ICHEP 2022 BOLOGNA

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

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ATLAS EXPERIMENT

Introduction – CP violation in the Higgs sector

Run 1 data identified H as a **CP-even scalar**

- Still room for CP-odd **admixtures** in the coupling behaviour – potential for **CP violation**

$$\sigma \sim |M_{SM} + M_{CP-odd}|^2 = M_{SM}^2 + \underbrace{M_{CP-odd}^2}_{\text{CP-even. Affects rates}} + \underbrace{2\mathcal{Re}(M_{SM}^* M_{CP-odd})}_{\text{CP-odd. Vanishes for CP-even observables}}$$

How to look for signs of CP violation in Higgs couplings?

- Modified **rates** – not immediately distinguishable from CP-even BSM
- Characteristic: **Interference** effects on **shapes** of **CP-odd** observables

→ Can extract **limits** from rate measurements, but dedicated CPV searches typically use **shape information**

Fermion couplings

- CP-odd contribution allowed at **tree level**
- Mainly third-generation couplings
- ttH production and H→ττ decays

Example model: $\mathcal{L}_{HFF} \propto \kappa_F \underbrace{(\cos\phi\, \bar{F}F}_{\text{even}} + \underbrace{\sin\phi \bar{F} i\gamma_5 F)}_{\text{odd}} H$

Boson couplings

- CP-odd contribution from higher order operators - **suppressed** by BSM scale
- VBF/VH production and WW/ZZ decays

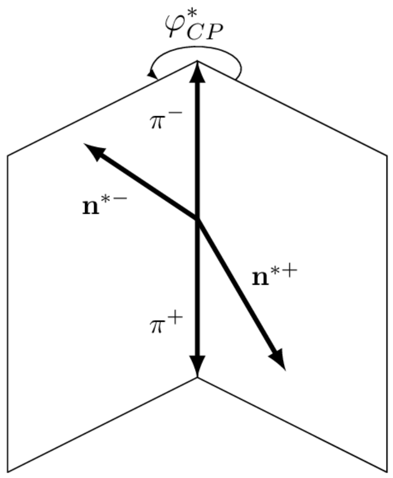
Example model: $\mathcal{L}_{HVV} \supset \mathcal{L}_{HVV,SM} + \underbrace{\frac{1}{\Lambda^2}}_{\text{BSM scale}} c\, \underbrace{H\tilde{V}_{\mu\nu}V^{\mu\nu}}_{\text{dim-6 CP-odd}} + \cdots$

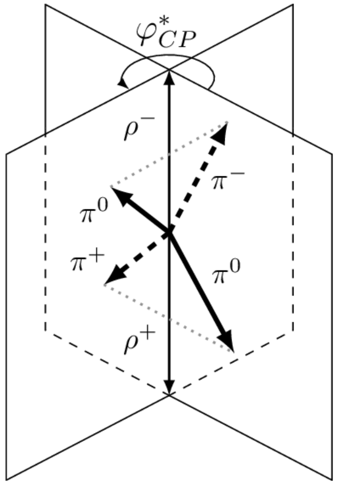
frequently: embedded in EFT framework

This talk: Selection of **latest** ATLAS results covering both fermion and boson couplings

