Higgs & CP (ATLAS & CMS)

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On behalf of the ATLAS and CMS Collaborations

Extended Scalar Sectors From All Angles

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Overview

- The observed Higgs boson at the LHC has been shown be consistent with the SM Higgs boson with quantum numbers $J^{CP} = 0^{++}$ since 2013, where a pure CP-odd state has been ruled out (refs: 1, 2, 3, 4)
  - For spin, charge-conjugation and parity
- However, the detection of a small CP-odd coupling of the observed Higgs boson in its production or decay would be an indication of a mixing of CP-even and CP-odd states, and be a sign of beyond-the-Standard-Model (BSM) physics
- This could be an indication of CP violation in the Higgs sector and potentially have implications in the matter-antimatter asymmetry of the Universe

CP-odd couplings to vector bosons and fermions

- The earliest property measurements of the Higgs boson have been done with vector bosons (γ, Z, W), and have since been studied with fermions (t, τ)
- The CP-odd coupling searches have largely been carried out for the following production and decays:
  - Vector boson fusion (VBF) production in final states: $\gamma\gamma$, ZZ, WW, $\tau\,\tau$
    - And as well, ggF + two jets and vector boson associated production (VH)
  - ttH, tH production in final states: $\gamma\gamma$, ZZ, WW, bb, $\tau\,\tau$
  - Higgs boson decays: ZZ, $\tau\,\tau$

CP-odd couplings to vector bosons and fermions (2)

- The CP-odd BSM couplings to fermions and vector bosons are different:
  - For fermions, e.g. ttH coupling, the CP-odd coupling enters via an additional γ_5 term in the Yukawa coupling

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

    - $\alpha = 0$ is pure CP-even, $\alpha \neq 0$ is mixing of even/odd CP states
    - One should note that this coupling enters at leading order in BSM models, e.g. 2HDM
  - For vector bosons, the couplings enter with dimension 6 operators, e.g. for SMEFT:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

    - The c_i include the BSM CP-odd couplings discussed here
    - And note that the couplings are 'suppressed' by Λ^2, the scale of the new physics, typically taken at 1 TeV

Couplings for vector boson couplings

- For CP-odd couplings, there are two EFT bases being used:
  - Higgs basis ("mass basis" after symmetry breaking):
    - Three couplings: $\tilde{c}_{zz}$, $\tilde{c}_{z\gamma}$, $\tilde{c}_{\gamma\gamma}$
  - Warsaw basis (before symmetry breaking):
    - Three couplings: $c_{H\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$
  - Each basis is a linear combination of the other
- ATLAS results are primarily in the Warsaw basis (the standard for SMEFT analyses)
- CMS measurements use a more general anomalous couplings framework, but also provides SMEFT results
  - Their CP-odd coupling, a_3 is proportional to $\tilde{c}_{zz}$, and they assume $\tilde{c}_{z\gamma} = \tilde{c}_{\gamma\gamma} = 0$
  - So a direct comparison of limits between ATLAS and CMS are limited
- One might note that VBF is essentially aligned with $\tilde{c}_{zz}$
  - sensitivity for $\tilde{c}_{z\gamma}$ ~ x2 worse, and much worse for $\tilde{c}_{\gamma\gamma}$

List of analyses covered in this talk (all full Run2)

ATLAS	Couplings: Yukawa or Vector bosons	Links
H -> $\tau\tau$	Yukawa	2022/12
ttH -> $\gamma\gamma$	Yukawa	2020/04
ttH -> bb	Yukawa	2023/03
H -> $\gamma\gamma$	Vector boson	2022/08
H -> $\tau\tau$ differential	Vector boson	2024/07
H -> ZZ* -> 4l	Vector boson	2023/04

CMS	Couplings: Yukawa or Vector bosons	Links
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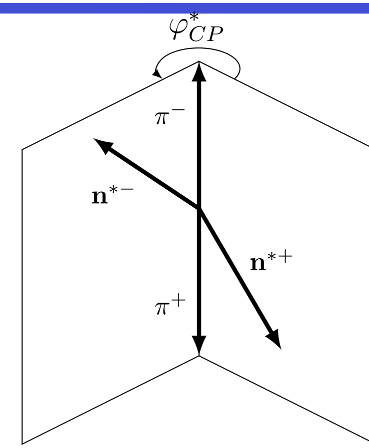
CP-odd in H -> ττ decays (H to fermion)

- The CP-odd angle ϕ_τ can be extracted from the differential distribution of the signed acoplanarity angle ϕ^*_{CP} of tau decay planes in Higgs rest frame:

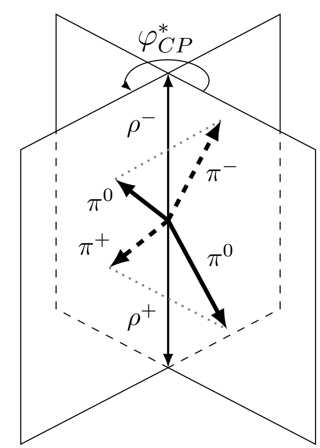
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H,$$

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

  - where $b(E_\pm)$ are known spectral functions
  - The decay planes (in zero-momentum frame) are defined with $\pi^\pm$ and impact parameter for single pion decays, and the other particles for $\pi^\pm\pi^0\nu$, etc decays:



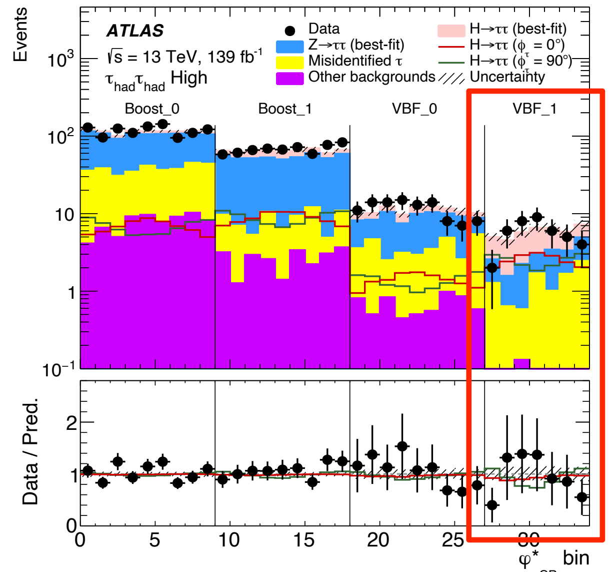
$\tau^+\tau^- \to \pi^+\nu\ \pi^-\nu$



$\tau^+\tau^- \to \rho^+\nu\ \rho^-\nu$

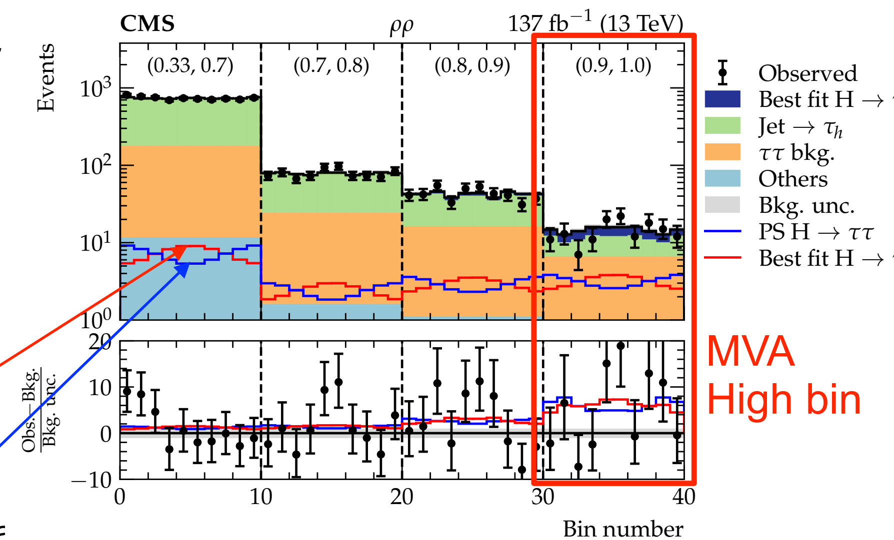
Extraction of ϕ^*_{CP} from H -> $\tau\tau$ decays

- Both ATLAS and CMS utilize several decay modes for $\tau_\ell \tau_h$ and $\tau_h \tau_h$
  - $\ell = e, \mu$, h is hadron, $\tau_h \tau_h$ is more sensitive
- ATLAS has four event categories:
  - VBF (low/high MVA), boosted ggF (low: $p_T^{\tau\tau}$ in 100-140 GeV or $\Delta R_{\tau\tau}$ > 1.5, and high: $p_T^{\tau\tau}$ > 140 GeV and $\Delta R_{\tau\tau}$ < 1.5)
- CMS uses a multi-class MVA to categorize events
- Backgrounds are mostly from $Z \to \tau\tau$, and fake-τ
  - Statistical fluctuations are 'symmetrized' in the background ϕ^*_{CP} distributions



