# Anomalous couplings of $H(125)^0$ boson: CMS perspective

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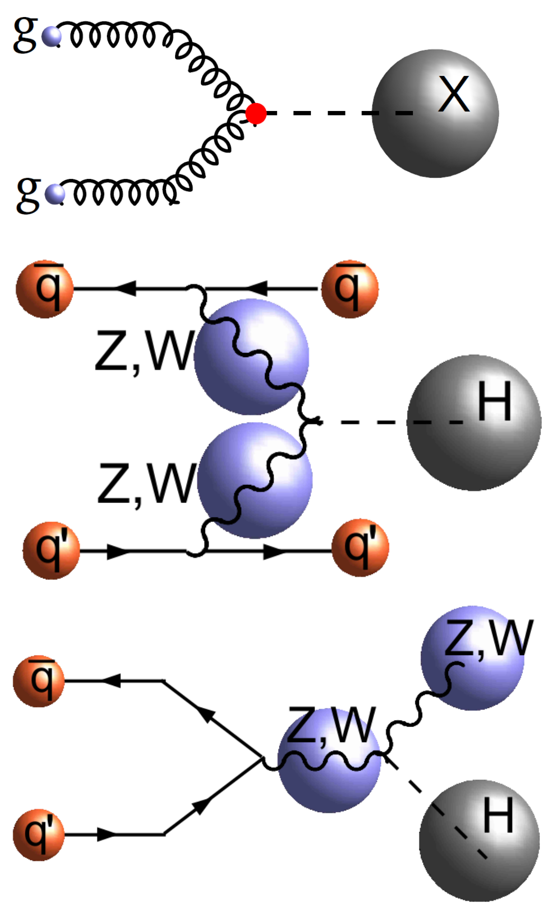
Special thanks to David Marzocca and Markus Schulze (theory) for discussion of anomalous effects and comparison of frameworks

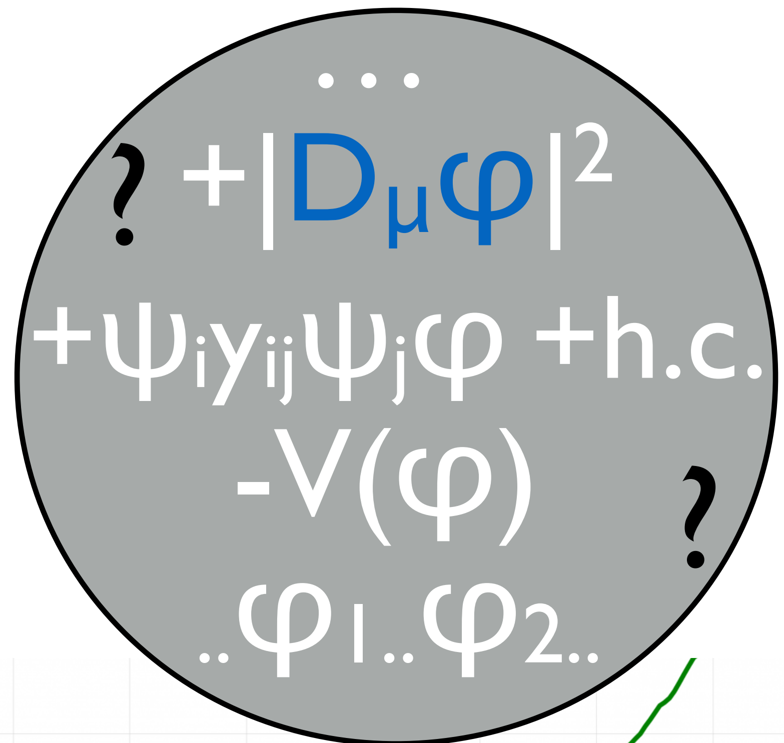
May 8, 2017

LHC Higgs Cross Sections Working Group meeting
Working Group 2 kickoff meeting post-YR4

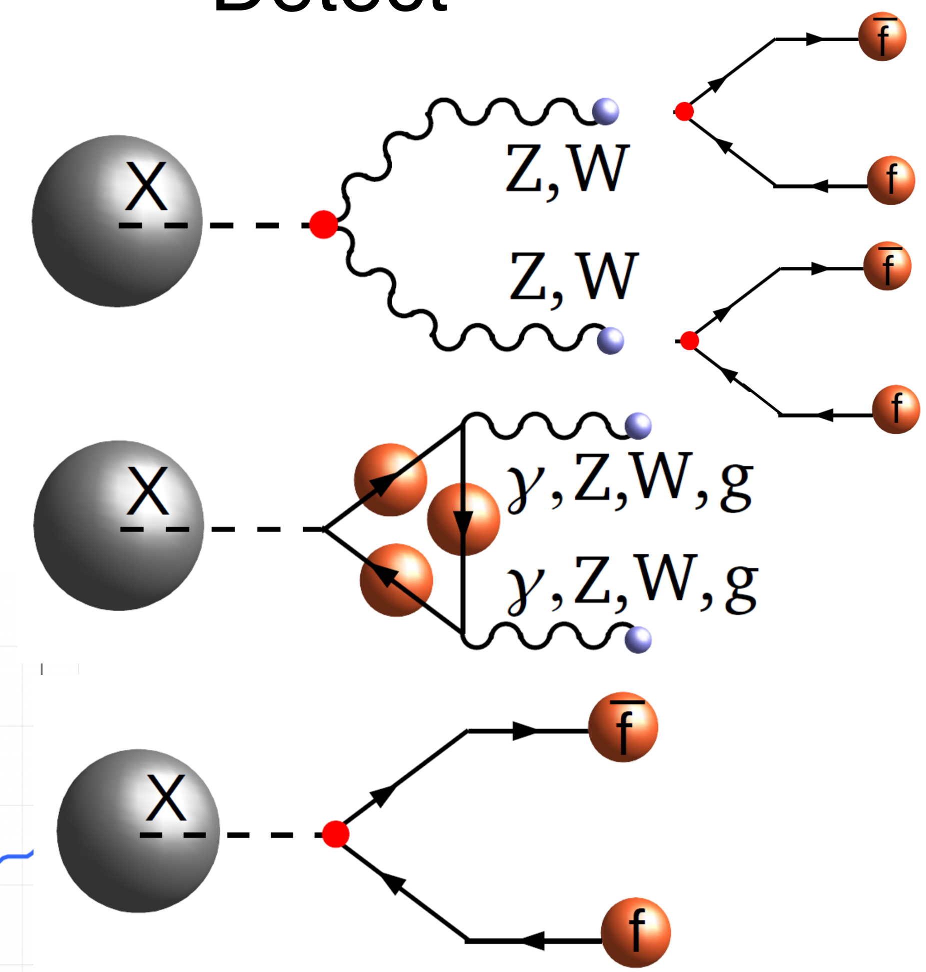
# Focus on $H^0$ boson anomalous couplings

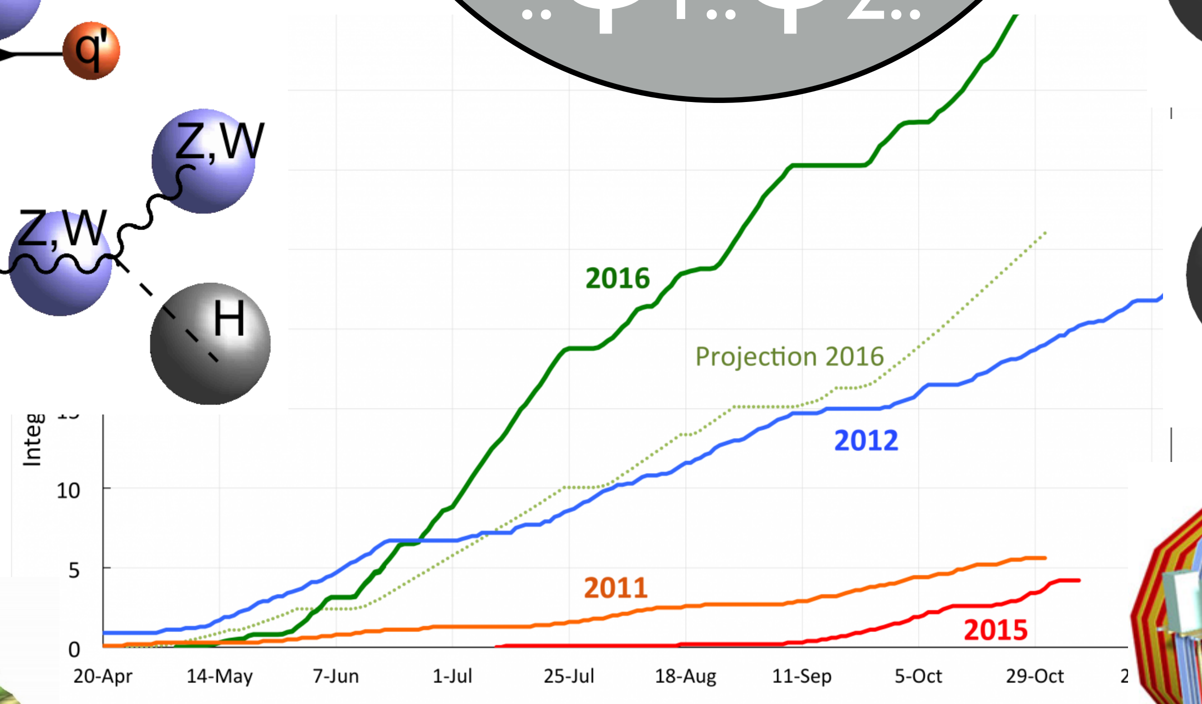
Produce

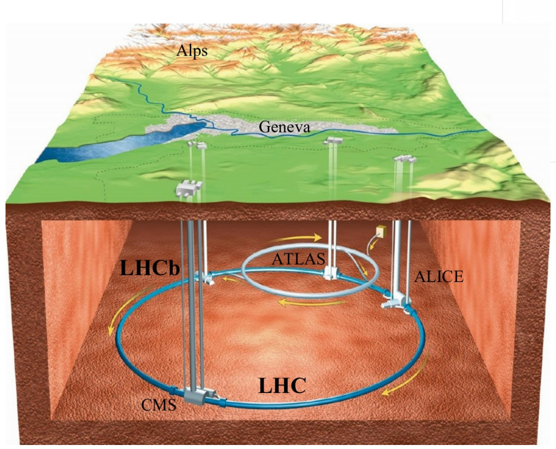


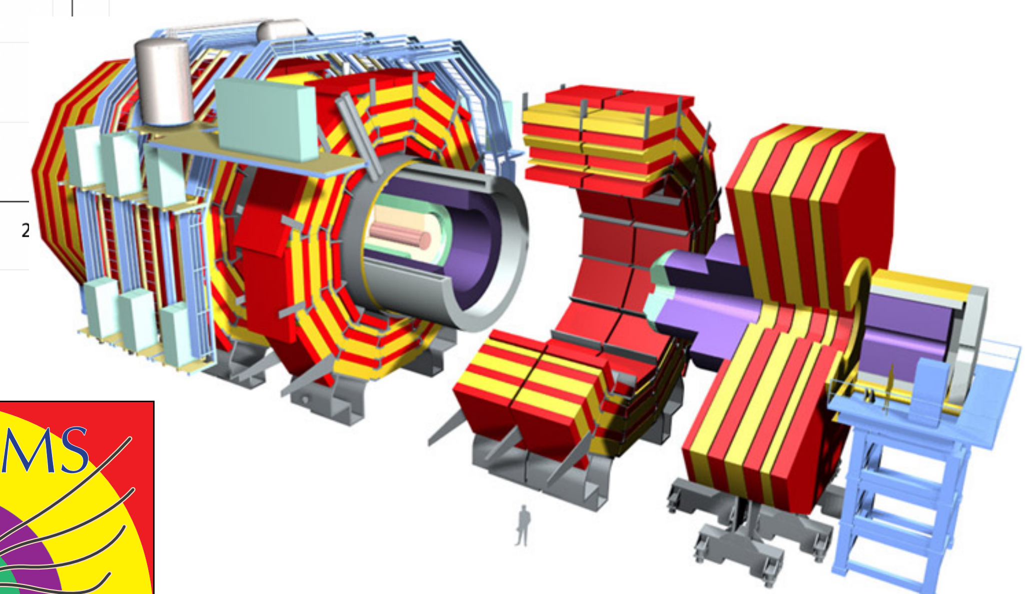




Detect

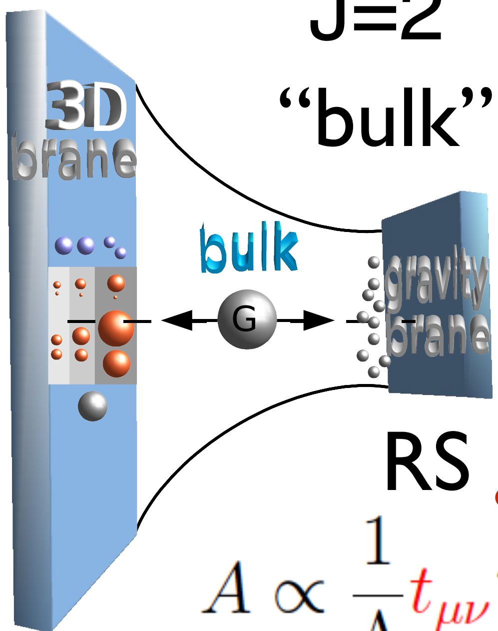


# “Exotic” Spin Studies in Run-1




J=2

“bulk” $g_5 \gg g_1$

RS $g_5 = g_1$

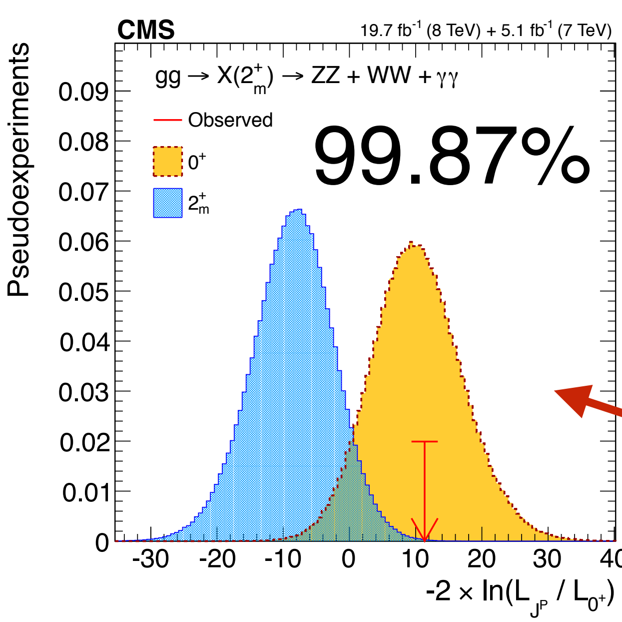
$$A \propto \frac{1}{\Lambda} t_{\mu\nu} \mathcal{T}^{\mu\nu}$$

