Search for CP violation in the Higgs sector at ATLAS and CMS

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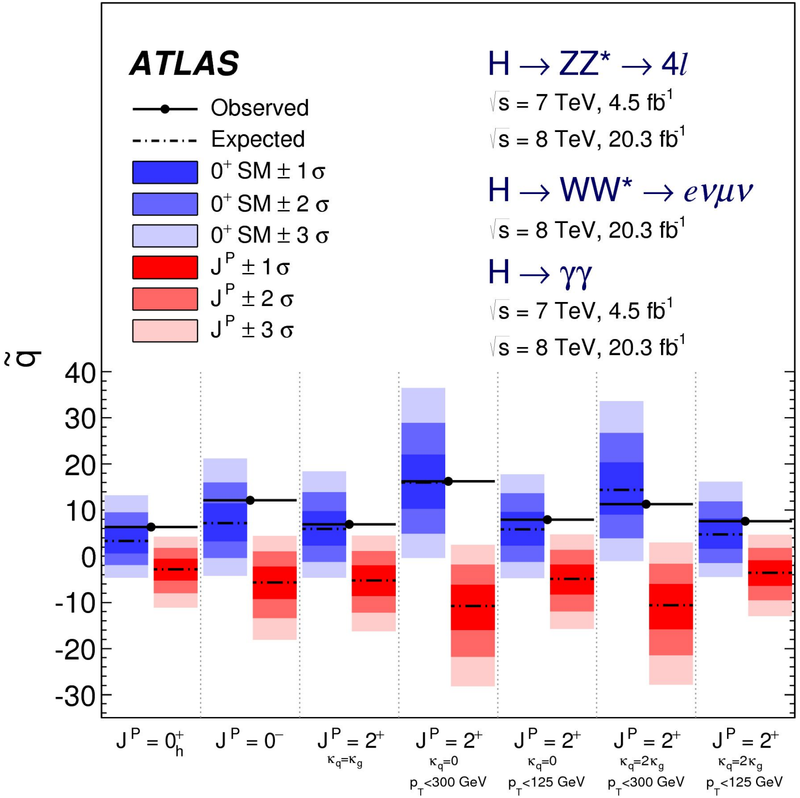
Moriond EW, March 21, 2026

What is already known about the Higgs?

- For the uninitiated...
- Basic properties of the (SM?) Higgs boson
  - Measured mass
    125.07 ± 0.09 (stat) ± 0.10 (syst) GeV(CMS),
    similar from ATLAS
  - Expected (measured) width
    - $3.2^{2.4}_{-1.7}$ MeV: CMS,
      Nat. Phys. 18, 1329−1334 (2022),
      similar from ATLAS
    - Expect 4.1 MeV
  - Spin 0, CP even
    - Already determined in Run 1



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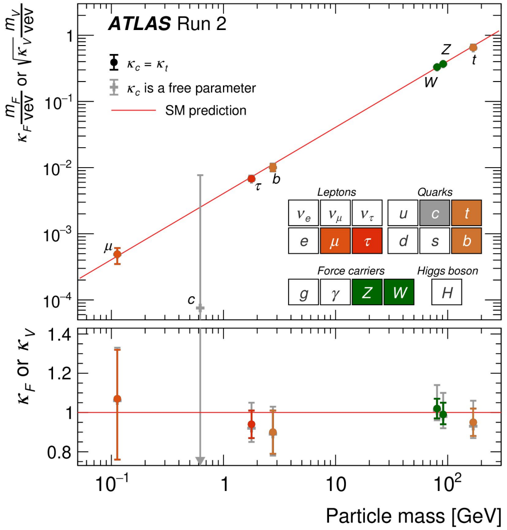
Why look for CP violation in the Higgs sector?

- Baryon asymmetry needs new CP violation
- The Higgs sector is a well-motivated place to look
- LHC precision measurements provide the test bed
- CP violation searches generally build upon previous work



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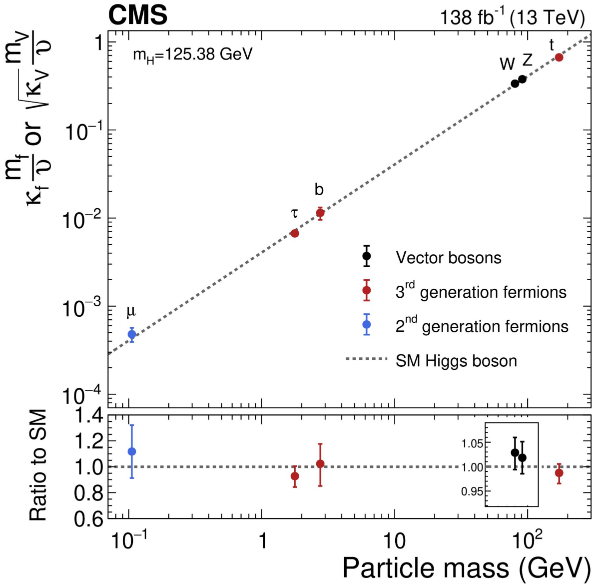

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Interpretations

- ATLAS
  - Interprets its results in terms of three CP-odd SMEFT operators, generally in the Warsaw basis

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathscr{O}_i^{(6)}$$

$$|\mathscr{M}|^2 = |\mathscr{M}_{SM}|^2 + 2\sum_i \frac{c_i}{\Lambda^2} Re(\mathscr{M}^*_{SM}\mathscr{M}_{BSM,i}) + \sum_i \sum_j \frac{c_i c_j}{\Lambda^4} Re(\mathscr{M}^*_{BSM,j}\mathscr{M}_{BSM,i})$$

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	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

- CMS
  - Starts from an **amplitude decomposition** for HVV interactions, with terms like a_3 for the CP-odd piece
  - Reports results in terms of e.g. f_{a3}, the fraction of the observed Higgs interaction strength that behaves like the CP-odd a_3 tensor structure

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \cdots}\,\mathrm{sgn}\left(\frac{a_3}{a_1}\right)$$

CP-sensitive Observables

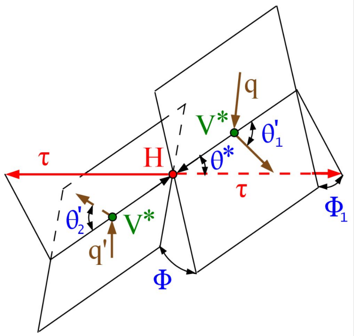
- $\Delta\phi_{jj}$ and related individual kinematic variables

- Matrix Element Likelihood Analysis (MELA)
  - Uses matrix elements to construct **per-event probabilities or discriminants** for different hypotheses
  - Can target **signal vs background** and/or **CP-even vs CP-odd or mixed states**

- Optimal observables
  - Built from the **interference term** between the SM CP-even amplitude and a CP-odd BSM amplitude

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

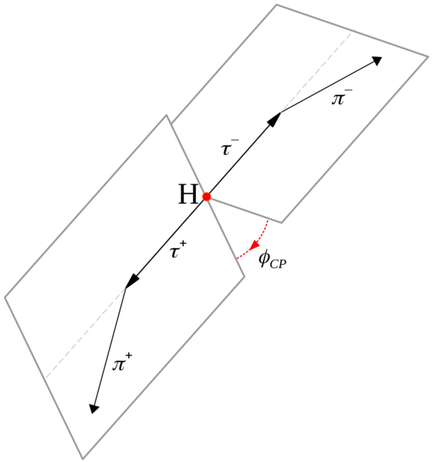
  - **CP-odd by construction**: it is symmetric with vanishing mean for a purely CP-even Higgs, and becomes asymmetric when CP-odd contributions are present



CP Violation in ffH Couplings

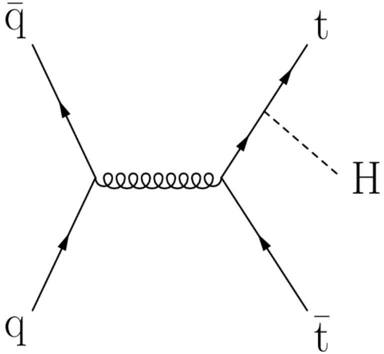
Sensitive to $\tau\tau$H

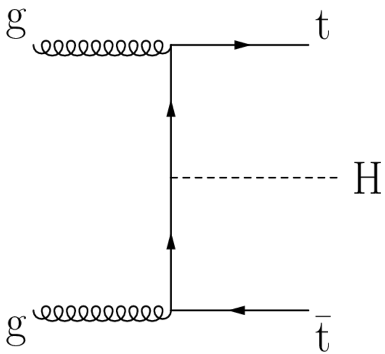
- CMS Run 2 H→$\tau\tau$
- ATLAS Run 2 H→$\tau\tau$



Sensitive to ttH

- (new) **ATLAS Run 2 ttH→multilepton**
- CMS Run 2 ttH→multilepton
- CMS Run 2 ttH→$\gamma\gamma$
- ATLAS Run 2 ttH→$\gamma\gamma$
- ATLAS Run 2 ttH→bb





