Constraints on anomalous Higgs boson couplings and EFT with the CMS experiment

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on behalf of the CMS Collaboration

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Motivation

10 years studying the Higgs boson

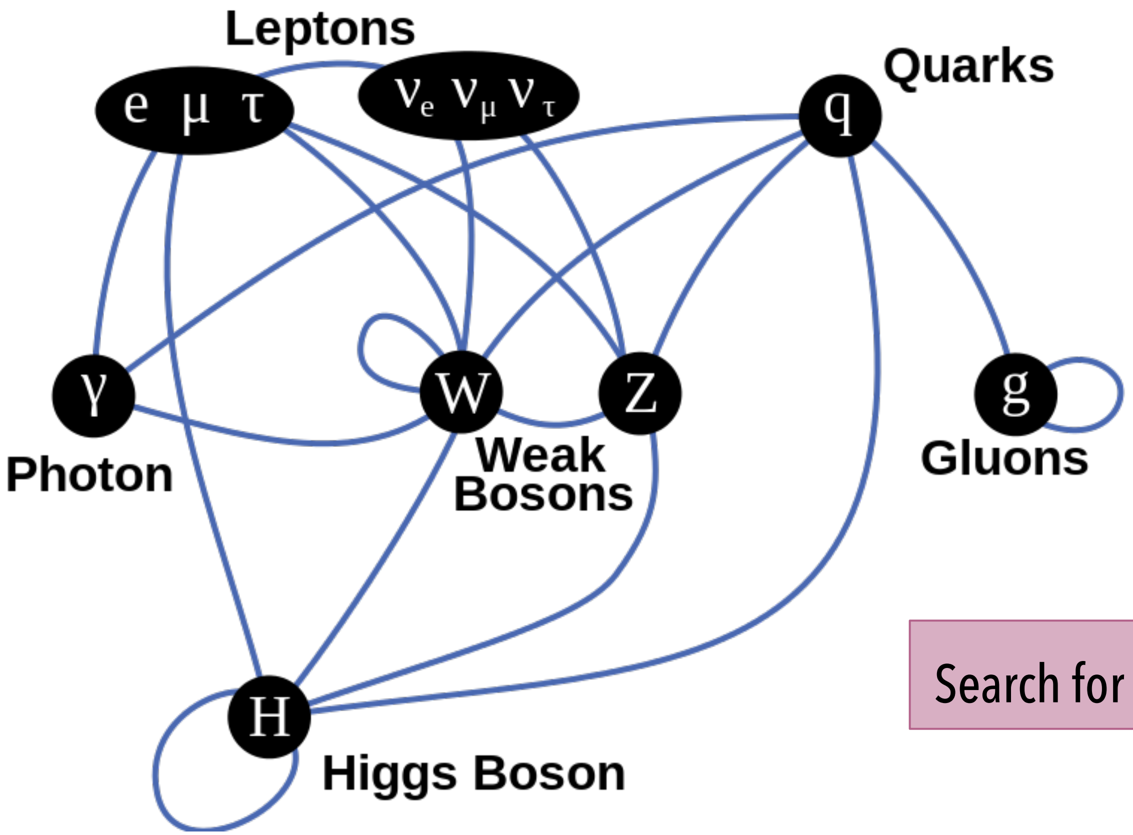
Run 1 → LHC data compatible with an SM H(125) of spin 0 and even CP

Run 2 → Precision era for Higgs physics +

J^{CP} studies:

Coupling to bosons

Coupling to fermions



CP is a property of the interaction

&

Matter asymmetry

CP-violating baryon-generating interaction

Search for Higgs Anomalous Couplings (AC) to bosons and fermions

Higgs AC to bosons | HVV parametrization

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

a_1^{VV} → If VV= WW, ZZ, Zγ → Tree-level SM

a_2^{VV} → If VV= gg → 1-loop SM

AC approach	SMEFT approach
$a_i^{ZZ}=a_i^{WW}$	SU(2) X U(1)
4 anomalous couplings:	$a_i^{ZZ} \neq a_i^{WW}$
a_2 (CP)	3 anomalous couplings:
a_3 ~~(CP)~~	a_2 (CP)
$a_{\Lambda 1}$ (CP)	a_3 ~~(CP)~~
$a_{\Lambda 1}^{Z\gamma}$ (CP)	$a_{\Lambda 1}$ (CP)

If VV= gg → 1 AC: a_3 ~~(CP)~~

1. Amplitude parametrization can be related to the **Higgs basis** EFT.
2. **Cross-section fraction:**

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

Higgs AC to fermions | Hff parametrization

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

SM-like ← κ_f

$\tilde{\kappa}_\mathrm{f}$ → Anomalous contribution

AC approach/SMEFT approach

1 Anomalous coupling:

$\tilde{\kappa}_\mathrm{f}$: ~~CP~~

Cross-section fraction:

$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_\mathrm{f}|^2}{|\kappa_\mathrm{f}|^2 + |\tilde{\kappa}_\mathrm{f}|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_\mathrm{f}}{\kappa_\mathrm{f}}\right)$$

κ_f and $\tilde{\kappa}_\mathrm{f}$ are **Yukawa coupling strength modifiers** related to the mixing angle $\alpha^{Hff} = \tan^{-1}\left(\frac{\tilde{\kappa}_\mathrm{f}}{\kappa_\mathrm{f}}\right)$

Higgs couplings analyses with the CMS experiment

Since 2021:

CMS Analysis	Channel	Measurement	Combined with	REF
HIG-19-009	on-Shell H → ZZ	HVV, Hgg, Htt	[Htt] H→$\gamma\gamma$ (HIG-19-013)	PRD 104 (2021) 052004
HIG-21-013	off-Shell H → ZZ	HVV	on-Shell H→ZZ	NP (2022) 01682
HIG-20-007	H → $\tau\tau$	HVV, Hgg, Htt	on-Shell H→ZZ + H→$\gamma\gamma$	arXiv:2205.05120 (PRD)
HIG-21-006	ttH and tH	Htt	on-Shell H→ZZ + H→$\gamma\gamma$	arXiv:2208.02686 (sub)
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"Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state"

On-Shell H→ZZ analysis

Channels: 4ℓ ($4e$, 4μ, $2e2\mu$)

Productions: ggH, VBF, VH, ttH.

Dedicated measurements (detector-level)

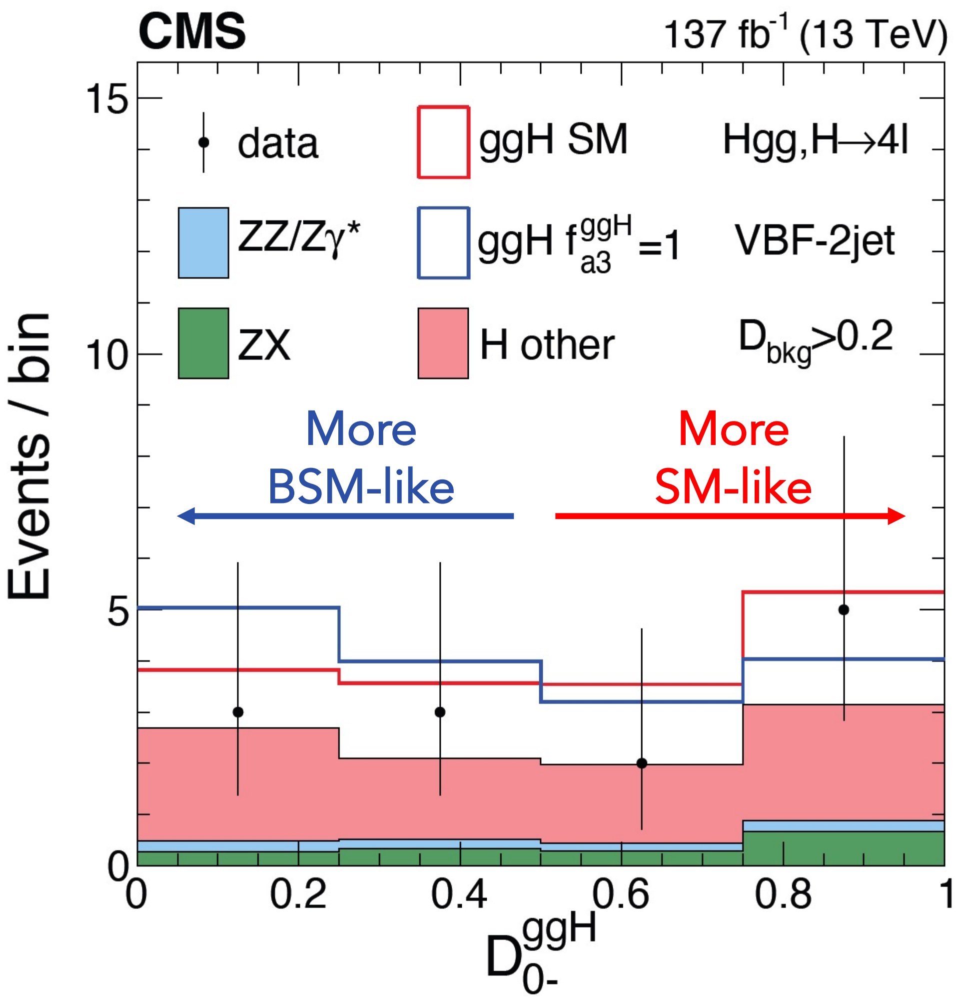
- Exploit full production and decay kinematic information with MELA-based discriminants.

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

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

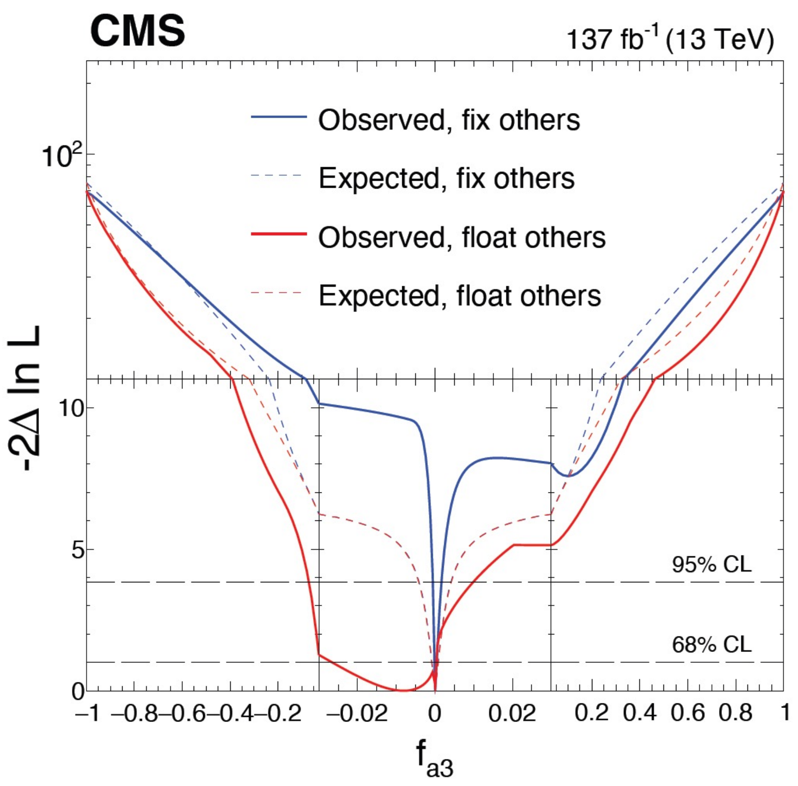
Multi-dimensional analysis:

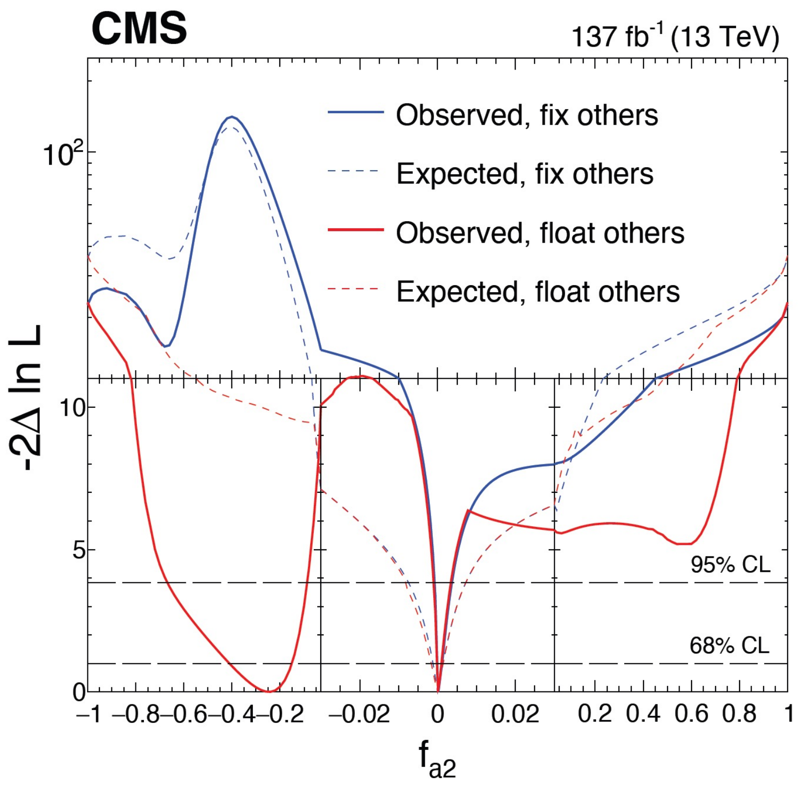
- Several parameters are simultaneously extracted.



H→ZZ Results | HVV (AC approach)

VBF & VH & H → 4ℓ

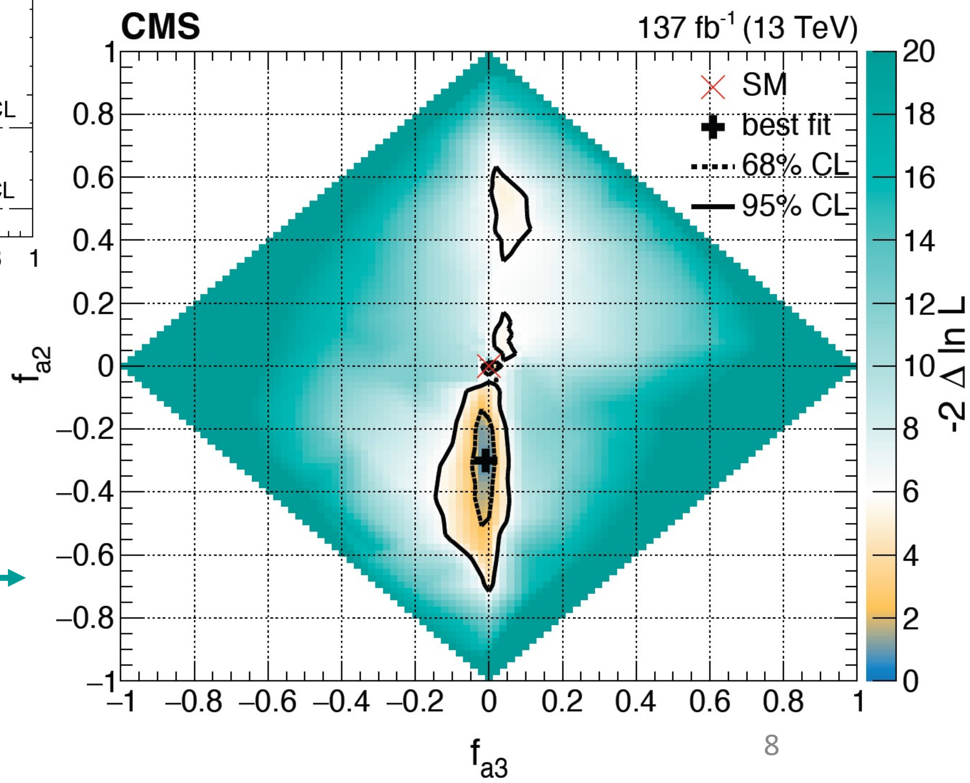




$f_{a\Lambda1}$ and $f_{a\Lambda1}^{Z\gamma}$ scans are also available

Notice we can also perform f_{a3}, f_{a2}, and $f_{a\Lambda1}$ scans in the SMEFT approach

- **Fix:** Other couplings are fixed to the SM expectation.
- **Float:** Other couplings are profiled in the fit



H→ZZ Results | HVV (SMEFT approach)

VBF & VH & H → 4ℓ

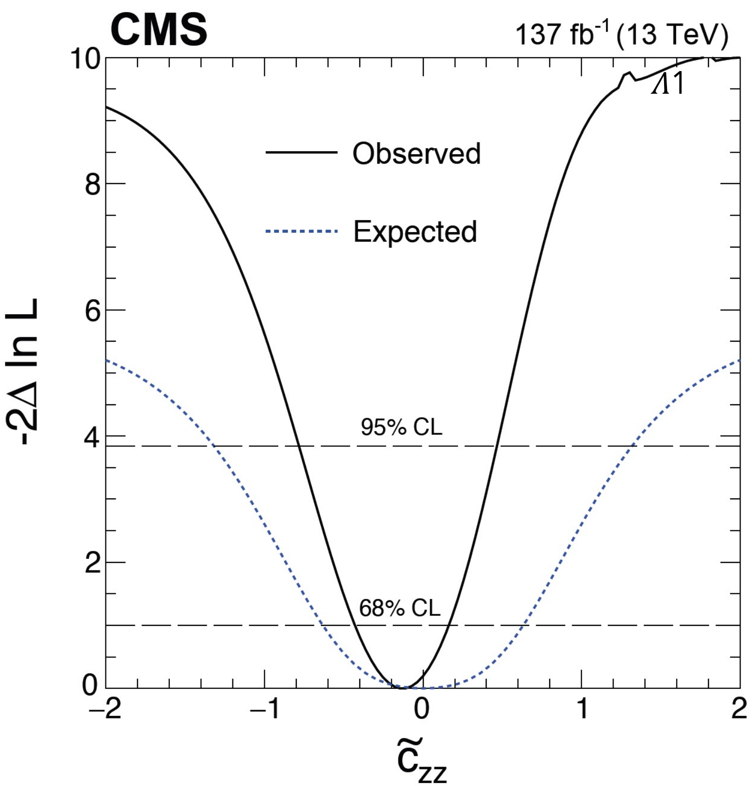
HVV parametrization can be related to the

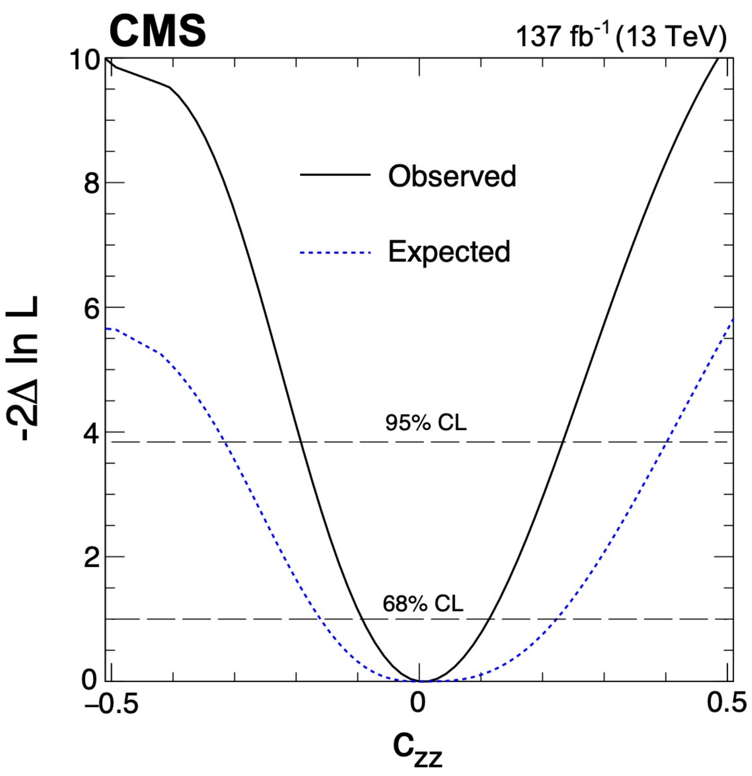
EFT couplings using the Higgs basis.

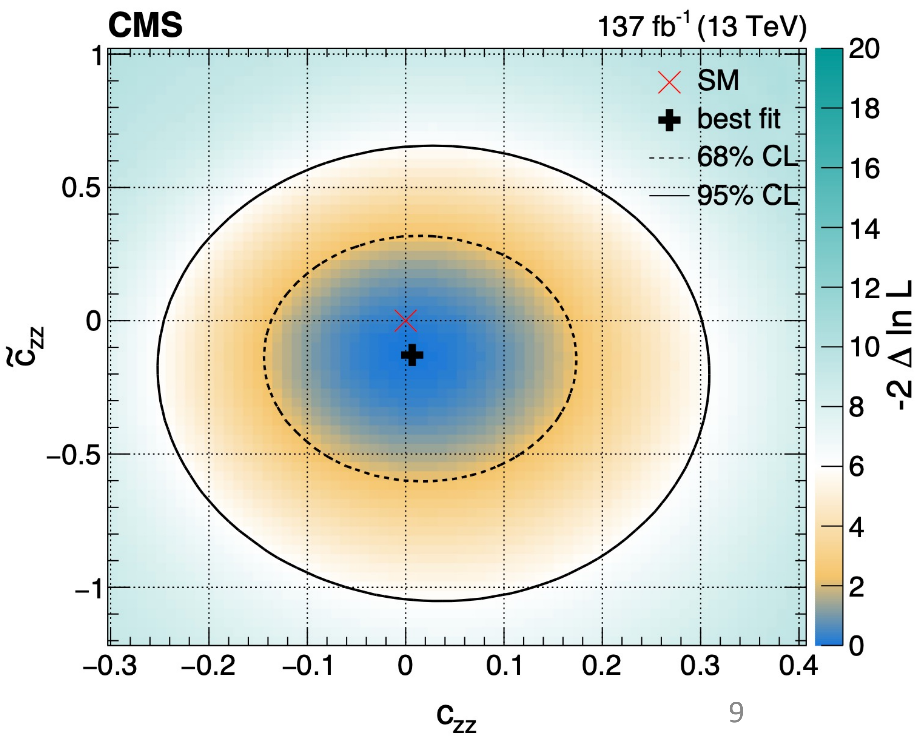
+ Results on Warsaw Basis

$$\delta c_z = \frac{1}{2}a_1 - 1 \qquad c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha}a_2$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{4\pi\alpha}\frac{\kappa_1}{(\Lambda_1)^2} \qquad \tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha}a_3$$







