UC SANTA BARBARA

U.S. DEPARTMENT OF ENERGY

Office of Science

Higgs EFT measurements @ CMS

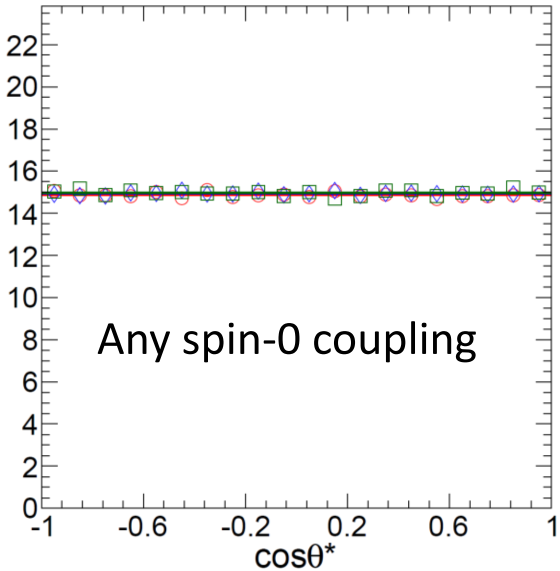
Ulascan Sarica

CMS EFT Workshop 2023
Sep. 5, 2023

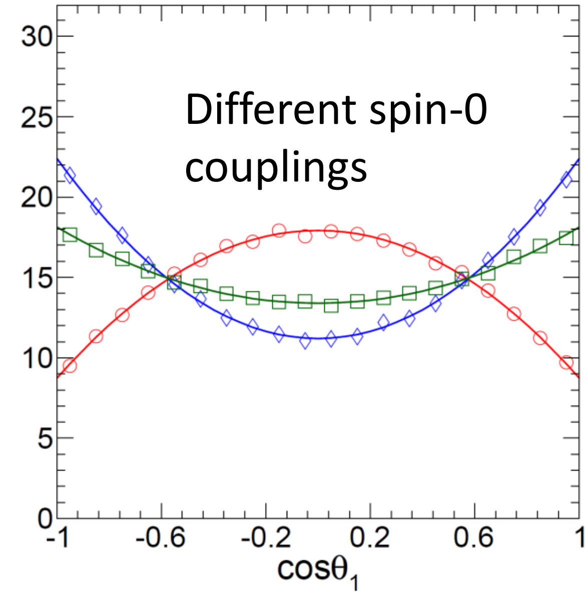
Single-Higgs EFT analyses

Spin-parity

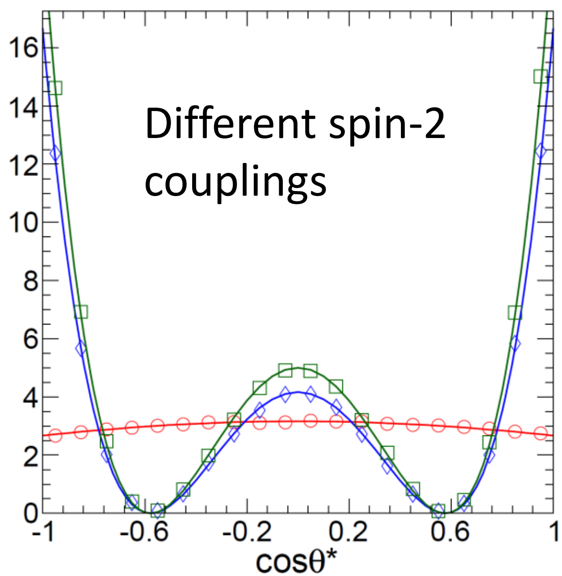
Angular correlations change for different Higgs boson spin and parity scenarios.

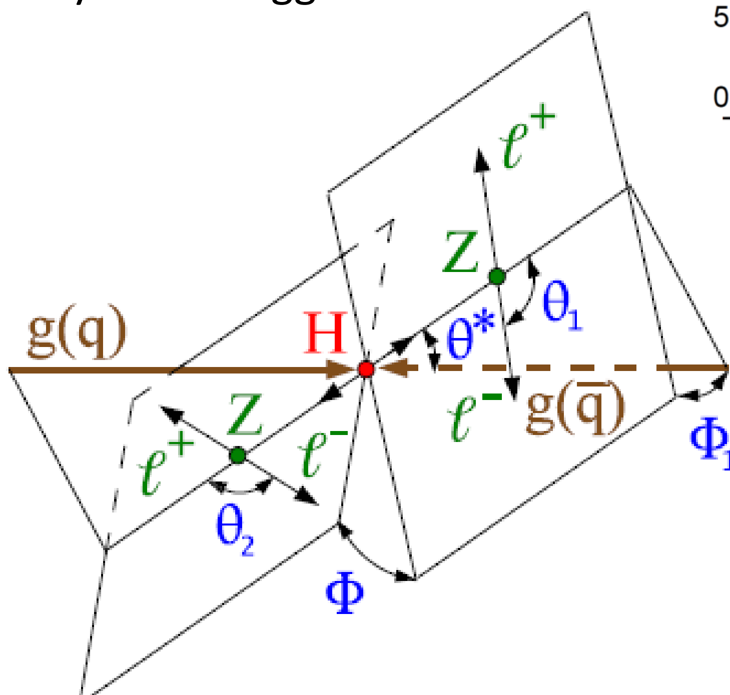


Can exploit such **information from** Higgs boson **production** (correlation between Higgs boson and associated particles) or decay (correlation between **decay** products) to measure the spin and parity of the Higgs boson

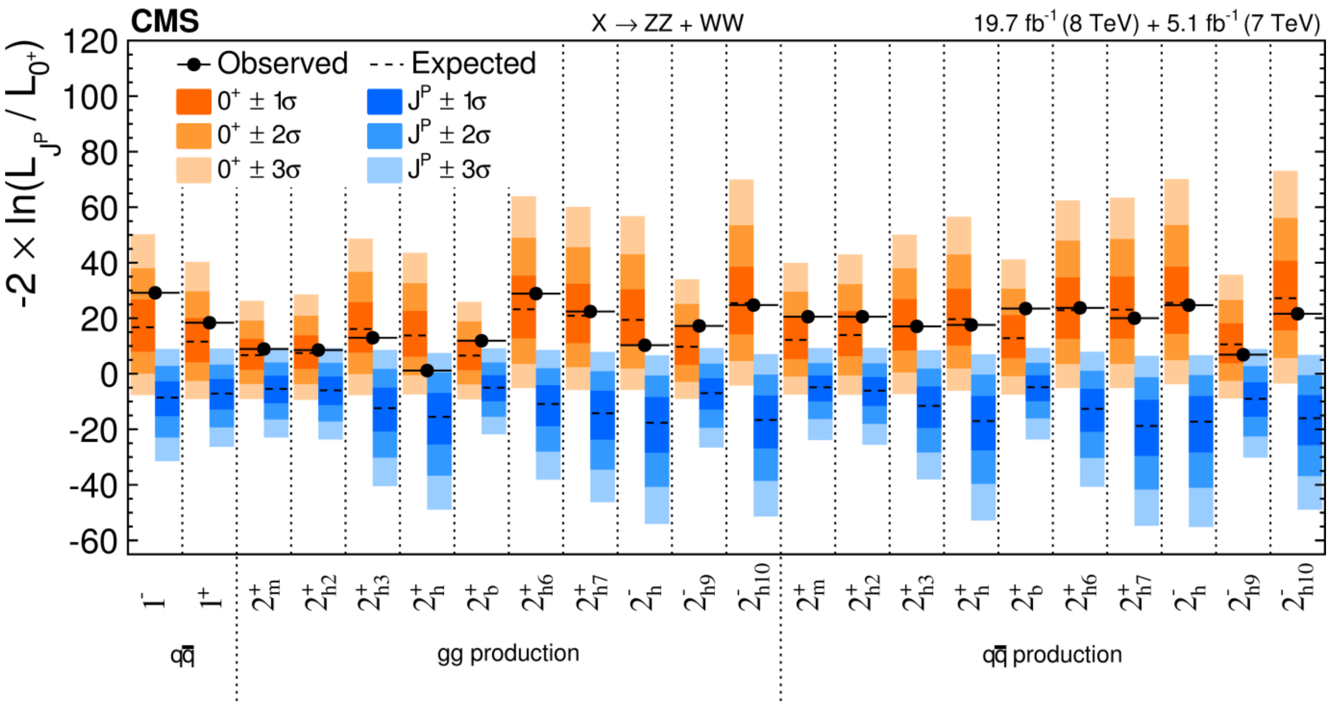


Plots from Refs. [1,2].





Spin from diboson decays

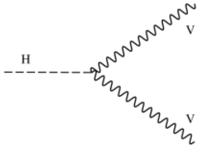


Extensive list of tests of spin-1 and -2 hypotheses from using ZZ, WW and $\gamma\gamma$ decays [link]

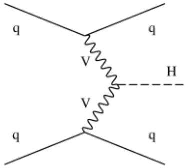
The Higgs boson is consistent with spin 0.

Spin-1 models excluded at >99.999% CL using $ZZ + WW$

Spin-2 models excluded at >99% CL using $ZZ + WW$ decays,
or at 99.87% for minimal gravitons using $ZZ + WW + \gamma\gamma$ decays



Anomalous HVV couplings



$$A(HVV) \sim \left[\boldsymbol{a_1} + e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} \left(+ e^{i\phi_{\Lambda 1}^{Z\gamma}} \frac{q_\gamma^2}{\left(\Lambda_1^{Z\gamma}\right)^2} \right) \ldots \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

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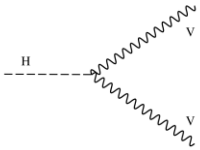
HVV amplitude
∝ SM-like $\boldsymbol{a_1}$ term
+ other BSM CP-even
or -odd contributions



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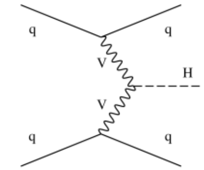

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Amplitude formalism in HVV equivalent to couplings in Higgs basis under $\mathrm{SU}(2) \times \mathrm{U}(1)$:

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

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[Link]

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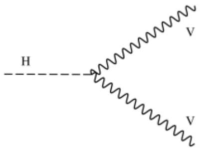

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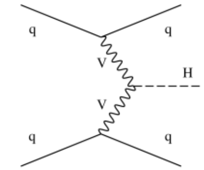

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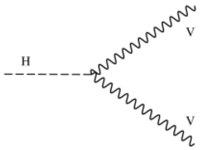
→ Many results in CMS expressed in terms of fractional xsec contributions:
$f_{ai} = |a_i|^2 \sigma_i / (|a_1|^2 \sigma_1 + |a_i|^2 \sigma_i)$ with $\phi_{ai} = 0$ or π



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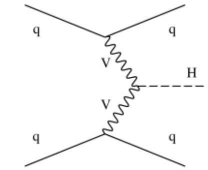

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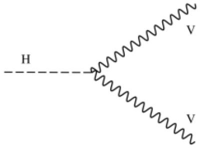
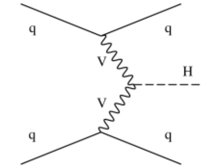
See also Jeff's talk for more details on these measurements

