CP violation in the Higgs

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Where to look for CP violation

We need CP violation (CPV) to explain the matter/anti-matter asymmetry in the universe.

It could be

1. In the quark sector
2. In the lepton sector
3. In the Higgs sector

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1. In the quark sector	Through the CKM matrix	mass vs flavour
2. In the lepton sector	Through the MNS matrix	mass vs flavour
3. In the Higgs sector	Through the ?? matrix	mass …

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General idea: mixing of eigenstates (not present in Higgs sector)

From the Higgs perspective

Higgs field responsible for electroweak symmetry breaking (EWSB) through 1st order phase transition

➔ To have baryon asymmetry inside the 'bubbles' that form and freeze in EWSB; the process needs to happen fast e.g. strong phase transition

Problem: that would require m_H<80 GeV…

From the Higgs perspective

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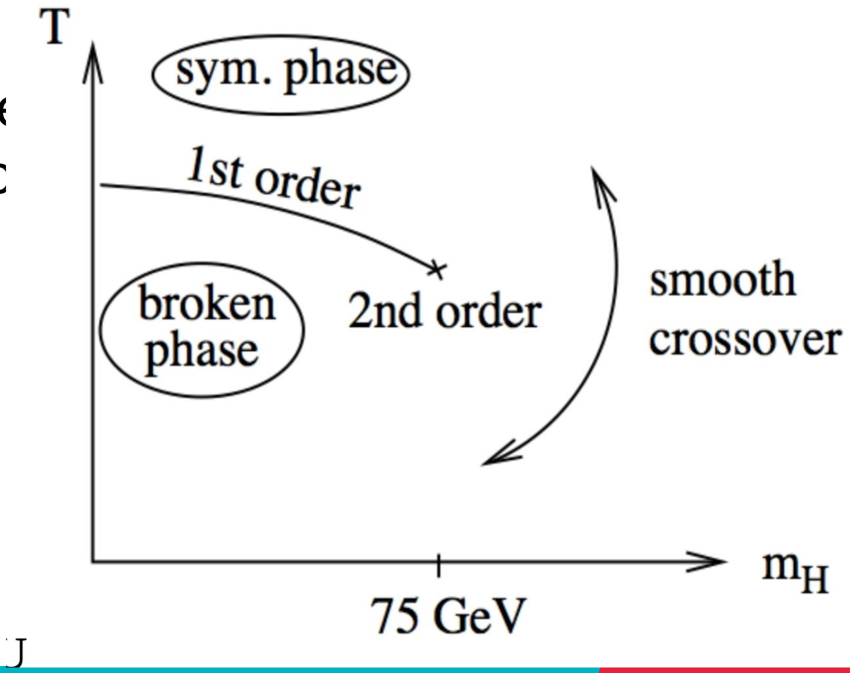

From the Higgs perspective

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Solution:

1) More Higgs bosons → Extra Higgs singlets/doublets/,,,
2) More sources of CP violation

Or both

Since Higgs field is related to EWSB it makes sense to look there…

Looking for CP violation in the Higgs

Current measurements of CPV are 8 orders of magnitude too small

In the SM:

- ➔ Mostly CPV through yukawa interactions, which also the Higgs has
- ➔ No CPV in leading order Higgs couplings
- ➔ CKM matrix propagates to higher order effects (tiny effect)

So we need BSM physics

Looking for CP violation in BSM Higgs

Most BSM theories predict CP violation in Hff couplings (yukawa)

$$\mathcal{L}_{\text{yuk}} = - \sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f \right) f H$$

However, CP violation in boson couplings is also possible and studied

➔ Pure CP-odd (fully CP violating) bosonic couplings excluded

Amplitudes

General amplitude structure for CP measurements:

$$|\mathcal{M}|^2 = c_{\text{even}}^2 \left|\mathcal{M}^{\text{CP-even}}\right|^2 + \underbrace{2 c_{\text{even}} c_{\text{odd}} \text{Re}[\mathcal{M}^{\text{CP-even}} \mathcal{M}^{\text{CP-odd}^*}]}_{\text{interference}} + c_{\text{odd}}^2 \left|\mathcal{M}^{\text{CP-odd}}\right|^2$$

CP can be tested either by:

- Distinguishing $\left|\mathcal{M}^{\text{CP-even}}\right|^2$ from $\left|\mathcal{M}^{\text{CP-odd}}\right|^2$ → CP-even observables.
- Constraining interference term→CP-odd observables.

Amplitudes

- In many cases, CP-odd observables are hard to measure
  - Require polarization information
  - Lots of angular measurements
- Also, often no obvious choices for CP-even observables.

