HVV Interactions in the context of EFT

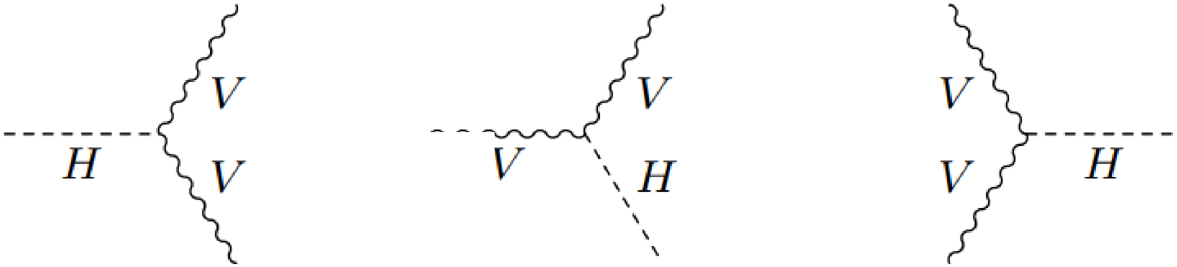
Fermilab EFT workshop September 5-6 2023

Jeffrey Davis

Johns Hopkins University

SMEFT in HVV interactions

- Historically HVV was studied without SU(2) x U(1) symmetry
- Targeted anomalous couplings (more general EFT)

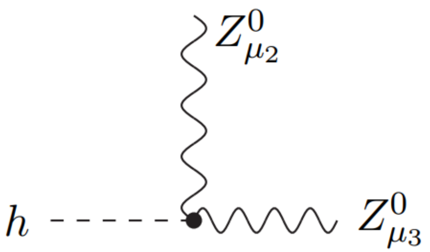


- More recently, SU(2) x U(1) symmetry introduced to anomalous coupling analysis (SMEFT interpretation)
  - *Constraints in natural mass eigenstate basis and rotated to Warsaw coefficients*

- STXS interpretations provide direct constraints on Wilson coefficients

SMEFT in HVV interactions

- Many SMEFT operators enter various HVV interactions
- Example taken from: arxiv:1704.03888



$$
\begin{aligned}
&+\frac{iv}{2}\left(\bar{g}^2+\bar{g}'^2\right)\eta_{\mu_2\mu_3}+\frac{iv^3}{2}\left(\bar{g}^2+\bar{g}'^2\right)\eta_{\mu_2\mu_3}\boxed{C^{\varphi\Box}}\\
&+\frac{3iv^3}{8}\left(\bar{g}^2+\bar{g}'^2\right)\eta_{\mu_2\mu_3}\boxed{C^{\varphi D}}+\frac{4i\bar{g}^2v}{\bar{g}^2+\bar{g}'^2}\boxed{C^{\varphi W}}(p_2^{\mu_3}p_3^{\mu_2}-p_2\cdot p_3\eta_{\mu_2\mu_3})\\
&+\frac{4i\bar{g}'^2v}{\bar{g}^2+\bar{g}'^2}\boxed{C^{\varphi B}}(p_2^{\mu_3}p_3^{\mu_2}-p_2\cdot p_3\eta_{\mu_2\mu_3})\\
&+\frac{i\bar{g}\bar{g}'v}{\bar{g}^2+\bar{g}'^2}\boxed{C^{\varphi WB}}\left(\eta_{\mu_2\mu_3}\left(-4p_2\cdot p_3+\bar{g}^2v^2+\bar{g}'^2v^2\right)+4p_2^{\mu_3}p_3^{\mu_2}\right)\\
&+\frac{4i\bar{g}^2v}{\bar{g}^2+\bar{g}'^2}\boxed{C^{\varphi\widetilde{W}}}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}+\frac{4i\bar{g}'^2v}{\bar{g}^2+\bar{g}'^2}\boxed{C^{\varphi\widetilde{B}}}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}\\
&+\frac{4i\bar{g}\bar{g}'v}{\bar{g}^2+\bar{g}'^2}\boxed{C^{\varphi\widetilde{W}B}}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}
\end{aligned}
$$

- 8 different operators to describe single vertex!
- However, only 3 sets are kinematically equivalent

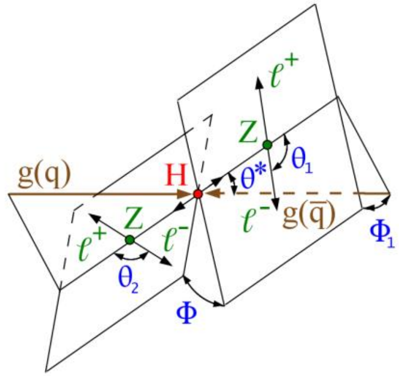
$C^{\varphi D}, C^{\varphi\Box}$	$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB}$	$C^{\varphi\tilde{W}}, C^{\varphi\tilde{B}}, C^{\varphi\tilde{W}B}$
SM-Like	CP-Even c_{zz}	CP-Odd $\tilde{c}_{zz}$

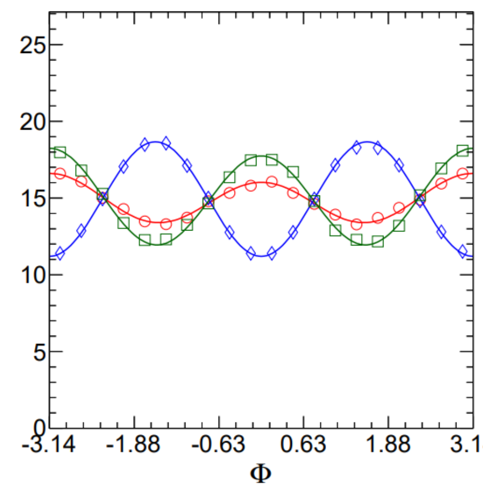
Anomalous Couplings and EFT

- HVV scattering amplitude parametrized in terms of 3 Lorentz tensor structures
- Couplings parametrized by g_i or a_i -> g_1(SM-Tree Level), g_2(CP-Even Dim-6) , g_4(CP-Odd Dim-6)

$$A(HV_1V_2) = \frac{1}{v} \left\{ M_{V_1}^2 \left(g_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV} (q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} + \frac{2 q_1 \cdot q_2}{M_{V_1}^2} g_2^{VV} \right) (\varepsilon_1 \cdot \varepsilon_2) - 2 g_2^{VV} (\varepsilon_1 \cdot q_2)(\varepsilon_2 \cdot q_1) - 2 g_4^{VV} \varepsilon_{\varepsilon_1 \varepsilon_2 q_1 q_2} \right\},$$