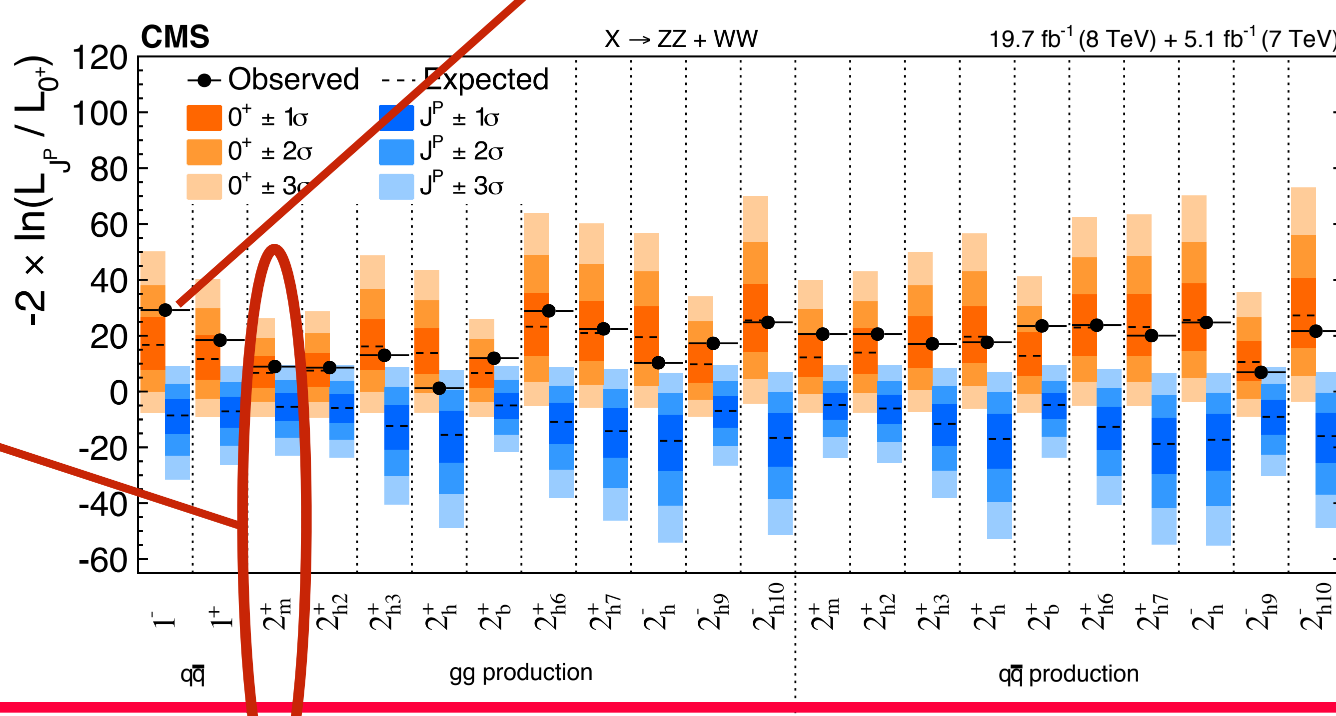
$$A(X \to V_1 V_2) = 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta}$$
$$+ g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left( f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left( 2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left( \epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left( g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left( \epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right)$$

- J=1,2 excluded with $H(125)^0$

J=1 excluded from angular and γγ

H→ZZ,WW,γγ




- Bottom line: study J=0 in Run2

# J=0 parameterization: target measurements

- Two equivalent parameterizations: Effective Lagrangian

ZZ

$$L(HVV) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 H Z^\mu \Box Z_\mu - \frac{\kappa_3}{2(\Lambda_Q)^2} m_Z^2 \Box H Z^\mu Z_\mu - \frac{1}{2} a_2 H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

$$+ a_1^{WW} m_W^2 H W^{+\mu} W_\mu^- - \frac{1}{(\Lambda_1^{WW})^2} m_W^2 H \left(\kappa_1^{WW} W_\mu^- \Box W^{+\mu} + \kappa_2^{WW} W_\mu^+ \Box W^{-\mu}\right)$$

$$- \frac{\kappa_3^{WW}}{\left(\Lambda_Q^{WW}\right)^2} m_W^2 \Box H W^{+\mu} W_\mu^- - a_2^{WW} H W^{+\mu\nu} W_{\mu\nu}^- - a_3^{WW} H W^{+\mu\nu} \tilde{W}_{\mu\nu}^-$$

WW

$$+ \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} H F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} H F^{\mu\nu} \tilde{Z}_{\mu\nu}$$

Zγ

$$- \frac{1}{2} a_2^{\gamma\gamma} H F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} H F^{\mu\nu} \tilde{F}_{\mu\nu}$$

γγ

$$- \frac{1}{2} a_2^{gg} H G_a^{\mu\nu} G_{\mu\nu}^a - \frac{1}{2} a_3^{gg} H G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a ,$$

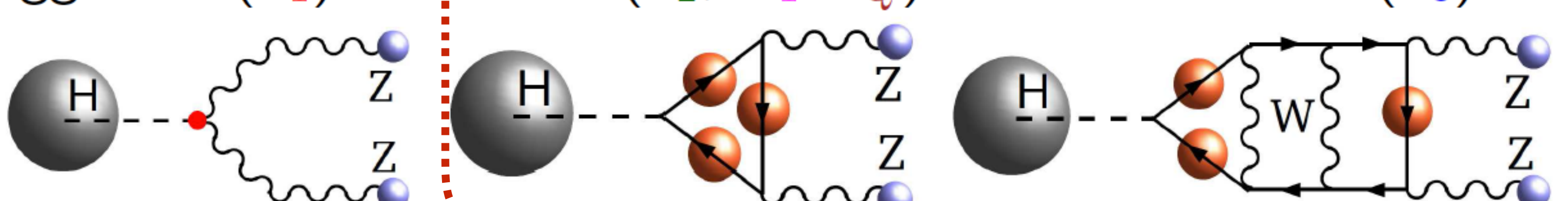
gg

- or Amplitude

$$A = \frac{1}{v} \left( \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_1+q_2)^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{q_1^2+q_2^2}{(\Lambda_1)^2} \right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

SM Higgs $0^+$: $(a_1)$ $CP$ | $\sim\%$ $(a_2,\ \Lambda_1\ \Lambda_Q)$ $CP$ | $\sim 10^{-10}$ ? $(a_3)$ $\not{CP}$

tiny in SM




(or beyond SM) (or beyond SM)

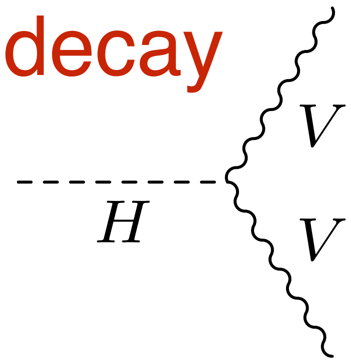
# Measurements: HVV and Hff

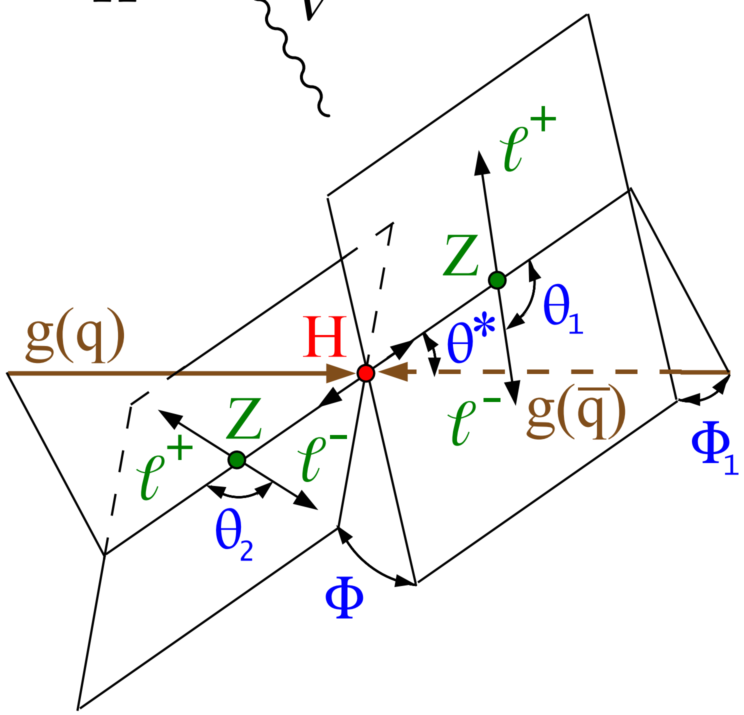
- Use VV→H→VV→4ℓ as an example of HVV studies

