Constraints on anomalous Higgs boson couplings to vector bosons and fermions in production and decay in the $H \rightarrow 4l$ channel

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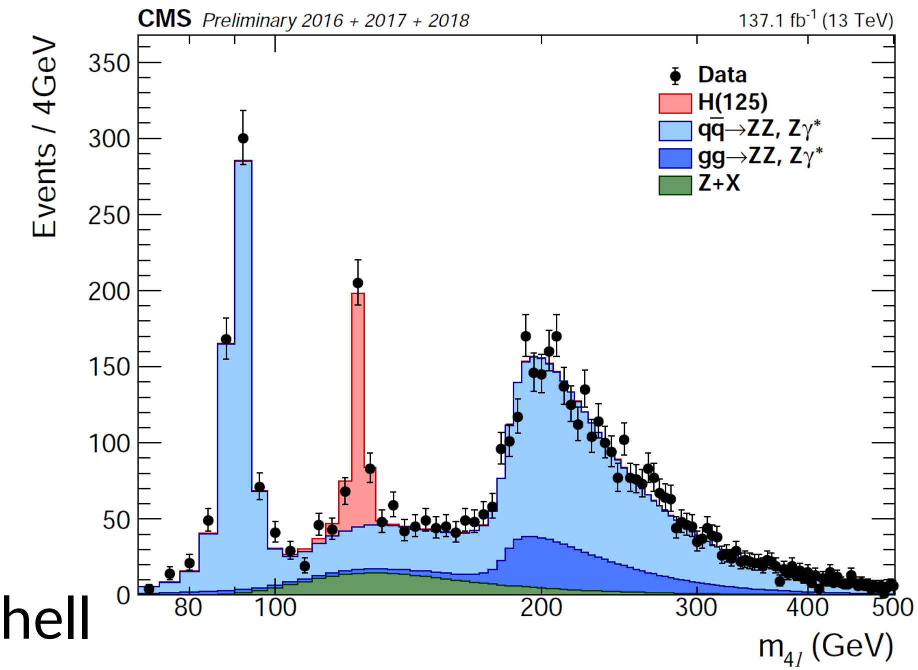
Intro

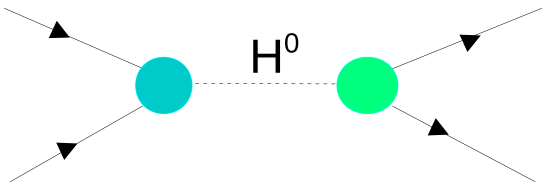
- **Precision coupling measurements:**
  - Characterize properties of the 125GeV boson
  - Probe new physics
  - Probe CP violation in Higgs sector



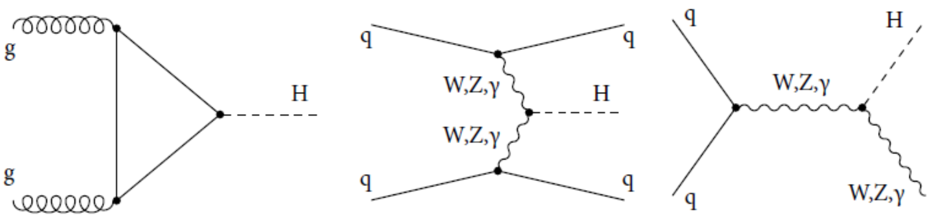
- **Focus on HVV/Hff couplings in H→4l**

  Dedicated analysis with full RunII data onshell HIG-19-009

  \+ first off-shell AC measurement HIG-18-002



- **Related papers results from CMS :**
  - H → ZZ measurements in CMS HIG-19-001
  - CP in H→ ττ HIG-20-006
  - CP in ttH with H→ γγ HIG-19-013
  - STXS-based measurement HIG-19-005
  - JHU generator frameworks review



Phenomenology and EFT

Parametrize H couplings in the mass eingestate basis:

$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}\left(\kappa_\mathrm{f} + \mathrm{i}\,\tilde{\kappa}_\mathrm{f}\gamma_5\right)\psi_\mathrm{f}$$

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V}1}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V}2}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_{\mathrm{V}1}+q_{\mathrm{V}2})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Notation:

$a_i^{VV} = g_i^{VV}$ for i = 1,2 $\quad a_3^{VV} = g_4^{VV}$

$$g_{\Lambda 1}^{ZZ,WW} = \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}, \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}$$

$$g_{\Lambda 1}^{Z\gamma} = \frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}$$

a1 SM
a2 CP even AC
a3 CP odd AC

Amplitude Related to a fundamental Lagrangian density
→ couplings related to the Lagrangian coefficients

$$\begin{aligned}\mathcal{L}_{\mathrm{hvv}} = \; & \frac{h}{v}\Big[(1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box}g^2 Z_\mu \partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} \\ & + (1+\delta c_w)\frac{g^2v^2}{2}W_\mu^+ W_\mu^- + c_{ww}\frac{g^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + c_{w\Box}g^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \mathrm{h.c.}\right) + \tilde{c}_{ww}\frac{g^2}{2}W_{\mu\nu}^+\tilde{W}_{\mu\nu}^- \\ & + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu} \\ & + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a\tilde{G}_{\mu\nu}^a\Big],\end{aligned}$$

$$\begin{aligned}\delta c_z &= \frac{1}{2}a_1 - 1 \\ c_{z\Box} &= \frac{m_Z^2 s_w^2}{e^2}\frac{\kappa_1}{(\Lambda_1)^2} \\ c_{zz} &= -\frac{2s_w^2c_w^2}{e^2}a_2 \\ \tilde{c}_{zz} &= -\frac{2s_w^2c_w^2}{e^2}a_3\end{aligned}$$

$$\begin{aligned}c_{gg} &= -\frac{1}{2\pi\alpha_s}a_2^{gg} \\ \tilde{c}_{gg} &= -\frac{1}{2\pi\alpha_s}a_3^{gg}\end{aligned}$$

Symmetries and more…

- Onshell Zγ and γγ couplings well constrained
- **Custodial symmetry**
- **Consider $g^{WW} = g^{ZZ}$**

$$g_1^{WW} = g_1^{ZZ}$$
$$g_2^{WW} = c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma},$$
$$g_4^{WW} = c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma},$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2},$$
$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}$$

5 independent HVV couplings

Or…

- **Consider SU(2)xU(1)** → enforces relations between couplings:

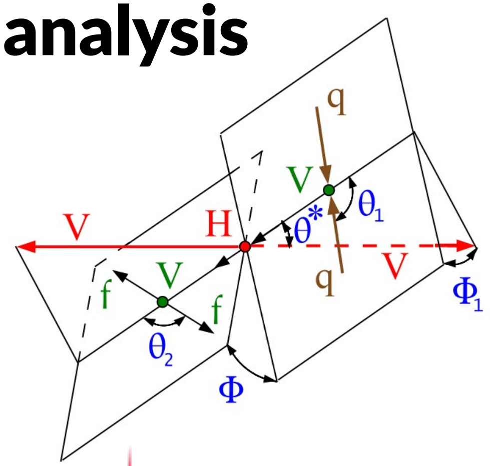
$$g_1^{WW} = g_1^{ZZ}$$
$$g_2^{WW} = c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma},$$
$$g_4^{WW} = c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma},$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2},$$
$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}$$

4 independent HVV couplings

Phenomenology and experiment

- AC parametrization presented is the **most general** Lorentz invariant form for dim 4 and 6 operators
- Existing and new tools allow rotations from mass eigenstate basis to others

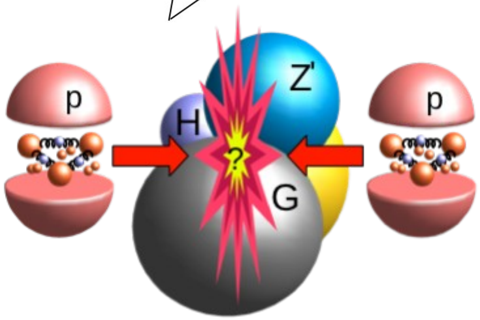
Necessary to perform an optimal and correct analysis



Use ME (MELA) or BDT discriminants that exploit all kinematic information to boost sensitivity

Use full detector simulation of anomalous couplings considered (JHUgen)

Techniques such as re-weighting solve the problem of simulating all the necessary AC contributions



Measuring the AC contributions

2 types of results:

Fractional AC contr. in signal strength:

Signal strength:

$$\mu_j = \sigma_j / \sigma_j^{\mathrm{SM}}$$

Effective fractional xsec:

$$f_{ai}^{\mathrm{VV}} = \frac{|a_i^{\mathrm{VV}}|^2 \, \alpha_{ii}^{(\mathrm{dec})}}{\sum_j |a_j^{\mathrm{VV}}|^2 \, \alpha_{jj}^{(\mathrm{dec})}} \, \mathrm{sign}\left(\frac{a_i^{\mathrm{VV}}}{a_1}\right)$$

