Dedicated measurements of CP and anomalous Higgs couplings

SM @ LHC 2023
Workshop July 13th 2023

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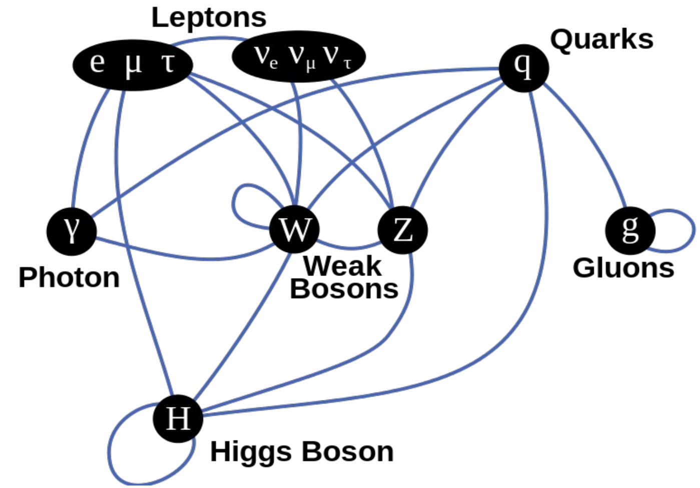
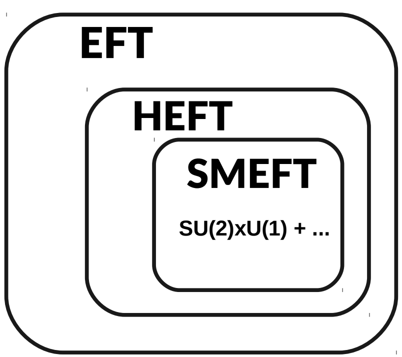
On behalf of the
ATLAS and **CMS** collaborations

Dedicated AC measurements

- Study Higgs Couplings to:
  - Uncover CPV in Higgs sector
  - Uncover BSM phenomena



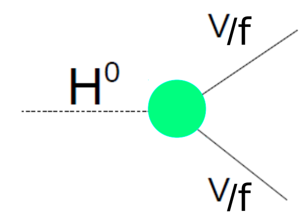
- What consists of a dedicated measurement
  - Targeted analysis
  - Dedicated sensitive observables to specific couplings
  - Gen + Full Detector simulation of AC effects (Interference effects, acceptance effects+)
- Measurements utilize EFT



$$\mathcal{L}_{\rm SM} = \mathcal{L}^{(4)}_{\rm SM} + \frac{1}{\Lambda}\cancel{\sum_k C_k^{(5)} Q_k^{(5)}} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Mass eigenstate basis + symmetries → **Higgs basis**

Weak eigenstate basis : **Warsaw basis**



EFT – basis

Mass eigenstate → Higgs basis

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \boxed{\frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V}1}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V}2}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V}1} + q_{\mathrm{V}2})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^*$$

$$+ \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

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

V = W,Z,g,γ
f = leptons + quarks

- Natural choice for Higgs couplings
- Less operators

Approach 1

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

Approach 2: SMEFT

SU(2)xU(1) + custodial sym.
set c_w^2 to SM value

custodial sym.
set $c_w^2 = 1$

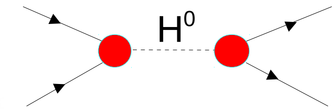
$$g_1^{WW} = g_1^{ZZ}$$
$$g_2^{WW} = c_w^2 g_2^{ZZ} \cancel{+ s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}},$$
$$g_4^{WW} = c_w^2 g_4^{ZZ} \cancel{+ s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}}$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}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

Weak eigenstate: Warsaw basis

- More general - used in EW TOP and Higgs sector
- SMEFT build in (SU(2)x U(1))
- Has many more dim 6 operators

Rotations between basis feasible and demonstrated in measurements !

HVV: H→4l CMS

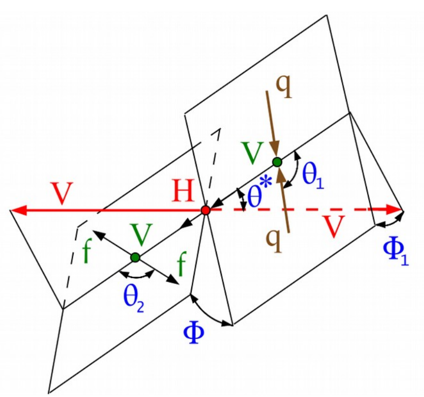


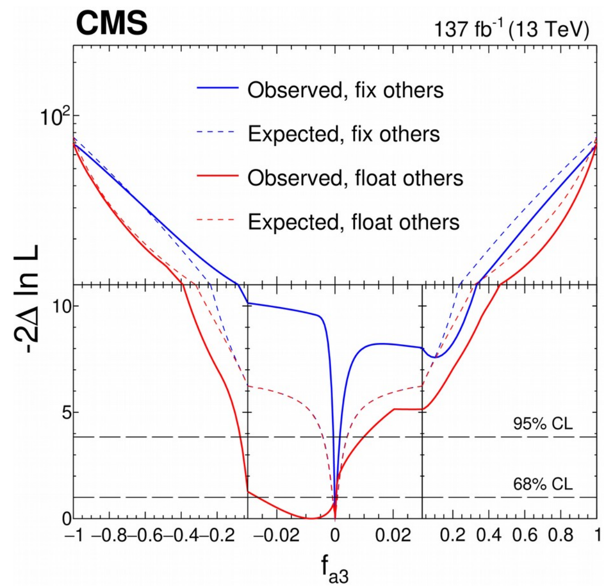
HIG-19-009

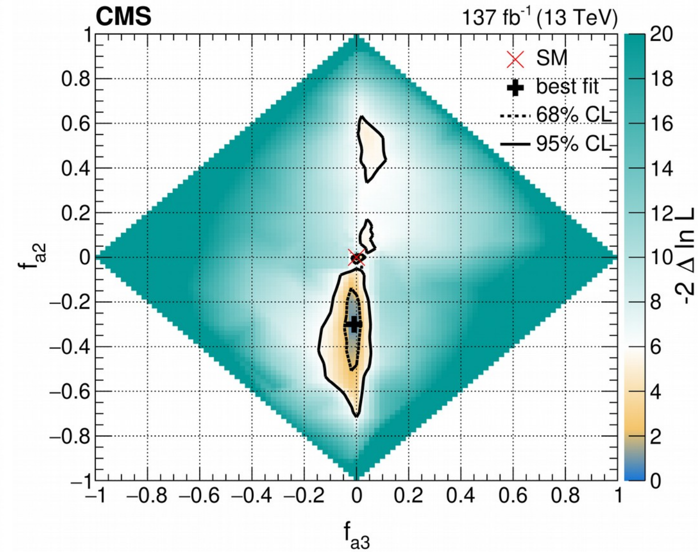
- 2e2μ, 4e, 4μ
- m4l 105 – 140 GeV + 6 categories targeting prod. modes.
- Approach 1 with 4 independent A.C. + SM
- Simultaneous scan of all AC considered
- Non-zero minima
- **SM consistent**

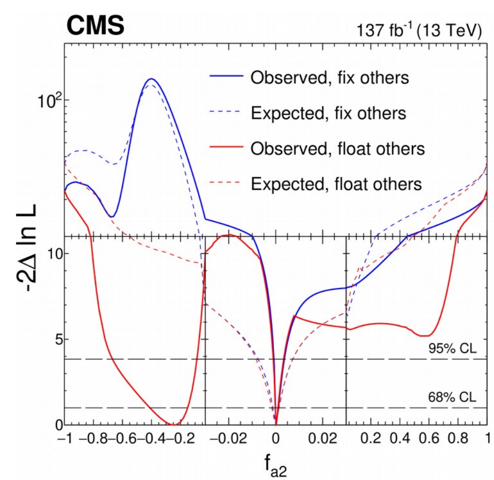
Effective fractional xsec:

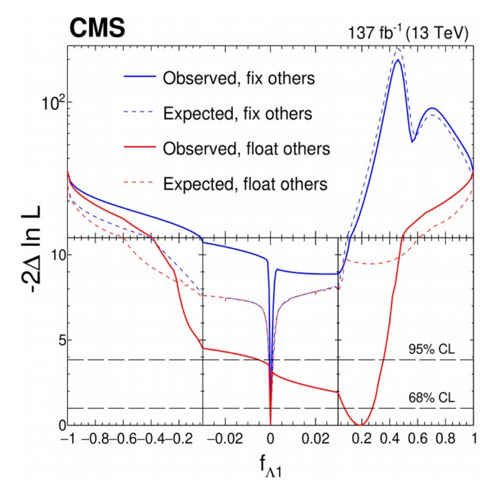
$$f_{ai}^{VV} = \frac{|a_i^{VV}|^2\,\alpha_{ii}^{(\mathrm{dec})}}{\sum_j |a_j^{VV}|^2\,\alpha_{jj}^{(\mathrm{dec})}}\,\mathrm{sign}\left(\frac{a_i^{VV}}{a_1}\right)$$

