Measurements of the CP structure of Higgs boson couplings with the ATLAS detector

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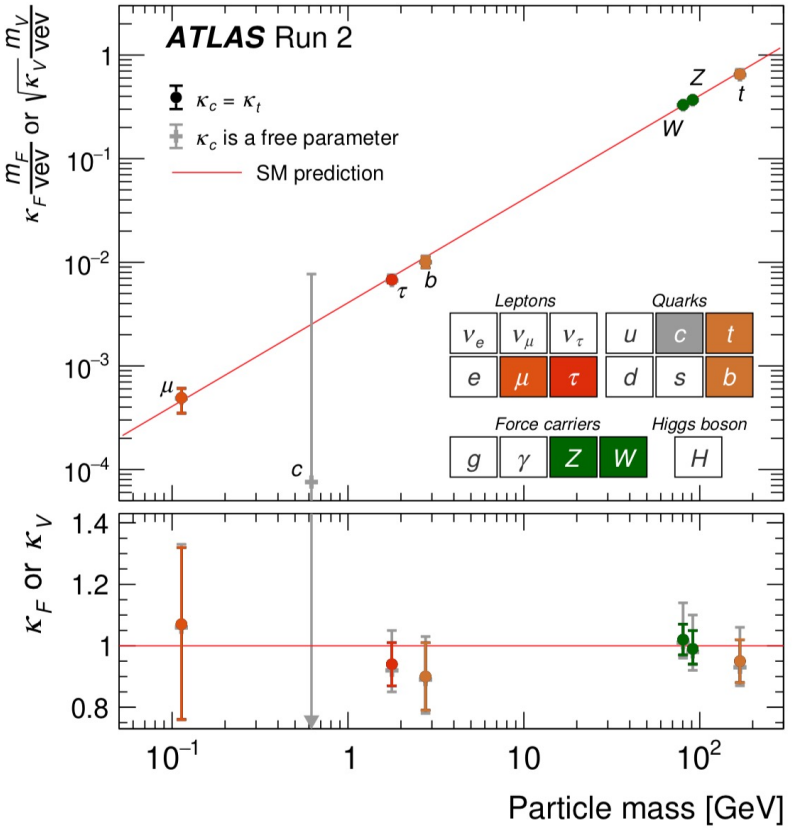
Introduction

- In general, additional **CP-violation** sources are needed to explain matter-antimatter asymmetry
  - Would be clear evidence of **physics beyond the SM**
- SM predicts a CP-even scalar Higgs boson $J^{CP} = 0^{++}$
- Today:
  - **Bosonic couplings**: HVV (based on EFT approach)
  - **Fermionic couplings**: direct Hff couplings



CPV in the Higgs sector

Bosonic couplings

- Modelled by higher-order-mass dimension terms in **EFT**
- Suppressed by powers in expansion scale Λ
- Explored in VBF prod., $H \to WW$ and $H \to ZZ$ decay channels

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

Fermionic couplings

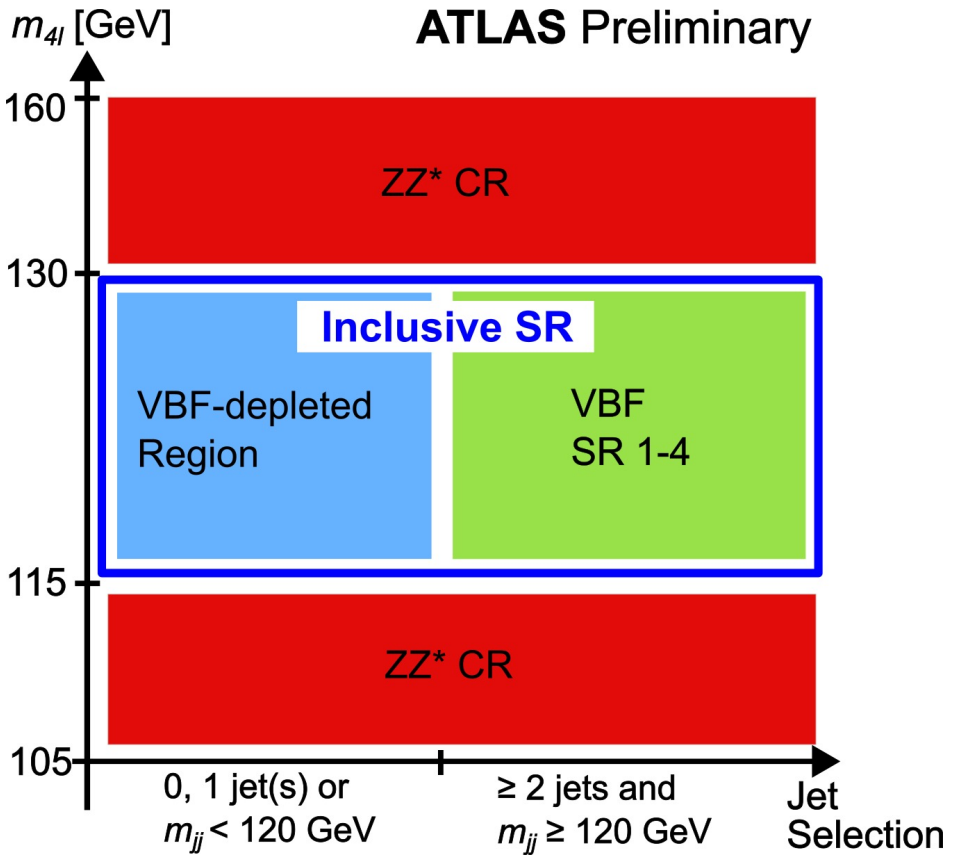
- CP-odd terms enter at the **same order** as CP-even terms
- Explored in $t\bar{t}H/tH$ production and $H \to \tau\tau$ decay channel
- Parameterised with a CP-mixing angle

$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

CERN-EP-2023-030

CPV in VBF prod. and Higgs $4l$ decay

- CP-odd effects in VBF production and $H \to ZZ^* \to 4l$ decay using SMEFT *optimal observables*
- Three PL fits depending on sensitivity to observable
  - *Decay-only*: **Inclusive SR** + **ZZ* sidebands** – dominated by ggF events
  - *Production-only*: Further split on **VBF regions** using a NN to discriminate VBF, VH and ggF
  - *Combined*: targets BSM signatures sensitive to both production and decay
- EFT shape-only analysis, ∴ independent from potential BSM rate changes



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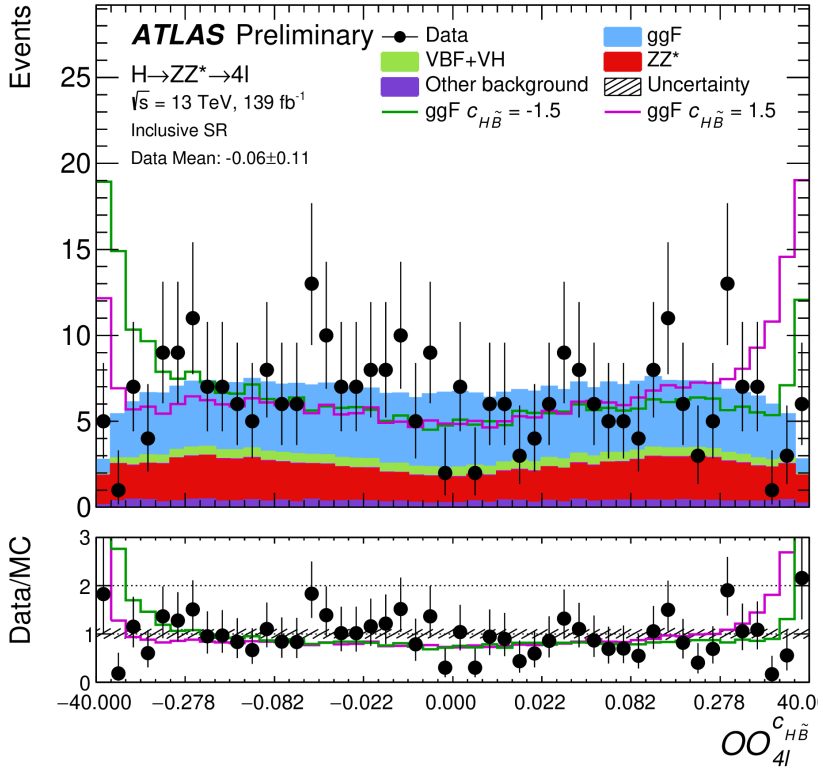
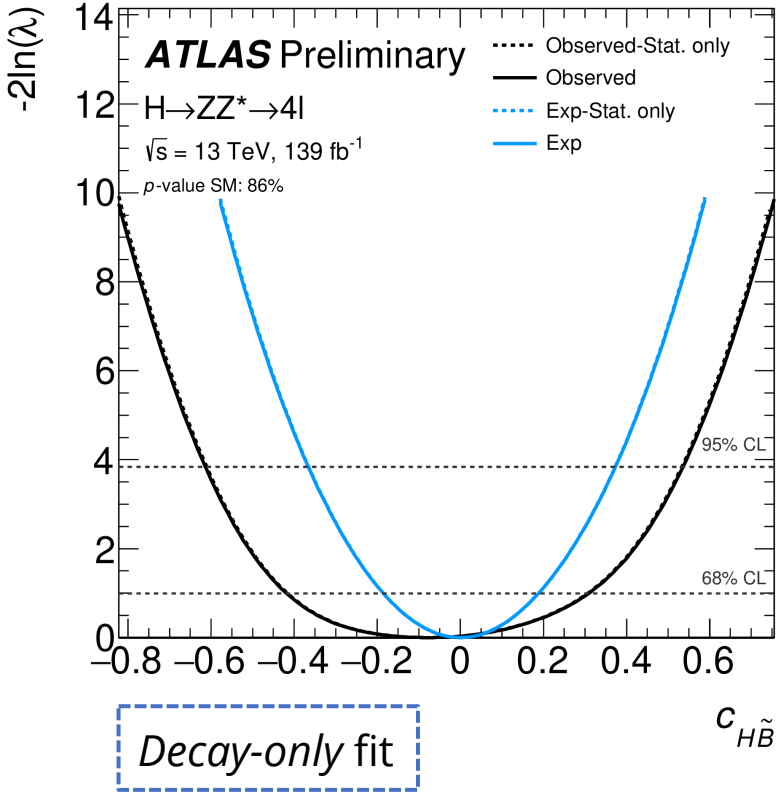
Reconstruction level limit extraction

- Optimal observables (OO) are built from the SM-BSM interference term which dominates

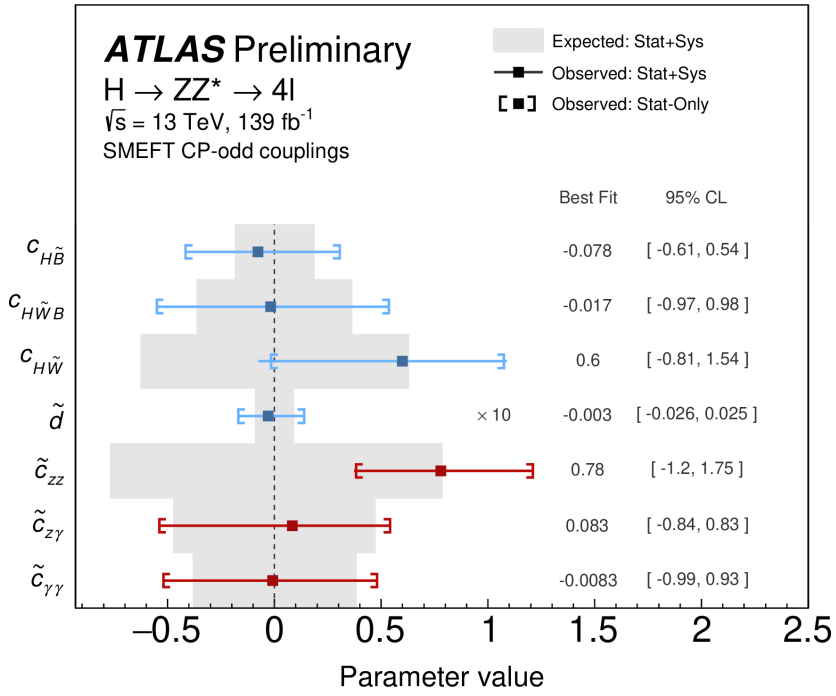
$$OO = \frac{2\Re\left(\mathcal{M}^{*}_{SM}\mathcal{M}_{BSM}\right)}{|\mathcal{M}_{SM}|^{2}}.$$