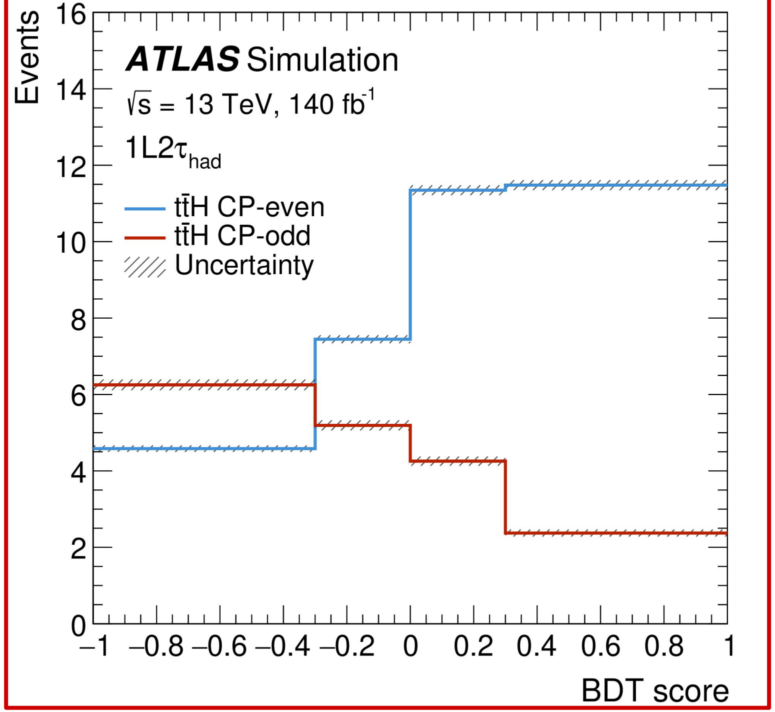
Partial Run 2 results are unlisted

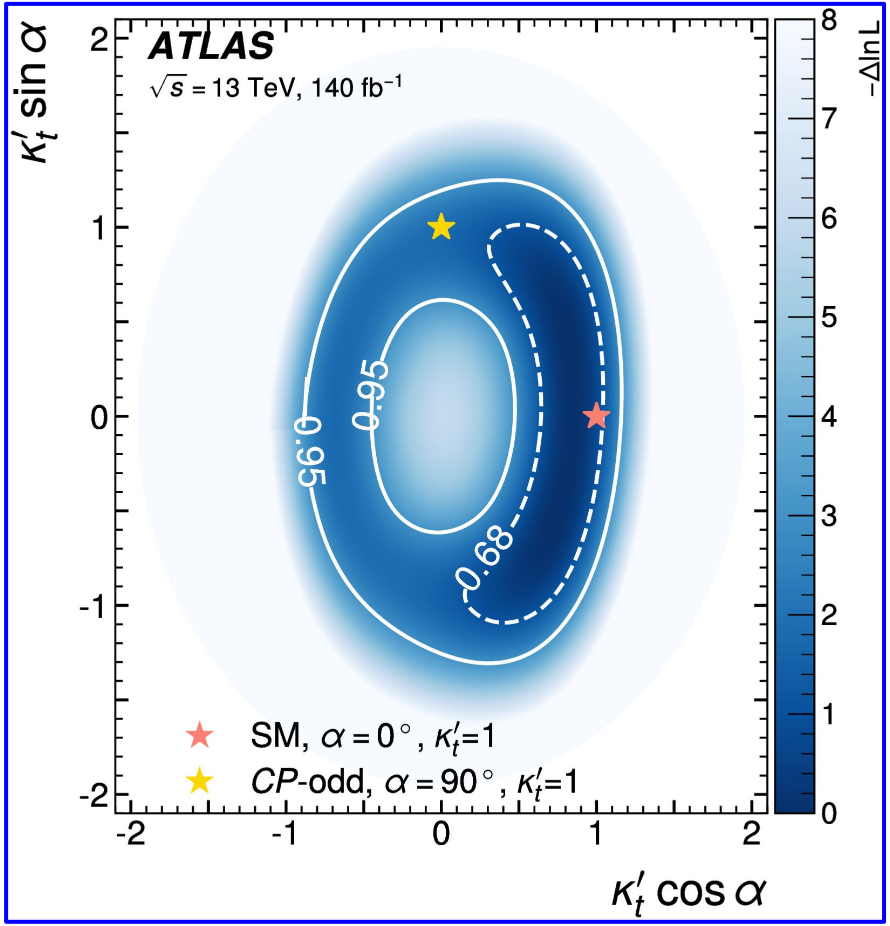
Will focus on new measurements of the CP properties of HVV interactions

ATLAS ttH ML

BDT to distinguish CP-even and CP-odd signals

|α|>62° excluded at 68% CL

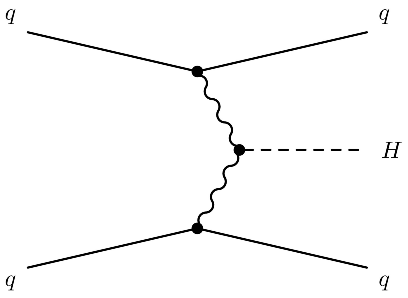


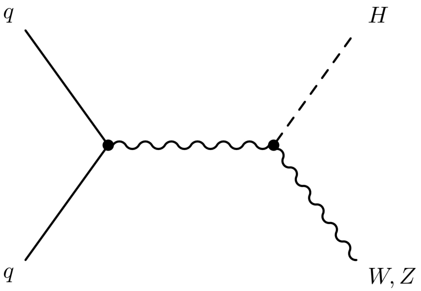


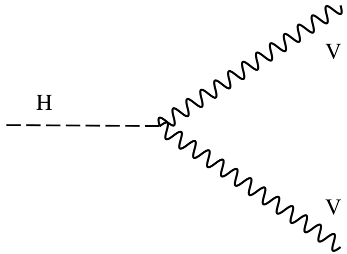
CP Violation in VVH Couplings

Sensitive to VVH

- (new) **ATLAS HVV Combination**
- (new) **ATLAS Run 2 VBF H→ττ**
- **CMS Run 2 VBF/VH H→ττ**
- (new) **ATLAS Run 2 W(lν)H(bb)**
- **CMS Run 2 VH(bb)**
- (new) **ATLAS Run 2+3 VBF H→γγ**
- **CMS Run 2 H→ZZ**
- CMS Run 2 H→γγ
- ATLAS Run 2 VBF H→γγ
- ATLAS Run 2 H→WW
- ATLAS Run 2 H→ZZ







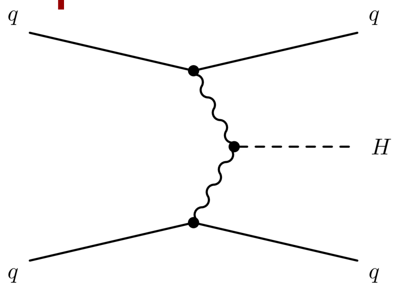
Partial Run 2 results are unlisted

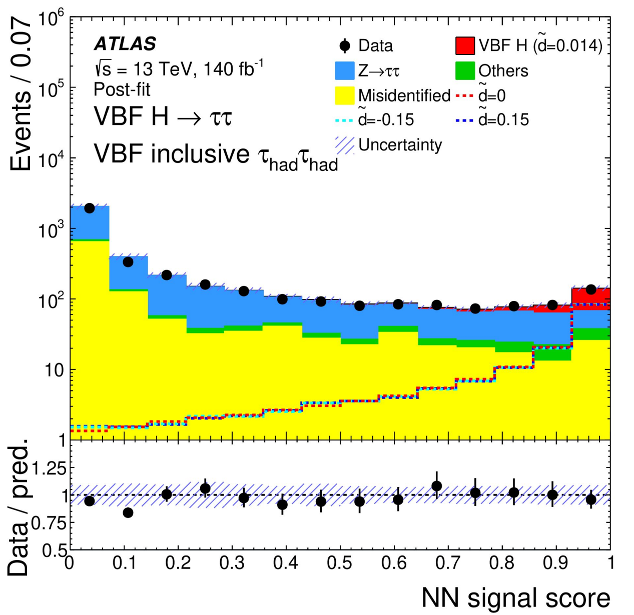
Will focus on new measurements of the CP properties of HVV interactions

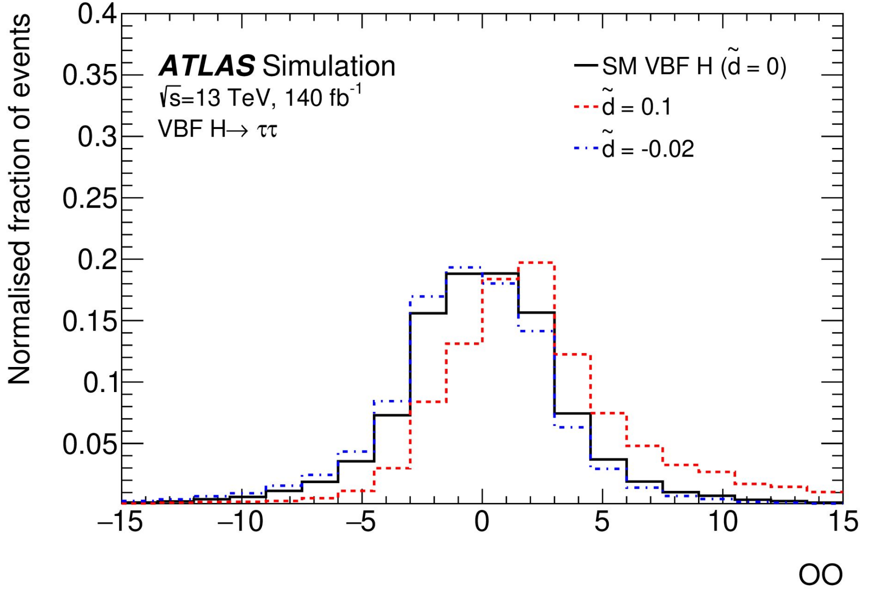
ATLAS VBF H→$\tau\tau$, NN categories + optimal observable fit

