Constraining anomalous Higgs boson couplings to virtual photons.

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Based on work in arxiv:2109.13363

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JHUGen Framework

See Talks: [H. Roskes at LHC EFT WG](#) [H. Roskes at Pheno 2020](#) [M. Xiao at ICHEP 2020](#) [U. Sarica at Higgs 2020](#) [A. Gritsan at LHC Higgs WG](#) [M. Schulze at LHC Higgs WG](#)

JHUGenerator https://spin.pha.jhu.edu/

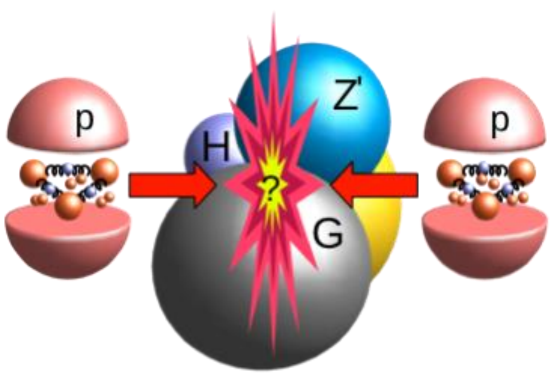
- Simulate wide range of processes involving spin 0,1,2 particles with a general coupling model

JHUGen MELA – Matrix Element Likelihood Approach

- Calculate observables to optimally isolate processes or operators
- Reweight generated samples from one hypothesis to another

JHUGenLexicon

- Tool for translation between different EFT bases and the JHUGen amplitude basis convention

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*                          JHU Generator v7.5.1                             *
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*                                                                           *
*   Spin and parity determination of single-produced resonances at hadron colliders   *
*                                                                           *
*      I. Anderson, S. Bolognesi, F. Caola, J. Davis, Y. Gao, A. V. Gritsan,  *
*   L. S. Mandacaru Guerra, Z. Guo, C. B. Martin, T. Martini, K. Melnikov, R. Pan,  *
*R. Rontsch, J. Roskes, U. Sarica, M. Schulze, N. V. Tran, A. Whitbeck, M. Xiao, Y. Zhou*
*               Phys.Rev. D81 (2010) 075022;  arXiv:1001.3396  [hep-ph],    *
*               Phys.Rev. D86 (2012) 095031;  arXiv:1208.4018  [hep-ph],    *
*               Phys.Rev. D89 (2014) 035007;  arXiv:1309.4819  [hep-ph],    *
*               Phys.Rev. D94 (2016) 055023;  arXiv:1606.03107 [hep-ph],    *
*               Phys.Rev. D102 (2020) 056022; arXiv:2002.09888 [hep-ph],    *
*               Phys.Rev. D102 (2021) 055045; arXiv:2104.04277 [hep-ph].    *
*                                             arXiv:2109.13363 [hep-ph].    *
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Anomalous Couplings and EFT

HVV couplings parameterized by tensor structures which allow for modelling of any EFT effects

$$A(HVV) = \frac{1}{v}\left\{ M_V^2\left(g_1^{VV} + \frac{\kappa_1^{VV}q_1^2 + \kappa_2^{VV}q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} + \frac{2q_1\cdot q_2}{M_V^2}g_2^{VV}\right)(\varepsilon_1\cdot\varepsilon_2) - 2g_2^{VV}(\varepsilon_1\cdot q_2)(\varepsilon_2\cdot q_1) - 2g_4^{VV}\varepsilon_{\varepsilon_1\varepsilon_2 q_1 q_2}\right\}.$$

Using JHUGenLexicon we can map these amplitude couplings to any other EFT basis we want:

Enforce SU(2) x U(1) to translate between Amplitude basis and EFT bases

$$\delta g_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2C_{H\Box} + \frac{6e^2}{s_w^2}C_{HWB} + \left(\frac{3c_w^2}{2s_w^2} - \frac{1}{2}\right)C_{HD}\right),$$

$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}C_{HWB} + \left(1 - \frac{1}{2s_w^2}\right)C_{HD}\right),$$

$$g_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 C_{HB} + c_w^2 C_{HW} + s_w c_w C_{HWB}\right),$$

$$g_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w\left(C_{HW} - C_{HB}\right) + \frac{1}{2}\left(s_w^2 - c_w^2\right)C_{HWB}\right),$$

$$g_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 C_{HB} + s_w^2 C_{HW} - s_w c_w C_{HWB}\right),$$

$$g_2^{gg} = -2\frac{v^2}{\Lambda^2}C_{HG},$$

$$g_4^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 C_{H\tilde{B}} + c_w^2 C_{H\widetilde{W}} + s_w c_w C_{H\widetilde{W}B}\right),$$

$$g_4^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w\left(C_{H\widetilde{W}} - C_{H\tilde{B}}\right) + \frac{1}{2}\left(s_w^2 - c_w^2\right)C_{H\widetilde{W}B}\right)$$

$$g_4^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 C_{H\tilde{B}} + s_w^2 C_{H\widetilde{W}} - s_w c_w C_{H\widetilde{W}B}\right),$$

$$g_4^{gg} = -2\frac{v^2}{\Lambda^2}C_{H\tilde{G}},$$

Couplings of interest CP-Even $Z\gamma, \gamma\gamma$ and CP-Odd $Z\gamma, \gamma\gamma$

External Constraints

M_W and Zff couplings could be affected by EFT operators

- EW precision measurements tightly constrain these shifts
- Allowed range much smaller than sensitivity of Higgs measurements

