CP structure and searches for CP violation in Higgs interactions

on behalf of the ATLAS and CMS collaborations

Tongguang Cheng (Beihang University)

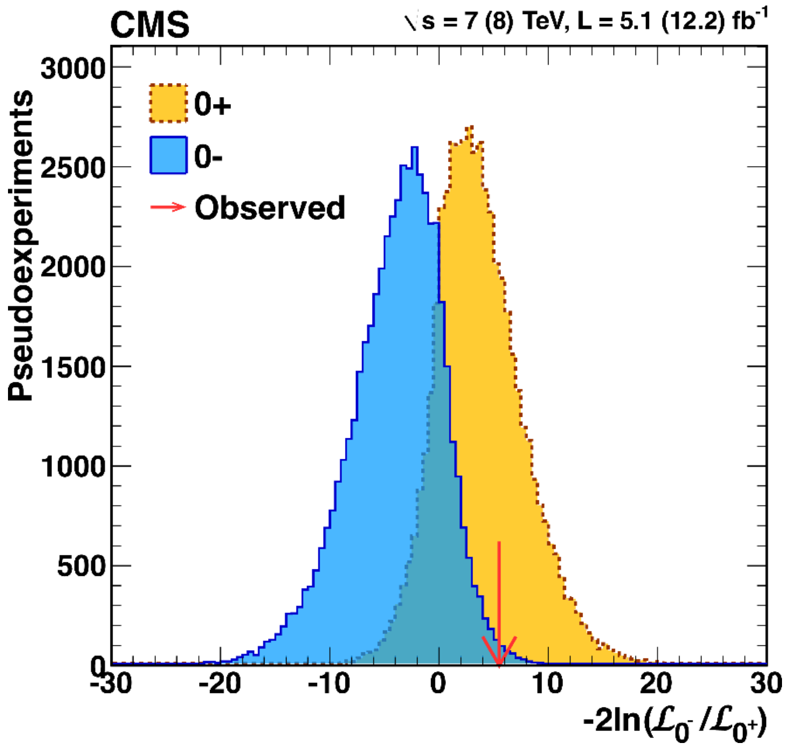
Outlines

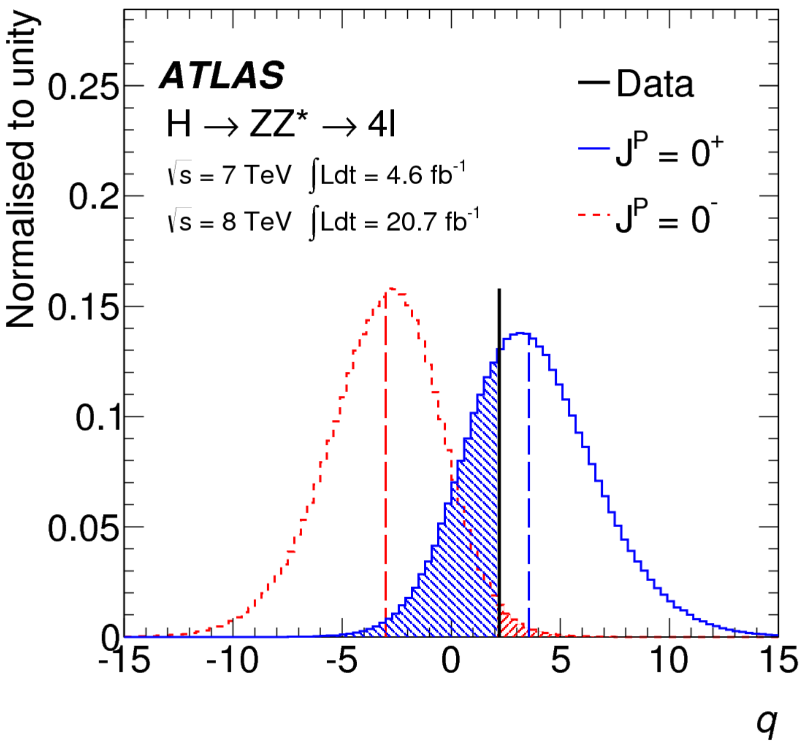
Higgs CP structure/CP violation in

- Higgs-fermion interactions
  - Higgs-**τ**
  - Higgs-top
- Higgs-gauge boson interactions
  - Higgs-W/Z
  - Higgs-gluon

Higgs turns (more than) ten

About 10 years ago, we published the first set of results on Higgs CP studies with the 7/8TeV collision data





[Phys. Rev. Lett. 110 (2013) 081803]

[Phys. Lett. B 726 (2013) 120]

Motivations to search for Higgs CP violation

- **Motivation from cosmology:**
  - CP-violation is an essential ingredient to understand of the matter anti-matter asymmetry in the Universe
  - One may interpret the baryogenesis as being induced by the CP-violating effect in the Higgs sector (see for e.g.,arXiv:2311.06949)

- **Motivation from theory:**

  BSM theories, such as 2HDM, contain Higgs CP violation
  - 2HDM : T. D. Lee, Phys. Rev. D 8, 1226 (1973)
    J. F. Gunion and H. E. Haber, Phys. Rev. D 72, 095002 (2005)
    I. Low, N. R. Shah and X. Wang, Phys. Rev. D 105, 035009 (2022)
  - MSSM : Bing Li and Carlos E. M. Wagner Phys. Rev. D 91, 095019 (2015)

Motivations to search for Higgs CP violation

$\boxed{H}$

was H^0

$J = 0$

[from PDG tables]

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.4}_{-1.7}$ MeV (assumes equal on-shell and off-shell effective couplings)

H Signal Strengths in Different Channels

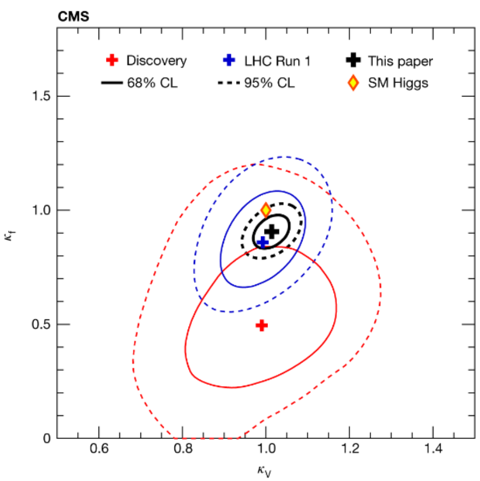
Combined Final States $= 1.03 \pm 0.04$
$WW^* = 1.00 \pm 0.08$
$ZZ^* = 1.02 \pm 0.08$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State $= 8 \pm 22$ (S = 1.9)

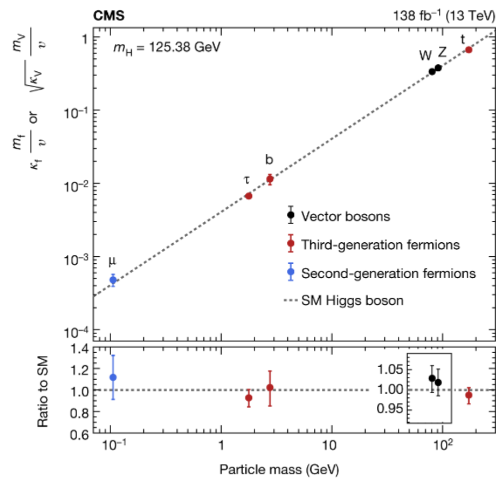
$b\bar{b} = 0.99 \pm 0.12$
$\mu^+\mu^- = 1.21 \pm 0.35$
$\tau^+\tau^- = 0.91 \pm 0.09$
$\gamma^*\gamma$ Final State $= 1.5 \pm 0.5$
Fermion coupling (κ_F) $= 0.95 \pm 0.05$
Gauge boson coupling (κ_V) $= 1.035 \pm 0.031$
$t\bar{t}H$ Production $= 1.10 \pm 0.18$
tH production $= 6 \pm 4$
H Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV $=$ 56.9 $\pm$ 3.4 pb

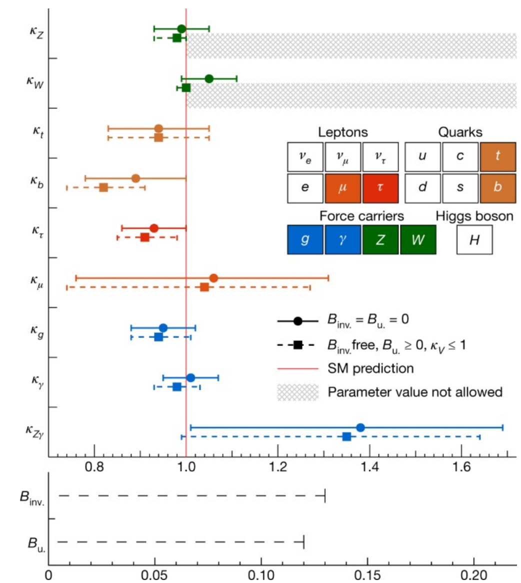
- **Data still allow BSM Higgs couplings**
- **CP mixing is not forbidden**

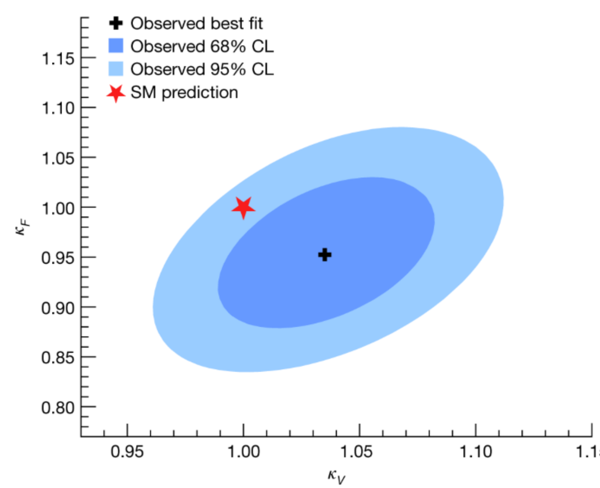
Higgs turns (more than) ten

Now we are able to study detailed structures on the Higgs couplings (not only the process rates)







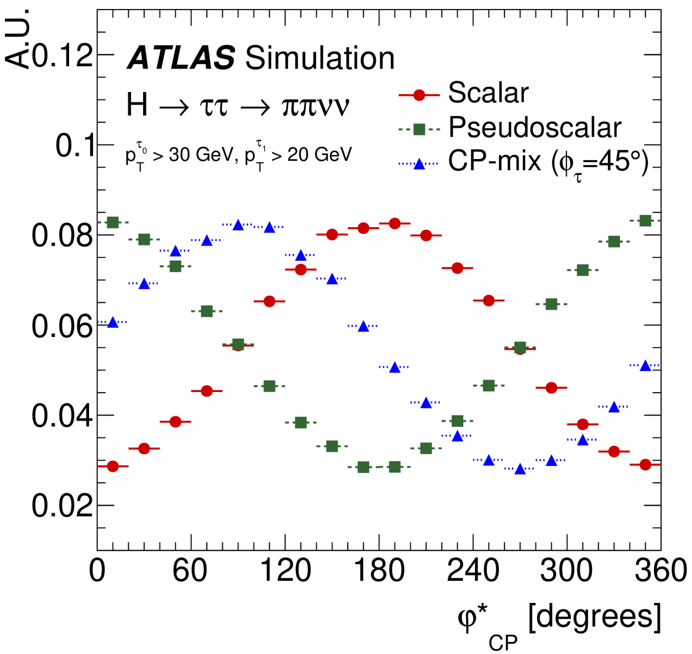


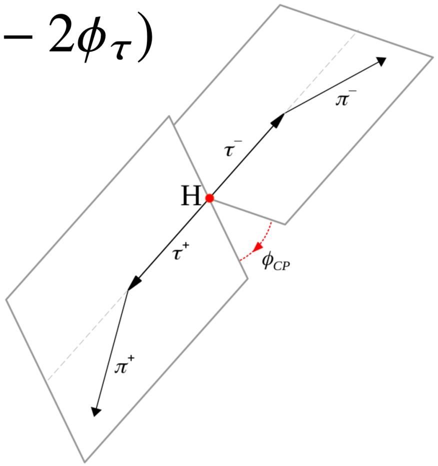
ATLAS: [Nature 607, pages 52-59 (2022)]
CMS: [Nature 607 (2022) 60]

CP structure in H decays to τ-leptons

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H\left(\boxed{\kappa_\tau \bar{\tau}\tau} + \boxed{\tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau}\right) \quad \tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

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



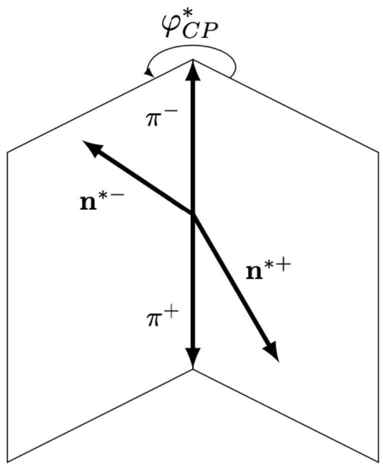


The cross section is modulated by the angular of two tau decay planes in the Higgs rest frame and the CP mixing angle ϕ_τ

ATLAS: Eur. Phys. J. C 83 (2023) 563
CMS: JHEP 06 (2022) 012

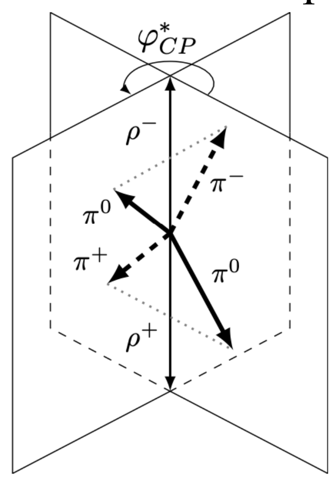
Reconstruction of τ-decay planes

Impact parameter method

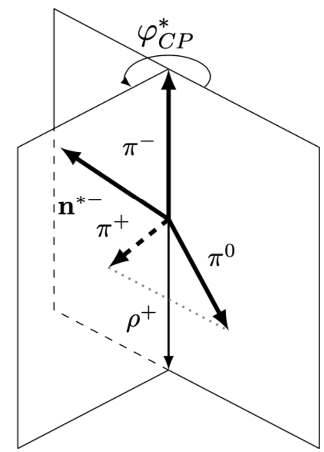


$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$

Neutral pion + IP method

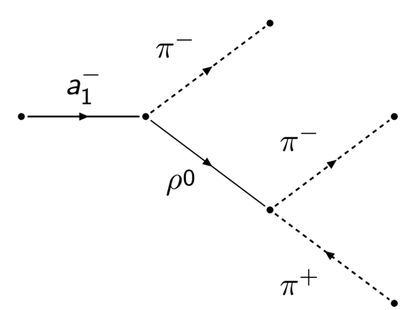


$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$



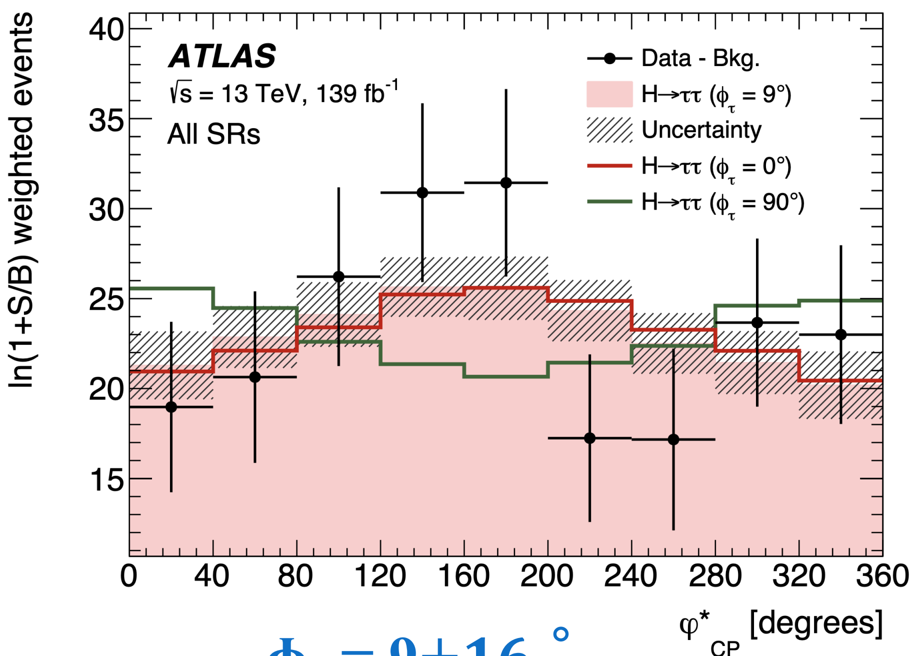
$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$

