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LPT Orsay

Exotic and CP violating Higgs Decays

Grenoble, 02 July 2014

Based on work with Roberto Vega-Morales 1405.1095,
and with Yi Chen, Ian Low, Roberto Vega-Morales, 1405.6723

Plan

- Intro: Higgs: where do we stand?
- Part 1: Exotic Higgs decays to hidden photon in 4-lepton channel
- Part 2: New CP violating observables in Higgs decays

Higgs:
where do we stand

Where do we stand

- Gazillion sigma evidence for a SM-like Higgs boson
- Higgs mass is 125.5 GeV, give or take a couple hundred MeV.
- Evidence for coupling both to SM gauge bosons and to fermions
- Evidence for gluon fusion and vector boson fusion production

Simplified Effective Higgs Lagrangian

$$\mathcal{L}_{h,\rm sim} = \frac{h}{v}\Big(\quad 2c_V m_W^2 W^+_\mu W^-_\mu + c_V m_Z^2 Z_\mu Z_\mu$$
$$- c_u \sum_{q=u,c,t} m_q \bar{q} q - c_d \sum_{q=d,s,b} m_q \bar{q} q - c_l \sum_{l=e,\mu\tau} m_l \bar{l} l$$
$$+ \frac{1}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu} \gamma_{\mu\nu}$$
$$- \frac{1}{2} c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z_{\mu\nu} \Big)$$

$$c_{WW} = c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} \qquad c_{ZZ} = c_{\gamma\gamma} + \frac{c_w^2 - s_w^2}{c_w s_w} c_{Z\gamma}$$

- Simpler effective theory with 7 free parameters
- <ALL> these parameters are meaningfully constrained by current Higgs data
- Standard Model limit: $c_V = c_f = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$

7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.03}$$

$$c_u = 1.30^{+0.23}_{-0.27}$$

$$c_d = 1.03^{+0.27}_{-0.17}$$

$$c_l = 1.10^{+0.18}_{-0.15}$$

$$c_{gg} = \frac{g_s^2}{16\pi^2}\left(-0.48^{+0.44}_{-0.17}\right)$$

$$c_{\gamma\gamma} = \frac{e^2}{16\pi^2}\left(0.2^{+2.8}_{-3.3}\right)$$

$$c_{Z\gamma} = \frac{e g_L}{\cos\theta_W 16\pi^2}\left(4^{+10}_{-19}\right)$$

using only Higgs data:

$$c_V = 1.03^{+0.08}_{-0.08}$$

Belusca-Maito, AA
arXiv: 1311.1113 + updates

Best fit and 68% CL range for parameters (warning, some errors very non-Gaussian)

Islands of good fit with negative cu, cd, cl ignored here

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} \approx 5.5$, with 7 d.o.f.
SM hypothesis is a perfect fit :-(((

Where do we stand

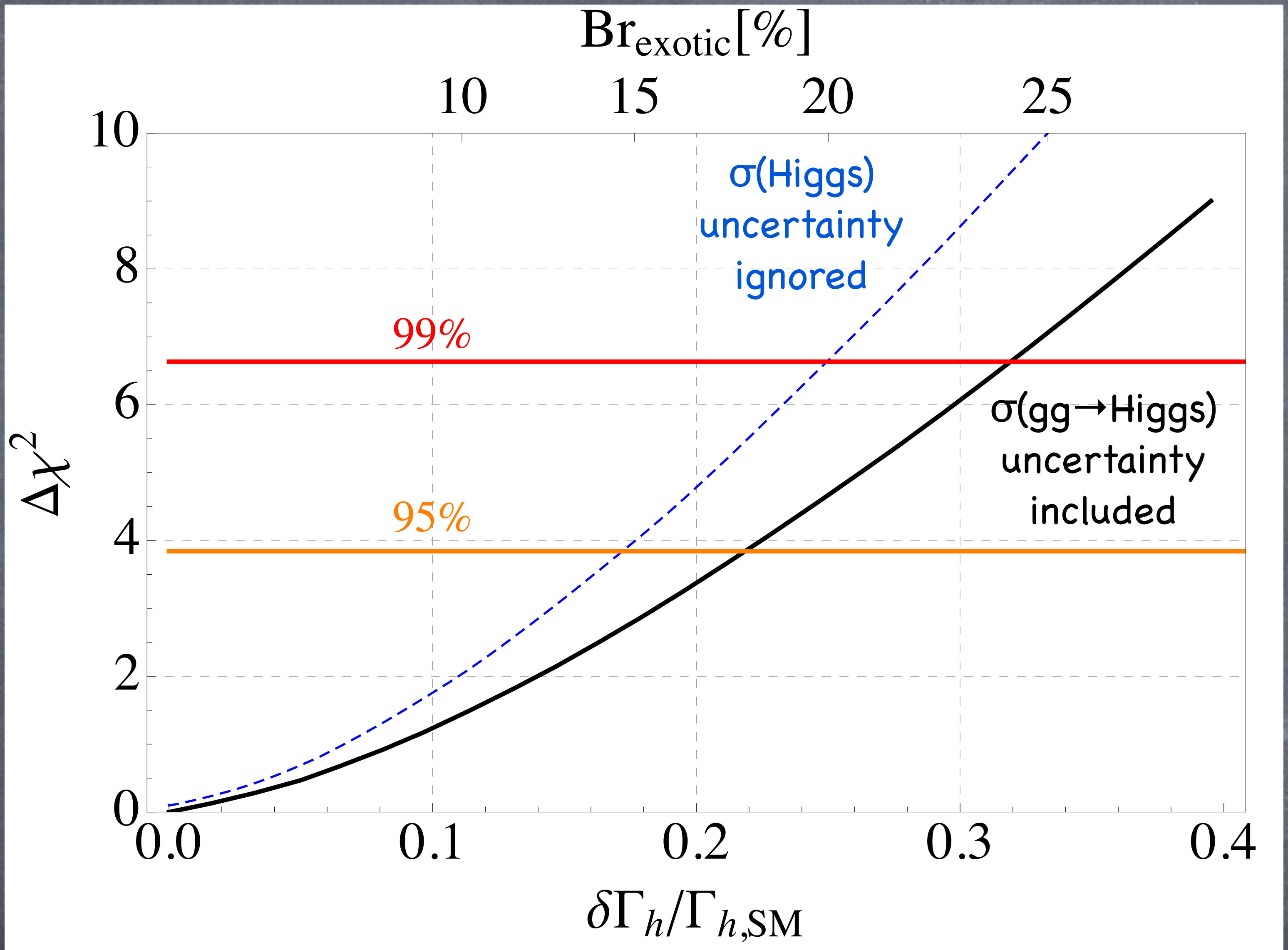
- Higgs is obnoxiously SM-like
- Dimension-6 operators contributing to Higgs couplings suppressed by the scale Λ of order < 1 TeV at most

c.f. with EWPT probing Λ~10 TeV,
or B physics probing Λ~100 TeV,
or Kaon physics probing Λ~10000 TeV

- NP reach will improve in the next LHC run, but not so much in terms of Λ
- However, there is plenty of room for exotic decays not predicted by the SM

Limits on exotic Higgs branching fraction

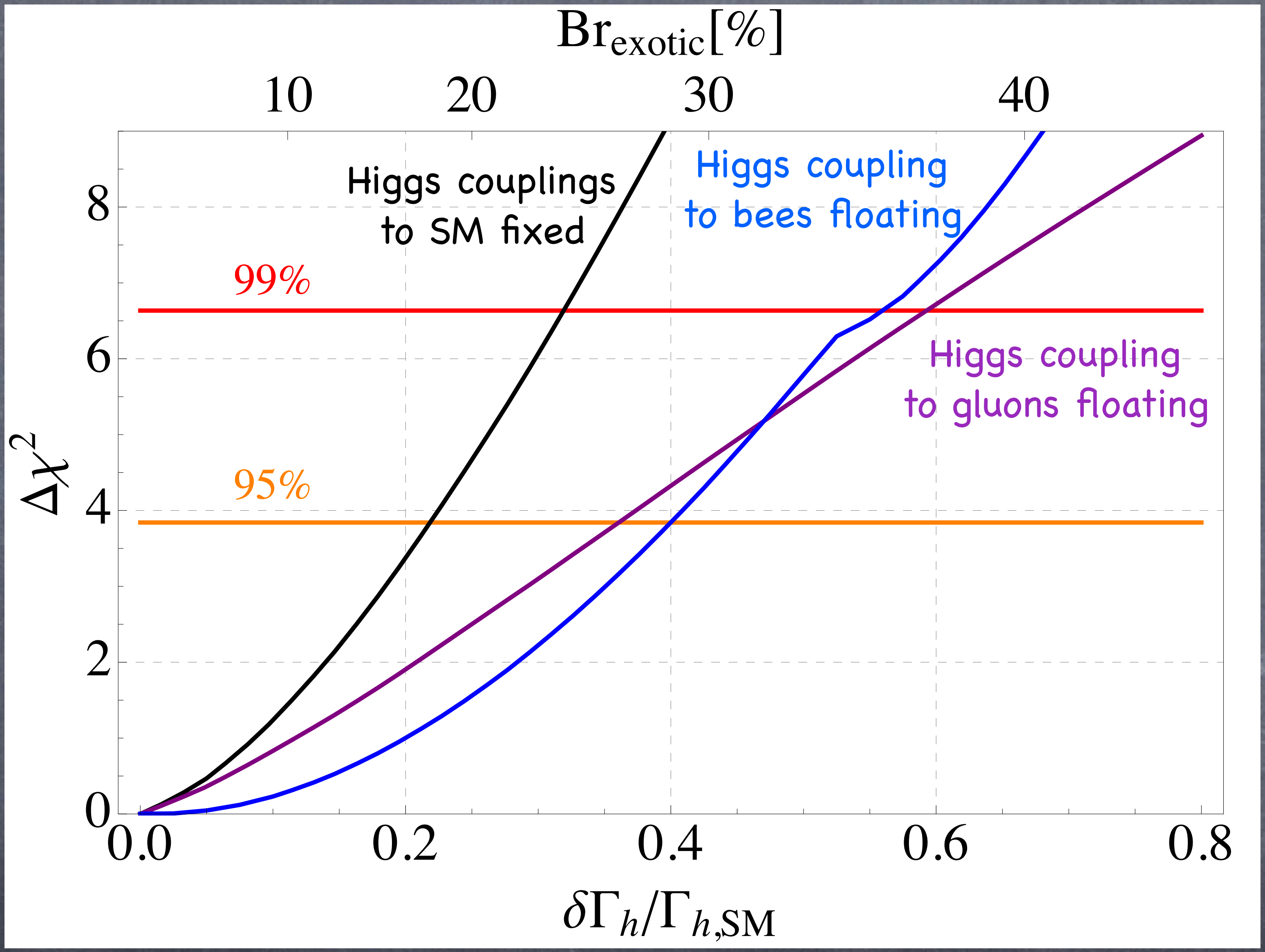
Assuming Higgs couplings to SM fixed



Br(h→exotic) ≲ 18% at 95% CL

Limits on exotic Higgs branching fraction

Allowing some Higgs couplings to SM to float



Br(h→exotic) $\lesssim$ 30% at 95% CL

Constraints on additional width

- If all couplings at SM value, exotic branching fraction larger than 18% disfavored at 95% CL

- Allowing new exotic width and, simultaneously, new contributions to Higgs couplings to SM gives even more wiggle room, typically up to 30% exotic branching fraction

- Direct limit on Higgs width from CMS: $\Gamma < 4.2\ \Gamma_{SM}$ @ 95% CL implying exotic branching fractions up to 80%

Exotic Higgs Decays - Why?