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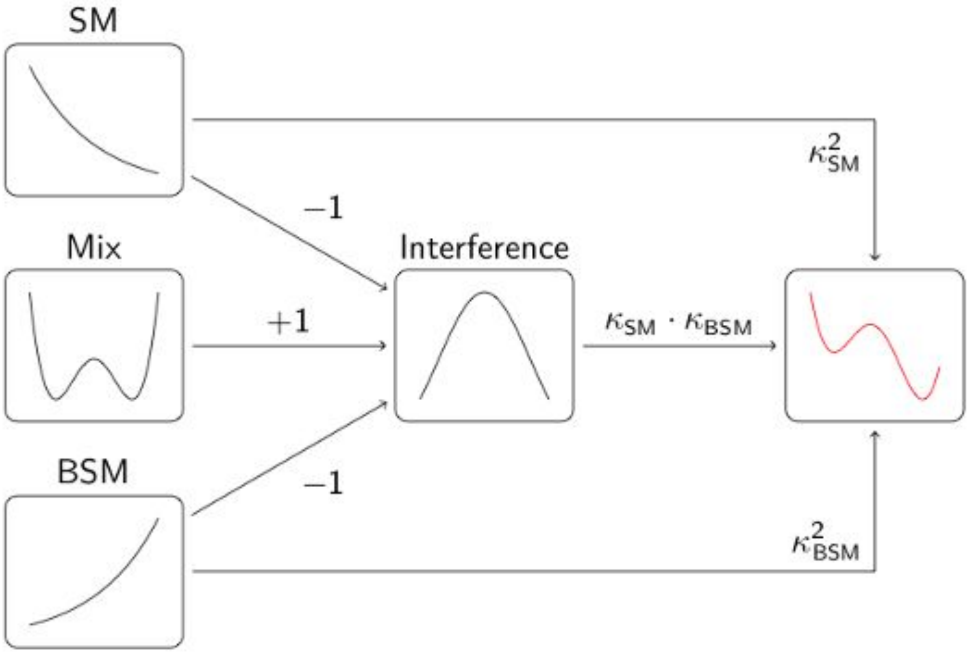
Interlude: new methods

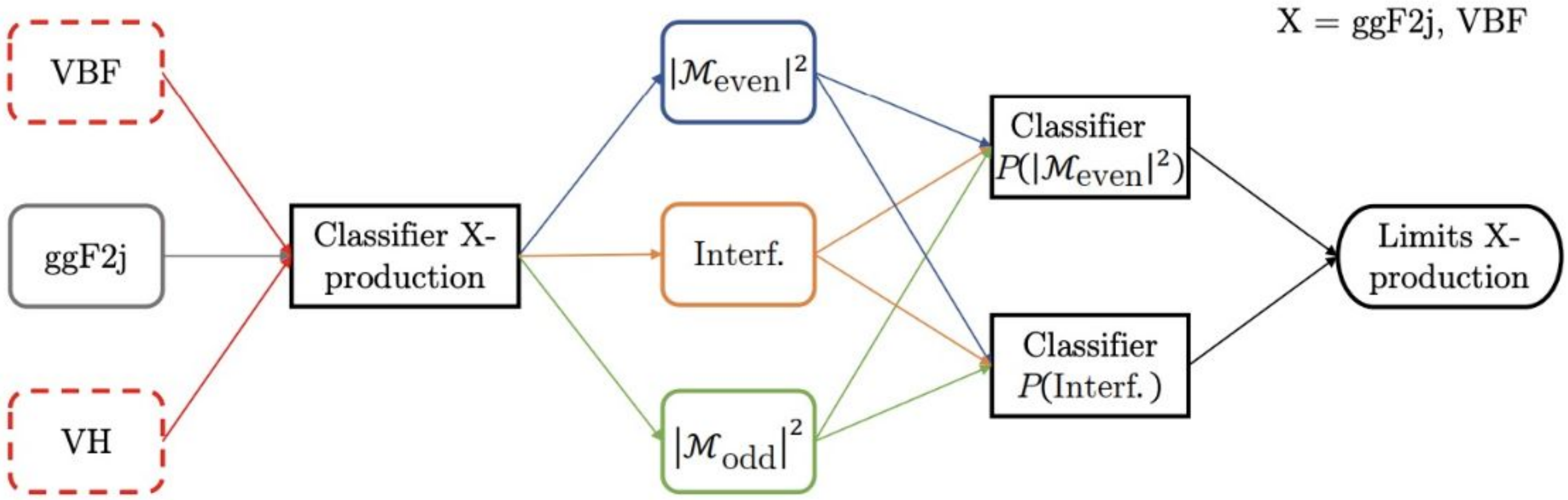
E.g Lagrangian morphing



$$T_{out}(\vec{g}_{target}) = \sum_{i=1}^{N_{input}} w_i(\vec{g}_{target}; \vec{g}_i) \cdot T_{in}(\vec{g}_i) \qquad \text{e.g. } T = \Delta\phi_{jj}$$

