# Higgs CP studies at ATLAS+CMS

12th International Workshop on the CKM Unitarity Triangle (CKM2023)

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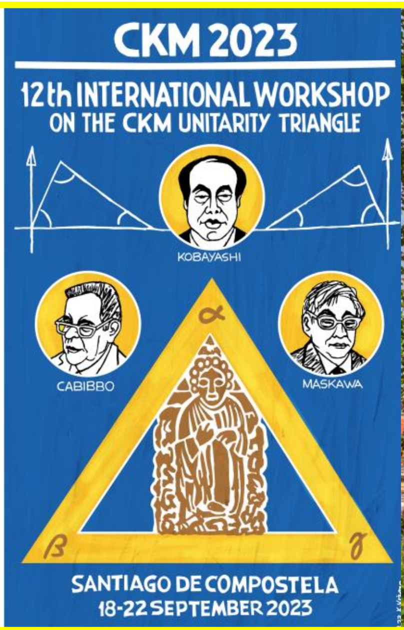
on behalf of ATLAS and CMS Collaborations




- The Higgs boson couplings have been measured by ATLAS and CMS experiments
  - Generally agree with the SM predictions
  - Precision: ~5% vector bosons (W,Z), ~7-12% heavier fermions (t, b, $\tau$) and ~20% $\mu$
  - **Still room for new physics**

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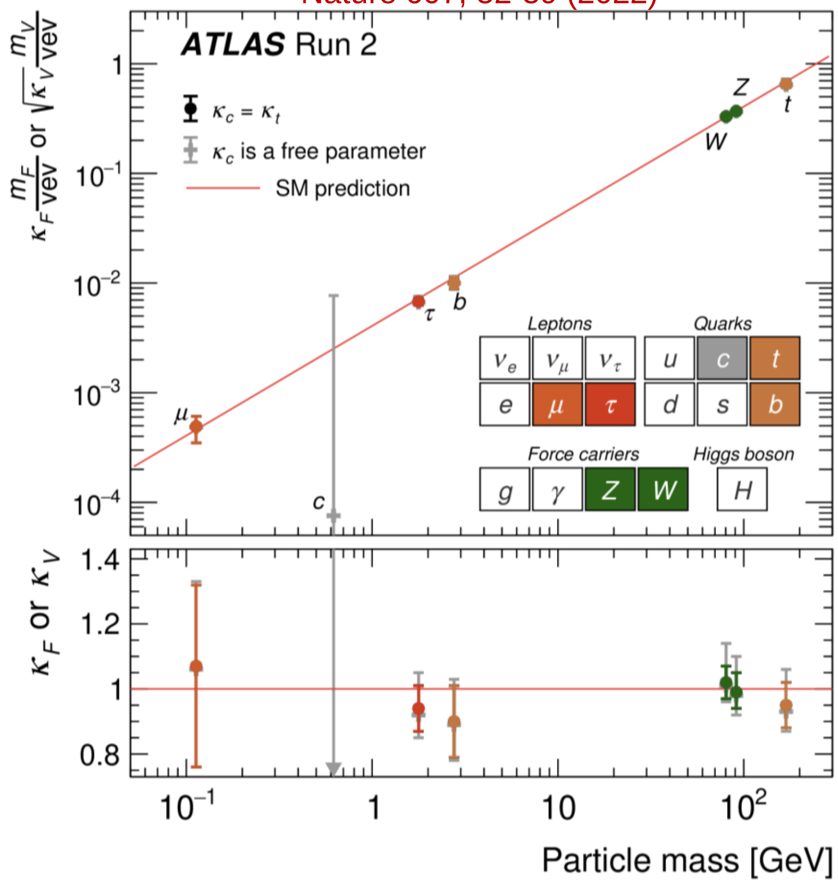
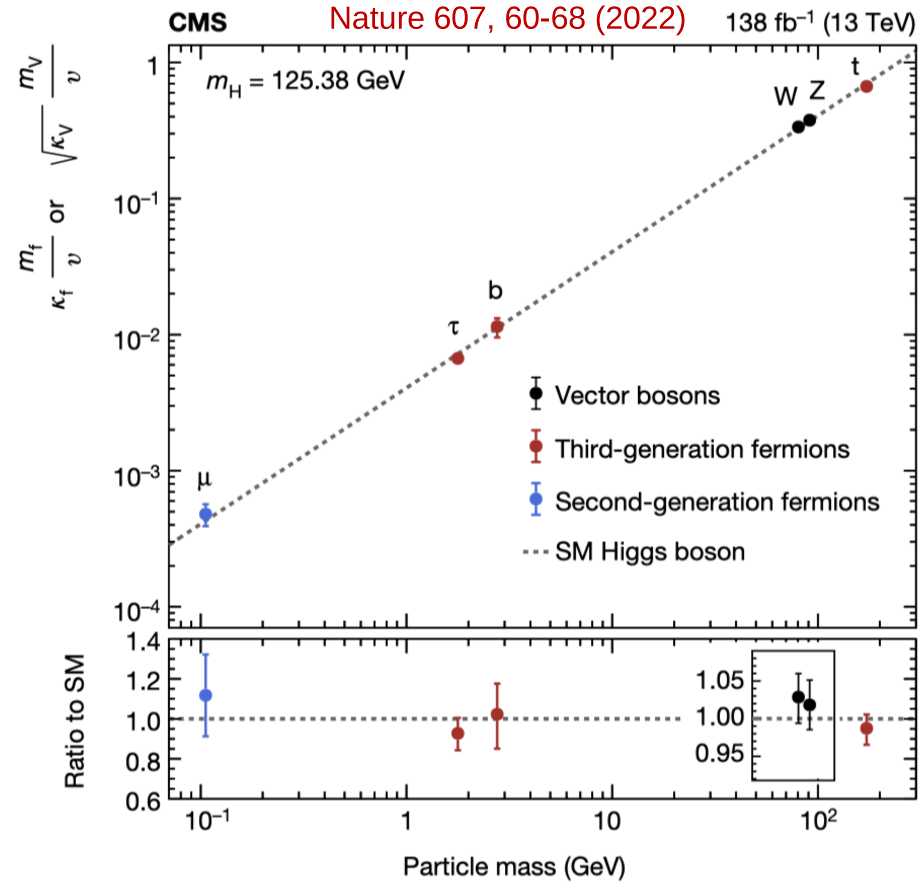


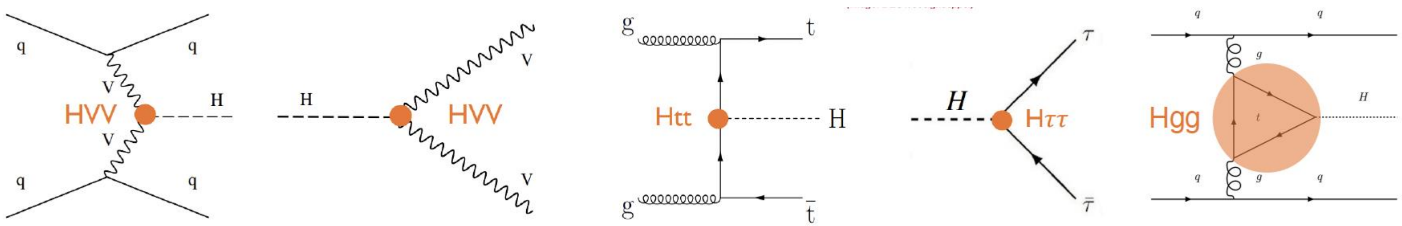

Nature 607, 60-68 (2022)




**Higgs couplings agree with SM over 3 orders of magnitude in mass!**

# Introduction: CP violation in the Higgs sector?

- The Higgs boson couplings have been measured by ATLAS and CMS experiments
  - Generally agree with the SM predictions
  - Precision: ~5% vector bosons (W,Z), ~7-12% heavier fermions (t, b, $\tau$) and ~20% $\mu$
  - **Still room for new physics**
- In the SM, the Higgs boson is predicted as CP-even
- Exploring CP-odd contributions in the Higgs sector
  - Pure CP-odd Higgs boson already ruled out during Run 1
  - Mixture of CP-even and CP-odd still allowed → New sources of CP violation ?
  - Check all couplings individually - Yukawa and gauge couplings can have different structure



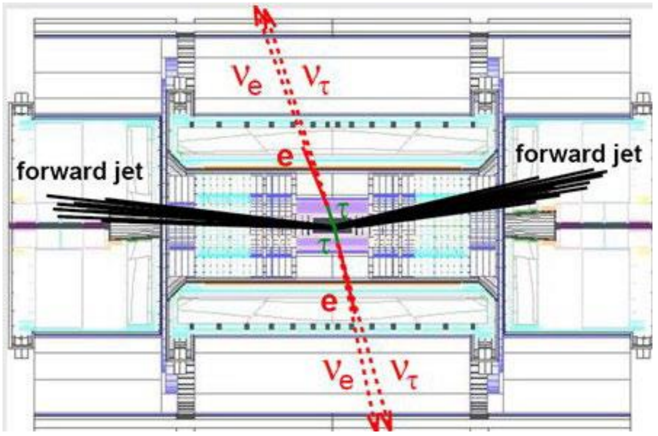

*CP-odd contributions*
*- HVV: suppressed with a $1/\Lambda^2$*
*- Hff: at tree-level*

**How to look for CPV in the Higgs sector?**

- Rate measurements → can not distinguish CP-even / CP-odd
- Measure shape effects on CP-sensitive observables:

angles, optimal observables, matrix elements, and others

Studied in production and/or decay



# CP parametrisations to probe HVV, Hgg and Hff couplings

**Anomalous couplings:**

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

CP-even

CP-odd

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

SM

CP-even

CP-odd

**Effective Lagrangians:**

$$\mathcal{L}_0^t = -\bar{\psi}_t\left(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\,\gamma_5\right)\psi_t\, X_0$$

$$\mathcal{L}_0^{\mathrm{loop}} = \Bigg\{ -\frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg}\, G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu}\right] - \frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\right] - \frac{1}{2}\left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\right] \Bigg\} X_0$$

$$\mathcal{L}_0^{Z,W} = \Bigg\{ c_\alpha \kappa_{\mathrm{SM}} \left[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\right] - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\right] - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}\, W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu}\right] - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \left(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\right)\right] \Bigg\} X_0$$

$$\sigma_i^{EFT} = \sigma_i^{SM} + \sigma_i^{int} + \sigma_i^{BSM}$$

BSM 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

Pure CPV effects appear only in interference terms

**Parameters**

- Ratios of cross-sections: $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$ $\quad f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_{j=1,2,3...}|a_j|^2\sigma_j}\,\mathrm{sign}\left(\frac{a_i}{a_1}\right)$

- CP-mixing angle $\alpha$ $\quad \kappa_t = k_t \cos\alpha$, $\quad \tilde{\kappa}_t = k_t \sin\alpha$

- $\tilde{d}$ parameter $\quad \tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$

- SMEFT coefficients

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

*just some examples*

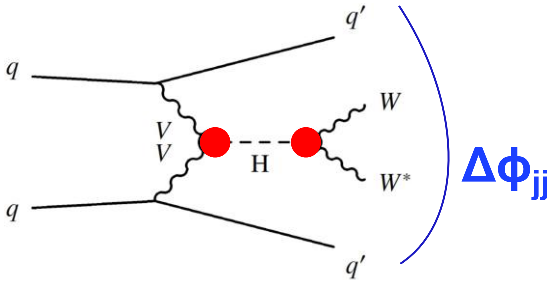
# LHC Run2 results testing the CP nature of the Higgs boson

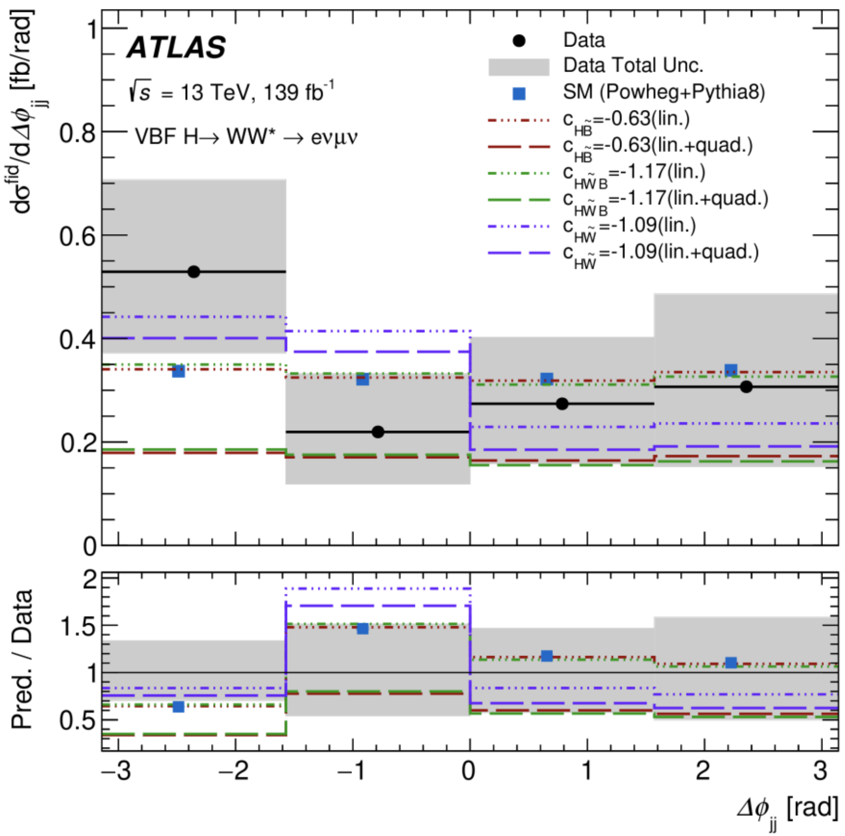
| Coupling | ATLAS | CMS |
|---|---|---|
| **HVV** | H→4l (all prod. modes), full Run2<br>Eur. Phys. J. C 80 (2020) 957<br>VBF with H→$\tau\tau$, 36 fb$^{-1}$, using *OO*<br>Phys. Lett. B 805 (2020) 135426<br>VBF with H→$\gamma\gamma$, full Run2, using *OO*<br>Phys. Rev. Lett. 131 (2023) 061802 NEW<br>VBF with H→ZZ*→4ℓ, full Run2, using *OO*<br>arXiv:2304.09612 NEW<br>VBF with H→WW*, full Run2, using signed $\Delta\phi_{jj}$<br>arXiv:2304.03053 NEW | H→$\tau\tau$, 36 fb$^{-1}$, using MELA disc.<br>PRD100,112002(2019)<br>H→4l (all prod. modes), combined with H→$\gamma\gamma$, full Run2<br>Phys. Rev. D 104 (2021) 052004<br>H→$\tau\tau$ (also combined with H→4l+yy), full Run2<br>Phys. Rev. D 108 (2023) 032013 NEW<br>Off-shell studies with H→ZZ→4l+2l2$\nu$, full Run2<br>Nature Phys. 18(2022)1329 NEW |
| **Hgg** | H→4l (all prod. modes), full Run2<br>Eur. Phys. J. C 80 (2020) 957<br>ggH+2j with H→WW*→e$\nu\mu\nu$, 36 fb$^{-1}$, signed $\Delta\phi_{jj}$<br>Eur. Phys. J. C 82 (2022) 622 | H→4l (all prod. modes), combined with H→$\gamma\gamma$, full Run2<br>Phys. Rev. D 104 (2021) 052004<br>H→$\tau\tau$ (also combined with H→4l+yy), full Run2<br>Pure CP-odd coupling excluded with 2.4$\sigma$<br>Phys. Rev. D 108 (2023) 032013 NEW |
| **H$\tau\tau$** | H→$\tau\tau$ (all prod. modes), full Run2, using $\phi_{CP}$<br>Pure CP-odd coupling excluded >3$\sigma$; $\alpha$=9±16º<br>Eur. Phys. J. C 83 (2023) 563 NEW | H→$\tau\tau$, full Run2, using $\phi_{CP}$<br>Pure CP-odd coupling excluded >3$\sigma$; $\alpha$=-1±19º<br>JHEP 06 (2022) 012 |
| **Htt** | ttH with H→$\gamma\gamma$, full Run2<br>Pure CP-odd coupling excluded >3$\sigma$; \|$\alpha$\|<43º @95%CL<br>PRL125,061802(2020)<br>H→4l (all prod. modes), full Run2<br>Eur. Phys. J. C 80 (2020) 957<br>ttH with H→bb, full Run2<br>arXiv:2303.05974 NEW | ttH with H→$\gamma\gamma$, full Run2, using MELA disc.<br>Pure CP-odd coupling excluded >3$\sigma$; \|$\alpha$\|<55º @95%CL<br>PRL125,061801(2020)<br>H→4l (all prod. modes), combined with H→$\gamma\gamma$, full Run2<br>Phys. Rev. D 104 (2021) 052004<br>H→$\tau\tau$ (also combined with H→4l+yy), full Run2<br>Phys. Rev. D 108 (2023) 032013 NEW<br>ttH with H→ML<br>JHEP 07 (2023) 092 NEW<br>ttH with H→bb<br>CMS-PAS-HIG-19-011 NEW |