VBF_1 high bin

ϕ^*_{CP}

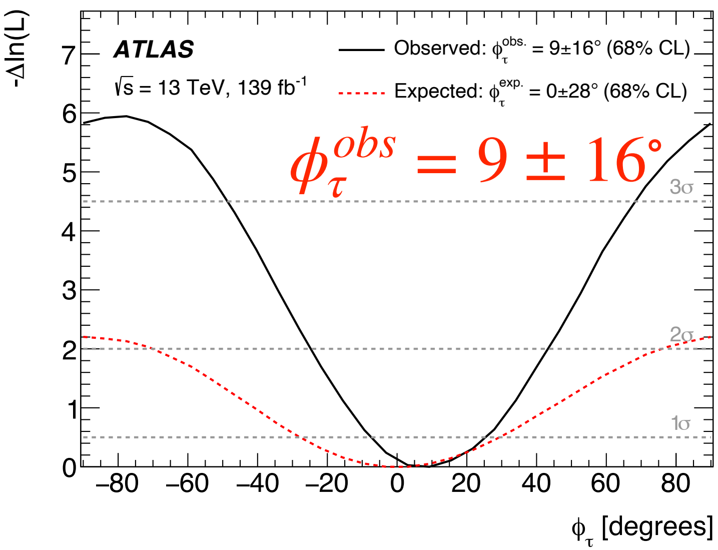


MVA High bin

ϕ^*_{CP} - red is CP-even

ϕ^*_{CP} - blue is CP-odd

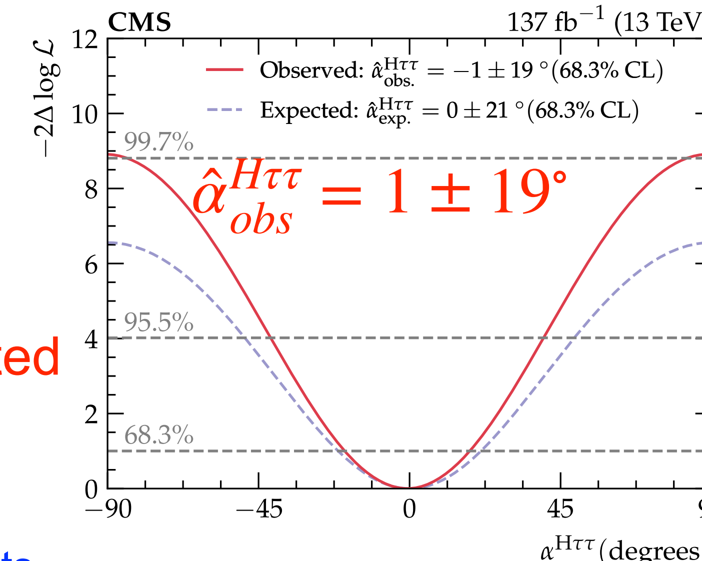
H -> ττ decays ϕ_τ and ϕ^*_{CP} results



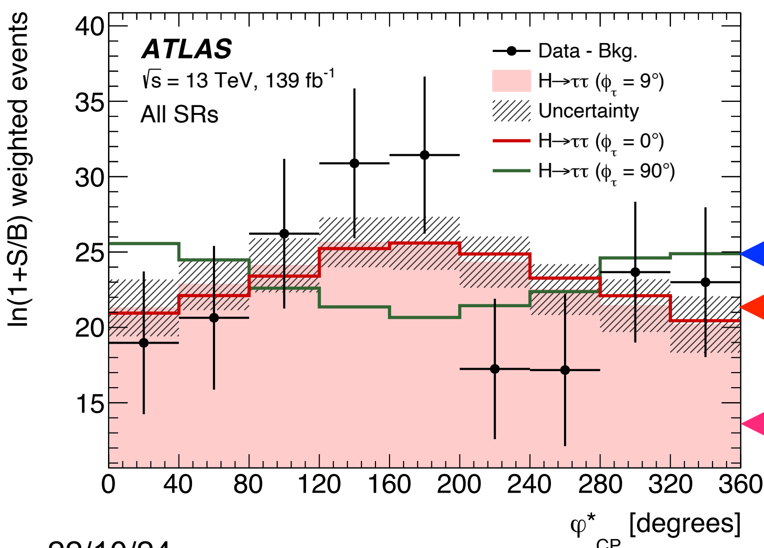
$\phi_\tau^{obs} = 9 \pm 16°$

CP-odd angle: ϕ_τ^{obs} or $\hat{\alpha}^{H\tau\tau}_{obs}$

syst $\approx 2°$
=> stats limited



$\hat{\alpha}^{H\tau\tau}_{obs} = 1 \pm 19°$

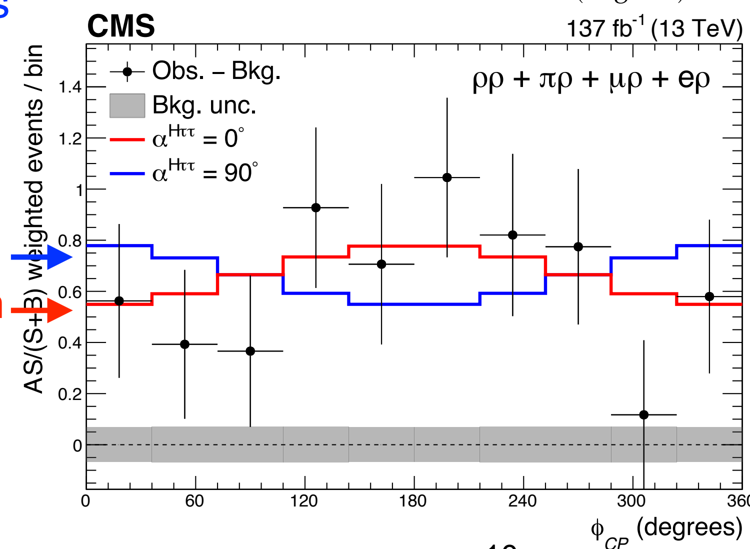


Weighted events vs ϕ^*_{CP}

blue is CP-odd

red is CP-even

pink is best-fit



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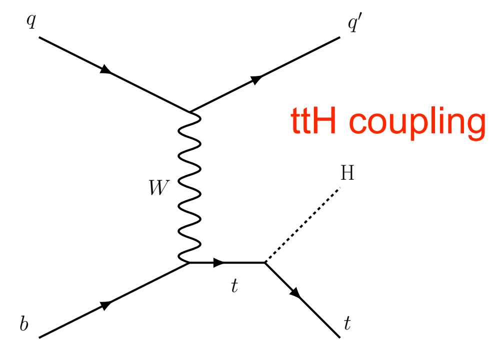
CP-odd couplings in ttH, tH

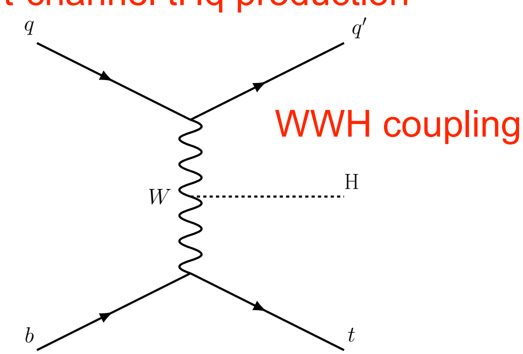
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_{\mathrm{t}}}{v}\bar{\psi}_{\mathrm{t}}(\kappa_{\mathrm{t}} + i\gamma_5\tilde{\kappa}_{\mathrm{t}})\psi_{\mathrm{t}}\mathrm{H}$$

- As for the $H \to \tau\tau$ decays, the Lagrangian can be expressed as a coupling modifier and angle, or two coupling modifiers
- For ttH/tH analyses, there are two "handles" to extracting CP-odd constraints:
  - For ttH, the spin correlations of the tt pair contain the information of the CP content of the interaction, as for $H \to \tau\tau$
    - Use kinematics of tt + H system
  - tH production in the SM is <20% of the ttH production due to destructive interference of two diagrams of the t-channel (tHq) production
    - Non-zero CP-odd coupling leads to a strong increase in tH x-sec
      - tH x-sec => x10 for pure CP-odd
    - the tH rate is used to constrain CP-odd couplings
    - tH normalization is sensitive to sign of κ_t