Interlude: new methods

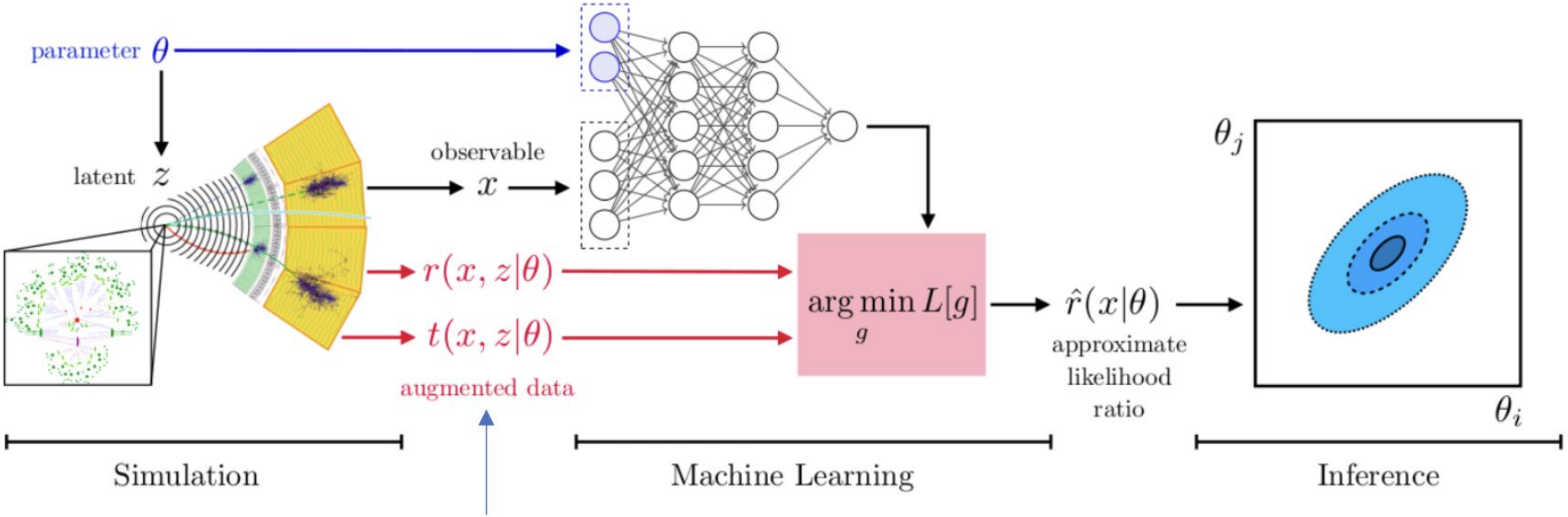
E.g Classifiers



Interlude: new methods

E.g Simulation based inference

[Brehmer et al.,1805.00013]



Matrix element information

Explicit BSM models

How can we generate these CPV interactions in concrete UV models?

- Fermion interactions
  - Simplest possibility: mixing with CP-odd BSM state (e.g. 2HDM)
  - Also possible: mixing with vector boson, loop-level contribution
- Gauge interactions
  - No tree-level CP-odd coupling possible → no CPV at the tree level
    - CP-odd scalar has no tree-level couplings to vector bosons.
  - Must be induced at the loop level.

⇒ Generic expectation: CPV in HVV couplings loop-suppressed in comparison to Hff couplings

Explicit BSM models

Most studied model:
complex 2HDM
with mixing between
two CP-even and
one CP-odd Higgs boson

Introduces that mixing of eigenstates we were missing!

$$\frac{\mathcal{M}^2}{v^2} = \begin{pmatrix} Z_1 & \mathrm{Re}(Z_6) & -\mathrm{Im}(Z_6) \\ & Y_2/v^2 + \frac{1}{2}Z_{345}^{+} & -\frac{1}{2}\mathrm{Im}(Z_5) \\ & & Y_2/v^2 + \frac{1}{2}Z_{345}^{-} \end{pmatrix}$$

$$R\mathcal{M}^2 R^\top = \mathrm{diag}(m_1^2, m_2^2, m_3^2)$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \\ a^0 \end{pmatrix} ,$$

CP violation through SMEFT

Taylor expansion of Lagrangian in terms of Λ: the scale of new physics

Effective Lagrangian

$$\mathcal{L} = \frac{1}{\Lambda^0}\mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(d=6)} + \ldots = \mathcal{L}_{\mathrm{NP}}$$

SM Lagrangian, no information about Λ

Weinberg operator corresponding to majorana-ν mass

Leading contribution for Higgs physics

Lagrangian with new particles at Λ

CP violation through SMEFT

Taylor expansion of Lagrangian in terms of Λ: the scale of new physics

Effective Lagrangian

$$\mathcal{L} = \frac{1}{\Lambda^0}\mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(d=6)} + \ldots = \mathcal{L}_{\mathrm{NP}}$$

$$\mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)}$$

Are all possible local interactions with c_i the Wilson coefficients - free parameters of model

2499 operators at d=6 with L= B=0, 60 CP-even operators with U(3)5 flavour symmetry

CP violation through SMEFT: Dimension 4

After redefining phases away in the SM part (dim<=4), 2 sources of CP violation remain

1. The phase in the CKM matrix, describing charged current interactions between W and left-handed quarks.
2. A combination of an angular parameter and the phase of the determinant of the quark matrix.
   - This phase should lead to an EDM of the neutron and composite nuclei.
   - The effects of this phase has not been observed so far and we have only stringent limits.

CP violation through SMEFT: Dimension 5

Neutrino masses can violate CP if they are complex!