Decay-only fit

Warsaw basis Higgs basis



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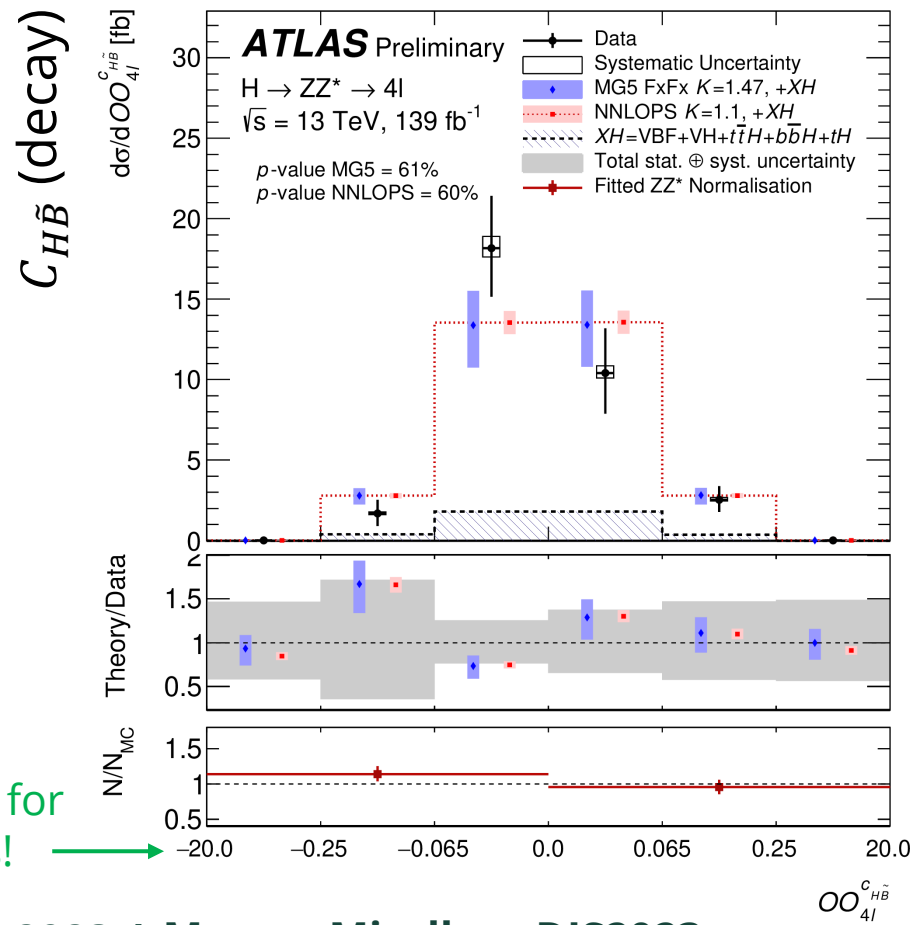
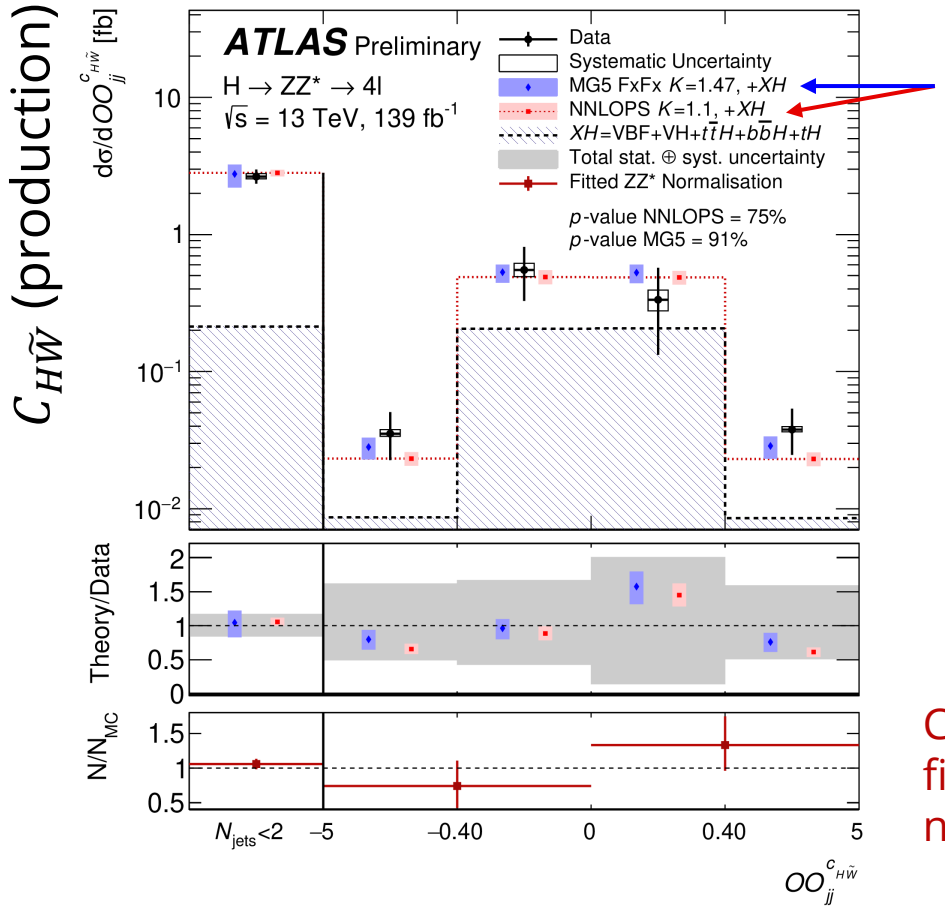
Differential OO cross-section results

- Unfolded differential OO cross-sections to fiducial phase space
- Simultaneous PL fits to m_{4l} in each bin, for each distributed observable



Watch out for bin ranges!



ggF MC normalised to N^{3}LO calculation

Comparison of fitted ZZ* norm. with MC

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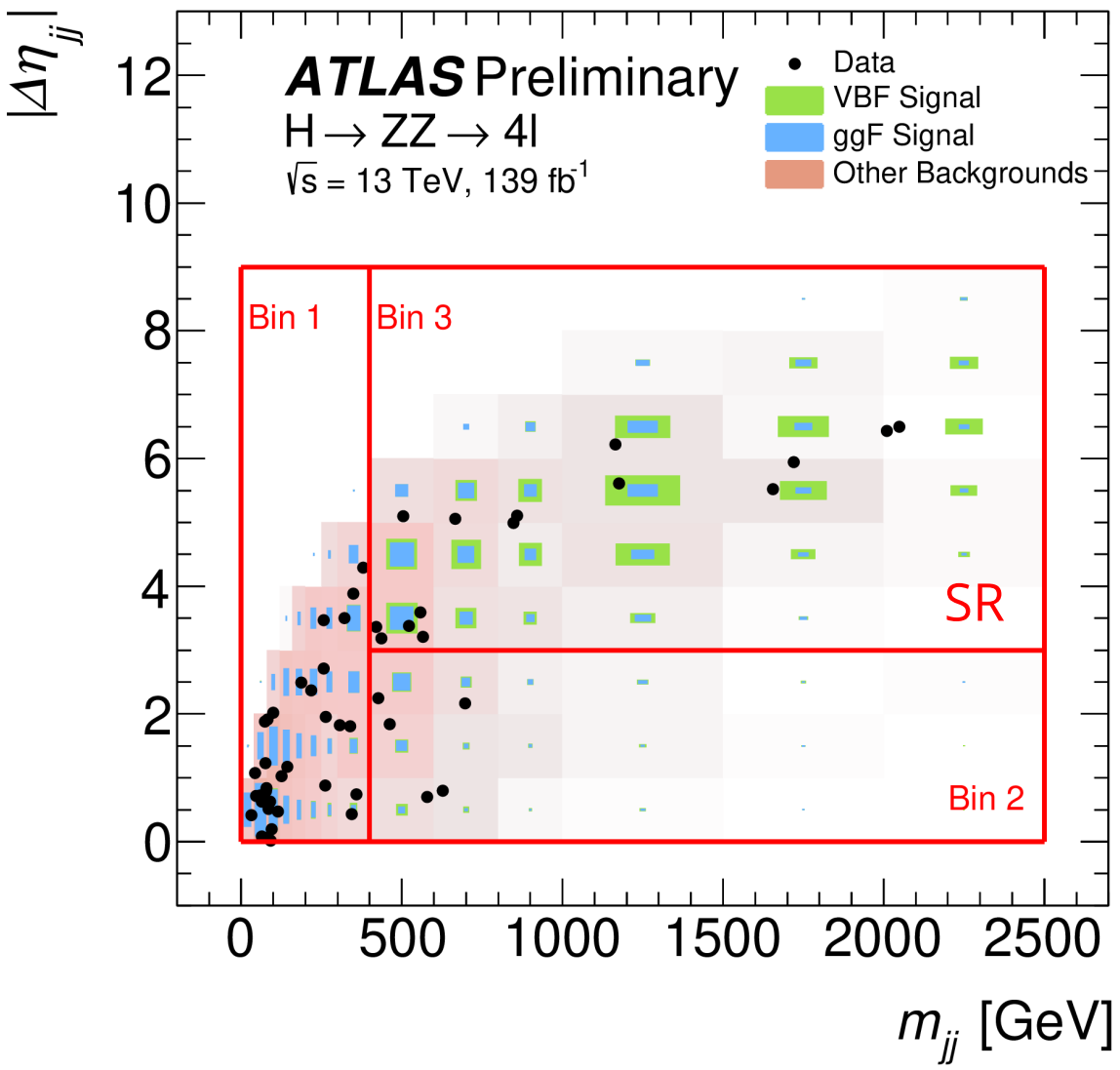
VBF production fiducial cross-section