Hττ coupling

ATLAS-CONF-2022-032





Target observable: Signed **Acoplanarity angle** between τ decay planes

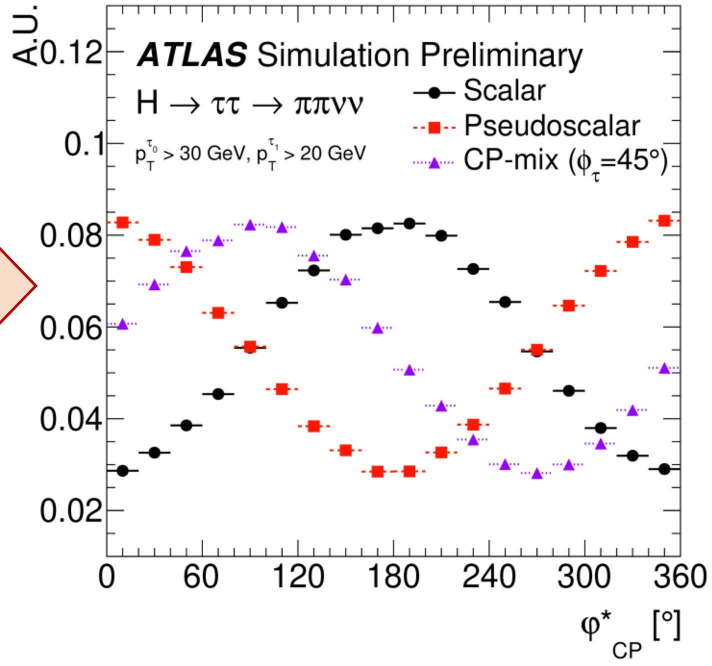
→ Exploit spin correlations

→ CP mixing angle directly visible as phase-shift

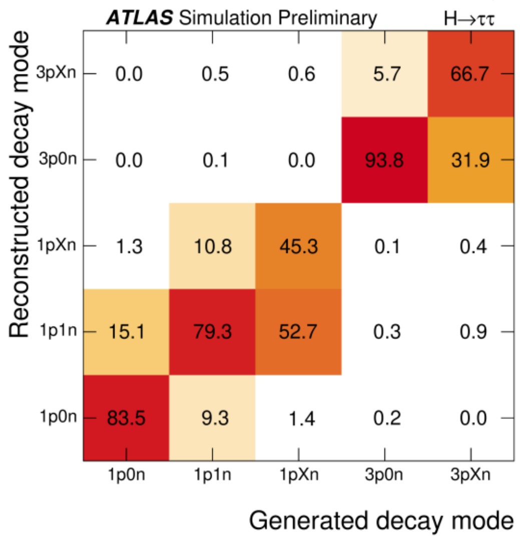
$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

Challenge: Reconstruct angle using visible τ decay products

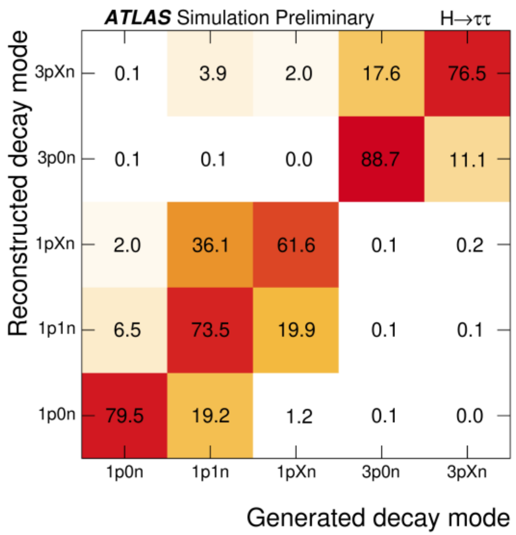
- Exploit **track impact parameters** and **neutral pions** ($\pi^0 \to \gamma\gamma$)
- Relies on excellent performance of **particle flow** based τ classification



