CP violation in the Higgs sector at CMS

A. Cagnotta – Higgs@Capri 6-10 Oct 2025

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Introduction

- The matter antimatter asymmetry observed universe implies CP violation

- The Standard Model can partially explain the CP violation needed
  - Look for other sources of violation
  - SM Higgs as a probe for CP violation
  - Search for Anomalous Couplings (AC)

$$CP|H\rangle \stackrel{?}{=} |H\rangle$$

Anomalous Couplings HVV

- The anomalous interaction of a spin 0 H with two spin-1 gauge boson V1 V2 can be written in terms of scattering amplitude

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)}$$

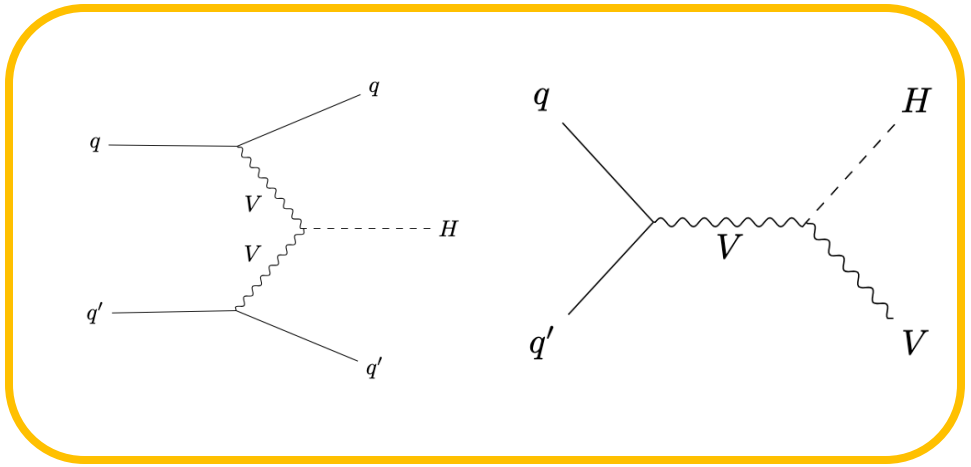
SM : VV = ZZ,WW

CP Even (higher order couplings) ($\Lambda_1 = 1TeV$)

CP Even

CP Odd

- 4 parameters to determine from data
  - $a_2, a_3, \Lambda_1, \Lambda_1^{Z\gamma}$



Anomalous Couplings HVV

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)}$$

a_1^{VV}: SM : VV = ZZ,WW

$\frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}$: CP Even (higher order couplings) $(\Lambda_1 = 1TeV)$

a_2^{VV}: CP Even

a_3^{VV}: CP Odd

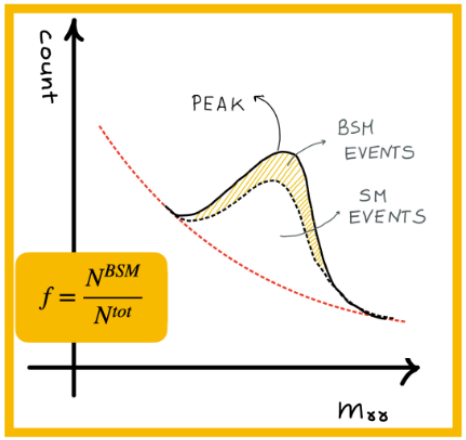
- What can be measured is

EFFECTIVE CROSS SECTION FRACTIONS

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3,\Lambda_1} |a_j|^2 \sigma_j} \qquad \phi_{ai} = arg(\frac{a_i}{a_1})$$

- Indipendent Γ_H
- Limited between [-1,1]

$$f_{ai} = f_{a2}, \boxed{f_{a_3}}, f_{\Lambda_1}, f_{\Lambda_1}^{CP}$$



Anomalous Couplings Hgg

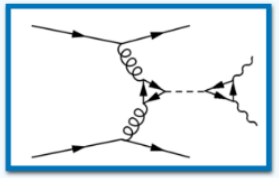
- $$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)}$$

  a_2^{VV}: CP even, SM

  a_3^{VV}: CP odd

- a_2 is the SM contribution in this case
  - one anomalous coupling a_3

Hgg COUPLING : V = gg

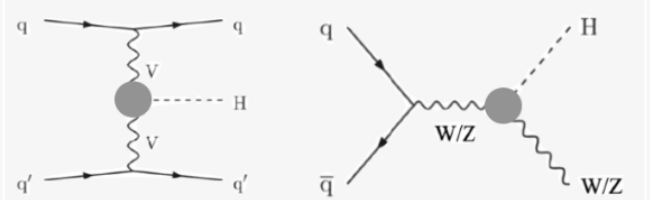


Two coupling from 2nd & 3rd term

- a_2^{VV} CP even, SM-like
- a_3^{VV} CP odd

One anomalous coupling: a_3^{ggH}

HVV COUPLING : V = WW,ZZ



Four couplings from each term

- a_1^{VV} CP even, SM-like (=2)
- a_2^{VV} CP even
- a_3^{VV} CP odd
- Λ_1

Four anomalous coupling parameters:

$a_2, a_3, \Lambda_1, \Lambda_1^{Z\gamma}$

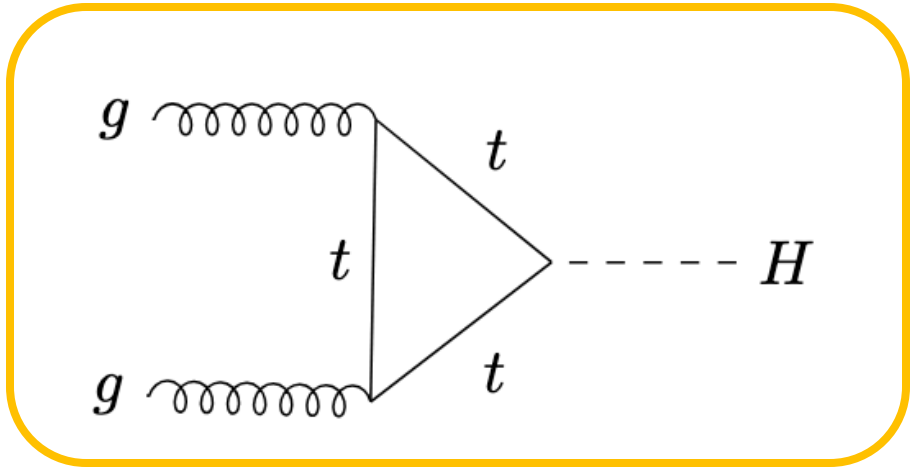
Anomalous Couplings Hff

- Anoumalous coupligs to fermions

$$A(Hff) = -\frac{m_f}{v}\bar{\psi}_f(k_f + i\tilde{k}_f\gamma_5)\psi_f$$

SM

CP odd



- Effective Cross section fraction

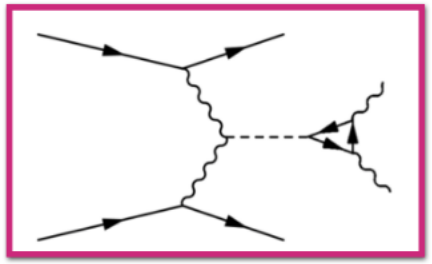
$$f_{CP}^{Hff} = \frac{|\tilde{k}_f|^2}{|k_f|^2 + |\tilde{k}_f|^2} sign\left(\frac{\tilde{k}_f}{k_f}\right)$$