Anomalous HVV couplings





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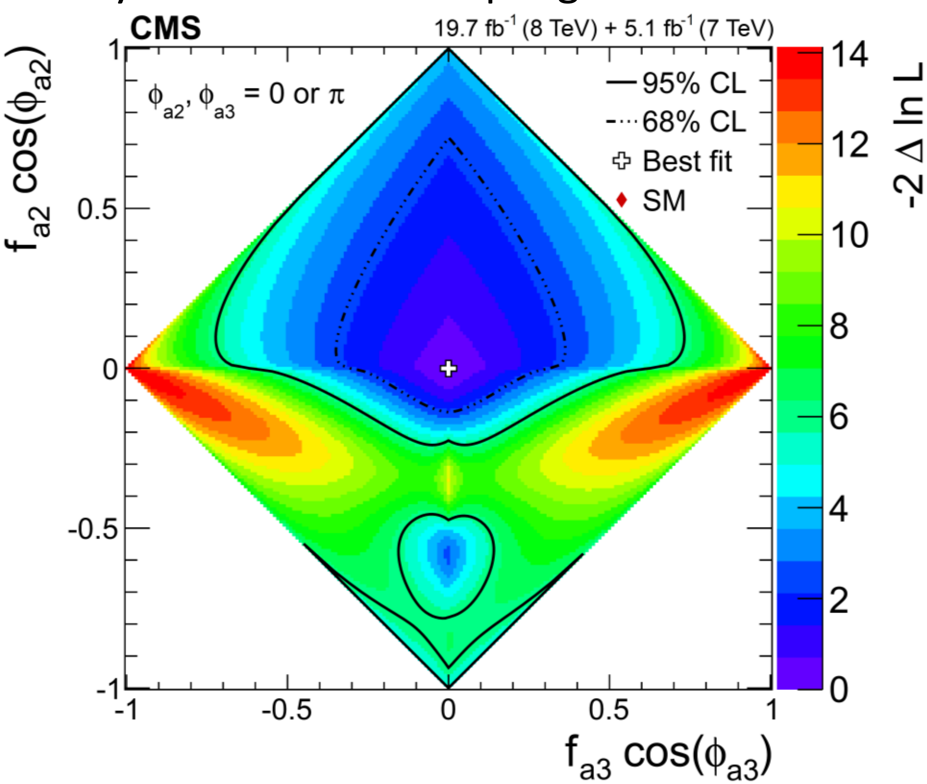
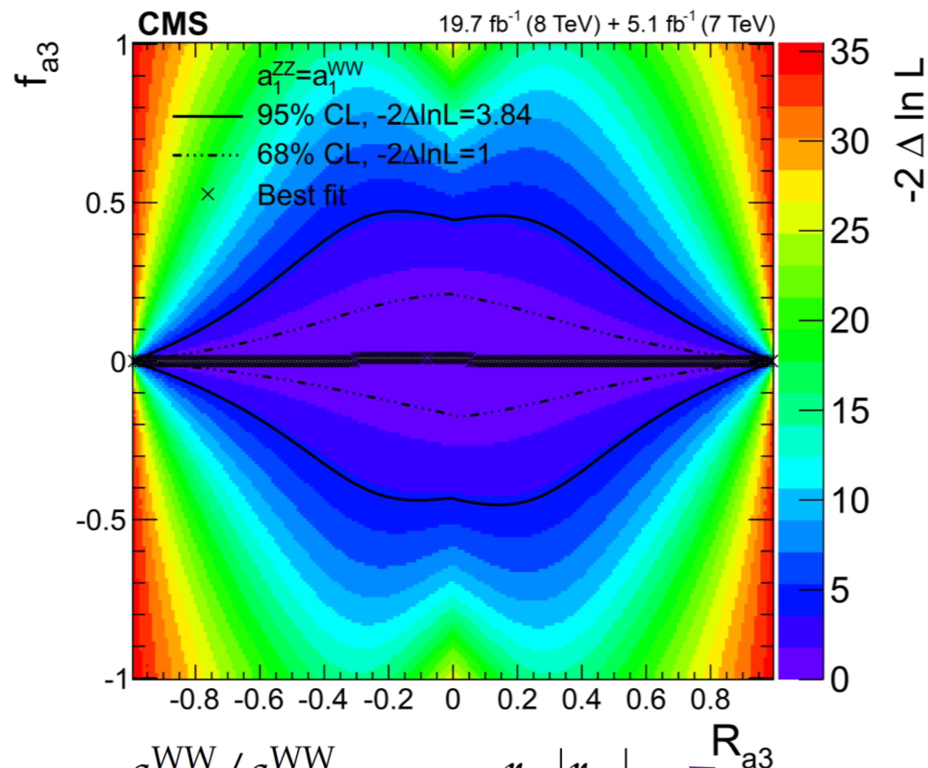
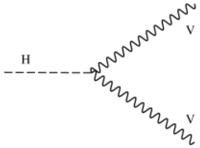
Early ideas to relax coupling relations from Run 1 decay-only $ZZ(+WW)$ measurements [link]:





$$r_{ai} = \frac{a_i^{\mathrm{WW}} / a_1^{\mathrm{WW}}}{a_i / a_1} \quad R_{ai} = \frac{r_{ai}|r_{ai}|}{1 + r_{ai}^2}$$



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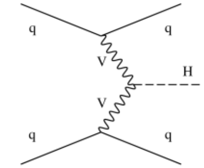

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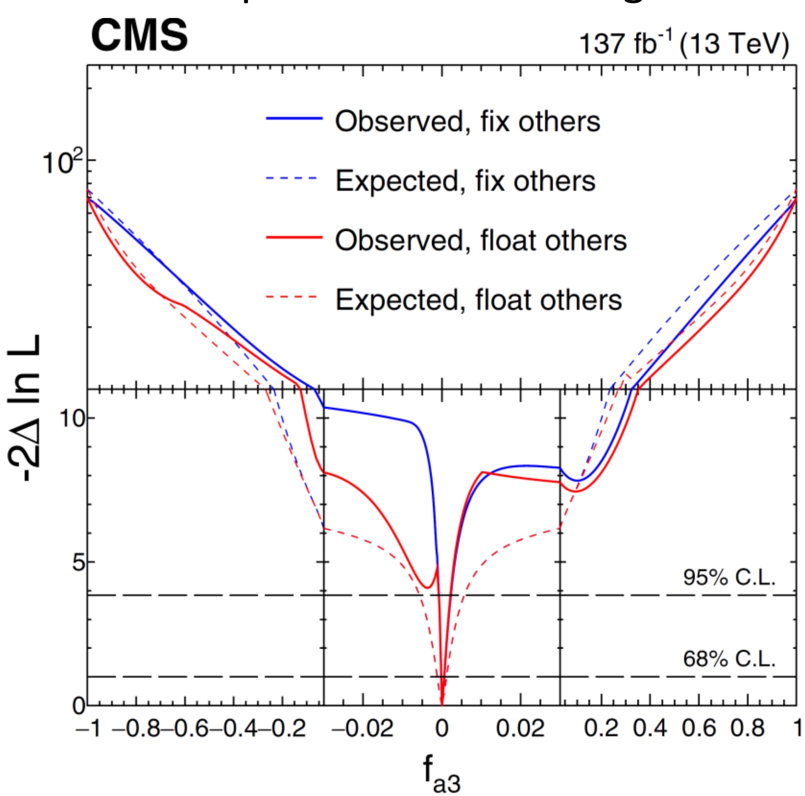
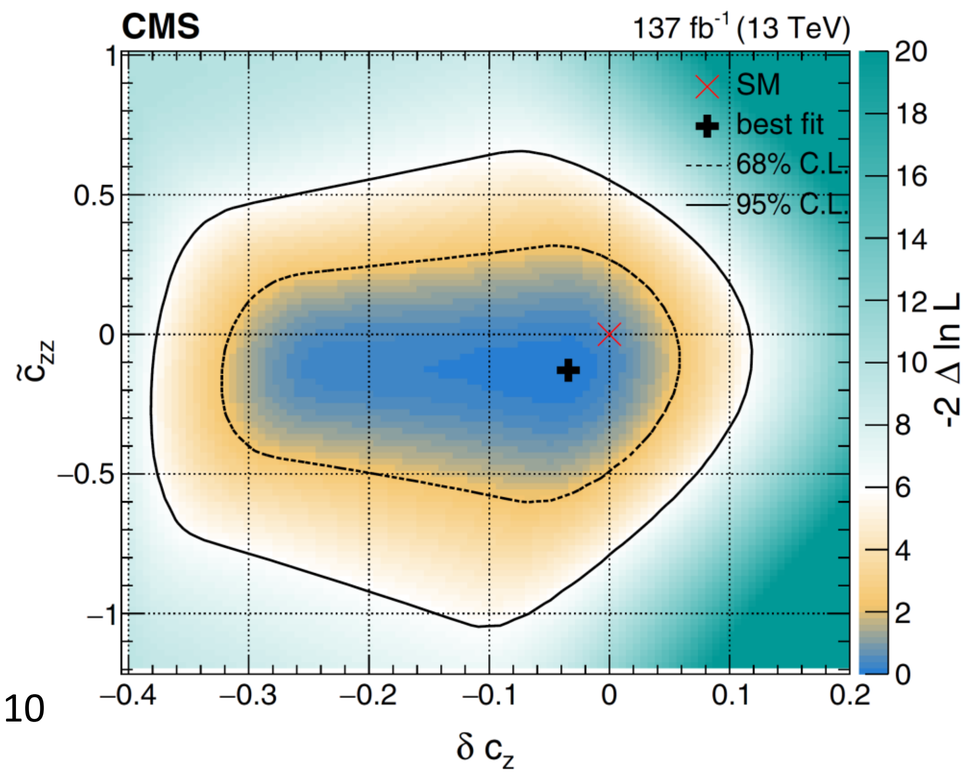
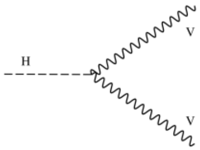
Run 2 $H \rightarrow ZZ$ measurements [link]:

→ Make use of HVV vertices in both Higgs decay and production

→ Optimized event categorization and observables to constrain on multiple couplings







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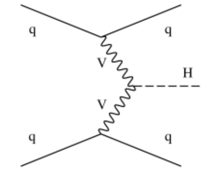

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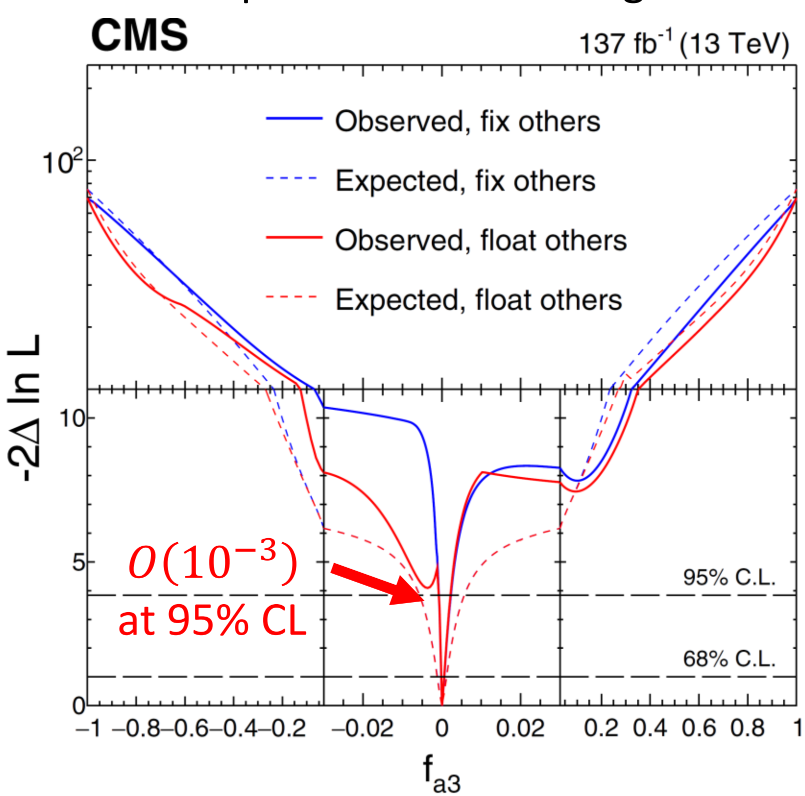

