CP properties of Higgs boson

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Higgs Potential 2024

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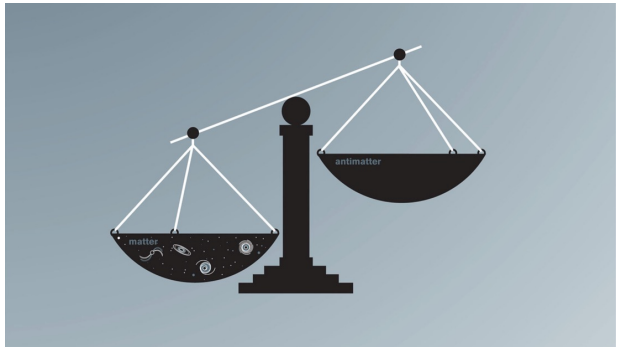
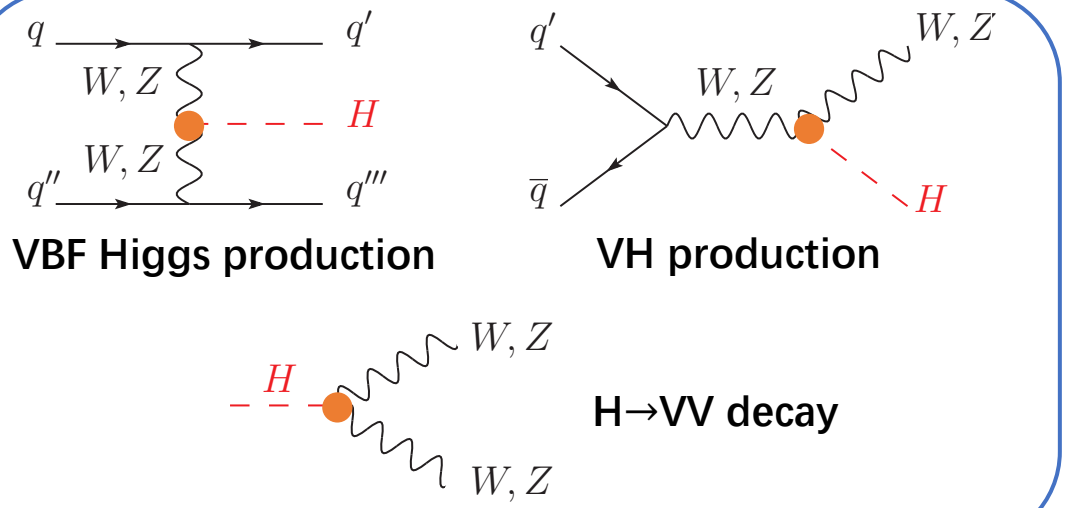
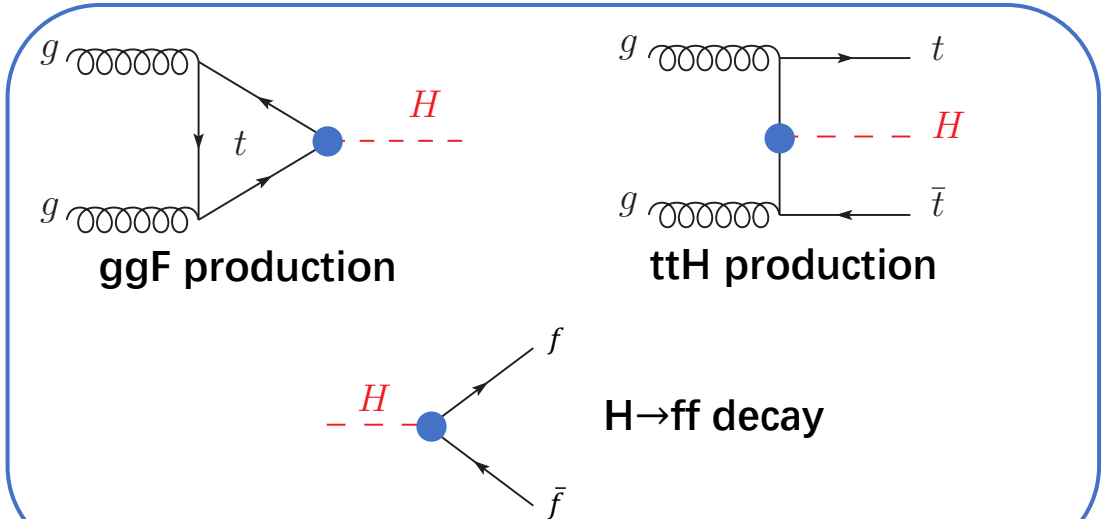
Introduction

- **CP violation: one of key conditions in baryon asymmetry.**
  - Existing CPV in SM: CKM, PMNS matrices, but NOT sufficient.
  - **Where is the other CP-violation source?**



- **CP properties in SM Higgs couplings: CP-even**
  - Any evidence of CPV might be a road to NEW PHYSICS!