- 18% exotic Higgs branching fraction means that the LHC cross section for exotic Higgs decays could easily be order picobarn
- The SM Higgs width is just 4 MeV, so even weakly coupled new physics can lead to a significant branching fraction for exotic decays. E.g., a new scalar X coupled as c|H|^2 |X|^2 corresponds to BR(h→X*X)=10% BR for c~0.01.
- Thanks to the large Higgs cross section even tiny exotic branching fractions may possibly be probed. For spectacular enough signatures we can probe BR~O(10^-5) now and BR~O(10^-9) in the asymptotic future. [Note that the Higgs was first <u>discovered</u> in the diphoton (BR~10^-3) and 4-lepton (BR~10^-4) channels]

Exotic Higgs Decays

This talk:

AA,Vega-Morales, 1405.1095

- Exotic Higgs decays in the golden channel in the hidden photon model

For much more see the Snowmass review

Curtin et al, 1312.4992

Hidden Photon
in the golden channel

Hidden photon model

- Model with a new light exotic gauge boson decaying to leptons
- Originally motivated by astrophysical anomalies (PAMELA/FERMI/AMS cosmic ray positron excess)
- Now, a popular benchmark model for hidden sector searches

Hidden photon model

Hidden photon X talking to SM vie hypercharge portal

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1-\epsilon^2\cos^{-2}\theta_W}{4}\hat{X}_{\mu\nu}\hat{X}_{\mu\nu} + \frac{1}{2}\hat{m}_X^2\hat{X}_\mu\hat{X}_\mu + \frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}\hat{X}_{\mu\nu}$$

One consequence of mixing: hidden photon couples to matter

$$g_{X,f} = \epsilon\, e\left[Q_f\left(1-\frac{\tan^2\theta_W m_X^2}{m_Z^2-m_X^2}\right)+T_f^3\frac{m_X^2}{\cos^2\theta_W(m_Z^2-m_X^2)}\right].$$

For small mass it mili-couples to electric current
(hence hidden photon)

Another consequence of mixing: hidden photon mixes with Z boson

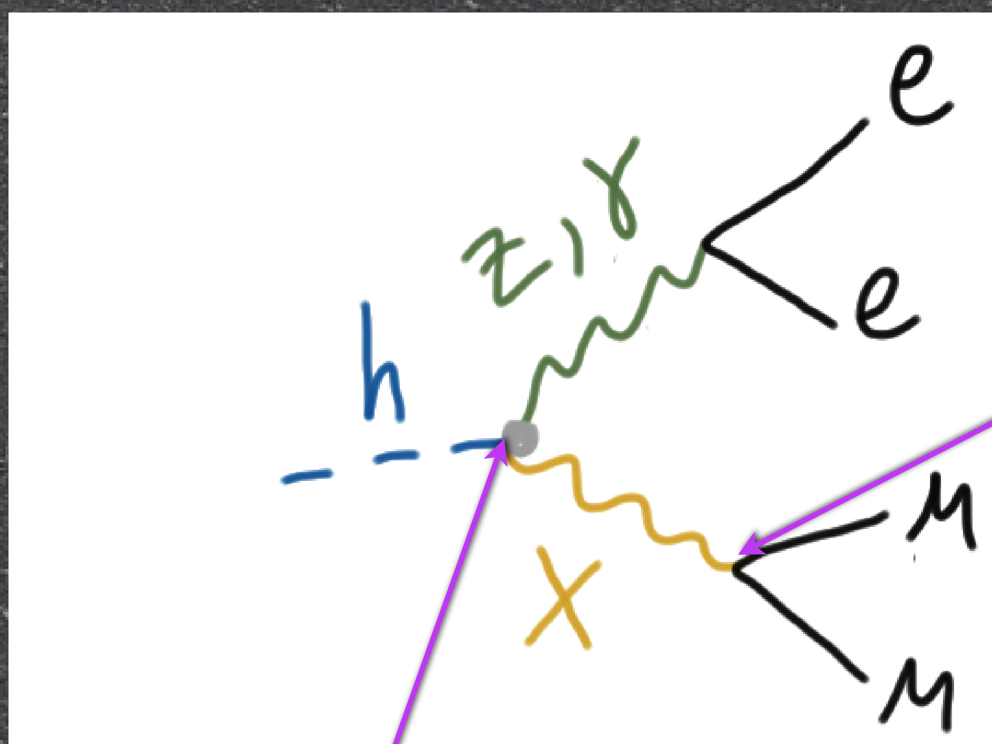
$$\hat{Z}_\mu = \cos\alpha Z_\mu + \sin\alpha X_\mu, \qquad \hat{X}_\mu = -\sin\alpha Z_\mu + \cos\alpha X_\mu, \qquad \alpha \approx \epsilon\tan\theta_W\frac{m_Z^2}{m_Z^2-m_X^2} + \mathcal{O}(\epsilon^2)$$

Therefore it couples to Higgs

$$\mathcal{L}_{hZX} = c_{hZX}\frac{m_Z^2}{v}hZ_\mu X_\mu, \qquad c_{hZX} = \frac{2\epsilon\tan\theta_W m_X^2}{m_Z^2-m_X^2} + \mathcal{O}(\epsilon^2).$$

Hidden photon in the golden channel

Higgs can decay as h → Z X → 4l!



$$g_{X,\ell} X_\mu \bar{\ell} \gamma_\mu \ell$$

$$c_{hZX} \frac{m_Z^2}{v} h Z_\mu X_\mu$$

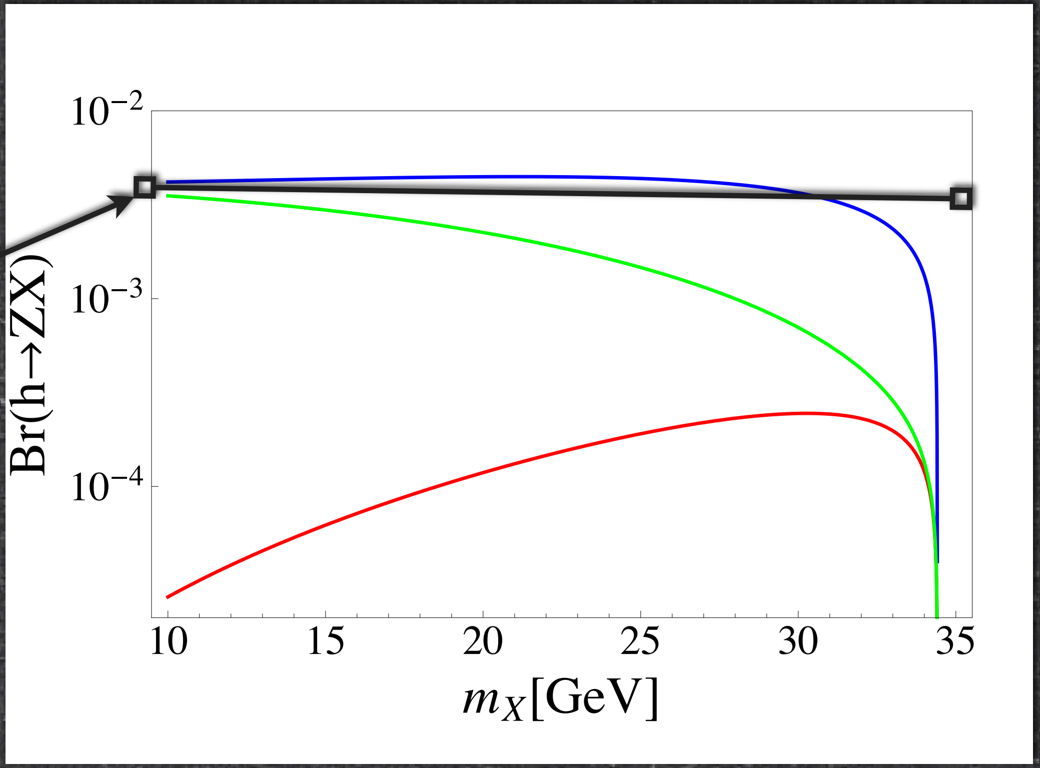
Hidden photon - constraints from 4l

Event count in the h → 4l channel

Channel	4e	2e2μ	4μ	4l
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
m_H = 125 GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
m_H = 126 GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

$$\frac{\Delta\Gamma_{h\to 4\mu}}{\Gamma^{\rm SM}_{h\to 4\mu}} < 0.90, \quad \frac{\Delta\Gamma_{h\to 2e2\mu}}{\Gamma^{\rm SM}_{h\to 2e2\mu}} < 0.83, \quad \frac{\Delta\Gamma_{h\to 4e}}{\Gamma^{\rm SM}_{h\to 4e}} < 1.27,$$

$$\frac{\Delta\Gamma_{h\to 4\ell}}{\Gamma^{\rm SM}_{h\to 4\ell}} < 0.52.$$



Hidden photon in the golden channel

Kinetic mixing with hidden photon affects Z mass and Z couplings to matter

$$m_Z^2 = \hat{m}_Z^2 + \epsilon^2 \frac{\tan^2\theta_W \hat{m}_Z^4}{m_Z^2 - \hat{m}_X^2} + \mathcal{O}(\epsilon^3),$$

$$g_{Z,f} = \hat{g}_{Z,f}\left(1 - \epsilon^2 \frac{\tan^2\theta_W m_Z^4}{(m_Z^2 - m_X^2)^2}\right) - \epsilon^2 \sqrt{g_L^2 + g_Y^2}\,\frac{\tan^2\theta_W m_Z^2}{m_Z^2 - m_X^2} Y_f,$$

Fitting to LEP-1 and W mass data

$$|\epsilon| \lesssim 0.024\,\sqrt{1 - \frac{m_X^2}{m_Z^2}} \qquad \text{at } 95\% \text{ C.L.},$$

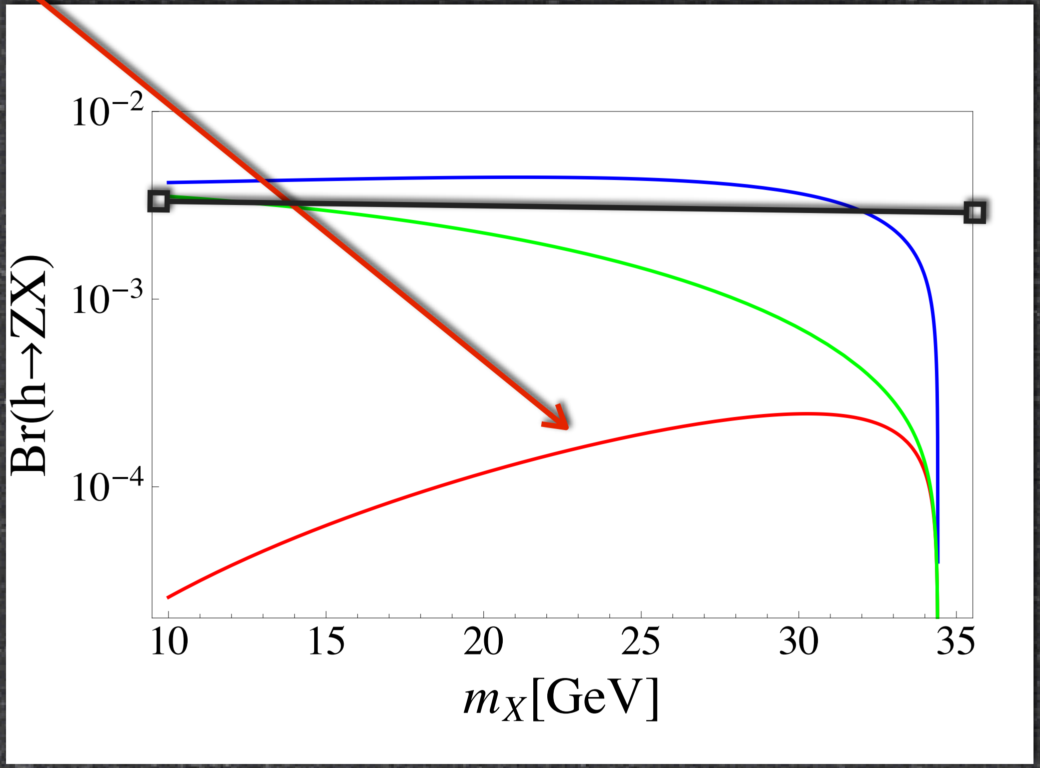
Hidden photon in the golden channel

Electroweak Precision Observables imply

$$|\epsilon| \lesssim 0.024 \sqrt{1 - \frac{m_X^2}{m_Z^2}} \qquad \text{at } 95\% \text{ C.L.},$$