CMS-HIG-17-011

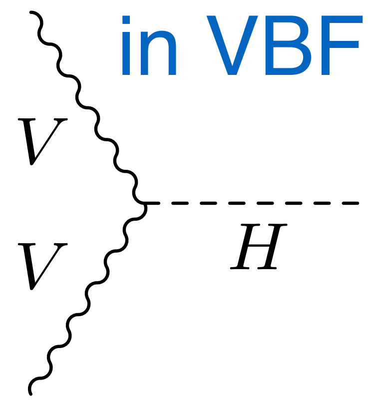
MC and techniques: MELA / JHUGen+MCFM

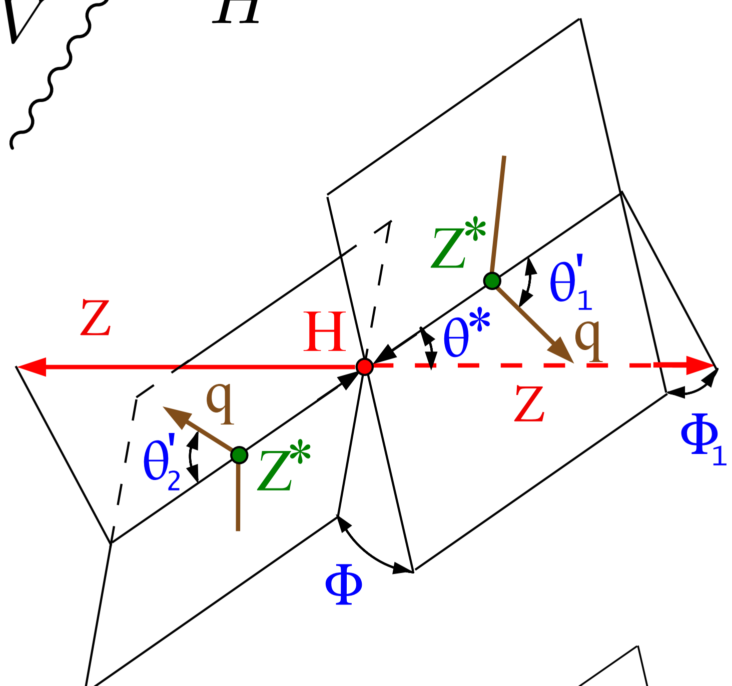
in decay



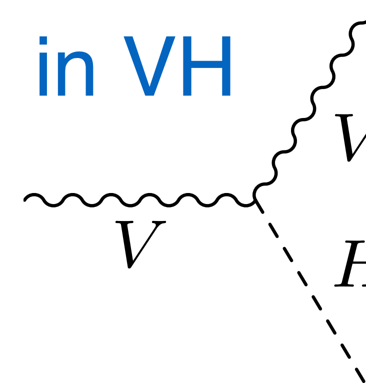



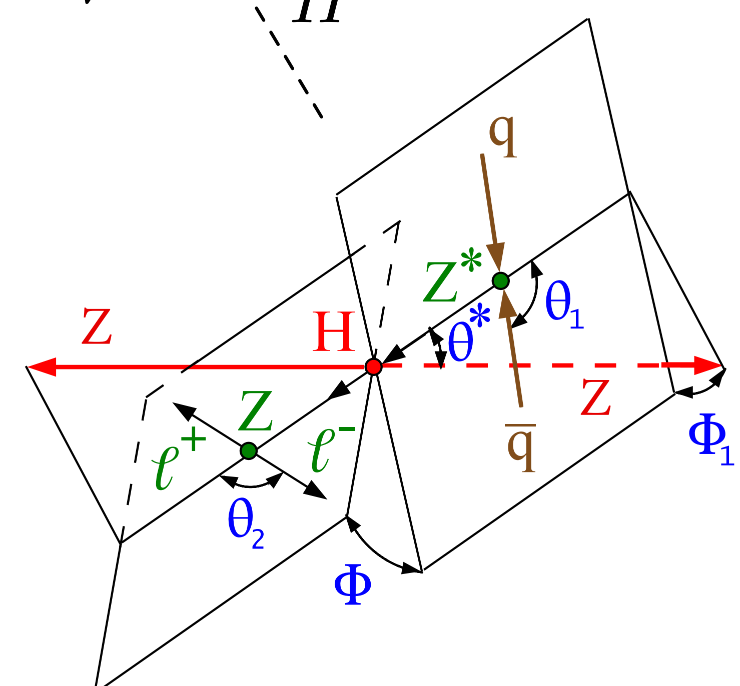

in VBF




in VH

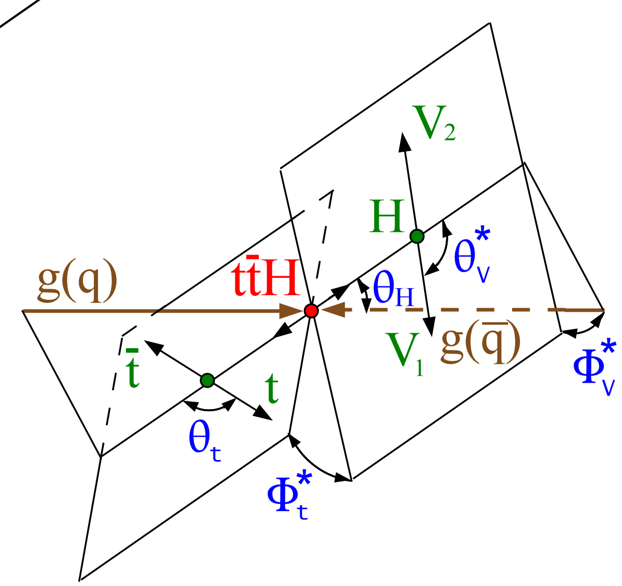


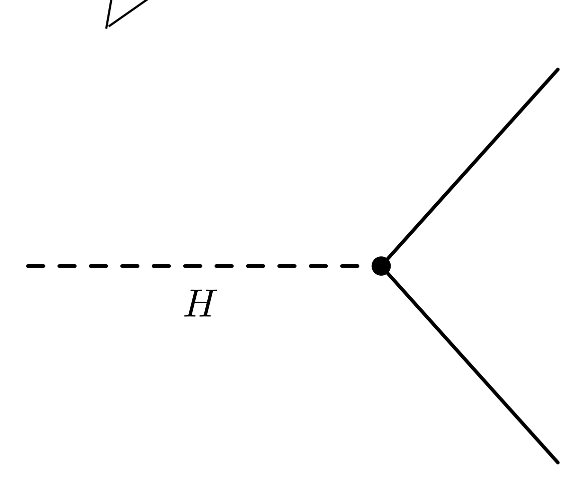




- No Hff yet

  not discussed today

$$\mathcal{A}(Hf\bar{f}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f$$



# Measurements in Run1 and Run2

MELA / JHUGen+MCFM

- Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs
  CMS-HIG-12-041, CMS arXiv:1212.6639 → $f_{a3}$ in $H\rightarrow 4\ell$ & hypothesis testing
- Measurement of the properties of a Higgs boson in the four-lepton final state
  CMS arXiv:1312.5353, CMS-HIG-13-002 $f_{a3}$ in $H\rightarrow 4\ell$ & more hypothesis testing
- Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV
  CMS arXiv:1411.3441, CMS-HIG-14-018 $f_{a3},f_{a2},f_{\Lambda 1}$ in $H\rightarrow WW,ZZ,Z\gamma^*,\gamma^*\gamma^*$ & testing
- Limits on the Higgs boson lifetime and width from its decay to four charged leptons
  CMS arXiv:1507.06656, CMS-HIG-14-036 $f_{\Lambda Q}$ in $H^*\rightarrow 4\ell$ offshell
- Combined search for anomalous pseudoscalar HVV couplings in VH production and H to VV decay
  CMS arXiv:1602.04305, CMS-HIG-14-035 $f_{a3}$ in $VH(\rightarrow bb)$ & combination

Run2

- Constraints on anomalous Higgs boson couplings in production and decay H->4l
  CMS-PAS-HIG-17-011 (also HIG-16-033) $f_{a3},f_{a2},f_{\Lambda 1},f_{\Lambda 1}^{Z\gamma}$ in $H\rightarrow 4\ell$, VBF, VH

JHUGen

- Evidence for the spin-0 nature of the Higgs boson using ATLAS data
  ATLAS arXiv:1307.1432 hypothesis testing

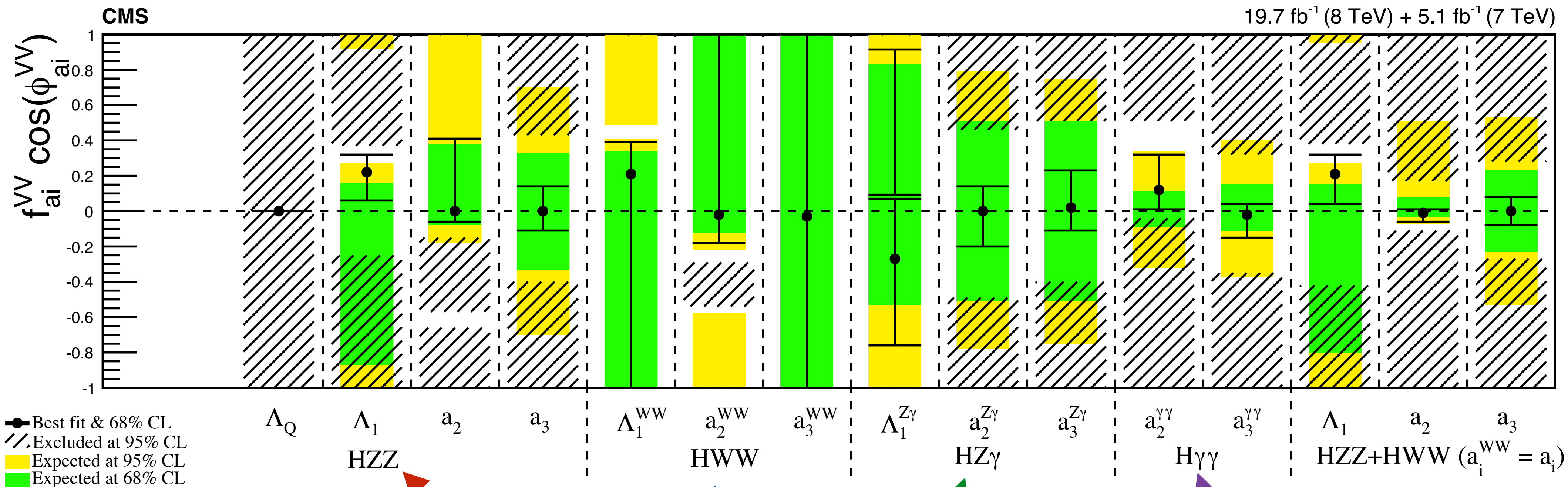
MG/JHUGen

- Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector
  ATLAS arXiv:1506.05669 $\{f_{a3}\},\{f_{a2}\}$ in $H\rightarrow ZZ,WW$ & hypothesis testing

HAWK

- Test of CP Invariance in vector-boson fusion production of the Higgs boson using the Optimal Observable method in the ditau decay channel with the ATLAS detector
  ATLAS arXiv:1602.04516: $\{f_{a3}\}$ in $VBF(H\rightarrow\tau\tau)$

# Summary of Measurements




ZZ

$$L(HVV) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 H Z^\mu \Box Z_\mu - \frac{\kappa_3}{2(\Lambda_Q)^2} m_Z^2 \Box H Z^\mu Z_\mu - \frac{1}{2} a_2 H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

WW

$$+ a_1^{WW} m_W^2 H W^{+\mu} W_\mu^- - \frac{1}{(\Lambda_1^{WW})^2} m_W^2 H \left(\kappa_1^{WW} W_\mu^- \Box W^{+\mu} + \kappa_2^{WW} W_\mu^+ \Box W^{-\mu}\right)$$

$$- \frac{\kappa_3^{WW}}{\left(\Lambda_Q^{WW}\right)^2} m_W^2 \Box H W^{+\mu} W_\mu^- - a_2^{WW} H W^{+\mu\nu} W_{\mu\nu}^- - a_3^{WW} H W^{+\mu\nu} \tilde{W}_{\mu\nu}^-$$

Zγ

$$+ \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} H F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} H F^{\mu\nu} \tilde{Z}_{\mu\nu}$$

γγ

$$- \frac{1}{2} a_2^{\gamma\gamma} H F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} H F^{\mu\nu} \tilde{F}_{\mu\nu}$$

gg

$$- \frac{1}{2} a_2^{gg} H G_a^{\mu\nu} G_{\mu\nu}^a - \frac{1}{2} a_3^{gg} H G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a ,$$

