SMEFT results in Higgs sector from CMS experiment

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HEPHY Vienna

02/09/2021

ÖPG-SPS Meeting 2021
Innsbruck, Austria

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Higgs in SMEFT

- Introduction to effective field theory (EFT) already covered in previous talks
- Can Higgs measurements bring anything new?

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Gupta, Pomarol, Riva (2014)

$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$
$\mathcal{L}_6^{(3)} - H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$

$\mathcal{L}_6^{(4)} - X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^{I\mu\nu}$
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$\mathcal{L}_6^{(5)} - \psi^2 H^3$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

Brivio (2020)

Operators written in Warsaw basis [Grzadkowski et al. (2010)]

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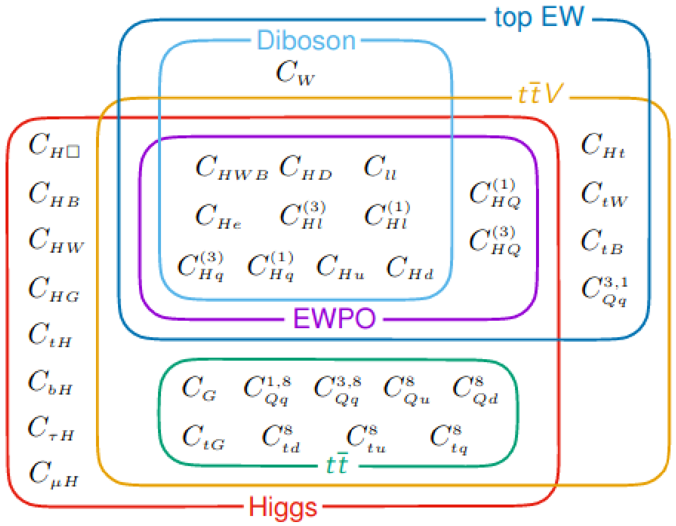
Synergy with top & electroweak measurements strengthens pinning down other operators too (& symmetry assumptions)



Ellis et al. (2020)

Pathways to probe EFT operators

Reinterpretation of existing measurements

- Use unfolded/detector-level distributions of observables in SM measurements
- Parameterize σ in terms of Wilson coefficients (WCs)
- Extract bounds on WC

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Dedicated EFT measurements

- Identify processes sensitive to particular set of WCs
- Simulate events with EFT hypotheses
- Perform direct measurements in terms of WC

Pathways to probe EFT operators

Reinterpretation of existing measurements

- 😁 Easy to combine different measurements
- ☹ Doesn't take into account acceptance effects due to EFT operators
- ☹ Observables already fixed → May miss subtle EFT effects

CMS-PAS-HIG-19-005

Dedicated EFT measurements

- 😁 Can design object & event selection conditions depending on EFT operators
- 😁 Construct dedicated observables sensitive to particular operators
- ☹ Can be non-trivial to combine with other measurements

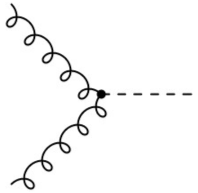
arXiv: 2104.12152

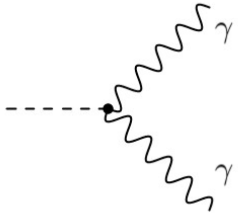
(Accepted by PRD for publication)

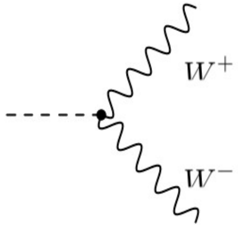
Combined measurement of Higgs properties

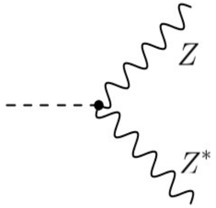
CMS-PAS-HIG-19-005

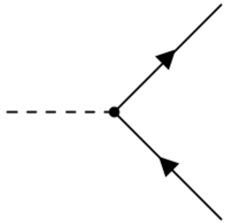
Input data for EFT analysis











Analysis	Decay tags	Production tags	Luminosity (fb^{-1})
$H \to \gamma\gamma$	$\gamma\gamma$	ggH, $p_T(H) \times$ N-jet bins	77.4
		VBF, $p_T(H\,jj)$ bins	
		ttH	35.9, 41.5
$H \to ZZ^{(*)} \to 4\ell$	4μ, $2e2\mu/2\mu 2e$, 4e	ggH, $p_T(H) \times$ N-jet bins	137
		VBF, m_{jj} bins	
		VH hadronic	
		VH leptonic, $p_T(V)$ bins	
		ttH	
$H \to WW^{(*)} \to \ell\nu\ell\nu$	$e\mu/\mu e$	ggH $\leq$ 2-jets	35.9
		VBF	
	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	77.4
		VH hadronic	
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		VH, high-$p_T(V)$	35.9
$H \to bb$	$W(\ell\nu)H(bb)$	WH leptonic	35.9, 41.5
	$Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$	ZH leptonic	
	bb	ttH, $t\bar{t} \to 0, 1, 2\ell +$ jets	77.4
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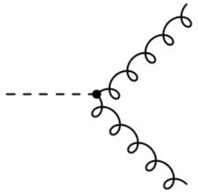
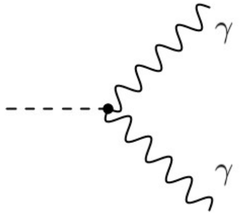
Higgs effective Lagrangian (HEL)

$$\mathcal{O}_g = (H^\dagger H) G^a_{\mu\nu} G^{a\mu\nu}$$



$$\mathcal{O}_\gamma = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$



$$\mathcal{O}_{HW} = i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

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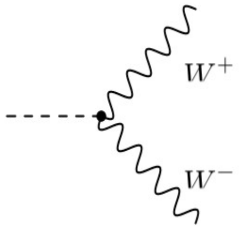
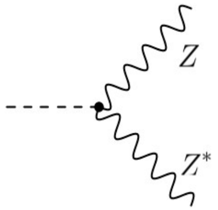
$$\mathcal{O}_W = i(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = i(H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$$





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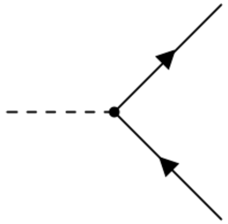

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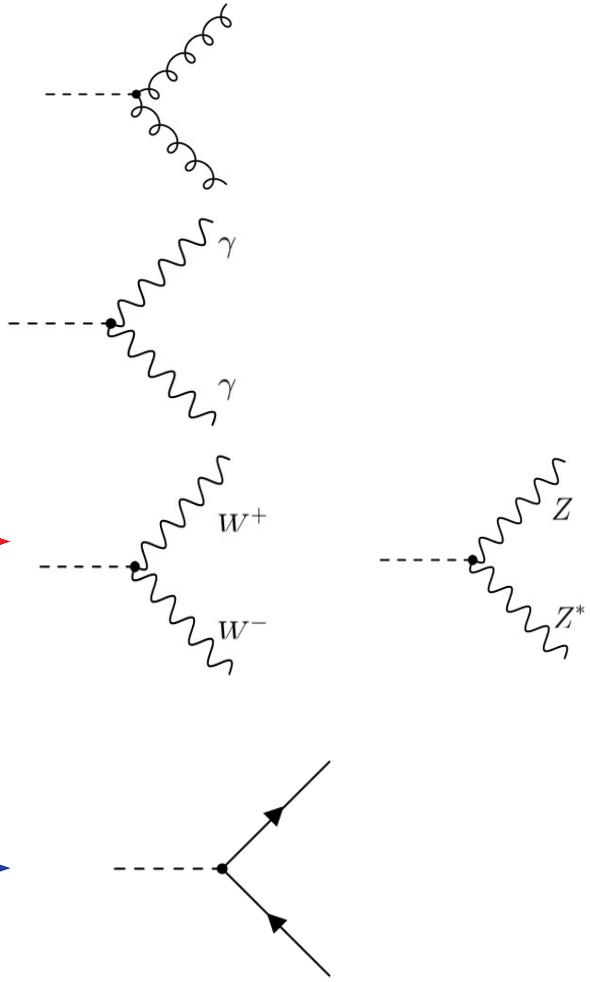

HEL Parameters	Definition
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2} \frac{f_A}{\Lambda^2}$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2} \frac{f_G}{\Lambda^2}$
$c_u \times 10$	$c_u = -v^2 \frac{f_u}{\Lambda^2}$
$c_d \times 10$	$c_d = -v^2 \frac{f_d}{\Lambda^2}$
$c_\ell \times 10$	$c_\ell = -v^2 \frac{f_\ell}{\Lambda^2}$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g} \frac{f_{HW}}{\Lambda^2}$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g} \frac{f_{WW}}{\Lambda^2}, c_B = \frac{2m_W^2}{g'} \frac{f_B}{\Lambda^2}$

f ← Wilson coefficient

Alloul, Fuks, Sanz (2013)

