Higgs Hunting

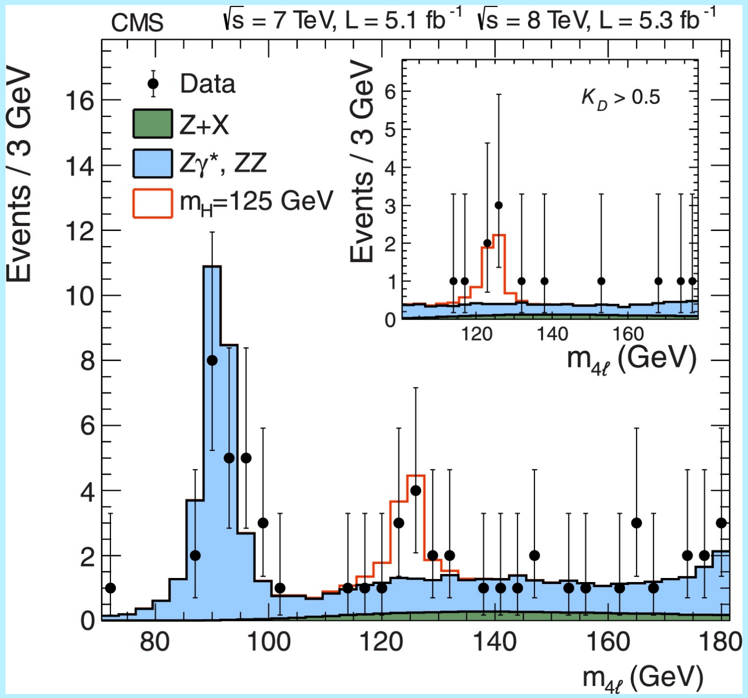
Higgs boson anomalous couplings and EFT interpretation at CMS

Angela Taliercio on behalf of **CMS collaboration**

12 Sept 2023

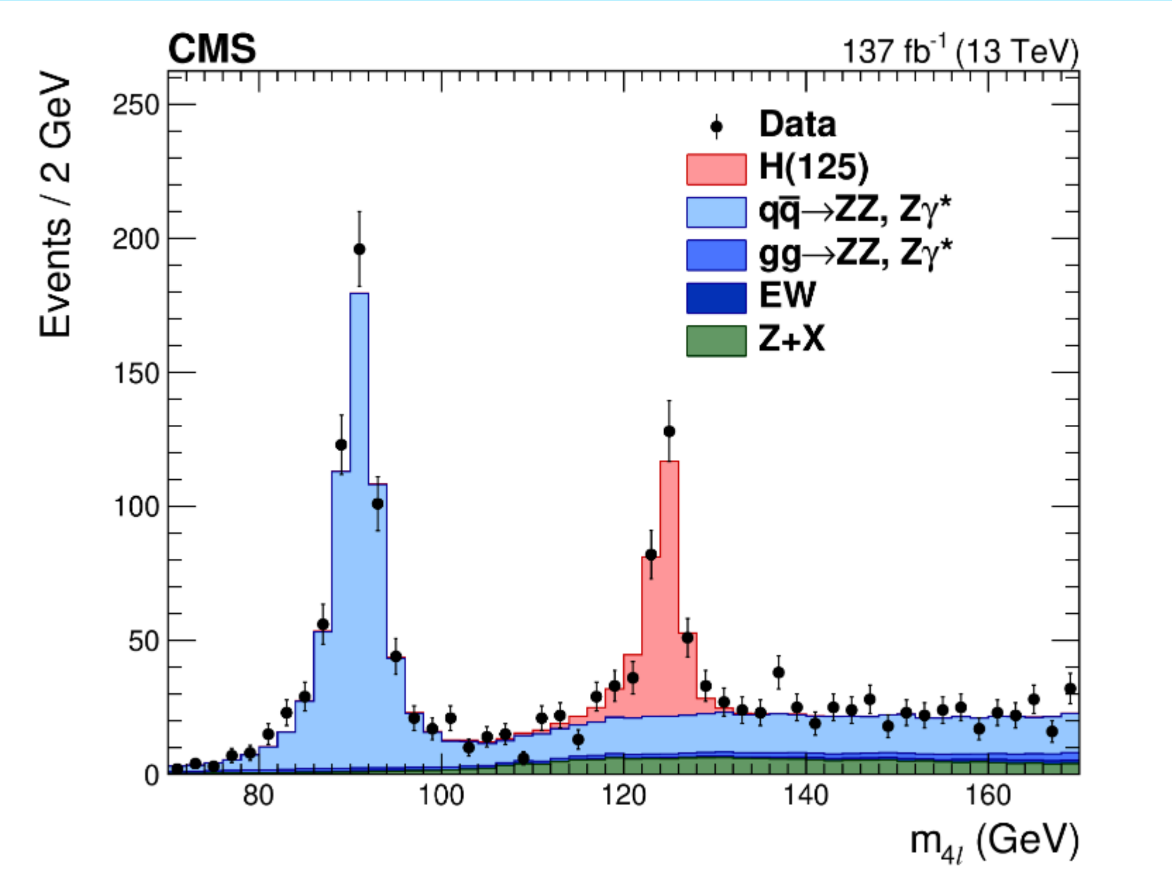
PLB 716 (2012) 30, Eur. Phys. J. C 81 (2021) 488

Higgs physics: overview



RunII

Around 8 million Higgs produced in Run2



Wide range of final state studied:

- H→WW*,ZZ* vector boson
- H to the **third generation** fermions
- H to the second generation fermions (**first evidence!!!**)

Access to new measurement:

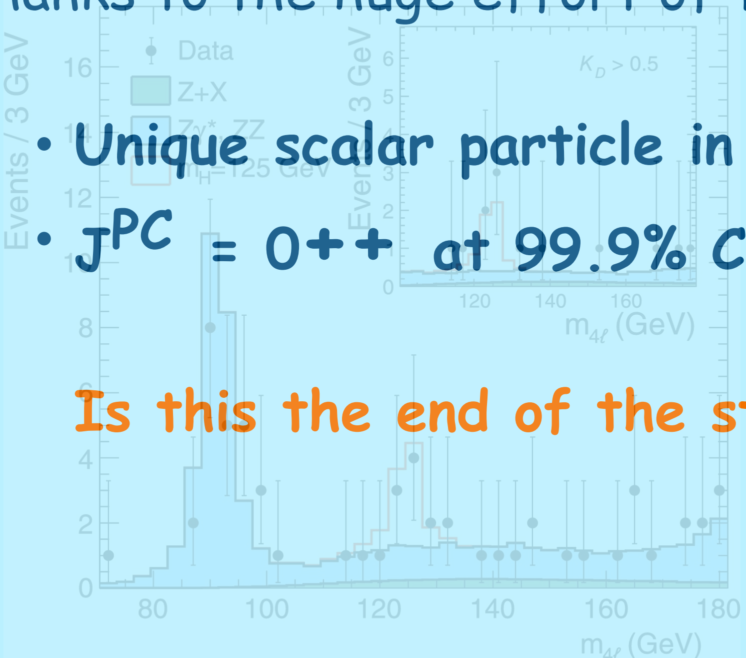
- Higgs self coupling in HH events

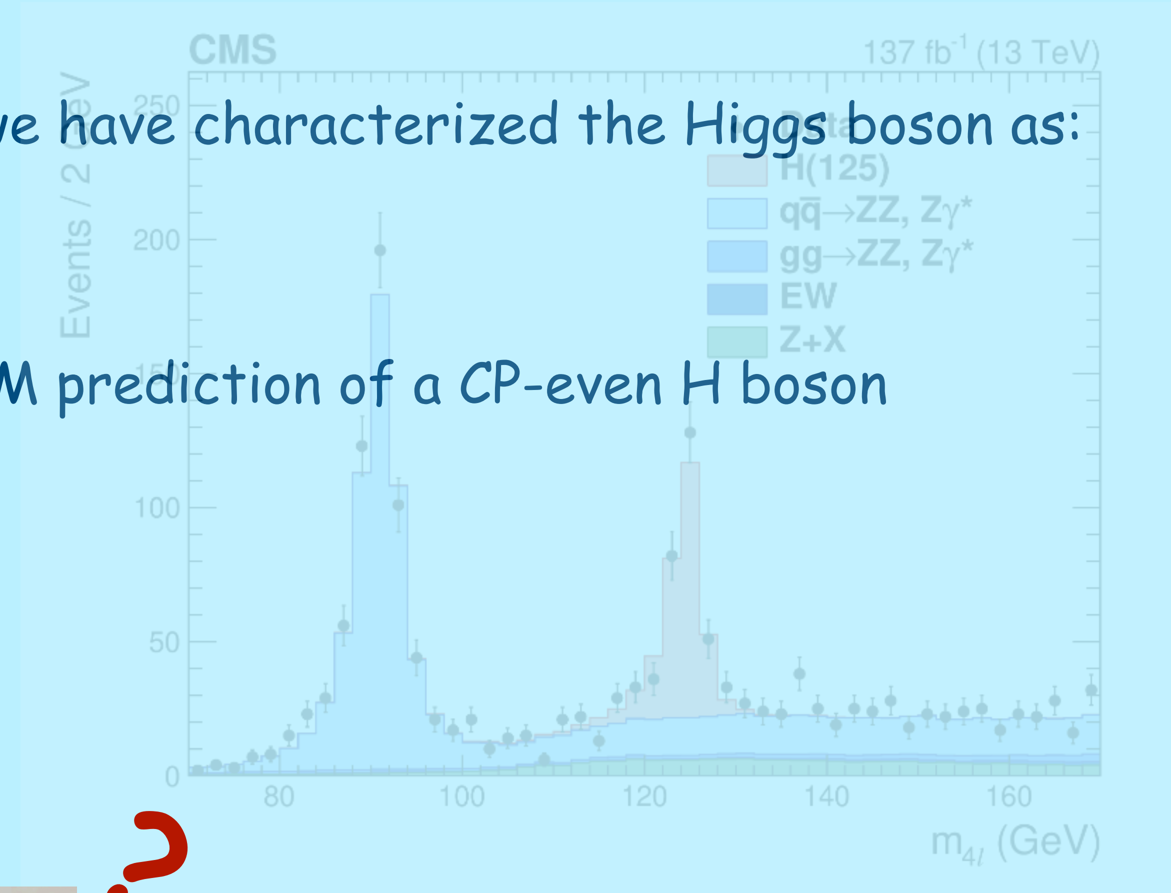
Searches for CP violation in the Higgs sector

Higgs decay branching fraction

$H \to b\bar{b}$	57.7%
$H \to WW$	21.5%
$H \to \tau\tau$	6.3%
$H \to c\bar{c}$	2.9%
$H \to ZZ$	2.6%
$H \to \gamma\gamma$	0.23%
$H \to \mu\mu$	0.02%

Higgs physics: overview





Thanks to the huge effort of the physics community we have characterized the Higgs boson as:

- **Unique scalar particle in the SM**
- J^{PC} = **0++ at 99.9% CL**, in agreement with SM prediction of a CP-even H boson

Is this the end of the story???