# Summary of Measurements

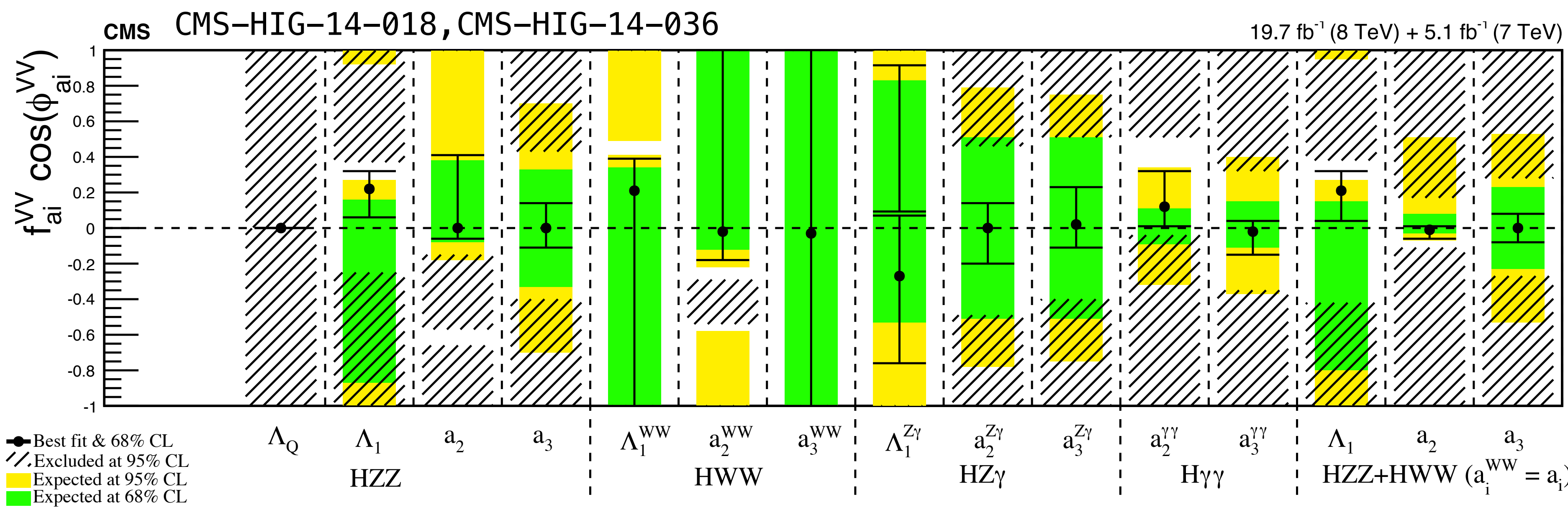
## $H^0$ SPIN AND $CP$ PROPERTIES

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|

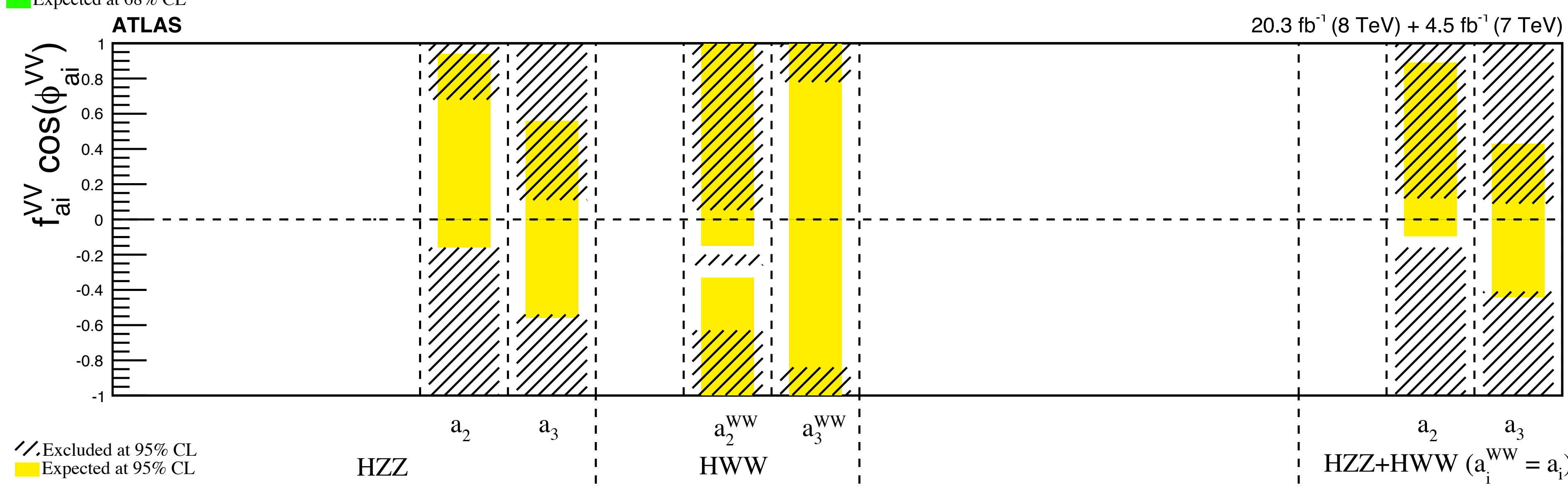
• • • We do not use the following data for averages, fits, limits, etc. • • •

- Run1 in H→VV (more on production, but same measurements)

CMS:




ATLAS:




arXiv:1506.05669

# Experimental Observables and Measurements

Measurements: $$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

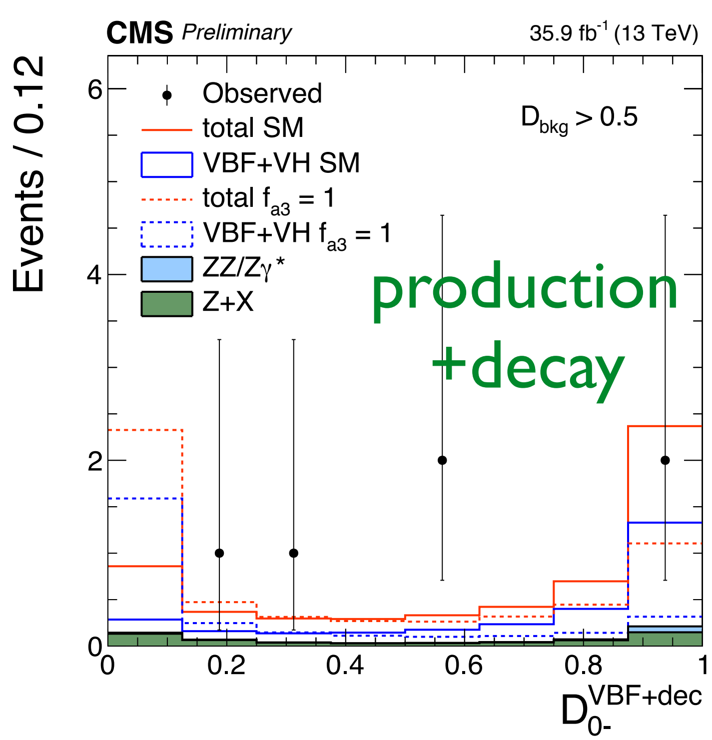
$$(1-f_{an})\,\mathcal{T}^{i,k}_{a1}(\vec{x}) + f_{an}\,\mathcal{T}^{i,k}_{an}(\vec{x}) + \sqrt{f_{an}(1-f_{an})}\,\mathcal{T}^{i,k}_{a1,an}(\vec{x};\phi_{an})$$

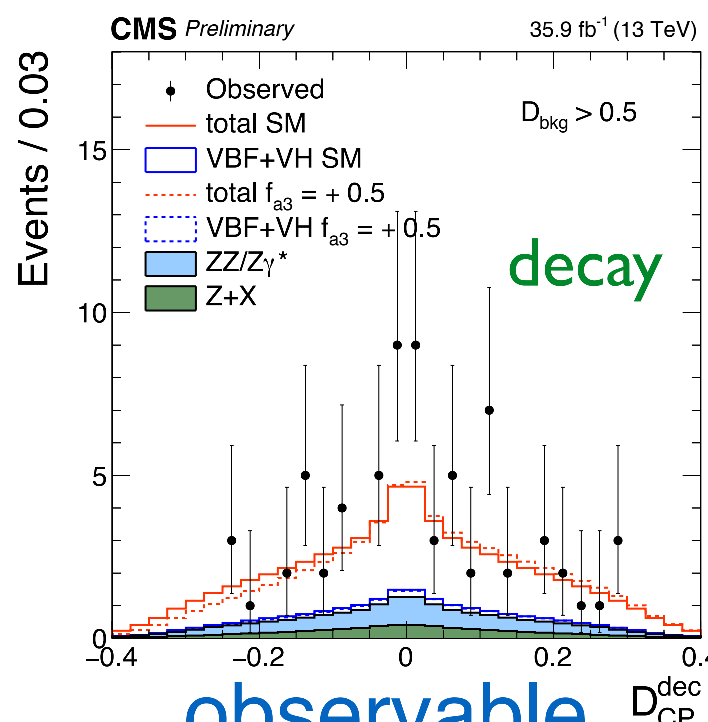
## Optimal MELA observables in 3D fit

$D_{bkg}$ $\quad D_{0-} = \frac{P_{0+}}{P_{0+}+P_{0-}}$ $\quad D_{CP} = \frac{P_{interference}}{P_{0+}+P_{0-}}$

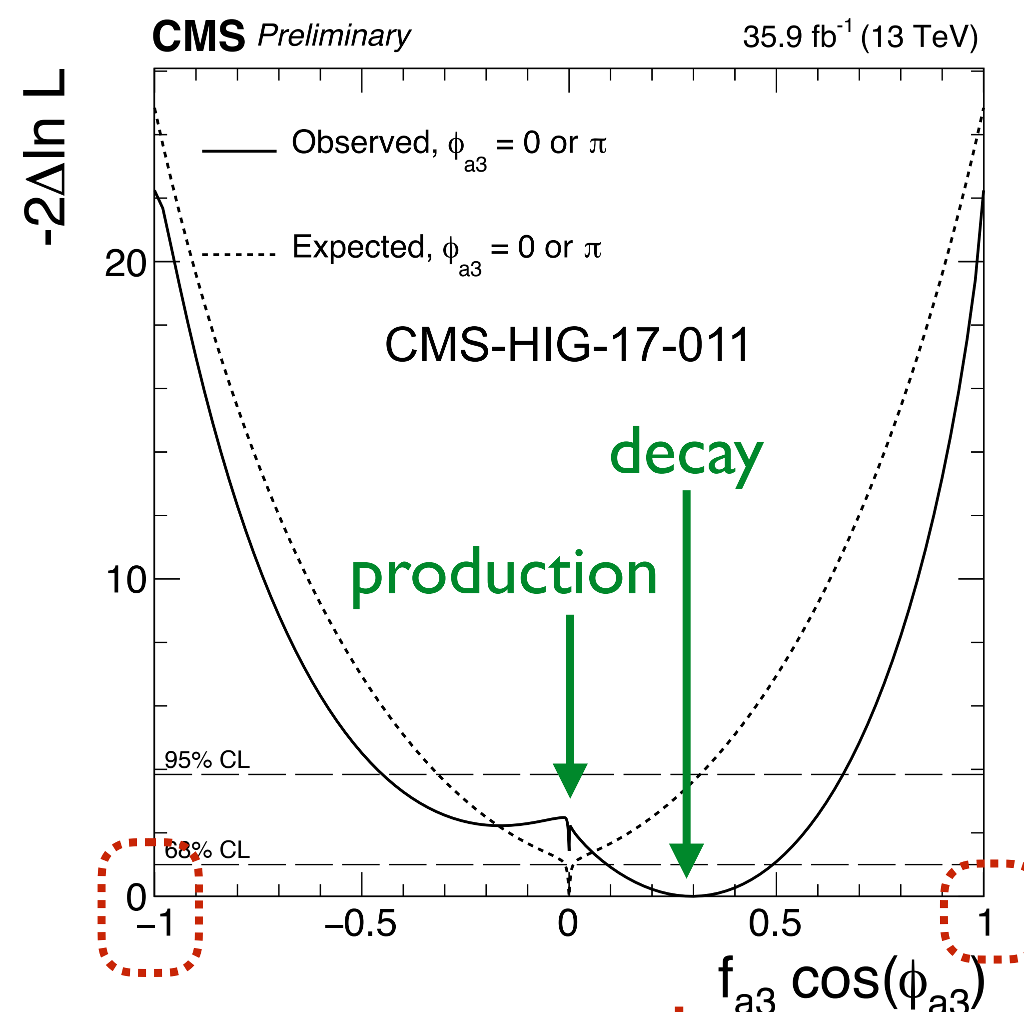
production&decay information in each category

## VV→H→VV→4ℓ




observable




measurement
[-1,1]

# Experimental Observables and Measurements

CMS-HIG-17-011

## Observables:

| category | VBF 2 jet-tagged | VH hadronic-tagged | Untagged |
|---|---|---|---|
| target | $qq'VV \to qq'H \to (jj)(4\ell)$ | $q\bar{q} \to VH \to (jj)(4\ell)$ | $H \to 4\ell$ |
| selection | $\mathcal{D}_{2jet}^{VBF}$ or $\mathcal{D}_{2jet}^{VBF,BSM} > 0.5$ | $\mathcal{D}_{2jet}^{ZH}$ or $\mathcal{D}_{2jet}^{ZH,BSM}$ or $\mathcal{D}_{2jet}^{WH}$ or $\mathcal{D}_{2jet}^{WH,BSM} > 0.5$ | not VBF-jets not VH-jets |
| $f_{a3}$ obs. | $\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{VBF+dec}, \mathcal{D}_{CP}^{VBF}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{VH+dec}, \mathcal{D}_{CP}^{VH}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{dec}, \mathcal{D}_{CP}^{dec}$ |
| $f_{a2}$ obs. | $\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{VBF+dec}, \mathcal{D}_{int}^{VBF}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{VH+dec}, \mathcal{D}_{int}^{VH}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{dec}, \mathcal{D}_{int}^{dec}$ |
| $f_{\Lambda1}$ obs. | $\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{VBF+dec}, \mathcal{D}_{0h+}^{VBF+dec}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{VH+dec}, \mathcal{D}_{0h+}^{VH+dec}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{dec}, \mathcal{D}_{0h+}^{dec}$ |
| $f_{\Lambda1}^{Z\gamma}$ obs. | $\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{Z\gamma,VBF+dec}, \mathcal{D}_{0h+}^{VBF+dec}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{Z\gamma,VH+dec}, \mathcal{D}_{0h+}^{VH+dec}$ | $\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{Z\gamma,dec}, \mathcal{D}_{0h+}^{dec}$ |

## Measurements:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\,(\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