- Anomalous couplings at Higgs production or decay vertex, visible in kinematic observables





Anomalous Couplings and EFT

- Higgs anomalous coupling (AC) measurements have been performed at the LHC in many decay channels.
- Direct constraints on Wilson coefficients from interpretations of STXS and AC
- One can easily relate HVV AC measurements to a broader EFT context (Wilson coefficients) with a few assumptions:
  - SU(2) x U(1) symmetry
  - W mass is precisely constrained $\Delta M_W = 0$
    - Not needed if $\frac{i}{v^2} c'_{H\ell} \left[\bar{\ell}\sigma_i\gamma_\mu\ell\right]\left[\Phi^\dagger\sigma^i \overleftrightarrow{D}^\mu \Phi\right] + \frac{1}{v^2} c_{\ell\ell}\left[\bar{\ell}\gamma_\mu\ell\right]\left[\bar{\ell}\gamma^\mu\ell\right]$ well known

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

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

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

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

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

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

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

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

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

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

arxiv:2109.13363

HVV analysis H->4l,ττ,γγ channel

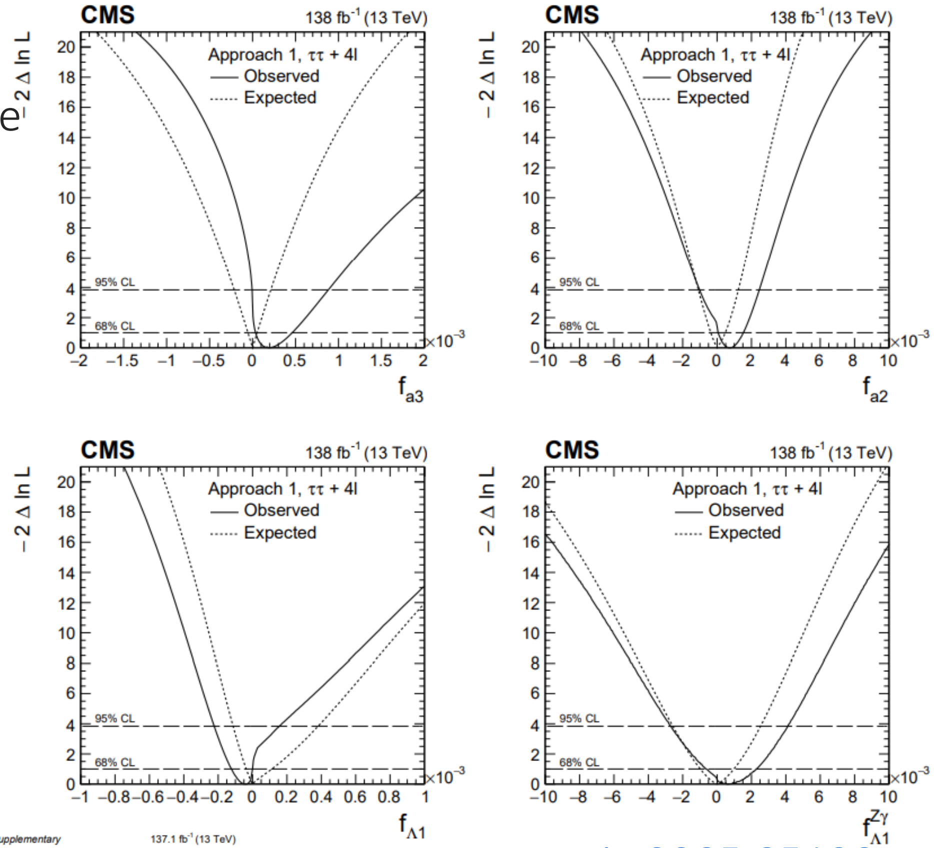
- Dedicated analysis probing HVV couplings using production and decay information across multiple channels

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

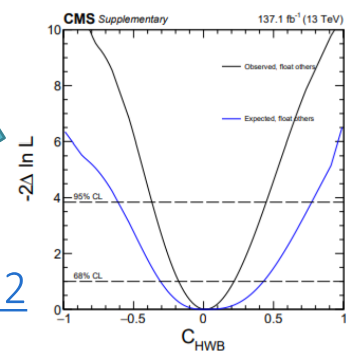
- Results presented in terms of fractional contribution of Anomalous Couplings to remove dependence on Higgs width

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \, \mathrm{sgn}\left(\frac{a_3}{a_1}\right)$$