Theoretical framework for CPV

- **Hff Yukawa couplings: Effective Lagrangian for CPV**
  - $\mathcal{L}_{eff} = -\frac{m_f}{v}\left[\bar{\Psi}_f \kappa_f (\cos\alpha + i \sin\alpha\, \gamma_5)\Psi_f\right]H$, with α for CP mixing. (ATLAS)
  - Or: $\mathcal{A}(Hff) = -\frac{m_f}{v}\bar{\Psi}_f\left(k_f + i\tilde{k}_f\gamma_5\right)\Psi_f$, with $f_{CP}^{Hff} = \frac{|\tilde{k}_f|^2}{|k_f|^2+|\tilde{k}_f|^2} sign\left(\frac{\tilde{k}_f}{k_f}\right)$ (CMS)

- **HVV gauge couplings: in 2 different interpretations**
  - Dimension-6 SMEFT in Warsaw basis (ATLAS)

    $\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_k \frac{c_k}{\Lambda^2}\mathcal{O}_k$, 3 independent couplings $c_{H\tilde{W}}, c_{H\tilde{B}}, c_{H\tilde{W}B}$ for 3 CP-odd H-V operators.
  - Anomalous couplings (CMS)

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f^{*(1)}_{\mu\nu} f^{*\mu\nu(2)} + a_3^{VV} f^{*(1)}_{\mu\nu} \tilde{f}^{*\mu\nu(2)}$$

SM : VV = ZZ,WW

CP Even (higher order couplings) ($\Lambda_1 = 1TeV$)

CP Even

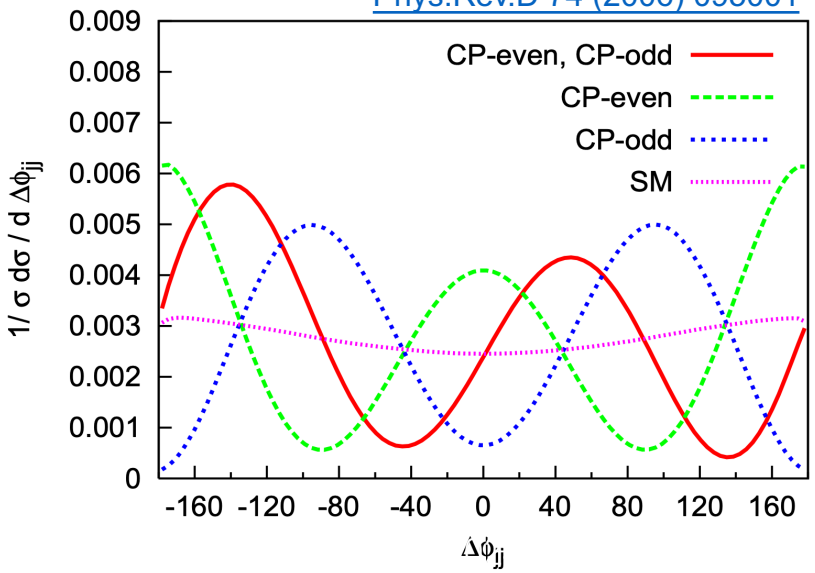
CP Odd

CPV effective cross section $f_{a3} = \frac{|a_3|^2\sigma_3}{\Sigma_j |a_j|^2 \sigma_j} sign\left(\frac{a_3}{a_1}\right)$

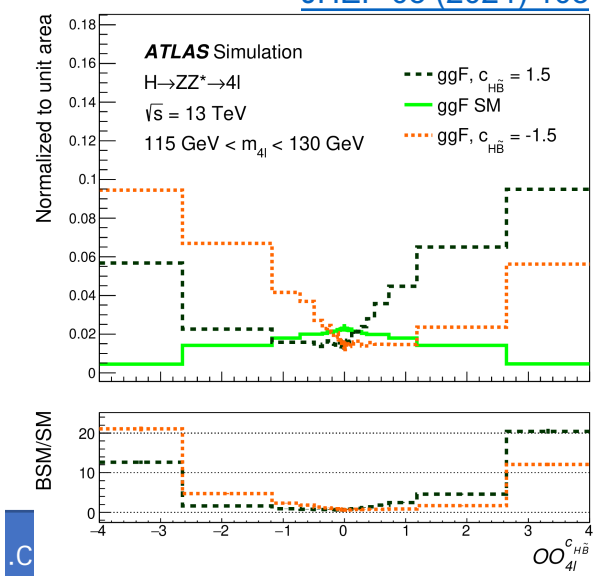
CP sensitive observables

- **Traditional kinematic CP-sensitive variable: $\Delta\Phi_{jj}^{signed}$**
  - Angular information in production process.
- **Machine learning / matrix element based observable:**
  - Optimal observable $\mathcal{OO} = \frac{2Re(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$
  - Matrix element based discriminants (MELA)
- **Pure shape analyses are always preferred.**