Higgs decay branching fraction

Higgs physics: overview

Thanks to the huge effort of the physics community we have characterized the Higgs boson as:

- **Unique scalar particle in the SM**
- **J^{PC} = 0++ at 99.9% CL** , in agreement with SM prediction of a CP-even H boson

Is this the end of the story???

With the precision that we have now, small HVV anomalous couplings are possible:

- **In BSM theories, H boson interactions may generate several of them, both CP even and CP odd**
- **It may also appear through loop corrections in SM processes, but the size of their contributions is beyond the current experimental sensitivity**
- **How do we even measure CP even/odd operators??**

Let's start with some maths

Anomalous coupling: Hff coupling

Anomalous effects in the H boson couplings to fermions can be parametrized using the following scattering amplitude

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

- Ψ_f is the Dirac spinor
- κ_f is the coupling strength
- m is the mass of the spinor
- v is the Higgs vacuum expectation value

In the SM k_f = 1 and $\tilde{k}_f$ = 0

The presence of both CP even and CP odd couplings will lead to CP violation

CP-even terms:

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

- ttH very sensitive to $k_f, \tilde{k}_f$

CP-odd terms:

$$|f_{CP}^{Hff}| = \left(1 + 2.38\left[\frac{1}{|f_{a_3}^{ggH}|}\right]\right)^{-1} = \sin^2\alpha^{Hff}$$

- Depending on the value of α we can have three possible CP scenarios
    - Purely Cp-even: α = 0 or α = 180
    - Purely Cp-odd: α = 90
    - Mixed: α ≠ 0, ≠ 90, ≠180

Anomalous coupling: HVV coupling

Anomalous effects in the H boson production (VBF, ZH, and WH), ggH production, H → VV decay, and partially in the tH and gg → ZH production, are described by the HV_1V_2 couplings

$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Under the SM assumption, the non-zero terms of that expression are only a_1^{WW} and a_1^{ZZ}, the rest of ZZ and WW coupling are considered anomalous contribution

$$f_{a_i} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3...} |a_j|^2 \sigma_j} \text{sign}\left(\frac{a_i}{a_1}\right)$$

- For the gg couplings, the only nonzero couplings are a_2 and a_3 , which are anomalous contributions due to BSM physics and do not account for interactions mediated by SM particles via loops

$$f_{a_3} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \text{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

Anomalous coupling: HVV coupling

Anomalous effects in the H boson production (VBF, ZH, and WH), ggH production, H → VV decay, and partially in the tH and gg → ZH production, are described by the HV_1V_2 couplings

$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

The a^{VV} couplings are CP-odd, and their presence together with any other CP-even couplings would result in CP violation in a given process

All the parameters in the equation can be access from data

Anomalous coupling: EFT interpretation

The sensitivity to anomalous couplings can be translated into sensitivity to higher dimensionality operators in EFT

$$L = L_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + (O(\Lambda^{-4}))$$

Among the anomalous contributions, considerations of symmetry and gauge invariance require $a^{Z\gamma} = a^{\gamma\gamma} = a^{gg} = 0$, $\kappa^{ZZ} = \kappa^{ZZ}$, $\kappa^{\gamma\gamma} = \kappa^{\gamma\gamma} = 0$, $\kappa^{gg} = \kappa^{gg} = 0$, and $\kappa^{Z\gamma} = 0$ we are left with:

- 4 HVV independent couplings (a_1, a_2, a_3, k_1/Λ_1):

$$\delta c_z = \frac{1}{2} a_1 - 1,$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{4\pi\alpha} \frac{\kappa_1}{(\Lambda_1)^2},$$

$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2,$$

$$\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3.$$

- 2 Hgg couplings (a_2^{gg}, a_3^{gg}):

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

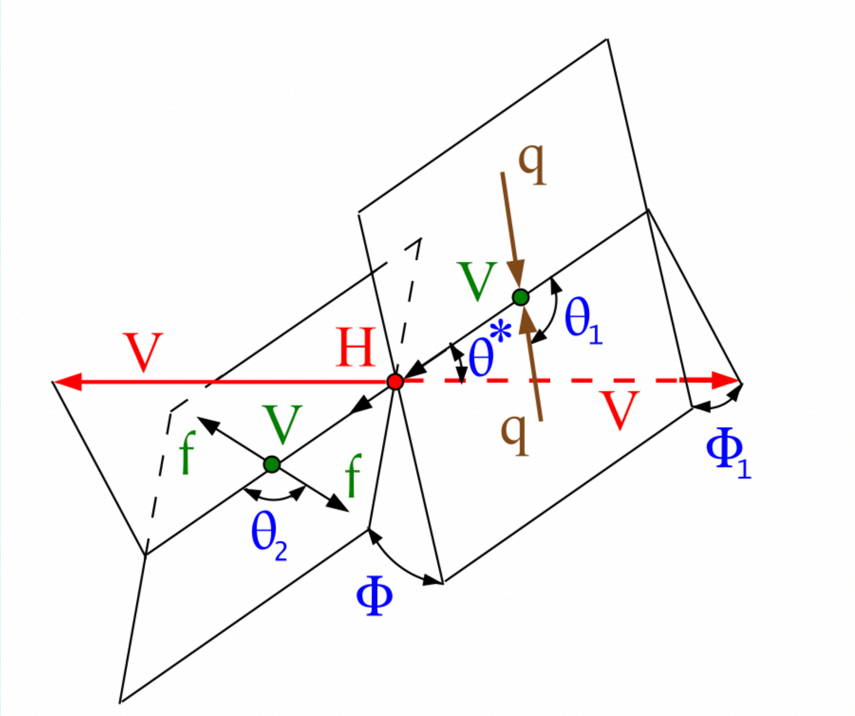
$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$

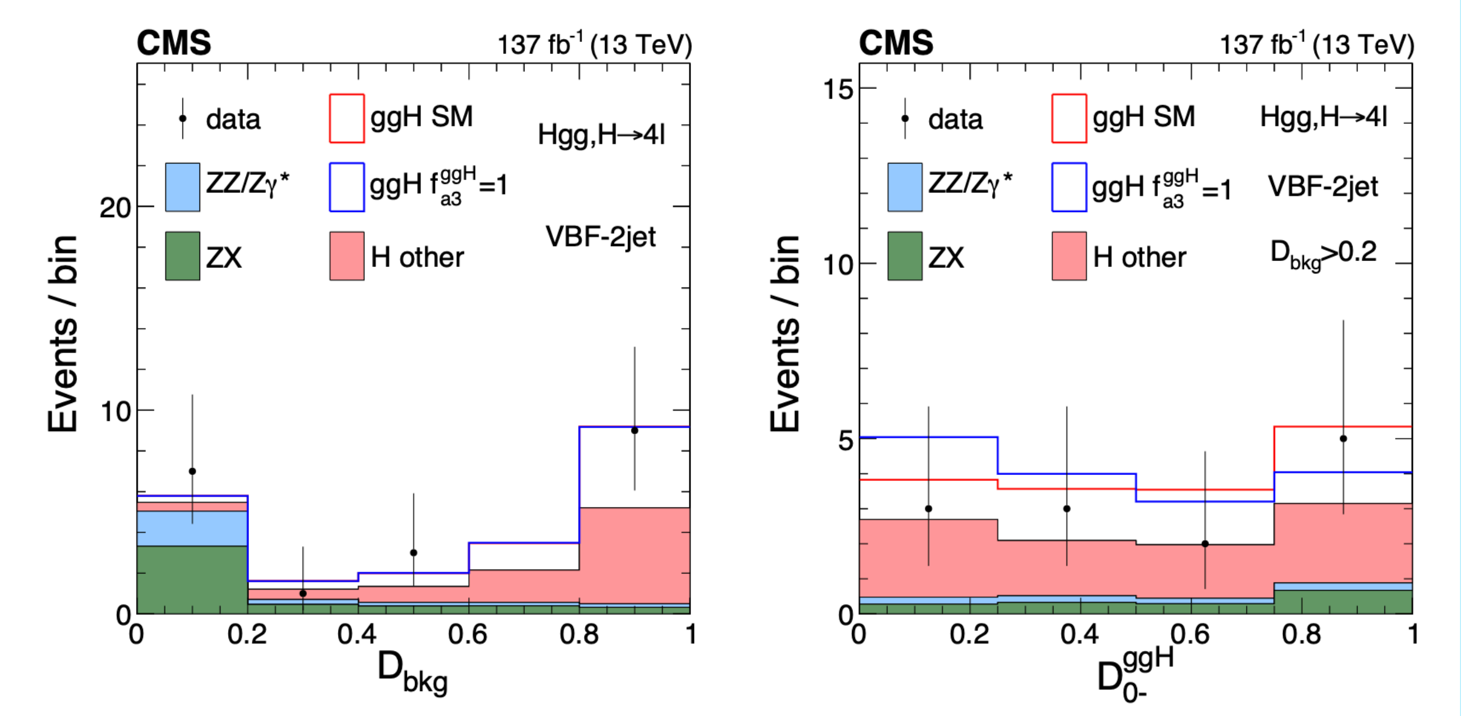
Phys. Rev. D 104, 052004

How do we measure CP operators

Kinematic distributions of particles are sensitive to the quantum numbers and anomalous couplings of the H boson, we can tag them with:

- **Matrix element methods** (MEM): build Neymann-Pearson-like discriminants based on a complete set of mass and angular input observables





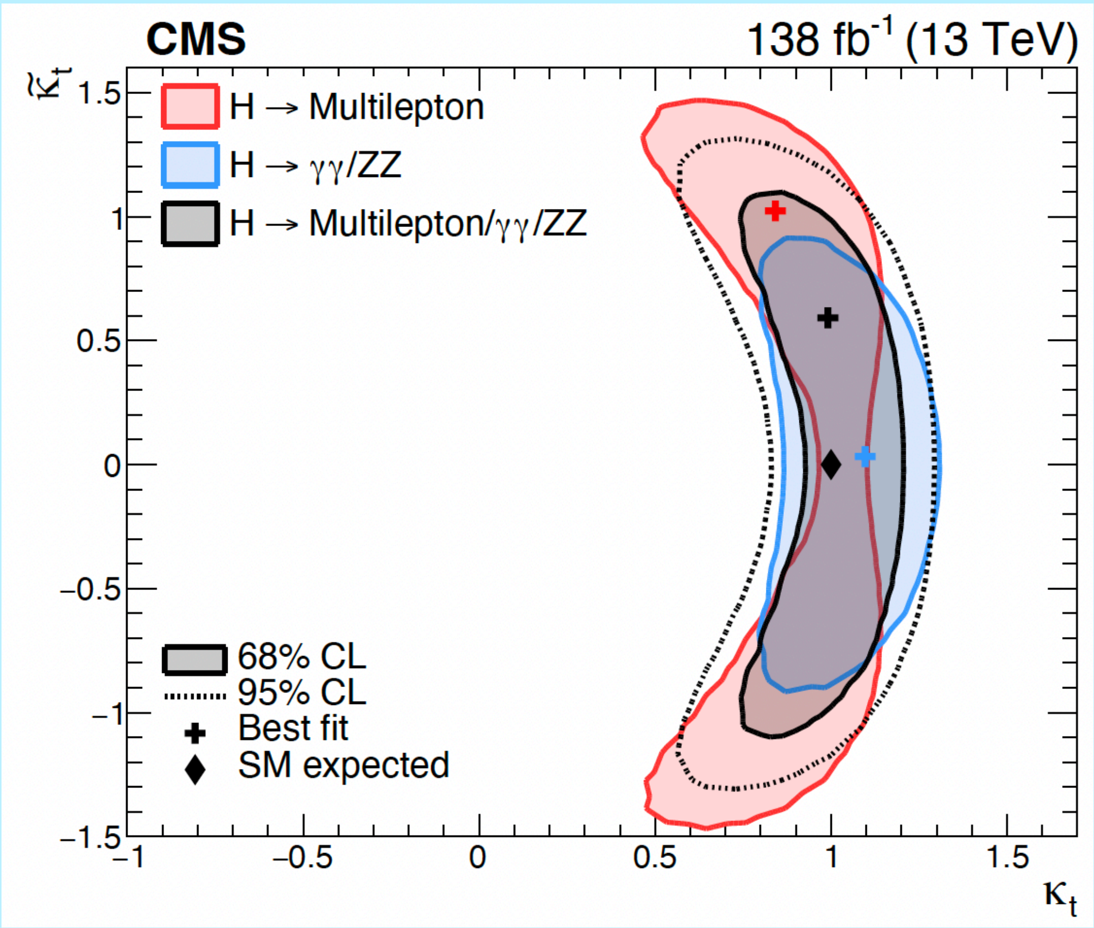
- **Machine learning** techniques: build NN classifiers to exploit correlations and boost the sensitivity

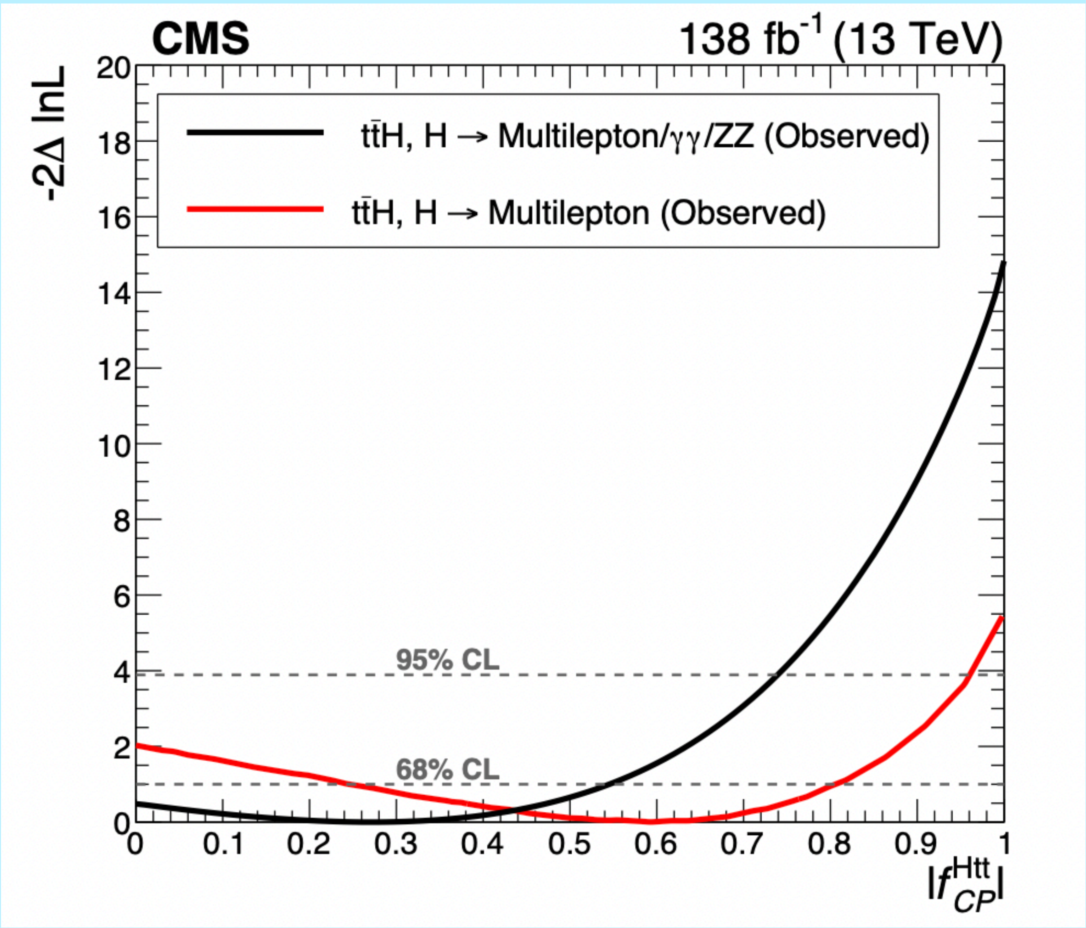
ttH/tH final state: Hff results

JHEP 07 (2023) 092

- H boson decays via H → WW or H → ττ, final states characterized by the presence of at least two leptons are studied.

Machine learning techniques are applied to these final states to enhance the separation of CP-even from CP-odd scenarios





- ttH very sensitive to $k_f, \tilde{k}_f$

  k_t = (−1.09, −0.74) or (0.77, 1.30)

  $\tilde{k}_t$ = (−1.4, 1.4)

- Pure CP odd coupling excluded by 3.7 SD

Phys. Rev. D 104, 052004

HVV coupling constraints in HZZ

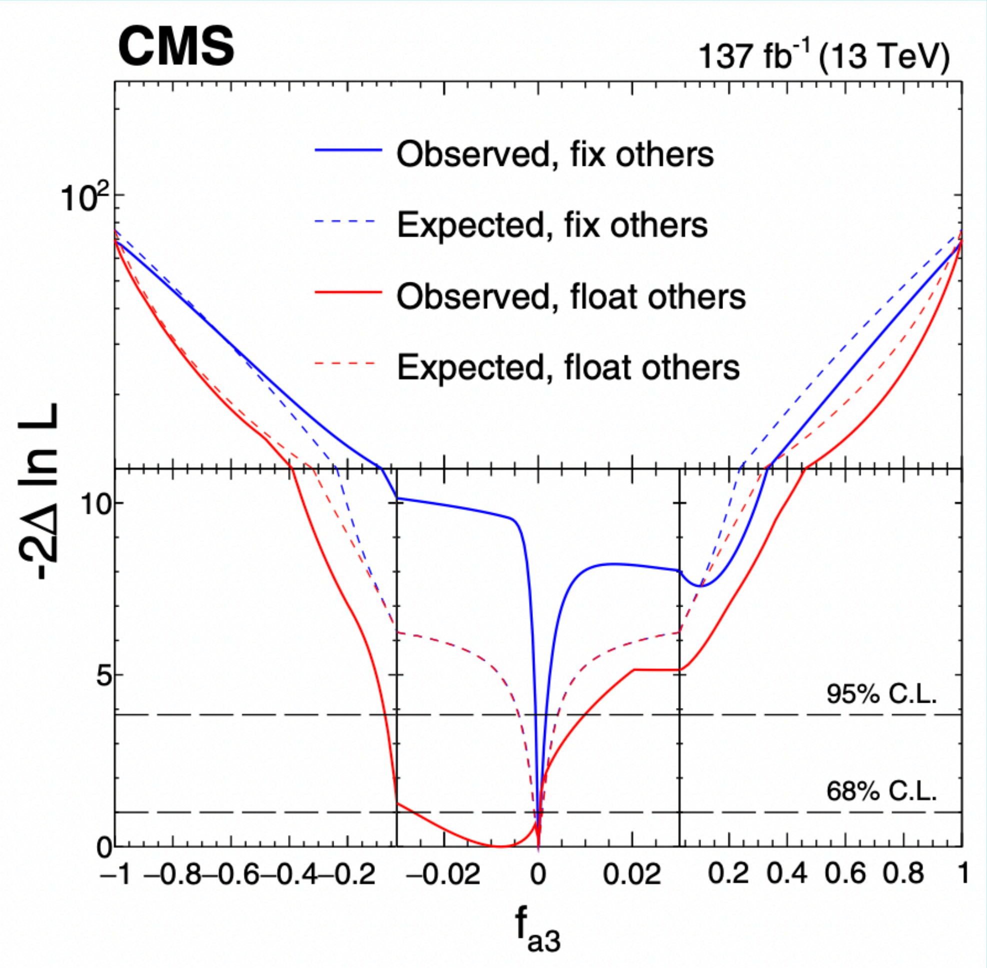
H boson coupling studied: ggH, VBF, VH, ttH, tH, bbH
- MELA discriminator used to define the different categories

search for CP violation anomalous couplings of the Higgs:
- interactions with fermions Hff
- interactions with vector bosons HVV
- EFT interpretation