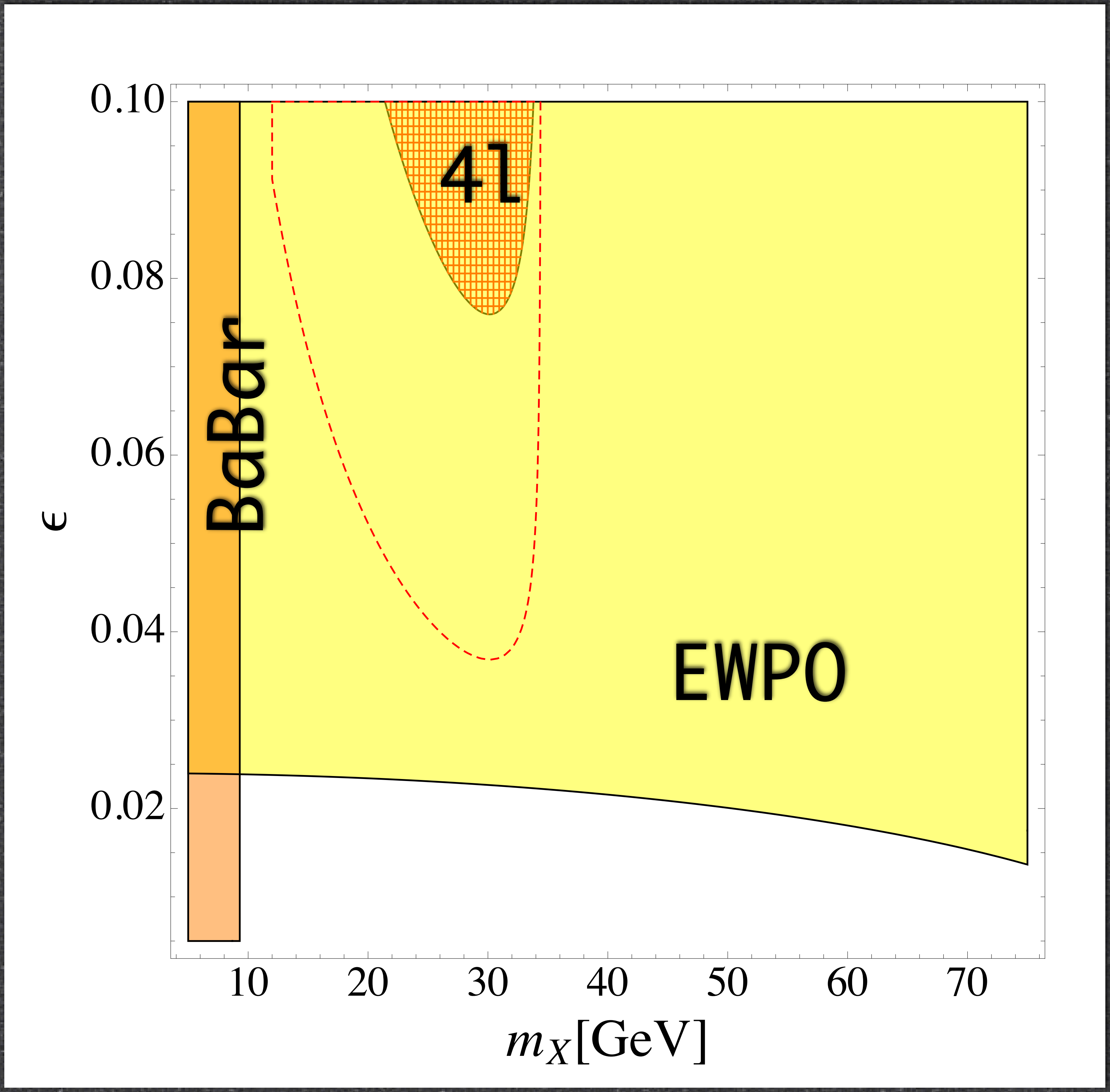
for 10 GeV < mX < mZ, and stronger bounds below from B-factories

Follows the bound on branching fraction h → Z X



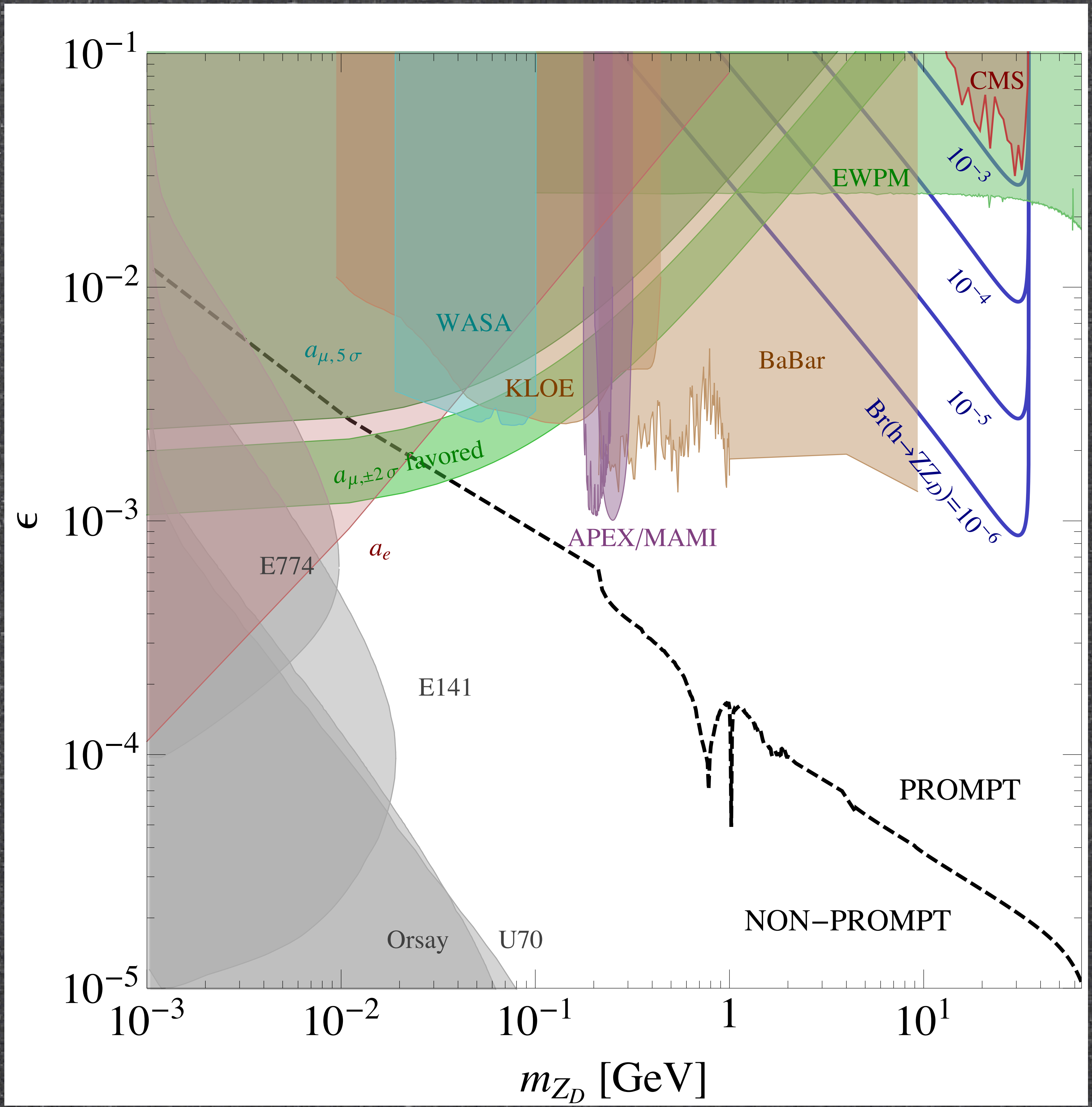
Hidden photon - constraints from 4l

Parameter Space



Hidden photon - constraints from 4l

Larger Parameter Space



Curtin et al, 1312.4992

Hidden photon in the golden channel

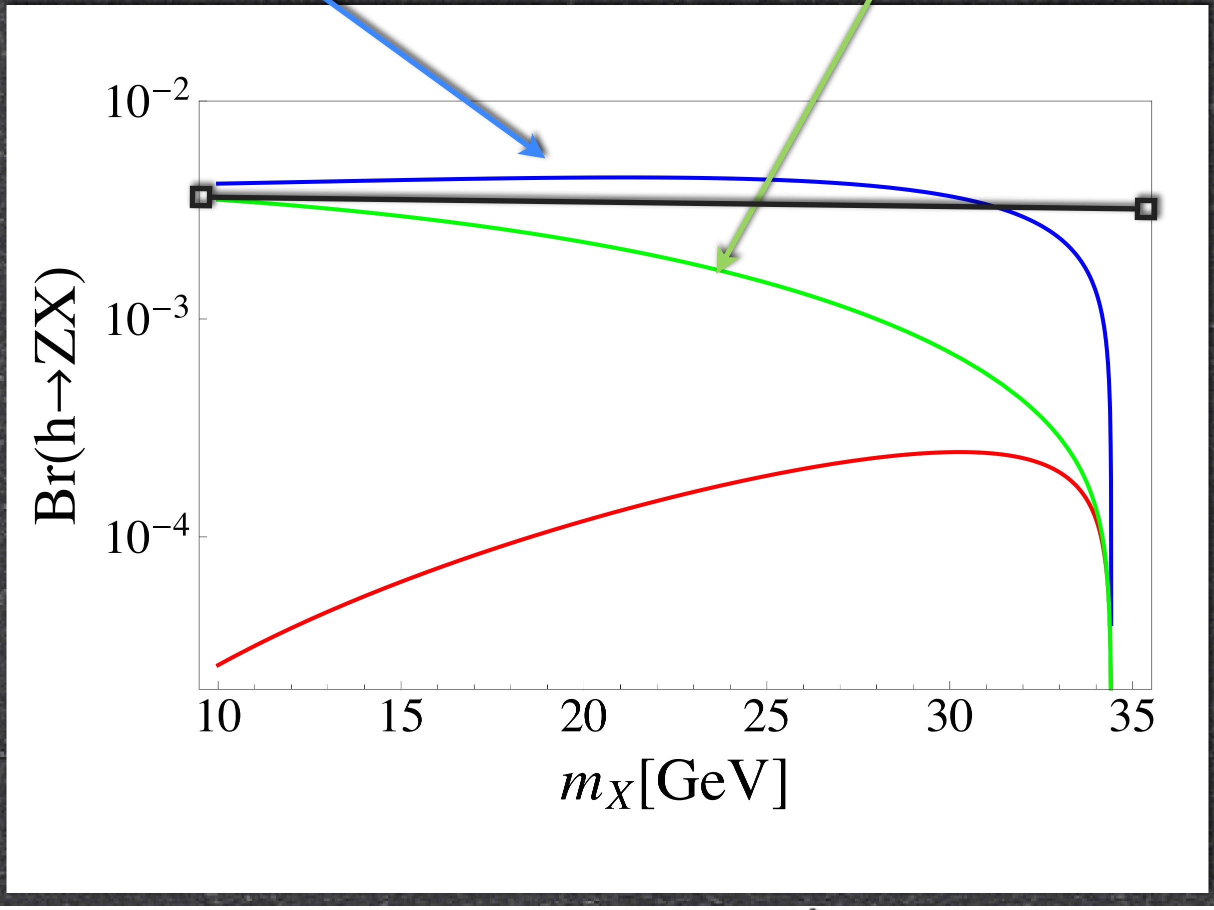
Simple modification of hidden photon model

$$\Delta\mathcal{L} = \frac{\epsilon_2}{\cos\theta_W}\left(\frac{|H|^2}{v^2} - \frac{1}{2}\right) B_{\mu\nu}\hat{X}_{\mu\nu} + \frac{\epsilon_3}{\cos\theta_W}\frac{|H|^2}{v^2}\tilde{B}_{\mu\nu}\hat{X}_{\mu\nu},$$

$\varepsilon_2 = 0.02$

$\varepsilon_3 = 0.02$

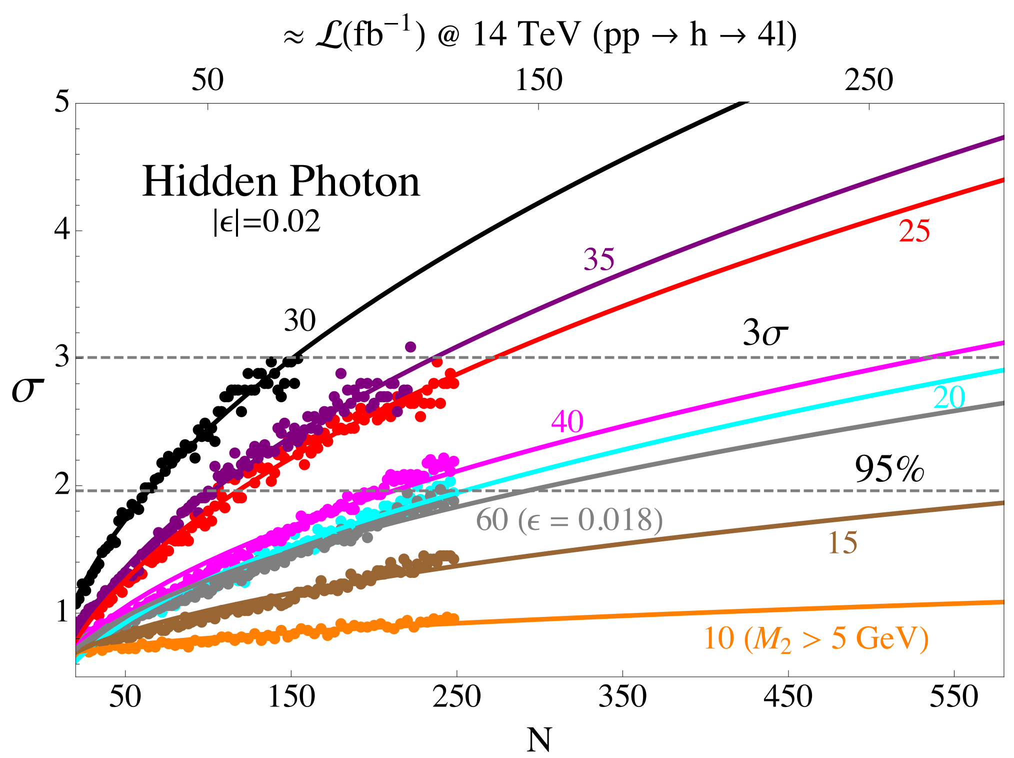
Larger branching fractions for h→ZX now allowed