- Assume Higgs width dependent on AC
- Rotate to constraint in Warsaw basis



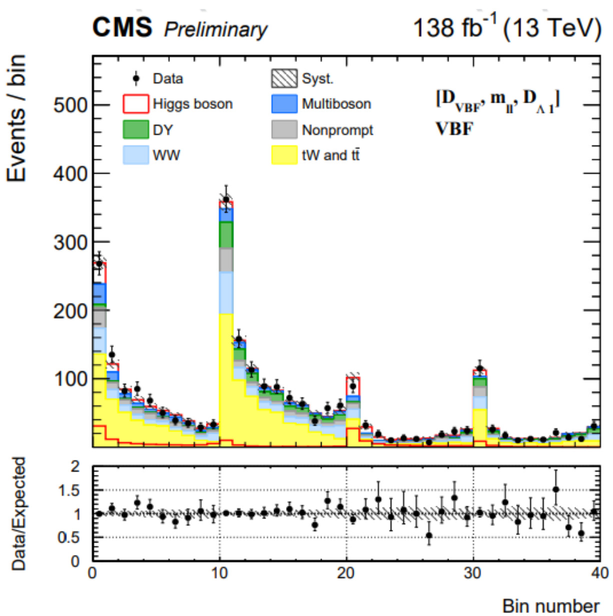
arxiv:2205.05120



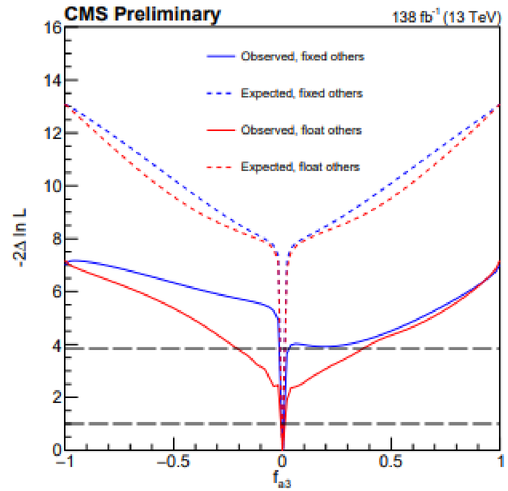
arxiv:2104.12152

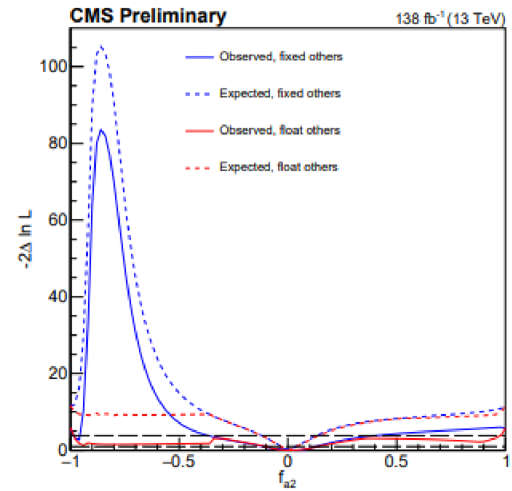
HVV analysis, H->WW channel

- Recent dedicated AC analysis uses WW channel
- Uses ggH,VBF,VH production information and 2l2v decay information



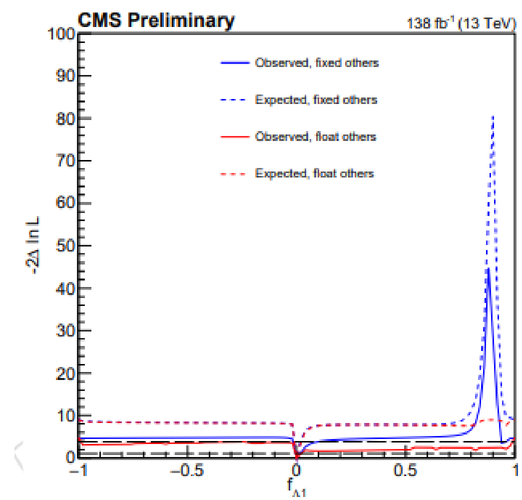
Unrolled Histogram of D_VBF, mll, D_L1 for VBF channel



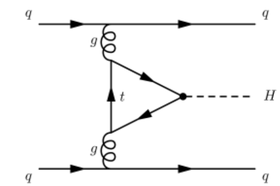


Assume SU(2)xU(1) and photon couplings -> 0

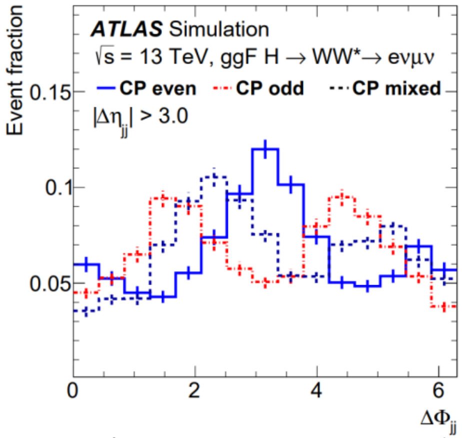
$$a_1^{WW} = a_1^{ZZ},$$
$$a_2^{WW} = c_w^2 a_2^{ZZ},$$
$$a_3^{WW} = c_w^2 a_3^{ZZ},$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2} = \frac{1}{c_w^2 - s_w^2}\left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} - 2 s_w^2 \frac{a_2^{ZZ}}{m_Z^2}\right),$$
$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2} = \frac{2 s_w c_w}{c_w^2 - s_w^2}\left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} - \frac{a_2^{ZZ}}{m_Z^2}\right),$$