- **Total width absorbed in signal strength**
- Most systematics cancel in the ratio
- Bounded [-1,1]
- **Scan f_{a2}, f_{a3}, $f_{\Lambda 1}$ ...**

Interpretation in terms of Lagr. Coefficients:

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

$$\Gamma_{\mathrm{tot}} = \sum_f \Gamma_f = \Gamma_{\mathrm{tot}}^{\mathrm{SM}} \times \sum_f \left(\frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_{\mathrm{tot}}^{\mathrm{SM}}} \times \frac{\Gamma_f}{\Gamma_f^{\mathrm{SM}}}\right) = \Gamma_{\mathrm{tot}}^{\mathrm{SM}} \times \sum_f \left(\mathcal{B}_f^{\mathrm{SM}} \times R_f(\vec{g}_j)\right)$$

$$R_{ZZ/Z\gamma^*/\gamma^*\gamma^*} = \left(\frac{g_1^{ZZ}}{2}\right)^2 + 0.1695\,(\kappa_1^{ZZ})^2 + 0.09076\,(g_2^{ZZ})^2 + 0.03809\,(g_4^{ZZ})^2$$
$$+ 0.8095\left(\frac{g_1^{ZZ}}{2}\right)\kappa_1^{ZZ} + 0.5046\left(\frac{g_1^{ZZ}}{2}\right)g_2^{ZZ} + 0.2092\,\kappa_1^{ZZ} g_2^{ZZ}$$
$$+ 0.1023\,(\kappa_2^{Z\gamma})^2 + 0.1901\left(\frac{g_1^{ZZ}}{2}\right)\kappa_2^{Z\gamma} + 0.07429\,\kappa_1^{ZZ}\kappa_2^{Z\gamma} + 0.04710\,g_2^{ZZ}\kappa_2^{Z\gamma}$$

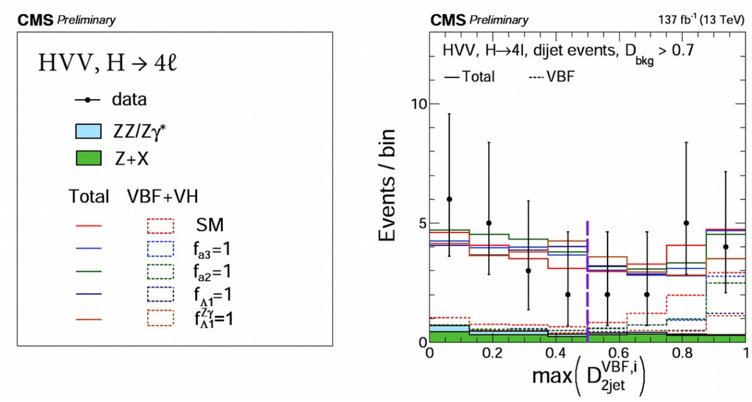
- Anomalous contributions modify the **total width**!
- **Interpret in couplings language**

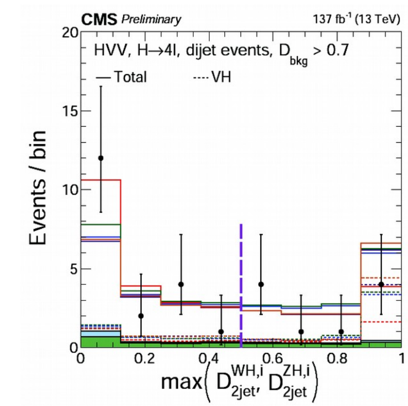
Event Selections and Observables

HIG-19-009

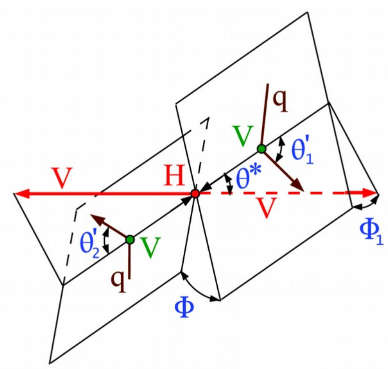
Onshell H → 4l analysis

- Consider 2e2μ,4μ and 4e Higgs decays
- Create categories rich in VBF / VH events
- Use MELA discr. to separate production mechanism and distinguish signal vs background
- Categorization discriminants dedicated to AC hypothesis to ensure optimal selection of events
- Specific categorization schemes for HVV and Hgg/Hff couplings





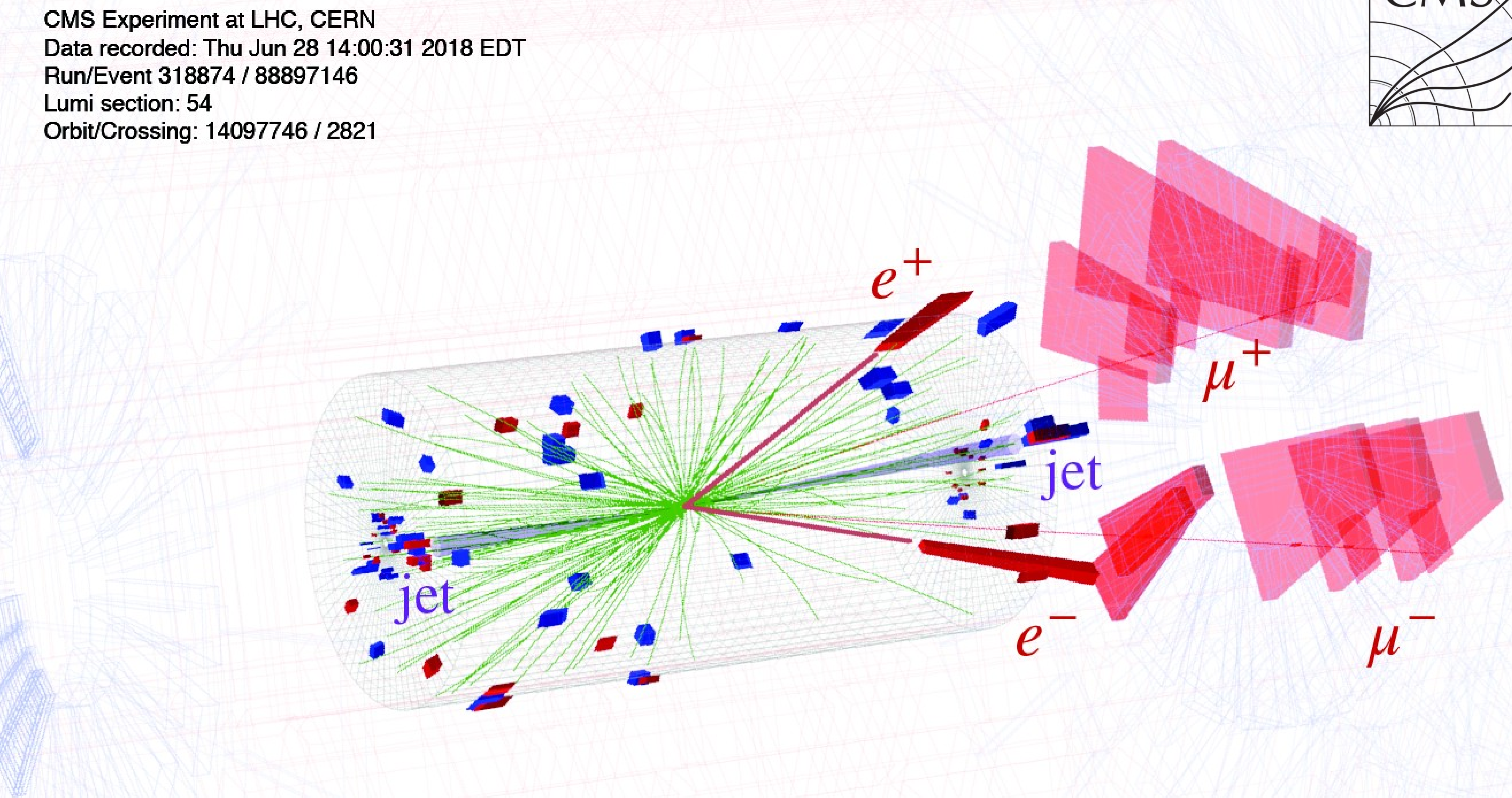
Observables and fits



- Create ME observables (MELA)
- Exploit **production** and **decay** information
- Exploit **interference** information
- Perform **template likelihood fits**
- Measure and interpreted to Lagrangian coefficients.