- Sensitivity to CP-odd operators at tree-level

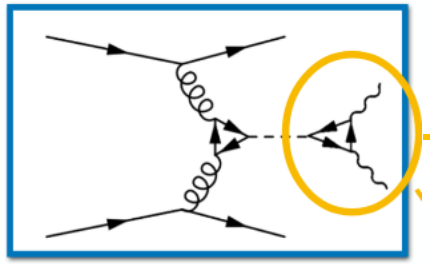
HVV and Hgg in $\gamma\gamma$ final state

HIG-24-006

- VBF and ggH channels are treated as two separated analysis



VBF ($f_{a3}, f_{a2}, f_{\Lambda_1}, f_{\Lambda_1}^{Z\gamma}$)



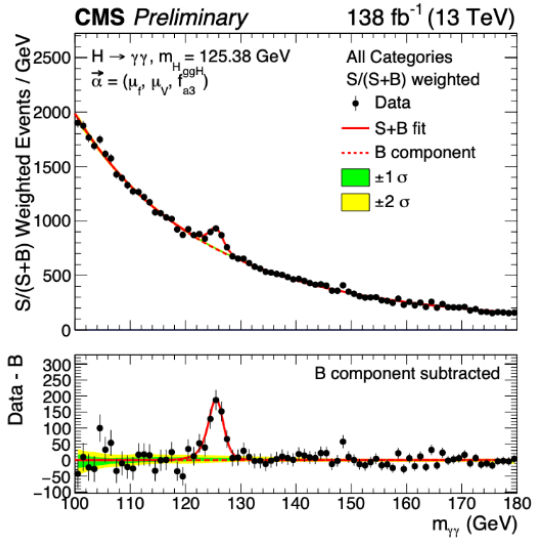
ggH+2Jets ($f_{a3}^{ggH}, f_{CP}^{Htt}$)

DIPHOTON PRESELECTION

$|\eta_{1,2}| < 2.5, p_T/m_{\gamma\gamma} > 1/3(1/4)$

	H/E	$\sigma_{i\eta i\eta}$	R_9	Iso_{ph}	Iso_{track}
EB; $R_9 > 0.85$	< 0.08	–	–	–	–
EB; $R_9 \leq 0.85$	< 0.08	< 0.015	> 0.5	< 4.0 GeV	< 6.0 GeV
EE; $R_9 > 0.90$	< 0.08	–	–	–	–
EE; $R_9 \leq 0.90$	< 0.08	< 0.035	> 0.8	< 4.0 GeV	< 6.0 GeV
Other preselection requirements					
leading photon $p_T > 35$ GeV sub-leading photon $p_T > 25$ GeV		$R_9 > 0.8$ OR $Iso_{ch} < 20$ GeV OR $Iso_{ch}/p_T < 0.3$ $m_{\gamma\gamma} > 100$ GeV			

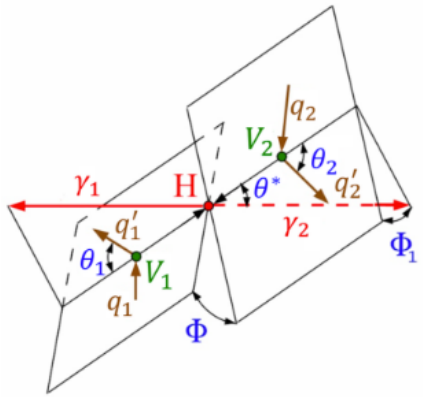
- Based on Full Run2 data
- Non-resonant background estimated from data



HVV and Hgg in $\gamma\gamma$ final state

HIG-24-006

- The discriminating variables are defined using
  - Matrix Element Likelihood Approach (MELA) + MVA
- MELA consists in the reduction of the 7 kinematic observables CP-sensitive to its minimum while retaining all important information

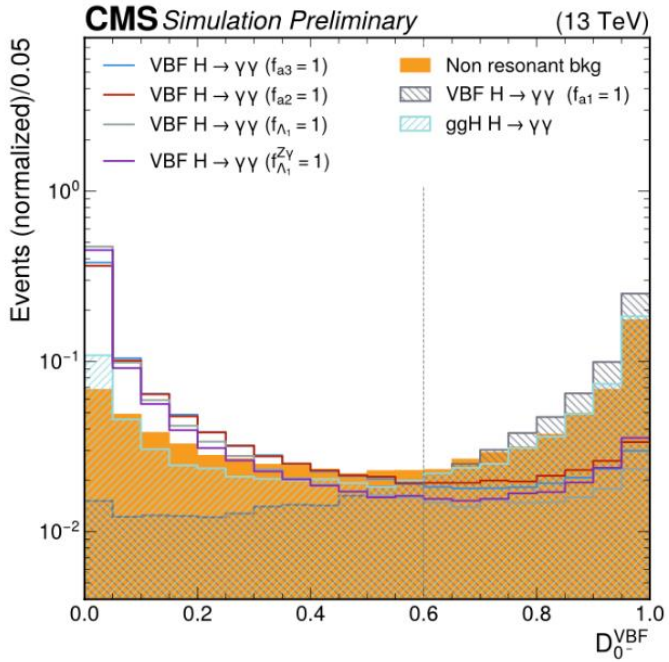


$$\mathscr{D}_{\rm BSM} = \frac{\mathscr{P}_{\rm SM}(\vec{\Omega})}{\mathscr{P}_{\rm SM}(\vec{\Omega}) + \mathscr{P}_{\rm BSM}(\vec{\Omega})}$$

Separate SM and BSM couplings

$$\mathscr{D}_{\rm int} = \frac{\mathscr{P}^{\rm int}_{\rm SM-BSM}(\vec{\Omega})}{\mathscr{P}_{\rm SM}(\vec{\Omega}) + \mathscr{P}_{\rm BSM}(\vec{\Omega})}$$