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

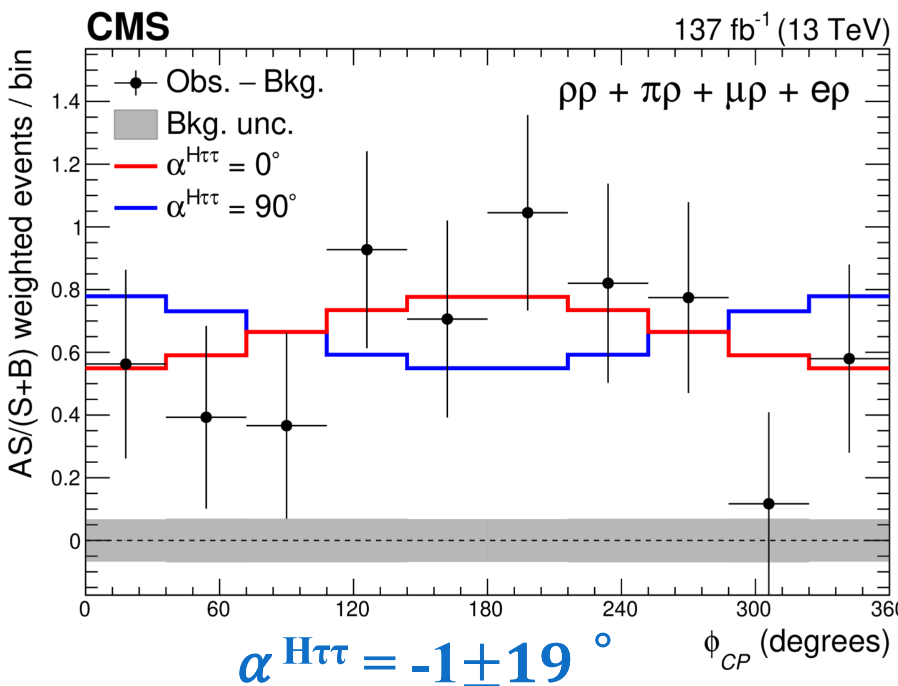


(Polarimetric vector method for $a_1^{3pr}a_1^{3pr}$)

CP structure in H decays to τ-leptons



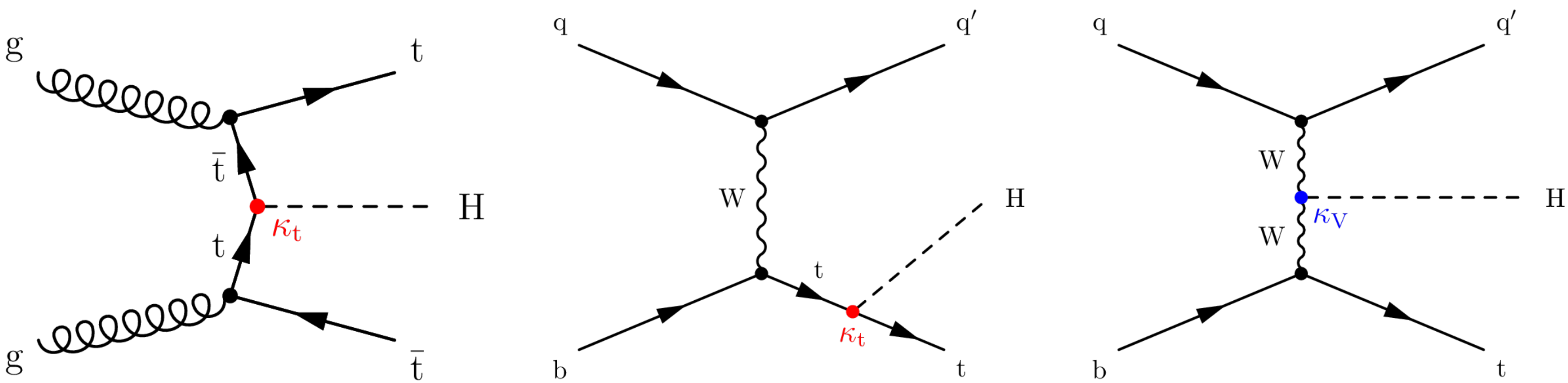
$\phi_\tau = 9 \pm 16\ °$



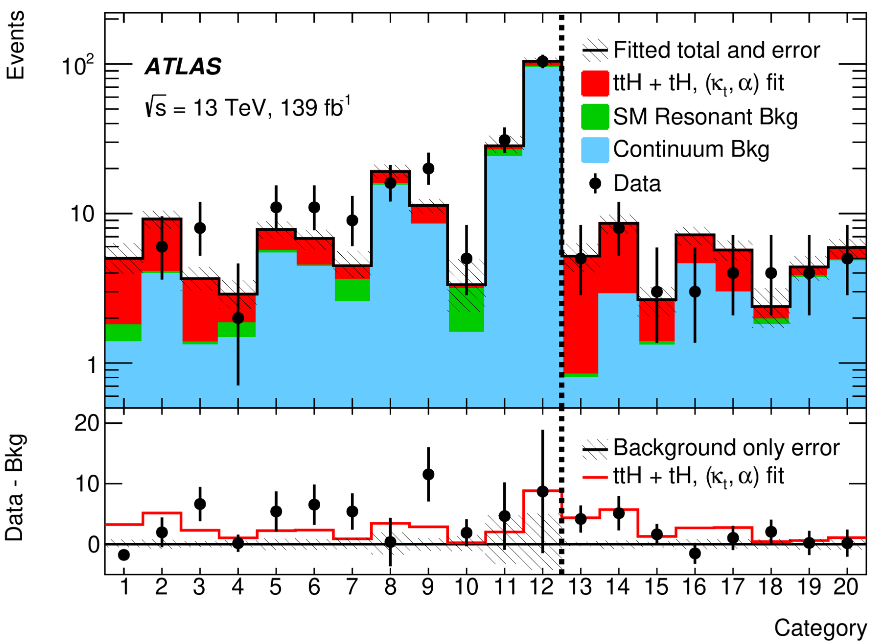
$\alpha^{H\tau\tau} = -1 \pm 19\ °$

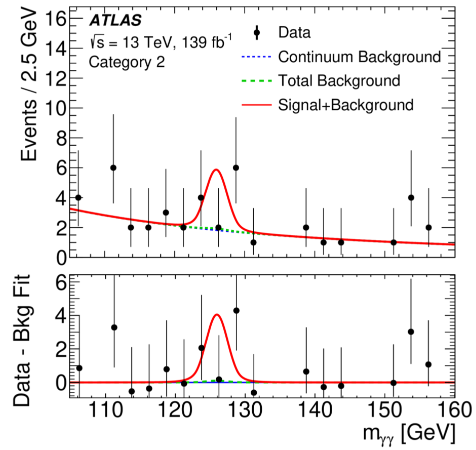
- ❑ Data with background subtracted are compared with pure CP-even and pure CP-odd assumptions.
- ❑ Pure CP-odd is strongly disfavor but there is still room for CP mixing in data.

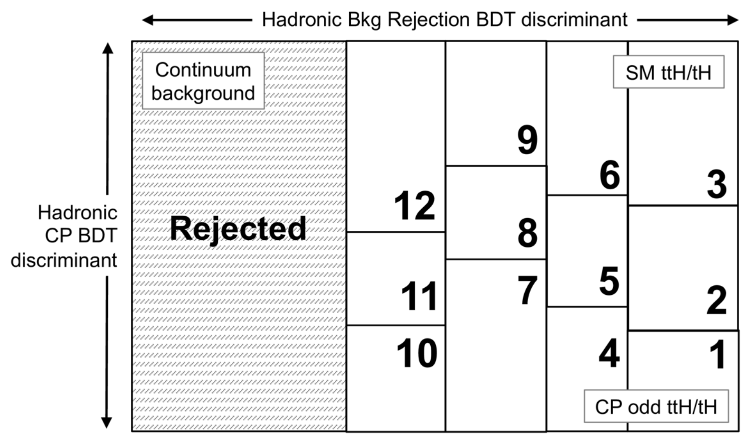
CP structures in Higgs-top interactions



CP structures in ttH+tH(Hγγ)





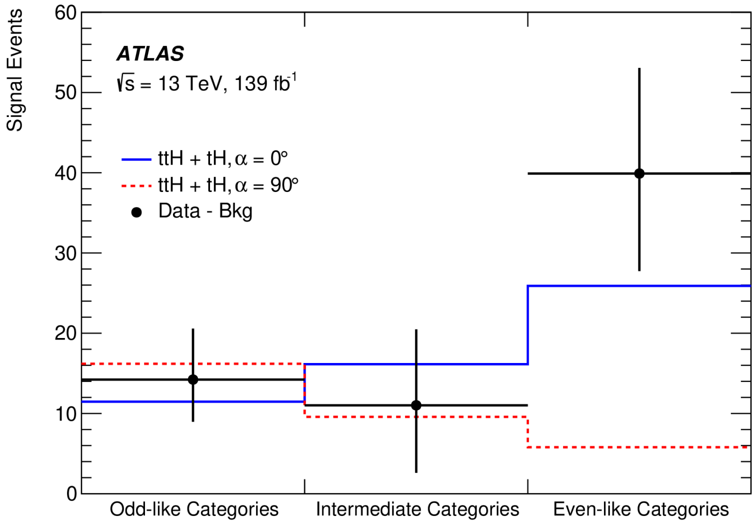


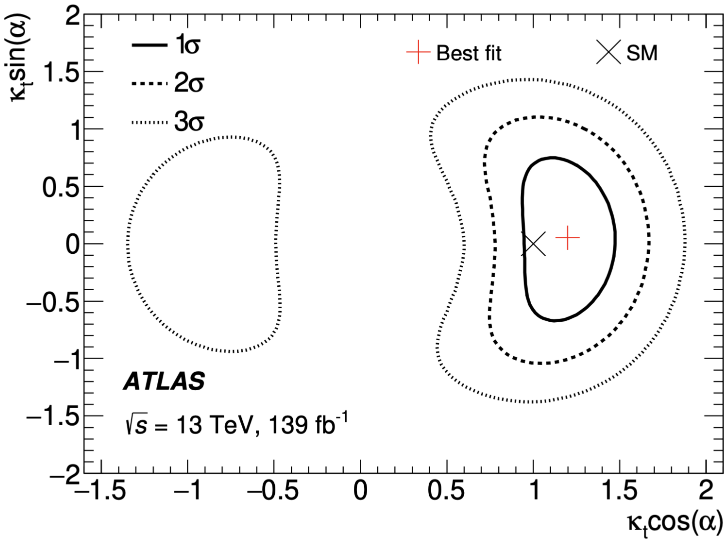
- Events are classified into leptonic and hadronic events and categorized according to bkg rejection and CP BDTs
- Signal extraction from the $m_{\gamma\gamma}$ spectrum

ATLAS Hγγ : [Phys. Rev. Lett. 125 (2020) 061802]

CP structures in ttH+tH(Hγγ)

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\boxed{\cos(\alpha)} + \boxed{i\sin(\alpha)\gamma_5}]\psi_t\}H$$

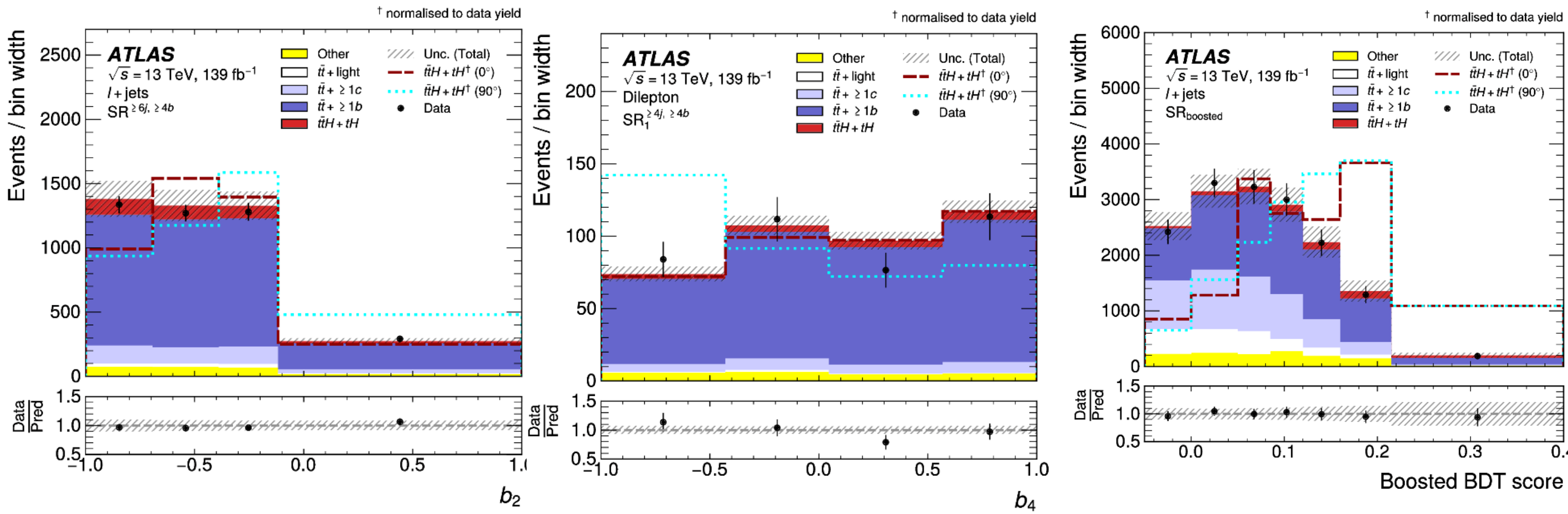




- Data with background subtracted are compared with CP-even and CP-odd signals in three categories
  - categorization based on events' CP BDT ranges
- CP mixing angle $|\alpha|<43^\circ$ @95% CL