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

$$\mathcal{D}_{\rm int}(\Omega) = \frac{\mathcal{P}_{\rm int}(\Omega)}{2\sqrt{\mathcal{P}_{\rm sig}(\Omega)\ \mathcal{P}_{\rm alt}(\Omega)}},$$



$$pp \to H \text{ jet jet } + X$$
$$\hookrightarrow e^+e^-\mu^+\mu^-$$

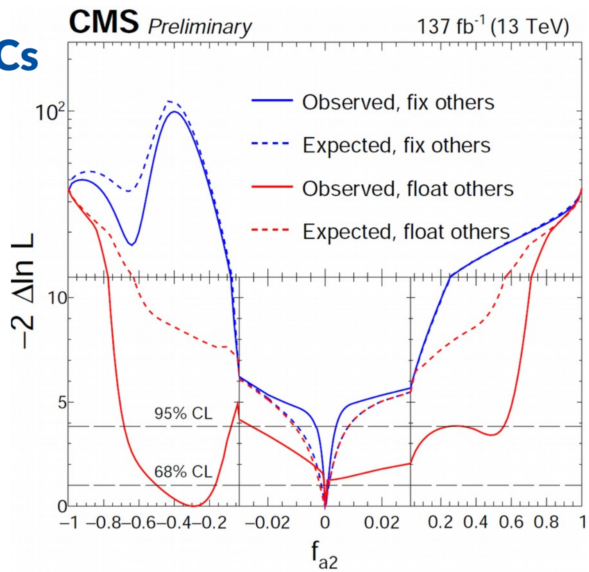
HVV couplings H→4l

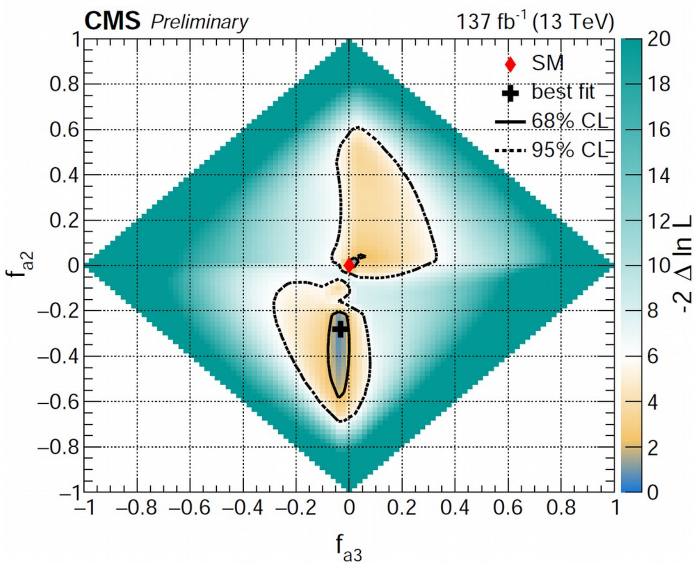
HIG-19-009

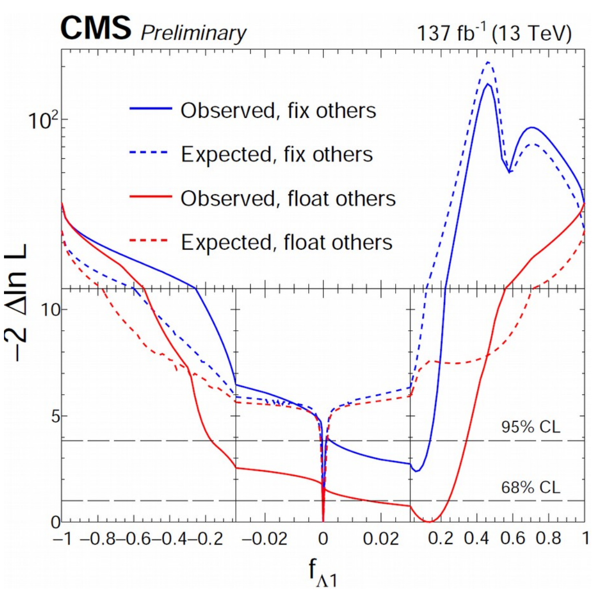
3 types of scans:

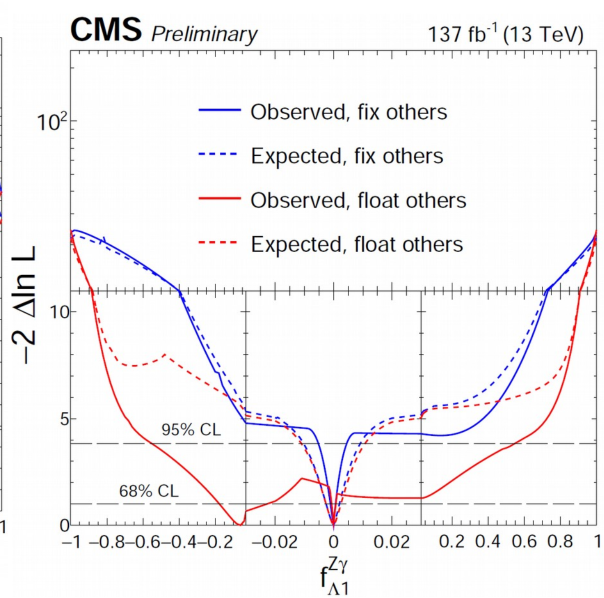
- Single parameter scans with other ACs fixed
- Simultaneous scans of multiple ACs (floating/profiling)
- 2D scans (floating)

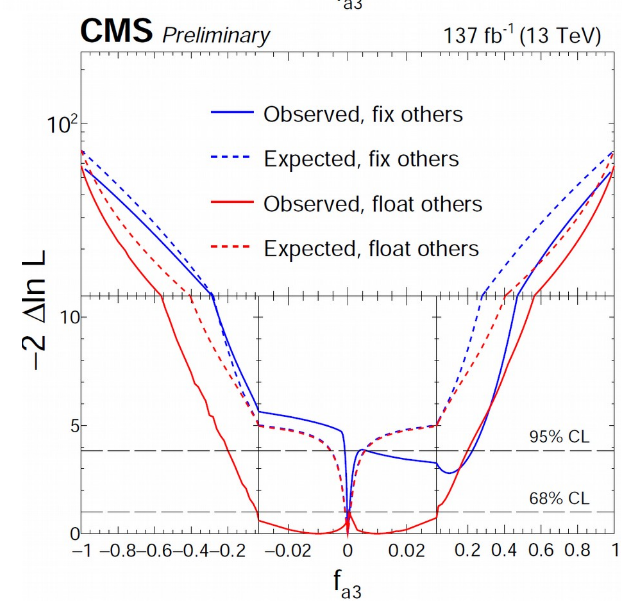
- Multiple minima, some away from 0
- Everything consistent with SM





