Measurement of top-Yukawa CP and Higgs EFT in 4l and $\tau\tau$ final states at CMS

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Introduction

Why CP violation matters?

- Baryon asymmetry of the universe requires CP violation
- CP violation in SM can’t explain the baryon asymmetry
- Additional CP violation needed to explain baryon asymmetry
- CP violation might exist in Higgs sector in some new physics models: 2HDM, SUSY

Our work in searching for CP violation :

- CP properties of the HVV couplings using the $4l$ final state: HIG-19-009(Phys. Rev. D 104 (2021) 05200
- gives a stronger constraint for HVV in $H\tau\tau$ channel which could be combined with $4l$: HIG-20-007(arXiv:2205.05120)

General discussion

The interactions concerned with Higgs are Hff and HV_1V_2, where V_1V_2 represents ZZ, $\gamma\gamma$, $Z\gamma$, WW or gg, f represents fermions. The general formation can be written as:

- $\mathcal{A}(Hff) = -\frac{m_f}{v}\overline{\psi_f}\left(\kappa_f + i\widetilde{\kappa_f}\gamma_5\right)\psi_f$

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

where $f^{(i)\mu\nu} = \epsilon_{Vi}^{\mu}q_i^{\nu} - \epsilon_{Vi}^{\nu}q_i^{\mu}$, $\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}f^{(i)\rho\sigma}$

Considerations of symmetry and gauge invariance require:

$$\kappa_1^{ZZ} = \kappa_2^{ZZ}, \kappa_1^{WW} = \kappa_2^{WW}, \ a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = \kappa_1^{gg} = \kappa_2^{gg} = \kappa_1^{Z\gamma} = \kappa_3^{VV} = 0$$

So we only have 13 parameters describing couplings of the H boson to EW gauge bosons:

$$a_1^{ZZ}, a_1^{WW}, a_2^{ZZ}, a_2^{WW}, a_3^{ZZ}, a_3^{WW}, \kappa_1^{ZZ}, \kappa_1^{WW}, \kappa_2^{Z\gamma}, a_2^{Z\gamma/\gamma\gamma}, a_3^{Z\gamma/\gamma\gamma}$$

and 2 parameters describing coupling Hgg: a_2^{gg}, a_3^{gg}

Each anomalous coupling corresponds to an EFT operator in Higgs basis.

Couplings of the H boson to EW gauge bosons

Since the H production in WW fusion and in ZZ fusion are very similar, we couldn't distinguish a_i^{ZZ}, a_i^{WW} in VBF.
We adopt 2 kinds of approaches.

1) Set $a_i^{ZZ} = a_i^{WW}$, $\kappa_i^{ZZ} = \kappa_i^{WW}$
2) Consider SU(2)×U(1) symmetry, we get:

$$a_1^{WW} = a_1^{ZZ}$$

$$a_2^{WW} = c_w^2 a_2^{ZZ} + s_w^2 a_2^{\gamma\gamma} + 2 s_w c_w a_2^{Z\gamma}$$

$$a_3^{WW} = c_w^2 a_3^{ZZ} + s_w^2 a_3^{\gamma\gamma} + 2 s_w c_w a_3^{Z\gamma}$$

$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{a_2^{\gamma\gamma} - a_2^{ZZ}}{m_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{a_2^{Z\gamma}}{m_Z^2}$$

$$\frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{a_2^{\gamma\gamma} - a_2^{ZZ}}{m_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{a_2^{Z\gamma}}{m_Z^2}$$

In addition, we set $a_2^{Z\gamma/\gamma\gamma} = a_3^{Z\gamma/\gamma\gamma} = 0$ for their negligible effects in our measurement.

Thus, in Approach 1), we have 5 independent parameters left: a_1^{ZZ}, a_2^{ZZ}, a_3^{ZZ}, κ_1^{ZZ}, $\kappa_2^{Z\gamma}$,
while only a_1^{ZZ}, a_2^{ZZ}, a_3^{ZZ}, κ_1^{ZZ} are independent in Approach 2).

There is a 1-1 correspondence between EFT operators and these couplings:

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

$$c_{zz} = -\frac{s_W^2 c_W^2}{2\pi\alpha} a_2,\ \widetilde{c_{zz}} = -\frac{s_W^2 c_W^2}{2\pi\alpha} a_3$$

Couplings of the H boson to EW gauge bosons

We can use the signal strength $\mu_j = \frac{\sigma_j}{\sigma_j^{SM}}$ and the fractional contributions f_{ai} of a given process j and a given parameter ai for parameterization.

For these 5 parameters, we have 4 f_{ai} :

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + \left|\kappa_2^{Z\gamma}\right|^2\sigma_{\Lambda 1}^{Z\gamma}} sgn\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + \left|\kappa_2^{Z\gamma}\right|^2\sigma_{\Lambda 1}^{Z\gamma}} sgn\left(\frac{a_2}{a_1}\right)$$

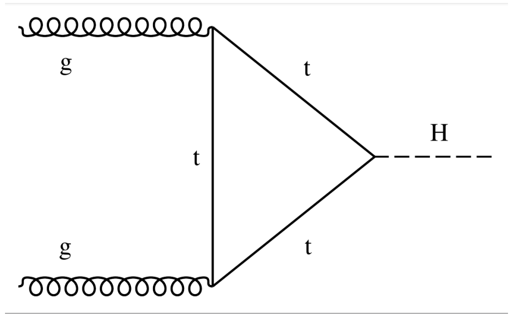
$$f_{\Lambda 1} = \frac{|\kappa_1|^2\sigma_{\Lambda 1}}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + \left|\kappa_2^{Z\gamma}\right|^2\sigma_{\Lambda 1}^{Z\gamma}} sgn\left(\frac{-\kappa_1}{a_1}\right)$$

$$f_{\Lambda 1}^{Z\gamma} = \frac{\left|\kappa_2^{Z\gamma}\right|^2\sigma_{\Lambda 1}^{Z\gamma}}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + \left|\kappa_2^{Z\gamma}\right|^2\sigma_{\Lambda 1}^{Z\gamma}} sgn\left(\frac{-\kappa_2^{Z\gamma}}{a_1}\right)$$

Where σ_{ai} represents the cross section of $ai = 1$ and other parameters are 0.

Hgg

For Hgg, considering the gluon fusion, we may give a simultaneous constraint of the four coefficients: a_2^{gg}/a_3^{gg} and $\kappa_t/\tilde{\kappa}_t$



There are 2 kinds of hypothesis:

1) Hgg as an effective coupling, with parameters a_2^{gg} and a_3^{gg} absorbing all SM and BSM loop contributions: we just measure a_2^{gg}/a_3^{gg} in ggH and $\kappa_t/\tilde{\kappa}_t$ in ttH/tH respectively.

2) Top quark dominants in the gluon fusion loop, so we can parameterize Hgg with $\kappa_t/\tilde{\kappa}_t$(contribution of top and bottom quarks) and a_2^{gg}/a_3^{gg}(BSM), and measure them in ggH combined with in ttH/tH .

a_2^{gg}/a_3^{gg} can be parameterized as:

$$c_{gg} = -\frac{1}{2\pi\alpha_s}a_2^{gg}, \widetilde{c_{gg}} = -\frac{1}{2\pi\alpha_s}a_3^{gg} \text{ in EFT} \quad \textbf{Or} \quad f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2+|a_3^{gg}|^2} sign\left(\frac{a_3^{gg}}{a_2^{gg}}\right), \mu_{ggH} = \frac{\sigma(ggH)}{\sigma_{SM}}$$

For $\kappa_t/\tilde{\kappa}_t$:

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2+|\tilde{\kappa}_t|^2} sign\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right), \mu_{Htt} = \frac{\sigma(Htt)}{\sigma_{SM}}$$

	CP-odd	CP-even
Hgg	a_3^{gg}	a_2^{gg}
Htt	$\tilde{\kappa}_t$	κ_t

Observables

Generic definition of Discriminant:

$$\mathcal{D}_{BSM} = \frac{\mathcal{P}_{SM}(\vec{\Omega})}{\mathcal{P}_{SM}(\vec{\Omega})+\mathcal{P}_{BSM}(\vec{\Omega})}, \quad \mathcal{D}_{int} = \frac{\mathcal{P}^{int}_{SM-BSM}(\vec{\Omega})}{\mathcal{P}_{SM}(\vec{\Omega})+\mathcal{P}_{BSM}(\vec{\Omega})}$$

BSM: the process with anomalous couplings
int: the interference part
$\mathcal{P}$: the probability density (square of matrix element) of a certain process and a given final state $\vec{\Omega}$ (information about the 4-momentum of outgoing particles)

With different process and couplings, we get several discriminants.
For example:

Using the definition of $\mathcal{D}_{BSM}$:

$$\mathcal{D}^{ggH}_{0-} = \frac{\mathcal{P}^{ggH}_{SM}}{\mathcal{P}^{ggH}_{SM} + \mathcal{P}^{ggH}_{0-}}$$

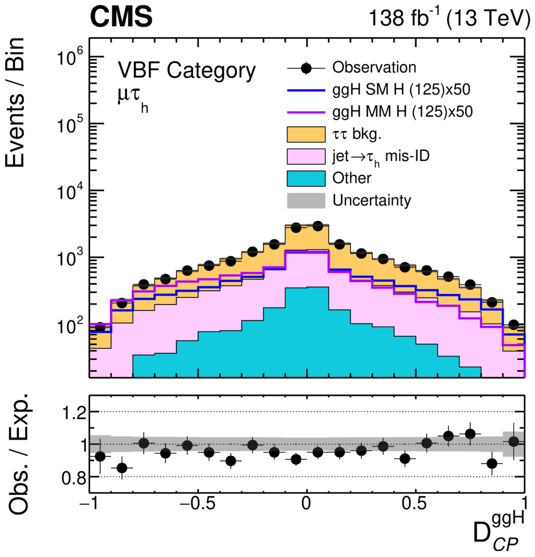
$$\mathcal{D}_{0-} = \frac{\mathcal{P}^{VBF}_{SM}}{\mathcal{P}^{VBF}_{SM} + \mathcal{P}^{VBF}_{0-}}$$

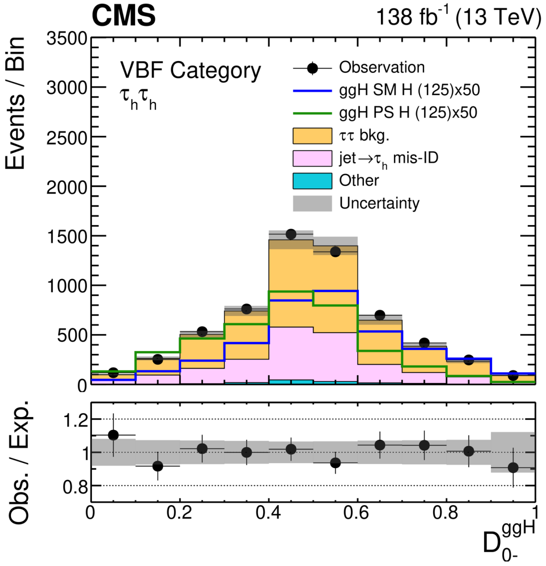
Using the definition of $\mathcal{D}_{int}$:

$$\mathcal{D}^{ggH}_{CP} = \frac{\mathcal{P}^{ggH}_{SM-0-}}{\mathcal{P}^{ggH}_{SM} + \mathcal{P}^{ggH}_{0-}}$$

$$\mathcal{D}^{VBF}_{CP} = \frac{\mathcal{P}^{VBF}_{SM-0-}}{\mathcal{P}^{VBF}_{SM} + \mathcal{P}^{VBF}_{0-}}$$

0^- means the CP-odd contribution to $\mathcal{P}$ of $a_3^{gg}(a_3^{ZZ})$
$\mathcal{D}^*_{0-}$ are sensitive to CP-odd term
$\mathcal{D}^*_{CP}$ are sensitive to the interference of CP-odd and CP-even terms



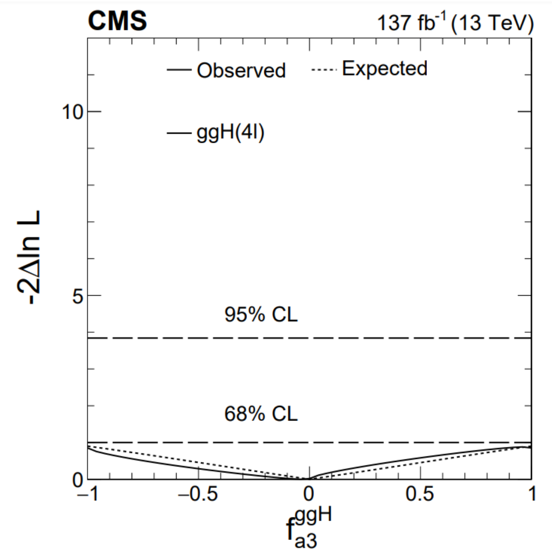


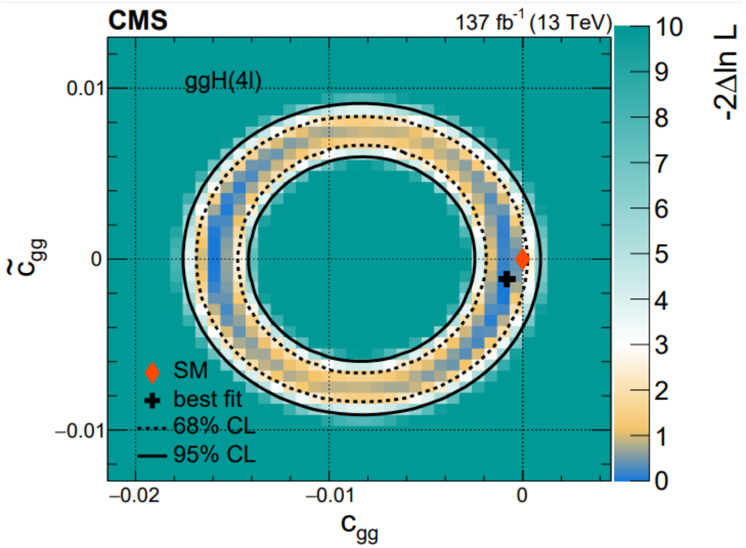
Use these Discriminant as our observables, and by fitting their distributions in MC samples to Data, we can give constraints on parameters.

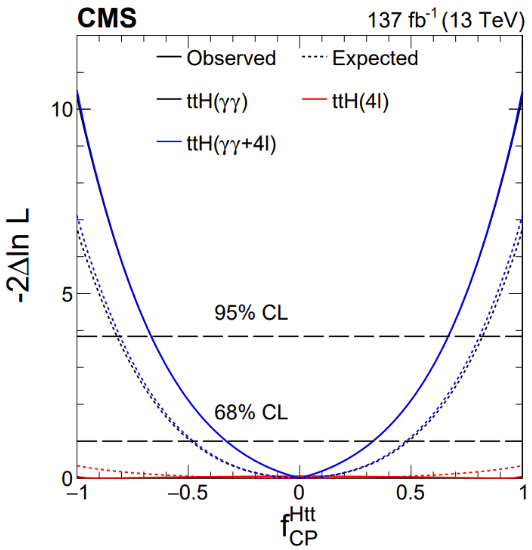
Results for Hgg in $4l$

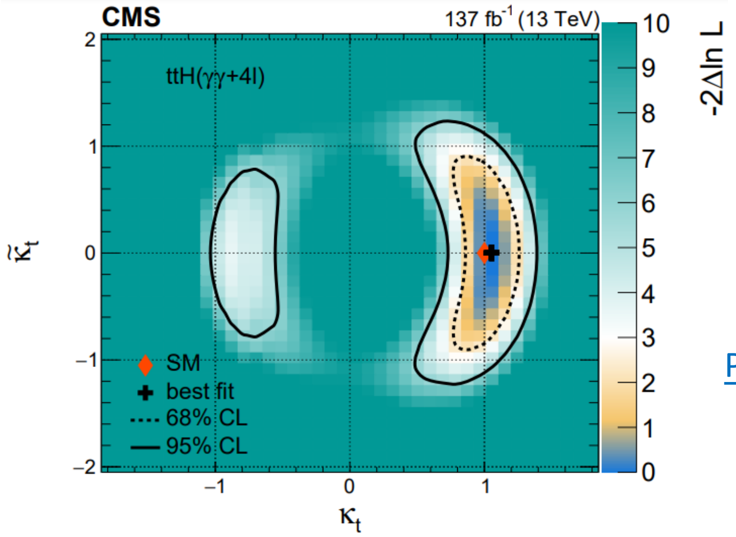
Measuring in ggH and ttH production, we get:

Hypothesis 1):









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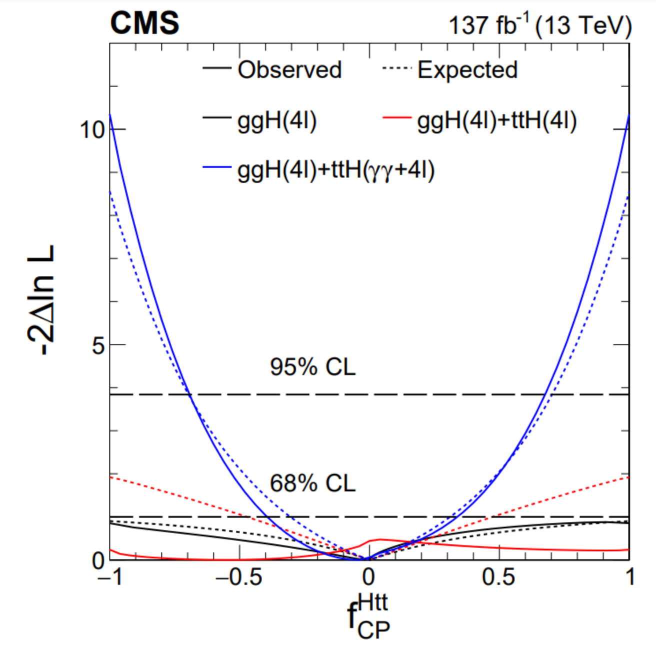
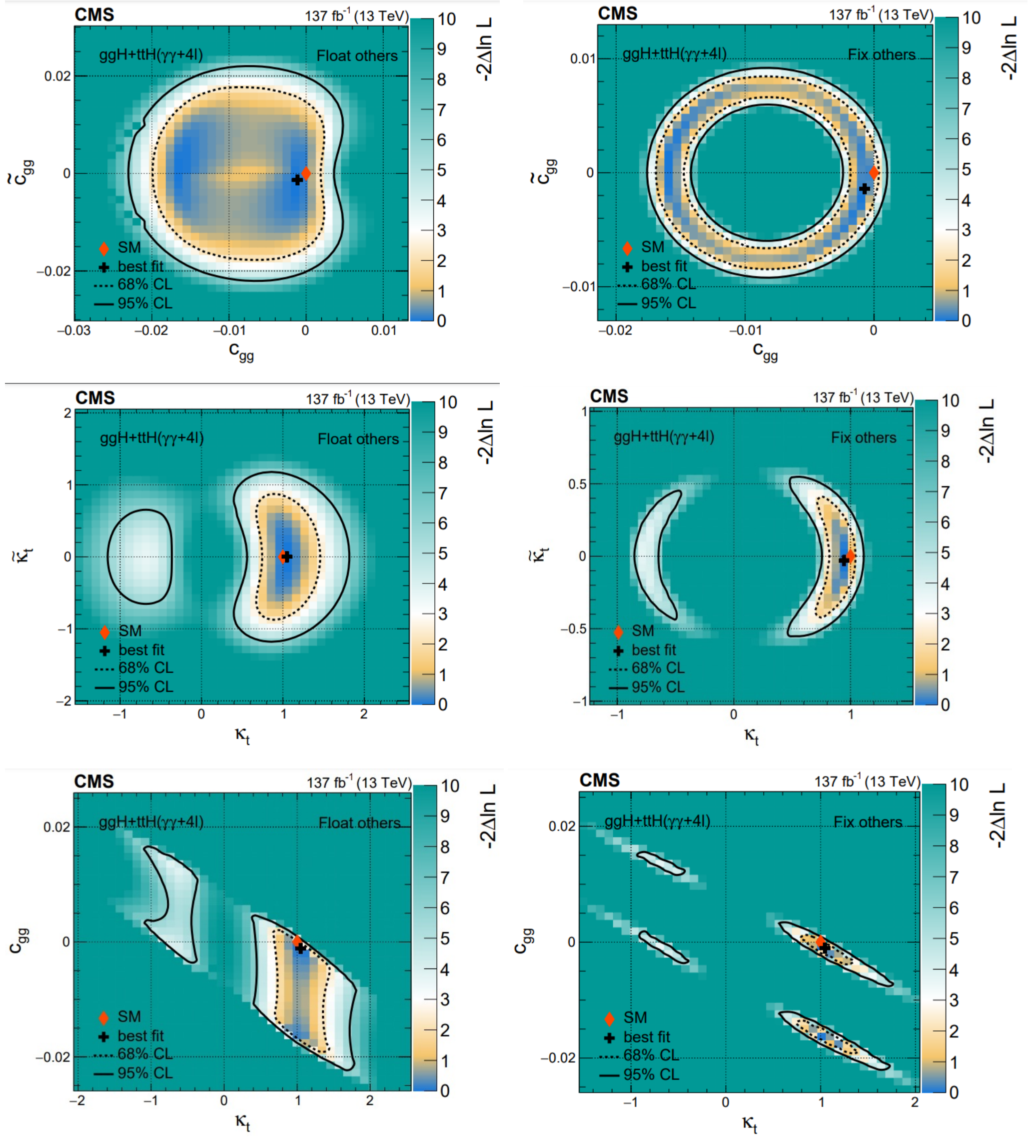
Results for Hgg in $4l$

Hypothesis 2):

ggH can be combined with $t\bar{t}H$ and tH.

$\frac{\sigma(\widetilde{\kappa_t}=1)}{\sigma(\kappa_t=1)}$ is 2.38 for ggH and is 0.391 for $t\bar{t}H$: gives a stronger constraint.





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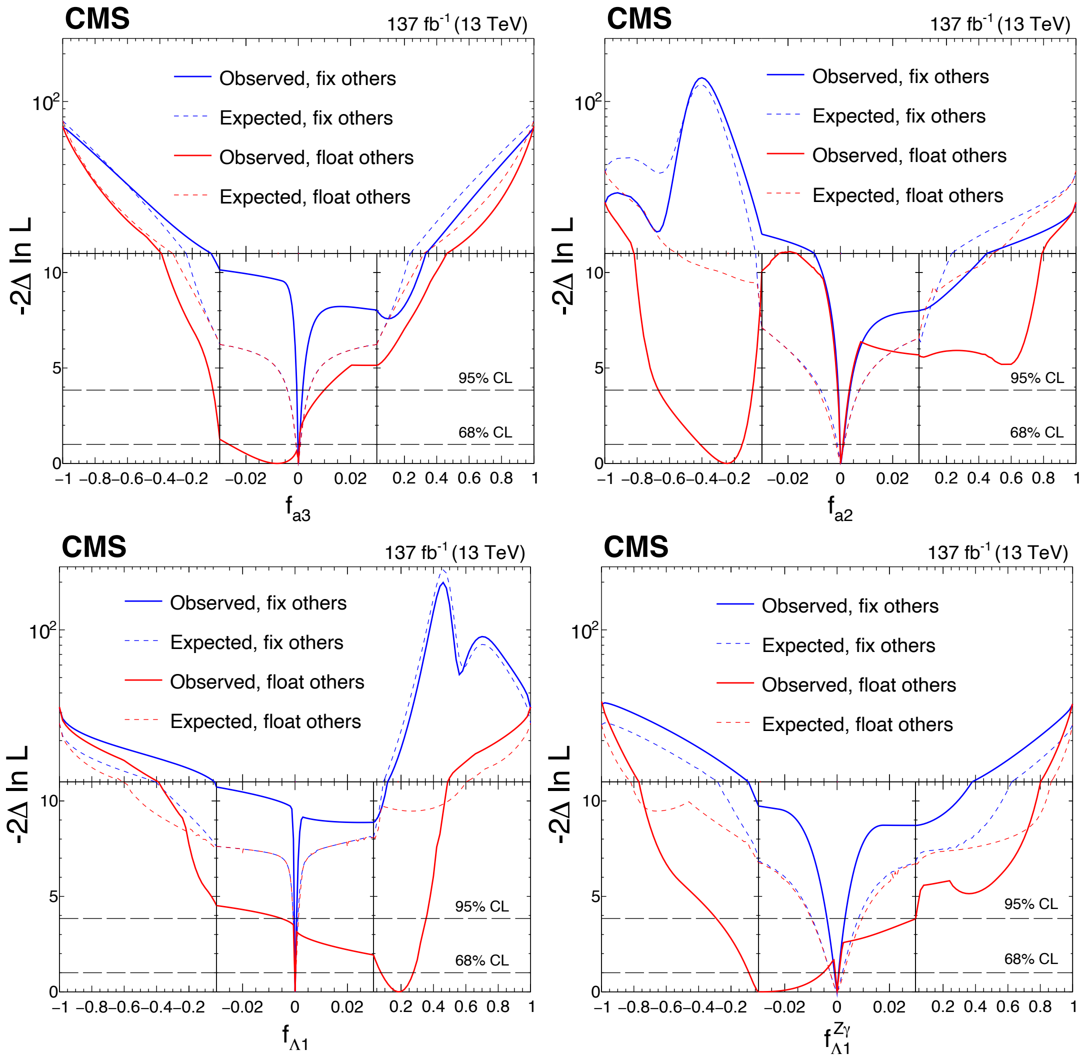
Results for HZZ/HWW in $4l$

Measuring in VBF and VH production, we get:

Approach 1):



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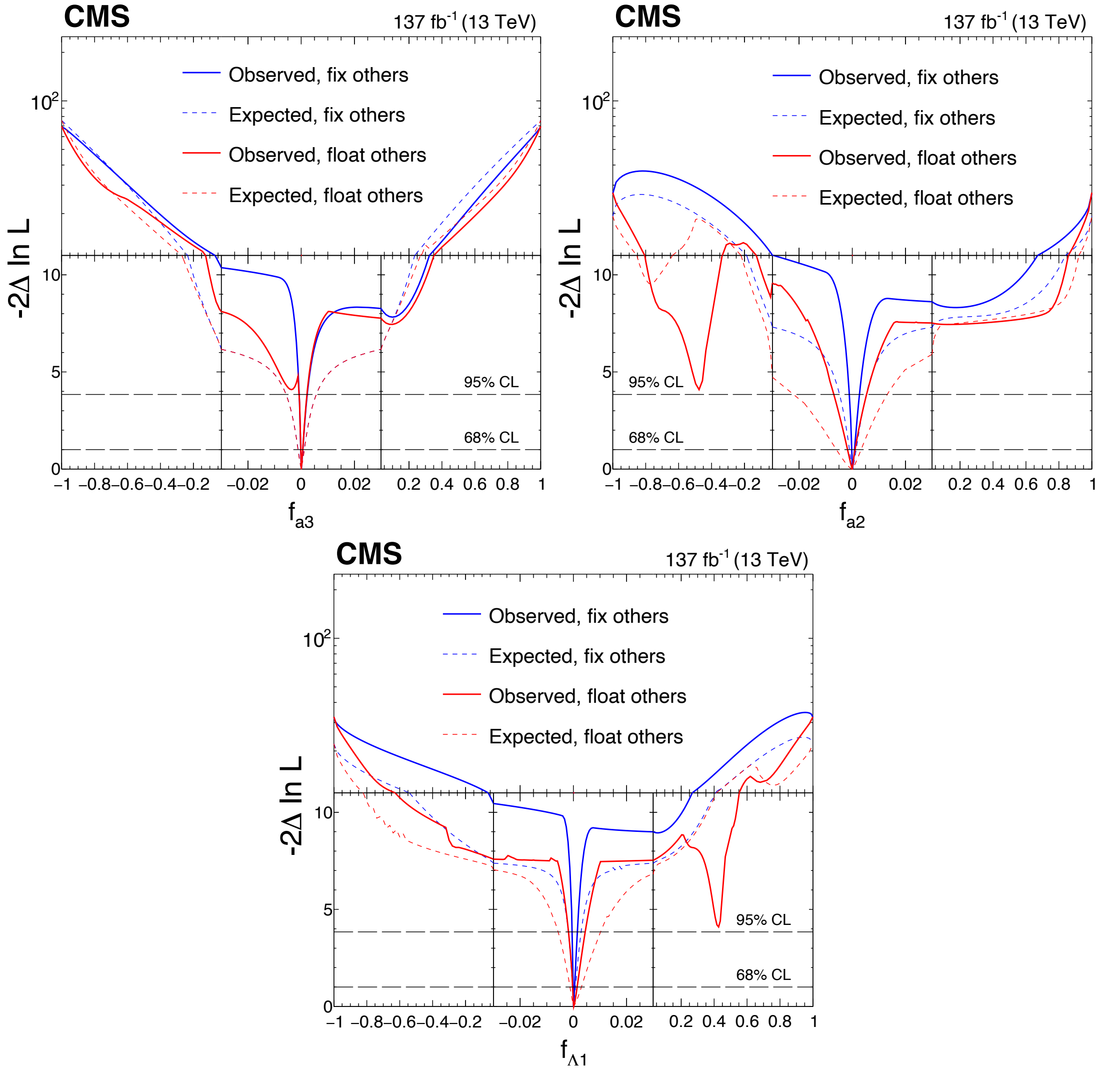
Results for HZZ/HWW in $4l$

Approach 2):



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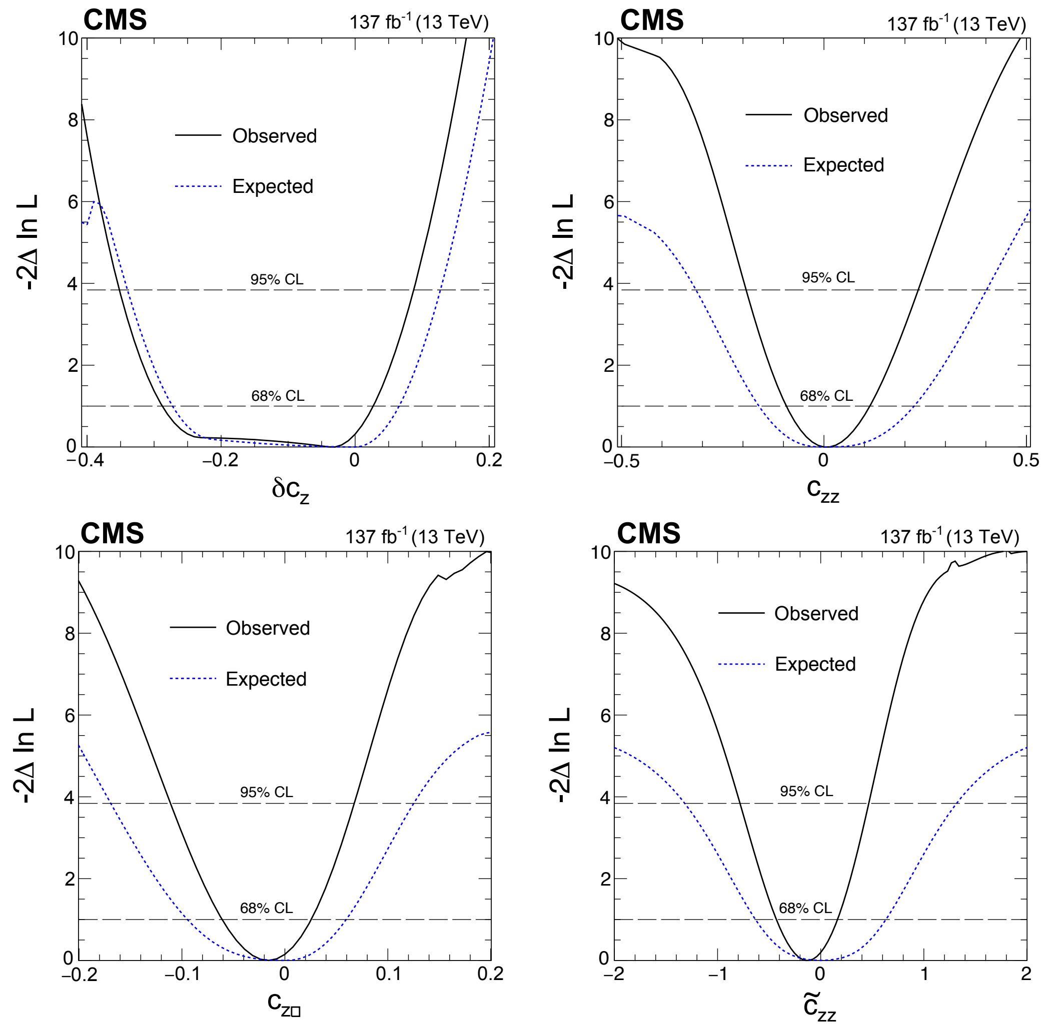
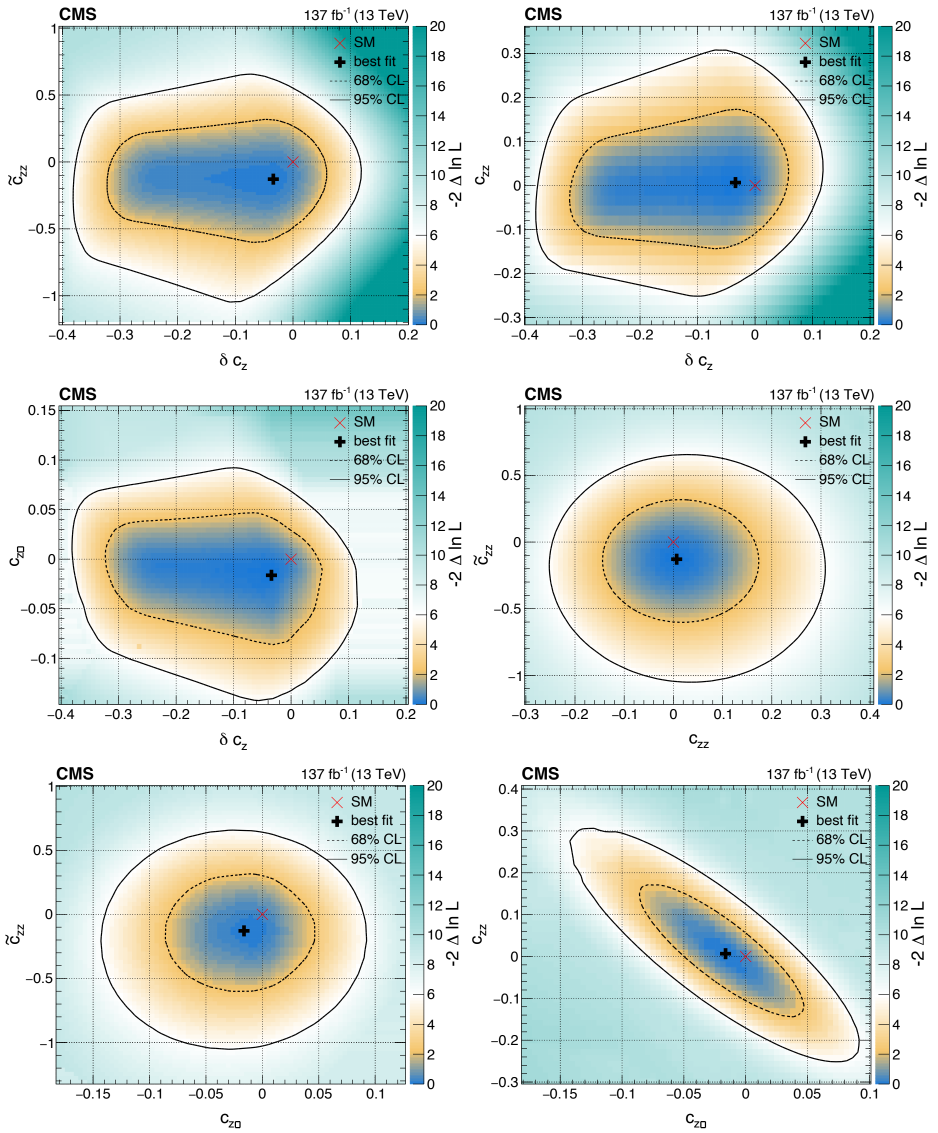
Results for HZZ/HWW in $4l$

Approach 2):





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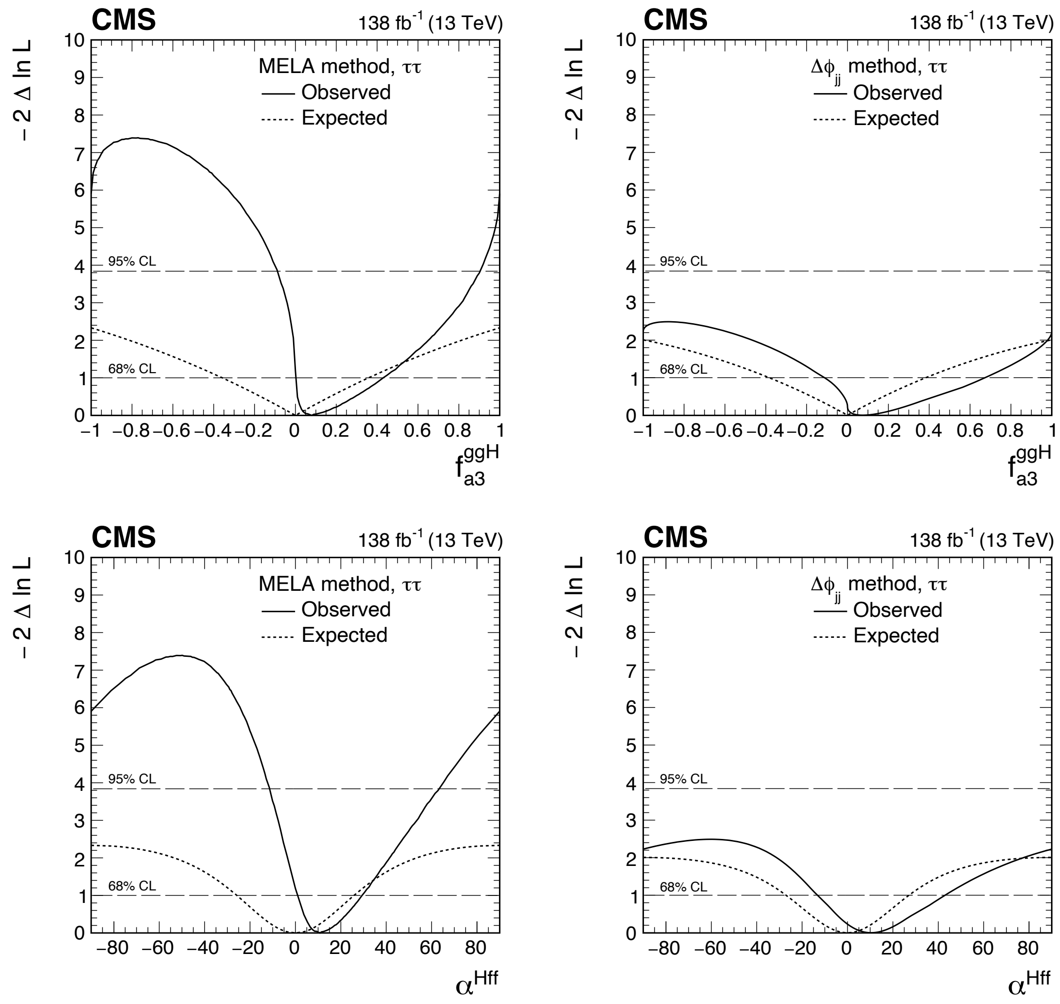
Results for Hgg in $\tau\tau$

We used MELA method and $\delta\phi_{jj}$ method respectively in ggH and ttH production:



$\delta\phi_{jj} = \phi(j_1) - \phi(j_2), \eta(j_1) > \eta(j_2)$

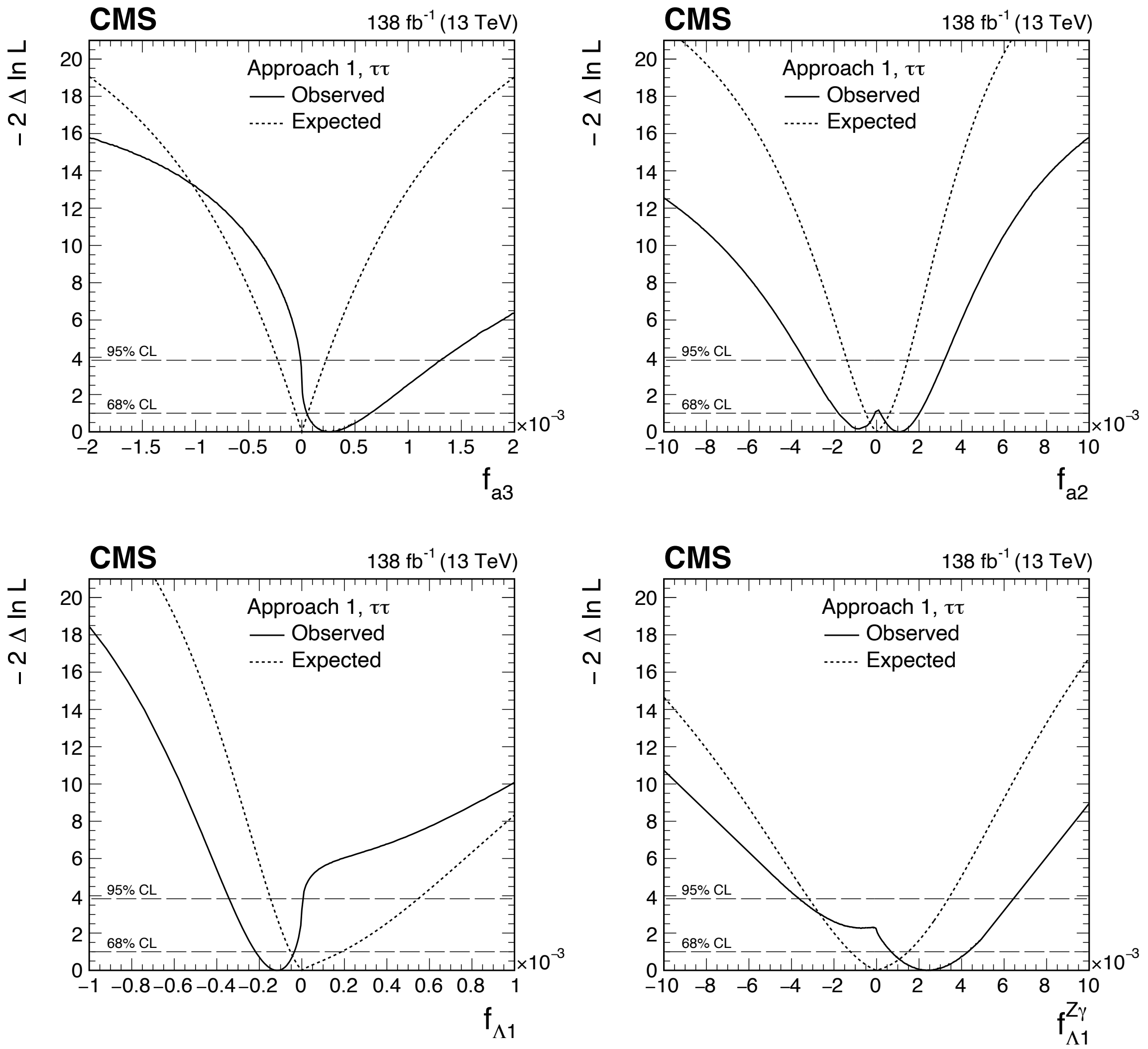
j_1 and j_2 are the leading two jets and $\delta\phi_{jj}$ is sensitive to CP violation.

We defined $\alpha^{Hff} = \tan^{-1}(\frac{\widetilde{\kappa_f}}{\kappa_f})$

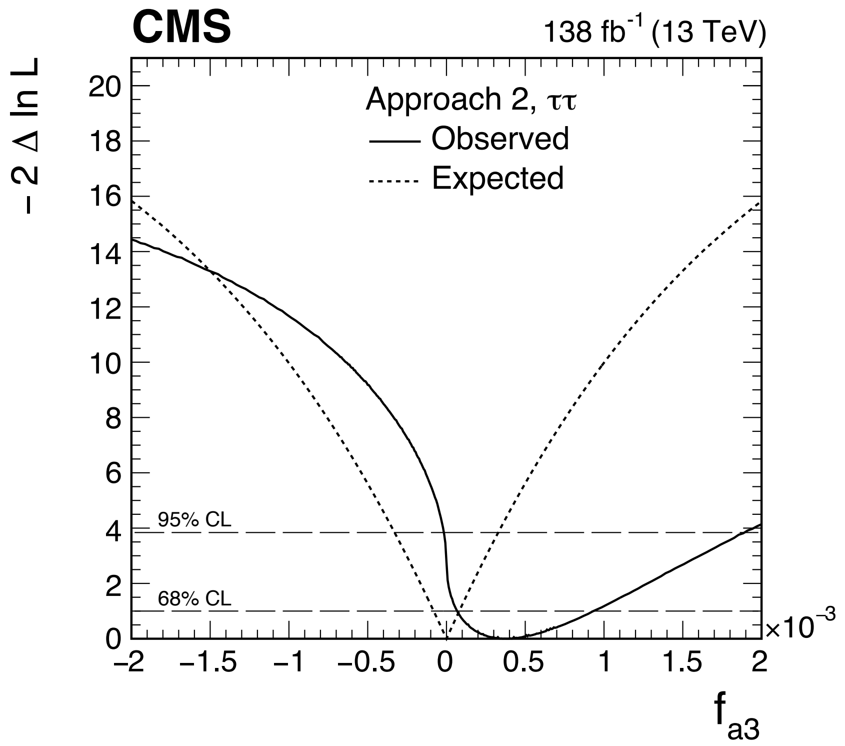
arXiv:2205.05120

Results for HZZ/HWW in $\tau\tau$

Approach 1):



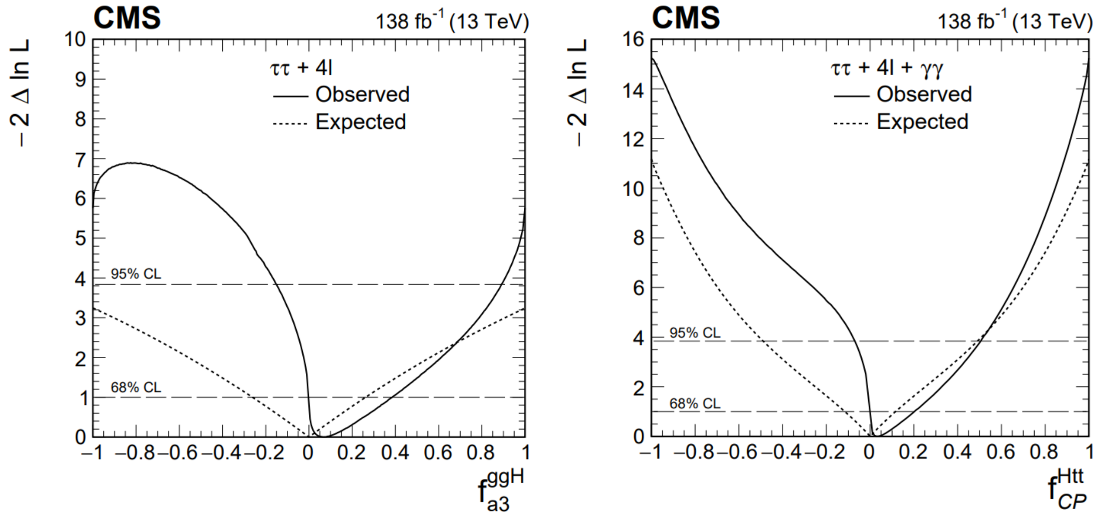
Approach 2):

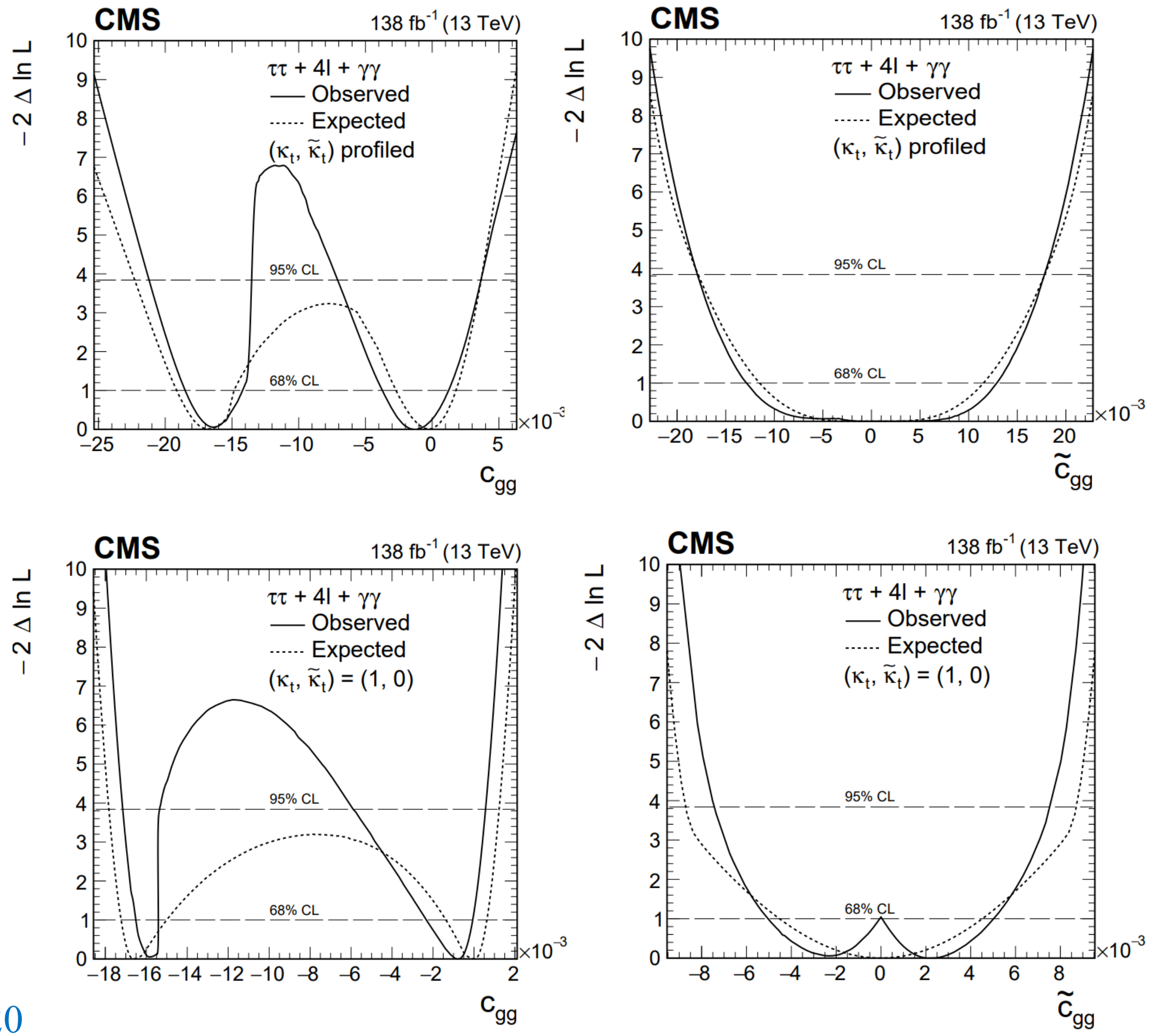


We applied additional considerations of custodial and SU(2) × U(1) symmetries, so only have a simple relation: $a_3^{WW} = \cos^2\theta_w\, a_3^{ZZ}$

Combination

Combining 4l and $\tau\tau$:





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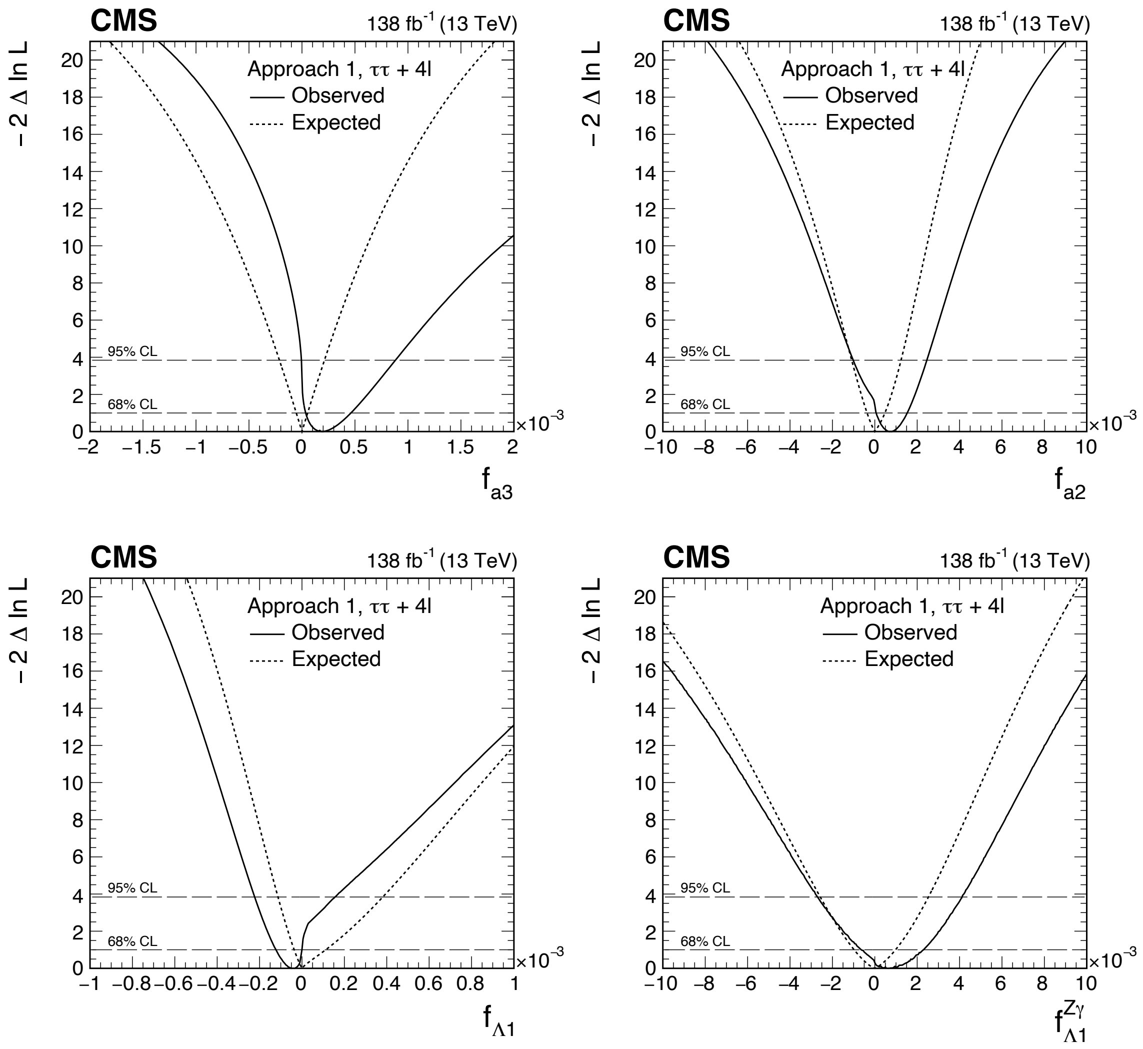
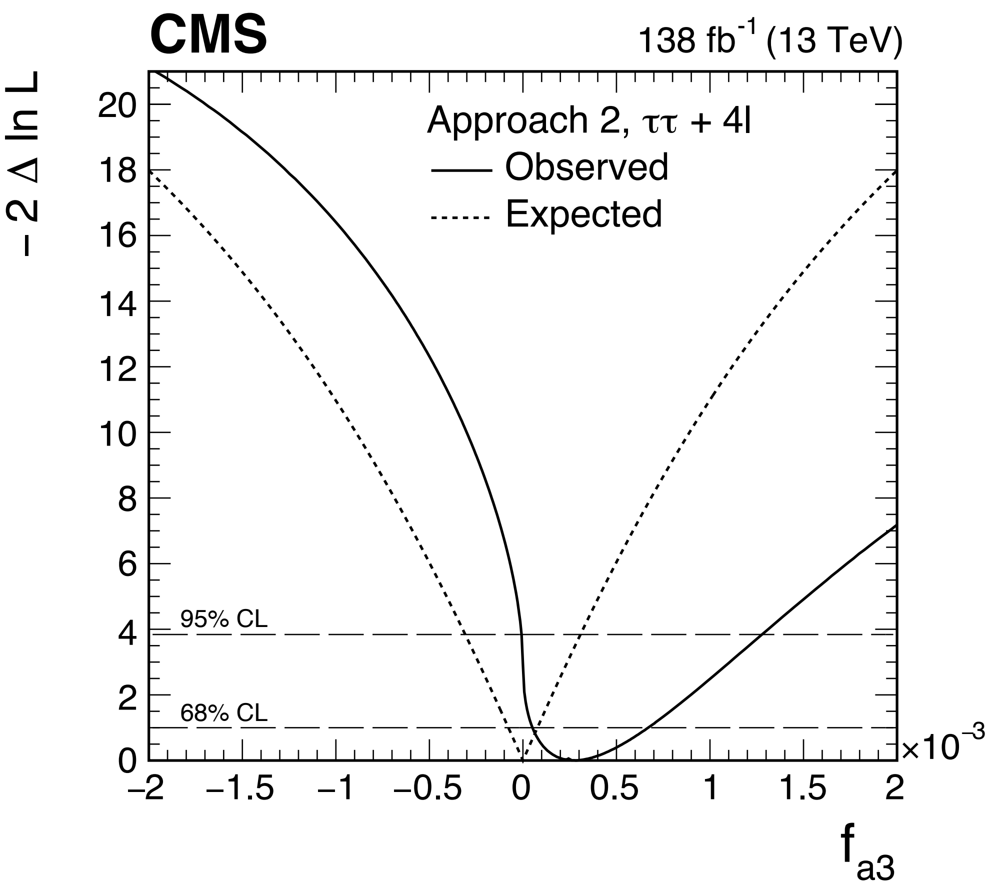
Combination





arXiv:2205.05120

Summary

- CP violation exists in HVV and Hff couplings
- Reduce the number of independent parameters due to Symmetries and other considerations
- Hgg and Htt couplings can be measured simultaneously
- Measure these CP related parameters in $4l$ and $\tau\tau$ channels and combine to give stronger results