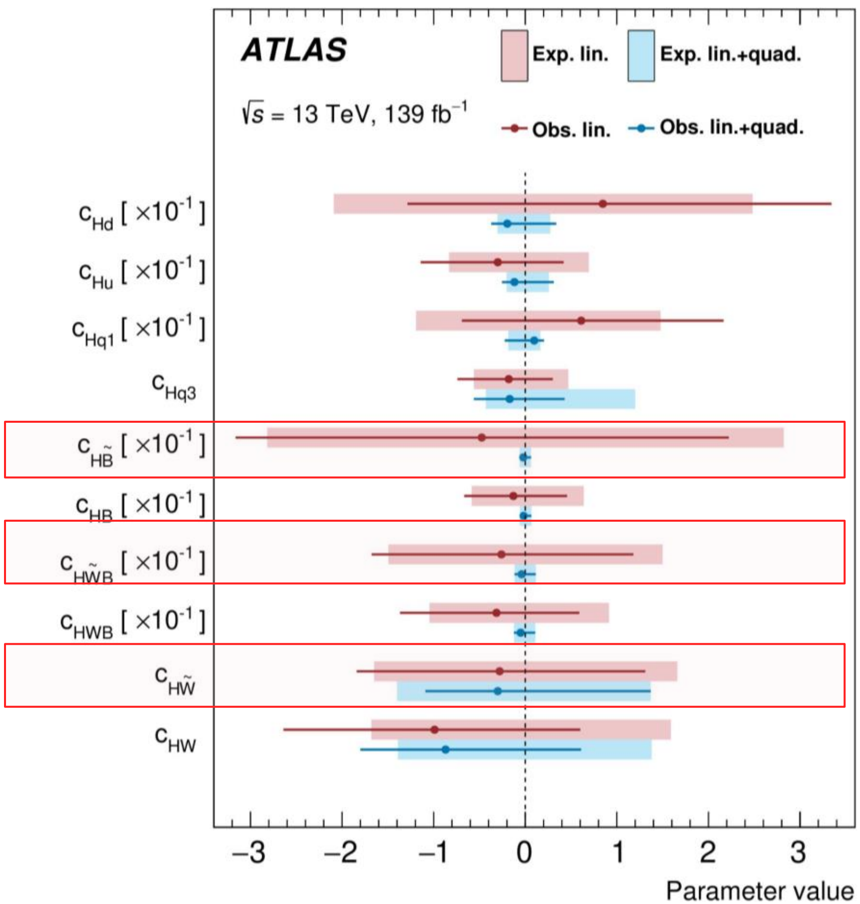
# HVV coupling: VBF H→WW* (ATLAS)

arXiv:2304.03053

- leptonic W decays (trigger), select 1 DF OS pair
- 2 BDTs to enhance S/B: select VBF, reject top+VV
  - exploit VBF topology using $m_{jj}$ and $\Delta y_{jj}$
  - bin SRs in both classifier outputs
  - independent ggF CR using third BDT
- profile LH to unfold data to particle-level for 13 observables, among which **"signed $\Delta\phi_{jj}$"** is sensitive to CP
- measure **3 CP-odd operators: cHB˜, cHW˜B** and **cHW˜** (Warsaw basis)
  - no deviation wrt. SM found



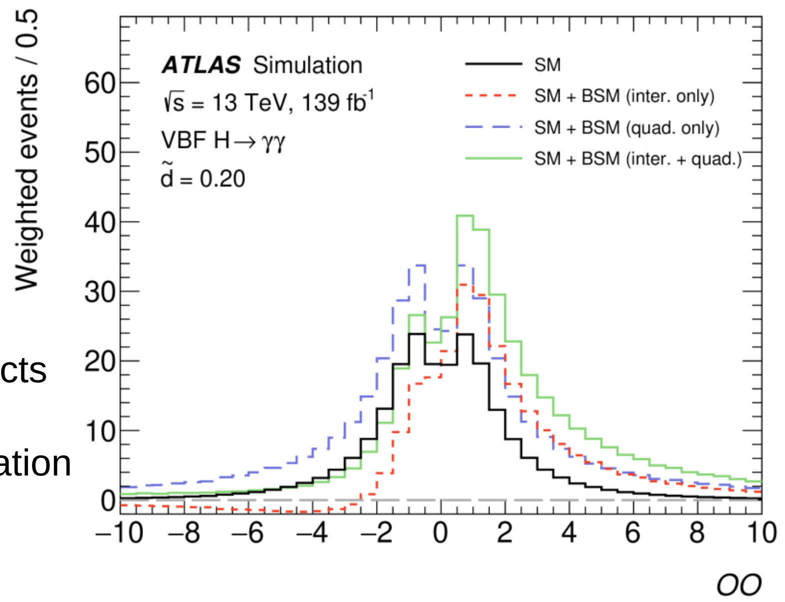



Phys. Rev. Lett. 131 (2023) 061802

- CP-admixture in HVV couplings probed using matrix element-based **optimal observables (*OO*)**

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

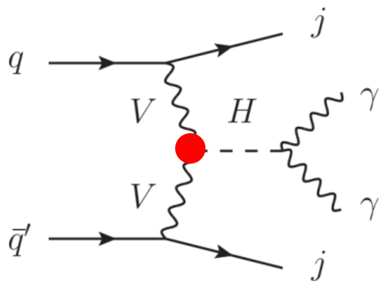
$$x_{1,2}^{\text{reco}} = \frac{m_{Hjj}}{\sqrt{s}} e^{\pm y_{Hjj}}$$

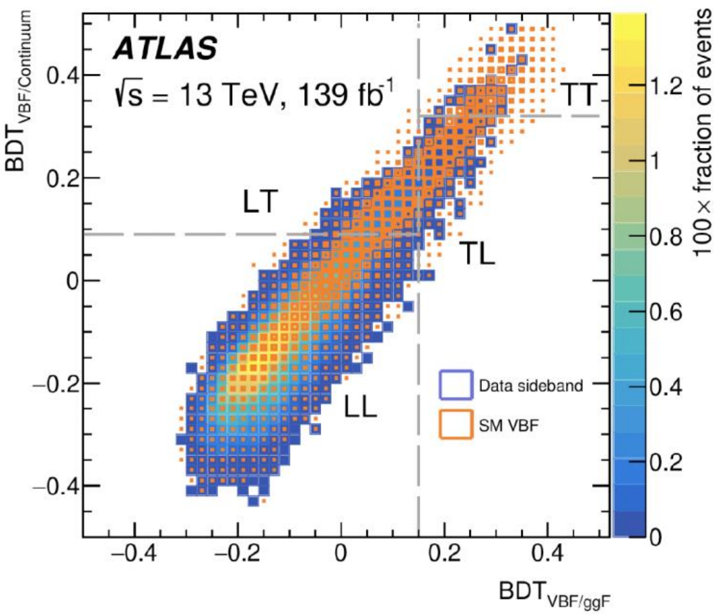



- calculated event-by-event in HAWK using reco. jets and Higgs decay products
- **captures full phase space information**, independent of decay mode
- symmetric and centered at zero in SM, while asymmetric in case of CP violation

**Selection and strategy**

- 2 *tight* identified & isolated photons + 2 jets with $|\eta_{jj}| > 2$
- Train 2 BDTs to separate VBF/ggF and VBF/continuum background (γγ, γj and jj)
- Define 3 SRs (TT, LT, TL) with plane of both BDT scores

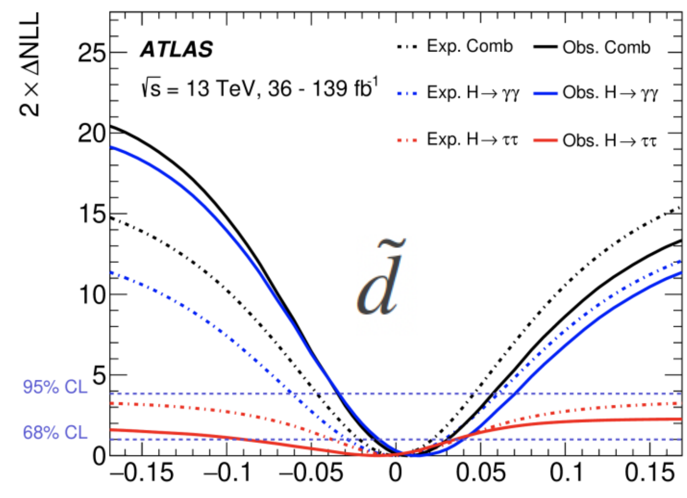


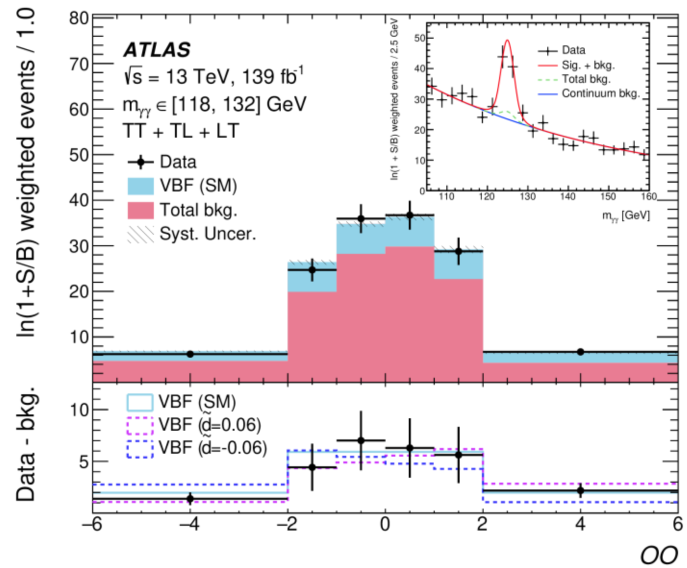
# HVV coupling: VBF H→γγ (ATLAS)

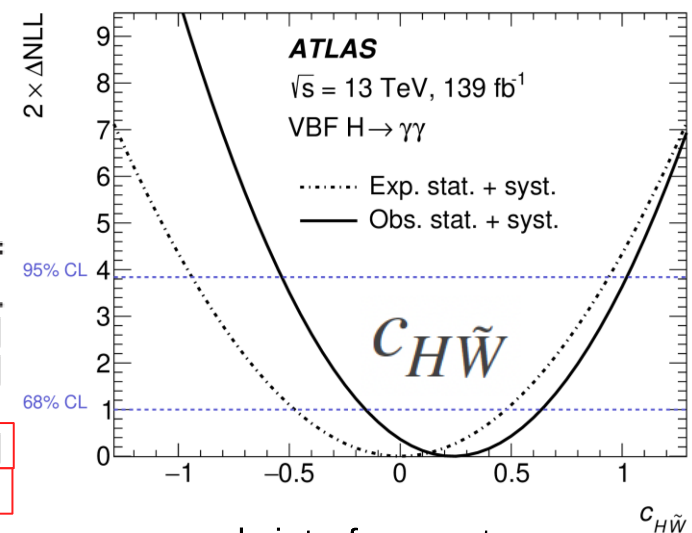
Phys. Rev. Lett. 131 (2023) 061802

- Signal extracted by combined maximum LH fit of the $m_{\gamma\gamma}$ spectrum in each *OO* bin (6 bins per SR → 18 bins)
- CP sensitivity using the shape of the observable (VBF normalisation free floated in the fit)
- Derive constraints for **$\tilde{d}$** and **1 CP-odd op. $c_{H\tilde{W}}$** (Warsaw basis) ($\tilde{d}$ combined with H→ττ)
- Results compatible with SM; limited by data statistics




uses interference + quad. terms $\tilde{d}$




only interference term

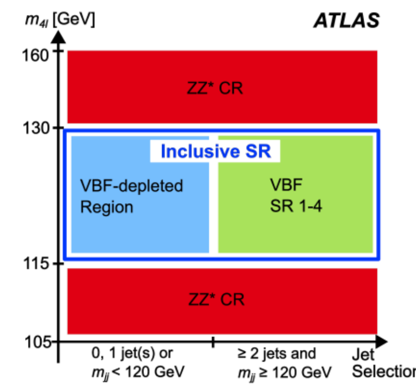
*most stringent constraints*

| | 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] |

# HVV coupling: VBF H→ZZ*→4ℓ (ATLAS)

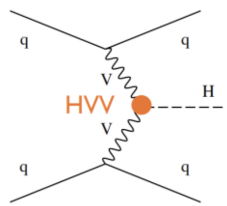
arXiv:2304.09612

- 4 *loose* identified & isolated leptons (pairing by flavour and mass)
- Main bkg.: VV
- Define two ***OOs*** to probe CP-odd component: for production (VBF enriched) and for decay (inclusive)
- 3-class NN trained to enhance the VBF purity → 4 VBF SRs defined with NN output