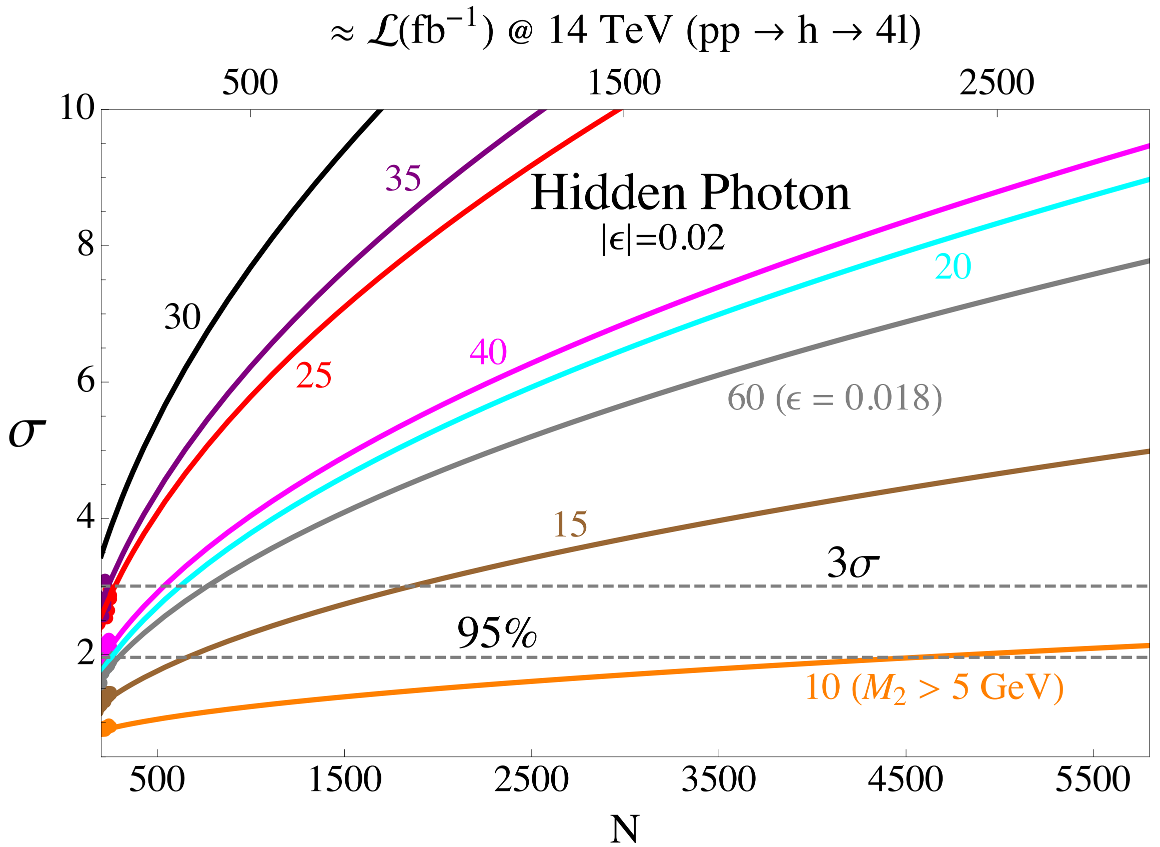


$$\Delta\mathcal{L}_{hXZ} = -\tan\theta_W X_{\mu\nu}\left(\epsilon_2 Z_{\mu\nu} + \epsilon_3\tilde{Z}_{\mu\nu}\right)$$

$$\Delta\mathcal{L}_{hX\gamma} = X_{\mu\nu}\left(\epsilon_2 A_{\mu\nu} + \epsilon_3\tilde{A}_{\mu\nu}\right)$$

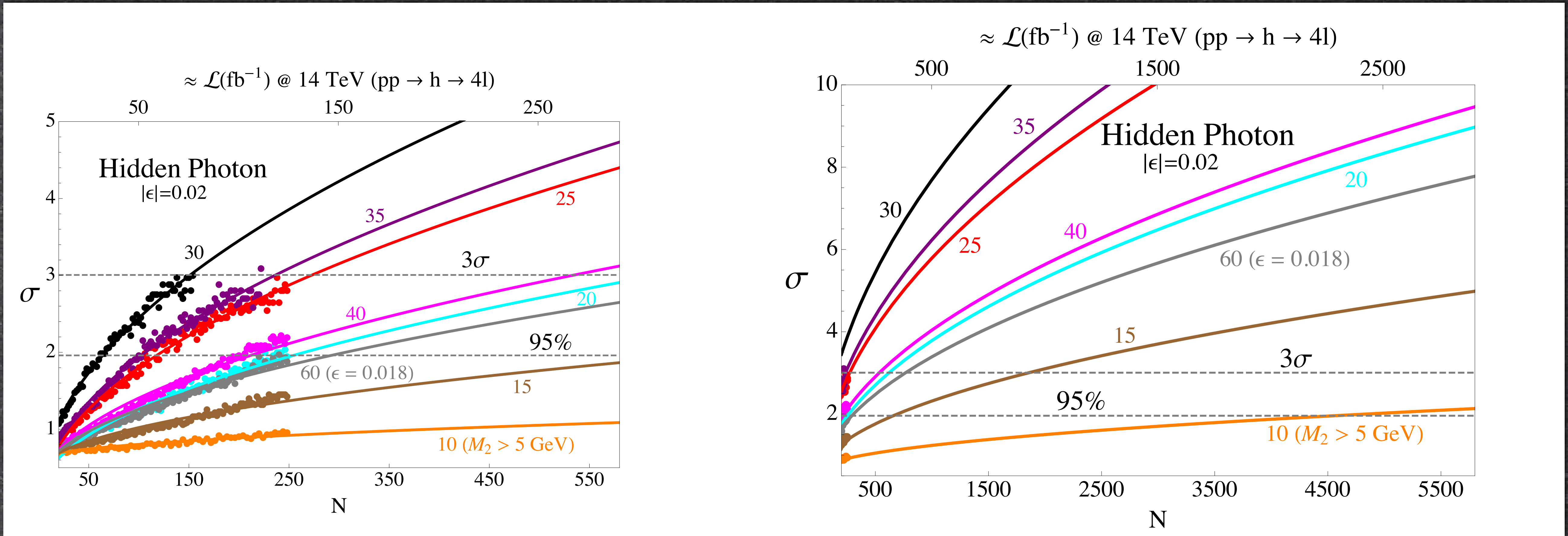
Hidden photon in the golden channel





m_X	ϵ	ϵ_2	ϵ_3	R
10	0.02	0	0	1.004
15	0.02	0	0	1.006
20	0.02	0	0	1.019
25	0.02	0	0	1.031
30	0.02	0	0	1.039
35	0.02	0	0	1.019
40	0.02	0	0	1.019
50	0.02	0	0	1.016
60	0.018	0	0	1.014

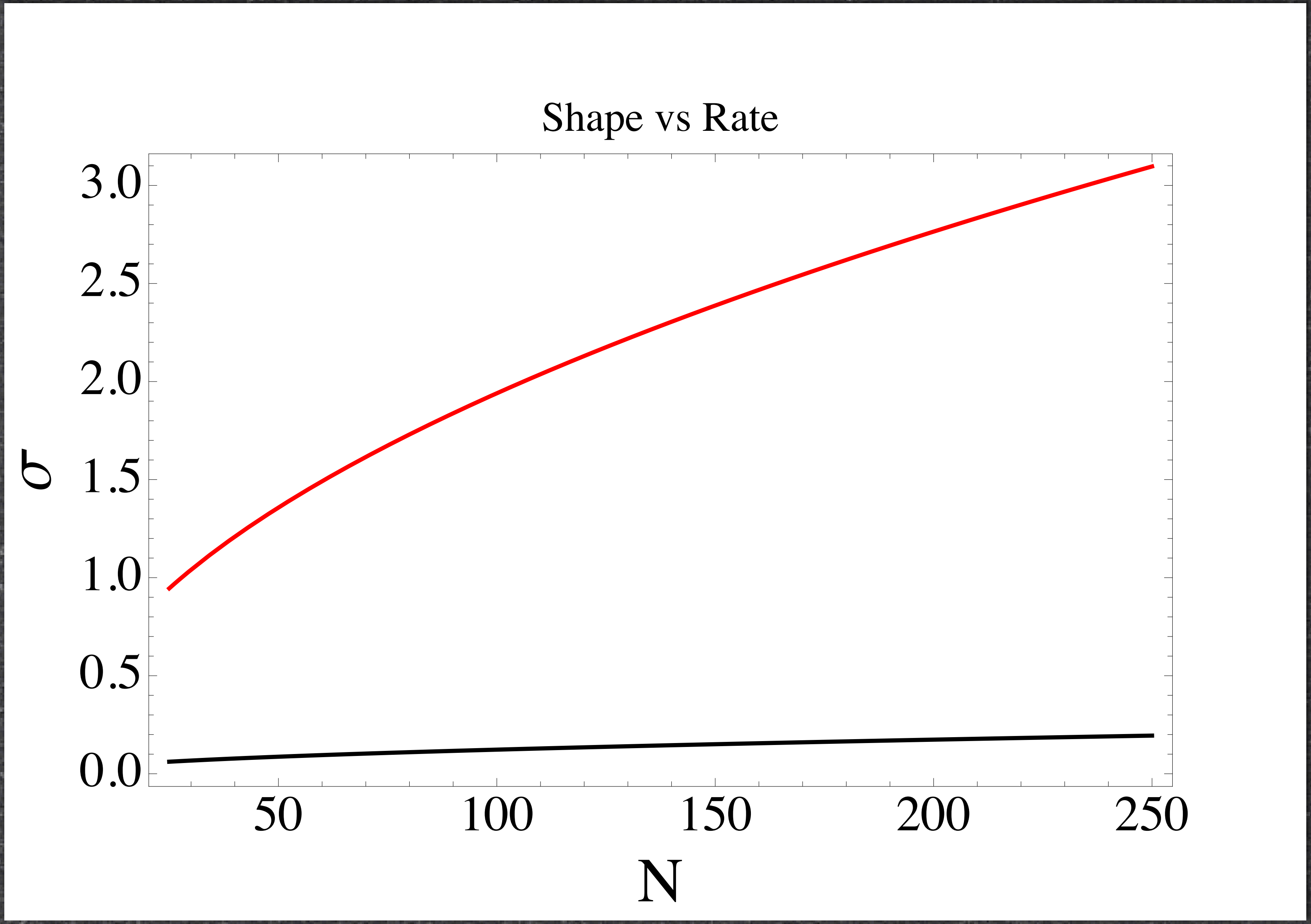
Hidden photon in the golden channel



- For mX close to 15-65 GeV vanilla model probed in LHC run-2
- Exclusion reach down to 10 GeV in high-luminosity LHC

Hidden photon in the golden channel

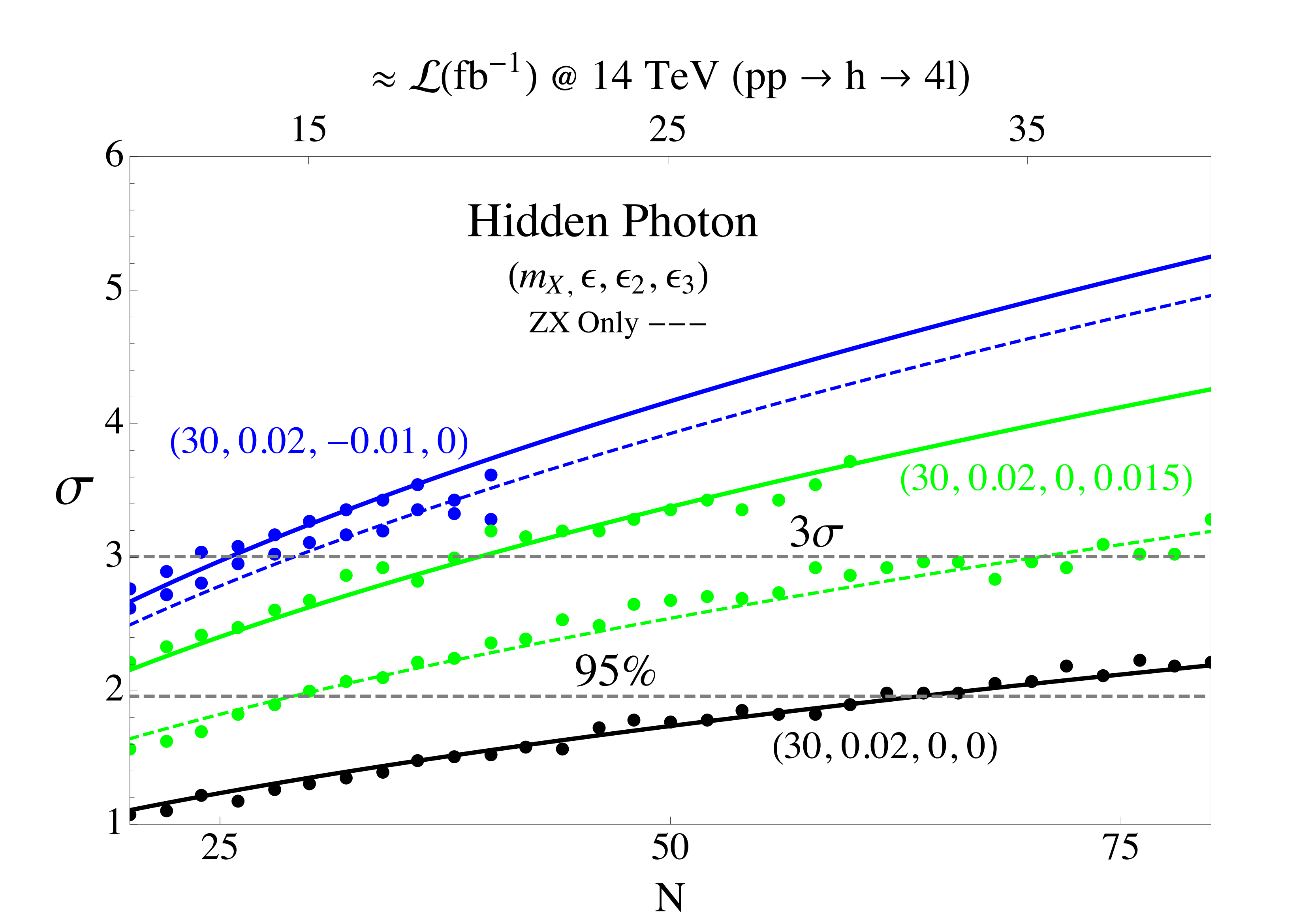
Practically all discrimination power from shape analysis