Higgs couplings analyses with the CMS experiment

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"Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production"

Off-Shell H→ZZ analysis

Channels: $2\ell 2\nu/4\ell$

Productions: ggH, VBF, VH.

m_{ZZ} line shape is sensitive to the presence of anomalous HVV

- Could affect the measurement of Γ_{Higgs}

$$\sigma^{\text{off-Shell}} \propto \sigma^{\text{on-Shell}}\, \Gamma_{Higgs}$$

$2\ell 2\nu$ → m_T^{ZZ}>300 GeV

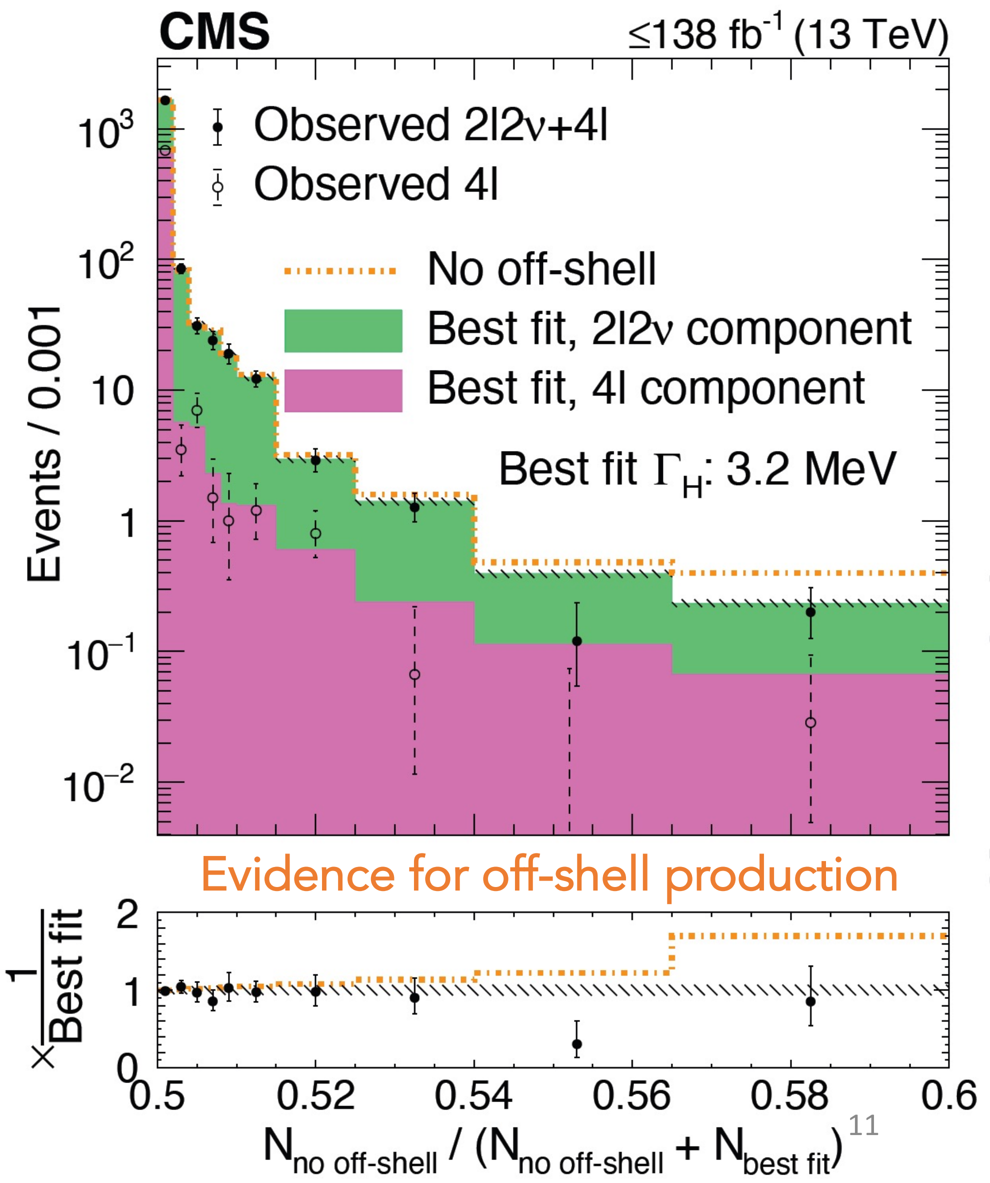
4ℓ events → MELA D^{VBF}_{2j}→ Sensitive to AC HVV.

Combined with:

Run 2 On-Shell 4ℓ → PRD 104 (2021) 052004

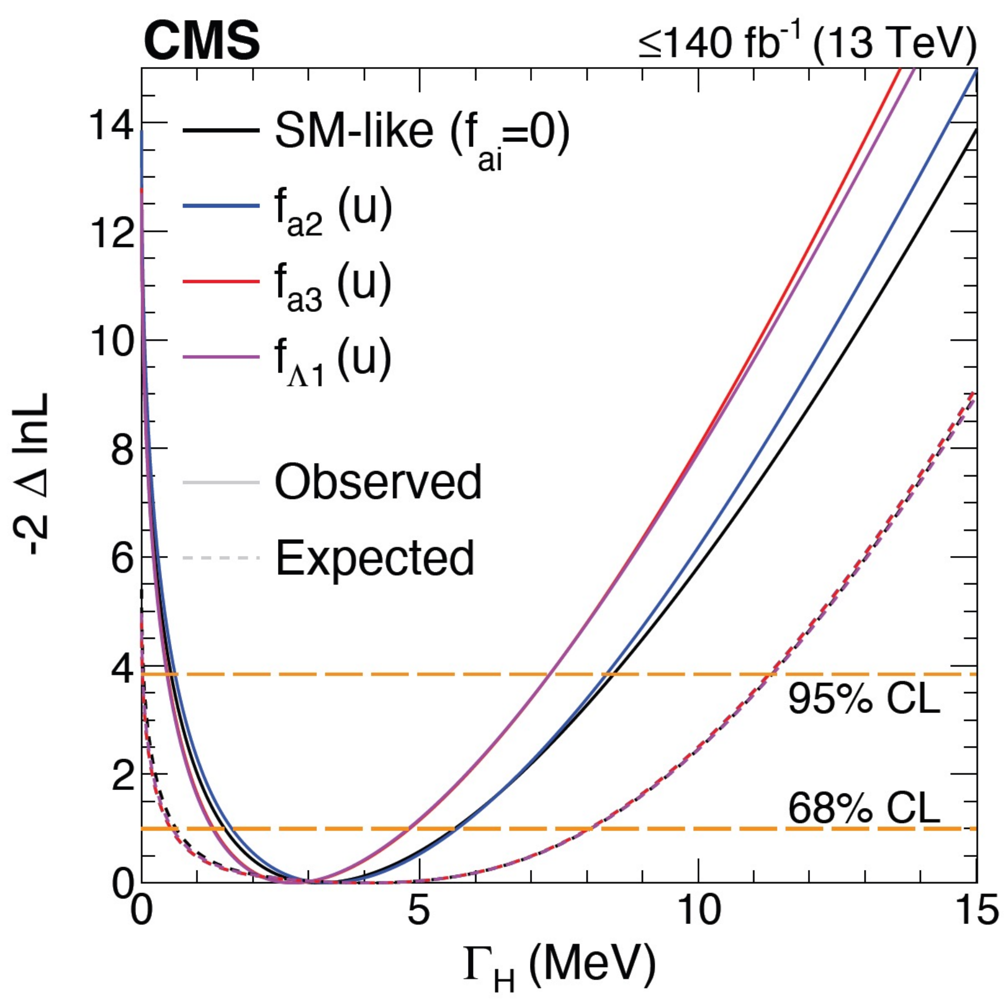
(2016-2017) Off-Shell 4ℓ → Phys. Rev. D 99, 112003 (2019)

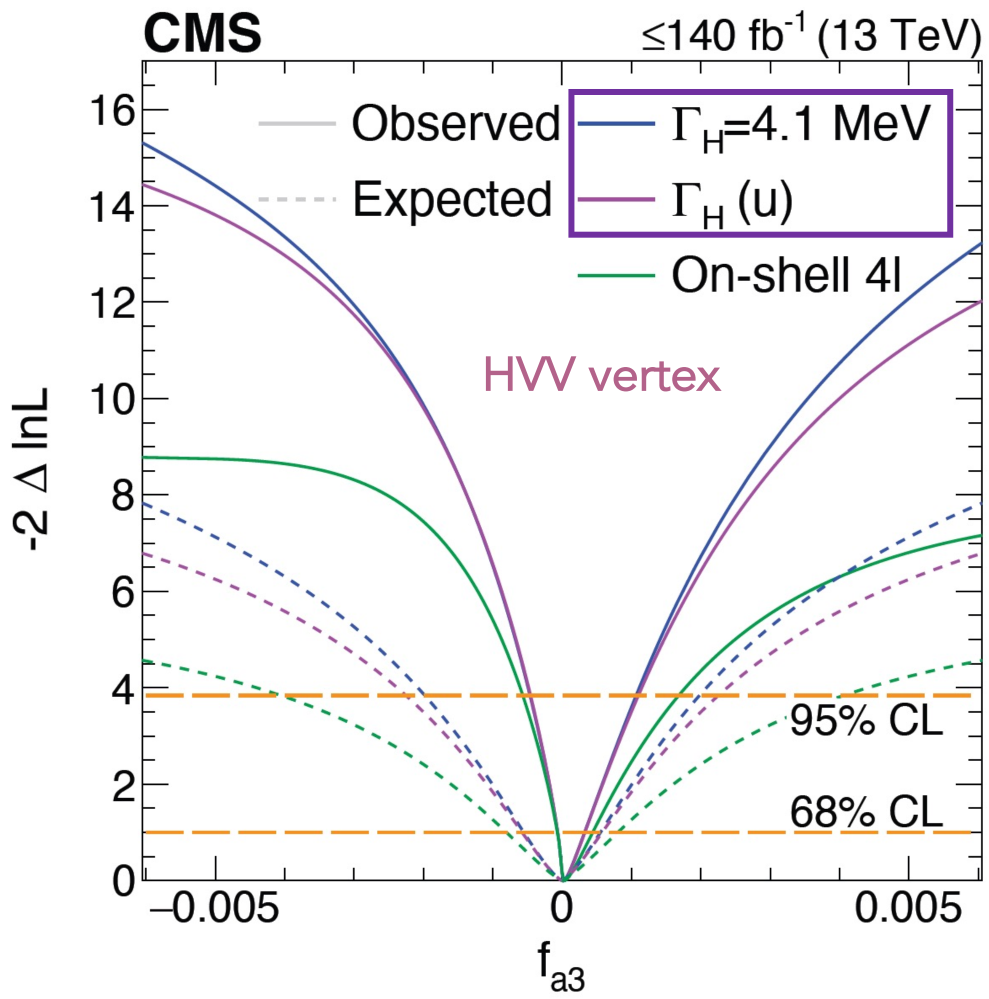
2015 On-Shell 4ℓ → *Phys. Lett. B* 775 (2017) 1