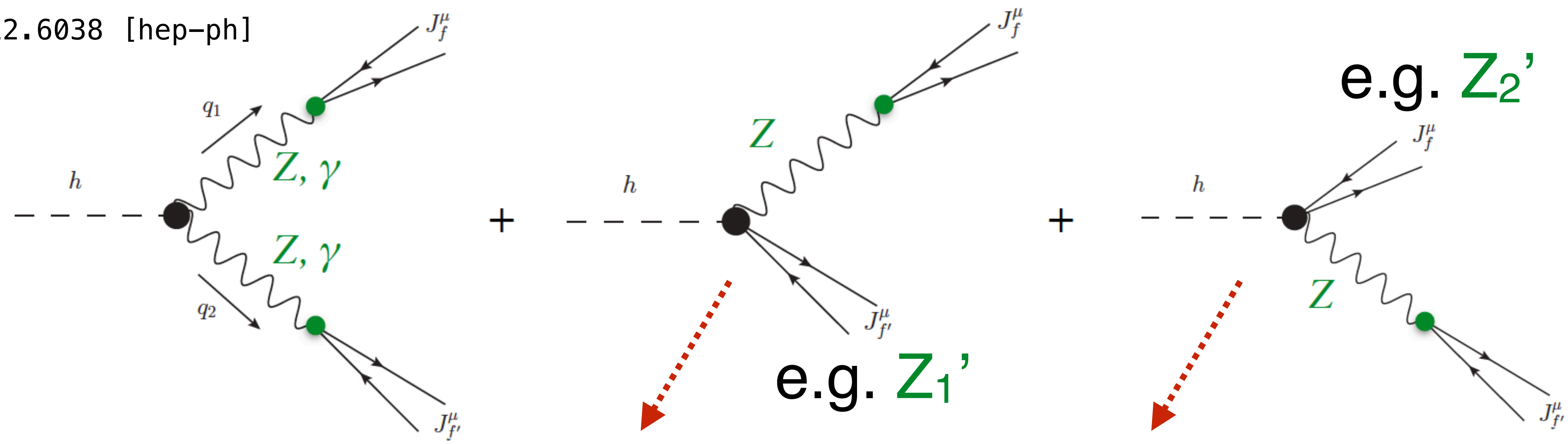
| Anomalous Coupling | Coupling Phase | Effective Fraction | Translation Constant |
|---|---|---|---|
| $a_3$ | $\phi_{a3}$ | $f_{a3}$ | $\sigma_1/\sigma_3 = 6.53$ |
| $a_2$ | $\phi_{a2}$ | $f_{a2}$ | $\sigma_1/\sigma_2 = 2.77$ |
| $\Lambda_1$ | $\phi_{\Lambda1}$ | $f_{\Lambda1}$ | $\sigma_1/\tilde{\sigma}_{\Lambda1} = 1.47 \times 10^4\ \text{TeV}^{-4}$ |
| $\Lambda_1^{Z\gamma}$ | $\phi_{\Lambda1}^{Z\gamma}$ | $f_{\Lambda1}^{Z\gamma}$ | $\sigma_1'/\tilde{\sigma}_{\Lambda1}^{Z\gamma} = 5.80 \times 10^3\ \text{TeV}^{-4}$ |

$$\frac{|a_i|}{|a_1|} = \sqrt{f_{ai}/f_{a1}} \times \sqrt{\sigma_1/\sigma_i}, \qquad f_{a1} = (1 - f_{\Lambda1} - f_{a2} - f_{a3} - \ldots)$$

- 1 or 2 measurements at a time (!)

# Contact terms and HVV amplitude

PO arXiv:1412.6038 [hep-ph]




$$\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta_1^{SM}(q_1^2,q_2^2)\right) g^{\alpha\beta}$$

combination of $\Lambda_1$ and $\Lambda_1^{Z\gamma}$

tiny SM

up to 26 (?) contact terms in qq'→q"q"'(H→4ℓ) (e.g. W'+us)

| couplings in PO formulation | couplings in AC or EFT formulation | |
|---|---|---|
| $\kappa_{ZZ}$ | $\frac{v}{2}\left(a_1 - 2\frac{m_Z^2}{(\Lambda_1)^2}\cos\phi_{\Lambda 1}\right)$ | μ & $f_{\Lambda 1}$ |
| $\epsilon_{ZZ}$ | $va_2$ | $f_{a2}$ |
| $\epsilon_{ZZ}^{CP}$ | $va_3$ | $f_{a3}$ |
| $\epsilon_{ZfR}$ | $-g_Z^{fR}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda 1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda 1}^{Z\gamma}$ | |
| $\epsilon_{ZfL}$ | $-g_Z^{fL}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda 1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda 1}^{Z\gamma}$ | |

$f_R = e_R, \mu_R, \tau_R, u_R, d_R, s_R, c_R, b_R, t_R$ →

$f_L = e_L, \mu_L, \tau_L, u_L, d_L, s_L, c_L, b_L, t_L$ →

thanks to David Marzocca

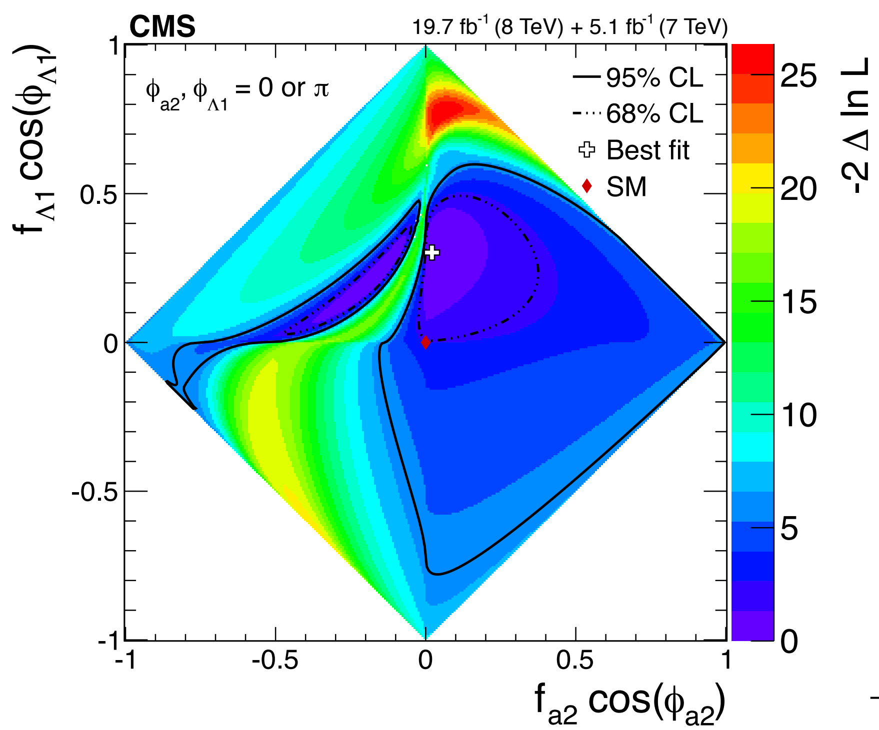
SM Zff

CMS-HIG-17-011

# Contact terms and HVV amplitude

- In decay $H\to VV\to 4\ell$ and with $\ell$ flavor universality ($\varepsilon_{Z\mu}=\varepsilon_{Ze}$)

  contact terms ($\varepsilon_{Z\ell_R}$, $\varepsilon_{Z\ell_L}$) ~ amplitudes ($\Lambda_1$, $\Lambda_1^{Z\gamma}$)




- Perform 2D fit ($\Lambda_1$, $\Lambda_1^{Z\gamma}$)

  get ($\varepsilon_{Z\ell_R}$, $\varepsilon_{Z\ell_L}$) or ($\Lambda_1$, $\Lambda_1^{Z\gamma}$)

← ($f_{\Lambda1}$,$f_{a2}$) done in the past, can do ($f_{\Lambda1}$,$f_{\Lambda1}^{Z\gamma}$)

| couplings in PO formulation | couplings in AC or EFT formulation |
|---|---|
| $\kappa_{ZZ}$ | $\frac{v}{2}\left(a_1 - 2\frac{m_Z^2}{(\Lambda_1)^2}\cos\phi_{\Lambda1}\right)$ |
| $\epsilon_{ZZ}$ | $va_2$ |
| $\epsilon_{ZZ}^{CP}$ | $va_3$ |
| $\epsilon_{ZfR}$ | $-g_Z^{fR}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda1}^{Z\gamma}$ |
| $\epsilon_{ZfL}$ | $-g_Z^{fL}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda1}^{Z\gamma}$ |

$\mu$ & $f_{\Lambda1}$

$f_{a2}$

$f_{a3}$

$f_R = e_R,\mu_R,\tau_R,u_R,d_R,s_R,c_R,b_R,t_R$ →

$f_L = e_L,\mu_L,\tau_L, u_L,d_L,s_L, c_L,b_L,t_L$ →

SM Zff

thanks to David Marzocca

CMS-HIG-17-011

# Contact terms and HVV amplitude

- In decay $H\to VV\to 4\ell$ and with $\ell$ flavor universality ($\varepsilon_{Z\mu}=\varepsilon_{Ze}$)

  contact terms ($\varepsilon_{Z\ell_R}$, $\varepsilon_{Z\ell_L}$) ~ amplitudes ($\Lambda_1$, $\Lambda_1^{Z\gamma}$)

- In production+decay $WW'+ZZ'\to H\to VV\to 4\ell$

flavor universality (SM) helps less ($\varepsilon_{Z\mu}=\varepsilon_{Ze}\sim\varepsilon_{Zu}=\varepsilon_{Zc}\sim\varepsilon_{Zd}=\varepsilon_{Zs}=\varepsilon_{Zb}$)

need both ZZ' and WW' fusion ($\varepsilon_{W\mu},\varepsilon_{We},\varepsilon_{Wu},\varepsilon_{Ws},\varepsilon_{Wd},\varepsilon_{Wc},\varepsilon_{Wb}$)

we cannot deal with 14 ZZ'+12 WW' (?) contact terms (still no FCNC)

opted to relate as in Zff and Wff

up to 26 (?) contact terms in $qq'\to q''q'''(H\to 4\ell)$

| | couplings in PO formulation | couplings in AC or EFT formulation | |
|---|---|---|---|
| | $\kappa_{ZZ}$ | $\frac{v}{2}\left(a_1 - 2\frac{m_Z^2}{(\Lambda_1)^2}\cos\phi_{\Lambda 1}\right)$ | $\mu$ & $f_{\Lambda 1}$ |
| | $\epsilon_{ZZ}$ | $va_2$ | $f_{a2}$ |
| | $\epsilon_{ZZ}^{CP}$ | $va_3$ | $f_{a3}$ |
| $f_R = e_R,\mu_R,\tau_R,u_R,d_R,s_R,c_R,b_R,t_R$ → | $\epsilon_{ZfR}$ | $-g_Z^{fR}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda 1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda 1}^{Z\gamma}$ | |
| $f_L = e_L,\mu_L,\tau_L, u_L,d_L,s_L, c_L,b_L,t_L$ → | $\epsilon_{ZfL}$ | $-g_Z^{fL}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda 1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda 1}^{Z\gamma}$ | |

thanks to David Marzocca

SM Zff

CMS-HIG-17-011

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we cannot deal with 14 ZZ'+12 WW' (?) contact terms (still no FCNC)

opted to relate as in Zff and Wff

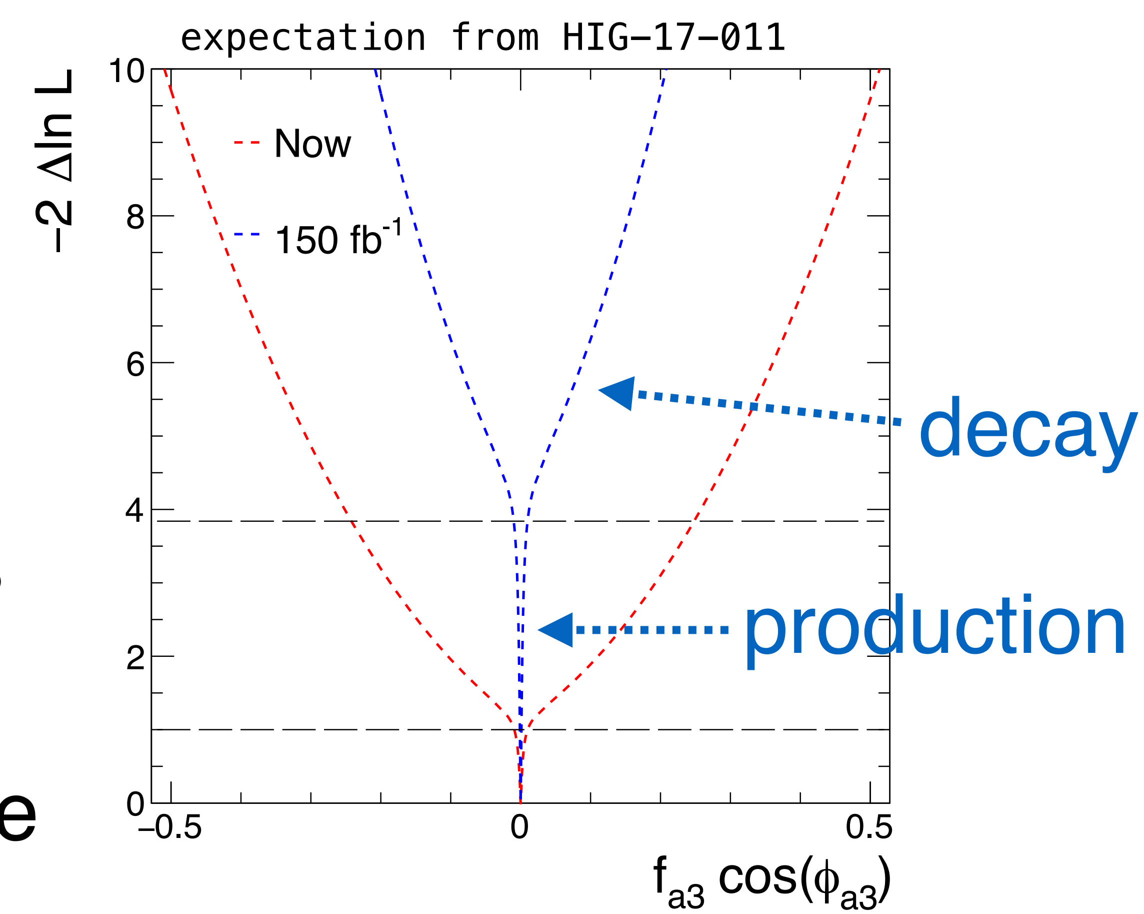
- In Run2:

  most focus will be on production

  need practical way to relate couplings

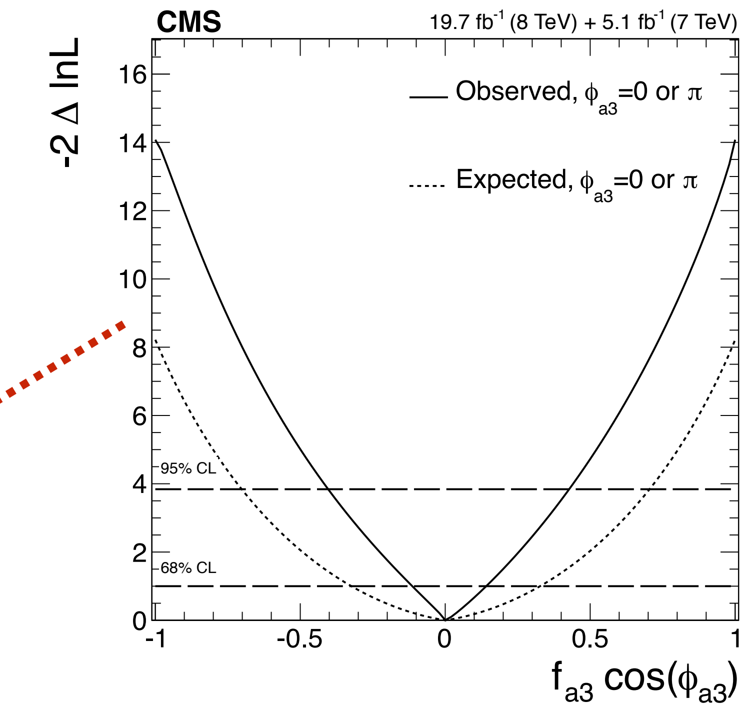
  assume $a_i^{ZZ} = a_i^{WW}$

  little difference to distinguish otherwise



# CMS vs. AC vs. EFT vs. PO vs…

- There is absolutely no difference between
  CMS vs. AC vs. EFT vs. PO
  except for treatment of the contact terms




- Here is an exercise of CMS→AC=EFT=PO

in communication to David Marzocca in Feb.2017:

(1) Following https://arxiv.org/pdf/1411.3441.pdf, we find that

$$-0.40 < f_{a3}\cos(\phi_{a3}) < 0.43 \qquad (1)$$

(2) Following https://arxiv.org/pdf/1411.3441.pdf and Table I for conversion from $f_{a3}$ to $a_3$, we find that

$$-2.05 < \frac{a_3}{a_1} < 2.19$$

$$\frac{|a_i|}{|a_1|} = \sqrt{f_{ai}/f_{a1}} \times \sqrt{\sigma_1/\sigma_i},$$

(3) Following Table II, we find that

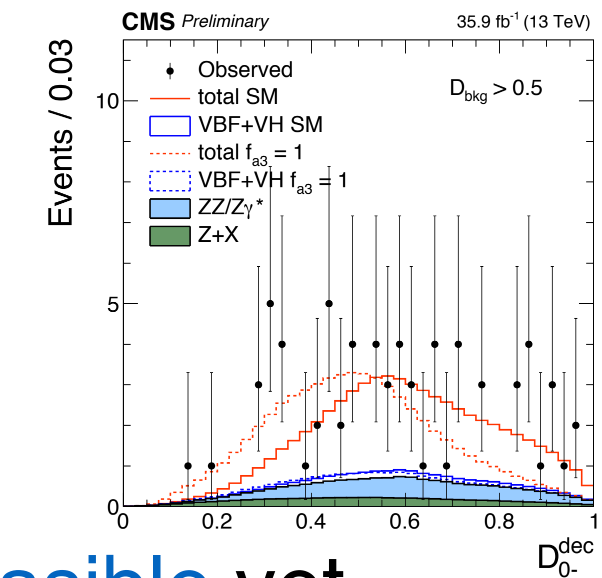
$$-4.10 < \frac{\epsilon_{ZZ}^{CP}}{\kappa_{ZZ}} < 4.38$$

| Anomalous Coupling | Coupling Phase | Effective Fraction | Translation Constant |
|---|---|---|---|
| $a_3$ | $\phi_{a3}$ | $f_{a3}$ | (3) $\sigma_1/\sigma_3 = 6.53$ |
| $a_2$ | $\phi_{a2}$ | $f_{a2}$ | $\sigma_1/\sigma_2 = 2.77$ |
| $\Lambda_1$ | $\phi_{\Lambda 1}$ | $f_{\Lambda 1}$ | $\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.47 \times 10^4$ TeV$^{-4}$ |
| $\Lambda_1^{Z\gamma}$ | $\phi_{\Lambda 1}^{Z\gamma}$ | $f_{\Lambda 1}^{Z\gamma}$ | $\sigma_1'/\tilde{\sigma}_{\Lambda 1}^{Z\gamma} = 5.80 \times 10^3$ TeV$^{-4}$ |

$f_{a2}^{VV}$, $f_{a3}^{VV}$ —invariant of notation, [-1,+1], meaning of cross section

# Issues (1) observables and (2) measurements

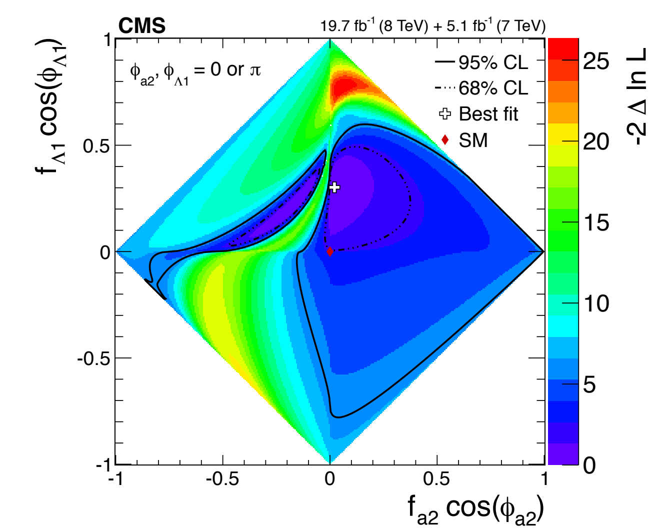
- Main issues facing experimental measurements:




(1) how to optimize observables for max. sensitivity
typically limit to 1-2 parameters with ~3D fit

multi-parameter fits possible, e.g. 8D in H→4ℓ
but limit to decay-only, not main focus, 13D not feasible yet…

CMS introduced optimal discriminants, ATLAS picked the idea (OO)
but do not need to agree between CMS / ATLAS




(2) how to reduce the number of free parameters
measure 1 or 2 couplings at a time
others relate (e.g. $a_i^{ZZ} = a_i^{WW}$) or set to zero/SM
reality: not practical to measure all at once
agreement between CMS / ATLAS ? (mostly agreed so far)

# Issue (3) $q^2$ validity

(3) VBF and VH limits are tighter than H→VV

because of larger $q^2$, cannot continue forever

possible to test validity e.g. with $p_T$ cuts (correlated with $q^2$), but:

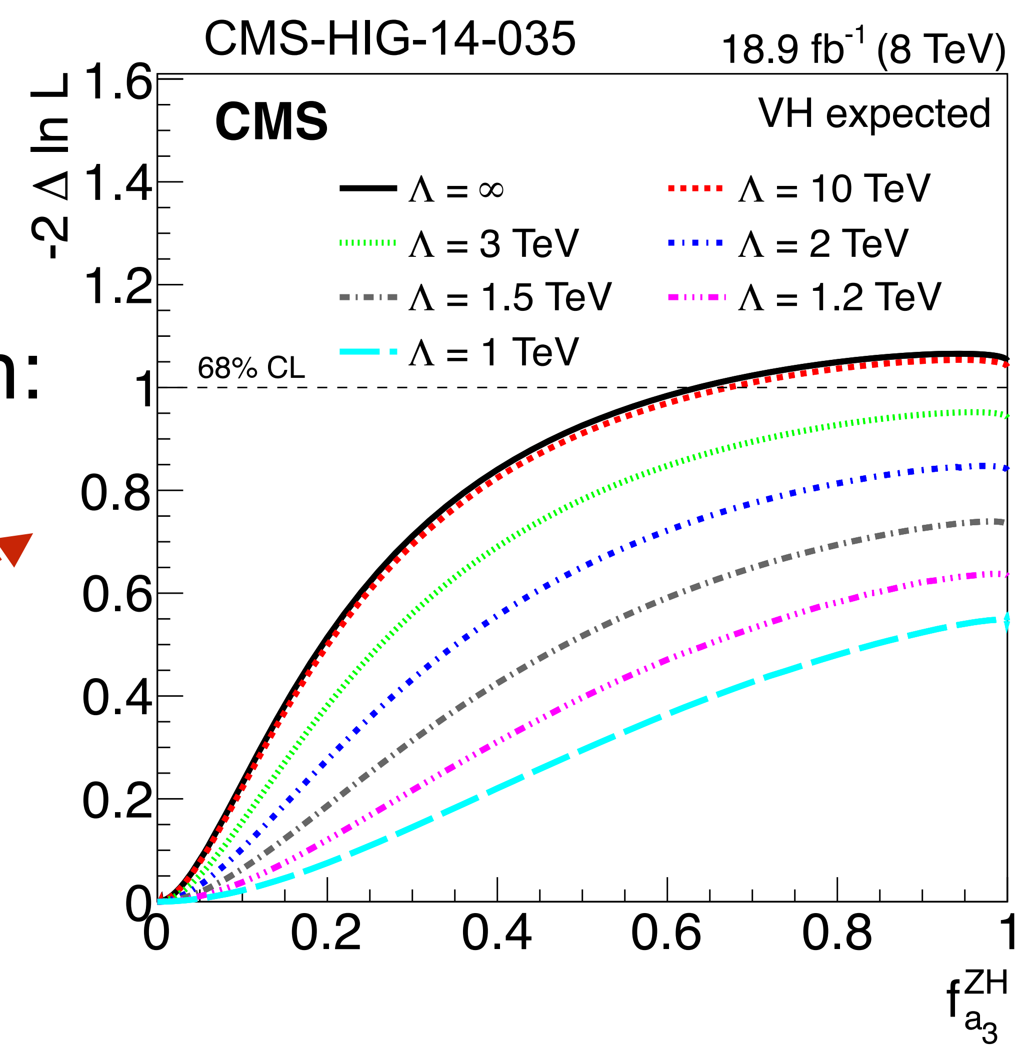
— not consistent between VBF, VH, H→VV

— nightmare for experimentalists
(redo everything for each selection)

Adopted practical and coherent approach:

refit with a $\Lambda^2$ cut-off on $q^2$
(data fixed, signal model changes)

$$g_i' \times \frac{\Lambda_i^4}{\left(\Lambda_i^2 + |q_1^2|\right)\left(\Lambda_i^2 + |q_2^2|\right)}$$



# Issue (4) extending to offshell

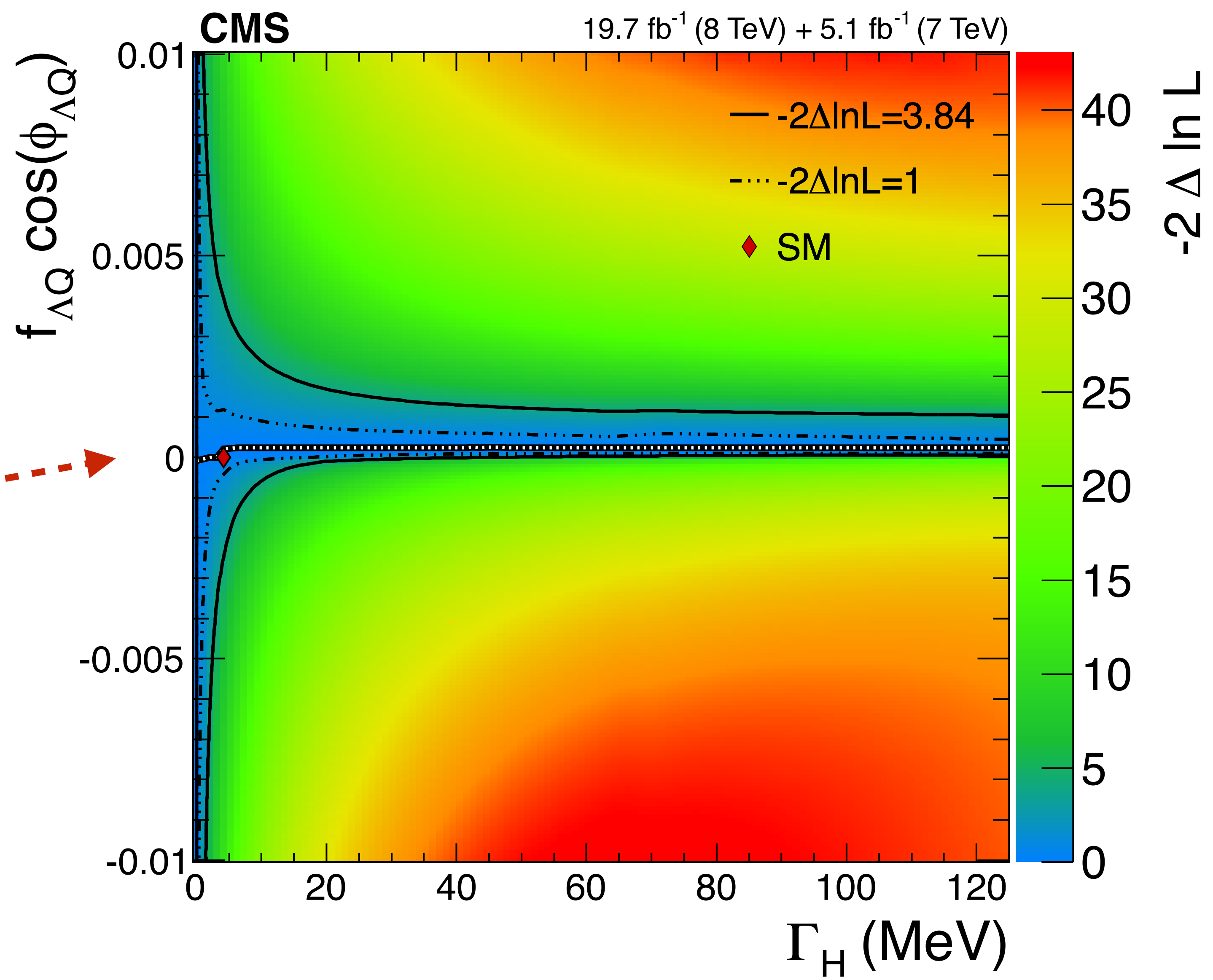
- ~10% of $H \to 4\ell$ in offshell, additional $(q_1+q_2)^2$ modeling