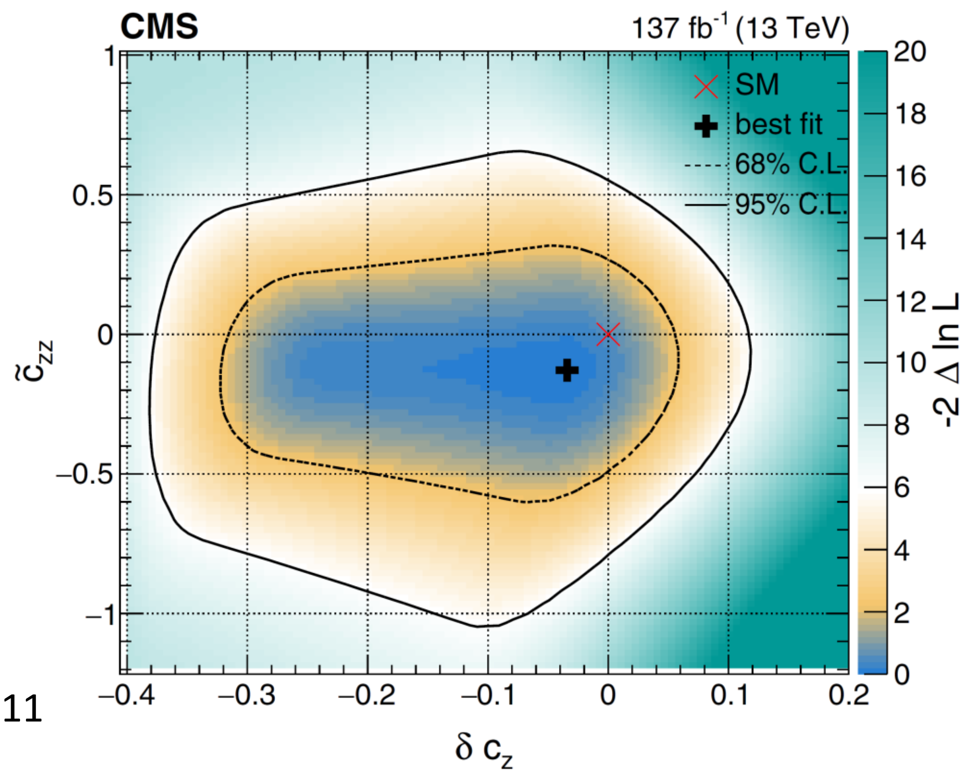

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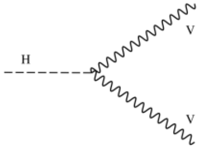

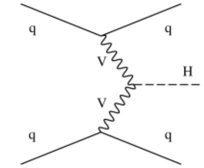

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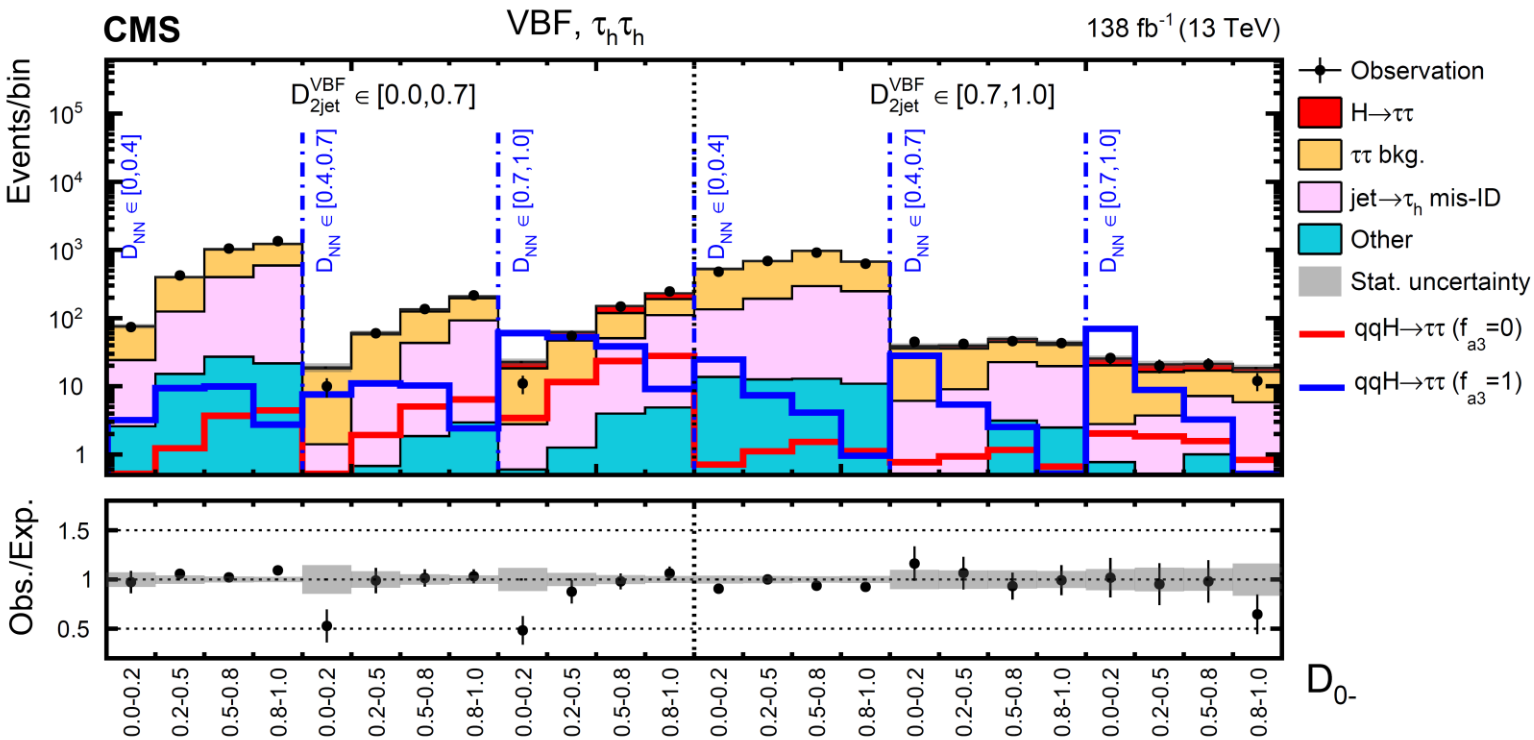
Run 2 $ZZ + \tau\tau$ combination [link]:

→ Additional sensitivity to VBF in $\tau\tau$ final state drastically improves limits.



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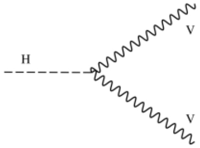

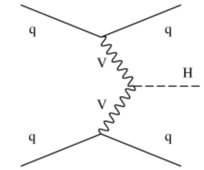

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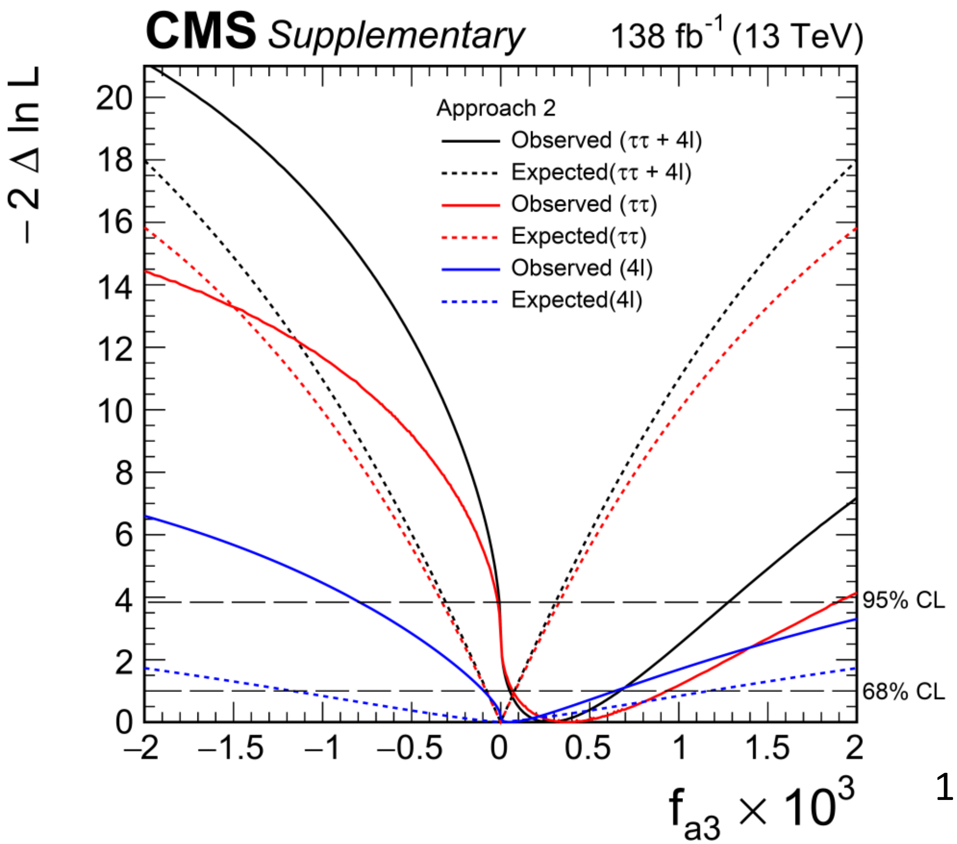
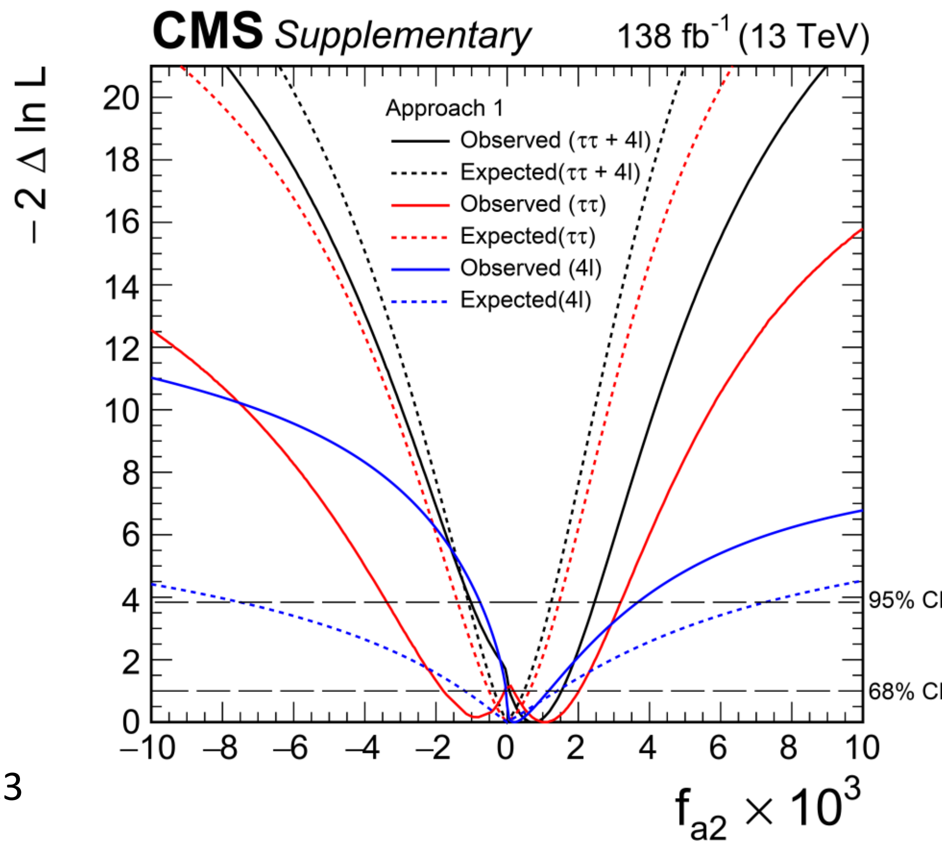
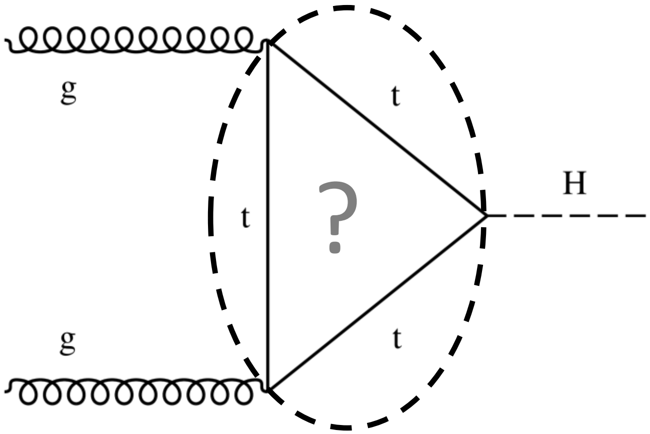
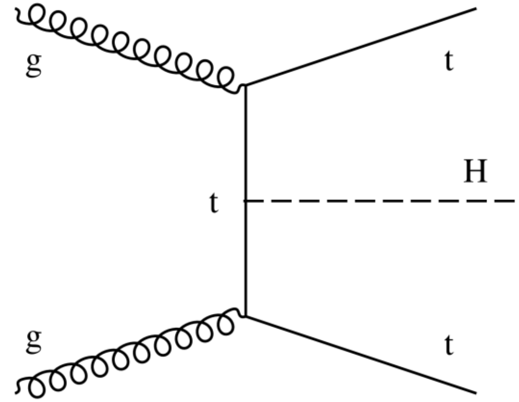
→ Constraints on different contributions typically of $O(< 10^{-3})$ at 95% CL





Anomalous Hgg/Htt couplings





$$A(Hgg) \sim \boldsymbol{a_2^{gg} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}} + a_3^{gg} \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Point-like (EFT) couplings
in the limit $m_{\mathrm{H}} < 2m_t$

$$A(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\boldsymbol{\kappa_t} + i\tilde{\kappa}_t \gamma_5) \psi_t$$

Direct modification can be probed
via $t\bar{t}H$ associated production [link]

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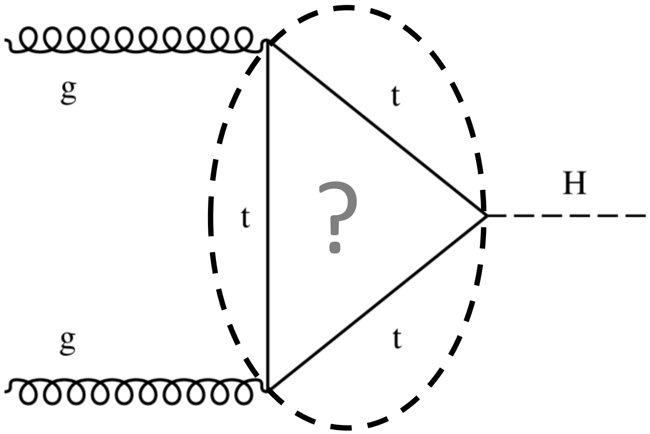

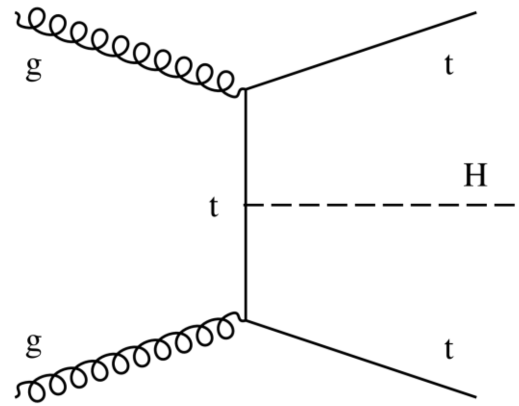

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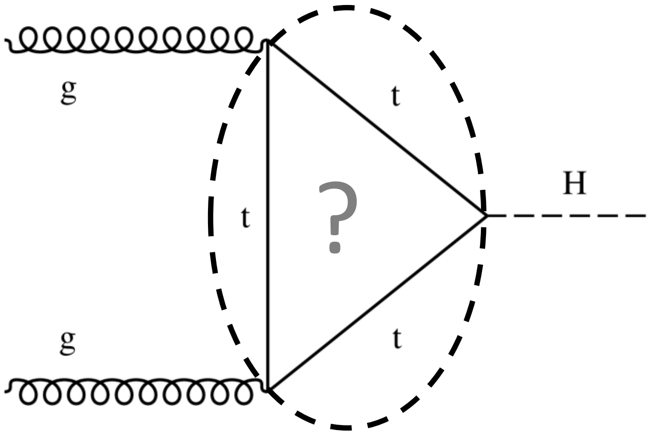
For an on-shell Higgs,

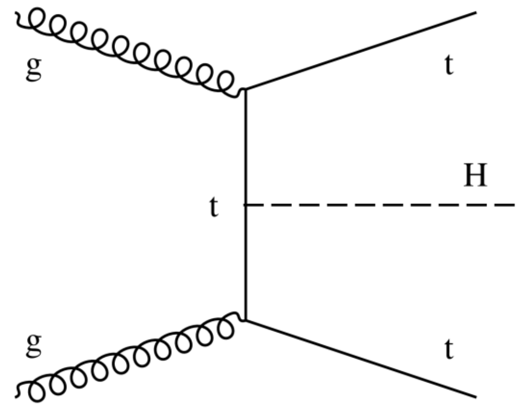
with $f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2+|a_3^{gg}|^2}\,\mathrm{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$ and $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2+|\tilde{\kappa}_t|^2}\,\mathrm{sgn}\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right)$,

the two fractions are related as $\left|f_{CP}^{Htt}\right| = \left[1 + 2.38\left(\frac{1}{\left|f_{a3}^{ggH}\right|} - 1\right)\right]^{-1}$.

(2.25 → 2.38 at NLO in QCD)

Anomalous Hgg/Htt couplings

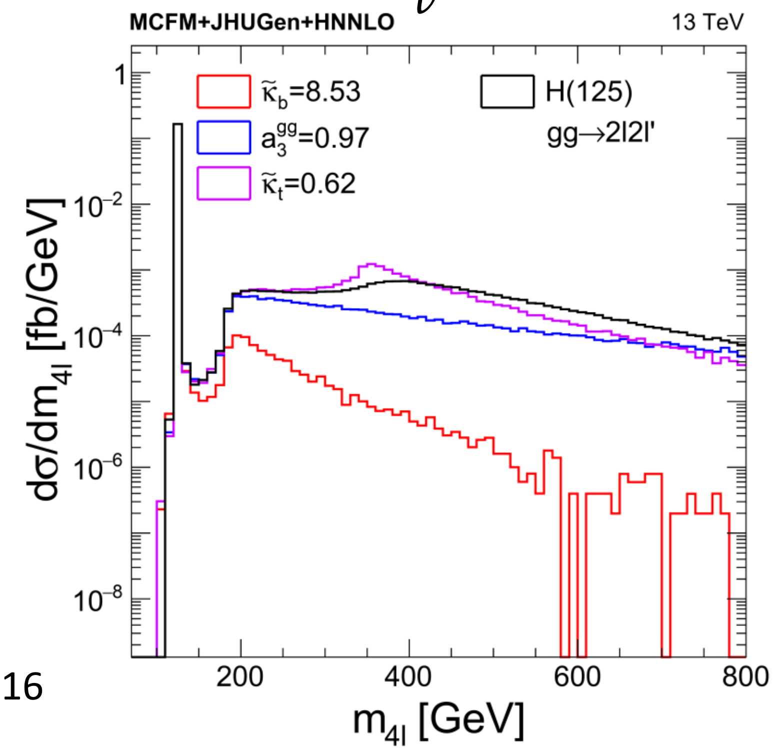




$$A(Hgg) \sim \boldsymbol{a_2^{gg} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}} + a_3^{gg} \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

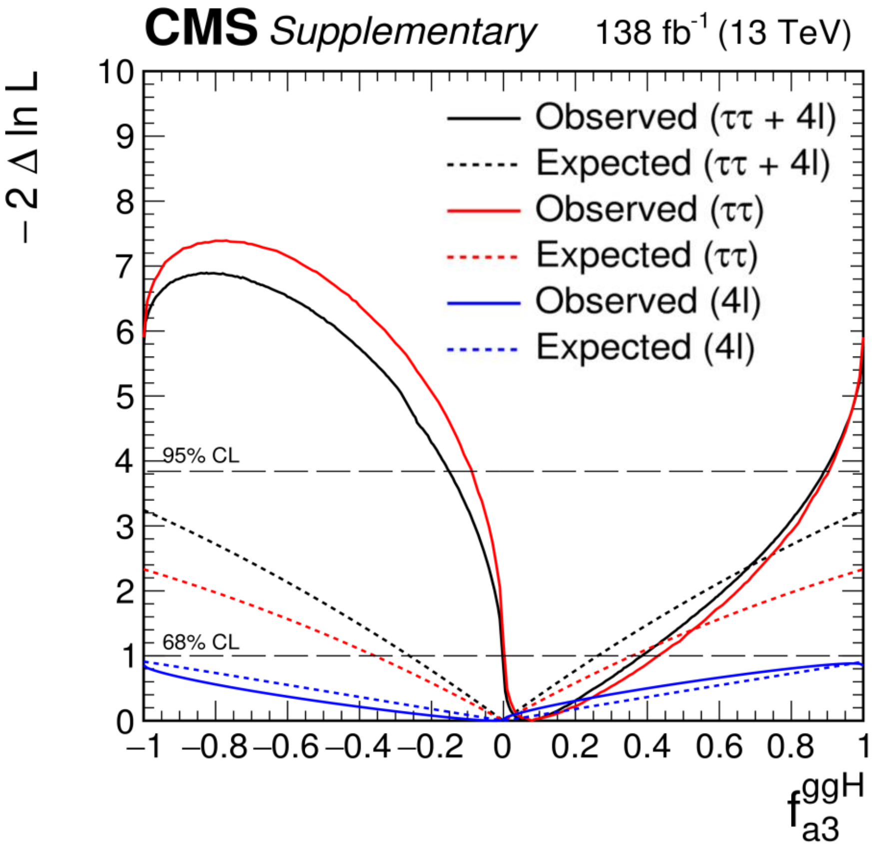
$$A(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\boldsymbol{\kappa_t} + i\tilde{\kappa}_t \gamma_5) \psi_t$$

[Link]



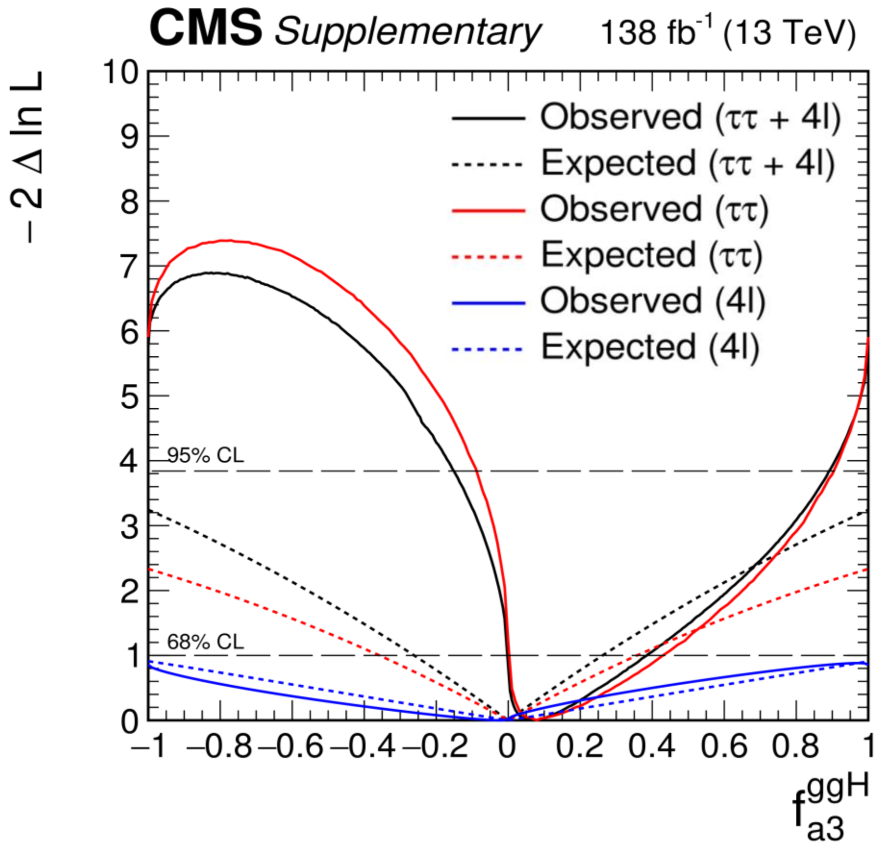
Note: For an off-shell Higgs, behavior different along m_{H^*}
→ Topic of another discussion

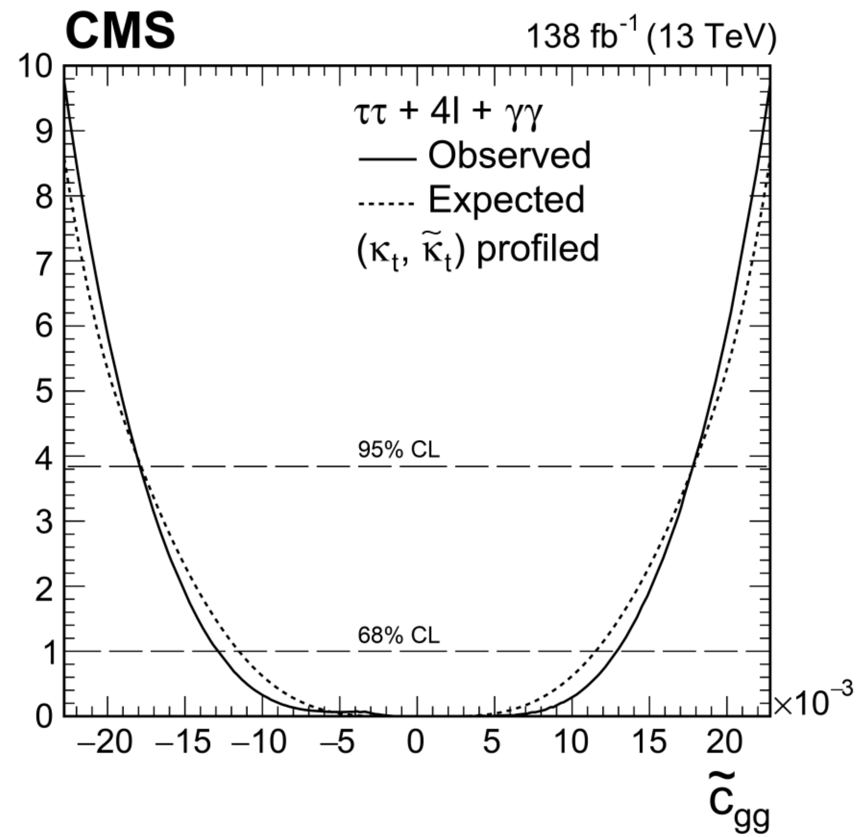
Anomalous Hgg/Htt couplings



Run 2 $4\ell + \tau\tau$ analysis [link]

Anomalous Hgg/Htt couplings

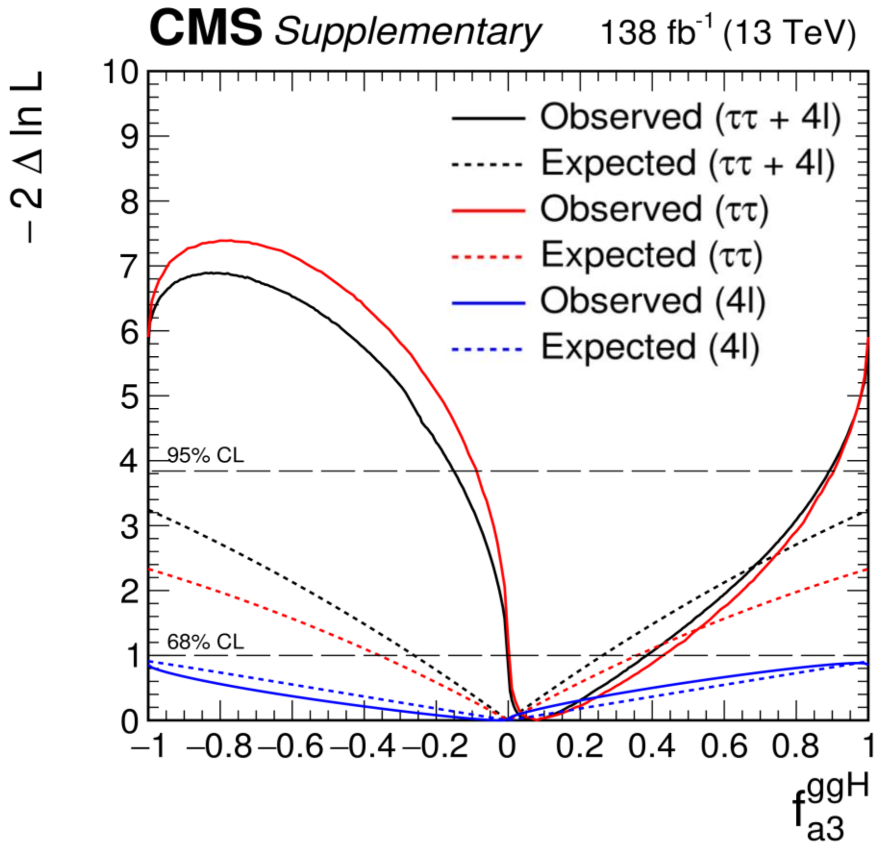


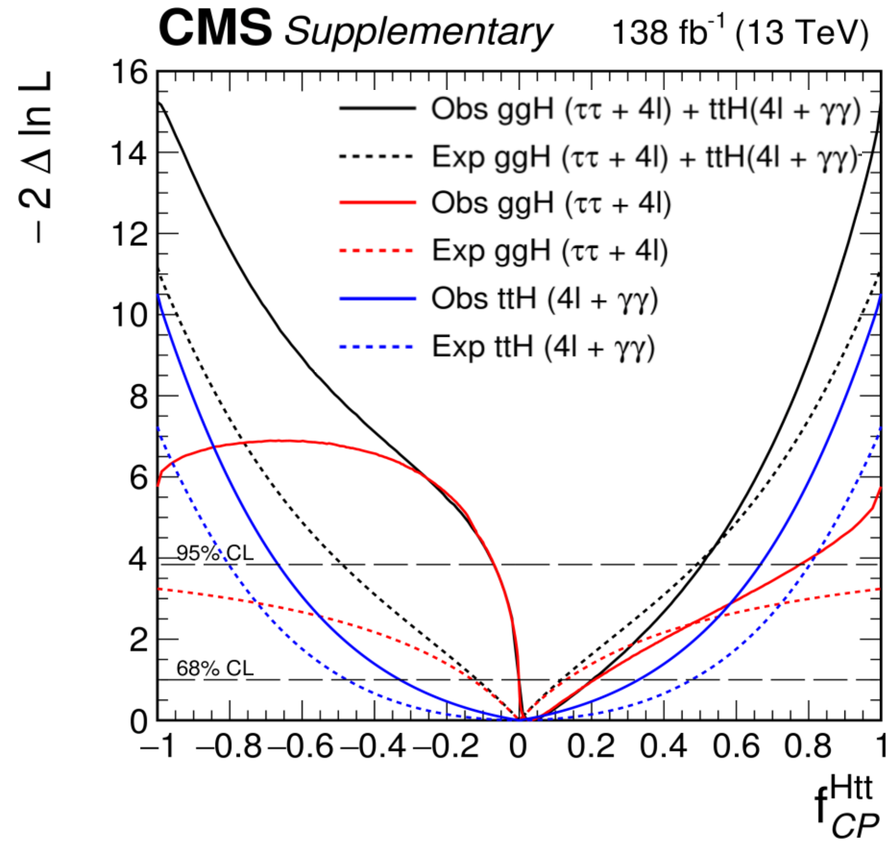


Run 2 $4\ell + \tau\tau$ analysis [link]

Also adding $t\bar{t}H, H \rightarrow \gamma\gamma$ [link]

Anomalous Hgg/Htt couplings

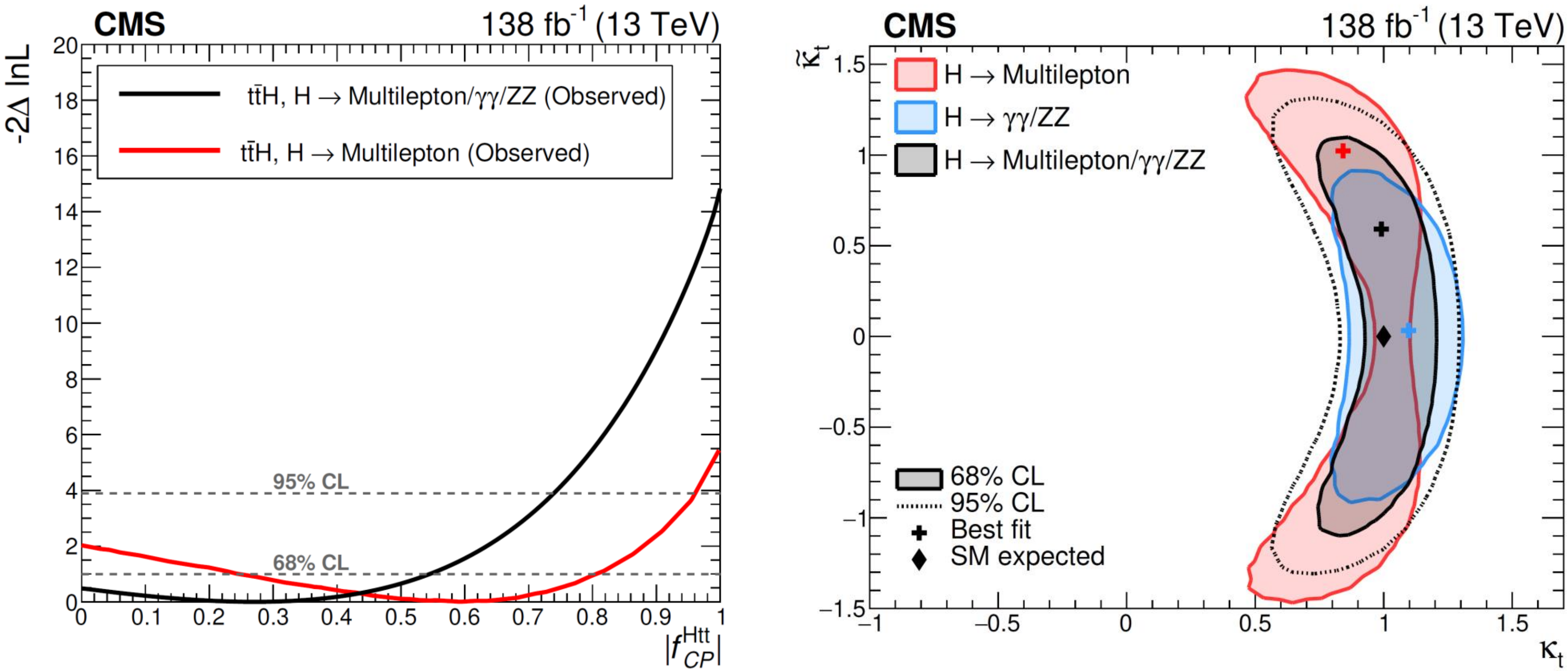




Run 2 $4\ell + \tau\tau$ analysis [link]

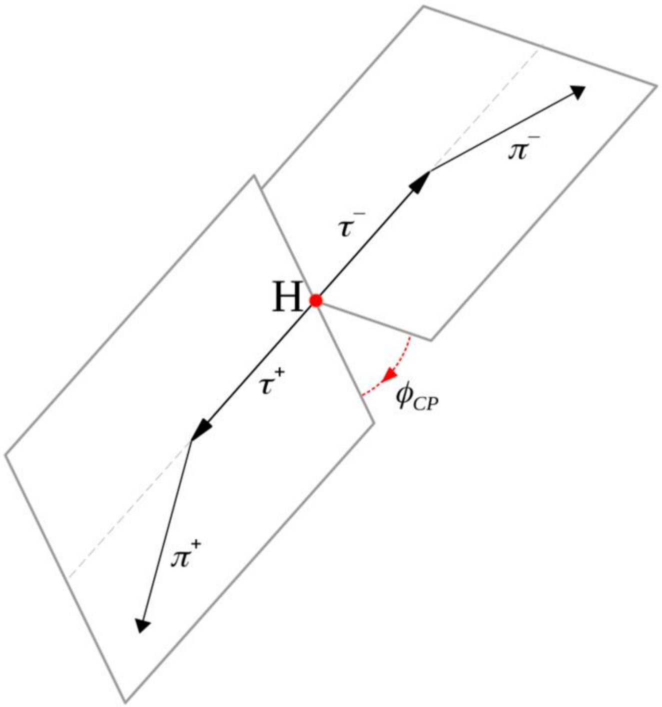
Also adding $t\bar{t}H, H \to \gamma\gamma$ [link]
→ Translate Hgg EFT to Htt couplings

More anomalous Htt couplings



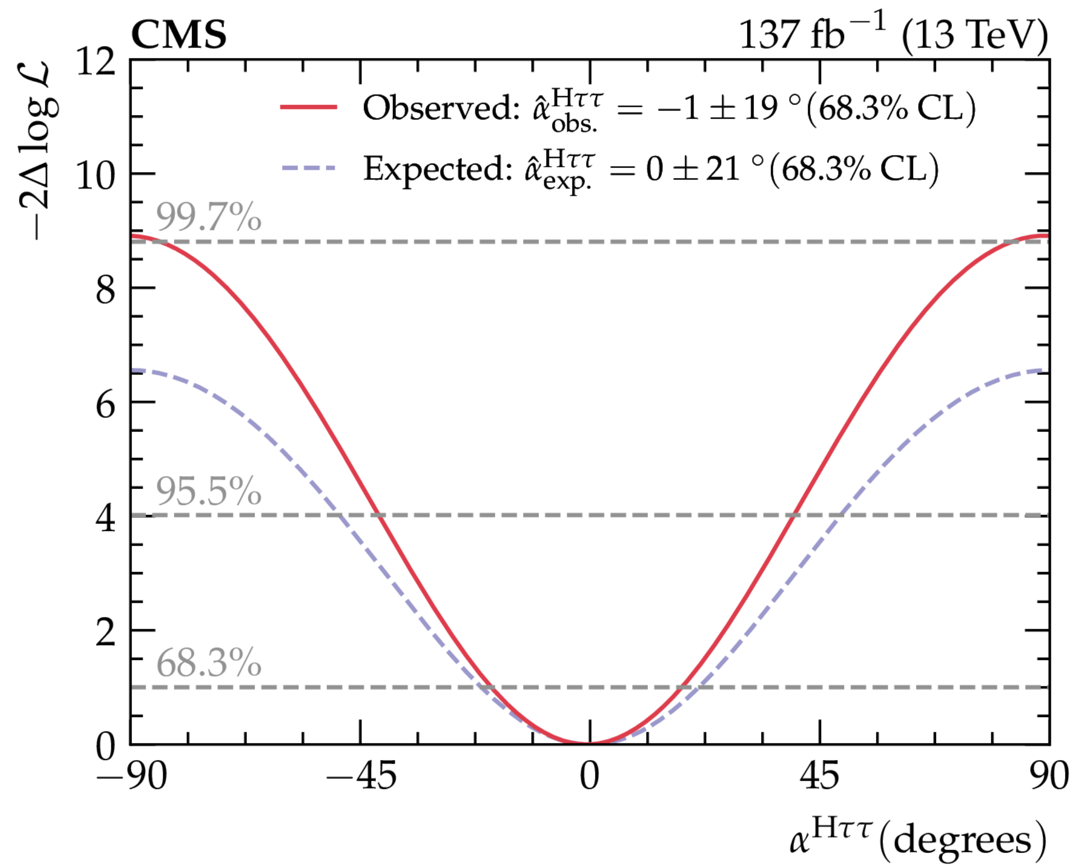
Another multilepton $t\bar{t}H + tH$ analysis combines with the 4ℓ and $\gamma\gamma$ channels:
$|f_{CP}^{Htt}| < 0.73$ @ 95% CL [link]

Anomalous $H\tau\tau$ couplings



Same amplitude/Lagrangian formalism as in Htt couplings to determine CP-violation in $H \rightarrow \tau\tau$ decays

[Link]



$$\alpha = \tan^{-1}\frac{\tilde{\kappa}_\tau}{\kappa_\tau}:$$

$[-42°, 40°]$ @ 95% CL

Di-Higgs EFT analyses

Couplings conventions in SMEFT & HEFT

$$\Delta\mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3$$
$$+ \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}\, t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a}$$
$$+ \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^a G^a_{\mu\nu}\tilde{\phi}\, t_R + \text{h.c.})$$

[Link]

$$\Delta\mathcal{L}_{\text{SILH}} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3$$
$$+ \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}\, t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu}$$

$$\Delta\mathcal{L}_{\text{HEFT}} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3$$
$$+ \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

Couplings conventions in SMEFT & HEFT

$$\Delta\mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 + \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a} + \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^aG^a_{\mu\nu}\tilde{\phi}t_R + \text{h.c.})$$

[Link]

$$\Delta\mathcal{L}_{\text{SILH}} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3 + \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\,G^a_{\mu\nu}G^{a\mu\nu}$$

$$\Delta\mathcal{L}_{\text{HEFT}} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

SILH/Warsaw → HEFT translation:
($C_{H,\text{kin}} = C_{H,\Box} - C_{HD}/4$)

HEFT	SILH	Warsaw
c_{hhh}	$1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1 - \frac{\bar{c}_H}{2} - \bar{c}_u$	$1 + \frac{v^2}{\Lambda^2}C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{\bar{c}_H+3\bar{c}_u}{4}$	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$128\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$64\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

Lost in translation?
Be careful about
→ Truncation prescription
→ Running α_s dependence

Benchmark models

JHEP 09 (2018) 057

Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	$-\frac{1.6}{3}$	-0.2
3	1.0	1.0	-1.5	0.0	$\frac{0.8}{3}$
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	$\frac{1.6}{3}$	$\frac{1.0}{3}$
6	2.4	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
7	5.0	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
9	1.0	1.0	1.0	-0.4	-0.2
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	$\frac{2.0}{3}$	$\frac{1.0}{3}$
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

Also 8: 15.0 1.0 0.0 $-2/3$ $-1/3$

JHEP 03 (2020) 091

benchmark	c_t	c_{hhh}	c_{tt}	c_{ggh}	c_{gghh}
1	0.94	3.94	$-\frac{1}{3}$	0.5	$\frac{1}{3}$
2	0.61	6.84	$\frac{1}{3}$	0.0	$-\frac{1}{3}$
3	1.05	2.21	$-\frac{1}{3}$	0.5	0.5
4	0.61	2.79	$\frac{1}{3}$	-0.5	$\frac{1}{6}$
5	1.17	3.95	$-\frac{1}{3}$	$\frac{1}{6}$	-0.5
6	0.83	5.68	$\frac{1}{3}$	-0.5	$\frac{1}{3}$
7	0.94	-0.10	1	$\frac{1}{6}$	$-\frac{1}{6}$

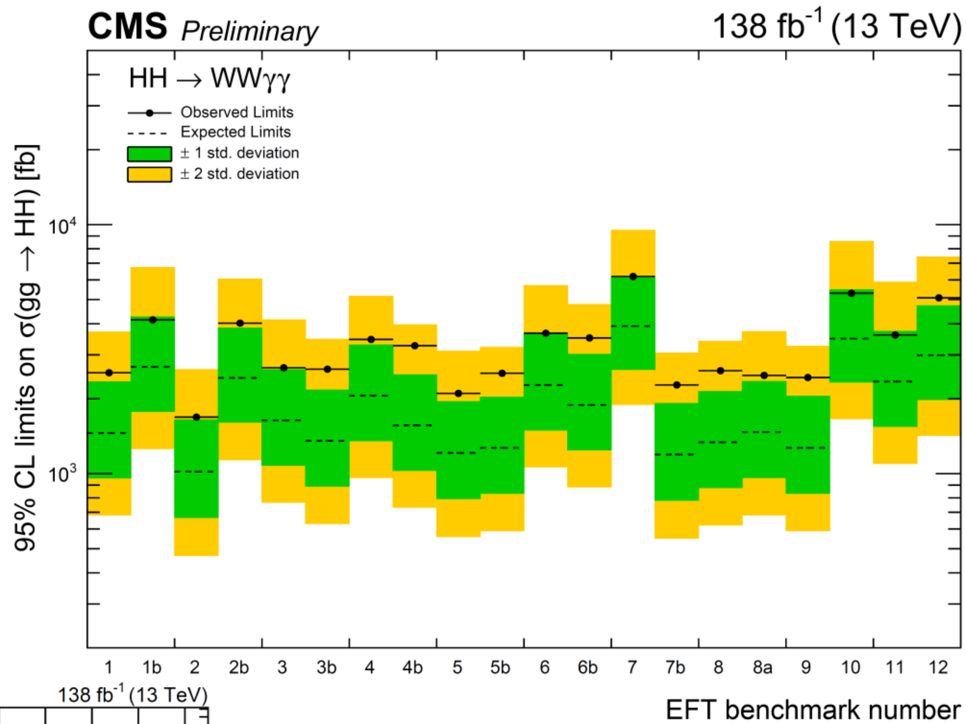
JHEP 03 BMs w/ exp. constraints [link] ⇒

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.11	1.10	0	0	0
2*	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4*	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6*	-0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	0.25
7	-0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$

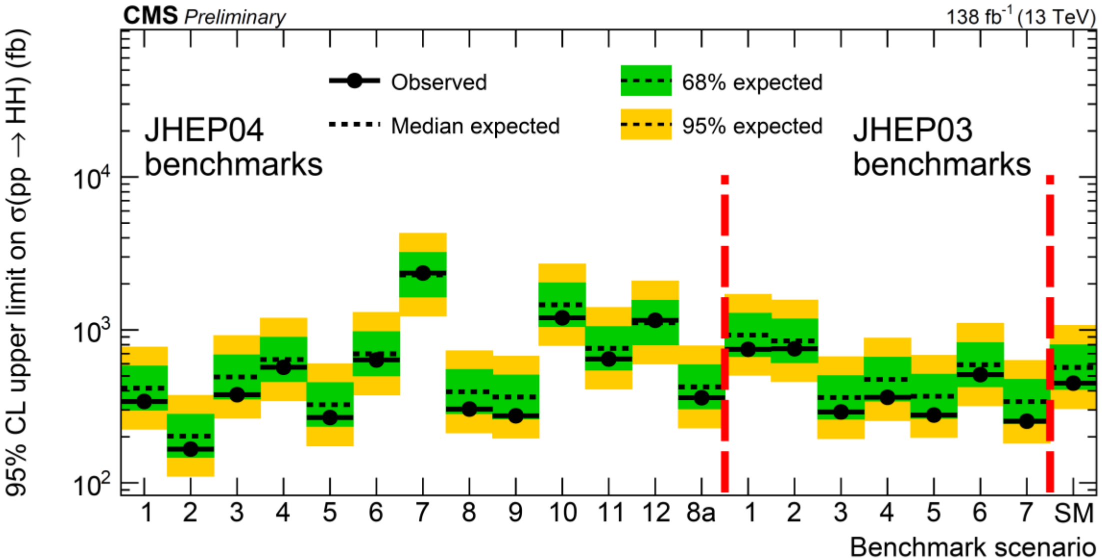
Di-Higgs EFT results typically presented in terms of limits on these 13+7 benchmark models and the SM

Constraints from $HH \to WW\gamma\gamma$ and $b\bar{b}WW$

$WW\gamma\gamma$ [link]



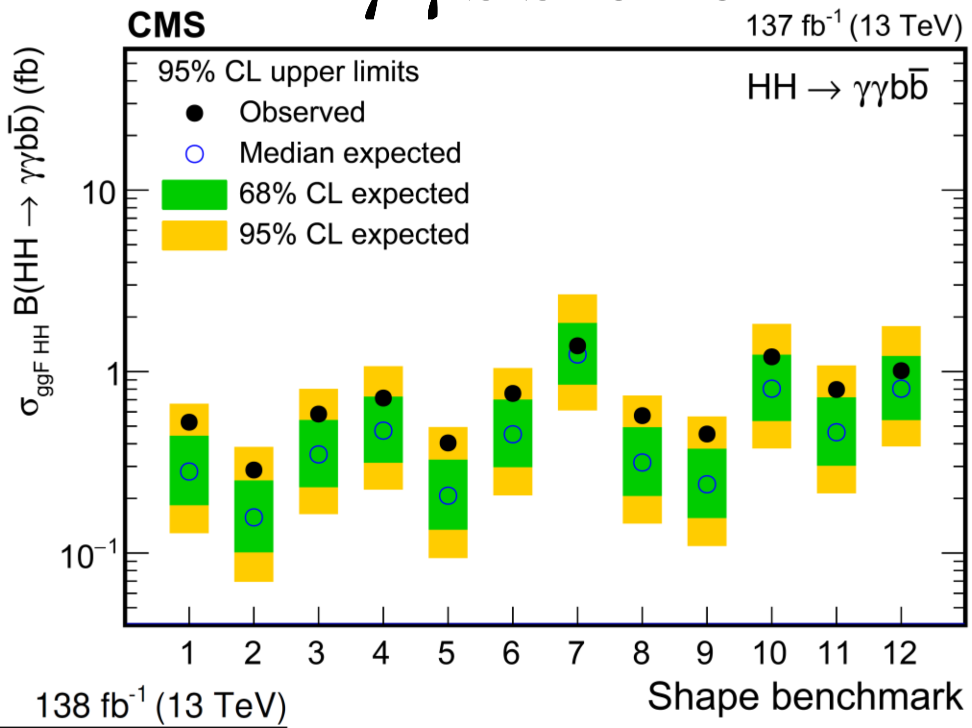
$b\bar{b}WW$ [link]



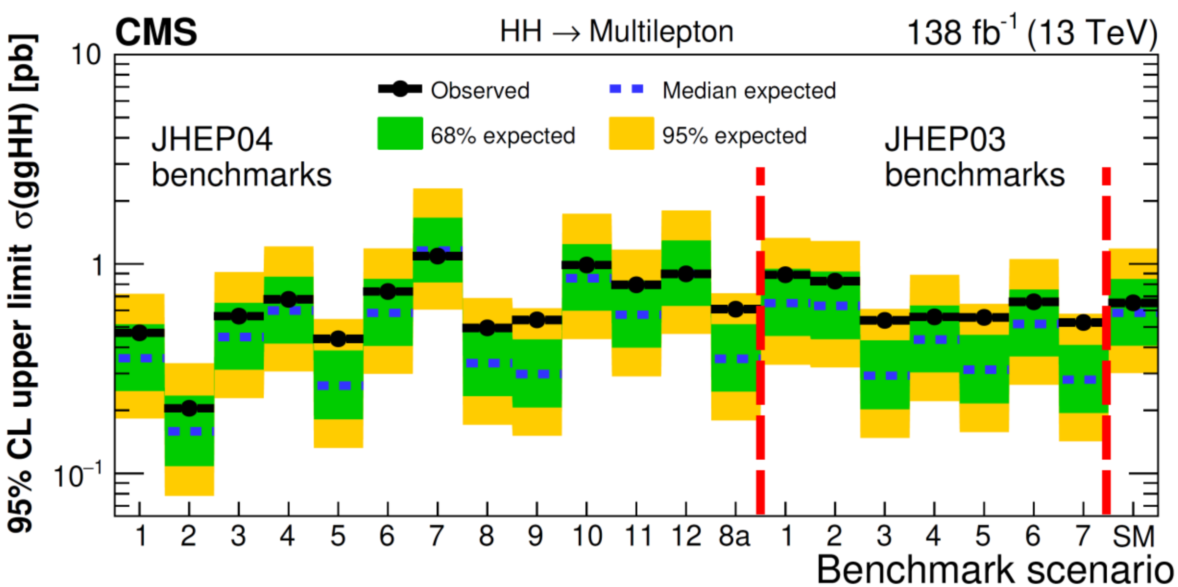
Limits in the range of 10^2-10^4 fb

Constraints from $HH \to \gamma\gamma b\bar{b}$ and

$\gamma\gamma b\bar{b}$ [link]

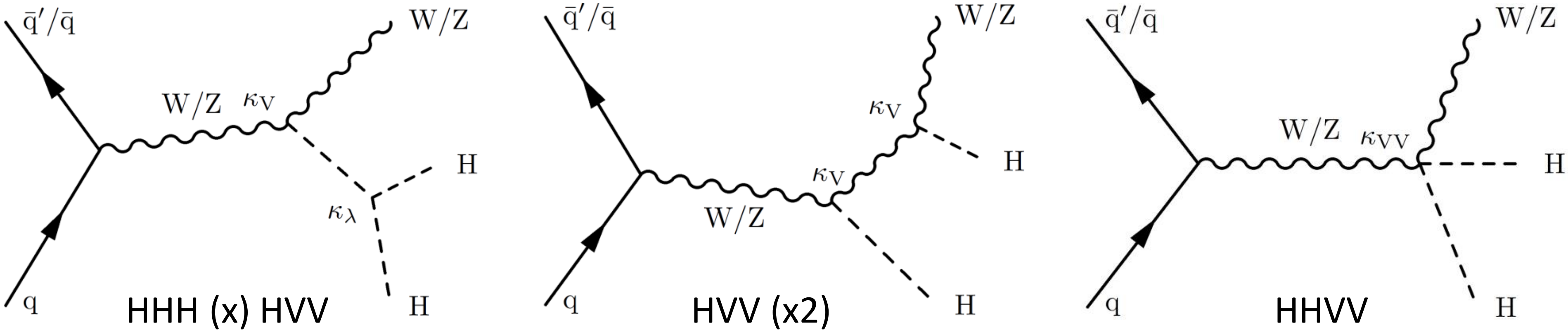


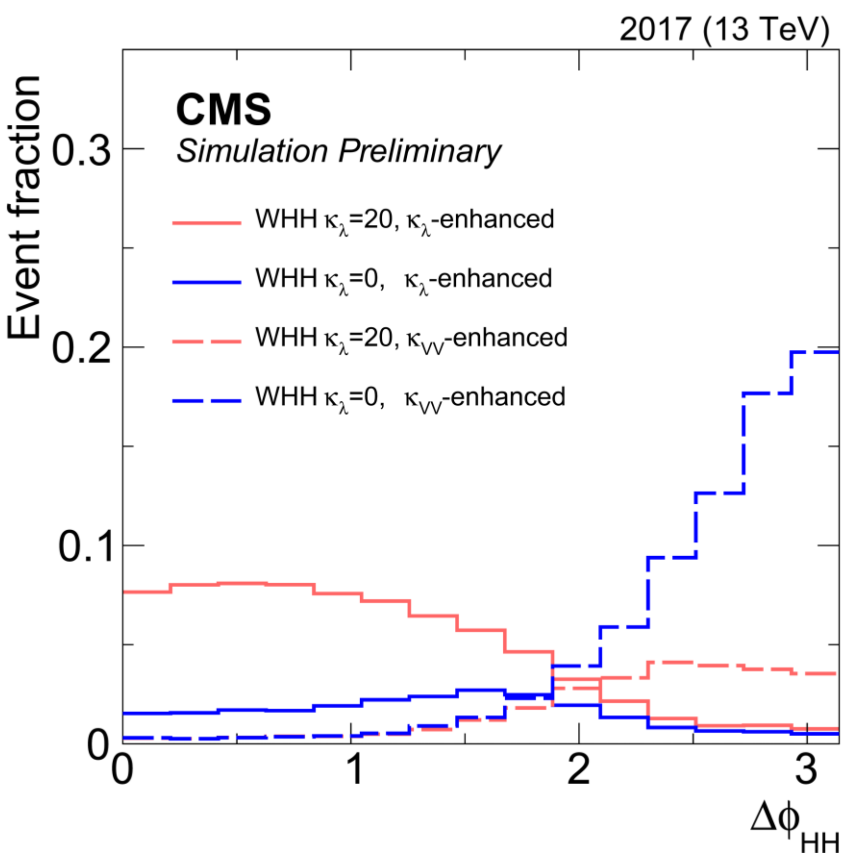
Multilepton ($HH, H \to WW/\tau\tau$) [link]



Limits in the range of 0.1-1 fb
→ JHEP 03 BMs not in the '21 $\gamma\gamma b\bar{b}$ publication
→ Stay tuned for HEFT+SMEFT combination in the near future

Di-Higgs in VHH





[Link]

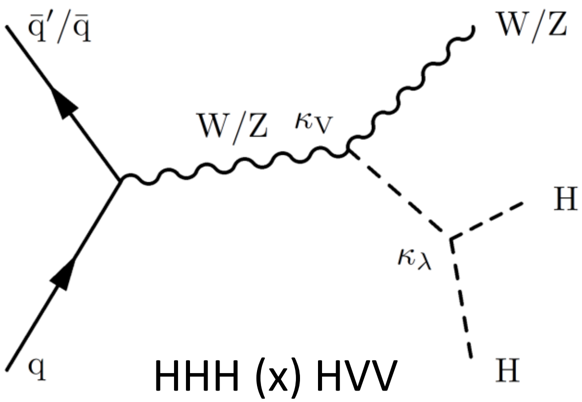
Can have proportions of
HHH (x) HVV, HVV (x2), and HHVV diagrams different from the SM

→ Examine $HH \to 4b$

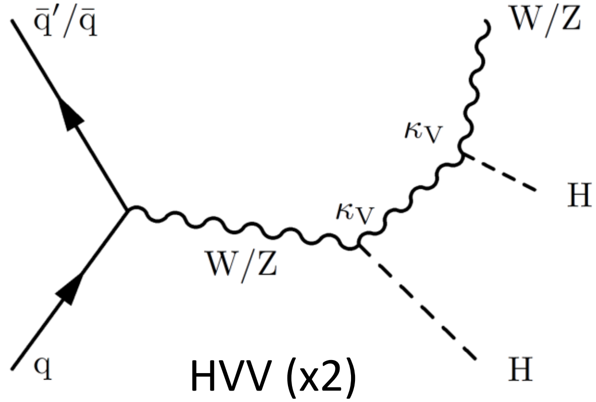
→ Complementary to HH-only results

→ Independent of κ_t and loop calculations

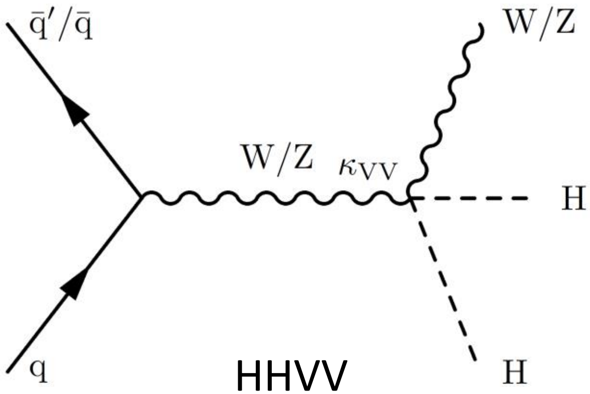
Di-Higgs in VHH



HHH (x) HVV



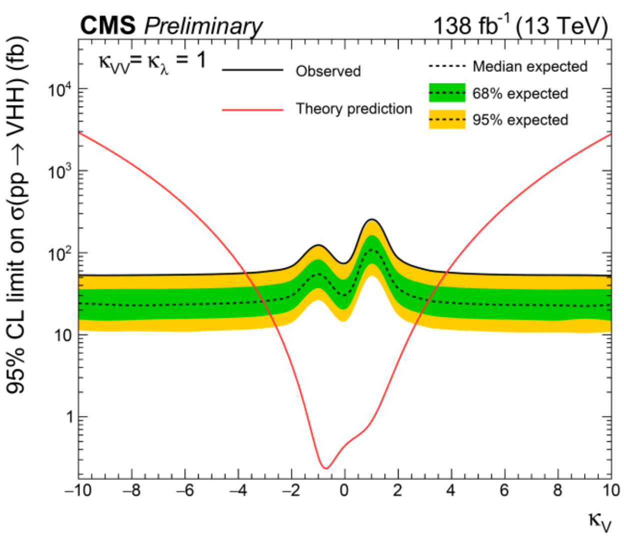
HVV (x2)



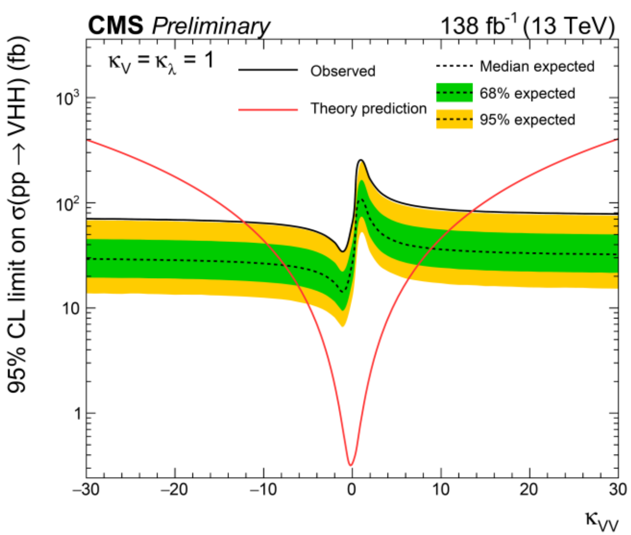
HHVV

[Link]

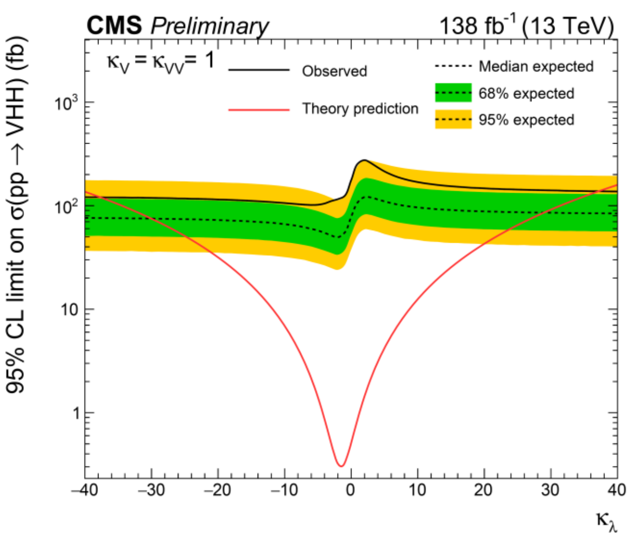
Results:



κ_V



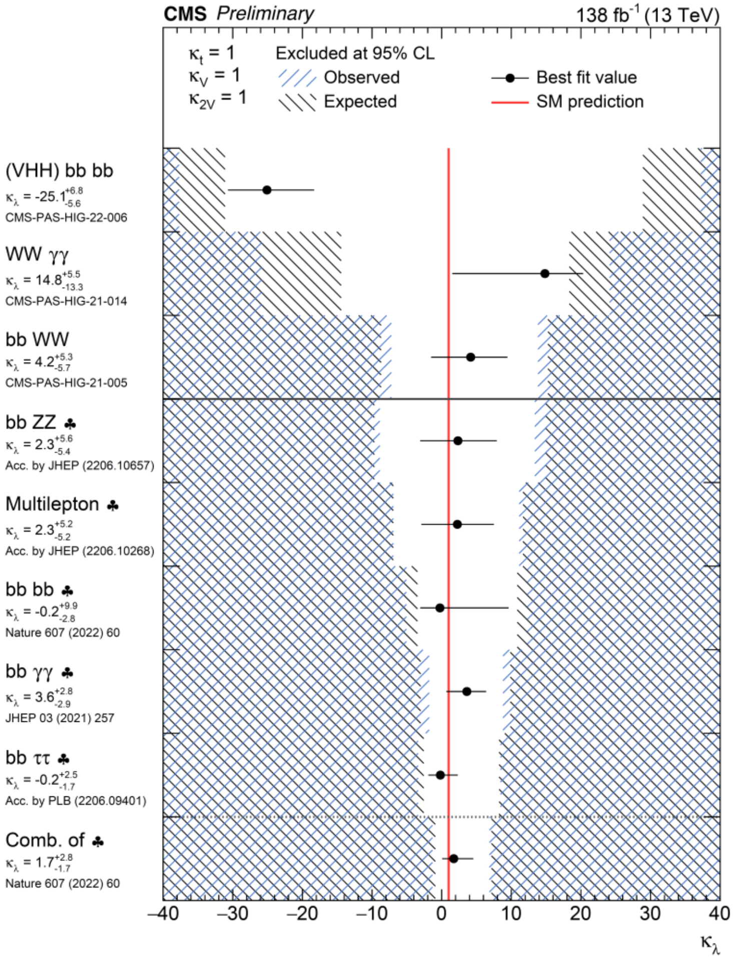
κ_{VV}



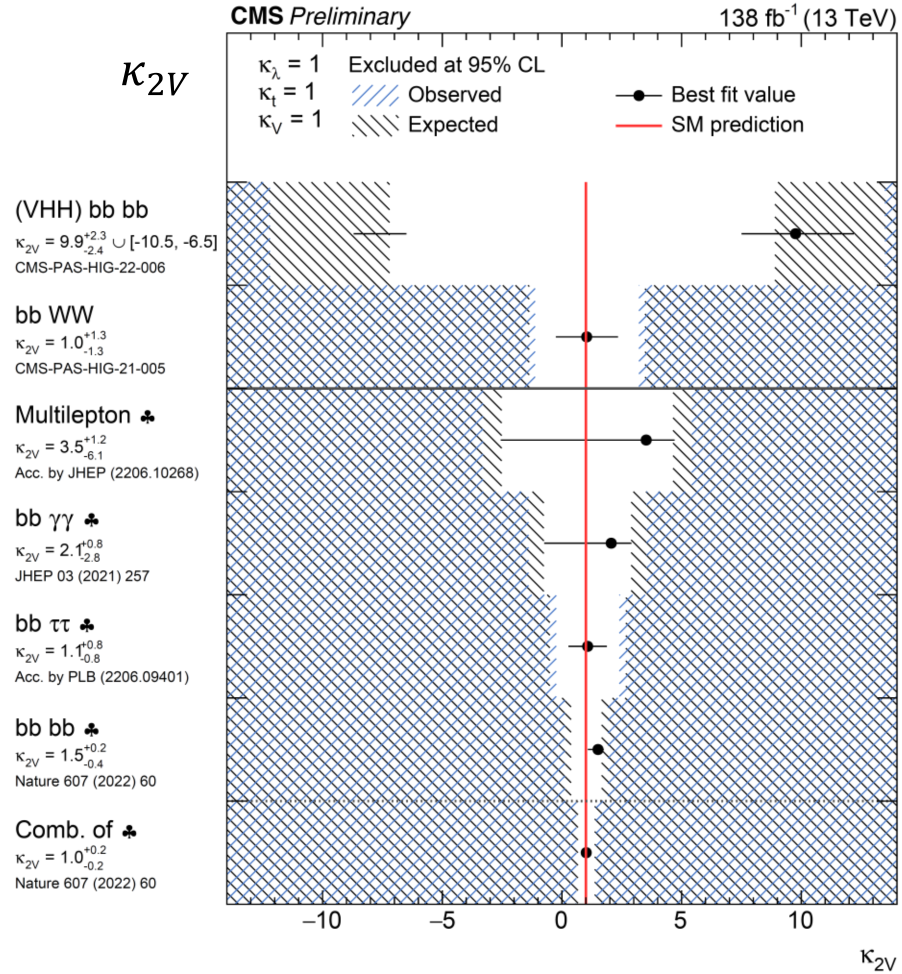
κ_λ

Di-Higgs κ_λ and κ_{2V} summary

κ_λ



κ_{2V}



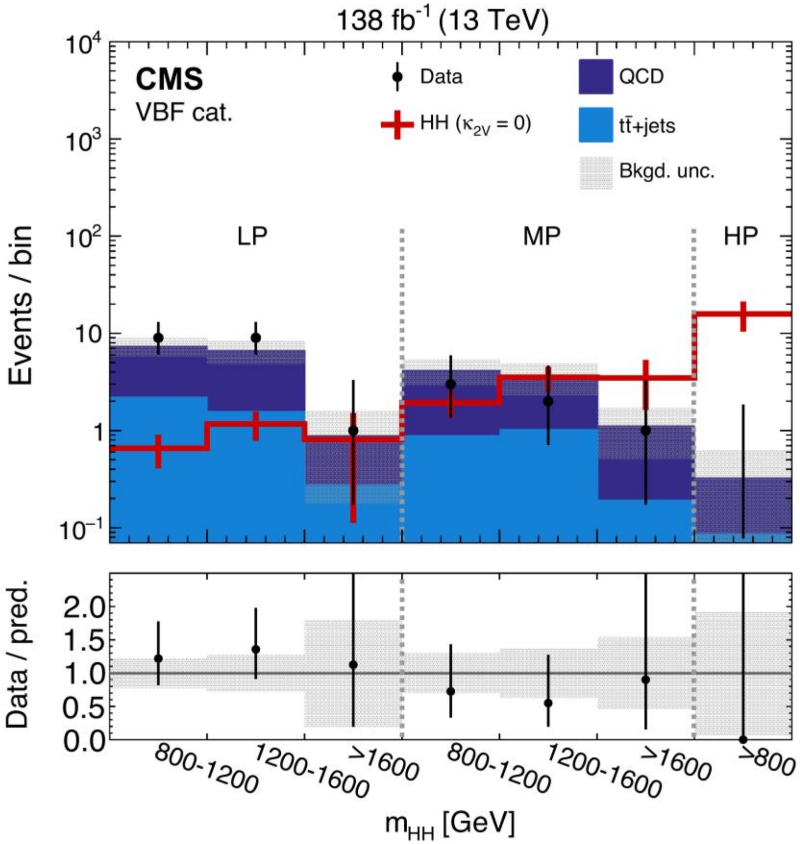
Summary of κ_λ and κ_{2V} limits from CMS analyses

→ Limits @ 95% CL from Nature publication:

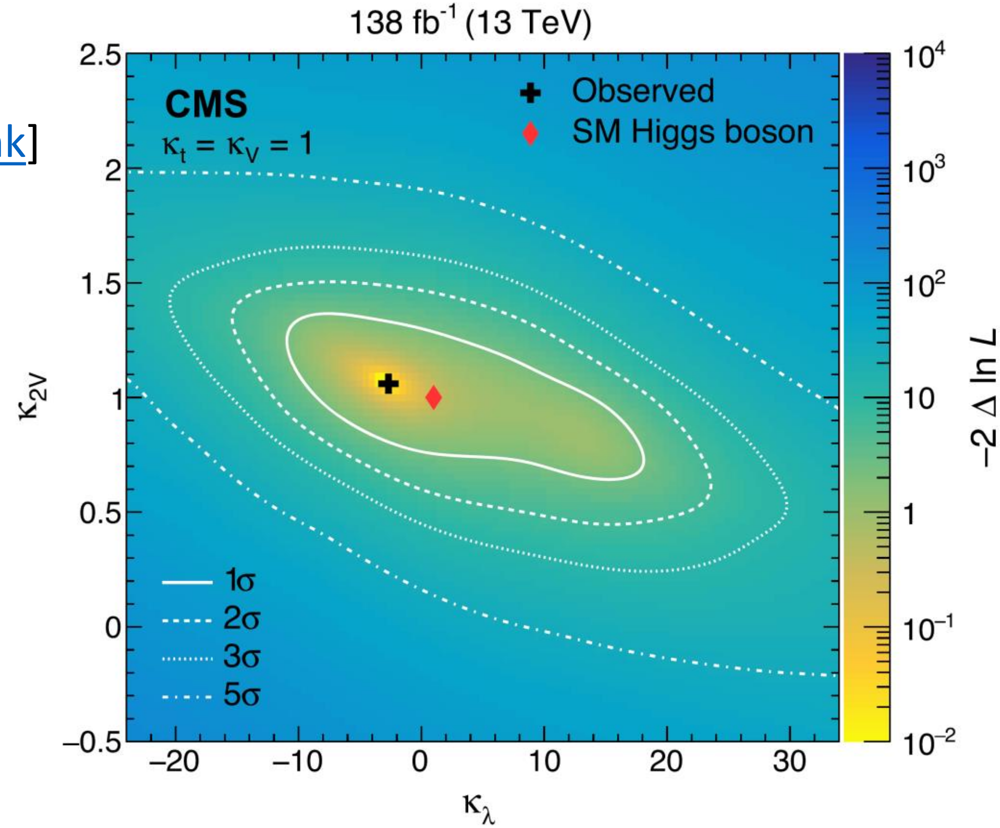
$$-1.24 < \kappa_\lambda < 6.49$$

$$0.67 < \kappa_{2V} < 1.38$$

Nonresonant $HH \rightarrow 4b$



[Link]



Recent publication in B2G:

Event categories for ggF and different levels of VBF purity
→ VBF categories shown above

Limits @ 95% CL:
$-9.9 < \kappa_\lambda < 16.9$
$0.62 < \kappa_{2V} < 1.41$

Long and successful history to understand EFT couplings relations in single-Higgs measurements since Run 1

Many new and exciting results to probe di-Higgs final states

Excellent progress in exploiting kinematic information and steps to probe rarer final states, more progress on the horizon.

No new physics yet ☹, but we have just started looking for it ☺.

Stay tuned for more exciting results in the future!