Can constrain both Zff and M_W to SM within our framework

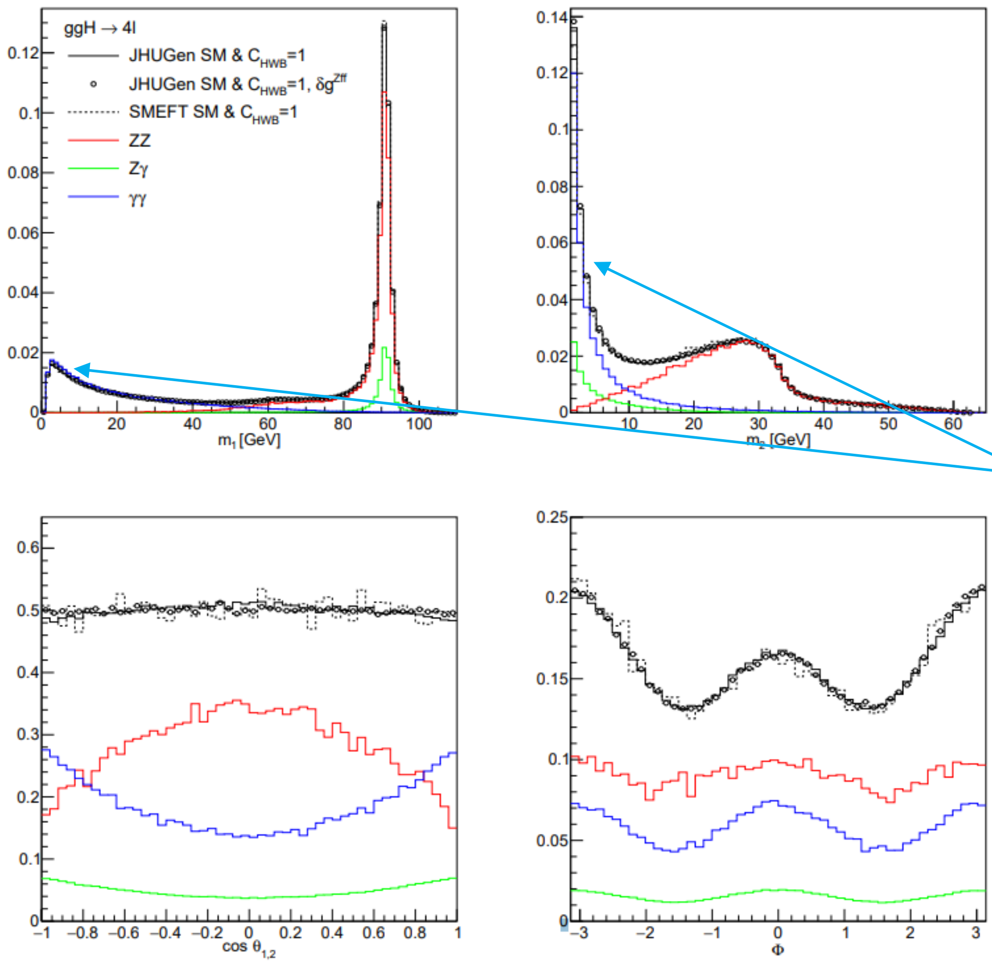
Leads to relations

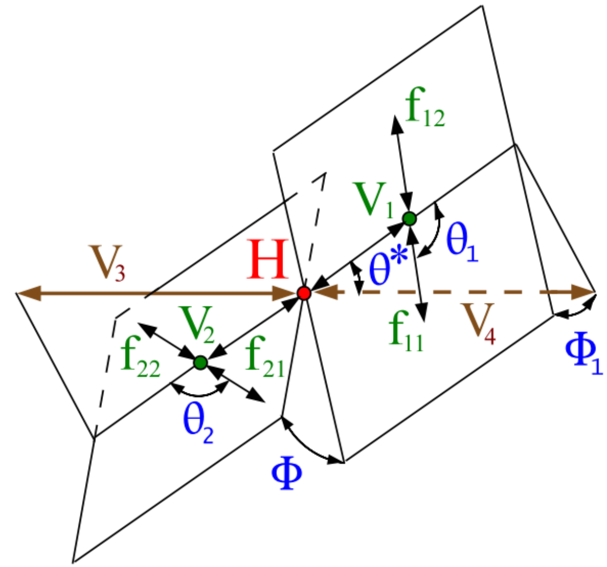
$$\delta g_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2C_{H\Box} + \frac{6e^2}{s_w^2}C_{HWB} + \left(\frac{3c_w^2}{2s_w^2} - \frac{1}{2}\right)C_{HD}\right)$$

	$\delta g_1^{ZZ} = \delta g_1^{WW}$	κ_1^{ZZ}	g_2^{ZZ}	$g_2^{Z\gamma}$	$g_2^{\gamma\gamma}$	g_4^{ZZ}	$g_4^{Z\gamma}$	$g_4^{\gamma\gamma}$	$\kappa_2^{Z\gamma}$	κ_1^{WW}	g_2^{WW}	g_4^{WW}
$c_{H\Box}$	0.1213	0	0	0	0	0	0	0	0	0	0	0
c_{HD}	0.2679	−0.0831	0	0	0	0	0	0	−0.1320	−0.1560	0	0
c_{HW}	0	0	−0.0929	−0.0513	−0.0283	0	0	0	0	0	−0.1212	0
c_{HWB}	0.1529	−0.0613	−0.0513	0.0323	0.0513	0	0	0	0.1763	0.0360	0	0
c_{HB}	0	0	−0.0283	0.0513	−0.0929	0	0	0	0	0	0	0
$c_{H\tilde{W}}$	0	0	0	0	0	−0.0929	−0.0513	−0.0283	0	0	0	−0.1212
$c_{H\tilde{W}B}$	0	0	0	0	0	−0.0513	0.0323	0.0513	0	0	0	0
$c_{H\tilde{B}}$	0	0	0	0	0	−0.0283	0.0513	−0.0929	0	0	0	0

Above: A numerical example of the relationship between the $C_{HX} = 1$ and mass eigenstate amplitude basis used in our analysis

Photons in H → 4l





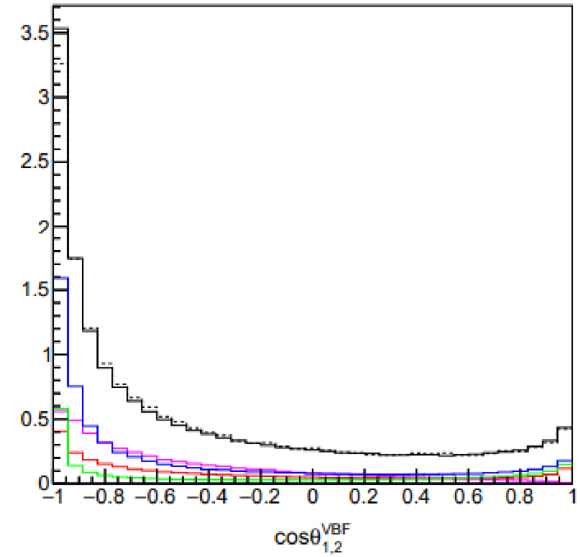
Anomalous photon couplings introduces contributions at low q^2

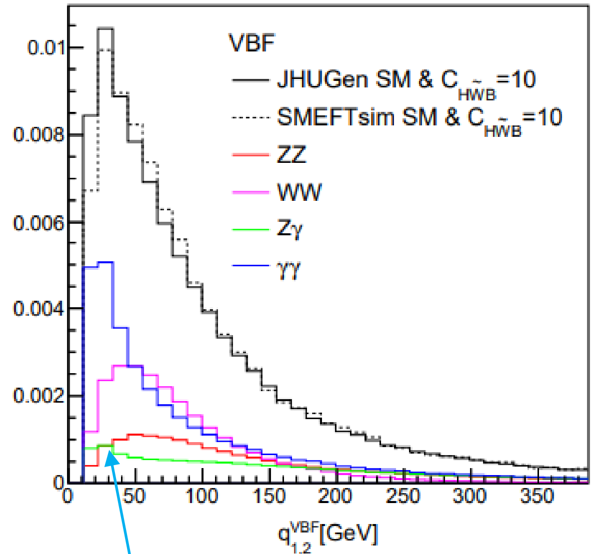
Example: Simulate SM & c_{HWB} = 10

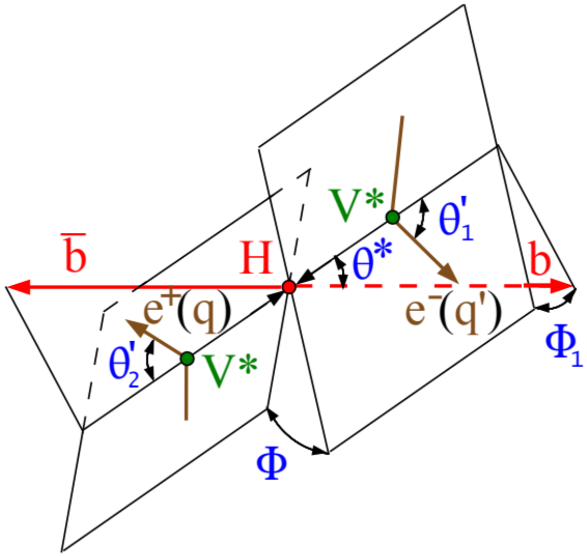
JHUGen (Amplitude basis) kinematic distributions equivalent to SMEFTSim (Warsaw Basis) with the proper rotation using JHUGenLexicon

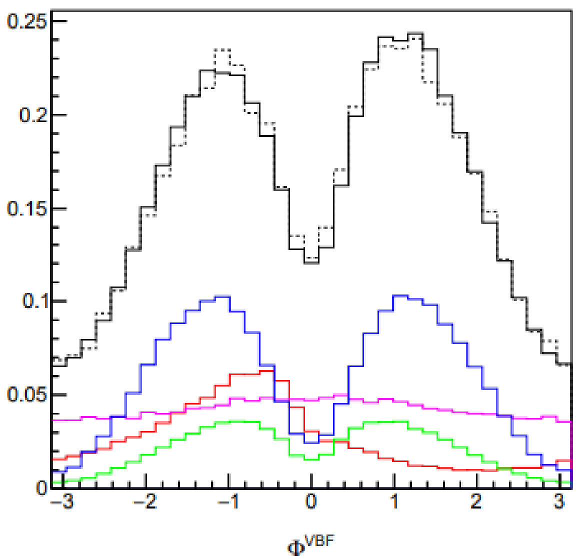
$$c_{HWB} = -0.0513 g_2^{ZZ} - 0.0323 g_2^{Z\gamma} - 0.0513 g_2^{\gamma\gamma}$$