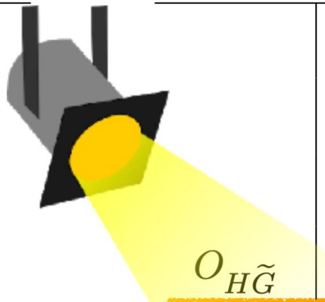
$$\mathrm{CP}[\mathscr{L}_{D=5}] = \left(1 + \frac{h}{\mathrm{v}}\right)^2 \frac{\mathrm{v}^2}{\Lambda_L} \left[c_{\alpha\beta} \bar{\nu}_\alpha \bar{\nu}_\beta + \bar{c}_{\alpha\beta} \nu_\alpha \nu_\beta \right]$$

Caveat: Dimension 5 usually ignored at LHC experiment do to Lepton-Baryon number violation

CP violation through SMEFT: Dimension 6

Consider CP violating wilson operators

$$\mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)}$$



Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\|H^\dagger D_\mu H\right\|^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_W	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_G	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

CP violation through SMEFT: Dimension 6

$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
$O_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
$O_{\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Consider CP violating wilson operators

$$\mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)}$$

$$\mathscr{L}_{\mathrm{SMEFT}} \supset \frac{h}{\mathrm{v}}\Big[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu$$

← **SM interactions**

$$+\tilde{c}_{ww} W^+_{\mu\nu}\widetilde{W}^-_{\mu\nu} + \tilde{c}_{\gamma\gamma} F_{\mu\nu}\widetilde{F}_{\mu\nu} + \tilde{c}_{z\gamma} F_{\mu\nu}\widetilde{Z}_{\mu\nu} + \tilde{c}_{zz} Z_{\mu\nu}\widetilde{Z}_{\mu\nu}\Big]$$

← **New CP violating interactions**

4 couplings $\tilde{c}_{\mathrm{vv}}$ from 3 Wilson coefficients $c_{H\tilde{B}}$, $c_{H\tilde{W}}$, $c_{H\tilde{W}B}$

Intermezzo: EDM

Note: I am not an expert on this!

Several EDMs are sensitive to CP violation in the Higgs sector via 2L Bar-Zee diagrams.

Bounds strongly depend on assumptions about

- First-generation Yukawa coupling
- Absence of other CP-violating BSM physics

Taking a look at some measurements

How to look for CPV in the Higgs sector

- Look for deviations in SM predictions for Higgs boson rate measurements
  - Cannot distinguish CP-even from CP-odd
- Measure shape effects on CP-sensitive observables: Angles, Optimal observables, etc

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- Look for deviations in SM predictions for Higgs boson rate measurements
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$$\mathcal{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

Fermionic couplings

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

Taking a look at some measurements

How to look for CPV in the Higgs sector

- Look for deviations in SM predictions for Higgs boson rate measurements
    - Cannot distinguish CP-even from CP-odd
- Measure shape effects on CP-sensitive observables: Angles, Optimal observables, etc

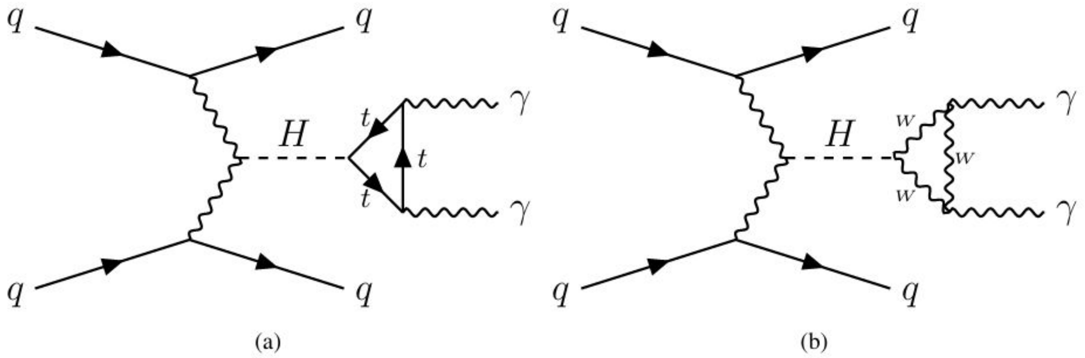
$$\mathscr{L}_{VVH} = \mathscr{L}_{SM} + \frac{c_i}{\Lambda^2}\phi \tilde{V}_{\mu\nu} V^{\mu\nu} + \dots$$

Bosonic couplings

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

Measurement: Di-photon

Vector-boson fusion production of a Higgs boson and subsequent decay into two photons $H \rightarrow \gamma\gamma$ via (a) a top-quark loop and (b) a W-boson loop.