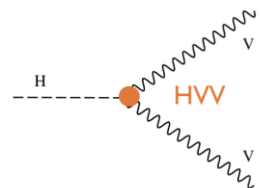


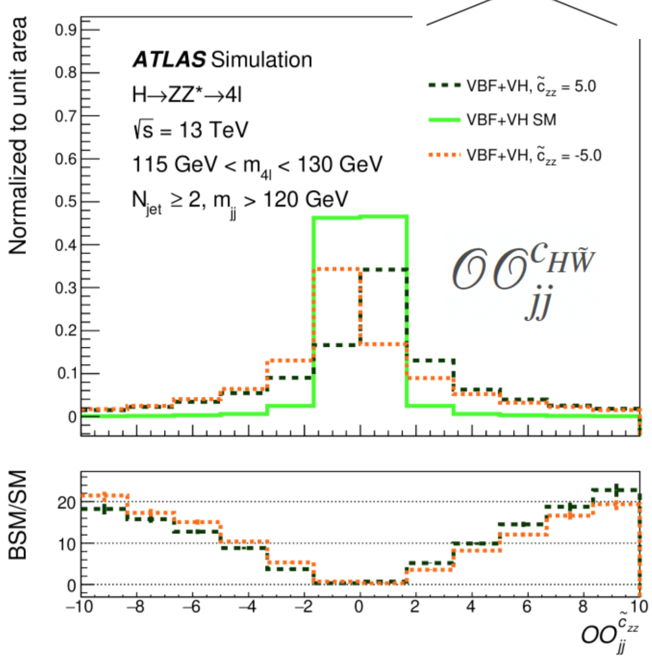

*OOs are constructed using matrix-elements calculated from:*
*- the 4-momentum of the reconstructed Higgs candidate and the two leading jets (for production)*
*- the 4-momenta of the four decay leptons (in case of decay)*

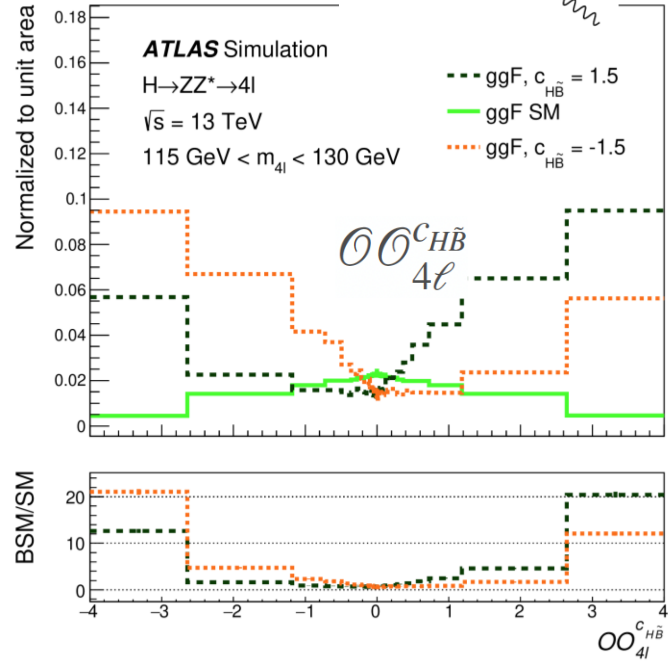
**Production $OO_{jj}$**

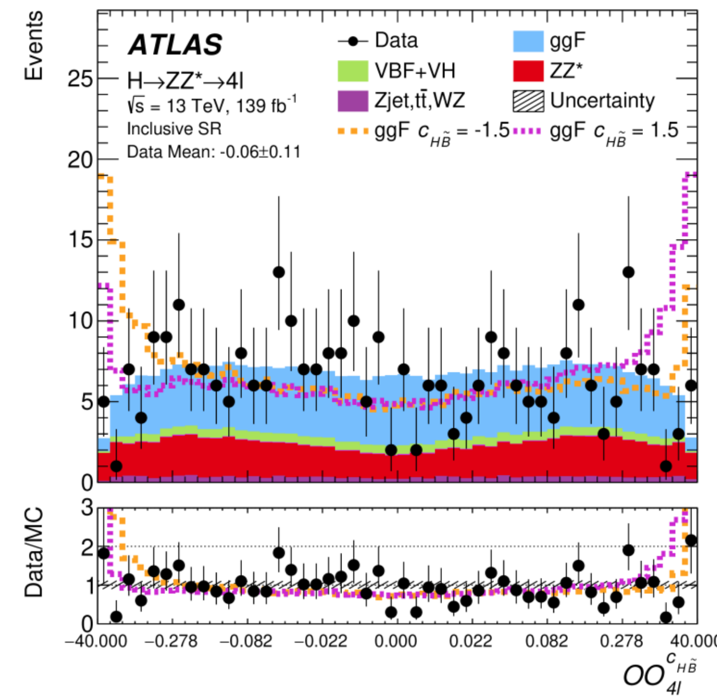



**Decay $OO_{4l}$**



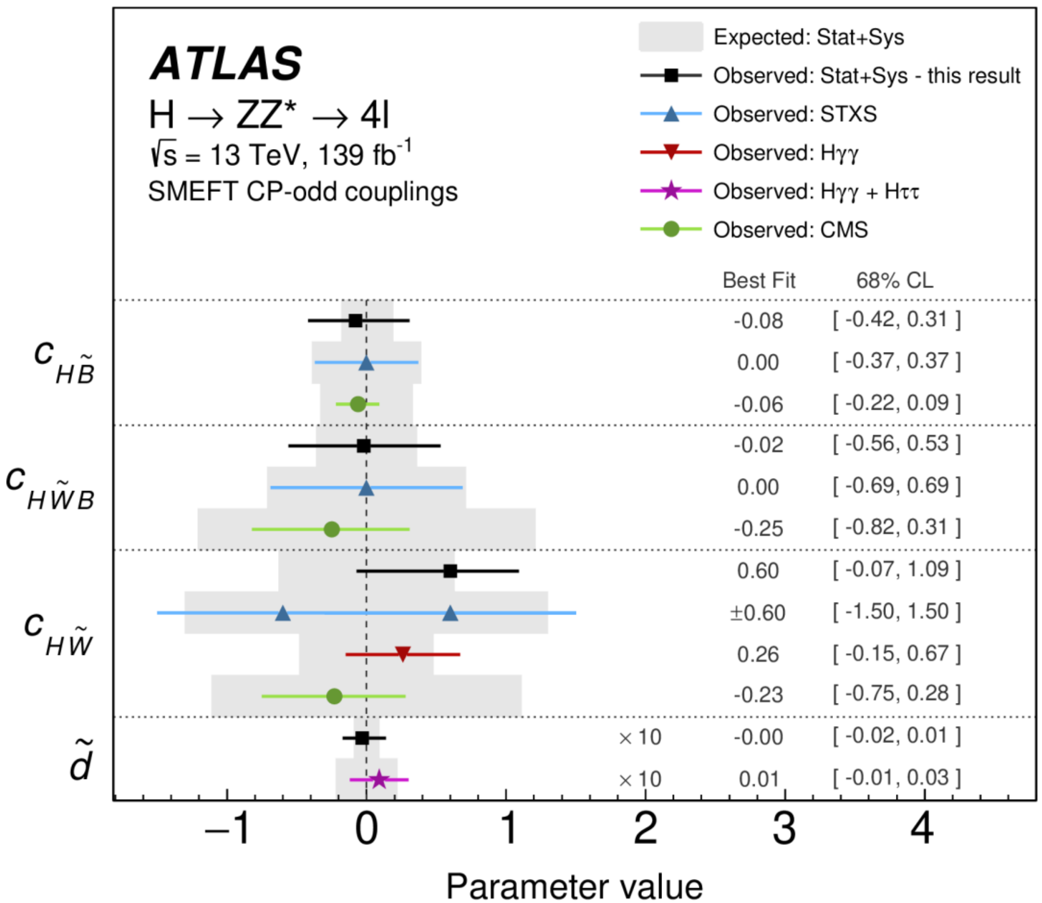



arXiv:2304.09612

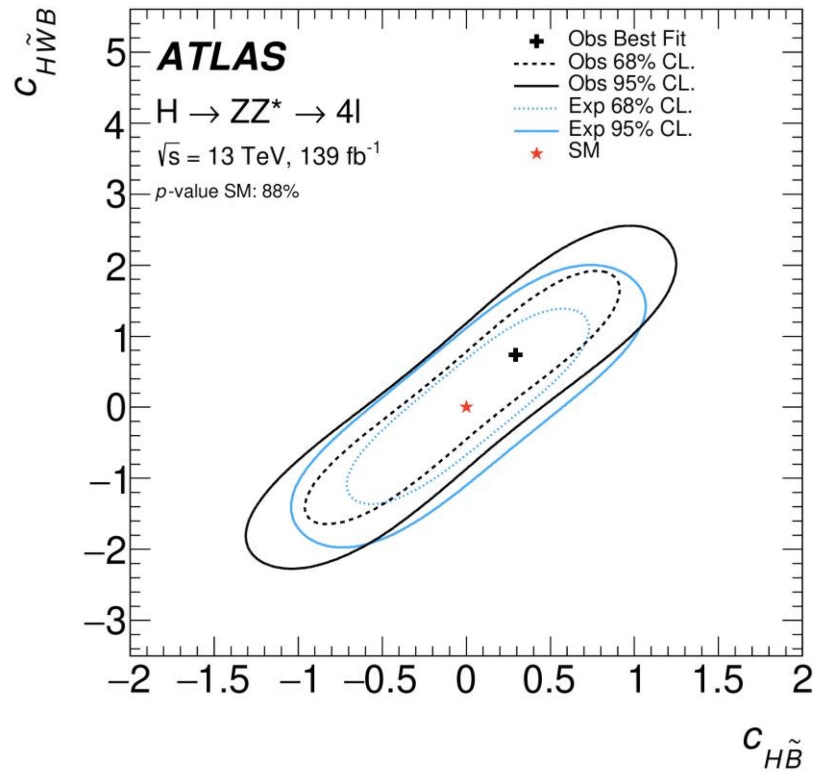
- Maximum LH fit performed for **3 CP-odd couplings** in Warsaw and Higgs basis, and for **$\tilde{d}$**
- Different CP-odd hypothesis are tested → 3 types of fits:
  - Production → CR(ZZ, VBF-dep)+SR(VBF1-4)
  - Decay → CR(ZZ)+SR(inclusive)
  - Combined → CR(ZZ)+SR(VBF-dep, VBF1-4)
- Coupling parameters are scanned individually and in 2D




decay

decay

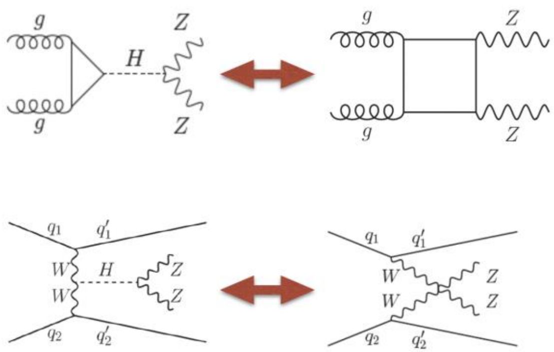
prod+decay

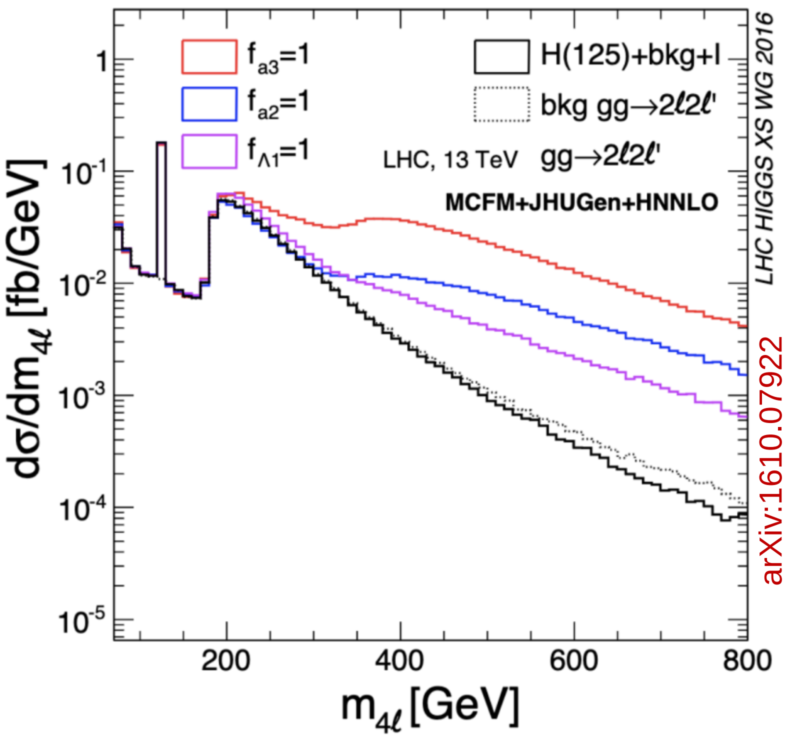



- Results competitive with H→ττ/γγ, STXS and CMS

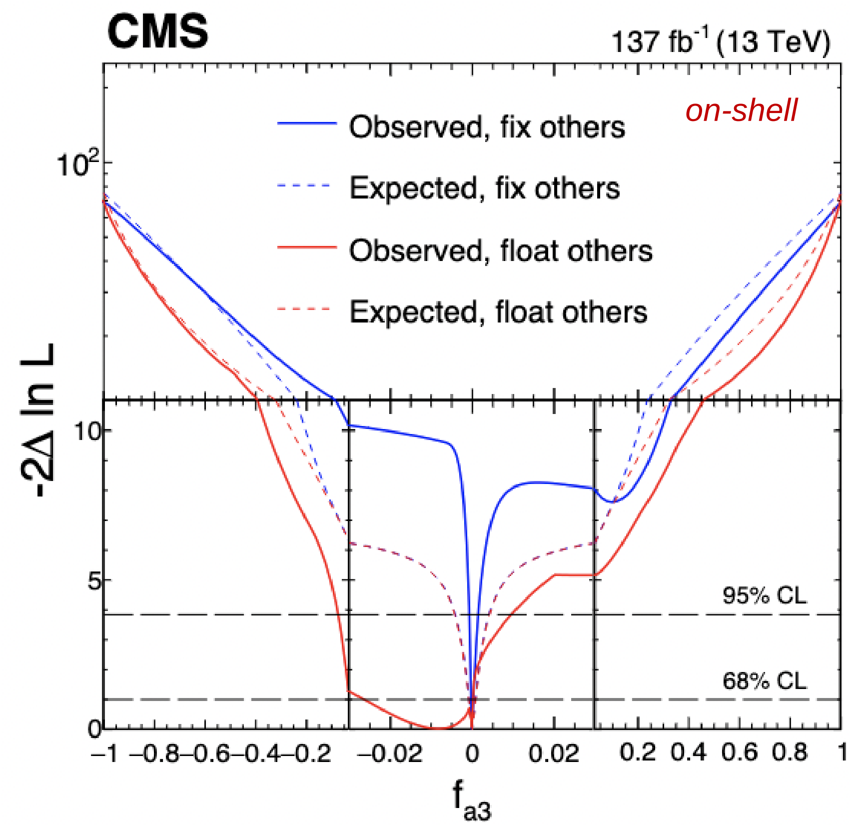
# HVV coupling from on- and off-shell events with ZZ (CMS)

- $H \rightarrow ZZ^* \rightarrow 4l$ events used to study several AC, including $f_{a3}$ using **matrix elements discriminants**