ATLAS Hγγ : Phys. Rev. Lett. 125 (2020) 061802

CP structures in ttH+tH(Hbb)

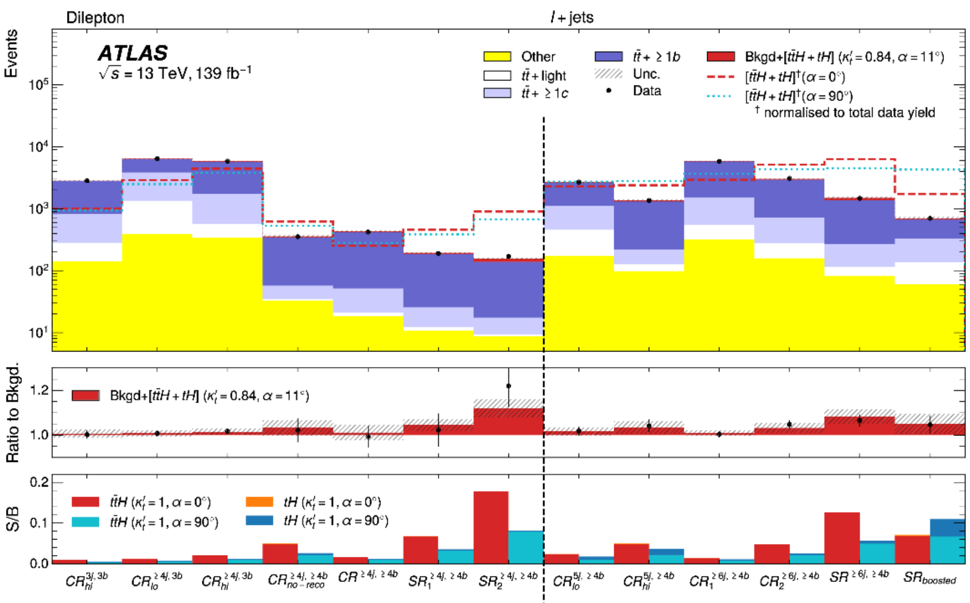


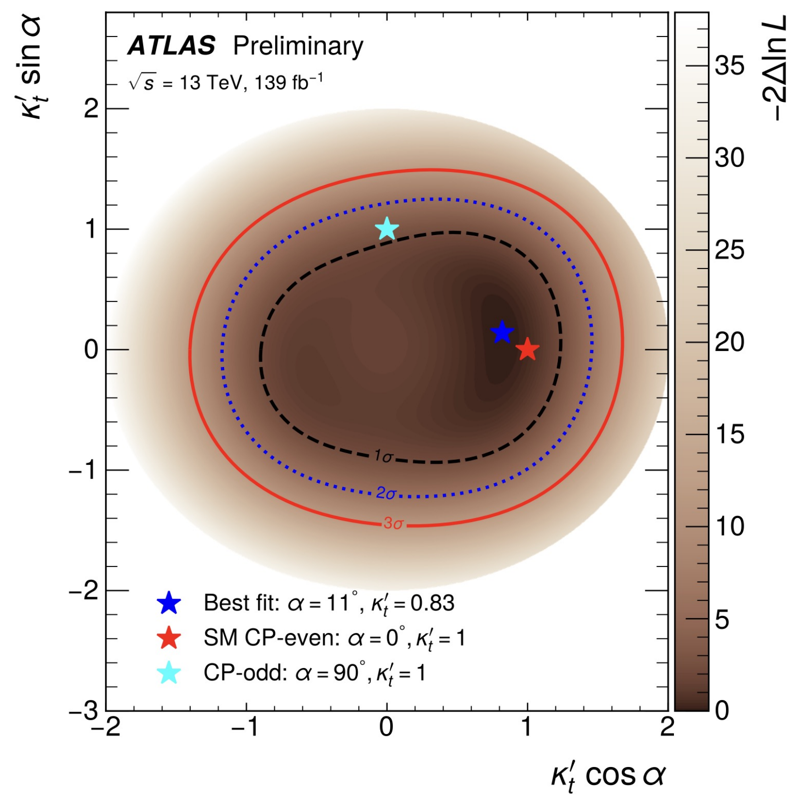
- Dedicated CP sensitive variables defined with top quark kinematics
  - b_4 for di-lepton, b_2 for lepton+jets, BDT for boosted lepton+jets

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

ATLAS Hbb [arxiv:2303.05974] (submitted to JHEP)

CP structures in ttH+tH(Hbb)



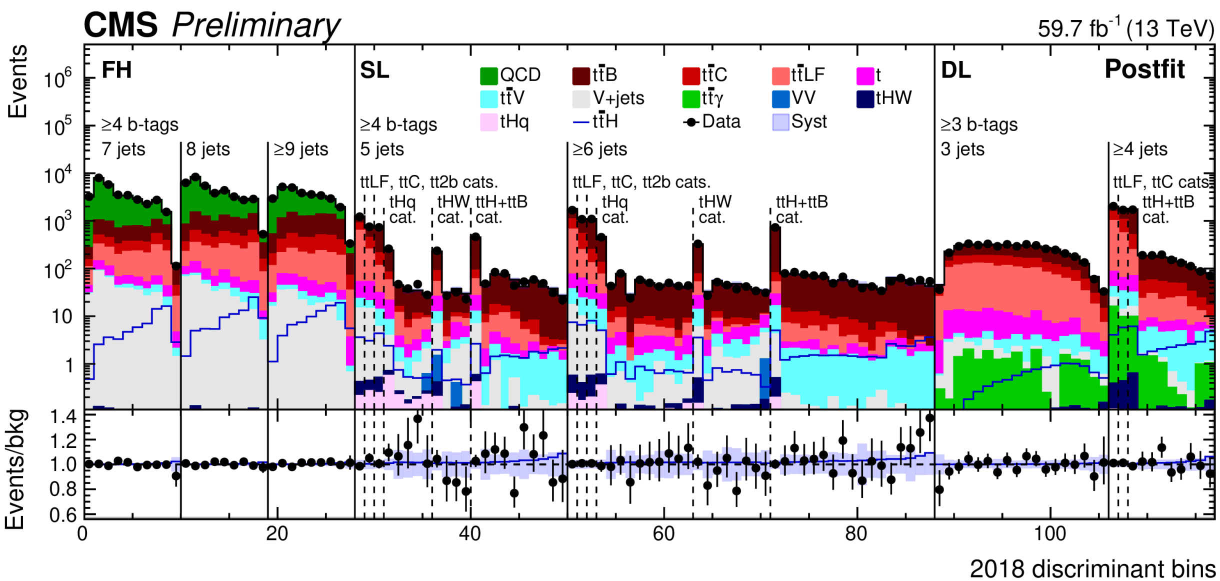


- ❑ Fit with κ_t' and α as free parameters in all analysis regions
- ❑ The middle panel above compares best-fit with bkg
- ❑ Likelihood scan indicates mixing angle

$$\alpha = 11^{\circ}\ {}^{+52}_{-73}$$

ATLAS Hbb arxiv:2303.05974 (submitted to JHEP)

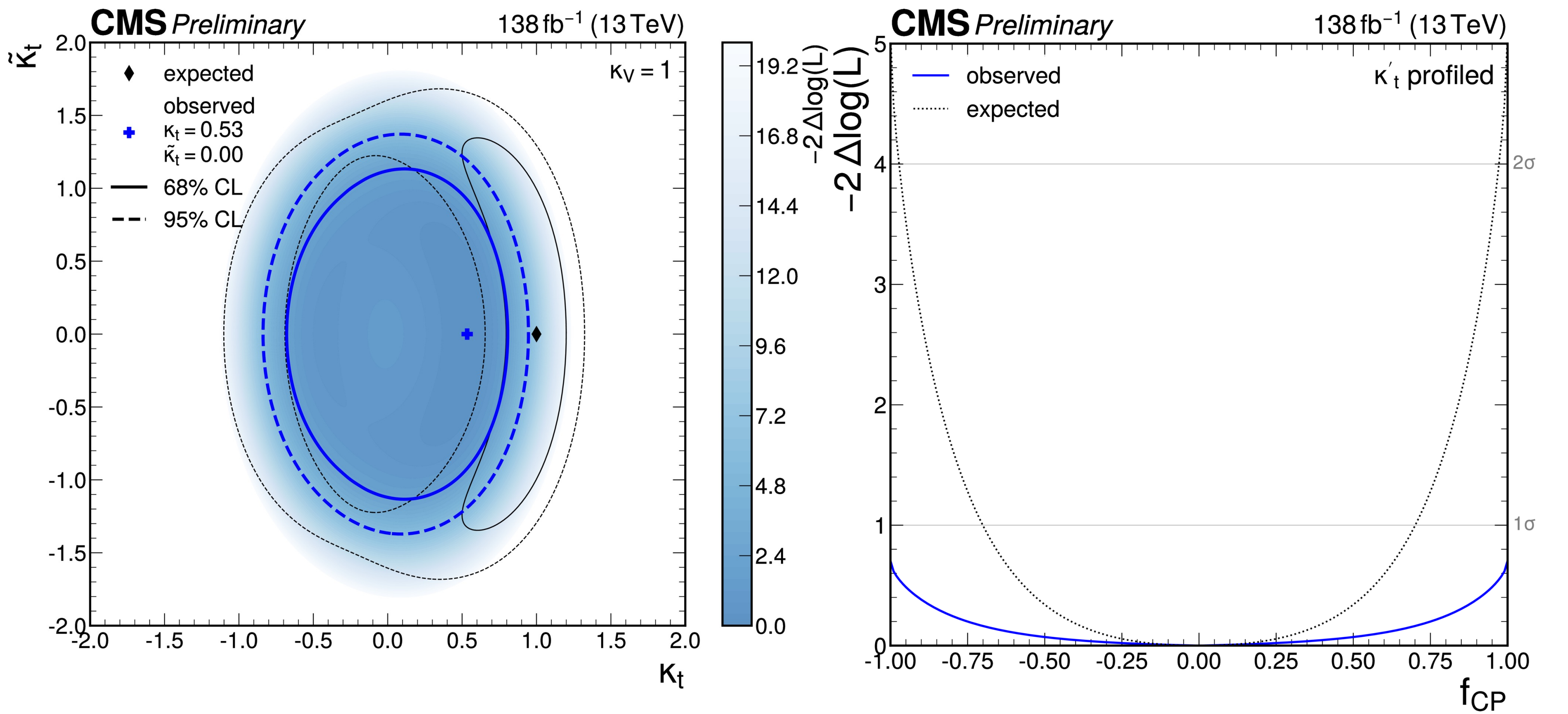
CP structures in ttH+tH(Hbb)



- ❑ Events are categorized as single-lepton, di-lepton, and full hadronic
- ❑ For each category,
  ANNs separate different signal or background processes.
- ❑ The signal is extracted in a simultaneous likelihood fit of the discriminating observable or of the event yield

CMS Hbb : [PAS HIG-19-011]

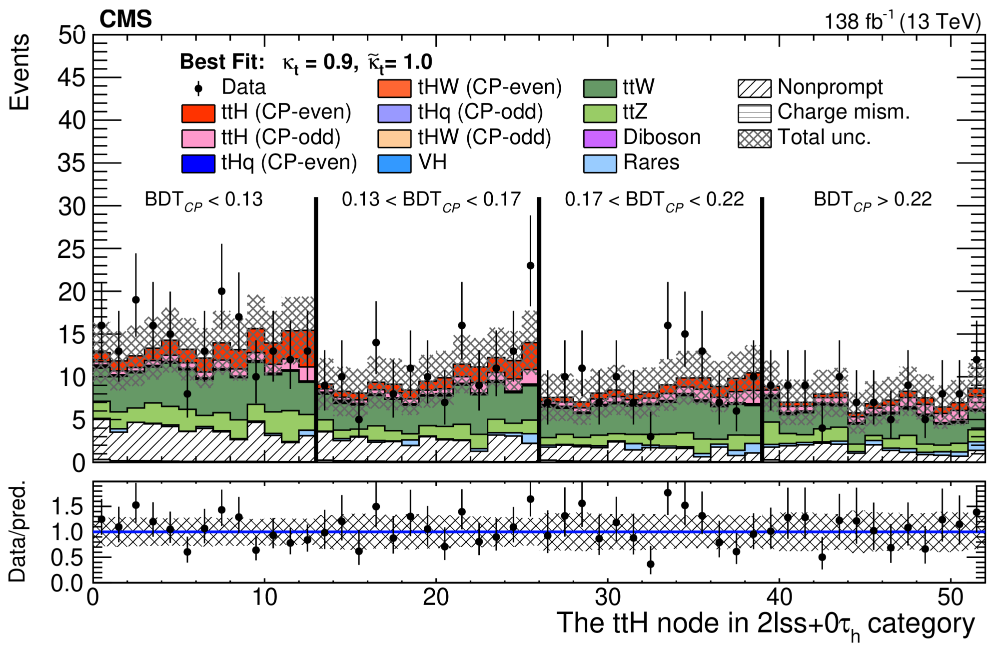
CP structures in ttH+tH(Hbb)



- ❑ Best fit at (+0.53, 0.00) from likelihood ratio as a function of κ_t and $\tilde{\kappa}_t$, with κ_V fixed at 1
- ❑ CP fraction f_{CP} is compatible with zero

CMS Hbb : PAS HIG-19-011

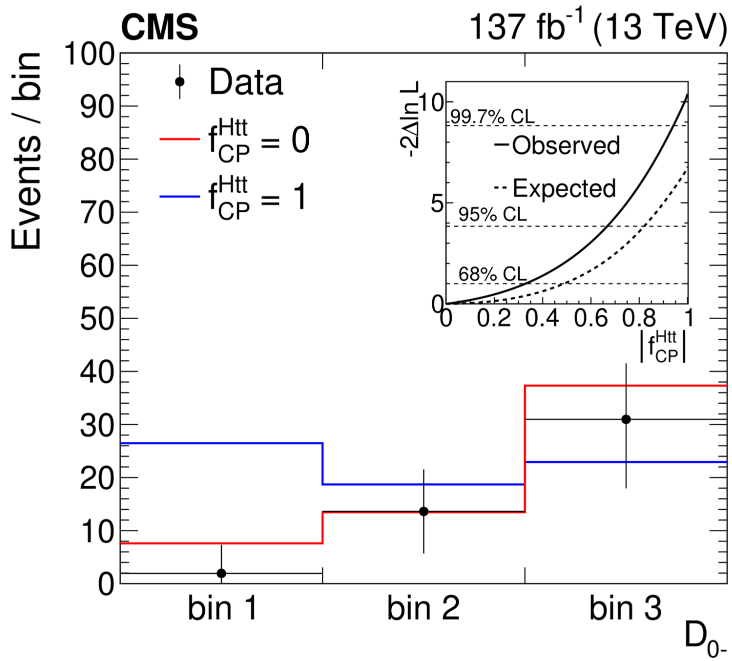
CP structures in ttH+tH(multi-lepton)