$\varepsilon = 0.02$

$m_X = 30$ GeV

Hidden photon in the golden channel

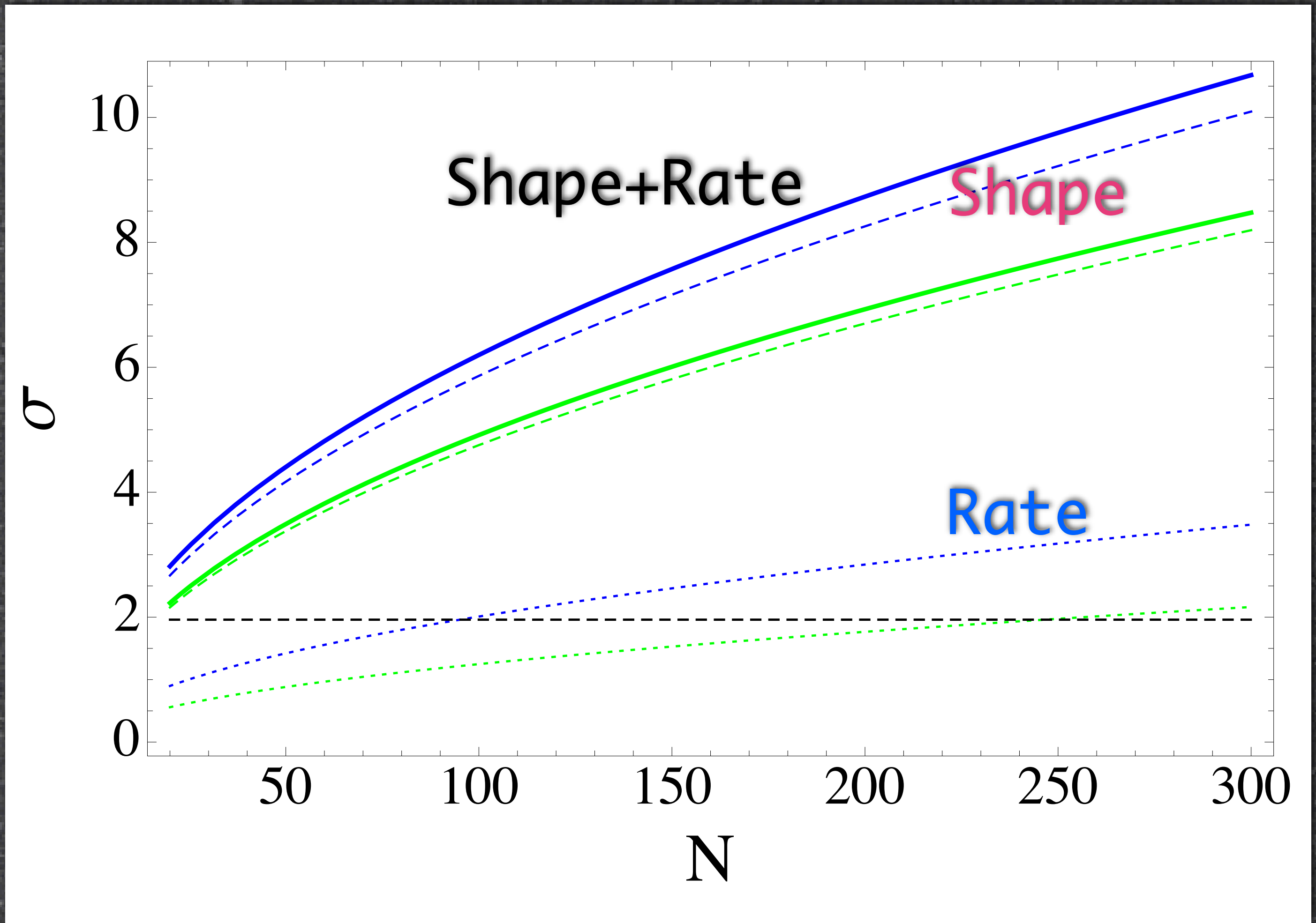


- Modified hidden photon model already being probed

$$\Delta\mathcal{L} = \frac{\epsilon_2}{\cos\theta_W}\left(\frac{|H|^2}{v^2} - \frac{1}{2}\right) B_{\mu\nu}\hat{X}_{\mu\nu} + \frac{\epsilon_3}{\cos\theta_W}\frac{|H|^2}{v^2}\tilde{B}_{\mu\nu}\hat{X}_{\mu\nu},$$

Hidden photon in the golden channel

Still better discrimination power from shape than rate



m_X	ϵ	ϵ_2	ϵ_3	R
10	0.02	0	0	1.004
15	0.02	0	0	1.006
20	0.02	0	0	1.019
25	0.02	0	0	1.031
30	0.02	0	0	1.039
30	0.02	0.01	0	1.33
30	0.02	0	0.015	1.20
35	0.02	0	0	1.019
40	0.02	0	0	1.019
50	0.02	0	0	1.016
60	0.018	0	0	1.014

Summary part 1

- Exotic Higgs decays may be the portal to new physics
- Large exotic decay rates readily possible if there exists a light BSM degree of freedom coupled to Higgs
- Exotic decays could show up in standard Higgs analyses, e.g. in the golden channel

New CP violating observables in Higgs decays

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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.

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

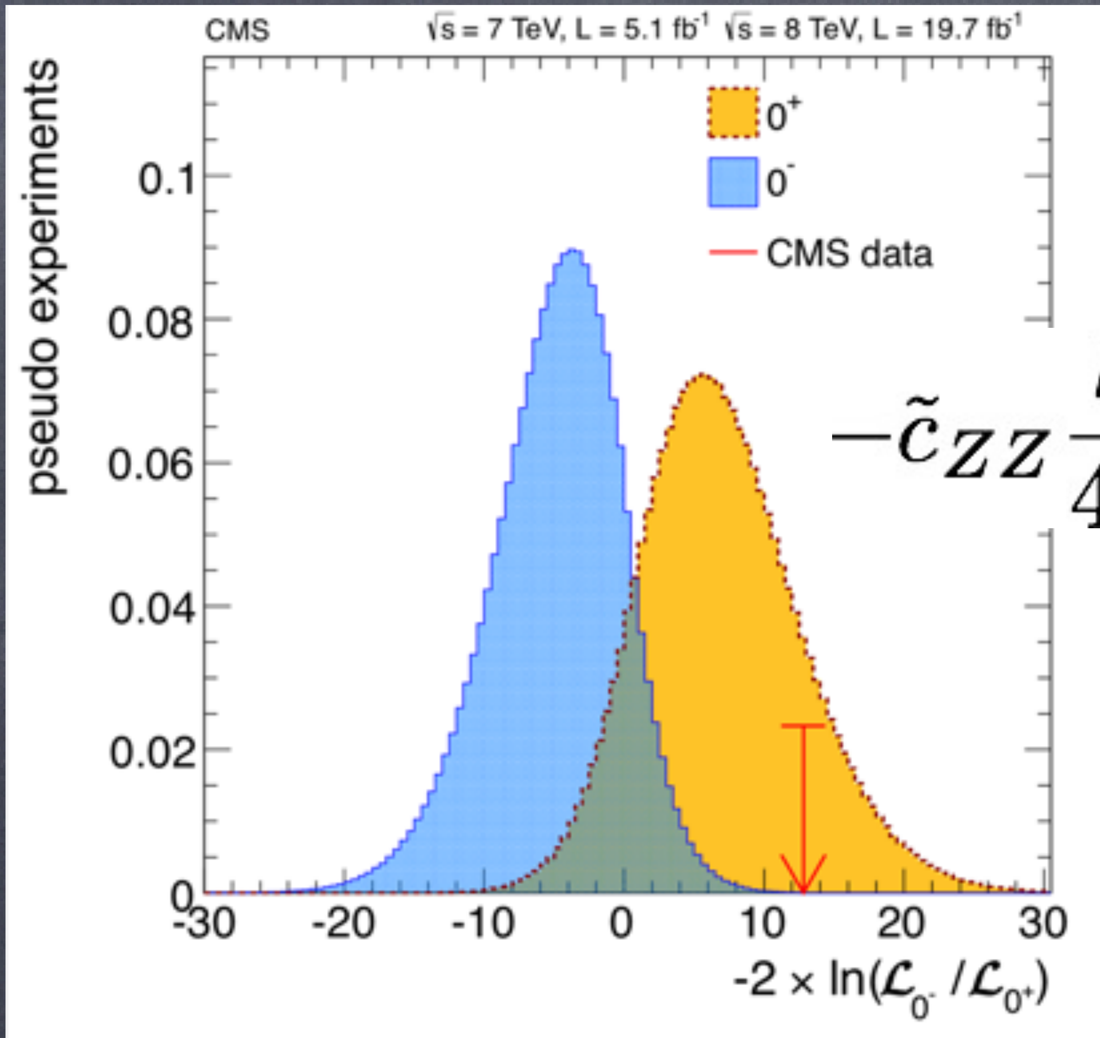
$$\mathcal{L}_{\rm CPV} \supset -\frac{h}{4v}\epsilon^{\mu\nu\rho\sigma}\left[\tilde{c}_{\gamma\gamma}\partial_\mu A_\nu \partial_\rho A_\sigma + 2\tilde{c}_{Z\gamma}\partial_\mu Z_\nu \partial_\rho A_\sigma + \tilde{c}_{ZZ}\partial_\mu Z_\nu \partial_\rho Z_\sigma\right]$$