Evidence for off-shell production

Off-Shell H→ZZ analysis Results | Combination with on-Shell H→ZZ





Γ_H = 3.2 [+2.4,-1.7] MeV (68% CL)

AC approach

Higgs couplings analyses with the CMS experiment

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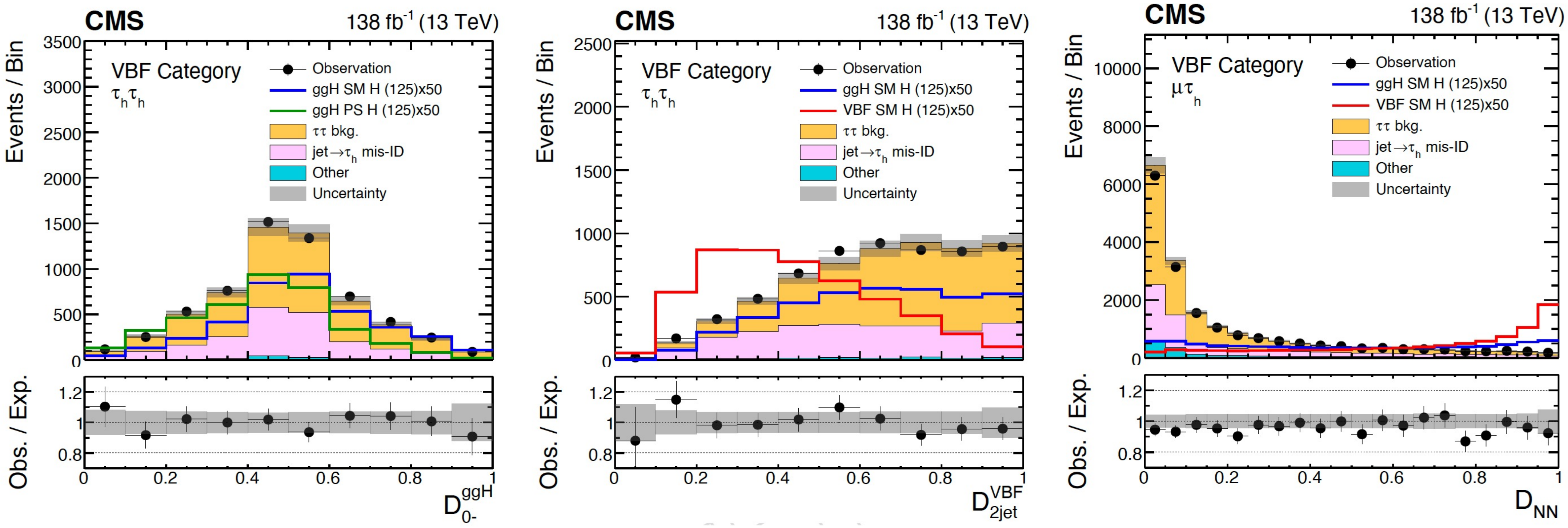
"Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau\tau$ final state"

H→ττ analysis

Channels: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$

VBF production analysis → HVV

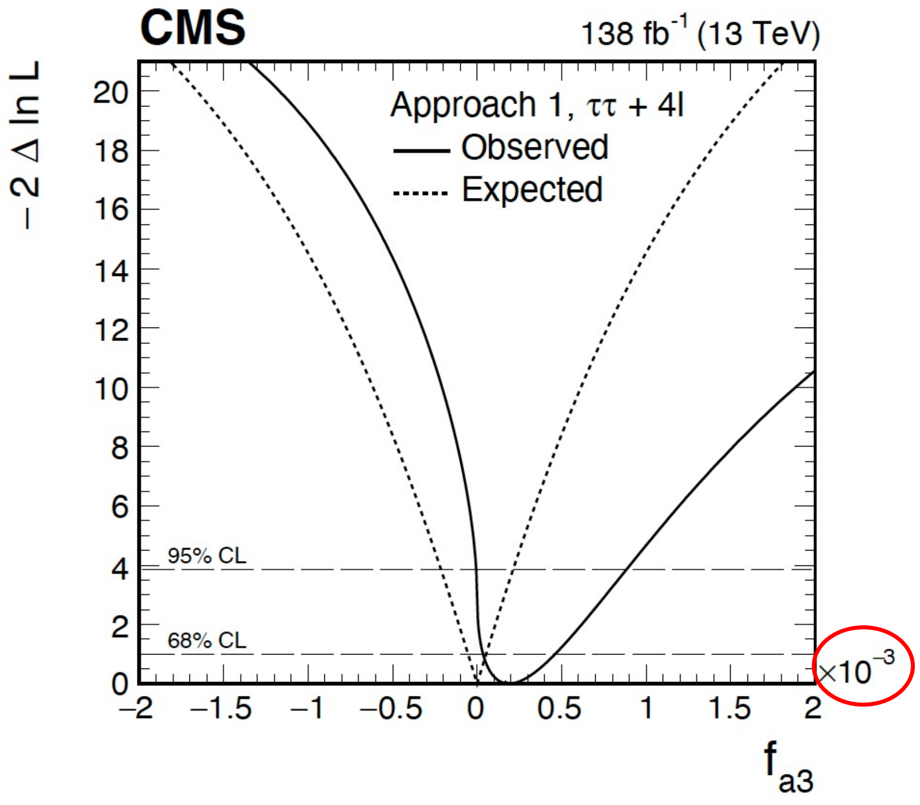
ggH production analysis → Hgg



Combined to construct 2D and 3D kinematic discriminants

H→ττ Results | HVV combining with H→ZZ (4ℓ)

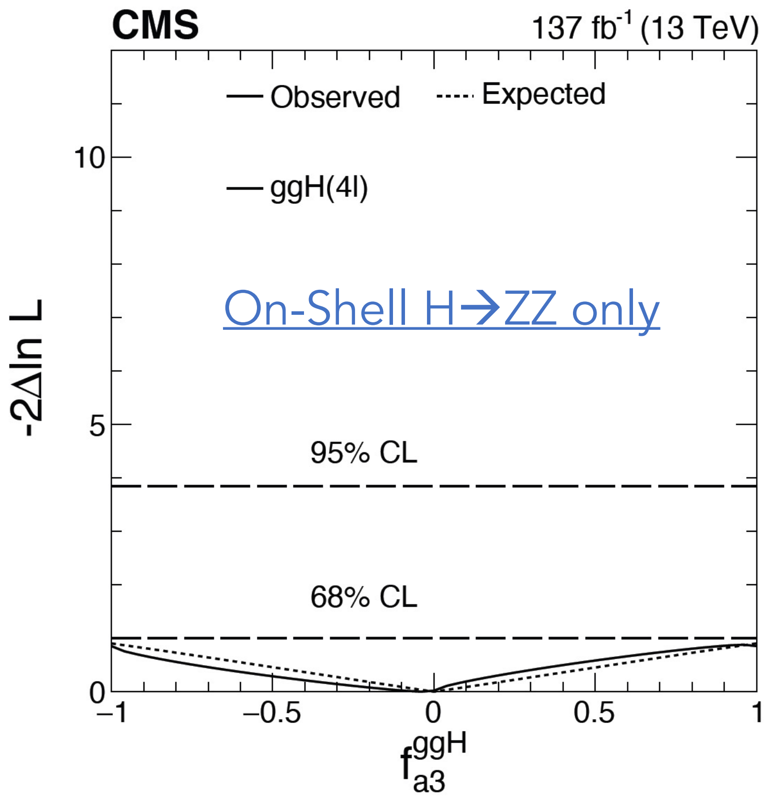
HVV vertex

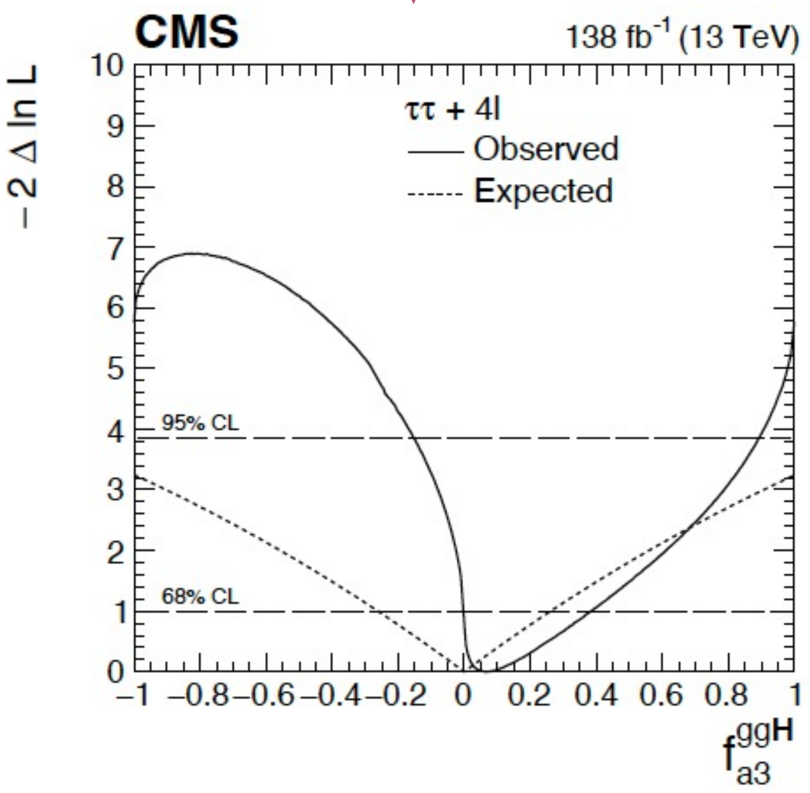


fa_2, $fa_{\Lambda1}$ and $fa_{\Lambda1}^{Z\gamma}$
also constrained (in backup)

Hgg vertex

+ Combination wih H→ττ

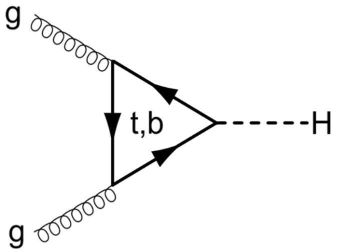


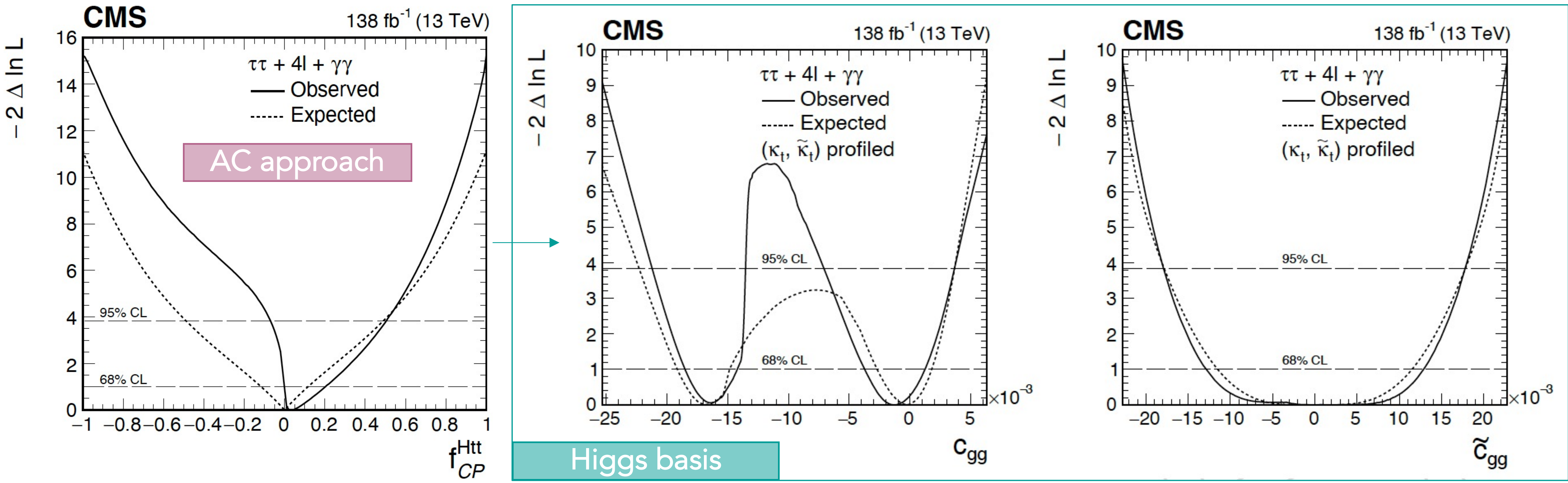


The pure CP-odd scenario of the Higgs boson coupling to gluons is excluded at 2.4σ