*Very wide and interesting set of results, we will focus only on fa3, EFT

- combined H→4l and H→γγ
  - included also ttH, H→γγ

→ **Parameters scanned: fa2, fa3, fΛ fΛq**

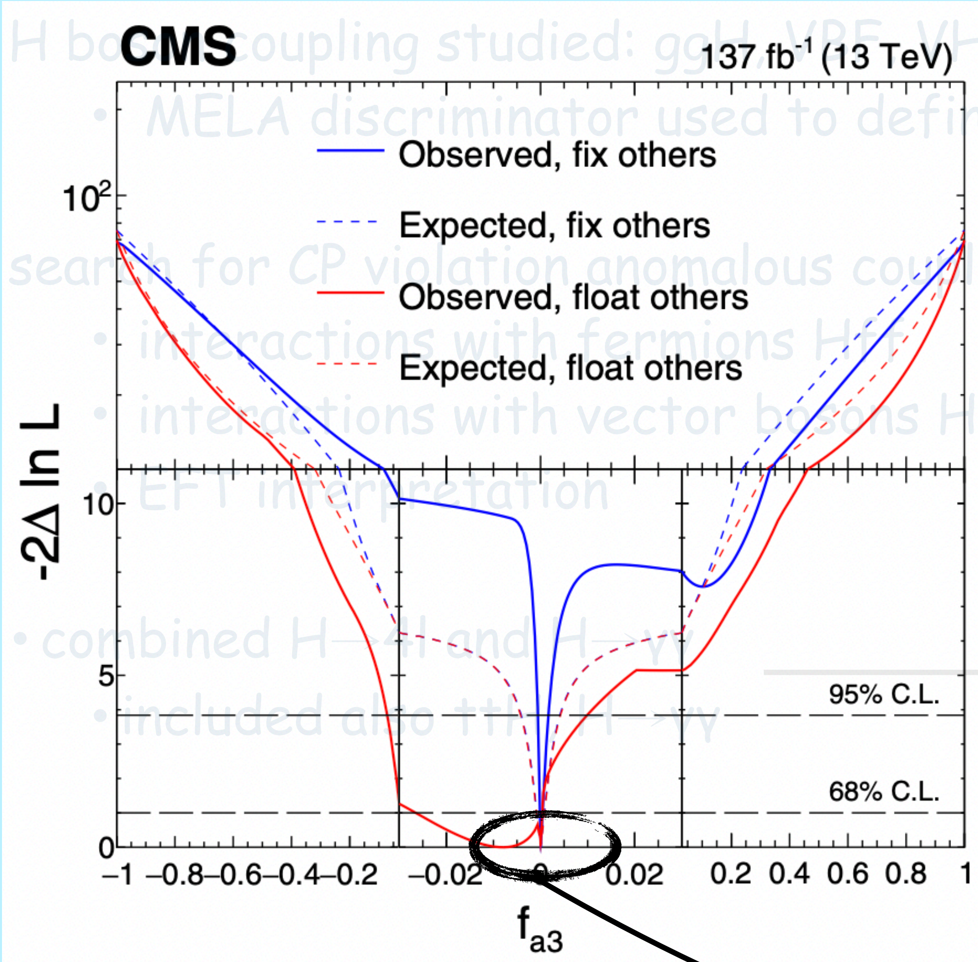


- Narrow minimum effect comes from utilizing production information
- Above 0.02 H→4l dominates
- Results are in agreement with the SM

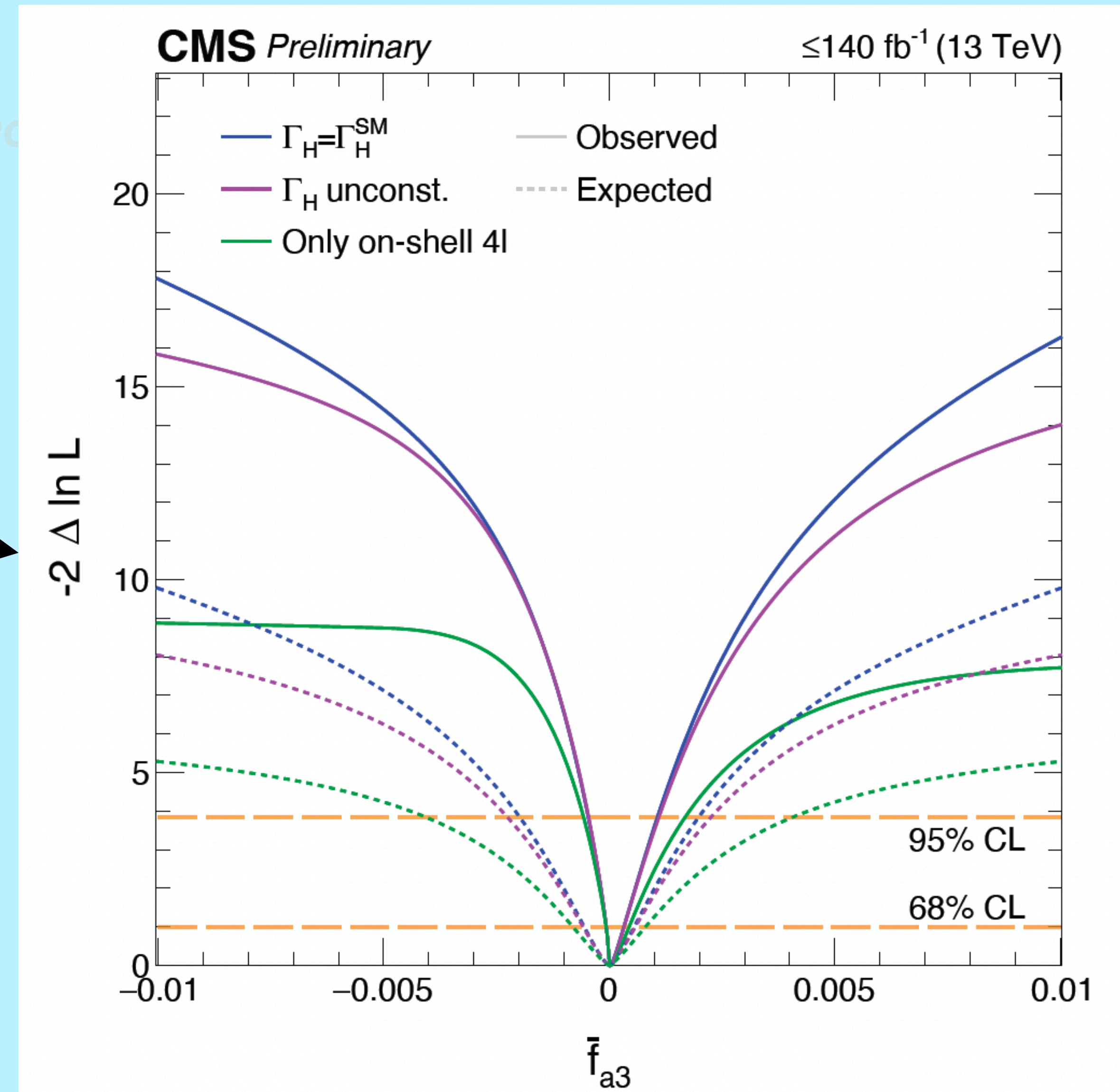
f_{a3} = [−0.00055, 0.00168] @95% CL

Nat. Phys. 18 (2022)

HVV coupling constraints in HZZ



- **HZZ off shell analysis** can be used to target a measurement of f_{a3} (= 10^{-5} theory target) and check how the Higgs width is further constrained, results are summarized in the plot



Parameter ($\times 10^5$)	Scenario	c.v.	Observed 68% | 95% CL	Expected 68% | 95% CL
$\bar{f}_{a3}$	$\Gamma_H = \Gamma_H^{SM}$	2.2	$[-6.4, 32]$ | $[-46, 107]$	$[-55, 55]$ | $[-198, 198]$
	Γ_H unconst.	2.4	$[-6.2, 33]$ | $[-46, 110]$	$[-58, 58]$ | $[-225, 225]$