Define regions based on number of hadronic/leptonic τ and signal vs. **background NN**

Fit OO in each region to extract signal: CP-odd contributions induce an asymmetry / distortion in the OO distribution

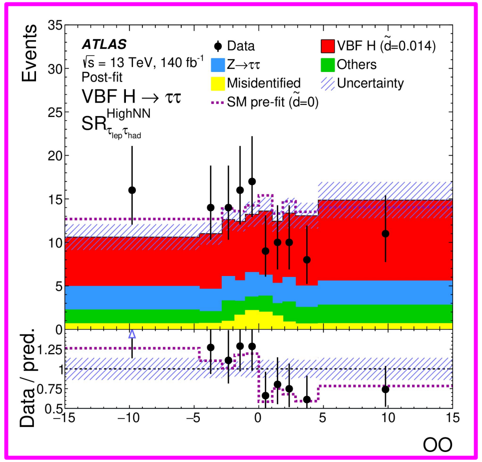


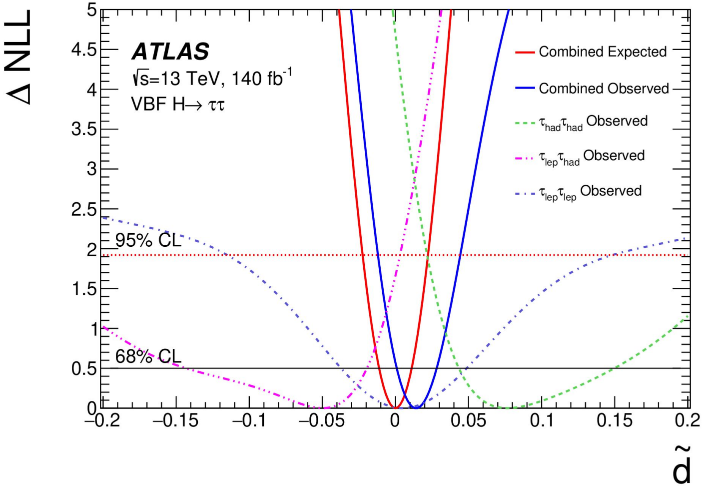


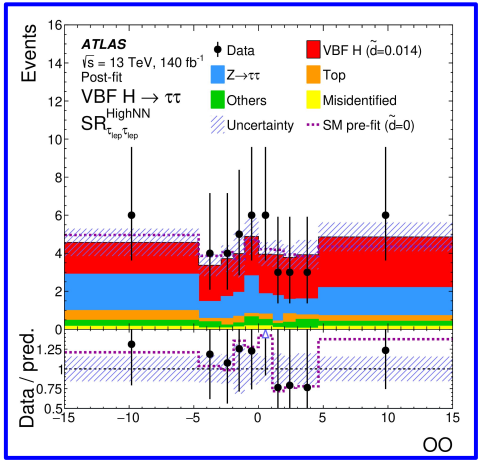


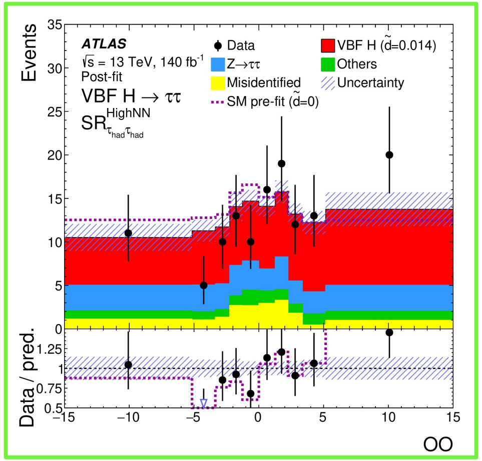
ATLAS VBF H→$\tau\tau$, Results

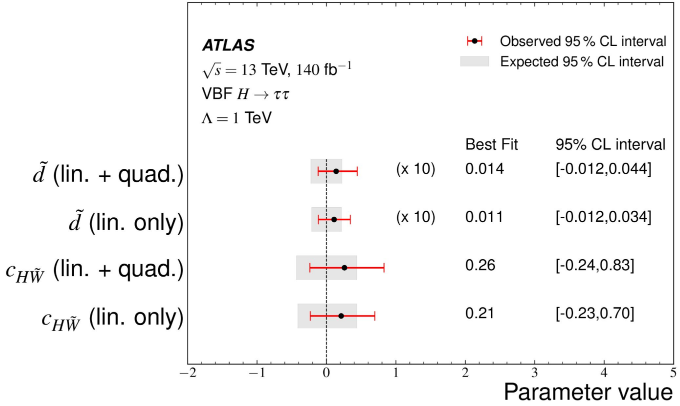
Observed limits consistent with SM; no evidence for CP-odd VVH admixture.









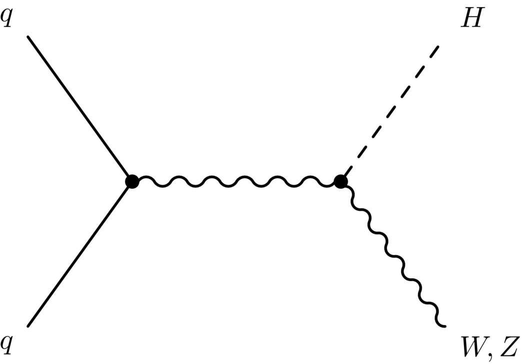


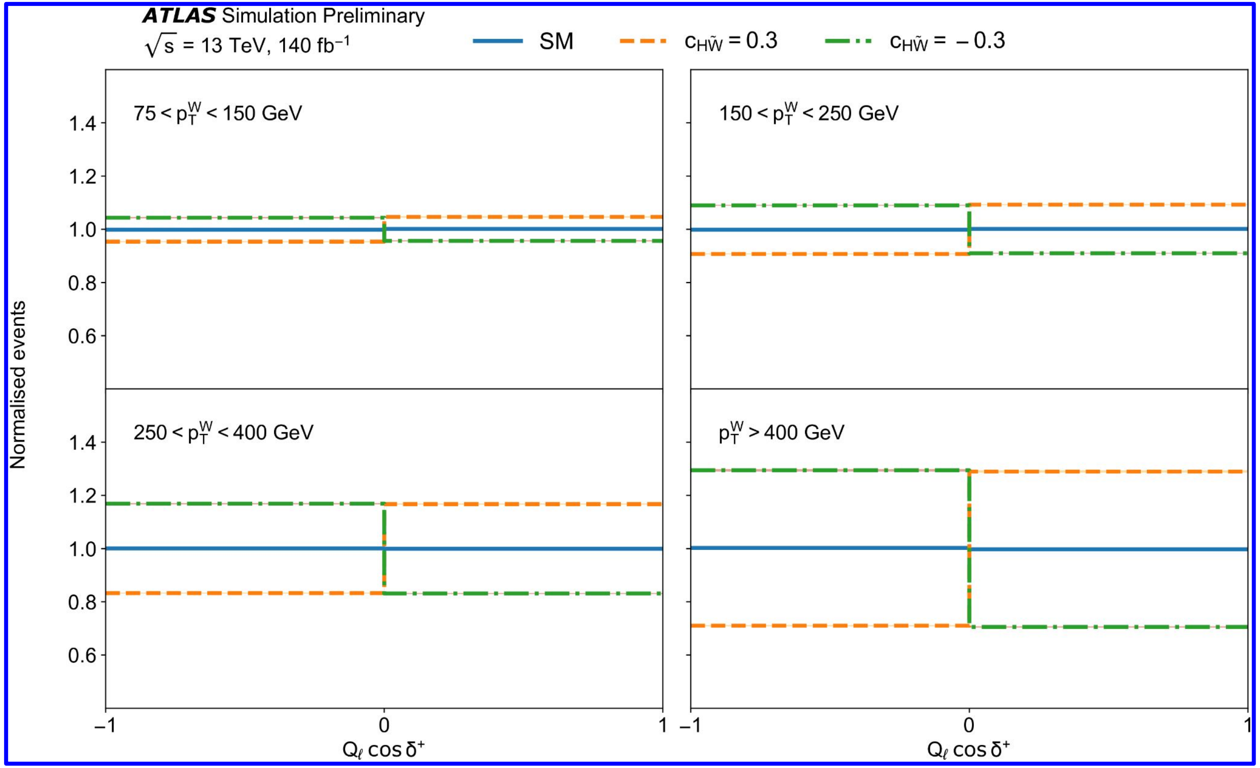
ATLAS WH(bb), Method

Selection/categorization similar to WH(bb) measurement, with NN fit to extract signal

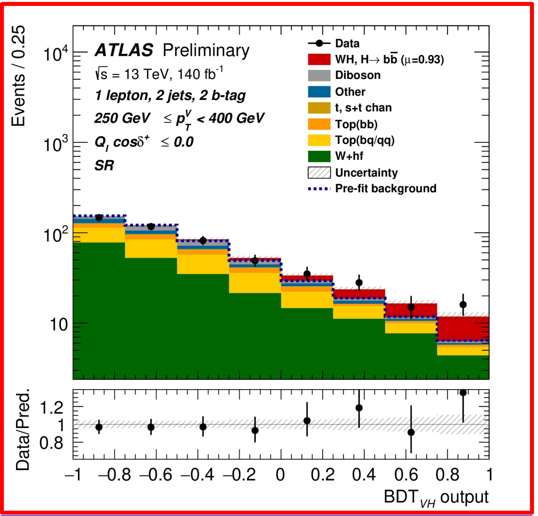
Extra categorization based on **CP-sensitive observable**:

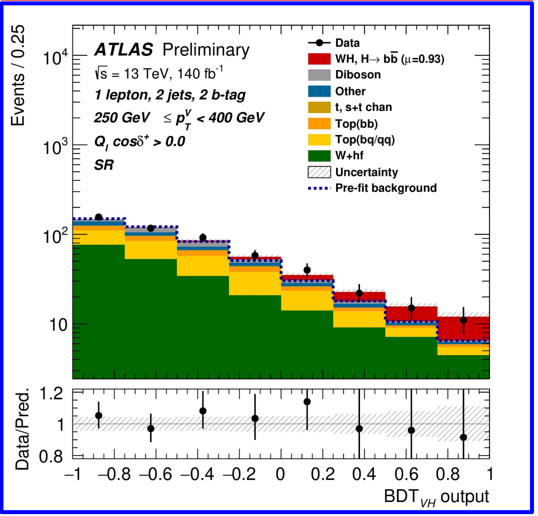
$$\cos\delta^{+} = \frac{\mathbf{p}_{\ell}^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_{\ell}^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}$$



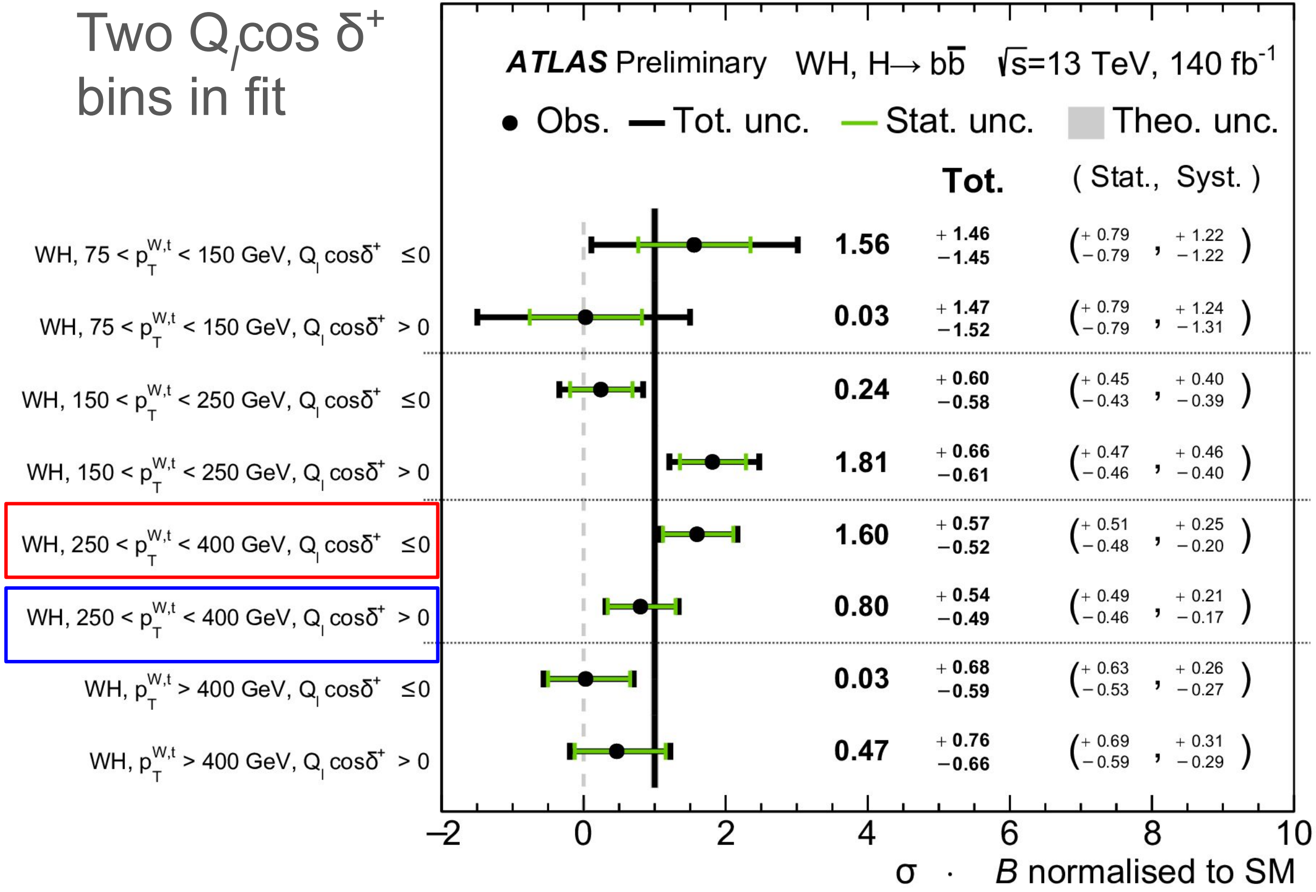


ATLAS WH(bb), Results





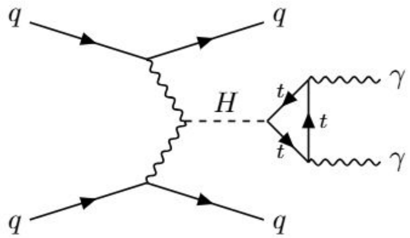
Two $Q_l \cos\delta^+$ bins in fit

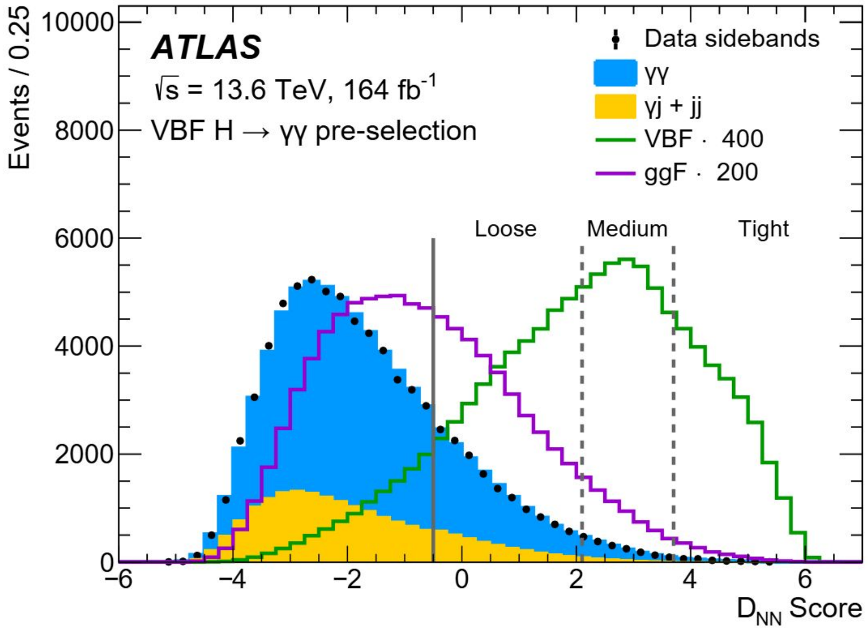


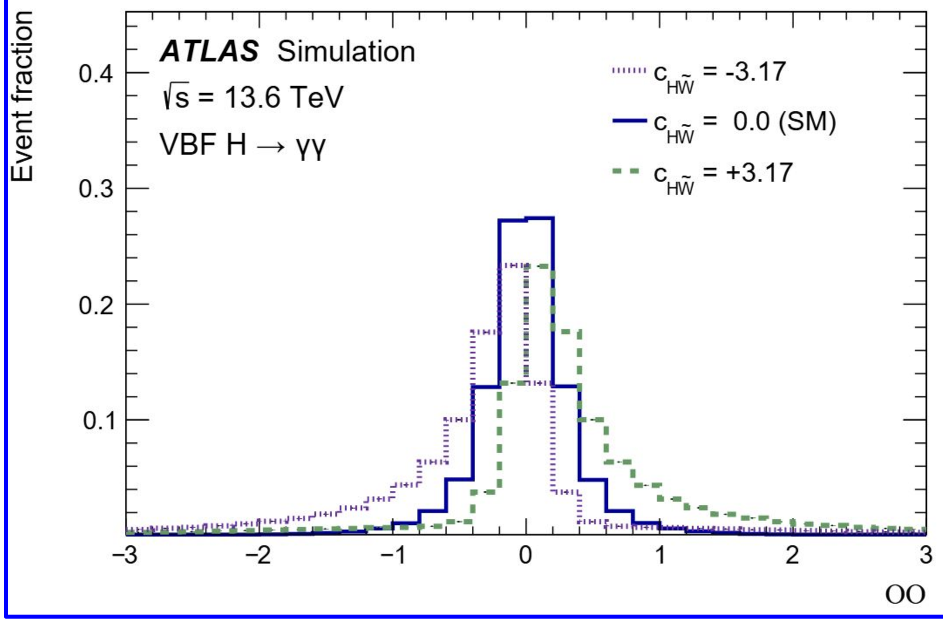
ATLAS VBF H→γγ, Method

Categorize events with **NN**

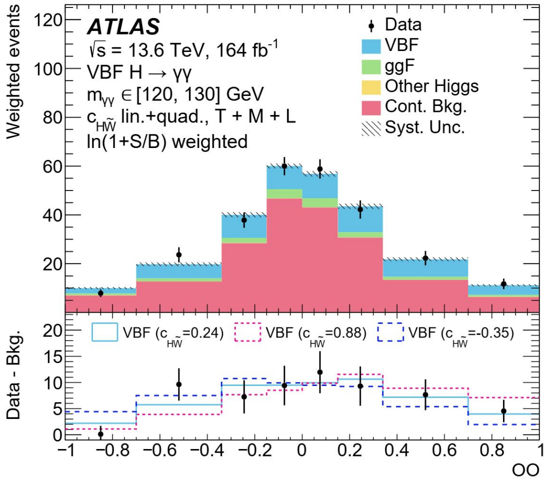
Fit to **OO distributions** to extract signal