H→ττ Results | Hff combining with H→ZZ (4ℓ) + ttH (2γ)

ggH loop is dominated by the top quark





The combination improves the limits on the anomalous coupling parameters typically by about 20–50%

Higgs couplings analyses with the CMS experiment |

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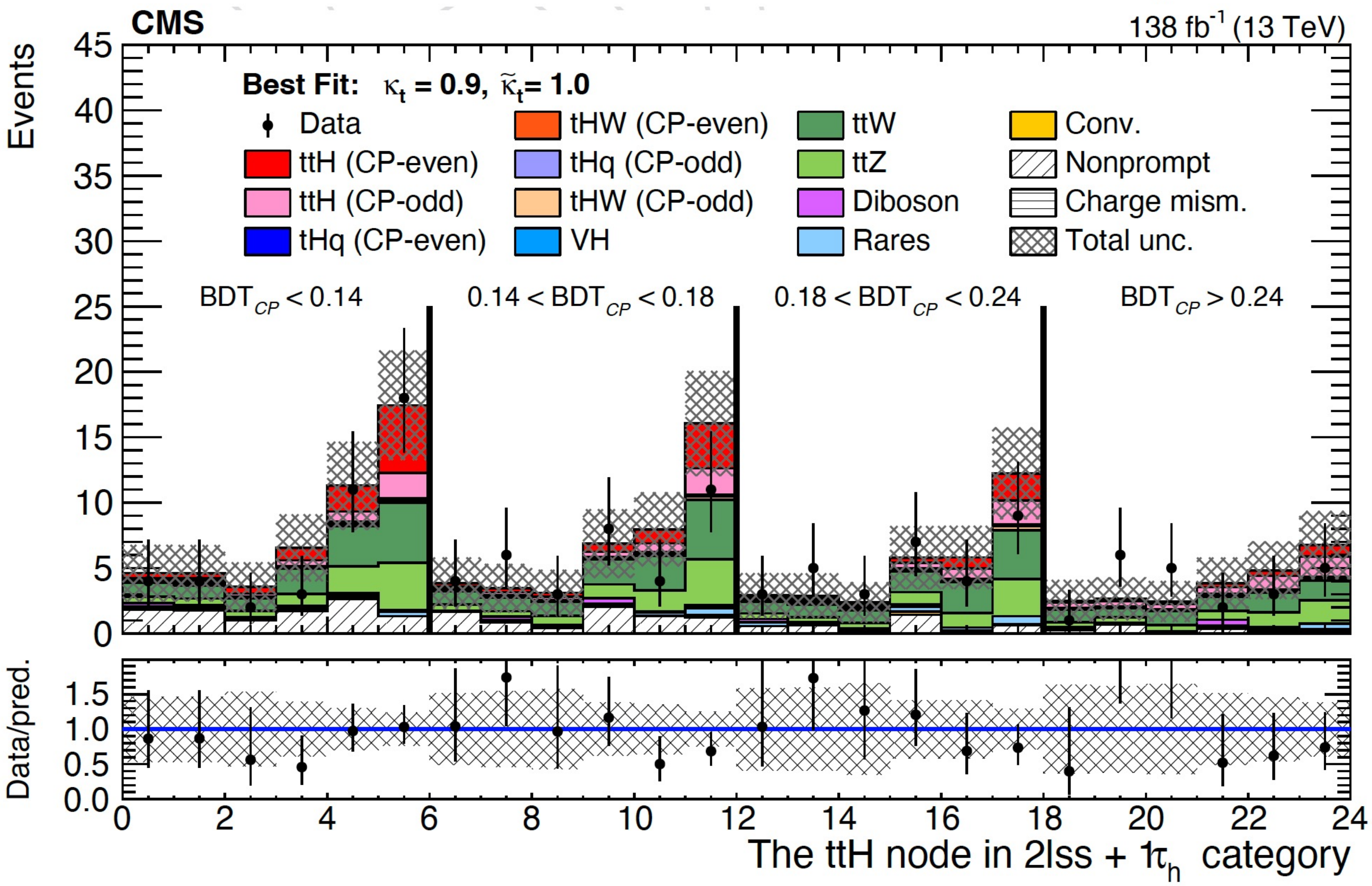
"Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s}$ = 13 TeV"

ttH & tH | Htt (Higgs coupling to fermions)

Channels: HWW/H$\tau\tau$

Productions: ttH & tH



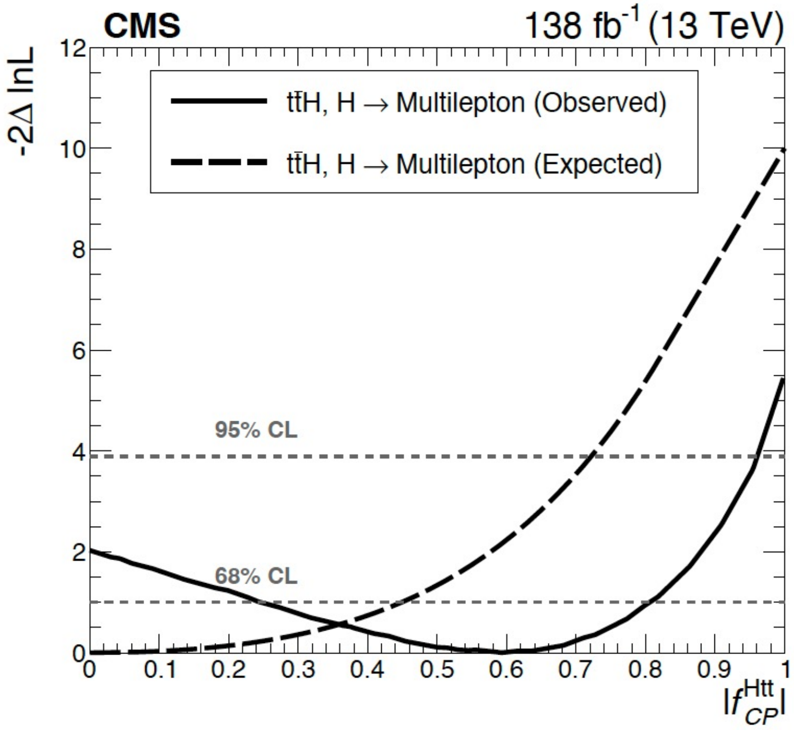
Machine learning techniques:

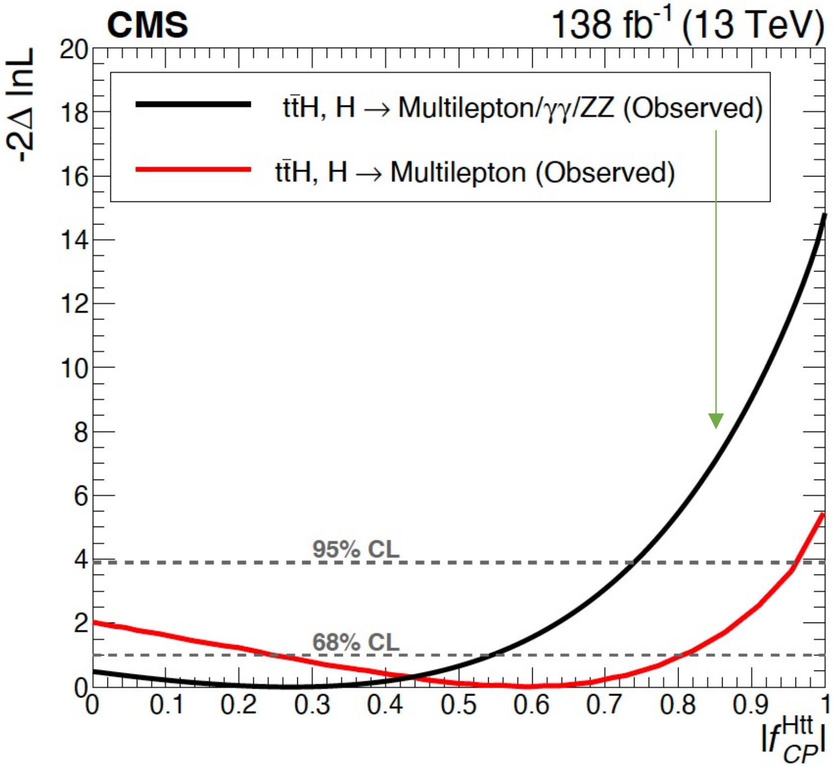
- BDT → m_{ttH} , ΔR_{jj} , $\Delta\eta$

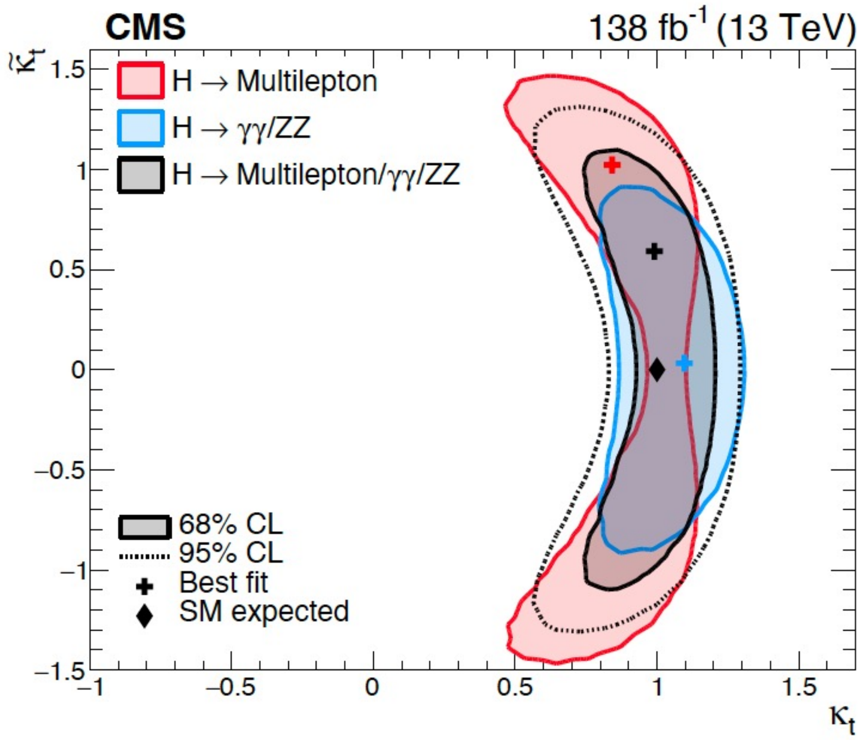
Events with less than 2-btagged jets

ttH & tH Results | Htt

$\left|f_{CP}^{Htt}\right|$= 0 (SM expectation)