Sensitive to interference between SM and BSM couplings

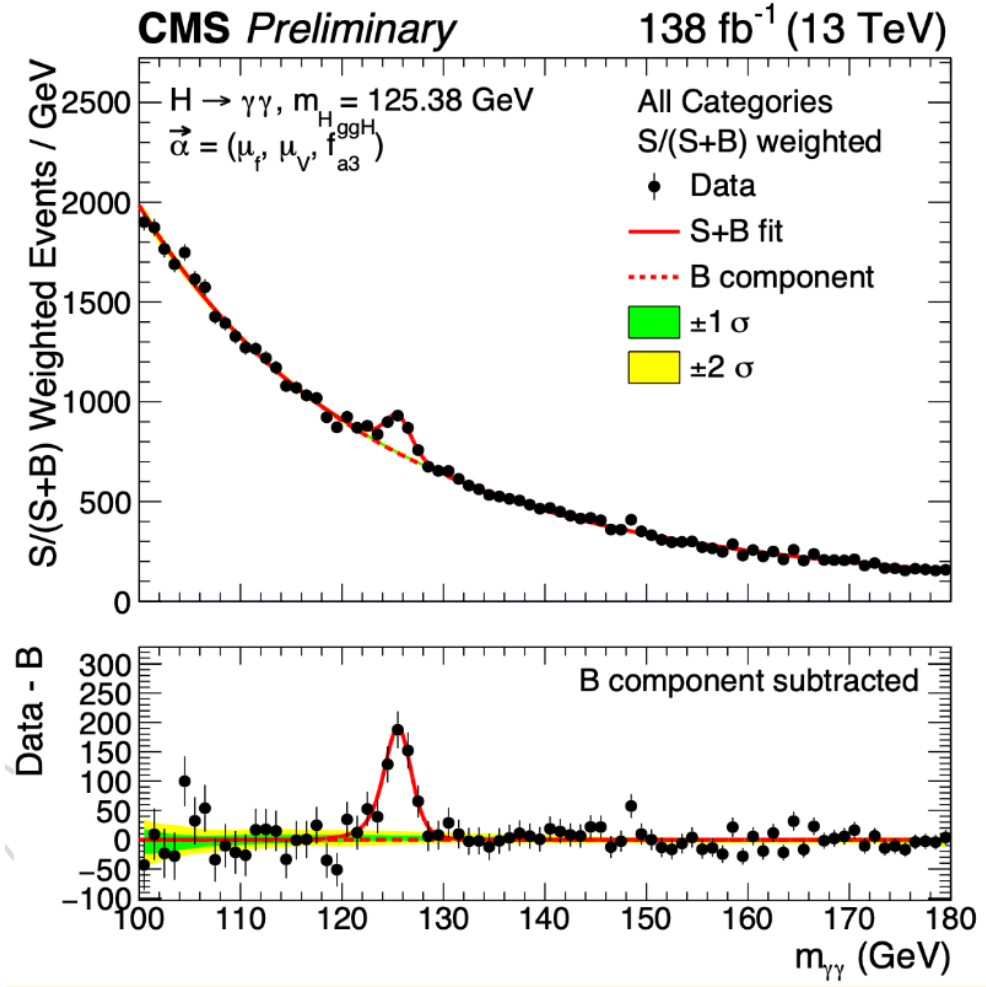


Each production mode has different MVA strategies, and so different Discriminating variables (D_{int})

HVV and Hgg in $\gamma\gamma$ final state

HIG-24-006

- Typical procedure for Signal/Background discrimination as in all $H\rightarrow\gamma\gamma$, applied to both HVV and ggH
- Binned maximum likelihood fitted with the following parameters of interest (two independent fits are done for HVV and Hgg)
  - signal strength per process ($\mu_j = \mu_V, \mu_f$) + anomalous cross section fraction (f_{ai})
  - HVV: f_{ai} (f_{a3} , f_{a2} , $f_{\Lambda 1}$, $f_{\Lambda 1}^{Z\gamma}$) is fitted and μ_V, μ_f are floating
  - ggH: f_{a3}^{ggH} is fitted and μ_V, μ_f are floating



HVV and Hgg in $\gamma\gamma$ final state

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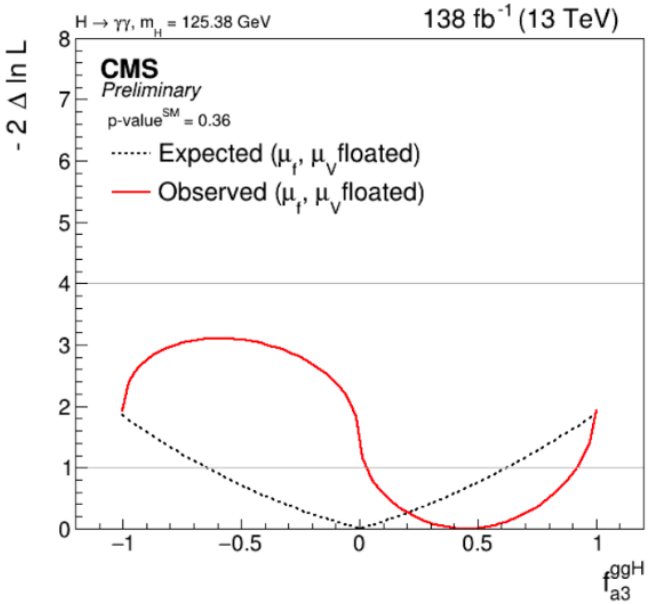
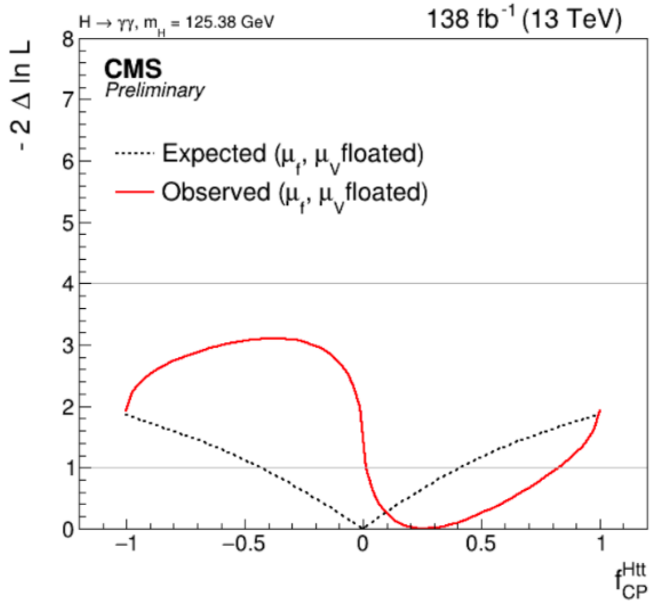
- Likelihood scan Hgg