Efficiency



Purity



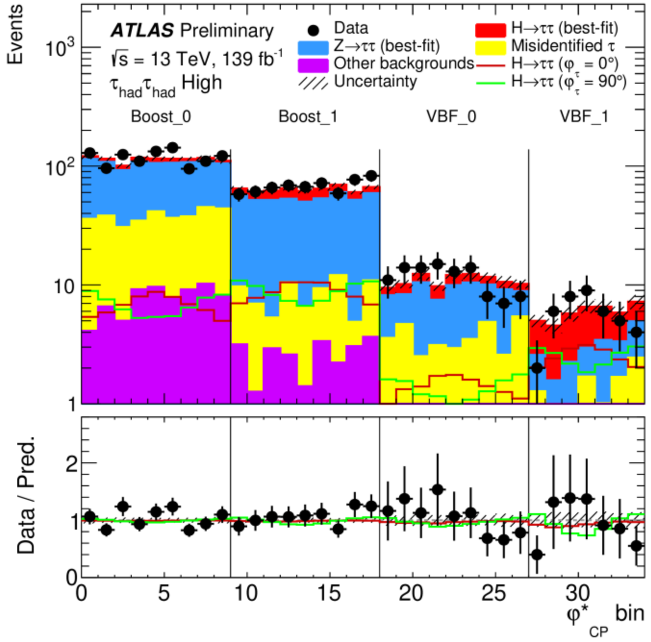
ATLAS-CONF-2022-032

Hττ coupling

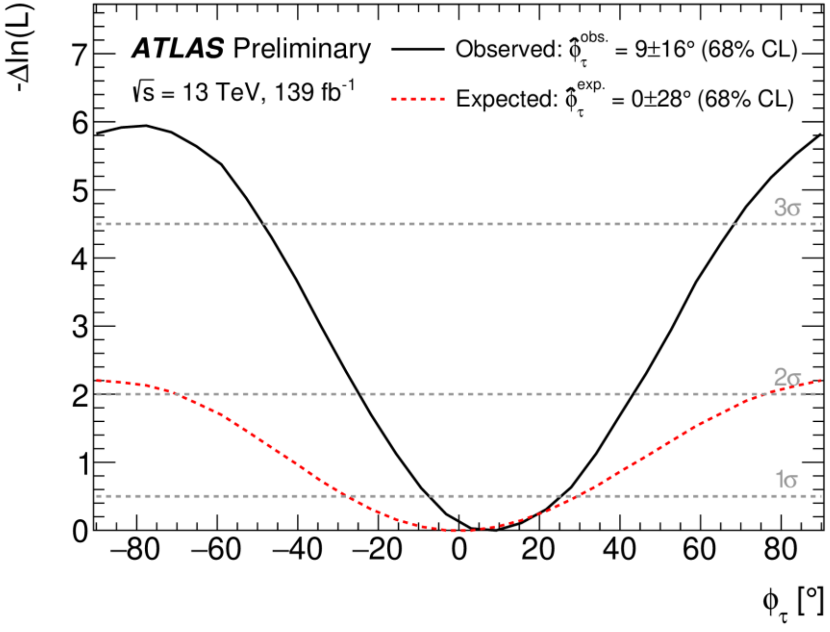
Use **ggF** (boosted) and **VBF** events

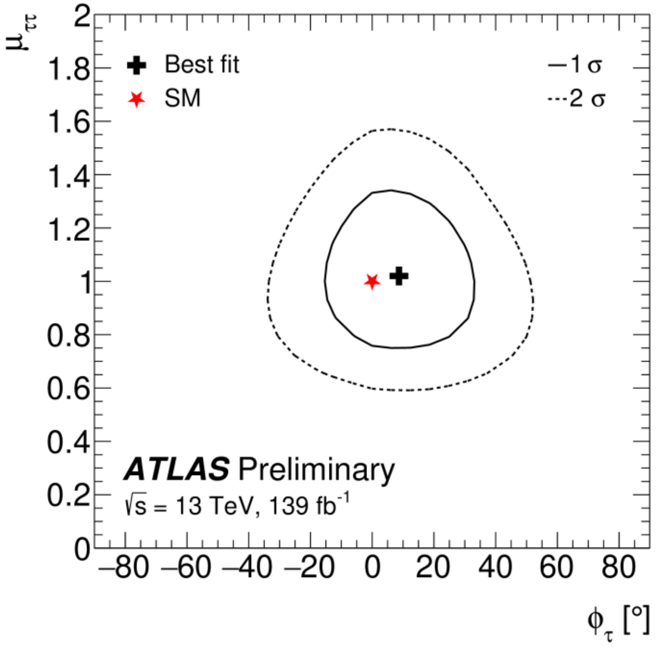
- Classify events by purity and **CP sensitivity** – driven by decay mode and angle resolution
- Use control regions to normalise dominant Z→ ττ background
- Floating signal normalisation – agnostic to pure rate effects
- In-situ calibration of π^0 energy and angular resolutions using Z→ ττ events

Sensitivity achieved by **combination** of all event types and categories



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





Results:

- Disfavour pure CP-odd at 3.4σ
- Still some space for CP-violation
- Analysis **statistically** limited