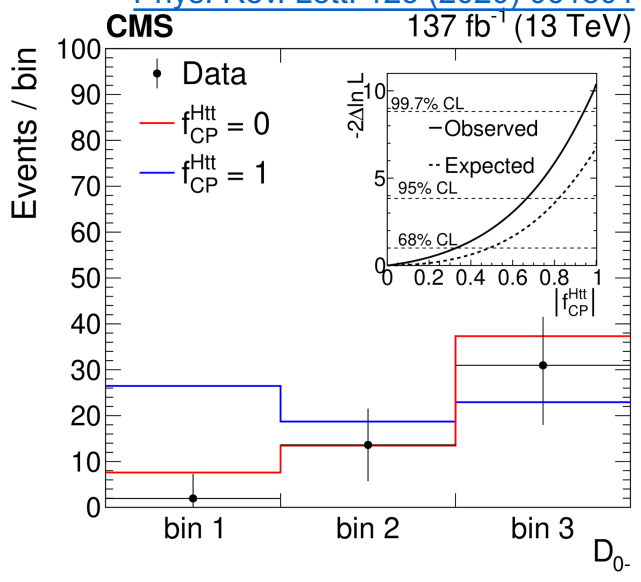
Phys.Rev.D 74 (2006) 095001



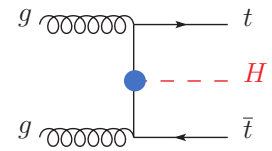
JHEP 05 (2024) 105



Phys. Rev. Lett. 125 (2020) 061801

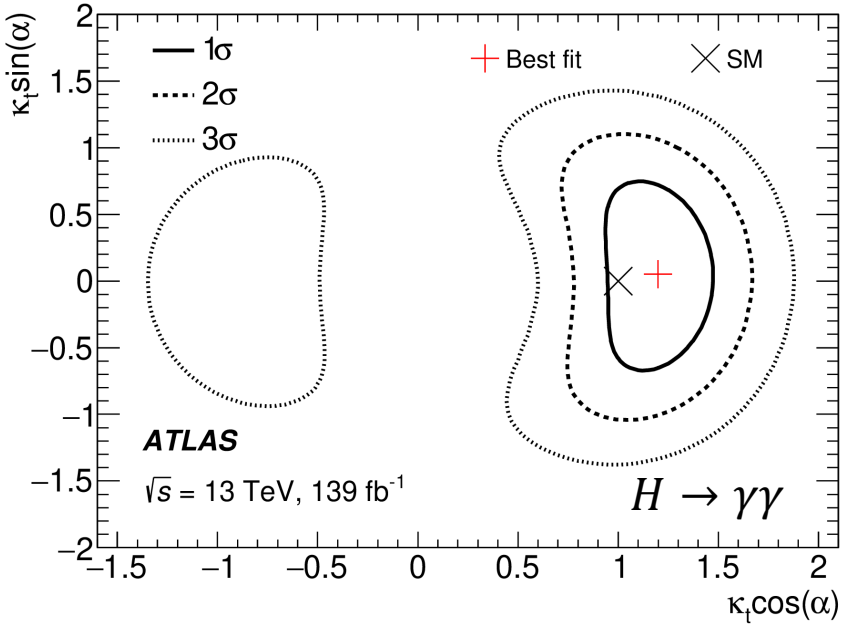


Hff coupling CP properties

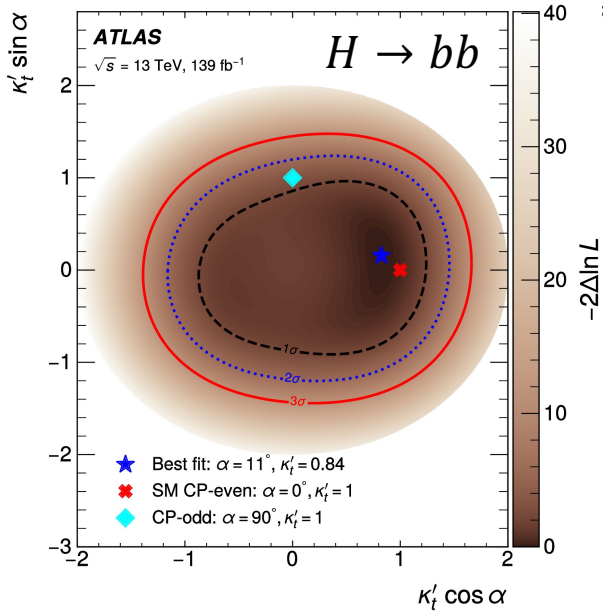


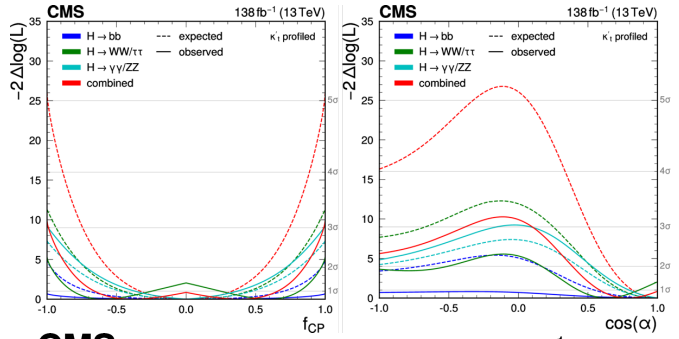
- **H-t Yukawa coupling in ttH/tH production:**
  - Direct H-t coupling. Fruitful studies in $H \to \gamma\gamma/bb/WW/\tau\tau$ channels by ATLAS and CMS.
  - No derivations from SM. Constraints are limited by statistics.