$\left|f_{CP}^{Htt}\right|$= 0.59 with an interval of (0.24, 0.81) at 68% CL

Combination: $\left|f_{CP}^{Htt}\right|$= 0.28 with an interval of $\left|f_{CP}^{Htt}\right|$ <0.55 at 68% CL

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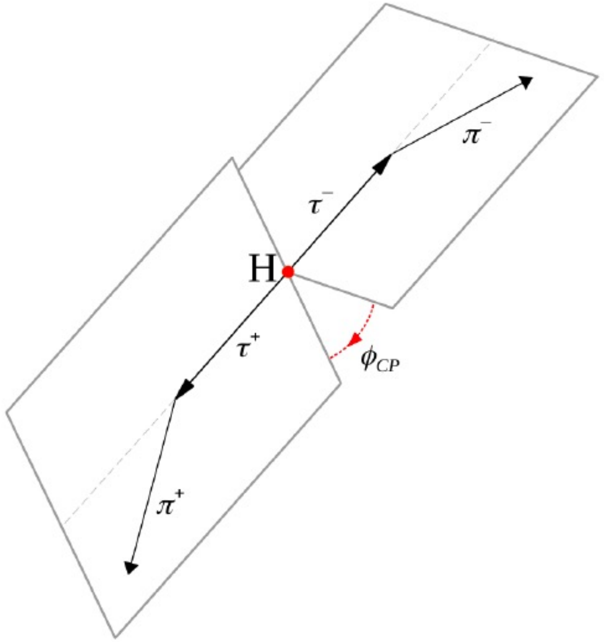
"Analysis of the CP structure of the Yukawa coupling between the Higgs boson and t leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV"

Higgs coupling to tau leptons

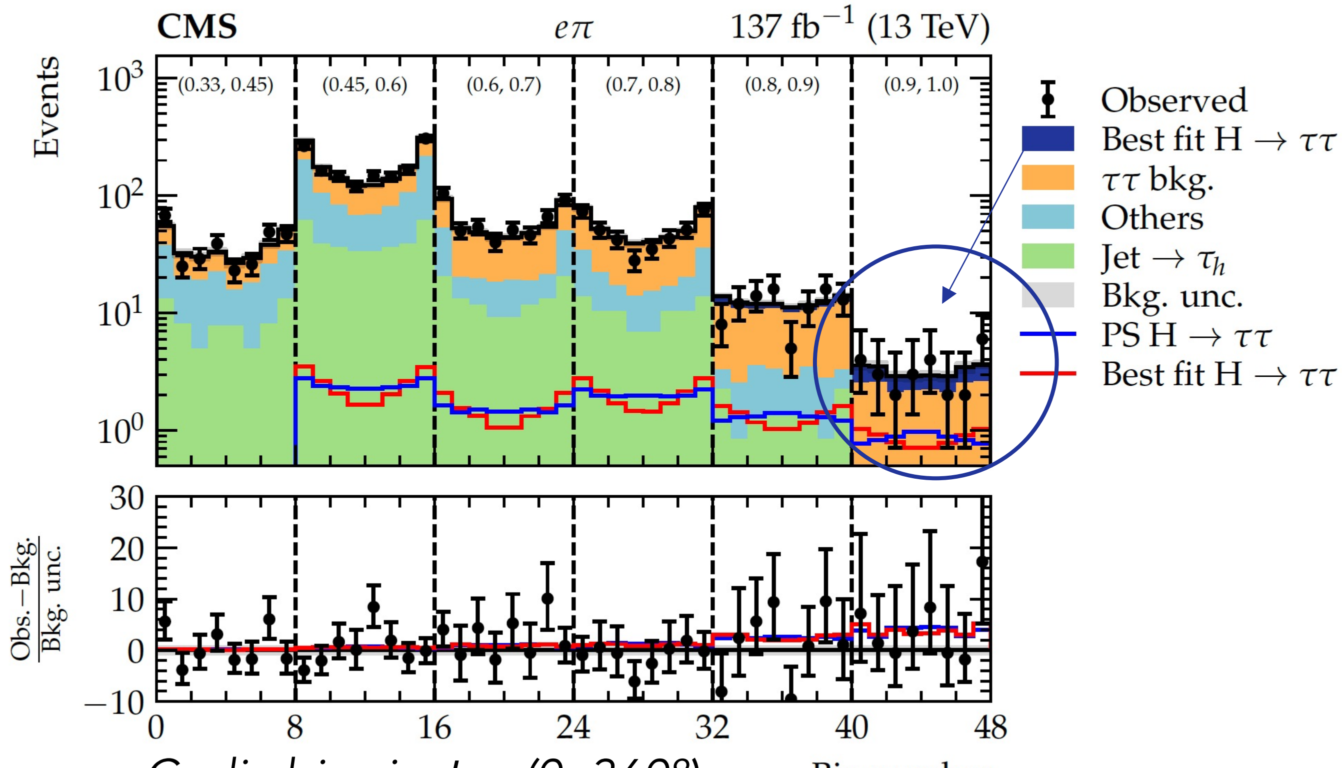
Channels: $\tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$

Productions: ggH, VBF, VH



Angular correlation between the decay planes of τ leptons

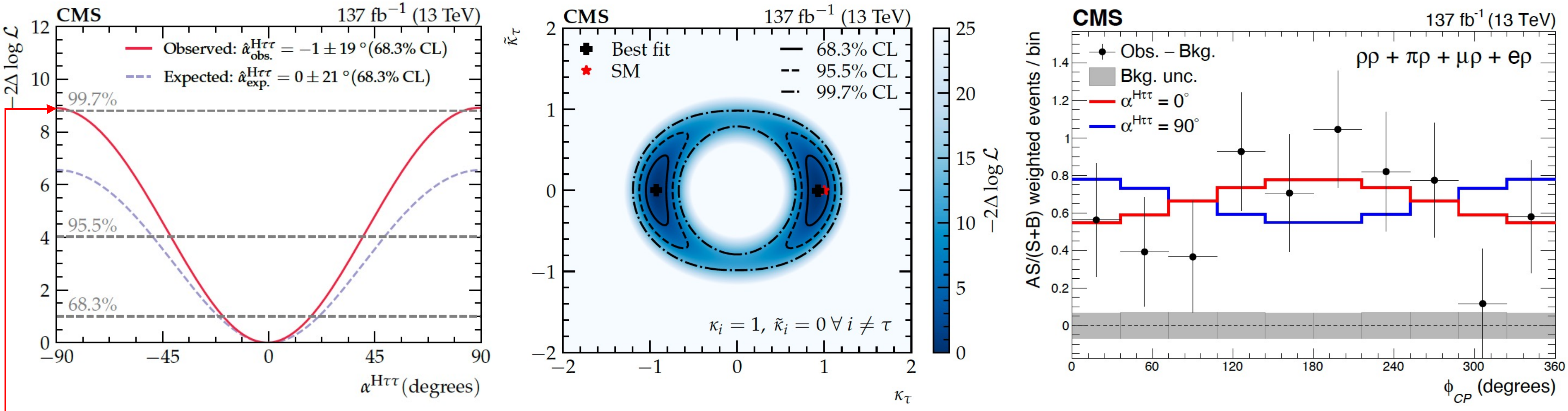
- MVA scores
- *ϕ_{CP} distributions*



Cyclic bins in ϕ_{CP} (0, 360°)

Higgs coupling to tau leptons

$$\alpha^{Hff} = \tan^{-1}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$



The data disfavour the pure CP-odd scenario at 3.0σ

Observed (expected) $\alpha^{H\tau\tau}$ = -1±19 (0±21) at the 68.3% CL

Conclusions

- J^{CP} studies in Higgs couplings to both fermions and bosons are important to determine its nature.
- The most stringent limits on CP violation and Higgs AC by the CMS experiment have been presented.

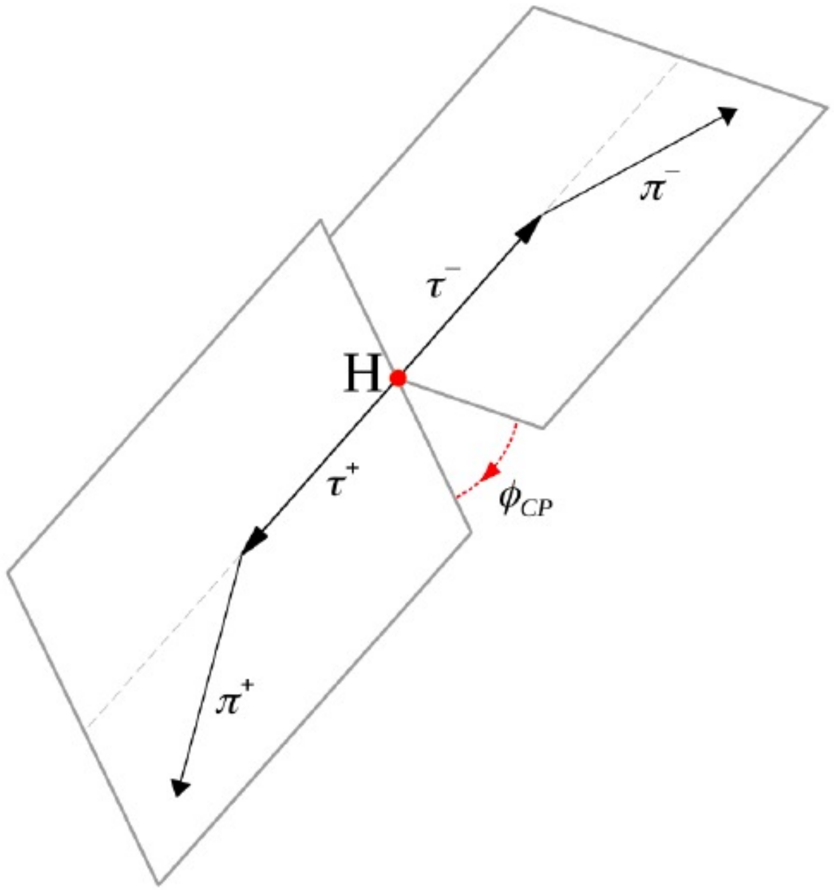
Growing field with many recent updates including new interpretations, and plenty more results to come in the future