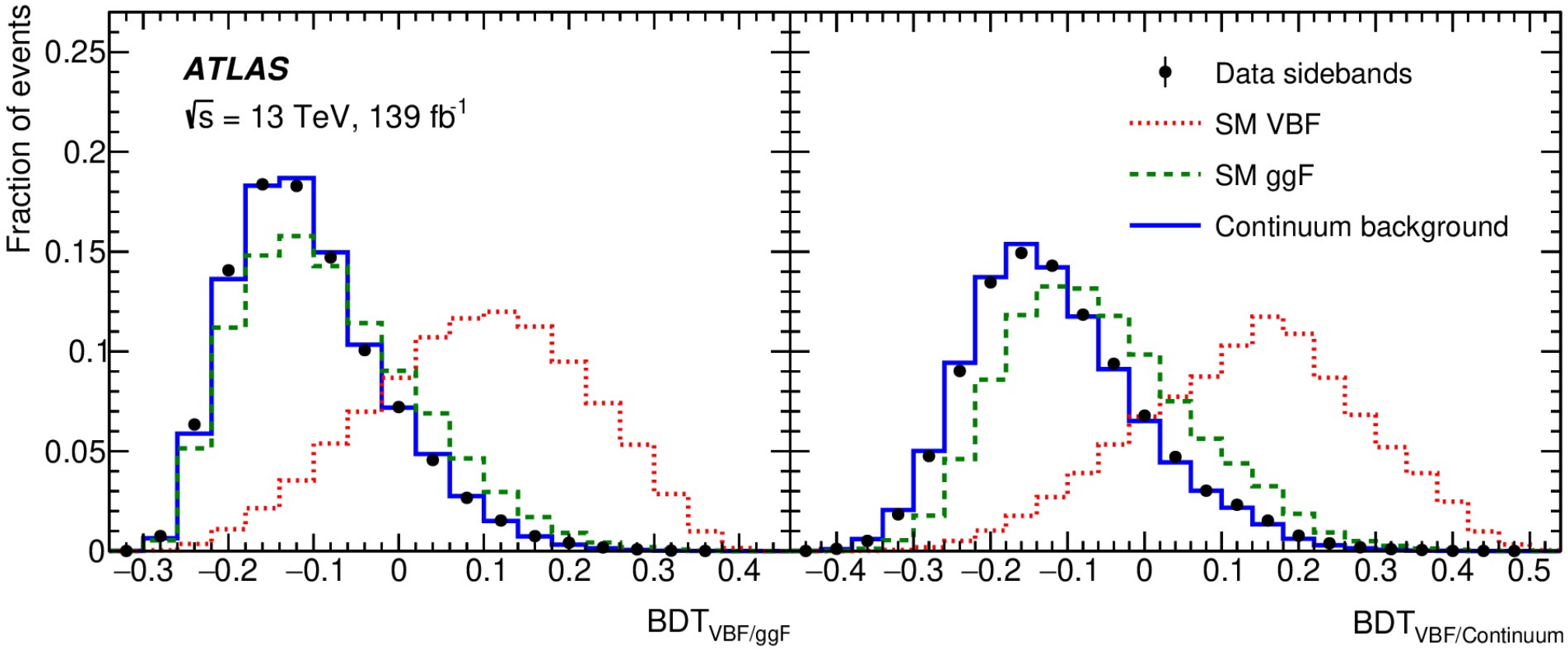
- Definition of VBF-enriched fiducial regions
- Two fiducial fits:
  - **With ggF** as part of signal – model independent result → 60% VBF purity
    $\sigma = 0.215^{+0.075\ +0.016}_{-0.063\ -0.013}$ fb
  - **Without ggF** – subtracting MC expectation introduces model dependency → 95% VBF purity
    $\sigma = 0.172^{+0.072\ +0.016}_{-0.062\ -0.018}$ fb
- Larger observed cross-sections than expected but SM compatible



arXiv:2208.02338

VBF production with $H \to \gamma\gamma$

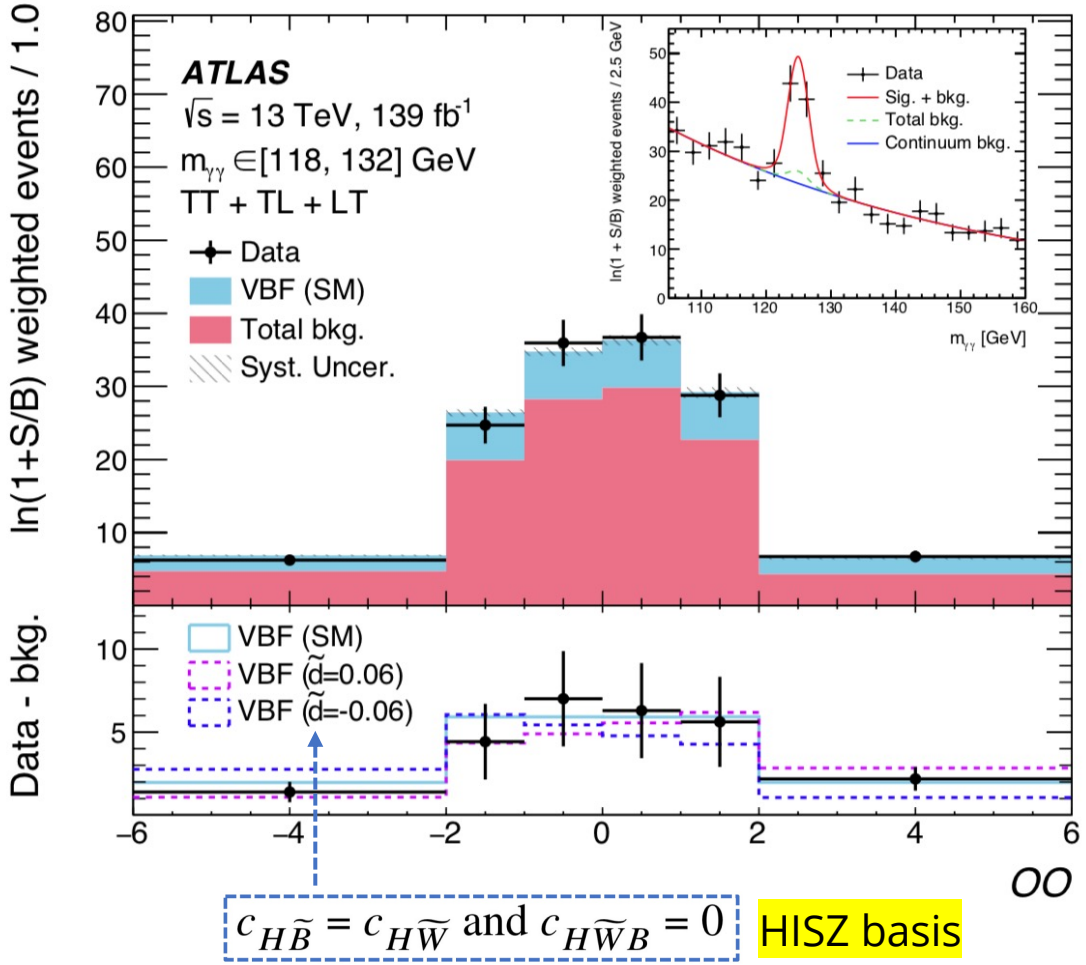
- CP-odd effects in VBF production $H \to \gamma\gamma$ using SMEFT *optimal observables*
- Two BDTs are used to enhance VBF signal and define 3 SRs

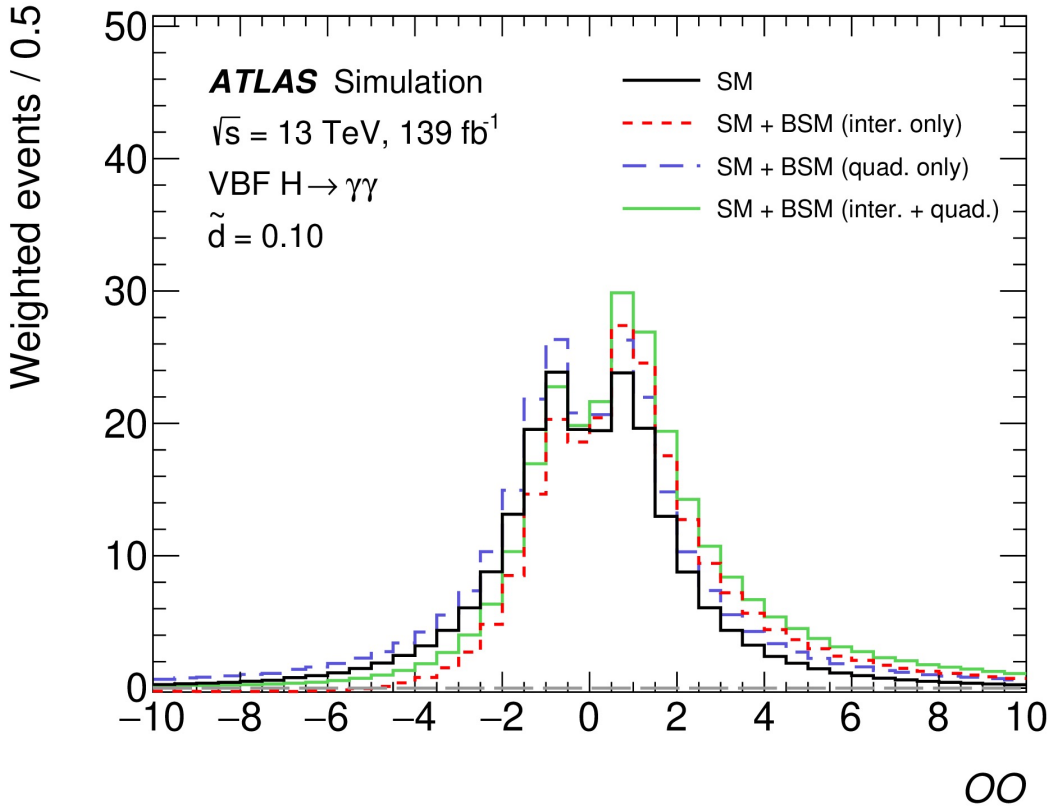


VBF production with $H \to \gamma\gamma$

arXiv:2208.02338

- VBF signal yields in OO bins is extracted with simultaneous PL fit to $m_{\gamma\gamma}$ spectra