Photons in VBF Higgs Production







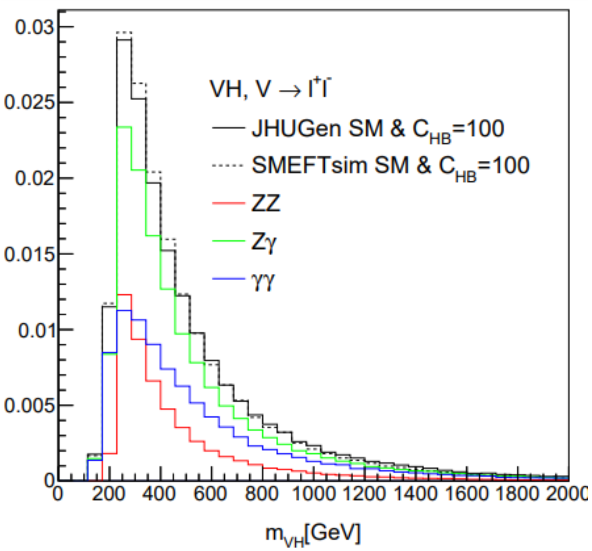


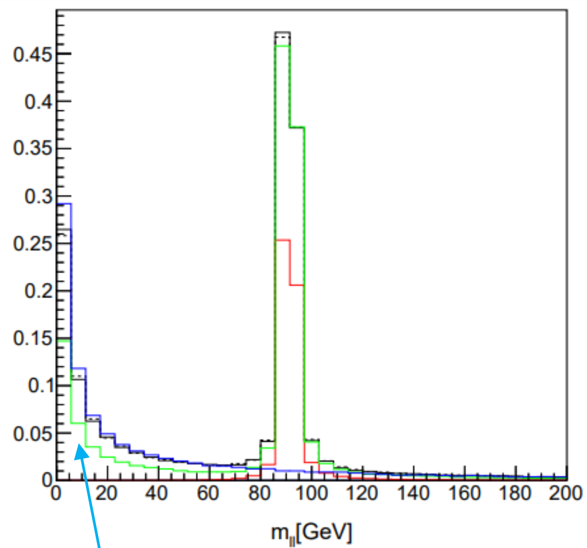
Anomalous photon couplings introduce enhanced $\gamma\gamma$ and $Z\gamma$ fusion contributions at low q^2

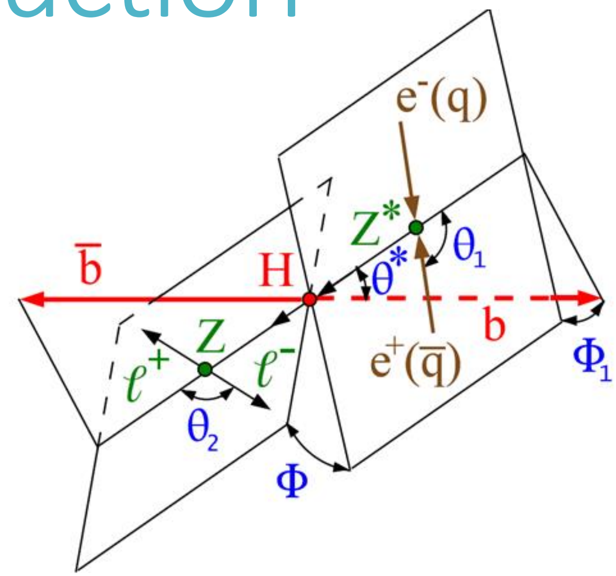
Example: Simulate VBF with SM Couplings & $C_{H\widetilde{W}B}$ = 10

$$C_{H\widetilde{W}B} = -0.0513 g_4^{ZZ} + 0.0323 g_4^{Z\gamma} + 0.0513 g_4^{\gamma\gamma}$$

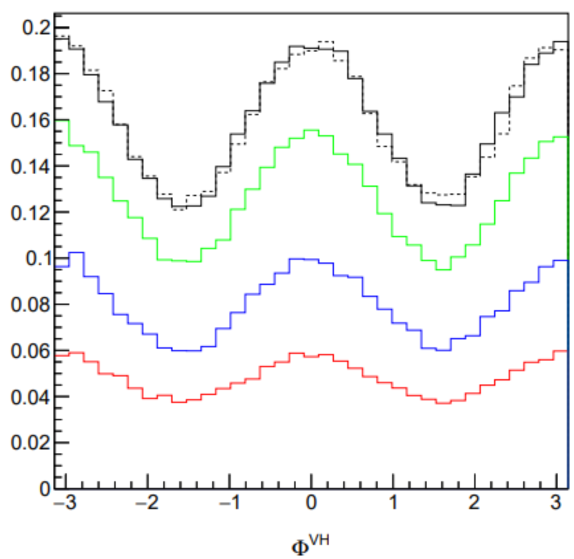
Photons in $Z/\gamma^{*}H$ Production







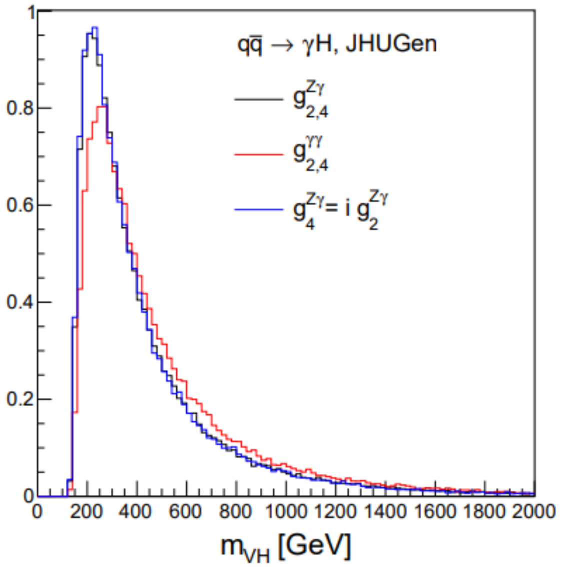
Anomalous photon couplings introduce $\gamma^{*}H$ contributions at low q^{2}

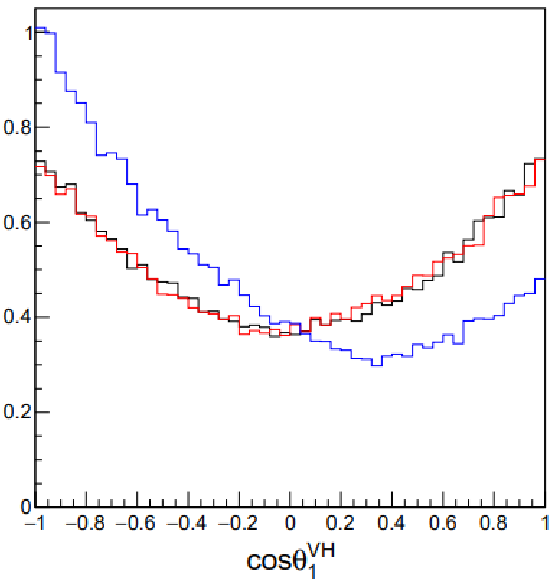


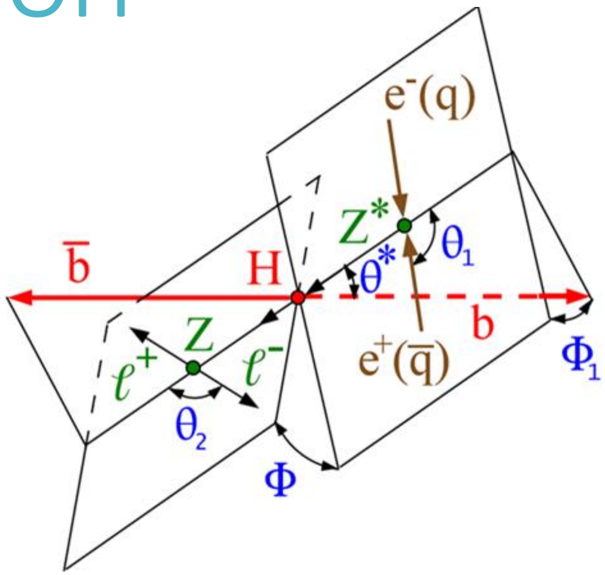
Example: Simulate $Z/\gamma^{*}H$ with SM Couplings & C_{HB} = 100

$$C_{HB} = -0.0283 g_2^{ZZ} + 0.0513 g_2^{Z\gamma} - 0.0929 g_2^{\gamma\gamma}$$

Photons in γH Production



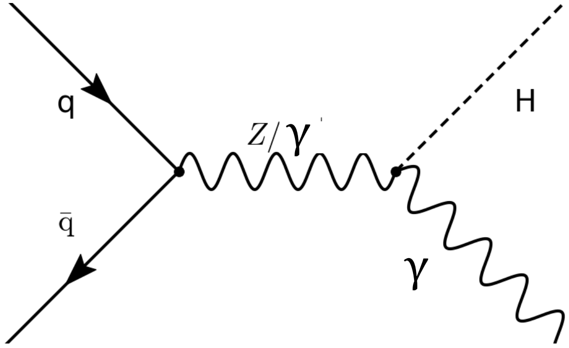




Anomalous photon couplings greatly increase rate of γH production

Signal is a Higgs with high pT photon

Unable to distinguish between real valued CP-Even and CP-Odd couplings



EFT Analysis

Measure Higgs cross sections as a function of anomalous couplings

$$\frac{d\sigma(i \to H \to f)}{d\vec{\Omega}} \propto \frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{\Gamma_{\text{tot}}}$$