→ Expect improvements with Run-3

Phys. Rev. Lett. 125 (2020) 061802

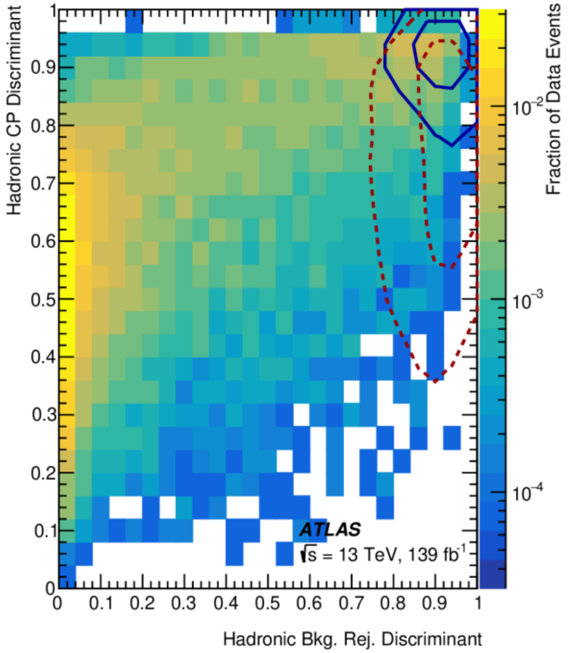
ttH coupling

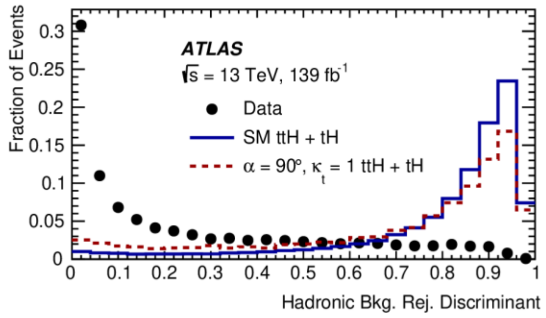
Explore top coupling using rare **production** modes

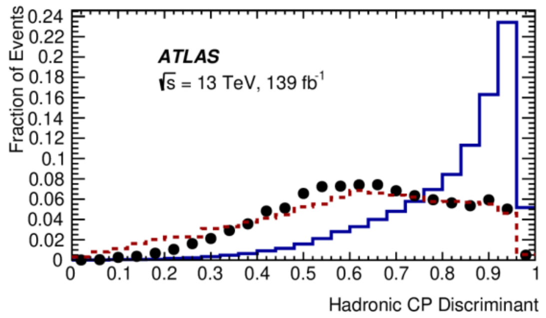
Existing measurement: t(t)H; **H→γγ**

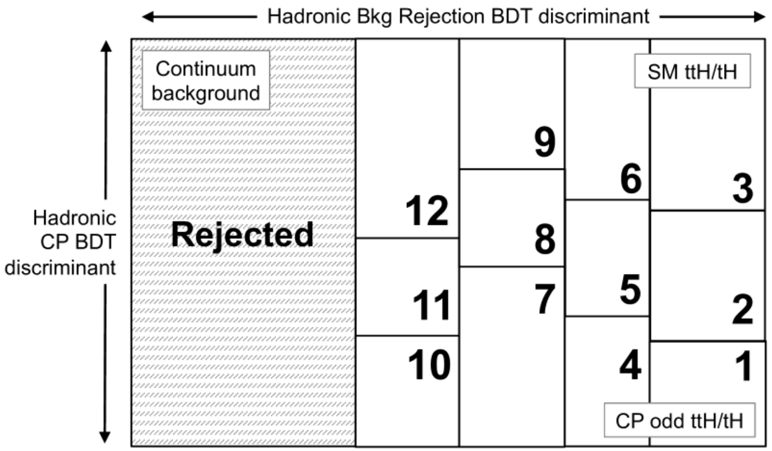
BDT discriminant to select CP-odd-enhanced phase-space
→ correlate with background suppression BDT

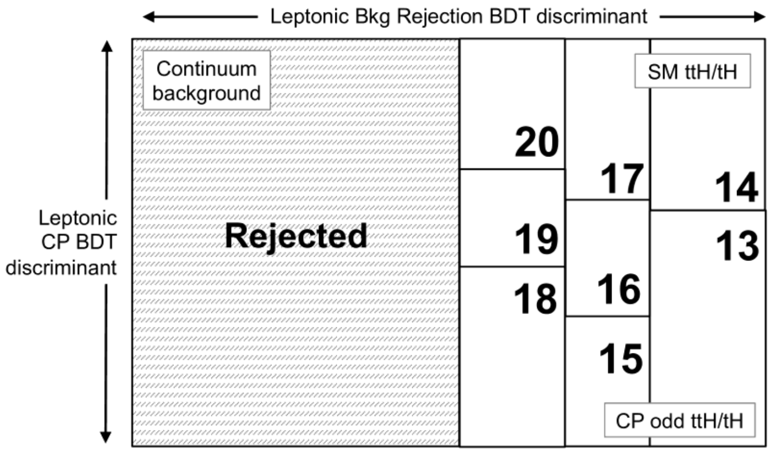
Combined fit of yields in 2D bins of discriminant
→ Exclude mixing angles above **43°** at 95% CL