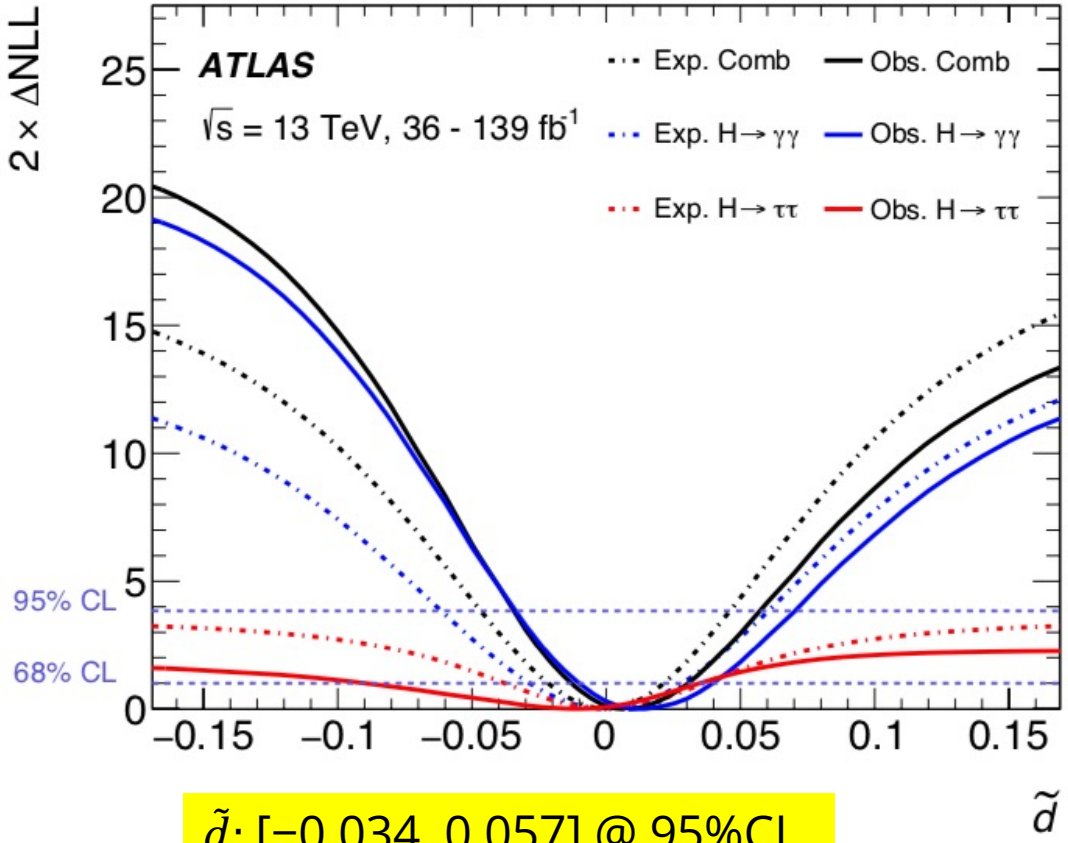




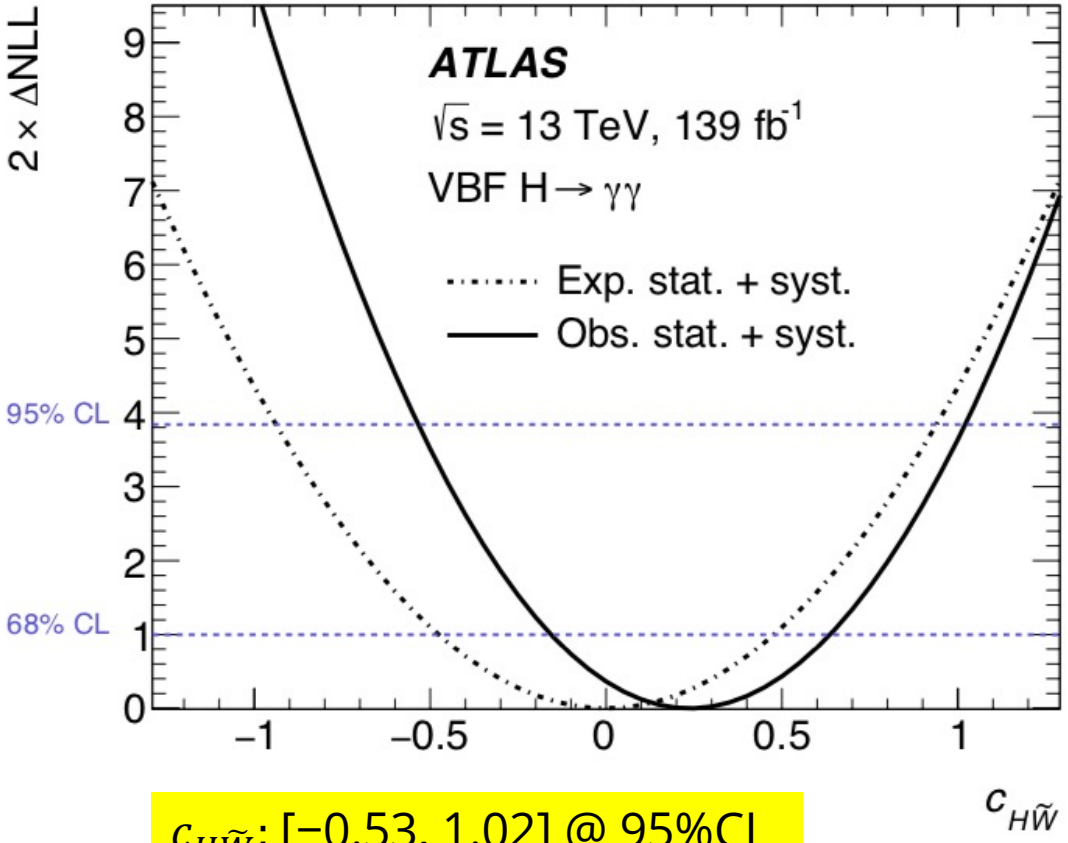
VBF production with $H \to \gamma\gamma$

arXiv:2208.02338

- NNL scans performed in combination to previous $H \to \tau\tau$ [Ref.] result
- Limits driven by interference terms



$\tilde{d}$: [−0.034, 0.057] @ 95%CL

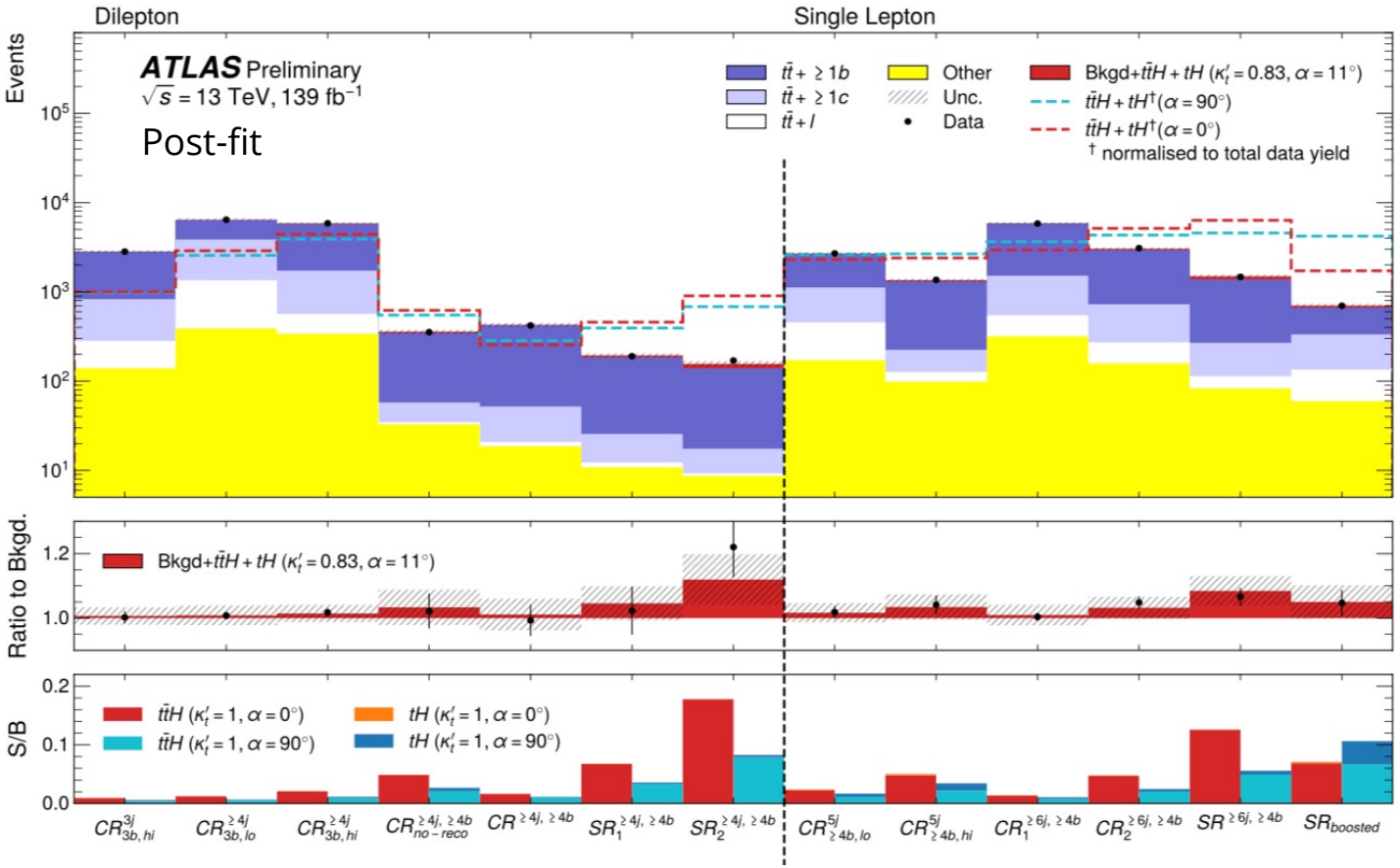


$c_{H\tilde{W}}$: [−0.53, 1.02] @ 95%CL

$t\bar{t}H/tH$ production with $H \to b\bar{b}$

arXiv:2303.05974

- Top Yukawa coupling is the largest in the SM, ideal place to search for BSM
- Two BDTs are used to enhance $t\bar{t}H$ signal in SRs: *reconstruction* and *classification* BDTs



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

- *Reconstruction* BDT: assign jets from Higgs/top decays
- *Classification* BDT: discriminate $t\bar{t}H$ signal

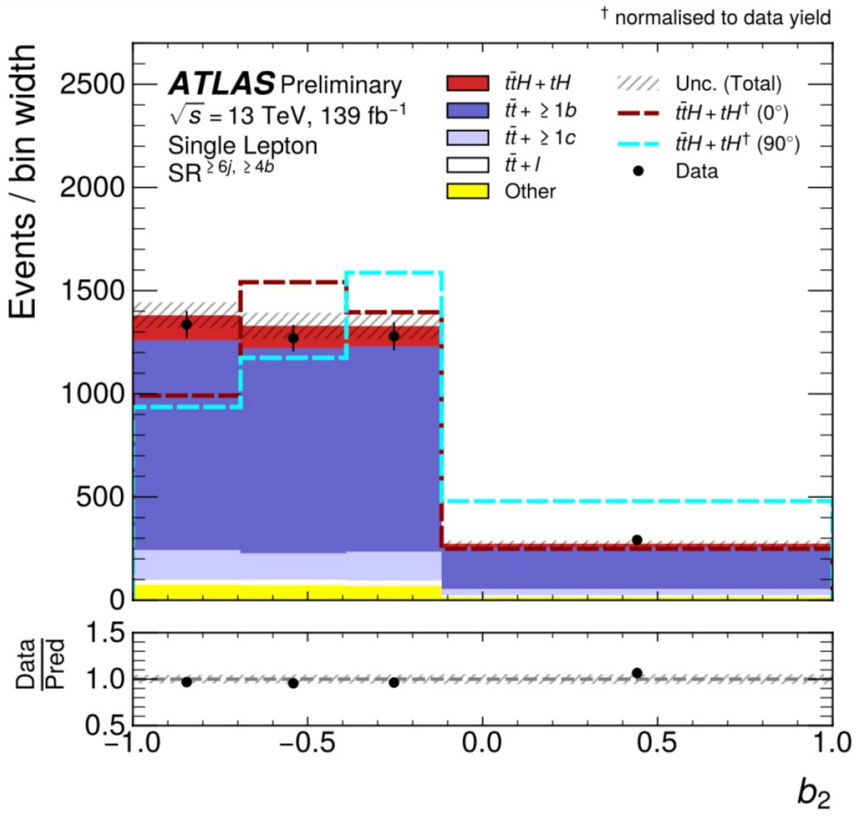
arXiv:2303.05974

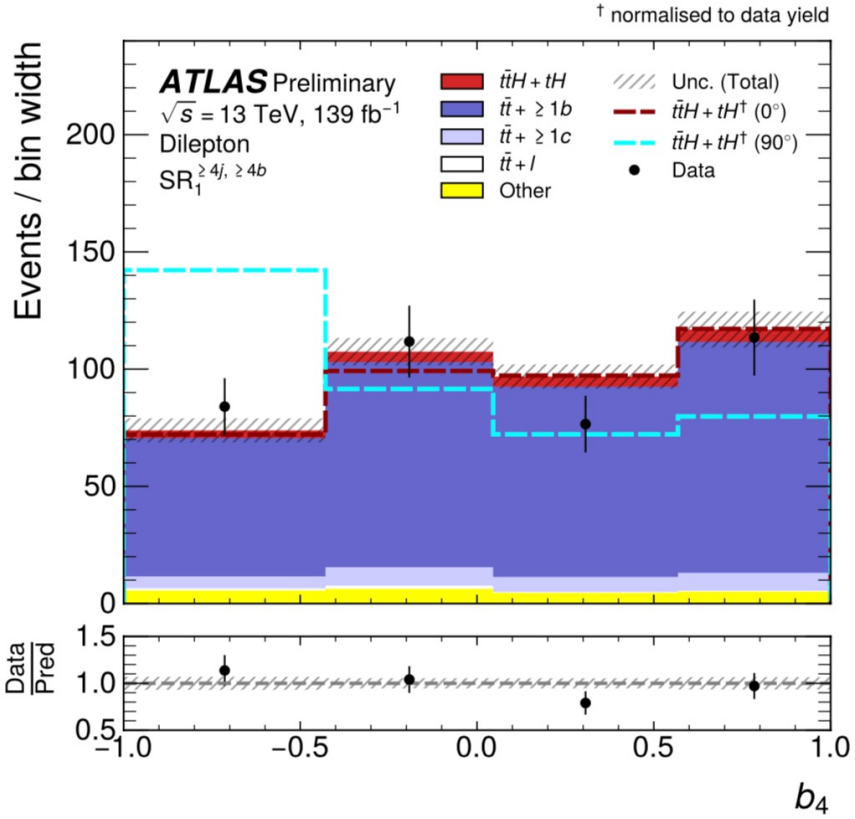
$t\bar{t}H/tH$ production with $H \to b\bar{b}$

- Two observables are used to provide best discrimination in SRs

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

- Indexes 1,2 denote the two top quarks
- Unit vector $\hat{n}$ points in the direction of beam line