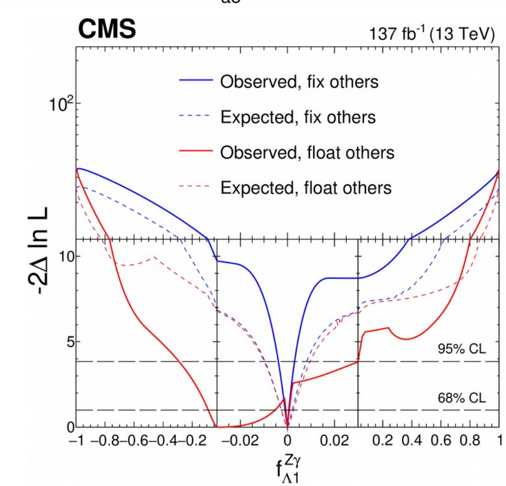




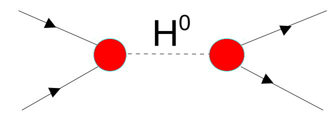








HVV: H→4l CMS



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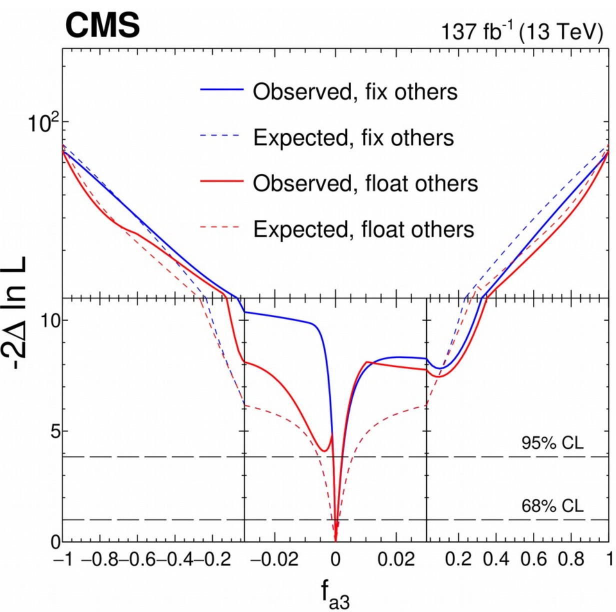
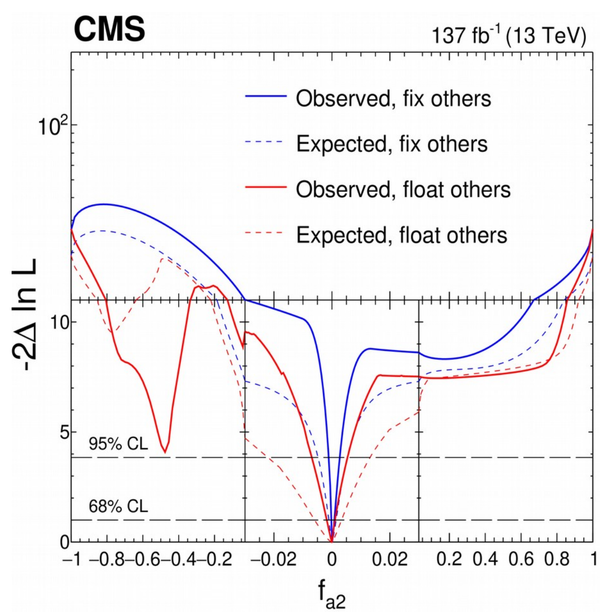
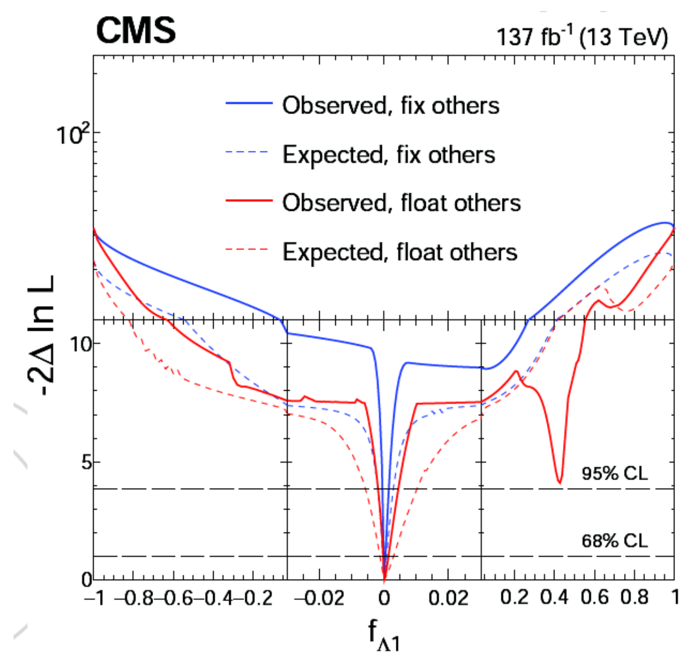


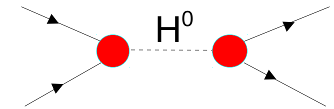


- SU(2)xU(1) sym. (SMEFT) with only 3 independent A.C.
- **Stringent constraints driven by production information**
- **Full Run2**
- **Minima consistent with SM**

Parameter	Scenario	Observed		Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	$[-0.00007, 0.00044]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.00055, 0.00168]$	$[-0.00412, 0.00412]$
	Approach 1	best fit	-0.00805	0.00000
	float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.02656, 0.00034]$	$[-0.00086, 0.00086]$
		95% CL	$[-0.07191, 0.00990]$	$[-0.00423, 0.00422]$
	Approach 2	best fit	0.00005	0.0000
	float $f_{a2}, f_{\Lambda 1}$	68% CL	$[-0.00010, 0.00061]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.00072, 0.00218]$	$[-0.0057, 0.0057]$



HVV: H→ 4l CMS



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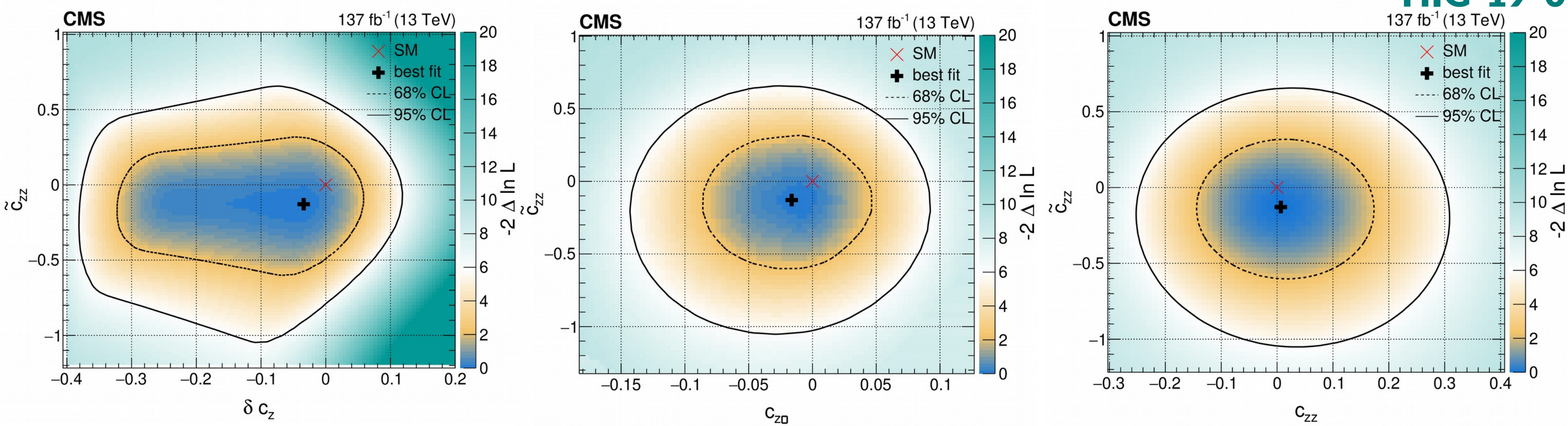
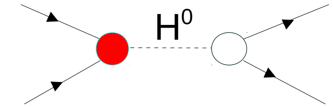