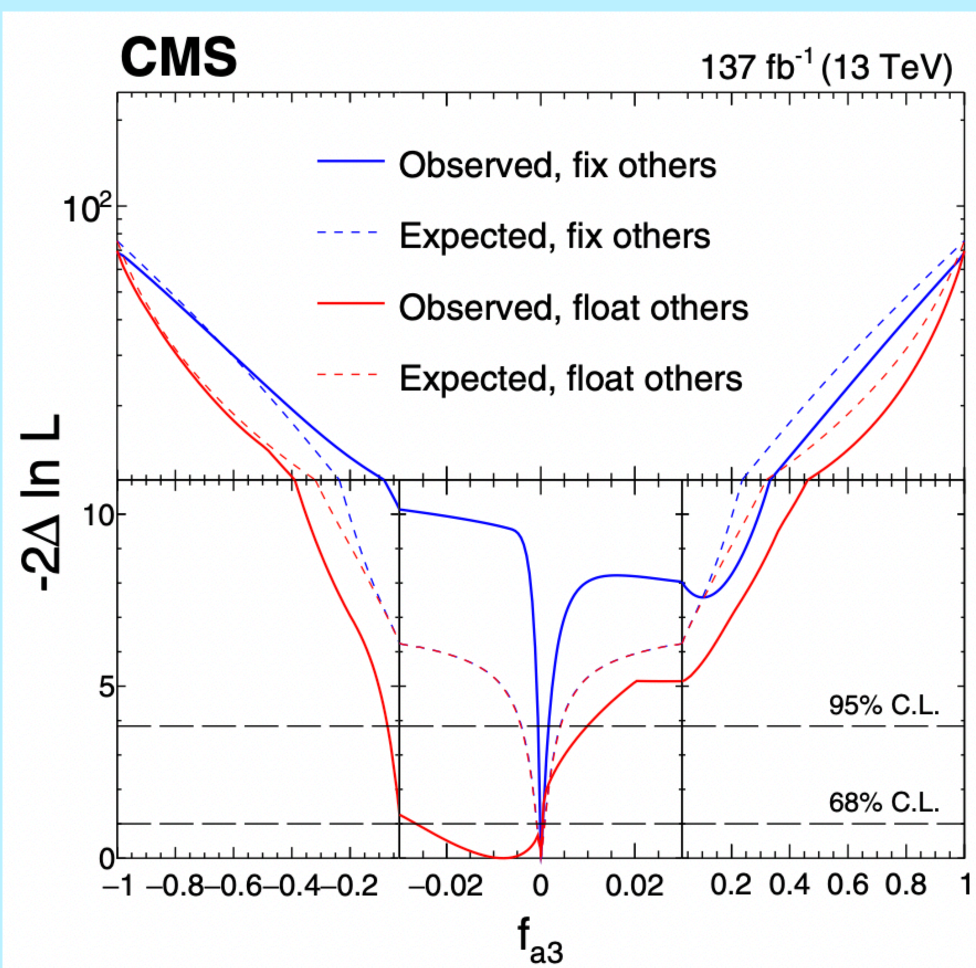
Phys. Rev. D 104, 052004

HVV coupling constraints in HWW

Final state: H → WW → μνeν

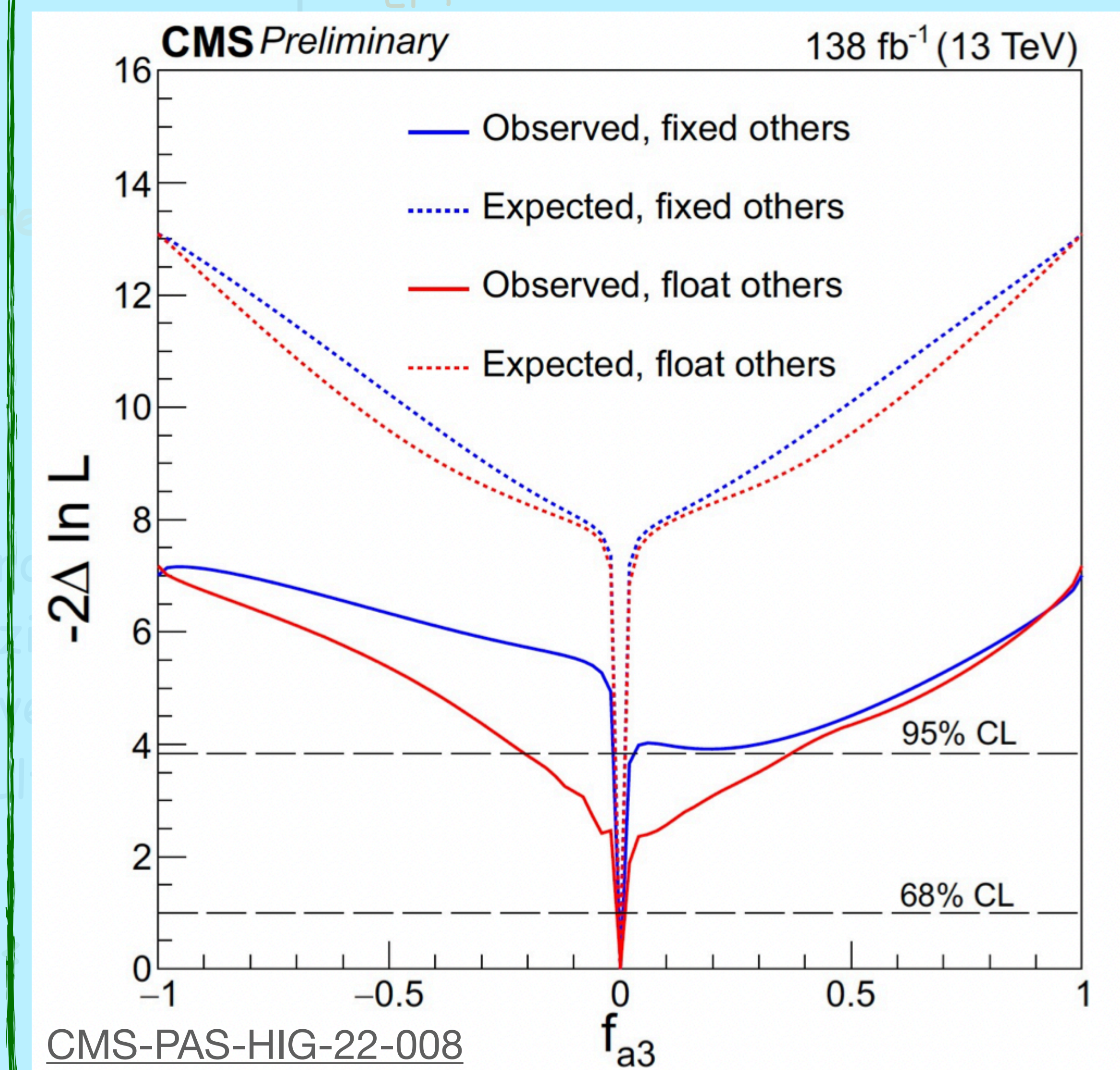
H boson coupling studied: ggH, VBF, VH
- MELA discriminator used to define the different categories
- reconstruction of boosted VH events

Main backgrounds: tt, DY, non-resonant WW and Wjets (estimated from data)



NEW!!!!

The same analysis can be performed in the HWW final state



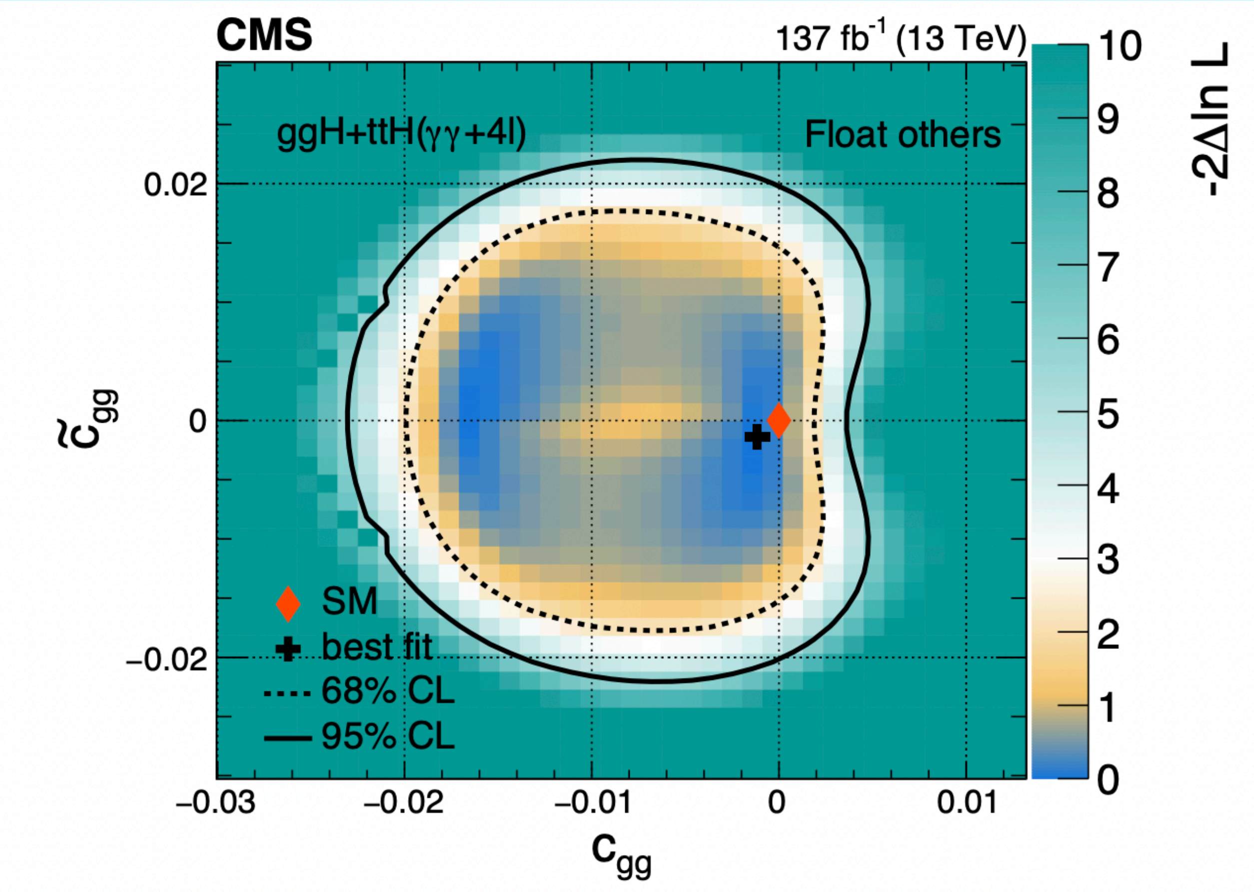
f_{a3} [-0.00083, 0.0035]