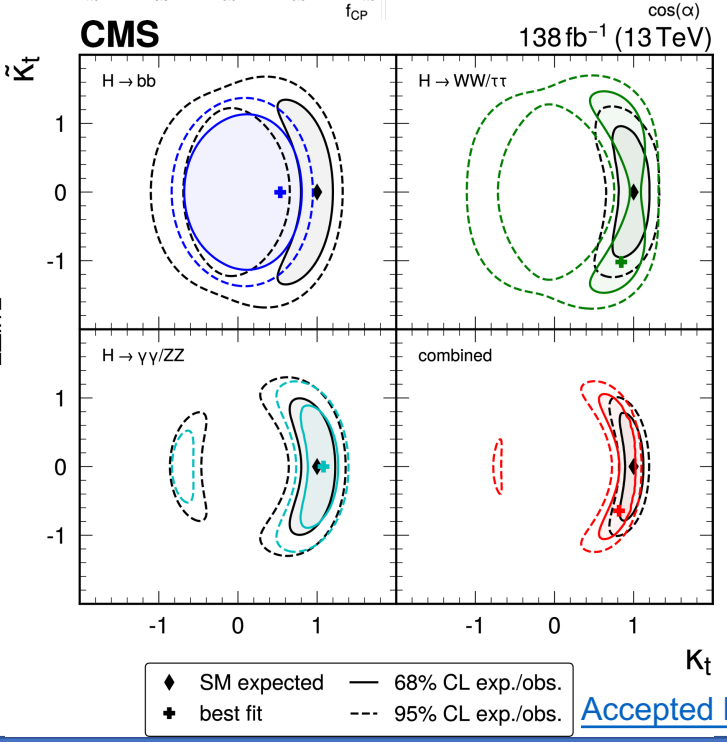
Phys. Rev. Lett. 125 (2020) 061802



Phys. Lett. B 849 (2024) 138469

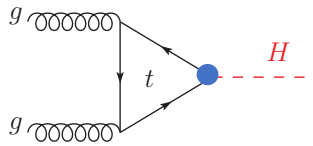






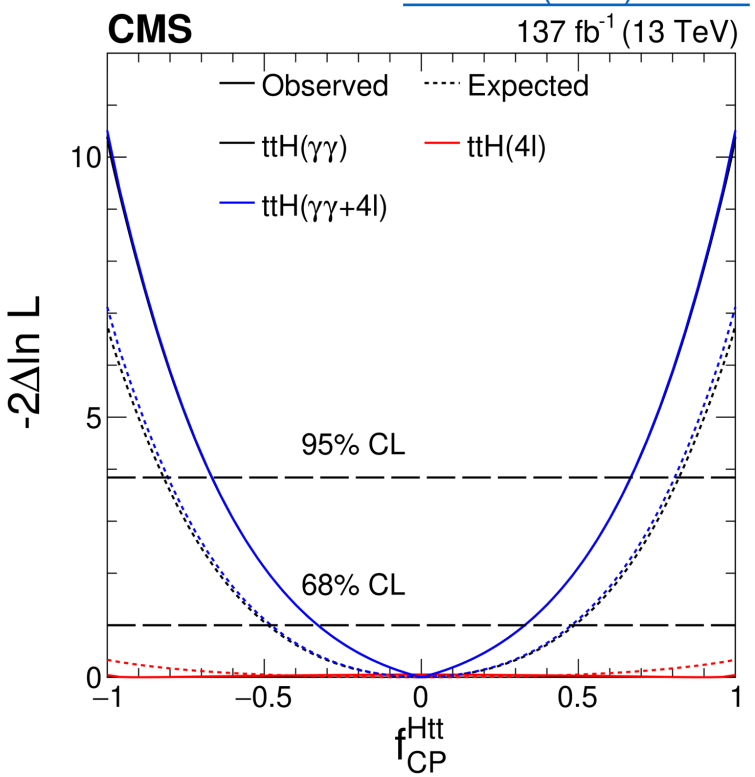
Accepted by JHEP

Hff coupling CP properties

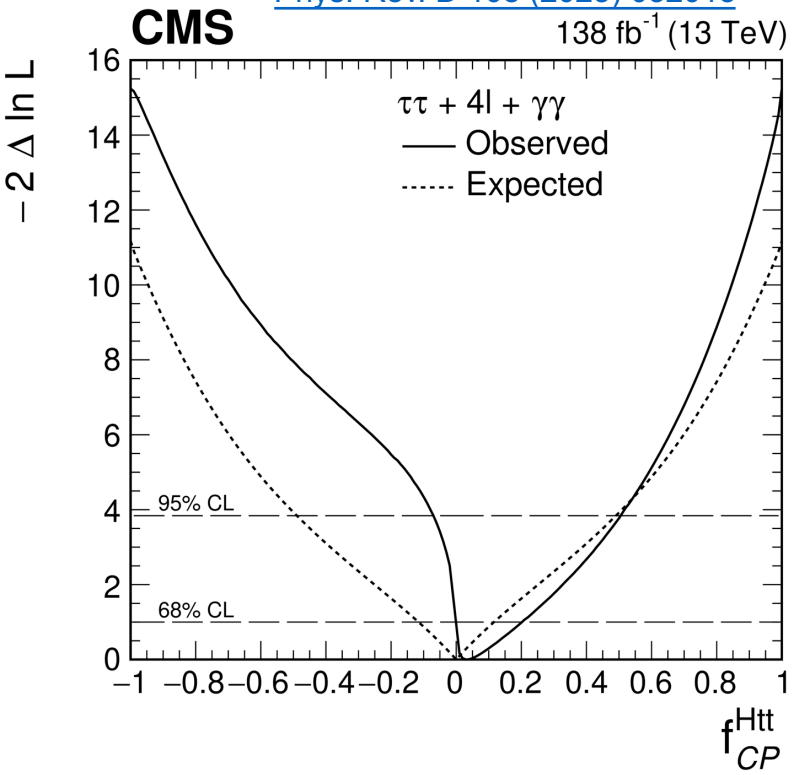


- **H-t Yukawa coupling in ggF production**
  - ggF is dominated by top loop, f_{CP}^{Htt} can be parameterized from f_{a3}^{Hgg}.
  - Indirect measurement but benefit from large ggF cross section ($H \to \gamma\gamma/\tau\tau/ZZ$).