Channels	Coupling	Observed
VBF & VH & $H \to 4\ell$	δc_z	$-0.03^{+0.06}_{-0.25}$
	c_{zz}	$0.01^{+0.11}_{-0.10}$
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$

Translated to Warsaw basis:

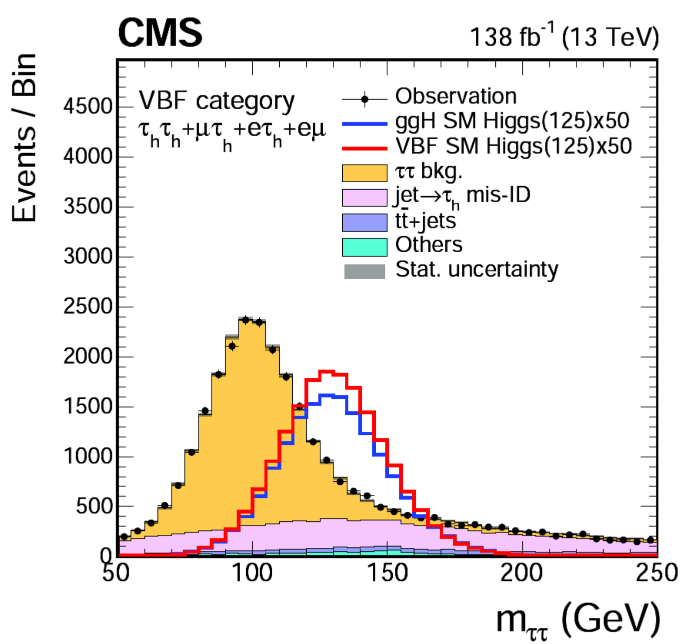
Channels	Coupling	Observed	Expected
VBF & VH & $H \to 4\ell$	$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
	c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
	c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
	c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
	c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
	$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
	$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
	$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

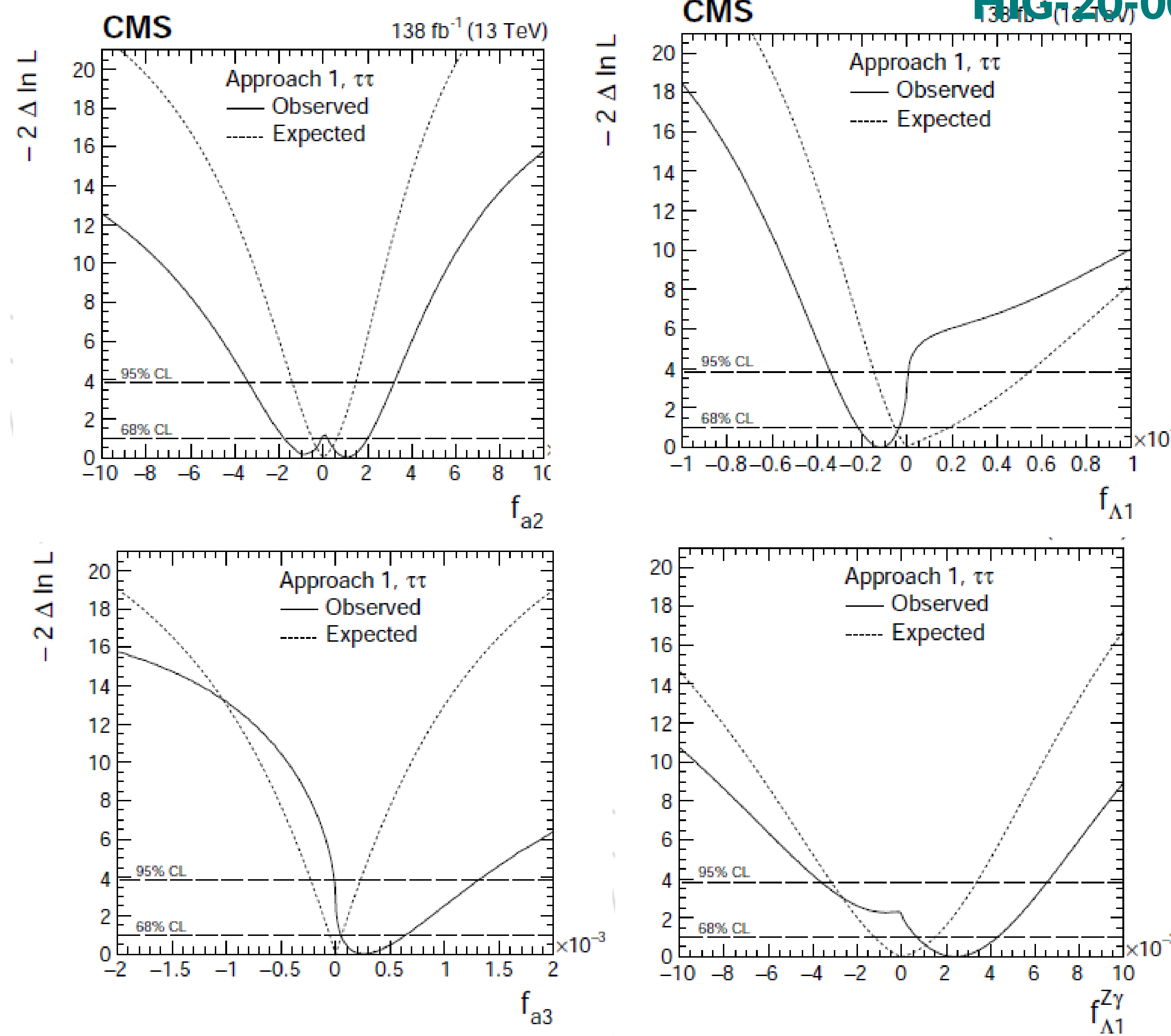
HVV: H→ττ + H→4l CMS



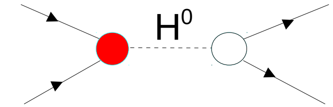
HIG-20-007

- Single AC scans
- Study production
- Utilize ME discr.
- Combine results with H4l