Maximum likelihood calculated for EFT hypothesis to match measured cross section/kinematic distributions

α are functions of kinematic observables $\vec{\Omega}$ factorized into both production and decay components

Γ_{tot} purely dependent on anomalous couplings

Higgs Width Calculation

$$\sigma(i \to H \to f) \propto \frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{\Gamma_{\text{tot}}}$$

Total width directly dependent on anomalous couplings

$$\Gamma_{\text{known}} = \Gamma_{\text{tot}}^{\text{SM}} \times \sum_f \left(\frac{\Gamma_f^{\text{SM}}}{\Gamma_{\text{tot}}^{\text{SM}}} \times \frac{\Gamma_f}{\Gamma_f^{\text{SM}}}\right) = \sum_f \Gamma_f^{\text{SM}} R_f$$

(Function of anomalous couplings)

$$f = b\bar{b}, c\bar{c}, W^+W^-, gg, \tau^+\tau^-, ZZ/Z\gamma^*/\gamma^*\gamma^*$$

Full analytic formulas are calculated for each R_f including photon couplings

R_f dependent on q^2cutoff

Values shown for $q^2 > (2m_f)^2$

$$\begin{aligned}
R_{ZZ/Z\gamma^*/\gamma^*\gamma^*} = \; & \left(\frac{g_1^{ZZ}}{2}\right)^2 + 0.17\left(\kappa_1^{ZZ}\right)^2 + 0.09\left(g_2^{ZZ}\right)^2 + 0.04\left(g_4^{ZZ}\right)^2 + 0.10\left(\kappa_2^{Z\gamma}\right)^2 \\
& +79.95\left(g_2^{Z\gamma}\right)^2 + 75.23\left(g_4^{Z\gamma}\right)^2 + 29.00\left(g_2^{\gamma\gamma}\right)^2 + 29.47\left(g_4^{\gamma\gamma}\right)^2 \\
& +0.81\frac{g_1^{ZZ}}{2}\kappa_1^{ZZ} + 0.50\frac{g_1^{ZZ}}{2}g_2^{ZZ} + 0\times\frac{g_1^{ZZ}}{2}g_4^{ZZ} - 0.19\frac{g_1^{ZZ}}{2}\kappa_2^{Z\gamma} \\
& -1.56\frac{g_1^{ZZ}}{2}g_2^{Z\gamma} + 0\times\frac{g_1^{ZZ}}{2}g_4^{Z\gamma} + 0.06\frac{g_1^{ZZ}}{2}g_2^{\gamma\gamma} + 0\times\frac{g_1^{ZZ}}{2}g_4^{\gamma\gamma} \\
& +0.21\kappa_1^{ZZ}g_2^{ZZ} + 0\times\kappa_1^{ZZ}g_4^{ZZ} - 0.07\kappa_1^{ZZ}\kappa_2^{Z\gamma} - 0.64\kappa_1^{ZZ}g_2^{Z\gamma} \\
& +0\times\kappa_1^{ZZ}g_4^{Z\gamma} + 0.00\kappa_1^{ZZ}g_2^{\gamma\gamma} + 0\times\kappa_1^{ZZ}g_4^{\gamma\gamma} + 0\times g_2^{ZZ}g_4^{ZZ} \\
& -0.05g_2^{ZZ}\kappa_2^{Z\gamma} - 0.51g_2^{ZZ}g_2^{Z\gamma} + 0\times g_2^{ZZ}g_4^{Z\gamma} - 0.02g_2^{ZZ}g_2^{\gamma\gamma} \\
& +0\times g_2^{ZZ}g_4^{\gamma\gamma} + 0\times g_4^{ZZ}\kappa_2^{Z\gamma} + 0\times g_4^{ZZ}g_2^{Z\gamma} + 0.36g_4^{ZZ}g_4^{Z\gamma} \\
& +0\times g_4^{ZZ}g_2^{\gamma\gamma} - 0.57g_4^{ZZ}g_4^{\gamma\gamma} + 1.80\kappa_2^{Z\gamma}g_2^{Z\gamma} + 0\times\kappa_2^{Z\gamma}g_4^{Z\gamma} \\
& -0.05\kappa_2^{Z\gamma}g_2^{\gamma\gamma} + 0\times\kappa_2^{Z\gamma}g_4^{\gamma\gamma} + 0\times g_2^{Z\gamma}g_4^{Z\gamma} - 1.84g_2^{Z\gamma}g_2^{\gamma\gamma} \\
& +0\times g_2^{Z\gamma}g_4^{\gamma\gamma} + 0\times g_4^{Z\gamma}g_2^{\gamma\gamma} - 2.09g_4^{Z\gamma}g_4^{\gamma\gamma} + 0\times g_2^{\gamma\gamma}g_4^{\gamma\gamma}
\end{aligned}$$

MELA Observables

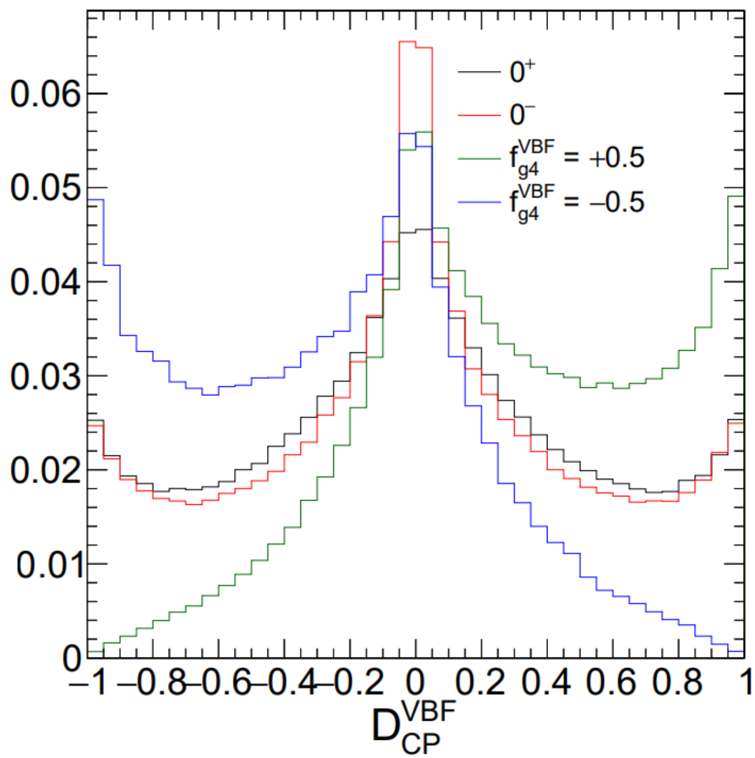
- Events have many kinematic observables
- We construct observables that utilize all kinematic information