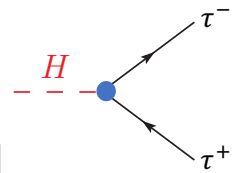
PRD 104 (2021) 052004



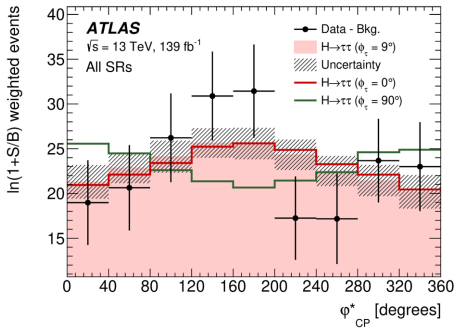
Phys. Rev. D 108 (2023) 032013

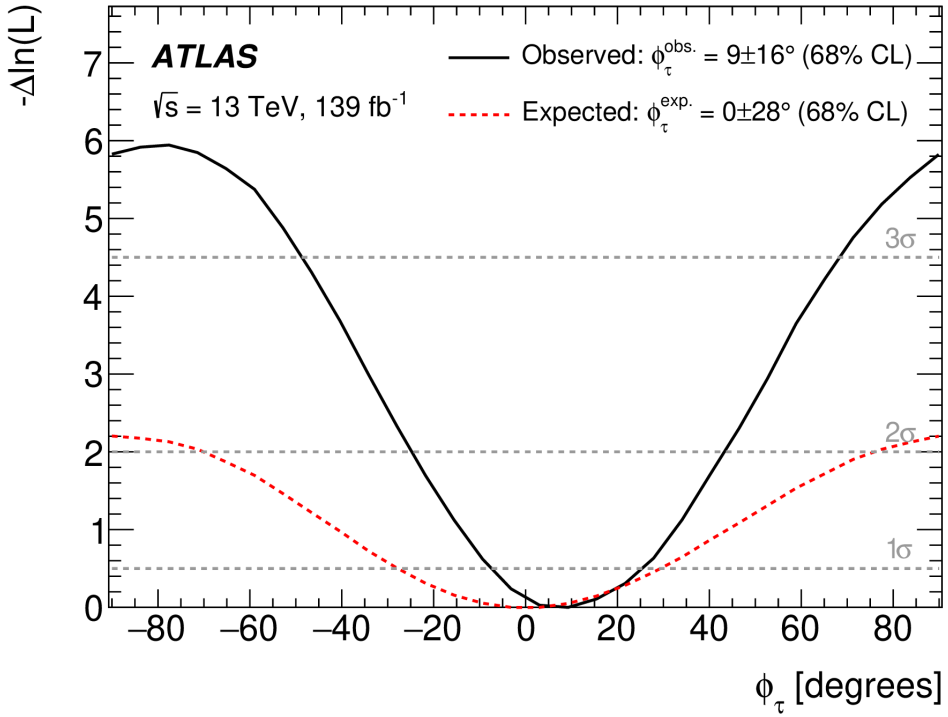


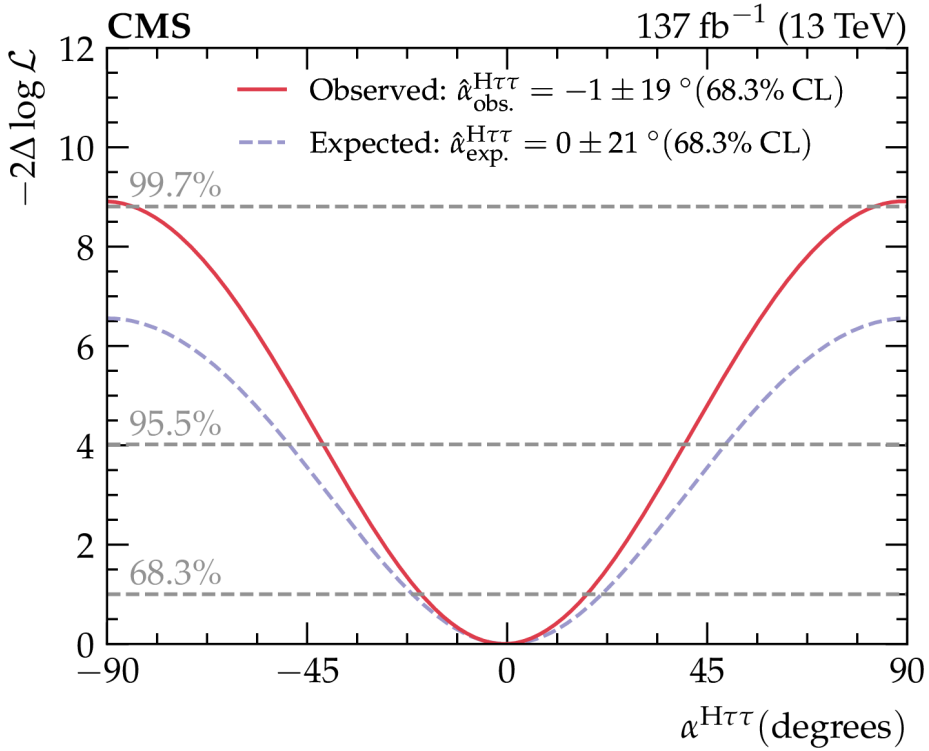
Hff coupling CP properties



- **H-τ Yukawa coupling in $H \to \tau\tau$**
  - CP property can be extrapolated from τ decay plane ϕ^*_{CP}.
  - Similar precision by ATLAS and CMS collaboration.