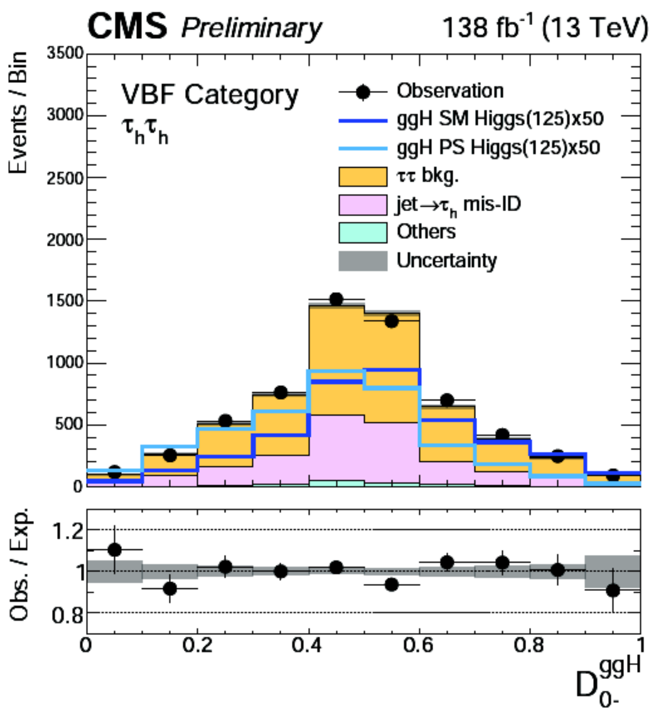


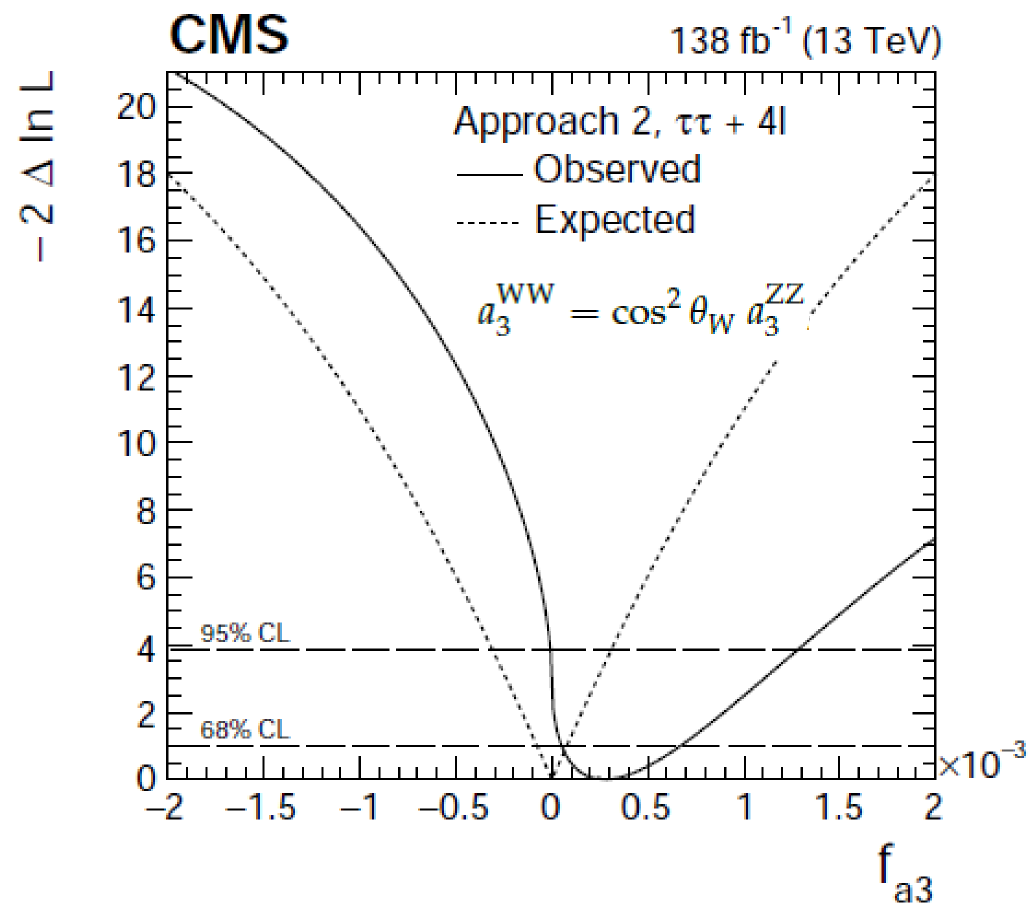
HVV: H→ττ + H→4l CMS



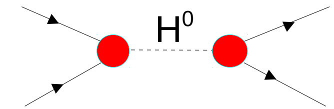
HIG-20-007

- SMEFT but study only a3
- High H→ ττ BR provides indispensable stat. contribution





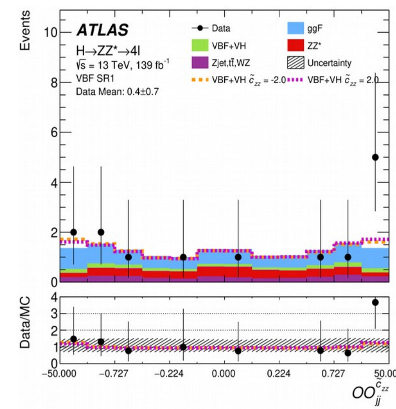
HVV in H→4l (ATLAS)

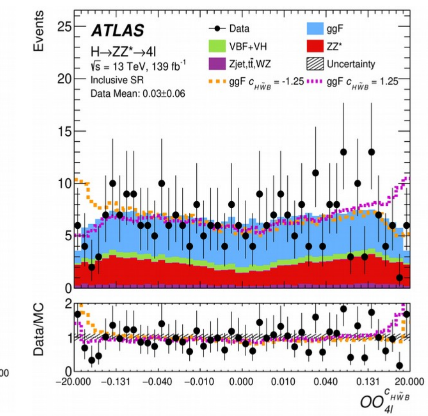


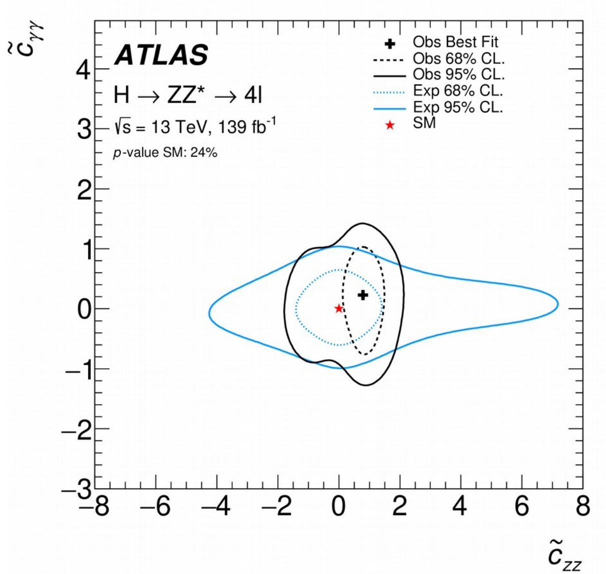
HIGG-2018-30

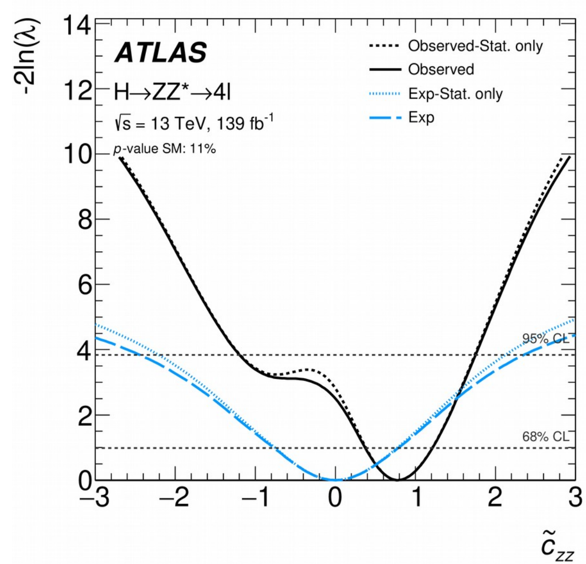
$$OO = \frac{2\Re\left(\mathcal{M}_{\rm SM}^{*}\mathcal{M}_{\rm BSM}\right)}{|\mathcal{M}_{\rm SM}|^2}$$

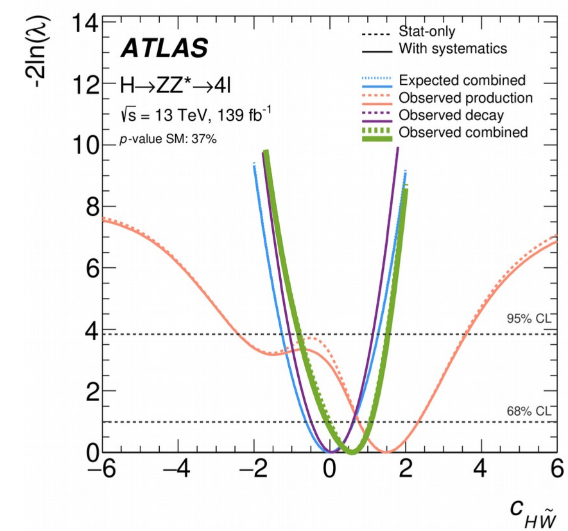
- Use ME based optimal observables
- Single AC fits each time
- Production only or Decay only analysis and then combined
- Warsaw + Higgs basis
- **Full Run2**



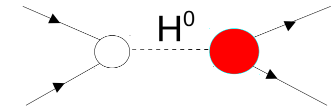








Yukawa ττH : H→ ττ CMS



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$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

Full Run2 data

Decay vertex probed

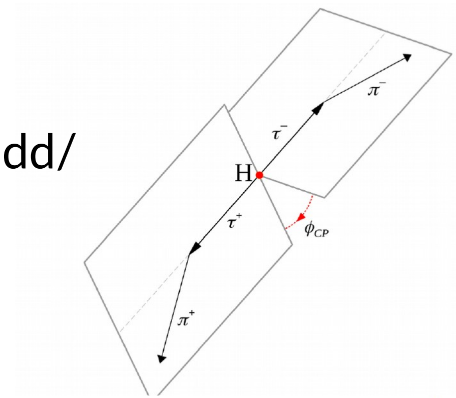
Use decays to ττ pair to measure CP odd/ even mixing in Hττ

