Study of the Higgs boson CP property in LHC and CEPC

— An Experimentalist Overview

IAS Program on High Energy Physics, HKUST, 12-16, Feb, 2023

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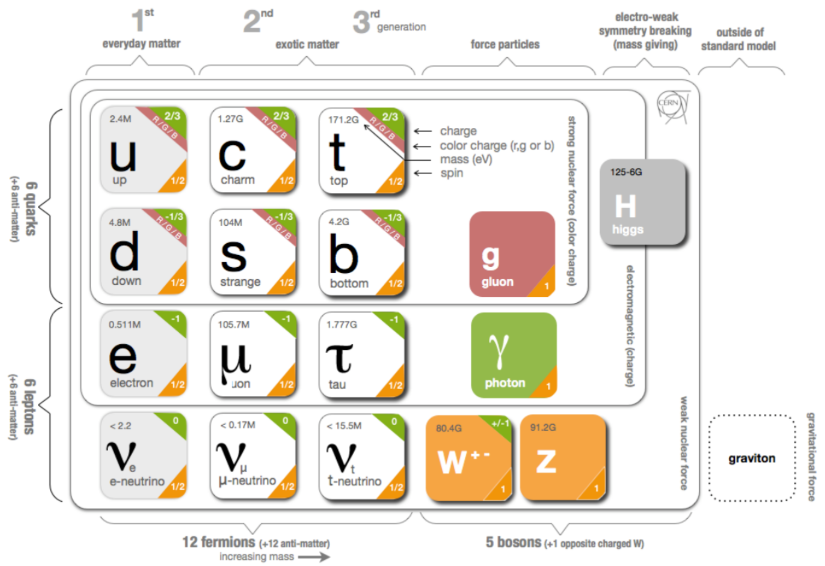
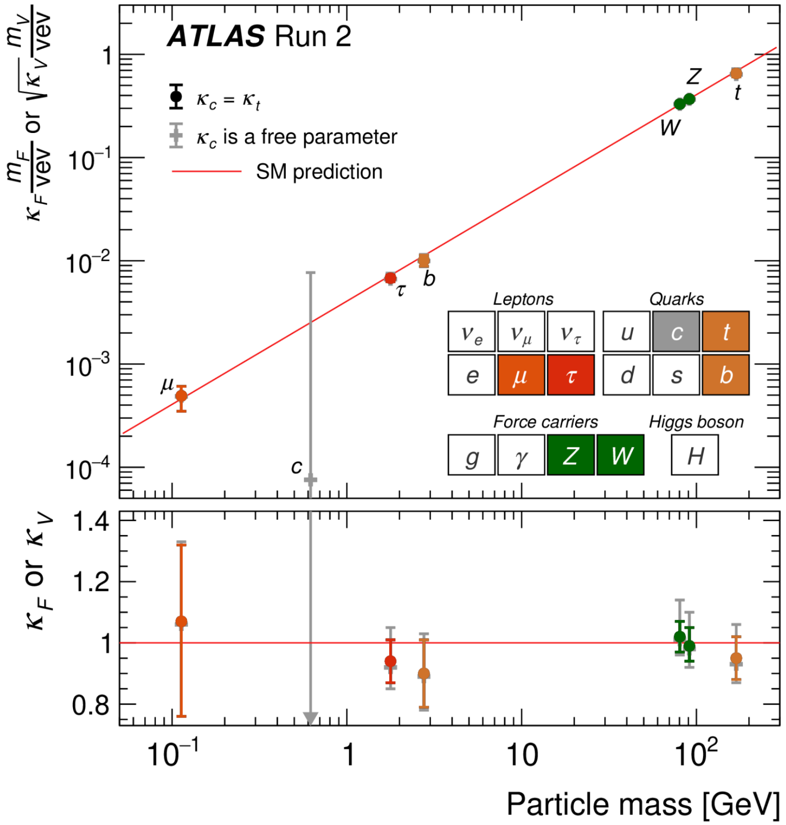
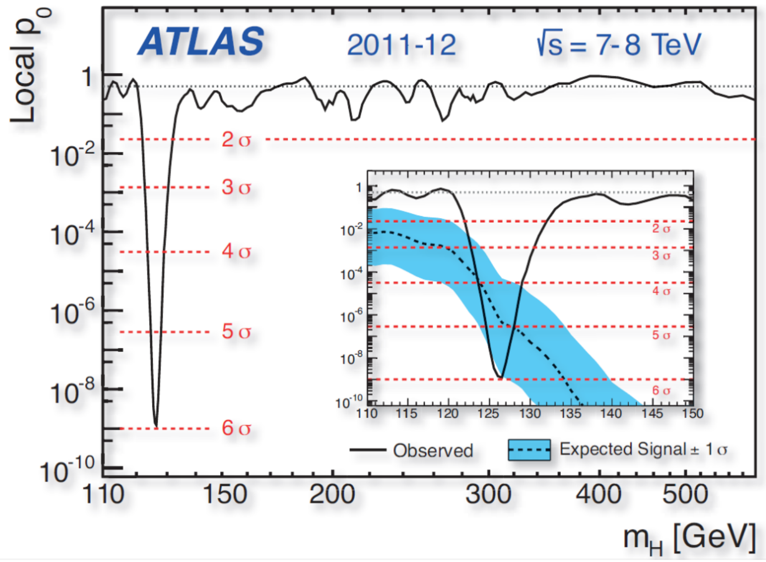
IHEP, CAS

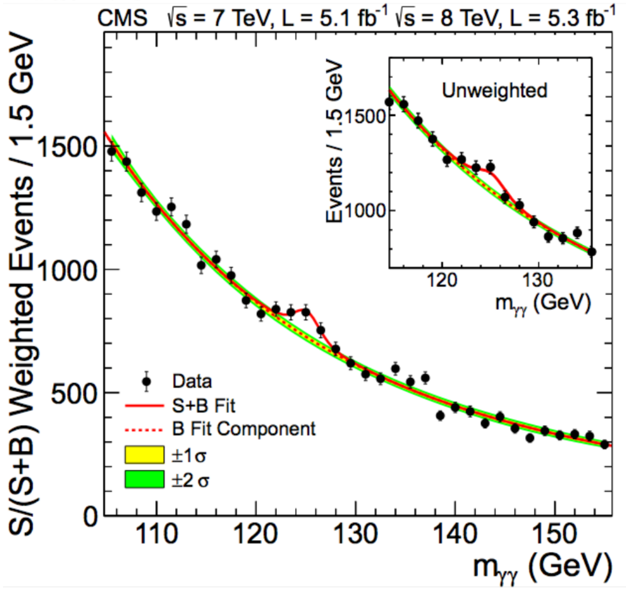
The Discovery of the Higgs boson



- The SM is a successful model of the particle physics
- The Higgs boson play the unique role in the SM of giving mass to other particles via EW SSB
- Was discovered by ATLAS and CMS in 2012 in bosonic channels

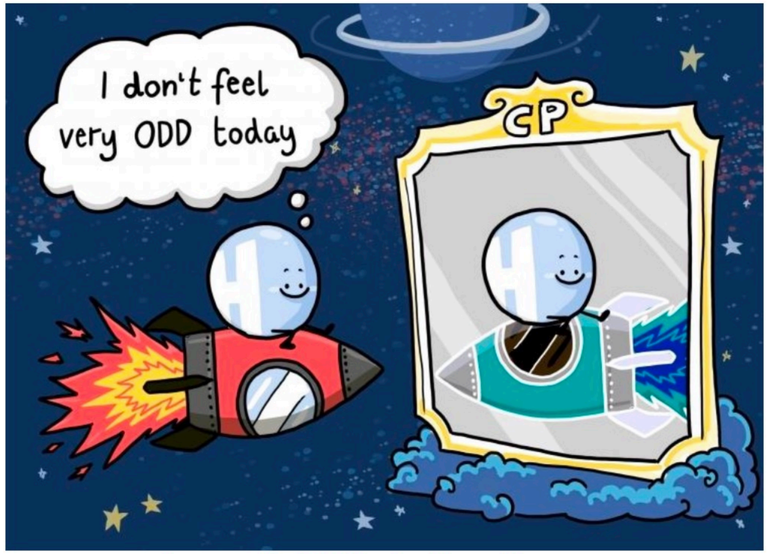






CP property of the Higgs boson

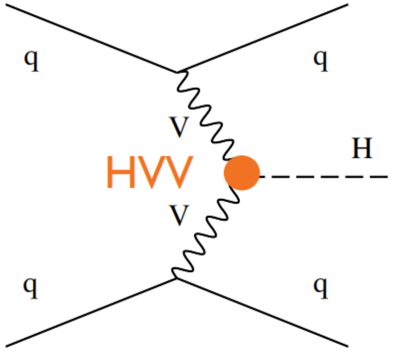
- Determining the CP structure is important in the High Energy Physics
- Key component for Sakharov condition to explain matter-antimatter asymmtry
  - ✓ Baryon number violation
  - ✓ C and CP violation
  - ✓ Interactions out of thermal equilibrium
- Need to find new source of CPV beside the CP phase in CKM which is not enough for matter-antimatter asymmetry

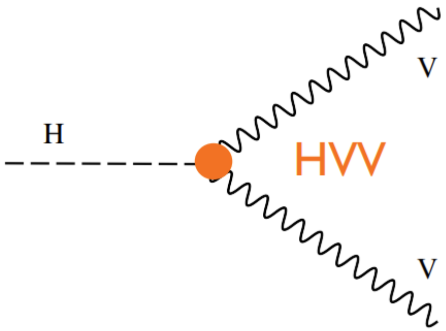


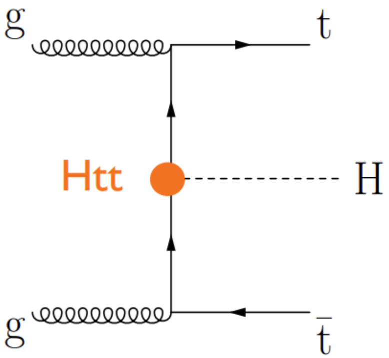
(image: DESY/designdoppel)

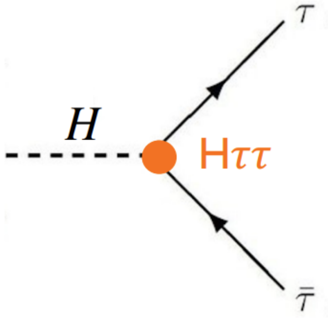
The Higgs boson could be a good portal

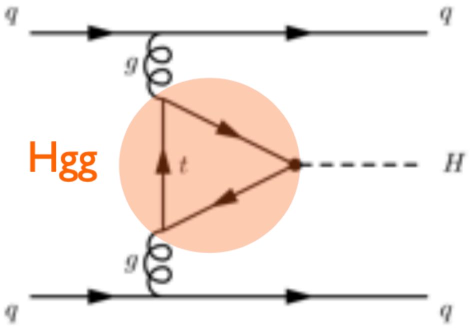
- In the SM, the Higgs boson is CP-even
- No strong constraint to exclude CP-odd contribution
  - ✓ Those new CP-odd component could be new scalars or new interactions











Recent ATLAS and CMS results

	ATLAS	CMS
H→ZZ*→ℓℓℓℓ	Eur. Phys. J. C 80 (2020) 957 [139 fb^{-1}, measured cross-section reinterpretation]	Phys. Rev. D 104 (2021) 052004 [137 fb^{-1}, anomalous coupling using MELA discriminator] arXiv:2202.06923 [Offshell measurement]
H→WW*→ℓνℓν	Eur. Phys. J. C 82 (2022) 622 [36.1 fb^{-1}]	arXiv:2208.02686 [138 fb^{-1}, muti-lepton]
H→ττ	arXiv:2212.05833 [139 fb^{-1}, Hff coupling] Phys. Lett. B 805 (2020) 135426 [36.1 fb^{-1}, VBF]	arXiv:2205.05120 [138 fb^{-1}, MELA discriminator] JHEP 06 (2022) 012 [138 fb^{-1}, Hff coupling]
H→γγ	arXiv:2208.02338 [139 fb^{-1}, VBF] Phys. Rev. Lett. 125 (2020) 061802 [139 fb^{-1}, ttH] JHEP 08 (2022) 027 [139 fb^{-1}, measured cross section reinterpretation]	Phys. Rev. Lett. 125 (2020) 061801 [137 fb^{-1},ttH]
H→bb	ATLAS-CONF-2022-016 [139 fb^{-1}, ttH/tH]	

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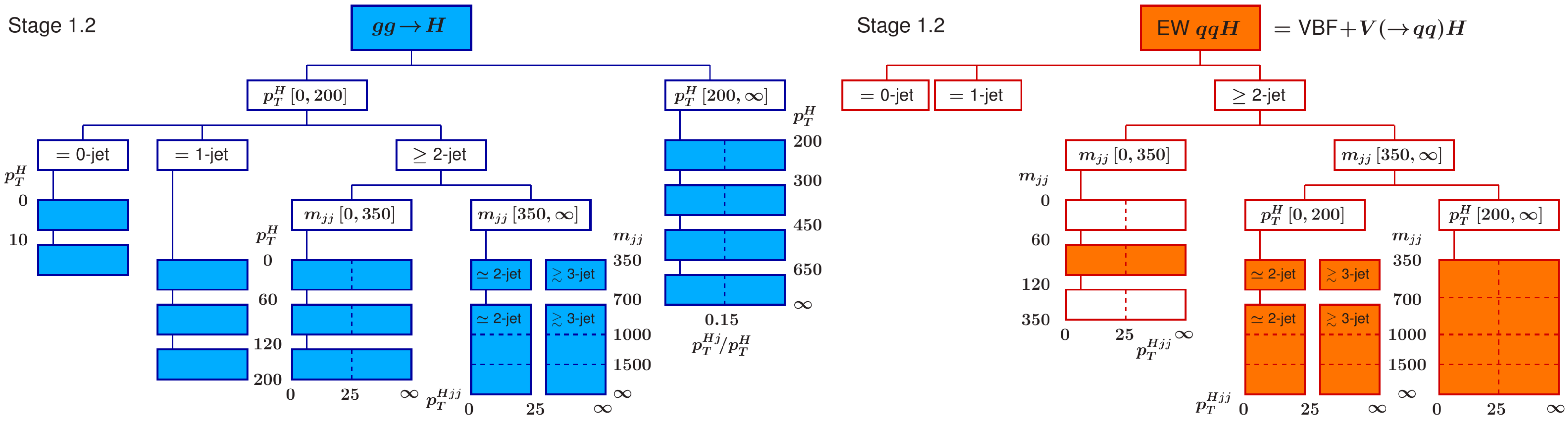
Strong connection between experimentalists and theorists for Higgs boson CP studies

Constrain CP-odd with differential measurements

- Differential/STXS cross-section measurements could be interpreted in terms of CP-odd contributions
- SMEFT approach used for both H→$\gamma\gamma$ and H→ZZ results

$$\mathcal{L}_{\text{eff}}^{\text{SMEFT}} \supset \quad c_{HG} O'_g + c_{HW} O'_{HW} + c_{HB} O'_{HB} + c_{HWB} O'_{HWB} + c_{H\widetilde{G}} \widetilde{O}'_g + c_{H\widetilde{W}} \widetilde{O}'_{HW} + c_{H\widetilde{B}} \widetilde{O}'_{HB} + c_{H\widetilde{W}B} \widetilde{O}'_{HWB}$$