  but we already deal with $q^2$ modeling

view as couplings for given $\Gamma_H$ or $\Gamma_H$ for given variation of couplings

tested $f_{\Lambda Q}$ for given $\Gamma_H$

CMS-HIG-14-036

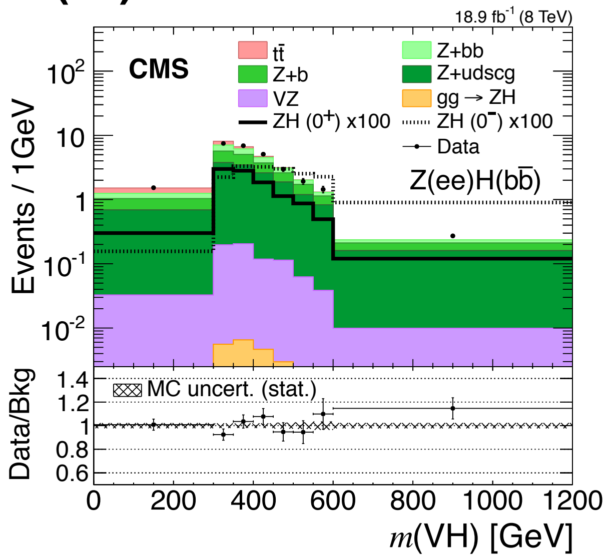



$$A = \frac{1}{v}\left(\left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_1+q_2)^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{q_1^2+q_2^2}{(\Lambda_1)^2}\right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

# Issue (5) relate the yields in combination

CMS-HIG-14-018
CMS-HIG-14-035

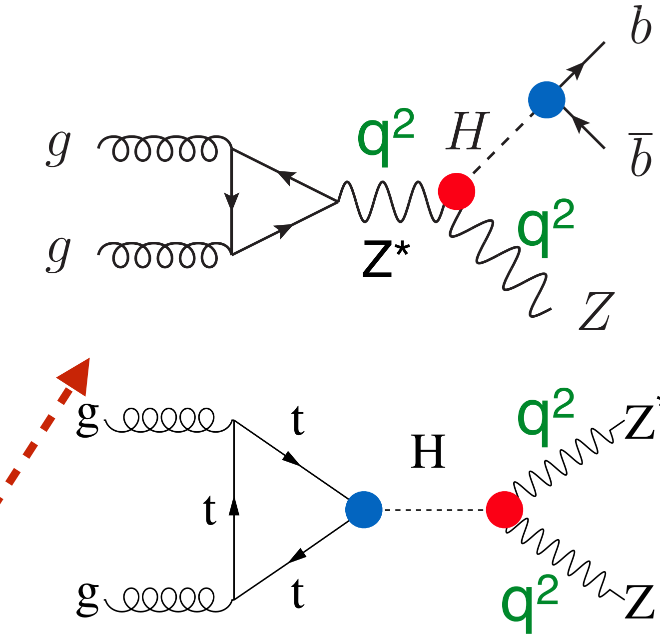
(5) We can relate the yields, e.g. VH(bb) vs H→VV

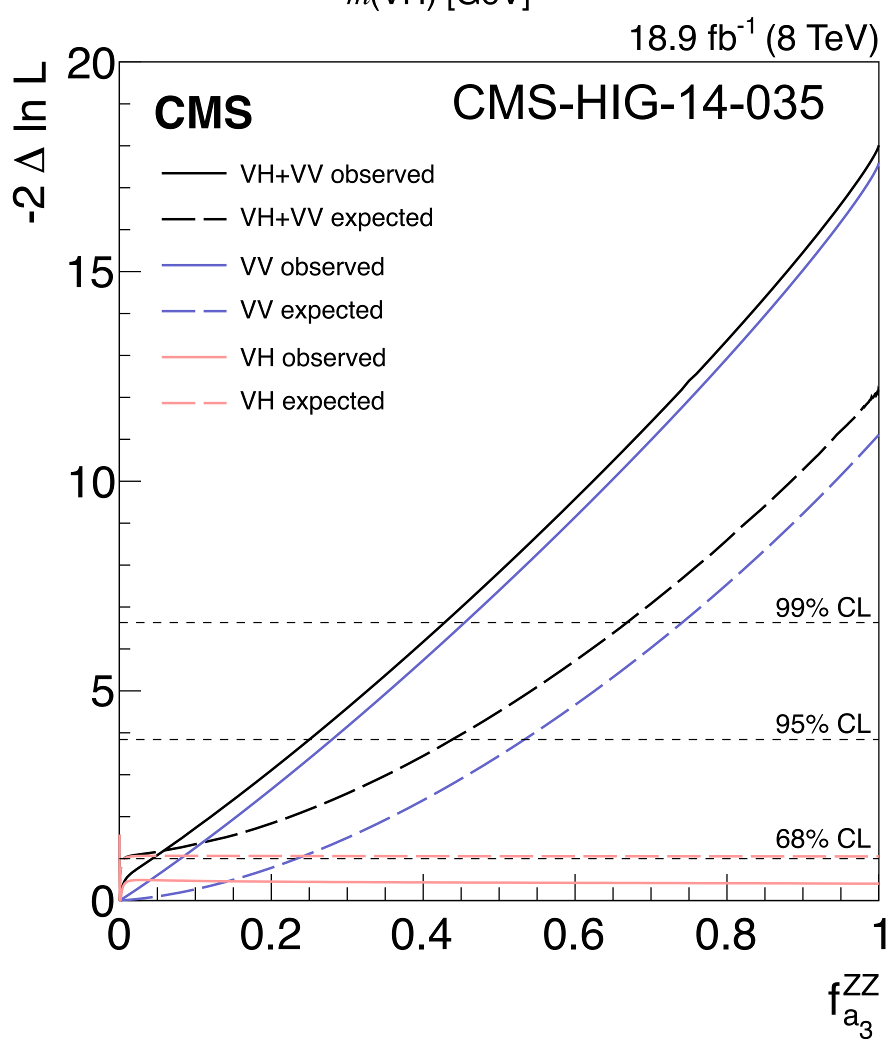



can get much tighter constraint

but assumption ttH/bbH=const

and $q^2$ validity



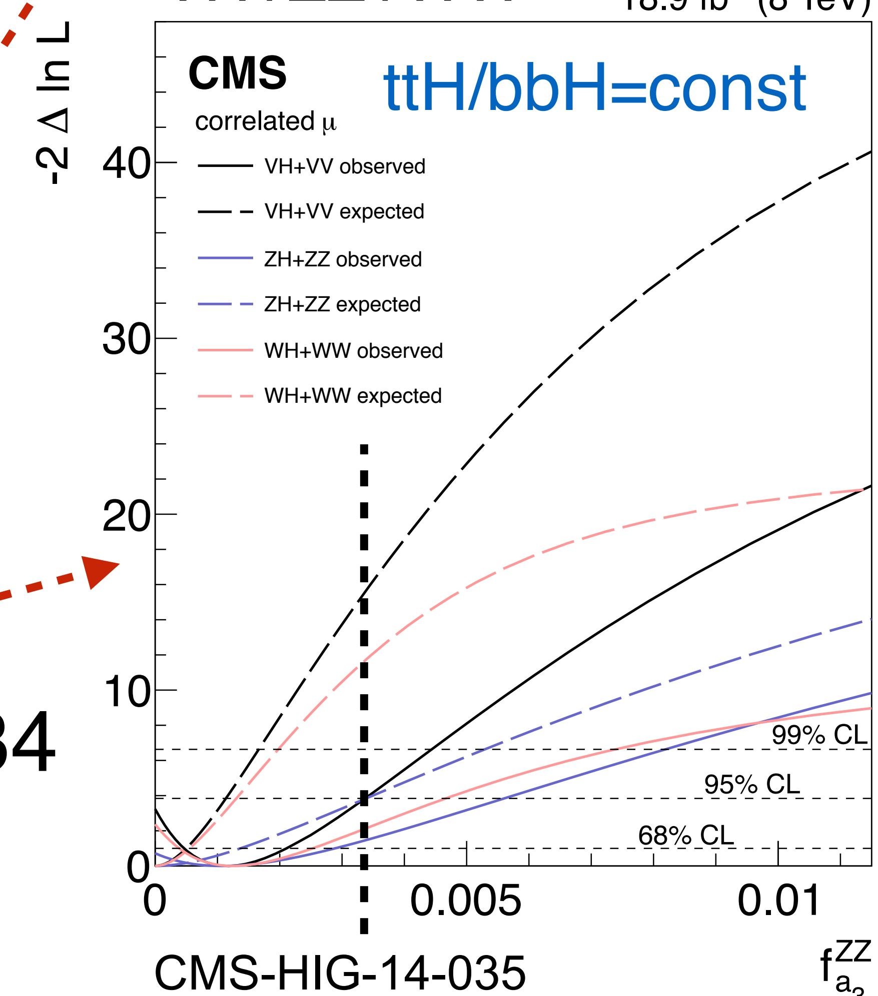

VH: $f_{a3}$<1 at 95% CL

H→VV: $f_{a3}$<0.28

Proper combination
(not Tevatron approach)

VH&VV: $f_{a3}$<0.0034

VH+ZZ+WW

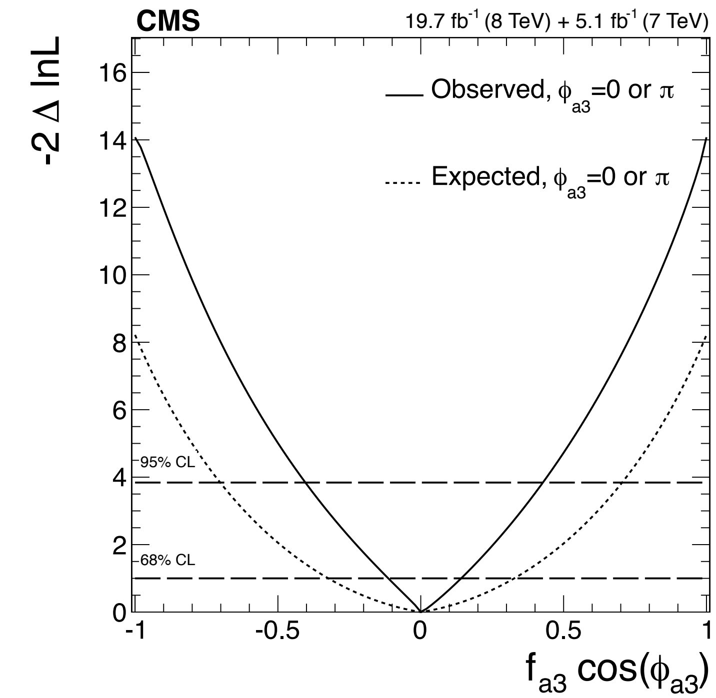



CMS-HIG-14-035

# Issue (6) complex couplings

- Hermitian L => real couplings => phase 0 or π

amplitude could have complex effective couplings
e.g. light particles in the loop (also $q^2$ related…)