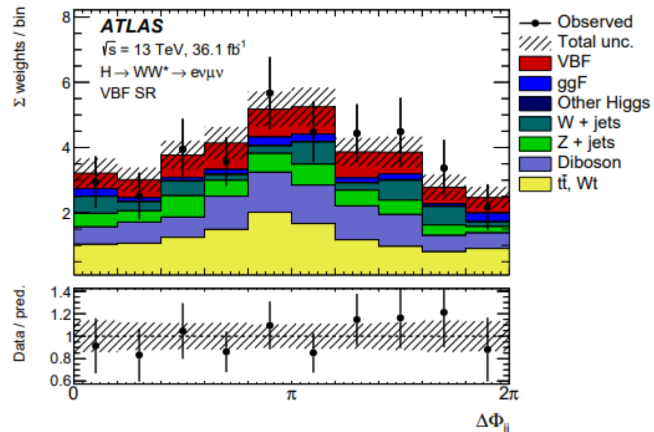


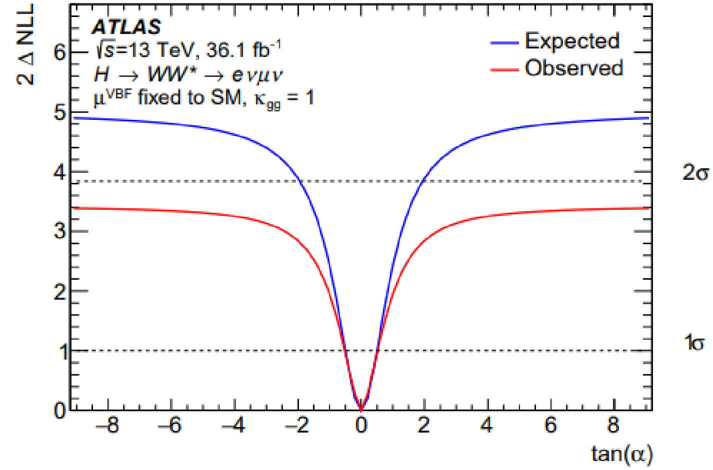
Hgg couplings, H->WW, ττ, 4l



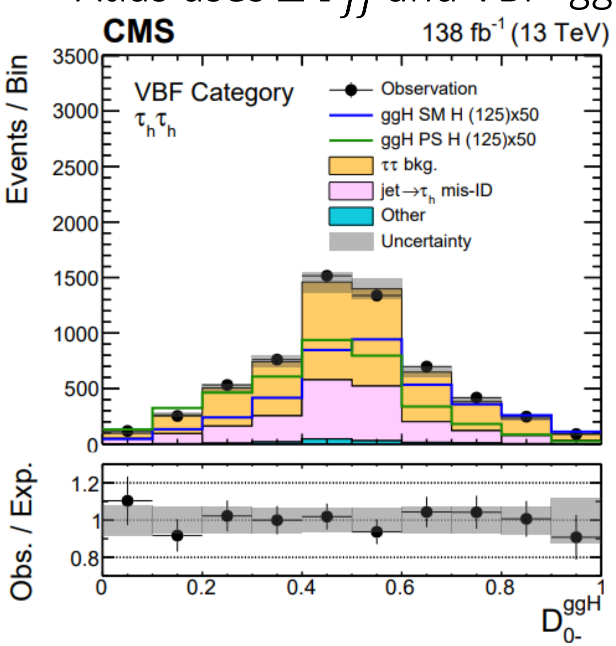
[Accepted by EPJC]







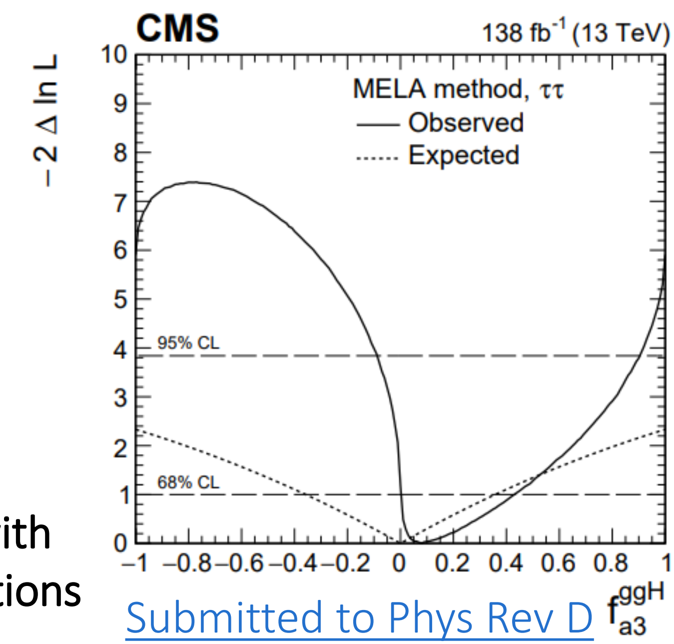
Atlas uses $\Delta\Phi_{jj}$ and VBF+ggH, H→WW



CMS uses MELA discriminants in recent result with ggH,VBF, H → ττ

H → ττ result combined with H → 4l

Both results consistent with Standard Model expectations



[Submitted to Phys Rev D]

Phenomenology of HVV interactions

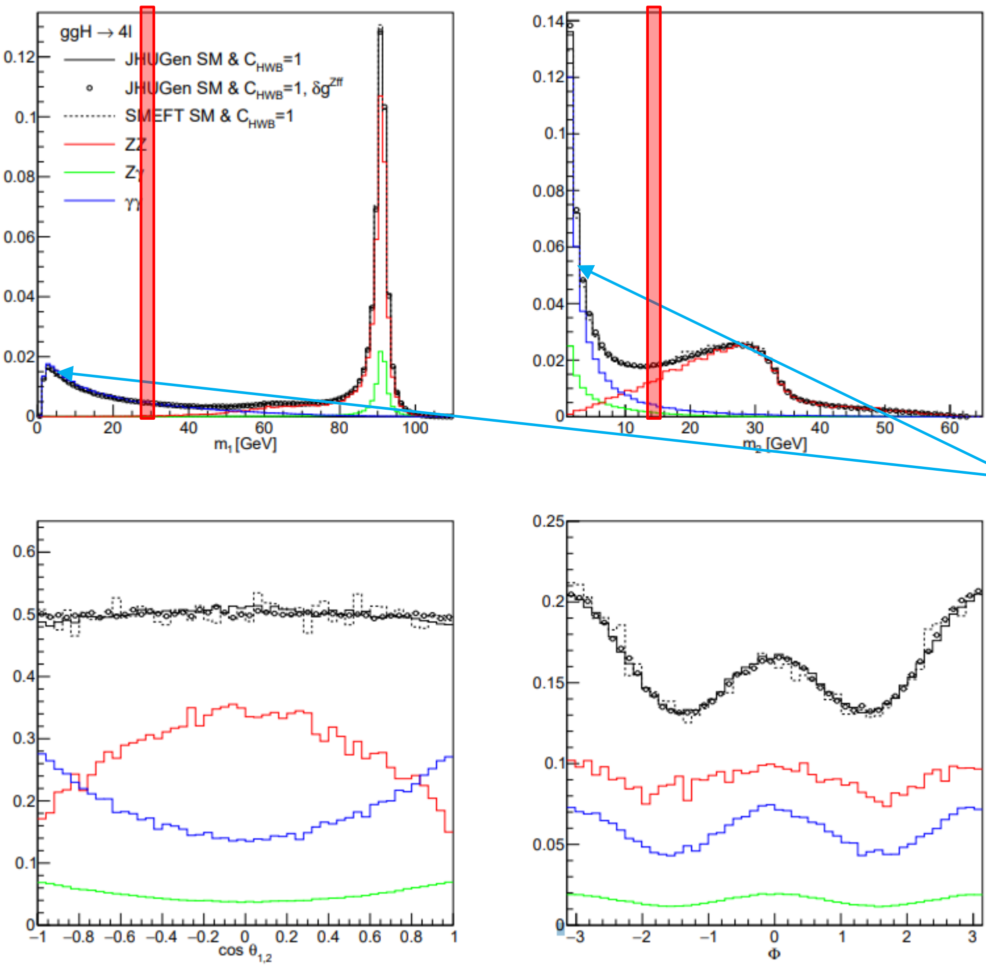
- Experiment is agnostic to choice of basis, physics has no preference of basis