$(c_{WW} + c_B)$ ← constrained to 0 by EWPD

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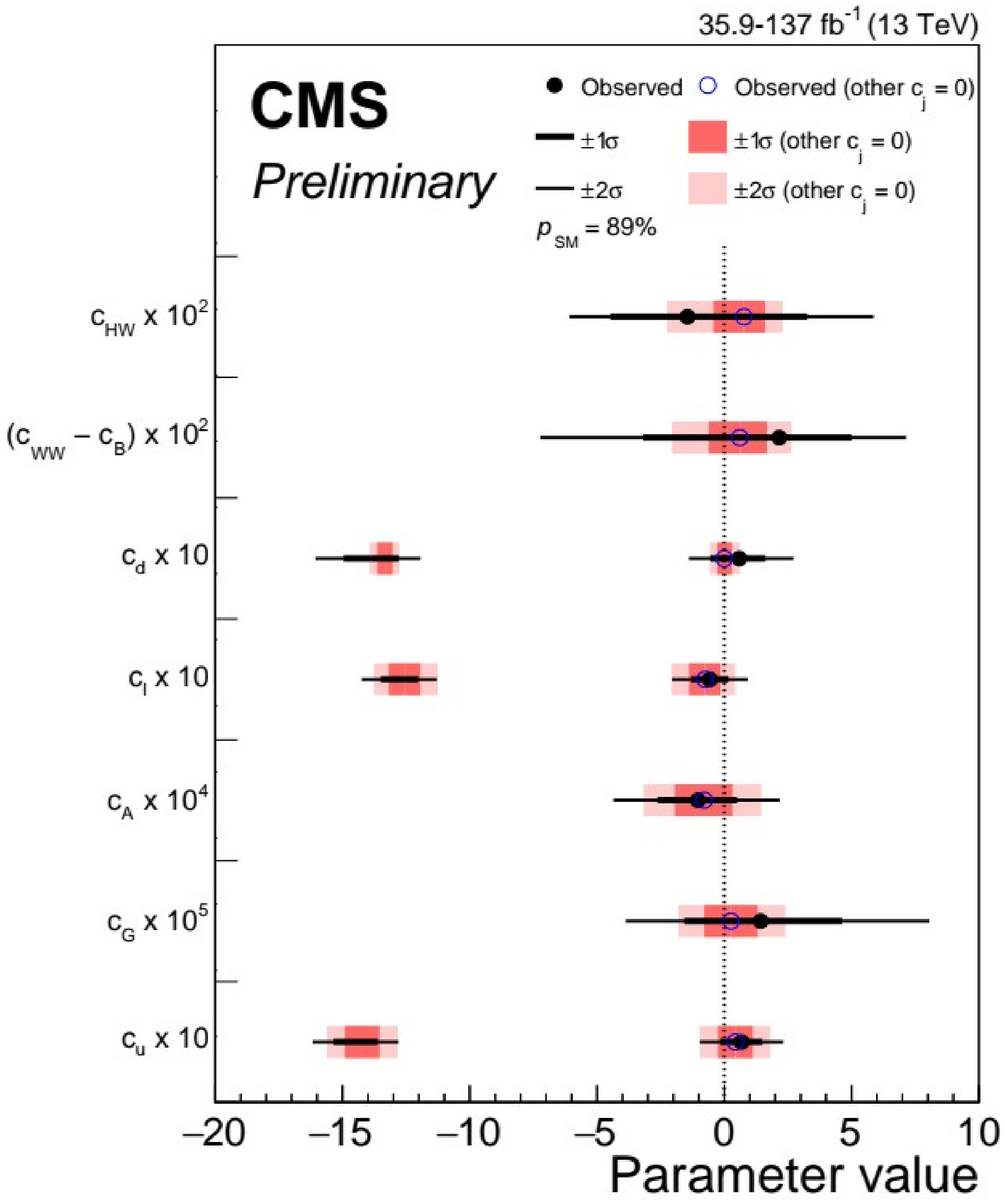
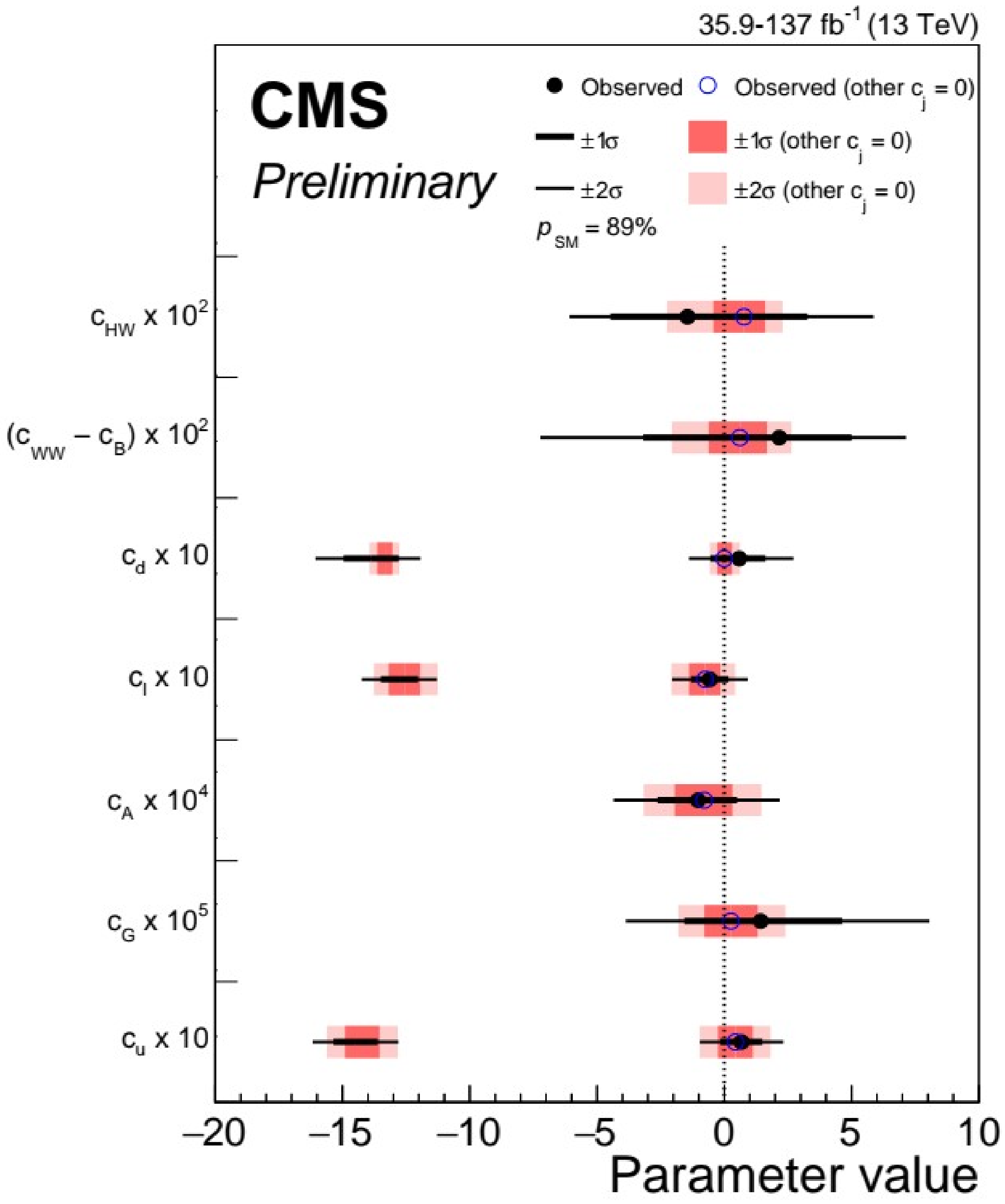


Two bounds reported for each WC:

1. Putting all other WCs to 0 → generally results to stronger bound
2. Profiling other WCs → gives a sense of correlation between operators

Combined measurement of Higgs properties



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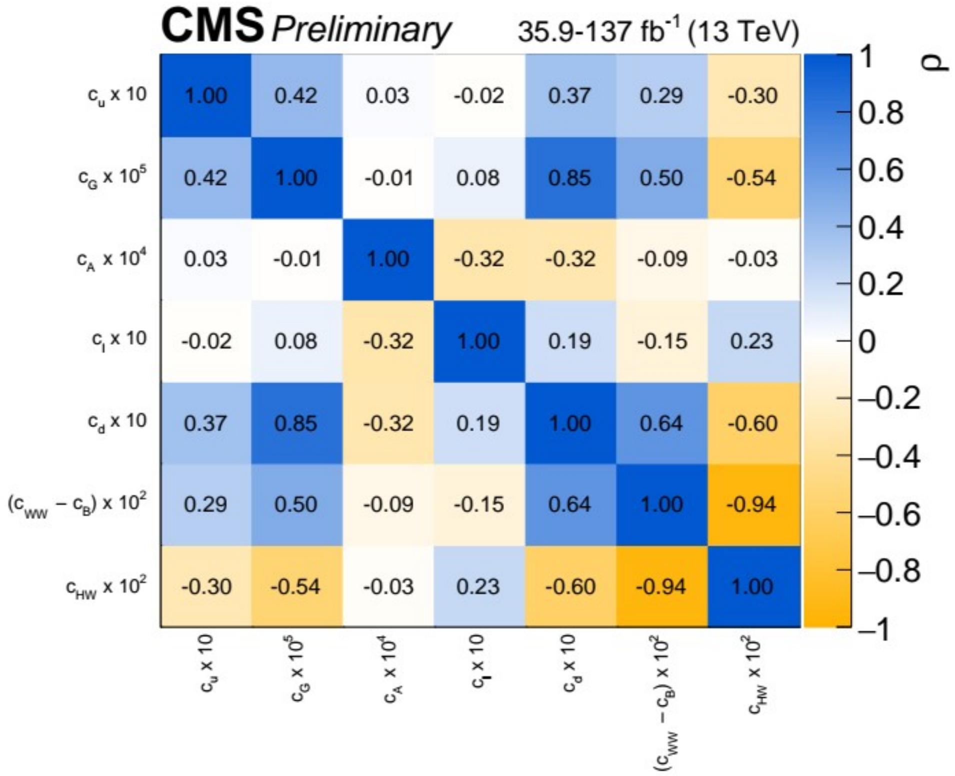