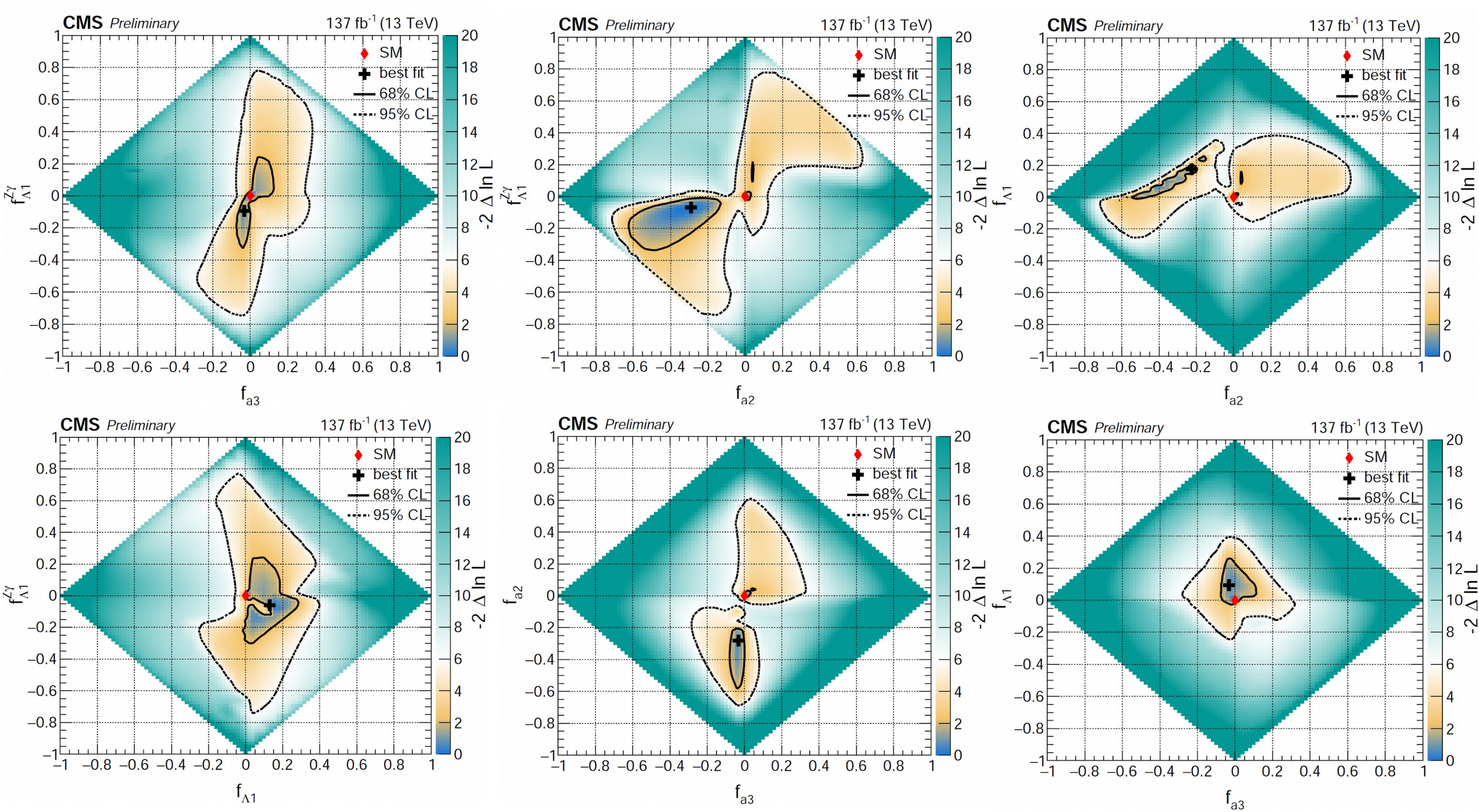






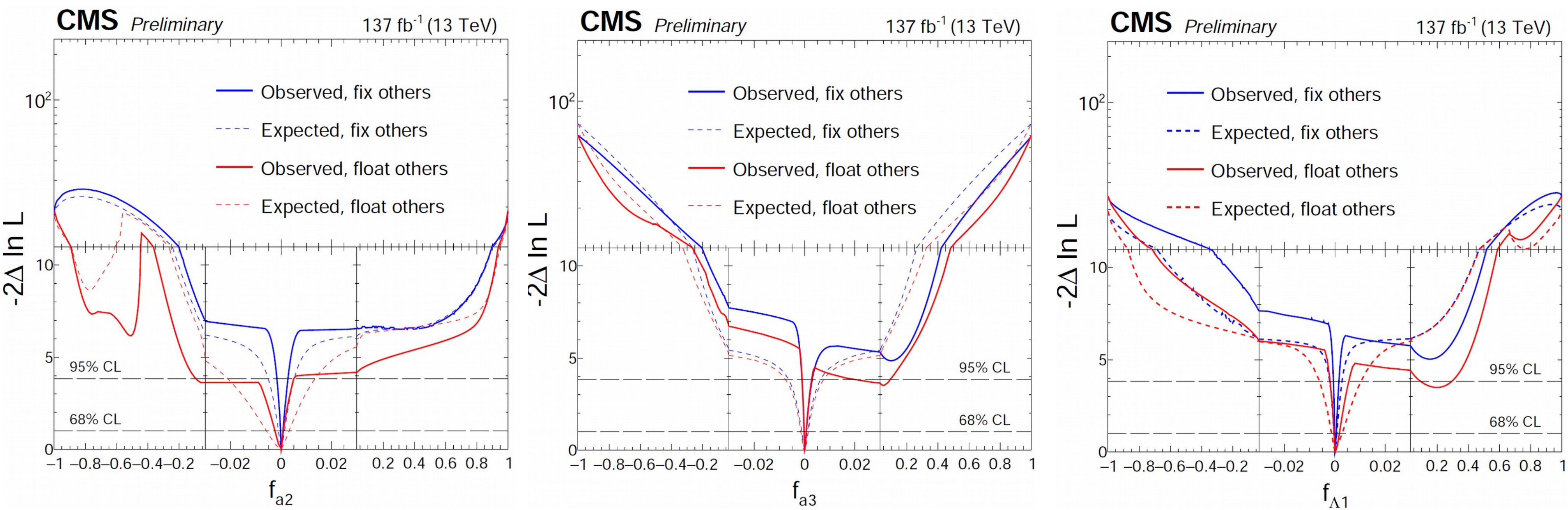
HVV couplings in H→4l

HIG-19-009



HVV couplings SU(2)xU(1)

HIG-19-009



- **Implement SU(2)XU(1) EFT relations**
  - Re-weight templates based on EFT
  - Independent anomalous couplings reduce to 3
  - Perform multi-parameter scans

  - Stringent limits on f_{a3}, f_{a2}, $f_{\Lambda 1}$
  - consistent with SM

Detailed numerical report of results in extra material section

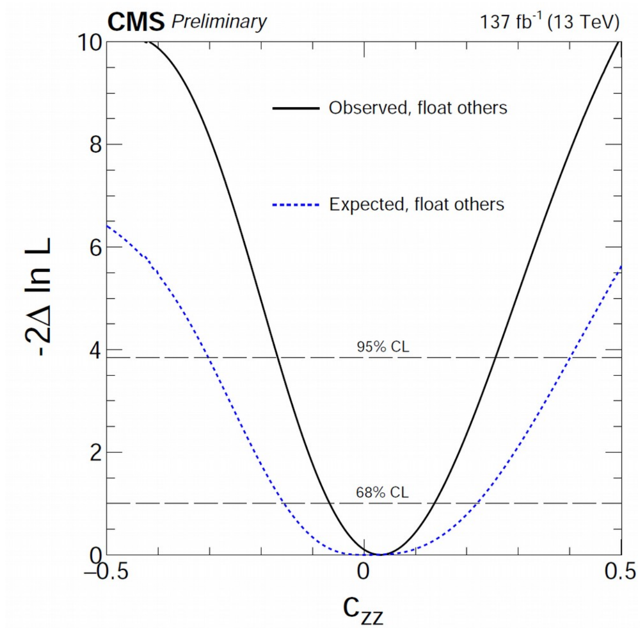
HVV couplings SU(2)xU(1)

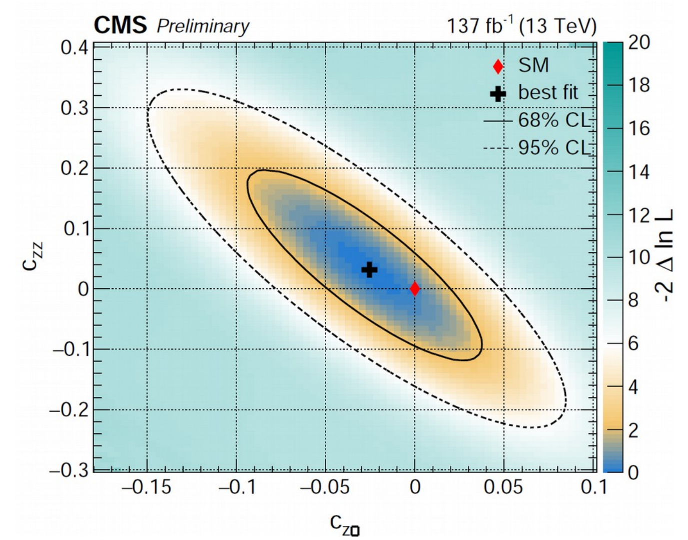
HIG-19-009

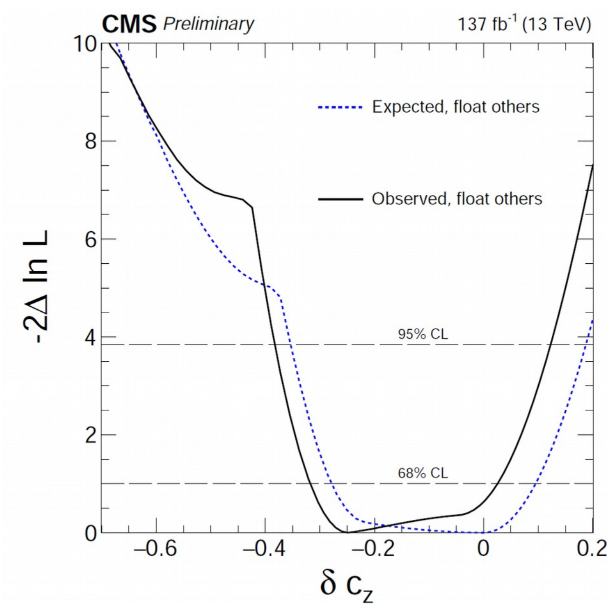
Implemented AC width modification

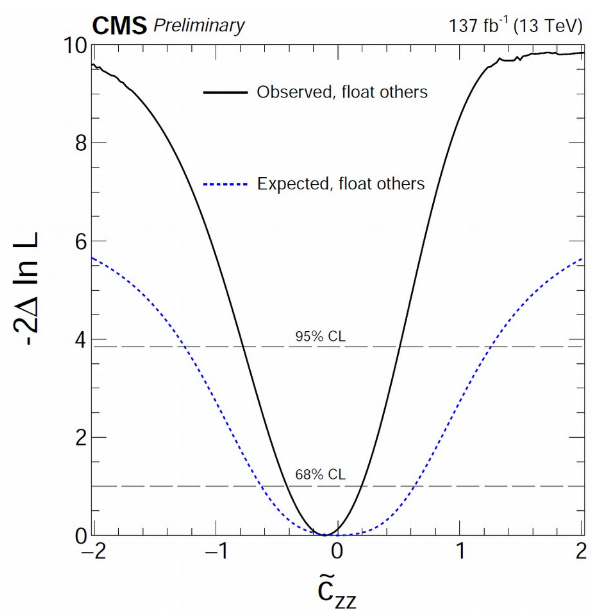
Interpret results to Lagr. coefficients with EFT relations