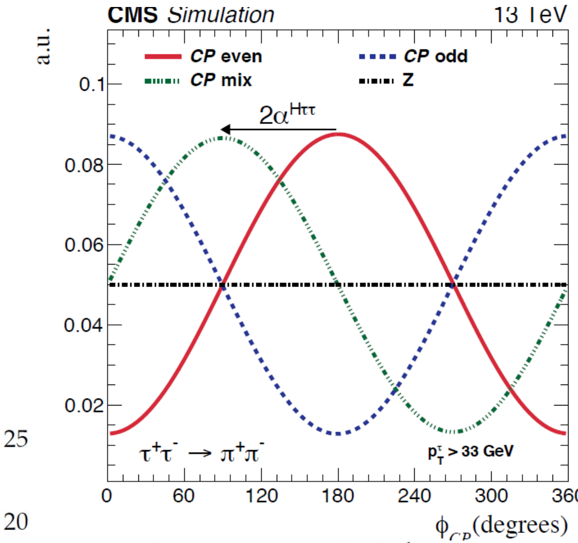
Use ~70% of τ BR:

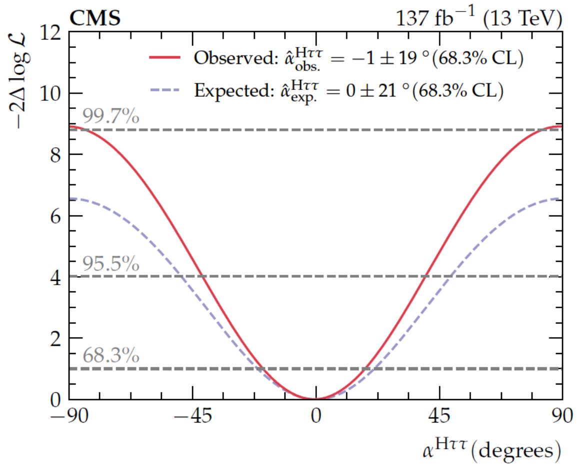
$\tau_h\tau_h$, $\tau_\mu\tau_h$ + $\tau_e\tau_h$

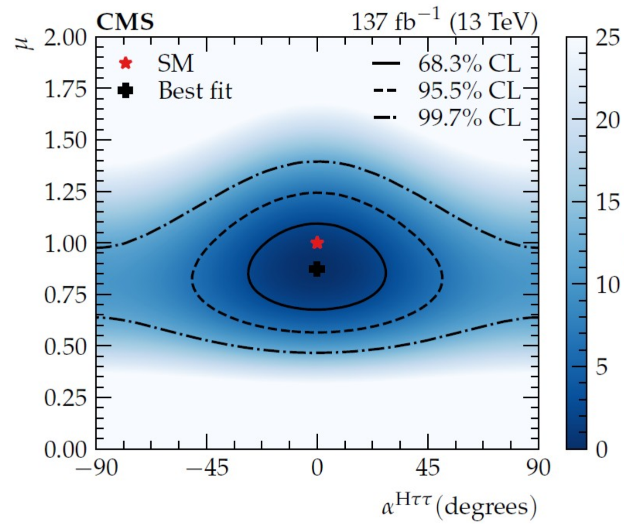
4 reconstruction methods of ϕ_{CP}

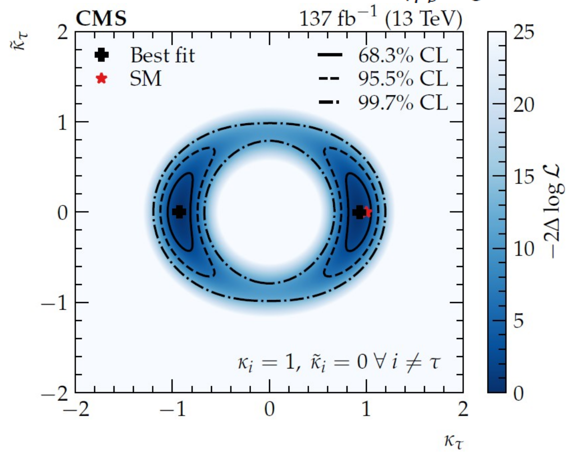
Pure CP odd excluded at 3σ



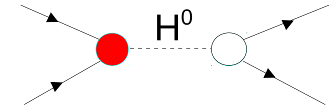








Hgg : using ggF in 4l,γγ,ττ CMS



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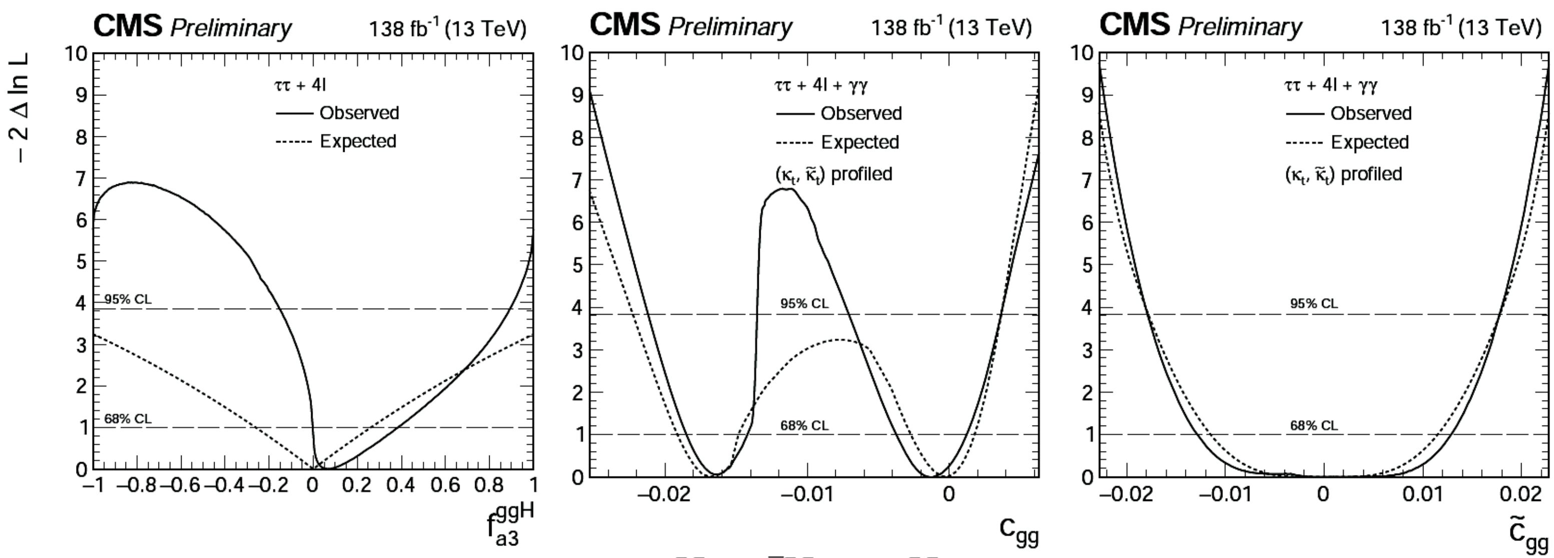


$$\mathcal{D}_{CP}^{\mathrm{ggH}} = \frac{\mathcal{P}_{\mathrm{SM-0-}}^{\mathrm{ggH}}}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{ggH}} + \mathcal{P}_{0-}^{\mathrm{ggH}}}.$$

$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg}$$

$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg}$$

Combination of H→4l, H→ττ, H→γγ

FULL RUN2

Measure CP sensitive fa3^{ggH} and μ_{ggH}

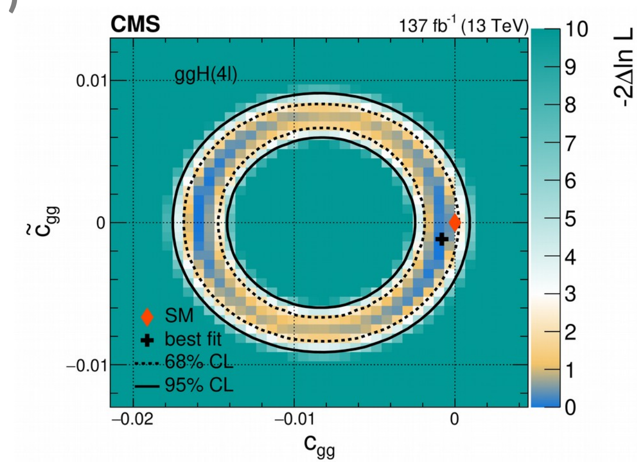
Use events in VBF2J to study ggH category

4 couplings fit simultaneously:

Constrain ktop measured from the tH,ttH process and study cgg

$\mathrm{tH}\ \&\ \mathrm{t\bar{t}H}\ \&\ \mathrm{ggH}$ (ttH,tH from: H→4l H→γγ)

Parameter	Scenario		68% CL / (10^{-2})
c_{gg}	Profiled	Observed	$-0.11^{+0.20}_{-0.26} \cup [-1.85, -1.42]$
		Expected	$0.00^{+0.18}_{-0.27} \cup [-1.91, -1.48]$
$\tilde{c}_{gg}$	Profiled	Observed	0.00 ± 1.29
		Expected	0.00 ± 1.15
c_{gg}	Fixed	Observed	$-0.08^{+0.07}_{-0.15} \cup [-1.65, -1.54]$
		Expected	$0.00^{+0.06}_{-0.14} \cup [-1.73, -1.50]$
$\tilde{c}_{gg}$	Fixed	Observed	$0.22^{+0.28}_{-0.22} \cup [-0.50, 0.00]$
		Expected	0.00 ± 0.45



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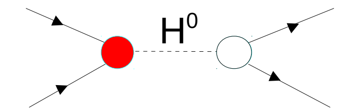
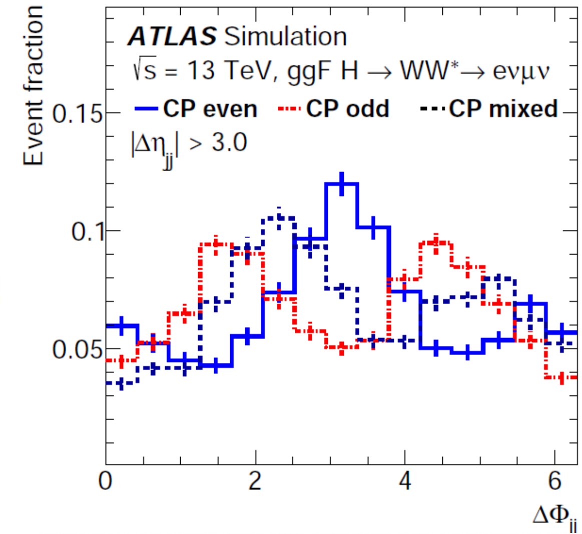
Hgg in H→WW*→ eνμν+jj (ATLAS)

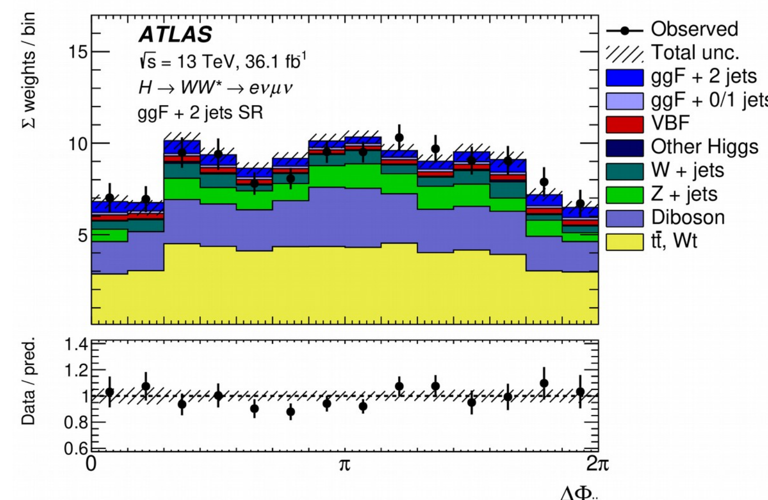


- Parameterization in terms of mixing angle and κ

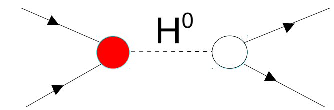
$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

- Use **production information**
- Assume HVV -SM like
- BDT to separate signal and background
- 12 categories – BDT and Δηjj
  - CP odd/even separation in ΔΦjj enhanced in high Δηjj
- Backgrounds constrained in CR





Hgg in H→WW*→ eνμν+jj (ATLAS)



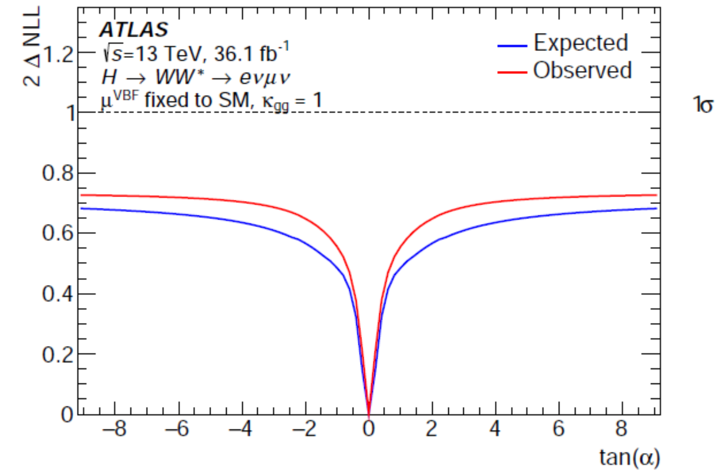
use BDT and ΔΦjj distributions for fitting

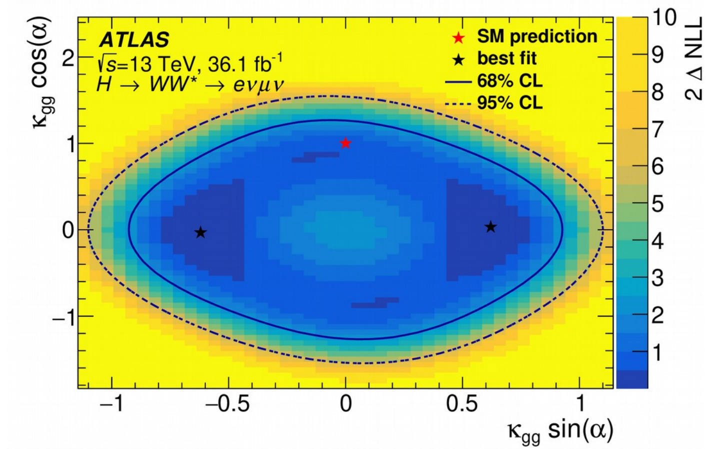
Fit Δφjj in SR: 3 BDT X 4 |Δηjj| regions

2 likelihood fits:

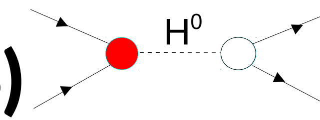
- Shape only considered scan (BSM rate floated)
- Shape + fix rate to BSM scenario