Simplified Template Cross Section scheme



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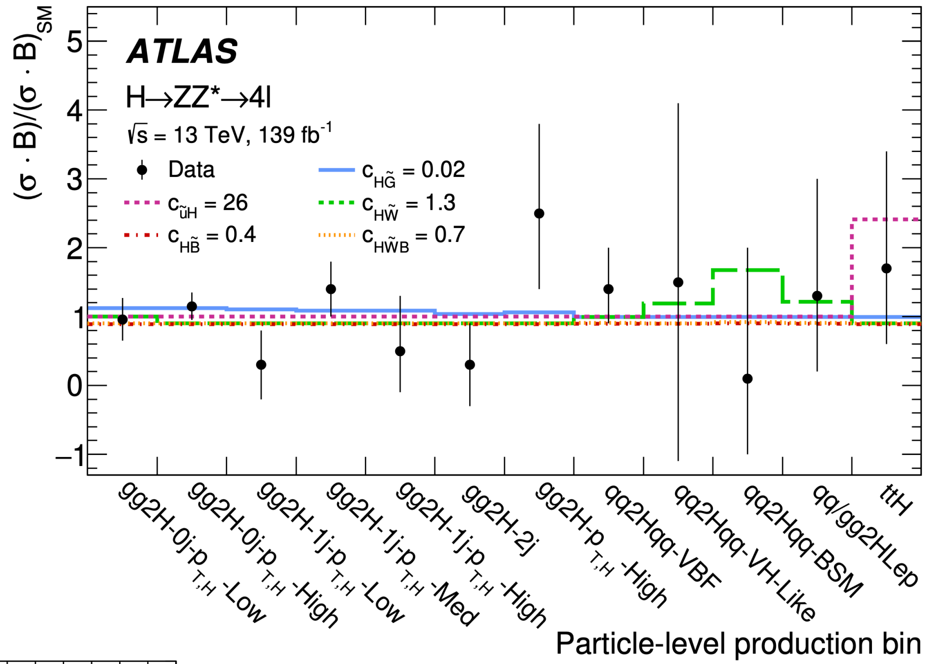
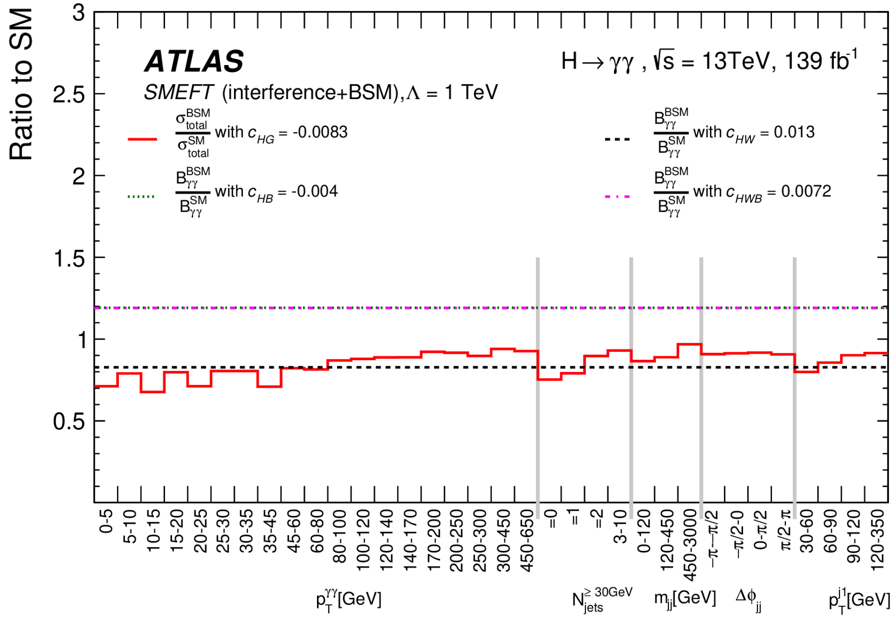
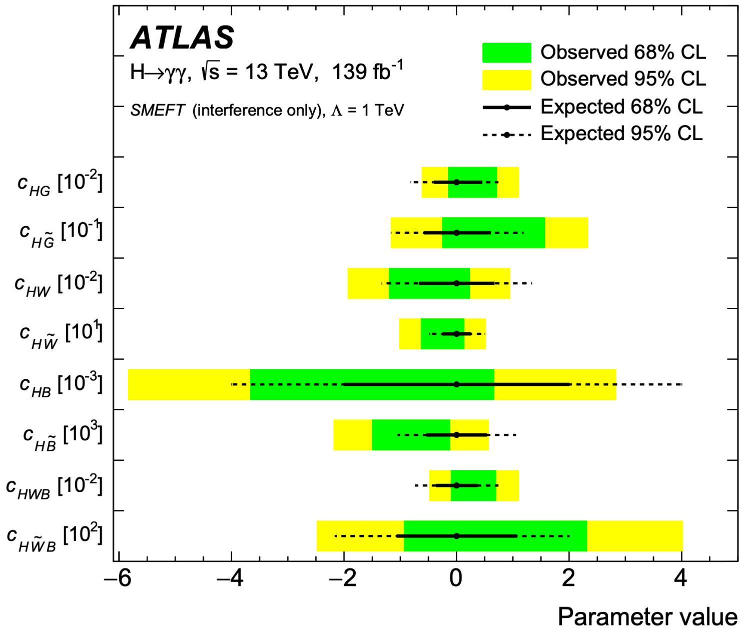
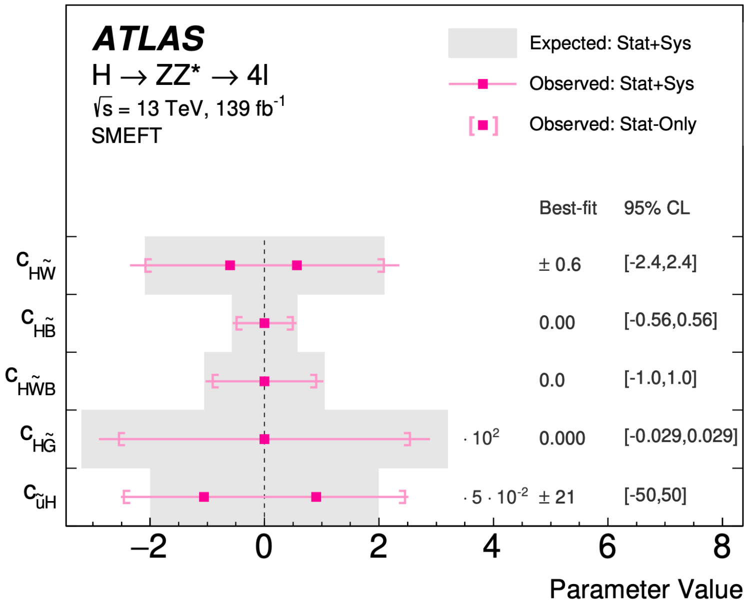








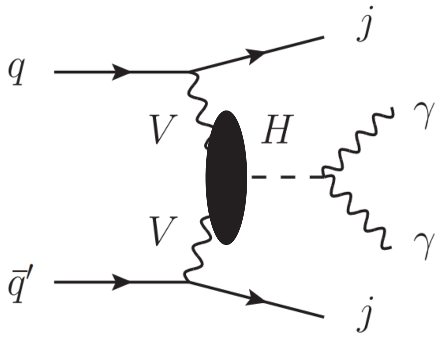
HVV CP structure with VBF $H\to\gamma\gamma/\tau\tau$

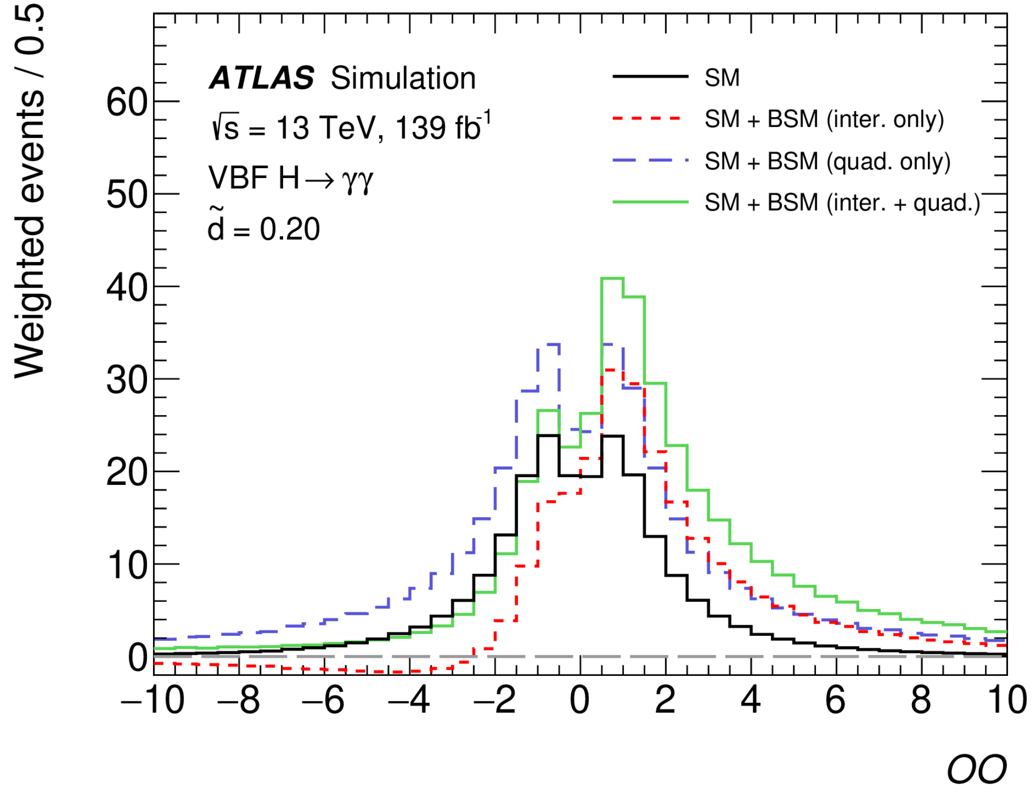
arXiv:2208.02338

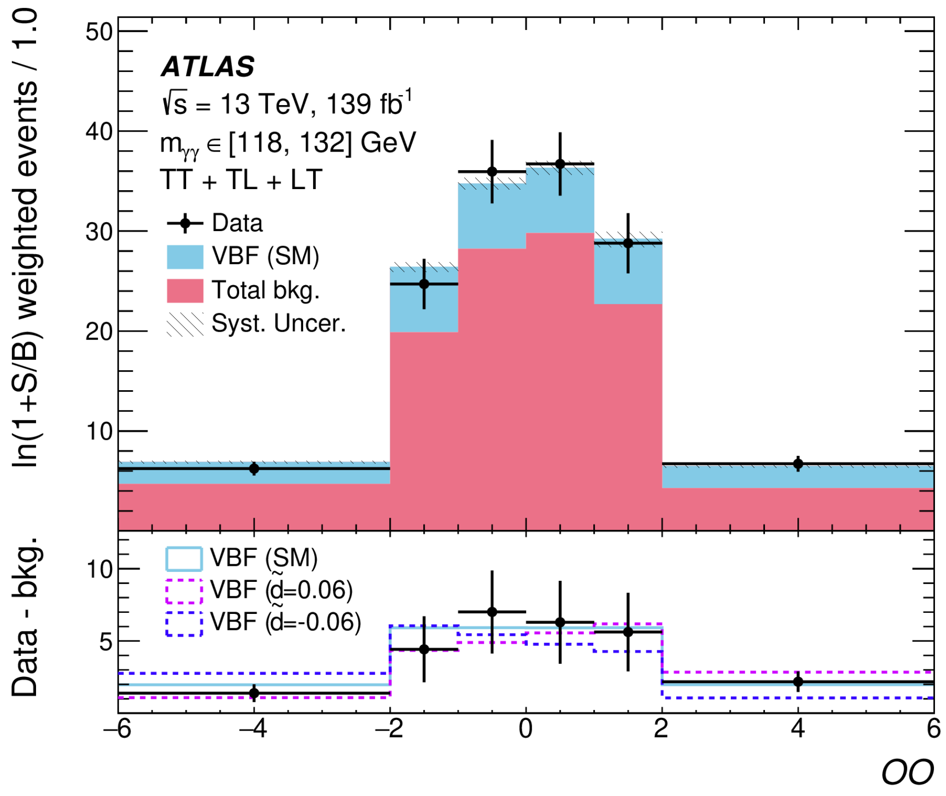
Phys. Lett. B 805 (2020) 135426

- Explore HVV CP property
- Interpreted results with two EFT bases
  - ✓ HISZ basis and SMEFT Warsaw basis
- Implement the Optimal Observable method
  - Better than $\Delta\phi_{jj}$
  - Independent on Higgs Boson decay

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







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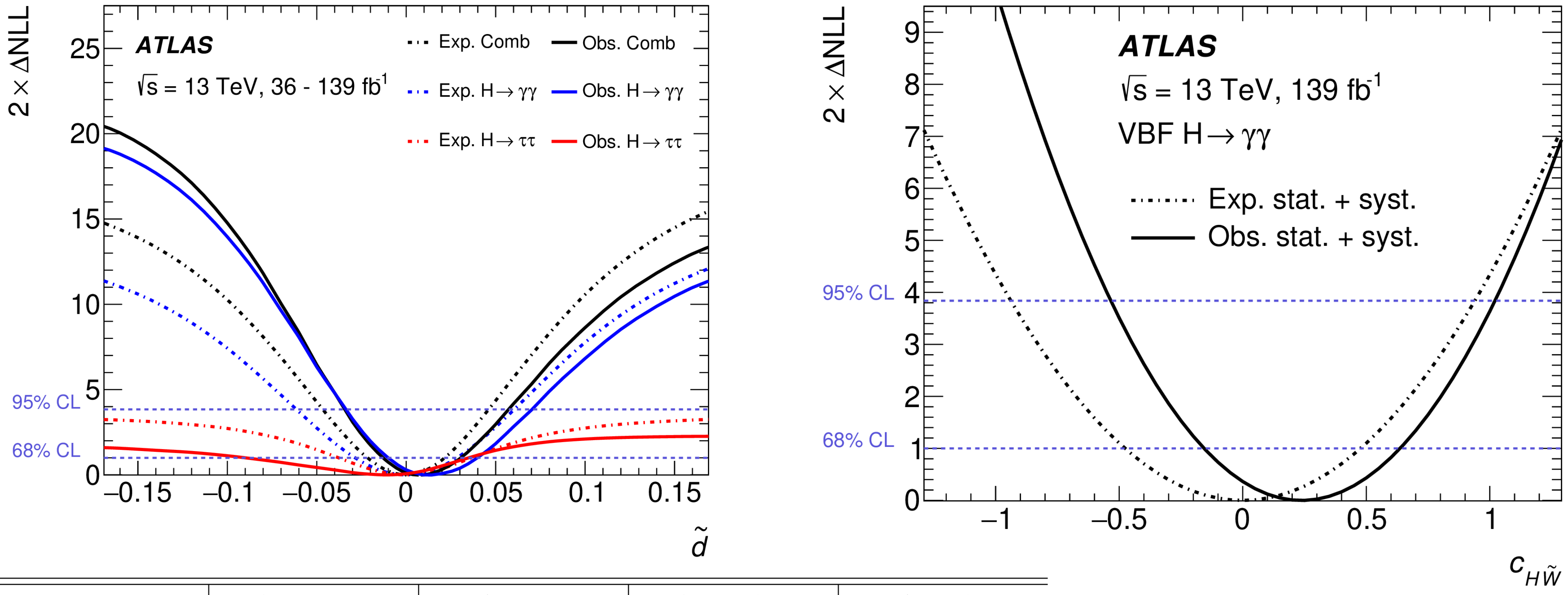


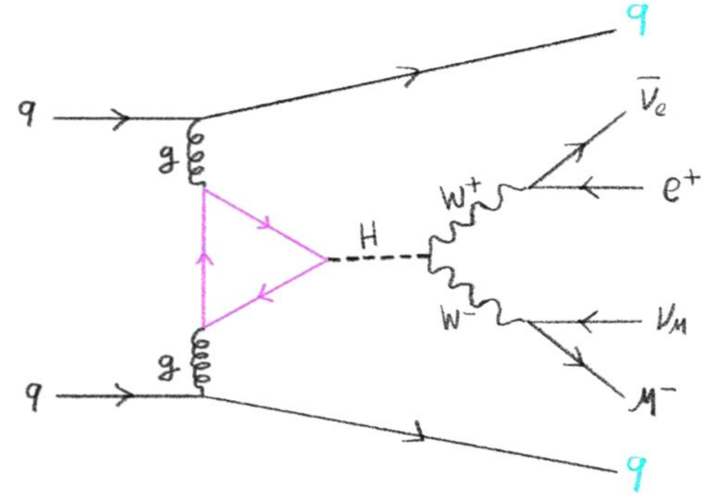
	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

✓ Compared to H→ZZ and H→γγ from cross section interpretation, this analysis has about 2 ~ 5 time better limits

Higgs-gluon coupling： H→WW*→eνμν

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

- EFT from the Higgs Characterization model
- Explore CP structure in Higgs-gluon interaction with events produced in ggH+2jets

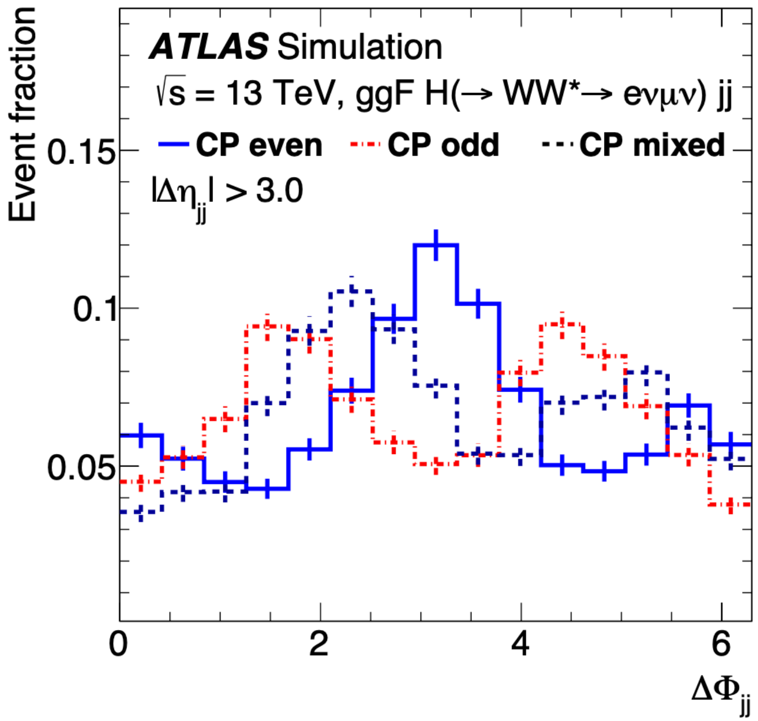


$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^{a}_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^{a}_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