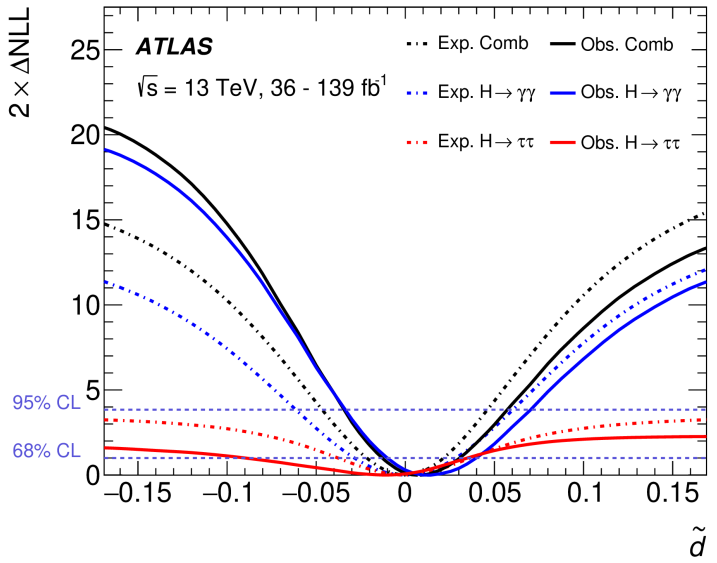




HVV coupling CP properties

- **Gauge coupling in VBF, VH and $H \to VV$ in ATLAS**
  - Can be probed from both production (VBF $H \to \gamma\gamma/\tau\tau$) and decay ($H \to WW/ZZ$) modes.
  - For VBF: a simplified assumption with $\tilde{d}$: $c_{H\tilde{W}} = c_{H\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d}$, $c_{H\tilde{W}B} = 0$.
  - Feasible for 2D and 3D constrain in $H \to WW/ZZ$ process.

Phys. Rev. Lett. 131 (2023) 061802



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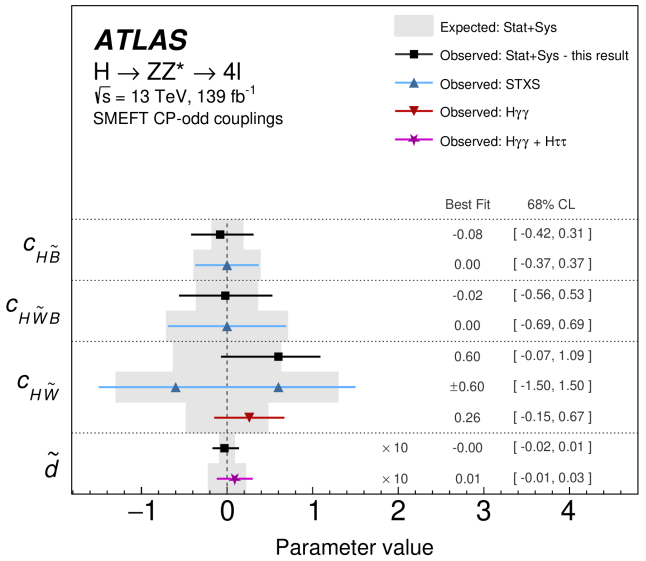

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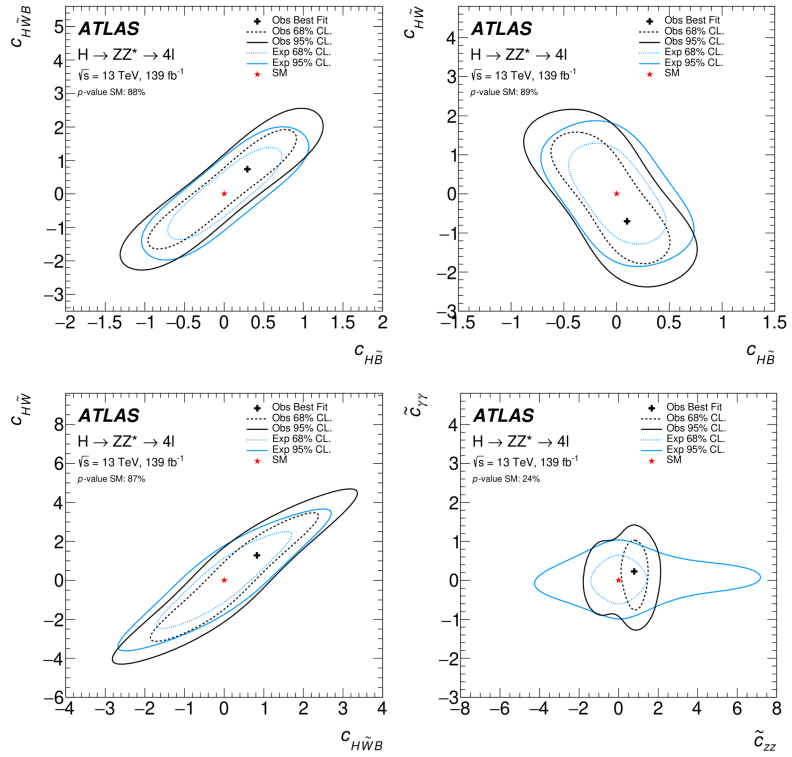
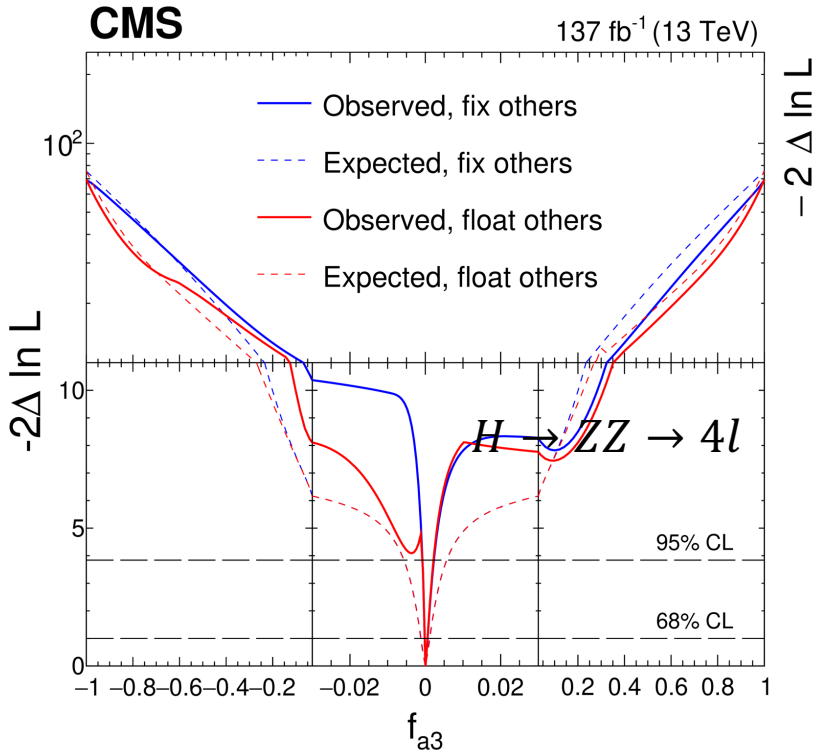