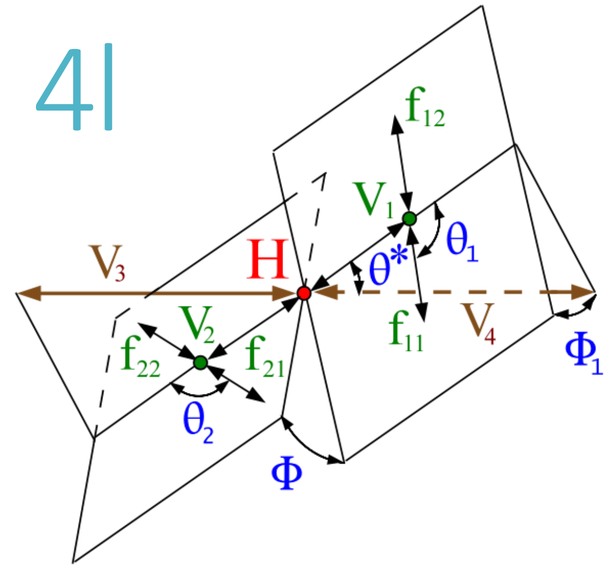
- However, we measure mass eigenstates in the detector
  - *A single Wilson coefficient will affect linear combination of many mass eigenstates*
  - *Not completely intuitive for an experimental physicist to visualize what a coefficient of gauge eigenstates will look like (Difficult to tune analysis for maximal sensitivity to Wilson coefficients)*
  - *Luckily there are tools to do this! Rosetta(SILH,Warsaw,Higgs Basis rotations), JHUGenLexicon (HVV AC basis rotations)*

	$\delta g_1^{ZZ} = \delta g_1^{WW}$	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
$C_{H\widetilde{W}}$	0	0	0	0	0	−0.0929	−0.0513	−0.0283	0	0	0	−0.1212
$C_{H\widetilde{W}B}$	0	0	0	0	0	−0.0513	0.0323	0.0513	0	0	0	0
$C_{H\widetilde{B}}$	0	0	0	0	0	−0.0283	0.0513	−0.0929	0	0	0	0

arxiv:2109.13363

Anomalous HVV in H → 4l





Anomalous photon couplings introduces contributions at low q^2

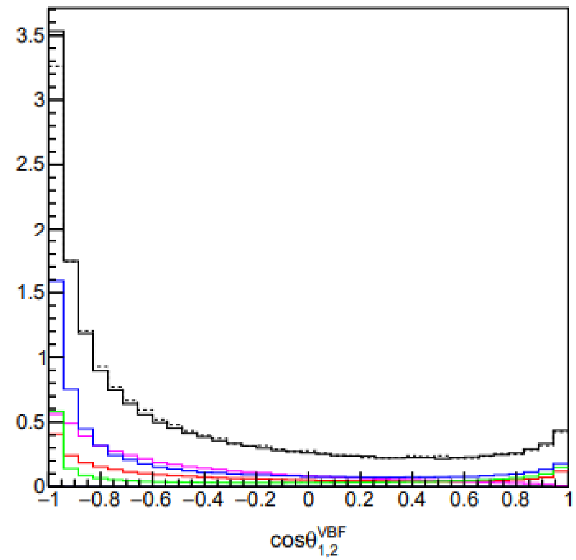
Example: Simulate SM & c_{HWB} = 10

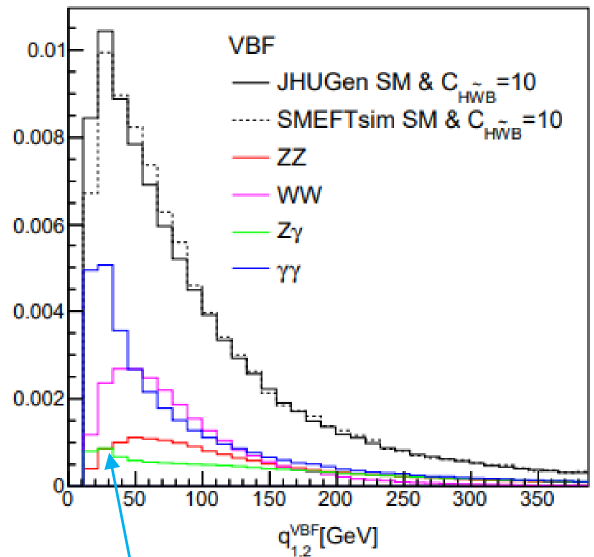
For a single Wilson coefficient 3 different eigenstates in decay with very different kinematic observables!

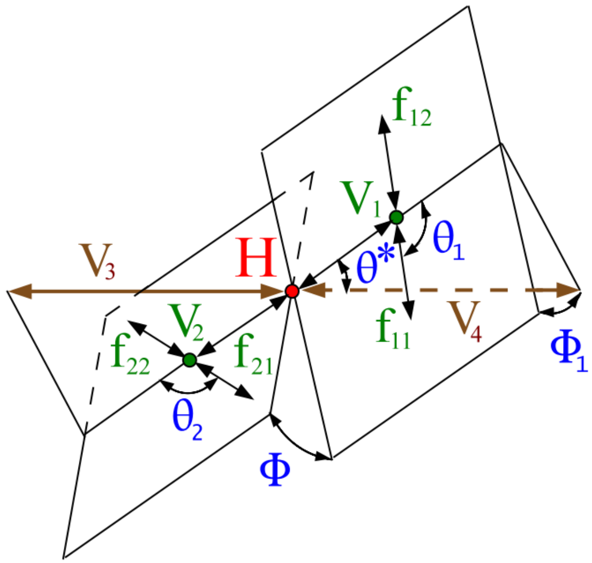
Standard MZ cuts will remove most AC signal