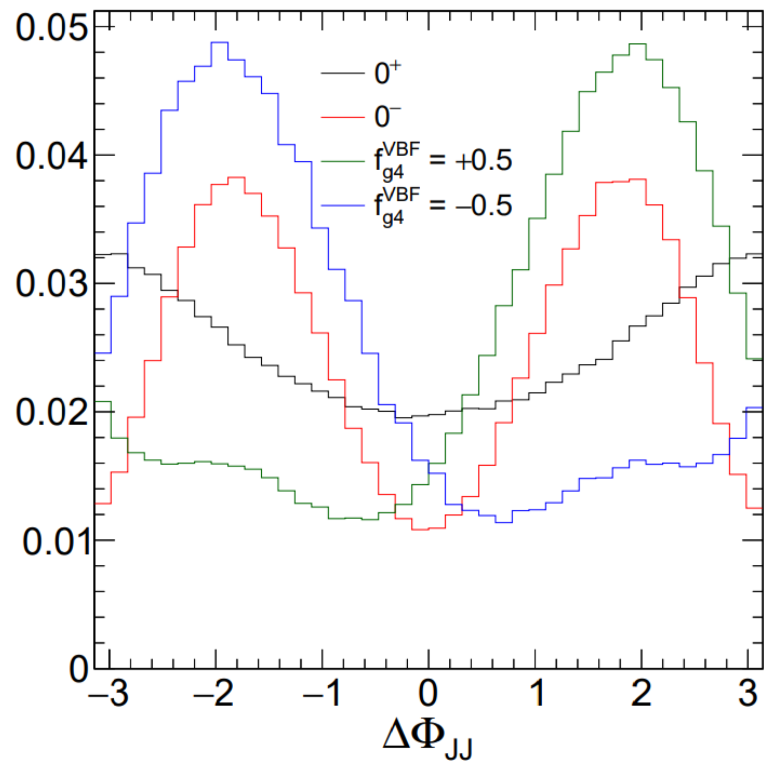
$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) \times \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}}$$

$$\frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{\Gamma_{\text{tot}}}$$

MELA calculates optimal observables from matrix elements to distinguish between various anomalous coupling hypotheses