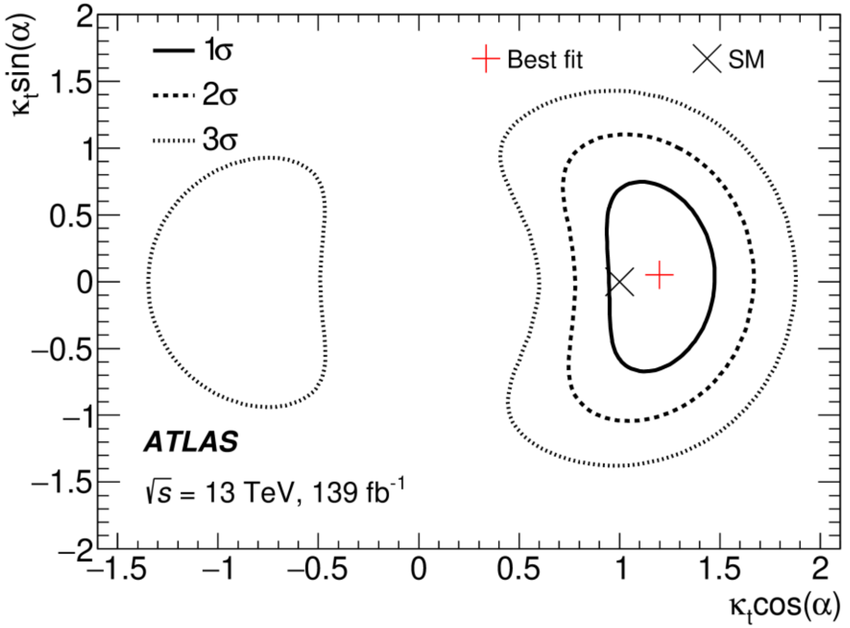












ATLAS-CONF-2022-016

ttH coupling

New, complementary: **ttH** measurement using **H→bb** decay

→ Form **top candidates** from jets & leptons to define **CP-sensitive observables**

Evaluated in multitude of signal regions

- exploit (b)-jet multiplicity and dedicated BDT classifiers

Challenge: Modelling of large tt+b background

→ Dominant uncertainty in measurement

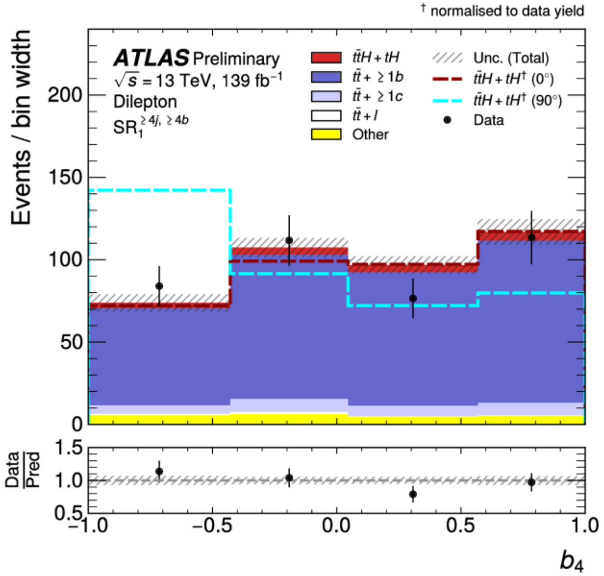
Results **consistent** with previous measurement in **γγ decay**