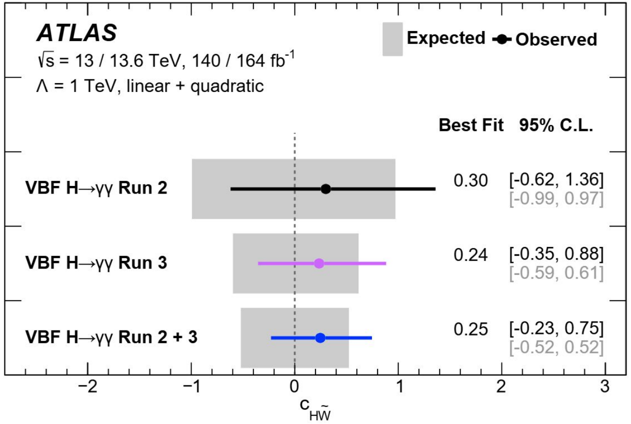


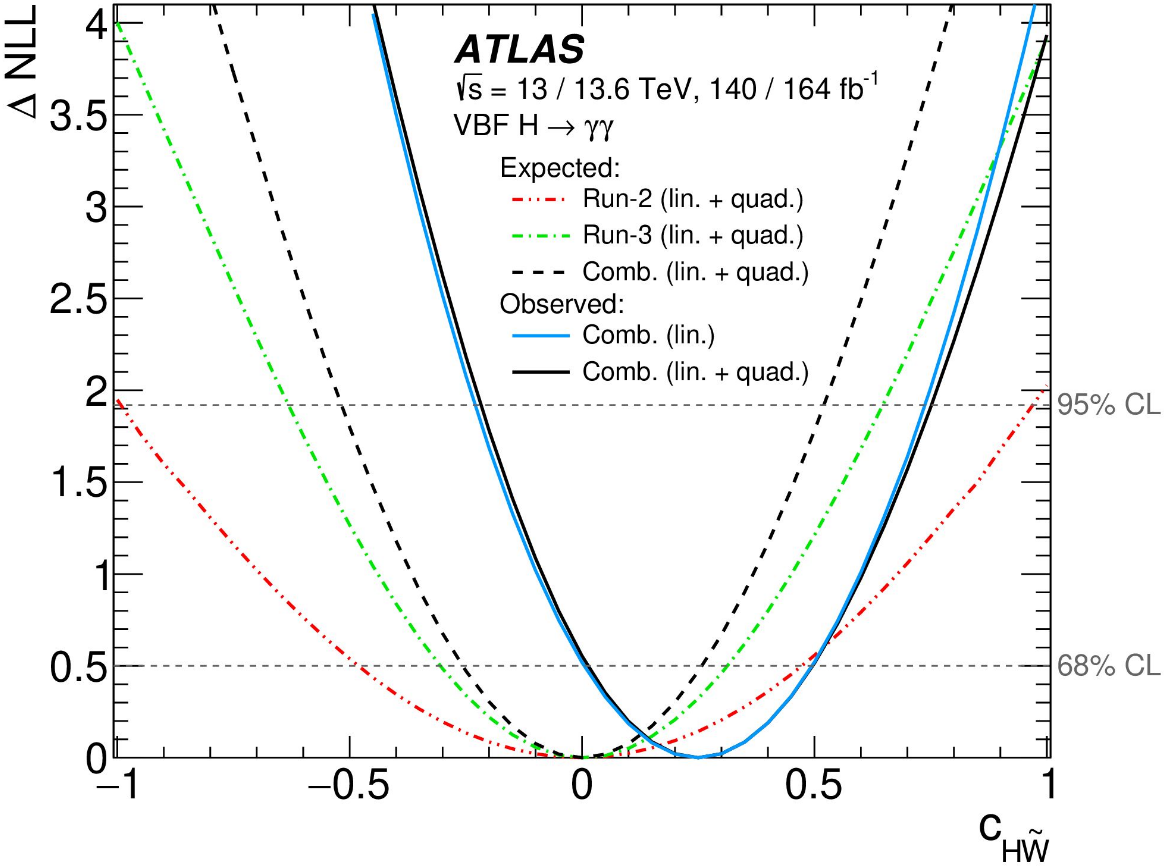




ATLAS VBF H→γγ, Results

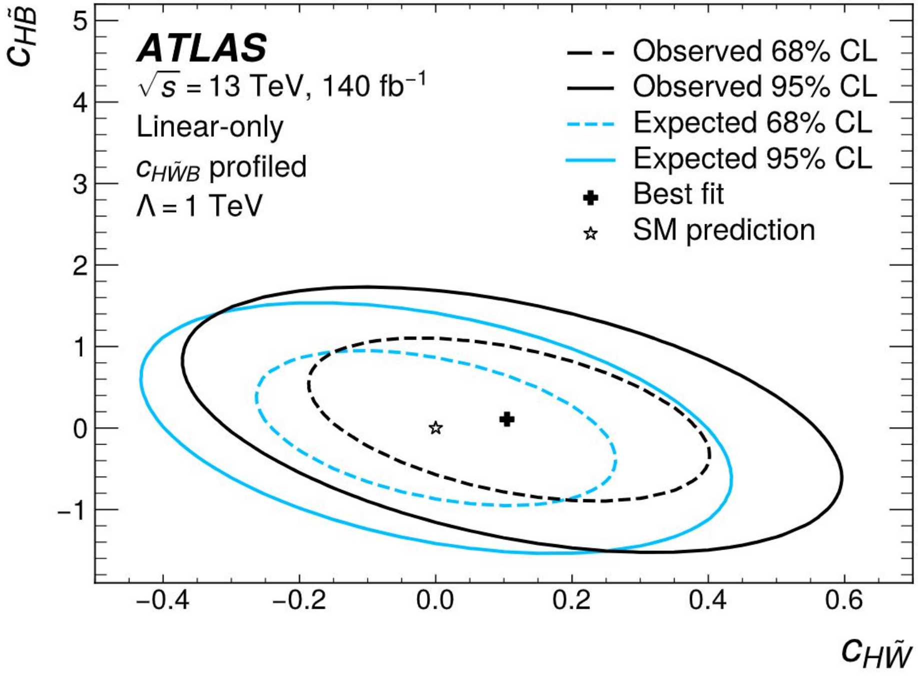


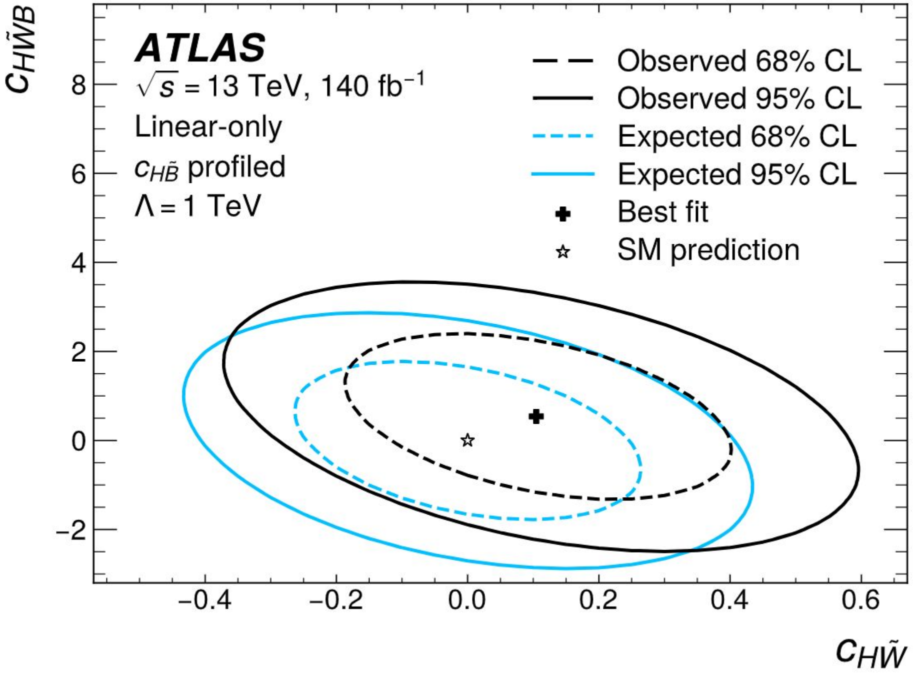




ATLAS VVH Combination

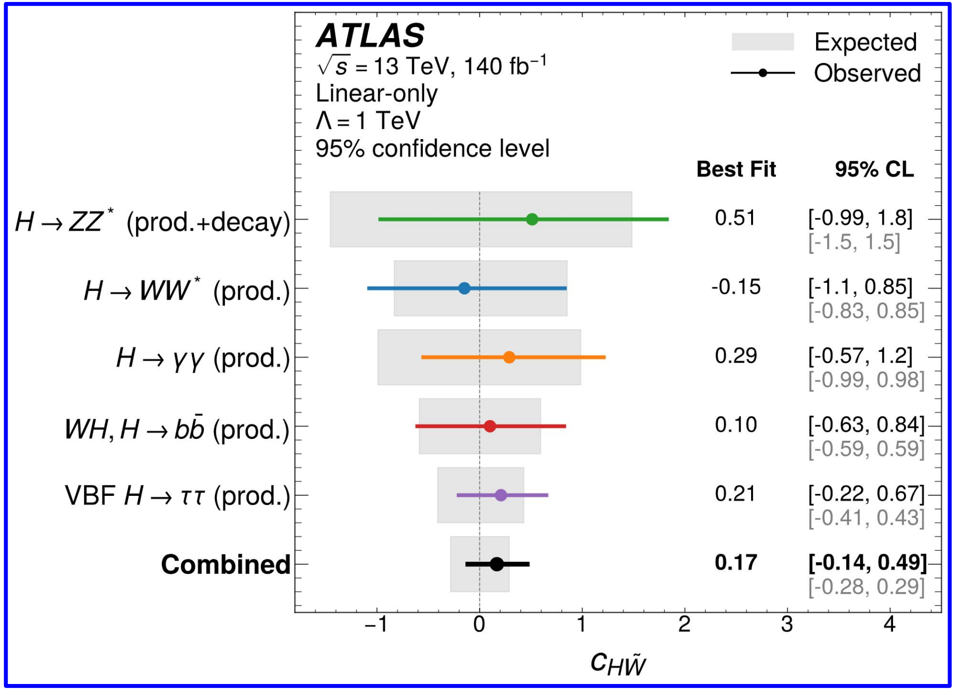
Simultaneous fit of all three parameters

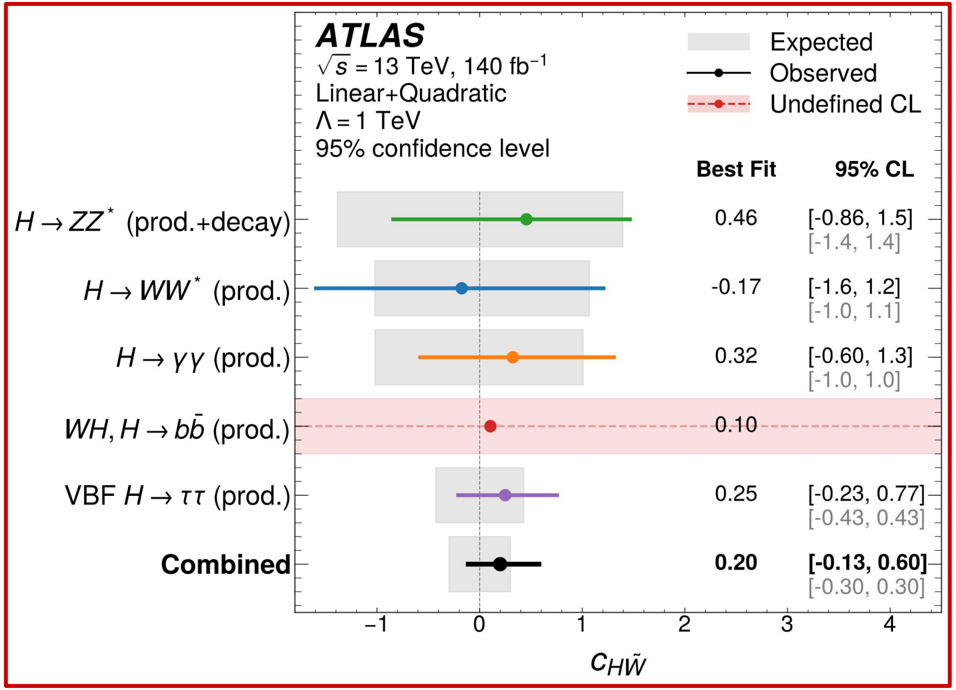