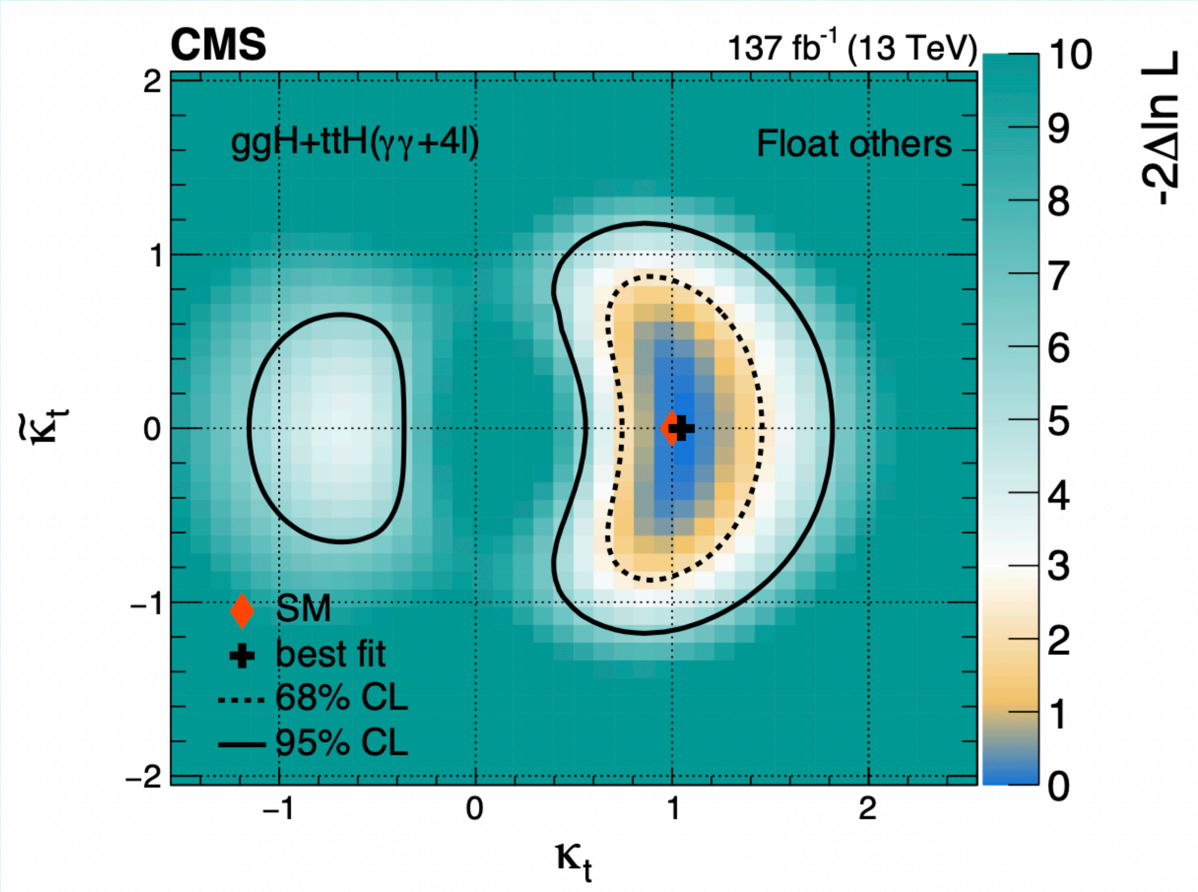
HVV coupling constraints in HZZ

It is possible to reinterpret Hff in the context of effective field theory

Assuming SU(2)xU(1) symmetry, we are left with 4 coefficients in the Hff Lagrangian

$$c_{gg} = \frac{1}{2\pi\alpha_S} a_2^{gg}, \tilde{c}_{gg} = \frac{1}{2\pi\alpha_S} a_3^{gg}, k_t, \tilde{k}_t$$





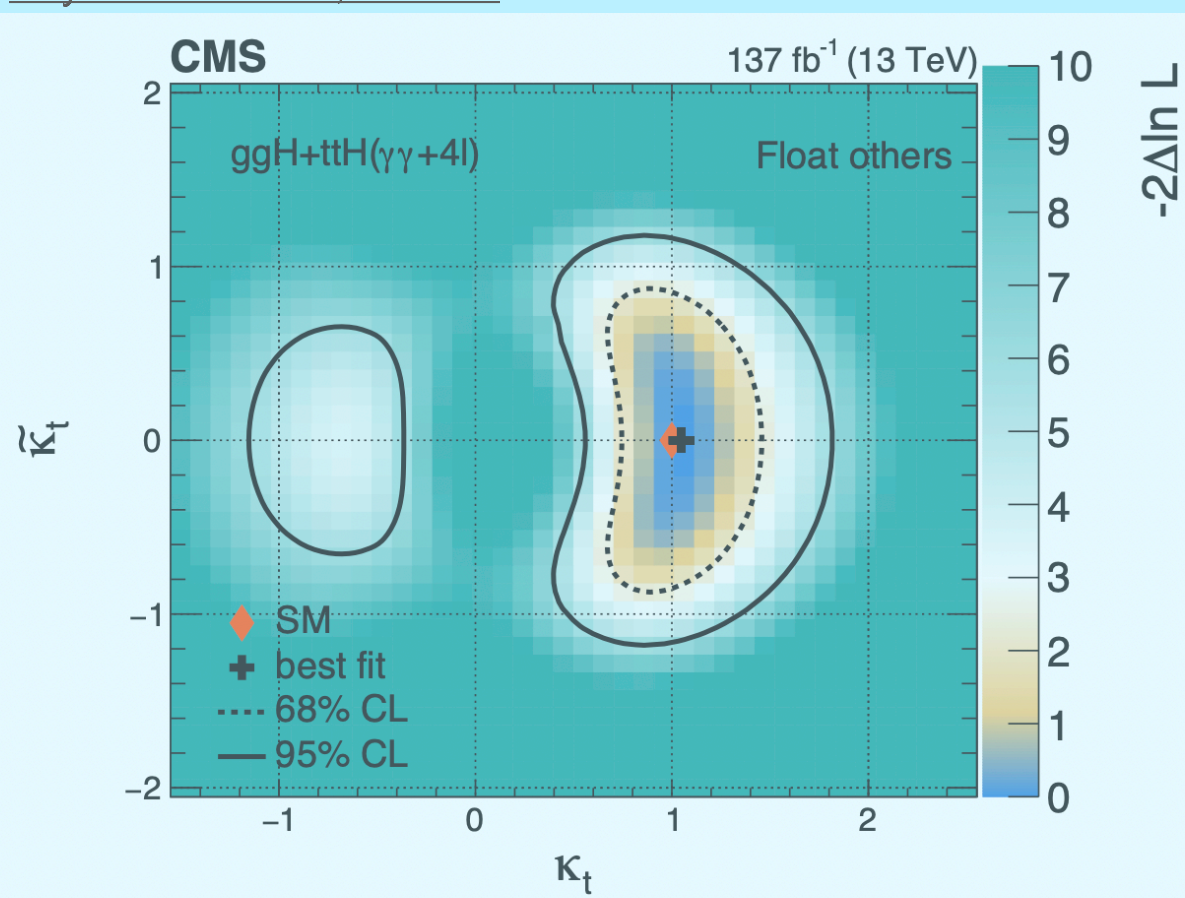
HVV coupling constraints in HZZ

Main background: tt+jets

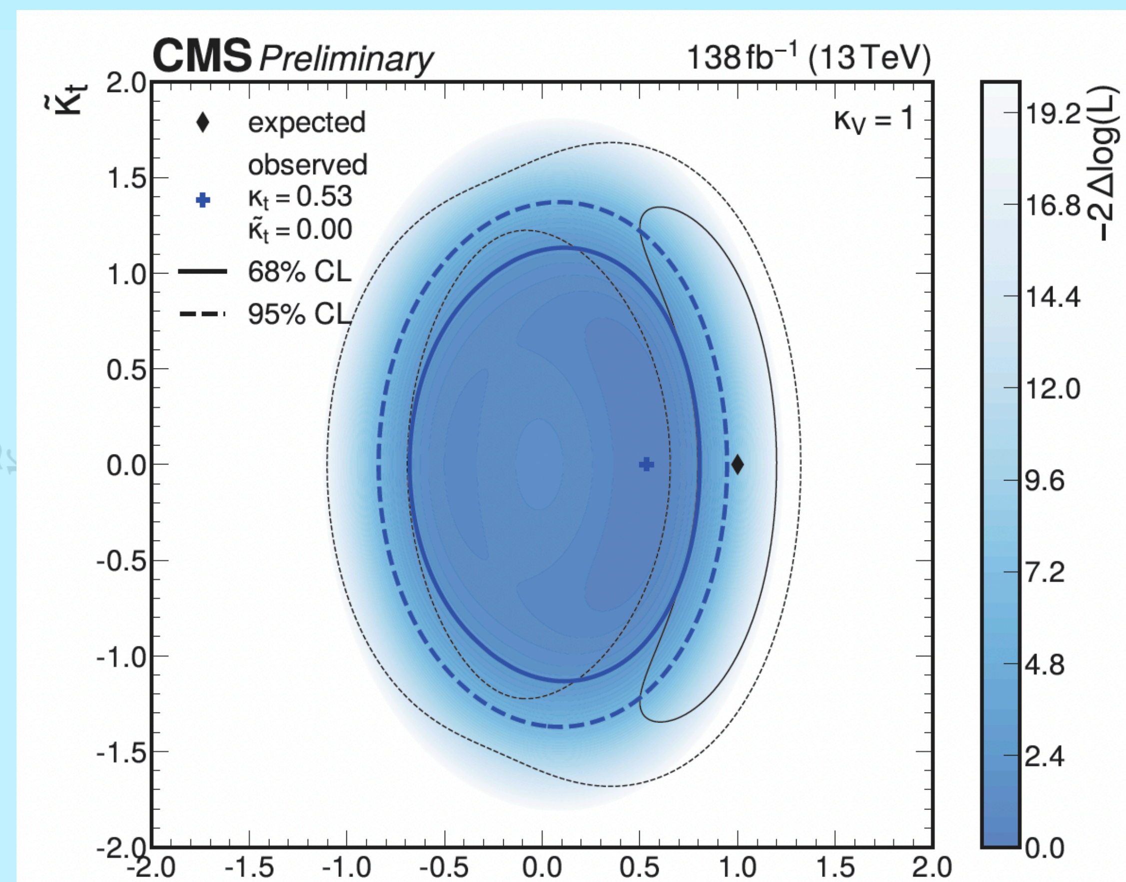
Events are divided into categories depending on the b jet multiplicity:
- In each category a dedicated NN is trained to separate signal vs bkg

The NN output is used in the final fit

Phys. Rev. D 104, 052004



New result from ttH, Hbb analysis!!