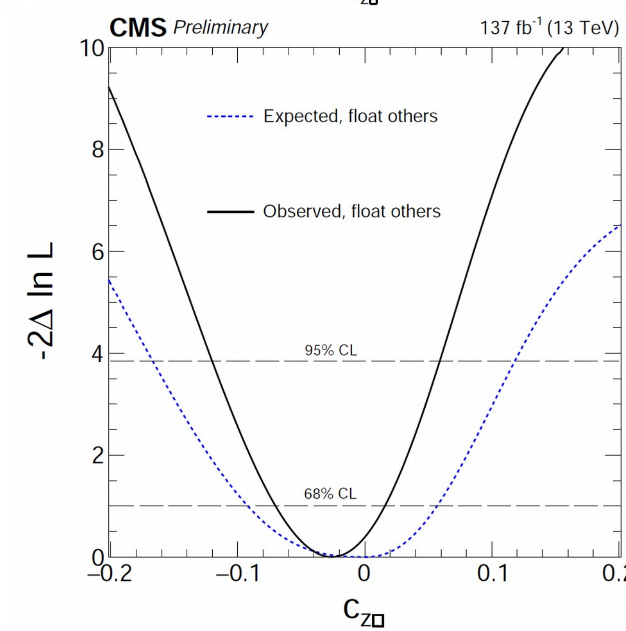
Perform 1D and 2D scans with other couplings profiled(floated)











HVV couplings SU(2)xU(1)

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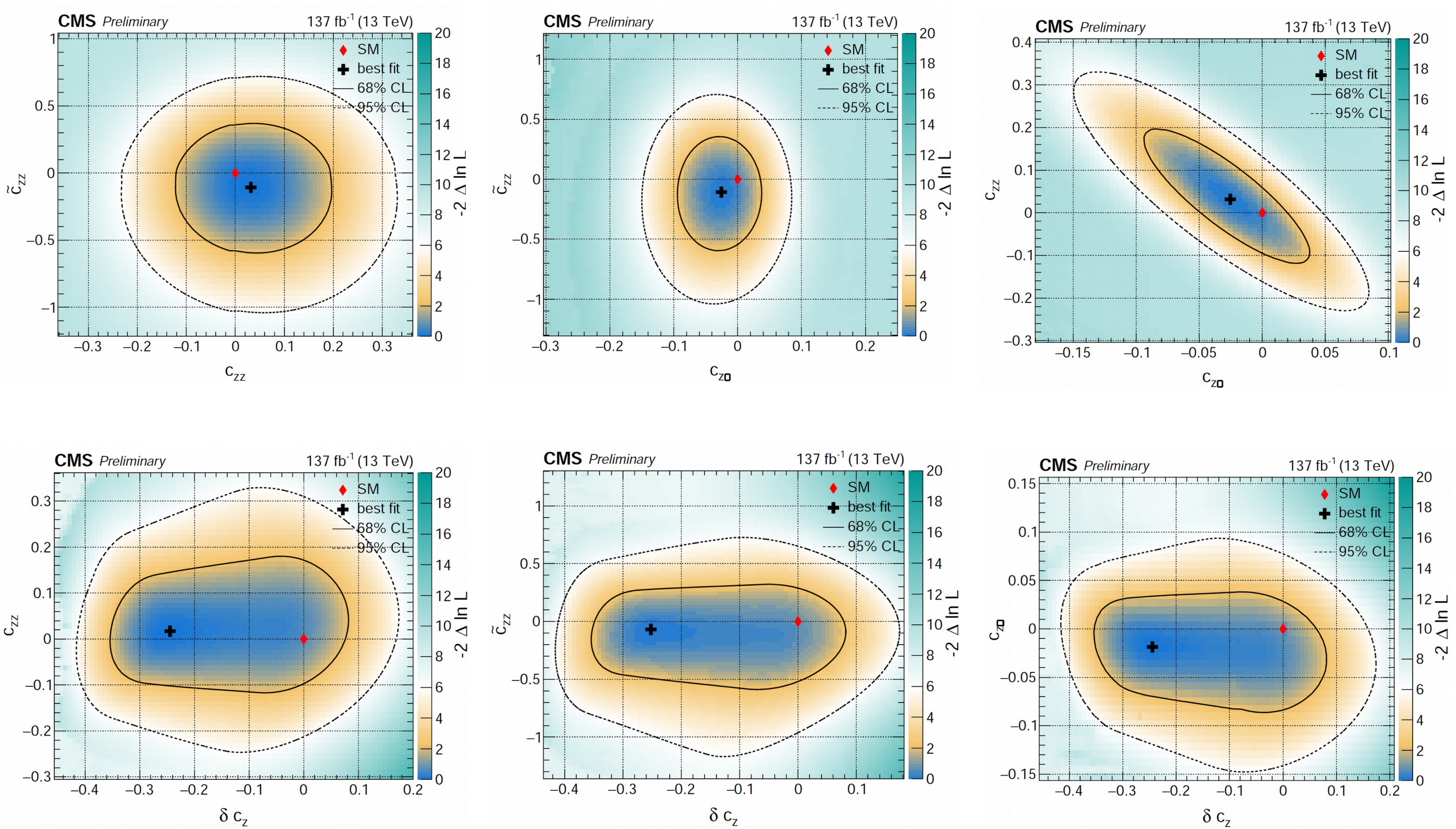
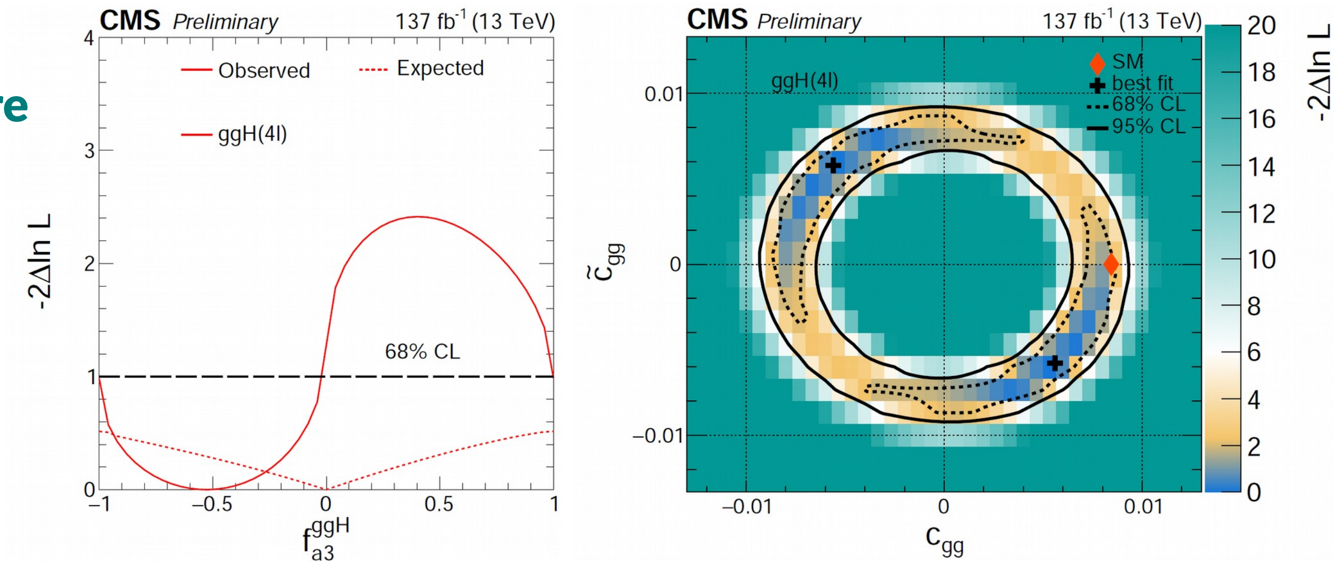


Hgg couplings with H→4l

HIG-19-009

Use production vertex to measure Hff/Hgg couplings

Measure cp sensitive f^{ggH}_{a3}



Interpret in terms of couplings

Hgg analysis show preference for maximal CP odd/even mixing

Parameter	Observed	Expected
f^{ggH}_{a3}	$-0.53^{+0.51}_{-0.47}$ $[-1,1]$	0 ± 1 $[-1,1]$

Htt couplings

HIG-19-009 HIG-19-013

Study CP structure with f^{Htt}_{CP} in:

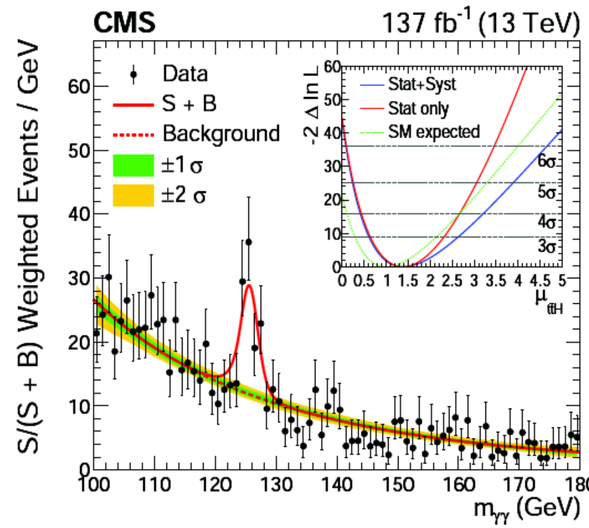
H → 4l

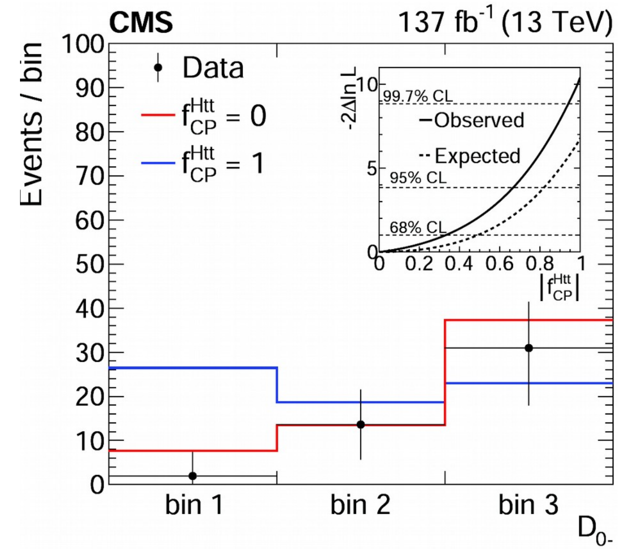
H → γγ

and combine

H→ γγ utilize BDT for D_{0-}

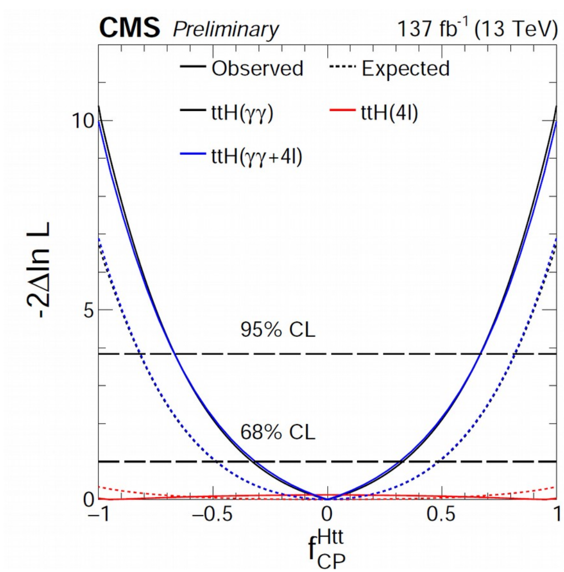
Simultaneous fit of mγγ in 12 categories

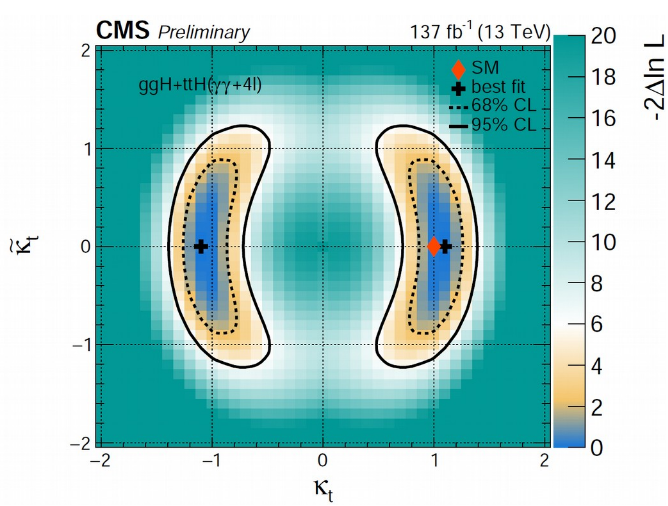




Interpret as top couplings

$$f^{Htt}_{CP} \quad 0.00 \pm 0.31\ [-0.67, 0.67]$$





Hff couplings in H→4l

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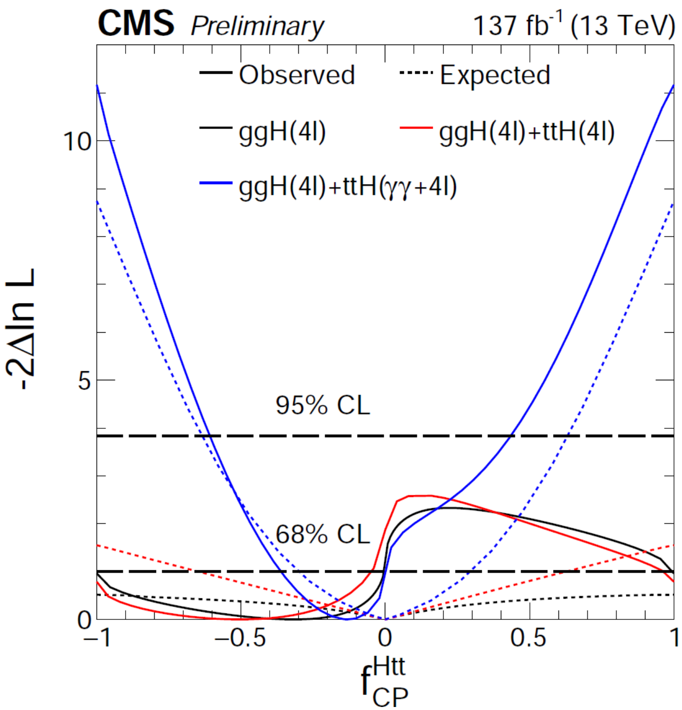
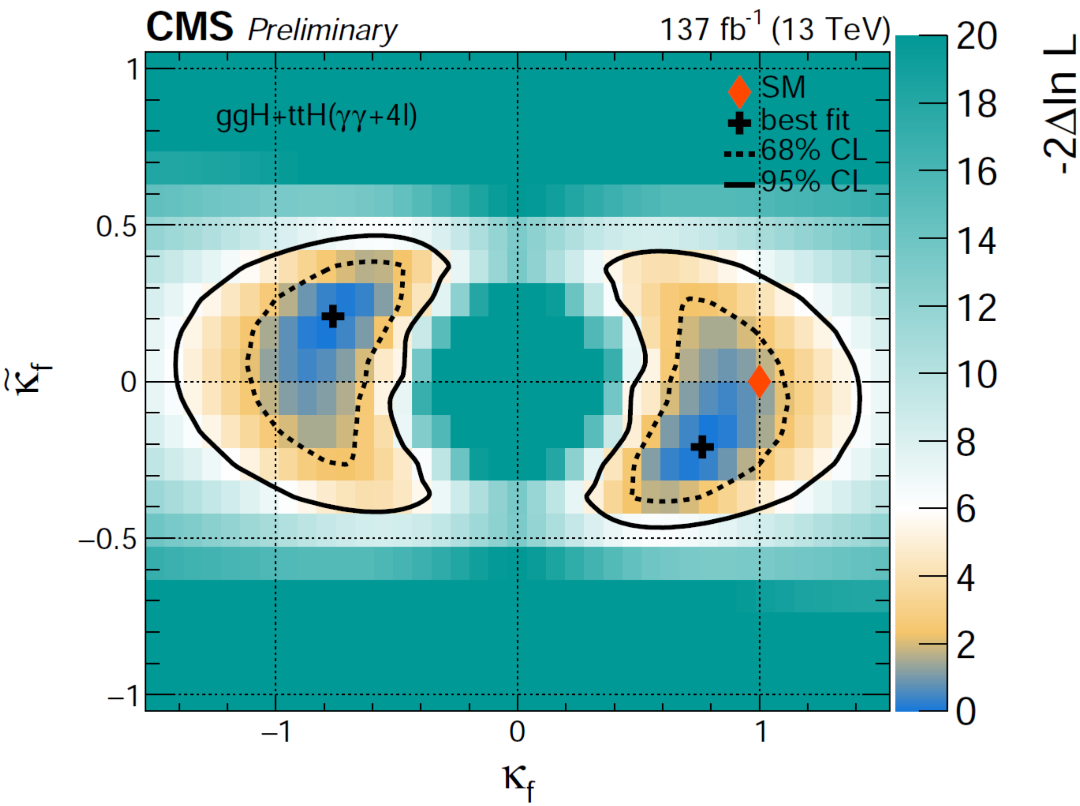