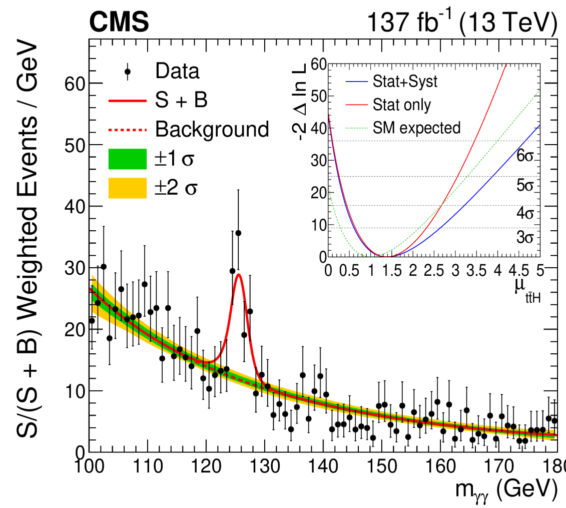


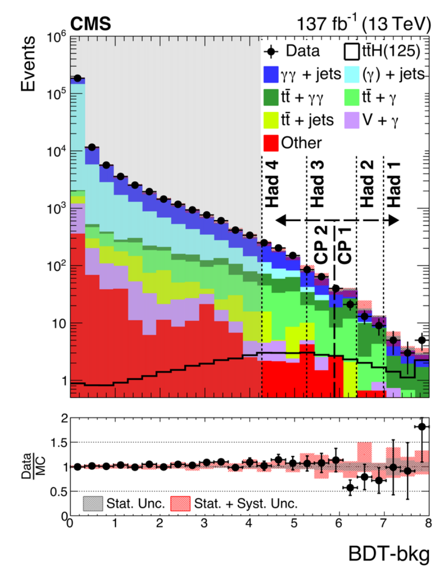
- Events are categorized as $2lSS + 0/1\tau_h$ and $3l + 0/1\tau_h$
- Multi-output ANN to separate and classify signal and background processes
- For each category, BDT is trained to separate CP-even/odd

CMS multi-lepton : JHEP 07 (2023) 092

CP structures in ttH+tH(Hγγ)



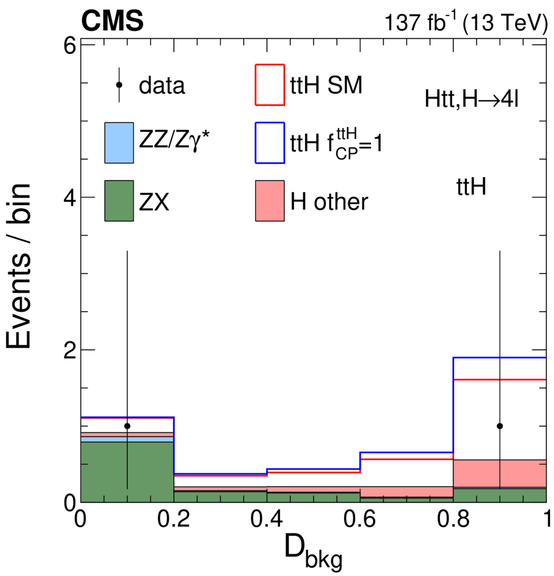


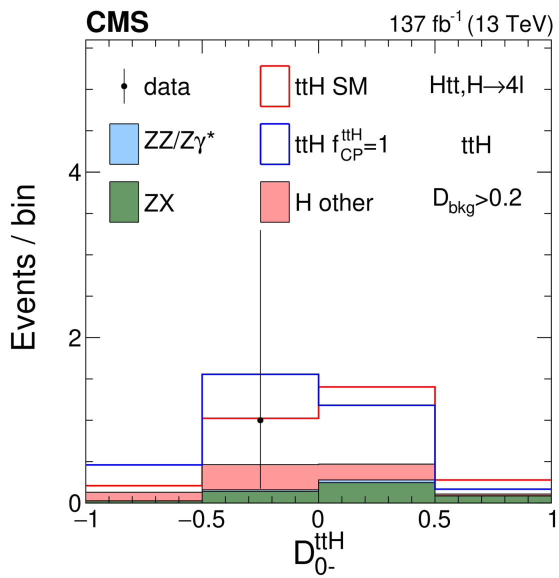


- Events are categorized according to
  - BDT to separate signal/background
  - D_{0-} is trained to separate CP-even/odd
- Fit $m_{\gamma\gamma}$ in all categories defined by BDT-bkg and D_{0-} simultaneously

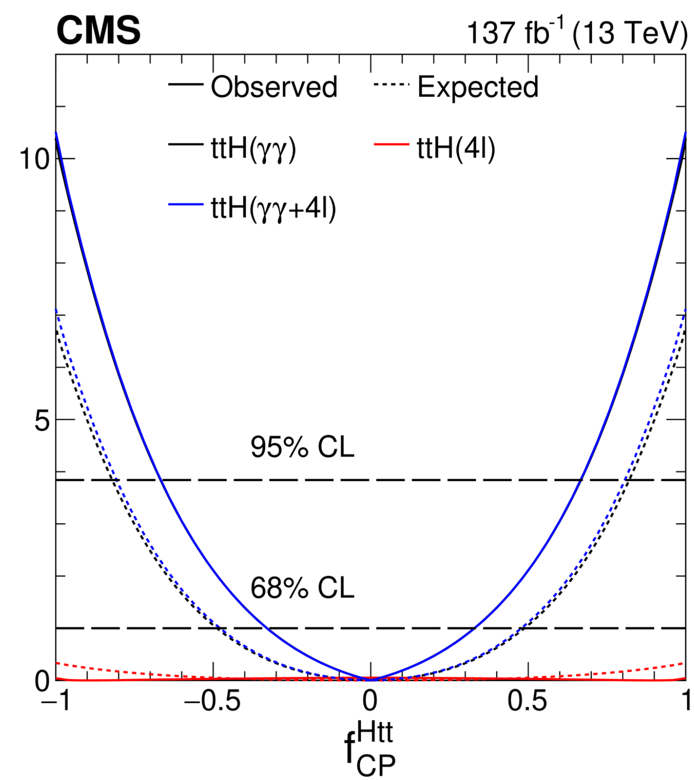
CMS Hγγ : Phys. Rev. Lett. 125 (2020) 061801

CP structures in ttH+tH(HZZ)





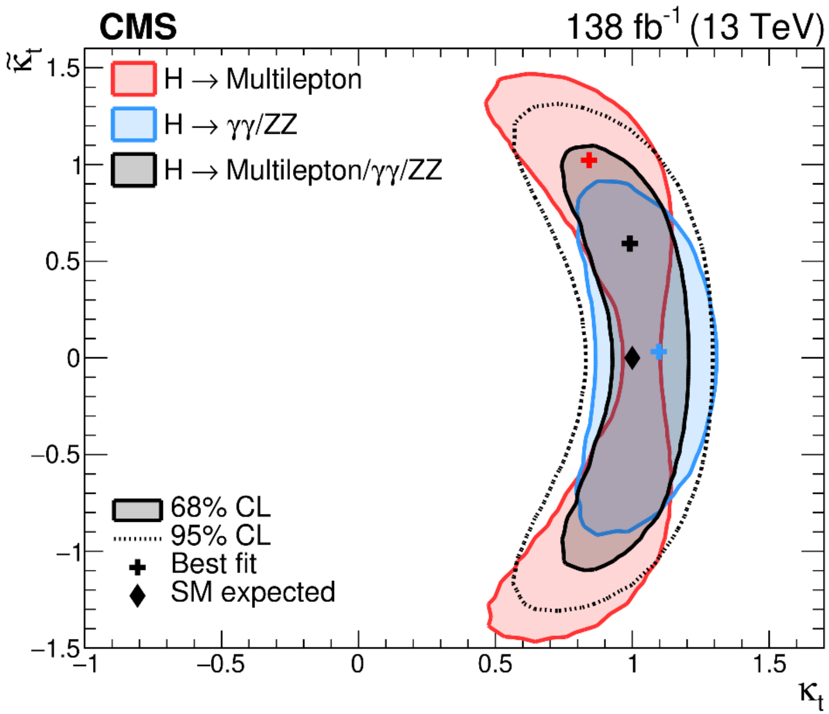
$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$



- ☐ MELA discriminants D_{bkg} and D_{0-} to separate sig/bkg and CP-even/odd
- ☐ f_{CP}^{Htt} is weakly constrained by H-to-4l

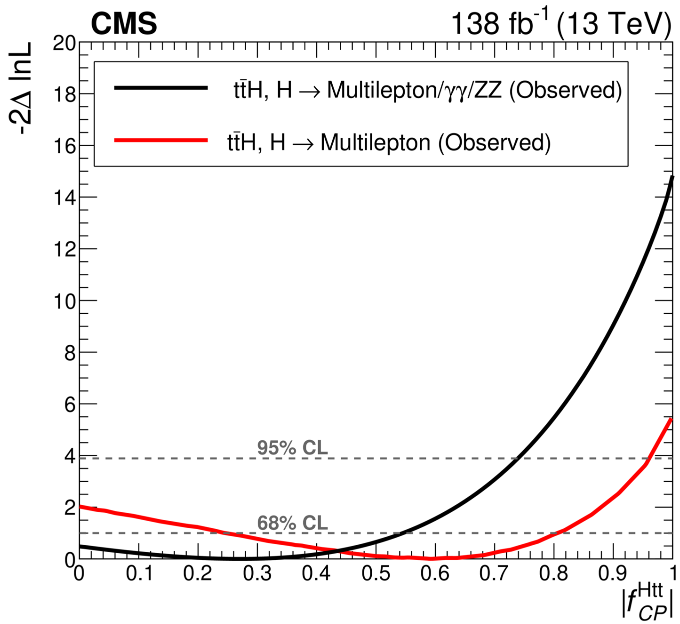
CMS HZZ4l : [Phys. Rev. D 104 (2021) 052004]

CP structures in ttH+tH



CMS γγ: [Phys.Rev. Lett. 125 (2020) 061801]
CMS ZZ: [Phys. Rev. D 104 (2021) 052004]

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \operatorname{sign}(\tilde{\kappa}_t/\kappa_t)$$



$|f_{CP}^{Htt}|$ = 0.28 (<0.55 at 1σ)

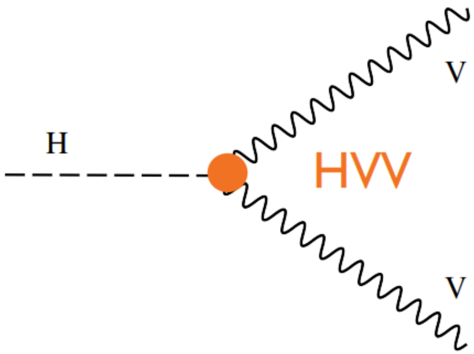
CP structures in Higgs-gauge boson

- Higgs-VV couplings measured based on the Effective Field Theory approach
- CP structure is explored with the Optimal Observable (OO)

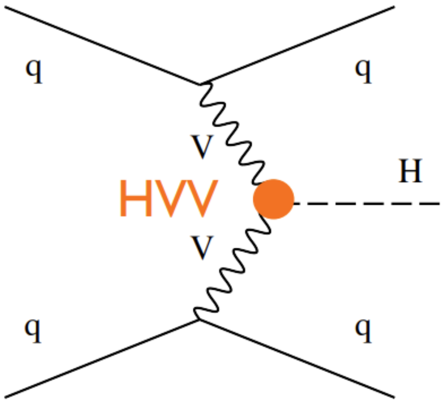
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

Three independent dim-6 operators for CP-odd in SMEFT

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



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



CP structures in Higgs-gauge boson

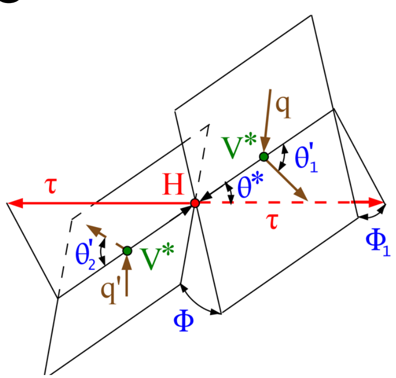
- Amplitude of HVV(ZZ, WW, $Z\gamma$, $\gamma\gamma$ and gg) are parameterized as

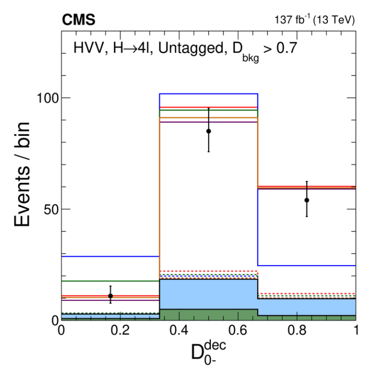
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + \boxed{a_3^{\mathrm{VV}}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

CP-odd

a_1 SM-like, a_3 CP-odd

- Build matrix-element based discriminants to tag different anomalous couplings

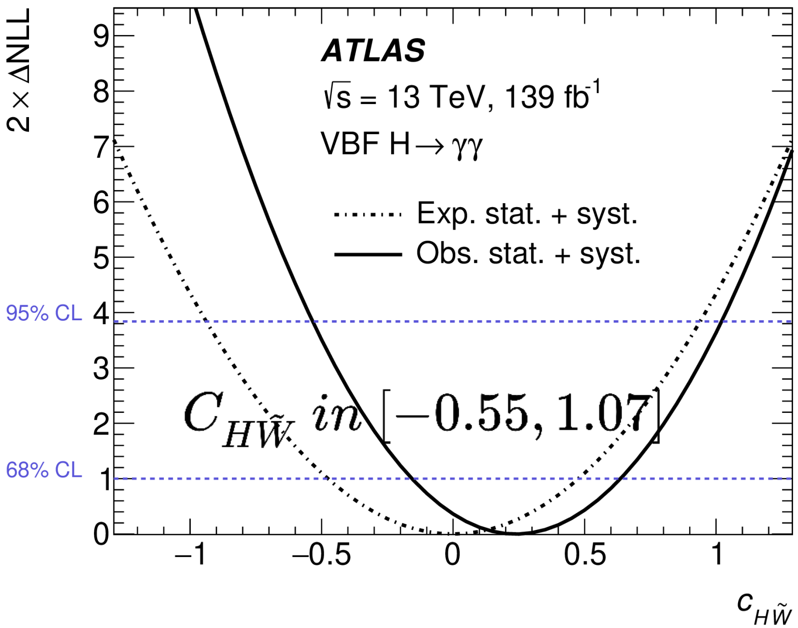


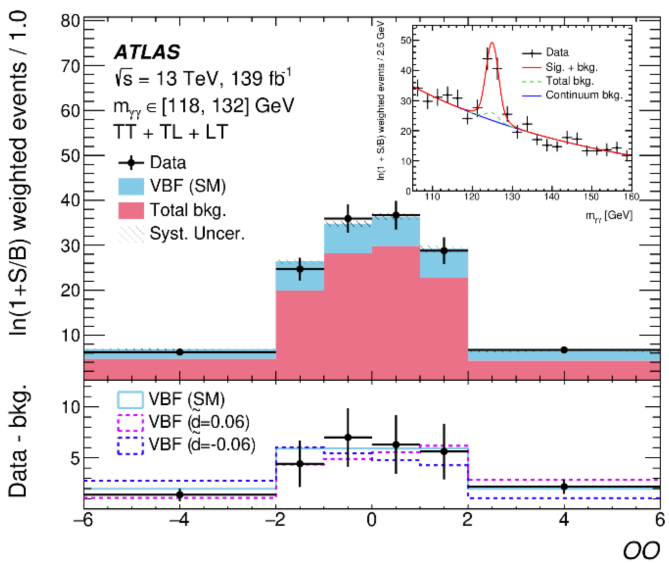


Coupling	Discriminant
a_3^{gg}	$\mathcal{D}_{0-}^{\mathrm{ggH}}$
a_3	$\mathcal{D}_{0-}$
a_2	$\mathcal{D}_{0h+}$
κ_1	$\mathcal{D}_{\Lambda 1}$
$\kappa_2^{Z\gamma}$	$\mathcal{D}_{\Lambda 1}^{Z\gamma}$