Measurement: Di-photon

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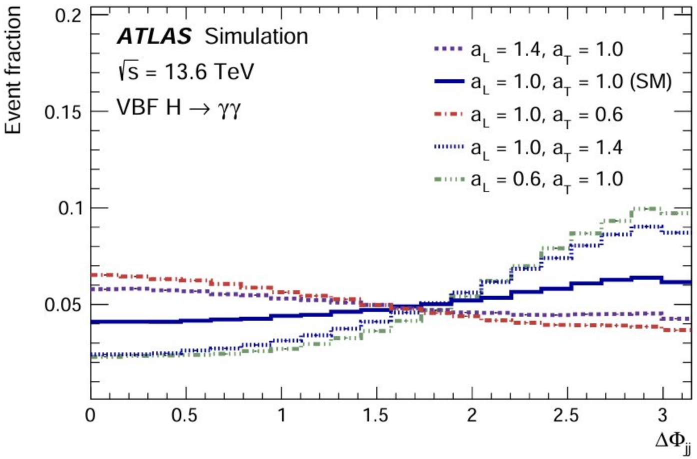
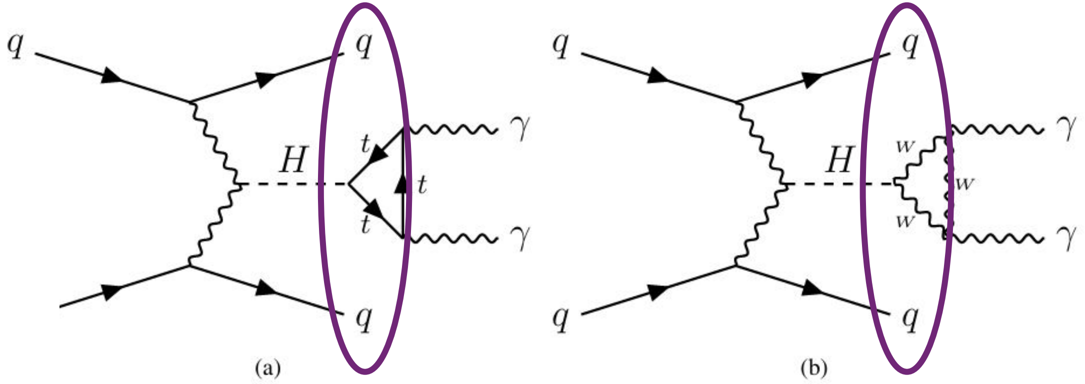
Angle between the jets





Measurement: Di-photon

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Using 'optimal observable'

$$\mathcal{OO}_i = \frac{2\mathrm{Re}\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM},i}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}\,.$$

With the SMEFT parameterization and remembering

$$|\mathcal{M}|^2 = c^2_{\mathrm{even}}\left|\mathcal{M}^{\mathrm{CP-even}}\right|^2 + \underbrace{2c_{\mathrm{even}}c_{\mathrm{odd}}\mathrm{Re}[\mathcal{M}^{\mathrm{CP-even}}\mathcal{M}^{\mathrm{CP-odd}^*}]}_{\text{interference}} + c^2_{\mathrm{odd}}\left|\mathcal{M}^{\mathrm{CP-odd}}\right|^2$$