Constrain Htt from ggH and ttH:

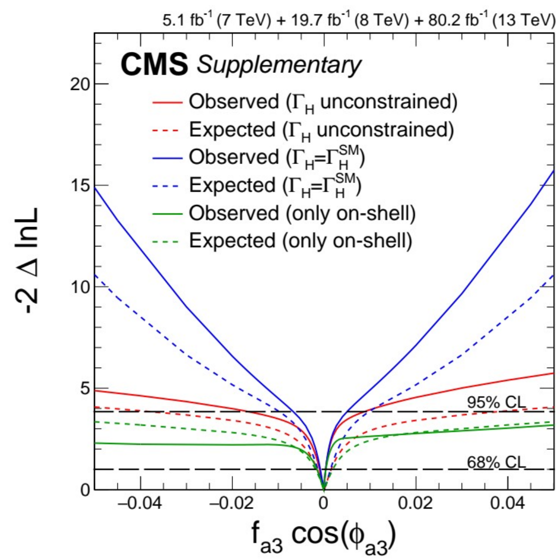
- In H→4l only :
  assume $\kappa_b = \kappa_t$ and for CP odd contributions also
- Combine H→4l result and H→γγ
  similar assumptions as in ttH combination

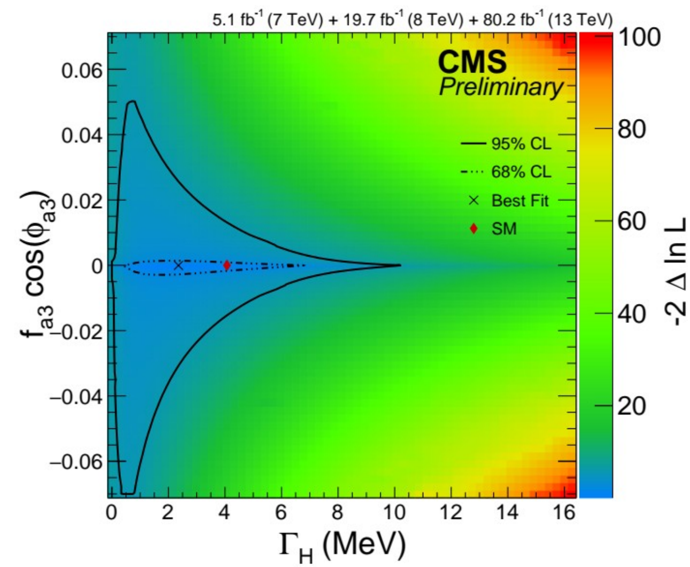
Detailed numerical report of results in extra material section

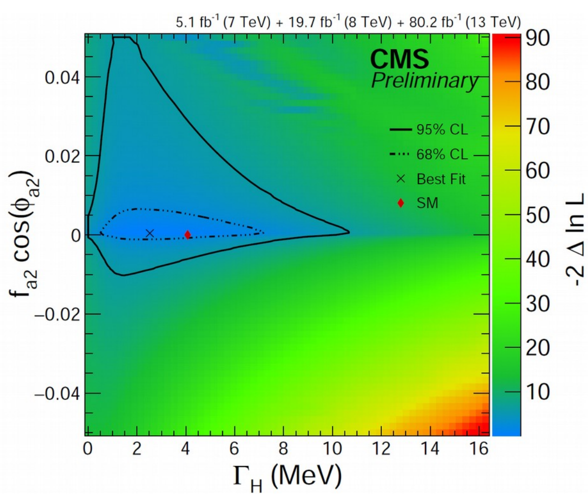
Offshell analysis with H→4l

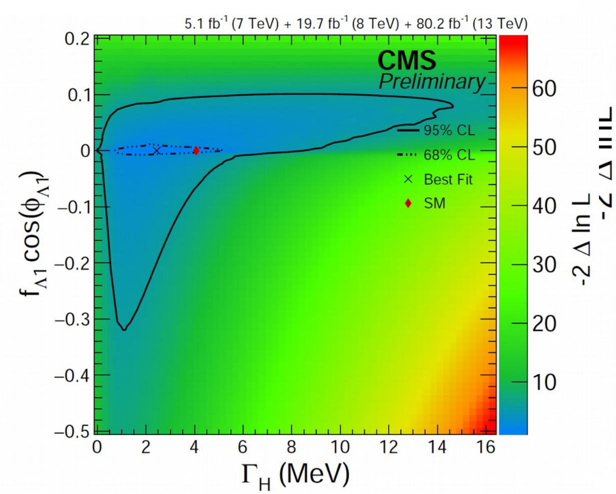
HIG-18-002

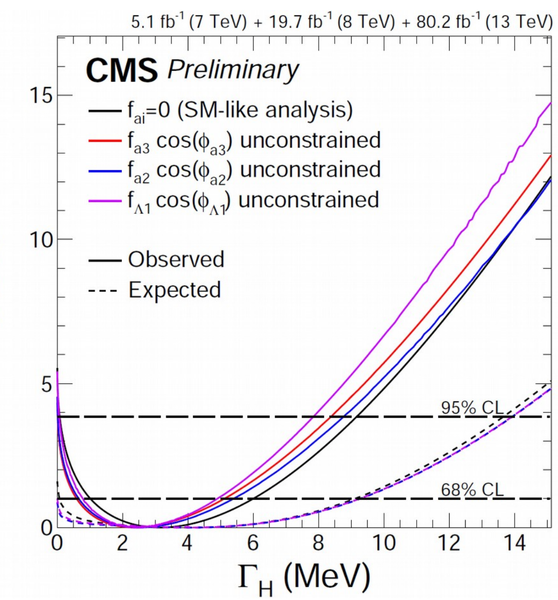
- AC can increase considerably the offshell signal yields
- Scan f_{a2}, f_{a3}, $f_{\Lambda1}$
- Individual AC scans
- Simpler categorization than onshell analysis
- Background interferes with signal → more challenging analysis
- **Combination of Run I and 2016+2017 data**
- **Combination of offshell and onshell analyses**











Conclusions

- **Probing the Higgs anomalous couplings is of paramount importance for the LHC experiments**
- **CMS investigates anomalous Higgs coupling measurements in multiple final states**

- **Technically challenging analyses:**
  - Full simulation of all phenomena studied
  - Exploit all available experimental information from decay and production
  - Statistical tools allow simultaneous multi AC parameter scans

- **Effective field theory**
- **Interpretation in terms of Lagrangian couplings**
- **Combined results across different final states**

Channels	Coupling	Observed	Expected	Observed correlation			
ggH	c_{gg}	$0.0056^{+0.0025}_{-0.0039}$	$0.0084^{+0.0007}_{-0.0084}$		1		
	$\tilde{c}_{gg}$	$-0.0058^{+0.0037}_{-0.0024}$	$0.0000^{+0.0085}_{-0.0085}$		+0.980	1	
$\mathrm{t\bar{t}H}$	κ_t	$1.06^{+0.14}_{-0.18}$	$1.00^{+0.15}_{-0.23}$		1		
	$\tilde{\kappa}_t$	$0.00^{+0.76}_{-0.72}$	$0.00^{+0.80}_{-0.80}$		0.000	1	
$\mathrm{t\bar{t}H + ggH}$	κ_f	$0.76^{+0.23}_{-0.21}$	$1.00^{+0.26}_{-0.39}$		1		
	$\tilde{\kappa}_f$	$-0.21^{+0.28}_{-0.12}$	0.00 ± 0.37		+0.745	1	
$\mathrm{VBF + VH + H \to 4\ell}$	δc_z	$-0.25^{+0.27}_{-0.07}$	$0.00^{+0.10}_{-0.28}$	1			
	c_{zz}	$0.03^{+0.10}_{-0.10}$	$0.00^{+0.22}_{-0.16}$	+0.144	1		
	$c_{z\Box}$	$-0.03^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$	−0.186	−0.847	1	
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$	+0.077	−0.016	+0.009	1

References:

- *Andrei V. Gritsan et al.* ,"New features in the JHU generator framework: constraining Higgs boson properties from on-shell and off-shell production", ***arXiv:2002.09888***