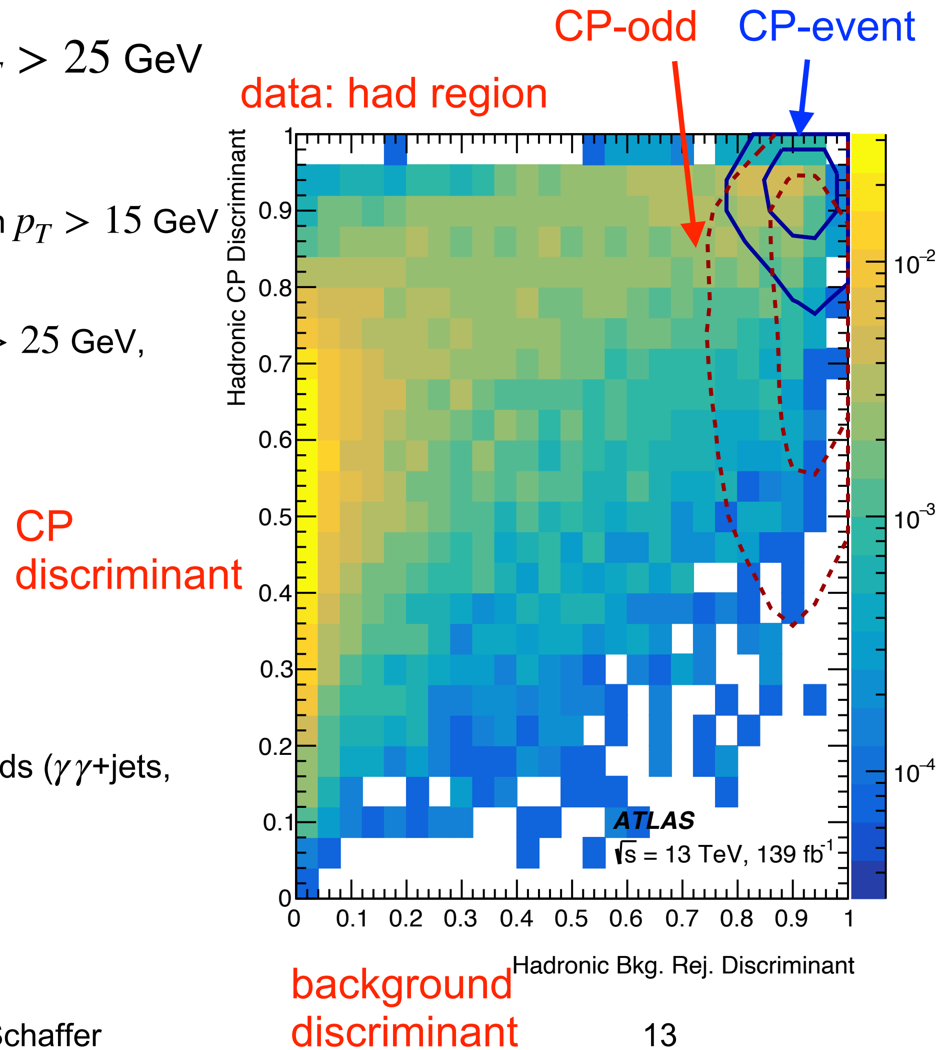


t-channel tHq production



ATLAS ttH, $H \to \gamma\gamma$

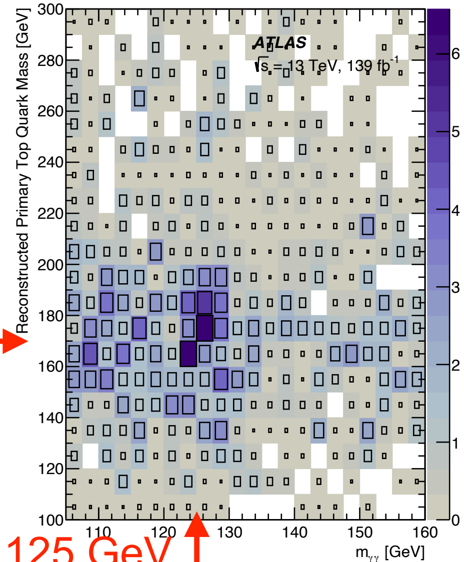
- The diphoton mass gives a clear signature for the Higgs decay
- Event selection: 2γ (>35,25 GeV), 1 tagged b-jet $p_T > 25$ GeV
- Two regions for the tt (or t) signature:
  - "Lep" region (semi-leptonic W decay): muon or electron $p_T > 15$ GeV (medium ID, isolated)
  - "Had" region (hadronic top decay, incl τ_h): ≥2 jets, $p_T > 25$ GeV, no lepton
- Top reconstruction uses BDT:
  - For Had: t_1 is top-scoring jet triplet,
  - For Lep: lepton + MET + best scoring jet
- For CP signal extraction 2 BDTs are used:
  - Bkg rejection BDT: separate ttH events from backgrounds ($\gamma\gamma$+jets, $t\bar{t}\gamma\gamma$)
  - CP BDT: separate CP-even from CP-odd



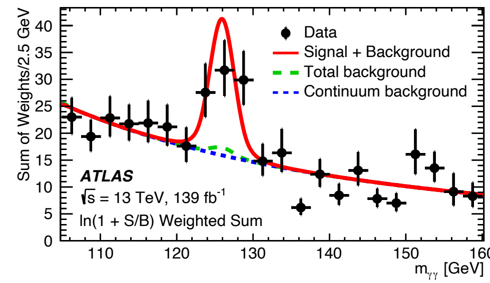
ATLAS ttH, $H \rightarrow \gamma\gamma$: Results

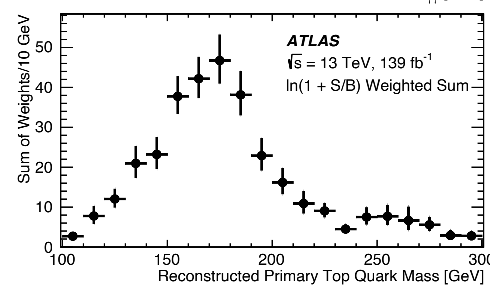
m_{top} vs $m_{\gamma\gamma}$

170 GeV



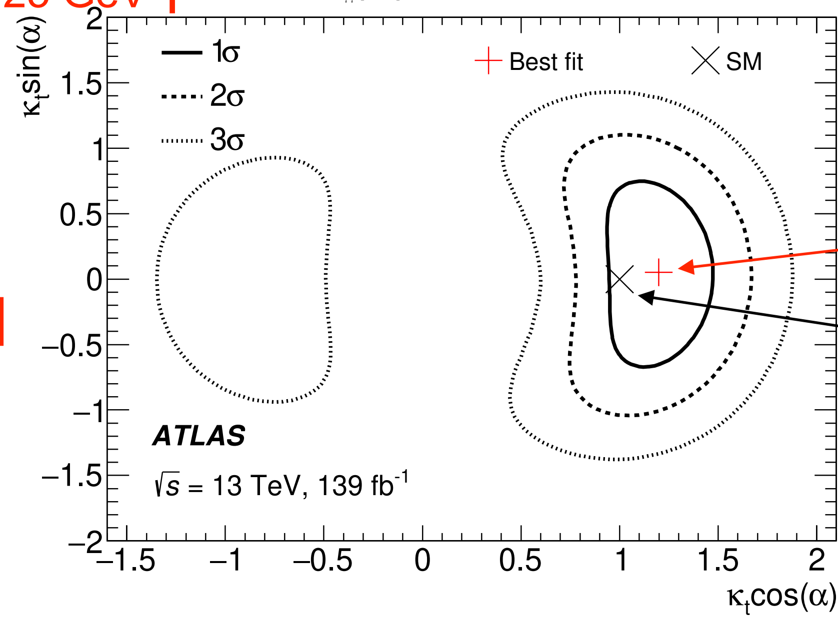
125 GeV





$\kappa_t sin(\alpha)$ vs $\kappa_t cos(\alpha)$

95% CL for α: [-43°,43°]



best fit

SM

ATLAS ttH, $H \to bb$

- Event selection:
  - isolated electron (tight ID), muon (medium ID), p_T > 27 (10) GeV 1st (2nd)
  - jet, p_T > 25 GeV, variable levels of b-tag efficiency
- Categorization:
  - Boosted Higgs: large R jet, p_T > 300 GeV, using DNN and variable b-tags
  - Dilepton: training region TR $\geq 4j, \geq 4b$, 3 CRs
  - ℓ+jets: TR $\geq 6j, \geq 4b$, 2 CRs
- 2 sets of BDTs for each category
  - Reconstruction: assign jets to Higgs or top decay
  - Classification: discriminate ttH from background
- CP-sensitive observables: using top-top kinematics or just rate
  - Boosted Higgs - yield is sensitive to tH, only use classification BDT
  - Dilepton (b_4) ℓ+jets where $\vec{p}_{1,2}$ are the two tops

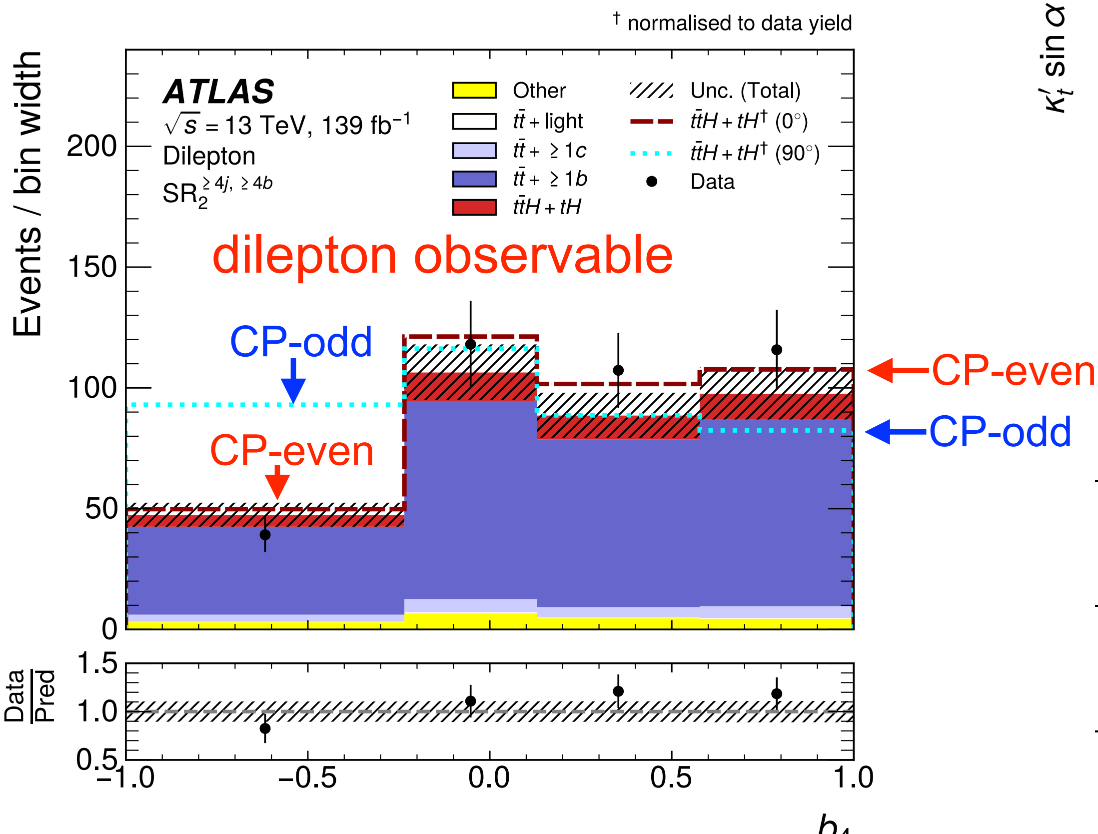
$$\frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|} \qquad \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