CMS-PAS-HIG-19-011

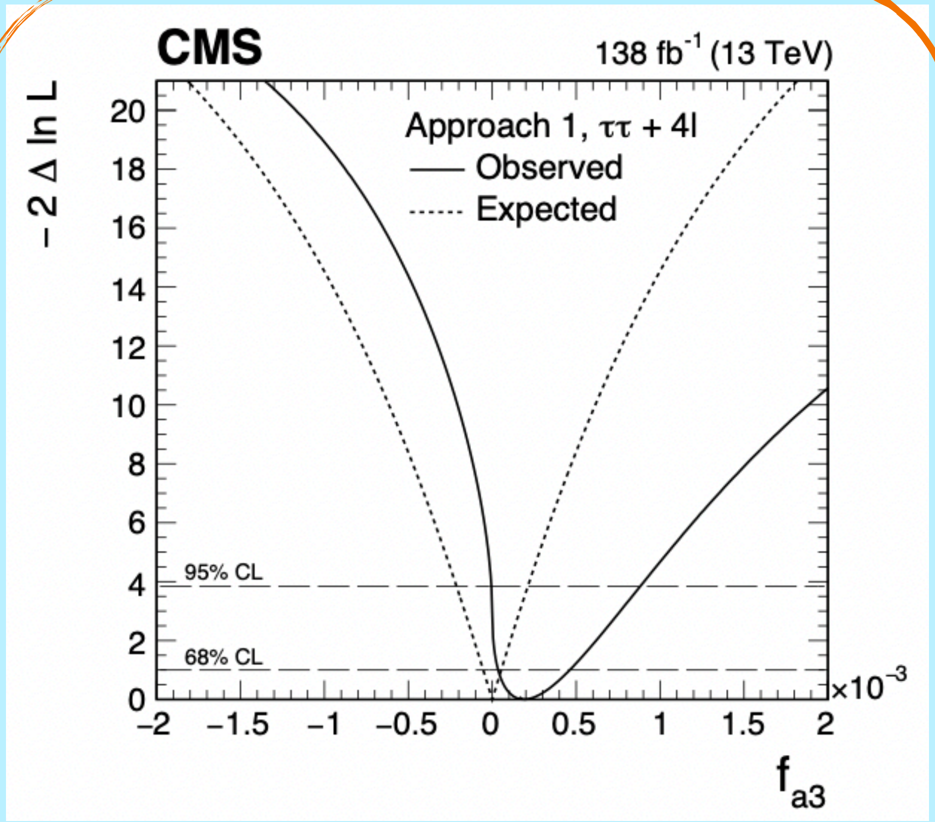
Phys. Rev. D 108, 032013

HVV limits in Hττ

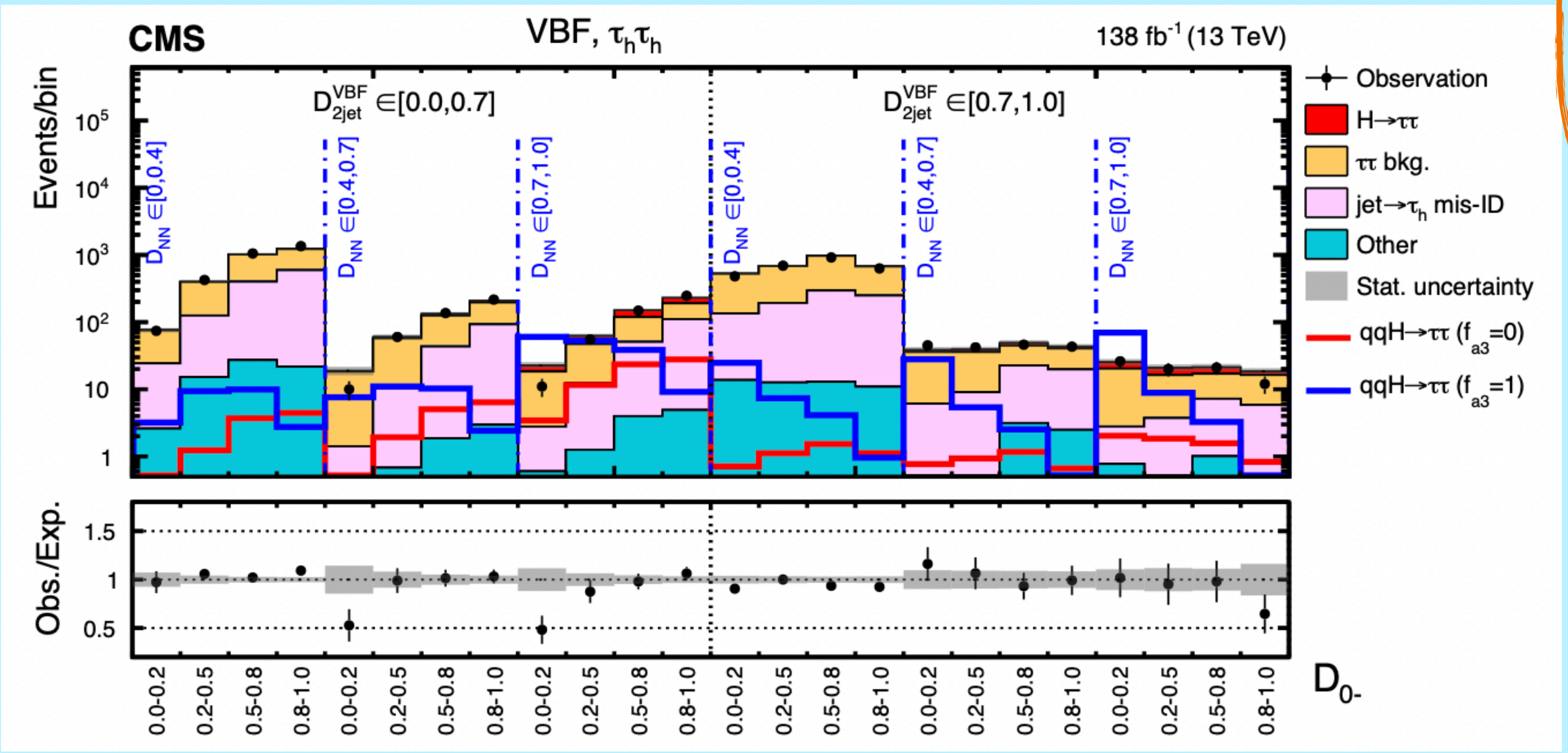
H boson coupling studied: ggH, VBF, VH, ttH, tH, bbH

search for CP violation anomalous couplings of the Higgs:
- interactions with fermions Hff
- interactions with vector bosons HVV

Final discrimination done thanks to MELA + ML:
the former provide optimal separation of the dominant backgrounds, while the latter is used to disentangle different signal hypotheses