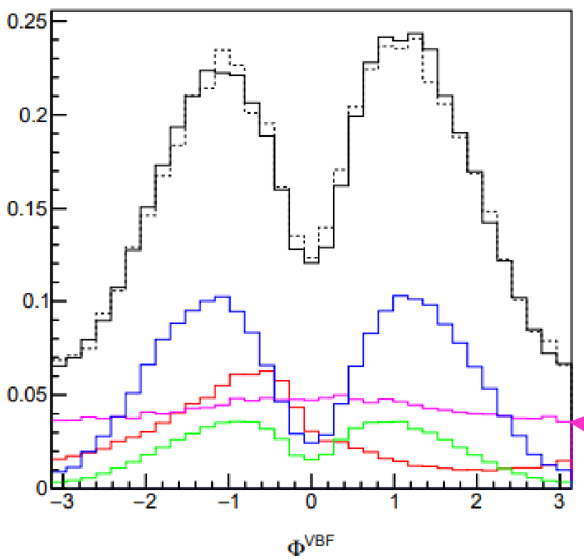
$c_{HWB} = -0.0513 g_2^{ZZ} - 0.0323 g_2^{Z\gamma} - 0.0513 g_2^{\gamma\gamma}$ + others not sensitive to in H-> 4l

Anomalous HVV in VBF









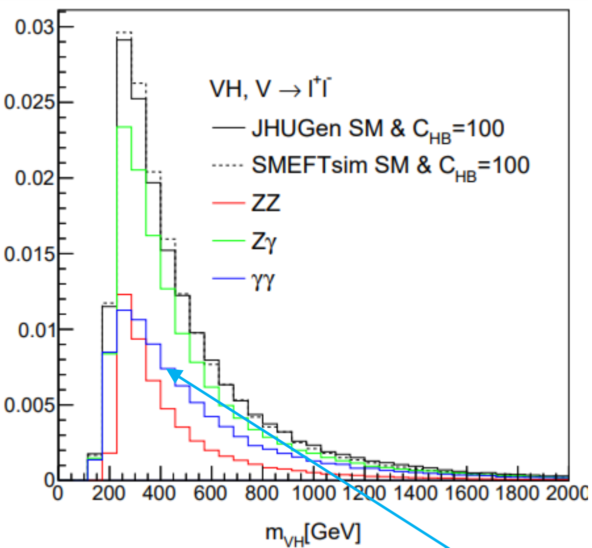
Anomalous photon couplings introduce enhanced $\gamma\gamma$ and $Z\gamma$ fusion contributions at low q^2

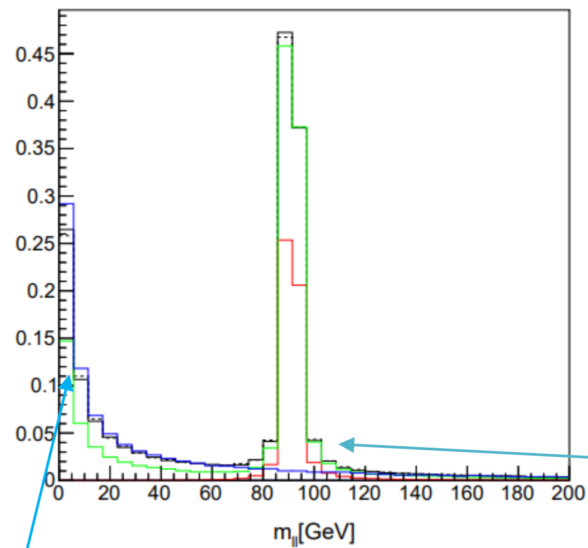
Example: Simulate SM & $\tilde{C}_{HWB}$ = 10

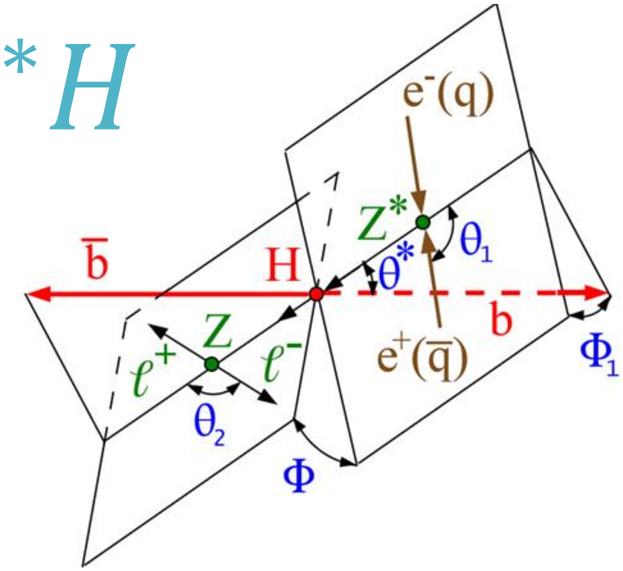
$$\tilde{C}_{HWB} = -0.0513 g_4^{ZZ} + 0.0323 g_4^{Z\gamma} + 0.0513 g_4^{\gamma\gamma}$$

Other non-zero Wilson coefficients such as C_{HW} will affect HWW interactions as well