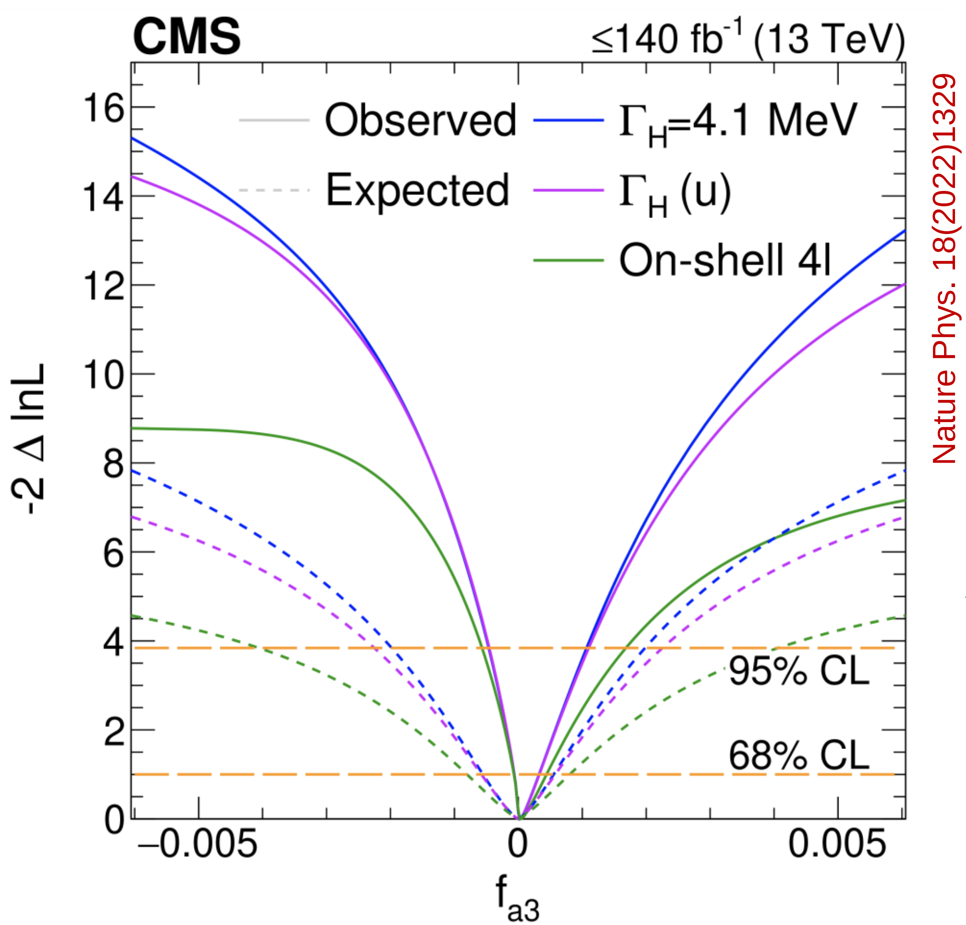

arXiv:1610.07922



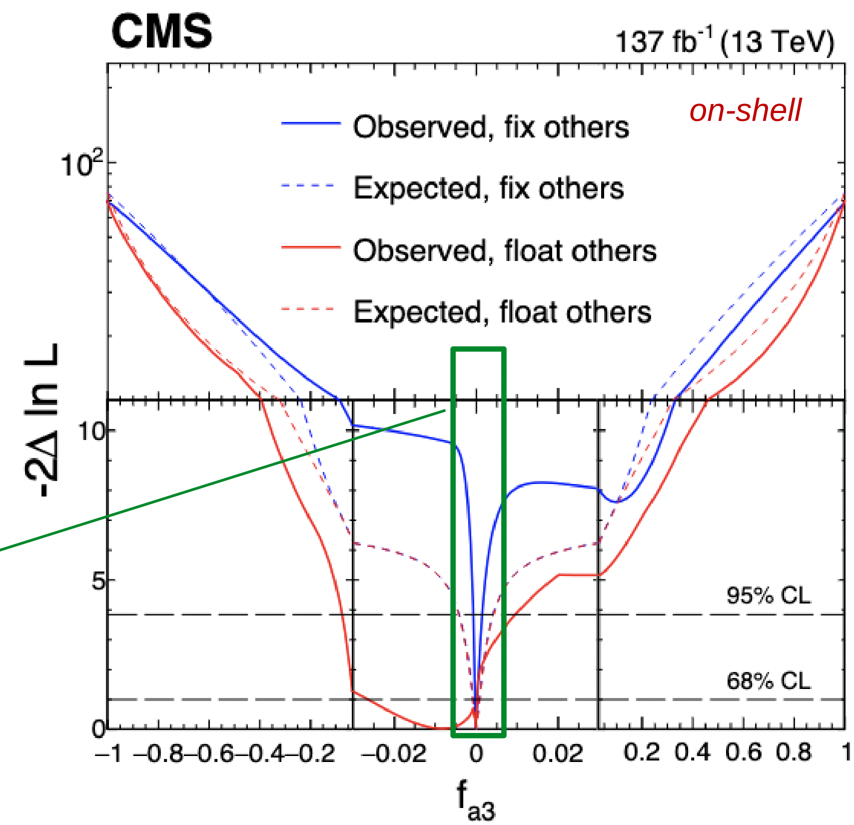

Phys. Rev. D 104 (2021) 052004

- Off-shell production rate in SM: ~10% of total cross-section
- Recently, both ATLAS and CMS have reported first **evidence of off-shell Higgs production in ZZ channel**

- CP-odd contributions → distinct kinematics in off-shell region
- More significant in VBF production mode




Nature Phys. 18(2022)1329




Phys. Rev. D 104 (2021) 052004

| Parameter | Condition | Observed | | | Expected | |
|---|---|---|---|---|---|---|
| | | Best fit | 68% CL | 95% CL | 68% CL | 95% CL |
| $f_{a3}$ ($\times 10^5$) | $\Gamma_H = \Gamma_H^{SM}$ | 2.2 | [−6.4, 32] | [−46, 107] | [−55, 55] | [−198, 198] |
| | $\Gamma_H$ (u) | 2.4 | [−6.2, 33] | [−46, 110] | [−58, 58] | [−225, 225] |

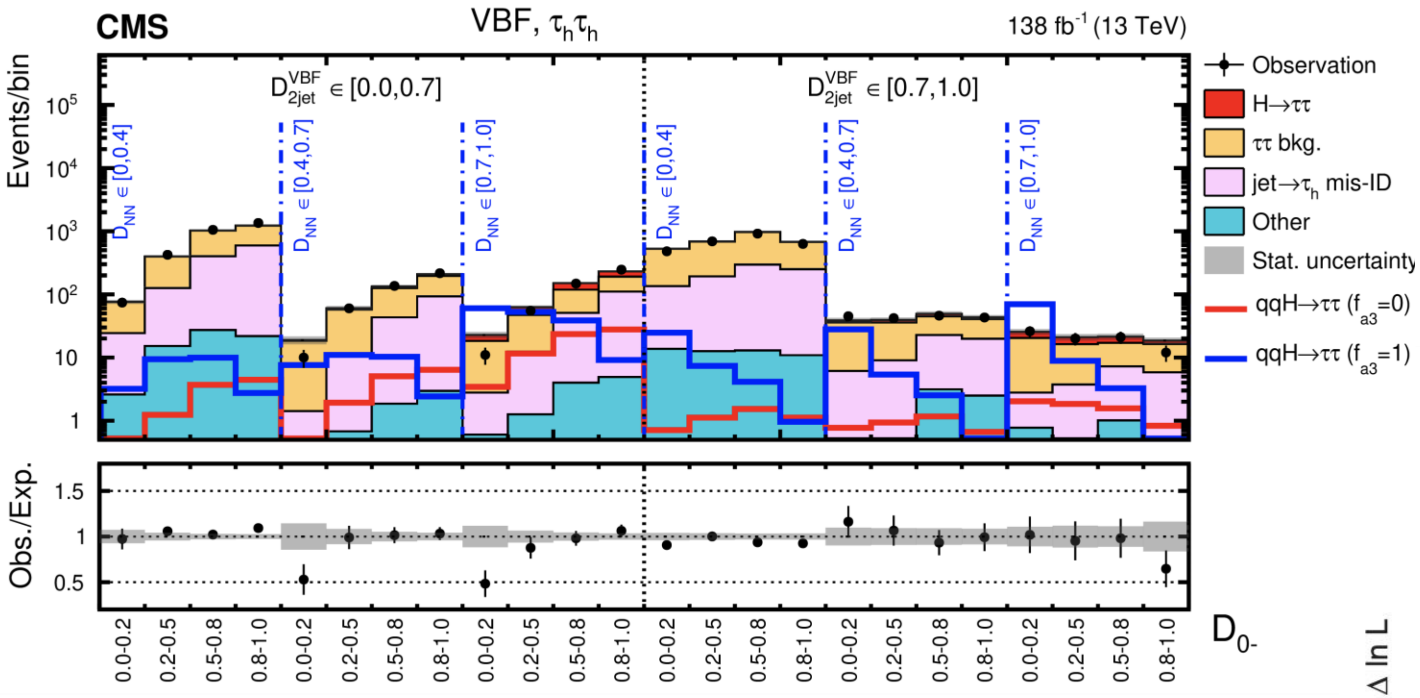
**Off-shell events bring ~10-50% improvement on limits !**

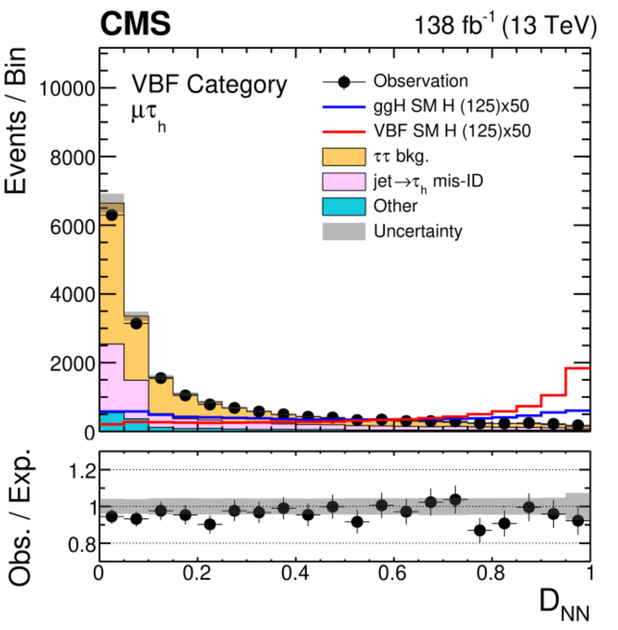
*Stringest CP violation test using off-shell data*

# HVV coupling in VBF/ggH/VH with H→ττ (CMS)

Phys. Rev. D 108 (2023) 032013

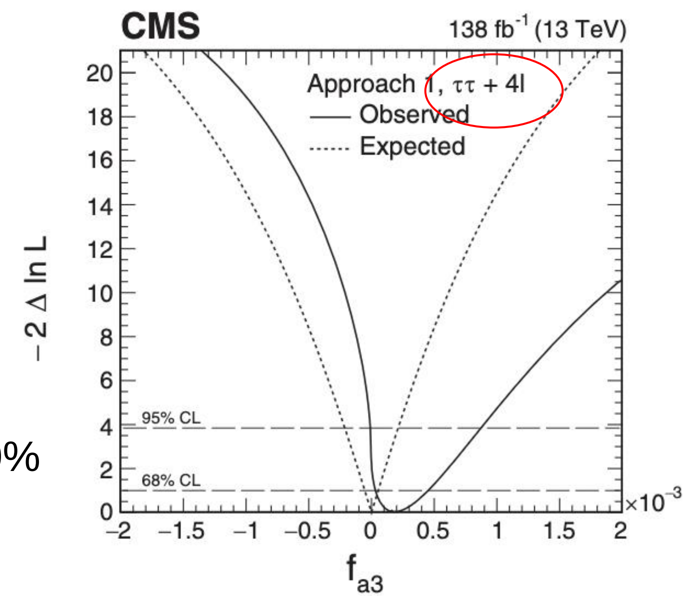
- Using 4 most sensitive ττ final states: $\tau_{had}\tau_{had}$, $e\tau_{had}$, $\mu\tau_{had}$ and eμ
- CP only studied in ggH and VBF+VH production (assuming SM kinematics in Higgs decay)
- Use NN to separate S/B and **matrix elements** as CP-sensitive disc.
  - complementary measurement using **"signed $\Delta\phi_{jj}$"**
- Similar strategy as in H→ZZ*→4l analysis, but larger stats. thanks to BR



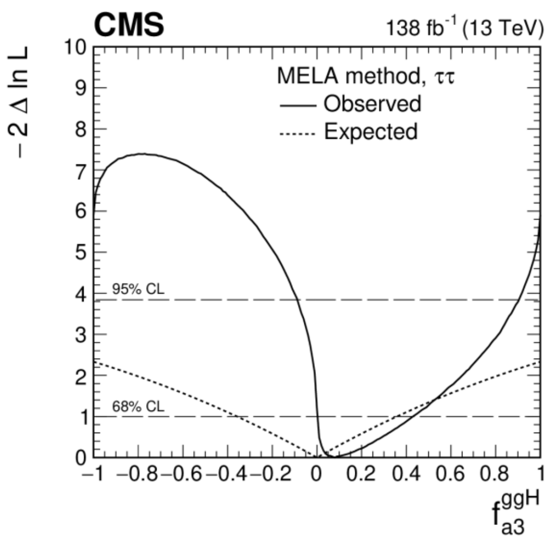



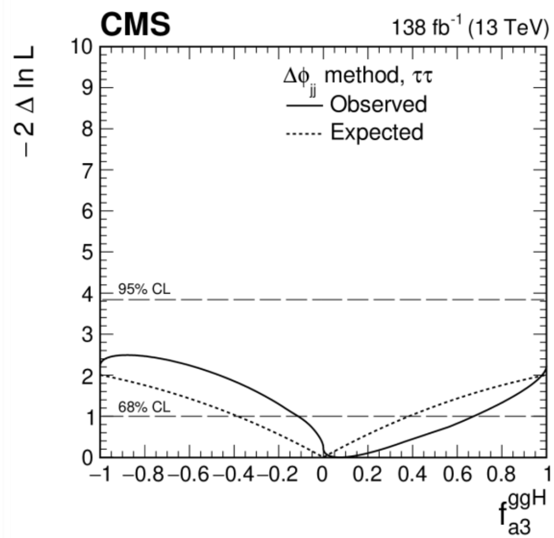

- Combination with limits from previous H→ZZ*→4l results: improvement up to 40%

**$f_{a3} < 1\cdot10^{-5}$**



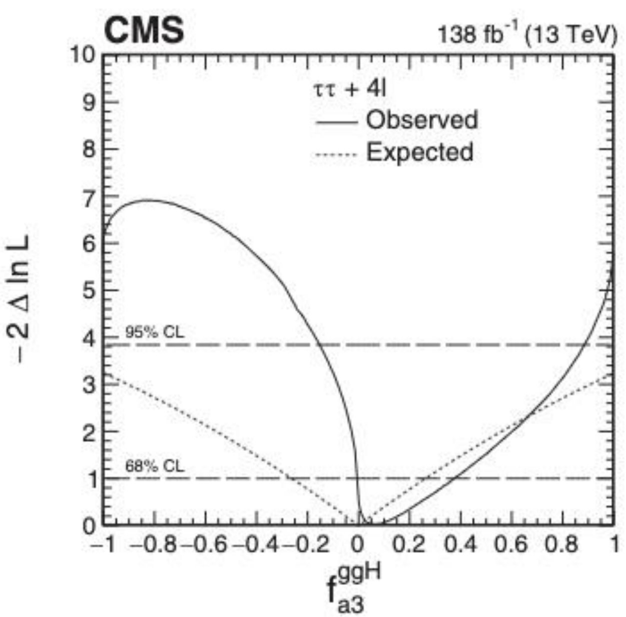
Phys. Rev. D 108 (2023) 032013

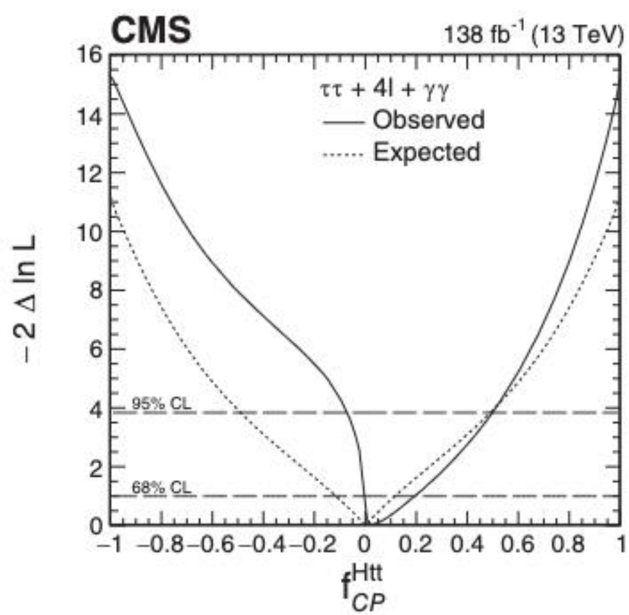



## Hgg

- Compatible limits between MELA and $\Delta\phi jj$
- Significant improvement in sensitivity using MELA
- Combination with H→ZZ* and H→γγ results: improvement ~30%