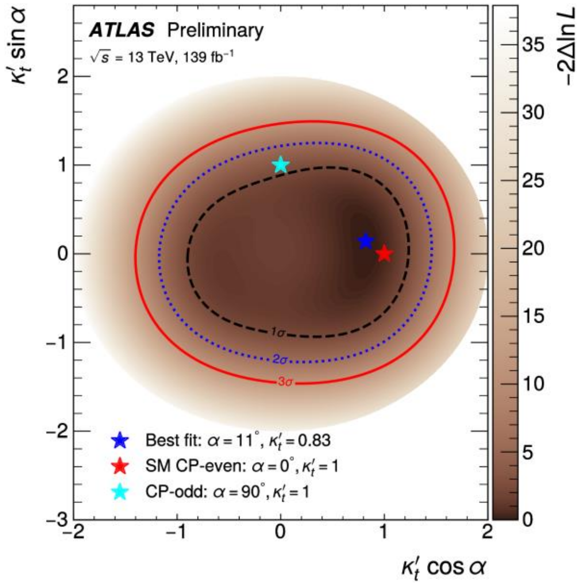
- Pure CP-odd disfavoured at 1.2σ level

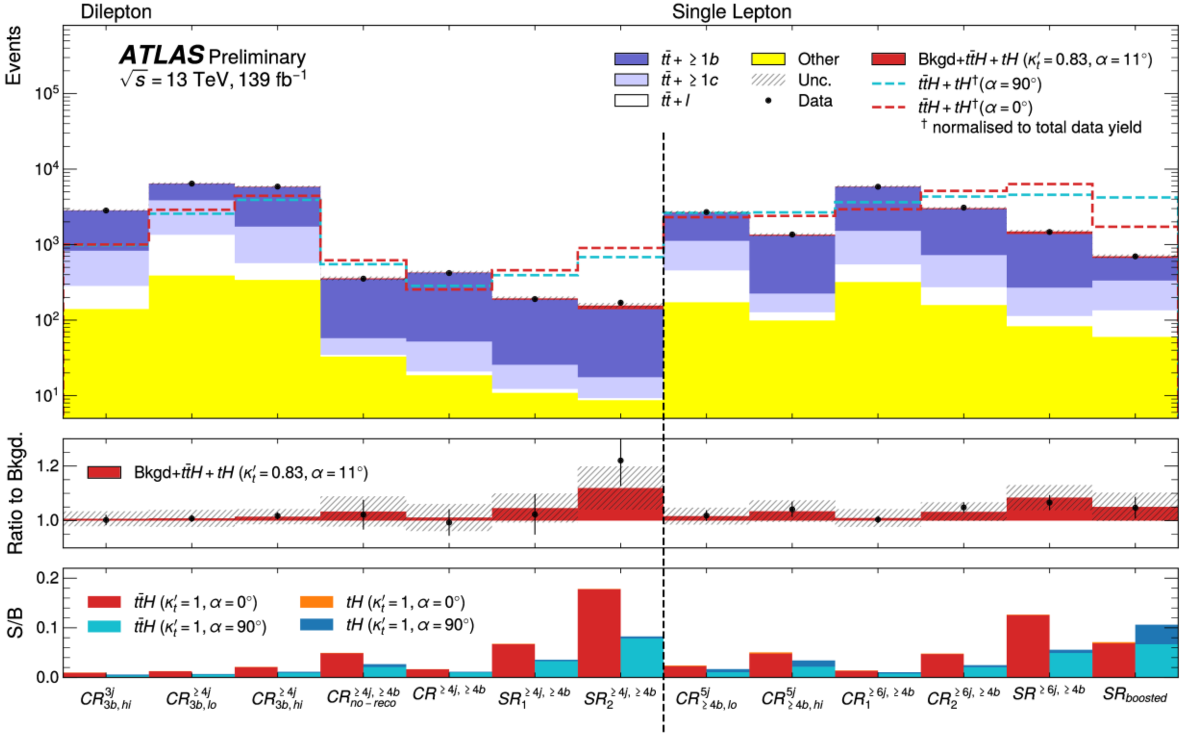
top candidates

beam axis

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







Boson couplings – VBF H→γγ

CERN-EP-2022-134

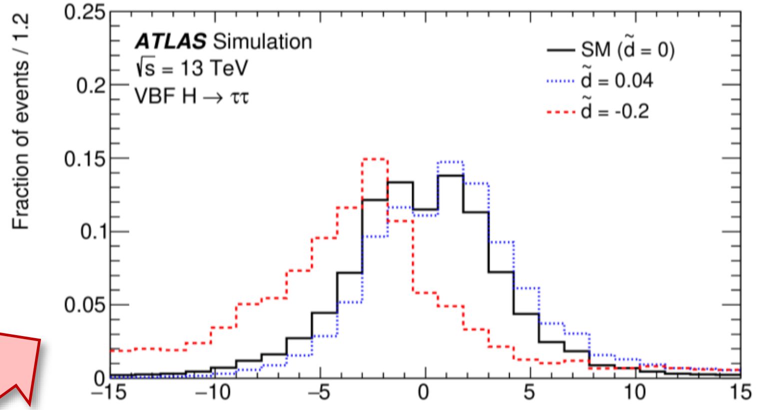


Figure: Phys. Lett. B 805 (2020) 135426

VBF signature allows probe of HVV vertex

→Exploit properties of **dijet system** (angle between Vqq planes)