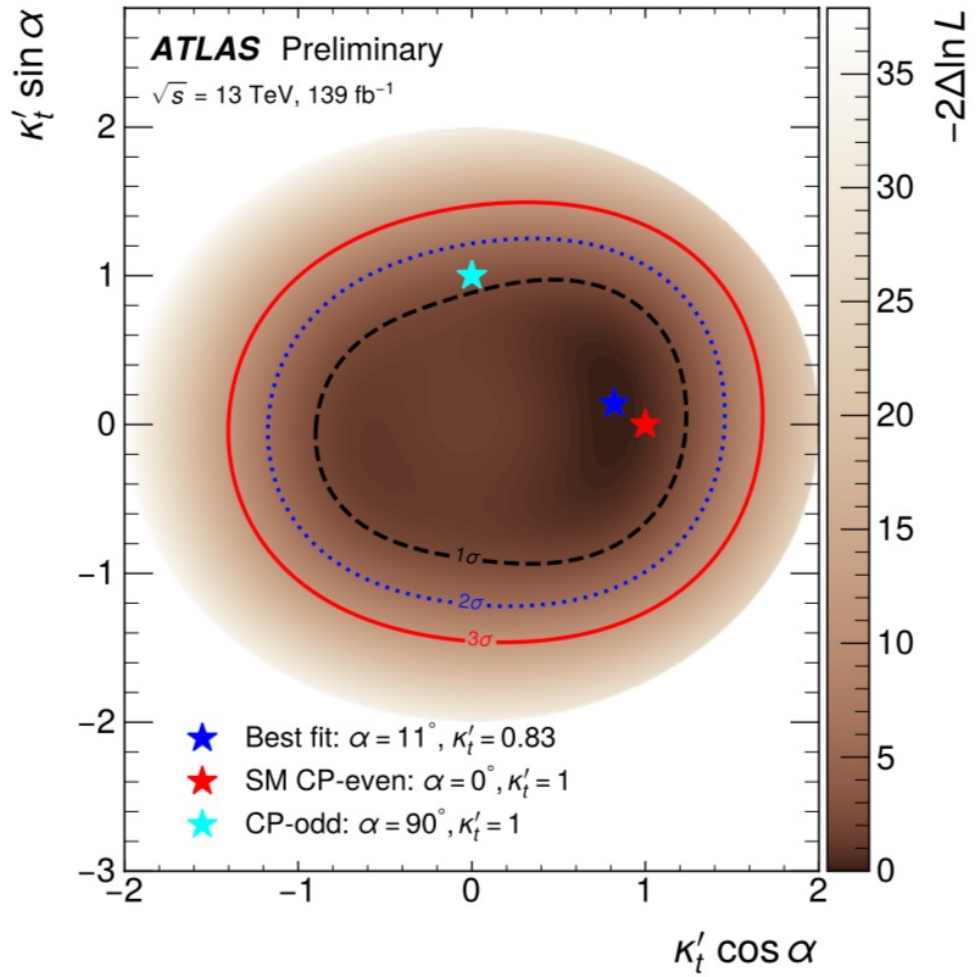




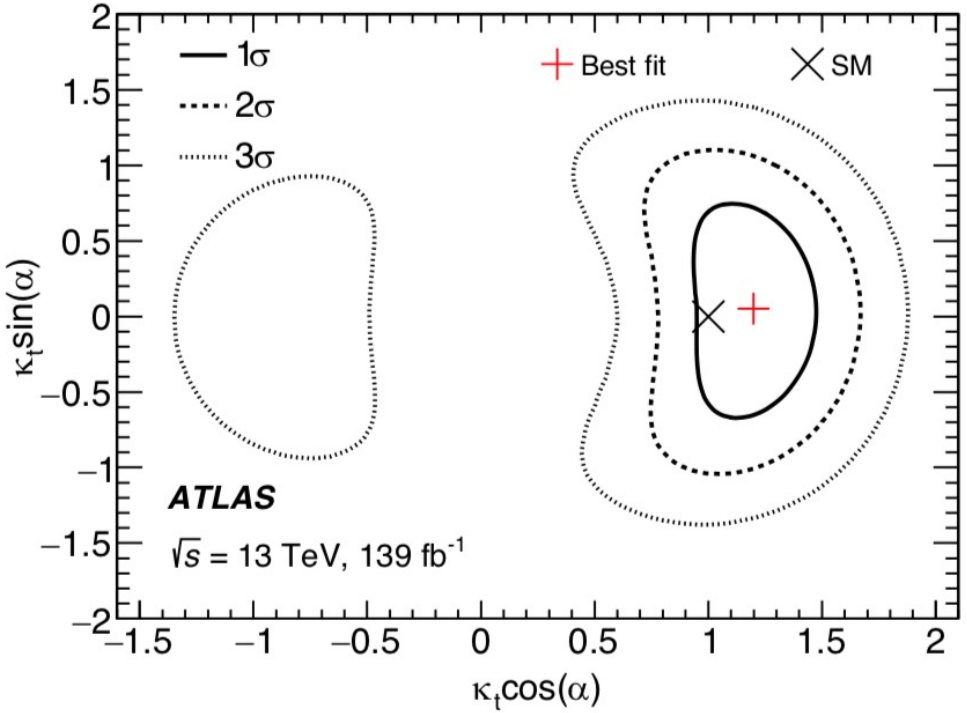
$t\bar{t}H/tH$ production with $H \to b\bar{b}$

arXiv:2303.05974

- Best-fit $\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$ at 68%CL and pure CP-odd coupling is excluded at 1.2σ



$t\bar{t}H/tH$ production with $H \to \gamma\gamma$ [Ref.]

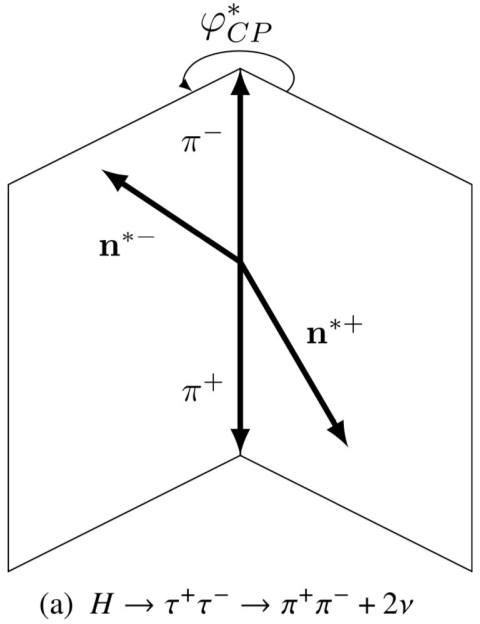


$\alpha < |43|^{\circ}$ at 95%CL and pure CP-odd coupling is excluded at 3.9σ

CP properties in $H \to \tau\tau$

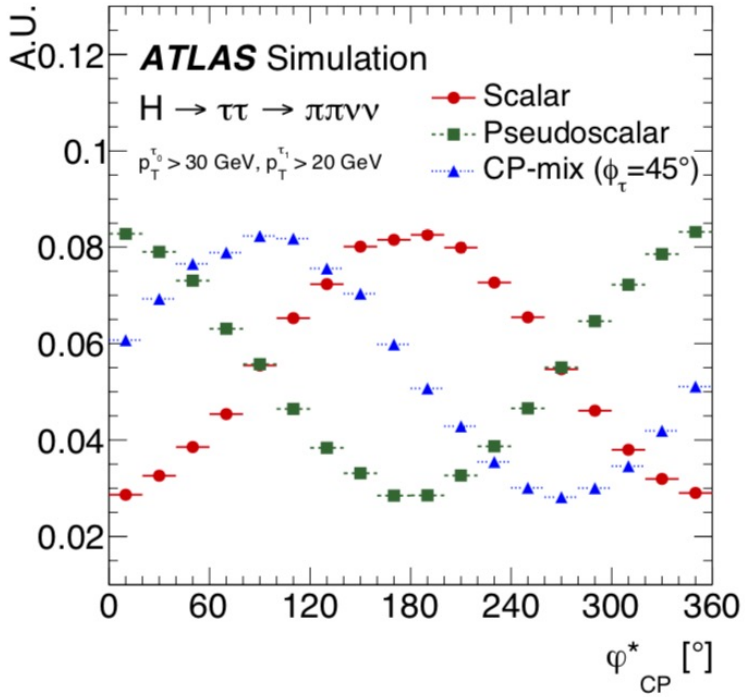
arXiv:2212.05833

- *Signed acoplanarity angle*, φ^*_{CP}, between τ-lepton decay planes used as a proxy for CP-mixing angle
  - Planes are spanned by impact parameter (IP) or τ decay products spatial momenta ($\pi^{\pm}, \pi^0$)