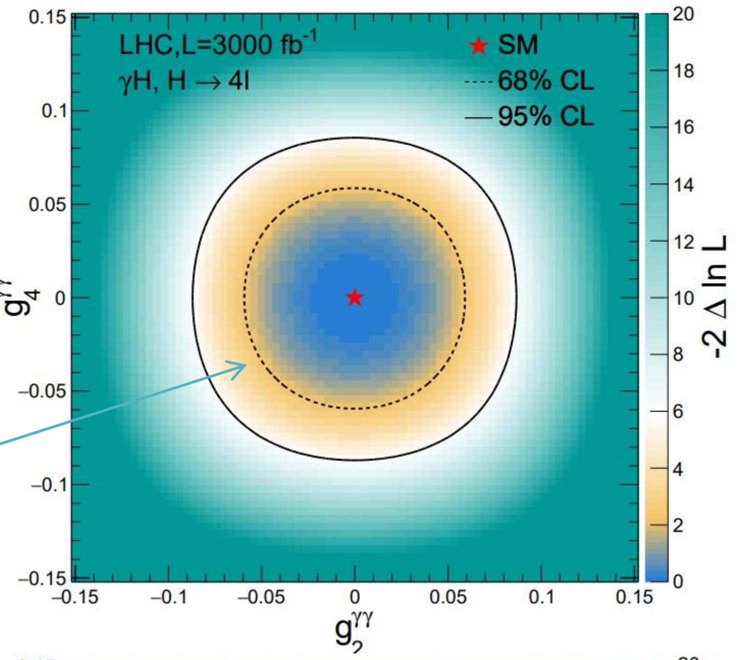
γH Constraints

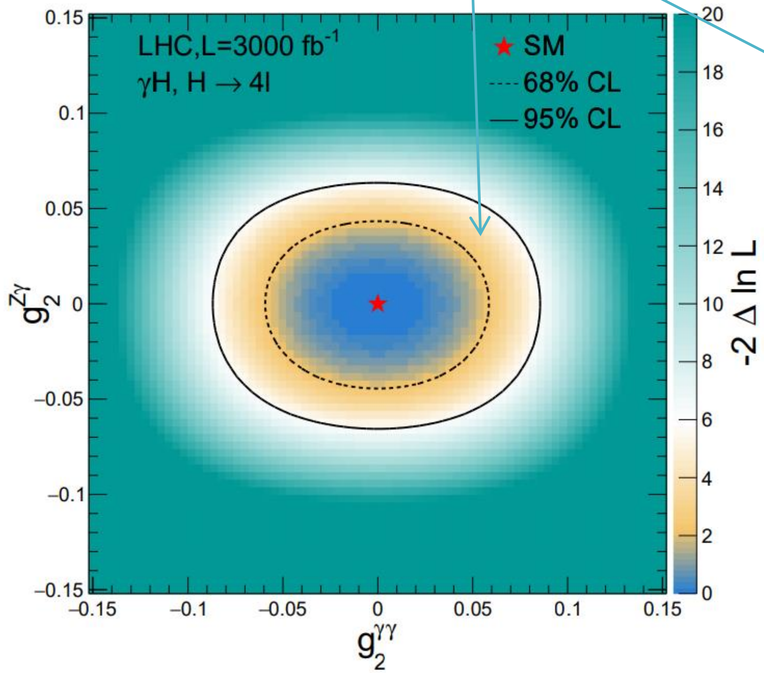
Only use production info from γH

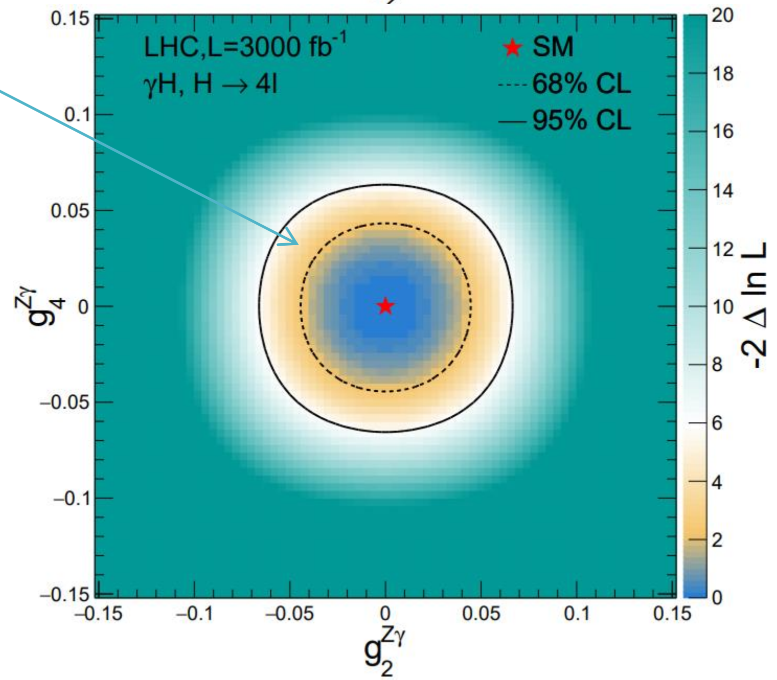
Unable to distinguish between

CP-Odd and CP-Even with only γH

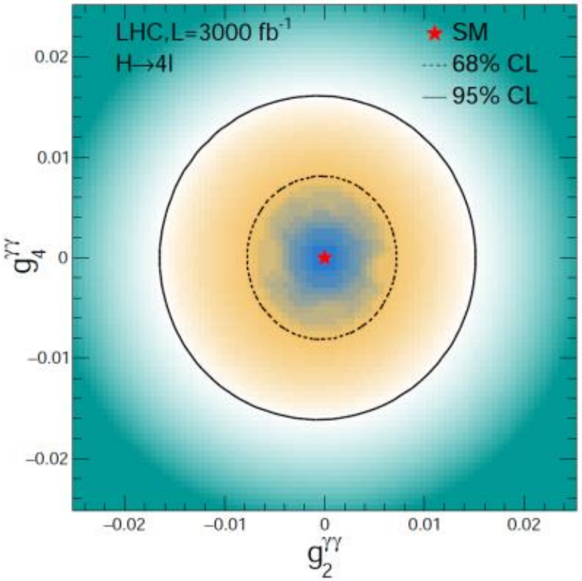
Constraints of Order ~ 0.05

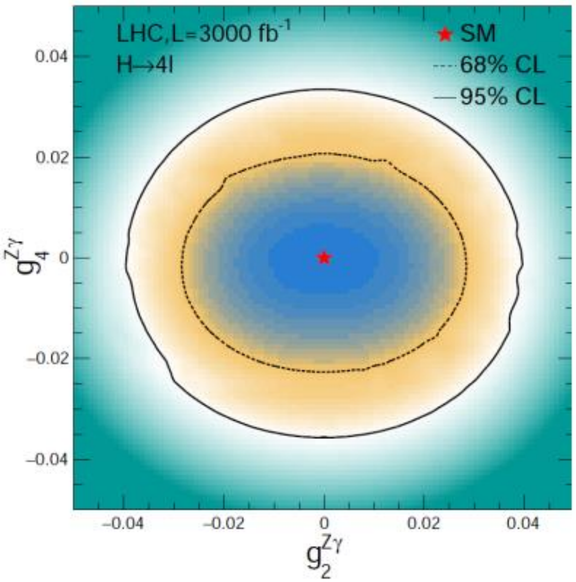


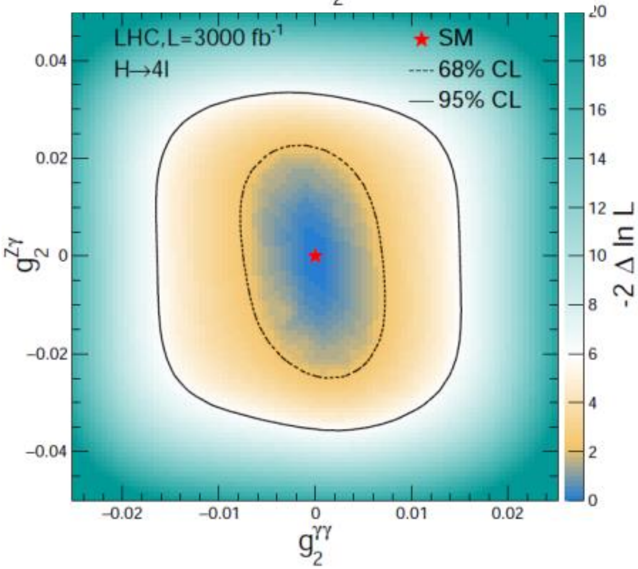




Constraints: Production + Decay







Using information from VBF, VH production + 4l decay

Tighter constraints on all couplings, Order ~0.01-0.02

γγ couplings better than Zγ

Constraints from Decays with On-Shell photons

Measurements of the rate of H → γγ and H → Zγ can be used to constrain anomalous Hγγ and HZγ couplings

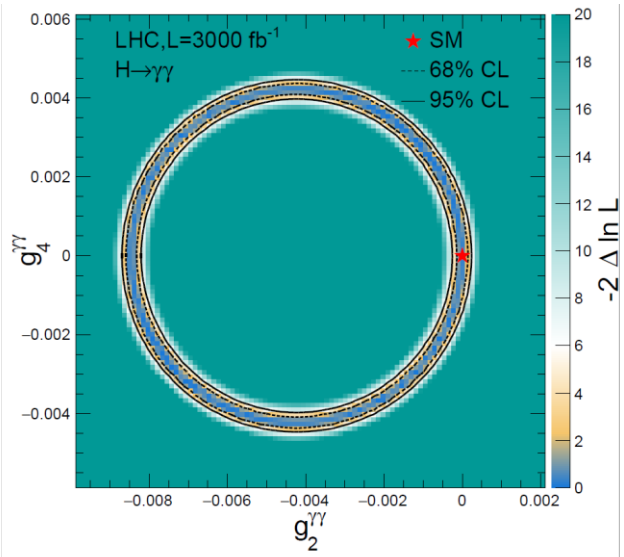
Expected constraints taken from Higgs Working Group 2 Report [arxiv:1902.00134](https://arxiv.org/abs/1902.00134)

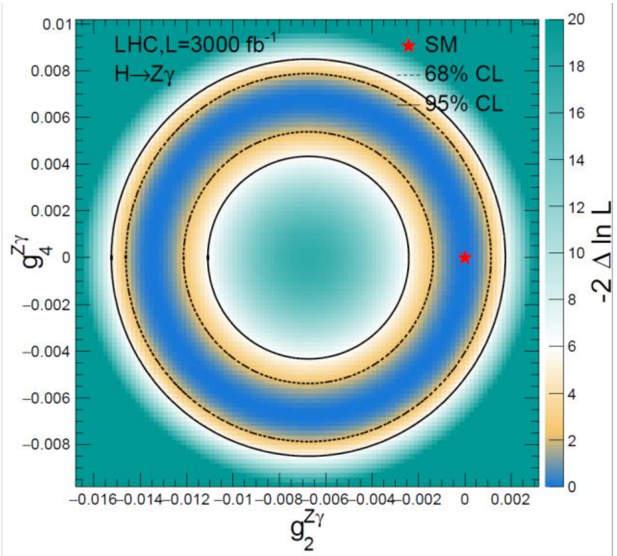
$$R_{\gamma\gamma} \simeq \frac{1}{\left(g_2^{\gamma\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{\gamma\gamma,\mathrm{SM}} + g_2^{\gamma\gamma}\right)^2 + \left(g_4^{\gamma\gamma}\right)^2\right]$$

$$R_{Z\gamma} \simeq \frac{1}{\left(g_2^{Z\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{Z\gamma,\mathrm{SM}} + g_2^{Z\gamma}\right)^2 + \left(g_4^{Z\gamma}\right)^2\right]$$

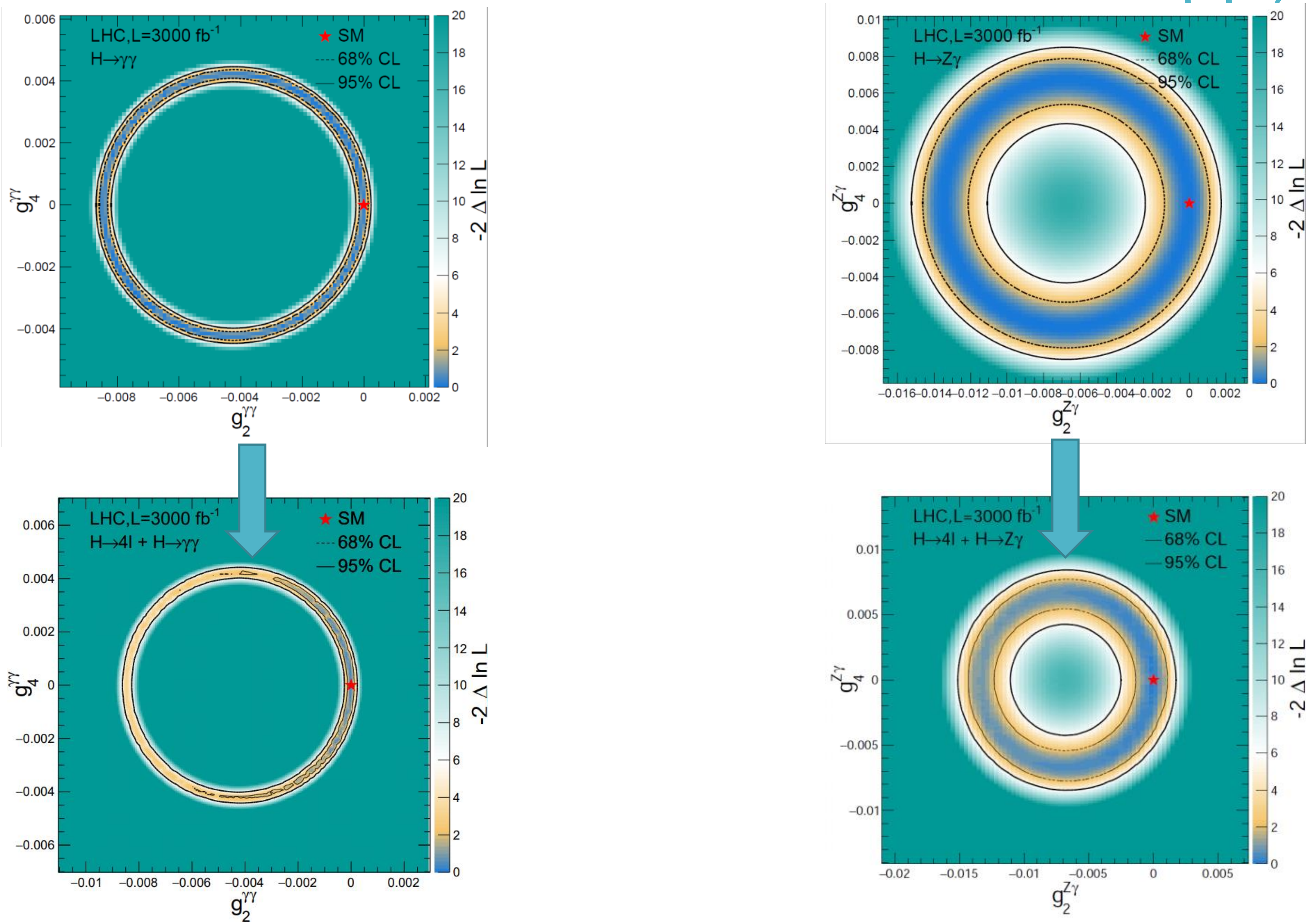
$$R_{\gamma\gamma} \simeq 1.00 \pm 0.05$$

$$R_{Z\gamma} \simeq 1.00 \pm 0.24$$





Full Combination: H-> 4l and H-> γγ ,Zγ



Conclusion

To increase sensitivity of Higgs coupling to virtual photons, need to push q^2 of analysis as low as possible