ATLAS VVH Combination

Similar results for **linear** vs. **linear+quadratic** terms

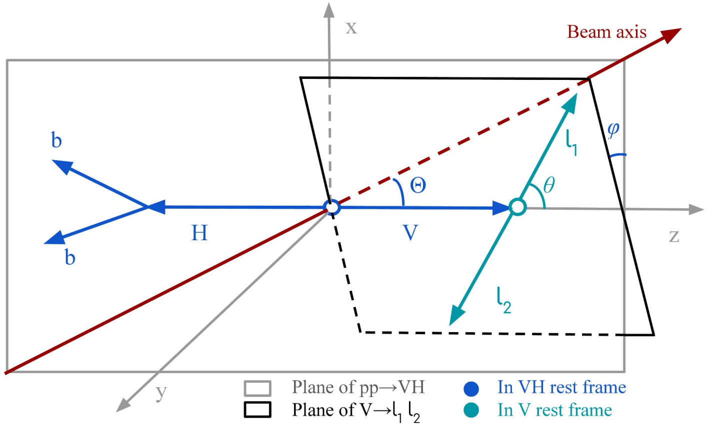


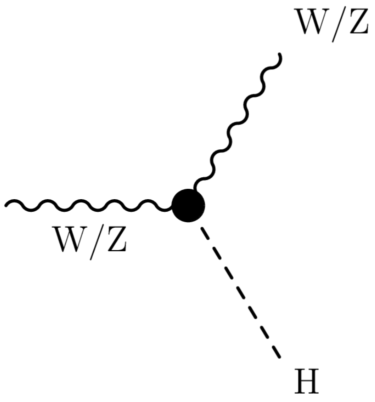


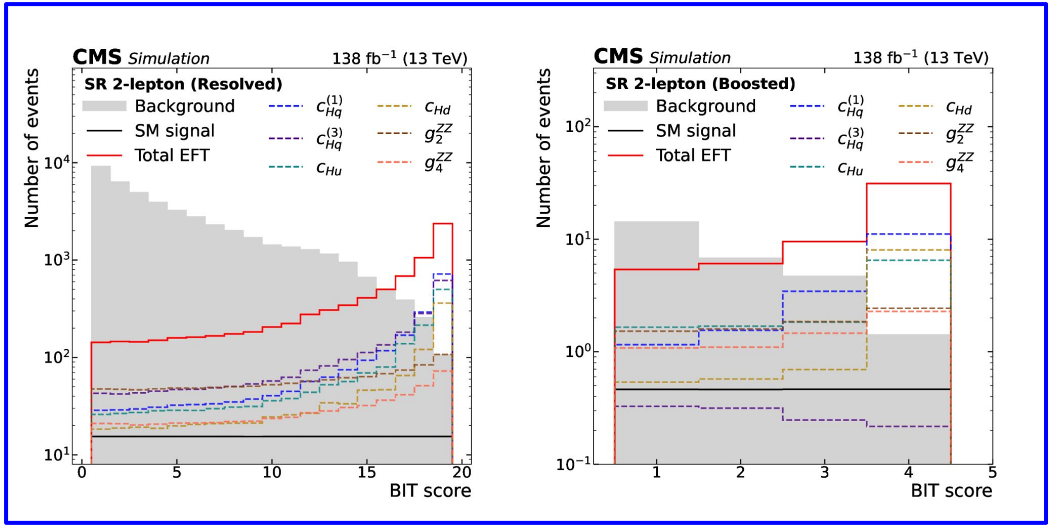
CMS VH(bb)

Include 0, 1, or 2L and boosted and resolved categories

BIT simultaneously separates signal/background and SM/BSM hypotheses.



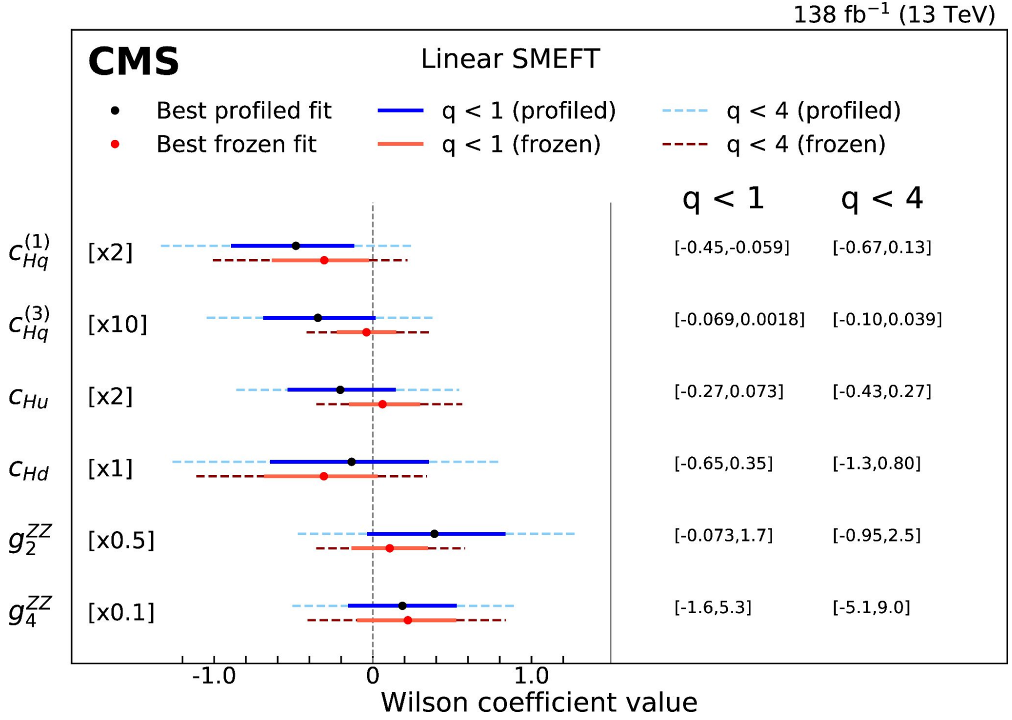


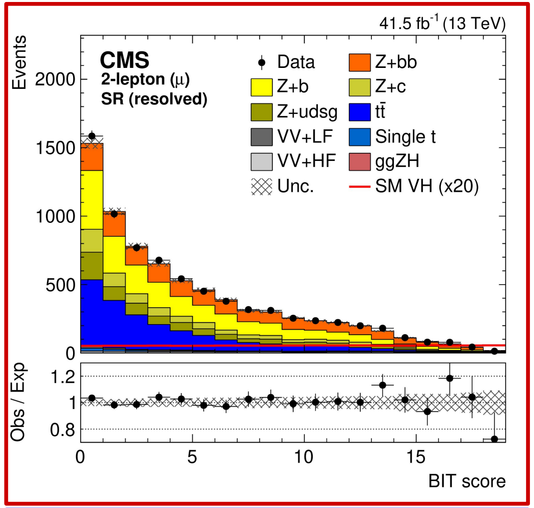


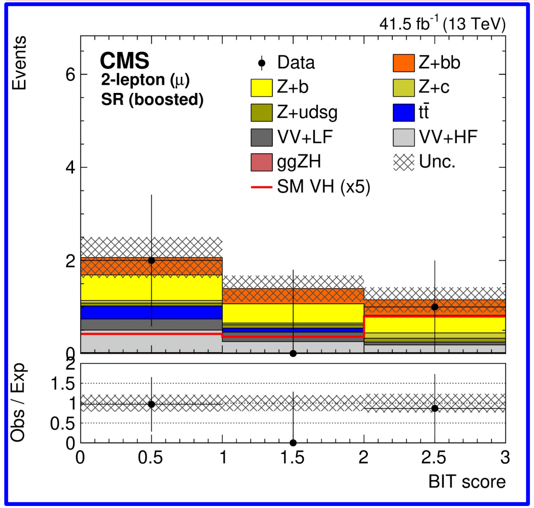
CMS VH(bb)

Example regions shown (**resolved** and **boosted** 2L)

No large deviations observed with respect to SM





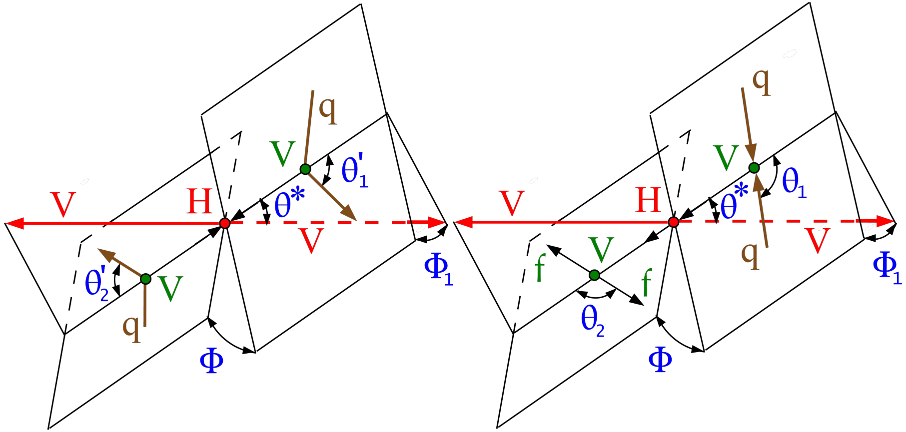


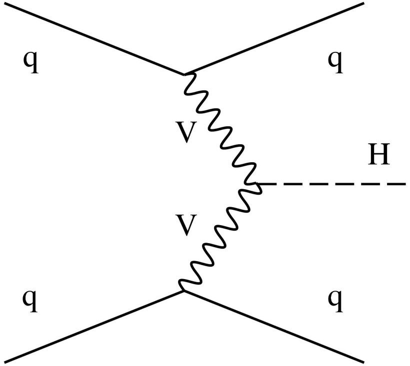
CMS H→ZZ

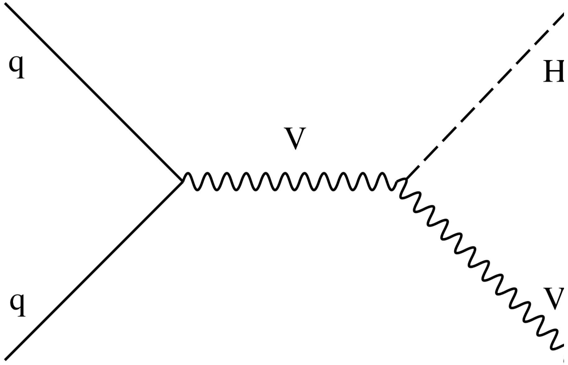
Production and decay each carry CP information

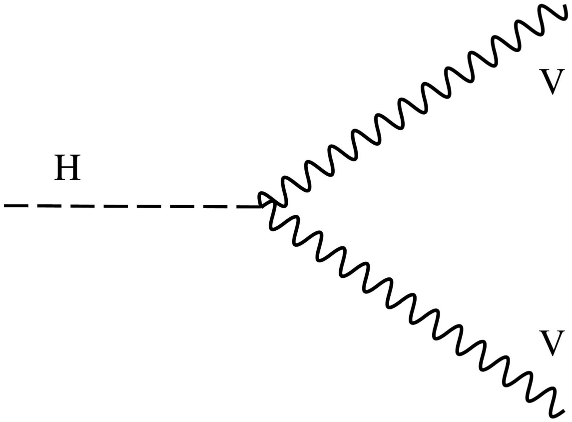
Angles in the Higgs rest frame capture it

MELA compresses this into discriminants



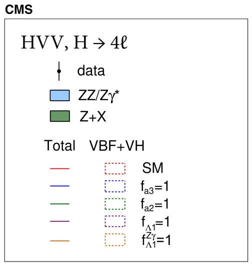


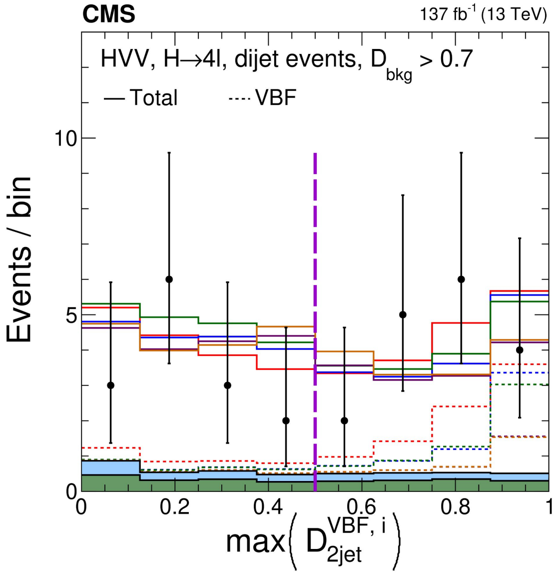


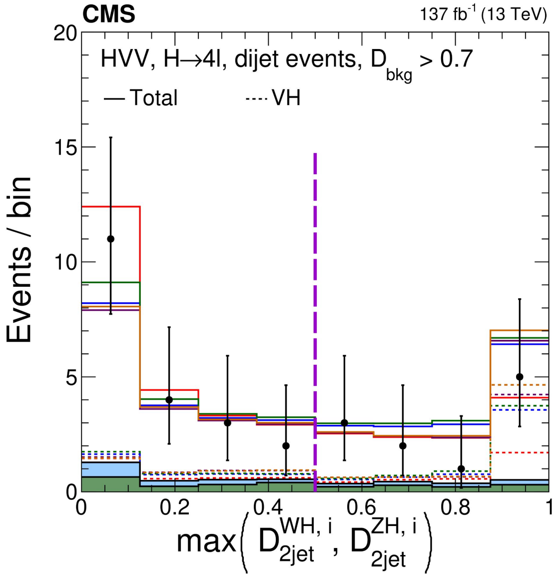


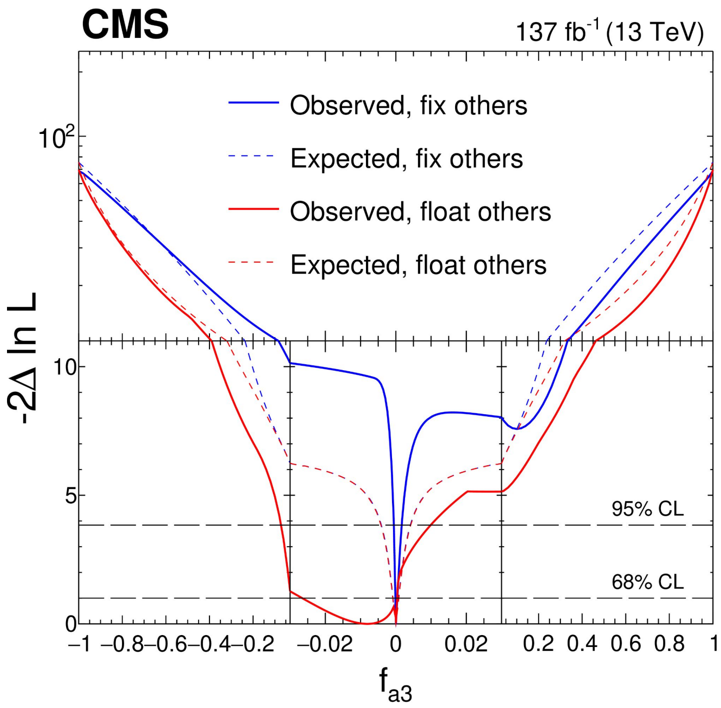
CMS H→ZZ

MELA-based fit constrains CP-odd admixture; results remain consistent with the SM.







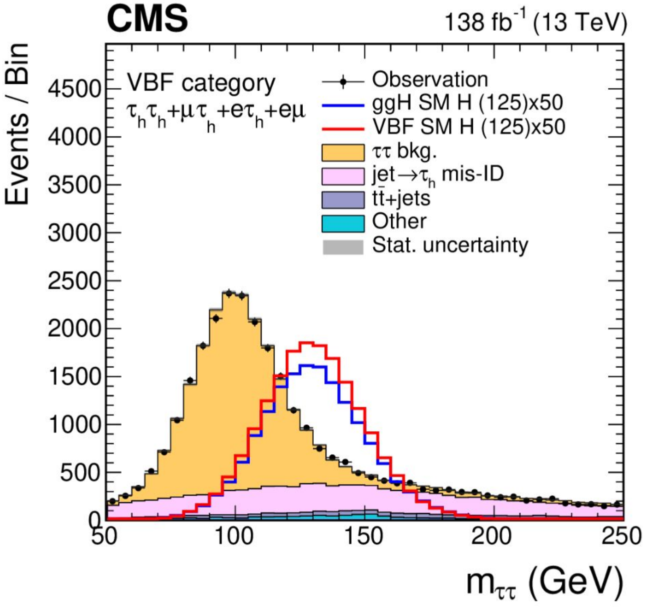


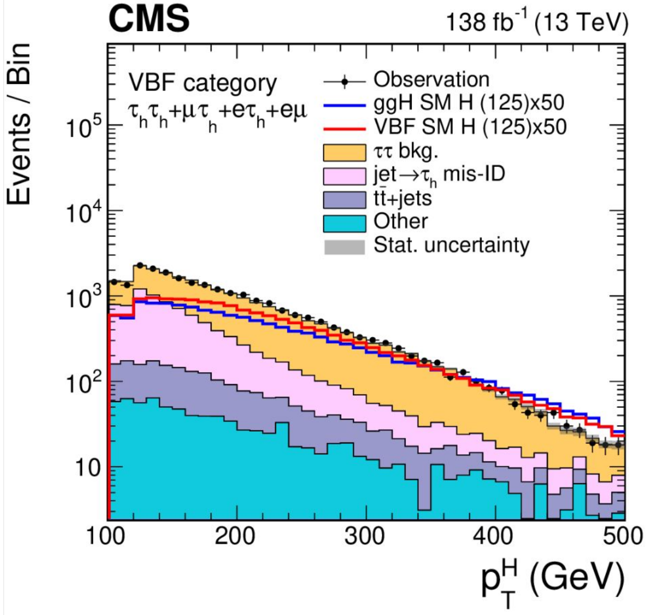
CMS VBF/VH H→ττ

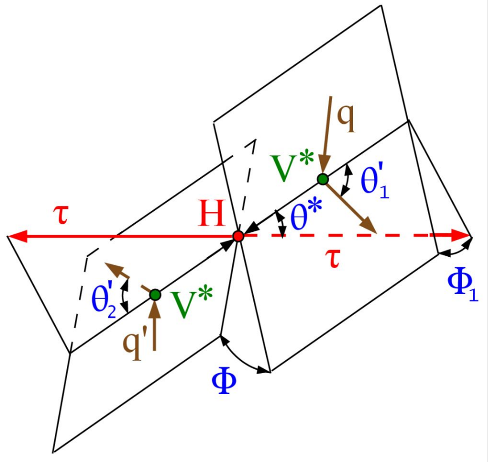
Sensitive to VVH through VBF/VH production

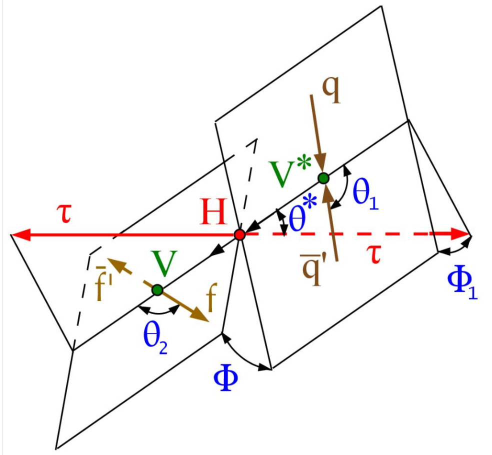
Also constrains anomalous ggH couplings

CP-odd observables built from production angles





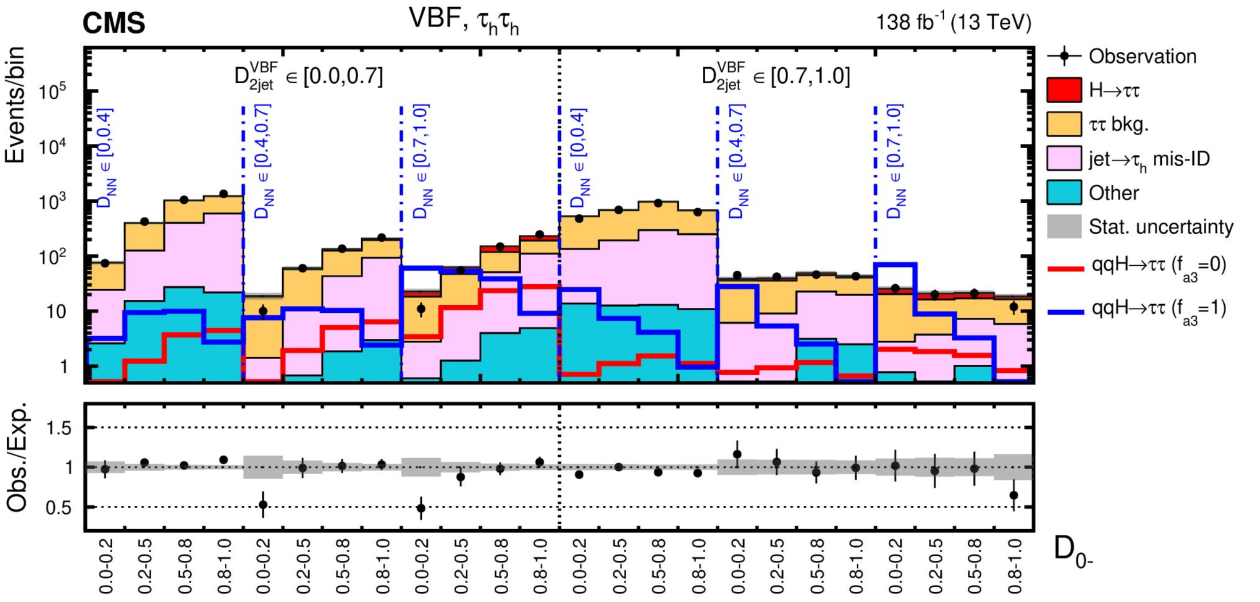


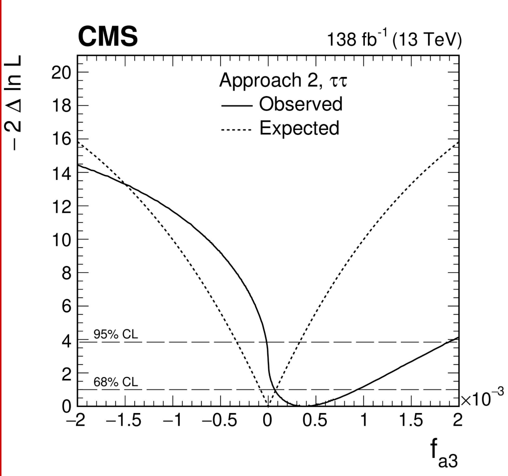


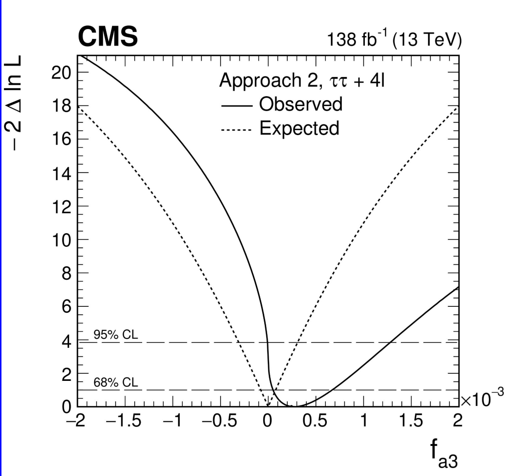
CMS VBF/VH H→ττ

MVA and MELA used to discriminate signal and background and SM vs. BSM signals

Results also **combined with H→4l**







Conclusion

- No evidence for CP violation in Higgs couplings yet, but sensitivity is improving rapidly.
- Analyses use complementary strategies: kinematic angles, MELA, optimal observables, ML classifiers”
- Current results constrain CP-odd HVV effects; future Run 3 and HL-LHC data will significantly improve reach

Backup