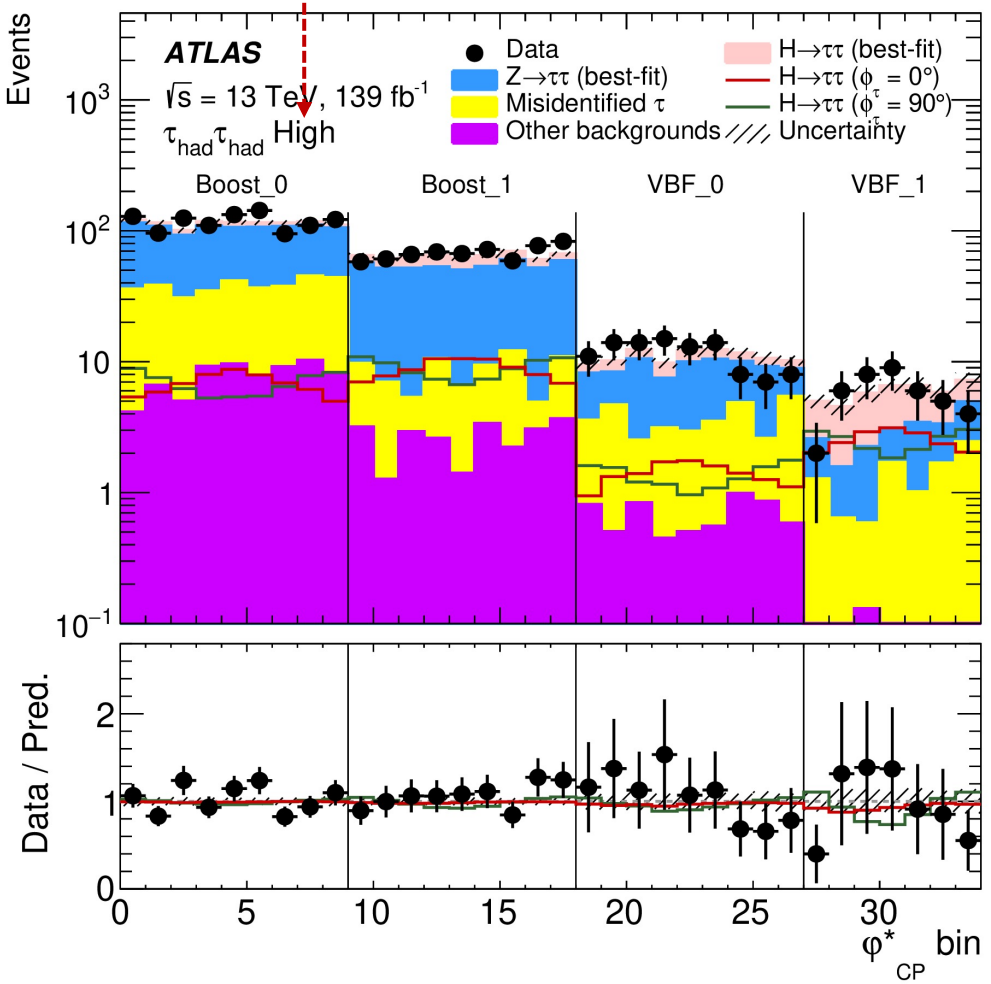


(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$

IP method



Split in relative dominance of decay channel

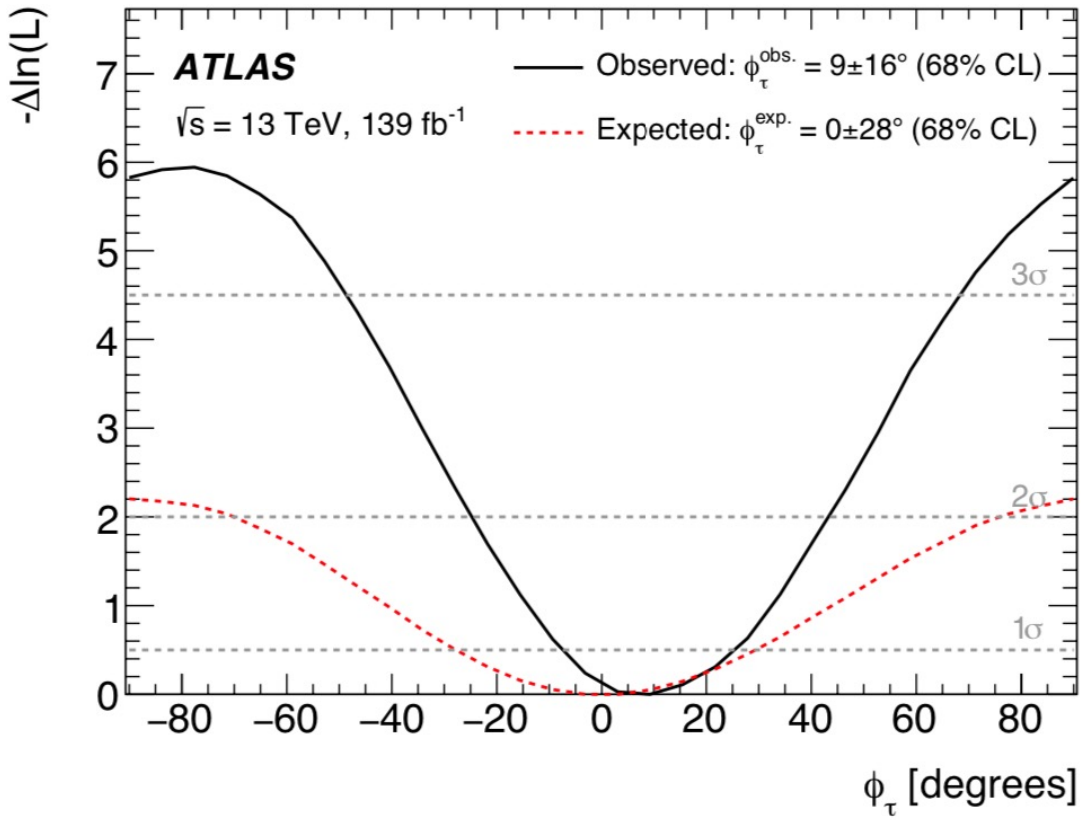


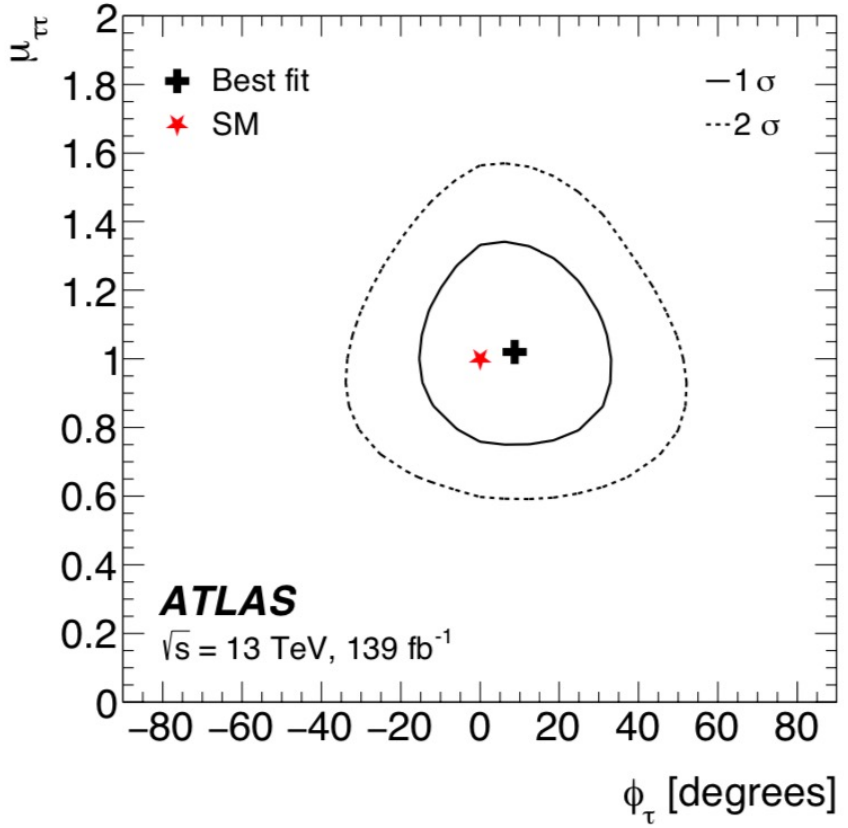
Regions split in di-tau decay channel and ggF/VBF production mode

CP properties in $H \to \tau\tau$

arXiv:2212.05833

- Best-fit $\phi_t = 9° \pm 16°$ at 68%CL and pure CP-odd coupling is excluded at 3.4σ
- Normalisation is free-floated → EFT shape-only analysis





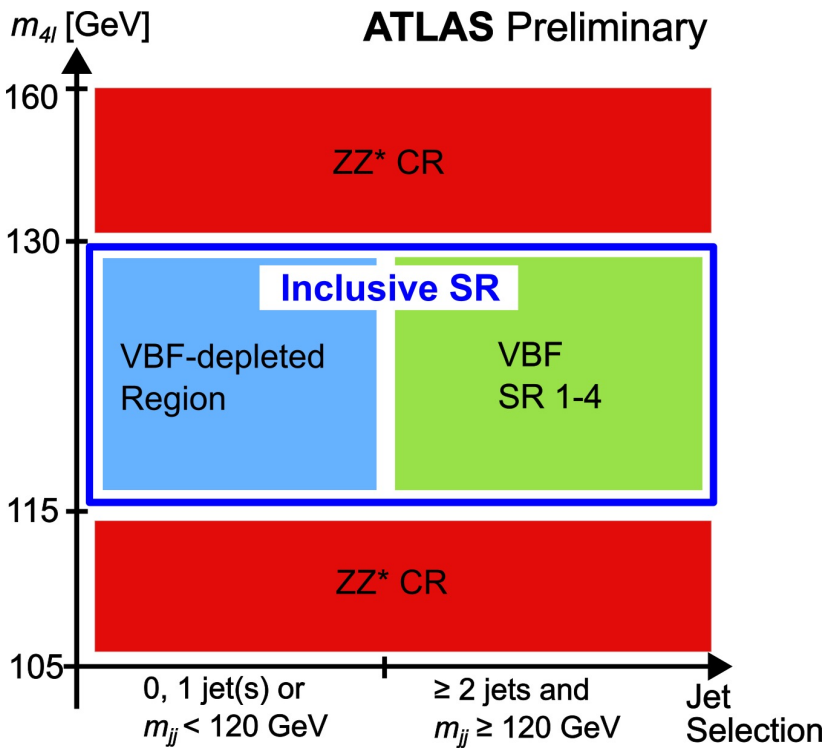
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\upsilon}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H,$$

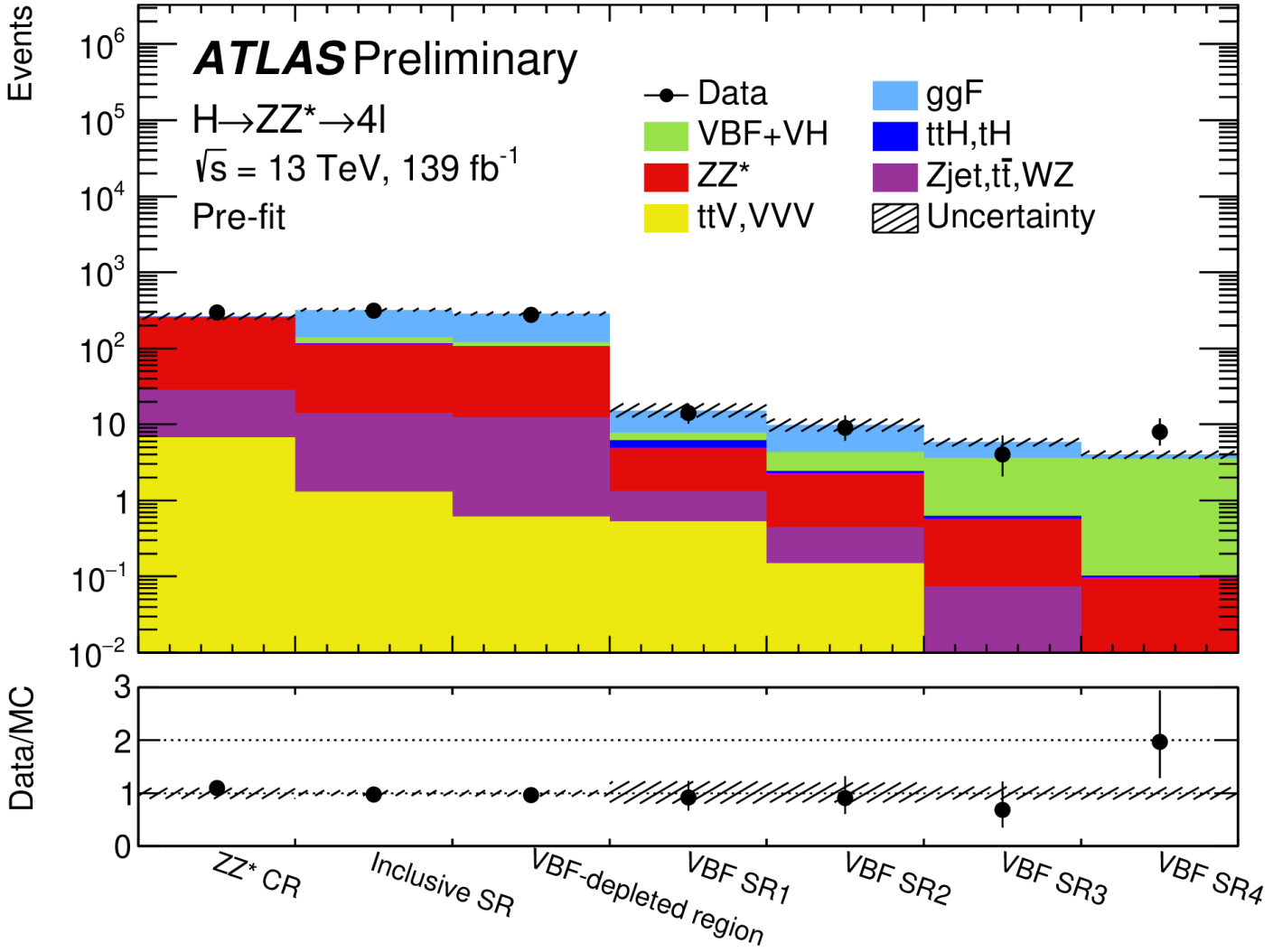
Summary

- Constrained possible new CPV sources in HVV and Hff couplings with Run 2 data
- New possibilities to perform **combinations** over multiple channels
- Most analysis dominated by **statistical uncertainties**
  - Interesting prospects for **Run 3** analysis
- Results shown are compatible with SM expectation
- No clear sign of CPV in Higgs sector yet but still room to explore
  - Pure CP-odd coupling are excluded $> 3\sigma$