CMS: Phys. Rev. D 104, 052004 (2021)

CP structures in VBF(Hγγ)



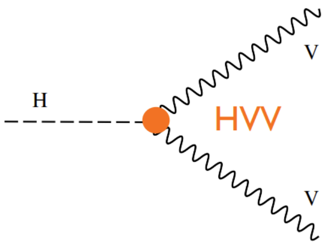


- ❑ Two BDTs are used to separate sig/bkg and VBF/ggH
- ❑ Four regions are defined based on two BDTs (TT,TL,LT, LL)
- ❑ Extract signals from simultaneous fit to the $m_{\gamma\gamma}$ spectra in all OO bin
- ❑ $C_{H\tilde{W}}$ is determined from CP violation contribution

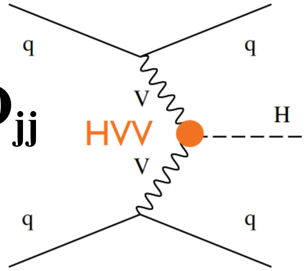
ATLAS VBFγγ: [Phys. Rev. Lett. 131 (2023) 061802]

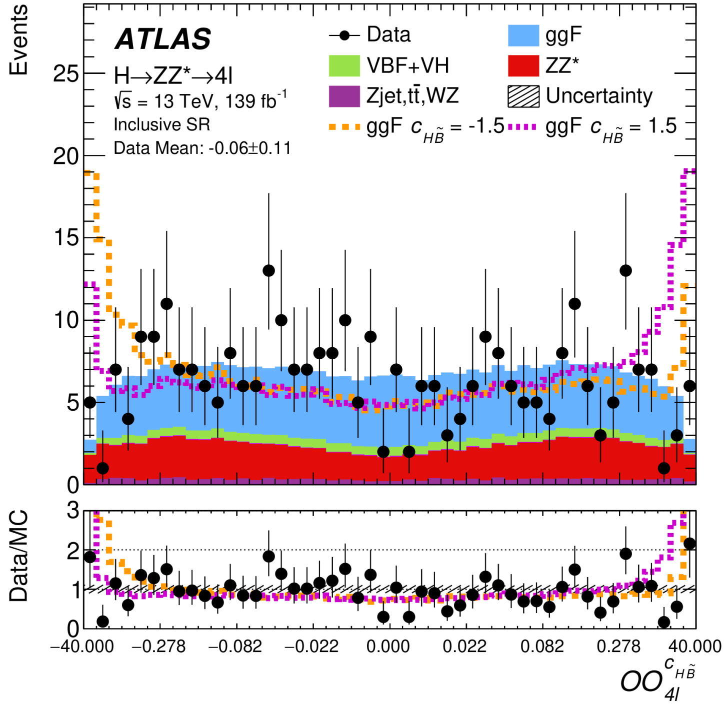
CP structures in HVV(Higgs-to-4l)

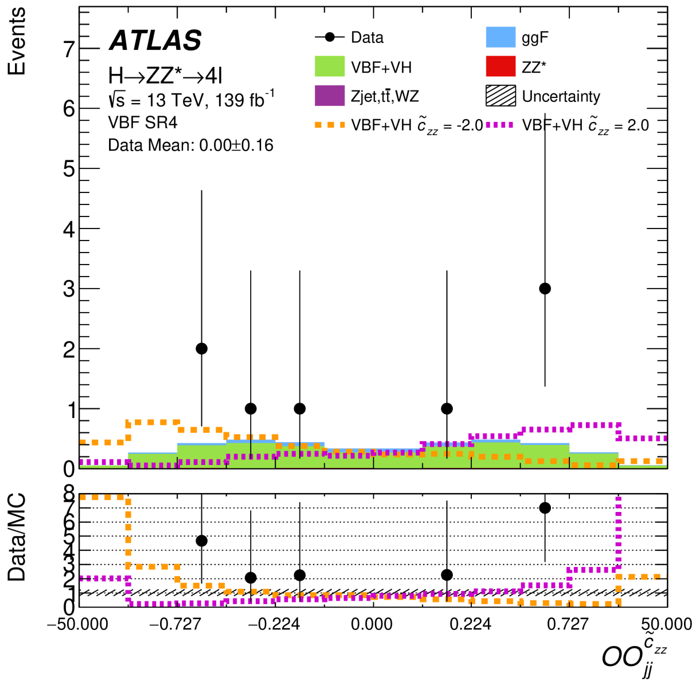
Decay OO_{4l}



Production OO_{jj}

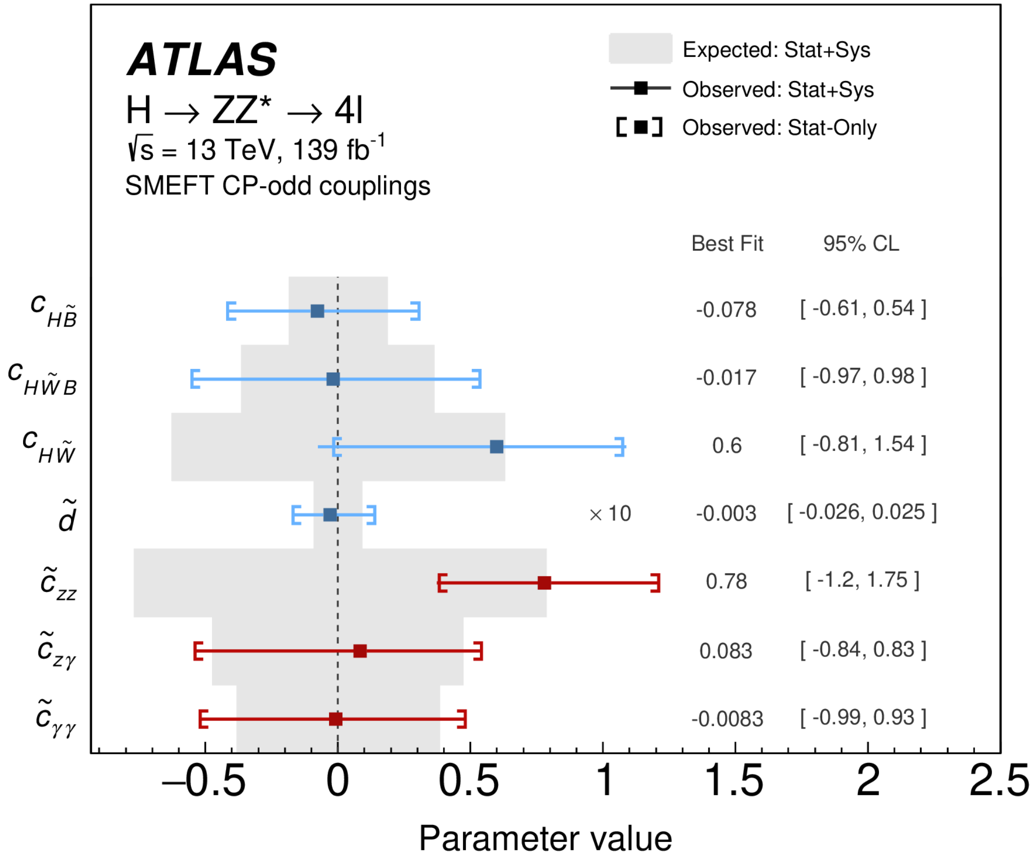


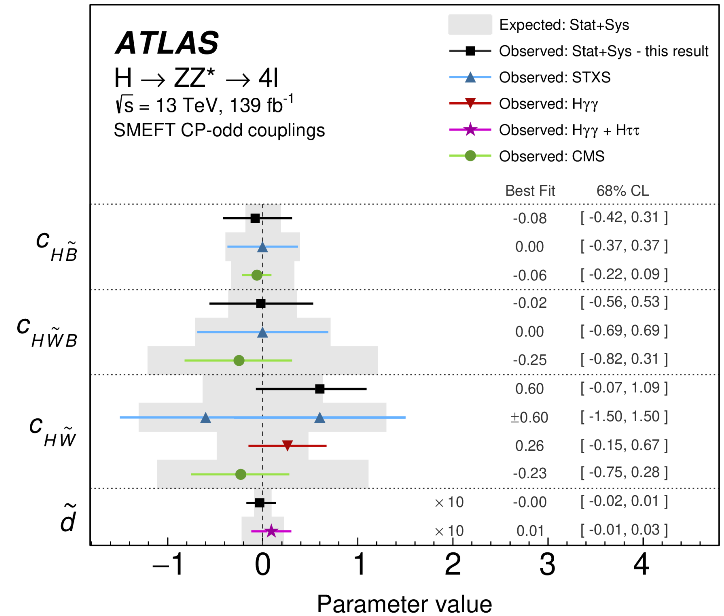




ATLAS Higgs-to-4l: arXiv:2304.09612 (submitted to JHEP)

CP structures in HVV(Higgs-to-4l)



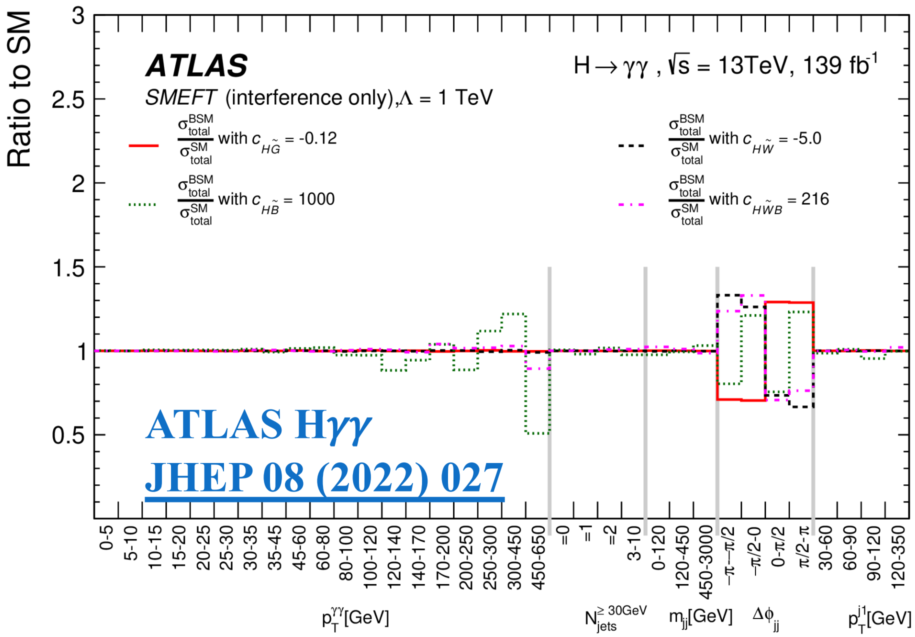


ATLAS Higgs-to-4l (submitted to JHEP)

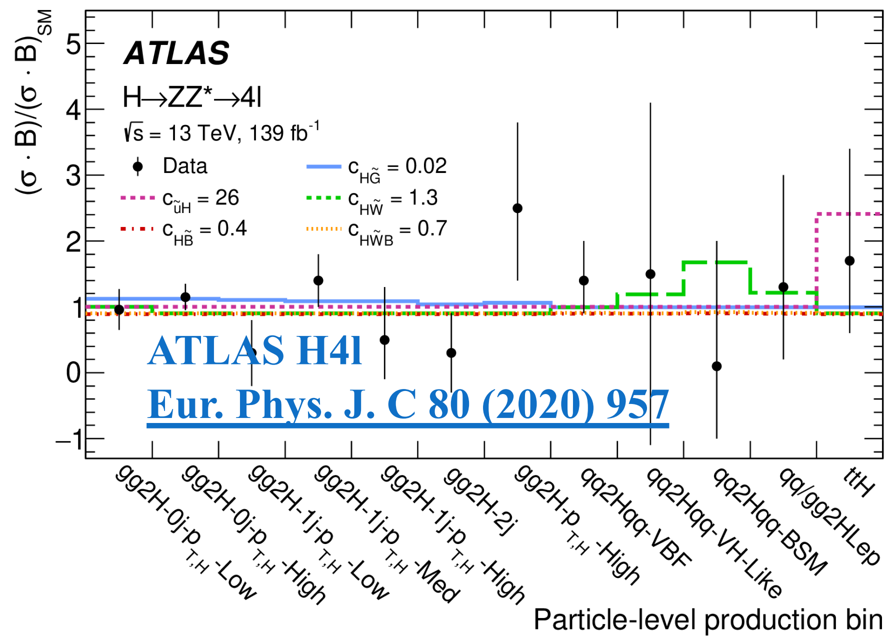
CMS: Phys. Rev. D 104, 052004 (2021)

Seven coefficients (3 for Warsaw basis, 3 for Higgs basis, 1 for simple parametrization) are constrained.