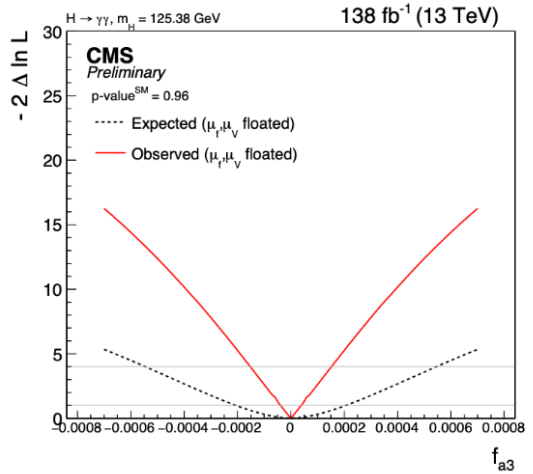
Parameter	Scenario	Observed 68% C.L.	Observed 95% C.L.	Expected 68% C.L.	Expected 95% C.L.
f_{a3}^{ggH}	ggH (4ℓ)	$-0.04^{+1.04}_{-0.96}$	$[-1, 1]$	0 ± 1	$[-1, 1]$
	ggH ($\tau\tau$)	$0.07^{+0.32}_{-0.07}$	$[-0.15, 0.89]$	0.00 ± 0.26	$[-1, 1]$
	ggH (W W)	$0.03^{+0.72}_{-0.38}$	$[-1, 1]$	$[-1, 1]$	$[-1, 1]$
	ggH ($\gamma\gamma$)	$\mathbf{0.45^{+0.47}_{-0.43}}$	$\mathbf{[-1, 1]}$	$\mathbf{0.00^{+0.63}_{-0.65}}$	$\mathbf{[-1, 1]}$
f_{CP}^{Htt}	tH, $t\bar{t}$H (4ℓ)	$\pm(0.88^{+0.12}_{-1.88})$	$[-1, 1]$	0 ± 1	$[-1, 1]$
	tH, $t\bar{t}$H ($\gamma\gamma$)	0.00 ± 0.33	$[-0.67, 0.67]$	0.00 ± 0.49	$[-0.82, 0.82]$
	tH, $t\bar{t}$H (4ℓ, $\gamma\gamma$)	0.00 ± 0.33	$[-0.67, 0.67]$	0.00 ± 0.48	$[-0.81, 0.81]$
	ggH (4ℓ)	$-0.01^{+1.01}_{-0.99}$	$[-1, 1]$	0 ± 1	$[-1, 1]$
	ggH ($\tau\tau$)	$0.03^{+0.17}_{-0.03}$	$[-0.07, 0.51]$	0.00 ± 0.12	$[-0.49, 0.49]$
	ggH, tH, $t\bar{t}$H (4ℓ)	$-0.56^{+1.56}_{-0.44}$	$[-1, 1]$	0.00 ± 0.47	$[-1, 1]$
	ggH, tH, $t\bar{t}$H (4ℓ, $\gamma\gamma$)	$-0.04^{+0.38}_{-0.36}$	$[-0.69, 0.68]$	0.00 ± 0.30	$[-0.70, 0.70]$
	ggH ($\gamma\gamma$)	$\mathbf{0.26^{+0.57}_{-0.25}}$	$\mathbf{[-1, 1]}$	$\mathbf{0.00^{+0.41}_{-0.43}}$	$\mathbf{[-1, 1]}$

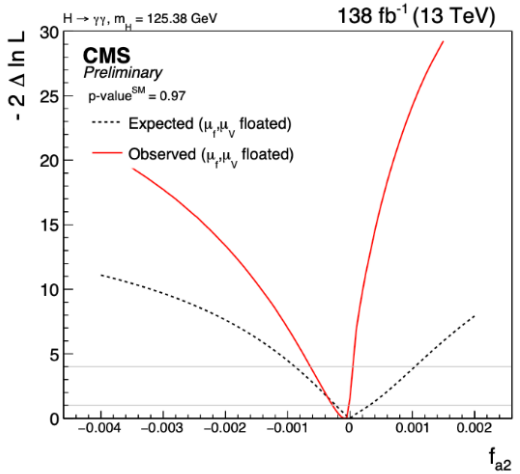
DRAFT

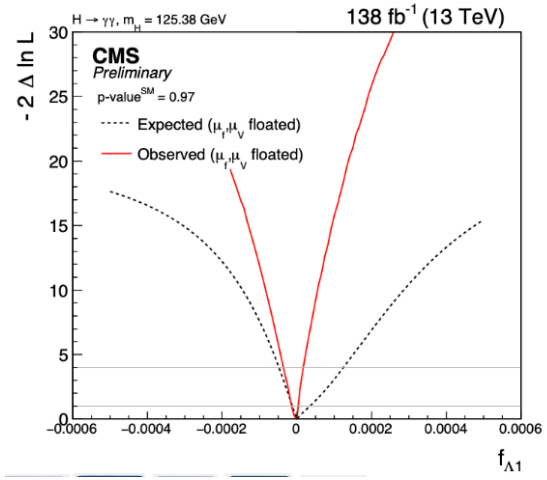
HVV and Hgg in $\gamma\gamma$ final state

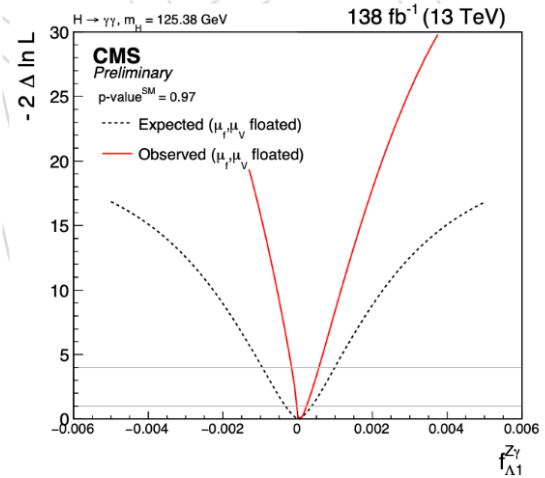
HIG-24-006

- Likelihood scan HVV









Parameter	Expected/(10^{-4}) $H \to \gamma\gamma$ (68% CL)	Observed/(10^{-4}) $H \to \gamma\gamma$ (68% CL)	Expected/(10^{-4}) $H \to 4\ell + H \to \tau^+\tau^-$ (68% CL)
f_{a3}	$0.0^{+2.1}_{-2.1}$	$0.00^{+0.39}_{-0.39}$	$[-0.5,0.5]$
f_{a2}	$0.0^{+3.1}_{-2.3}$	$-0.81^{+0.65}_{-2.0}$	$[-4,5]$
$f_{\Lambda 1}$	$0.0^{+0.35}_{-0.12}$	$-0.014^{+0.032}_{-0.14}$	$[-0.4,1.1]$
$f_{\Lambda 1}^{Z\gamma}$	$0.0^{+3.7}_{-3.3}$	$0.83^{+1.5}_{-0.92}$	$[-10,10]$