ATLAS ttH, $H \rightarrow bb$: Results

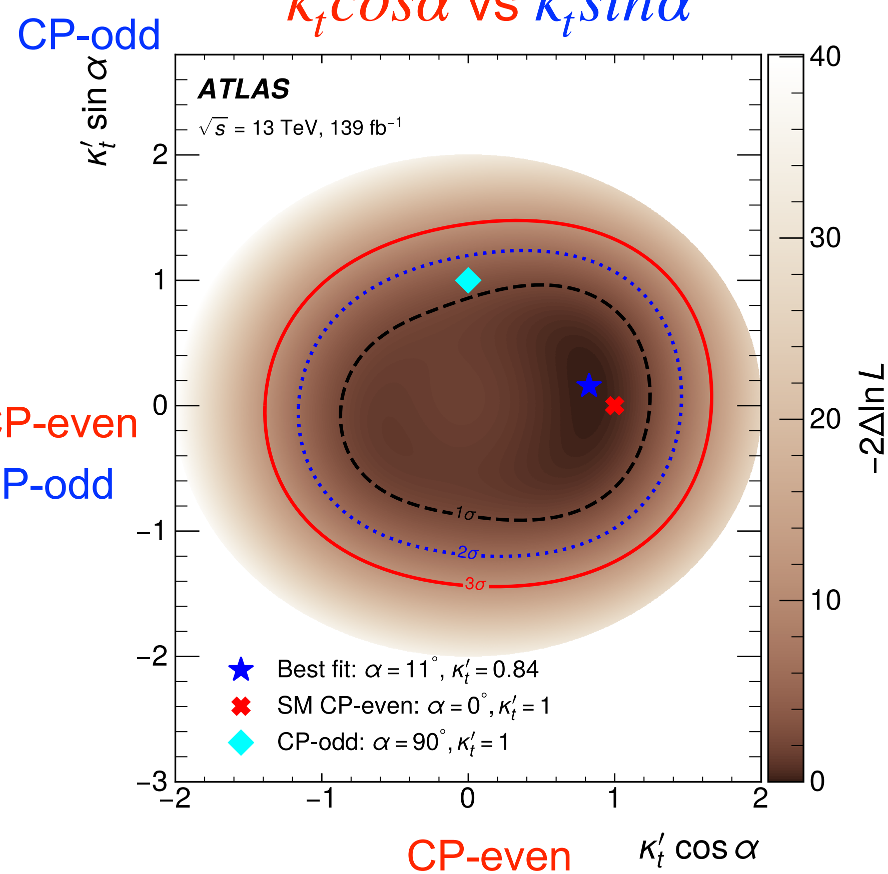
Best fit: $\alpha = 11^\circ\,^{+52^\circ}_{-73^\circ}$ and $\kappa_t' = 0.84^{+30}_{-46}$

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

SM: $\alpha = 0$, $\kappa_t' = 1$

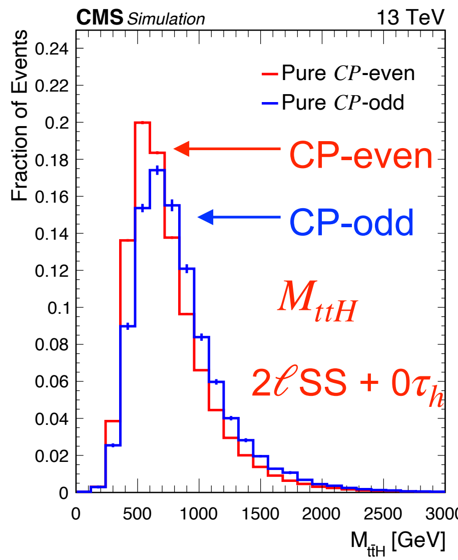


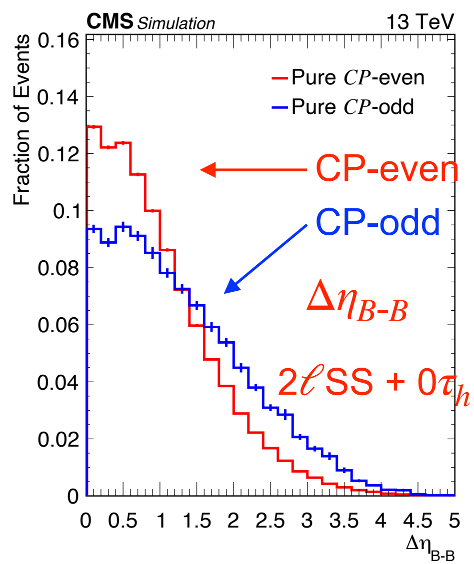
$\kappa_t' cos\alpha$ vs $\kappa_t' sin\alpha$



CMS ttH, H -> multleptons

- Multileptons concern $H \rightarrow WW$ and $H \rightarrow \tau\tau$ decays
    - Leptons come from both Higgs and top decays
- Event selection and background estimate:
    - prompt leptons selected with BDT-classifier, extra leptons rejected with loose requirements, and DNN used for τ-leptons
    - Channels: 2ℓSS + $0\tau_h$, 2ℓSS + $1\tau_h$, 3ℓ + $0\tau_h$
        - 1ℓ from top decay, others from 2nd top, W or τ_ℓ, SS - same sign
        - 1st two: $\geq$3 jets, last: $\geq$2 jets
    - require b-jets tagged with DeepJet discriminator
    - DNN used to separate into ttH, tH and backgrounds (ttW, other)
        - reducible bkgs: mis-ID leptons, conversions ($t\bar{t}\gamma$), electron charge flips
- CP discriminant for ttH (BDT$_{CP}$)
    - Separate discriminant in each channel (based on 16 to 25 variables)
- Fit includes BDT$_{CP}$, and rates for tH, backgrounds and CRs