1σ constraints on CP mixing angle

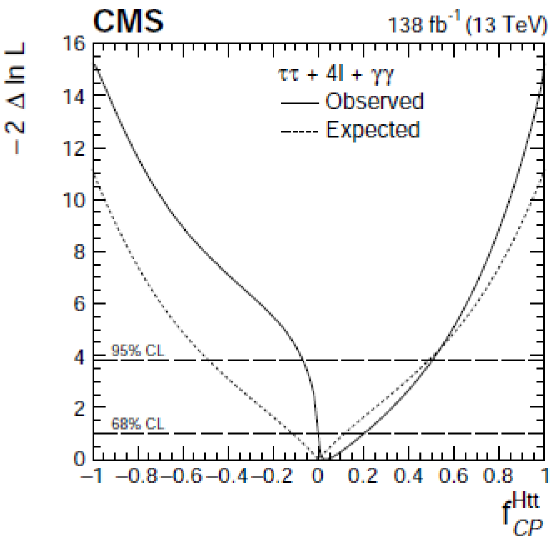


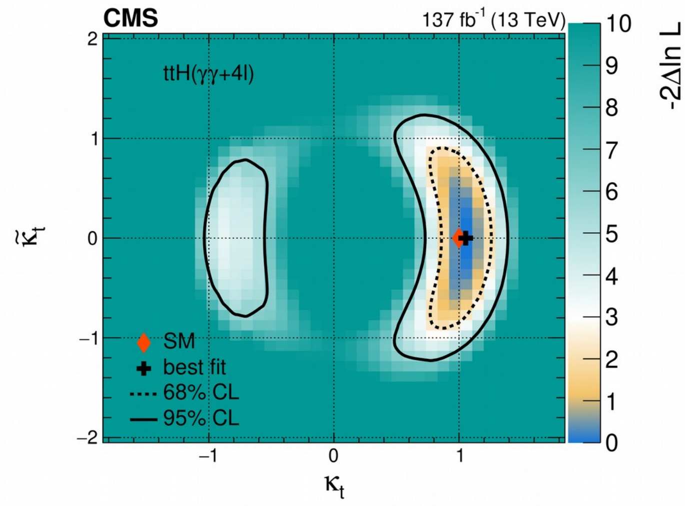


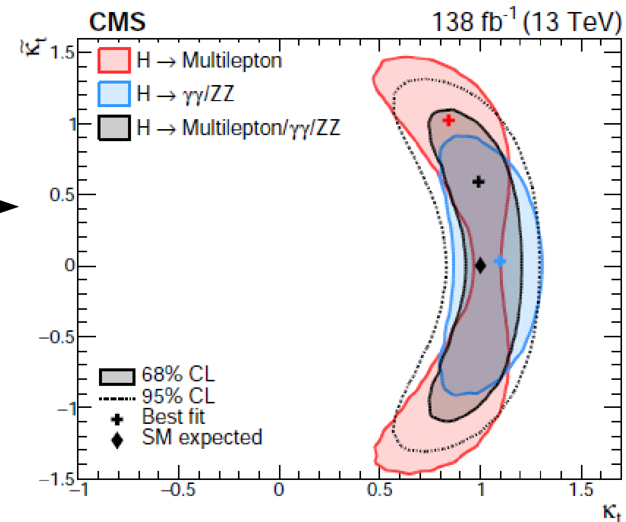
Yukawa ttH : ttH(ggH),H→4l/γγ/ττ/WW (CMS)



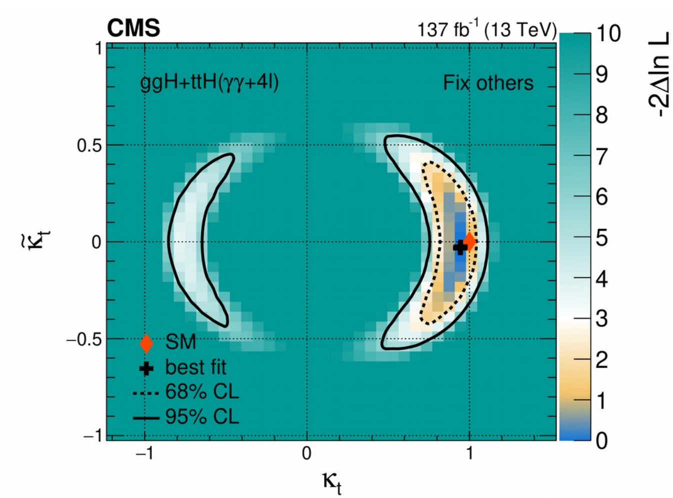
HIG-20-007
HIG-21-006







- **Measure f_{CP}^{Htt} in production**
- **Combine**
  - **H→ 4l**
  - **H→ττ** **+ Also multi- lepton(ττ/WW) +ZZ+γγ**
  - **H→γγ**

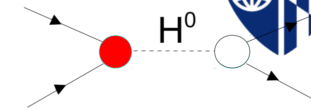


- **Combine measurements with uncorrelated μs**
- **Interpret as top couplings**

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

Phys, Rev. Lett. 125 (2020) 061802

Yukawa ttH with ttH,H→γγ (ATLAS)



Analysis targets **CP mixing angle and kt**

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

Classify ttH events in **hadronic** and **leptonic**

- lept: require at least single isolated lepton
- had: at least 2 jets

Use **production information**

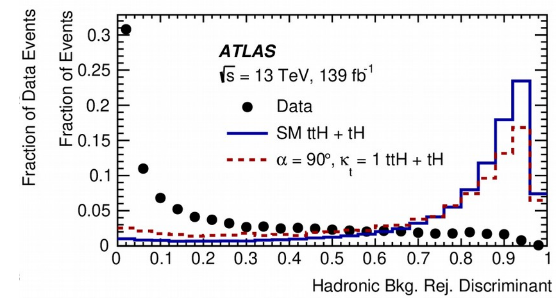
Dedicated signal-background BDT

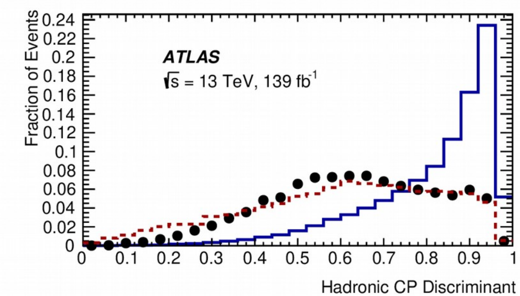
BDT CP: use top and diphoton system kinematics

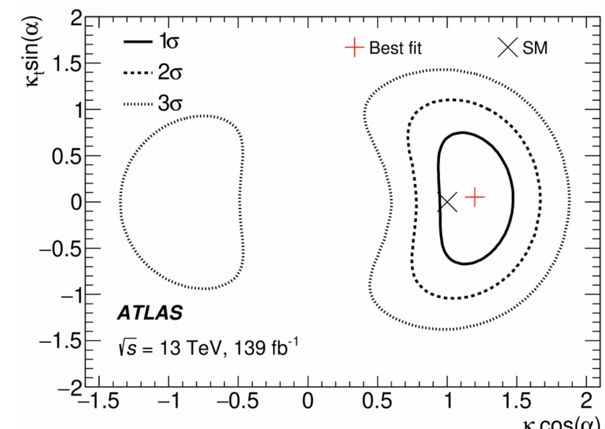
Fit mγγ in overall 20 categories (12Had + 8Lept)

Tightly constrain pure CP odd ttH coupling

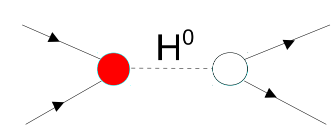
Full Run 2







Yukawa tH/ttH, H→ bb (ATLAS)