CP structures from differential measurements



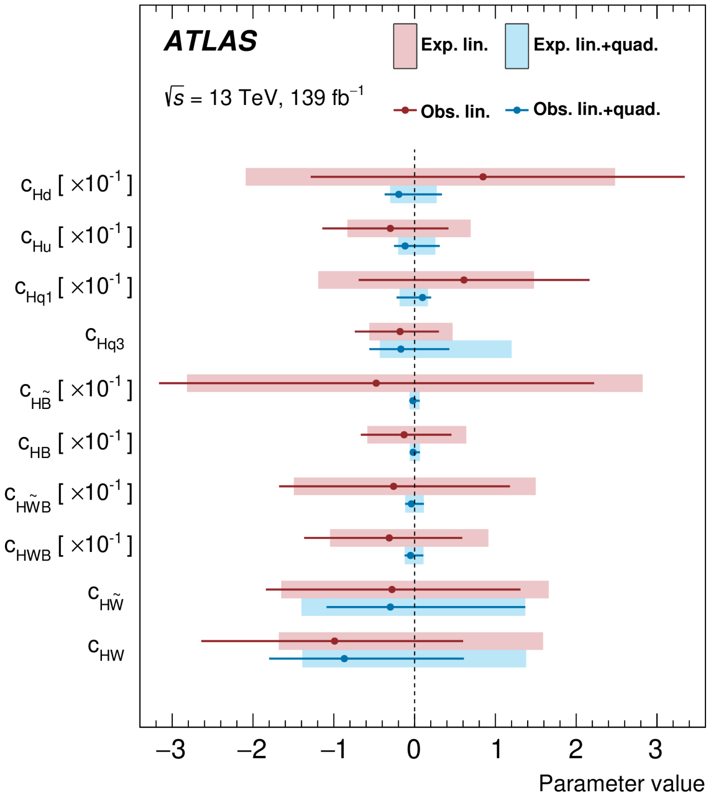
ATLAS Hγγ
JHEP 08 (2022) 027



ATLAS H4l
Eur. Phys. J. C 80 (2020) 957

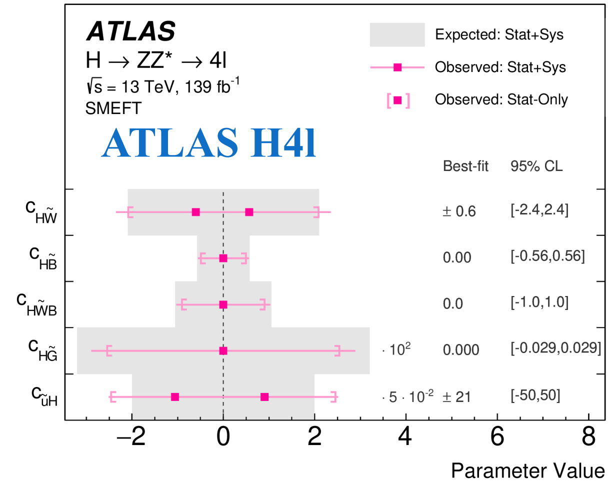
- ❑ Differential observables related to Higgs production/decay can be used probe CP structures
- ❑ Binned cross section based on STXS have sensitivity to CP-odd EFT coefficients

CP structures from differential measurements



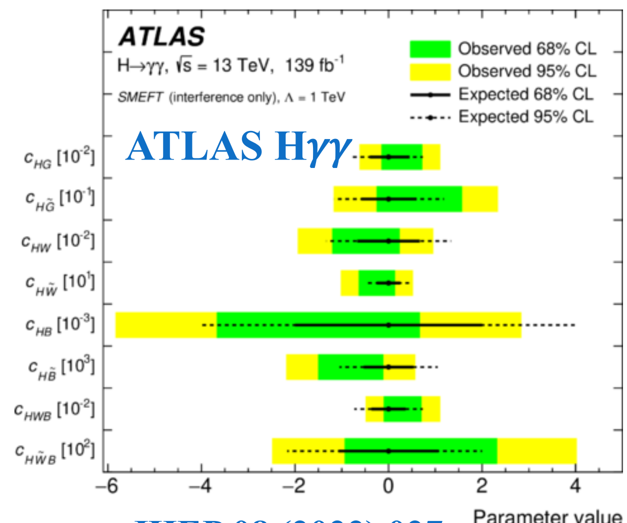
ATLAS HWW

[Phys. Rev. D 108, 072003 (2023)]



ATLAS H4l

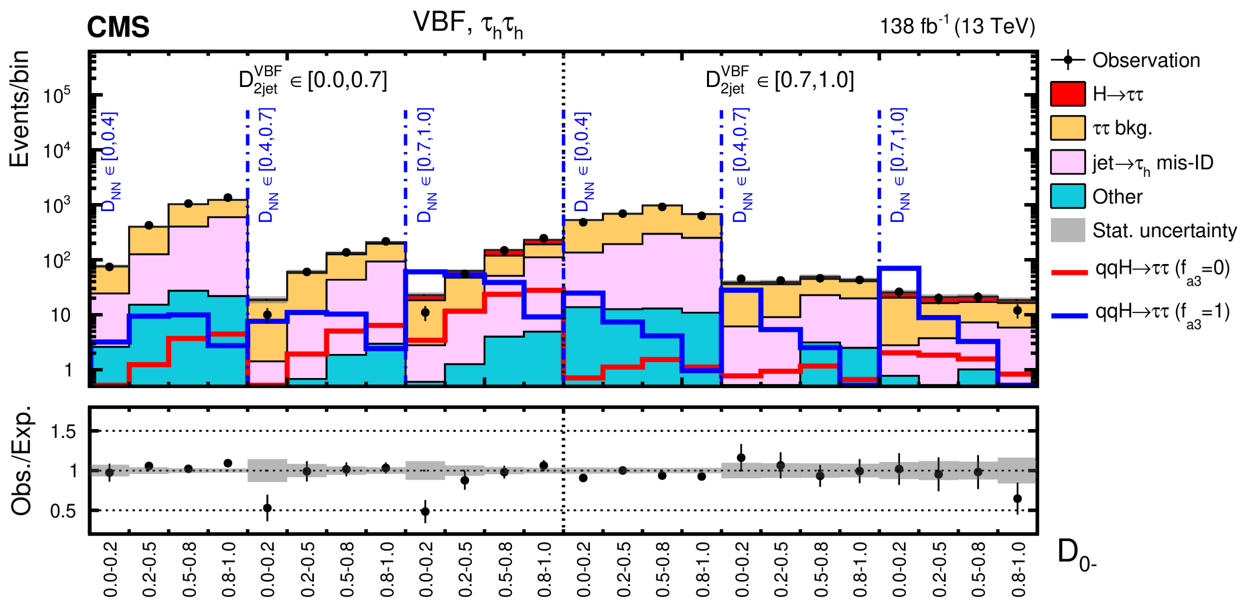
[Eur. Phys. J. C 80 (2020) 957]



ATLAS H$\gamma\gamma$

[JHEP 08 (2022) 027]

CP structures in VBF ($H\tau^+\tau^-$)

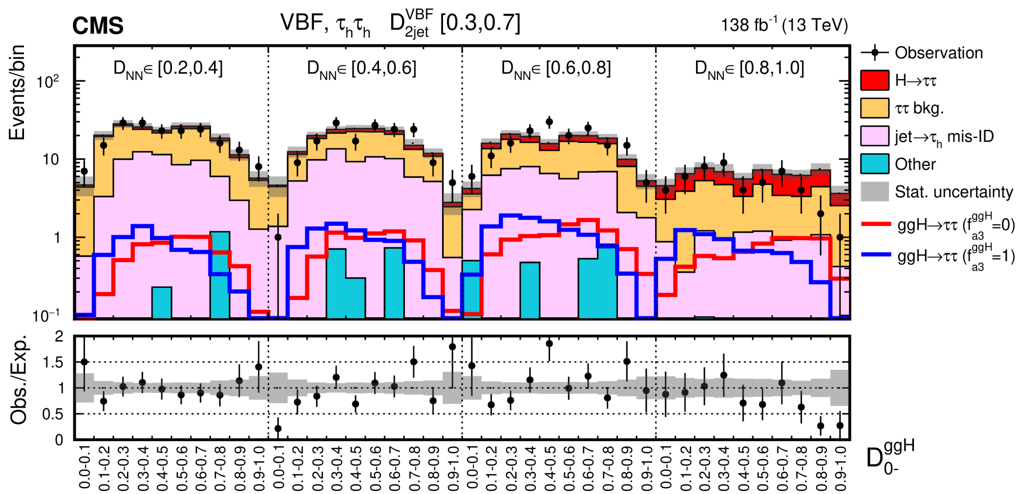


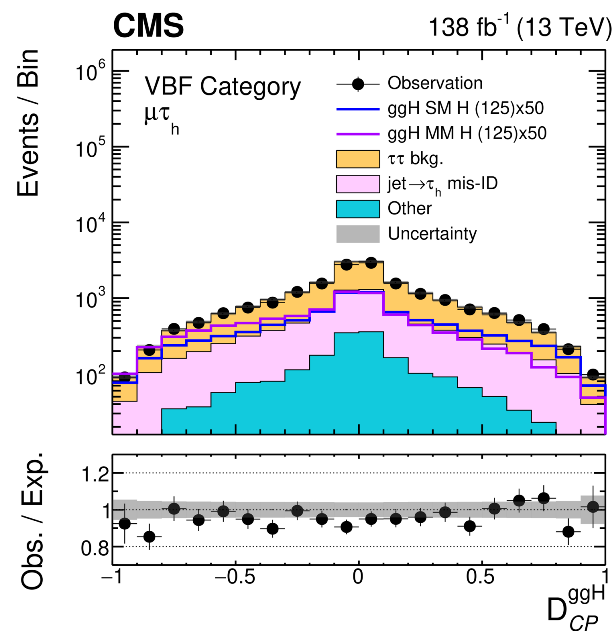
- Three MELA discriminants are used
  - D_{2jet}^{VBF} to tag VBF production
  - D_{0-} to separate SM HVV with pure CP HVV
  - D_{CP}^{VBF} sensitive to the interference between the CP-odd and CP-even (asymmetric distribution for pure CP events)

CMS: Phys. Rev. D 108 (2023) 032013

CP structures in ggH ($H\tau^+\tau^-$)

Higgs-gluon anomalous couplings are constrained by measuring ggH production





- ❑ Three MELA discriminants are used
  - ❑ D_{2jet}^{VBF} separate ggH from VBF
  - ❑ D_{0-}^{ggH} separate SM ggH with pure CP odd ggH
  - ❑ D_{CP}^{ggH} sensitive to the interference between the CP-odd and CP-even (asymmetric distribution for pure CP events)

CMS: Phys. Rev. D 108 (2023) 032013

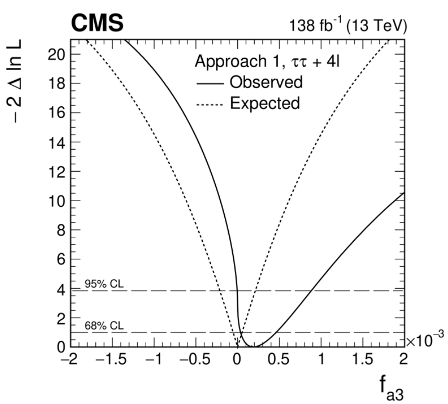
CP structure in ggH, HVV (H4l+ $H\tau^+\tau^-$)

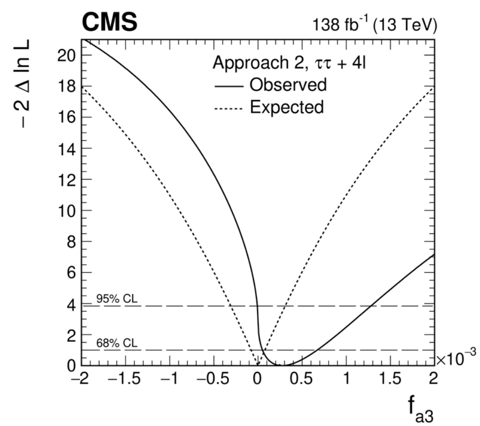
H4l+ Hτ+τ- are combined to constrain Higgs-gluon/HVV interactions

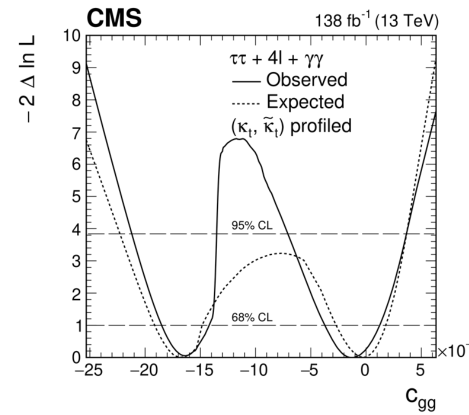
- ❑ CP-odd Higgs-gluon interaction $\tilde{c}_{gg}$ is consistent with zero
- ❑ Two approaches to interpret CP mixing in Higgs-VV interactions
  - ❑ Approach-1 $a_3^{WW} = a_3^{ZZ}$
  - ❑ Approach-2 $a_3^{WW} = cos^2(\theta_w)a_3^{ZZ}$

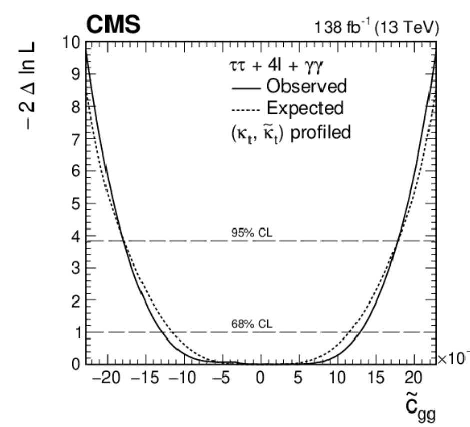
CP-even : $$c_{gg} = -\frac{1}{2\pi\alpha_S}a_2^{gg},$$

CP-odd : $$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S}a_3^{gg},$$









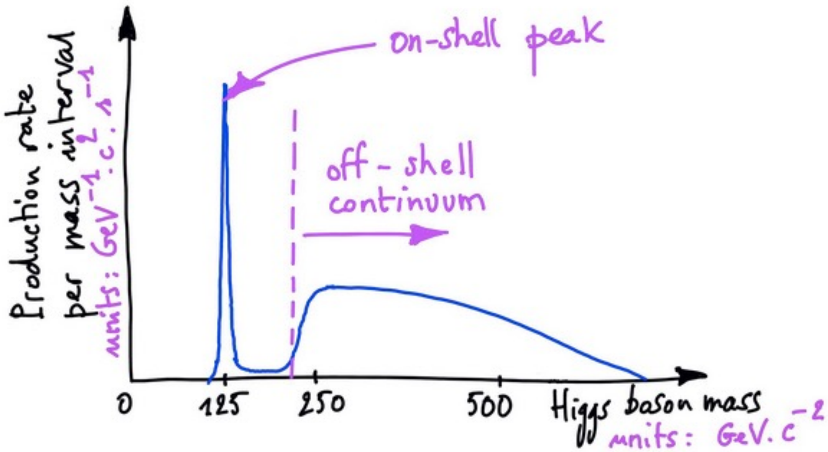
CMS: [Phys. Rev. D 108 (2023) 032013]

CP structure from off-shell measurement

Higgs production rate: $d\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2 + m_H^2\Gamma_H^2} dq_H^2$

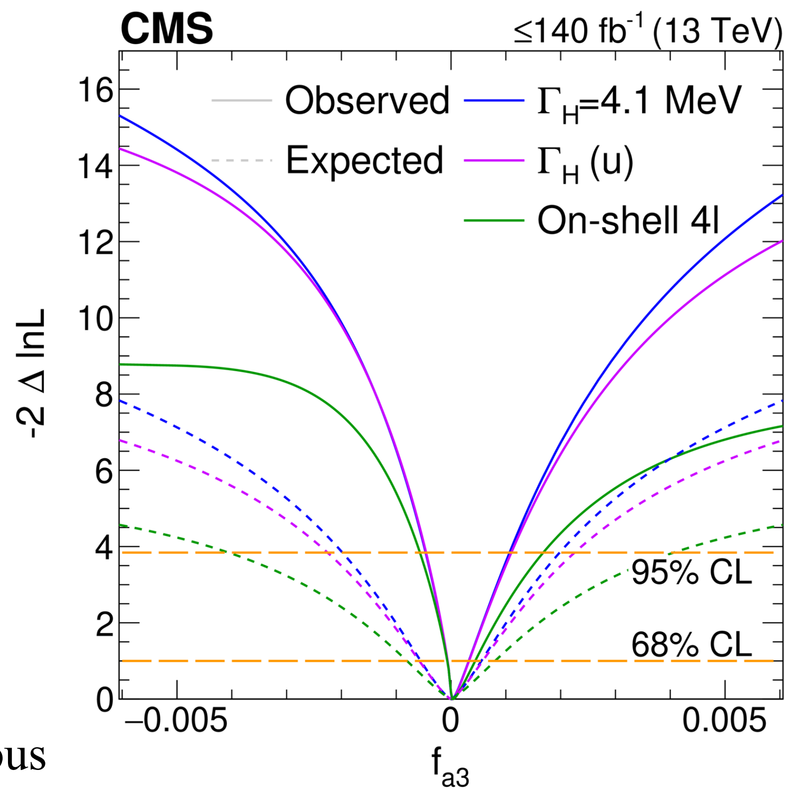
$$\sigma^{on-shell} \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_H} \propto \boxed{\mu_{on-shell}}$$

$$\sigma^{off-shell} \propto \int \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2} dq_H^2 \propto \mu_{off-shell} \propto \boxed{\mu_{on-shell} \times \Gamma_H/\Gamma_{SM}}$$



- Off-shell cross section is sensitivity to BSM effect, and can be used to constrain anomalous CP-odd HZZ couplings

Fig. from https://cms.cern/news/life-higgs-boson



CMS: Nat. Phys. 18 (2022) 1329

Summary

The CP structure of the Higgs boson is studied in different Higgs production and decay final states with Run-2 data

- Pure CP-odd is excluded for Higgs-τ and Higgs-top interactions. CP-mixing in the Higgs-fermion interaction is constrained.