- 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

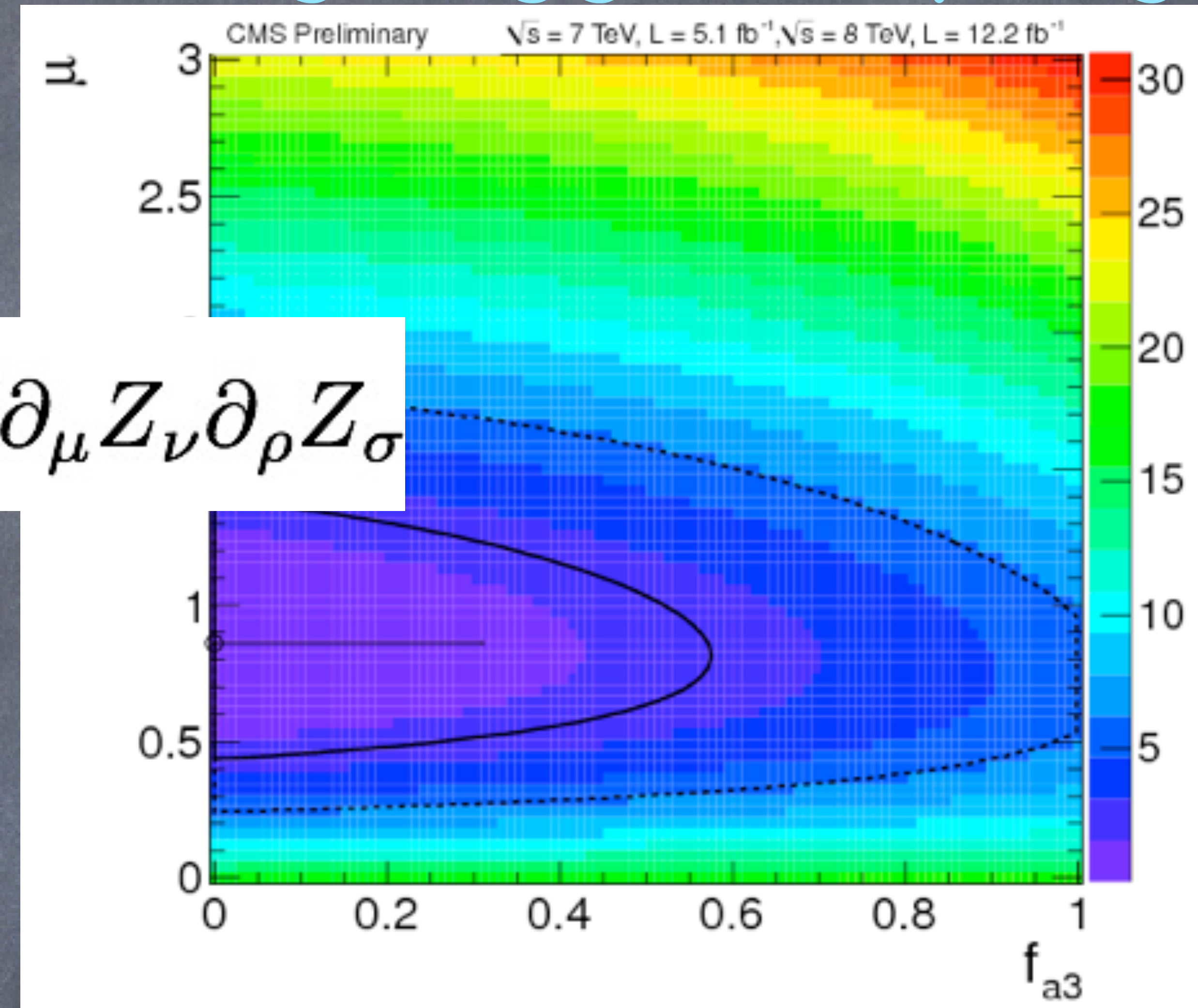
see e.g. Belusca-Maito 1404.5343

- 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



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

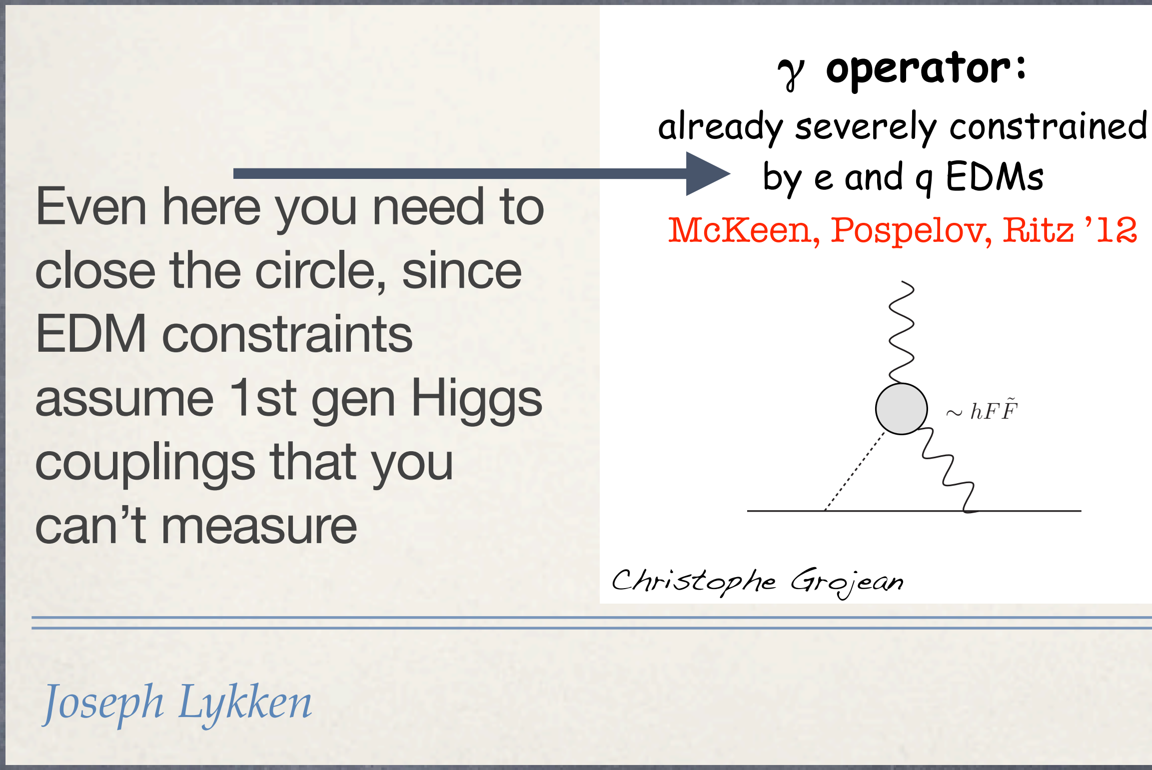


- Only tells that pure SM coupling to ZZ preferred over pure CP violating coupling to ZZ
- Useless at this point

- 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



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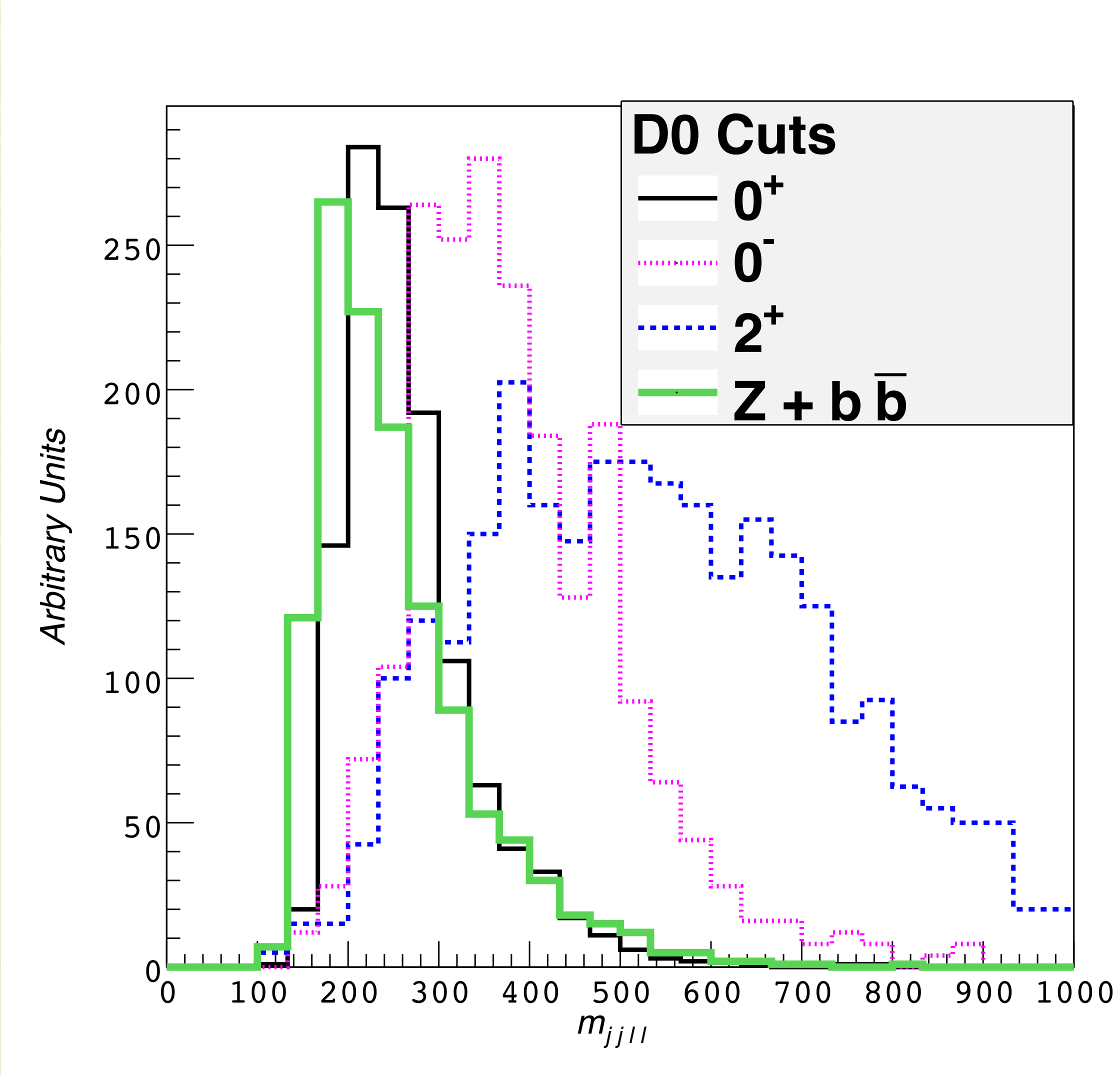

Ellis, Hwang, VS, You. 1208.6002

How to search for CP violating Higgs couplings

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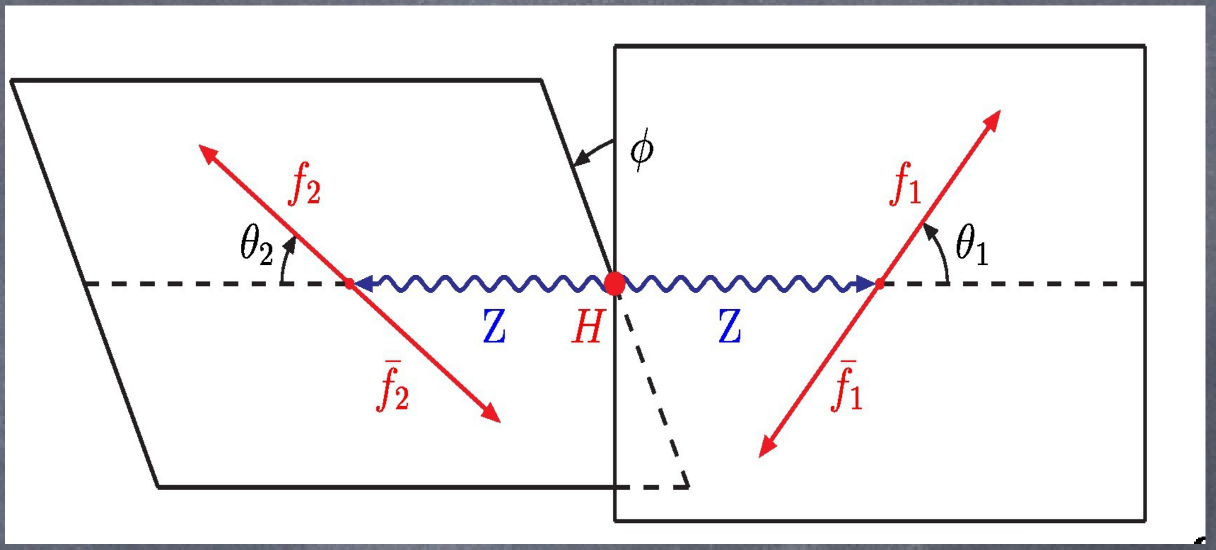
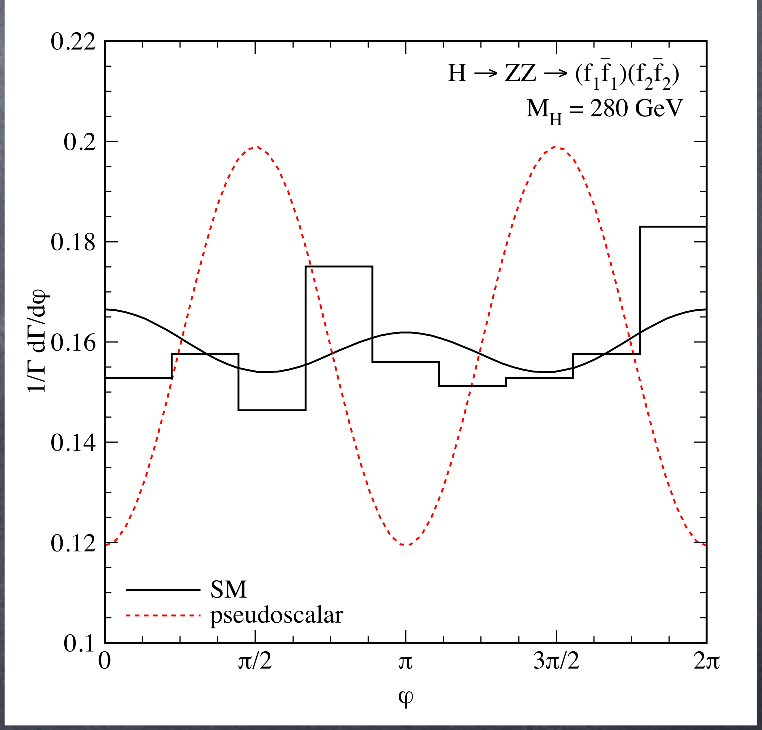




