applied to Higgs decay involving 3 observable particle: a pair of CP conjugate + 1 neutral particle
- Also relevant for 2-to-2 scattering processes with a pair of CP conjugate + Higgs + 1 other neutral particle
- Can be studied at hadron or lepton colliders
- New handle on CP violating Higgs couplings to Z and γ