Combined H→4l, H→ττ that leads to f_{a3} = [-0.00001, 0.00088] @95% CL



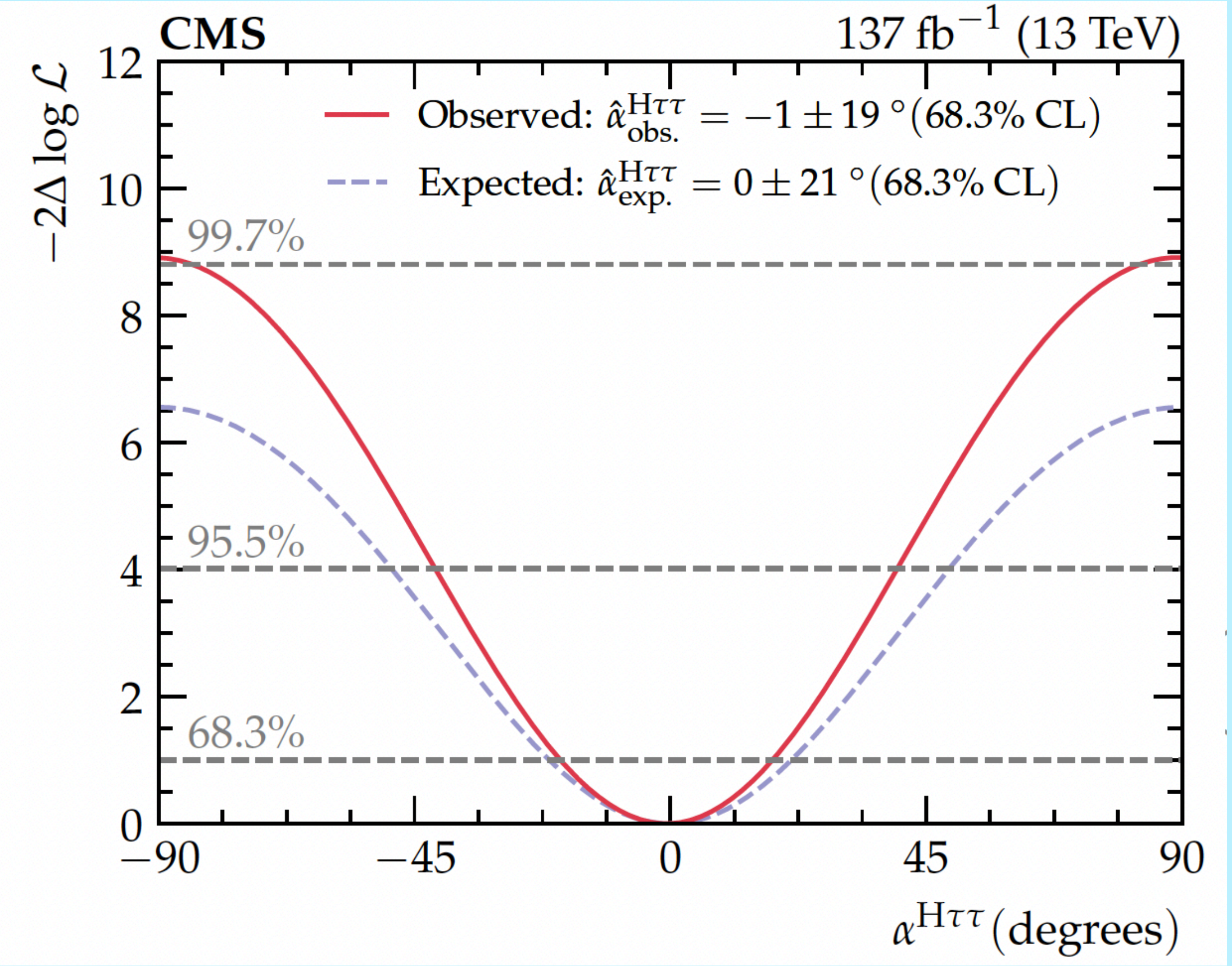
CP structure of the Yukawa coupling Hττ final state

We can write the lagrangian for the τ Yukawa couplings in terms of CP-odd and CP-even components:

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

The effective mixing angle $\alpha^{H\tau\tau}$ for the Hττ coupling is defined in terms of the coupling strengths as:

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



- Depending on the value of α we can have three possible CP scenarios
  - Purely Cp-even: α = 0 or α = 180
  - Purely Cp-odd: α = 90
  - Mixed: α ≠ 0, ≠ 90, ≠180

Pure CP odd coupling excluded by 3 SD

Higgs couplings combination: EFT results

SM Lagrangian can be extended by:

$$L_{HEL} = L_{SM} + \sum_j \frac{f_j O_j}{\Lambda^2} + (O(\Lambda^{-4}))$$

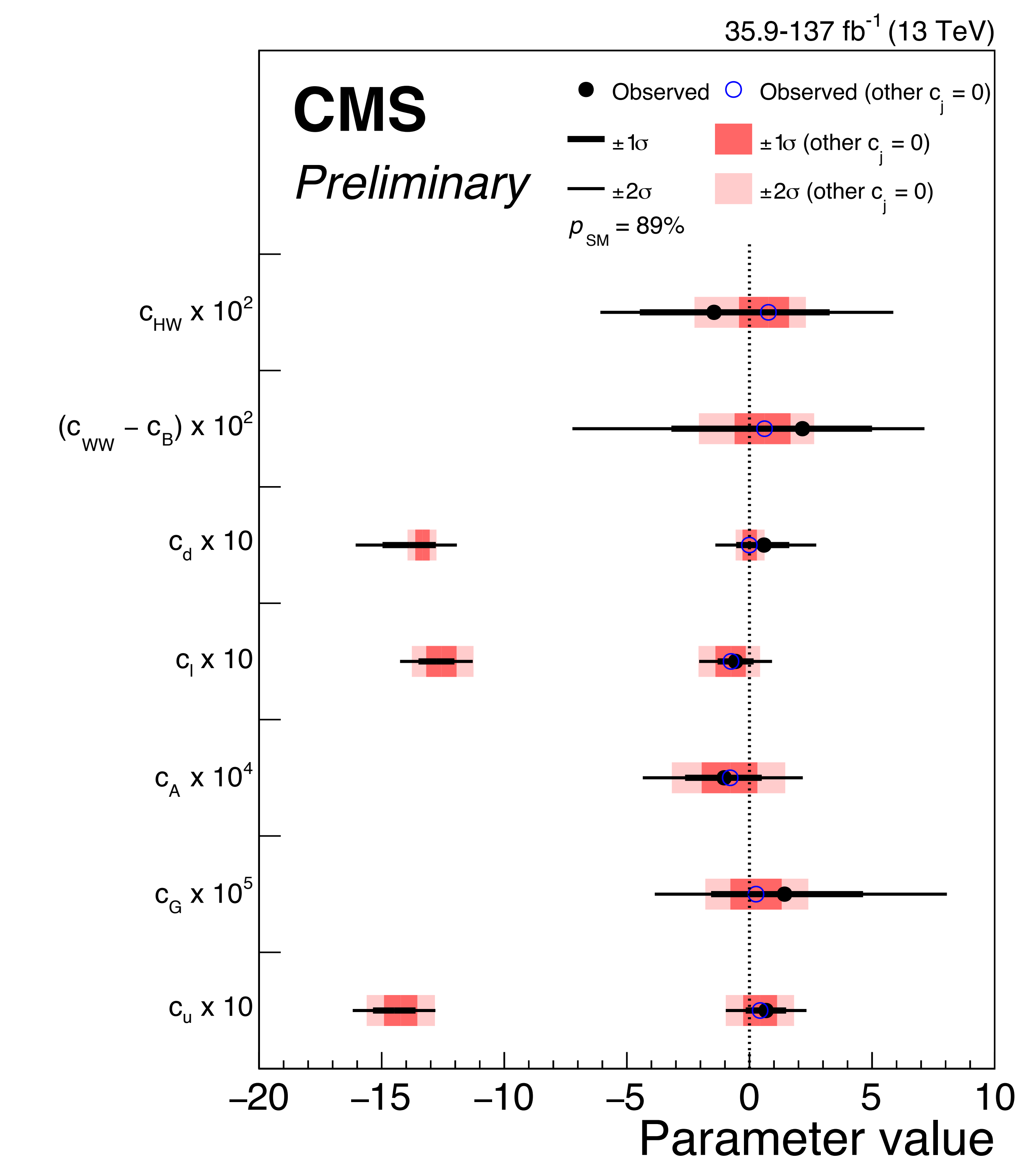
$$\sigma_i^{EFT} = \sigma_i^{SM} + \sigma_i^{int} + \sigma_i^{BSM}$$

Where:

- σ_i^{int} is the is the leading term in the EFT expansion and accounts for the interference with the SM amplitude
- σ_i^{BSM} is the SM independent term

Results are presented as a function of $c_j = f_j/\Lambda^2$ in STXS bins:

$$\mu_i(c_i) = \frac{\sigma_i^{EFT}}{\sigma_i^{SM}}$$



Conclusion

- Small CP-violating **anomalous couplings** in the SM or new BSM scenarios including CP-odd terms are **not excluded yet:**
  - **CP-odd top-Higgs excluded at 3.7 SD**

- The sensitivity to anomalous couplings can be translated into sensitivity to higher dimensionality operators in EFT

- re-interpretation of STXS measurements, allows to **set direct constraints to EFT coefficients** (HEL basis)

- So far, **all the results are in agreement with the predictions of the SM**

Stay tuned for new Run3 results!!!

Backup

Higgs couplings combination: EFT results

- A combination of the the analysis $H \to ZZ$, $H \to \gamma\gamma$, $H \to WW$, $H \to bb$, $H \to \tau\tau$, $H \to \mu\mu$ has been done
- Luminosity up to 137 fb^{-1}
- All signal productions mechanisms that contribute less than 0.1% to the total signal expectation in each category are neglected during the fit

Analysis	Decay tags	Production tags	Luminosity (fb^{-1})	References
$H \to \gamma\gamma$	$\gamma\gamma$	ggH, $p_T(H) \times$ N-jet bins VBF, $p_T(H\,jj)$ bins	77.4	[53]
		ttH	35.9, 41.5	[54], [55]
$H \to ZZ^{(*)} \to 4\ell$	$4\mu, 2e2\mu/2\mu2e, 4e$	ggH, $p_T(H) \times$ N-jet bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH	137	[56]
$H \to WW^{(*)} \to \ell\nu\ell\nu$	$e\mu/\mu e$	ggH $\leq$ 2-jets VBF	35.9	[57]
	$ee+\mu\mu$	ggH $\leq$ 1-jet		
	$e\mu$+jj	VH hadronic		
	3ℓ	WH leptonic		
	4ℓ	ZH leptonic		
$H \to \tau\tau$	$e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$	ggH, $p_T(H) \times$ N-jet bins VH hadronic VBF	77.4	[58]
		VH, high-$p_T(V)$	35.9	[59]
$H \to bb$	$W(\ell\nu)H(bb)$	WH leptonic	35.9, 41.5	[60], [61]
	$Z(\nu\nu)H(bb), Z(\ell\ell)H(bb)$	ZH leptonic		
	bb	ttH, $t\bar{t} \to 0, 1, 2\ell +$ jets	77.4	[62]
		ggH, high-$p_T(H)$ bins	35.9	[63]
ttH production with $H \to$ leptons	2ℓss, 3ℓ, 4ℓ, $1\ell+2\tau_h$, 2ℓss$+1\tau_h$, $3\ell+1\tau_h$	ttH	35.9, 41.5	[64], [65]
$H \to \mu\mu$	$\mu\mu$	ggH VBF	35.9	[66]