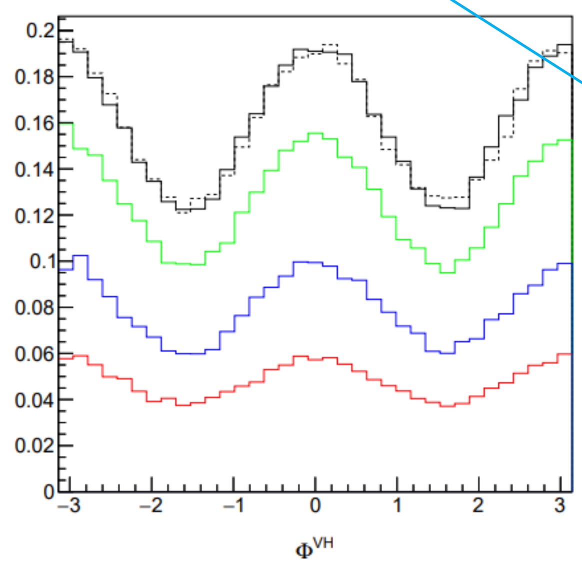
Anomalous HVV in $Z/\gamma^* H$







Tagging VH with $m_{ll} = M_Z$ could miss new physics



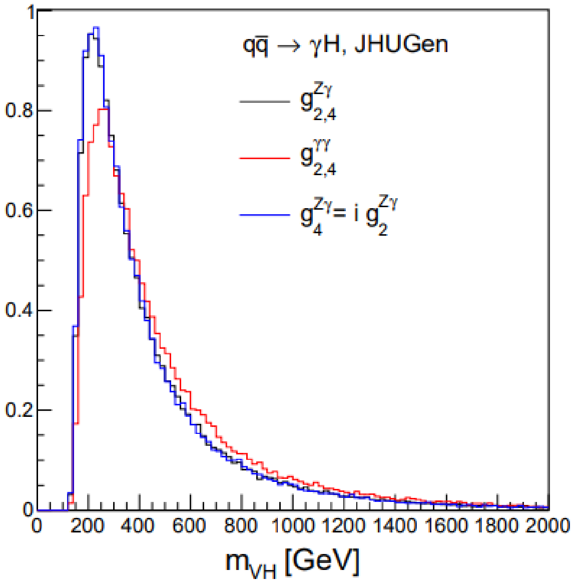
Again, anomalous photon couplings introduce $\gamma^* H$ contributions at low q^2

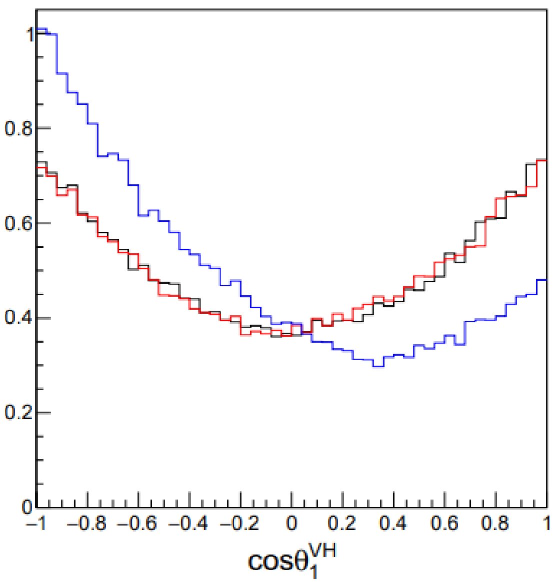
Example: Simulate SM & c_{HB} = 10

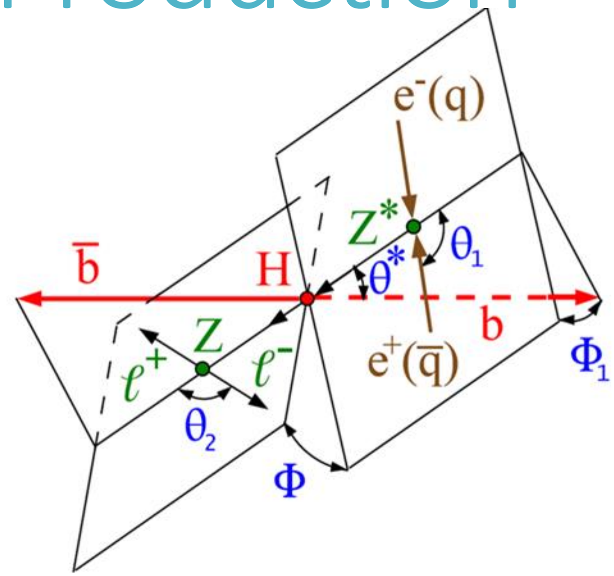
$$c_{HB} = -0.0283 g_2^{ZZ} + 0.0513 g_2^{Z\gamma} - 0.0929 g_2^{\gamma\gamma}$$

Note: Anomalous HWW couplings appear in WH process from c_{HB}

Anomalous HVV in $\gamma\, H$ Production







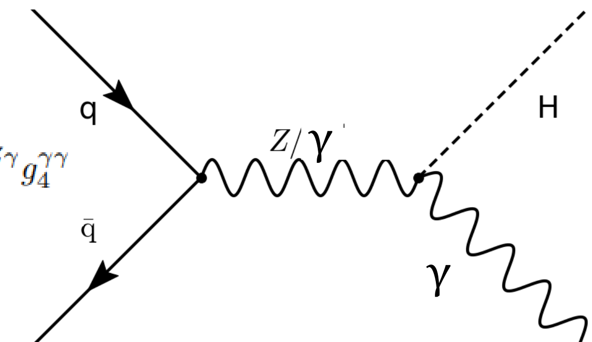
Anomalous HVV couplings may enhance production modes with small SM predicted cross-section (not targeted in current analysis)

Example: γ H production (Higgs + on-shell γ)

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

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

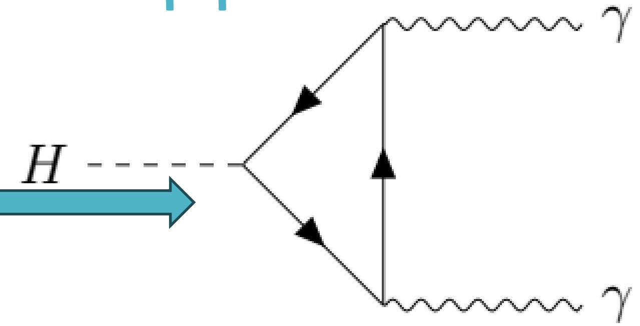
SM predicted cross-section ~ 5fb



Anomalous HVV in H-> γγ

H-> γγ is at leading order, a one-loop process

- Any heavy charged particle can enter this loop
- W boson, top, bottom quark etc.
- (Some heavy fourth generation quark)



In the high mass limit we can treat all of the SM particles in the loop as an effective point like coupling that mimics the SM CP-structure and XS. Assume other couplings well constrained

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

$$R_{\gamma\gamma} \simeq \frac{1}{\left(g_2^{\gamma\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{\gamma\gamma,\mathrm{SM}} + g_2^{\gamma\gamma}\right)^2 + \left(g_4^{\gamma\gamma}\right)^2\right] \qquad g_2^{\gamma\gamma,\mathrm{SM}} = 0.00423$$