- Anomalous coupling/SMEFT coefficient studies set up constraint on CP structures in Higgs-to-gauge boson interactions

No significant CPV in Higgs interaction have been observed. But the possibility of CP-mixing Higgs interactions is still allowed by the data.

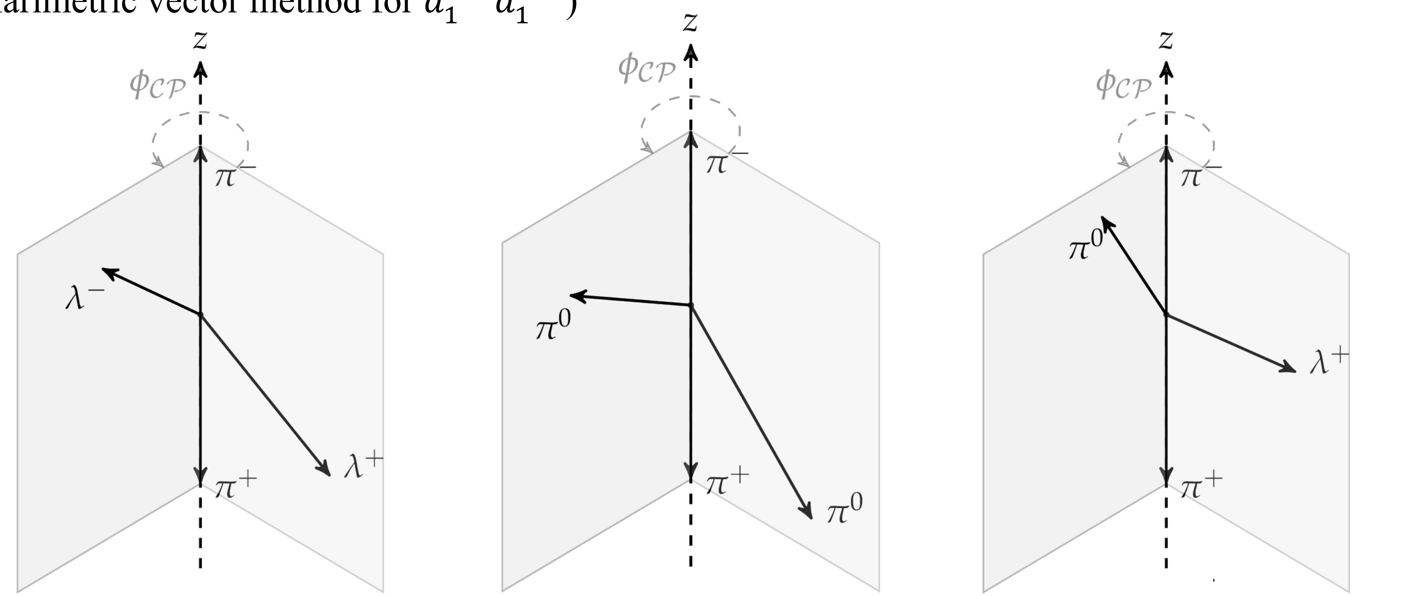
Backup

Reconstruction of τ-decay planes

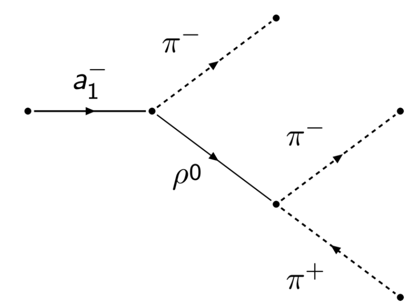
Impact parameter method
(Polarimetric vector method for $a_1^{3pr}a_1^{3pr}$)

Neutral-pion method

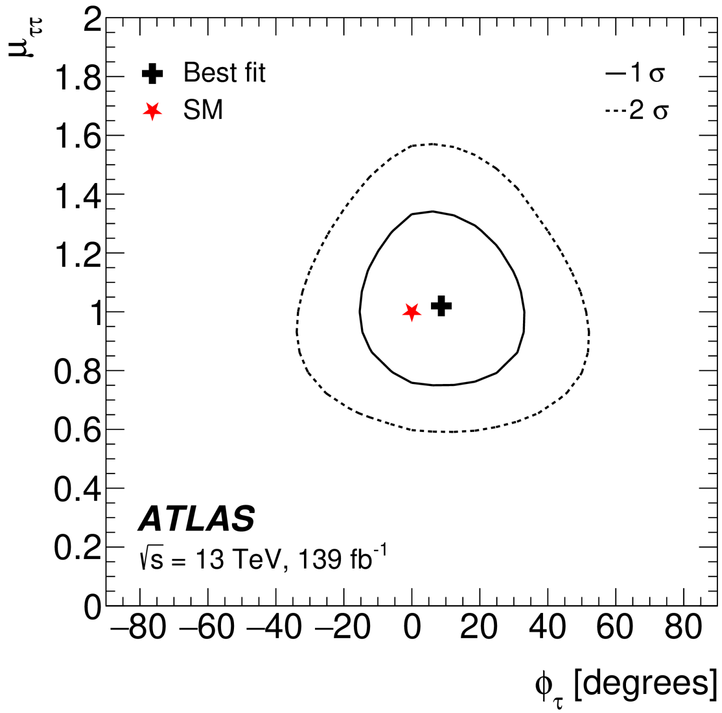
Combined method

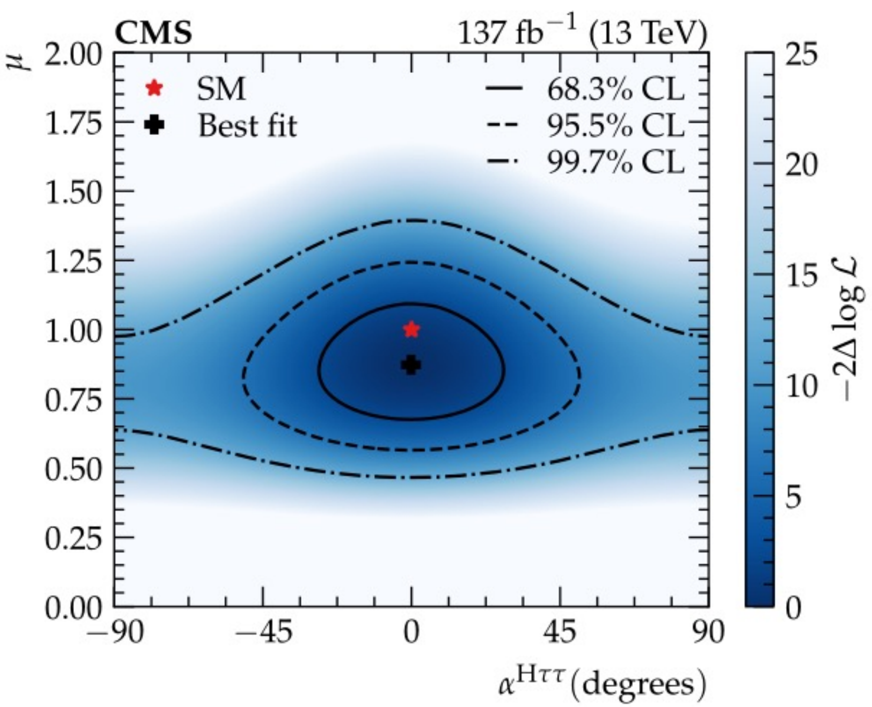


Mode	$e^\pm\nu\nu$	$\mu^\pm\nu\nu$	$h^\pm\nu$	$h^\pm\pi^0\nu$	$h^\pm\pi^0\pi^0\nu$	$h^\pm h^\mp h^\pm\nu$
Type	τ_e	τ_μ	τ_h	τ_h	τ_h	τ_h
$\mathcal{B}(\%)$	17.8	17.4	11.5	25.9	9.5	9.8
Resonance	—	—	—	$\rho(770)$	$a_1(1260)$	$a_1(1260)$
Symbol	e	μ	π	ρ	a_1^{1pr}	a_1^{3pr}



CP structure in H decays to τ-leptons

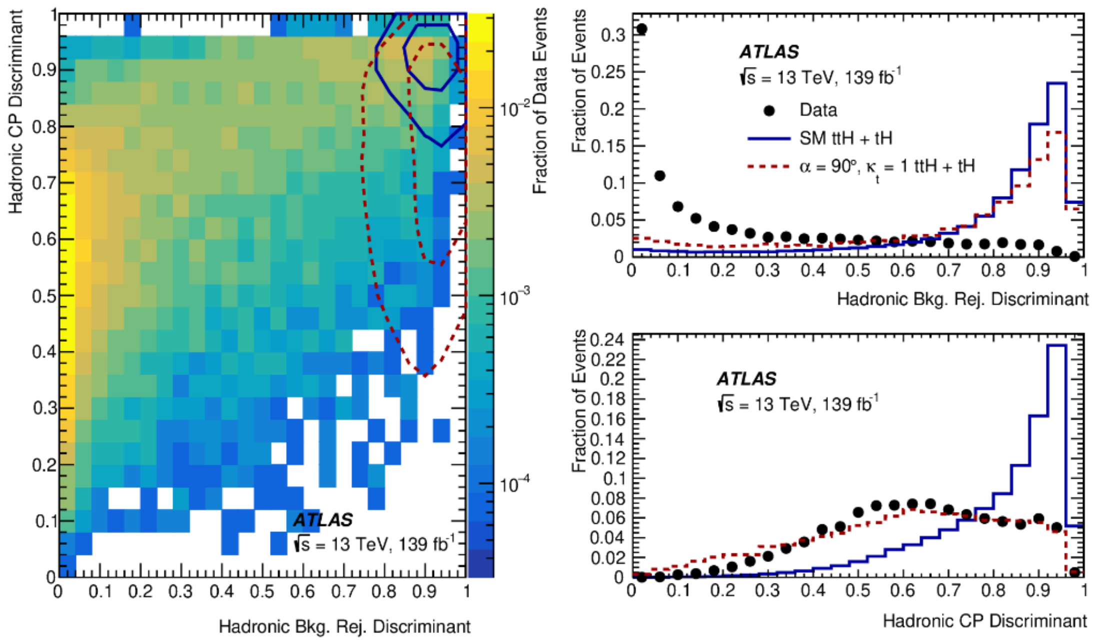




$\phi_\tau = 9 \pm 16\ ^\circ$

$\alpha^{H\tau\tau} = -1 \pm 19\ ^\circ$

CP structures in ttH+tH(Hγγ)



- Events are classified into leptonic events (at least one top decay leptonically) and hadronic events
- BDTs are trained for sig/bkg (bkg rejection BDT) and CP-even/odd separation (CP BDT)

ATLAS Hγγ : [Phys. Rev. Lett. 125 (2020) 061802]

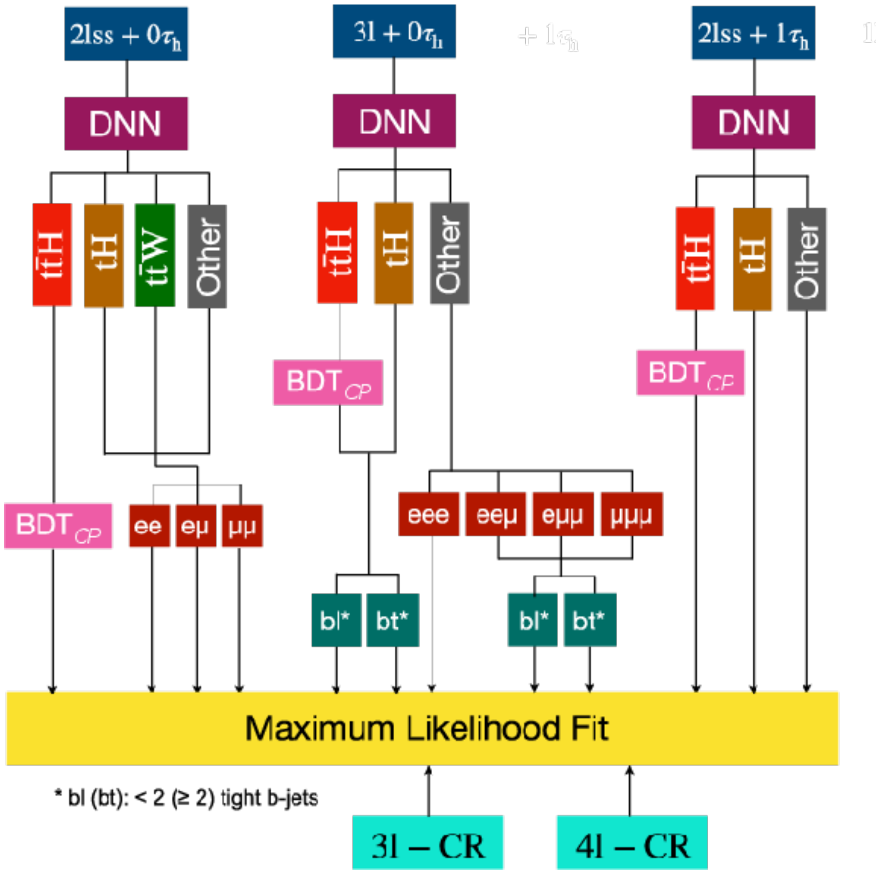
CP structures in ttH+tH (Hbb)