Backup

SR and CR event categorisation





CPV in VBF prod. and Higgs $4l$ decay

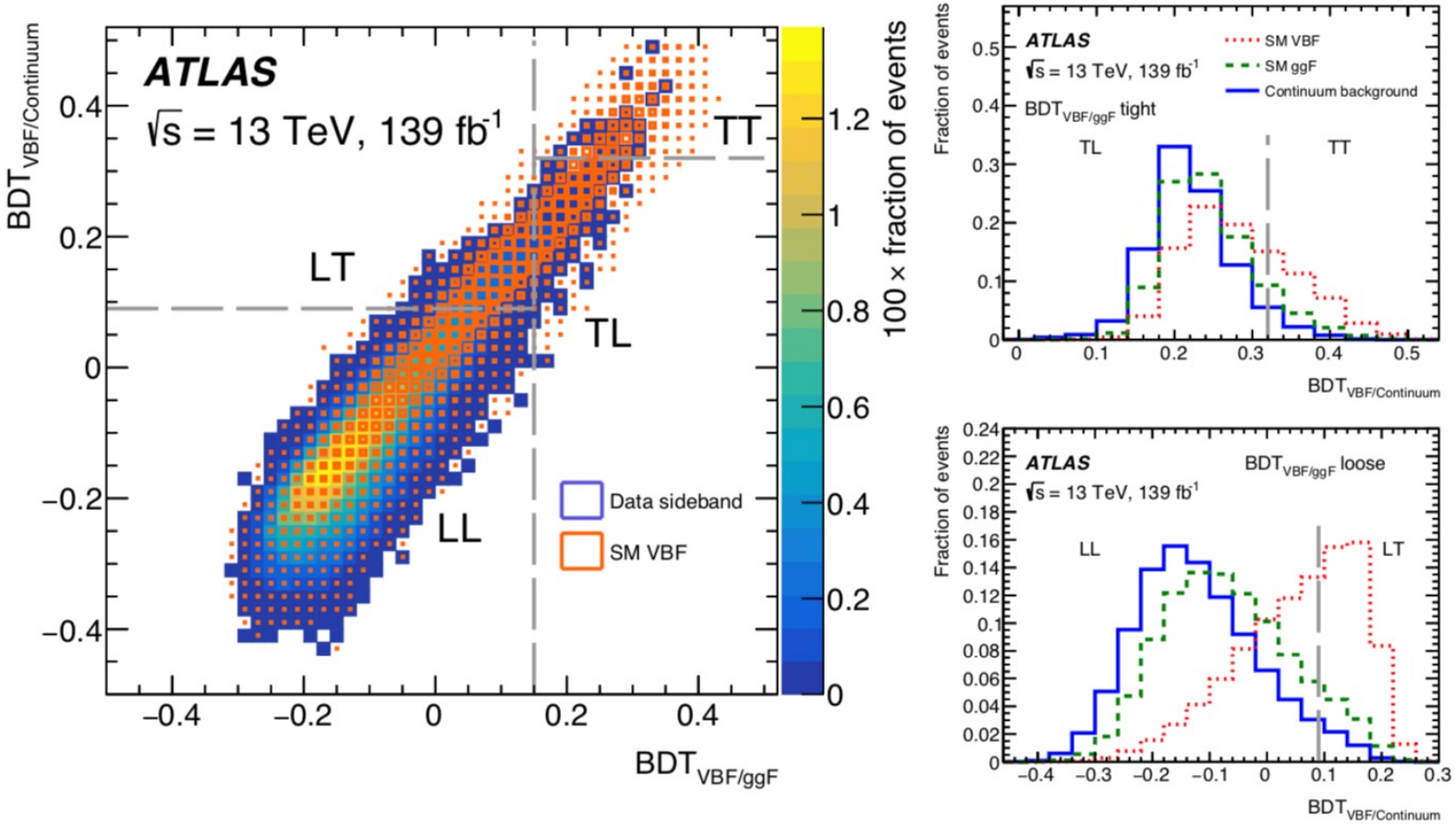
Table 1: The expected and observed confidence intervals at 68% and 95% CL for the CP-odd Wilson coefficients for an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV. Only one Wilson coefficient is fitted at a time while all others are set to zero. The observed best fit value and p-value for agreement with the SM is provided. The last column indicates whether the limits come from production (prod), decay or a combination of production and decay (comb). All couplings scale as $1/\Lambda^2$ with the assumed value of $\Lambda = 1$ TeV.

EFT coupling	Expected		Observed		Best-fit	SM	Fit type
parameter	68% CL	95% CL	68% CL	95% CL	value	p-value	
$c_{H\widetilde{B}}$	$[-0.18, 0.19]$	$[-0.37, 0.37]$	$[-0.42, 0.31]$	$[-0.61, 0.54]$	-0.078	0.86	decay
$c_{H\widetilde{W}B}$	$[-0.36, 0.36]$	$[-0.72, 0.72]$	$[-0.56, 0.53]$	$[-0.97, 0.98]$	-0.017	0.99	decay
$c_{H\widetilde{W}}$	$[-0.63, 0.63]$	$[-1.26, 1.28]$	$[-0.07, 1.09]$	$[-0.81, 1.54]$	0.60	0.37	comb
$\widetilde{d}$	$[-0.009, 0.009]$	$[-0.018, 0.018]$	$[-0.017, 0.014]$	$[-0.026, 0.025]$	-0.003	0.86	decay
$\widetilde{c}_{zz}$	$[-0.77, 0.79]$	$[-2.4, 2.4]$	$[0.37, 1.21]$	$[-1.20, 1.75]$	0.78	0.11	prod
$\widetilde{c}_{z\gamma}$	$[-0.47, 0.47]$	$[-0.76, 0.76]$	$[-0.54, 0.54]$	$[-0.84, 0.83]$	0.083	0.93	decay
$\widetilde{c}_{\gamma\gamma}$	$[-0.38, 0.38]$	$[-0.76, 0.77]$	$[-0.52, 0.48]$	$[-0.99, 0.93]$	-0.01	0.99	decay

VBF production fiducial cross-section

VBF–enriched region	Signal for cross-section estimates	Purity of VBF signal	Expected cross-section [fb]	Observed cross-section [fb]
$N_{\text{jets}} \geq 2,\ m_{jj} \geq 400$ GeV	All production modes	59 %	$0.134^{+0.065\ +0.014}_{-0.053\ -0.012}$	$0.215^{+0.075\ +0.016}_{-0.063\ -0.013}$
$\lvert\Delta\eta_{jj}\rvert \geq 3.0$	VBF $+VH$ $+ttH$	95 %	$0.088^{+0.063\ +0.017}_{-0.053\ -0.020}$	$0.172^{+0.072\ +0.016}_{-0.062\ -0.018}$

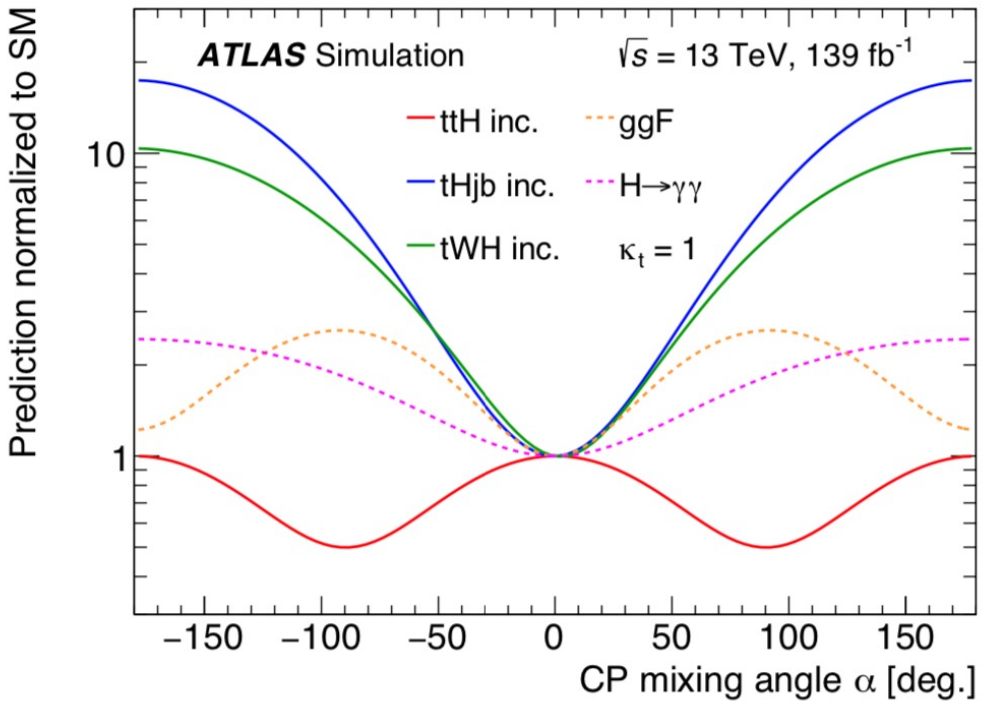
VBF production with $H \rightarrow \gamma\gamma$

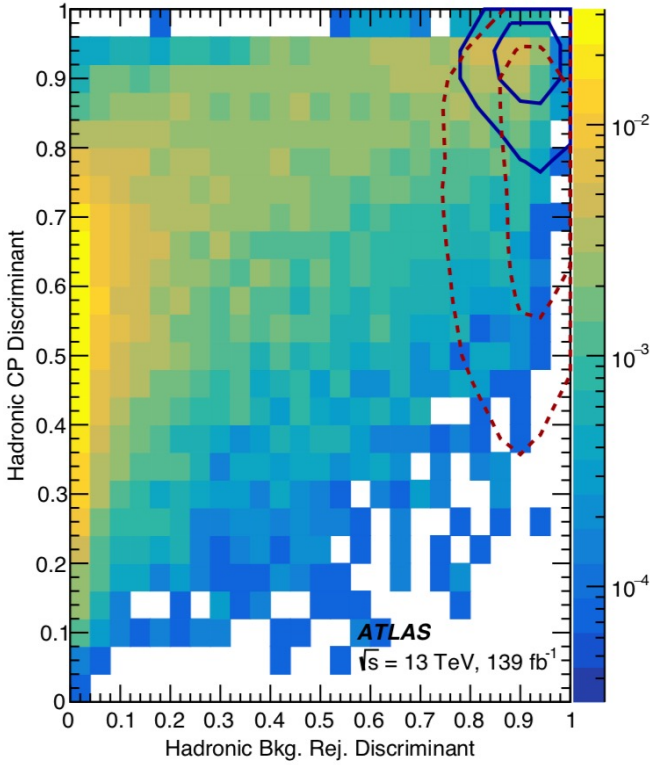


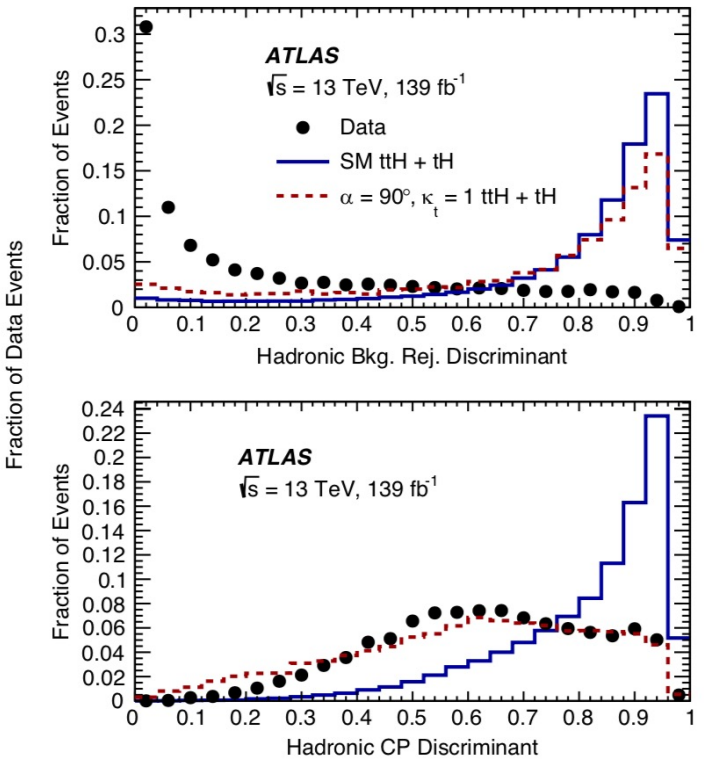
- First L/T corresponds to VBF/ggF BDT discriminant
- Second L/T corresponds to VBF/Cont. discriminant