Measurement: Di-photon

shown for various configurations of the Wilson coefficient *cHWtilde*

One parameter only

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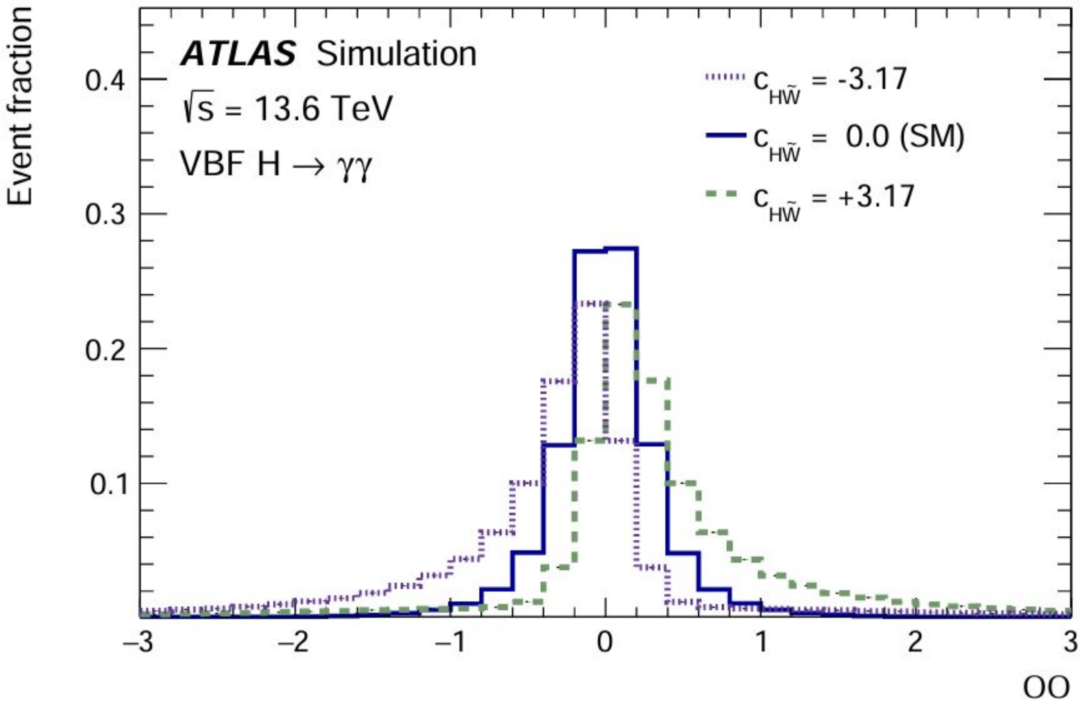
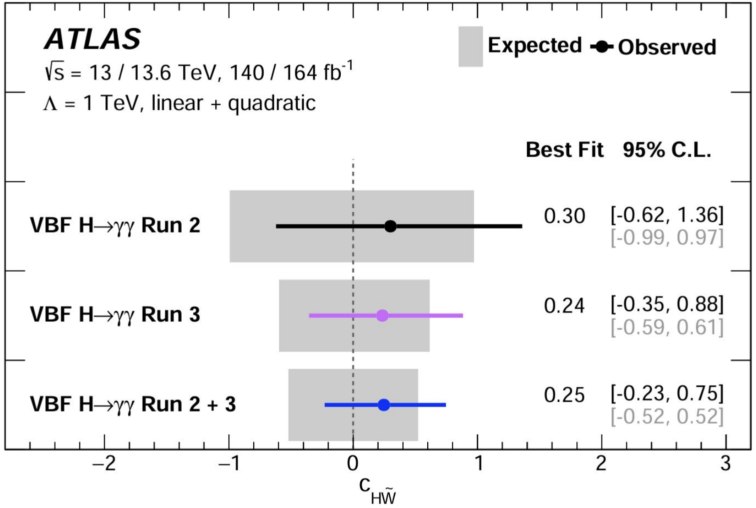
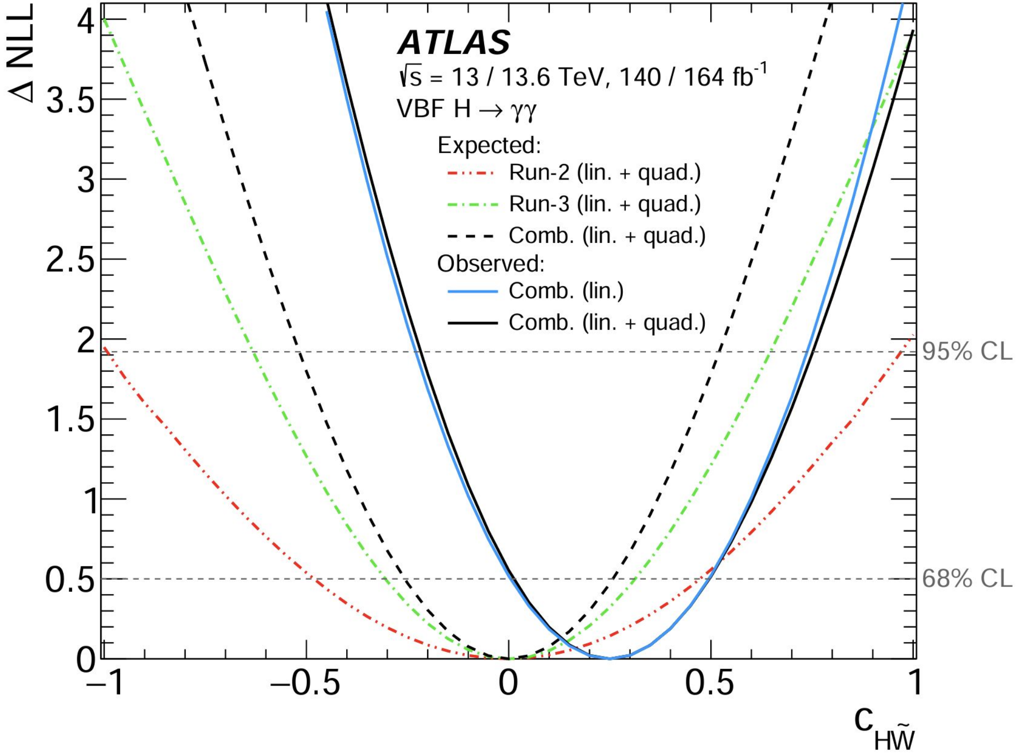


Measurement: Di-photon

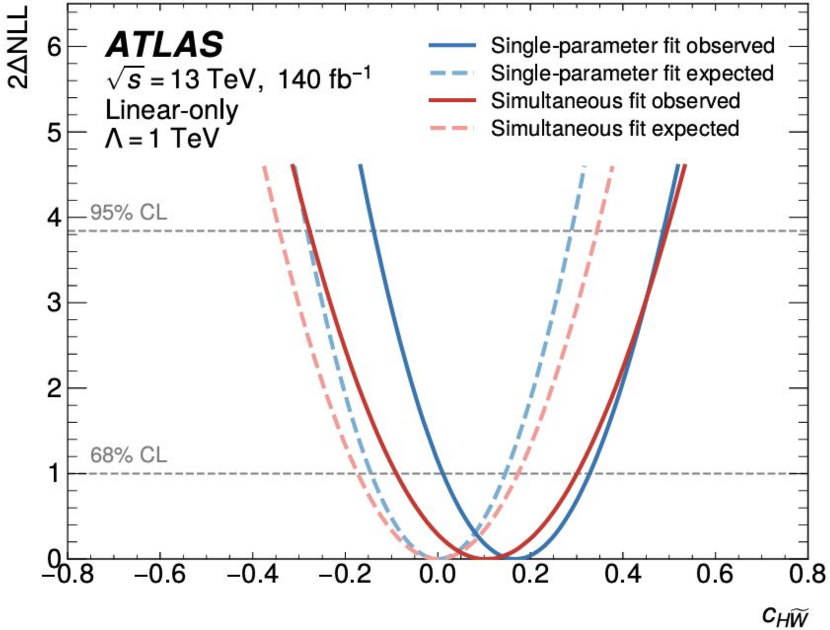
Compatible with the SM in Run 2 and Run 3
➔ Similar deviations