HVV coupling CP properties

- **Gauge coupling in VBF, VH and $H \to VV$ in CMS**
  - Anomalous coupling f_{a3} for CP,
  - Partial results are extrapolated to SMEFT coefficients. GOOD for ATLAS+CMS combination.

Phys. Rev. D 104 (2021) 052004



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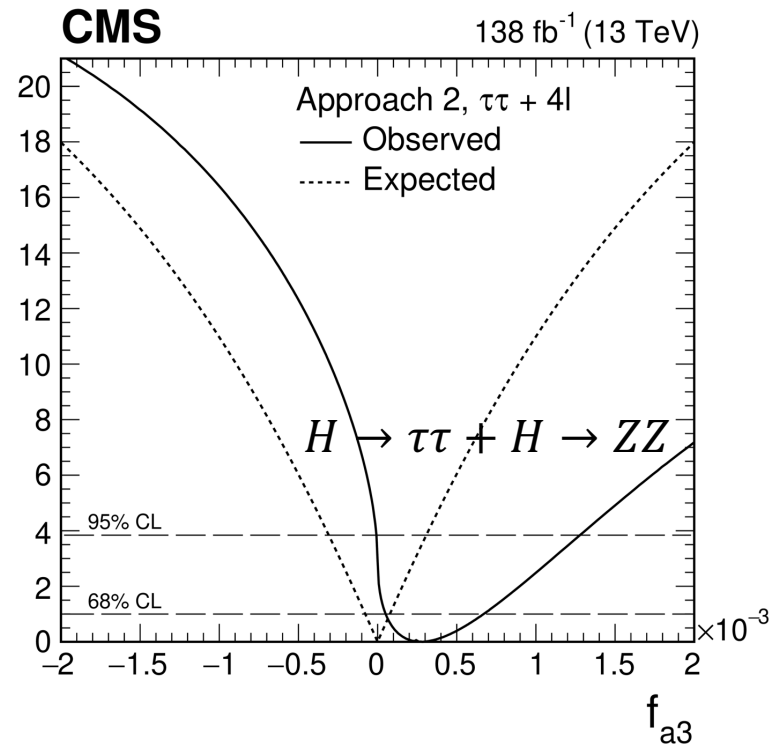

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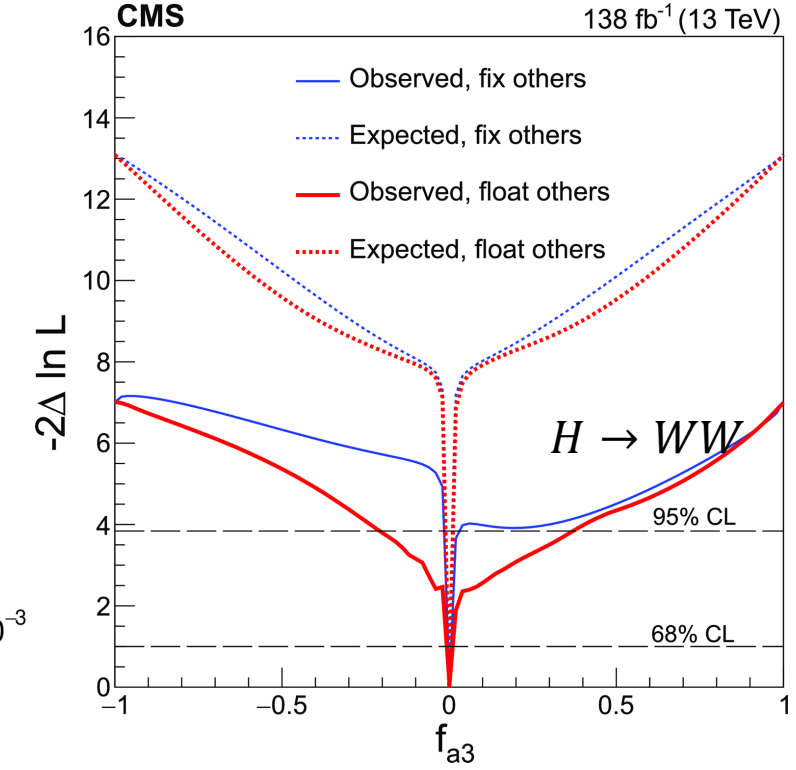
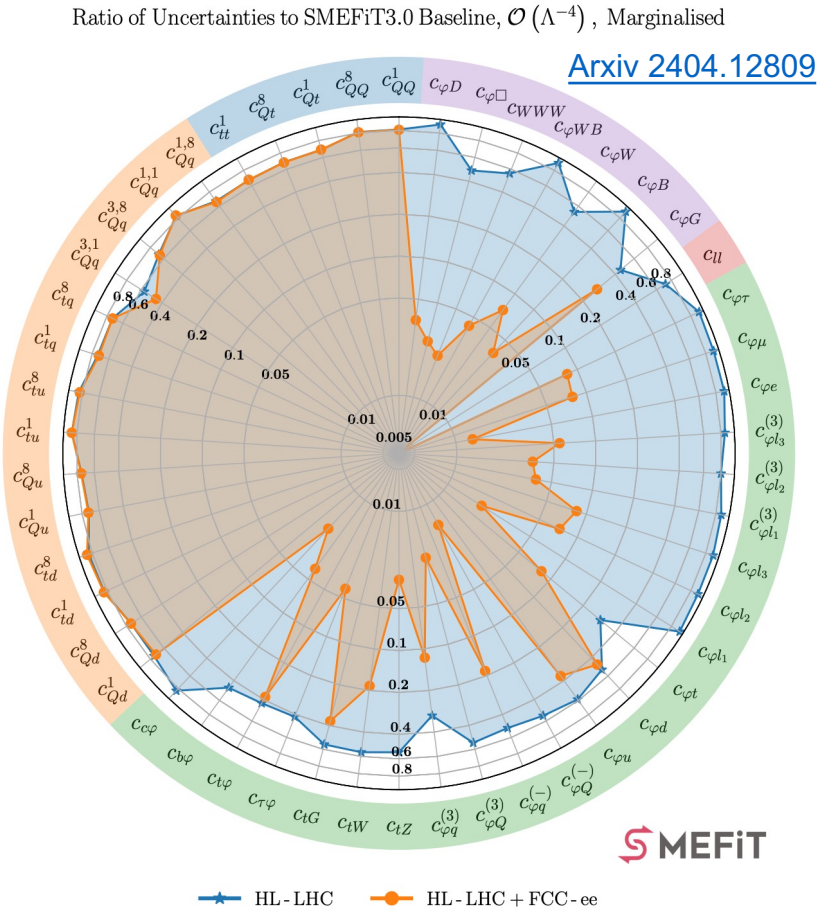