As an example, take recent ATLAS H-> γγ signal strength $\mu_{\gamma\gamma} = 1.04^{0.10}_{-0.09}$

Solving for 95% confidence bounds on $g_2^{\gamma\gamma}$ $g_4^{\gamma\gamma}$

$g_2^{\gamma\gamma}$ ~[-0.0087, 0.0003],

$g_4^{\gamma\gamma}$~[-0.0016, 0.0016]

arXiv:2207.00348

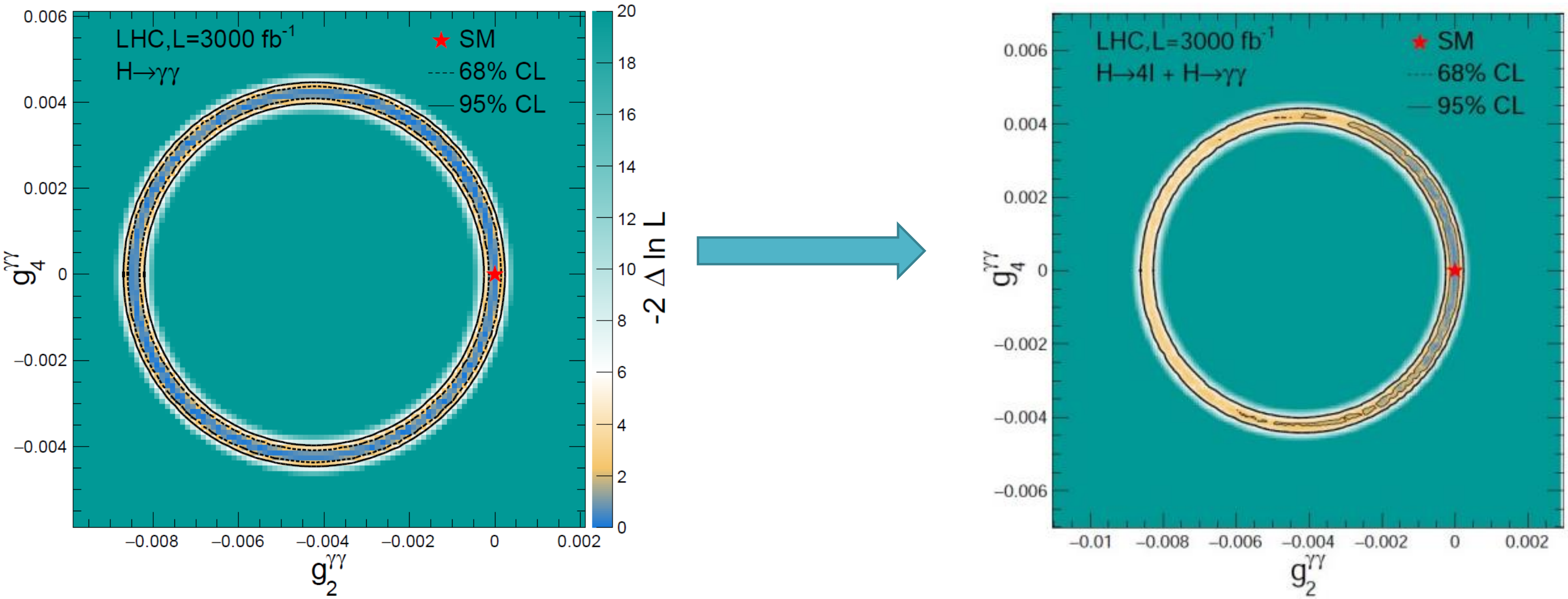
Importance of Combining Channels

Bounds on certain couplings may be well constrained as in the case of H->Zγ and H-> γγ

No Way to Extract CP-Information from these channels

Can only be constrained in combination with HVV measurements

-H->4f decay, VBF and VH production



Example: Projected constraints on γγ couplings for HL-LHC with only H->γγ and H->γγ + H->4l (production and decay)

Conclusion

- Studies of HVV interactions is ongoing at LHC.
  - New combinations and decay channels being targeted
  - Anomalous couplings target SMEFT operators
    - *Enforced SU(2) x U(1) symmetry*

- Important to tune analysis to be sensitive to EFT effects
  - Possible new/enhanced production modes (γH)
  - Expand phase space of analysis to cover EFT effects (low q^2)

- Extract as much information out of every channel as possible!
  - Ex: Assuming yy couplings are best constrained by H->yy
    - *Lose information about CP-Structure*

Backup

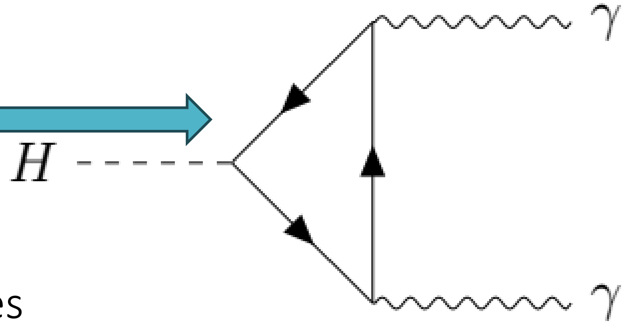
Anomalous HVV in H-> Zγ

H-> Zγ is just as H->γγ , a loop process

Any heavy charged particle can enter this loop

W boson, top, bottom quark etc.

(Some heavy fourth generation quark)



In the high mass limit we can treat all of the SM particles in the loop as an effective point like coupling that mimics the SM CP-structure and XS

$$R_{Z\gamma} \simeq \frac{1}{\left(g_2^{Z\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{Z\gamma,\mathrm{SM}} + g_2^{Z\gamma}\right)^2 + \left(g_4^{Z\gamma}\right)^2\right] \quad g_2^{Z\gamma,\mathrm{SM}} = 0.00675$$

As an example, take recent CMS H-> Zγ signal strength $\mu_{Z\gamma} = 2.4^{0.9}_{-0.9}$ arxiv:2204.12945

Solving for 95% confidence bounds on $g_2^{Z\gamma}$ $g_4^{Z\gamma}$ -> $g_2^{Z\gamma}$ ~[-0.019, 0.005], $g_4^{Z\gamma}$~[- 0.01, 0.01]