CP-even component CP-even component

$\Delta\phi_{jj}$ is used as the CP sensitive discriminant

Scenario	Parameters
CP-even (SM)	$\kappa_{gg} = 1, \cos(\alpha) = 1$
CP-odd	$\kappa_{gg} = 1, \cos(\alpha) = 0$
CP-mixed	$\kappa_{gg} = 1, \cos(\alpha) = \frac{1}{\sqrt{2}}$

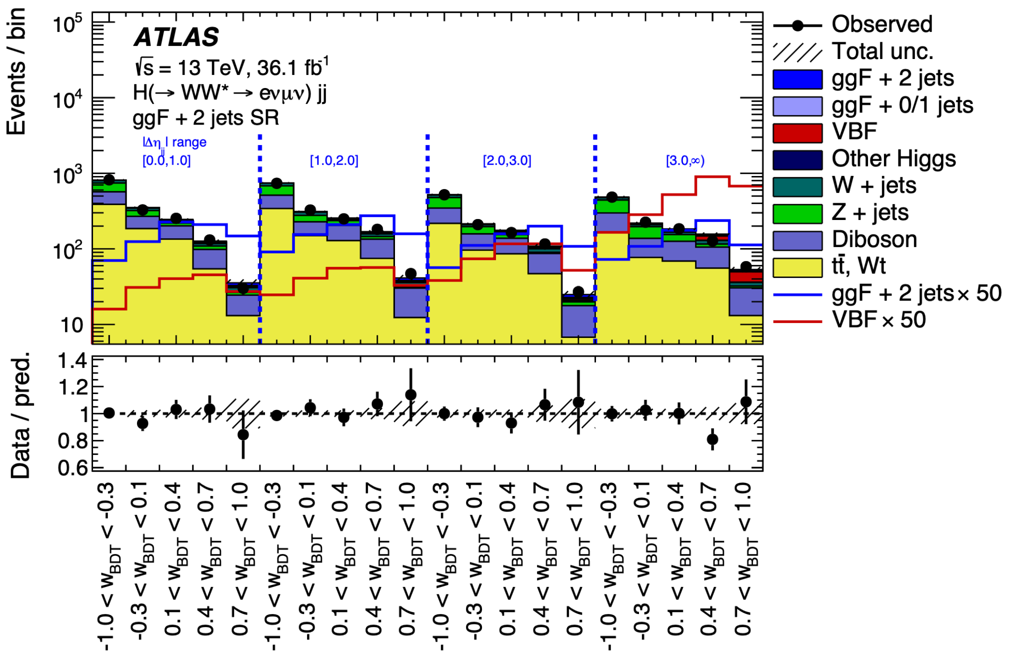


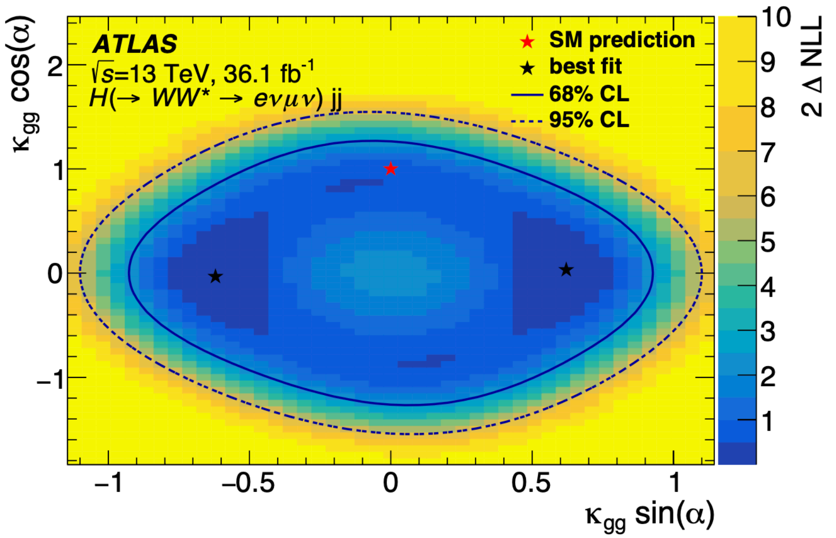
- Selected 2 opposite sign, different flavor leptons selected with ≧ 2jets
- Additional kinematic selection
- BDT training to further separate signal with Top, WW and Z→$\tau\tau$ events
- Low BDT regions for background modeling

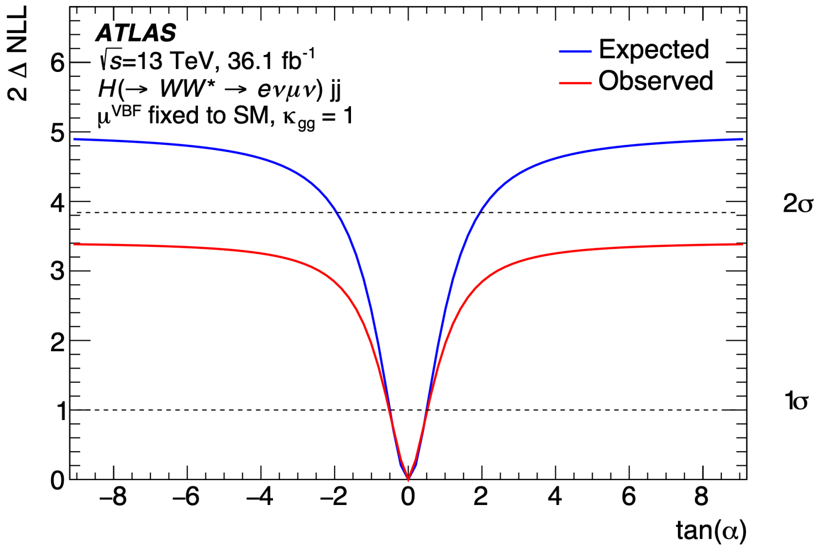
Higgs-gluon coupling: $H \to WW^* \to e\nu\mu\nu$

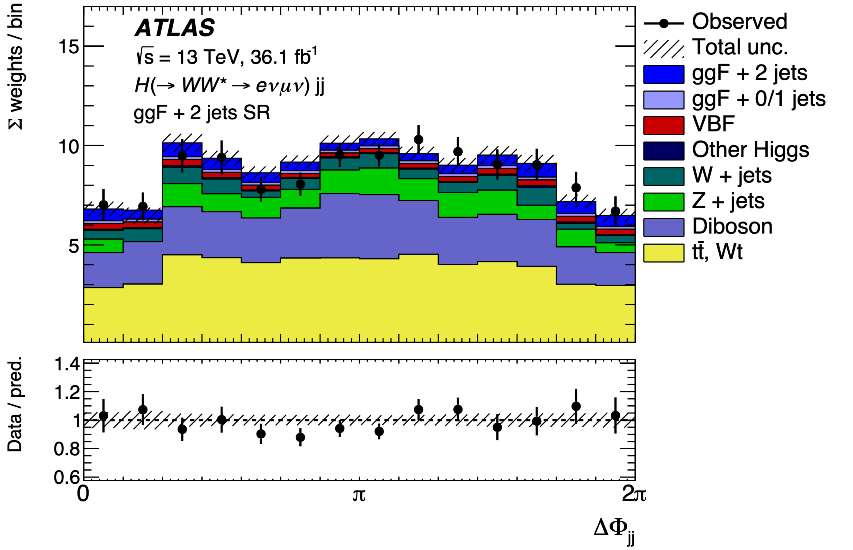
[Eur. Phys. J. C 82 (2022) 622]

- Results obtained with a fit to $\Delta\phi_{jj}$ distribution in total 12 event regions (3 BDT ×4 $|\Delta\phi_{jj}|$ bins)
  - Low BDT regions used for bkg constraints
- Shape+norm fit to provide best fit on $\tan(\alpha)$
  - $\tan(\alpha) = 0.0 \pm 0.4(\text{stats.}) \pm 0.3(\text{syst.})$









H→ZZ→ℓℓℓℓ

[Phys. Rev. D 104 (2021) 052004]

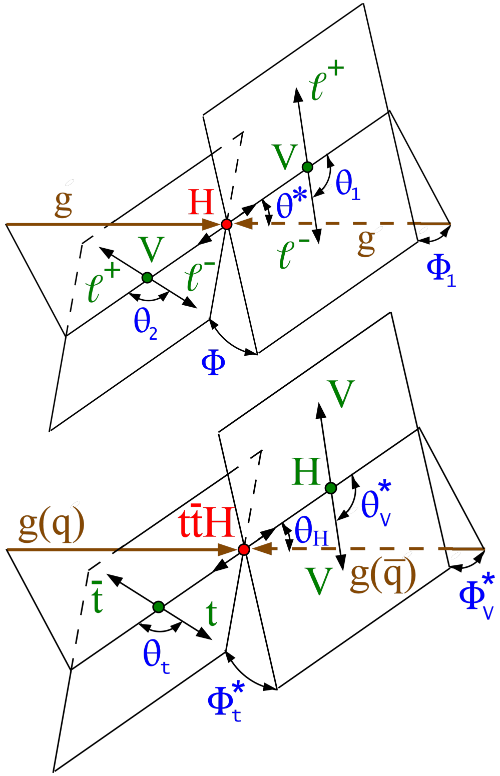
Multiple production modes involved

Explore generic HVV and Hff couplings

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

tree-level SM-like | CP-even anomalous couplings | CP-odd anomalous coupling

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$



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

$$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{\mathrm{gg}}|^2}{|a_2^{\mathrm{gg}}|^2 + |a_3^{\mathrm{gg}}|^2}\,\mathrm{sign}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right)$$

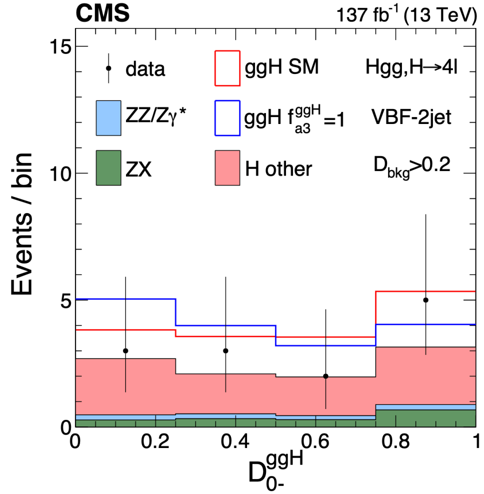
$$f_{ai}^{\mathrm{VV}} = \frac{|a_i^{\mathrm{VV}}|^2 \alpha_{ii}^{(2e2\mu)}}{\sum_j |a_j^{\mathrm{VV}}|^2 \alpha_{jj}^{(2e2\mu)}}\,\mathrm{sign}\left(\frac{a_i^{\mathrm{VV}}}{a_1}\right)$$

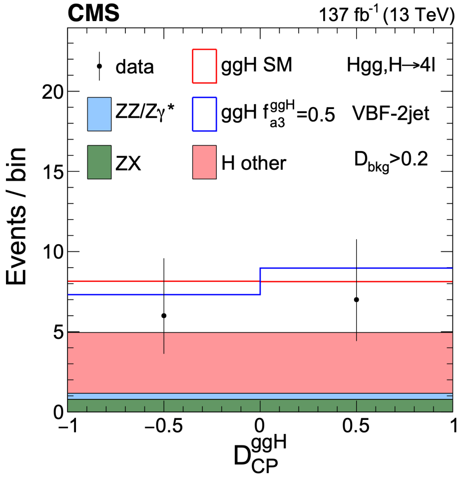
Enhance Higgs signal purity and build CP sensitive observable with MELA technique by exploring the angular distributions etc, improve separation with BDT.

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

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

Explore CP-odd component



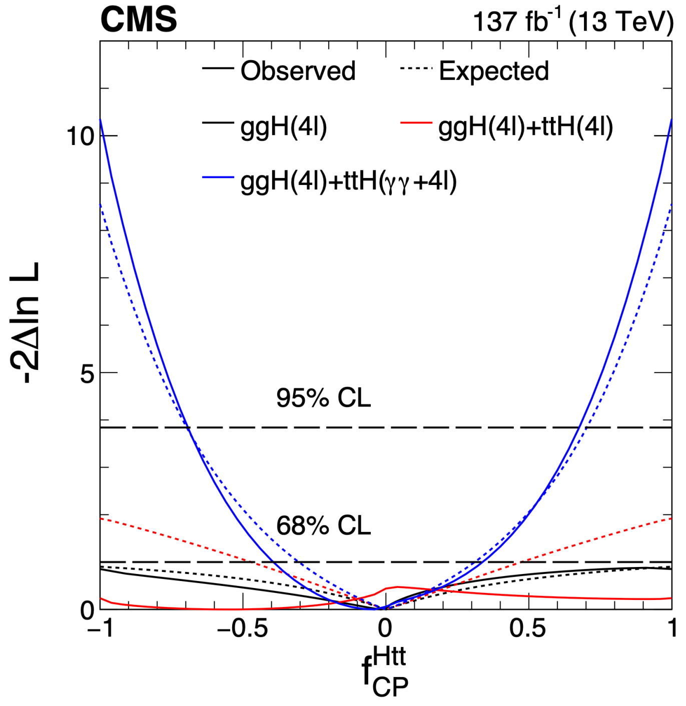


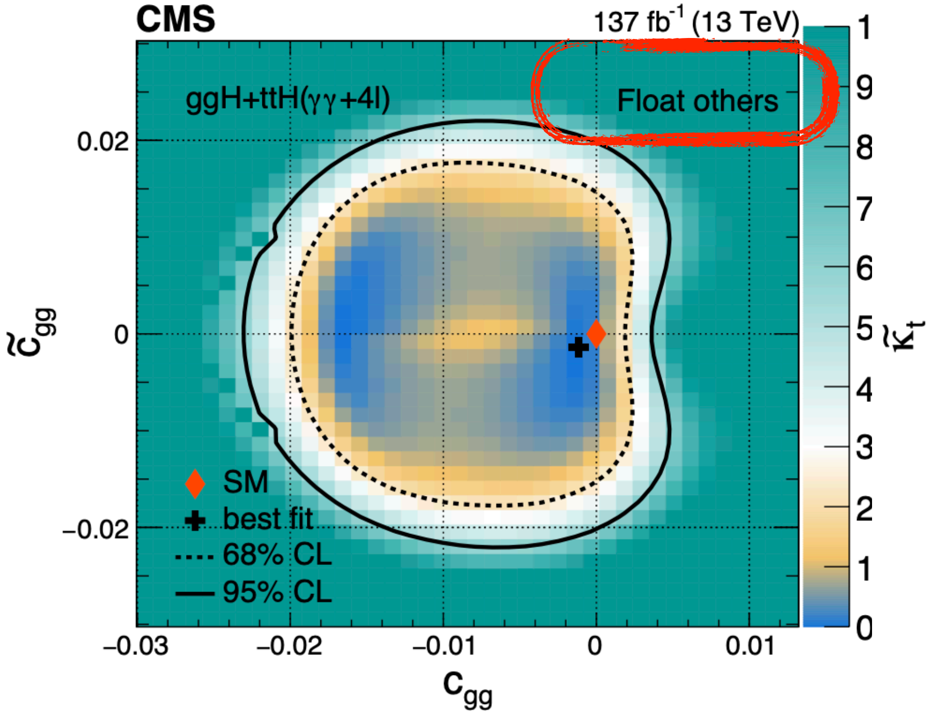
Similar strategy is also performed in H→ττ channel

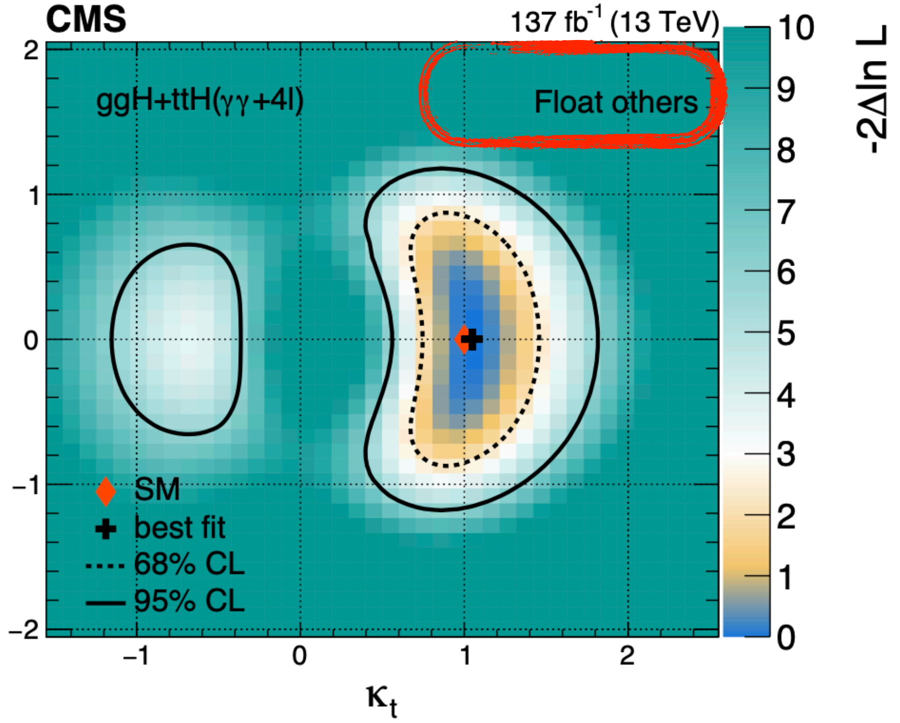
[arXiv:2205.05120]