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{TR}^{\geq 4j, \geq 4b}$)	$\mathrm{CR}^{\geq 4j, \geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j, \geq 4b}$	$\mathrm{BDT}^{\geq 4j, \geq 4b} \in [-1, -0.086)$	b_4
	$\mathrm{SR}_1^{\geq 4j, \geq 4b}$	$\mathrm{BDT}^{\geq 4j, \geq 4b} \in [-0.086, 0.186)$	b_4
	$\mathrm{SR}_2^{\geq 4j, \geq 4b}$	$\mathrm{BDT}^{\geq 4j, \geq 4b} \in [0.186, 1]$	b_4
ℓ+jets ($\mathrm{TR}^{\geq 6j, \geq 4b}$)	$\mathrm{CR}_1^{\geq 6j, \geq 4b}$	$\mathrm{BDT}^{\geq 6j, \geq 4b} \in [-1, -0.128)$	b_2
	$\mathrm{CR}_2^{\geq 6j, \geq 4b}$	$\mathrm{BDT}^{\geq 6j, \geq 4b} \in [-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j, \geq 4b}$	$\mathrm{BDT}^{\geq 6j, \geq 4b} \in [0.249, 1]$	b_2
ℓ+jets ($\mathrm{TR}_{\text{boosted}}$)	$\mathrm{SR}_{\text{boosted}}$	$\mathrm{BDT}^{\text{boosted}} \in [-0.05, 1]$	$\mathrm{BDT}^{\text{boosted}}$

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

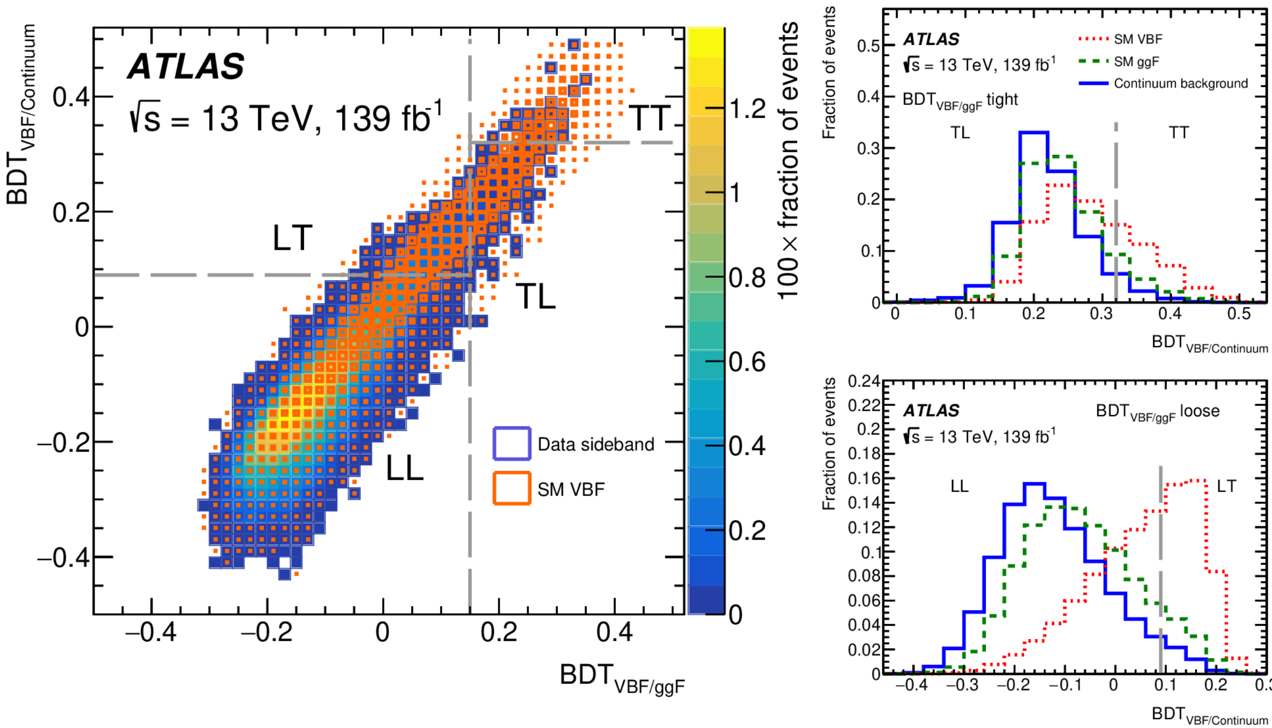
ATLAS Hbb arxiv:2303.05974

CP structures in ttH+tH(multi-lepton)



CMS multi-lepton : [JHEP 07 (2023) 092]

CP structures in VBF(Hγγ)



- ❑ Two BDTs are used to separate sig/bkg and VBF/ggH
- ❑ Four regions are defined based on two BDTs

ATLAS VBFγγ: [Phys. Rev. Lett. 131 (2023) 061802]

CP structure in HVV

Wilson coefficients	Operator structure	Fit distr	Paramater order	95% Confidence interval [TeV^{-2}] Expected	Observed
c_{HW}	$H^\dagger H W^n_{\mu\nu} W^{n\mu\nu}$	$\Delta\phi_{jj}$	lin	[−1.7, 1.6]	[−2.6, 0.60]
			lin + quad	[−1.4, 1.4]	[−1.8, 0.61]
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−5.9, 6.4]	[−6.7, 4.6]
			lin + quad	[−0.59, 0.66]	[−0.60, 0.66]
c_{HWB}	$H^\dagger \tau^n H W^n_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−10, 9]	[−14, 5.9]
			lin + quad	[−1.2, 1.1]	[−1.2, 1.1]
c_{Hq1}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	p_T^{j1}	lin	[−12, 15]	[−6.9, 22]
			lin + quad	[−1.9, 1.7]	[−2.2, 2.0]
c_{Hq3}	$(H^\dagger i\overleftrightarrow{D}^n_\mu H)(\bar{q}\tau^n\gamma^\mu q)$	p_T^{j1}	lin	[−0.56, 0.47]	[−0.74, 0.30]
			lin + quad	[−0.43, 1.2]	[−0.56, 0.43]
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	p_T^{j1}	lin	[−8.3, 6.9]	[-11, 4.2]
			lin + quad	[−2.0, 2.6]	[−2.5, 3.1]
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	p_T^{j1}	lin	[−21, 25]	[−13, 33]
			lin + quad	[−3.0, 2.7]	[−3.7, 3.4]
$c_{H\tilde{W}}$	$H^\dagger H \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$	$\Delta\phi_{jj}$	lin	[−1.7, 1.7]	[−1.8, 1.3]
			lin + quad	[−1.4, 1.4]	[−1.1, 1.4]
$c_{H\tilde{B}}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−28, 28]	[−32, 22]
			lin + quad	[−0.62, 0.62]	[−0.63, 0.63]
$c_{H\tilde{W}B}$	$H^\dagger \tau^n H \tilde{W}^n_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$	lin	[−15, 15]	[−17, 12]
			lin + quad	[−1.2, 1.1]	[−1.2, 1.1]

ATLAS HWW
Phys. Rev. D 108, 072003 (2023)

CP structure in HVV

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1 $f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	best fit	0.00004	0.00000
		68% CL	$[-0.00007, 0.00044]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.00055, 0.00168]$	$[-0.00412, 0.00412]$
	Approach 1 float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	best fit	-0.00805	0.00000
		68% CL	$[-0.02656, 0.00034]$	$[-0.00086, 0.00086]$
		95% CL	$[-0.07191, 0.00990]$	$[-0.00423, 0.00422]$
	Approach 2 float $f_{a2}, f_{\Lambda 1}$	best fit	0.00005	0.0000
		68% CL	$[-0.00010, 0.00061]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.00072, 0.00218]$	$[-0.0057, 0.0057]$
f_{a2}	Approach 1 $f_{a3} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	best fit	0.00020	0.0000
		68% CL	$[-0.00010, 0.00109]$	$[-0.0012, 0.0014]$
		95% CL	$[-0.00078, 0.00368]$	$[-0.0075, 0.0073]$
	Approach 1 float $f_{a3}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	best fit	-0.24679	0.0000
		68% CL	$[-0.41087, -0.15149] \cup [-0.00008, 0.00065]$	$[-0.0017, 0.0014]$
		95% CL	$[-0.66842, -0.08754] \cup [-0.00091, 0.00309]$	$[-0.0082, 0.0073]$
	Approach 2 float $f_{a3}, f_{\Lambda 1}$	best fit	-0.00002	0.0000
		68% CL	$[-0.00178, 0.00103]$	$[-0.0060, 0.0033]$
		95% CL	$[-0.00694, 0.00536]$	$[-0.0206, 0.0131]$
$f_{\Lambda 1}$	Approach 1 $f_{a3} = f_{a2} = f_{\Lambda 1}^{Z\gamma} = 0$	best fit	0.00004	0.00000
		68% CL	$[-0.00002, 0.00022]$	$[-0.00016, 0.00026]$
		95% CL	$[-0.00014, 0.00060]$	$[-0.00069, 0.00110]$
	Approach 1 float $f_{a3}, f_{a2}, f_{\Lambda 1}^{Z\gamma}$	best fit	0.18629	0.00000
		68% CL	$[-0.00002, 0.00019] \cup [0.07631, 0.27515]$	$[-0.00017, 0.00036]$
		95% CL	$[-0.00523, 0.35567]$	$[-0.00076, 0.00134]$
	Approach 2 float f_{a3}, f_{a2}	best fit	0.00012	0.0000
		68% CL	$[-0.00021, 0.00141]$	$[-0.0013, 0.0030]$
		95% CL	$[-0.00184, 0.00443]$	$[-0.0056, 0.0102]$
$f_{\Lambda 1}^{Z\gamma}$	Approach 1 $f_{a3} = f_{a2} = f_{\Lambda 1} = 0$	best fit	-0.00001	0.0000
		68% CL	$[-0.00099, 0.00057]$	$[-0.0026, 0.0020]$
		95% CL	$[-0.00387, 0.00301]$	$[-0.0096, 0.0082]$
	Approach 1 float $f_{a3}, f_{a2}, f_{\Lambda 1}$	best fit	-0.02884	0.0000
		68% CL	$[-0.09000, -0.00534] \cup [-0.00068, 0.00078]$	$[-0.0027, 0.0026]$
		95% CL	$[-0.29091, 0.03034]$	$[-0.0099, 0.0096]$

CMS: Phys. Rev. D 104, 052004 (2021)

CP structure in HVV+ $H\tau^+\tau^-$

4l+ττ

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}	$0.7^{+0.8}_{-0.6}$	$[-1.0, 2.5]$	$0.0^{+0.5}_{-0.4}$	$[-1.1, 1.2]$
	$f_{\Lambda 1}$	$-0.04^{+0.04}_{-0.08}$	$[-0.22, 0.16]$	$0.00^{+0.11}_{-0.04}$	$[-0.11, 0.38]$
	$f_{\Lambda 1}^{Z\gamma}$	$0.7^{+1.6}_{-1.3}$	$[-2.7, 4.1]$	$0.0^{+1.0}_{-1.0}$	$[-2.6, 2.5]$
Approach 2	f_{a3}	$0.28^{+0.39}_{-0.23}$	$[-0.01, 1.28]$	0.00 ± 0.08	$[-0.30, 0.30]$

CMS: Phys. Rev. D 108 (2023) 032013

CP structure in HVV+ H$\tau^+\tau^-$

$$\mu_{\mathrm{ggH}} = 1.1068\kappa_t^2 + 0.0082 - 0.1150\kappa_t + 2.5717\tilde{\kappa}_t^2 + 1.0298(12\pi^2 c_{gg})^2 + 2.3170(8\pi^2\tilde{c}_{gg})^2 + 2.1357(12\pi^2 c_{gg})\kappa_t - 0.1109(12\pi^2 c_{gg}) + 4.8821(8\pi^2\tilde{c}_{gg})\tilde{\kappa}_t.$$

Parameter	Observed		Expected	
	68% CL	95% CL	68% CL	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	$[-0.49, 0.49]$

Parameter	Scenario		68% CL / (10^{-2})	95% CL / (10^{-2})
c_{gg}	Profiled	Observed	$-0.11^{+0.20}_{-0.26} \cup [-1.85, -1.42]$	$[-2.12, -1.35] \cup [-0.71, 0.36]$
		Expected	$0.00^{+0.18}_{-0.27} \cup [-1.91, -1.48]$	$[-2.23, 0.37]$
$\tilde{c}_{gg}$	Profiled	Observed	0.00 ± 1.29	$[-1.79, 1.79]$
		Expected	0.00 ± 1.15	$[-1.78, 1.78]$
c_{gg}	Fixed	Observed	$-0.08^{+0.07}_{-0.15} \cup [-1.65, -1.54]$	$[-1.71, -1.54] \cup [-0.59, 0.05]$
		Expected	$0.00^{+0.06}_{-0.14} \cup [-1.73, -1.50]$	$[-1.78, 0.12]$
$\tilde{c}_{gg}$	Fixed	Observed	$0.22^{+0.28}_{-0.22} \cup [-0.50, 0.00]$	$[-0.74, 0.75]$
		Expected	0.00 ± 0.45	$[-0.87, 0.87]$

CMS: Phys. Rev. D 108 (2023) 032013

CP structure in off-shell HVV

Parameter	Condition	Best fit	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
Γ_H (MeV)	SM-like	3.2	$[1.5, 5.6]$	$[0.5, 8.5]$	$[0.6, 8.1]$	$[0.03, 11.3]$
	f_{a2} (u)	3.4	$[1.6, 5.7]$	$[0.6, 8.4]$	$[0.5, 8.0]$	$[0.02, 11.3]$
	f_{a3} (u)	2.7	$[1.3, 4.8]$	$[0.5, 7.3]$	$[0.5, 8.0]$	$[0.02, 11.3]$
	$f_{\Lambda 1}$ (u)	2.7	$[1.3, 4.8]$	$[0.5, 7.3]$	$[0.6, 8.1]$	$[0.02, 11.3]$
$f_{a2}\,(\times 10^5)$	$\Gamma_H = \Gamma_H^{SM}$	79	$[6.6, 225]$	$[-32, 514]$	$[-78, 70]$	$[-359, 311]$
	Γ_H (u)	72	$[2.7, 216]$	$[-38, 503]$	$[-82, 73]$	$[-413, 364]$
$f_{a3}\,(\times 10^5)$	$\Gamma_H = \Gamma_H^{SM}$	2.2	$[-6.4, 32]$	$[-46, 107]$	$[-55, 55]$	$[-198, 198]$
	Γ_H (u)	2.4	$[-6.2, 33]$	$[-46, 110]$	$[-58, 58]$	$[-225, 225]$
$f_{\Lambda 1}\,(\times 10^5)$	$\Gamma_H = \Gamma_H^{SM}$	2.9	$[-0.62, 17]$	$[-11, 46]$	$[-11, 20]$	$[-47, 68]$
	Γ_H (u)	3.1	$[-0.56, 18]$	$[-10, 47]$	$[-11, 21]$	$[-48, 75]$

CMS: Nat. Phys. 18 (2022) 1329