Large correlation between operators affecting H-V coupling

Significant correlation between c_G and many other WCs

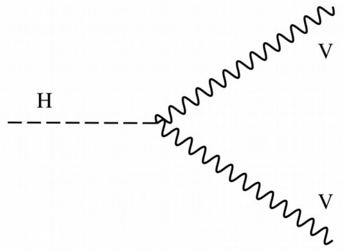
(increase in rate due to production and decay width can not be separated)

Anomalous couplings in H→ 4 leptons

arXiv: 2104.12152

Probing

4 HZZ couplings (HWW couplings related by symmetry)
2 Hgg couplings (1 CP-even + 1 CP-odd)
2 Htt couplings (1 CP-even + 1 CP-odd)



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

$$f^{(i)\mu\nu} = \epsilon_{\mathrm{V}i}^{\mu} q_{\mathrm{V}i}^{\nu} - \epsilon_{\mathrm{V}i}^{\nu} q_{\mathrm{V}i}^{\mu}, \quad \tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i),\rho\sigma}$$

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

SM: $a_1^{WW} = a_1^{ZZ} = 2$, $\kappa_f = 1$, others 0

Anomalous couplings in H→ 4 leptons

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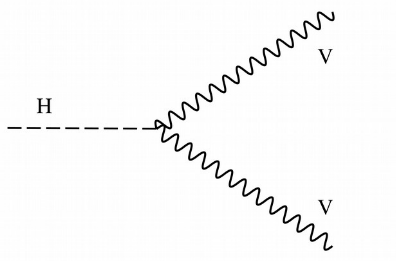

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$a_1^{\gamma\gamma} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = 0$

$\kappa_1^{ZZ} = \kappa_2^{ZZ}$

$\kappa_1^{WW} = \kappa_2^{WW}$

$\kappa_3^{\gamma\gamma} = 0$

Requirements of Gauge invariance

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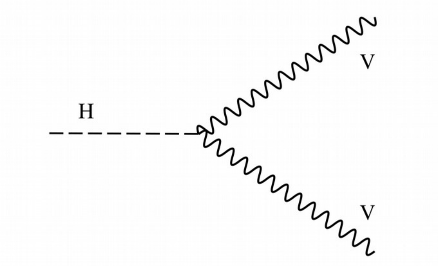

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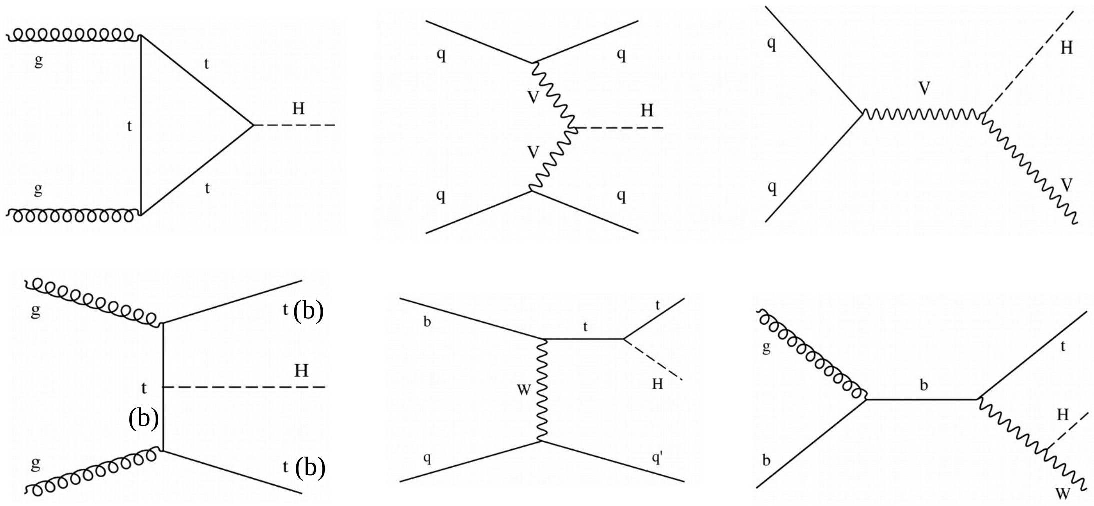
Production mechanisms included:



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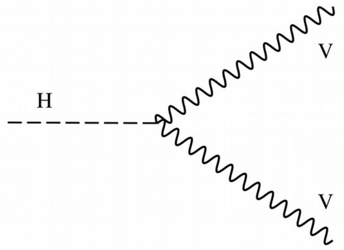

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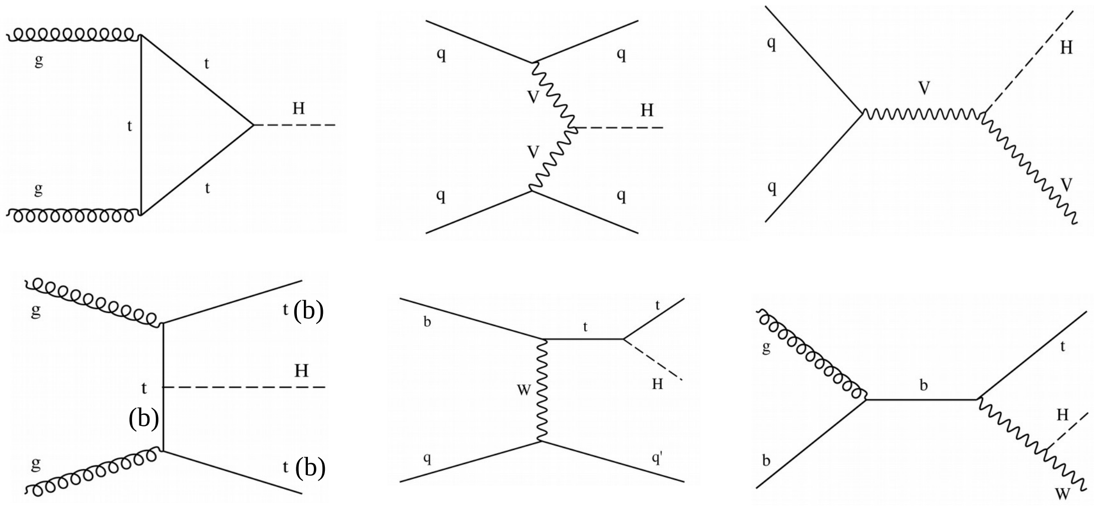
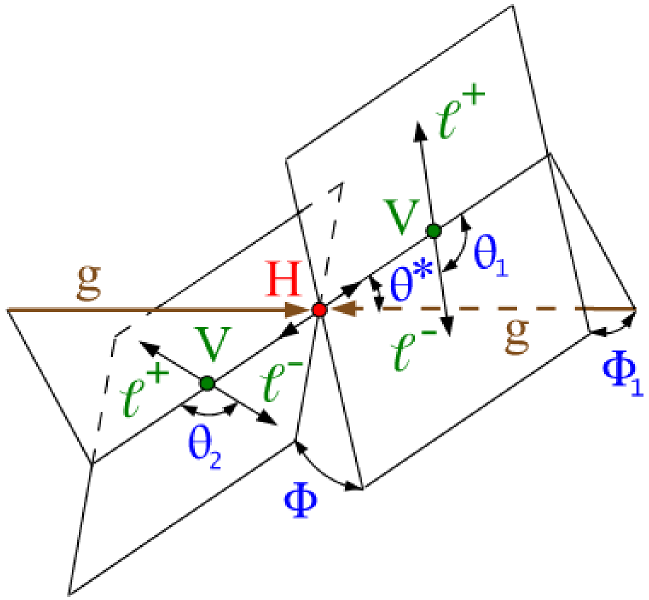


Method

Matrix element likelihood estimator (MELA) used to build discriminants sensitive to individual anomalous coupling including CP-sensitive observables

BDT used to separate CP-even & CP-odd Htt couplings

} Exploiting maximum information from event kinematics



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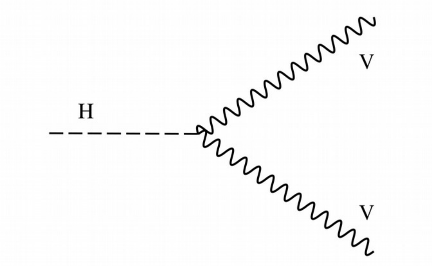
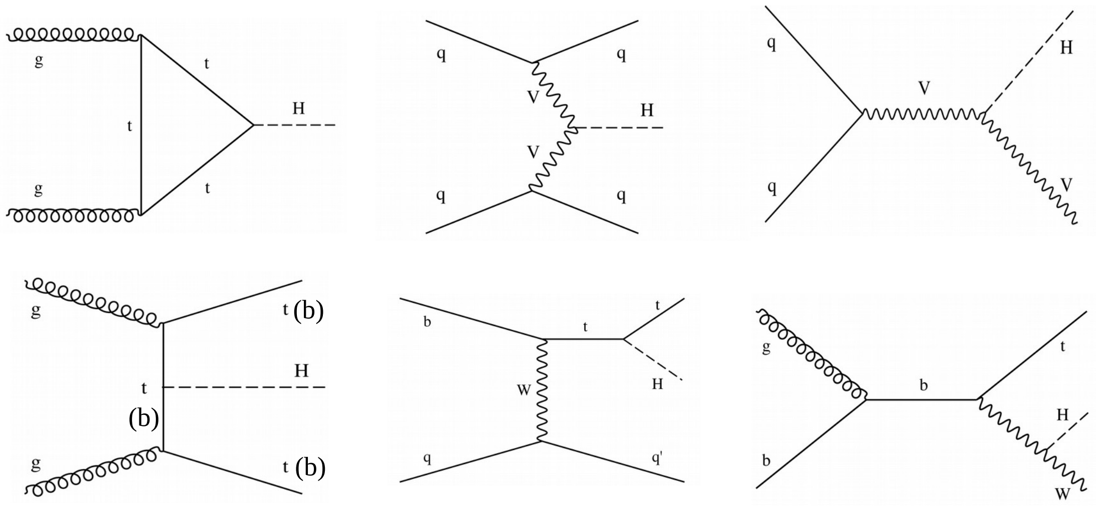


$$A(\mathrm{HV_1V_2}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right]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

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

SM: $a_1^{WW} = a_1^{ZZ} = 2$, $\kappa_f = 1$, others 0

Production mechanisms included:

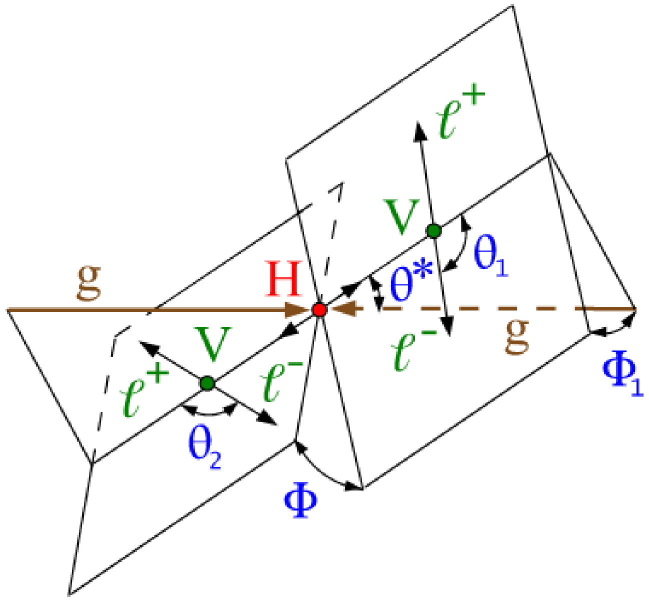


Method

Matrix element likelihood estimator (MELA) used to build discriminants sensitive to individual anomalous coupling including CP-sensitive observables

Exploiting maximum information from event kinematics

BDT used to separate CP-even & CP-odd Htt couplings



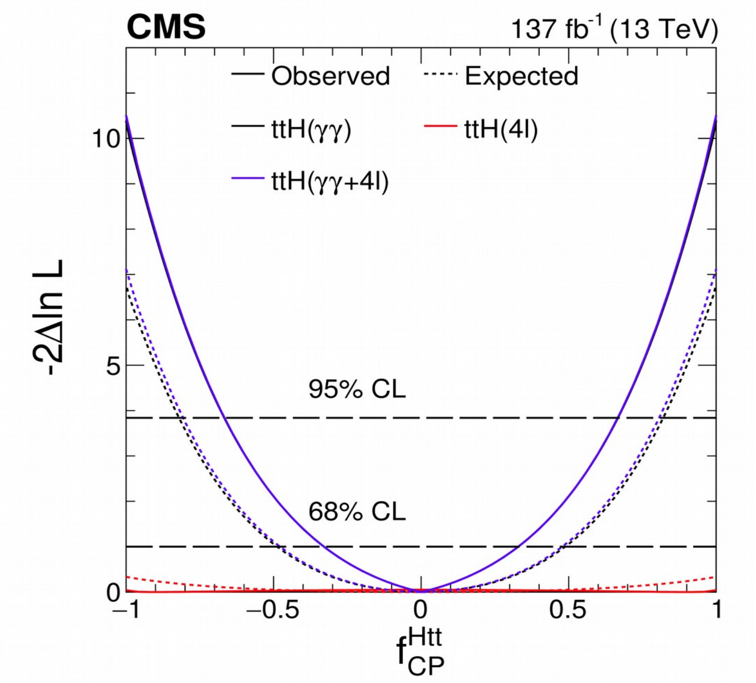
EFT Results

Reported in Higgs basis under SU(2)xU(1) symmetry → translated into Warsaw basis

Anomalous couplings in H$\rightarrow$ 4 leptons

arXiv: 2104.12152

Results from ttH+tH categories



H-t coupling

Sensitivity to fermionic couplings parameterized in terms of

σ/σ_{SM} & $f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} \text{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$

Results combined with ttH($\rightarrow \gamma\gamma$)

$\rightarrow$ Significant improvement in sensitivity

Anomalous couplings in H→ 4 leptons

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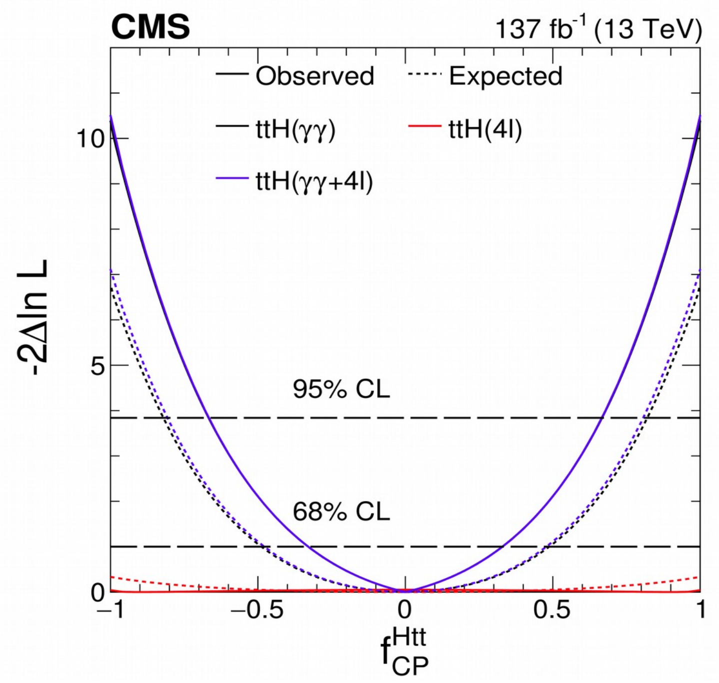

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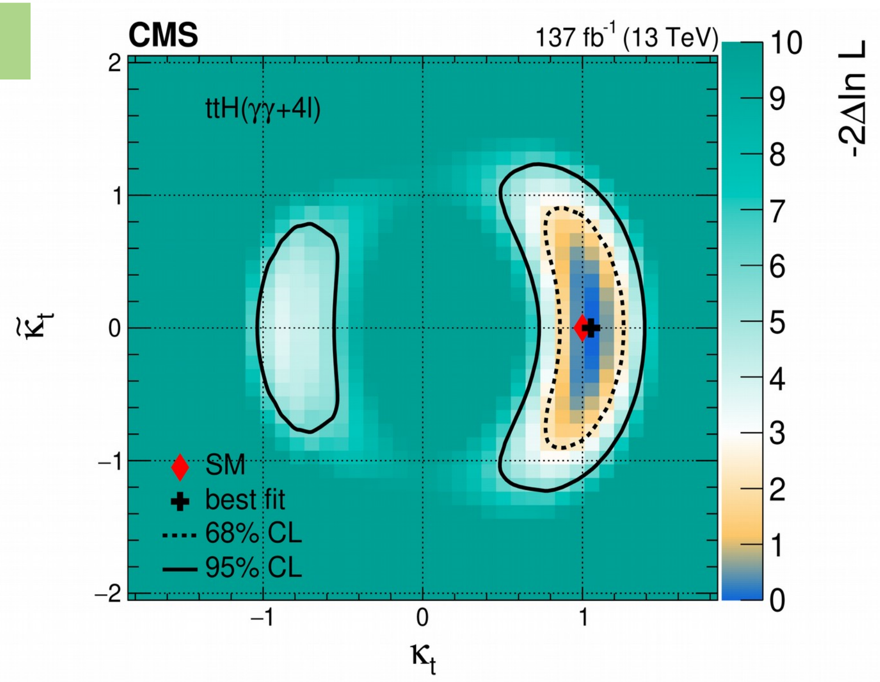


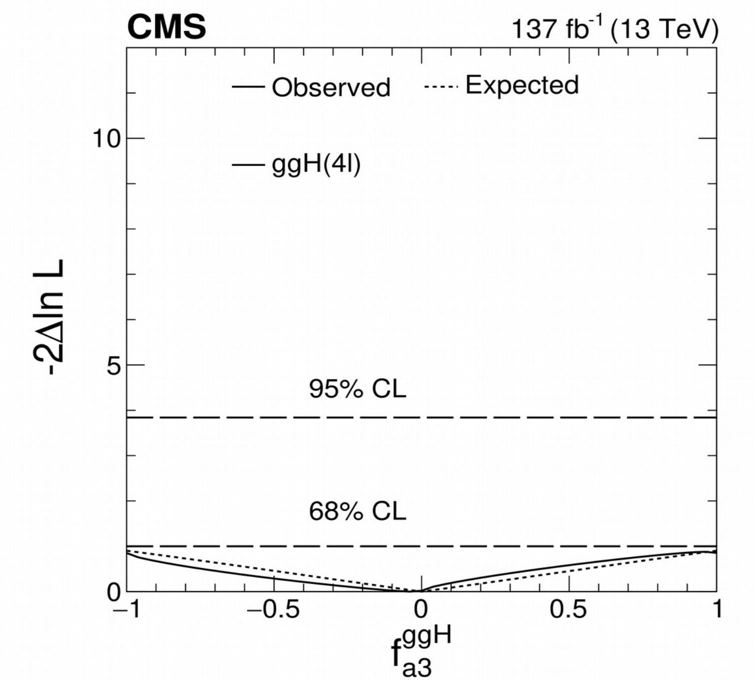
Data consistent with SM prediction

Measuring only yield ($\kappa_t^2 + \tilde{\kappa}_t^2$) produces a ring in 2-D scan of log-likelihood

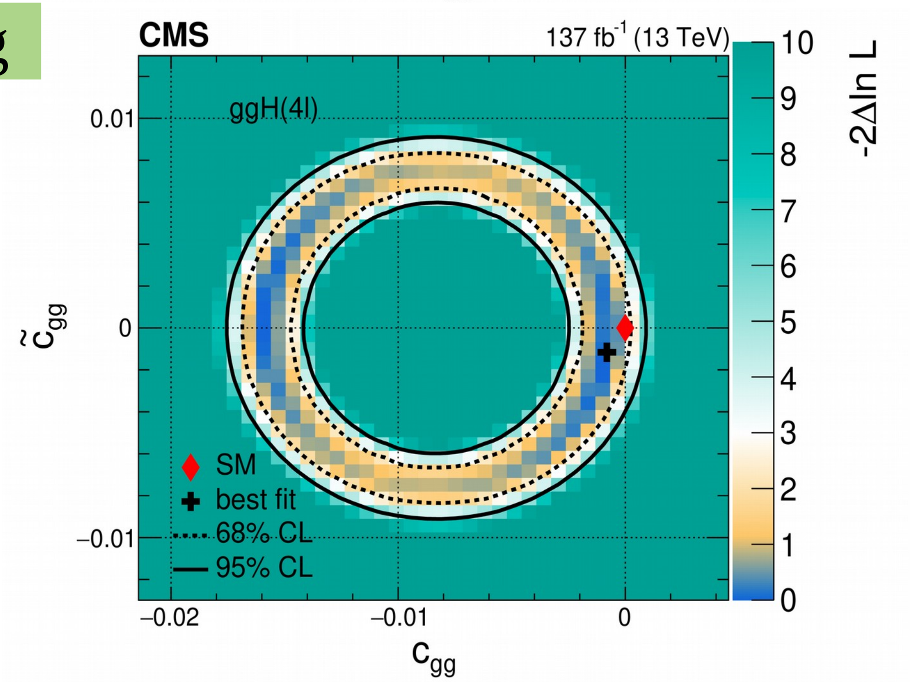
← CP-sensitive measurement resolves regions within ring

Anomalous couplings in H→ 4 leptons

arXiv: 2104.12152



H-g coupling



Sensitivity to bosonic couplings parameterized in terms of

σ/σ_{SM} &
$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \, \mathrm{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

Anomalous couplings expressed in terms of WC in Higgs basis

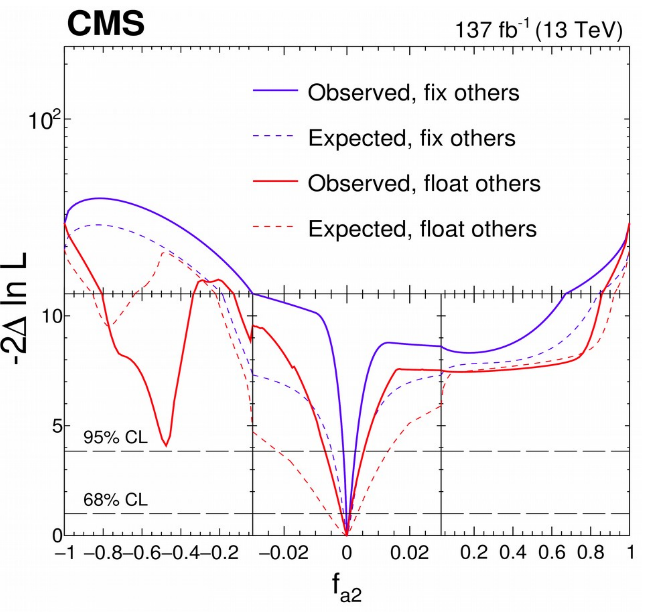
$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg},$$
$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$

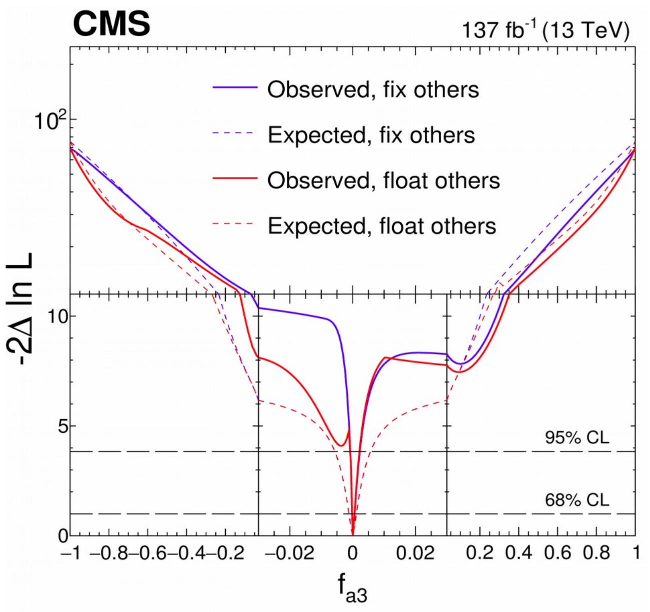
Data consistent with SM prediction

Small sensitivity worsens resolution within ring ☹

Anomalous couplings in H → 4 leptons

arXiv: 2104.12152





Sensitivity to bosonic couplings parameterized in terms of

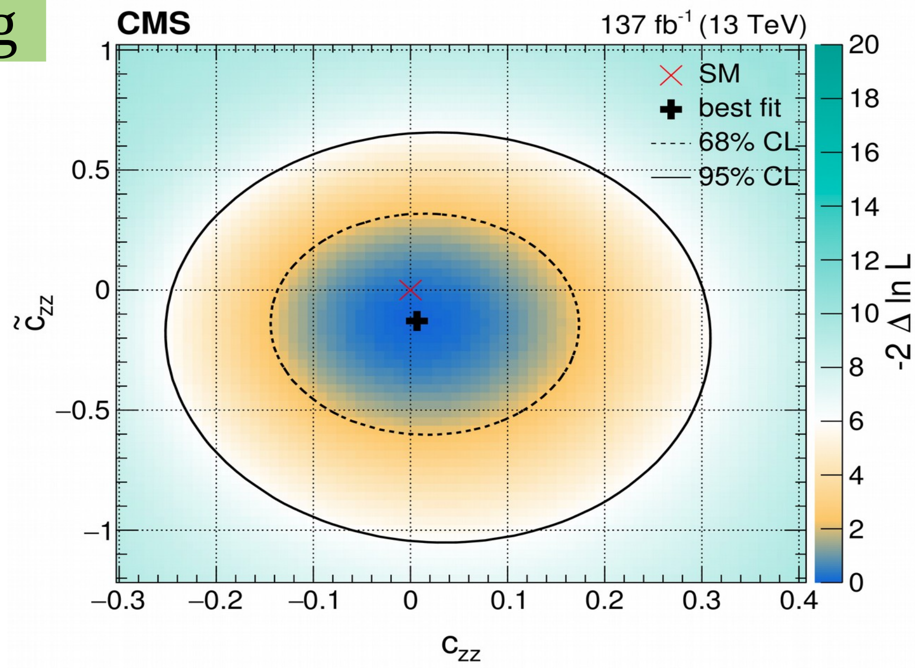
$$\sigma/\sigma_{SM} \quad \& \quad f_{ai}^{VV} = \frac{|a_i^{VV}|^2 \alpha_{ii}^{(2e2\mu)}}{\sum_j |a_j^{VV}|^2 \alpha_{jj}^{(2e2\mu)}} \operatorname{sign}\left(\frac{a_i^{VV}}{a_1}\right)$$

Anomalous couplings expressed in terms of WC in Higgs basis

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

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

H-Z coupling



Data consistent with SM prediction

Correlation with other WCs washes out the ring

Conclusion & Outlook

- Area of EFT measurements emerging as a new center of attention
- Increasing interest by both communities: theory & experiment
- Still a number of places to reach consensus upon

Impact of NLO QCD &/ EW corrections in EFT fit

Inclusion of quadratic terms in EFT fit

Impact of dimension-8 operators

+ ...

- LHC provides an unique opportunity of EFT measurements in Higgs sector (along with other sectors)
- Follow the latest happenings in LHC EFT working group

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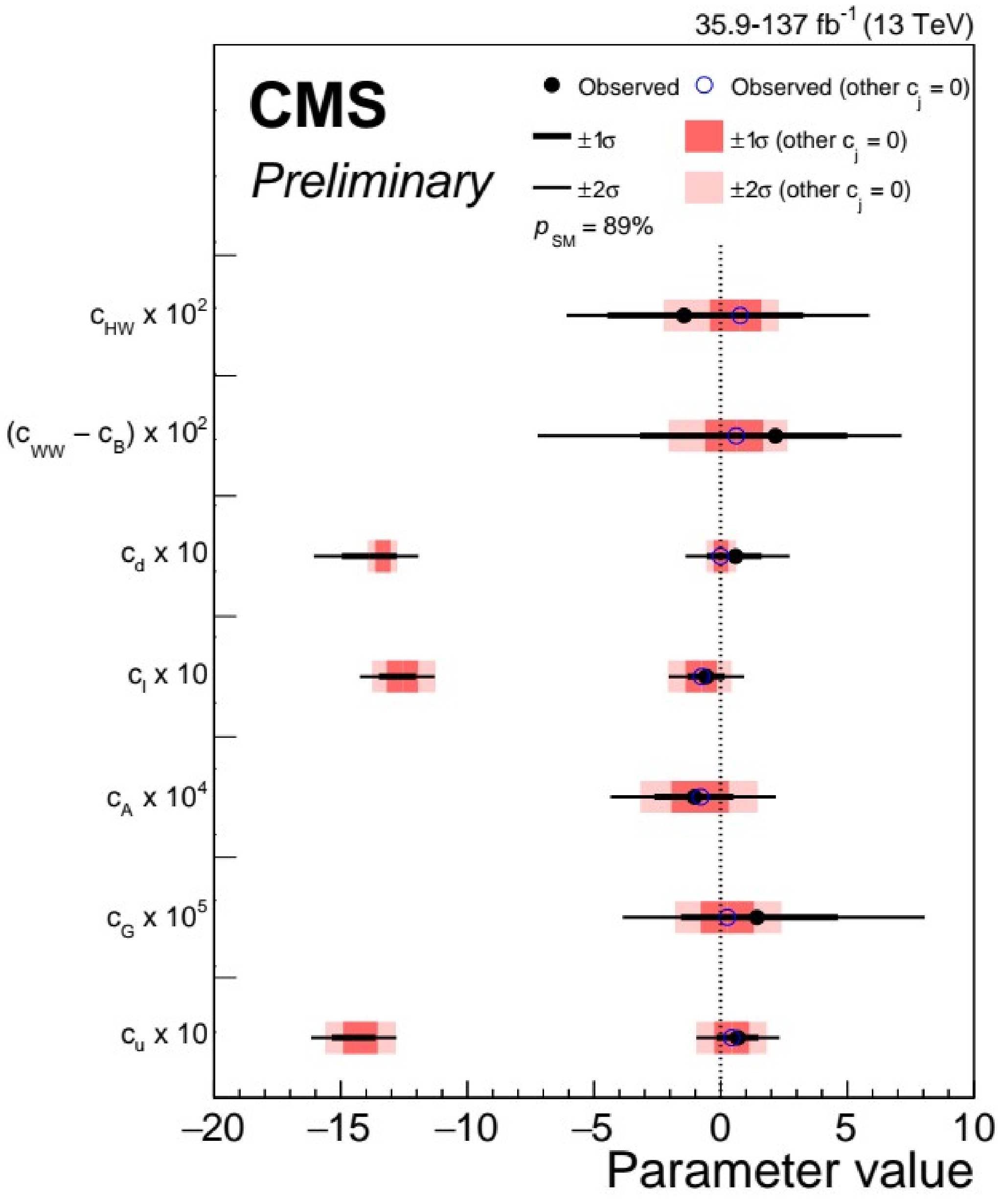
Extra material

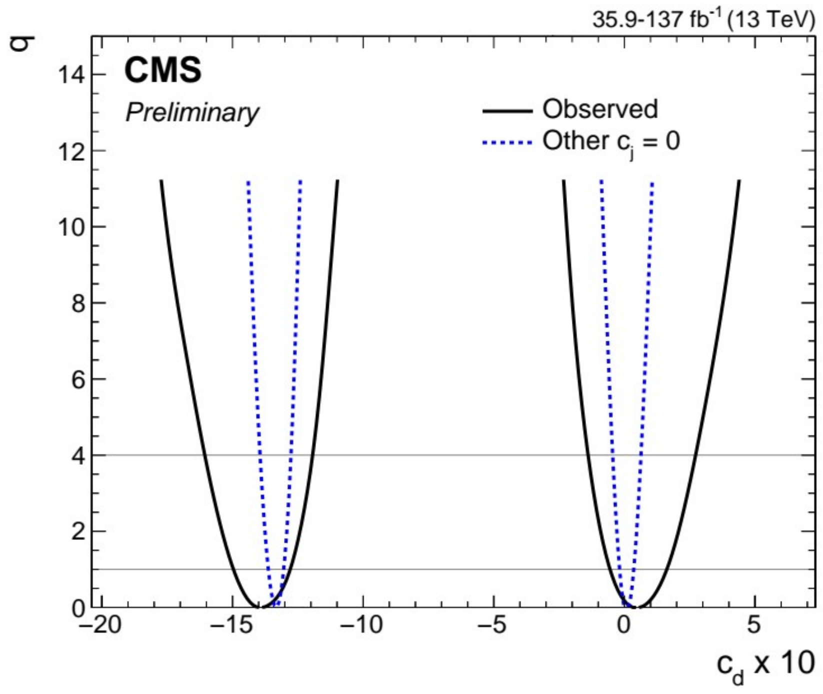
Combined measurement of Higgs properties



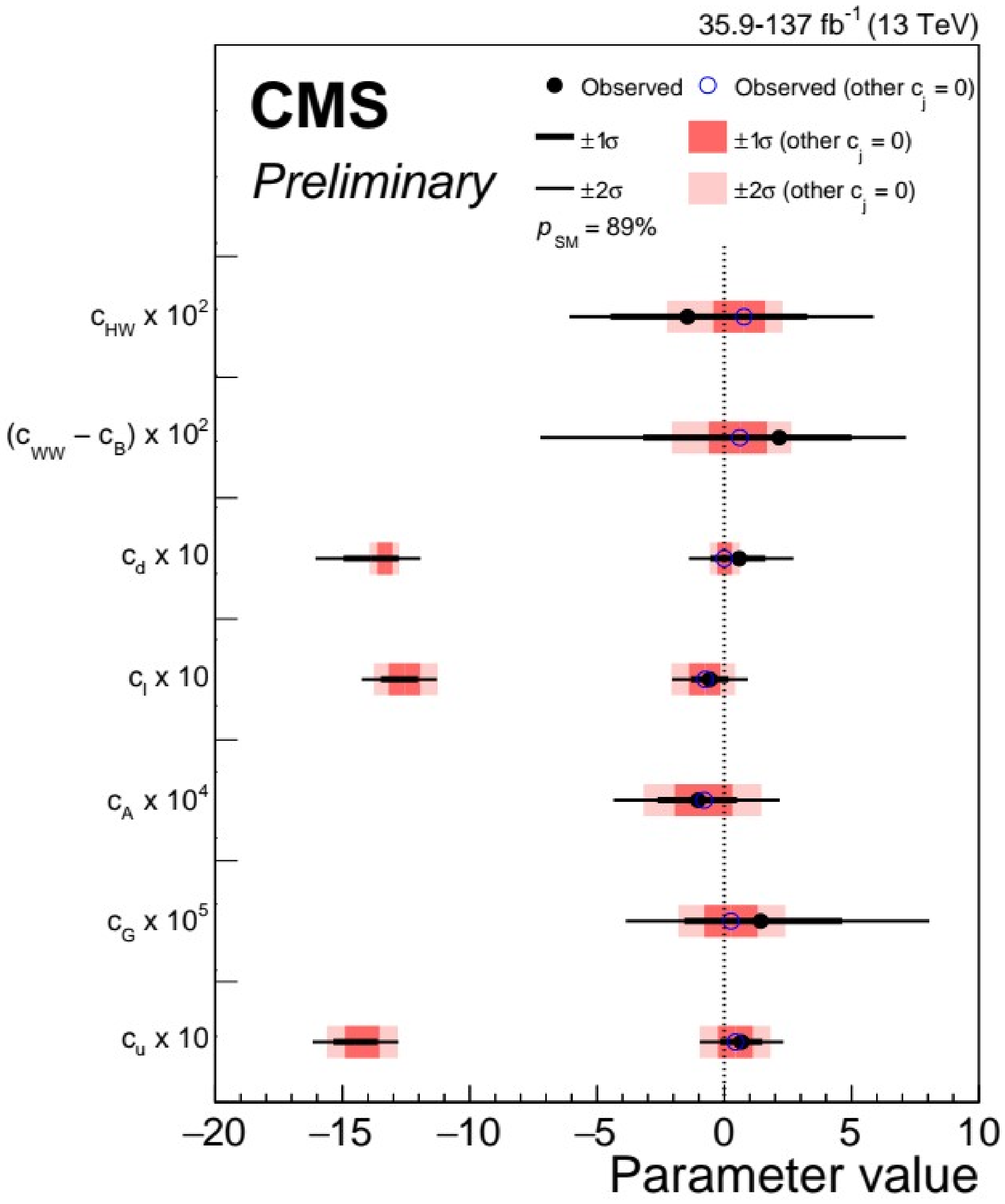
Two bounds reported for each WC:

1. With putting all other WCs to 0 → generally results to stronger bound
2. Profiling other WCs → gives a sense of correlation between operators

Not sensitive to sign of 'Yukawa-like' operators



Combined measurement of Higgs properties



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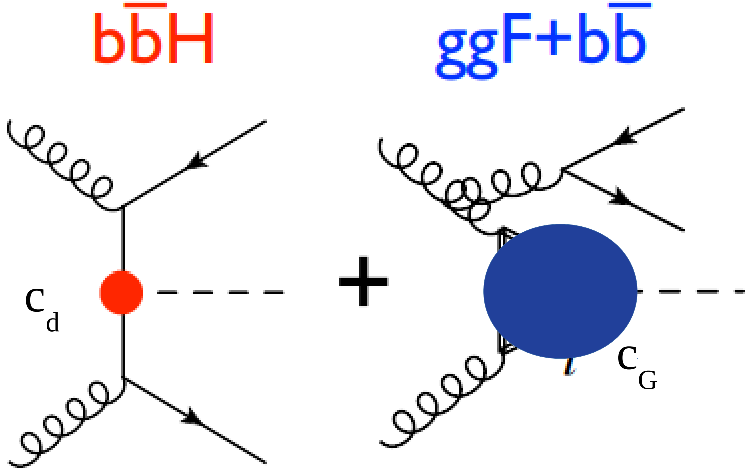
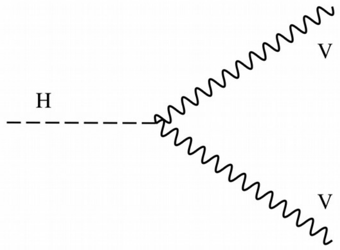


Including bbH measurements can help to alleviate sign ambiguity for c_d

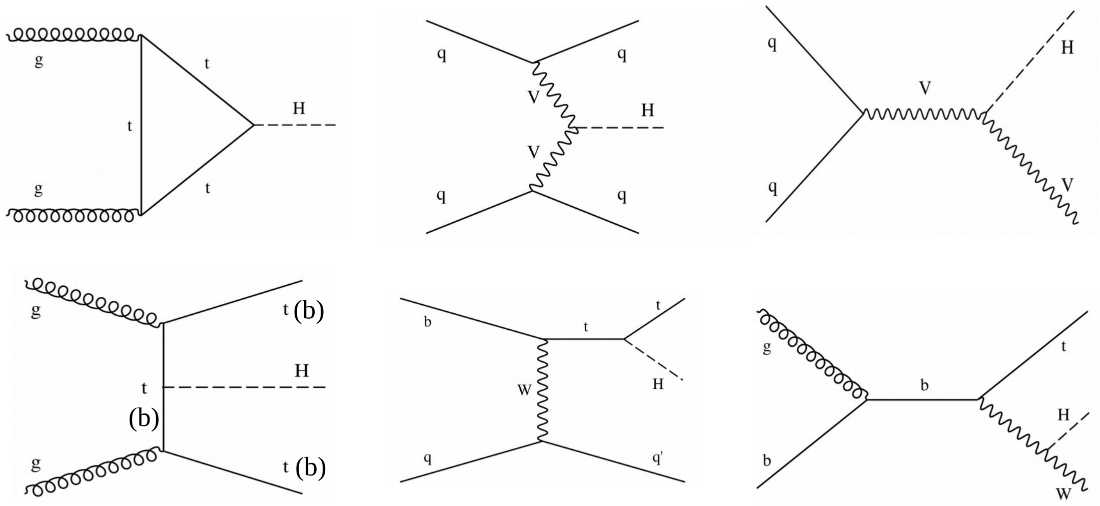
Measurement of anomalous couplings in H → 4 leptons

<u>Probing</u>

Up to 5 HZZ couplings
2 Hgg couplings (1 CP-even + 1 CP-odd)
2 Htt couplings (1 CP-even + 1 CP-odd)



<u>Production mechanisms included:</u>



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

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

$a_1^{gg} = \kappa_1^{gg} = \kappa_2^{gg} = 0$

$a_1^{\gamma\gamma} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = 0$

$\kappa_1^{ZZ} = \kappa_2^{ZZ}$

$\kappa_1^{WW} = \kappa_2^{WW}$

$\kappa_3^{\gamma\gamma} = 0$

Requirements of Gauge invariance

SU(2)xU(1) symmetry relates W, Z couplings

$$a_1^{\mathrm{WW}} = a_1^{\mathrm{ZZ}} + \frac{\Delta m_\mathrm{W}}{m_\mathrm{W}},$$

$$a_2^{\mathrm{WW}} = c_\mathrm{w}^2 a_2^{\mathrm{ZZ}} + s_\mathrm{w}^2 a_2^{\gamma\gamma} + 2 s_\mathrm{w} c_\mathrm{w} a_2^{\mathrm{Z}\gamma},$$

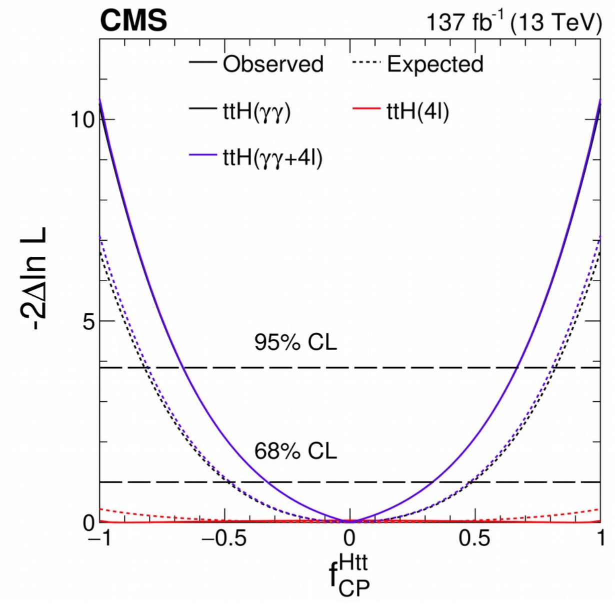
$$a_3^{\mathrm{WW}} = c_\mathrm{w}^2 a_3^{\mathrm{ZZ}} + s_\mathrm{w}^2 a_3^{\gamma\gamma} + 2 s_\mathrm{w} c_\mathrm{w} a_3^{\mathrm{Z}\gamma},$$

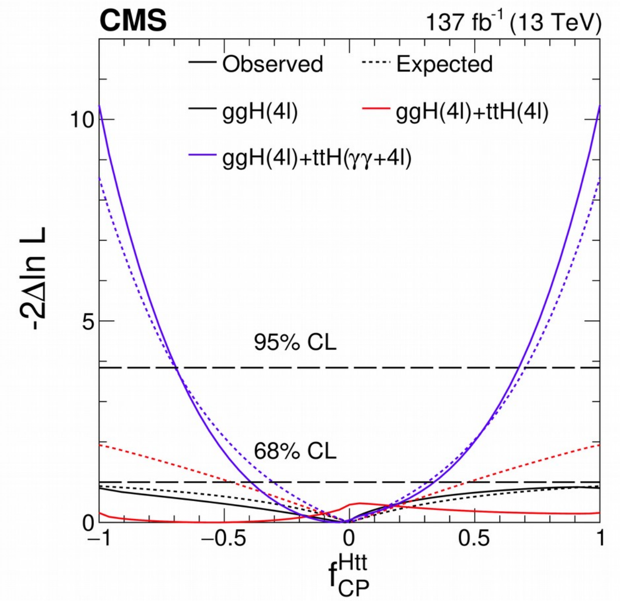
$$\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2}(c_\mathrm{w}^2 - s_\mathrm{w}^2) = \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + 2 s_\mathrm{w}^2 \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_\mathrm{Z}^2} + 2\frac{s_\mathrm{w}}{c_\mathrm{w}}(c_\mathrm{w}^2 - s_\mathrm{w}^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_\mathrm{Z}^2},$$

$$\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_\mathrm{w}^2 - s_\mathrm{w}^2) = 2 s_\mathrm{w} c_\mathrm{w}\left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_\mathrm{Z}^2}\right) + 2(c_\mathrm{w}^2 - s_\mathrm{w}^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_\mathrm{Z}^2},$$

arXiv: 2104.12152

Measurement of anomalous couplings in H → 4 leptons





ttH

ggH + ttH

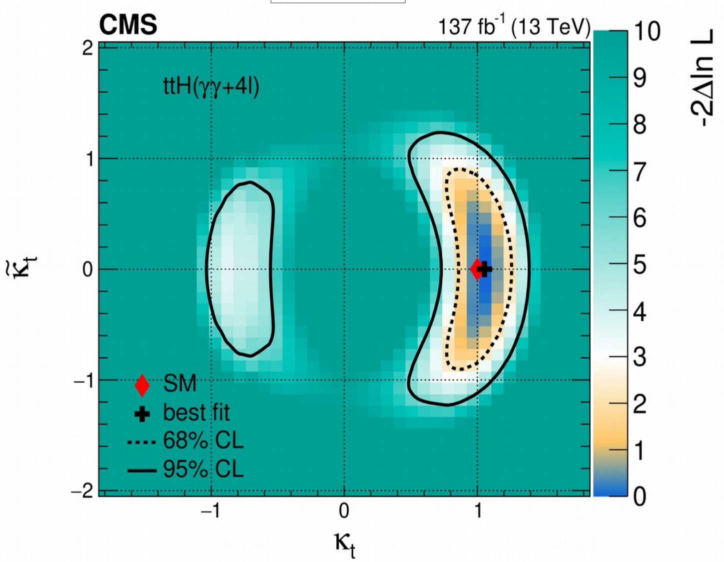
Sensitivity to fermionic couplings parameterized in terms of

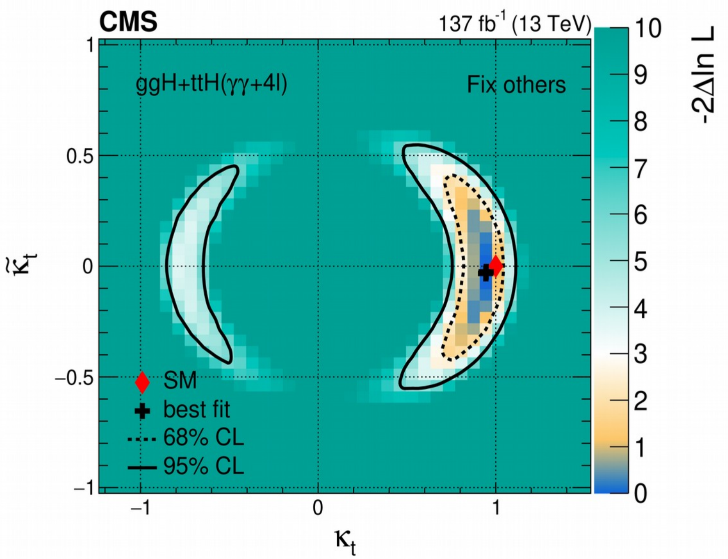
$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

$\sigma(\tilde{\kappa}_f = 1)/\sigma(\kappa_f = 1)$

2.38 for ggH
0.39 for ttH

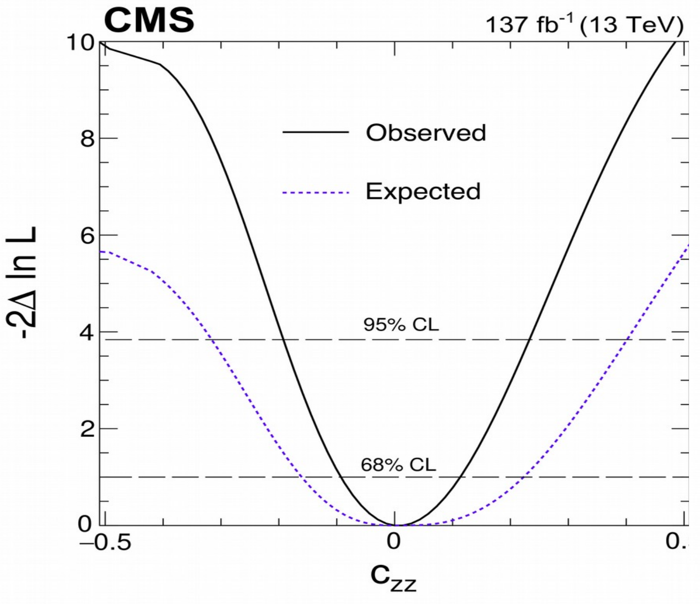
6.08 for $f_{CP}^{ttH}=1$ w.r.t. $f_{CP}^{ttH}=0$ (SM)

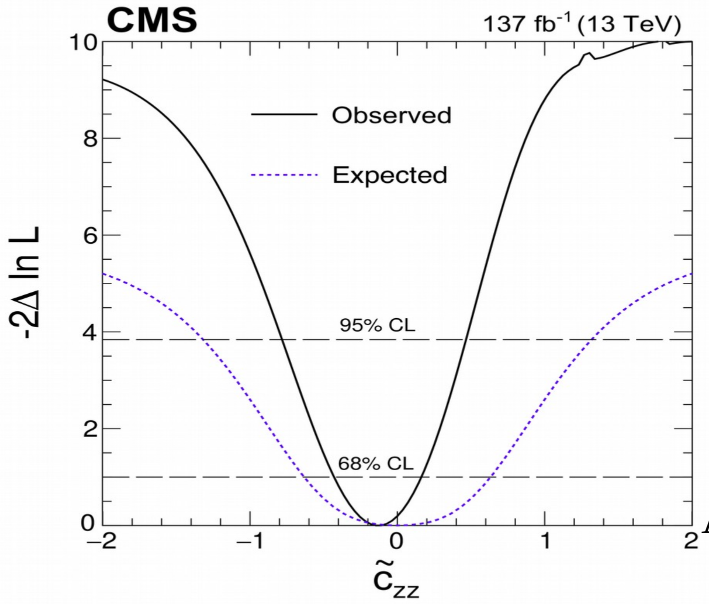




H-t coupling

Measurement of anomalous couplings in H$\rightarrow$ 4 leptons





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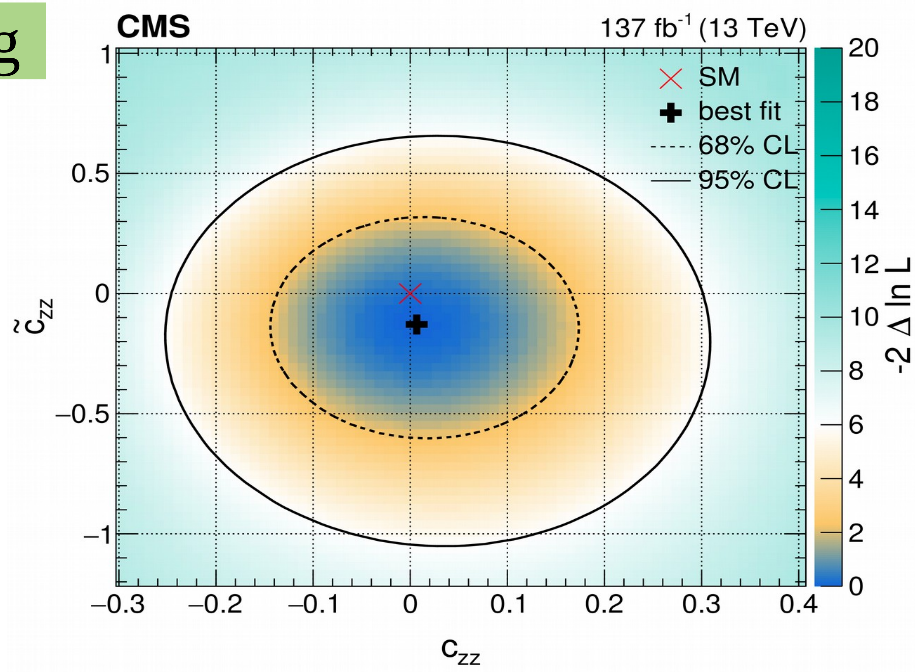
H-V coupling



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