H→ZZ→ℓℓℓℓ

[Phys. Rev. D 104 (2021) 052004]





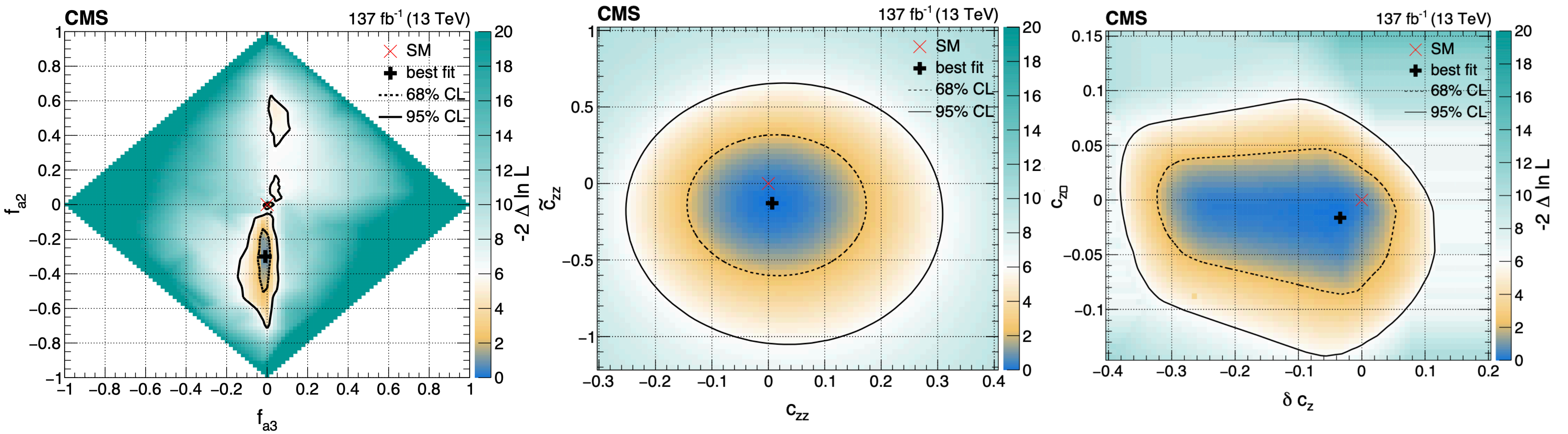


Constraints on Hff/Hgg coupling in SMEFT Higgs basis

Channels	Coupling	Observed	Expected	Observed correlation			
				c_{gg}	$\tilde{c}_{gg}$	κ_t	$\tilde{\kappa}_t$
tH & $t\bar{t}$H & ggH	c_{gg}	$-0.0012^{+0.0022}_{-0.0174}$	$0.0000^{+0.0019}_{-0.0196}$	1	−0.050	−0.941	+0.029
	$\tilde{c}_{gg}$	$-0.0017^{+0.0160}_{-0.0130}$	$0.0000^{+0.0138}_{-0.0138}$		1	+0.046	−0.568
	κ_t	$1.05^{+0.25}_{-0.20}$	$1.00^{+0.34}_{-0.26}$			1	+0.168
	$\tilde{\kappa}_t$	$-0.01^{+0.69}_{-0.67}$	$0.00^{+0.71}_{-0.71}$				1

$H \to ZZ \to \ell\ell\ell\ell$

Phys. Rev. D 104 (2021) 052004



Constraints on HVV coupling in SMEFT Higgs basis

Channels	Coupling	Observed	Expected	Observed correlation δc_z	c_{zz}	$c_{z\Box}$	$\tilde{c}_{zz}$
VBF & VH & $H \to 4\ell$	δc_z	$-0.03^{+0.06}_{-0.25}$	$0.00^{+0.07}_{-0.27}$	1	$+0.241$	-0.060	-0.009
	c_{zz}	$0.01^{+0.11}_{-0.10}$	$0.00^{+0.22}_{-0.16}$		1	-0.884	$+0.058$
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$			1	$+0.020$
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$				1

$H\to\tau\tau$ coupling structure

JHEP 06 (2022) 012 arXiv:2212.05833

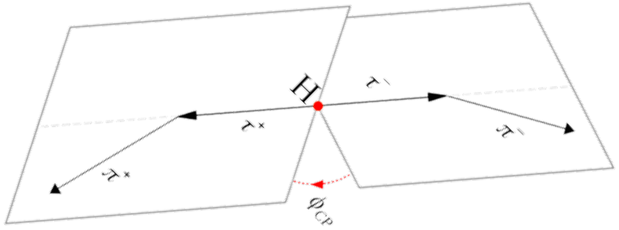
The CP-mixing is parametrized to be sensitive to the angular of two tau planes from the Higgs Boson in the Higgs Boson center-of-mass frame

$$\frac{d\Gamma}{d\phi_{CP}}(H\to\tau^+\tau^-)\sim 1-b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP}-2\alpha^{H\tau\tau})$$

CP-mixing

$$\mathcal{L}_Y=-\frac{m_\tau}{v}H(\kappa_\tau\bar{\tau}\tau+\tilde{\kappa}_\tau\bar{\tau}i\gamma_5\tau)$$

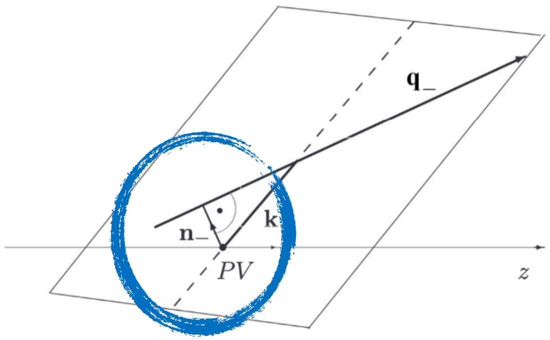
$$\tan(\alpha^{H\tau\tau})=\frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

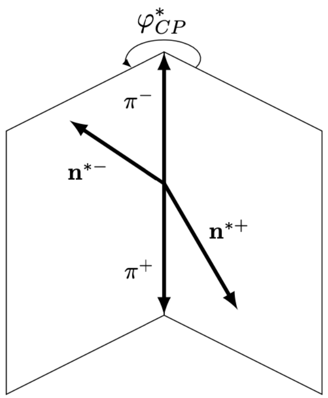


Depending on tau decays: several method developed to reconstructive ϕ_{CP}

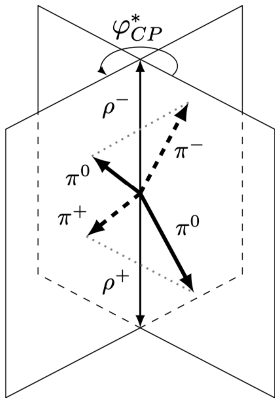
Notation	Decay mode	Branching fraction	
ℓ	$\ell^\pm\bar{\nu}\nu$	35.2%	**Impact parameter method**
1p0n	$h^\pm\nu$ $(\pi^\pm\nu)$	11.5% (10.8%)	
1p1n	$h^\pm\pi^0\nu$ $(\pi^\pm\pi^0\nu)$	25.9% (25.5%)	**Neutral pion method (+IP method)**
1pXn	$h^\pm\geq 2\pi^0\nu$ $(\pi^\pm 2\pi^0\nu)$	10.8% (9.3%)	
3p0n	$3h^\pm\nu$ $(3\pi^\pm\nu)$	9.8% (9.0%)	

Impact parameter

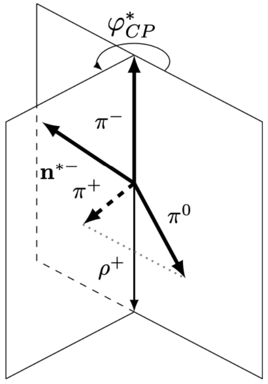




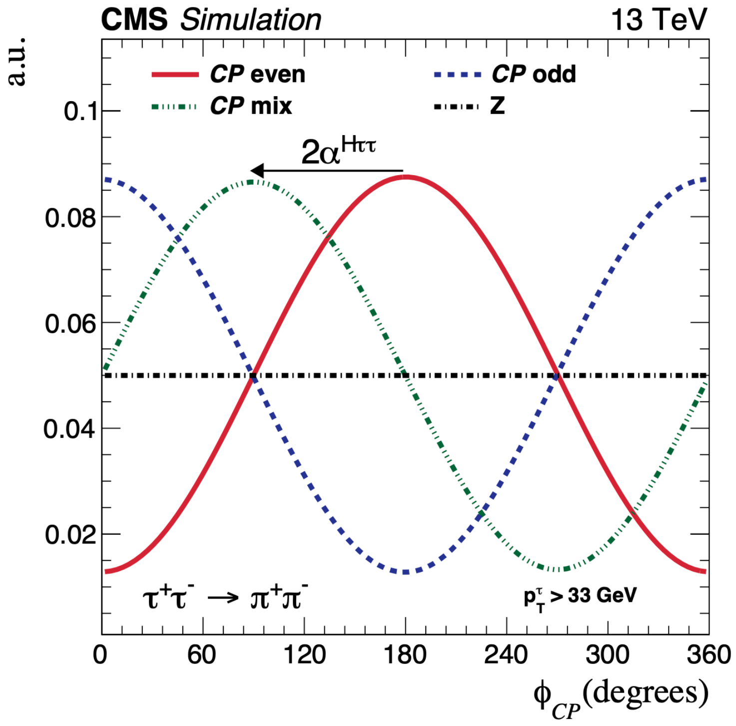
$H\to\tau^+\tau^-\to\pi^+\pi^-+2\nu$



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



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



H→ττ coupling structure

[JHEP 06 (2022) 012] [arXiv:2212.05833]

Current data prefer CP-even case

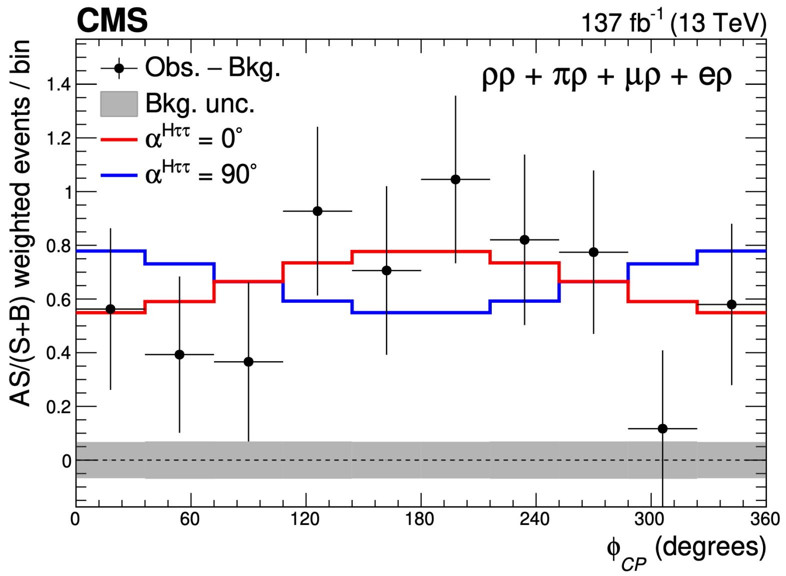
$\alpha^{H\tau\tau}$ = -1±19 deg. (±21 deg.)

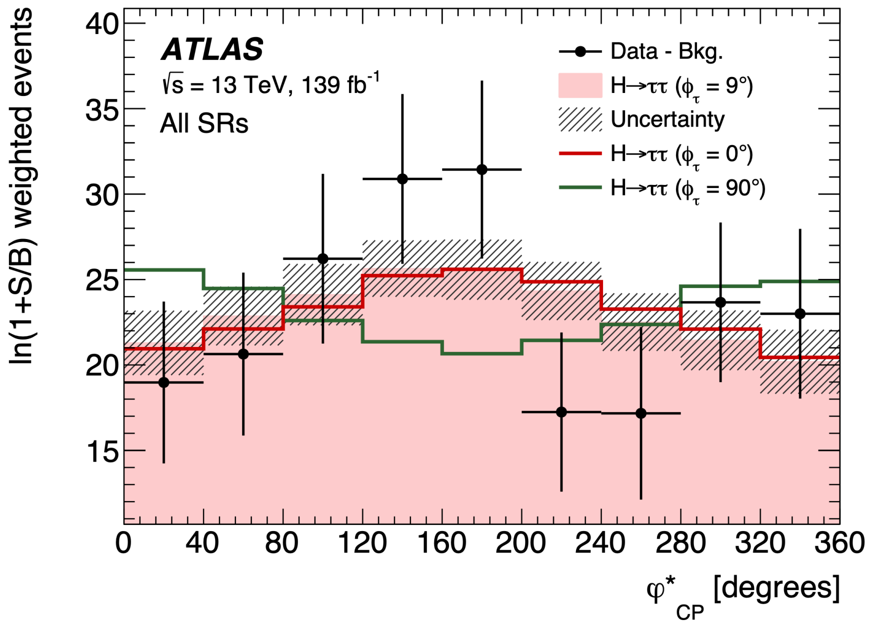
Pure CP-odd excluded @ 3σ

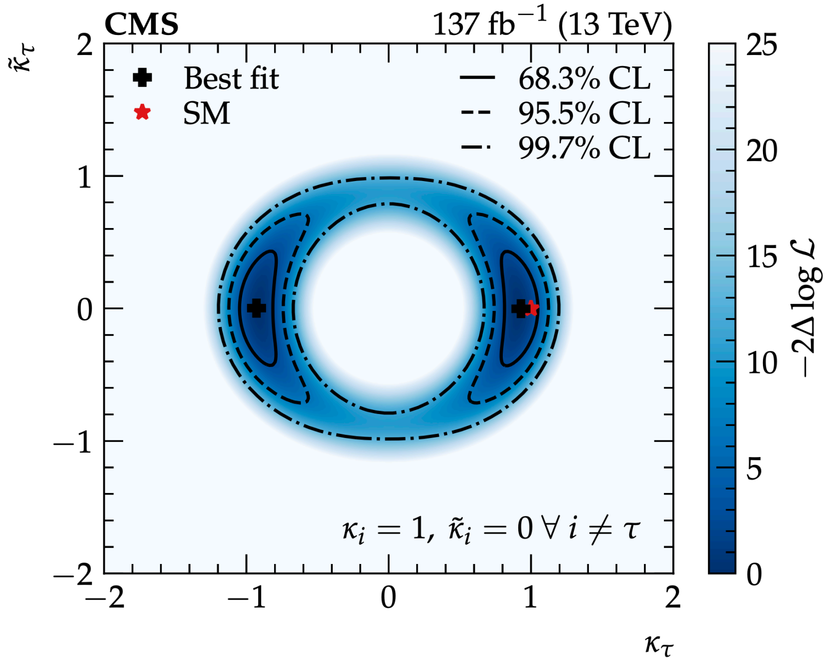
Similar strategy analysis done by ATLAS

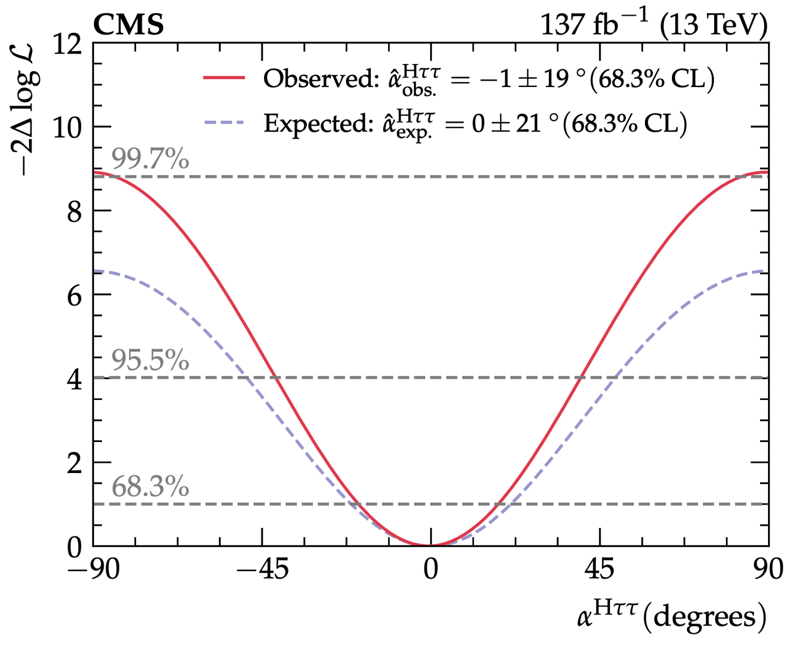
ϕ_τ = 9±16 deg. (±28 deg.)