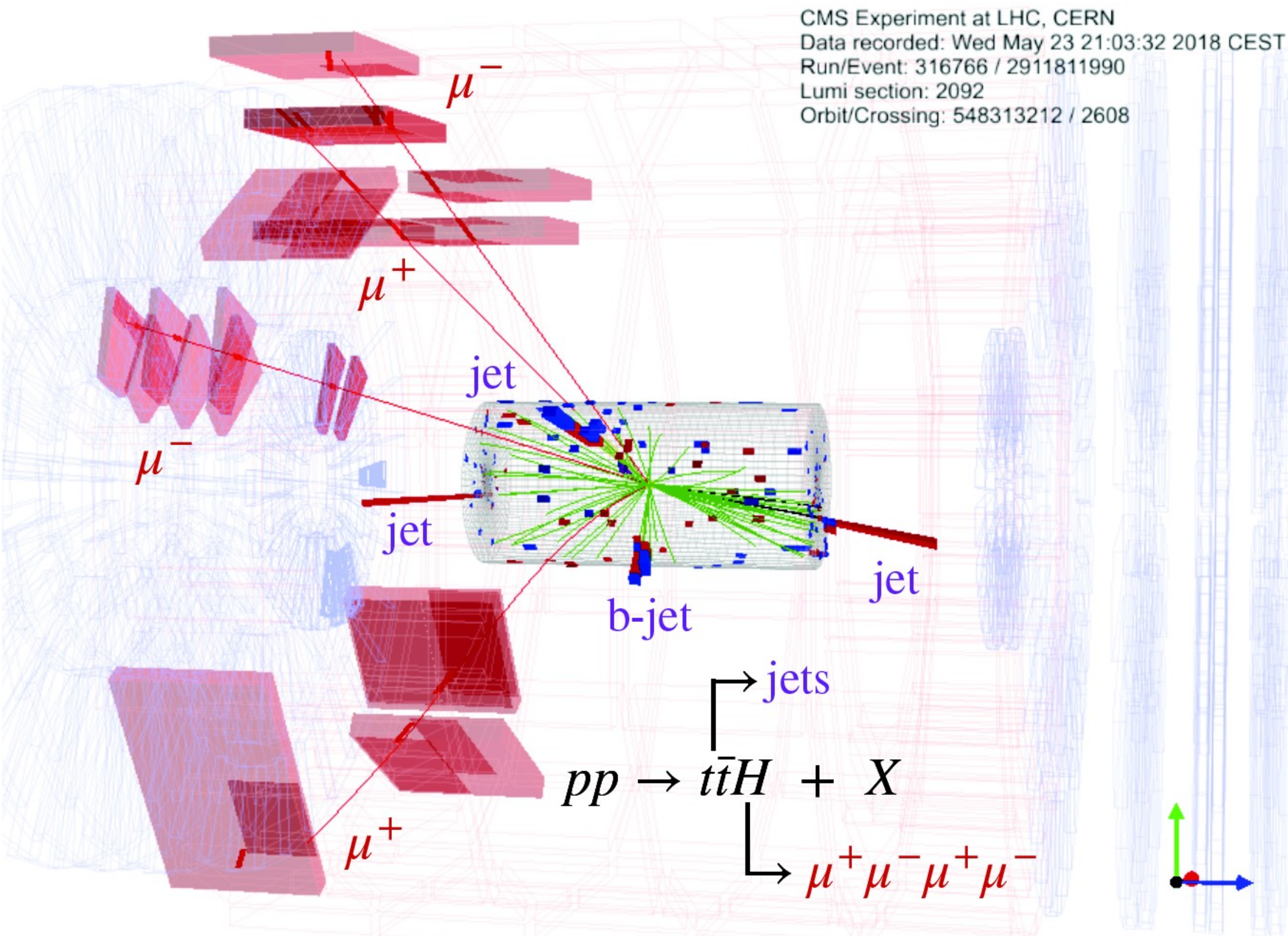
- *The CMS collaboration*,"Measurements of properties of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s}$=13 TeV", ***https://cds.cern.ch/record/2668684***

- *A. M. Sirunyan et al.* ,"Measurements of Higgs boson properties from on-shell and off-shell production in the four-lepton final state", ***Phys. Rev. D 99, 112003***

- *A. M. Sirunyan et al.* ,"Measurements of $t\bar{t}$H production and the CP structure of the Yukawa interaction between the Higgs boson and top quark in the diphoton decay channel", ***arXiv:2003.10866***

Extra material

$t\bar{t}$H event display



Summary of HVV/Hff results

HIG-19-009

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00000	0.00000
	$f_{a2}=f_{\Lambda 1}=f_{\Lambda 1}^{Z\gamma}=0$	68% CL	$[-0.00017, 0.00017]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.0010, 0.0038] \cup [0.01, 0.24]$	$[-0.0056, 0.0056]$
	Approach 1	best fit	± 0.010	0.00000
	float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.042, 0.034]$	$[-0.00088, 0.00088]$
		95% CL	$[-0.20, 0.20]$	$[-0.0057, 0.0057]$
	Approach 2	best fit	0.00005	0.0000
	float $f_{a2}, f_{\Lambda 1}$	68% CL	$[-0.00013, 0.00066]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.0010, 0.0028] \cup [0.024, 0.092]$	$[-0.0074, 0.0074]$
f_{a2}	Approach 1	best fit	0.00000	0.0000
	$f_{a3}=f_{\Lambda 1}=f_{\Lambda 1}^{Z\gamma}=0$	68% CL	$[-0.00031, 0.00098]$	$[-0.0012, 0.0013]$
		95% CL	$[-0.0033, 0.0039]$	$[-0.0095, 0.0081]$
	Approach 1	best fit	-0.29	0.0000
	float $f_{a3}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.50, -0.18] \cup [-0.00024, 0.00052]$	$[-0.0018, +0.0013]$
		95% CL	$[-0.68, -0.05] \cup [-0.027, 0.185] \cup [0.38, 0.55]$	$[-0.0106, 0.0081]$
	Approach 2	best fit	-0.0001	0.0000
	float $f_{a3}, f_{\Lambda 1}$	68% CL	$[-0.0024, 0.0008]$	$[-0.0053, 0.0033]$
		95% CL	$[-0.0209, 0.0133]$	$[-0.0869, 0.0055]$
$f_{\Lambda 1}$	Approach 1	best fit	0.00000	0.00000
	$f_{a3}=f_{a2}=f_{\Lambda 1}^{Z\gamma}=0$	68% CL	$[-0.00009, 0.00022]$	$[-0.00016, 0.00025]$
		95% CL	$[-0.00036, 0.00110] \cup [0.002, 0.135]$	$[-0.00081, 0.00112]$
	Approach 1	best fit	0.13	0.00000
	float $f_{a3}, f_{a2}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.00012, 0.00015] \cup [0.02, 0.24]$	$[-0.00017, 0.00036]$
		95% CL	$[-0.16, -0.01] \cup [-0.0056, 0.3423]$	$[-0.00089, 0.00144]$
	Approach 2	best fit	0.00019	0.0000
	float f_{a3}, f_{a2}	68% CL	$[-0.00017, 0.00168]$	$[-0.0012, 0.0029]$
		95% CL	$[-0.0019, 0.0055] \cup [0.10, 0.29]$	$[-0.0060, 0.0103]$
$f_{\Lambda 1}^{Z\gamma}$	Approach 1	best fit	-0.0004	0.0000
	$f_{a3}=f_{a2}=f_{\Lambda 1}=0$	68% CL	$[-0.0010, 0.0014]$	$[-0.0026, 0.0020]$
		95% CL	$[-0.0063, 0.0060] \cup [0.05, 0.21]$	$[-0.0102, 0.0091]$
	Approach 1	best fit	-0.06	0.0000
	float $f_{a3}, f_{a2}, f_{\Lambda 1}$	68% CL	$[-0.18, -0.02] \cup [-0.00049, 0.00058]$	$[-0.0026, 0.0025]$
		95% CL	$[-0.53, 0.52]$	$[-0.011, 0.011]$

Hgg/Hff results

HIG-19-009 HIG-19-013

Parameter	Scenario	Observed	Expected
f_{CP}^{Htt}	$t\bar{t}H$ ($H \to 4\ell$)	$\pm 1 \mp 2$ $[-1, 1]$	0 ± 1 $[-1, 1]$
	$t\bar{t}H$ ($H \to \gamma\gamma$) [26]	0.00 ± 0.33 $[-0.67, 0.67]$	0.00 ± 0.49 $[-0.82, 0.82]$
	$t\bar{t}H$ ($H \to 4\ell$ & $\gamma\gamma$)	0.00 ± 0.31 $[-0.67, 0.67]$	0.00 ± 0.48 $[-0.82, 0.82]$
	ggH ($H \to 4\ell$)	$-0.32^{+0.31}_{-0.68}$ $[-1, 1]$	0 ± 1 $[-1, 1]$
	ggH & $t\bar{t}H$ ($H \to 4\ell$)	$-0.50^{+0.45}_{-0.50}$ $[-1, 1]$	0.00 ± 0.65 $[-1, 1]$
	ggH & $t\bar{t}H$ ($H \to 4\ell$ & $\gamma\gamma$)	$-0.13^{+0.13}_{-0.24}$ $[-0.61, 0.43]$	0.00 ± 0.29 $[-0.63, 0.63]$

H→4l off-shell

HIG-18-002

anomalous couplings :
→ increase the number of off-shell events