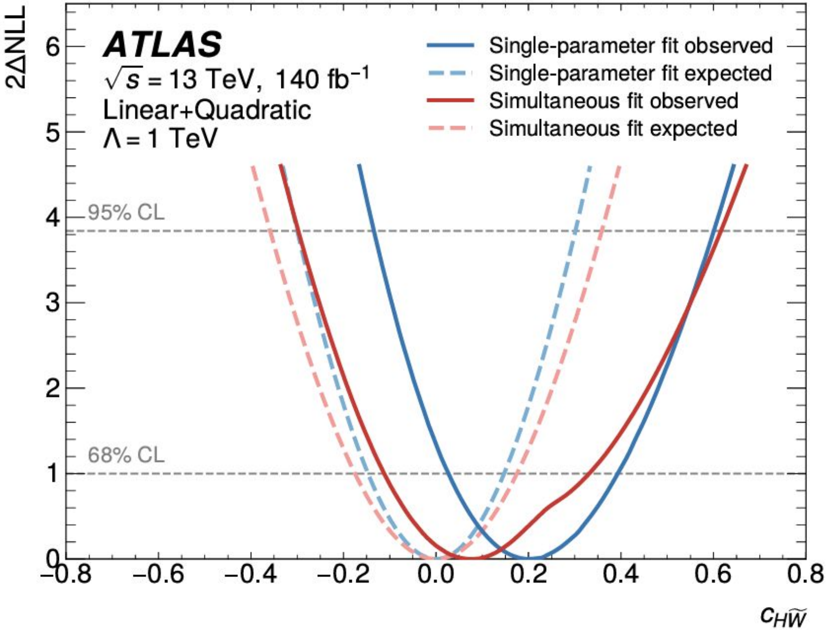




Measurement: Combined SMEFT CP

Results from $H \rightarrow \tau\tau$, $H \rightarrow WW*$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ*$, and WH,$H \rightarrow b\bar{}b$ channels are combined.





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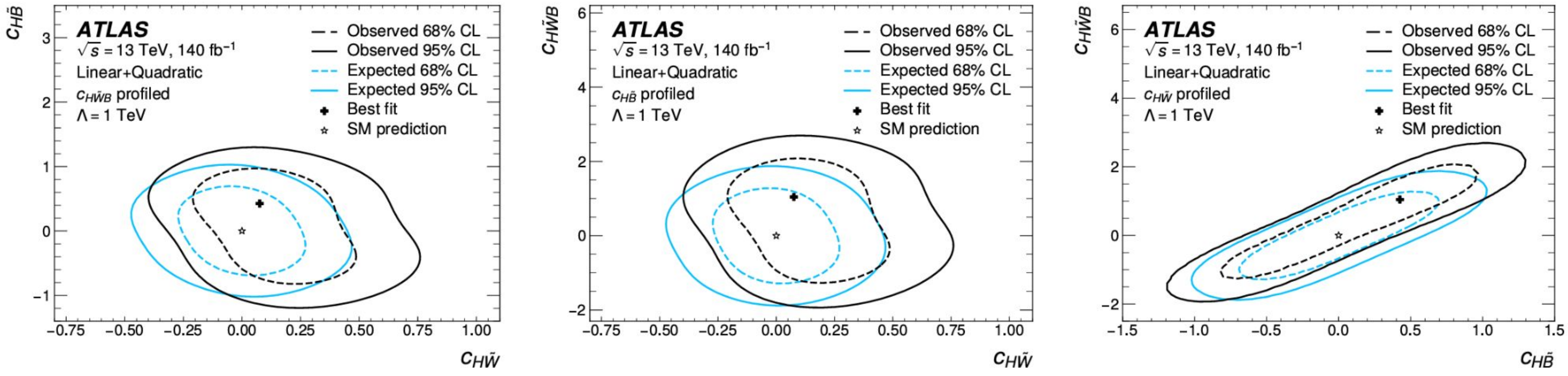

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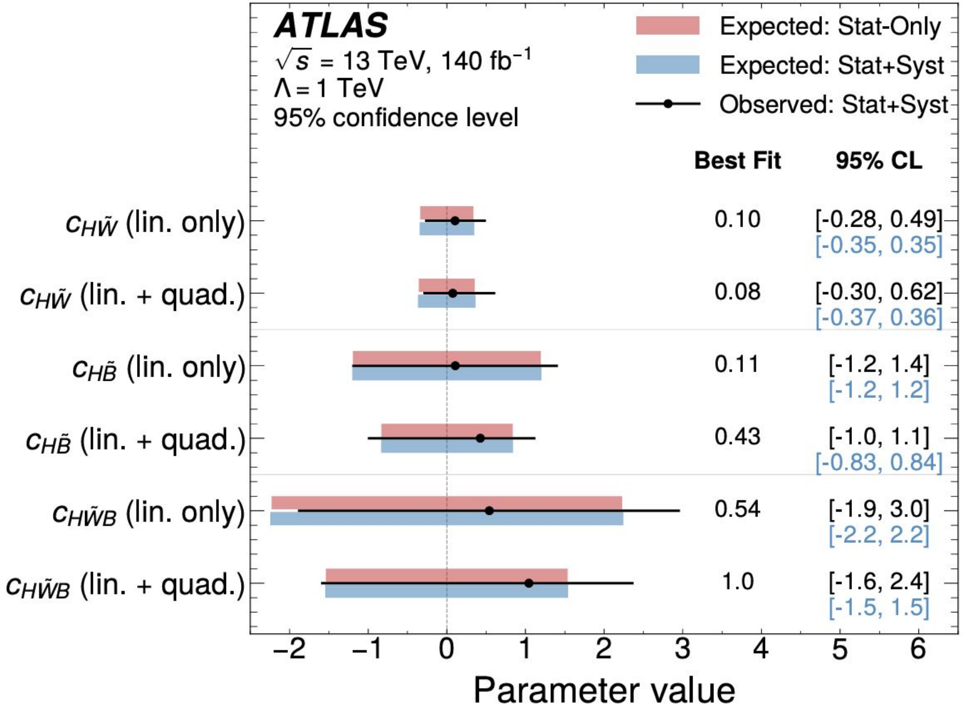
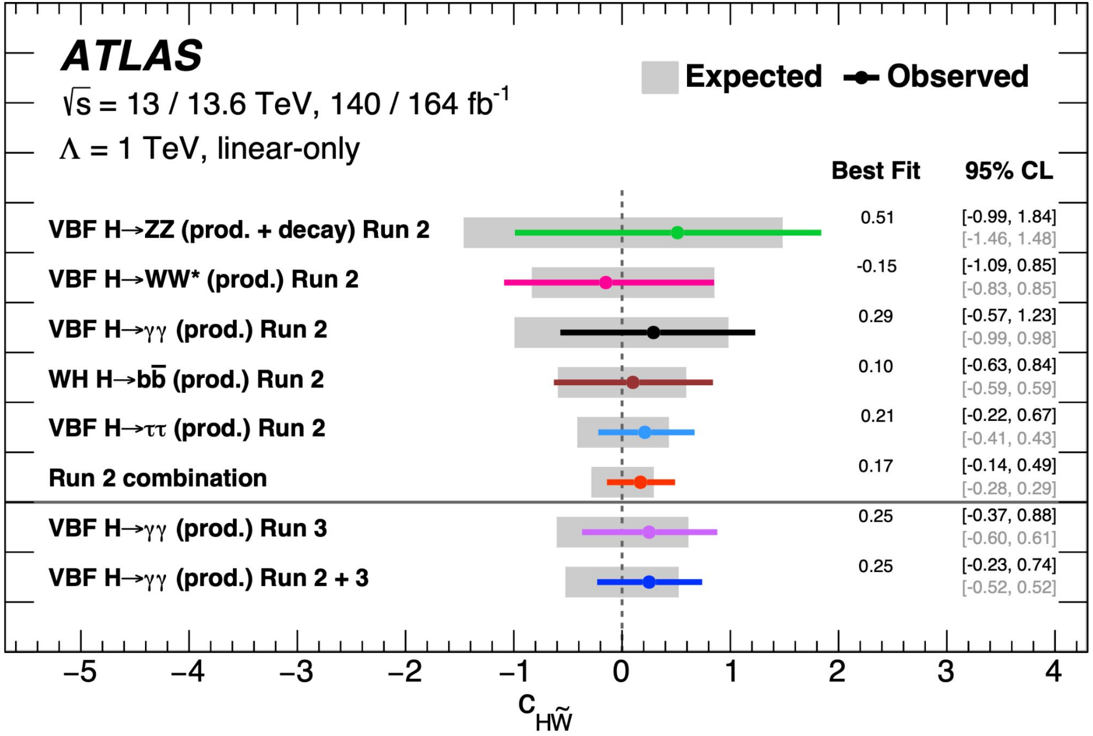


Measurements

No sign for CP violation in Higgs sector yet

➔ Going towards not being statistically limited finally

➔ Some small deviations all in the same direction



Conclusions

Characterizing the CP nature of the Higgs boson is an important goal for the (HL-)LHC
Key points to remember:

- Novel analysis methods promise significant precision improvements,
  - Should not rely on assumption that only one Higgs coupling deviates from SM → need more global analyses,
- Correlated parameters and CP dependencies in backgrounds
- Concrete BSM models allow to exploit complementarity with direct searches, etc