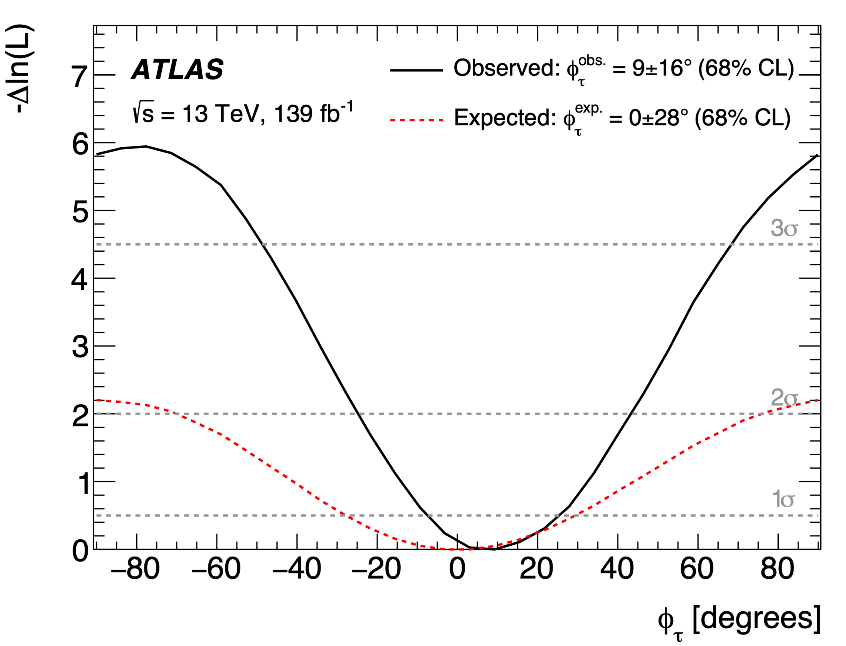
Pure CP-odd excluded @ 3.4σ











CP structure in Higgs-Top interaction

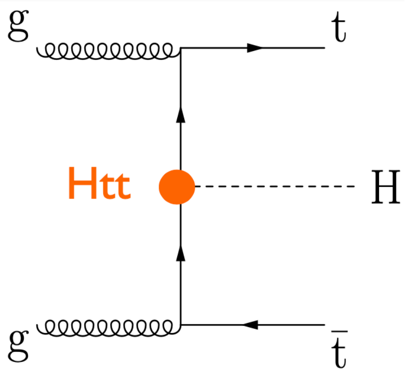
Phys. Rev. Lett. 125 (2020) 061802

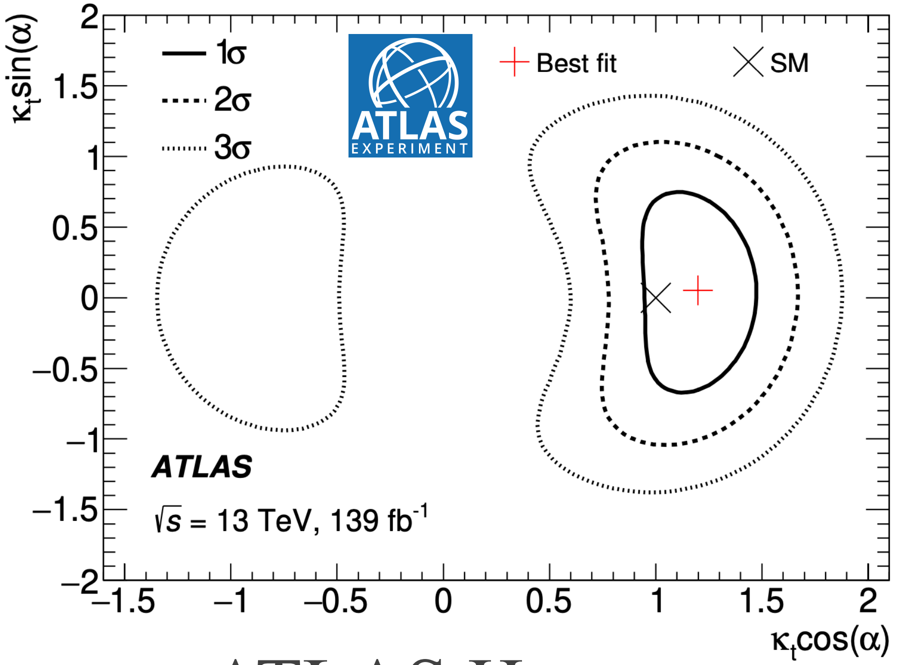
$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H$$

CP-even CP-odd

$$\kappa_t = k_t \cos\alpha$$

$$\tilde{\kappa}_t = k_t \sin\alpha$$

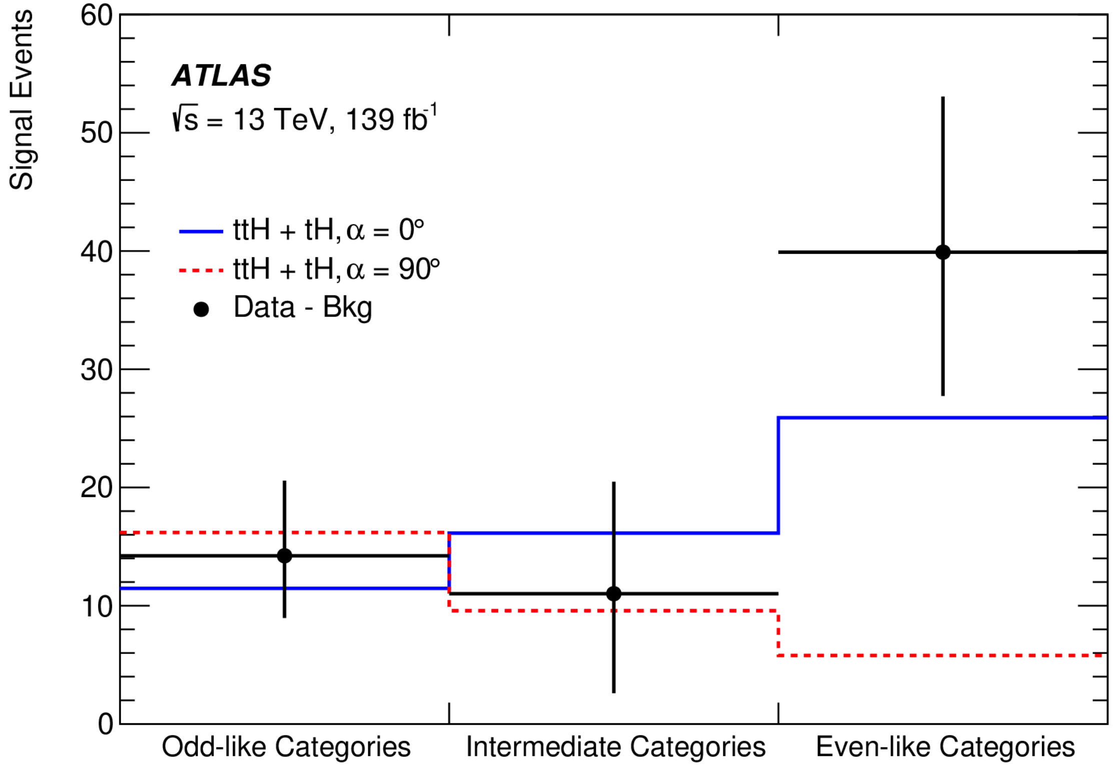




ATLAS H→$\gamma\gamma$

Mixing angle |α|<43° @95% CL

Pure CP-odd excluded @3.9σ



CP structure in Higgs-Top interaction

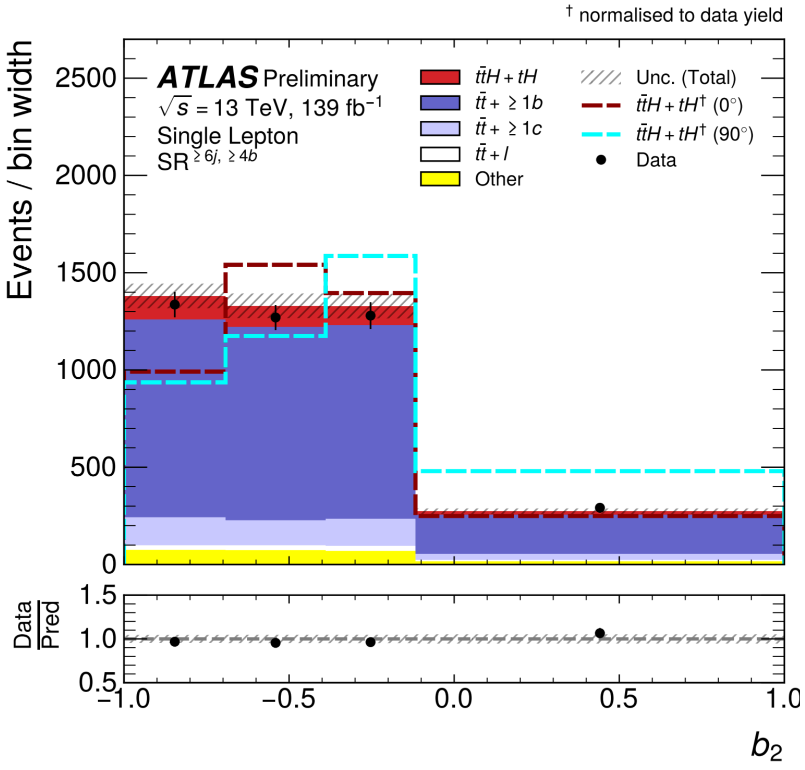
ATLAS-CONF-2022-016

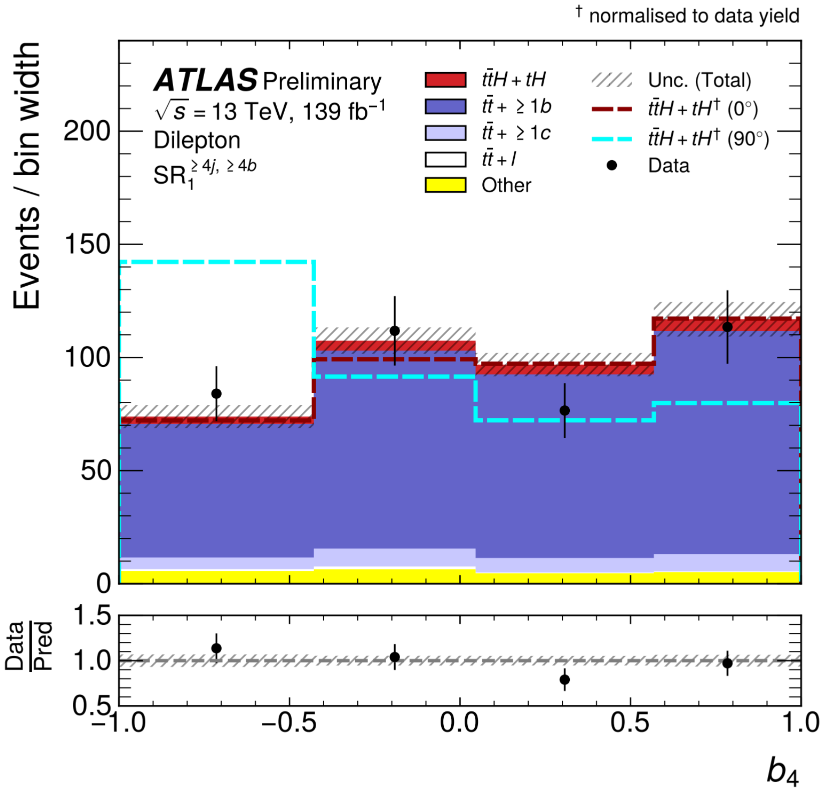
Two CP sensitive variables defined with top quark kinematic information in 1ℓ+jets and 2ℓ channel

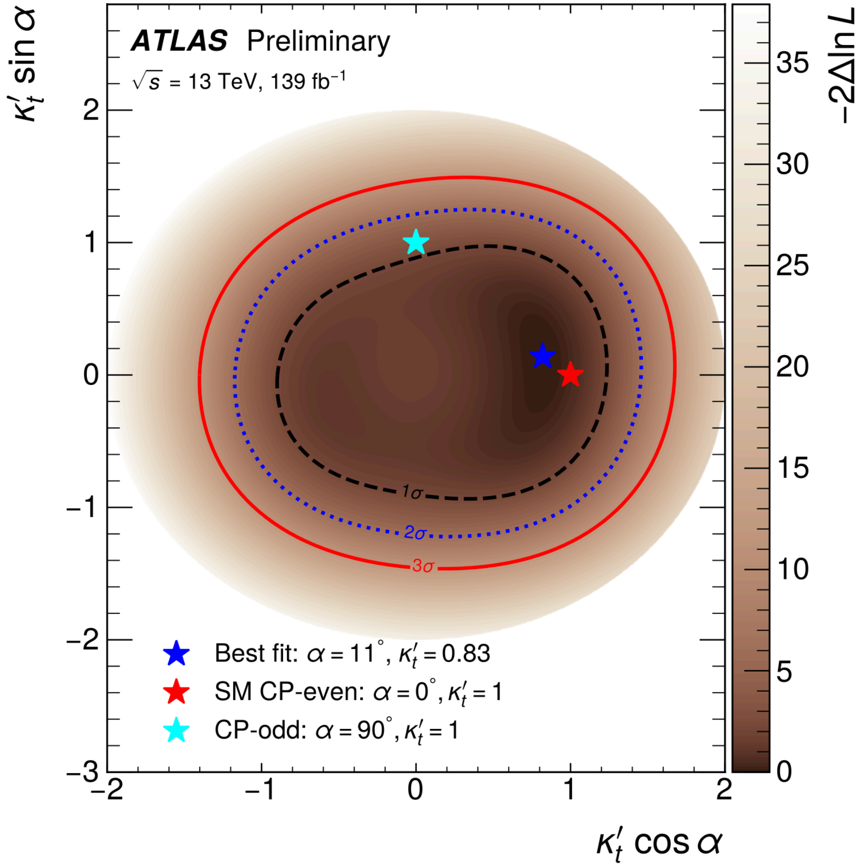
$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

ATLAS H→bb

$\vec{p}_{1,2}$ are top momenta, $\hat{n}$ is the unit vector for z-axis







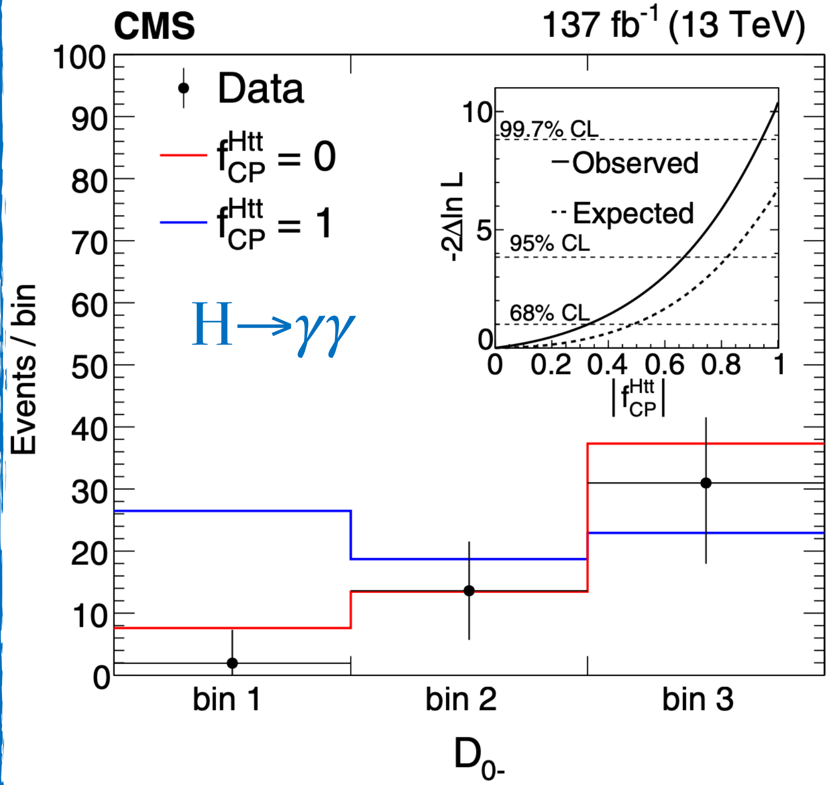
CP structure in Higgs-Top interaction

Phys. Rev. Lett. 125 (2020) 061801   arXiv:2208.02686

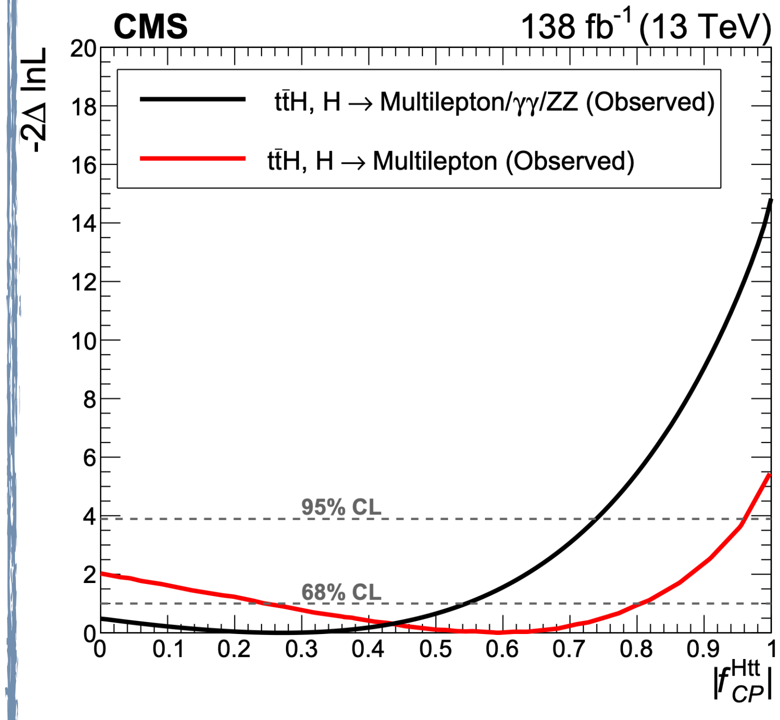
$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H \qquad f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^{\,2}}{\tilde{\kappa}_t^{\,2}+\kappa_t^{\,2}}$$