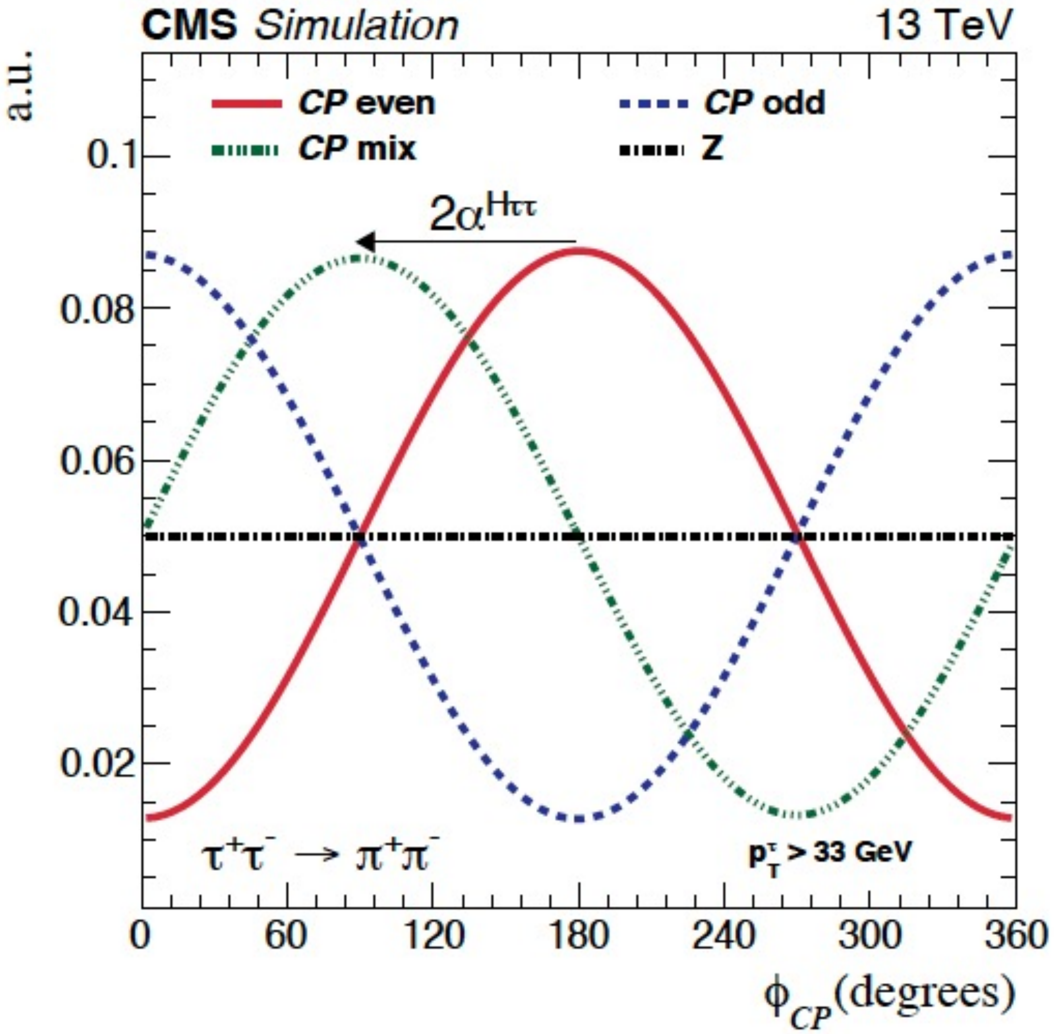
- The leading uncertainty is statistical → the precision will increase with the accumulation of more collision data.
- Additional Run 2 AC analyses are still to be released soon.

Back-up slides

Higgs AC to fermions | Mixing angle

κ_f and $\tilde{\kappa}_f$ are **Yukawa coupling strength modifiers** related to the mixing angle $\alpha^{Hff} = \tan^{-1}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$





Effective Field Theory |

Direct searches at the LHC find no new particles

Suggests an energy gap between SM and BSM motivating the use of EFT.

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \bar{c}_i^{(6)} \, \mathcal{O}_i^{(6)}$$

$\mathcal{O}_\mathrm{i}^{(5)}$ → violate lepton number
$\mathcal{O}_\mathrm{i}^{(7)}$ → violate lepton or baryon number
$\mathcal{O}_\mathrm{i}^{(8)}$ → Suppressed by $1/\Lambda^4$ → Typically neglected

Particles with m << Λ → Operators ($\mathcal{O}_i$) obey SM symmetries.

Effects of new physics mapped onto $\mathcal{O}_i^{(6)}$ → contribution scale as $(E/\Lambda)^2$

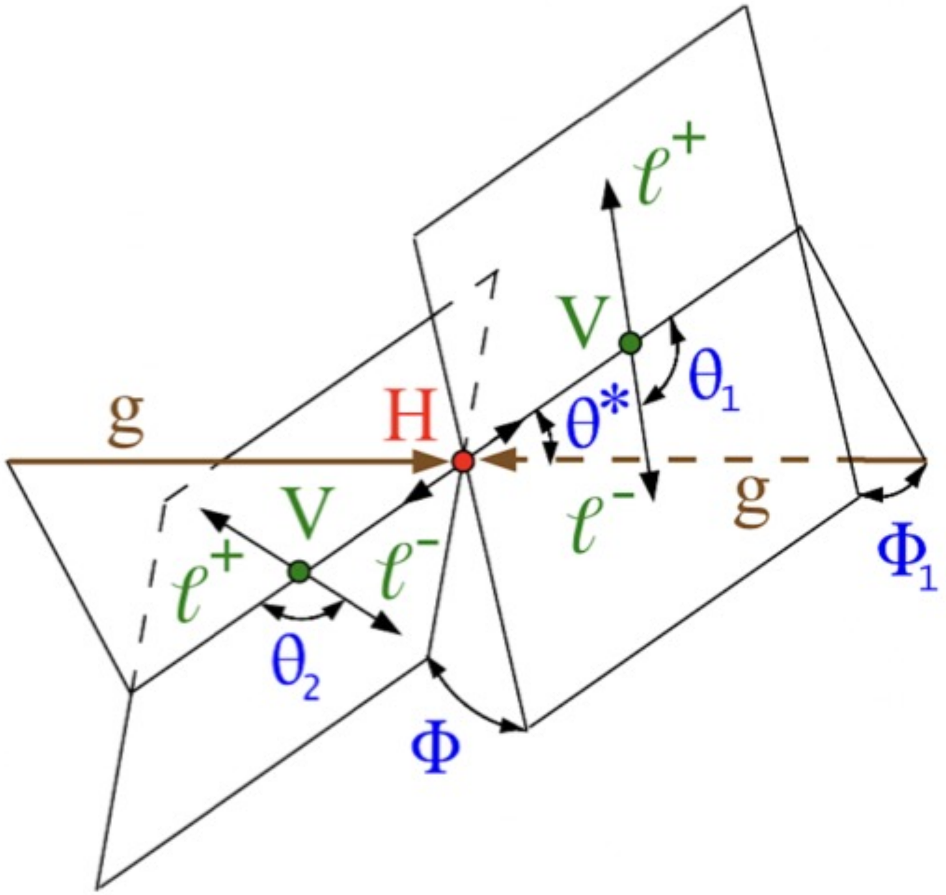
$\bar{c}_i^{(6)}$ (Wilson coefficient) → strength of the new interactions

EFT only valid at E < Λ

Measurement of Higgs couplings |

<u>Dedicated measurements (detector-level)</u>

Dedicated discriminants and full simulation of Signal PDFs.

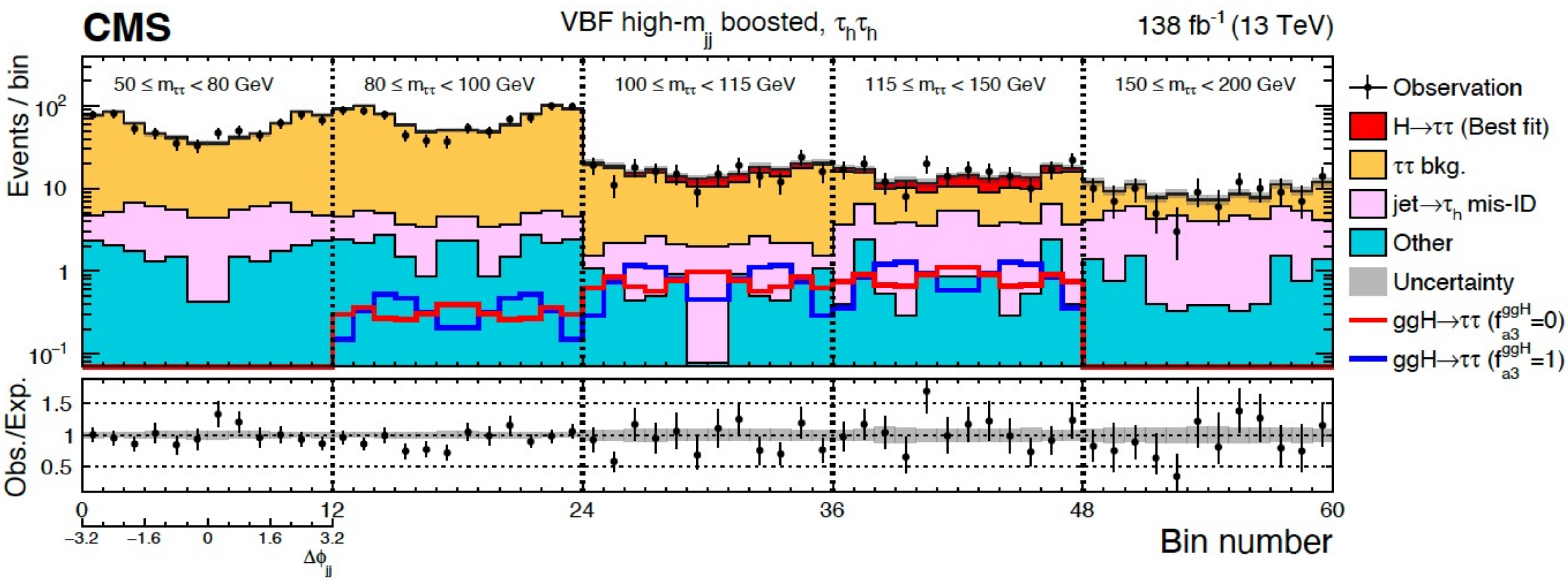


Exploit full production and decay kinematic information with ME or ML-based discriminants.

<u>Sensitive to higher dimensional operators in the EFT</u>

✓ Can target production mode, Higgs coupling and interference.