Miller et al.
hep-ph/0210077

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

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

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

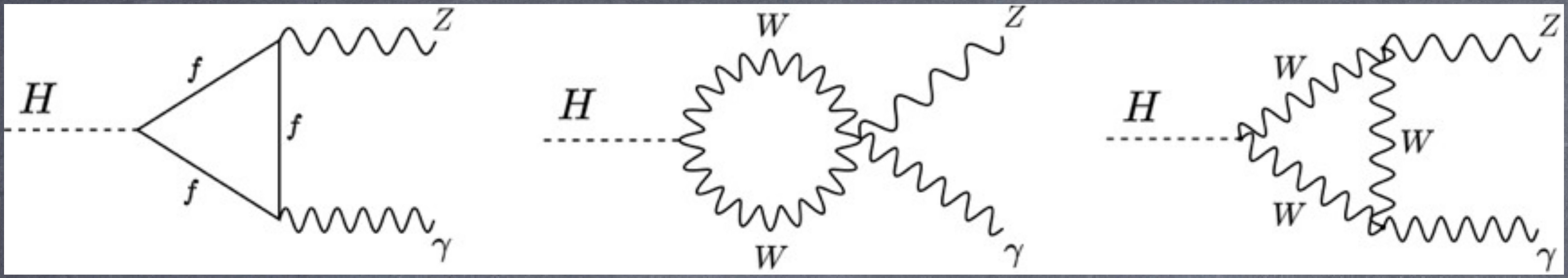
- In absence of strong phases, one needs to resort to triple product asymmetries, which require 4 visible momenta in final state

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

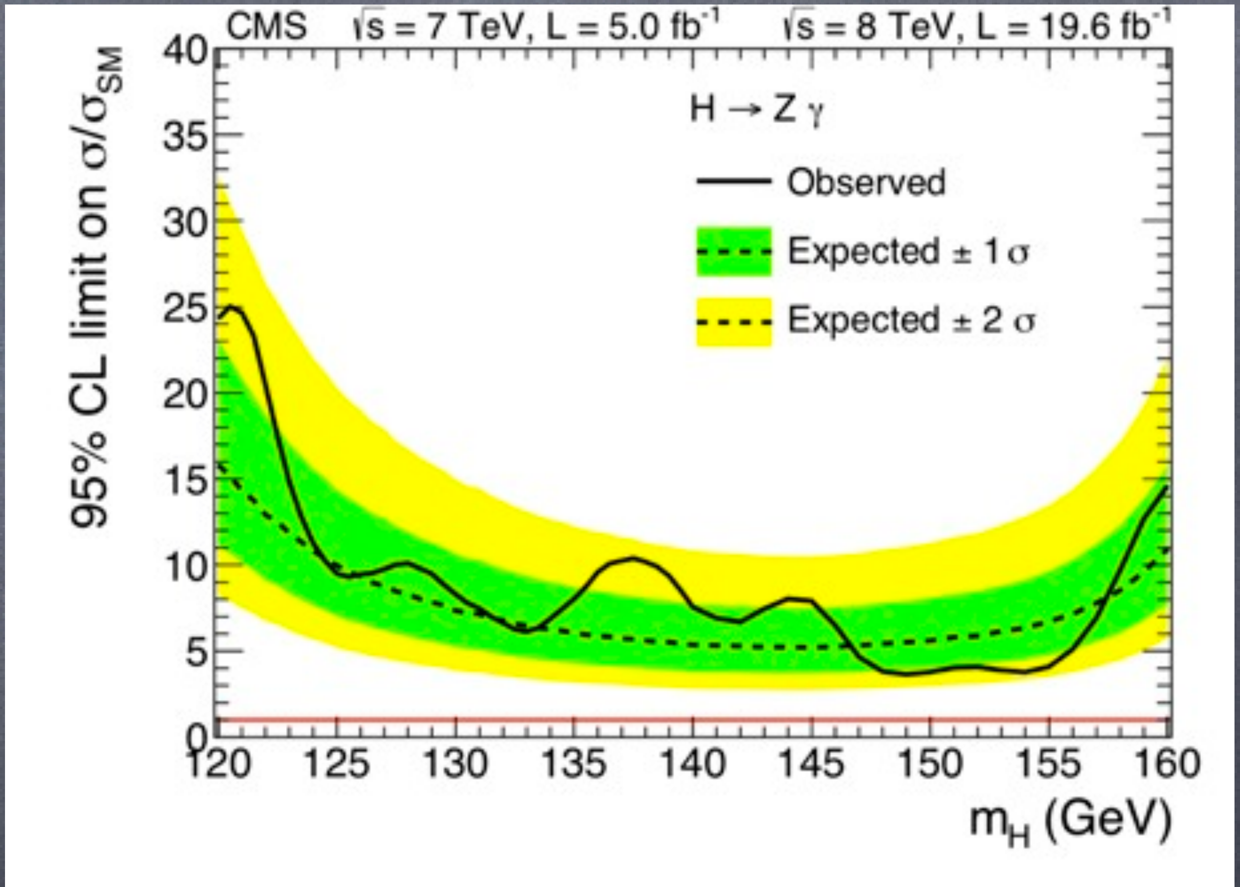
CP violation in 3-body Higgs decays

- 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



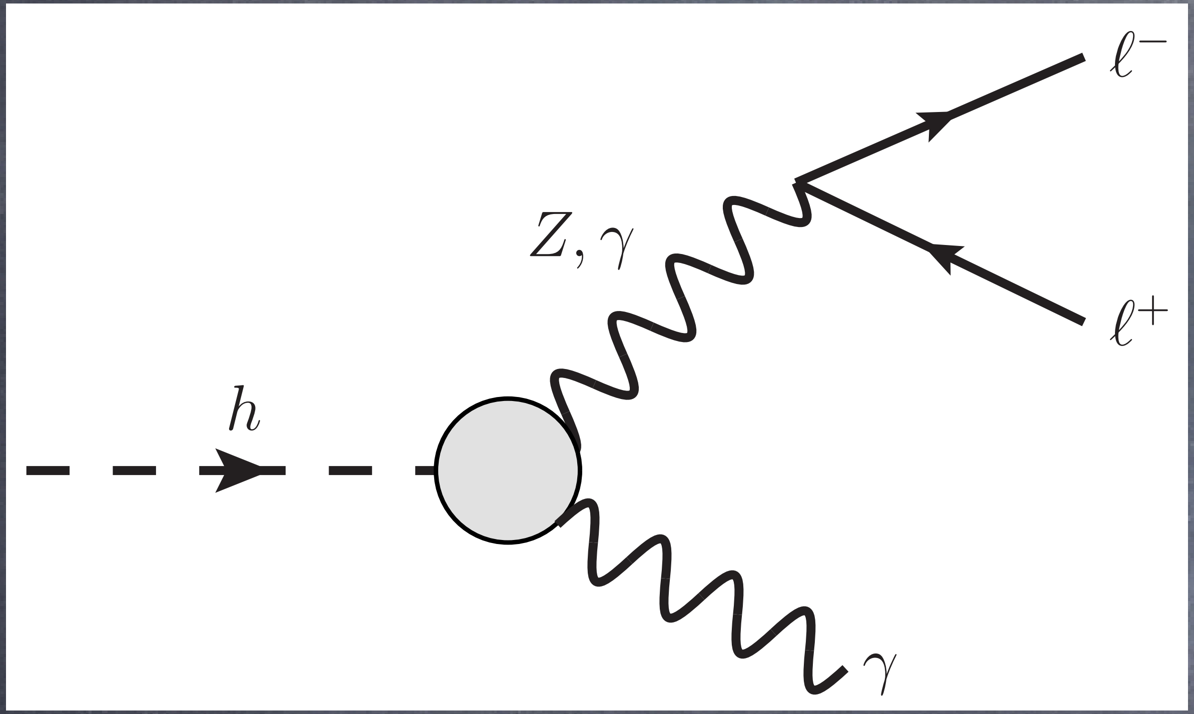
- In SM, loop level decays with branching fraction 0.16%
- Current limits order of magnitude larger
- Room for large CP violating Higgs coupling to Zγ from BSM

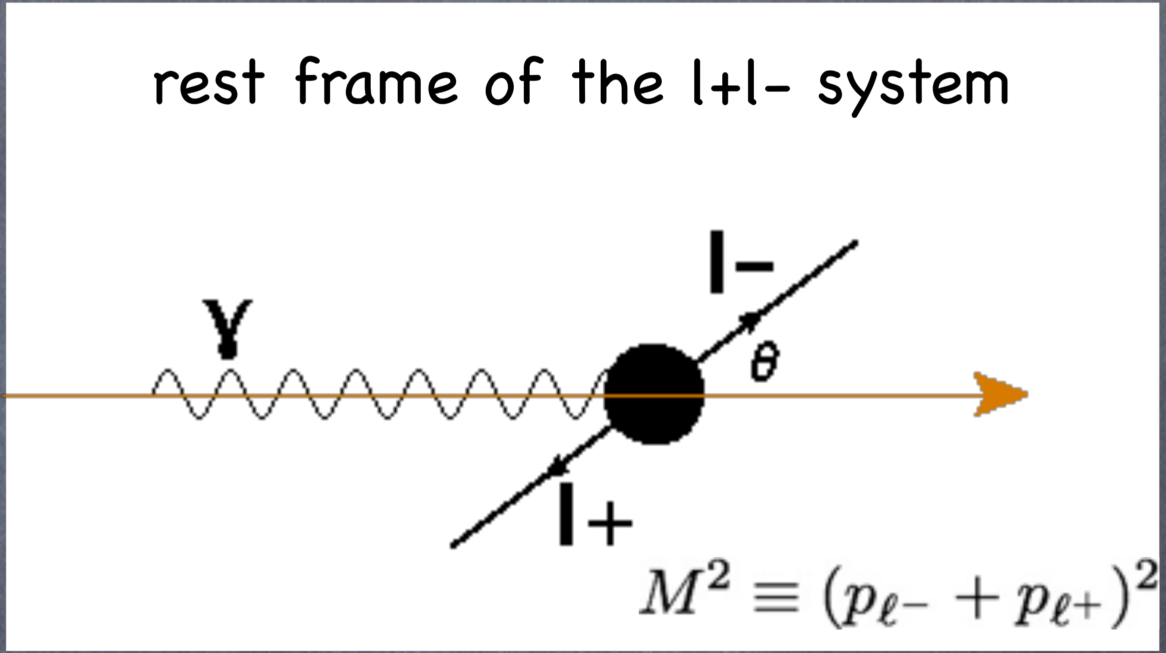


Higgs decays to Zγ in BSM

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

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





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

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

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

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

CP violation in h→l-l+γ decays

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

C: θ→π-θ

CP: θ→π-θ

P

CP: θ→π-θ

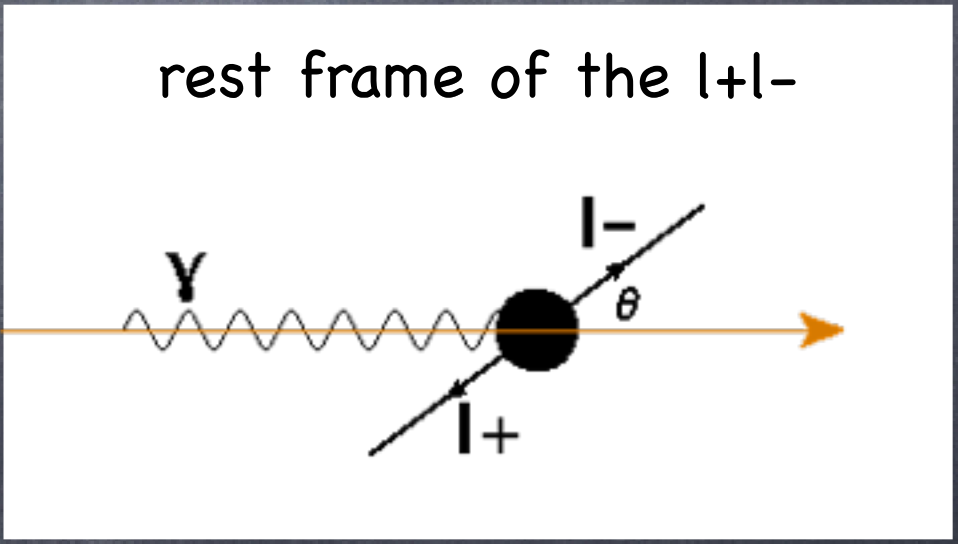
$$L_{-1} = \mathcal{M}(-1,-1/2,-1/2) \quad \overset{C}{\longleftrightarrow} \quad R_{-1} = \mathcal{M}(-1,+1/2,+1/2)$$