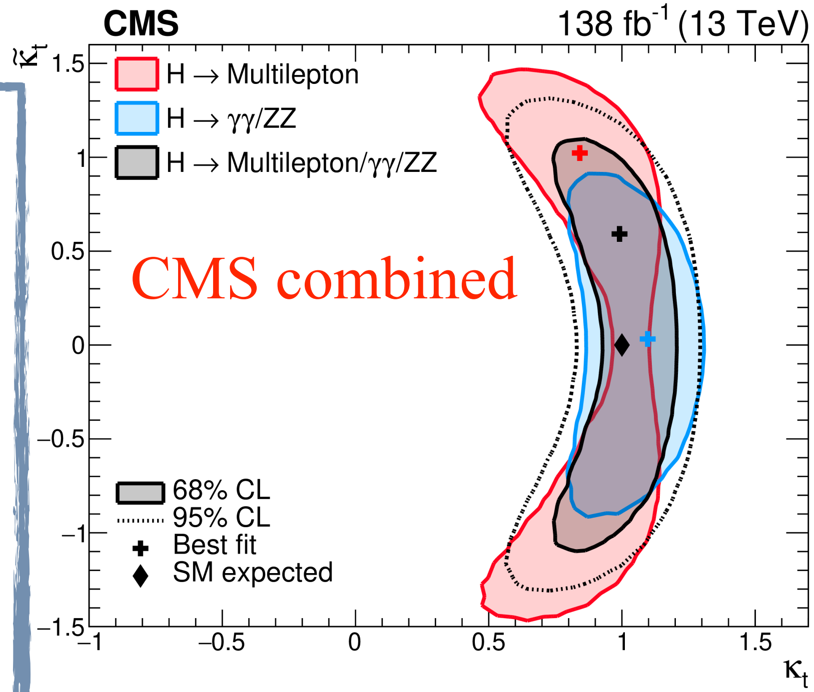
CP-even   CP-odd

MELA-based CP sensitive observable to extract CP-odd information



Complicated final state, ML-based observable for CP measurement





Pure CP-odd excluded @3.7σ

H→γγ only exclude @3.2σ

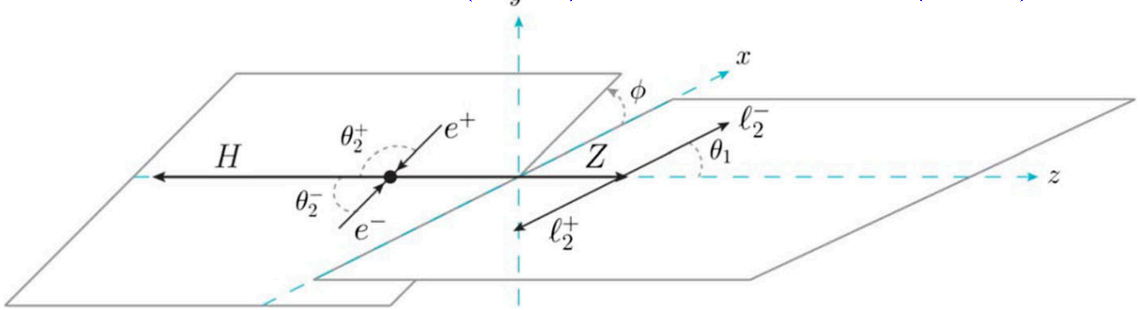
Higgs CP measurement in CEPC

Eur. Phys. J. C 82, 981 (2022)

Effective Lagrangian in Higgs basis

$$\mathcal{L}_{\rm eff} \supset c^{(1)}_{ZZ} H Z_\mu Z^\mu + c^{(2)}_{ZZ} H Z_{\mu\nu} Z^{\mu\nu} + c_{Z\tilde{Z}} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$
$$+ c_{AZ} H Z_{\mu\nu} A^{\mu\nu} + c_{A\tilde{Z}} H Z_{\mu\nu} \tilde{A}^{\mu\nu}$$
$$+ H Z_\mu \bar{\ell}\gamma^\mu (c_V + c_A \gamma_5)\ell + Z_\mu \bar{\ell}\gamma^\mu (g_V - g_A\gamma_5)\ell$$
$$- g_{\rm em} Q_\ell A_\mu \bar{\ell}\gamma^\mu \ell,$$

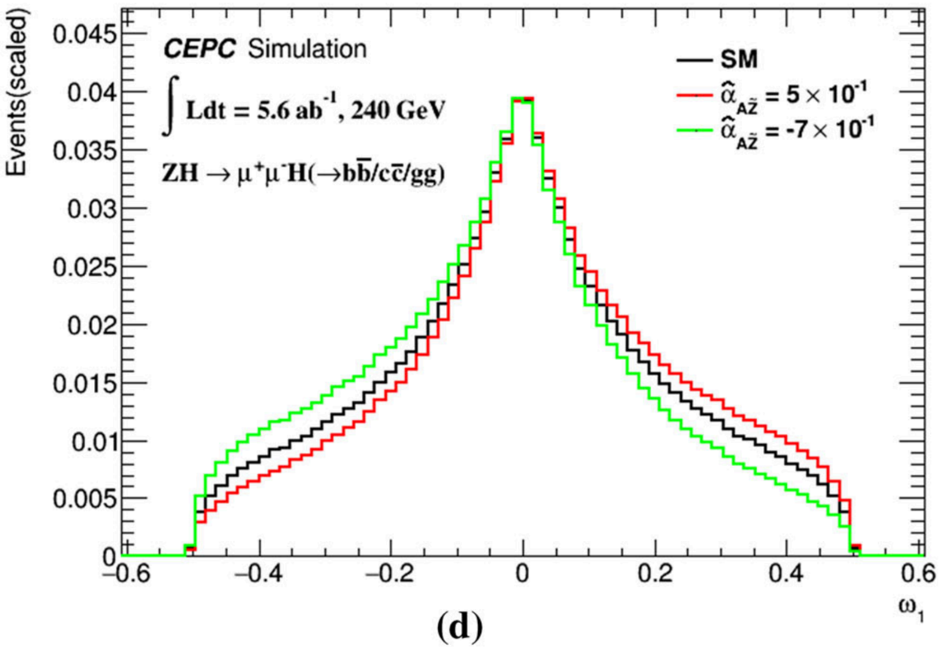
Theoretical framework follows
Ref. JHEP11(2014)028 and JHEP03(2016)050

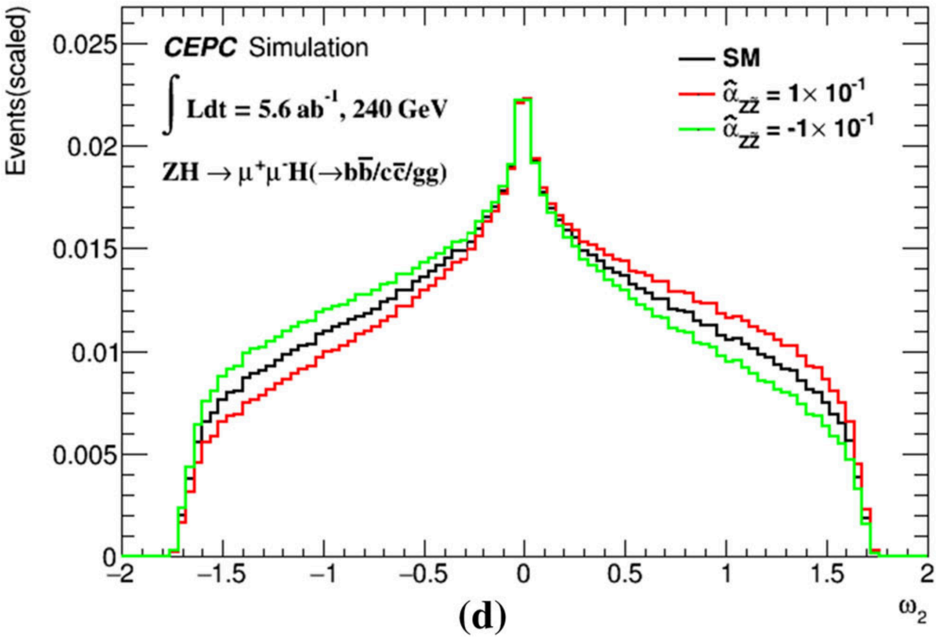


CP-sensitive variables defined from angular distributions as discriminators

$$\omega_1 = \frac{J_{odd_1}(\theta_1, \theta_2, \phi)}{J_{even}(\theta_1, \theta_2, \phi)}$$

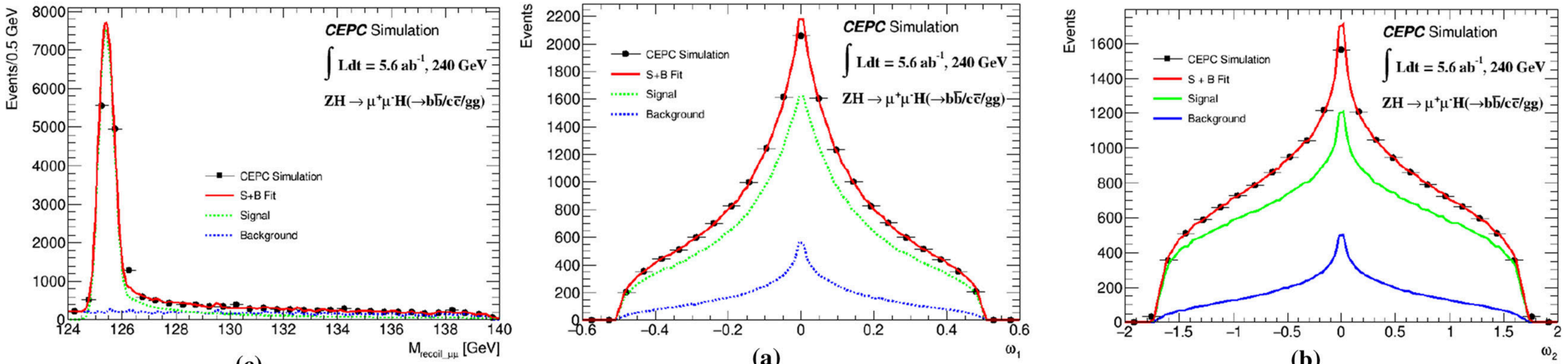
$$\omega_2 = \frac{J_{odd_2}(\theta_1, \theta_2, \phi)}{J_{even}(\theta_1, \theta_2, \phi)}$$



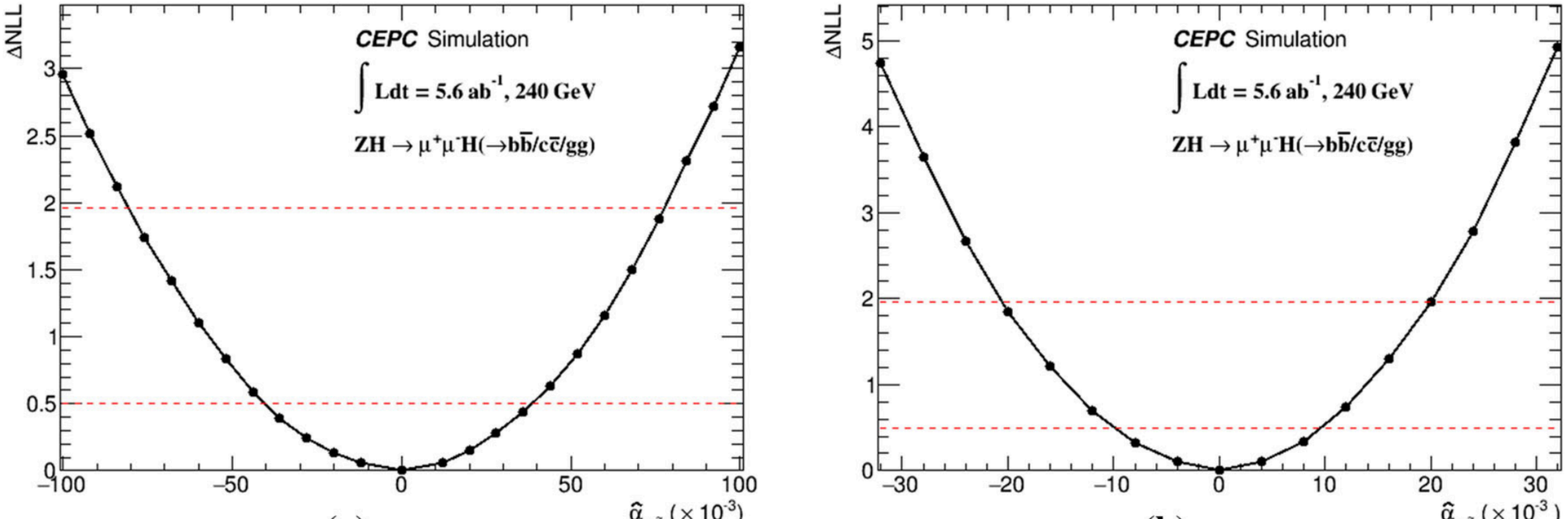


Higgs CP measurement in CEPC

Eur. Phys. J. C 82, 981 (2022)



(c) (a) (b)

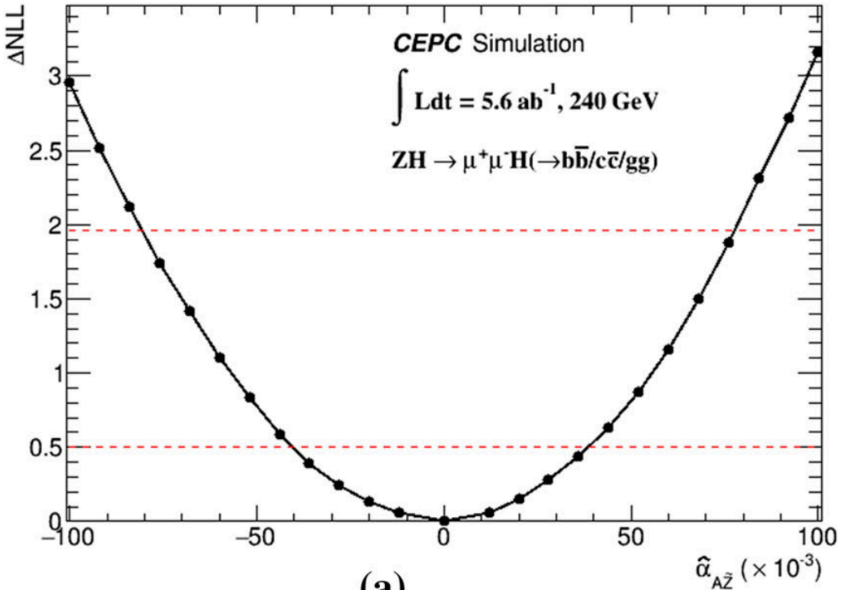


(a) (b)

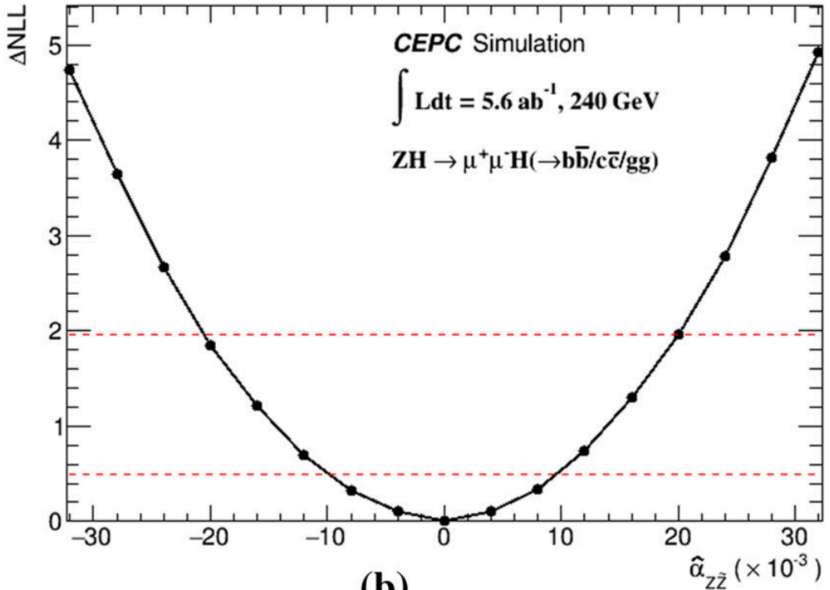
Higgs CP measurement in CEPC

Eur. Phys. J. C 82, 981 (2022)