H$\tau\tau$

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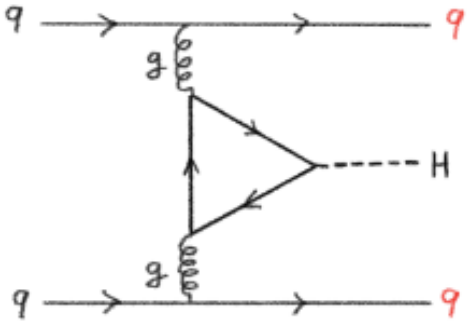
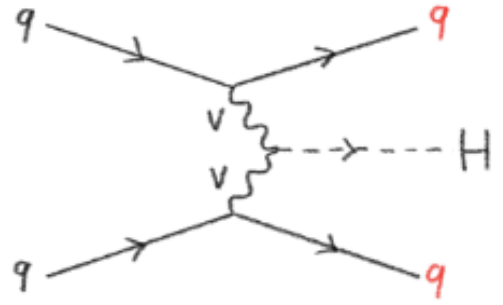
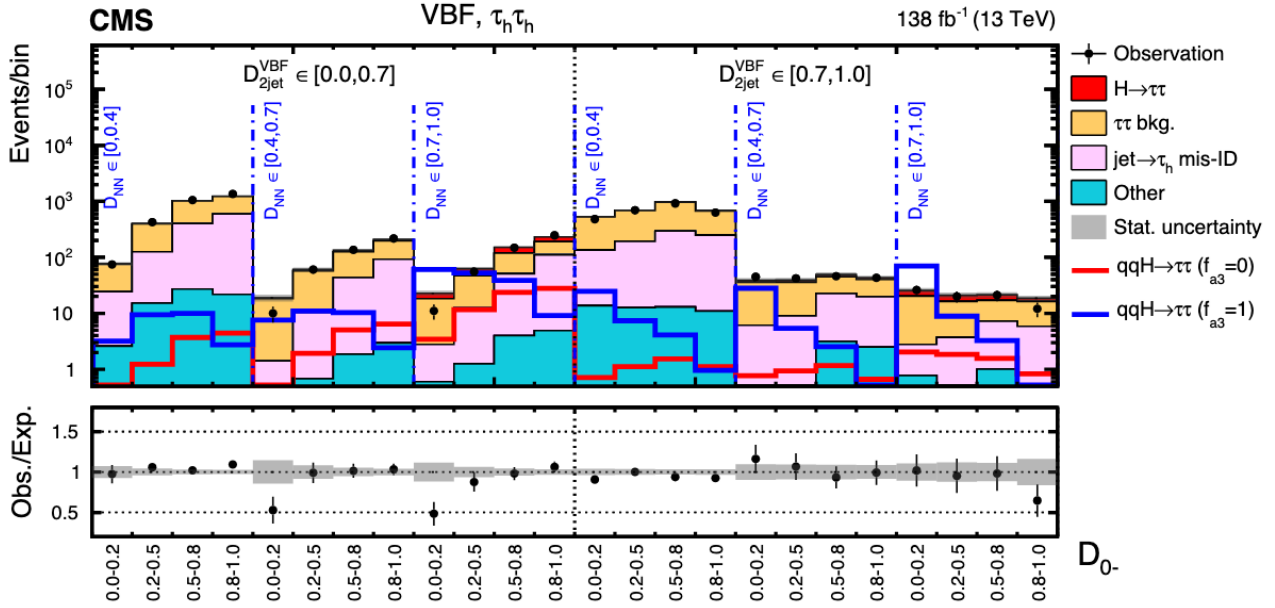


- HVV and Hgg production probed in the H→$\tau\tau$ final state
  - $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, eμ channels considered
- Based on Full Run2 dataset
- For both production modes, MELA and MVA used for discrimination





Hττ

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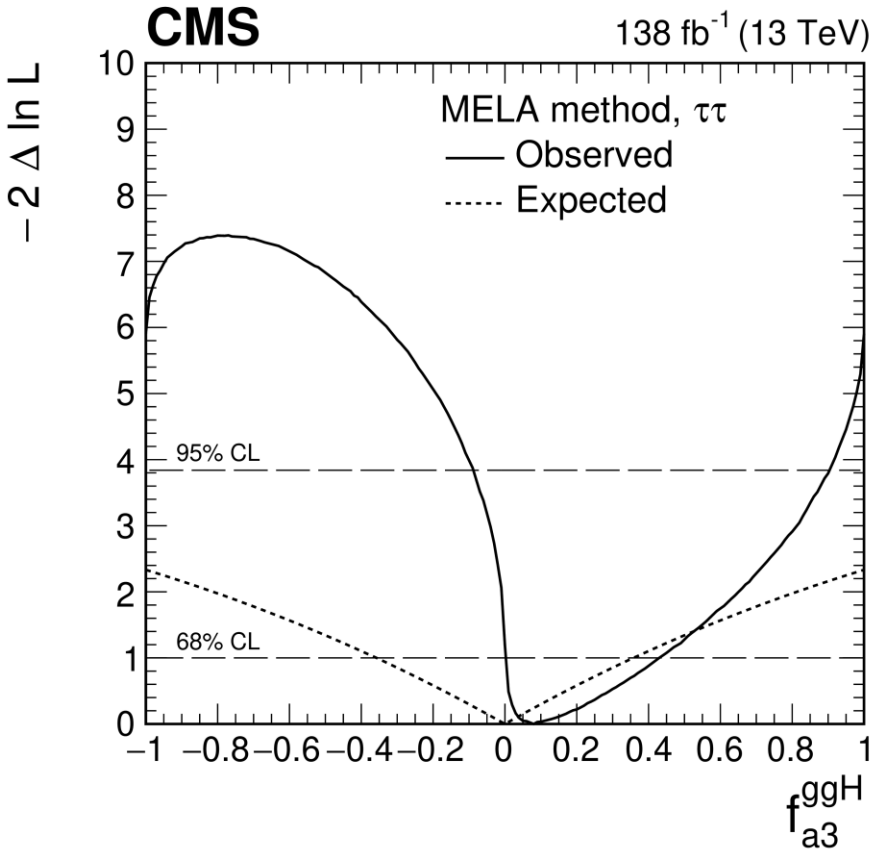
- Hgg results

Parameter	Method	Observed		Expected	
		68% CL	95% CL	68% CL	95% CL
f_{a3}^{ggH}	MELA	$0.08^{+0.35}_{-0.08}$	$[-0.09, 0.90]$	0.00 ± 0.36	—