H→ττ analysis | Discriminants



$H \to \tau\tau$ analysis | Constraints

Approach	Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
Approach 1	f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$
	f_{a2}	$0.7^{+0.8}_{-0.6}$	$[-1.0, 2.5]$	$0.0^{+0.5}_{-0.4}$	$[-1.1, 1.2]$
	$f_{\Lambda 1}$	$-0.04^{+0.04}_{-0.08}$	$[-0.22, 0.16]$	$0.00^{+0.11}_{-0.04}$	$[-0.11, 0.38]$
	$f_{\Lambda 1}^{Z\gamma}$	$0.7^{+1.6}_{-1.3}$	$[-2.7, 4.1]$	$0.0^{+1.0}_{-1.0}$	$[-2.6, 2.5]$
Approach 2	f_{a3}	$0.28^{+0.39}_{-0.23}$	$[-0.01, 1.28]$	0.00 ± 0.08	$[-0.30, 0.30]$

Parameter	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
f_{a3}^{ggH}	$0.07^{+0.32}_{-0.07}$	$[-0.15, 0.89]$	0.00 ± 0.26	—
f_{CP}^{Htt}	$0.03^{+0.17}_{-0.03}$	$[-0.07, 0.51]$	0.00 ± 0.12	$[-0.49, 0.49]$

Parameter	Scenario		68% CL / (10^{-2})	95% CL / (10^{-2})
c_{gg}	Profiled	Observed	$-0.11^{+0.20}_{-0.26} \cup [-1.85, -1.42]$	$[-2.12, -1.35] \cup [-0.71, 0.36]$
		Expected	$0.00^{+0.18}_{-0.27} \cup [-1.91, -1.48]$	$[-2.23, 0.37]$
$\tilde{c}_{gg}$	Profiled	Observed	0.00 ± 1.29	$[-1.79, 1.79]$
		Expected	0.00 ± 1.15	$[-1.78, 1.78]$
c_{gg}	Fixed	Observed	$-0.08^{+0.07}_{-0.15} \cup [-1.65, -1.54]$	$[-1.71, -1.54] \cup [-0.59, 0.05]$
		Expected	$0.00^{+0.06}_{-0.14} \cup [-1.73, -1.50]$	$[-1.78, 0.12]$
$\tilde{c}_{gg}$	Fixed	Observed	$0.22^{+0.28}_{-0.22} \cup [-0.50, 0.00]$	$[-0.74, 0.75]$
		Expected	0.00 ± 0.45	$[-0.87, 0.87]$

Higgs AC to bosons | Lagrangian

$$A(HV_1V_2) = \frac{1}{v}\left\{M_{V_1}^2\left(g_1^{VV} + \frac{\kappa_1^{VV}q_1^2 + \kappa_2^{VV}q_2^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{(\Lambda_Q^{VV})^2} + \frac{2q_1\cdot q_2}{M_{V_1}^2}g_2^{VV}\right)(\varepsilon_1\cdot\varepsilon_2) - 2g_2^{VV}(\varepsilon_1\cdot q_2)(\varepsilon_2\cdot q_1) - 2g_4^{VV}\varepsilon_{\varepsilon_1\varepsilon_2 q_1 q_2}\right\},$$

"The parametrization of the amplitude can be related to a fundamental Lagrange density function using the Higgs basis which is based on an effective field theory expansión up to dimension six. The relevant SU(3) X SU(2) X U(1) invariant Lagrangian for H boson interactions with gauge bosons"

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

Higgs AC to bosons | Lagrangian

$$A(HV_1V_2) = \frac{1}{v}\left\{M_{V_1}^2\left(g_1^{VV} + \frac{\kappa_1^{VV}q_1^2 + \kappa_2^{VV}q_2^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{(\Lambda_Q^{VV})^2} + \frac{2q_1\cdot q_2}{M_{V_1}^2}g_2^{VV}\right)(\varepsilon_1\cdot\varepsilon_2) - 2g_2^{VV}(\varepsilon_1\cdot q_2)(\varepsilon_2\cdot q_1) - 2g_4^{VV}\varepsilon_{\varepsilon_1\varepsilon_2 q_1 q_2}\right\},$$

"The generality of the amplitude parametrization allows to uniquely represent each EFT coefficient in the Lagrangian by an anomalous coupling limiting our couplings to real-valued numbers"

$$\delta c_z = \frac{1}{2}g_1^{ZZ} - 1, \quad c_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_2^{ZZ}, \quad c_{z\Box} = \frac{M_Z^2 s_w^2}{e^2}\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, \quad \tilde{c}_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_4^{ZZ},$$

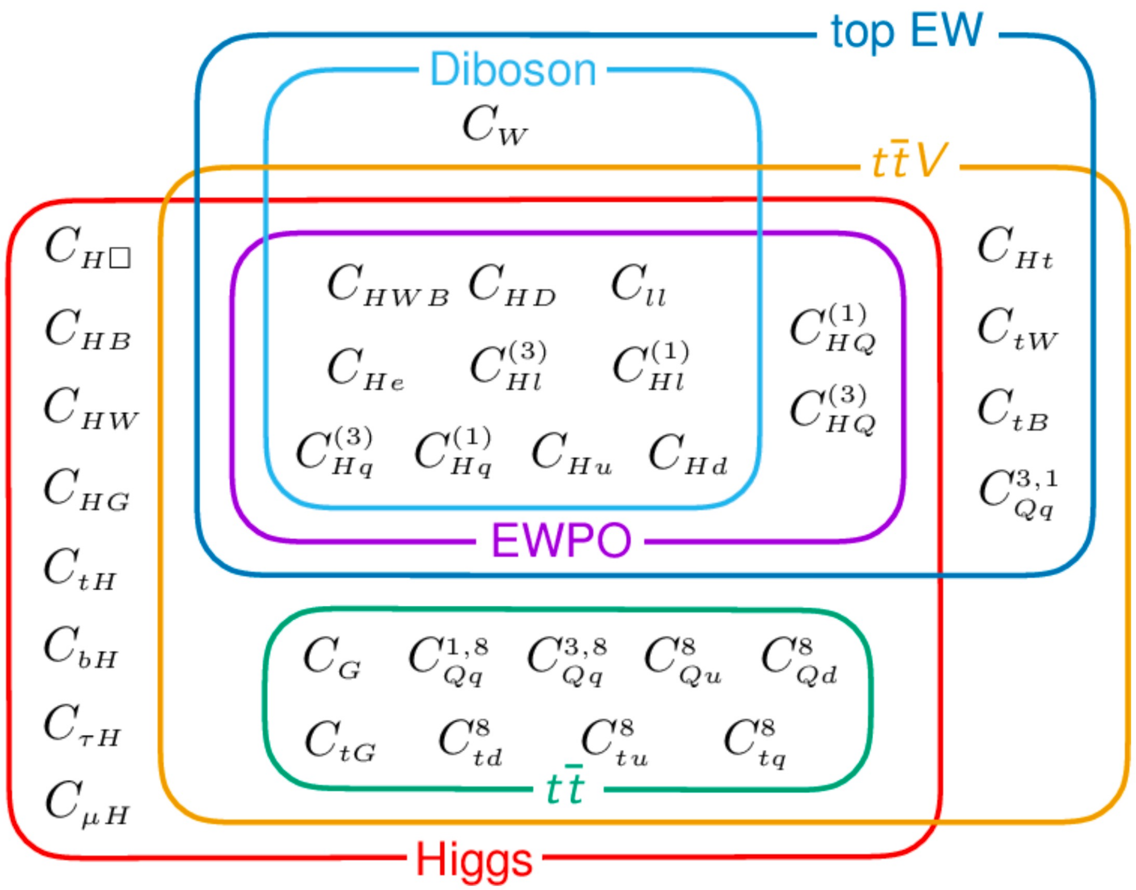
$$\delta c_w = \frac{1}{2}g_1^{WW} - 1, \quad c_{ww} = -\frac{2s_w^2}{e^2}g_2^{WW}, \quad c_{w\Box} = \frac{M_W^2 s_w^2}{e^2}\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}, \quad \tilde{c}_{ww} = -\frac{2s_w^2}{e^2}g_4^{WW},$$

$$c_{z\gamma} = -\frac{2s_wc_w}{e^2}g_2^{Z\gamma}, \quad \tilde{c}_{z\gamma} = -\frac{2s_wc_w}{e^2}g_4^{Z\gamma}, \quad c_{\gamma\Box} = \frac{s_wc_w}{e^2}\frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2}\kappa_2^{Z\gamma},$$

$$c_{\gamma\gamma} = -\frac{2}{e^2}g_2^{\gamma\gamma}, \quad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2}g_4^{\gamma\gamma}, \quad c_{gg} = -\frac{2}{g_s^2}g_2^{gg}, \quad \tilde{c}_{gg} = -\frac{2}{g_s^2}g_4^{gg}.$$

Basis of dimension 6 operators

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \bar{c}_i^{(6)}\, \mathcal{O}_i^{(6)}$$



<u>Warsaw basis</u>

Popular SMEFT basis in the theoretical community

<u>Higgs basis</u>

Experimentally convenient to express EFT in terms of mass eigenstates after EWSB

Related to Warsaw basis through linear transformations

H→ZZ Results | HVV (SMEFT approach – Warsaw basis)

HVV parametrization can be related to the

EFT couplings using the **Warsaw basis.**

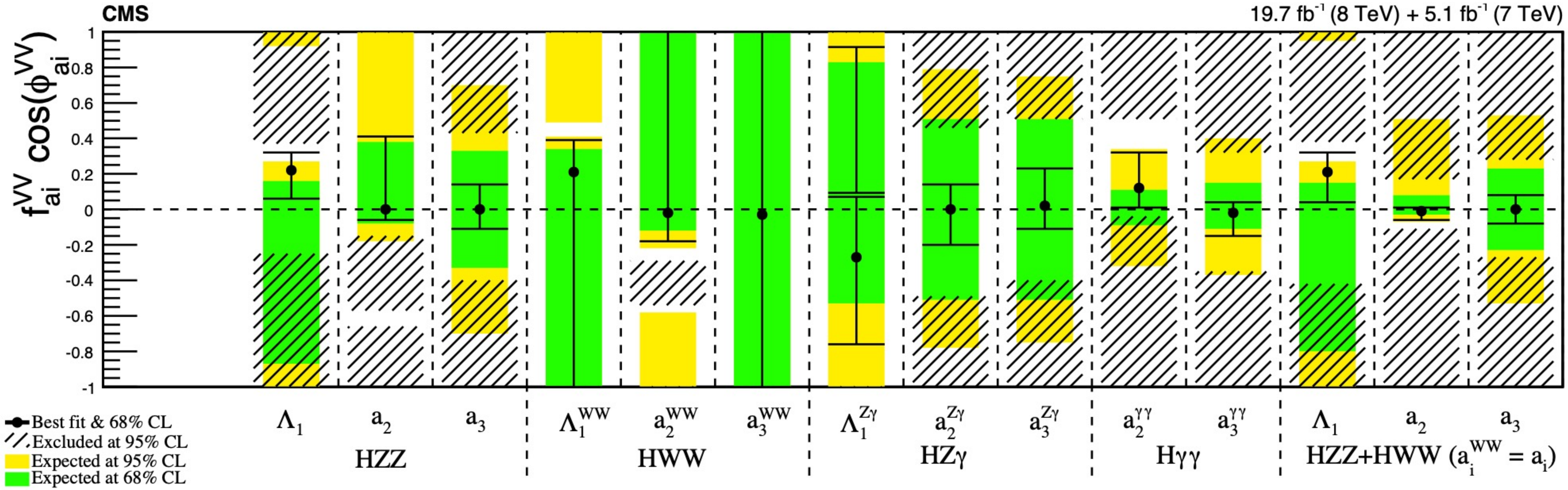
TABLE IX. Summary of constraints on the HVV coupling parameters in the Warsaw basis of SMEFT. For each coupling constraint reported, three other independent operators are left unconstrained, where only one of the three operators c_{HW}, $c_{HW\mathrm{B}}$, and $c_{H\mathrm{B}}$ is independent, and only one of $c_{H\tilde{W}}$, $c_{H\tilde{W}\mathrm{B}}$, and $c_{H\tilde{\mathrm{B}}}$ is independent.

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

CMS analysis from Run 1

LHC Run 1 → Couplings to EW bosons

"Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV"



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

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