	HL-LHC	CLIC	CEPC	
Collider	pp	e^+e^-	e^+e^-	e^+e^-
E (GeV)	14,000	3000	240	240
$\mathcal{L}\ (\text{fb}^{-1})$	3000	5000	5600	20,000
$\tilde{c}_{Z\gamma}\ (1\sigma)$	[−0.22, 0.22]	[−0.18, 0.18]	[−0.30, 0.27]	[−0.16, 0.14]
$\tilde{c}_{ZZ}\ (1\sigma)$	[−0.33, 0.33]	[−0.12, 0.12]	[−0.06, 0.06]	[−0.03, 0.03]



(a)

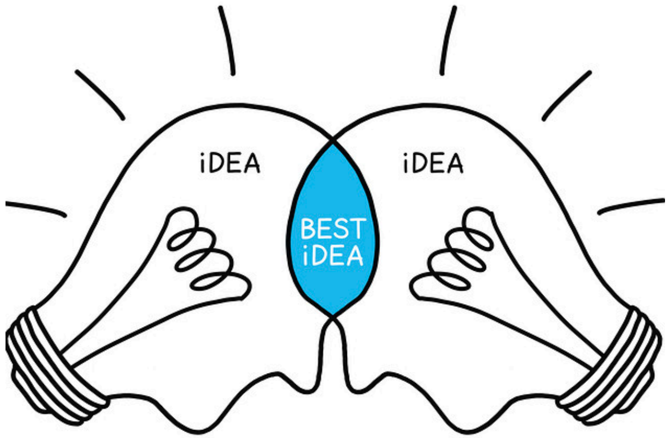


(b)

Summary

- Studies of the Higgs boson CP property is crucial for particle physics recent days
- Extensive analyses done by the ATLAS and CMS experiments to build a complete view of the Higgs CP properties and search for potential anomalies would resulting the “odd” CP phenomena
- Recent results show that data agrees with the SM predictions → still limited by the low statistics
  - ✓Huge improvement expected from HL-LHC upgrade
  - ✓Strong constraints from Future Higgs factory
- Purely CP-odd coupling has been excluded → still room for CP-mixing

Collaboration between experimentalist and theorist would be very much appreciated



感谢聆听
Thanks for listening

Backup

Higgs CP

- With all final state particles reconstructed, we can perform a Matrix Element based analysis of the underlying Higgs CP mixing angle Φ. The Higgs decay amplitude can be expressed as

$$|\mathcal{M}|^2 \propto A + B\cos(2\phi) + C\sin(2\phi),$$
$$\propto I_1\cos^2(\phi) + I_2\sin(\phi)\cos(\phi) + I_3\sin^2(\phi)$$

- Two observables can be reconstructed per event for the CP test
  - Optimal Observable (M. Davier et. al, Phys. Lett. B306,1993, 411): OO = I_2/I_1
  - ME angle $\Delta\Phi_{ME}$, defined as

$$|\mathcal{M}|^2 \propto A + \sqrt{B^2+C^2}\cos(\Delta\phi_{ME} - 2\phi)$$
$$\cos(\Delta\phi_{ME}) = \frac{B}{\sqrt{B^2+C^2}}, \quad \sin(\Delta\phi_{ME}) = \frac{C}{\sqrt{B^2+C^2}}$$

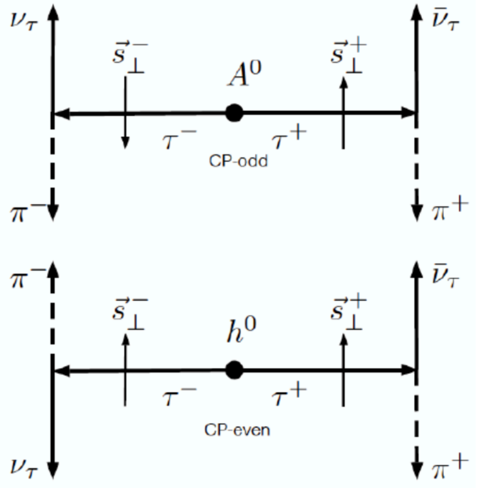
At low mixing angle values, the two perform similarly, while in high values of Φ, $\Delta\Phi_{ME}$ is better

CP test in H→ττ decay

- CP-odd Yukawa coupling can enter the Lagrangian at dim-4, thus sensitive at tree-level rather than with the dim-6 operators in HVV

$$-g_\tau\left(\cos\phi\bar{\tau}\tau+\sin\phi\bar{\tau}i\gamma_5\tau\right)h$$

Φ is the mixing angle. Φ=0 (Φ=π/2) means SM (CP odd)



- CP of Hττ coupling can be distinguished by the transverse tau spin correlations

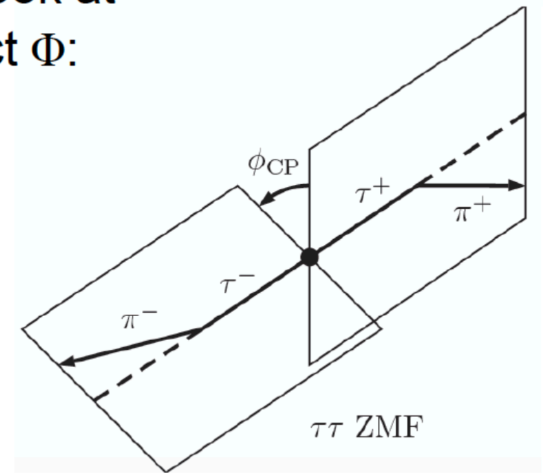
$$\Gamma(H,A\to\tau^-\tau^+)\ \sim\ 1-s_z^{\tau^-}s_z^{\tau^+}\pm s_T^{\tau^-}s_T^{\tau^+}$$

Sensitive to CP (H vs A)

- For example, with the τ→πν decay, one can look at the angle between tau decay planes to extract Φ:

$$\frac{d\Gamma\left(h\to\tau\tau\to\pi^+\pi^-+2\nu\right)}{d\phi_{CP}}\propto 1-\frac{\pi^2}{16}\cos\left(\phi_{CP}-2\phi\right)$$

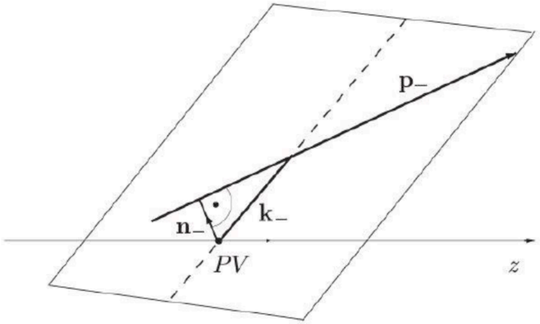
- It is experimentally challenging because the neutrinos are not reconstructed



CP test in H→ττ decay

- There are two methods to extract CP from H→ττ decay:

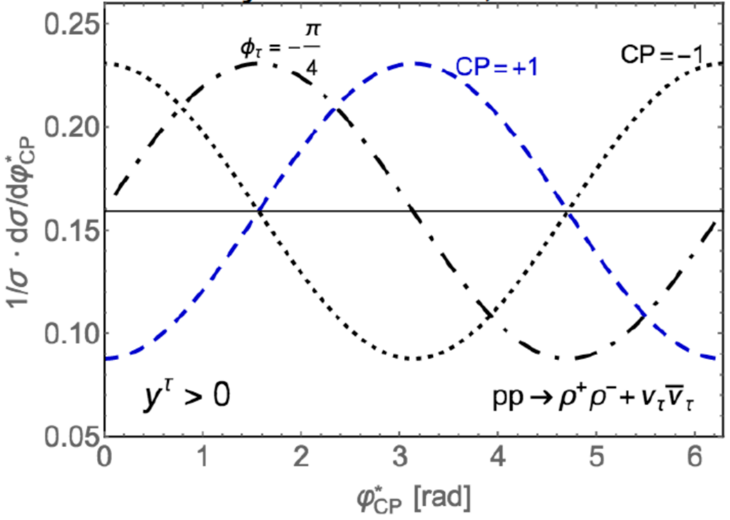
  Impact Parameter (IP) method:
  - Approximately reconstruct the tau decay plane from its leading track and IP
  - Best for the $\tau\to\pi\nu$ decay. The analyzing power is compromised for other tau decays

  Using the $\tau\to\rho\nu\to\pi^{\pm}\pi^{0}\nu$ decay:
  - The tau decay plane can be approximately reconstructed by the track and neutral pion
  - However, the relative energy of $\pi^{\pm}$, π^{0} need to be classified in order to maximize the analyzing power

- In order to use the two methods, the tau decay modes (substructure) need to be well differenciated (next few slides)

Phys. Rev. D92, 096012



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A few extra references:
EPJC 74 (2014) 3164, Phys. Rev. D88 076009,
Phys. Lett. B579 (2004) 157, Phys. Lett. B543 (2002) 227

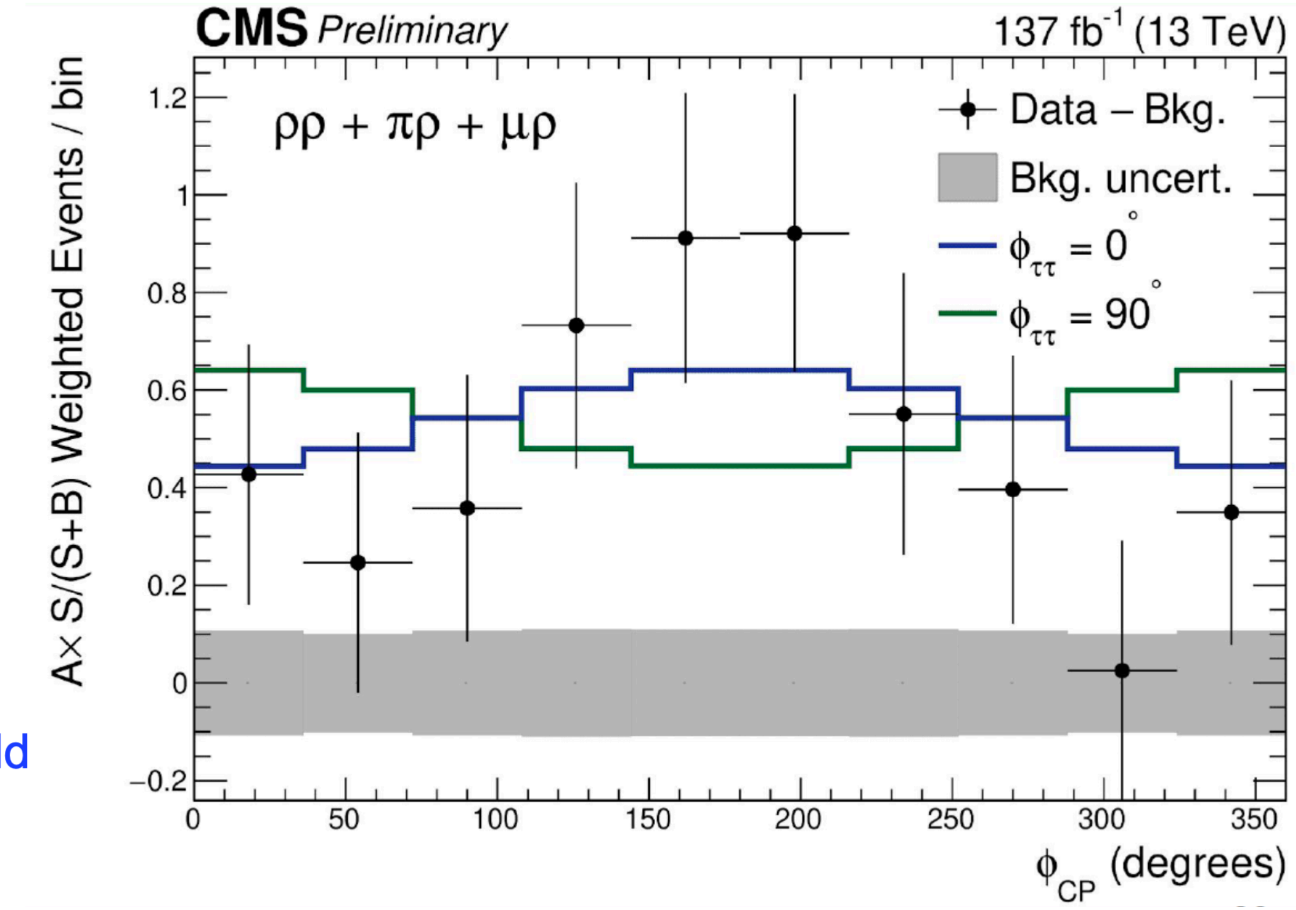
Higgs CP in $H \to \tau\tau$: ϕ_{CP} distribution

The results from the most sensitive channels are weighted and combined into a plot of $\boldsymbol{\phi}_{CP}$

Each BDT/NN score window is weighted by A*S/(S+B), being A the “average asymmetry”:

$$A = \frac{1}{N_{bins}} \sum^{N_{bins}} \frac{|CP^{even} - CP^{odd}|}{|CP^{even} + CP^{odd}|}$$

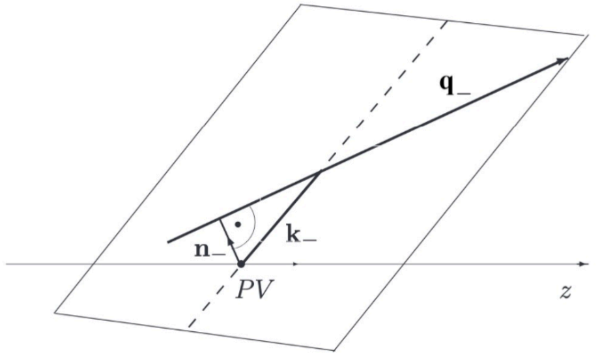
Background is subtracted from data.
(Grey band: unc. on subtracted bkg.)



$H \to \tau\tau$ decays consistent with SM.
CP-even case preferred over CP-odd case with 3.2σ (2.3σ expected).

Higgs CP in H→ττ: ϕ_{CP} reconstruction

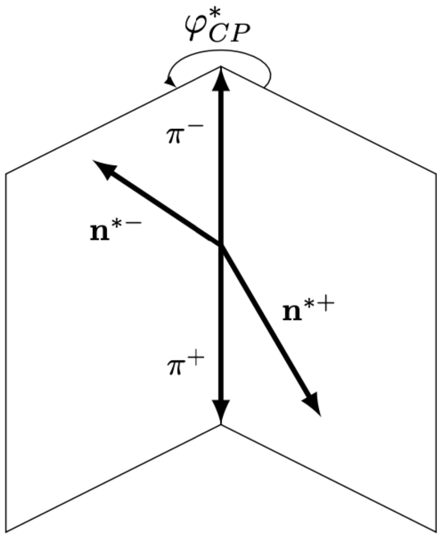
H→ττ decay CP



Impact parameter

directional distance of closest approach of charged particle's track to reconstructed PV of the event

4-vectors boosted to the rest frame of visible di-τ Zero Momentum Frame (e.g. two decay charged particles)



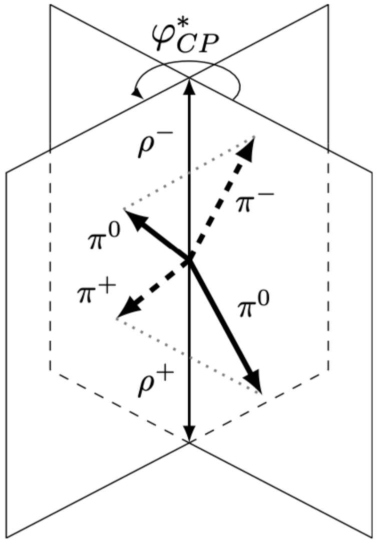
$$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$$

impact parameter

$$\varphi^* = \arccos(\hat{\mathbf{n}}_\perp^{*+} \cdot \hat{\mathbf{n}}_\perp^{*-})$$

$$O^*_{CP} = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{n}}_\perp^{*+} \times \hat{\mathbf{n}}_\perp^{*-})$$

$$\varphi^*_{CP} = \begin{cases} \varphi^* & \text{if } O^*_{CP} \geq 0 \\ 360^\circ - \varphi^* & \text{if } O^*_{CP} < 0 \end{cases}$$



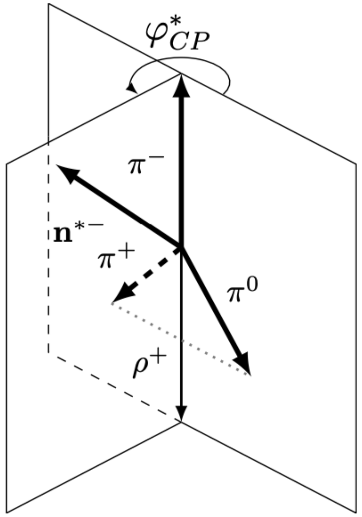
$$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$$

ρ decay plane

$$\varphi^* = \arccos(\hat{\mathbf{q}}_\perp^{*0+} \cdot \hat{\mathbf{q}}_\perp^{*0-})$$

$$O^*_{CP} = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{q}}_\perp^{*0+} \times \hat{\mathbf{q}}_\perp^{*0-})$$

$$\varphi^{*\prime} = \begin{cases} \varphi^* & \text{if } O^*_{CP} \geq 0 \\ 360^\circ - \varphi^* & \text{if } O^*_{CP} < 0 \end{cases} \quad \varphi^*_{CP} = \begin{cases} \varphi^{*\prime} & \text{if } y^\rho_+ y^\rho_- \geq 0 \\ \varphi^{*\prime} + 180^\circ & \text{if } y^\rho_+ y^\rho_- < 0 \end{cases} \quad y^\rho_\pm = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}$$



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

impact parameter + ρ decay plane

CP parametrization for HVV and Hgg couplings

ATLAS parametrisation

- Lagrangian in Higgs characterisation framework

$$\mathcal{L}_{eff} = H\left\{ c_\alpha \kappa_{SM}\left[\frac{1}{2}\frac{2m_V^2}{v}Z_\mu Z^\mu + g_{HWW}W_\mu W^\mu\right] - \frac{1}{4}\frac{1}{\Lambda}s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{1}{2}\frac{1}{\Lambda}s_\alpha \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right\}$$

$$\mathcal{L}_0^{\text{loop}} = -\frac{1}{4}\left(\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \kappa_{Agg} g_{Hgg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right) H\,,$$

- $\boldsymbol{k_{AVV}/k_{HVV}}$ or similar extracted from the fit

- Other parametrisation in VBF $H \to \tau\tau$ which has CP-odd contribution parametrised by $\tilde{d}$

$$\tilde{d} = \frac{1}{4}\frac{v}{\Lambda}\frac{k_{AVV}}{k_{SM}}\tan\alpha$$

CMS parametrisation

Scattering amplitude:

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

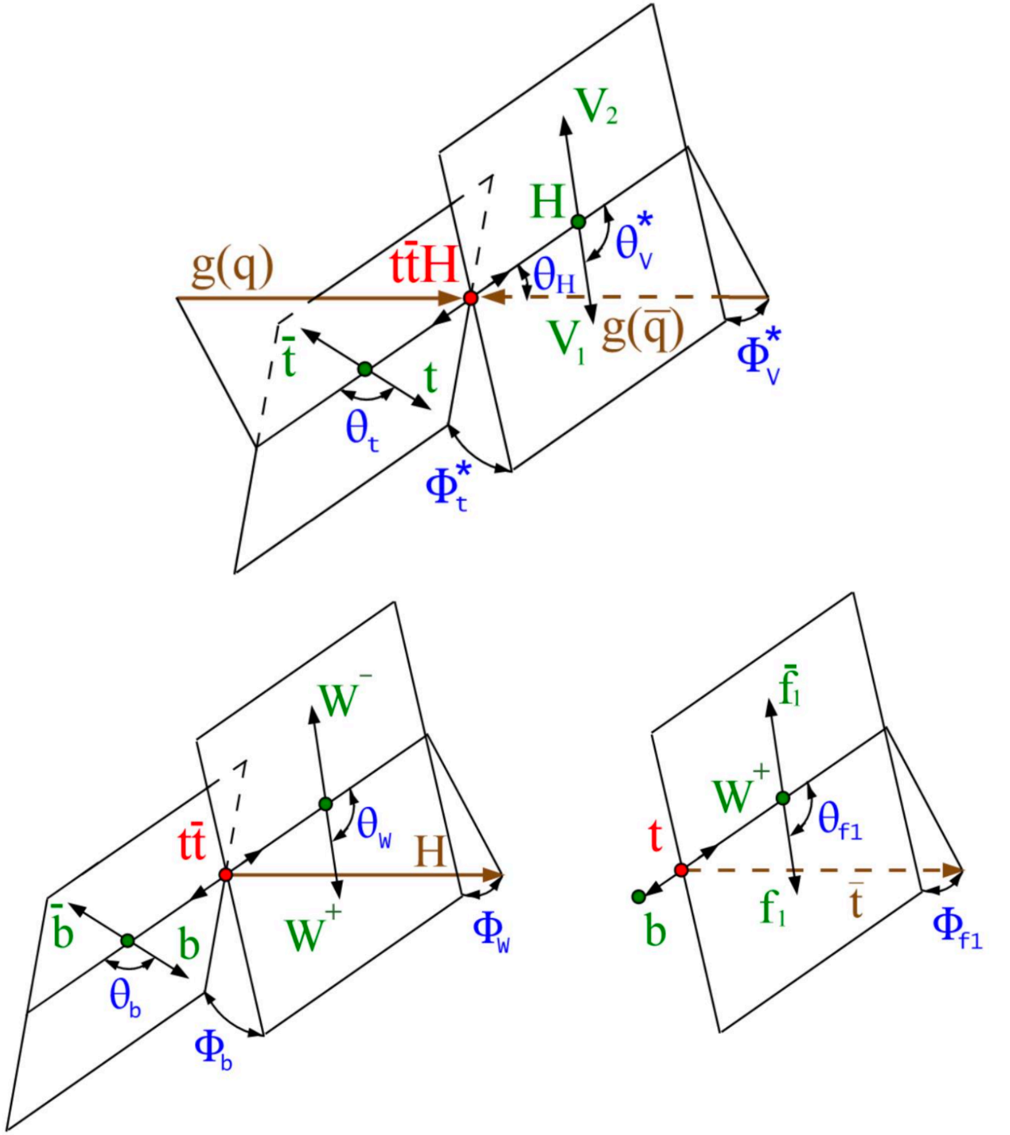
f_{a3} parameter extracted from the fit (ratio of cross sections)

$$f_{a3}^{\text{ggH}} = \frac{|a_3^{\text{gg}}|^2}{|a_2^{\text{gg}}|^2 + |a_3^{\text{gg}}|^2}\,\text{sign}\left(\frac{a_3^{\text{gg}}}{a_2^{\text{gg}}}\right).$$

ttH CP couplings

(i) $m_{t\bar{t}H}$: invariant mass of the $t\bar{t}H$ system;
(ii) θ_H: angle between the H boson direction and the incoming partons in the $t\bar{t}H$ frame;
(iii) θ^*_V: angle of the $H \to VV(f\bar{f})$ decay with respect to the opposite $t\bar{t}$ direction in the H frame;
(iv) Φ^*_V: angle between the production plane, defined by incoming partons and H, and $H \to VV(f\bar{f})$ decay plane;
(v) θ_t: angle between the top-quark direction and the opposite Higgs direction in the $t\bar{t}$ frame;
(vi) Φ^*_t: angle between the decay planes of the $t\bar{t}$ system and $H \to VV(f\bar{f})$ in the $t\bar{t}H$ frame;
(vii) m_{tt}: invariant mass of the $t\bar{t}$ system;
(viii) θ_W: angle between W^+ and opposite of the $b\bar{b}$ system in the W^+W^- frame;
(ix) Φ_W: angle between the production $(b\bar{b})(W^+W^-)H$ plane and the plane of the W^+W^- system in the $t\bar{t}$ frame;
(x) θ_b: angle between the b quark and opposite of the W^+W^- system in the $b\bar{b}$ frame;
(xi) Φ_b: angle between the planes of the $b\bar{b}$ and W^+W^- systems in the $t\bar{t}$ frame;
(xii) m_{Wb1} or m_{Wb2}: invariant mass of the W^+b or $W^-\bar{b}$ system;
(xiii) θ_{f1} or θ_{f2}: angles between fermion direction and opposite of the b or $\bar{b}$ quark in the W^+ or W^- frame;
(xiv) Φ_{f1} or Φ_{f2}: angle between the W^+ or W^- decay plane and the $\bar{t}W^+b$ or $tW^-\bar{b}$ plane in the t or $\bar{t}$-quark frame;
(xv) $m_{f1\bar{f}1}$ or $m_{f2\bar{f}2}$: invariant mass of the $f_1\bar{f}_1$ or $f_2\bar{f}_2$ system.

Pheno paper PRD94,055023 (2016)



ttH CP couplings

Pheno paper PRD94,055023 (2016)

$$f_{CP} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}, \qquad \phi_{CP} = \arg(\tilde{\kappa}_f/\kappa_f), = 0 \text{ or } \pi.$$

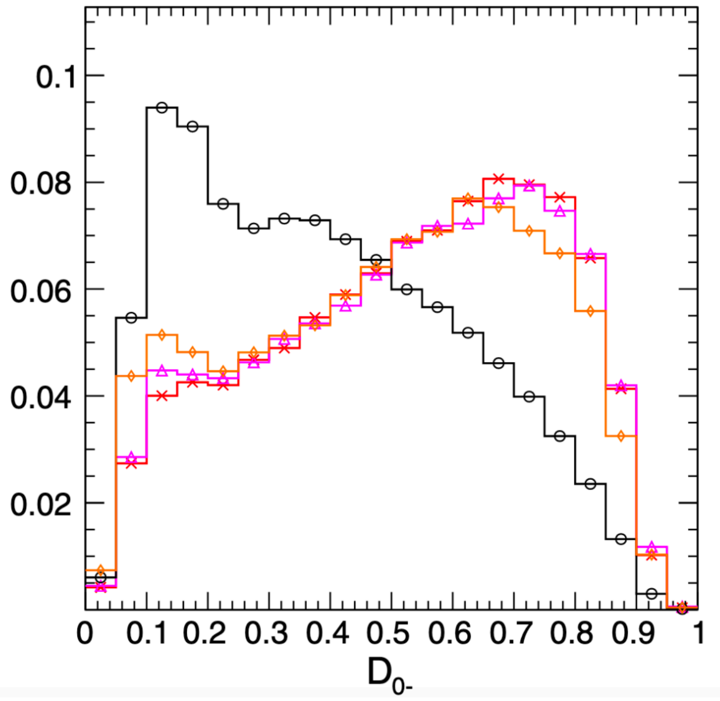
$=\sin^2\alpha$

$$\mathcal{P}_{\rm sig}(\vec{x}_i; f_{CP}, \phi_{CP}) = (1 - f_{CP})\mathcal{P}_{0^+}(\vec{x}_i) + f_{CP}\mathcal{P}_{0^-}(\vec{x}_i) + \sqrt{f_{CP}(1-f_{CP})}(\mathcal{P}_{\rm int}(\vec{x}_i)\cos\phi_{CP} + \mathcal{P}^{\perp}_{\rm int}(\vec{x}_i)\sin\phi_{CP}), \quad (6$$

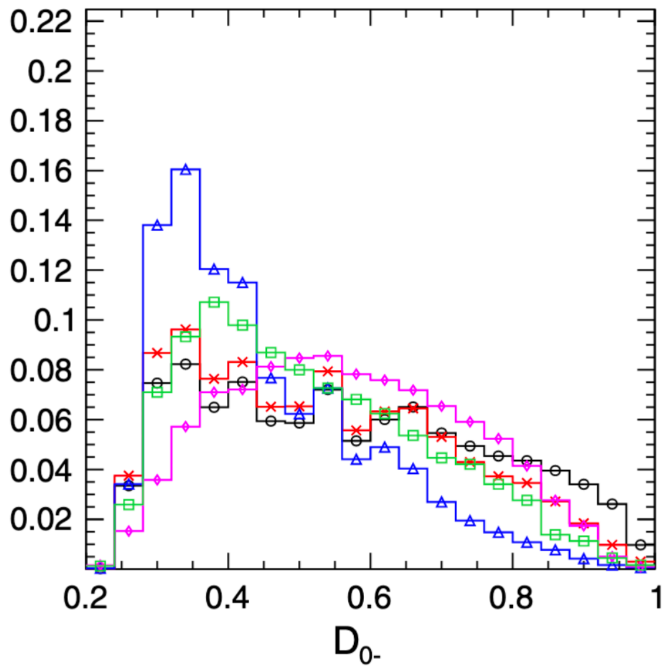
$$\mathcal{D}_{0-} = \frac{\mathcal{P}_{0^+}(\vec{\Omega})}{\mathcal{P}_{0^+}(\vec{\Omega}) + \mathcal{P}_{0^-}(\vec{\Omega})}$$

$$\mathcal{D}_{CP} = \frac{\mathcal{P}_{\rm int}(\vec{\Omega})}{\mathcal{P}_{0^+}(\vec{\Omega}) + \mathcal{P}_{0^-}(\vec{\Omega})}$$

$$\mathcal{D}^{\perp}_{CP} = \frac{\mathcal{P}^{\perp}_{\rm int}(\vec{\Omega})}{\mathcal{P}_{0^+}(\vec{\Omega}) + \mathcal{P}_{0^-}(\vec{\Omega})}$$



Hff-induced ttH CP-odd (red, magenta)
Hff-induced ttH CP-even (black)
ttγγ background (orange)



Hff-induced tH CP-odd (red)
Hff-induced tH CP-even (blue)
HVV-induced tH considered background (black)

Only D_{0-} discriminant is used in CMS analysis (using a BDT instead of using MEM)

D_{CP} requires flavor of tt decay particles, not possible in full hadronic and semi-leptonic, dropped in this analysis

CEPC Higgs CP

Fit on ϕ

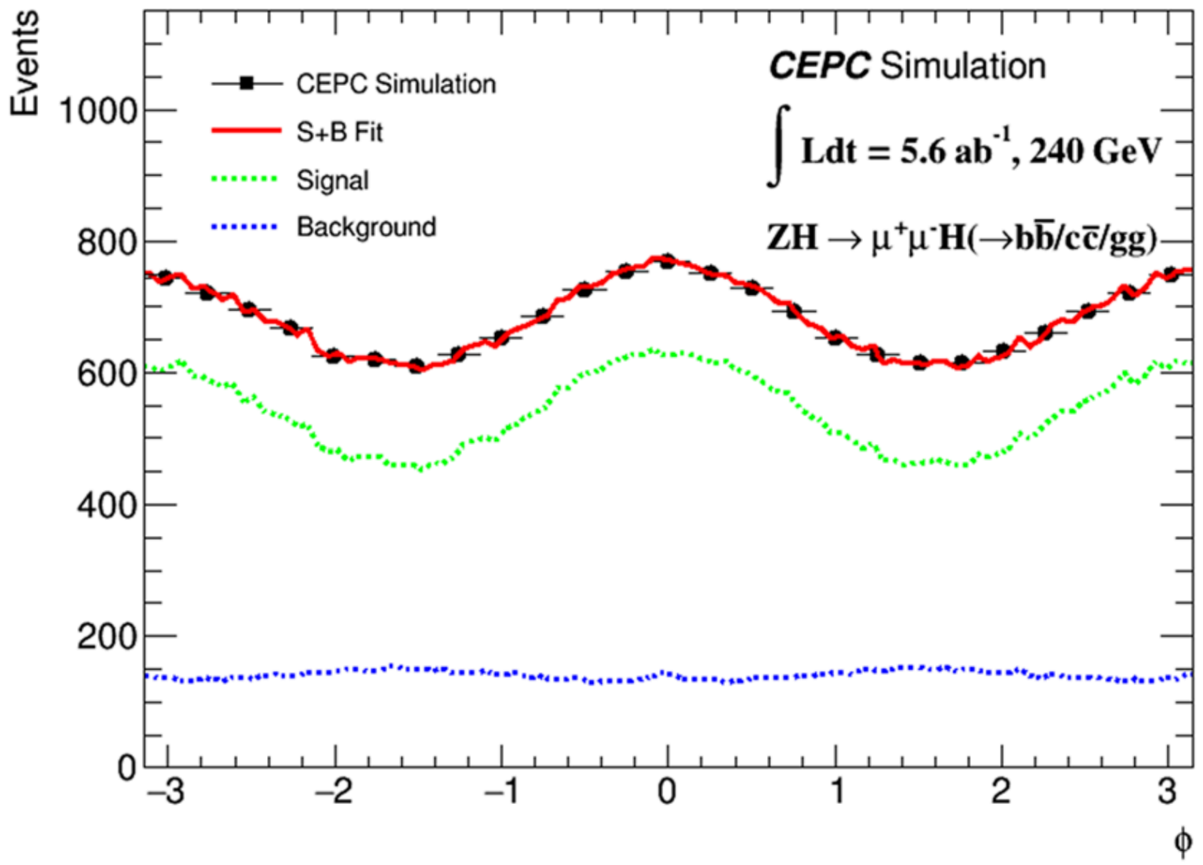


Table 2 Summary of 1σ and 2σ bounds on $\hat{\alpha}_{A\tilde{Z}}$ and $\hat{\alpha}_{Z\tilde{Z}}$ from various analyses by fitting to ϕ and fitting to ω through $\mu^+\mu^- H$ process which is shown in Sects. 5.1 and 5.2.

	$\hat{\alpha}_{A\tilde{Z}}(\times 10^{-2})$	$\hat{\alpha}_{Z\tilde{Z}}(\times 10^{-2})$
	ω-fitting	
68% CL(1σ)	[−4.16, 3.88]	[−1.06, 1.00]
95% CL(2σ)	[−8.10, 7.82]	[−2.06, 2.01]
	ϕ-fitting	
68% CL(1σ)	[−4.42, 4.21]	[−1.35, 1.24]
95% CL(2σ)	[−8.66, 8.45]	[−2.62, 2.51]