Hττ

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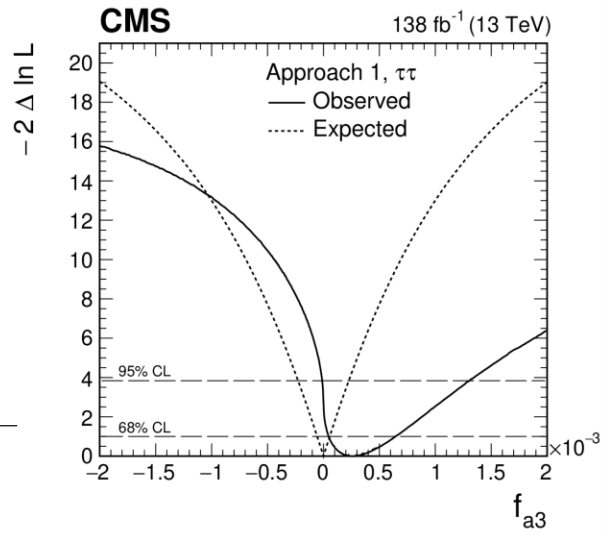
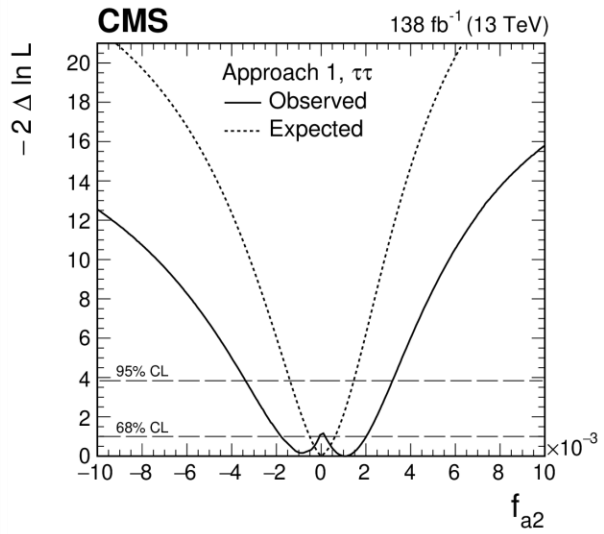
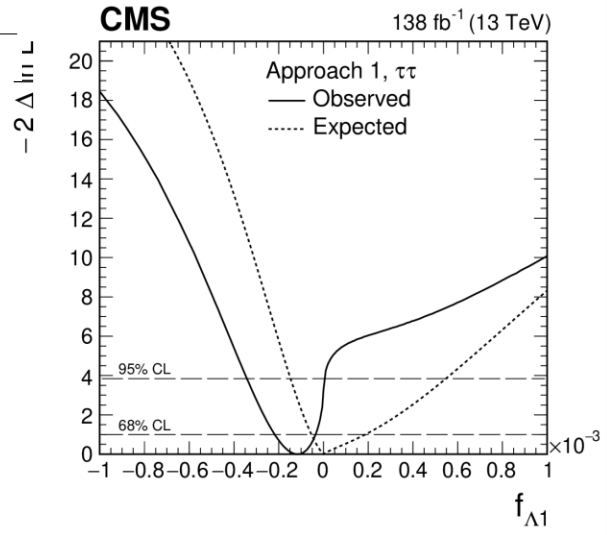
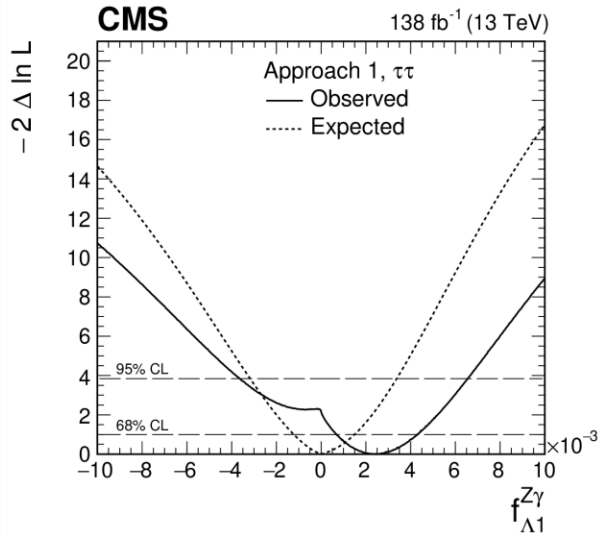
- HVV results

Approach	Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
		68% CL	95% CL	68% CL	95% CL
Approach 1	f_{a3}	$0.28^{+0.38}_{-0.23}$	$[-0.01, 1.30]$	0.00 ± 0.06	$[-0.23, 0.23]$
	f_{a2}	$1.1^{+0.9}_{-0.9} \cup [-1.8, -0.1]$	$[-3.4, 3.2]$	$0.0^{+0.6}_{-0.5}$	$[-1.4, 1.5]$
	$f_{\Lambda 1}$	$-0.12^{+0.08}_{-0.10}$	$[-0.34, 0.01]$	$0.00^{+0.19}_{-0.05}$	$[-0.15, 0.55]$
	$f_{\Lambda 1}^{Z\gamma}$	2.5 ± 1.8	$[-3.6, 6.6]$	$0.0^{+1.5}_{-1.2}$	$[-3.2, 3.4]$
Approach 2	f_{a3}	$0.40^{+0.53}_{-0.33}$	$[-0.01, 1.90]$	0.00 ± 0.08	$[-0.33, 0.33]$









ttH and tH production

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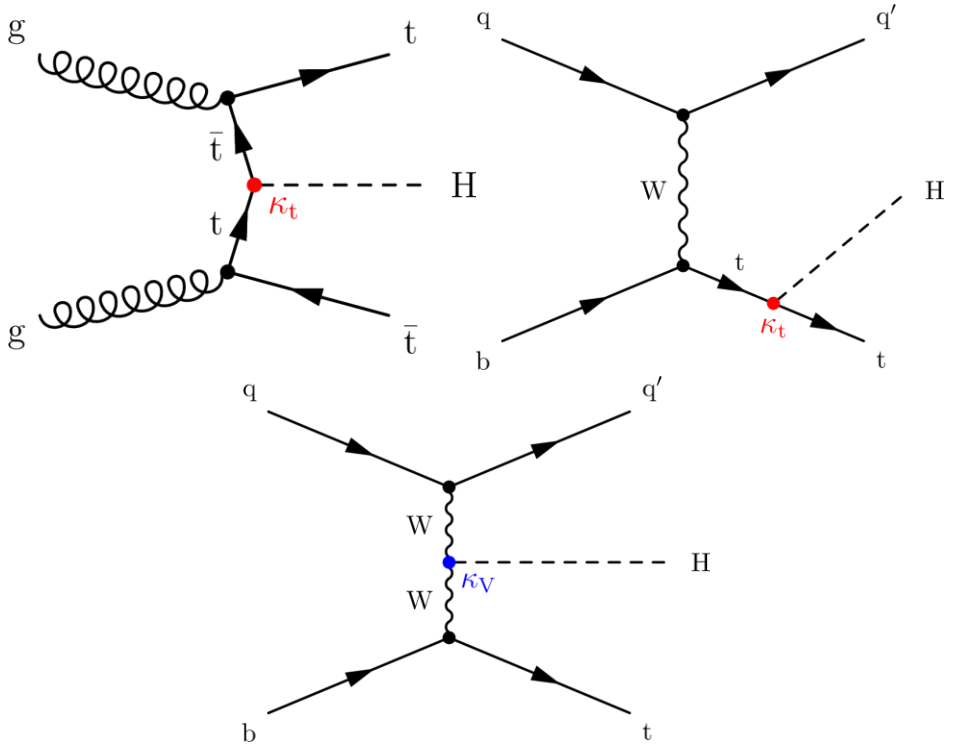
- The combined measurement of ttH and tH production provides a probe of CP -odd admixtures in the top-Higgs coupling through interfering contributions
- Based on full Run2 dataset
- Targeting the H→bb decays in 3 final states
  - Fully Hadronic (FH), 0 lep and ≥ 4 b-jets
  - Single Lepton (SL), 1 lep and ≥ 4 b-jets
  - Dilepton (DL), 2 lep and ≥ 3b-jets