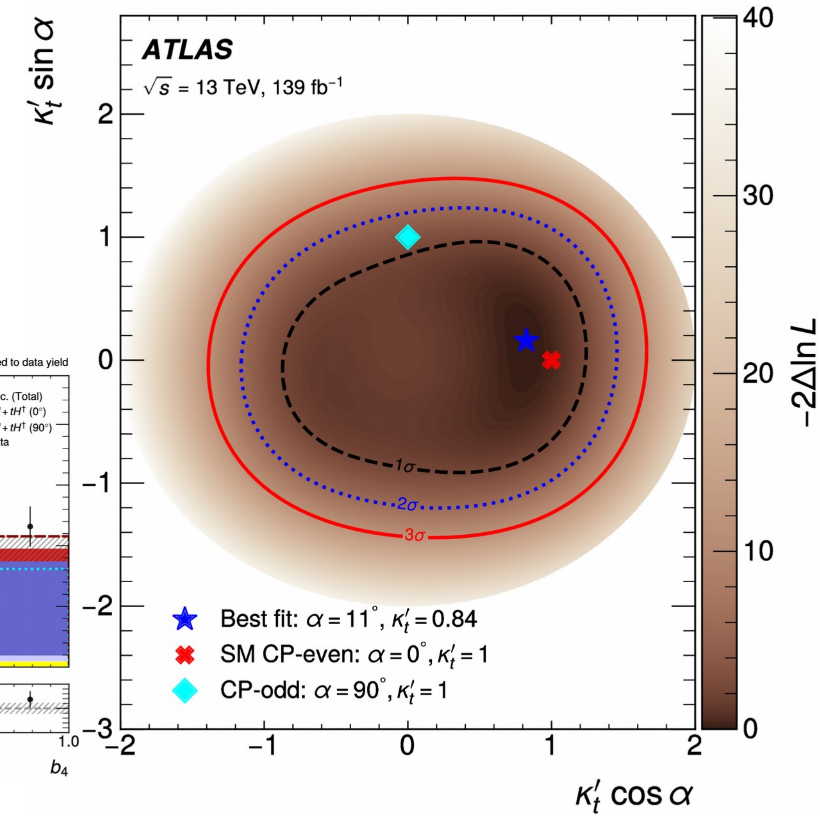
HIGG-2020-003

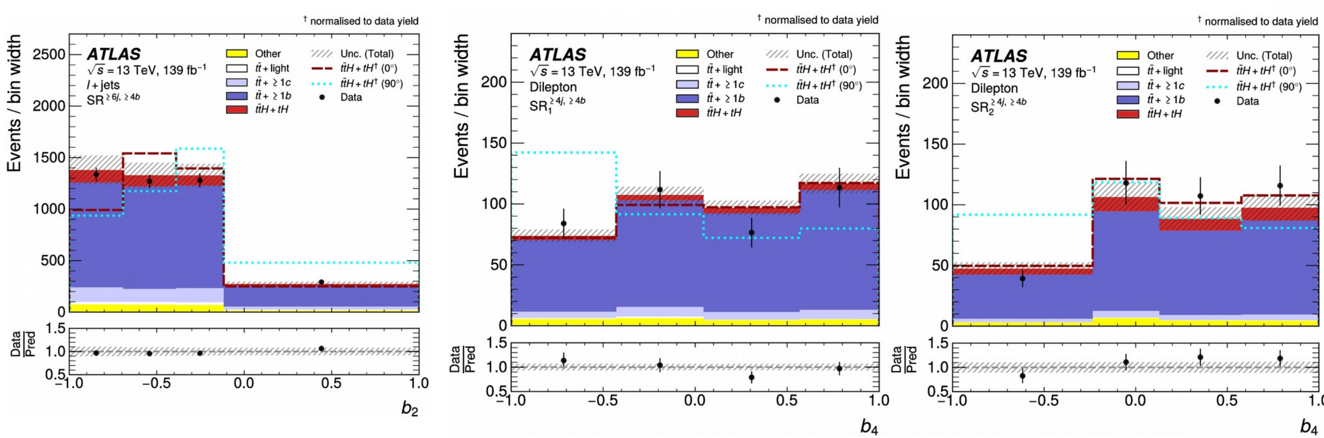
- Dedicated observables
- Requires top 4 vectors
- Background modeling challenging
- **Full Run2**

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

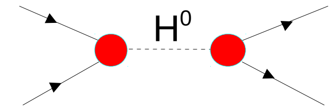
$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$



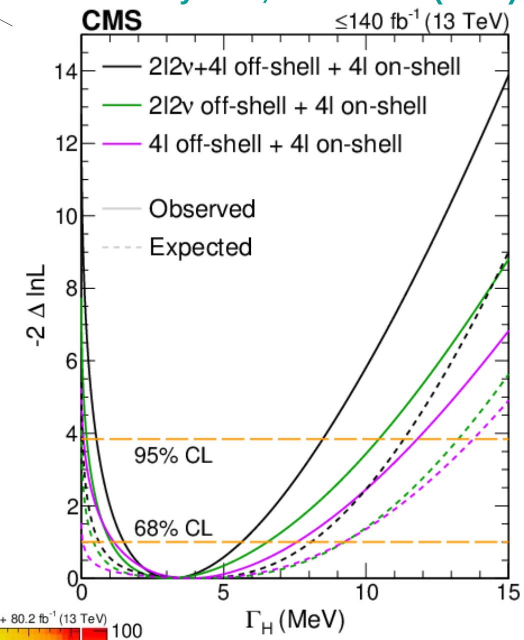


Off-shell studies in H→4l +2l2ν (CMS)

- Use same formalism as on-shell H→4l AC analysis
- M4l > 220 GeV (2e2μ, 4e, 4μ)
- Design categories targeting ggF + EW production of the Higgs
- Use ME based observables + m4l
- Consider 1 AC at a time
- Constrain Higgs width + AC
- Combine with H→ ZZ→ 2l2ν

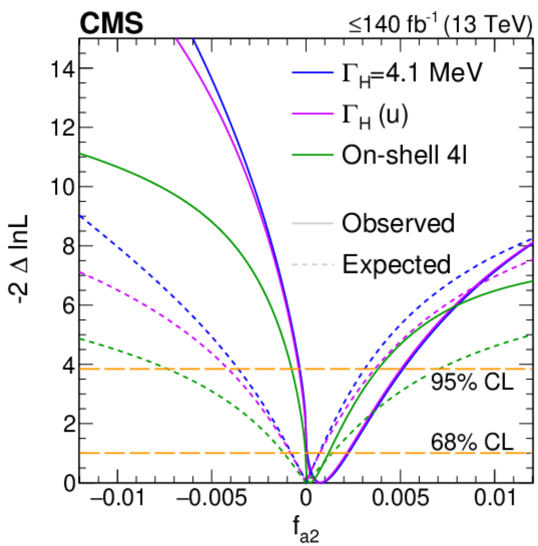


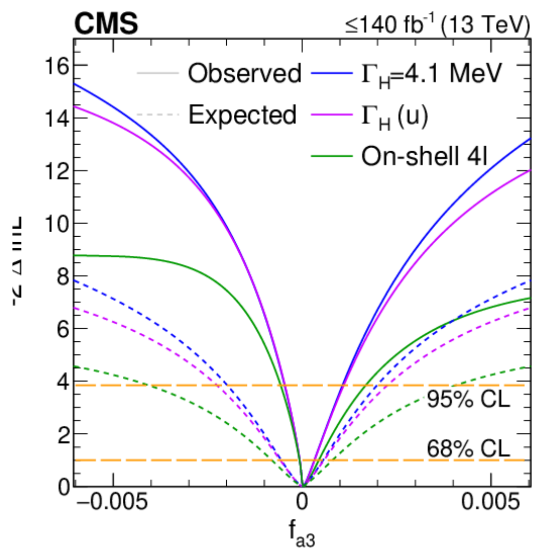
HIG-21-013
Nat. Phys. 18, 1329–1334 (2022)



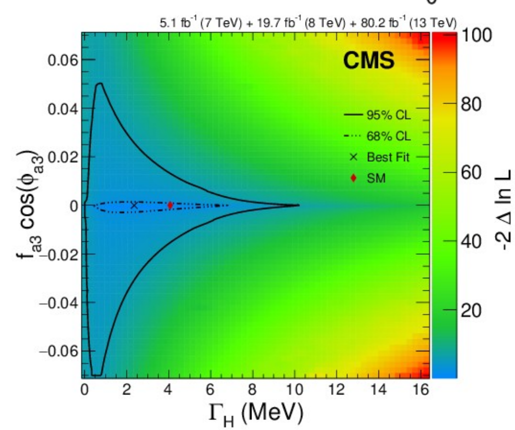
$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \mathrm{MeV}$$

HIG21-013





HIG18-002



Summary

- Full on program at the LHC studying Higgs anomalous coupling with dedicated measurements
- Multiple results both from ATLAS and CMS

- Target Hff /HVV couplings within EFT framework
- Combinations with mutliple final states
- Results consistent with SM
- Full Run2

Anomalous couplings

- Utilize EFT as a framework for studying the couplings

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \cancel{\frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)}} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- Study low energy approximations of UV complete theory on the SM
- Truncate at certain order + consider cut-off scale
- Study impact of said operator to the couplings
-

Effective Lagrangian and couplings (Higgs basis)

(arXiv:2002.09888)

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

$$\mathcal{L}_{hff} = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f\, h$$

Necessary to consider impact of AC in Γ:

$$\sigma(i \to H \to f) \propto \frac{\left(\sum \alpha_{jk}g_jg_k\right)\left(\sum \alpha_{lm}g_lg_m\right)}{\Gamma_{\mathrm{tot}}}$$

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

$$\begin{aligned}
&\delta c_z = \frac{1}{2}g_1^{ZZ} - 1\,, \qquad c_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_2^{ZZ}\,, \qquad c_{z\Box} = \frac{M_Z^2s_w^2}{e^2}\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}\,, \qquad \tilde{c}_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_4^{ZZ}\,, \\
&\delta c_w = \frac{1}{2}g_1^{WW} - 1\,, \qquad c_{ww} = -\frac{2s_w^2}{e^2}g_2^{WW}\,, \qquad c_{w\Box} = \frac{M_W^2s_w^2}{e^2}\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}\,, \qquad \tilde{c}_{ww} = -\frac{2s_w^2}{e^2}g_4^{WW}\,, \\
&c_{z\gamma} = -\frac{2s_wc_w}{e^2}g_2^{Z\gamma}\,, \qquad \tilde{c}_{z\gamma} = -\frac{2s_wc_w}{e^2}g_4^{Z\gamma}\,, \qquad c_{\gamma\Box} = \frac{s_wc_w}{e^2}\frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2}\kappa_2^{Z\gamma}\,, \\
&c_{\gamma\gamma} = -\frac{2}{e^2}g_2^{\gamma\gamma}\,, \qquad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2}g_4^{\gamma\gamma}\,, \qquad c_{gg} = -\frac{2}{g_s^2}g_2^{gg}\,, \qquad \tilde{c}_{gg} = -\frac{2}{g_s^2}g_4^{gg}\,.
\end{aligned}$$