Constraints on Anomalous Couplings of the Higgs Boson to Vector Bosons and Fermions with the CMS

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On Behalf of CMS Collaboration

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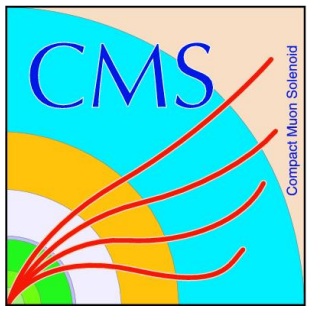
November 25th, 2021



Introduction

Phys.Rev.D 104 (2021) 5,052004

- Search for anomalous Hgg couplings
  - Kinematics of jets from gluon fusion with extra jets
- Search for anomalous Htt couplings
  - Kinematics of jets from gluon fusion with extra jets
  - Kinematics of top decays from ttH and tHq
- Search for anomalous HVV couplings
  - Kinematics of jets from VBF and VH productions
  - Kinematics of leptons $H \to ZZ$
- Measure corresponding EFT coefficients

Parameterization of Amplitudes

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

$$A\left(\mathrm{HV_1\ V_2}\right) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}\left(q_{\mathrm{V1}} + q_{\mathrm{V2}}\right)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu},$$

$$V_1 V_2 : ZZ, Z\gamma, \gamma\gamma, WW, gg.$$

Cross section fraction:

- Htt: $f_{\mathrm{CP}}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_\mathrm{f}|^2}{|\kappa_\mathrm{f}|^2 + |\tilde{\kappa}_\mathrm{f}|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_\mathrm{f}}{\kappa_\mathrm{f}}\right)$
- Hgg: $f_{a3}^{\mathrm{ggH}} = \frac{\left|a_3^{\mathrm{gg}}\right|^2}{\left|a_2^{\mathrm{gg}}\right|^2 + \left|a_3^{\mathrm{gg}}\right|^2}\,\mathrm{sign}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right)$
- HVV: $f_{ai}^{\mathrm{VV}} = \frac{\left|a_i^{\mathrm{VV}}\right|^2 \alpha_{ii}^{(2\mathrm{e}2\mu)}}{\sum_j \left|a_j^{\mathrm{VV}}\right|^2 \alpha_{jj}^{(2\mathrm{e}2\mu)}}\,\mathrm{sign}\left(\frac{a_i^{\mathrm{VV}}}{a_1}\right)$

Event Categorization for *Htt* and *Hgg*

	Untagged	VBF-1jet	VBF-2jet	VH-leptonic	VH-hadronic	$t\bar{t}$H-leptonic	$t\bar{t}$H-hadronic
ggH sig	182.98	15.50	6.70	0.35	4.68	0.02	0.18
VBF sig	7.23	3.28	7.23	0.05	0.28	0.01	0.05
WH sig	2.68	0.22	0.22	1.07	1.17	0.03	0.03
ZH sig	2.20	0.14	0.15	0.26	0.78	0.02	0.05
$b\bar{b}$H sig	1.90	0.13	0.08	0.03	0.07	0.00	0.01
$t\bar{t}$H sig	0.43	0.00	0.08	0.14	0.15	0.68	0.86
$(\tilde{\kappa}_t = 1.6)$	(0.45)	(0.00)	(0.12)	(0.15)	(0.15)	(0.87)	(1.18)
tH sig	0.14	0.01	0.10	0.04	0.03	0.04	0.03
Signal	197.89	19.31	14.57	2.00	7.40	0.80	1.23
$q\bar{q} \to 4\ell$ bkg	210.50	6.93	1.92	2.23	1.87	0.08	0.04
$gg \to 4\ell$ bkg	19.79	1.53	0.56	0.38	0.24	0.01	0.01
EW bkg	3.43	0.18	1.37	0.26	0.57	0.24	1.07
Z + X bkg	77.94	2.46	4.88	1.20	3.29	0.21	1.07
Total	509.55	30.41	23.30	6.05	13.38	1.33	3.41
Observed	539	27	20	10	12	0	2

Event Categorization for *HVV*

	Untagged	Boosted	VBF-1jet	VBF-2jet	VH-leptonic	VH-hadronic
ggH sig	171.46	6.48	15.15	10.44	0.35	5.99
VBF sig	5.06	1.18	2.64	8.60	0.06	0.54
($a_3/a_2/\kappa_1/\kappa_2^{Z\gamma}$)	(0.29/0.29/0.05/0.09)	(0.69/0.54/0.52/0.48)	(0.12/0.09/0.03/0.05)	(6.10/4.95/1.91/1.83)	(0.03/0.02/0.01/0.01)	(0.28/0.21/0.07/0.07)
WH sig	2.18	0.43	0.29	0.22	1.11	1.20
($a_3/a_2/\kappa_1/\kappa_2^{Z\gamma}$)	(1.93/3.15/0.72/0.00)	(3.81/3.20/6.28/0.00)	(0.83/0.92/0.22/0.00)	(1.20/1.05/2.04/0.00)	(2.75/2.86/3.47/0.00)	(3.43/3.33/2.93/0.00)
ZH sig	1.87	0.34	0.16	0.16	0.26	0.79
($a_3/a_2/\kappa_1/\kappa_2^{Z\gamma}$)	(0.99/1.89/0.68/1.17)	(1.87/1.66/4.14/12.34)	(0.30/0.35/0.12/0.27)	(0.56/0.51/1.30/3.88)	(0.42/0.48/0.65/1.82)	(1.42/1.53/1.84/4.69)
$b\bar{b}H$ sig	1.84	0.04	0.13	0.09	0.03	0.09
$t\bar{t}H$ sig	1.65	0.04	0.00	0.32	0.13	0.19
tH sig	0.13	0.02	0.01	0.12	0.04	0.05
Signal	184.1	8.5	18.4	19.8	1.9	8.8
($a_3/a_2/\kappa_1/\kappa_2^{Z\gamma}$)	(178.2/180.3/176.4/176.2)	(12.9/12.0/17.5/19.4)	(16.5/16.7/15.7/15.6)	(18.7/17.4/16.1/16.6)	(3.7/3.9/4.6/2.3)	(11.4/11.4/11.1/11.0)
$q\bar{q} \to 4\ell$ bkg	206.05	1.89	6.78	2.78	2.21	2.30
$gg \to 4\ell$ bkg	19.05	0.38	1.52	0.76	0.37	0.31
EW bkg	3.50	0.66	0.20	1.98	0.23	0.85
Z + X bkg	69.87	3.73	2.46	9.70	1.20	4.10
Total	481.3	15.1	29.3	34.9	5.9	16.24
($a_3/a_2/\kappa_1/\kappa_2^{Z\gamma}$)	(475.4/477.5/473.6/473.4)	(19.5/18.6/24.1/26.0)	(27.4/27.6/26.6/26.5)	(33.8/32.4/31.1/31.6)	(7.7/7.9/8.6/6.3)	(18.83/18.78/18.54/18.47)
Observed	512	18	27	30	10	13

Kinematic Discriminants and Matrix Element Approach

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

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

$\mathcal{D}_{0^-}(\mathbf{\Omega}) = \frac{\mathcal{P}_{0^-}(\mathbf{\Omega})}{\mathcal{P}_{0^+}(\mathbf{\Omega})+\mathcal{P}_{0^-}(\mathbf{\Omega})}$, $\mathcal{D}_{\text{CP}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{0^+}(\mathbf{\Omega})\,\mathcal{P}_{0^-}(\mathbf{\Omega})}}$,

$\mathcal{D}_{\text{bkg}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})+\mathcal{P}_{\text{bkg}}(\mathbf{\Omega})}$, $\mathcal{D}_{\Lambda_1}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\Lambda_1}(\mathbf{\Omega})}{\mathcal{P}_{\Lambda_1}(\mathbf{\Omega})+\mathcal{P}_{\text{SM}}(\mathbf{\Omega})}$

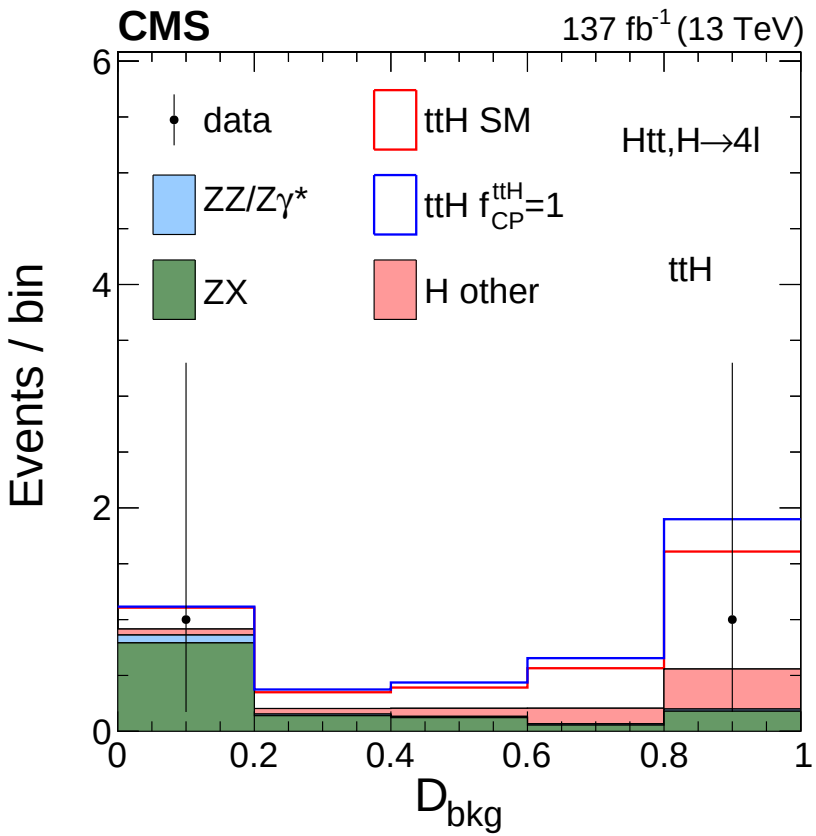
- $\mathcal{D}_{0^-}$: distinguish CP-odd from CP-even
- $\mathcal{D}_{\text{CP}}$: measure the interference term
- $\mathcal{D}_{\text{bkg}}$: separate Higgs production from non-Higgs processes
- $\mathcal{D}_{\Lambda_1}$: sensitive to κ_1/Λ_1 term

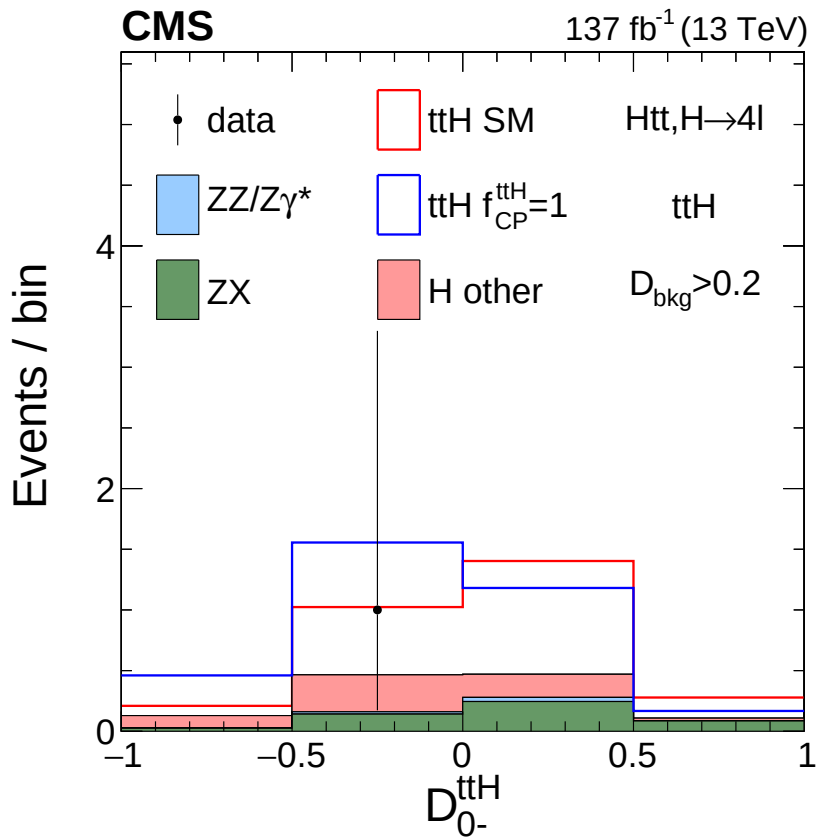
Observables

Category	Selection	Observables $\vec{x}$ for fitting
Scheme 1		
VBF-1jet	$\mathcal{D}_{1\text{jet}}^{\text{VBF}} > 0.7$	$\mathcal{D}_{\text{bkg}}$
VBF-2jet	$\mathcal{D}_{2\text{jet}}^{\text{VBF}} > 0.5$	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{2\text{jet}}^{\text{VBF}}, \mathcal{D}_{0-}^{\text{ggH}}, \mathcal{D}_{\text{CP}}^{\text{ggH}}$
VH-hadronic	$\mathcal{D}_{2\text{jet}}^{\text{VH}} > 0.5$	$\mathcal{D}_{\text{bkg}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\text{bkg}}$
$\text{t}\bar{\text{t}}$H-hadronic	see Section 3	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{t}\bar{\text{t}}\text{H}}$
$\text{t}\bar{\text{t}}$H-leptonic	see Section 3	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{t}\bar{\text{t}}\text{H}}$
Untagged	none of the above	$\mathcal{D}_{\text{bkg}}$
Scheme 2		
Boosted	$p_{\text{T}}^{4\ell} > 120\,\text{GeV}$	$\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$
VBF-1jet	$\mathcal{D}_{1\text{jet}}^{\text{VBF}} > 0.7$	$\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$
VBF-2jet	$\mathcal{D}_{2\text{jet}}^{\text{VBF}} > 0.5$	$\mathcal{D}_{\text{bkg}}^{\text{EW}}, \mathcal{D}_{0\text{h}+}^{\text{VBF+dec}}, \mathcal{D}_{0-}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda 1}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda 1}^{\text{Z}\gamma,\text{VBF+dec}}, \mathcal{D}_{\text{int}}^{\text{VBF}}, \mathcal{D}_{\text{CP}}^{\text{VBF}}$
VH-hadronic	$\mathcal{D}_{2\text{jet}}^{\text{VH}} > 0.5$	$\mathcal{D}_{\text{bkg}}^{\text{EW}}, \mathcal{D}_{0\text{h}+}^{\text{VH+dec}}, \mathcal{D}_{0-}^{\text{VH+dec}}, \mathcal{D}_{\Lambda 1}^{\text{VH+dec}}, \mathcal{D}_{\Lambda 1}^{\text{Z}\gamma,\text{VH+dec}}, \mathcal{D}_{\text{int}}^{\text{VH}}, \mathcal{D}_{\text{CP}}^{\text{VH}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$
Untagged	none of the above	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0\text{h}+}^{\text{dec}}, \mathcal{D}_{0-}^{\text{dec}}, \mathcal{D}_{\Lambda 1}^{\text{dec}}, \mathcal{D}_{\Lambda 1}^{\text{Z}\gamma,\text{dec}}, \mathcal{D}_{\text{int}}^{\text{dec}}, \mathcal{D}_{\text{CP}}^{\text{dec}}$

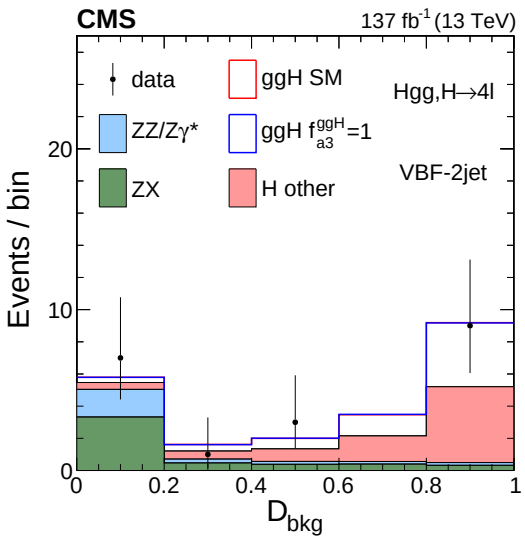
The list of kinematic observables used for category selection and fitting in categorization Schemes 1 and 2

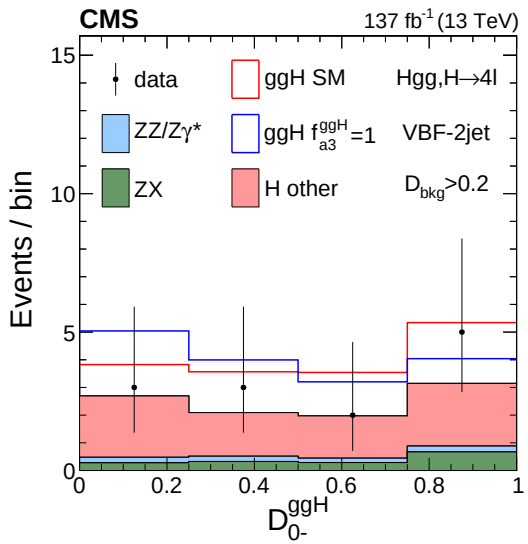
Observables in *ttH* Category in Scheme 1

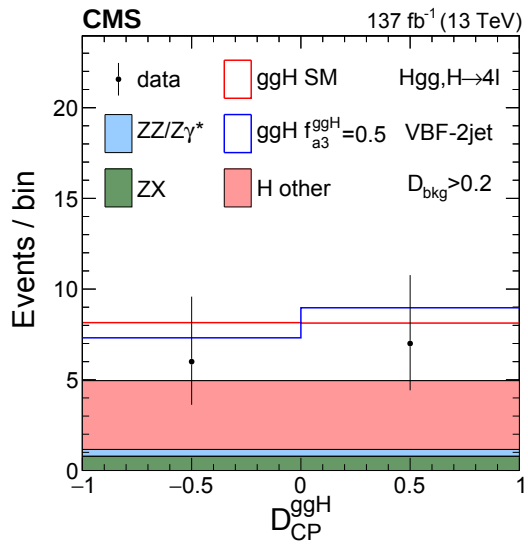




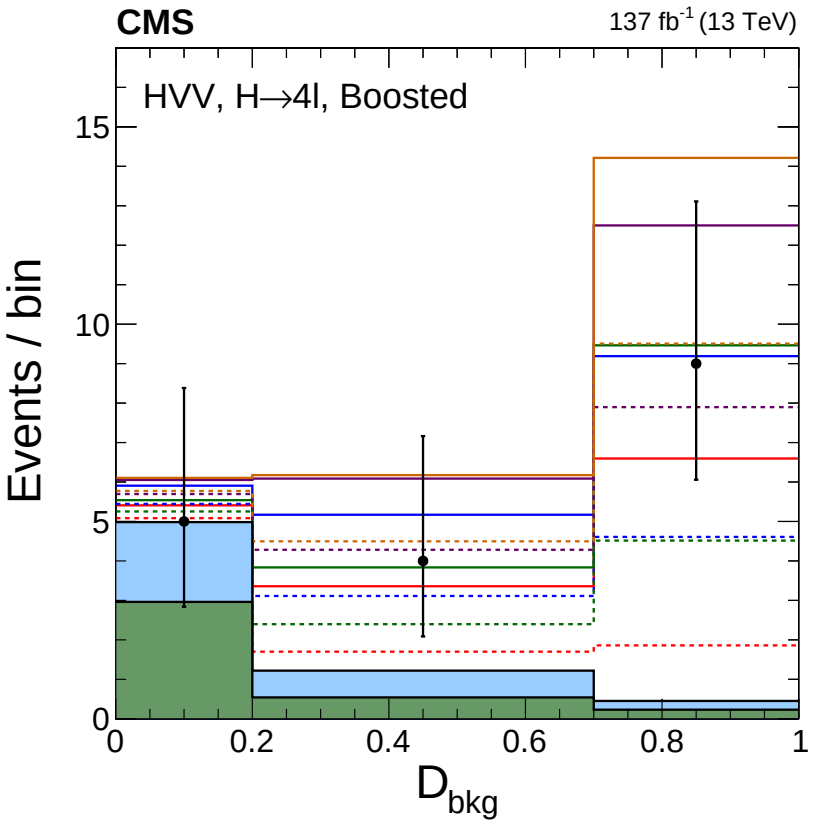
Observables in VBF-2jet Category in Scheme 1

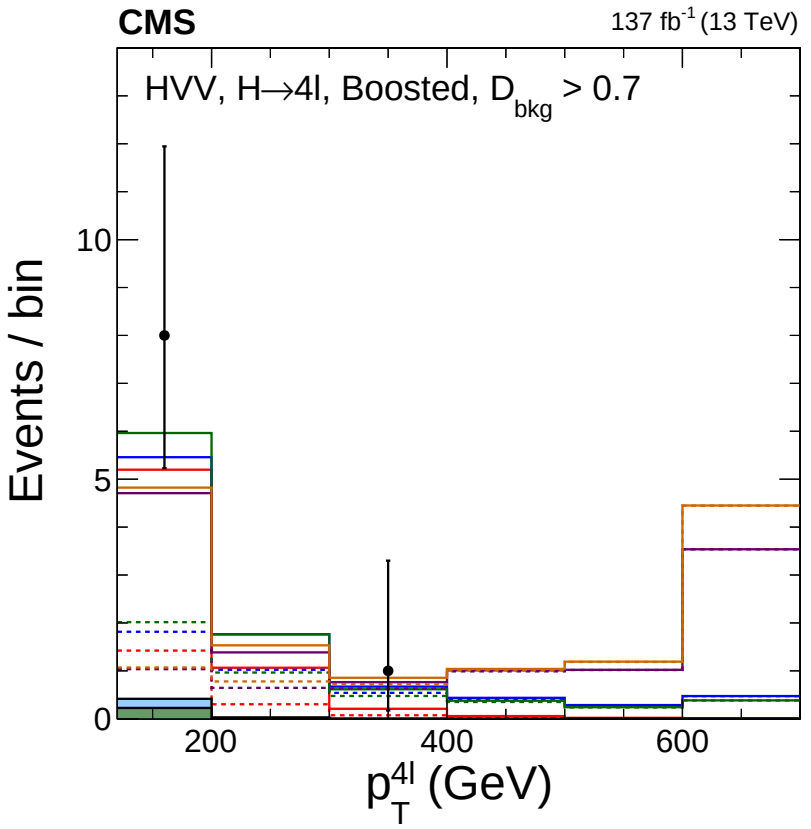






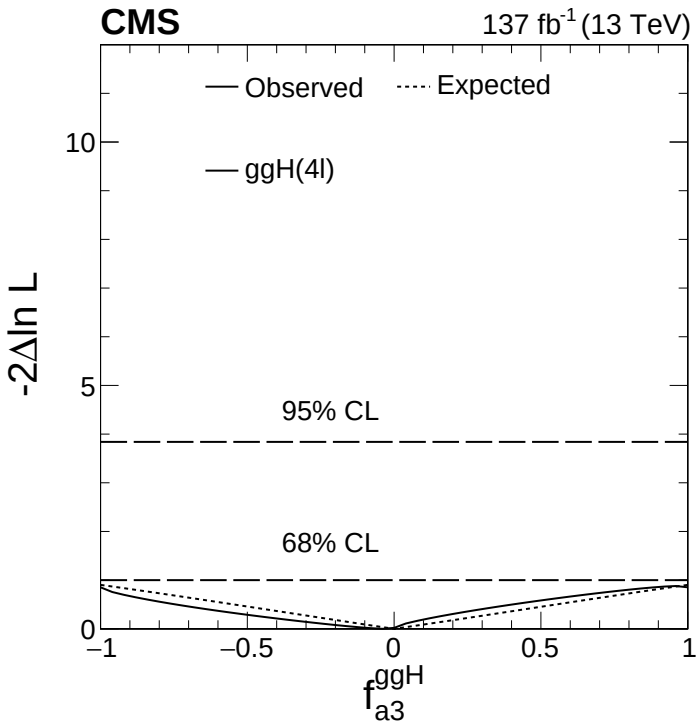
Observables in Boosted Category in Scheme 2

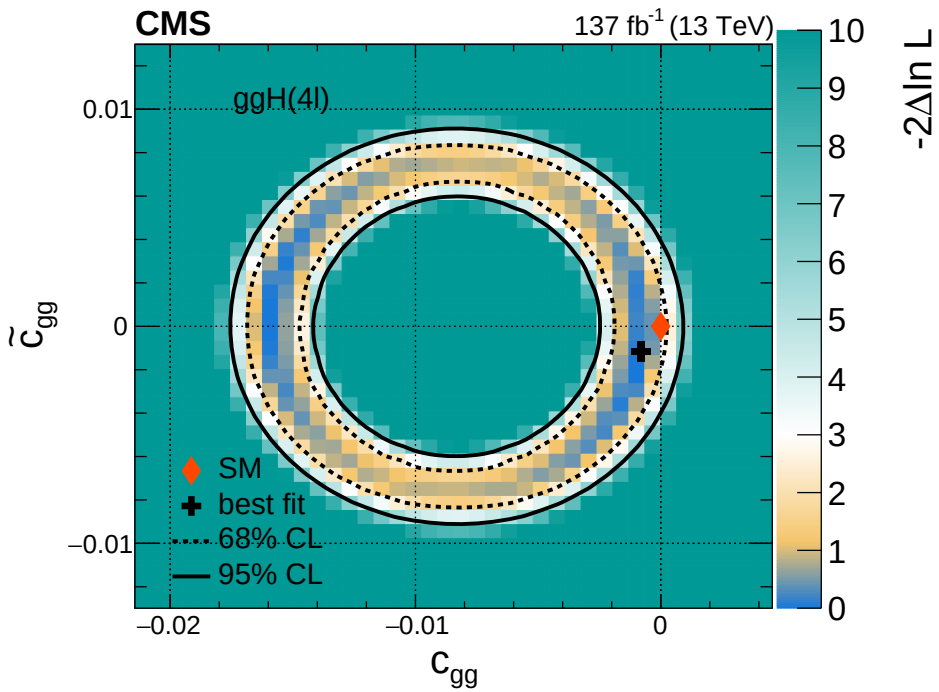




Constraints on *Hgg* Coupling

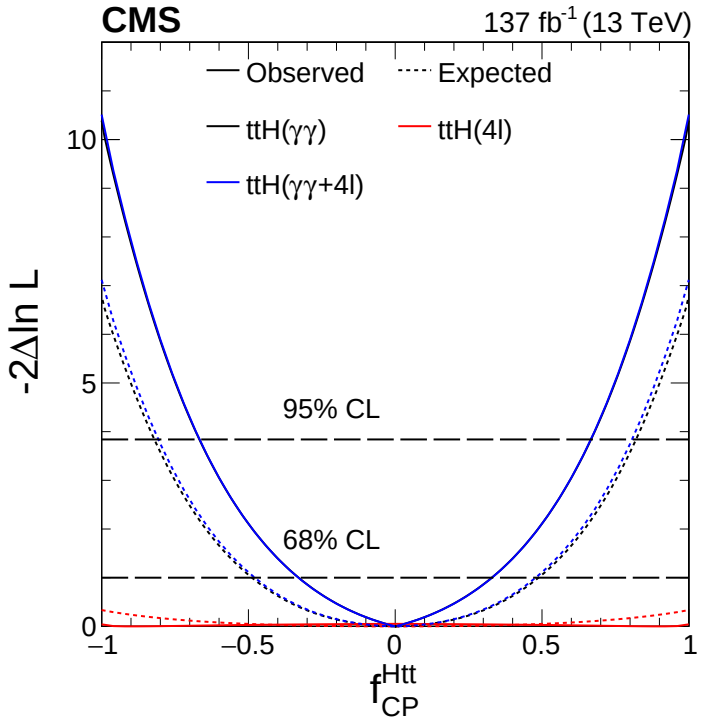
$$f_{a3}^{ggH} = \frac{\left|a_3^{gg}\right|^2}{\left|a_2^{gg}\right|^2+\left|a_3^{gg}\right|^2}\,\mathrm{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right), \qquad c_{gg} = -\frac{1}{2\pi\alpha_S}a_2^{gg}, \quad \tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S}a_3^{gg}$$

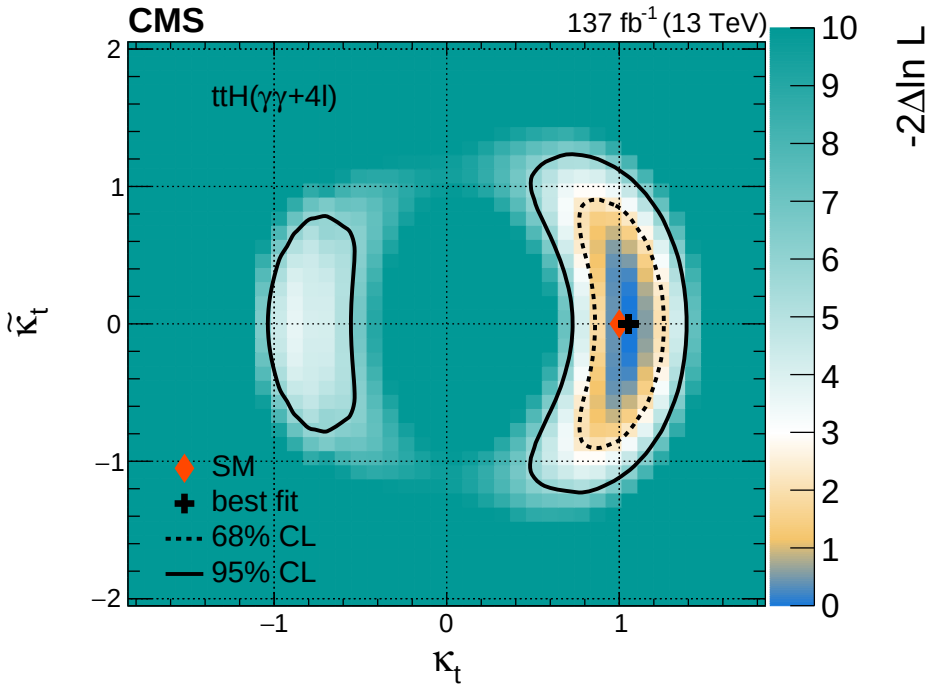




Constraints on *Htt* Coupling

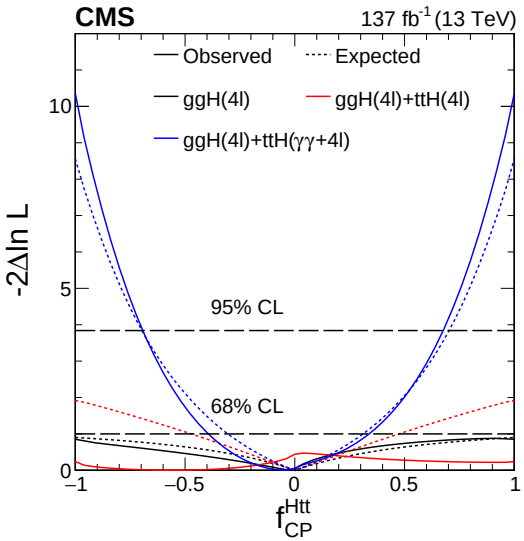
$$f_{\mathrm{CP}}^{\mathrm{Htt}} = \frac{|\tilde{\kappa}_{\mathrm{t}}|^2}{|\kappa_{\mathrm{t}}|^2+|\tilde{\kappa}_{\mathrm{t}}|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_{\mathrm{t}}}{\kappa_{\mathrm{t}}}\right)$$

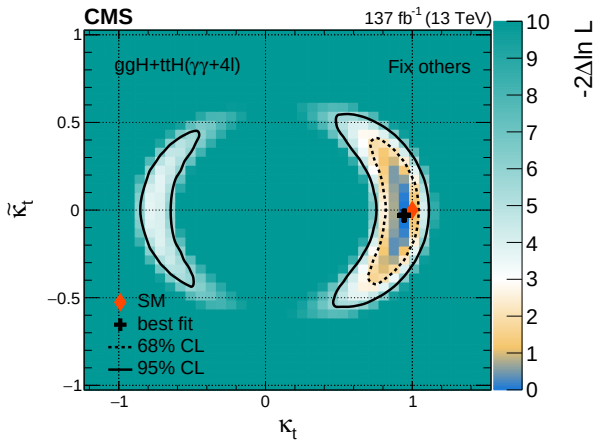


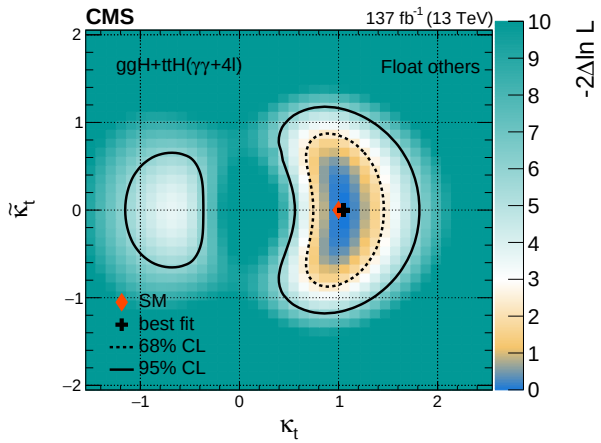


- *tHq* process included
- *tHq* has interference between *HWW* and *Htt*

Constraints on *Htt* Coupling via Combining *ttH* with *ggH*







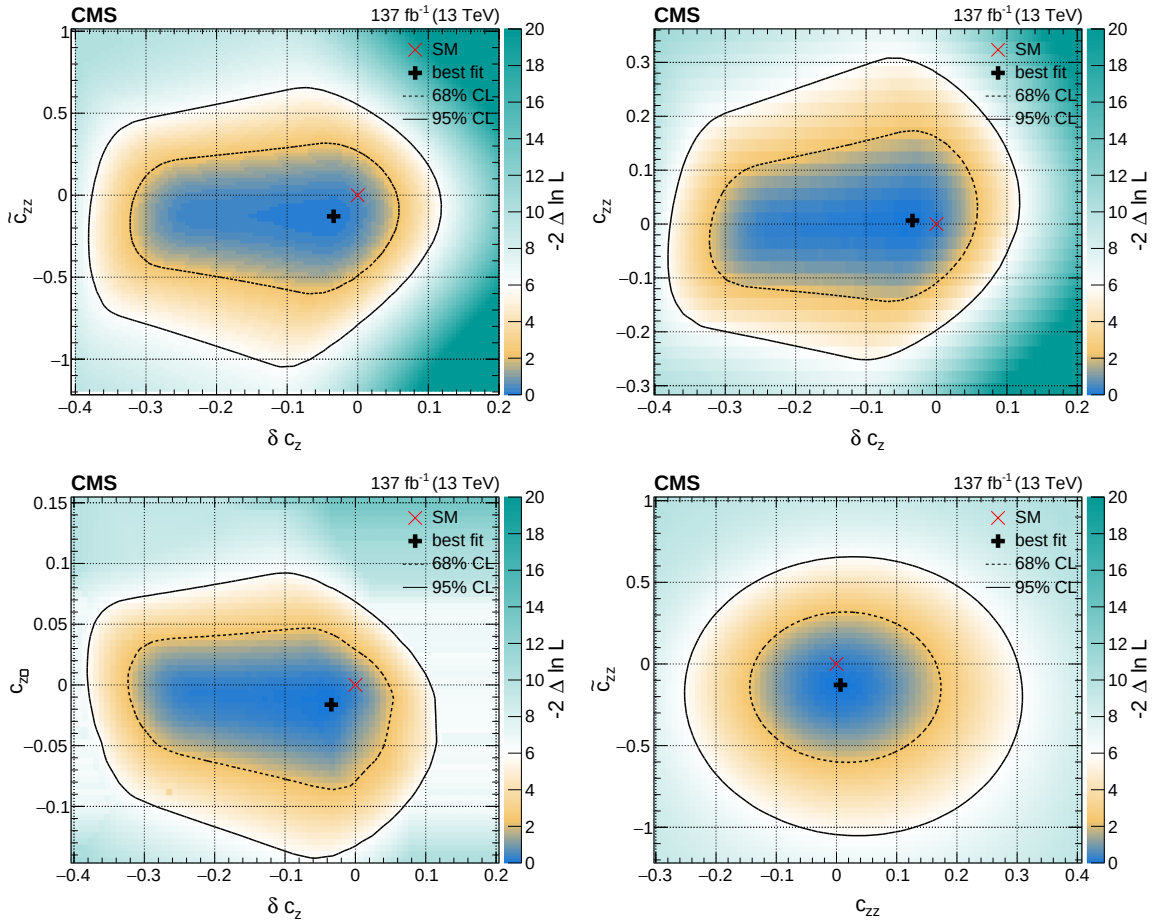
$$ggH\text{: } \frac{\sigma(\tilde{\kappa_f}=1)}{\sigma(\kappa_f=1)} = 2.38, \qquad ttH\text{: } \frac{\sigma(\tilde{\kappa_f}=1)}{\sigma(\kappa_f=1)} = 0.391$$

NOT simple addition of two independent results

Constraints on *HVV* Coupling in EFT Higgs Basis

$$\delta c_z = \frac{1}{2} a_1 - 1, \quad c_{z\Box} = \frac{m_Z^2 s_w^2}{4\pi\alpha} \frac{\kappa_1}{(\Lambda_1)^2}$$

$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2, \quad \tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3$$



Summary

Measurements of anomalous couplings using full Run2 data in $H \to 4\ell$ final state

- Explore Higgs production and decay($H \to 4\ell$)
- Measure *HVV* ,*Hgg* and *Htt* anomalous couplings,
- especially CP property
- All anomalous couplings are measured at the same time
- Results also presented in EFT coefficients framework.