ttH and tH production

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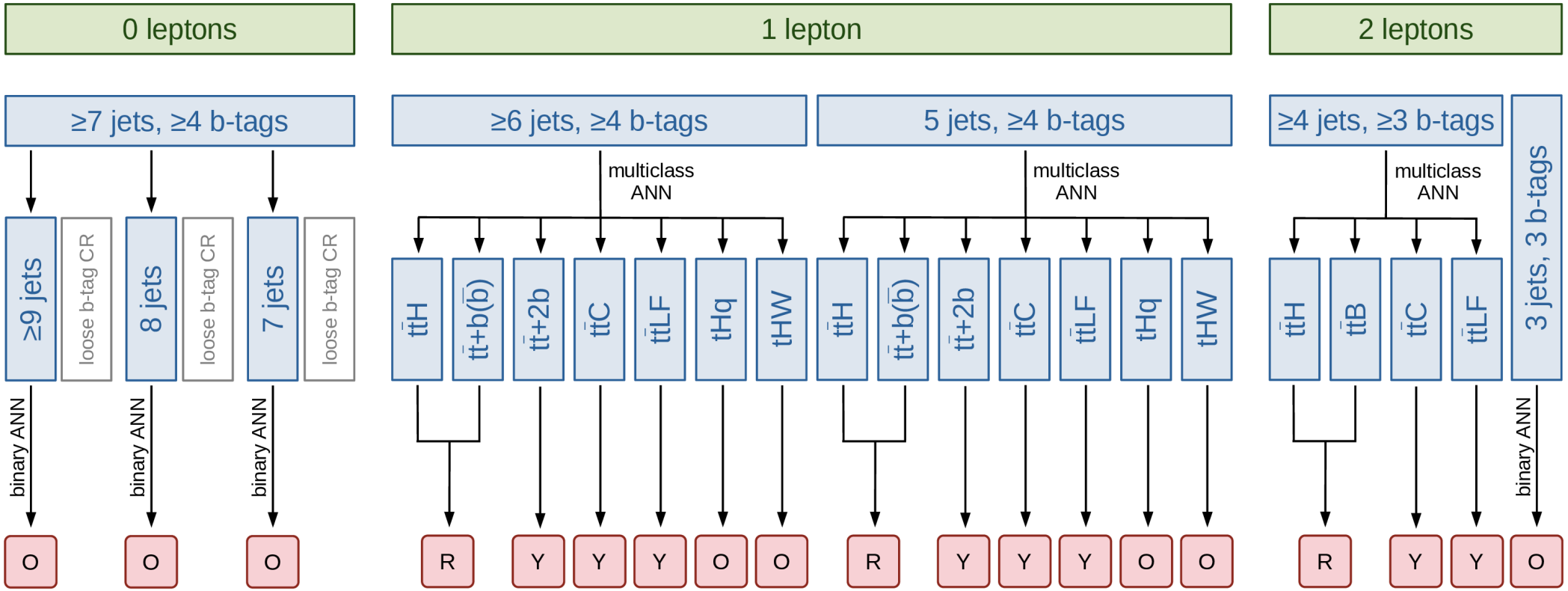
- Main background represented by tt+jets events
- Defined one ANN for each category and channel



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

ttH and tH production

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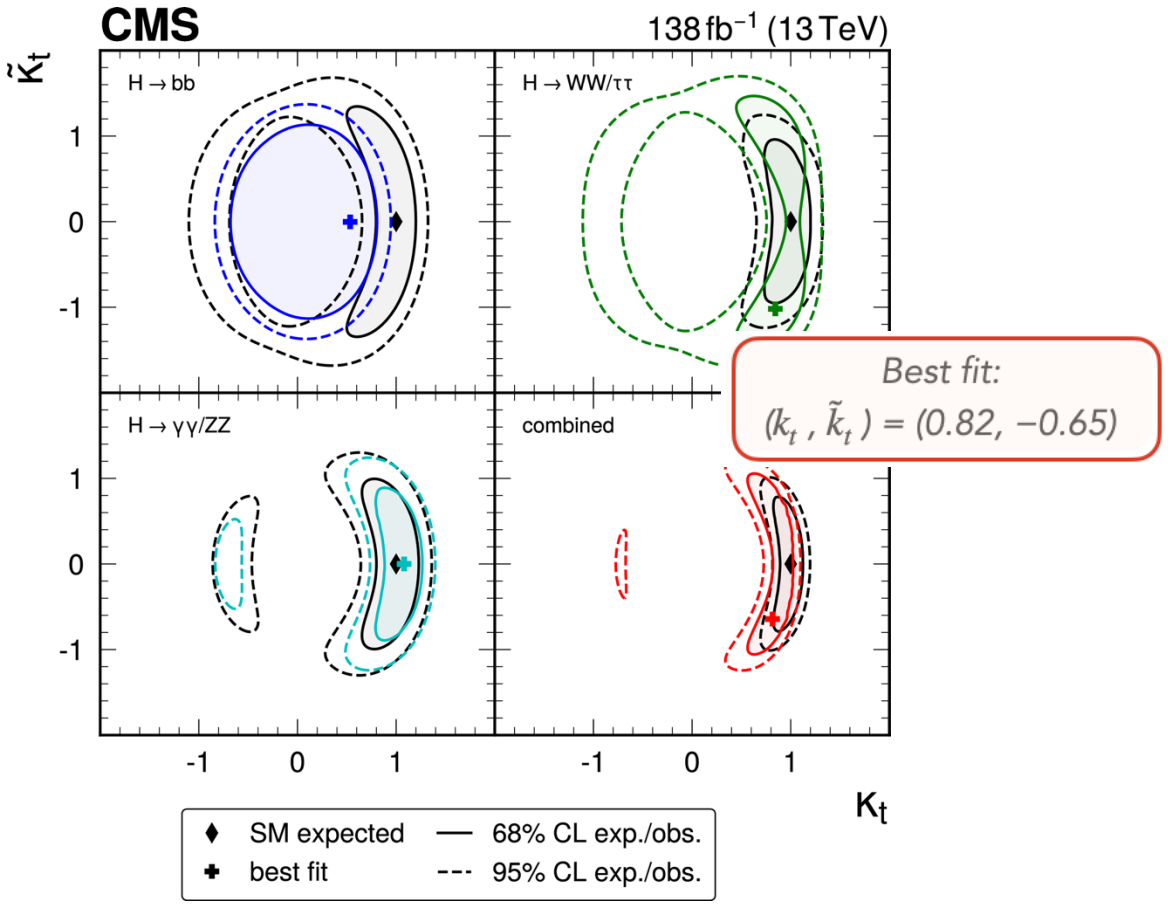
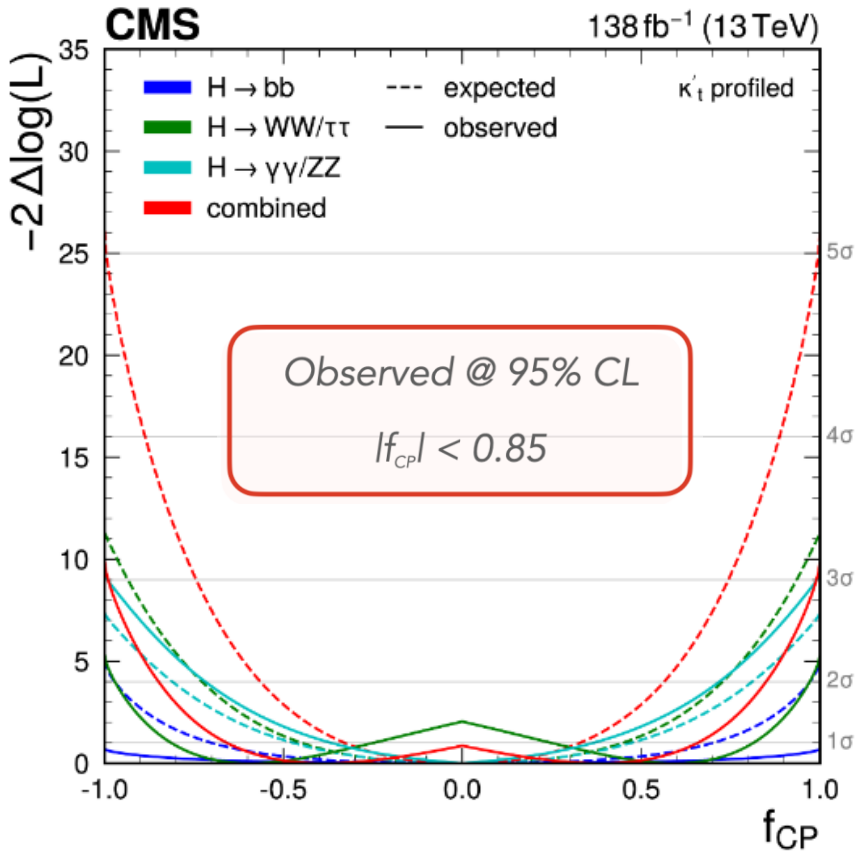
- The results has been given in 5 different interpretations
  - focusing on CP structure of Top-Higgs couplig