Higgs CP in future experiments

- **Higgs CP would also be an interesting topic for future Higgs factory.**
  - Extrapolations and expectations for HL-LHC, FCC-ee, ILC, CEPC are always ongoing…

Arxiv 2404.12809



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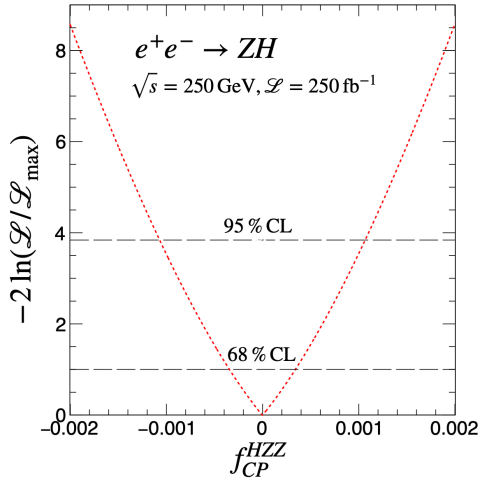

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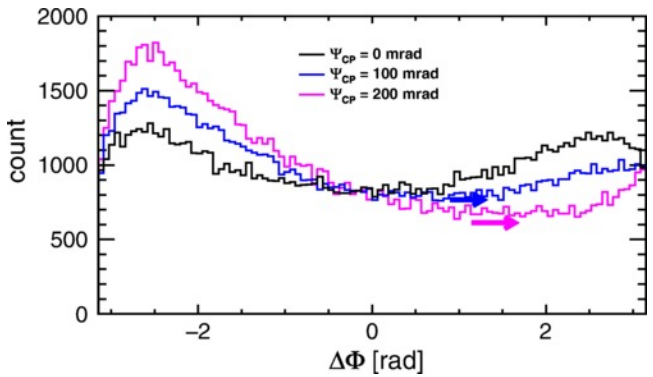

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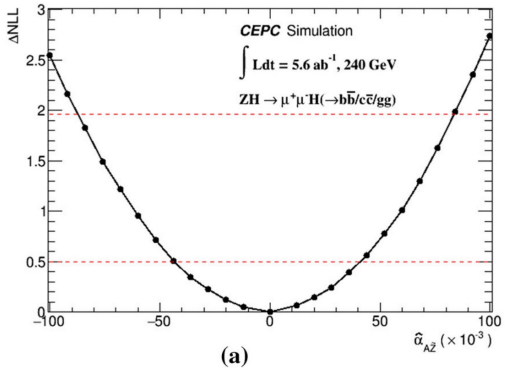

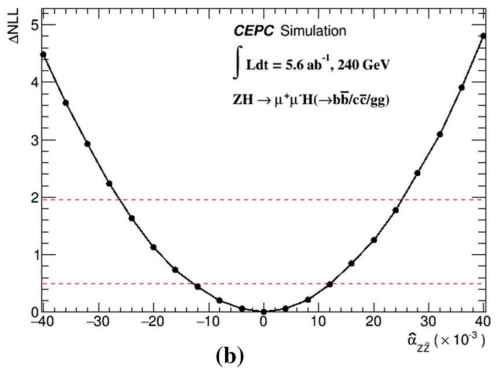

Summary

- **We are looking for new CP-violation sources beyond SM**
  - Higgs physics is a precious portal to study CP structures in Yukawa and gauge couplings.

- **Fruitful measurements has been performed for both ATLAS and CMS**
  - From both production mode and decay mode, covers many possibilities.
    - Opportunities in some un-covered channels, e.g. VH for HVV.
  - Observed results are compatible with SM: NO CP-violation observed ☹
  - Precision is mainly limited by LHC statistics

    Improvement can be expected for Run 3, channel combination, HL-LHC!

- **Future Higgs factory will bring giant improvement**
  - Hope we can see it soon!

Thanks for your attention!