$t\bar{t}H/tH$ production with $H \to \gamma\gamma$

- Top Yukawa coupling is the largest in the SM, ideal place to search for BSM
- Two BDTs are used to enhance ttH signal in *Lep* and *Had* SRs
- Additional BDT to reconstruct top candidate

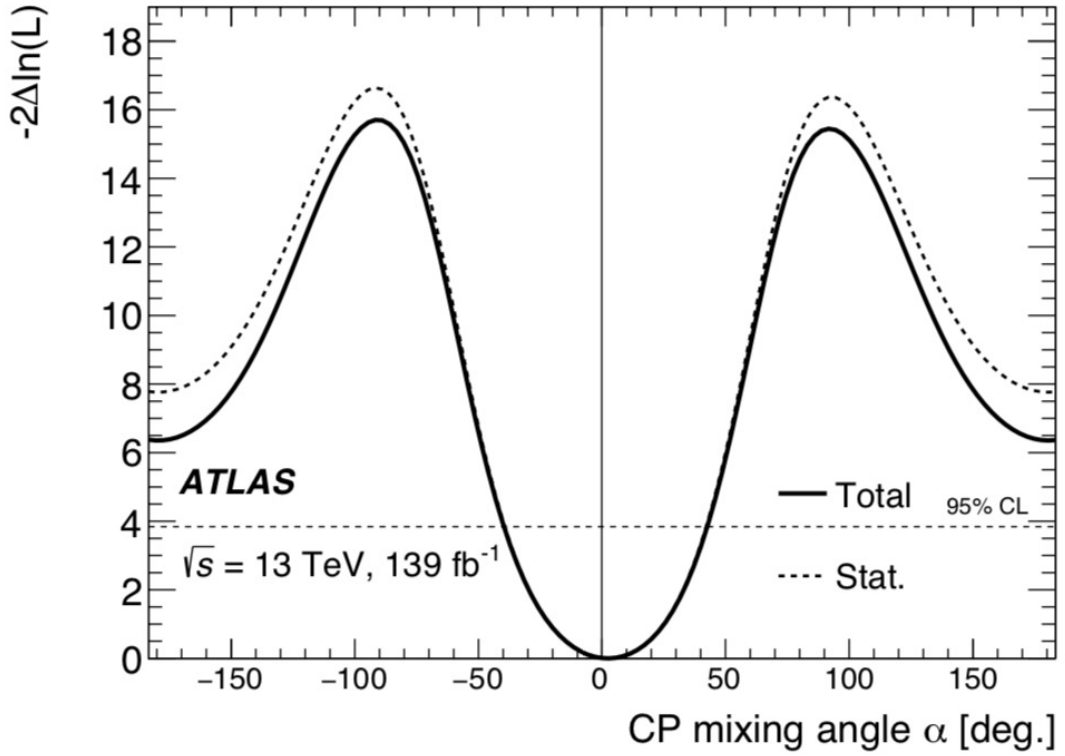


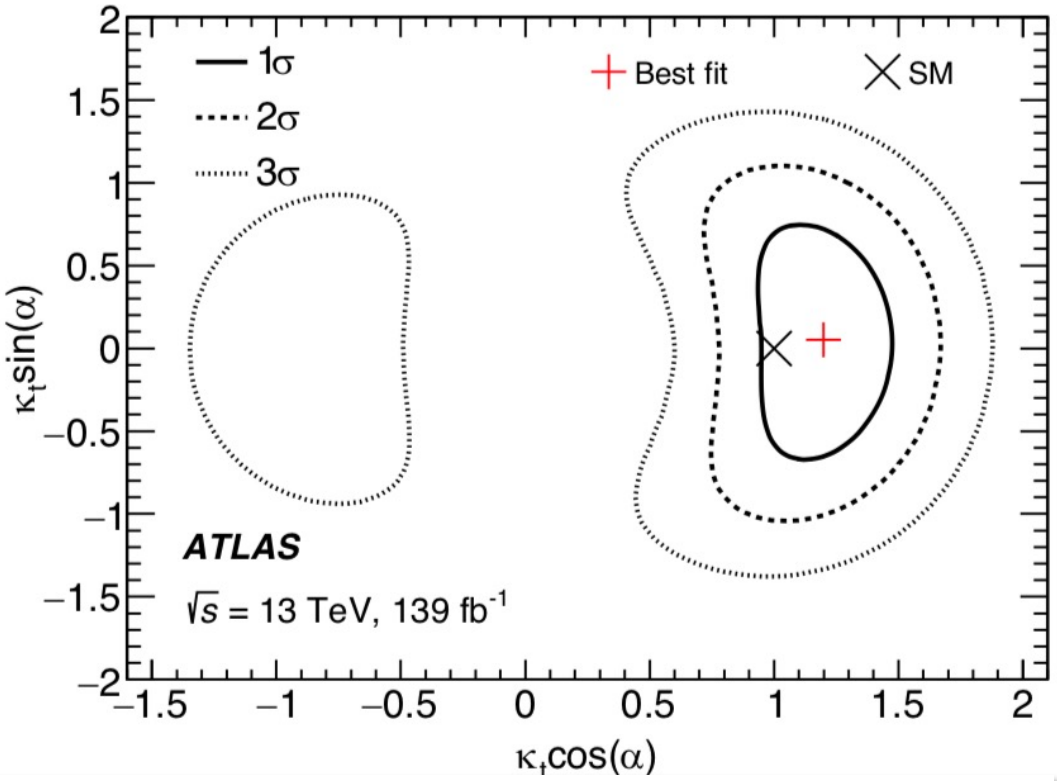




$t\bar{t}H/tH$ production with $H \to \gamma\gamma$

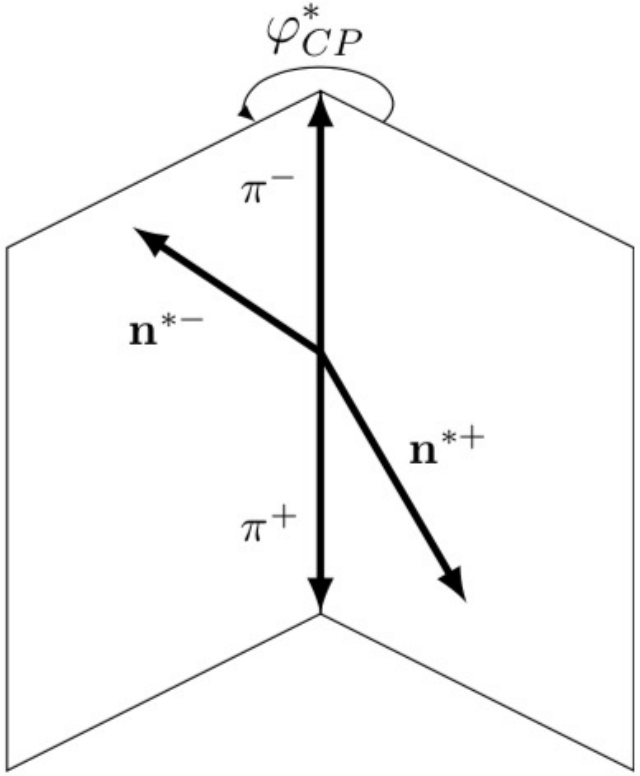
- 1D and 2D limits on CP-mixing angle
- $\alpha < |43|°$ at 95%CL and pure CP-odd coupling is excluded at 3.9σ



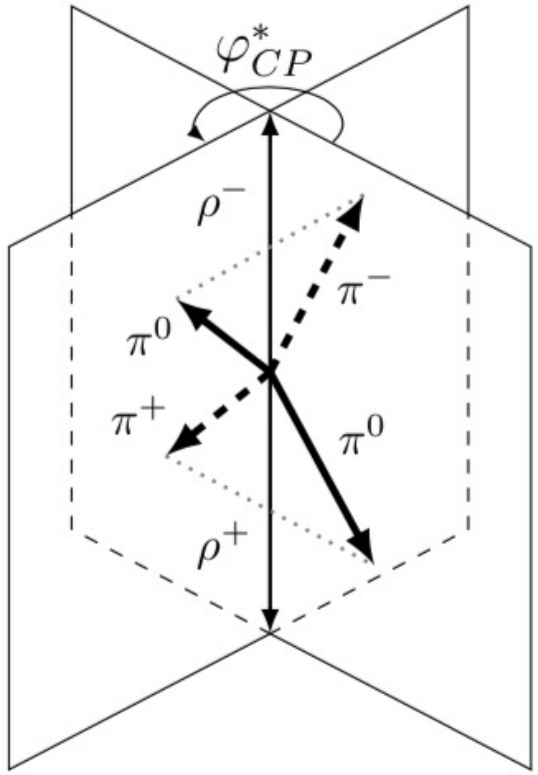


$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5]\psi_t\}H$$

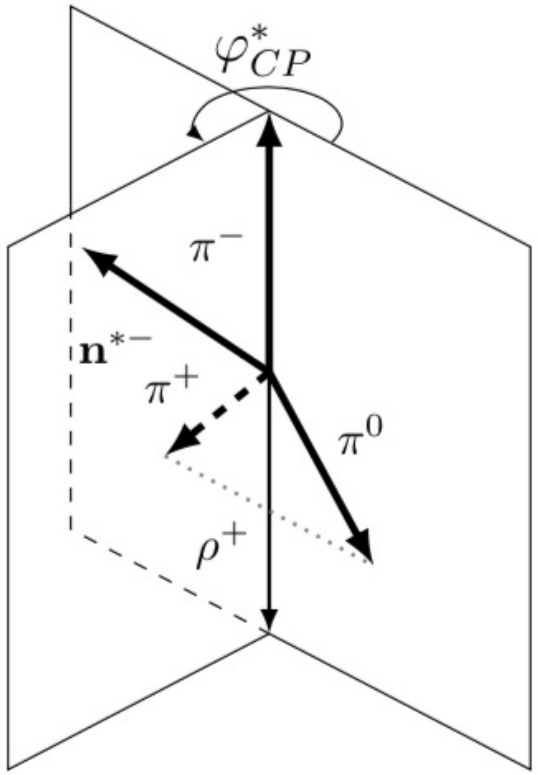
CP properties in $H \to \tau\tau$



(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$



(b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$



(c) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$

CP properties in $H \to \tau\tau$: channels

Notation	Decay mode	Branching fraction
ℓ	$\ell^{\pm}\bar{\nu}\nu$	35.2%
1p0n	$h^{\pm}\nu$ ($\pi^{\pm}\nu$)	11.5% (10.8%)
1p1n	$h^{\pm}\pi^0\nu$ ($\pi^{\pm}\pi^0\nu$)	25.9% (25.5%)
1pXn	$h^{\pm} \geq 2\pi^0\nu$ ($\pi^{\pm}2\pi^0\nu$)	10.8% (9.3%)
3p0n	$3h^{\pm}\nu$ ($3\pi^{\pm}\nu$)	9.8% (9.0%)

Decay channel	Decay mode combination	Method	Fraction in all τ-lepton-pair decays
$\tau_{\text{lep}}\tau_{\text{had}}$	ℓ–1p0n	IP	8.1%
	ℓ–1p1n	IP–ρ	18.3%
	ℓ–1pXn	IP–ρ	7.6%
	ℓ–3p0n	IP–a_1	6.9%
$\tau_{\text{had}}\tau_{\text{had}}$	1p0n–1p0n	IP	1.3%
	1p0n–1p1n	IP–ρ	6.0%
	1p1n–1p1n	ρ	6.7%
	1p0n–1pXn	IP–ρ	2.5%
	1p1n–1pXn	ρ	5.6%
	1p1n–3p0n	ρ–a_1	5.1%

CP properties in $H \to \tau\tau$

- Combined post-fit φ^*_{CP} distribution in all decay channels