Summary

- Probed Higgs CP properties in multiple channels (in this presentation $H \to bb$,$H \to \tau\tau$,$H \to \gamma\gamma$(
- Tested for possible CP-odd admixtures in Higgs couplings to fermions and bosons
- Used advanced techniques: MELA , MVA.

ggH production

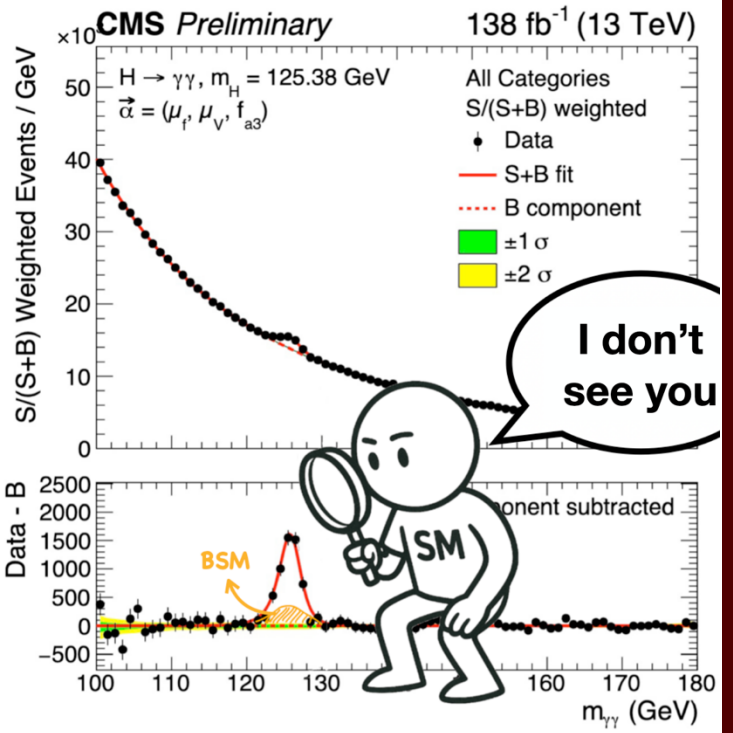
		Observed		Expected	
		68% C.L.	95% C.L.	68% C.L.	95% C.L.
f_{a3}^{ggH}	ggH (4ℓ)	$-0.04^{+1.04}_{-0.96}$	$[-1,1]$	0 ± 1	$[-1,1]$
	ggH ($\tau\tau$)	$0.07^{+0.32}_{-0.07}$	$[-0.15,0.89]$	0.00 ± 0.26	$[-1,1]$
	ggH (W W)	$0.03^{+0.72}_{-0.38}$	$[-1,1]$	$[-1,1]$	$[-1,1]$
	ggH ($\gamma\gamma$)	$\mathbf{0.45^{+0.47}_{-0.43}}$	$\mathbf{[-1,1]}$	$\mathbf{0.00^{+0.63}_{-0.65}}$	$\mathbf{[-1,1]}$
f_{CP}^{Htt}	tH, t$\bar{t}$H (4ℓ)	$\pm(0.88^{+0.12}_{-1.88})$	$[-1,1]$	0 ± 1	$[-1,1]$
	tH, t$\bar{t}$H ($\gamma\gamma$)	0.00 ± 0.33	$[-0.67,0.67]$	0.00 ± 0.49	$[-0.82,0.82]$
	tH, t$\bar{t}$H (4ℓ, $\gamma\gamma$)	0.00 ± 0.33	$[-0.67,0.67]$	0.00 ± 0.48	$[-0.81,0.81]$
	ggH (4ℓ)	$-0.01^{+1.01}_{-0.99}$	$[-1,1]$	0 ± 1	$[-1,1]$
	ggH ($\tau\tau$)	$0.03^{+0.17}_{-0.03}$	$[-0.07,0.51]$	0.00 ± 0.12	$[-0.49,0.49]$
	ggH, tH, t$\bar{t}$H (4ℓ)	$-0.56^{+1.56}_{-0.44}$	$[-1,1]$	0.00 ± 0.47	$[-1,1]$
	ggH, tH, t$\bar{t}$H (4ℓ, $\gamma\gamma$)	$-0.04^{+0.38}_{-0.36}$	$[-0.69,0.68]$	0.00 ± 0.30	$[-0.70,0.70]$
	ggH ($\gamma\gamma$)	$\mathbf{0.26^{+0.57}_{-0.25}}$	$\mathbf{[-1,1]}$	$\mathbf{0.00^{+0.41}_{-0.43}}$	$\mathbf{[-1,1]}$

VVH production

Parameter	Expected/(10^{-4}) H $\to \gamma\gamma$ (68% CL)	Observed/(10^{-4}) H $\to \gamma\gamma$ (68% CL)	Expected/(10^{-4}) $H \to 4\ell + H \to \tau^+\tau^-$ (68% CL)
f_{a3}	$0.0^{+2.1}_{-2.1}$	$0.00^{+0.39}_{-0.39}$	$[-0.5,0.5]$
f_{a2}	$0.0^{+3.1}_{-2.3}$	$-0.81^{+0.65}_{-2.0}$	$[-4,5]$
$f_{\Lambda 1}$	$0.0^{+0.35}_{-0.12}$	$-0.014^{+0.032}_{-0.14}$	$[-0.4,1.1]$
$f_{\Lambda 1}^{Z\gamma}$	$0.0^{+3.7}_{-3.3}$	$0.83^{+1.5}_{-0.92}$	$[-10,10]$

DRAFT

Conclusion

- **No evidence** of CP violation in the Higgs sector so far.
- **Strong constraints** on anomalous couplings with Run-2 data (138 fb^{-1}).
- **Run3 & HL-LHC outlook:** much higher sensitivity, possibility to spot tiny CP-odd components.

- 👉 **Take-home message:**
  The Higgs still behaves *too well*... but the hunt for CP violation is far from over! 🔍