CMS ttH, H -> multleptons: Results

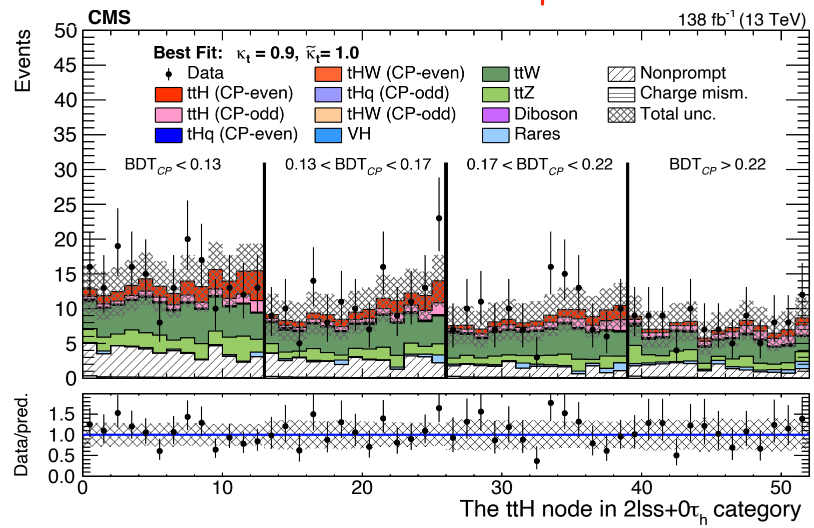
2ℓSS + 0τ channel

fit: red - CP-even
pink - CP-odd

Best fit: κ_t=0.9, $\tilde{\kappa}_t$=1.0

Small excess in CP-odd enriched region

Compatible with SM w/in 68%CL

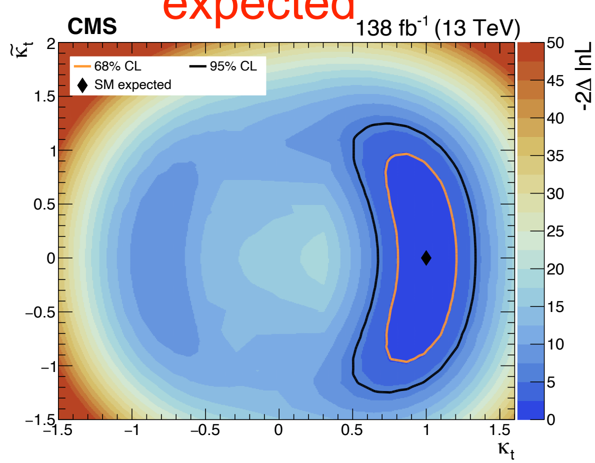


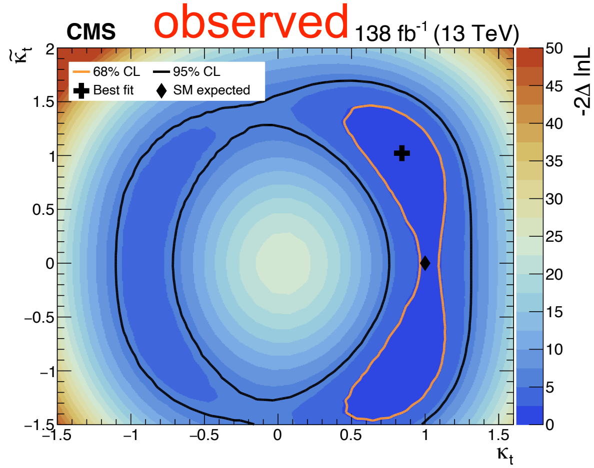
BDT_{CP}

expected

observed

κ_t vs $\tilde{\kappa}_t$

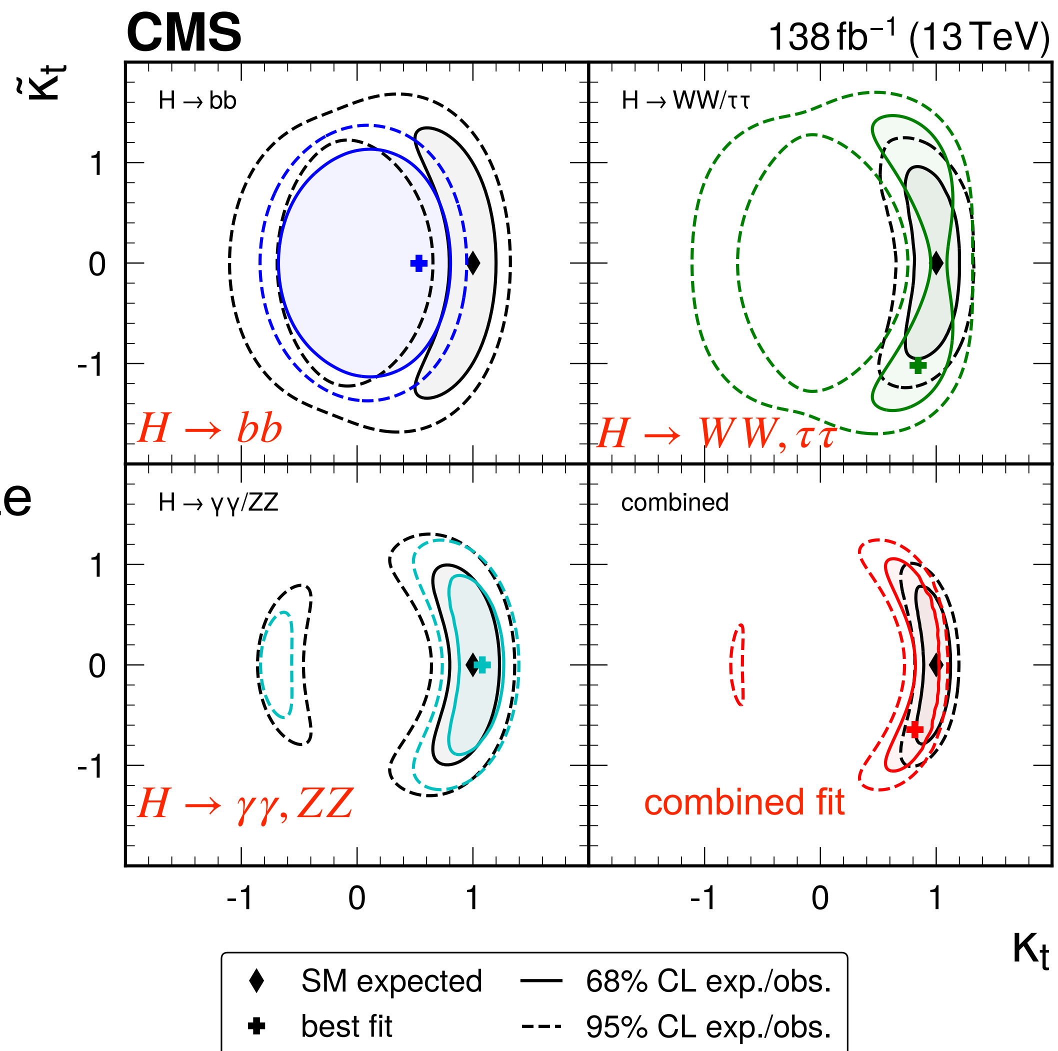




CMS ttH, H -> bb

- Categories:
  - 0-lepton (fully hadronic)
  - 1-lepton (includes tH)
  - 2-leptons (ttH)
- Use ANN to separate signal/bkg, and categorize into SR/CR
- κ_t vs $\tilde{\kappa}_t$ is combined with earlier CMS measurements
  - $WW/\tau\tau$ and $\gamma\gamma/4\ell$

colored lines - obs, black - exp



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CP-odd measurements for Vector Bosons

- CMS has studied CP-odd couplings in the context of a more general anomalous couplings analysis (see ref)
  - Here we focus on CP-odd coupling, a_3, and the effective cross-section ratio

$$f_{a_3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_3|^2 \sigma_3},$$

    - where a_1 is the SM a^{VV} assuming $a^{ZZ} = a^{WW}$, custodial symmetry, σ_i is cross section assuming a_i=1, $a_{\neq i}$=0.
  - CMS measurements in VBF/VH using the dijet kinematics, and concern a_3^{ZZ}, with $a_3^{Z\gamma} = a_3^{\gamma\gamma} = 0$
    - a_3^{ZZ} is proportional to $\tilde{c}_{zz}$ of the Higgs basis
  - CMS measurements are also performed for ggF + 2jets for a_3^{gg} ($\propto \tilde{c}_{gg}$)
- ATLAS has measurements of CP-odd couplings in the Warsaw basis: $c_{H\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$
  - These are performed for VBF using $\Delta\phi_{jj}$ (fiducial measurements), and optimal observables (see next),
  - As well as in the decay kinematics of $H \to 4\ell$ decays with optimal observables

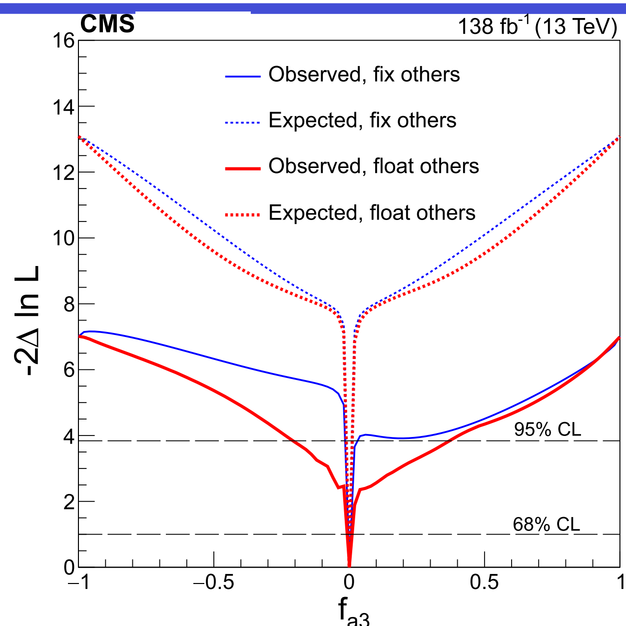
Optimal Observables with SM/BSM matrix elements

- For the SMEFT Lagrangian: $$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$
  - The x-sec is proportional: $$|\mathcal{M}|^2 = \left| \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_{\mathrm{BSM},i} \right|^2$$
  - This expands to terms linear and quadratic in M_{BSM}, which can be used to build two optimal observables:
  - $OO_1 = \frac{2\Re\left(M_{\mathrm{SM}}^* M_{\mathrm{BSM}}\right)}{\left|M_{\mathrm{SM}}\right|^2}$ and $OO_2 = \frac{\left|M_{\mathrm{BSM}}\right|^2}{\left|M_{\mathrm{SM}}\right|^2}$, M are LO matrix elements
  - Note that OO_1 is asymmetric for CP-odd couplings, and OO_2 is symmetric - i.e. only changes the x-sec
- ATLAS measurements primarily use OO_1 to look for an asymmetry
- CMS uses both, reformulated, as discriminants (MELA):
  - OO_1: $D_{\mathrm{int}} = \frac{P^{\mathrm{int}}_{\mathrm{SM\text{-}BSM}}}{P_{\mathrm{SM}} + P_{\mathrm{BSM}}}$, OO_2: $D_{\mathrm{BSM}} = \frac{P_{\mathrm{SM}}}{P_{\mathrm{SM}} + P_{\mathrm{BSM}}}$

CMS $H \to WW$: VBF, VH

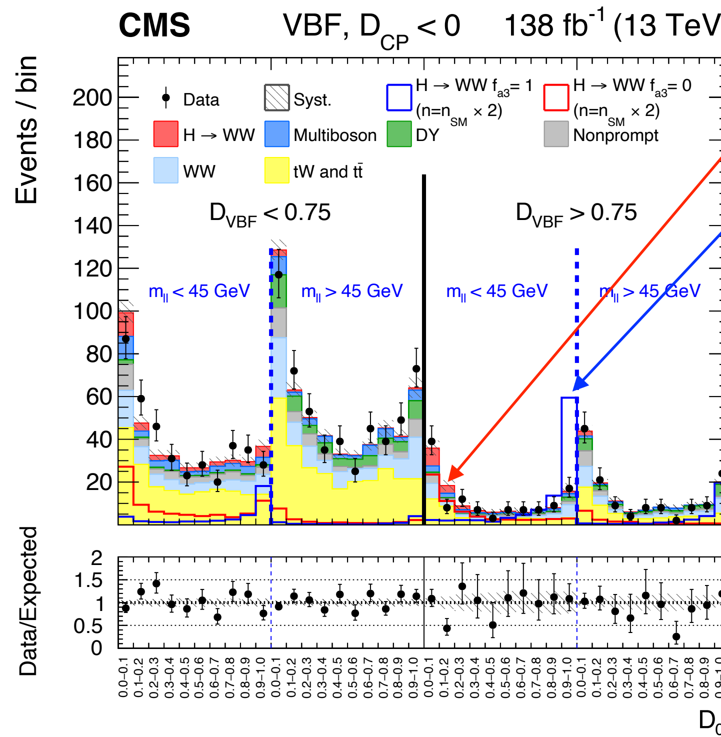
- Two approaches (applies to all anomalous coupling measurements):
  - 1) $a_3^{WW} = a_3^{ZZ}$,
  - 2) $a_3^{WW} = c_W^2 a_3^{ZZ}$, SMEFT equivalent, enforce SU(2)xU(1) (c_W is cosine of weak mixing angle)
  - We will quote SMEFT results (see refs. for 1)
- Event categories
  - HVV: VBF - 2 jets m_{jj} > 120 GeV, VH - 2 jets m_{jj} 60-120 GeV or boosted jet(s), ggH - 0,1 jet
  - ggH: ggH - 2 jets m_{jj} > 120 GeV
  - CRs for $\tau\tau$, top, WW
- Discriminants for a_3 VBF and ggH analyses:
  - VBF: D_{sig}(VBF vs Bkg), D_{BSM}, D_{int}, $m_{\ell\ell}$ (for WW decay effects)
  - ggH: D_{sig}(VBF vs Bkg), D_{BSM}, D_{int}
  - ggH 0,1-jet: $D(m_{\mathrm{T}}, m_{\ell\ell})$ from SM analysis

CMS $H \to WW$: VBF, VH: SMEFT Results



f_{a_3} - shape: q^2 larger for VBF than decay

VBF cat for $D_{\text{int}} < 0$

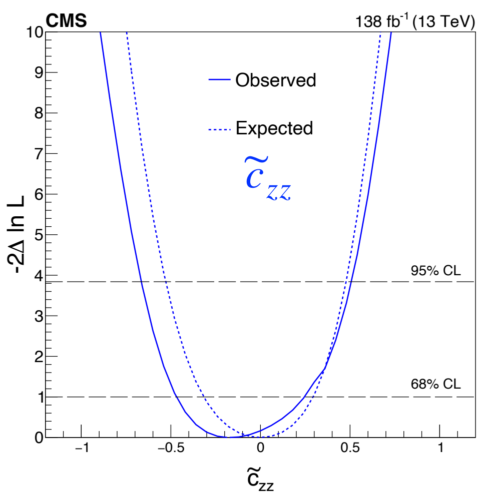


pure CP-even

pure CP-odd

n_{SM} x 2

D_{BSM}



$\tilde{c}_{zz} = -0.17^{+0.42}_{-0.30}$ $(0.0^{+0.29}_{-0.32}$ exp) three floating parameters in fit

VBF: f_{a_3} = $0.8^{+2.7}_{-1.6}$ $(0.0^{+1.1}_{-0.8}$ exp) x 10^{-3} other parameters fixed

ggH: $f_{a_3} = -0.034^{+0.3}_{-0.7}$ $(0.0^{+1.0}_{-1.0}$ exp)

CMS $H \to \tau\tau$: ggH+2jets, and VBF, VH

- Channel with best sensitivity - uses $\tau_\ell\tau_\ell$, $\tau_\ell\tau_h$, and $\tau_h\tau_h$
- Measure two f_{a_3}, in both ggH+2jets, and VBF/VH:
  - $f_{a_3}^{ggH}$: find similar sensitivity with $\Delta\phi_{jj}$ and MELA
  - f_{a_3} (VBF/VH): use MELA ($\Delta\phi_{jj}$ less sensitive)
- 3 Event categories
  - 0-jet: ggH, VBF: 2 jets m_{jj} > 300 GeV, $|\Delta\eta_{jj}|$ > 2.5 for both VBF and ggH+2jets, boosted: rest
- Discriminants:
  - NN for separating VBF/ggH+2jets from bkg
  - D_{2jet}^{VBF} - for ggH to separate from VBF
  - For both analyses: D_{BSM} - with $|M_{\text{BSM}}|^2$ term , D_{int} - BSM/SM interference term

CMS $H \rightarrow \tau\tau$ production results

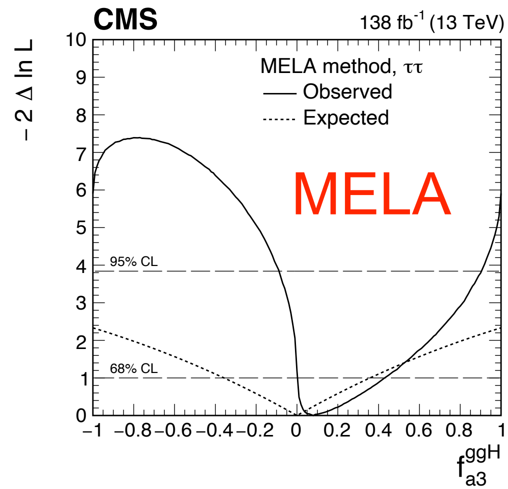
MELA results for ggH + 2jets

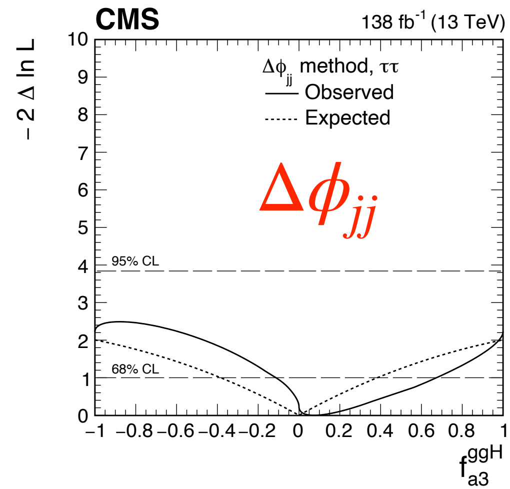
ggH: $f_{a_3} = -0.08^{+0.35}_{-0.08}$ (0.0 ± 0.36 exp)

Combined with $H \rightarrow 4\ell$

ggH: $f_{a_3} = -0.07^{+0.32}_{-0.07}$ (0.0 ± 0.26 exp)

Comparison of MELA and $\Delta\phi_{jj}$ for $f_{a_3}^{ggH}$





MELA results for VBF, VH

VBF: $f_{a_3} = 0.40^{+0.53}_{-0.33}$ (0.0 ± 0.08 exp) x 10^{-3}

Combined with $H \rightarrow 4\ell$

VBF: $f_{a_3} = 0.28^{+0.39}_{-0.23}$ (0.0 ± 0.08 exp) x 10^{-3}

From $H \rightarrow WW$

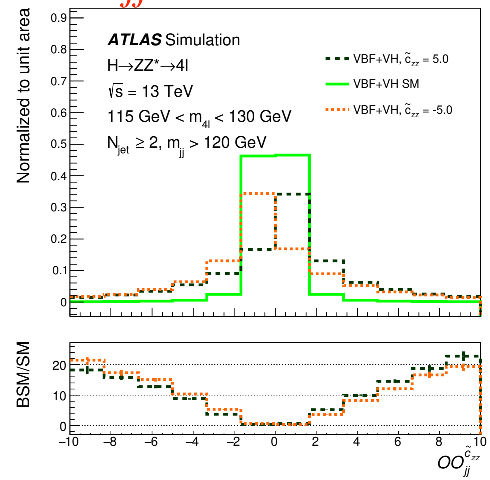
ggH: $f_{a_3} = -0.034^{+0.3}_{-0.7}$ ($0.0^{+1.0}_{-1.0}$ exp)

VBF: $f_{a_3} = 0.8^{+2.7}_{-1.6}$ ($0.0^{+1.1}_{-0.8}$ exp) x 10^{-3}

ATLAS $H \to ZZ^* \to 4\ell$ production and decay

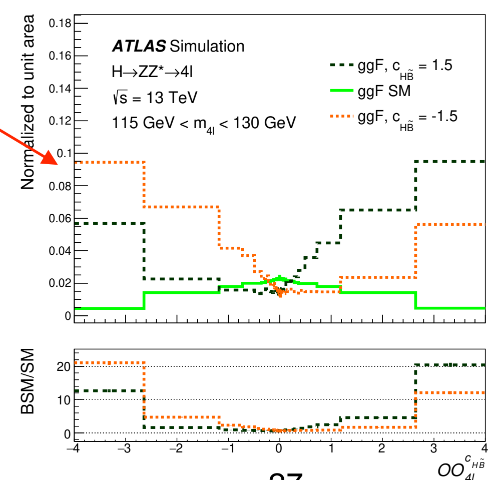
- Shape analysis: look for asymmetry in
  - $$OO_1 = \frac{2\Re\left(M_{\rm SM}^* M_{\rm BSM}\right)}{\left|M_{\rm SM}\right|^2}$$
- SMEFT: both Higgs and Warsaw bases
- Fits production (VBF) and/or 4ℓ decay
  - $\tilde{c}_{zz}$ is only sensitive to VBF production
  - $c_{H\widetilde{W}}$ is sensitive to both production and decay
  - $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$ is sensitive to only decay
- NN discriminant used for VBF/ggH+2jet separation
- BDT discriminant for ggH - qqZZ background separation
- Effects of ignoring the $\left|M_{\rm BSM}\right|^2$ term are < 10%

OO_{jj} equal-size bins

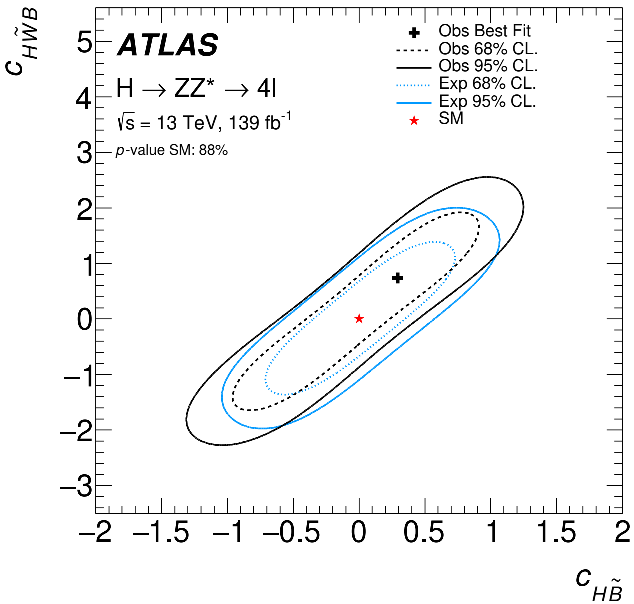


$OO_{4\ell}$ equally populated bins

tails are important

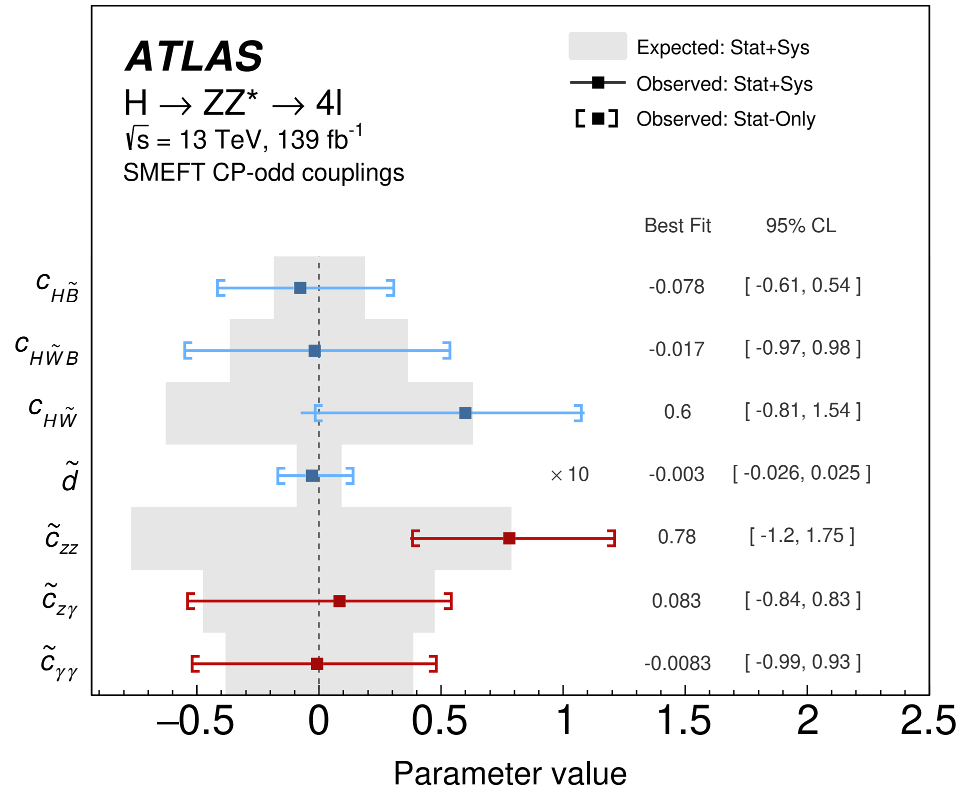


ATLAS $H \rightarrow Z^*Z^* \rightarrow 4\ell$: Results



$c_{H\widetilde{B}}$ vs $c_{H\widetilde{W}B}$ 68% and 95% CL from decay

CP-odd coupling results in Warsaw and Higgs bases

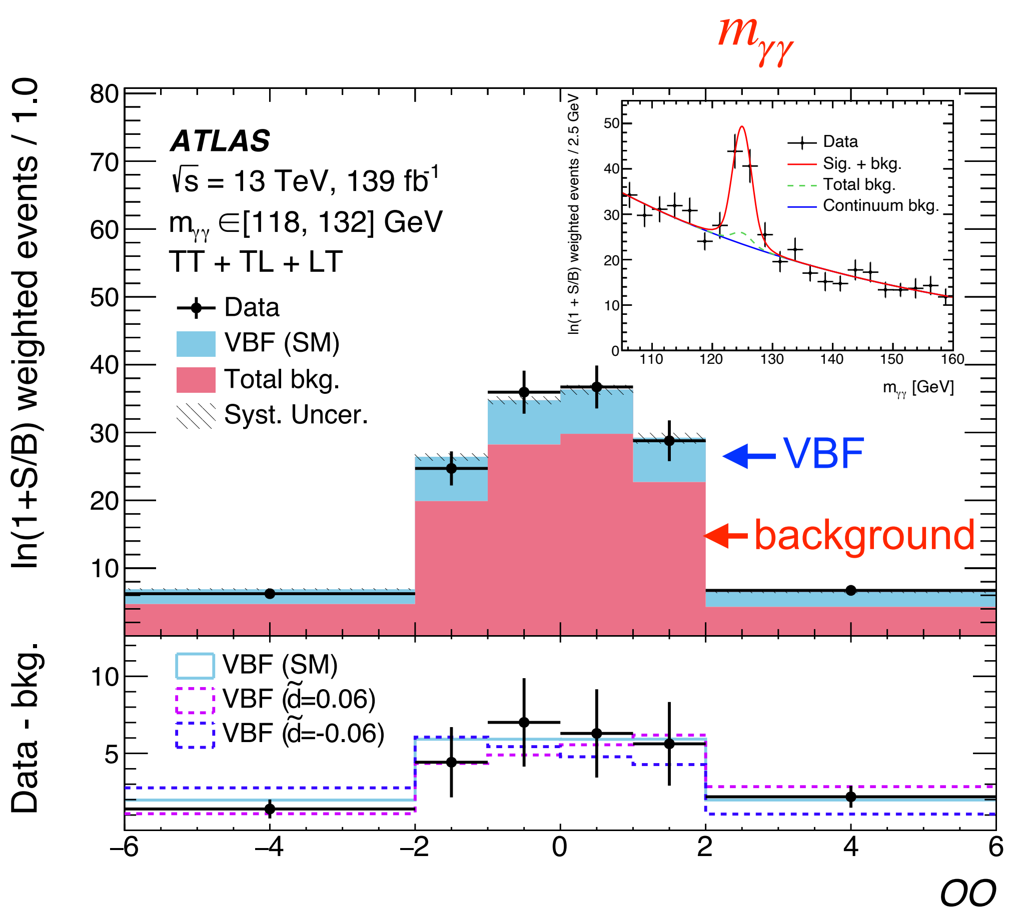


ATLAS $H \rightarrow \gamma\gamma$ VBF production

- Same approach as for $H \rightarrow ZZ^* \rightarrow 4\ell$
- Shape analysis for

$$OO_1 = \frac{2\Re\left(M^*_{\rm SM} M_{\rm BSM}\right)}{\left|M_{\rm SM}\right|^2}$$

- Discriminants: 2 BDTs for
  - VBF/ggF, and
  - VBF/continuum bkg
  - 10% Improved VBF discrimination relative standard analysis
  - Loose VBF sel: $|\Delta\eta_{jj}| < 2$, $\eta^{Zepp} < 5$ $(|\eta_{\gamma\gamma} - (\eta_{j1} + \eta_{j2})/2|)$



Optimal observable

ATLAS $H \rightarrow \gamma\gamma$ VBF production: Results

Table 1: Observed and expected 68% and 95% confidence intervals for $\tilde{d}$ and $c_{H\tilde{W}}$. Results for scenarios with the interference-only (noted as 'inter. only') term and interference-plus-quadratic terms (noted as 'inter.+quad.') are both presented. Combined results for $\tilde{d}$ including the $H \rightarrow \tau\tau$ analysis are shown. The expected results of $H \rightarrow \tau\tau$ are slightly different from Ref. due to the different correlation scheme between their signal region and control region.

		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 $H \rightarrow \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
$\tilde{d}$	Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\widetilde{W}}$	$c_{H\tilde{W}}$ (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]

quadratic term has little effect

expected 68% CL

expected 95% CL

observed 68% CL

observed 95% CL

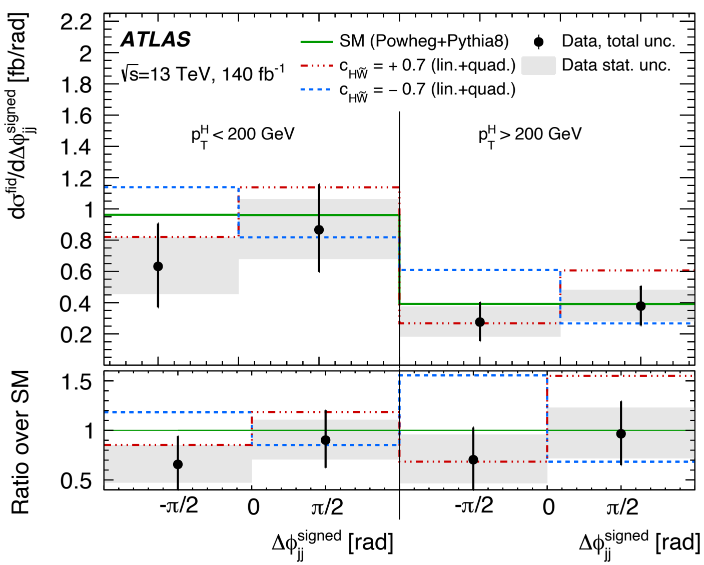
~25% improved sensitivity over $H \rightarrow ZZ^* \rightarrow 4\ell$

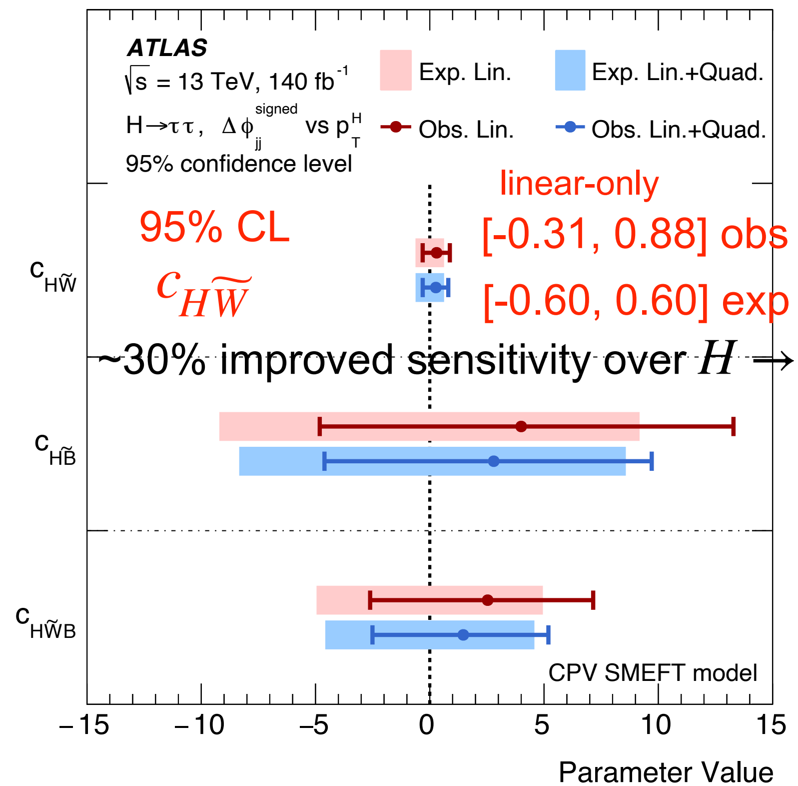
Also measure $\tilde{d}$ constraints (HISZ basis) to compare and combined with previous $H \rightarrow \tau\tau$ measurement:

$$\frac{\Lambda^2}{v^2}\tilde{d} = c_{H\widetilde{W}} = c_{H\widetilde{B}}, c_{H\widetilde{W}B} = 0$$

ATLAS $H \to \tau\tau$ VBF production: differential

- Unfolded $\Delta\phi_{jj}$ vs p_T^H is used for CP-odd couplings fit
  - m_{jj} > 300 GeV, $|\Delta\eta_{jj}|$ > 3.4, p_T^{jj} > 30 GeV - better VBF/ggF separation
- results better than $H \to \gamma\gamma$, expect improvements with OO
  - quadratic term has little effect





95% CL $c_{H\widetilde{W}}$ linear-only
[-0.31, 0.88] obs
[-0.60, 0.60] exp

~30% improved sensitivity over $H \to \gamma\gamma$

Note: $H \to WW$ diff. meas. limits from $\Delta\phi_{jj}$:
$c_{H\widetilde{W}}$ linear 95% CL: [-1.8, 1.3] obs, [-1.7, 1.7] exp

Results summary: 95% CL limits (ttH from 2d)

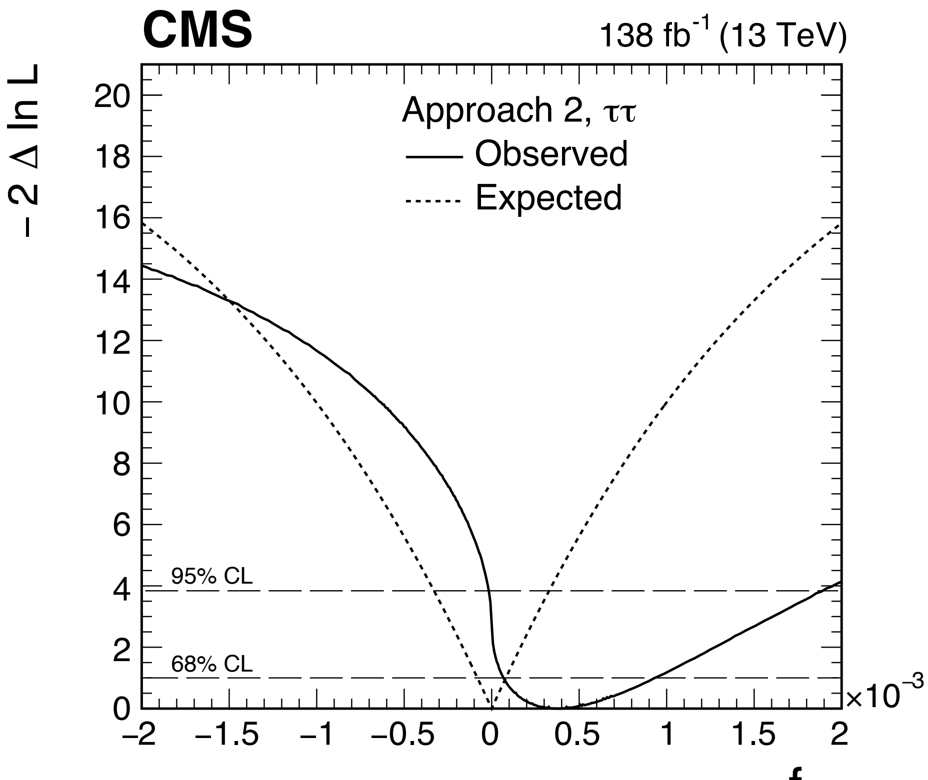
	ATLAS		CMS	
	obs	exp	obs	exp
$H \to \tau\tau$ decay (deg)	±34	[-70, 75]	[-42, 40]	±21
ttH/tH $H \to bb$ $\tilde{\kappa}_t$	±1.2		±1.4	±1.7
ttH/tH $H \to \gamma\gamma$	±1.1		±1.2	±1.3
ttH/tH $H \to WW,\tau\tau$			±1.7	±1.2
ttH/tH combined			±1.1	±1.0
VBF $H \to WW$ $f_{a_3}(10^{-3})$			[−7.6,59.]	[−3.4,4.3]
VBF $H \to \tau\tau$			[−0.01,1.9]	[−0.33,0.33]
VBF $H \to \tau\tau$, $H \to 4\ell$			[−0.01,1.3]	[−0.30,0.30]
VBF $H \to 4\ell$ $c_{H\widetilde{W}}$	[−0.81, 1.5]	[−1.3, 1.3]		
VBF $H \to \gamma\gamma$	[-0.53, 1.02]	[-0.9, 0.9]		
VBF $H \to \tau\tau$	[-0.31, 0.88]	[-0.6, 0.6]		

Summary

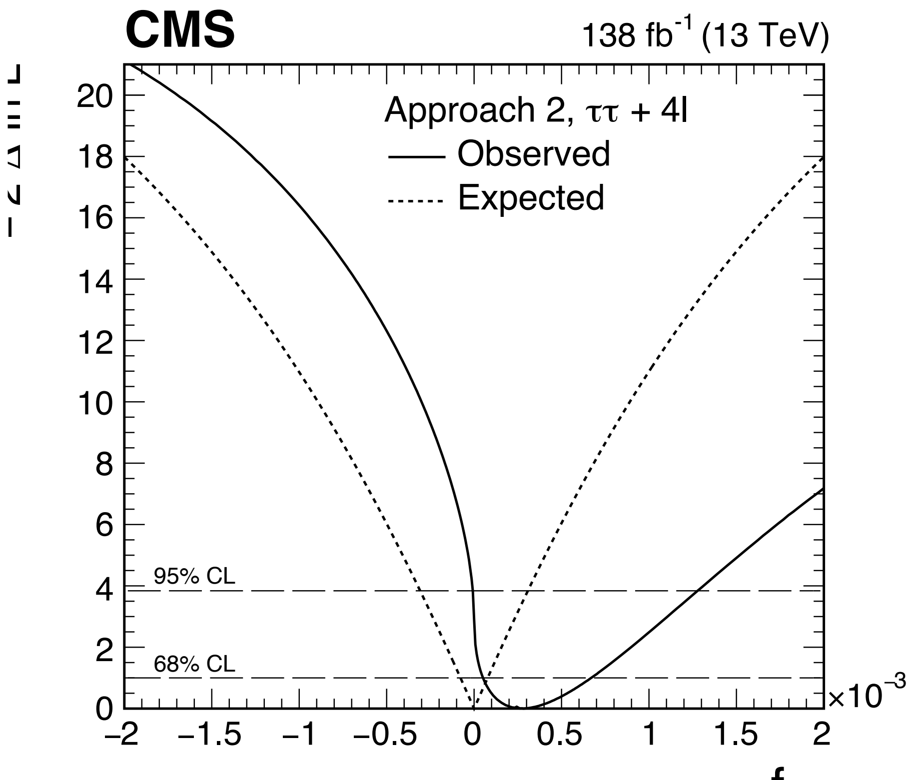
- Constraints on CP-odd couplings to the Higgs boson are now available for most analyses of interest for full Run 2
  - These cover both couplings to fermions and vector bosons
  - Expect a few more results to complete Run 2
  - Other fiducial differential ($\Delta\phi_{jj}$) results are available for EFT analysis
- Currently no evidence for a deviation from the SM
- Measurements are largely statistics-dominated, leaving room for improved constraints
- Limit combinations has largely been done within CMS and is on-going within ATLAS
- Would probably be good to combine ATLAS and CMS results
  - Requires some discussions…

Backup

CMS $H \to \tau\tau$ VBF production results



$H \to \tau\tau$



$H \to \tau\tau + H \to 4\ell$

VBF: f_{a_3} = $0.40^{+0.53}_{-0.33}$ $(0.0 \pm 0.08$ exp) x 10^{-3}

VBF: f_{a_3} = $0.28^{+0.39}_{-0.23}$ $(0.0 \pm 0.08$ exp) x 10^{-3}