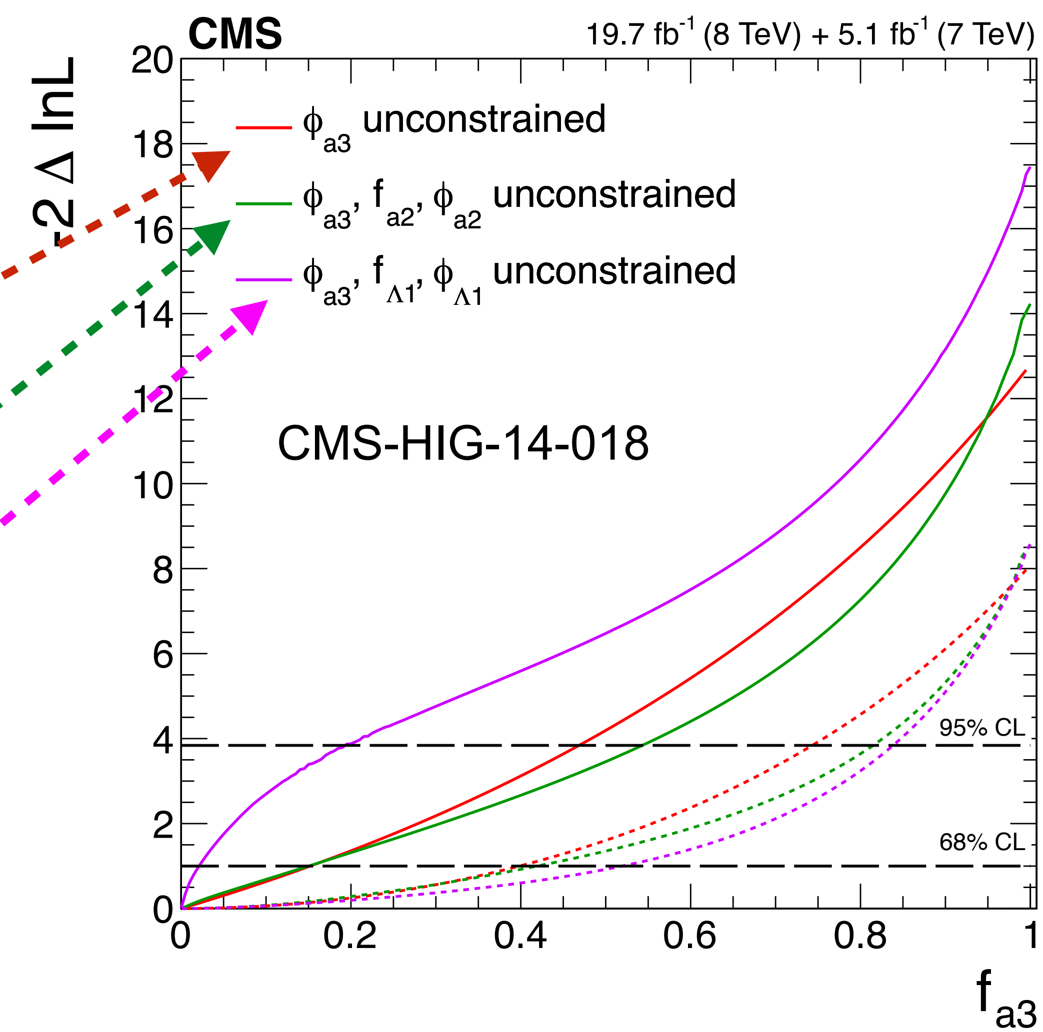



- Experimentally: consistency of the data with SM

check complex phases
as a consistency test

tested arbitrary phases (profiled)

profiled other couplings and phases



# Issue (7) dealing with the contact terms

- Current CMS approach: stick to flavor universality ("early stage")

  contact terms ($\varepsilon_{Z\ell_R}$, $\varepsilon_{Z\ell_L}$) = amplitudes ($\Lambda_1$, $\Lambda_1^{Z\gamma}$)

  works with $\ell$ flavor universality ($\varepsilon_{Z\mu}$=$\varepsilon_{Ze}$)

  may perform ($f_{\Lambda 1}$,$f_{\Lambda 1}^{Z\gamma}$) fit to cover full plane ($\varepsilon_{Z\ell_R}$, $\varepsilon_{Z\ell_L}$) explicitly

  in production need to assume relationship (e.g. as in Vff)

- Expanding beyond flavor universality ("advanced stage")

  in principle trivial, can write anything in the amplitude

  in practice analysis nightmare with ~14 ZZ' + 12 WW' (?) terms

  little sensitivity to distinguish
  also note: we test 1-2 parameters at a time

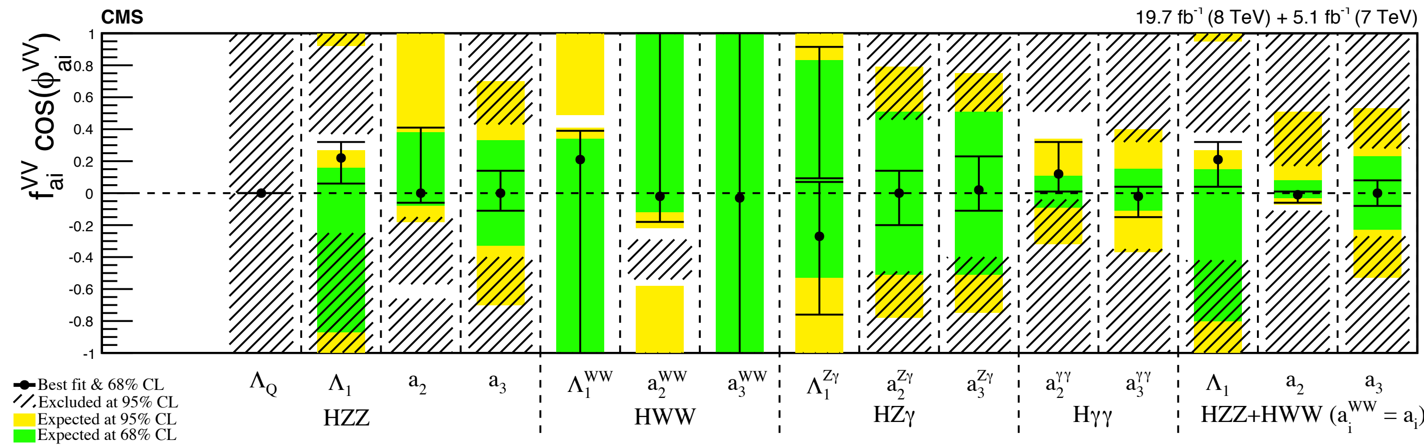
  there is also a developer nightmare: years of development already

  introduce as it becomes needed (with available statistics)

# Summary

- Experimental goal: consistency of data with SM thru measurements:

extensive set of anomalous H couplings in both production & decay




- Consistent with AC/EFT/PO framework

  with flavor universality at the moment (but can extend as needed)

- Stay open to tests beyond framework (esp. common across LHC)

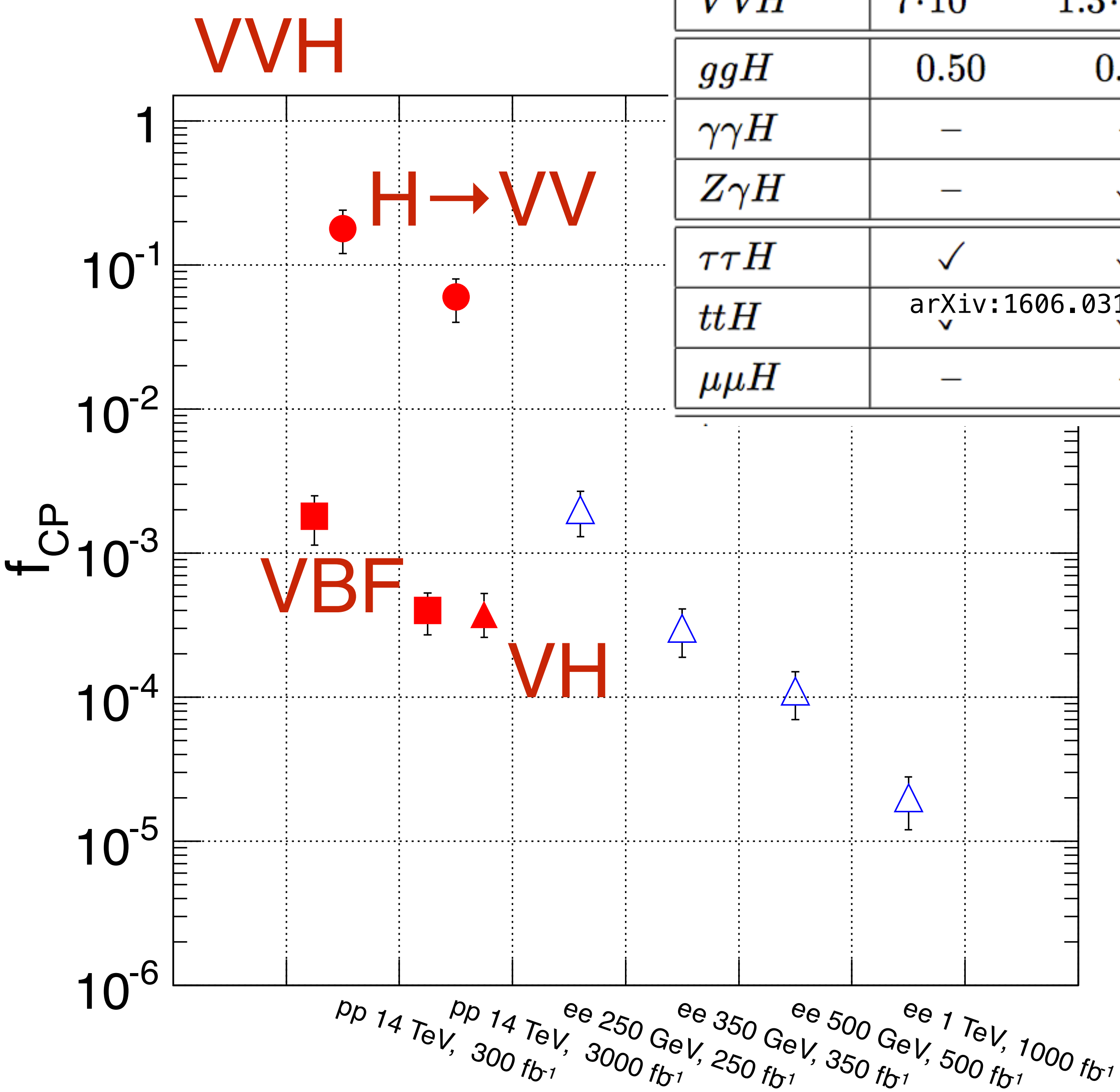
- Working model with
  (1) observables
  (2) measurements (and relationship)
  (3) $q^2$ range validity testing
  (4) offshell approach
  (5) yield relationship in combination
  (6) complex couplings test

# BACKUP

# Snowmass 2013: anomalous H couplings

arXiv:1309.4819
arXiv:1310.8361

- Prospects:




| Collider | $pp$ | $pp$ | $e^+e^-$ | $e^+e^-$ | $e^+e^-$ | $e^+e^-$ | $\gamma\gamma$ | $\mu^+\mu^-$ | target |
|---|---|---|---|---|---|---|---|---|---|
| E (GeV) | 14,000 | 14,000 | 250 | 350 | 500 | 1,000 | 126 | 126 | (theory) |
| $\mathcal{L}$ (fb$^{-1}$) | 300 | 3,000 | 250 | 350 | 500 | 1,000 | 250 | | |
| spin-$2^+_m$ | $\sim10\sigma$ | $\gg10\sigma$ | $>10\sigma$ | $>10\sigma$ | $>10\sigma$ | $>10\sigma$ | | | $>5\sigma$ |
| $VVH^\dagger$ | 0.07 | 0.02 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | $< 10^{-5}$ |
| $VVH^\ddagger$ | $4{\cdot}10^{-4}$ | $1.2{\cdot}10^{-4}$ | $7{\cdot}10^{-4}$ | $1.1{\cdot}10^{-4}$ | $4{\cdot}10^{-5}$ | $8{\cdot}10^{-6}$ | – | – | $< 10^{-5}$ |
| $VVH^\diamond$ | $7{\cdot}10^{-4}$ | $1.3{\cdot}10^{-4}$ | ✓ | ✓ | ✓ | ✓ | – | – | $< 10^{-5}$ |
| $ggH$ | 0.50 | 0.16 | – | – | – | – | – | – | $< 10^{-2}$ |
| $\gamma\gamma H$ | – | – | – | – | – | – | 0.06 | – | $< 10^{-2}$ |
| $Z\gamma H$ | – | ✓ | – | – | – | – | – | – | $< 10^{-2}$ |
| $\tau\tau H$ | ✓ | ✓ | 0.01 | 0.01 | 0.02 | 0.06 | ✓ | ✓ | $< 10^{-2}$ |
| $ttH$ | arXiv:1606.03107 ✓ | ✓ | – | – | 0.29 | 0.08 | – | – | $< 10^{-2}$ |
| $\mu\mu H$ | – | – | – | – | – | – | – | ✓ | $< 10^{-2}$ |

$^\dagger$ estimated in $H \to ZZ^*$ decay mode
$^\ddagger$ estimated in $V^* \to HV$ production mode
$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode