Studies of Higgs boson CP

Higgs2022 - Pisa
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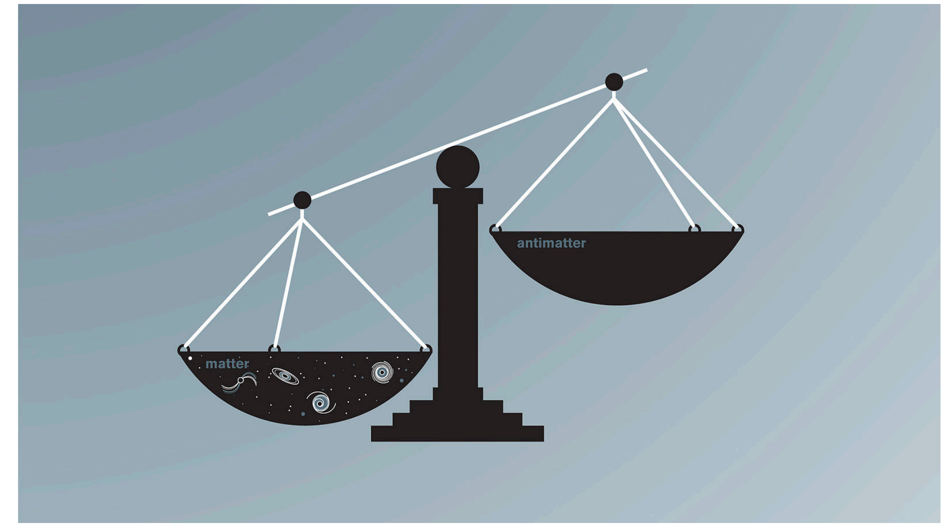
on behalf of the ATLAS and CMS collaborations

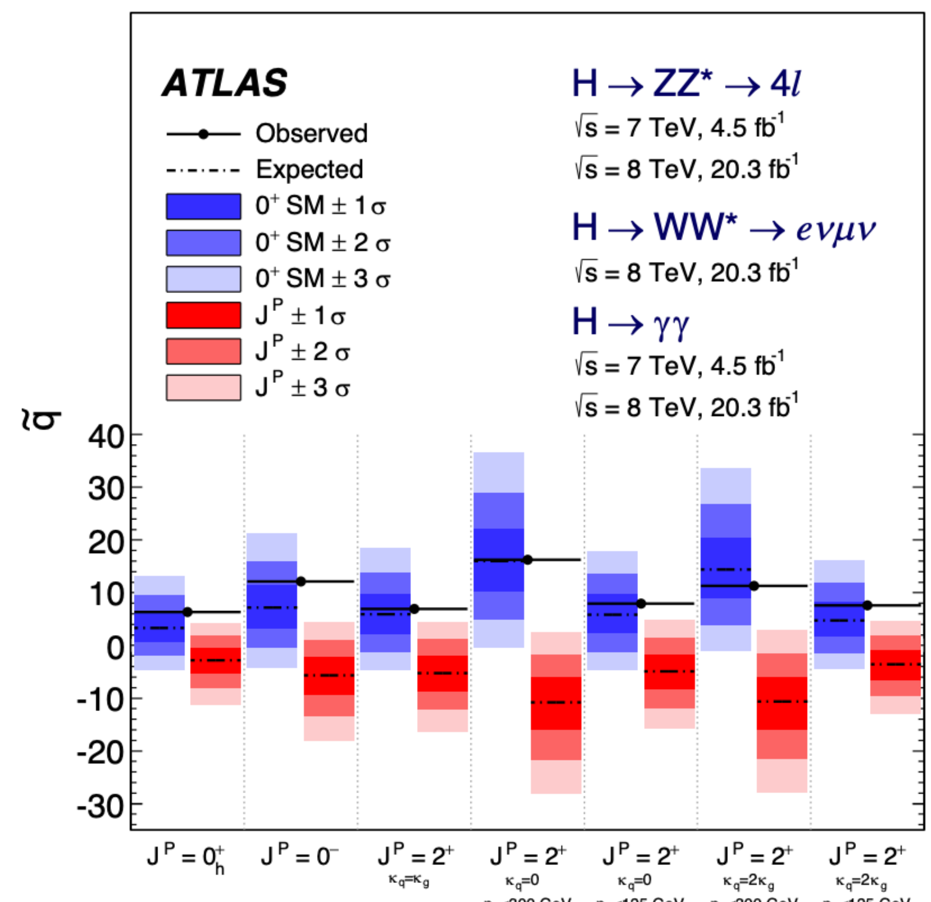
Introduction

- **CP violation is one of the three Sakharov conditions** need to explain the baryon asymmetry of the universe
- A few sources of CP violation exist already in the Standard Model: CKM, PMNS matrices
    - ***However, they are significantly insufficient to account for the cosmic asymmetry***



Additional CP violating sources will be unequivocal signs of physics beyond the standard model!

- **The Standard Model Higgs boson is a CP-even scalar with $J^{CP} = 0^{++}$**
- Multiple measurement were performed in Run-1 in ATLAS and CMS testing various spin and parity models
    - Comparing the SM predictions with various alternative CP models
    - **Pure CP-odd Higgs excluded by more than 3σ by both experiments**



CP violation in the Higgs sector?

- CP violation in the Higgs sector can be found either in:
  - Extended Higgs sector models, for example 2HDM: searches for pseudo-scalar Higgs A^0
  - **Anomalous Higgs boson couplings with gauge bosons and fermions**
    - **CP admixture couplings are still allowed experimentally!** *[the focus of this talk]*

How to look for CPV in the Higgs sector?

- Look for deviations in SM predictions for Higgs boson rate measurements ⇒ Can not distinguish CP-even from CP-odd
- Measure shape effects on CP-sensitive observables: Angles, Optimal observables, MELA, $\Delta\phi_{jj}$ and others

Where to look for CPV in the Higgs sector?

Fermionic couplings

- Affected at Tree-level: most notably with heavier third generation fermions (taus and top quarks)
- Probed in ttH production, and $H \to \tau\tau$ decays
- Typically modelled with a mixing angle between CP-even and CP-odd couplings

$$\mathscr{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

Bosonic couplings

- Modelled with higher order operators suppressed by BSM scale Λ
  - typically in EFT framework
- Probed in VBF/VH production, and $H \to WW$ and $H \to ZZ$ decays

$$\mathscr{L}_{VVH} = \mathscr{L}_{SM} + \frac{c_i}{\Lambda^2}\phi \tilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

HVV couplings

- Probing CP violation in HVV ($VV = WW, ZZ, Z\gamma, \gamma\gamma, gg$) interactions typically uses EFT approach
- Pure CPV effects appear in interference only terms

CP-even affecting only rates

$$\sigma \sim |\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2Re\mathcal{M}_{SM}\mathcal{M}_{CP-odd} + |\mathcal{M}_{CP-odd}|^2$$

Pure CP-odd, causing shape changes to CP sensitive observables only

- **Interactions of Higgs and vector gauge bosons can be parameterized by:**

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

a_1 SM like (CP-even)

$a_2, \kappa_1, \kappa_2^{Z\gamma}$ **anomalous CP-even**

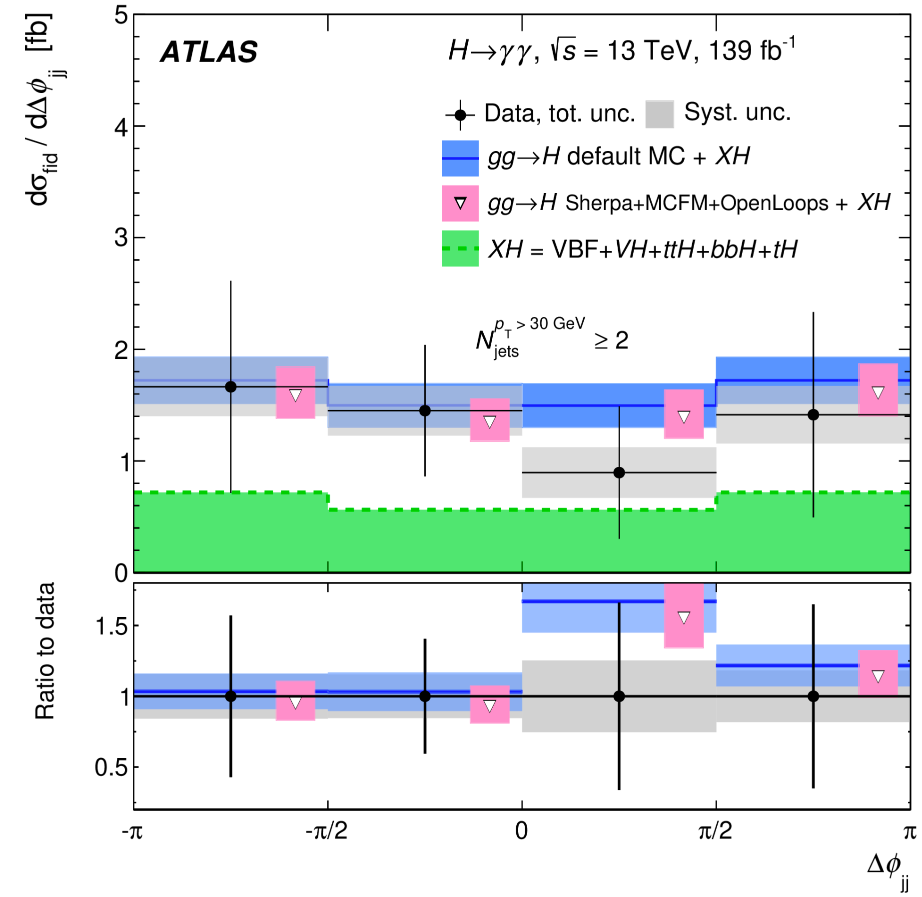
a_3 **anomalous CP-odd**

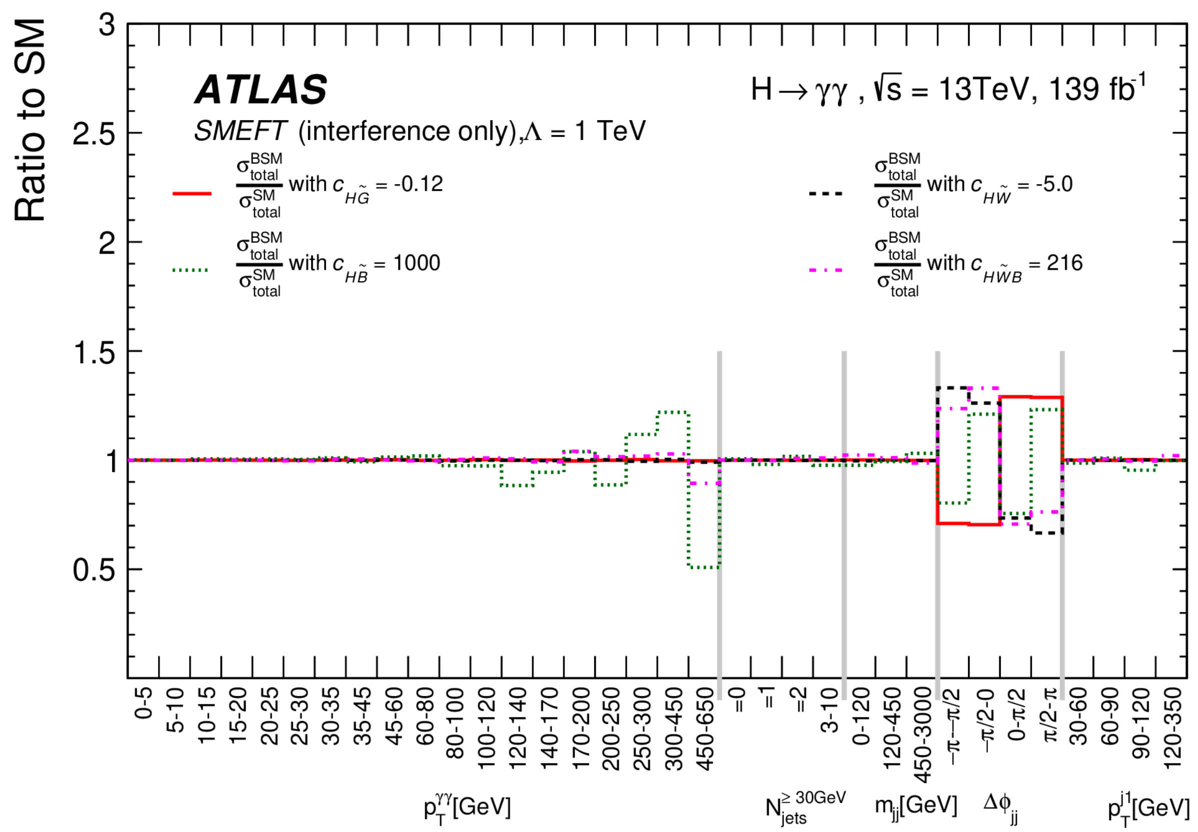
Today's menu

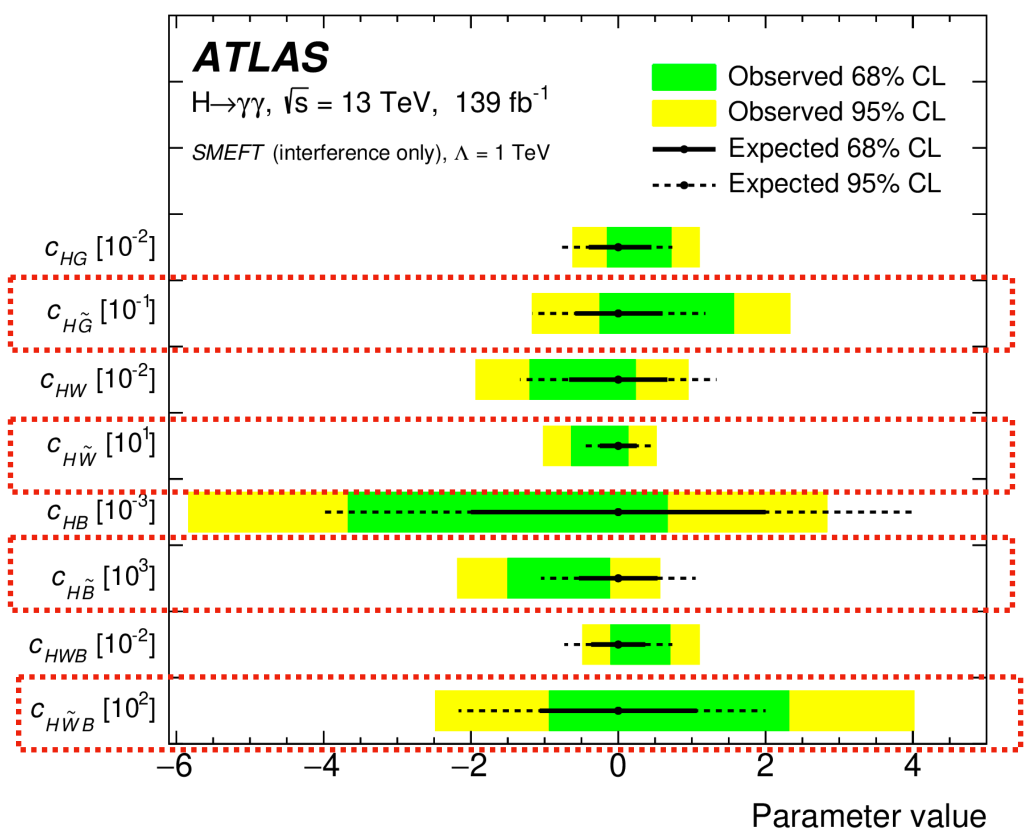
- **ATLAS HIGG-2019-13** : limits on HVV in $H \to \gamma\gamma$ using differential cross sections, *JHEP 08 (2022) 027*
- **ATLAS HIGG-2020-08** : $H \to \gamma\gamma$ CP studies in VBF
- **CMS HIG-20-007** : Limits on HVV in VBF in $H \to \tau\tau$ channel, accepted in Phys. Rev. D
- **CMS HIG-19-009** : Limits on HVV using $H \to ZZ$ decays, Phys. Rev. D 104 (2021) 052004

ATLAS: CPV from $H \to \gamma\gamma$ differential cross-sections

- **EFT interpretation of the $H \to \gamma\gamma$ differential cross-section measurement using full Run-2 data using the SMEFT Warsaw basis**
  - Using unfolded cross-section measurements as input
  - Signal is extracted from fit to $m_{\gamma\gamma}$ distributions
- Using simultaneous fit of five observable $(p_T^{\gamma\gamma}, N_{jet}, m_{jj}, \Delta\phi_{jj}, p_T^{j1})$ and their correlations
  - **Pure CPV sensitivity from signed $\Delta\phi_{jj}$ (rapidity ordered)**
- **Limits set on $c_{H\tilde{G}}, c_{H\tilde{W}}, c_{H\tilde{B}}$ and $c_{H\tilde{W}B}$**







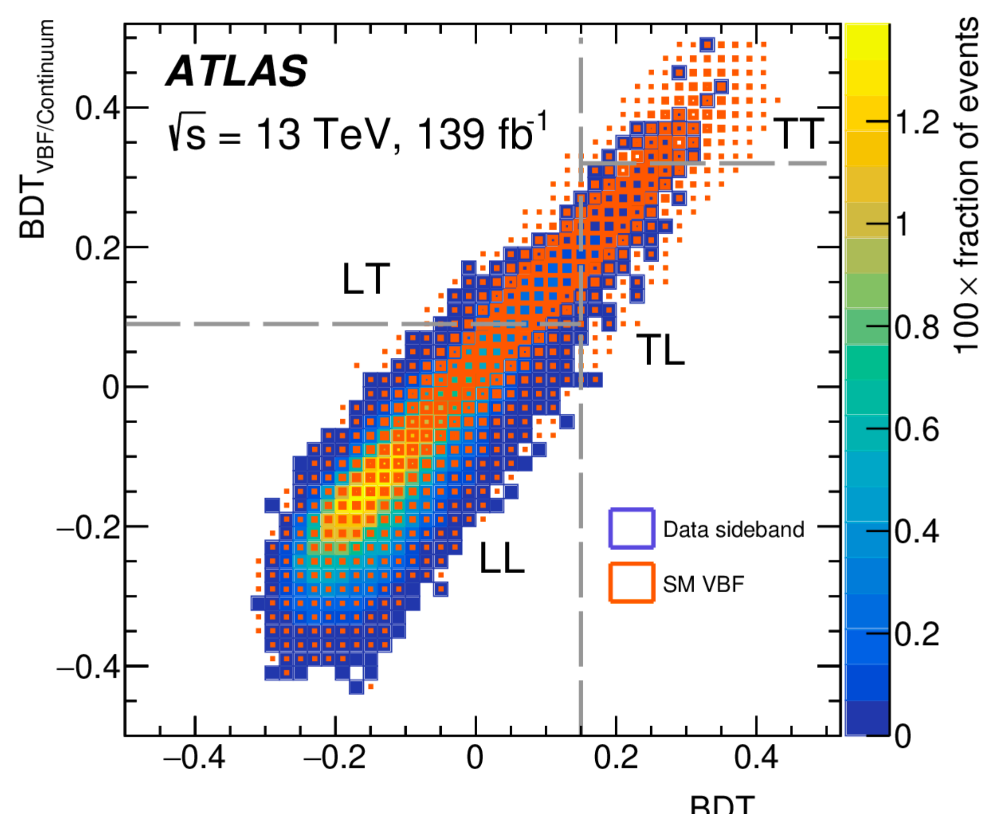
ATLAS: CPV in VBF using $H \rightarrow \gamma\gamma$

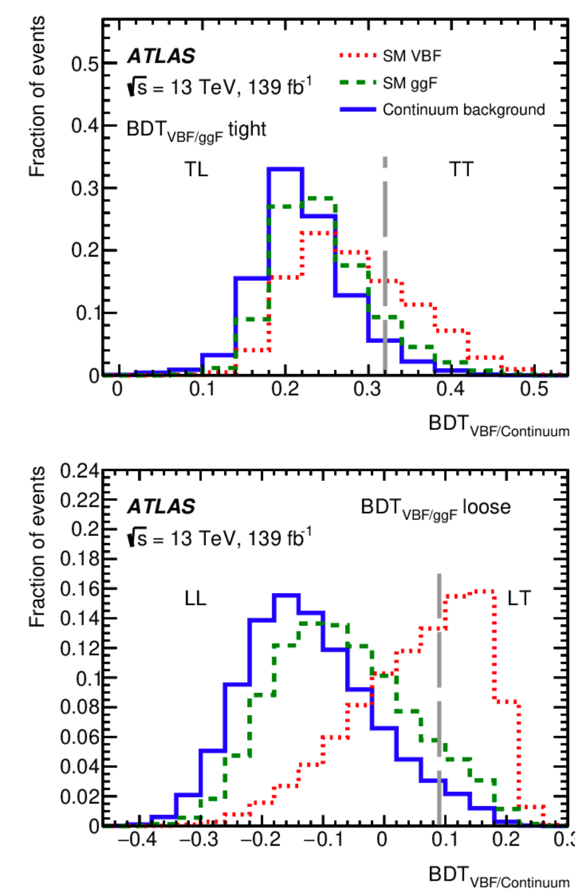
- **EFT interpretations using VBF enriched region in the $H \rightarrow \gamma\gamma$ channel**
- Using two EFT bases: HISZ and SMEFT Warsaw basis to model CP violating effects
  - HISZ basis: settling limit on $\tilde{d}$ parameter $\tilde{d} = -\frac{m_W^2}{\Lambda^2} c_{\tilde{W}W}, \quad \tilde{d}_B = -\frac{m_W^2}{\Lambda^2} tan^2\theta_W c_{\tilde{B}B}$
  - SMEFT Warsaw basis: setting limits on $c_{H\tilde{W}}$: $\mathcal{L}_{\text{SMEFT}}^{\text{CP-odd}} \supset \frac{c_{H\tilde{W}}}{\Lambda^2} H^\dagger H W^I_{\mu\nu} W^{\mu\nu I}$

- **Using optimal observable ($\mathcal{OO}$) as CP-sensitive observable**
  - $\mathcal{OO}$ mean is 0 in the SM, deviation from 0 is a sign of BSM

$$OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

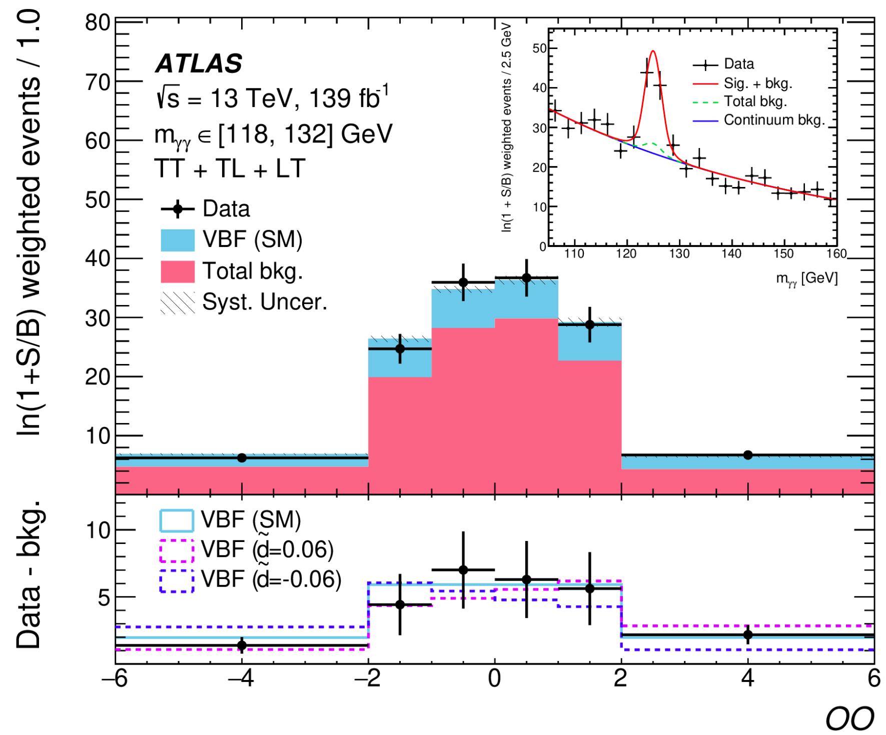
- **Increasing VBF signal purity using 2 BDTs: VBF vs ggF and VBF vs irreducible background**



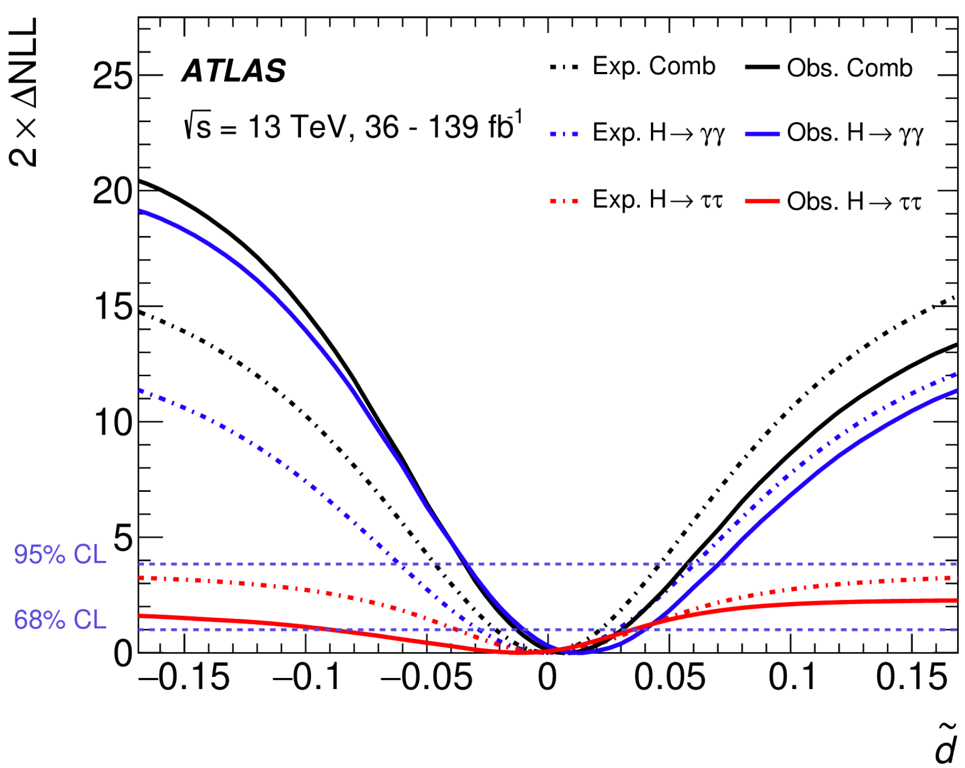


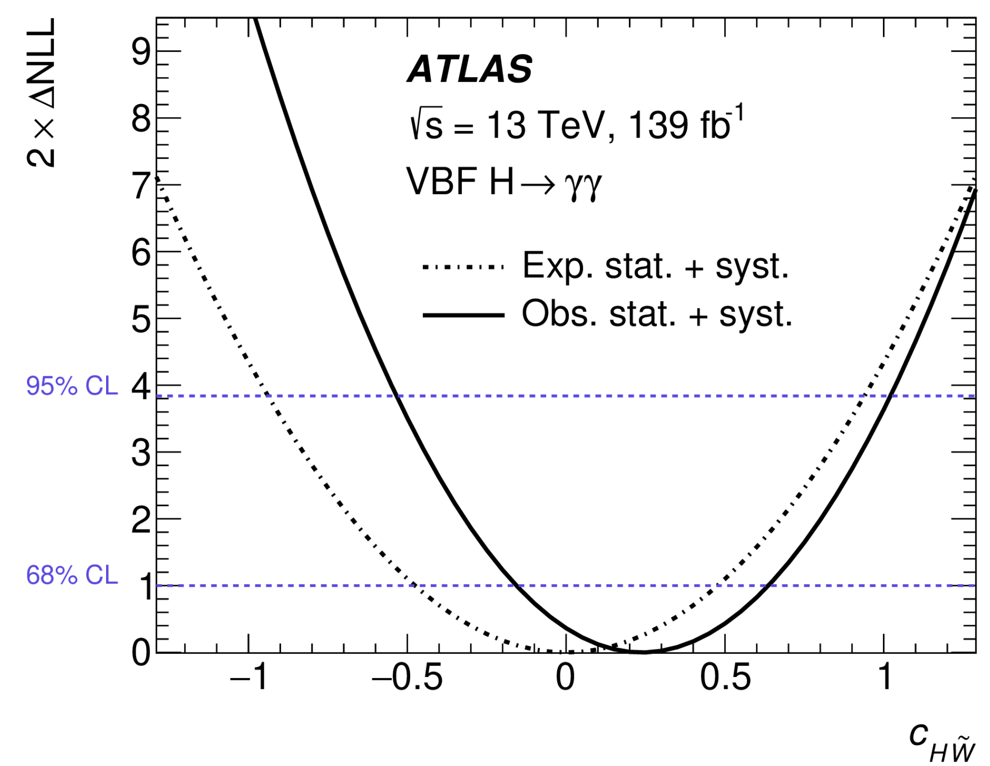
ATLAS: CPV in VBF using $H \to \gamma\gamma$ (2)

- Measurement performed in 6 $\mathcal{OO}$ bins
- **Pure CPV sensitivity using the shape of the $\mathcal{OO}$ observable (VBF normalisation is float in the fit)**
- Limits extracted from NLL curves scanning different BSM couplings



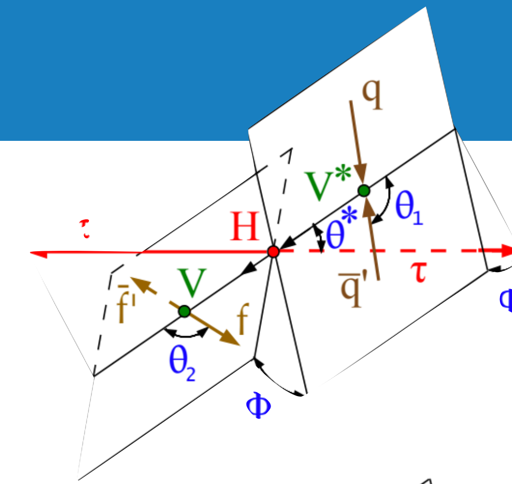
- **Results are combined with $H \to \tau\tau$ (Phys. Lett. B 805 (2020) 135426) results providing most stringent existing limits on CP violation in HVV couplings**
  - Significant improvement (~factor 5) with respect to same limits on $c_{H\tilde{W}}$ from differential measurement

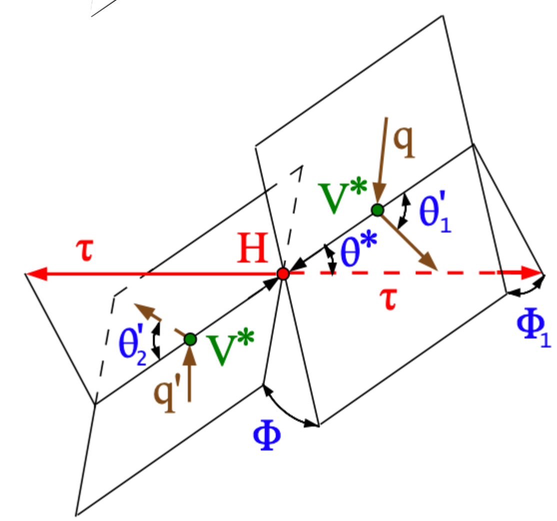




CMS: CPV in HVV using $H \to \tau\tau$

- **Using $H \to \tau\tau$ channel to probe CPV using kinematics of jets from the initial state (VBF and ggF)**
- Two approaches used to relate ZZ and WW couplings
  - Approach 1: $a_i^{ZZ} = a_i^{WW}, \kappa_1^{ZZ} = \kappa_1^{WW}$
  - Approach 2 (SMEFT): SU(2) X U(1)





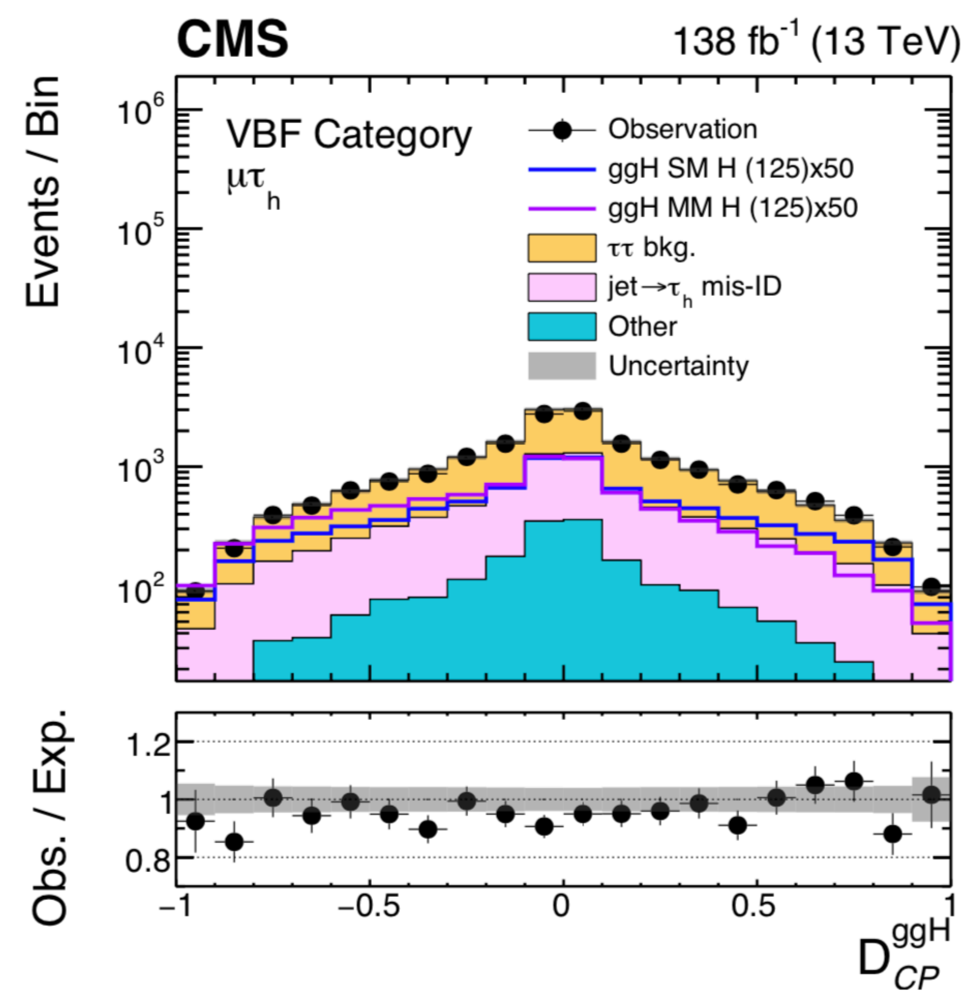
- Effect on cross-section parametrized as:

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

- Measuring 4 fractions: $f_{a2}, f_{a3}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$
  - And one fraction for gluons f_{a3}^{ggH} $\quad f_{a3}^{\rm ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \operatorname{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$
- **Using matrix element variables (MELA) to exploit production and decay information:**

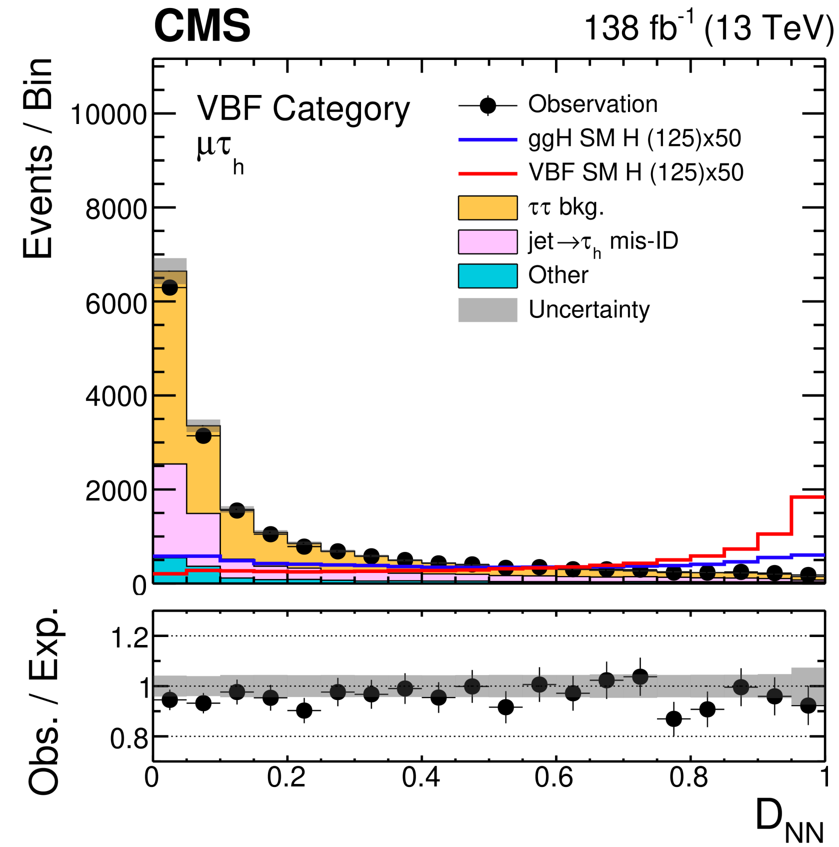
$$\mathcal{D}_{\rm BSM} = \frac{\mathcal{P}_{\rm SM}(\vec{\Omega})}{\mathcal{P}_{\rm SM}(\vec{\Omega}) + \mathcal{P}_{\rm BSM}(\vec{\Omega})},$$

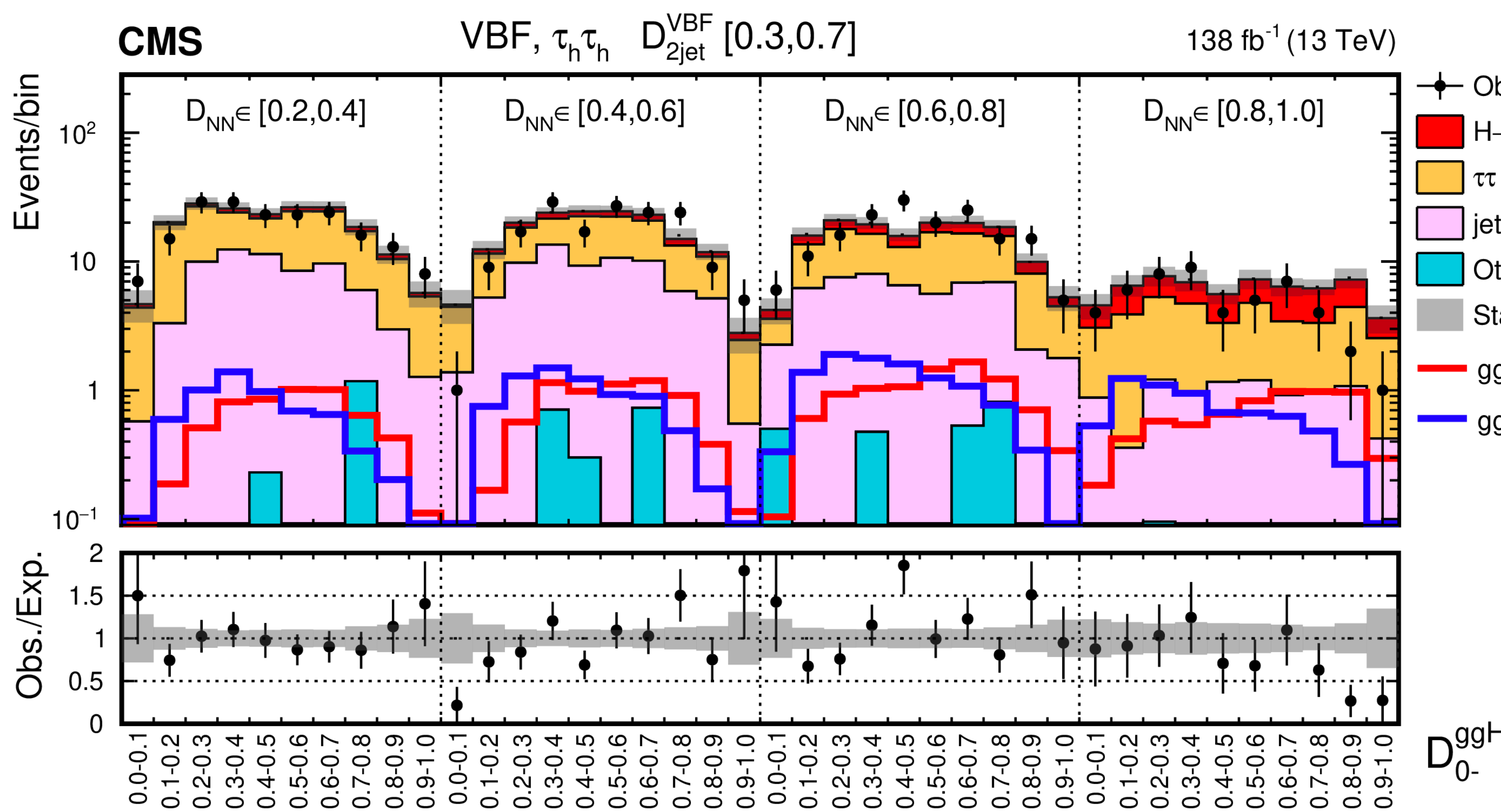
$$\mathbf{\Omega}^{\rm assoc} = \{\theta_1^{\rm VBF}, \theta_2^{\rm VBF}, \theta^{*\rm VBF}, \Phi^{\rm VBF}, \Phi_1^{\rm VBF}, q_1^{2,\rm VBF}, q_2^{2,\rm VBF}\}$$



CMS: CPV in HVV using $H \rightarrow \tau\tau$ (2)

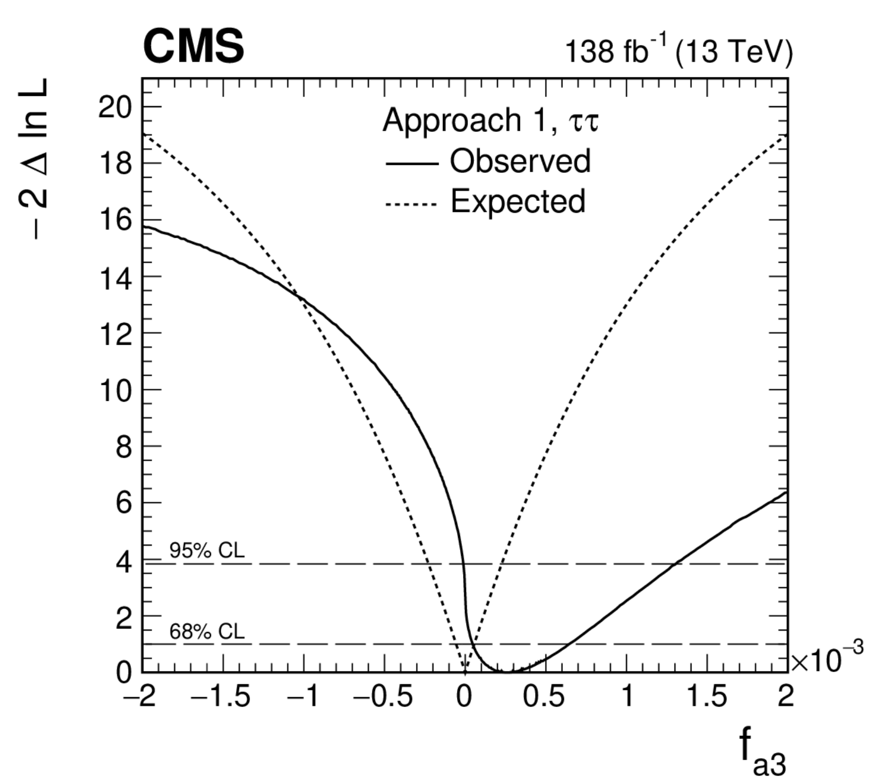
- Using 4 most sensitive $\tau\tau$ channels: $h_\tau h_\tau$, $h_\tau \mu$, $h_\tau e$, $e\mu$
- **Analysis probing ggH and VBF+VH**
- **A DNN is used to separate signal and background in the VBF category, output score D_{NN}**
- Events split in 3 categories and fitted distributions are built from 3 or 4 CP sensitive NN variables
  - **Complementary measurement using signed $\Delta\phi_{jj}$**

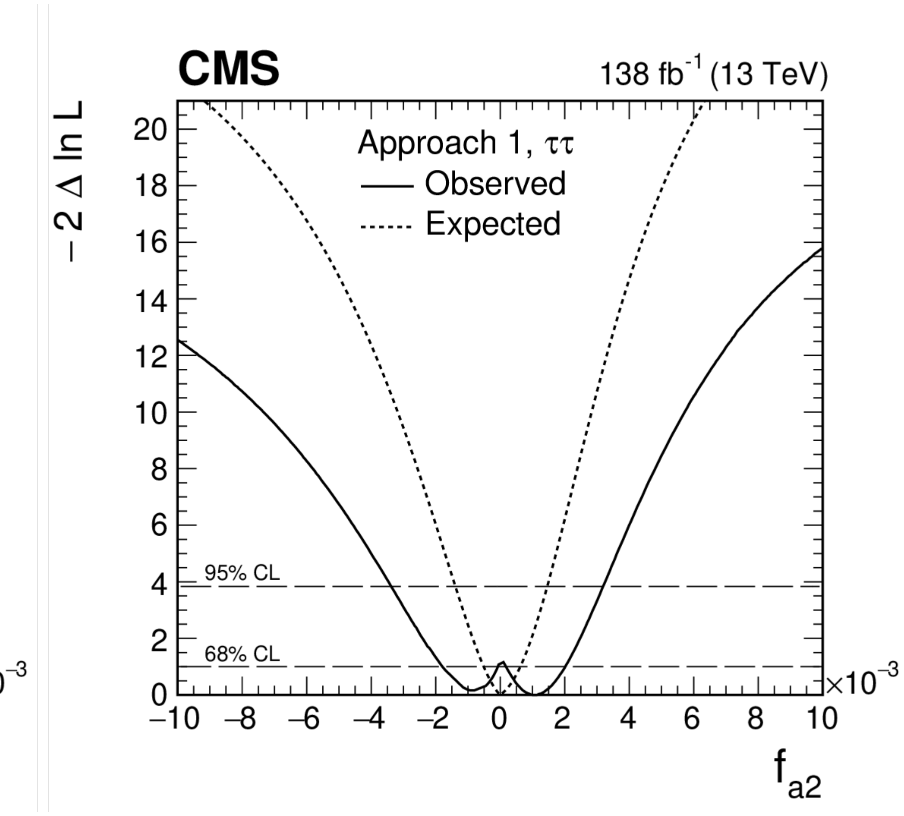




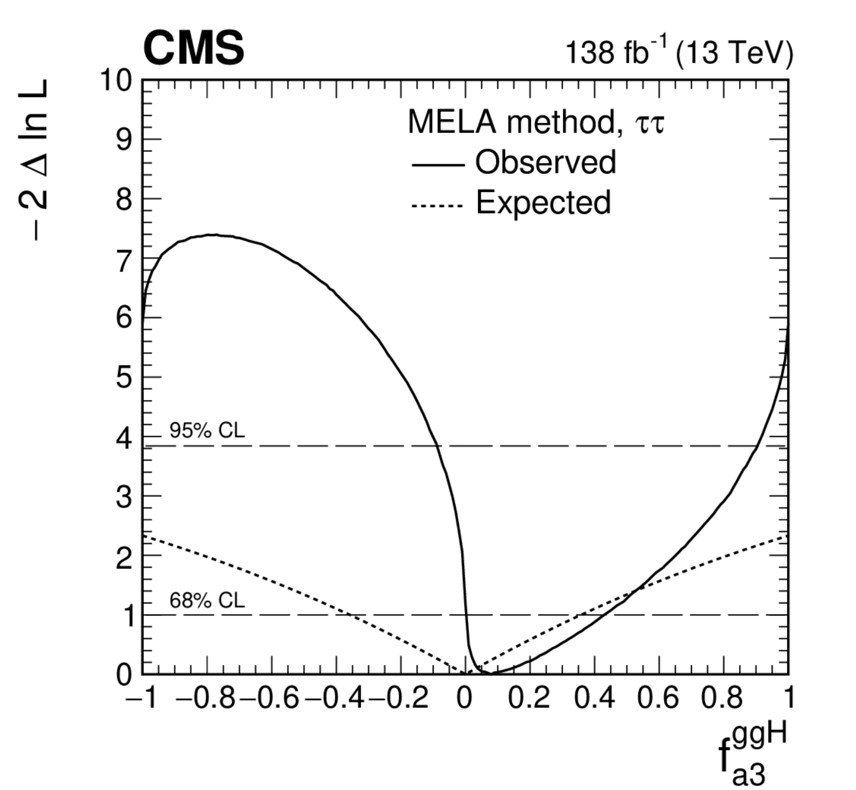
CMS: CPV in HVV using $H \to \tau\tau$ (3)

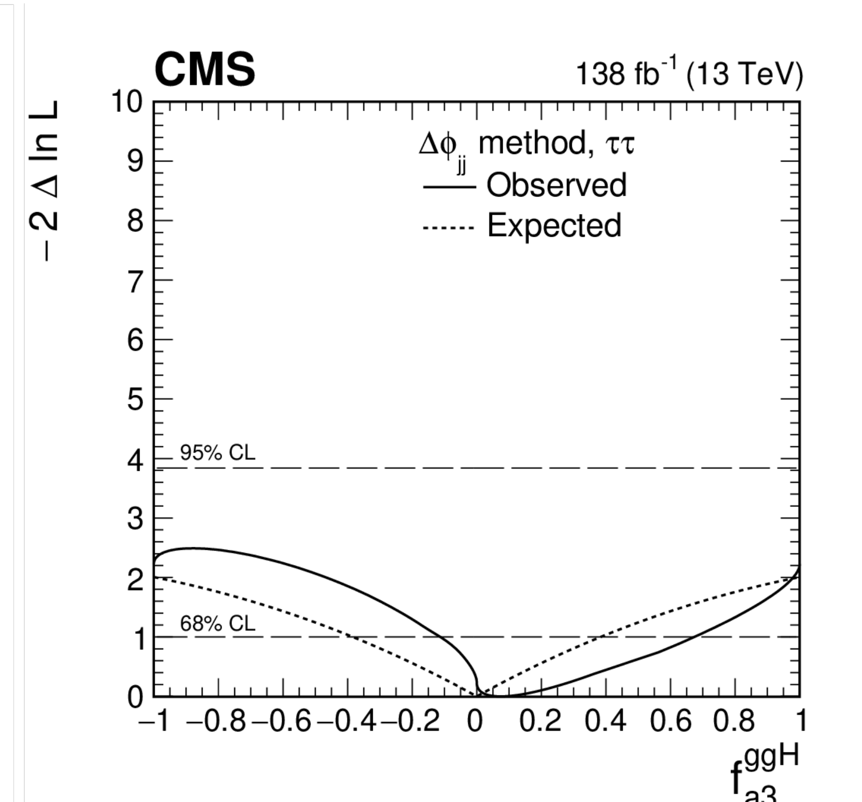
- **Limits are set via scans of NLL curves**
- Results for HVV parameters in Approach 1
  - For VBF and ggH





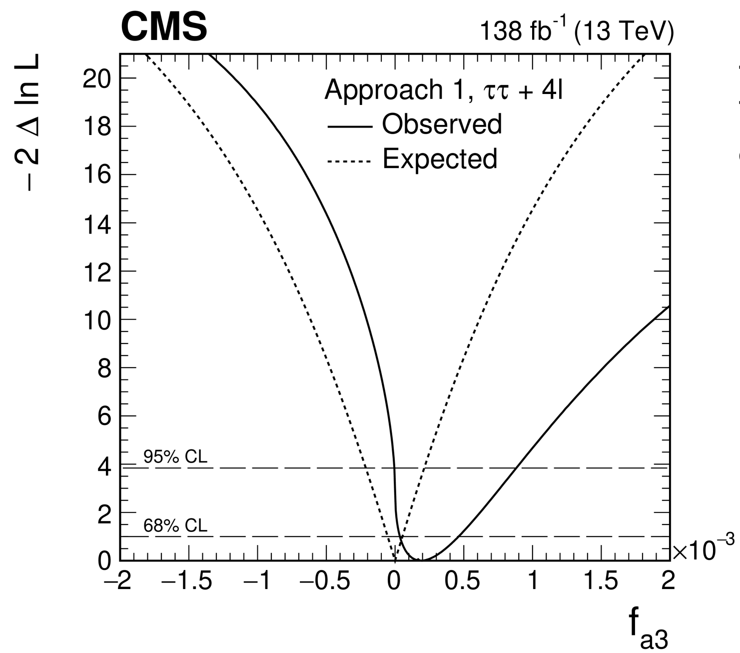
- **Compatible limits between MELA and $\Delta\phi_{jj}$**
  - Significant improvement in sensitivity using MELA

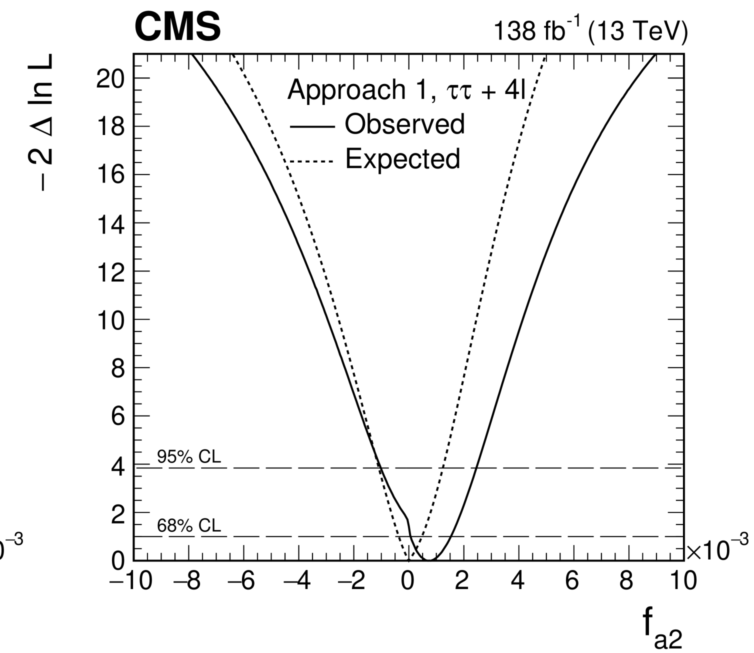




CMS: CPV in HVV combinations

- **Combination with limits from previous $H \to ZZ$ results** (Phys. Rev. D 104 (2021) 052004)
    - Combination results in improvement up to 40%
    - Pure CP-odd scenario is excluded with a observed (expected) significance of 2.4 (1.8) σ
    - $H \to ZZ$ observed (expected) measurement of $c_{H\tilde{W}} = -0.23^{+0.51}_{-0.52}$ $(0.00^{+1.11}_{-1.11})$

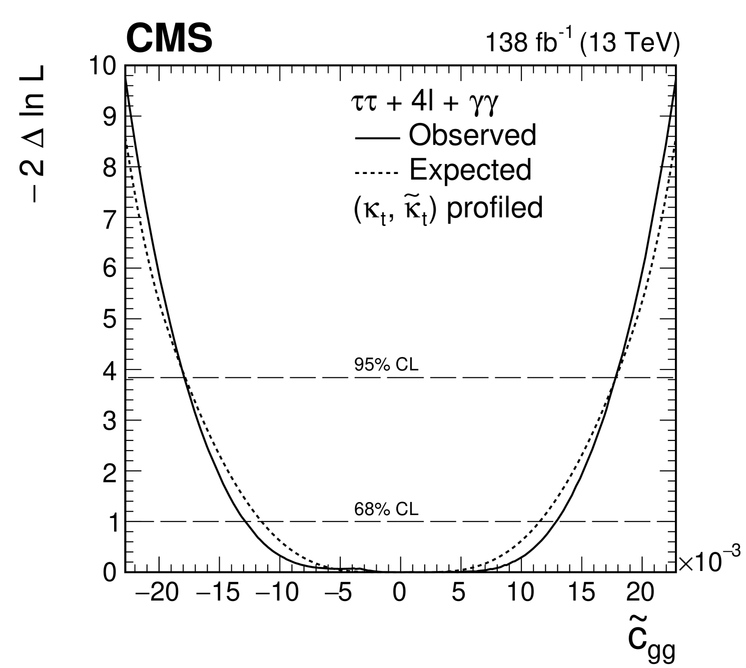




Approach	Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
Approach 1	f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$
	f_{a2}	$0.7^{+0.8}_{-0.6}$	$[-1.0, 2.5]$	$0.0^{+0.5}_{-0.4}$	$[-1.1, 1.2]$
	$f_{\Lambda1}$	$-0.04^{+0.04}_{-0.08}$	$[-0.22, 0.16]$	$0.00^{+0.11}_{-0.04}$	$[-0.11, 0.38]$
	$f_{\Lambda1}^{Z\gamma}$	$0.7^{+1.6}_{-1.3}$	$[-2.7, 4.1]$	$0.0^{+1.0}_{-1.0}$	$[-2.6, 2.5]$
Approach 2	f_{a3}	$0.28^{+0.39}_{-0.23}$	$[-0.01, 1.28]$	0.00 ± 0.08	$[-0.30, 0.30]$

- **Combination with $H \to ZZ$ and $H \to \gamma\gamma$** (Phys. Rev. Lett. 125 (2020) 061801), **results for $\tilde{c}_{gg}$ and f_{a3}^{ggH}**
- Combination results in improvement factor 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	$[-0.49, 0.49]$



Hff couplings

- **Higgs Yukawa couplings can be generically decomposed to CP-even (κ_f) and CP-odd ($\tilde{\kappa}_f$) contributions:**

$$\mathscr{L}_{Y,f} = -\frac{m_f}{v}\bar{\psi}_f(\kappa_f + i\gamma^5\tilde{\kappa}_f)H\psi_f$$

- Fraction of CP violation in these Yukawa interactions then be parameterised using a CP-mixing angle α

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\tilde{\kappa}_f|^2 + |\kappa_f|^2} = \sin^2(\alpha)$$

- CP violation in Yukawa interactions is probed via **top quarks and tau leptons**
  - $H \to \tau\tau$: sensitivity to the CP mixing angle can be probed through spin correlations
  - Higgs-Top: Access via $t\bar{t}H$ and tH production modes
    - **Using CP-sensitive observables constructed using MVA techniques**

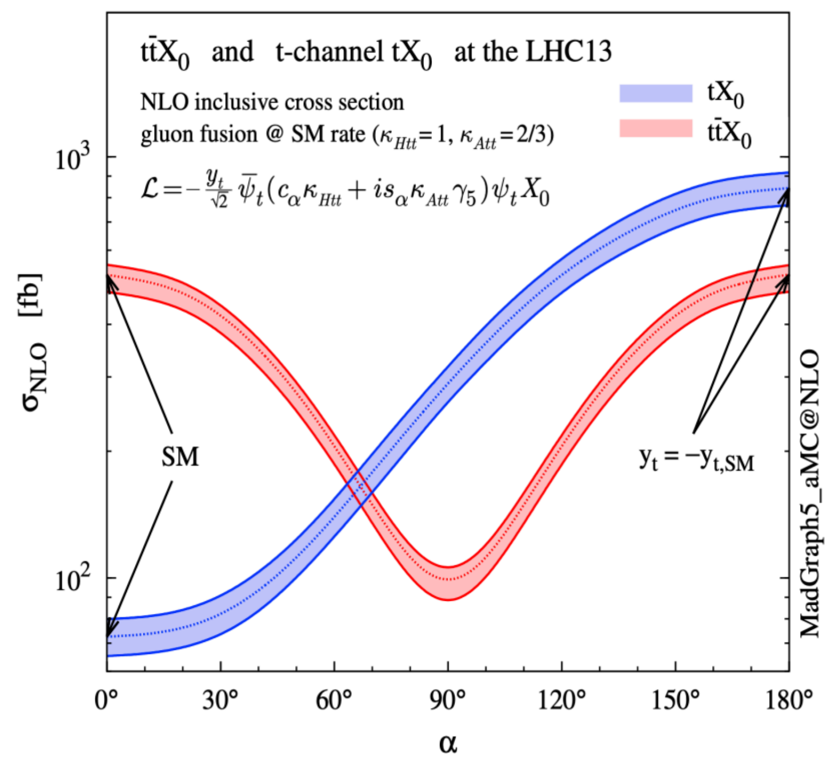
Today's menu

- **ATLAS CONF-2022-016: CP studies in $t\bar{t}H$ and tH events with $H \to b\bar{b}$**
- **CMS HIG-21-006 : CP analysis in $t\bar{t}H$,tH multi-lepton and combination with other channels**
- **ATLAS CONF-2022-032: CP studies of $H \to \tau\tau$ decays**
- **CMS HIG-20-006 : CP studies of $H \to \tau\tau$ decays**

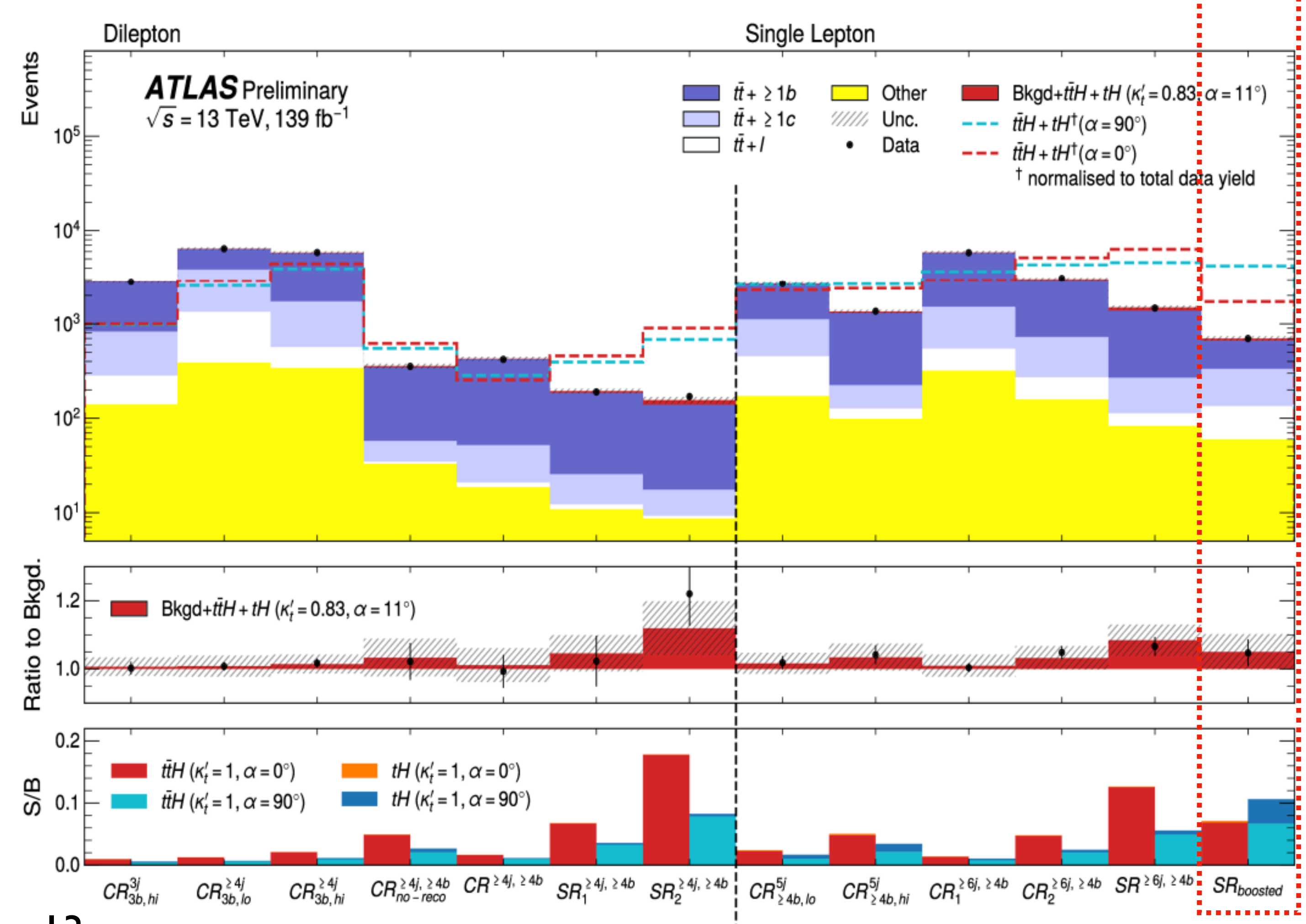
ATLAS: CP violation in $t\bar{t}H$ and tH

- **Explore CP violation in Higgs top coupling CP using $t\bar{t}H$ and tH production modes**
  - $t\bar{t}H$ is symmetric around zero whereas tH is sensitive to relative sign
- **BDTs used for reconstructing Higgs boson candidate**
  - exploit angular and kinematic differences in events caused by CP effects
- Control regions (CRs) to constrain $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$
- **Sensitivity to α and κ_t from CP-sensitive observables:**

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|},$$

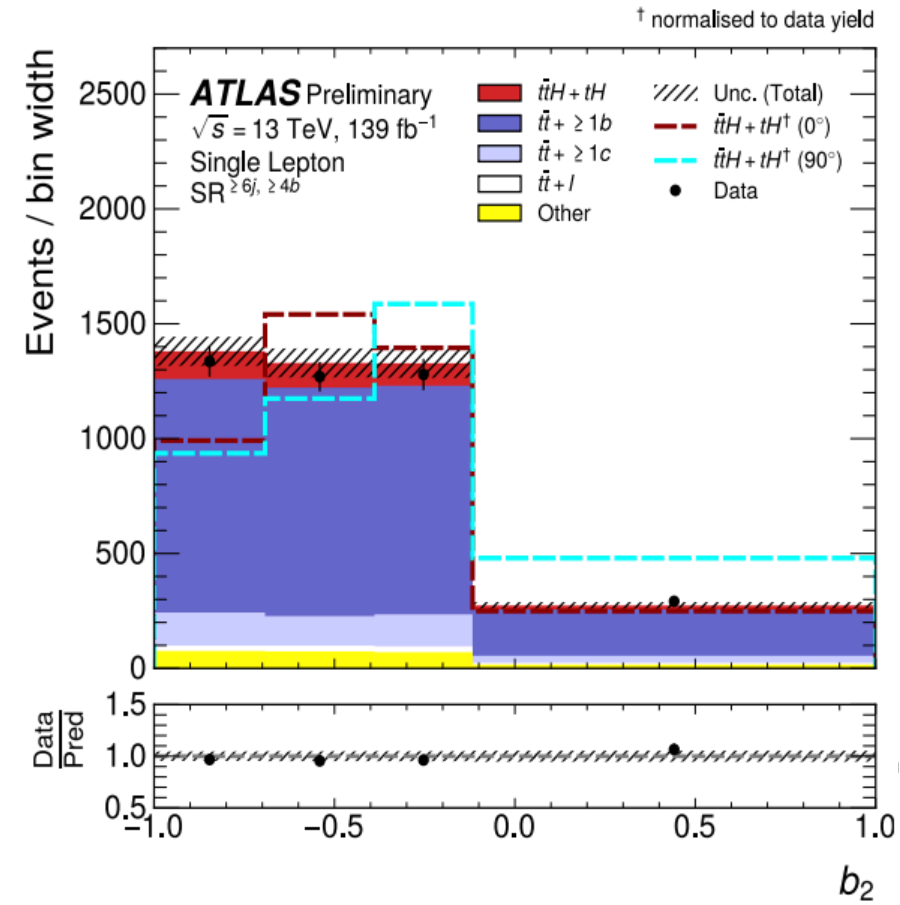


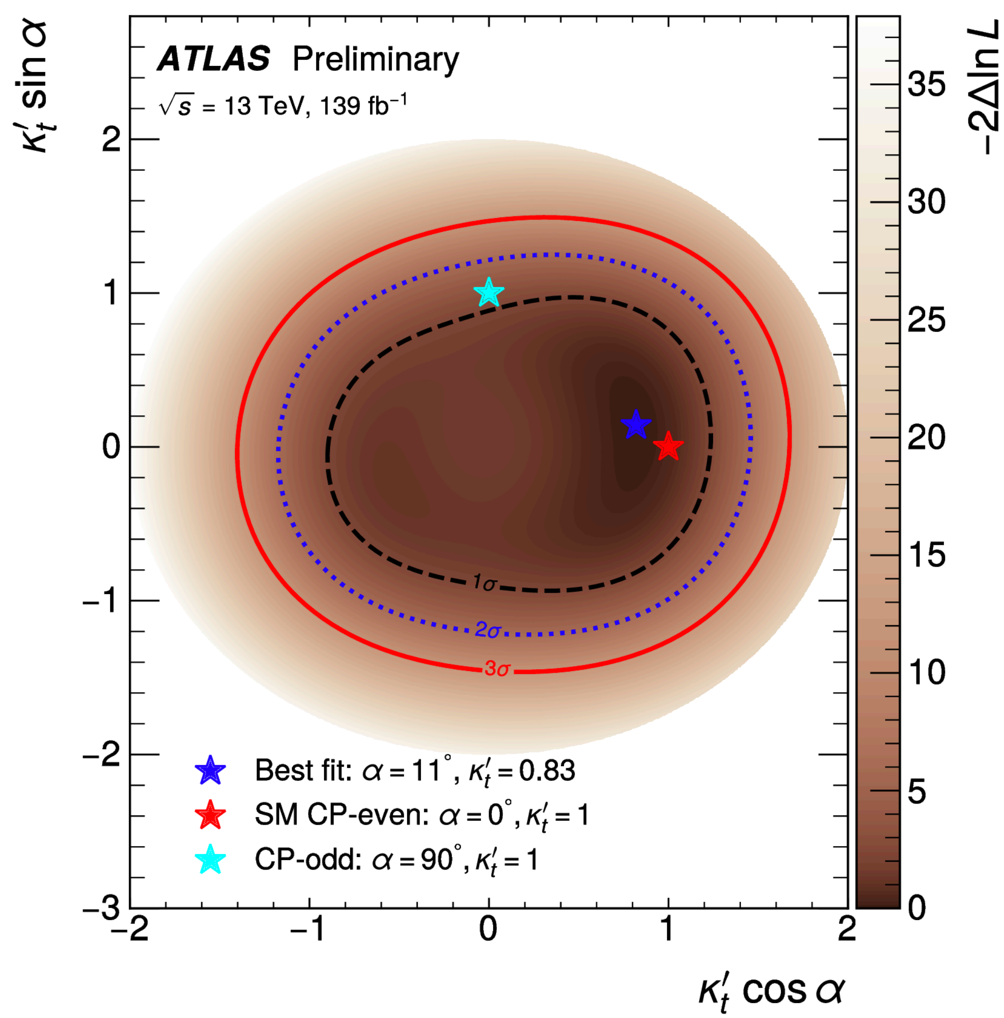
Enhancement in the tH CP-odd case from the boosted channel

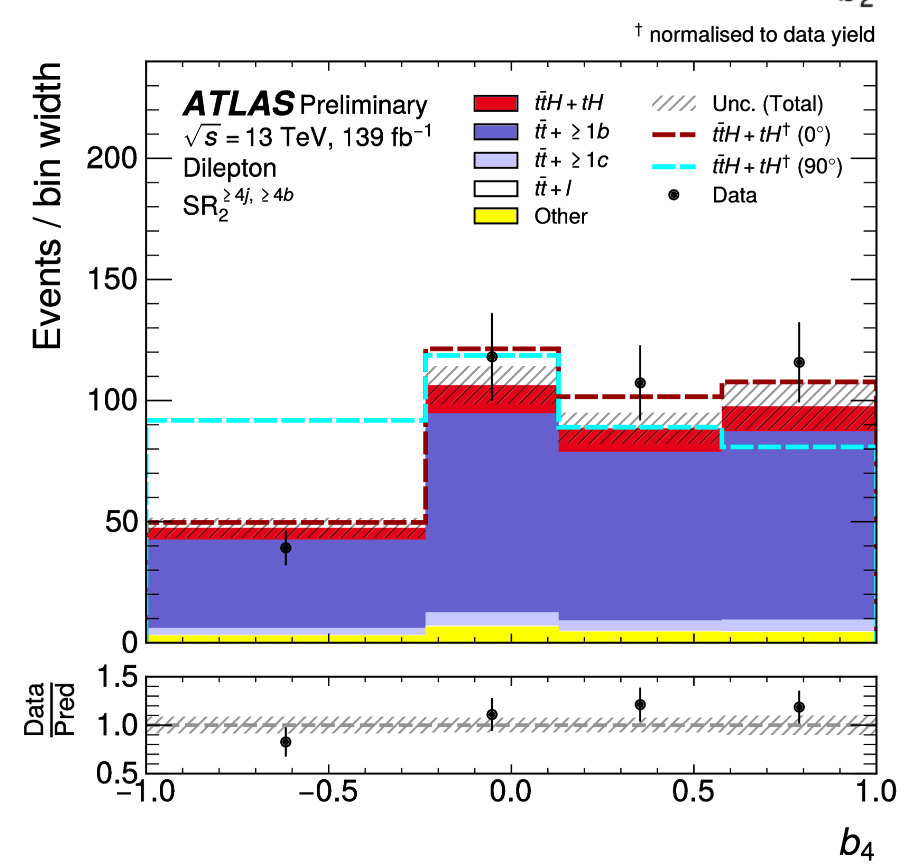


ATLAS: CP violation in $t\bar{t}H$ and tH (2)

- **Limits on CPV (κ_t and α) parameters extracted from simultaneous fit to all regions**
  - In addition to CP sensitive observables
- Limits on $\alpha = 11^{+56}_{-77}$ ° and $k_t' = 0.83^{+0.3}_{-0.46}$
  - Uncertainty dominated by background modelling ($tt + \geq 1b$)
- **Results compatible with limits from $H \to \gamma\gamma$,** Phys. Rev. Lett. 125 (2020) 061802

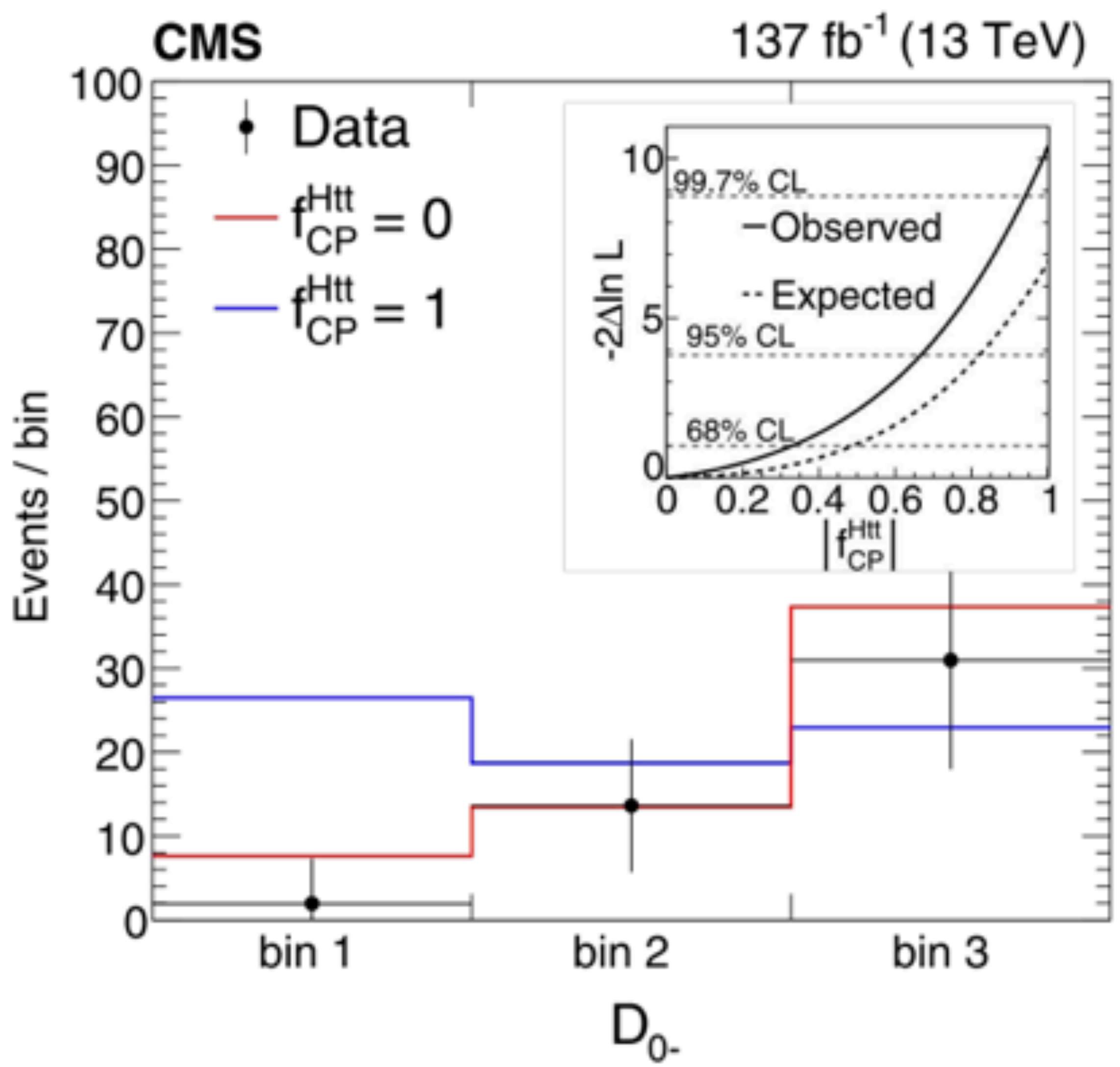


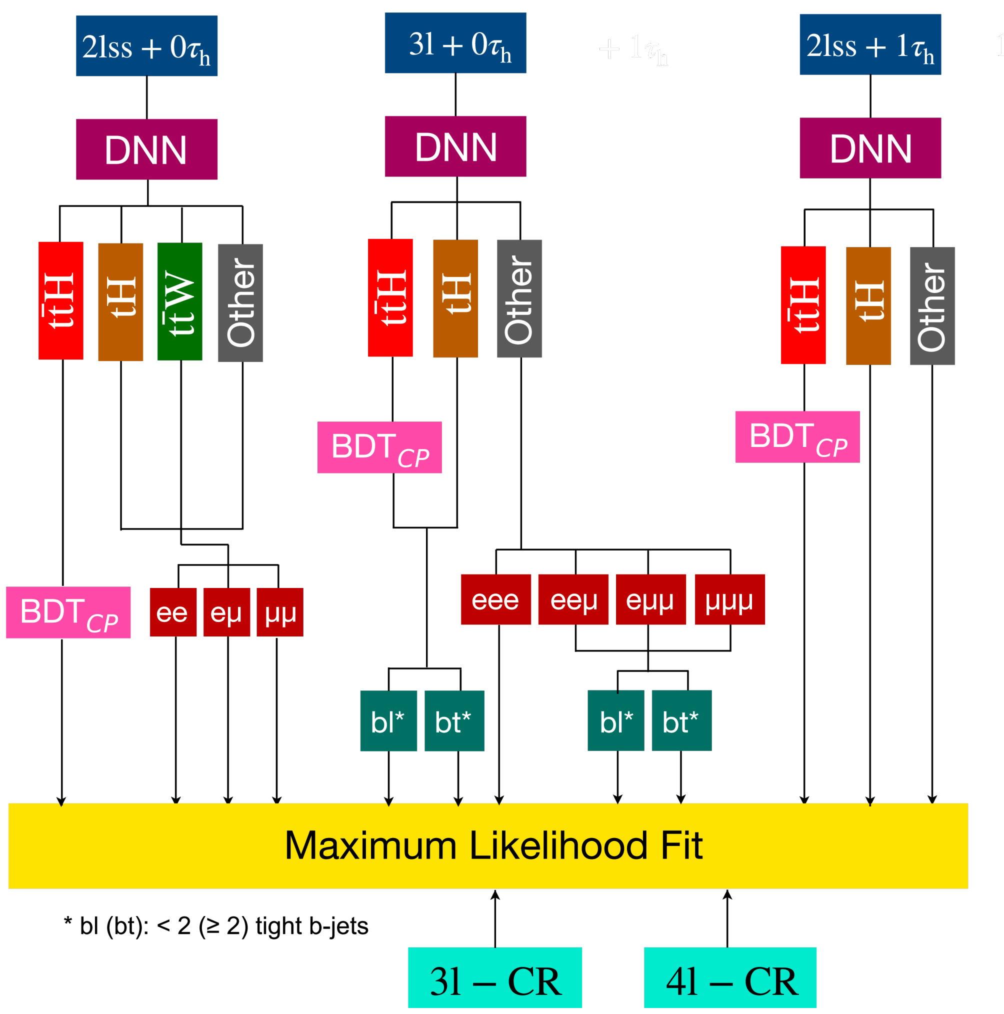




CMS: CP violation in $t\bar{t}H$ and tH (1)

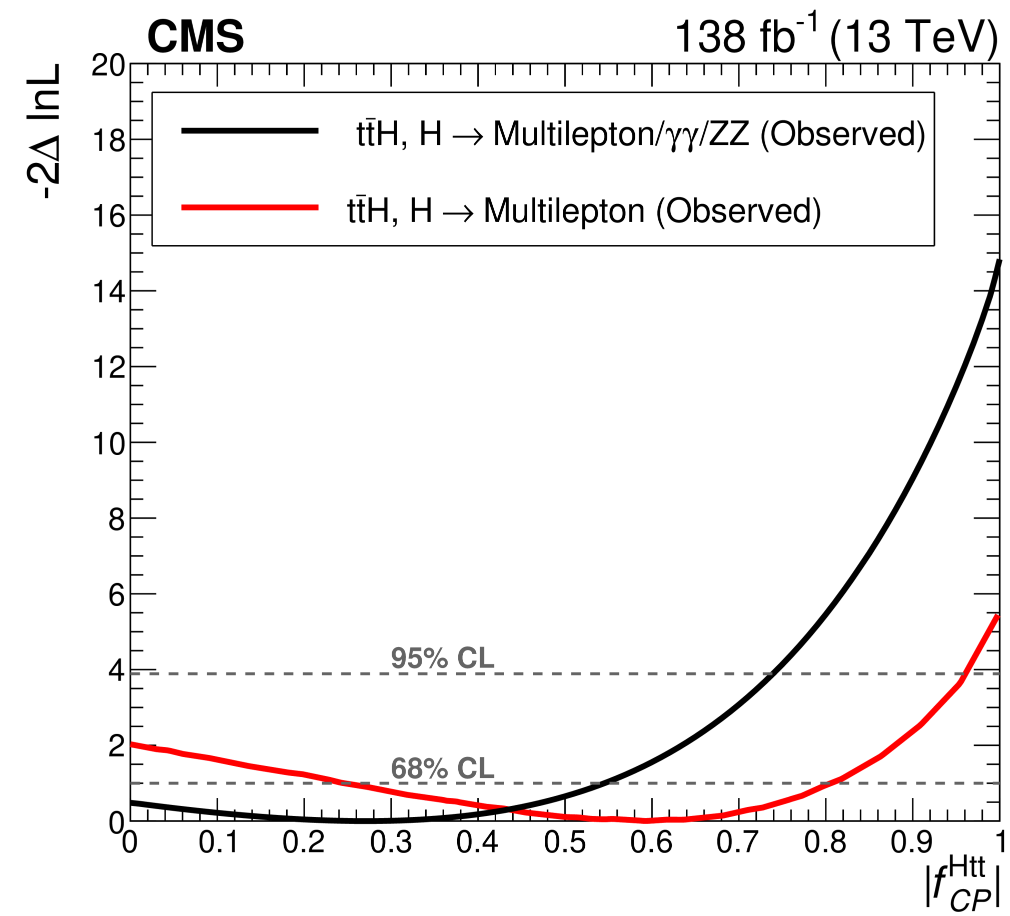
- **Explore CP violation in Higgs top coupling CP using $t\bar{t}H$ and tH production**
  - **Combing information from different multiple Higgs decays: $\gamma\gamma, ZZ, WW, \tau\tau, bb$**
  - With top quark decaying leptonically or hadronically,
  - final states characterized by the presence of at least two leptons
- **Using MVA based classification for signal and background discrimination and for CP-even and CP-odd scenarios**



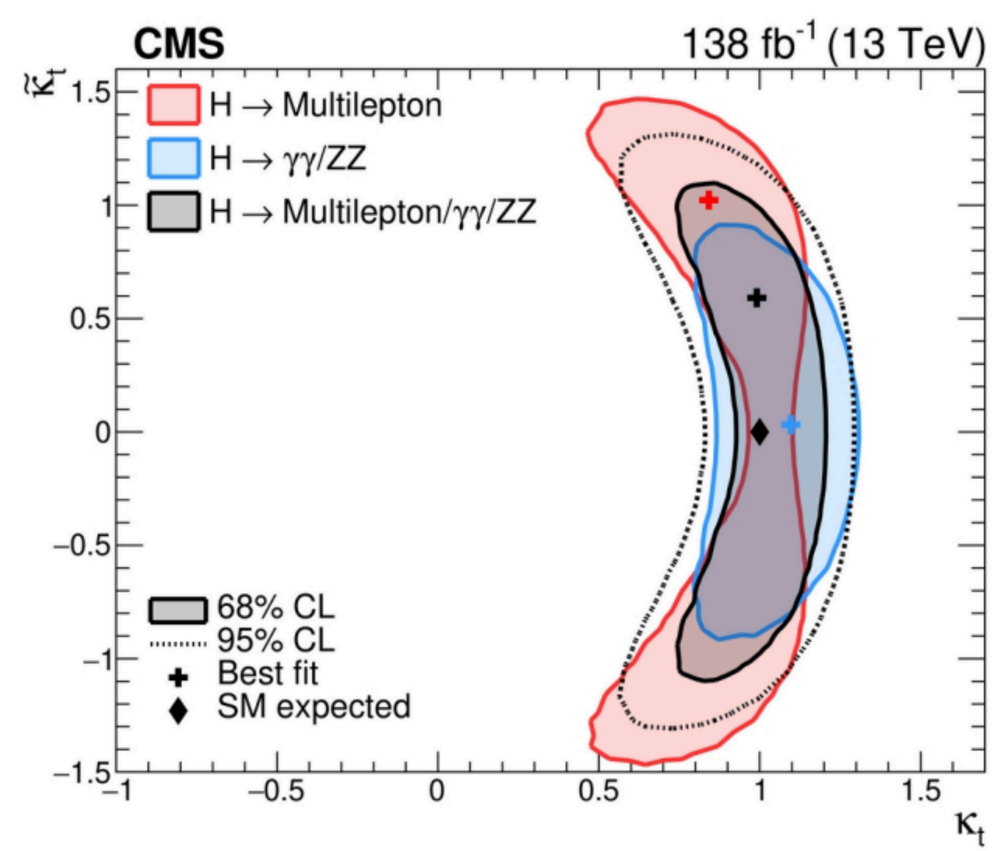


CMS: CP violation in $t\bar{t}H$ and tH (2)

- Extracting 2D limits on κ_t and $\tilde{\kappa}_t$ coupling modifiers
- No deviations from SM predictions:
  - **Measured $|f_{CP}^{Htt}|$ = 0.59 with an interval of (0.24, 0.81) at 68% CL**

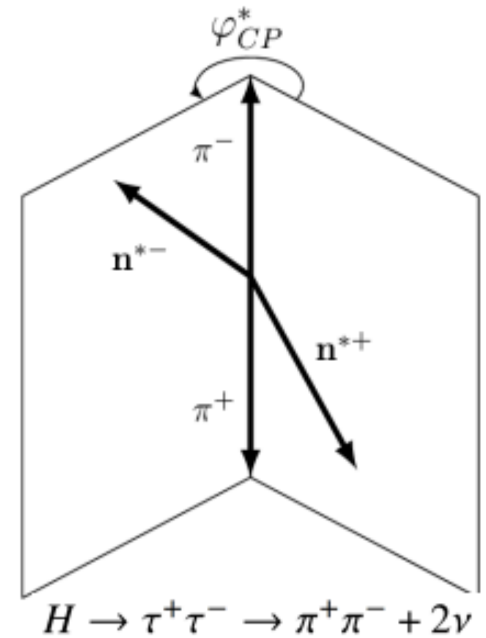


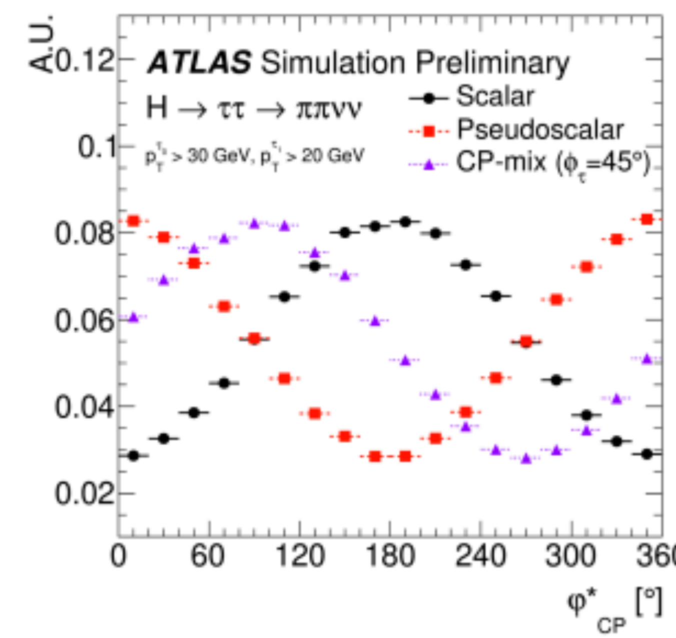
- **Combination with ggH as top quark has leading contributions to ggH effects couplings**
  - Assuming ggH loop is dominated by top quark



ATLAS: CP violation in $H \to \tau\tau$

- **Sensitivity to CPV from measurement of angle between τ lepton decay planes: ϕ_{CP}**
    - Using ϕ^*_{CP} as proxy (due to neutrinos)





- **Measurement performed in 24 signal categories and 10 control regions**
    - Targeting different decay modes

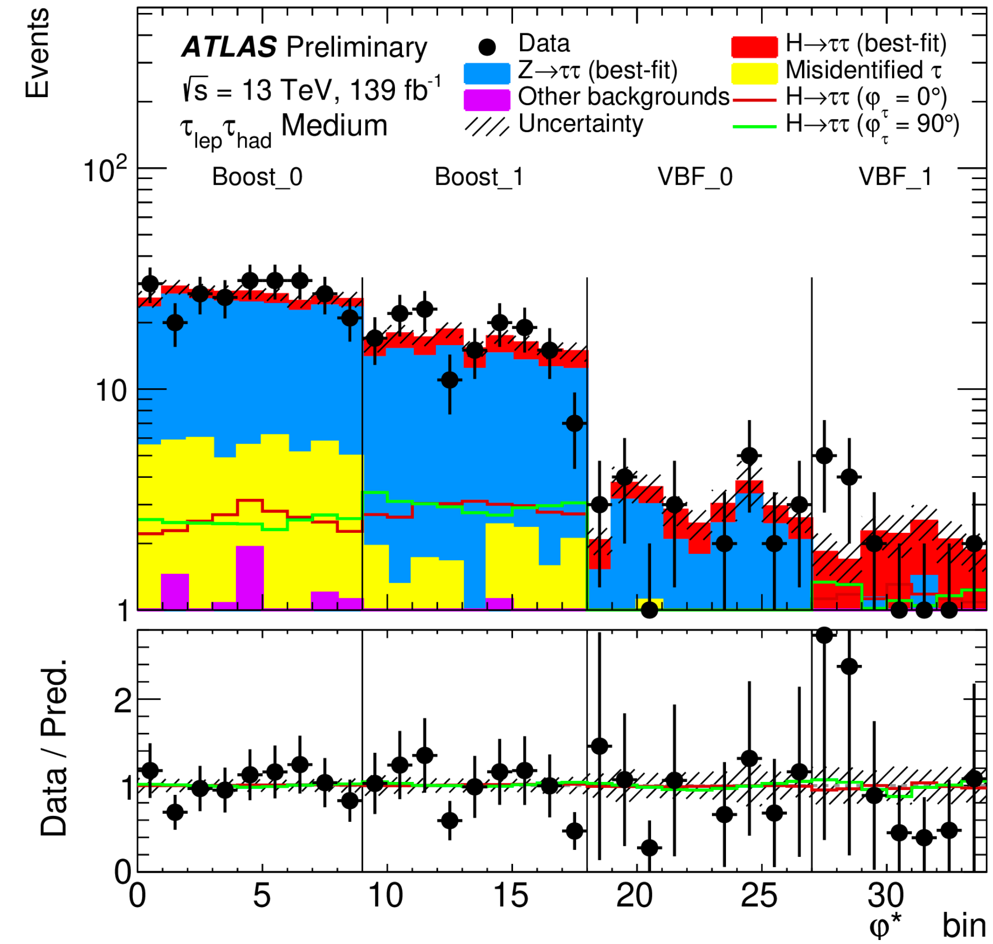
$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

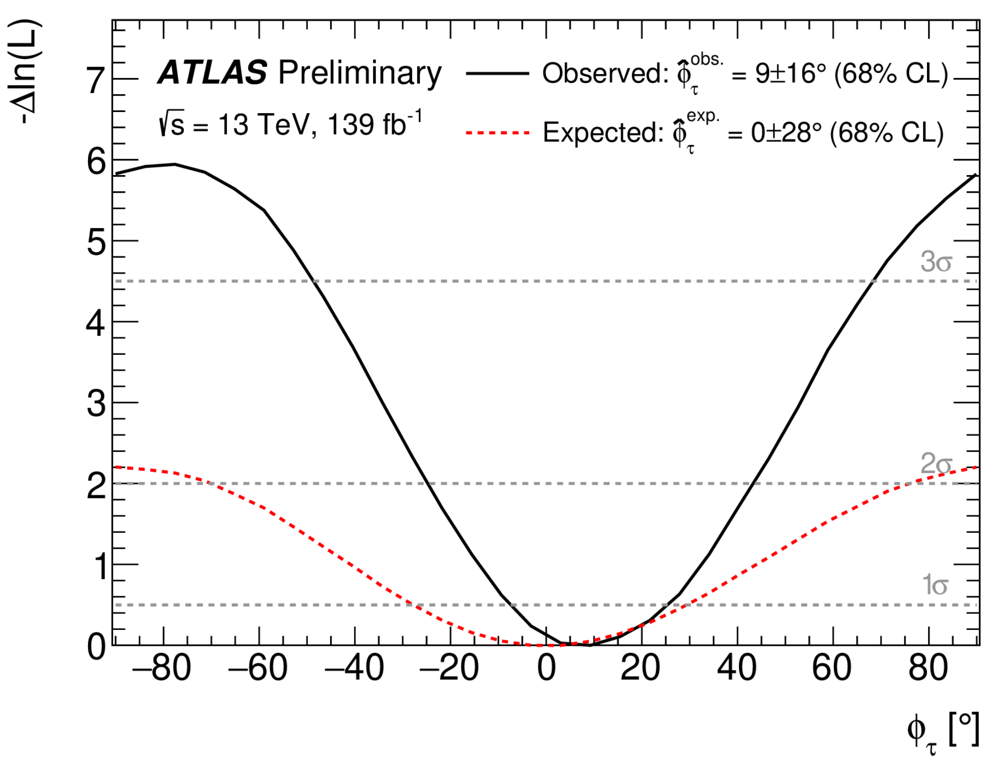
Decay channel	Decay mode combination	Method	Fraction in all τ lepton pair decays
$\tau_{lep}\tau_{had}$	ℓ-1p0n	IP	8.1%
	ℓ-1p1n	IP-ρ	18.3%
	ℓ-1pXn	IP-ρ	7.6%
	ℓ-3p0n	IP-a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n-1p0n	IP	1.3%
	1p0n-1p1n	IP-ρ	6.0%
	1p1n-1p1n	ρ	6.7%
	1p0n-1pXn	IP-ρ	2.5%
	1p1n-1pXn	ρ	5.6%
	1p1n-3p0n	ρ-a_1	5.1%

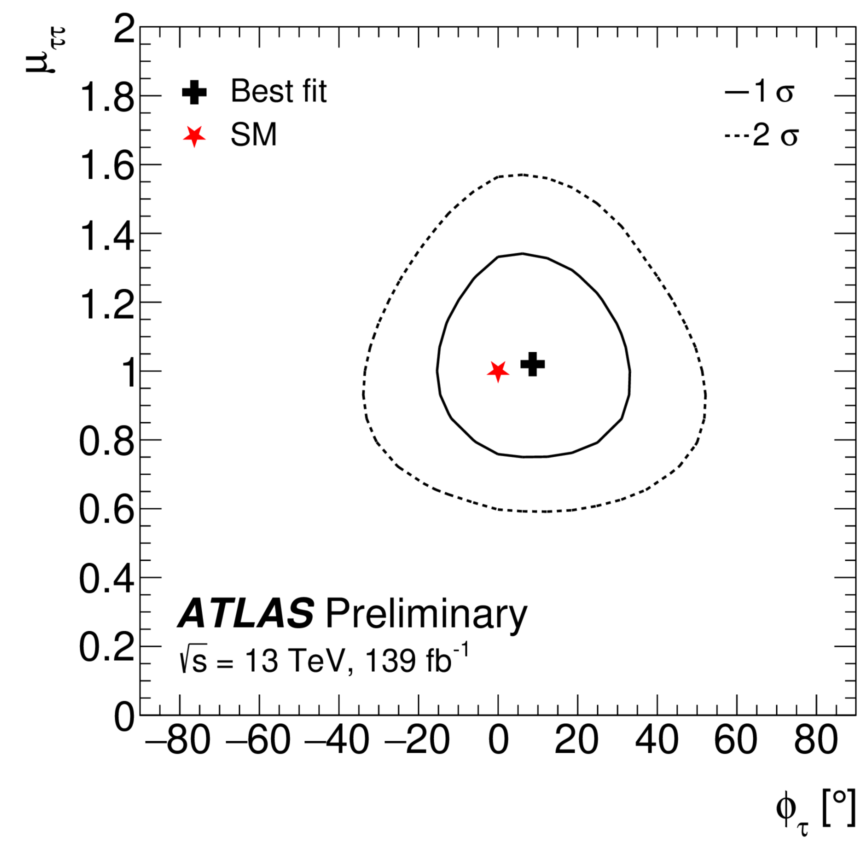
- Angle reconstruction relies on exploring track impact parameters and π^0 decays
    - Decay plane reconstruction using ρ plane method for π^0 and IP method for other decays

ATLAS: CP violation in $H \to \tau\tau$ (2)

- **CP mixing angle is extracted from simultaneous fit to all regions**
  - Exploiting shape only information by floating signal strength
  - Constraining dominant background ($Z \to \tau\tau$) from dedicated control regions
- Limits are statistically limited with leading systematic uncertainty from jet calibration
- **Best fit value for $\phi_\tau = 9 \pm 16\,^\circ$ (compatible with SM)**
- Pure CP odd ($\phi = 90^o$) excluded at 3.4 sigma

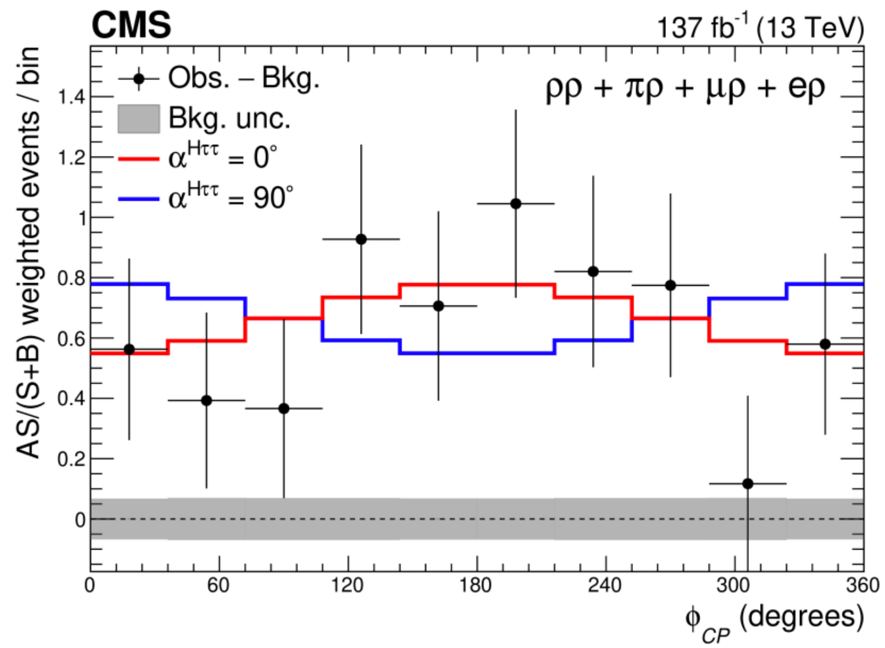




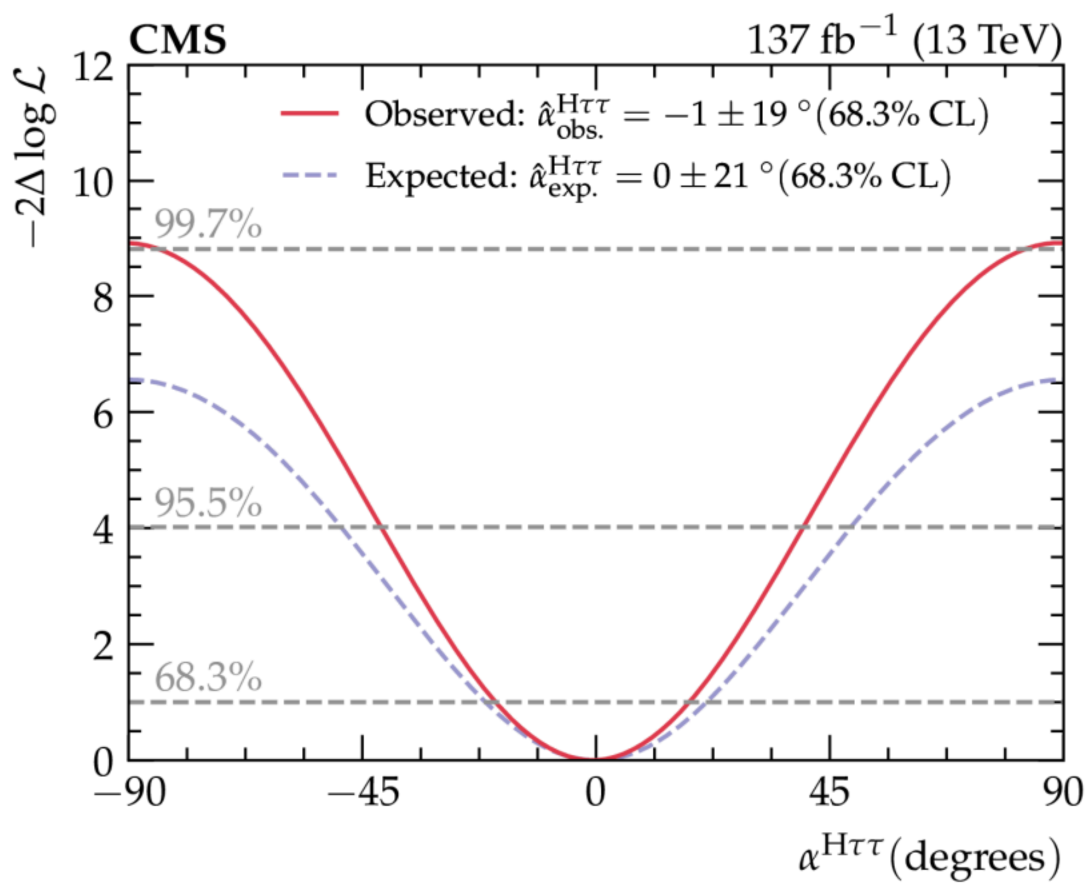


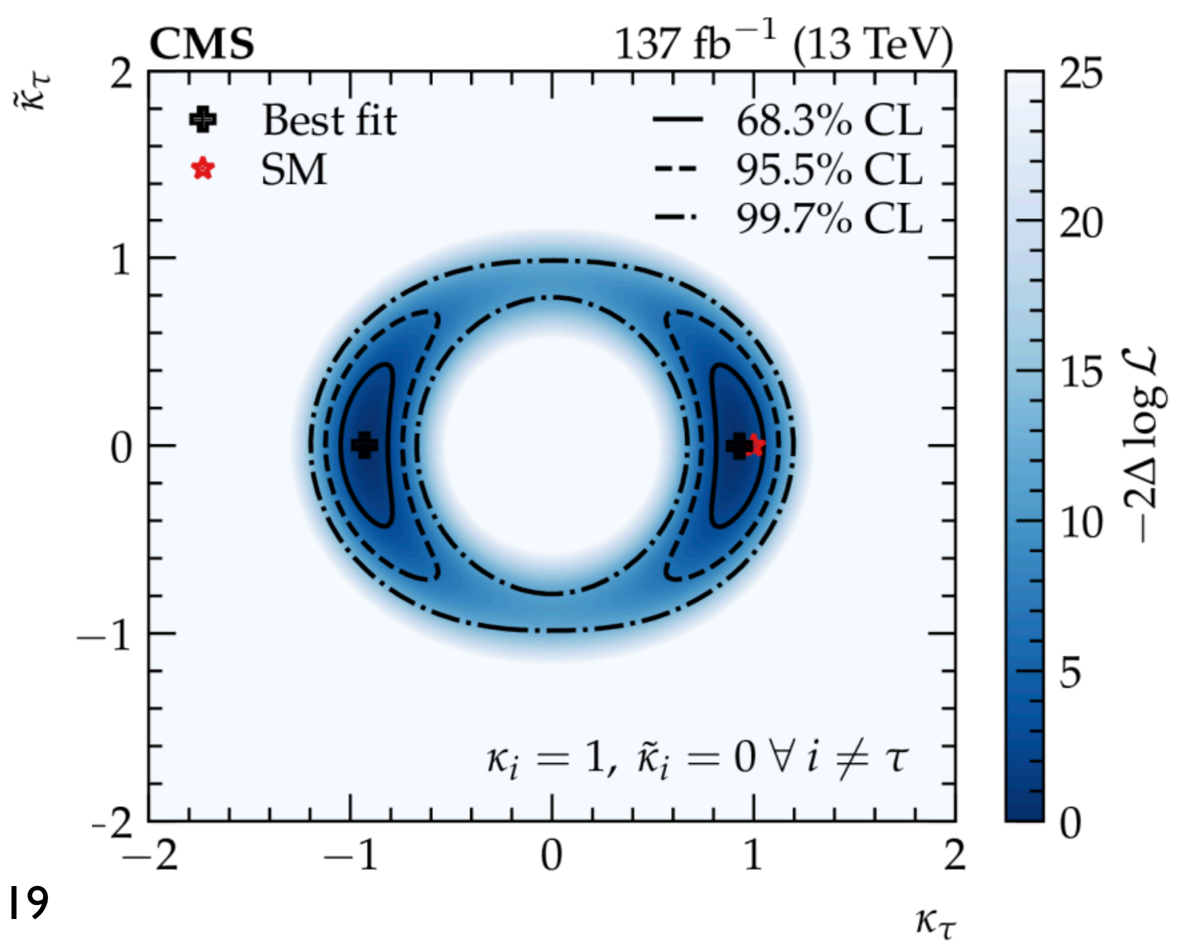
CMS: CP violation in $H \to \tau\tau$

- **Using transverse spin correlations of tau leptons to probe CP mixing angle**
- Using Acoplanar angle (same as ATLAS)
- Using NN to separate Signal to background
- Most backgrounds estimated using data control regions
- Considering different final states: $eh_\tau + \mu h_\tau + h_\tau h_\tau$



$$\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})^\circ$$

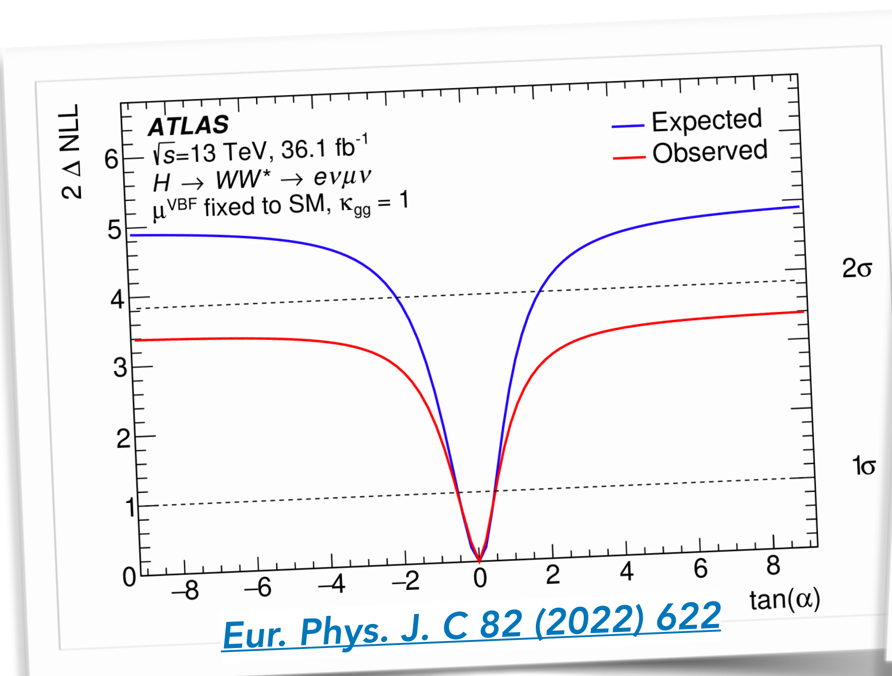




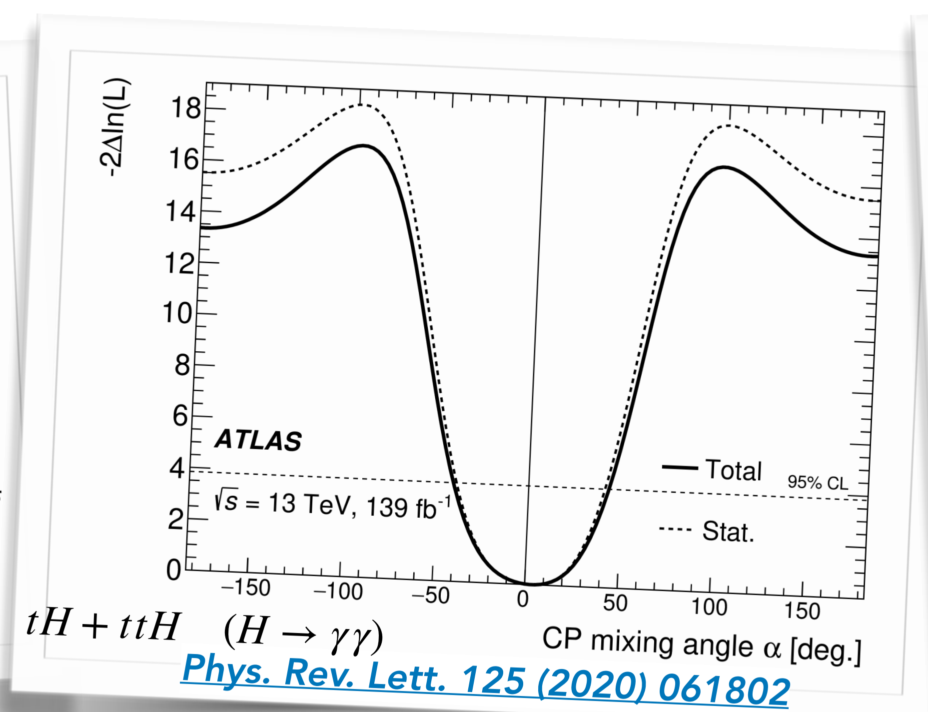
Summary

- Search for CP violation in the Higgs sector is very active area of research by both experiments
- **Measurements probe setting constraints on anomalous couplings of fermionic and boson couplings**
- Measurement performed in all main decay channels probing CPV effects in the production and decay
- **All limits are compatible with SM predictions**
- **Stringent limits set on CPV HVV, HGG and Htt and $H\tau\tau$ couplings**
- **Pure CP-odd couplings excluded by multiple measurement at $\geq 3\sigma$**

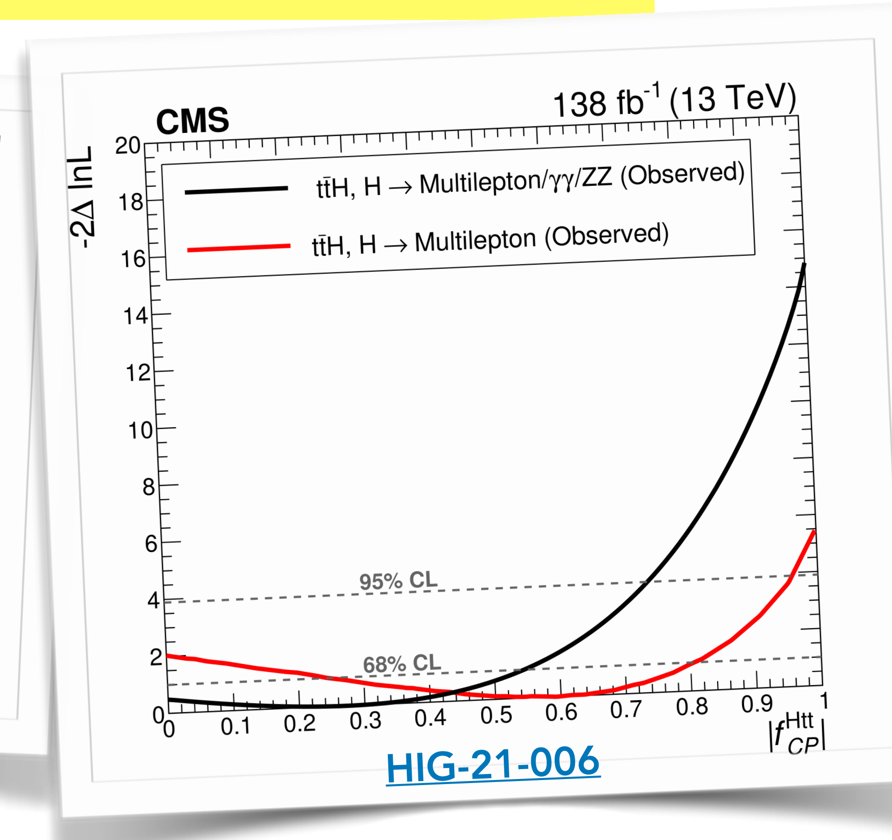
Stay tuned for more Run-2 measurement and combination and for Run-3!



Eur. Phys. J. C 82 (2022) 622



$tH + ttH \quad (H \to \gamma\gamma)$
Phys. Rev. Lett. 125 (2020) 061802



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