C: 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 ⇒

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



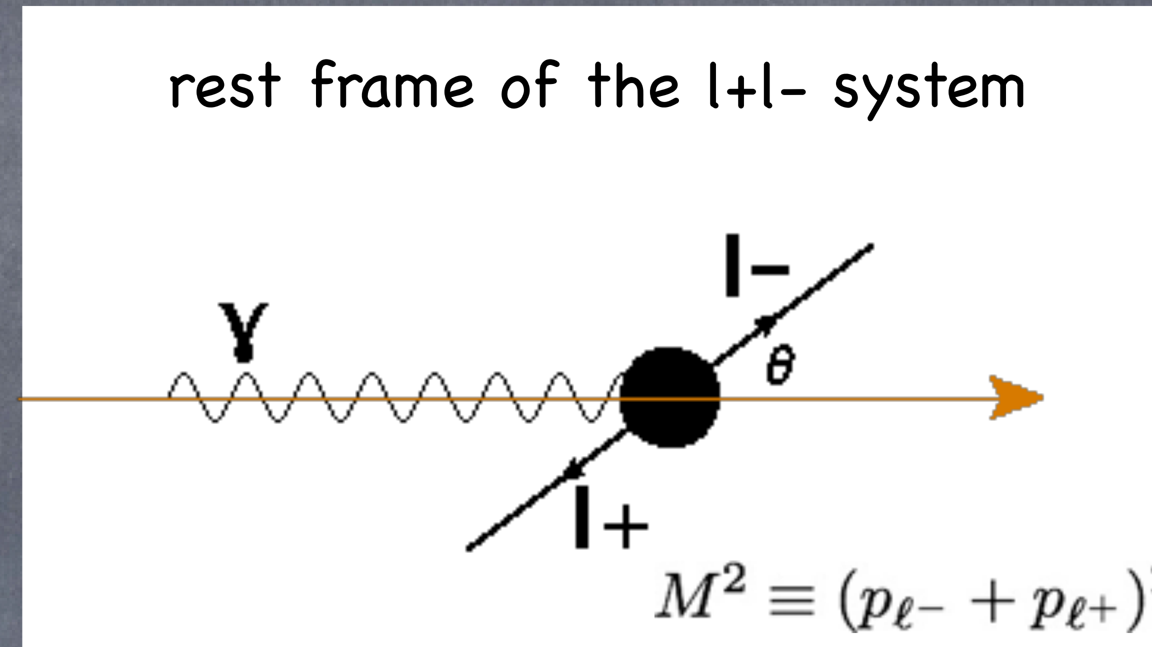
$$d\Gamma \sim |L_{+1}(\cos\theta)|^2 + |L_{+1}(-\cos\theta)|^2 + |R_{+1}(\cos\theta)|^2 + |R_{+1}(-\cos\theta)|^2$$

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

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

C

θ→π-θ

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

CP θ→π-θ

P

θ→π-θ CP

C

θ→π-θ

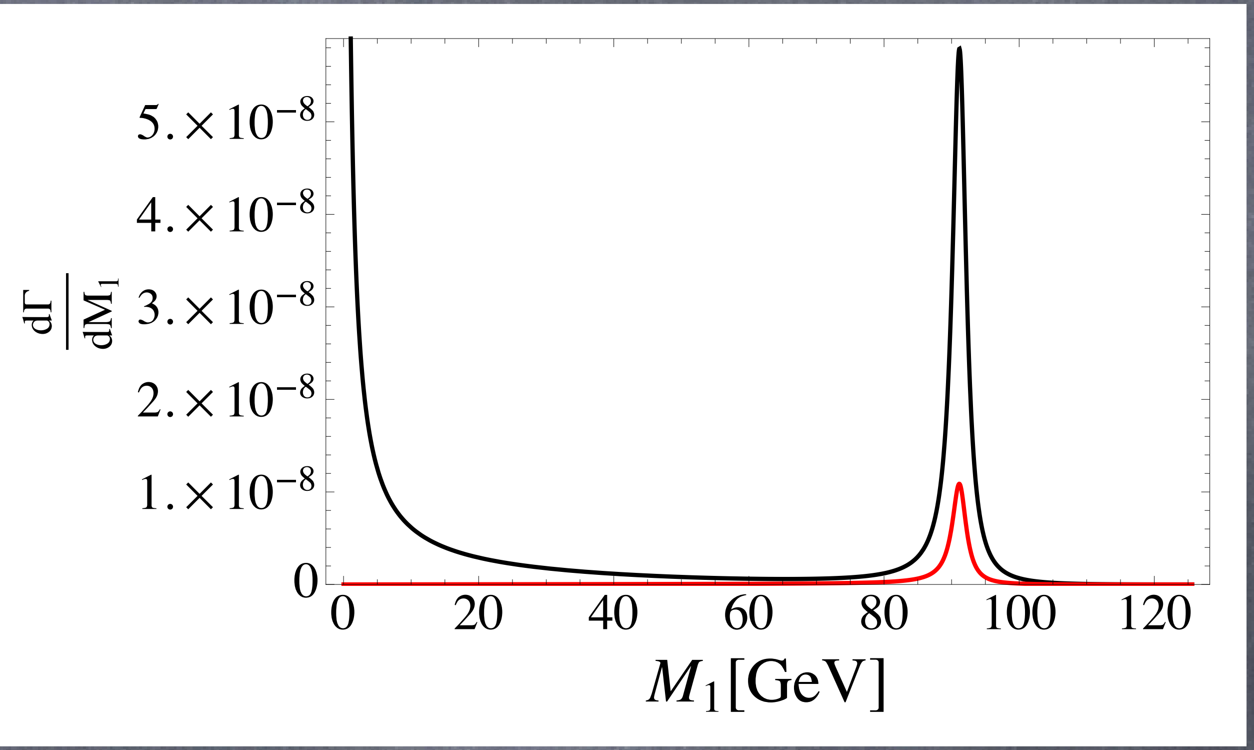
$$L^V_{-1}=g_{V,L}\frac{(1-\cos\theta)(c_{V\gamma}-i\tilde{c}_{V\gamma})M(m_h^2-M^2)}{2\sqrt{2}v(M^2-m_V^2+im_V\Gamma_V)}$$

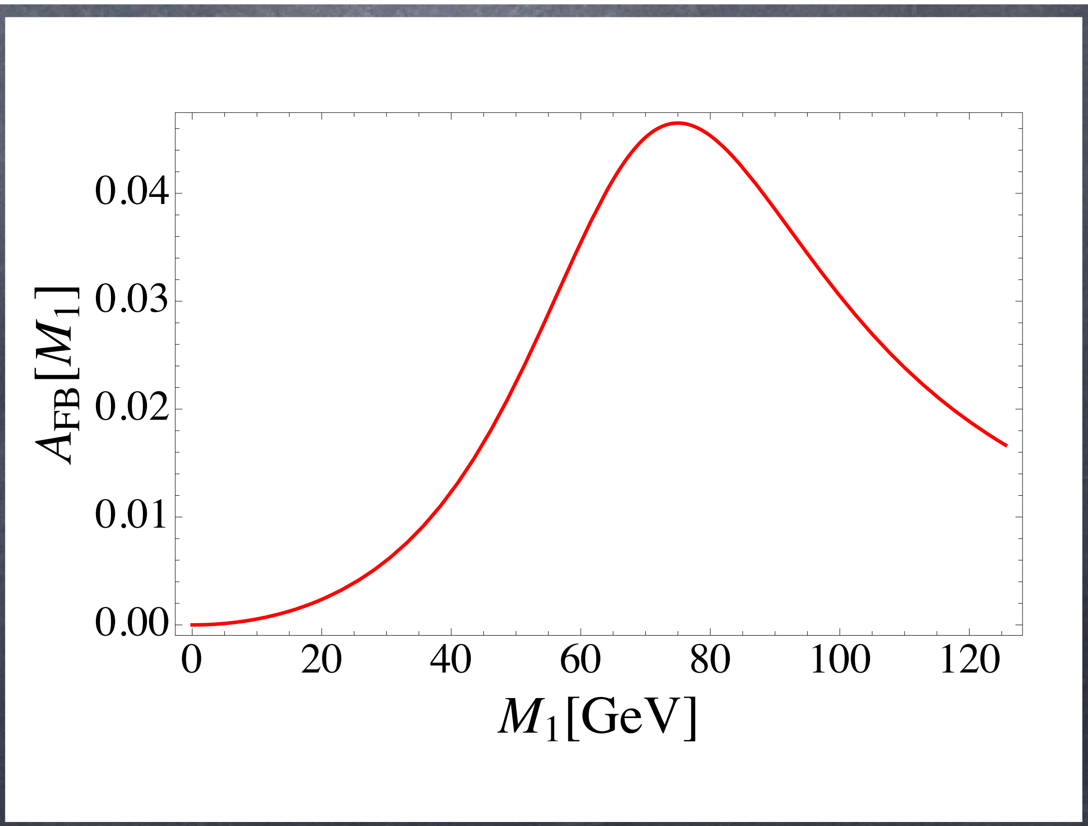
$$R^V_{-1}=g_{V,R}\frac{(1+\cos\theta)(c_{V\gamma}-i\tilde{c}_{V\gamma})M(m_h^2-M^2)}{2\sqrt{2}v(M^2-m_V^2+im_V\Gamma_V)}$$

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

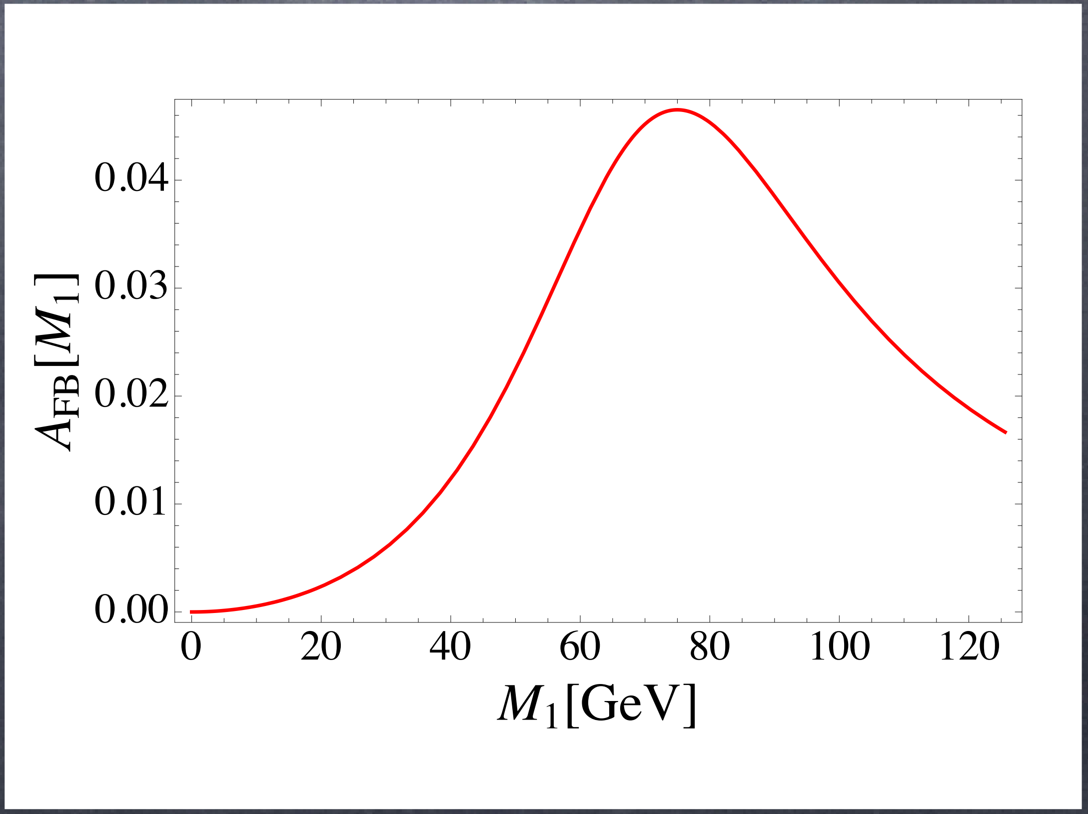
- Integrated asymmetry suppressed by Γz/mZ, but otherwise no parametric suppression

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

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

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

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



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

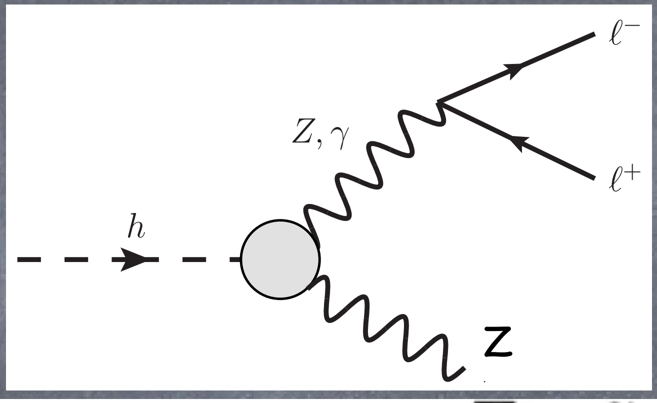
- $h \to Z\gamma$ with leptonic Z decay routinely searched for
- For CP violation, one has to fight not only symmetric Higgs background, but also symmetric non-Higgs SM background
- Standard cut-based analysis in $h \to Z\gamma$ channel has signal to background of order 1/100. Then sensitivity estimated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

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

Better signal to background using matrix element methods implies better sensitivity

Chen, Vega-Morales; work in progress

Related CP violating Higgs processes



- h→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+→ 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+→ h γ: large asymmetry but small rate

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

Summary of part 2

- 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