| | Observed | |
|---|---|---|
| Parameter | 68% CL | 95% CL |
| $f_{a3}^{ggH}$ | $0.07^{+0.32}_{-0.07}$ | $[-0.15, 0.89]$ |
| $f_{CP}^{Htt}$ | $0.03^{+0.17}_{-0.03}$ | $[-0.07, 0.51]$ |

$$|f_{CP}^{Hff}| = \left(1 + 2.38\left[\frac{1}{|f_{a_3}^{ggH}|}\right]\right)^{-1} = \sin^2\alpha^{Hff}$$

**Pure CP-odd Hgg coupling excluded with 2.4σ**

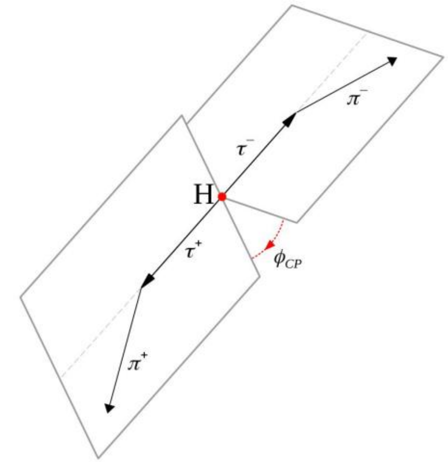
*most stringent constraints in Hgg*

Eur. Phys. J. C 83 (2023) 563

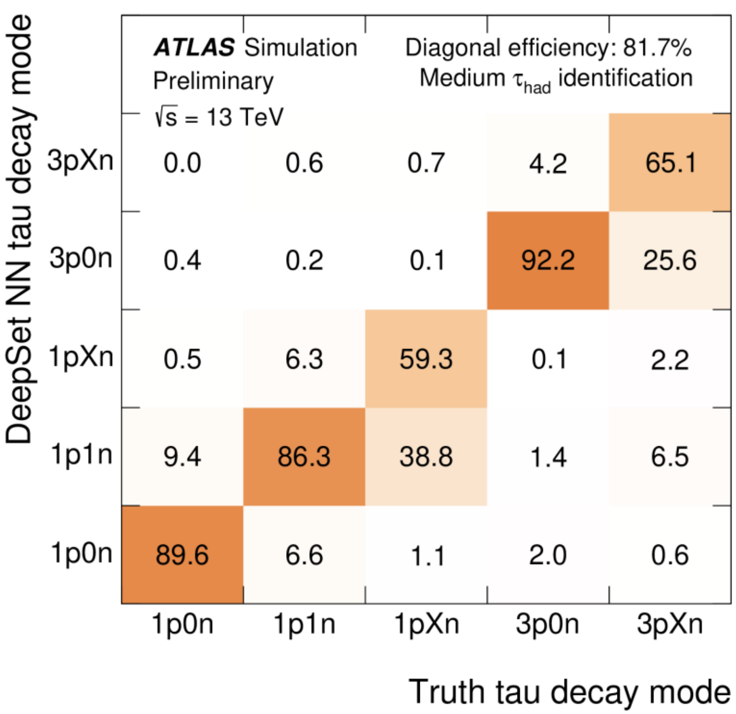
The CP-mixing angle is parametrized to be sensitive to the angle between the two tau planes from the Higgs boson in the Higgs boson CM frame ($\phi_{CP}$):

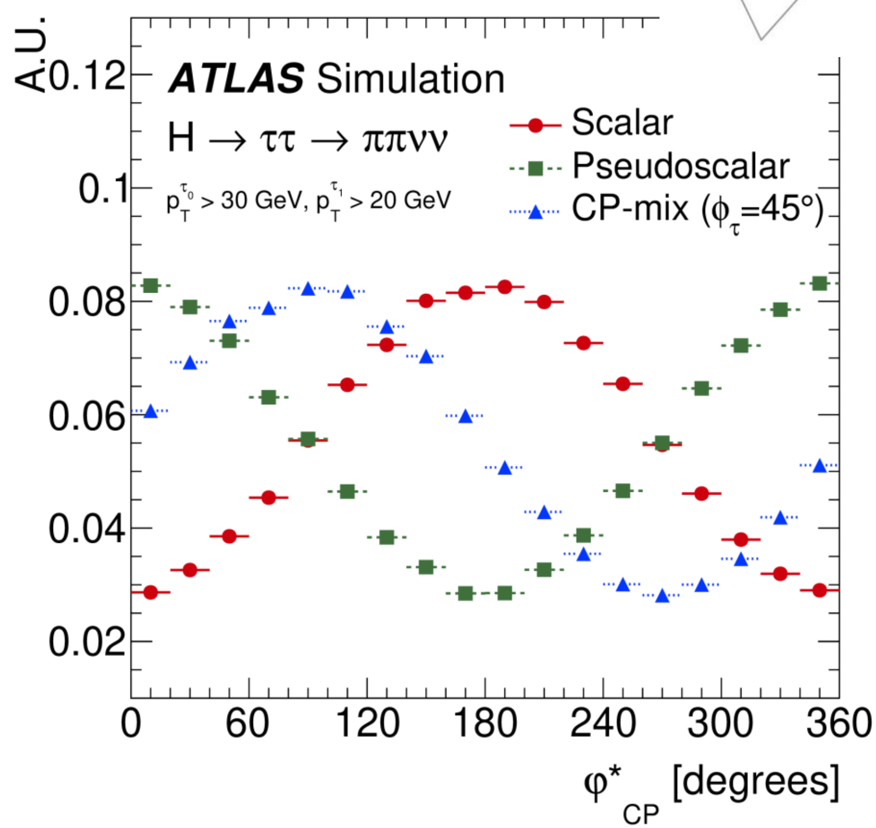
$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

CP-mixing




DNN used to identify 5 classes of $\tau_{had}$ decays
- necessary to reconstruct spin-sensitive observables



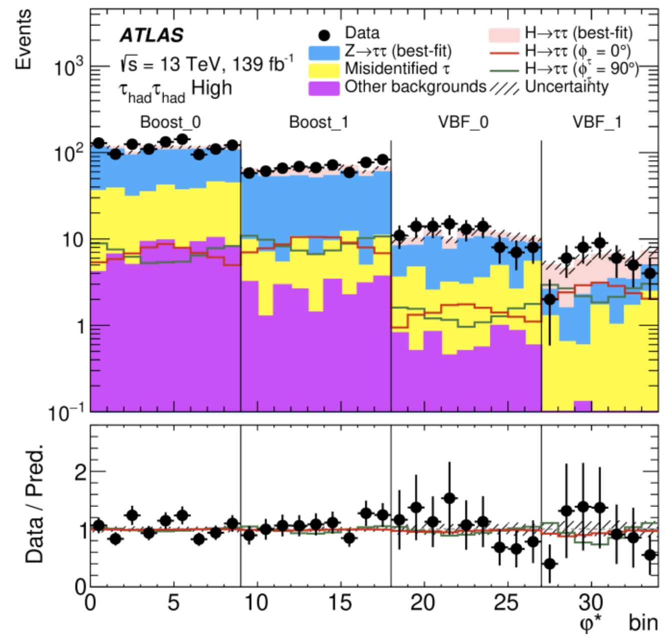



Eur. Phys. J. C 83 (2023) 563

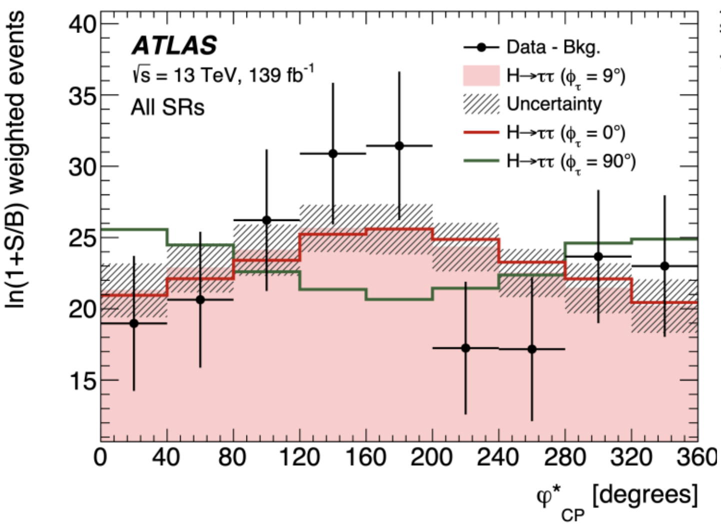
- Use $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ final states,
2 VBF-enriched (with BDTs) and 2 ggH-enriched regions (cut-based)
- SRs and Z CR defined by $m_{\tau\tau}^{MMC}$
- Define high, medium, low regions depending on properties of decay products
- Generate different CP-mixed templates using TauSpinner
- Maximum LH fit performed for all regions to extract:

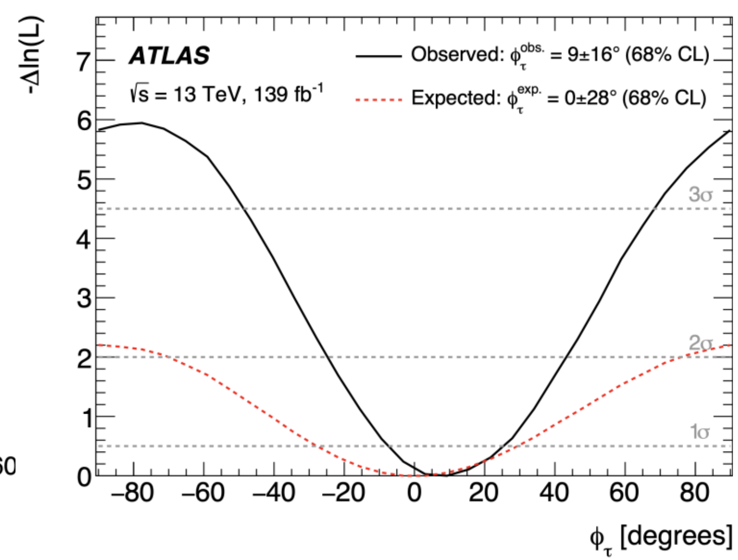
**$\phi_\tau$ = 9±16° (0±28° exp.)**
**Pure Hττ CP-odd excluded @ 3.4σ**

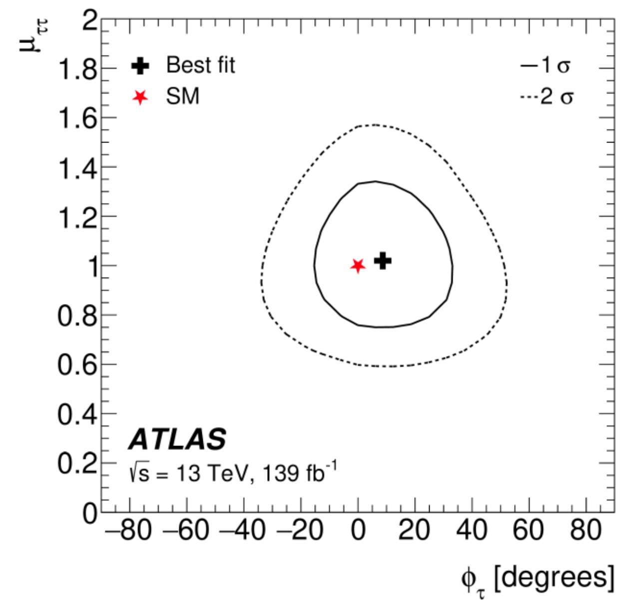
*quite similar to CMS results*




- Statistically limited, main systematic uncertainties from jets



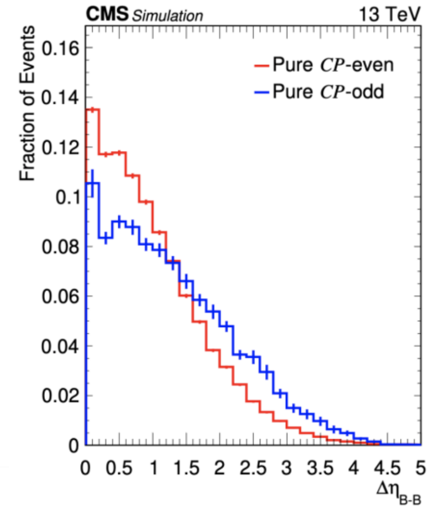



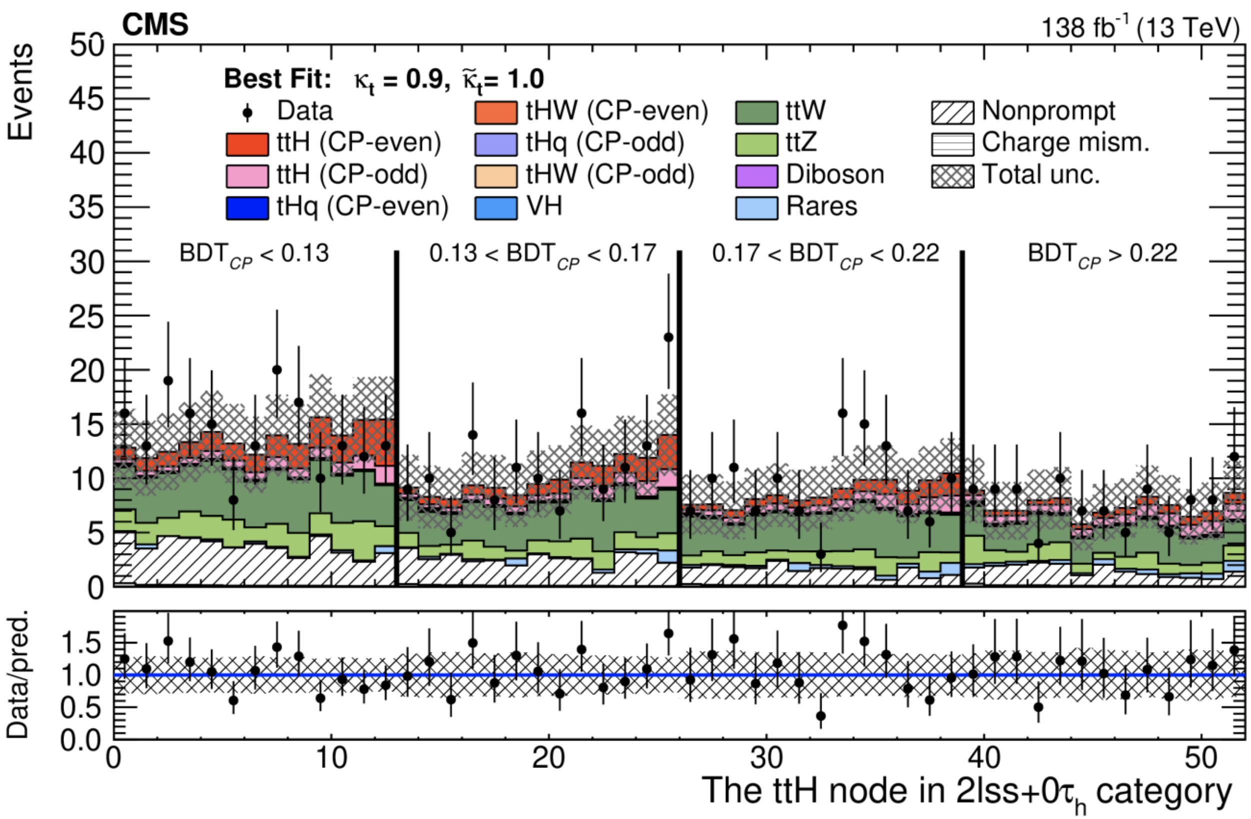



# Htt coupling: ttH using several decay modes (CMS)

JHEP 07 (2023) 092

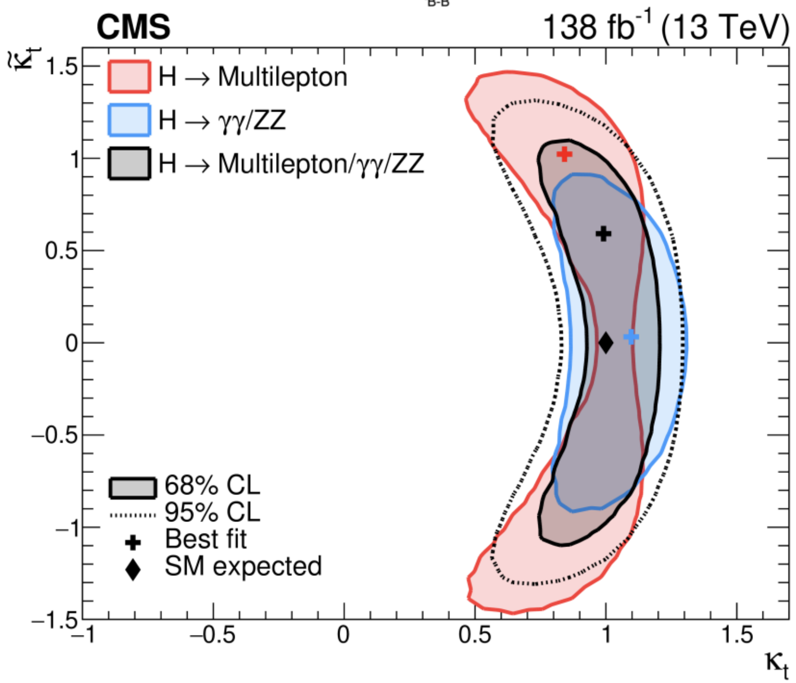
- Results exploring ttH with H→γγ, H→multilepton (WW* and ττ: 2lSS+0τ, 2lSS+1τ, 3l+0τ) and H→bb decays
- MVAs used to separate CP-even/odd states




**$|f_{CP}^{Htt}|$< 0.55 at 68%CL**

**Pure Htt CP-odd coupling excluded @ 3.7σ**



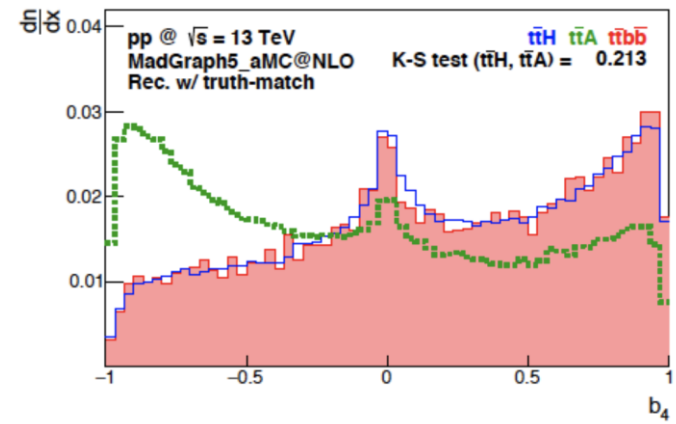
# Htt coupling: ttH with H→bb (ATLAS)

arXiv:2303.05974

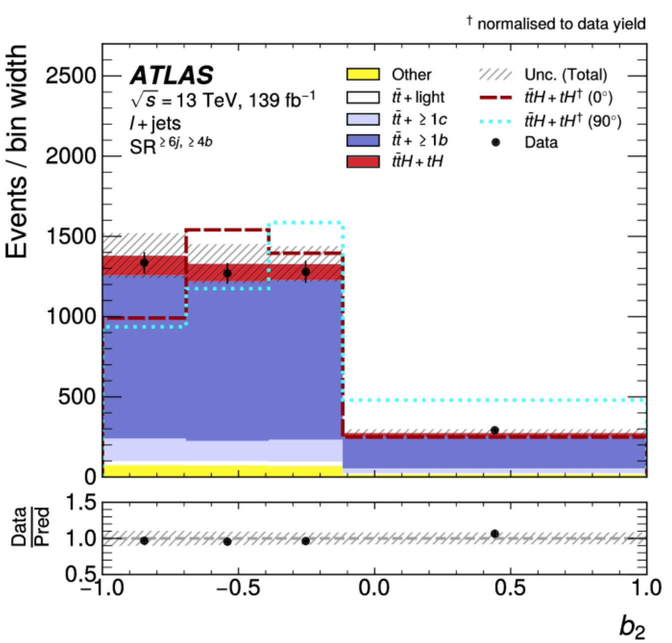
- Explore 1$\ell$+jets (also boosted region) and 2$\ell$ channels with 4b in final state
- Main bkgs.: tt+bb
- Train MVAs to reconstruct Higgs/top from jets and to categorize events
- Define CP-sensitive observables per region:
  - dedicated CP-observables for 1$\ell$ (resolved) and 2$\ell$ defined with top quark kinematic information: $b_2$ and $b_4$

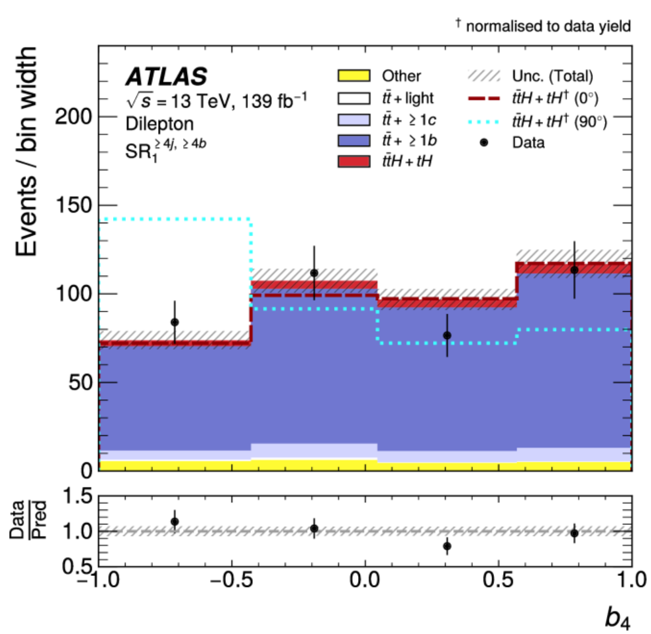
$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}, \text{ and } b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

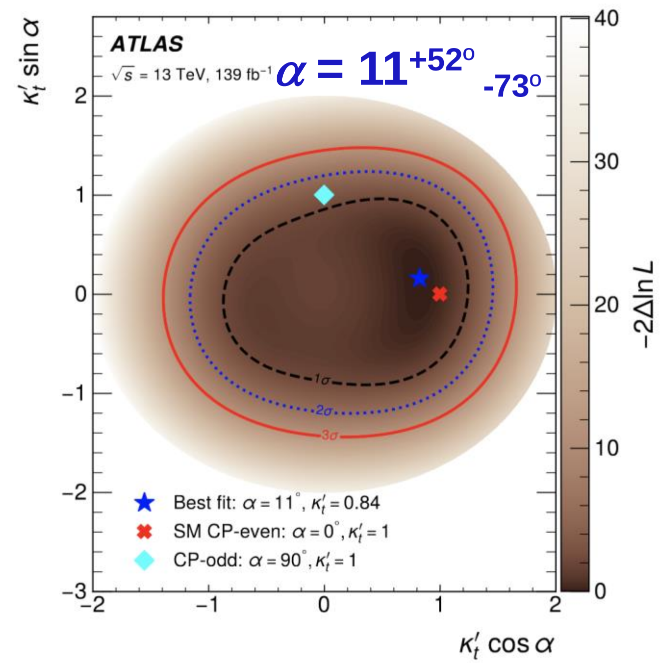
  - $\Delta\eta_{\ell\ell}$ in 2$\ell$
  - BDT for boosted region for CP-even/odd separation
- Extract mixing angle $\phi_t$ ($\alpha$) and $\kappa_t$
- Results limited by syst. unc.




**Pure Htt CP-odd disfavoured at 1.2σ**



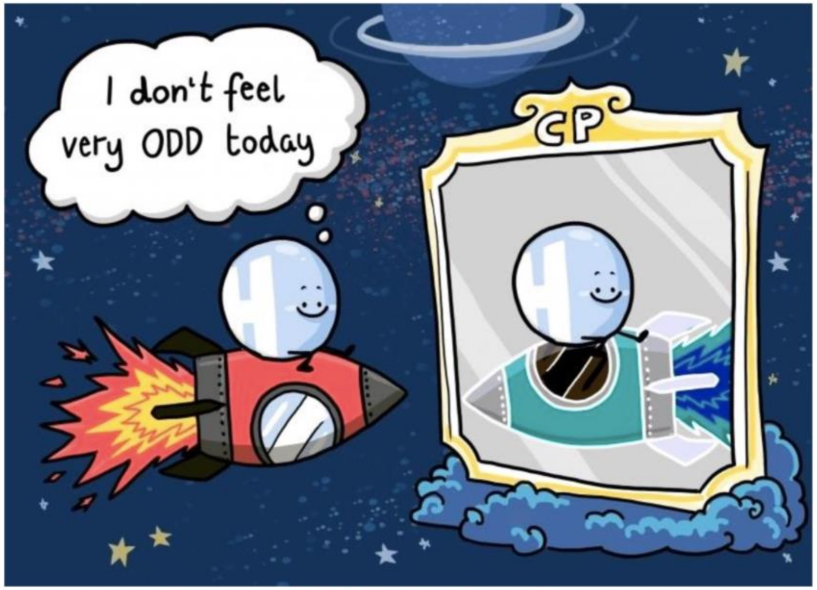



# Summary

- Understanding the Higgs boson's CP properties is a crucial aspect in particle physics today

- ATLAS and CMS have looked for BSM contributions and set limits on CP anomalous couplings in the Higgs boson interactions with vector bosons (HVV), gluons (Hgg), and fermions (Hff)
- Results are limited by statistical unc., and consistent with SM so far
- Purely CP-odd fermionic and bosonic Higgs couplings already excluded, but admixtures still possible

- Need to keep exploring CP violation in Higgs couplings
- A huge improvement is expected with more data from upcoming future LHC runs ☺
- For the moment, neglecting effect of operators on backgrounds...




*(image: DESY/designdoppel)*

**Discussions between theorists and experimentalists are very much appreciated !**

# THANKS FOR YOUR ATTENTION

maria.moreno.llacer@cern.ch

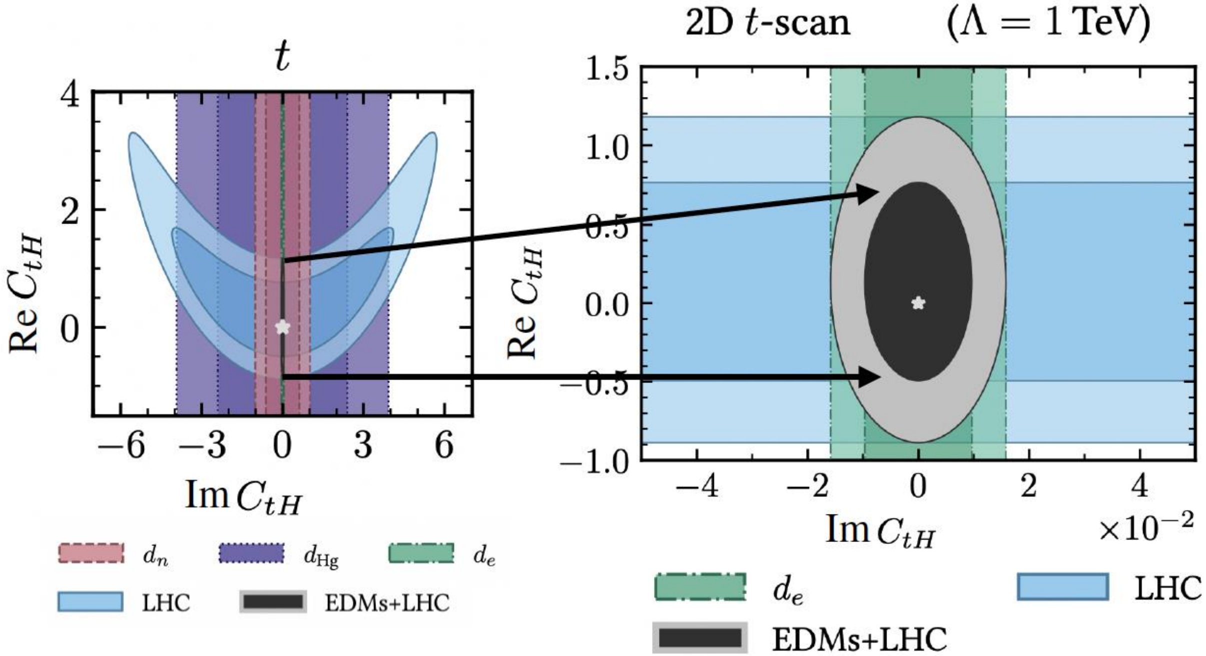

Work produced with the support of ASFAE/2022/010 project (Generalitat Valenciana)
and LEO22-1-603 Leonardo Grant for Researchers in Physics (BBVA Foundation)

Aleks Smolkovic @ TOP2022

J. Brod et al. 2203.03736

# Indirect probes

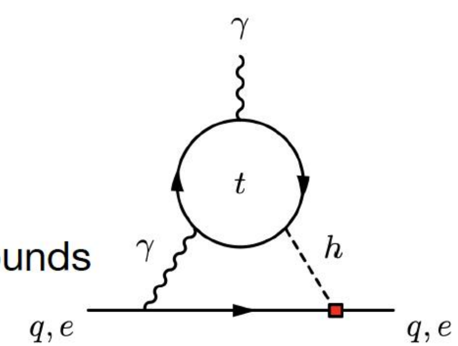
Interplay of LHC and EDM constraints:




Translates to

$|\tilde{\kappa}| \lesssim 0.5$ (LHC),

$|\tilde{\kappa}| \lesssim 0.01$ (EDM)

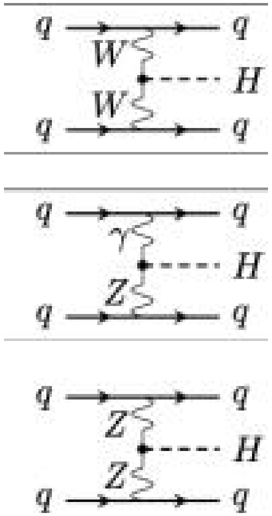



However, relaxing the assumption of SM $y_e, y_q$ evades the EDM bounds

Another interesting interplay: allowing for $\tilde{\kappa}_b$ allows for some (but not total) cancelation between $\tilde{\kappa}_b$ and $\tilde{\kappa}_t$, in line with $h \to b\bar{b}$

A. Smolkovic: CP of the top quark Yukawa 4

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



# Htt coupling: ttH with H→bb (ATLAS)

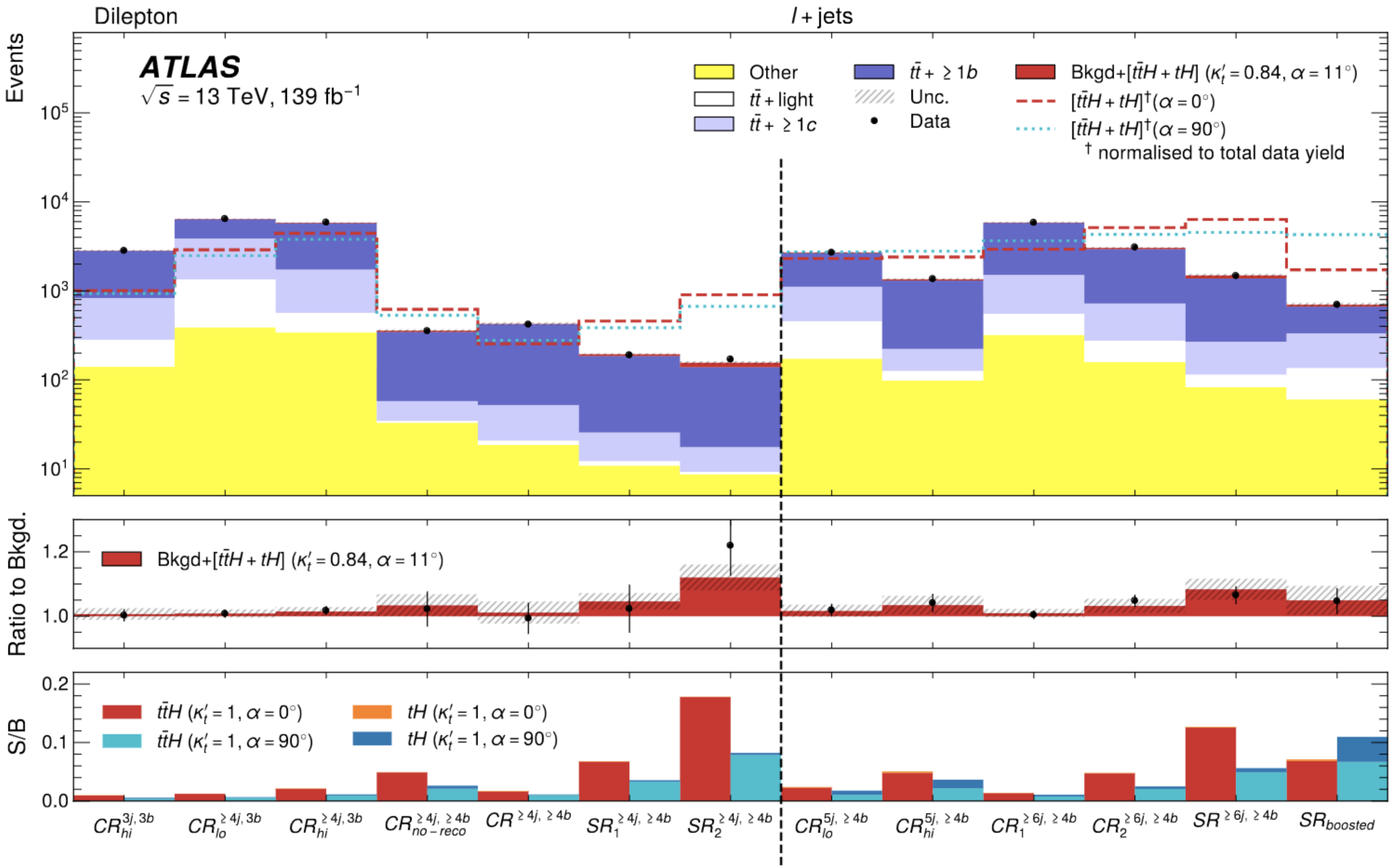
CP interference tH

$$N_{t\bar{t}H}(k'_t, \alpha) = k'^2_t c^2_\alpha N_{\text{CP-even}} + k'^2_t s^2_\alpha N_{\text{CP-odd}}$$

$$N_{tH}(k'_t, \alpha) = A\, k'^2_t c^2_\alpha + B\, k'^2_t s^2_\alpha + C\, k'_t c_\alpha + D\, k'_t s_\alpha + E\, k'^2_t c_\alpha s_\alpha + F$$

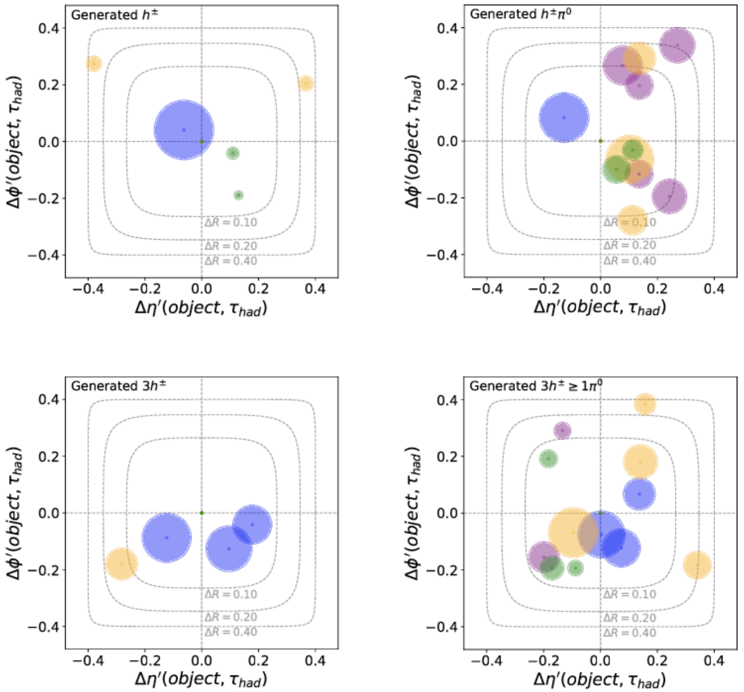
CP interference tH and WH

WH




arXiv:2303.05974

# Substructure of hadronic τ-lepton decays

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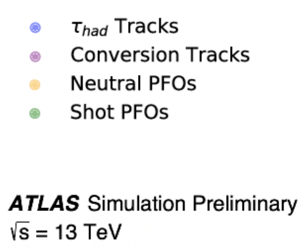
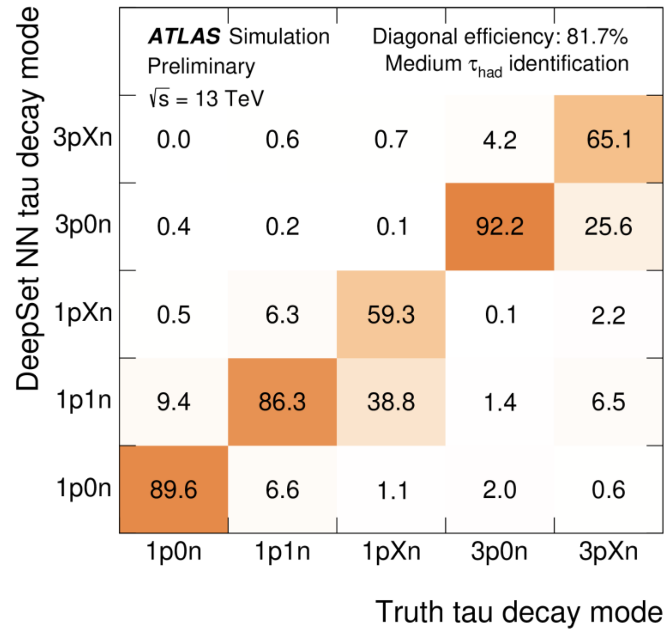
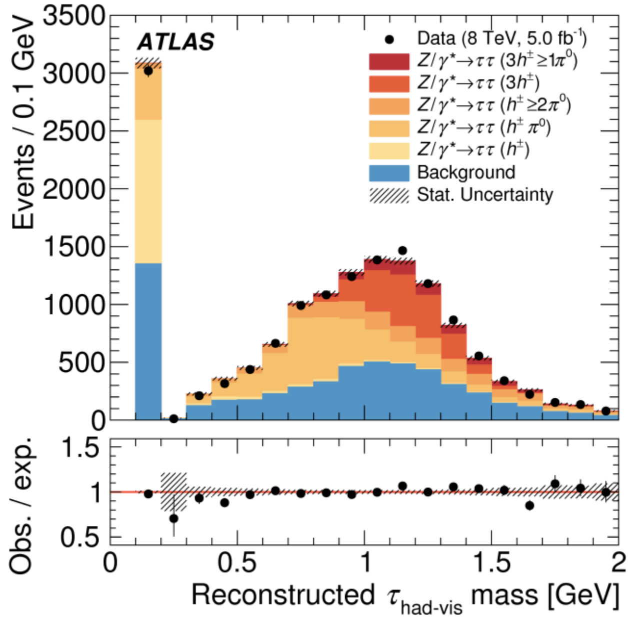


**CP discriminant: $\phi_{CP}$**

(angle between the τ decay planes in the Higgs rest frame)

→ The mixing angle $\phi_{\tau\tau}$ can be extracted by fitting this function:

$$\frac{d\Gamma}{d\phi_{\mathrm{CP}}} \propto \cos(\phi_{\mathrm{CP}} - 2\phi_{\tau\tau})$$

**Event reconstruction:**

Dedicated algorithms and MVAs to reconstruct $\tau_h$ and distinguish its decay mode

Several channels ($\mu,\pi,\rho,a_1^{1pr},a_1^{3pr}$)×($\pi,\rho, a_1^{1pr},a_1^{3pr}$)

τ planes can't be reconstructed exactly → use approximations

$\tau_l \to l^{\pm}\nu\nu$ (35%)

$\tau_h \to \pi^{\pm}\nu$ (12%)

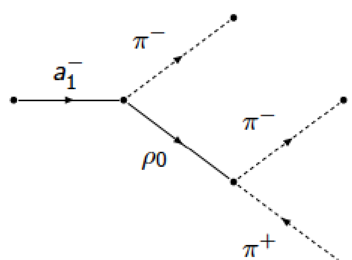
$\to \rho^{\pm}\nu \to \pi^{\pm}\pi^0\nu$ (26%)

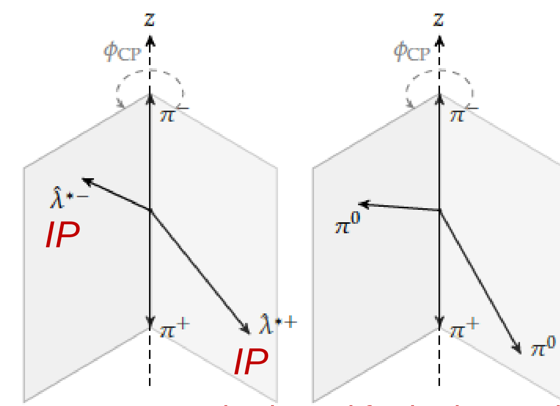
$\to a_1^{\pm}\nu \to \pi^{\pm}\pi^0\pi^0\nu$ (10%)

$\to a_1^{\pm}\nu \to \pi^{\pm}\rho^0\nu \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$ (10%)

Impact parameter method: define planes using charged particle direction and its IP vector

Neutral pion method




*Impact parameter method used for both taus (left), π0 method used for both taus (right)*

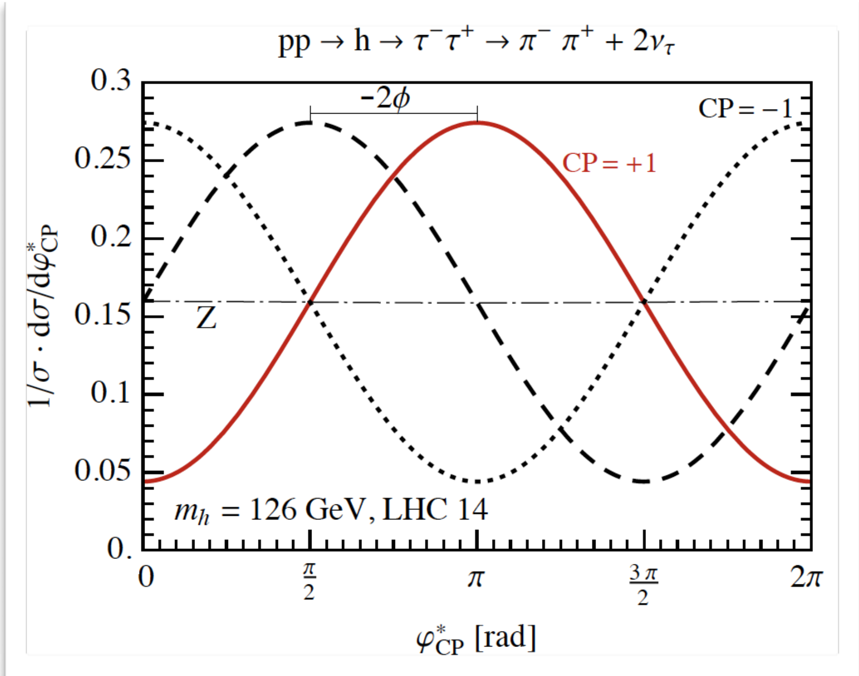
- Higgs decay probability ($\beta_\tau = 1$):

$$\Gamma_{h\to\tau^-\tau^+} \sim 1 - \vec{s}_z^{\,-}\vec{s}_z^{\,+} + \cos(2\phi_h)(\vec{s}_T^{\,-}\vec{s}_T^{\,+}) - \sin(2\phi_h)[(\vec{s}_T^{\,-}\times\vec{s}_T^{\,+})\cdot\hat{k}^{\tau^-}]$$

CP even — CP odd

- $\vec{s}_{z,T}^{\,\pm}$ - longitudinal, transverse vectors of $\tau^\pm$ spin in its rest frame with respect to $\hat{k}^{\tau^-} = \hat{e}_z$
- Higgs CP information encoded in the transverse component
- $$\frac{1}{\Gamma}\frac{d\Gamma(h\to\pi^+\pi^- + 2\nu)}{d\varphi^*_{CP}} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_h)\right]$$

- $2\phi_h$ can be determined from the shift of the fitted $\varphi_{CP}$ distribution with respect to the red curve for which $\phi_h = 0$.
- Precision on $\phi_h$ depends on the number of events and the size of the amplitude



# Higgs CP

- With all final state particles reconstructed, we can perform a Matrix Element based analysis of the underlying Higgs CP mixing angle $\Phi$. 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 $\Phi$, $\Delta\Phi_{ME}$ is better

Xin Chen @ Americas Workshop on Linear Colliders 2017

# 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

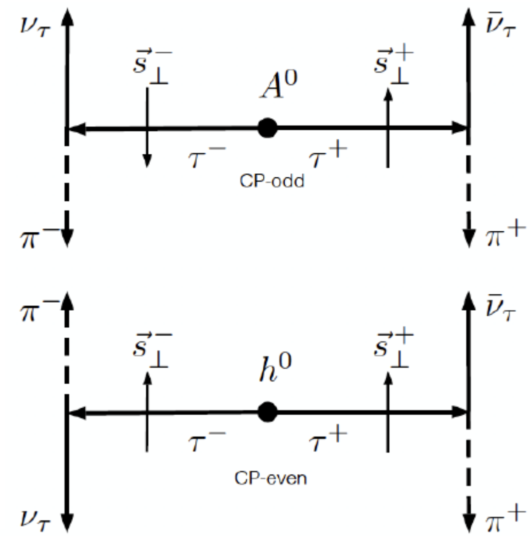
$$-g_\tau\left(\cos\phi\bar{\tau}\tau+\sin\phi\bar{\tau}i\gamma_5\tau\right)h$$

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

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

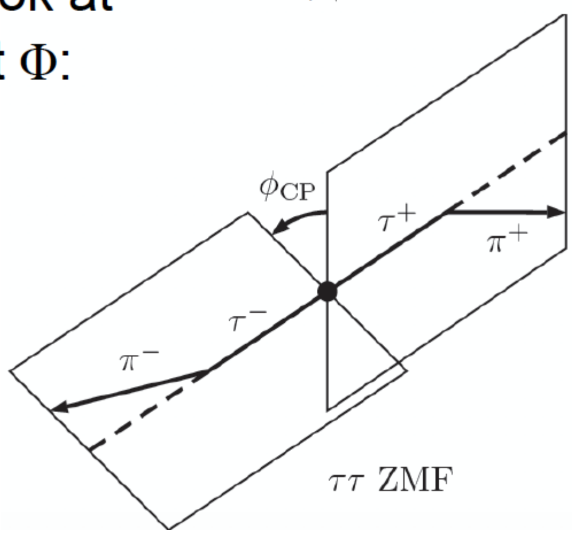
Sensitive to CP (H vs A)




- 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

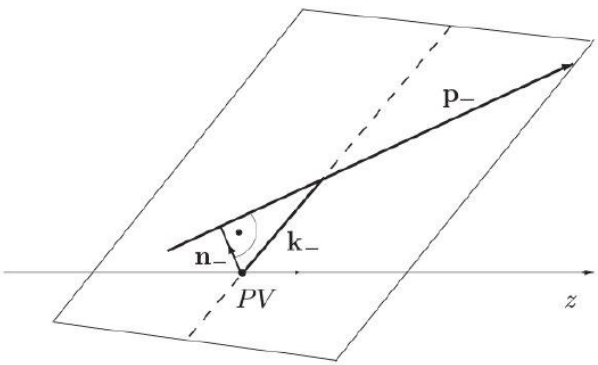


# CP test in H→ττ decay

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

Impact Parameter (IP) method:

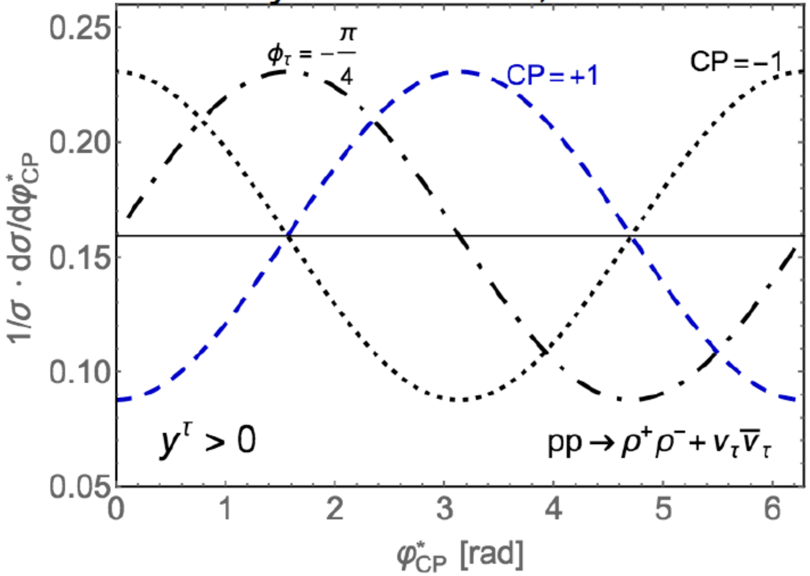
- Approximately reconstruct the tau decay plane from its leading track and IP
- Best for the $\tau \to \pi\nu$ decay. The analyzing power is compromised for other tau decays




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 $\pi^{\pm}$, $\pi^{0}$ need to be classified in order to maximize the analyzing power

Phys. Rev. D92, 096012




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

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

6

**$J^{CP} = 0^{++}$ ?**

Phys.Rev.Lett.125(2020)061802

No deviations found in CP properties of the Higgs couplings to gauge bosons

*Caveat: in those, CP-odd contributions enter only via higher-order operators*

**NEW: pseudoscalar admixture directly tested in top-Higgs interaction using ttH/tH events with H→γγ**

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

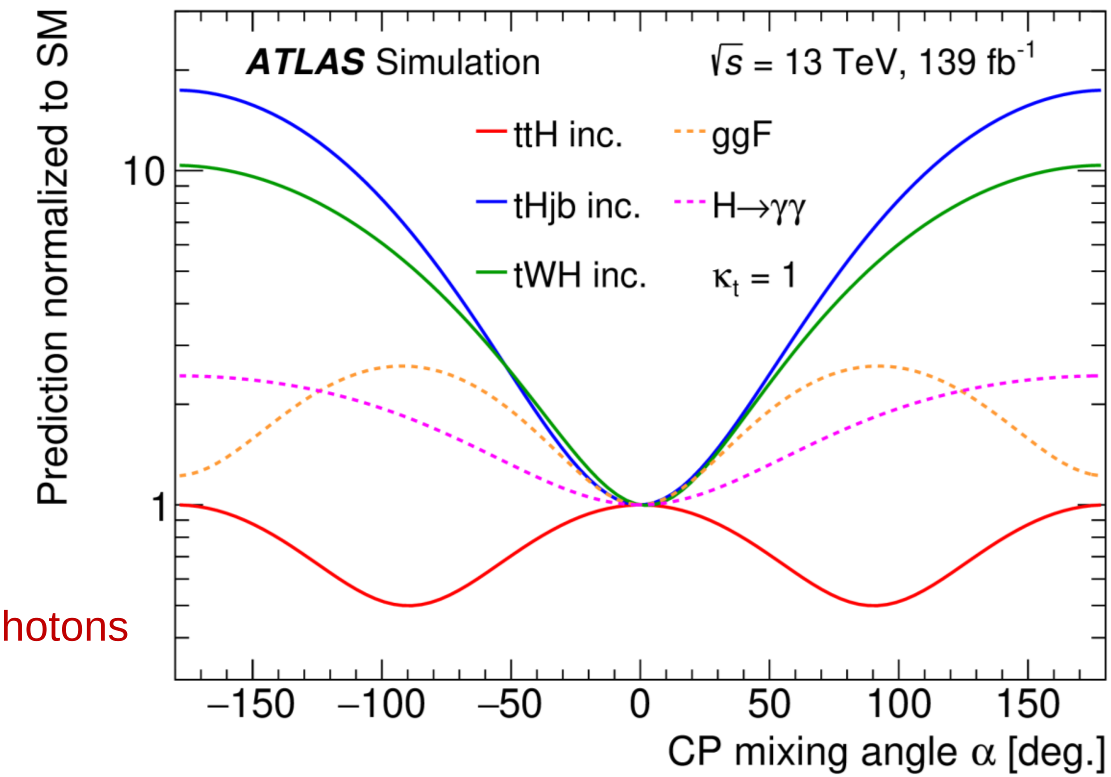
CP

SM: $(\kappa_t, \tilde{\kappa}_t) = (1, 0)$

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

CP mixing angle: $\alpha$

*Rate variation vs.* CP mixing angle $\alpha$




CP-odd contributions would alter:

- rates and kinematics of *ttH* and *tH* processes
  - *tH* also sensitive to the sign of $y_t$
- loop-induced Higgs couplings to gluons and photons

# Is the top-Higgs coupling a pure scalar interaction ?

**$J^{CP} = 0^{++}$ ?**

Phys.Rev.Lett.125(2020)061802

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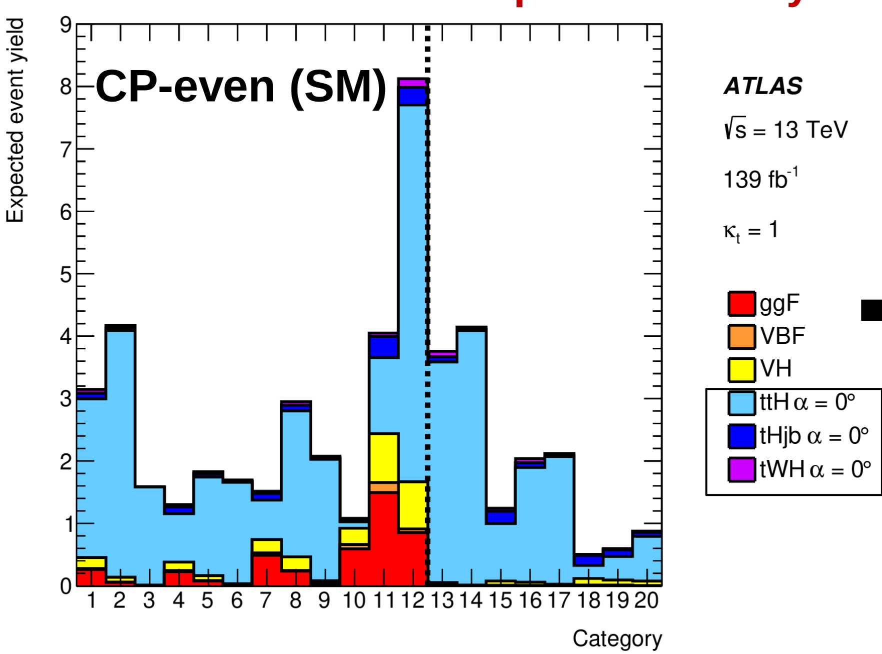
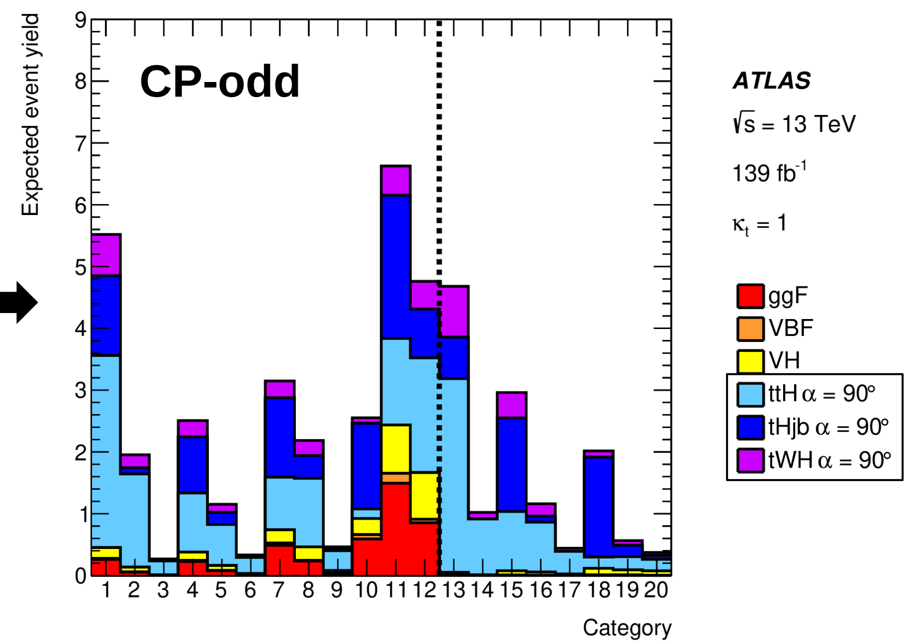
$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H \qquad \text{SM: } (\kappa_t, \tilde{\kappa}_t) = (1,0) \qquad \begin{aligned}\kappa_t &= k_t \cos\alpha \\ \tilde{\kappa}_t &= k_t \sin\alpha\end{aligned}$$

ATLAS EXPERIMENT
1D fit: CP mixing angle $\alpha$
2D fit: $k_t \cos\alpha$ vs $k_t \sin\alpha$

CMS
1D fit: $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{sign}(\tilde{\kappa}_t/\kappa_t)$

**Expected event yields in each analysis region**



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No deviations found in CP properties of the Higgs couplings to gauge bosons

*Caveat: in those, CP-odd contributions enter only via higher-order operators*

**NEW: pseudoscalar admixture directly tested in top-Higgs interaction using ttH/tH events with H→γγ**

$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H \qquad \text{SM: } (\kappa_t, \tilde{\kappa}_t) = (1,0) \qquad \begin{aligned} \kappa_t &= k_t \cos\alpha \\ \tilde{\kappa}_t &= k_t \sin\alpha \end{aligned}$$

ATLAS:
1D fit: CP mixing angle $\alpha$
2D fit: $k_t \cos\alpha$ vs $k_t \sin\alpha$

CMS: 1D fit: $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$

**signal yields parametrised as function of ($k_t$ , $\alpha$) or ($\mu_{ttH}$ , $f_{CP}^{Htt}$) CP parameters**

Signal parametrisation

Models used

ATLAS:
ttH, tHjb & tWH @NLO
Higgs Characterisation

CMS:
ttH @LO
*JHUGEN with* MELA