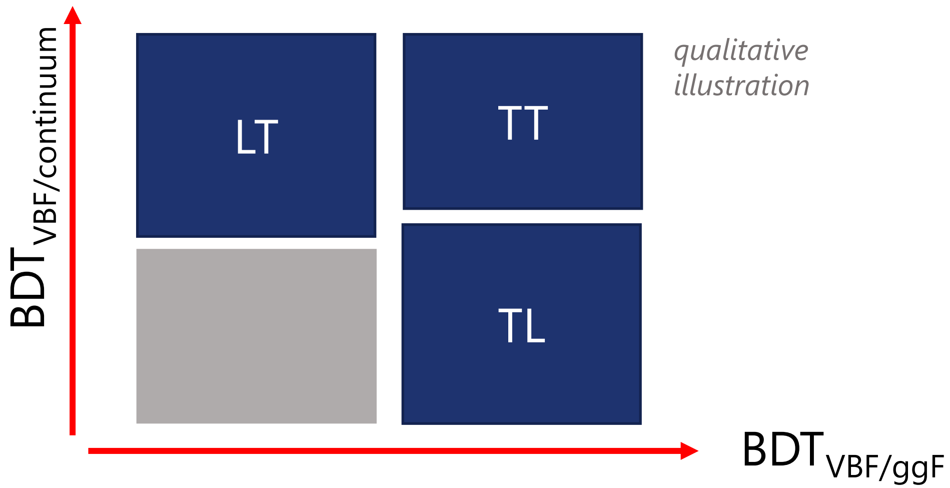
Combine information: **Optimal observable** (matrix element discriminant)

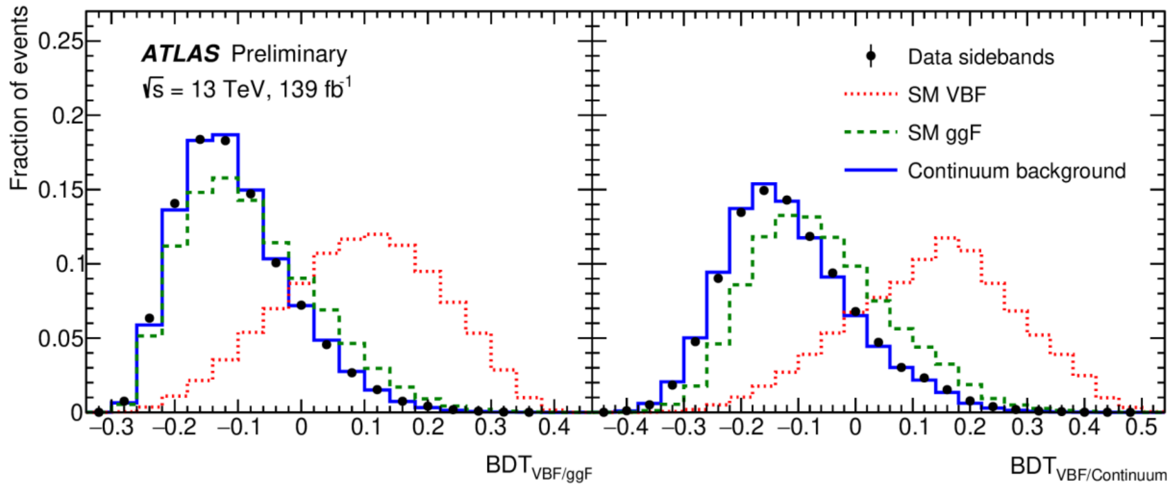
- Direct measure of interference impact
- **Vanishing mean** if CP conserved

$$\boxed{OO_1(\boldsymbol{c}) = \frac{\overbrace{|\mathcal{M}_{\mathrm{Mix}}(\boldsymbol{c})|^2 - |\mathcal{M}_{\mathrm{SM}}|^2 - |\mathcal{M}_{\mathrm{BSM}}(\boldsymbol{c})|^2}^{2\mathcal{R}e(M^*_{SM}M_{CP-odd})}}{|\mathcal{M}_{\mathrm{SM}}|^2}}$$

High-statistics measurement in H→γγ decay mode

→Enrich signal using 2D BDT classification and VBF dijet topology





Boson couplings – VBF H→γγ

CERN-EP-2022-134

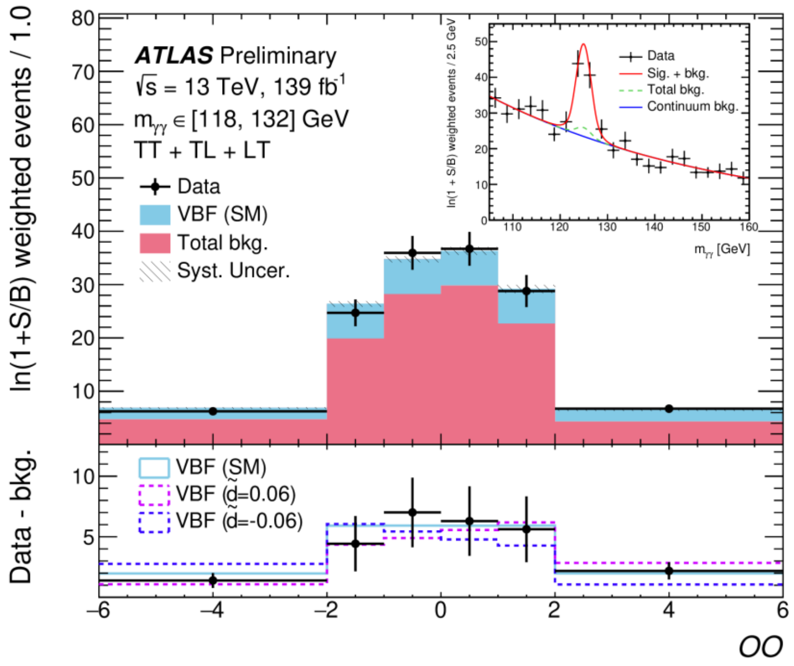
Pure **shape analysis** – signal rates float in fit

- Avoids model-dependence from total XS parameterisation

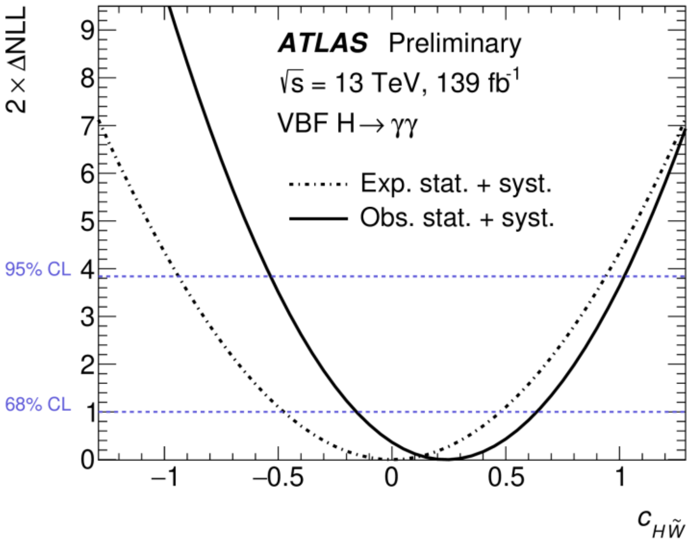
Results **consistent with SM** (symmetric OO)

Interpretation in **EFT framework** – Warsaw and HISZ bases

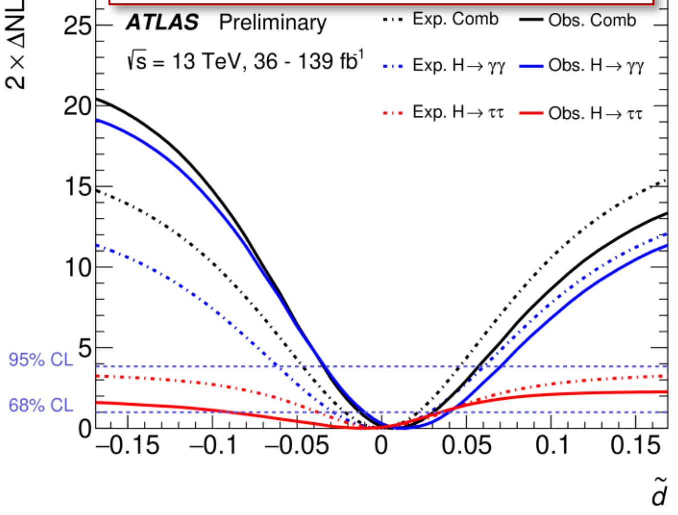
- Improve strongest existing bounds on CP-violating HVV couplings
- Combination with previous measurement in VBF H→ττ: Further improvement of bounds
- Sensitivity driven by **interference** rather than quadratic EFT term



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



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



Summary and outlook

CP structure of Higgs coupling: Highly active field for run-2 measurements

→ Still space for **CP-odd** admixture, potential source for **CP violation**

→ Would be clear evidence for **BSM physics**

Efforts concentrate in two areas: **Fermion** and **Boson** couplings

- Combine use of production and decay vertices for maximum sensitivity
- Use of dedicated CP-sensitive observables – ability to distinguish CPV from other BSM

Today: Some recent example from ATLAS

- Starting to probe **rare & challenging topologies** for CP information
- Converging on methodologies and interpretations - combinations
- More ongoing & potential in Run-3 – more to follow!