Calculated Γ_H as a function of anomalous couplings

Measuring γH cross section can provide decent constraints on virtual photon couplings

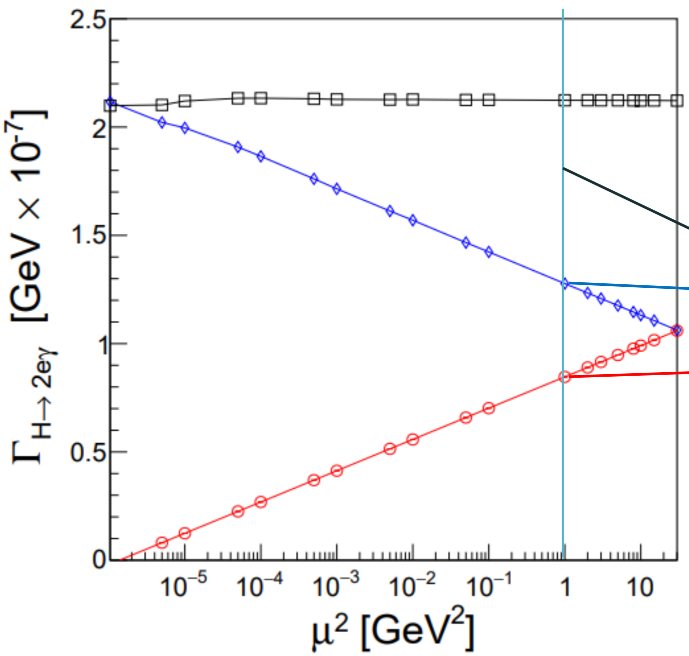
Using full information from VBF, VH production and H→4l decay provides the tightest constraints from HVV measurements

Total Width Calculation

Higgs decay to fermions through virtual photons have sharp peaks for small $q^2 = (p_{f+} + p_{f-})^2$

Developed procedure to handle singularities at low q^2

For details on derivation see arxiv:2109.13363



Approximate $\Gamma_{H\to 2e\gamma}$ width by measuring partial widths at given q^2 cut.

$$\Gamma_{H\to 2\ell\gamma} = \Gamma_{H\to 2\ell\gamma}\Big|_{q^2_{2\ell}\geq\mu^2} + SF\,\Gamma_{H\to\gamma\gamma}$$

Lepton scale factor SF is a function of q^2

Similar forms could be calculated for decays to quarks

Analytic Decay Rates

$$R_{\gamma\gamma} = 1.60932\left(\frac{g_1^{WW}}{2}\right)^2 - 0.69064\left(\frac{g_1^{WW}}{2}\right)\kappa_t + 0.00912\left(\frac{g_1^{WW}}{2}\right)\kappa_b - 0.49725\left(\frac{g_1^{WW}}{2}\right)(N_c Q^2 \kappa_Q)$$
$$+0.07404\,\kappa_t^2 + 0.00002\,\kappa_b^2 - 0.00186\,\kappa_t\kappa_b$$
$$+0.03841\,(N_c Q^2 \kappa_Q)^2 + 0.10666\,\kappa_t\,(N_c Q^2 \kappa_Q) - 0.00136\,\kappa_b\,(N_c Q^2 \kappa_Q)$$
$$+0.20533\,\tilde\kappa_t^2 + 0.00006\,\tilde\kappa_b^2 - 0.00300\,\tilde\kappa_t\tilde\kappa_b$$
$$+0.10252\,(N_c Q^2 \tilde\kappa_Q)^2 + 0.29018\,\tilde\kappa_t\,(N_c Q^2 \tilde\kappa_Q) - 0.00202\,\tilde\kappa_b\,(N_c Q^2 \tilde\kappa_Q)\,.$$

$$g_2^{\gamma\gamma,Q} = -\frac{\alpha}{3\pi} N_c Q^2 \kappa_Q\,, \qquad g_4^{\gamma\gamma,Q} = -\frac{\alpha}{2\pi} N_c Q^2 \tilde\kappa_Q.$$

Effective Hγγ couplings mimic heavy quark effects

$R_{\gamma\gamma}$ can be cast in terms of anomalous photon couplings

- Fix HWW couplings to SM value
- Fix Hff couplings to SM value

$$R_{\gamma\gamma} \simeq \frac{1}{\left(g_2^{\gamma\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{\gamma\gamma,\mathrm{SM}} + g_2^{\gamma\gamma}\right)^2 + \left(g_4^{\gamma\gamma}\right)^2\right]$$

Higgs production with photon (γH)

To date there has been no search for γH(125) production at LHC or LEP

γH production has extremely low SM cross-section

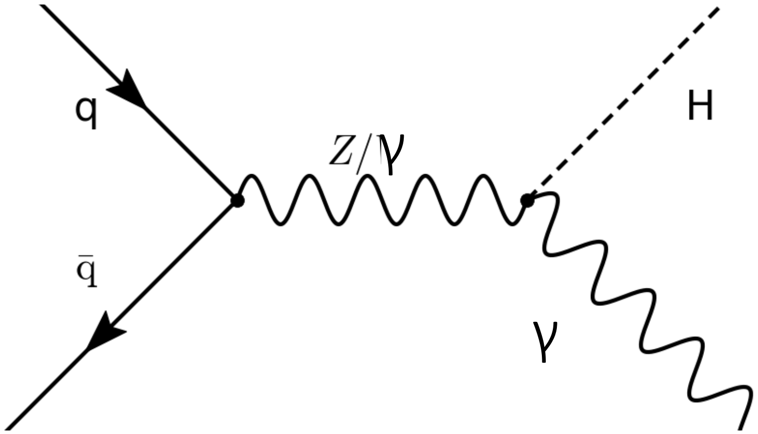
- ~.1 events expected with entire LHC and HL-LHC dataset

Anomalous HZγ and Hγγ couplings dramatically enhance expected γH yield above SM for relatively small coupling values

$$\frac{\sigma(q\bar{q}\to\gamma H)}{\sigma_{\rm ref}^{\gamma H}} = \left(g_2^{Z\gamma}\right)^2 + \left(g_4^{Z\gamma}\right)^2 + 0.553\,(g_2^{\gamma\gamma})^2 + 0.553\,(g_4^{\gamma\gamma})^2 - 0.578\,g_2^{Z\gamma}g_2^{\gamma\gamma} - 0.578\,g_4^{Z\gamma}g_4^{\gamma\gamma}$$

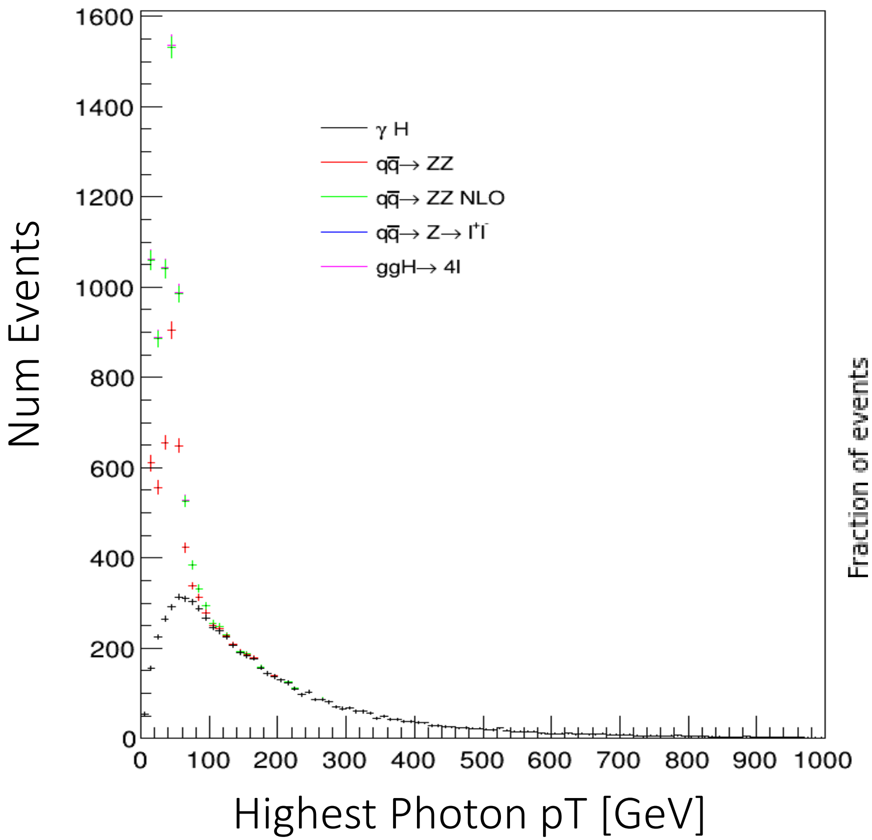
$$\sigma_{\rm ref}^{\gamma H} = 1.33\times 10^4\ \rm fb$$

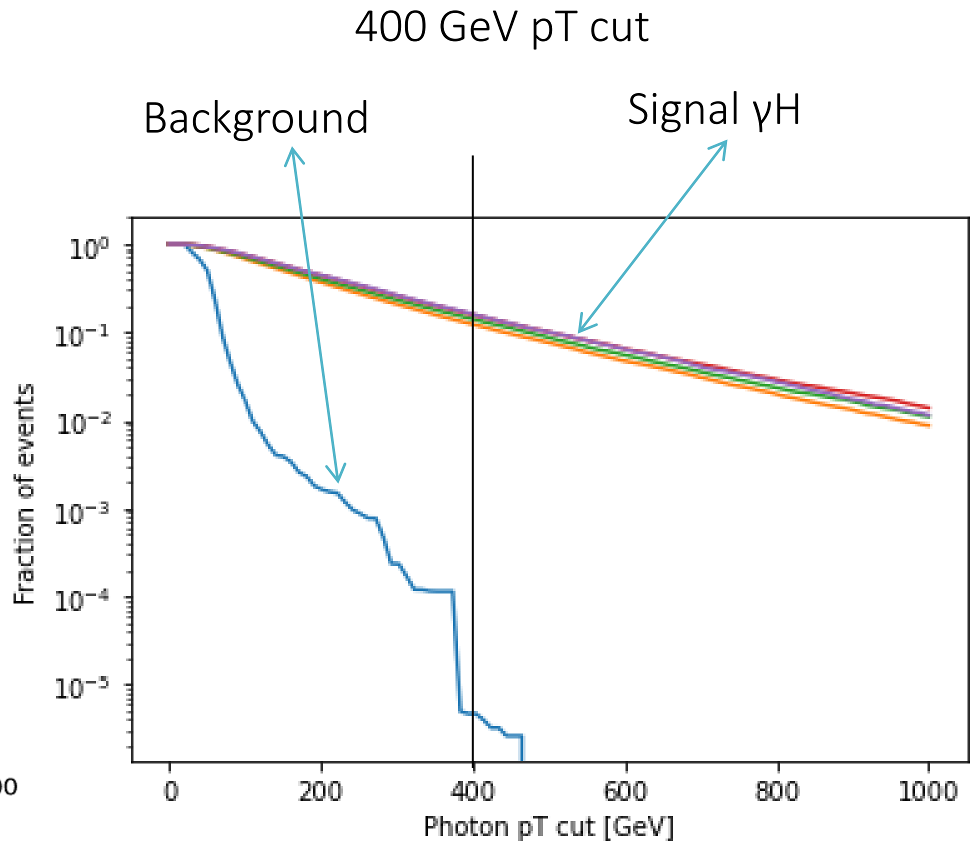
For $g_2^{Z\gamma}$= 1, expect ~ 2×10^5 events



γH Background

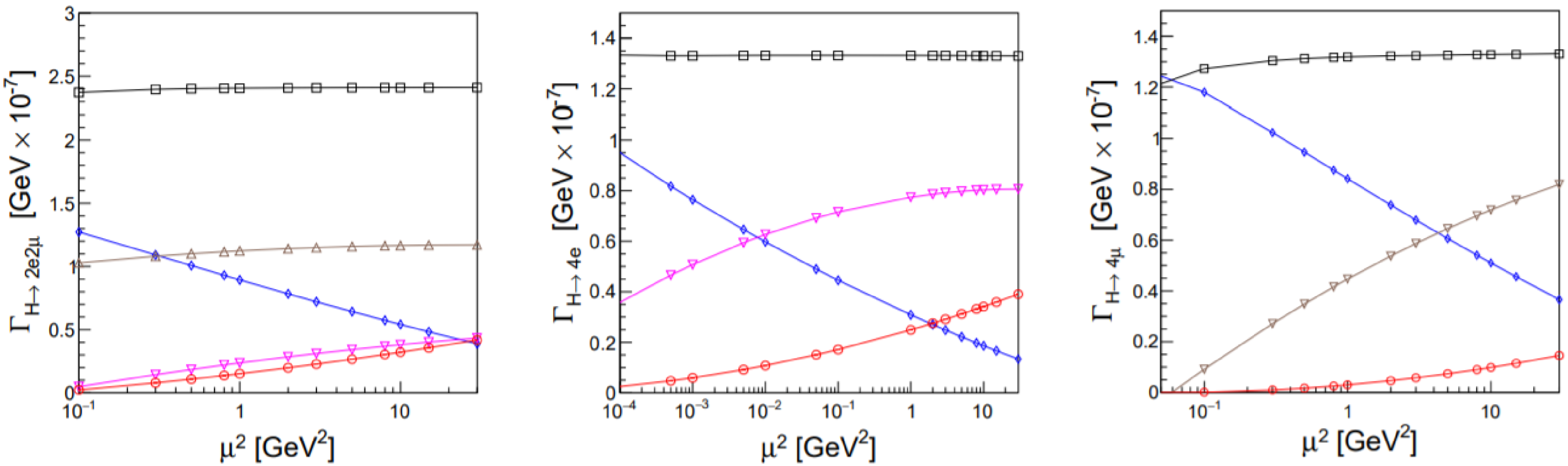
Main Sources of background are ggH and qqZZ
qqbar->ZZ/Z γ *->4l background is generated with POWHEG + Pythia hadronization.





Total Width Calculation

$$\begin{aligned}\Gamma_{H\to 2\ell 2\ell'} &= \Gamma_{H\to 2\ell 2\ell'}\Big|_{q^2_{2\ell}\geq\mu^2,\, q^2_{2\ell'}\geq\mu^2} \\ &+\frac{\alpha}{2\pi}\left[\frac{2}{3}\log\left(\frac{\mu_\ell^2}{m_\ell^2}\right)-\frac{10}{9}\right]\Gamma_{H\to 2\ell'\gamma}\Big|_{q^2_{2\ell'}\geq\mu^2}+\frac{\alpha}{2\pi}\left[\frac{2}{3}\log\left(\frac{\mu_{\ell'}^2}{m_{\ell'}^2}\right)-\frac{10}{9}\right]\Gamma_{H\to 2\ell\gamma}\Big|_{q^2_{2\ell}\geq\mu^2} \\ &+\left(\frac{\alpha}{2\pi}\right)^2\left[\frac{2}{3}\log\left(\frac{\mu_\ell^2}{m_\ell^2}\right)-\frac{10}{9}\right]\left[\frac{2}{3}\log\left(\frac{\mu_{\ell'}^2}{m_{\ell'}^2}\right)-\frac{10}{9}\right]2\,\Gamma_{H\to\gamma\gamma}+\mathcal{O}(\mu^2/M_H^2),\end{aligned}$$



Total Width Calculation

Similarly, we can use this procedure for decays to quarks

$$\Gamma_{H\to 2j\gamma} = \Gamma_{H\to 2j\gamma}\Big|_{q_{2q}^2 \geq \mu^2} + \left[\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) + \frac{\alpha}{\pi}\frac{11}{9}\log\left(\frac{\mu^2}{M_Z^2}\right)\right] 2\,\Gamma_{H\to\gamma\gamma} + \mathcal{O}(\mu^2/M_Z^2)$$

Hadron form factor unknown/ hard to derive (resonances)