CP violation results in the ATLAS experiment

R. Gonçalo (U.Coimbra / LIP) on behalf of the ATLAS Collaboration

Higgs Hunting, Orsay-Paris, Sep.12-14 2022

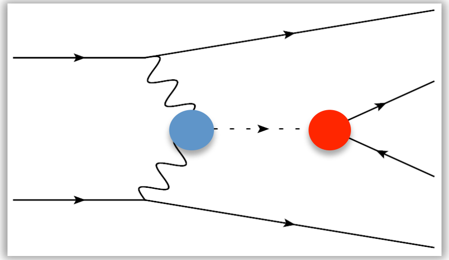
CP Violation in the Higgs Sector?

- Sakharov conditions for a matter-dominated universe require CP violation[1]
- Some CP-violating processes are well known and measured:
  - Described with complex phases in CKM-matrix - quark mixing
  - Maybe in PNMS-matrix as well - neutrino mixing
- But insufficient, by orders of magnitude, to explain baryon asymmetry[1]
- CP violation in Higgs sector?
  - Possible in some models with extended Higgs sector (e.g. some 2HDMs)
  - **Mixing** of scalar (CP-even) and pseudo-scalar (CP-odd) Higgs states would make CP violation an enticing possibility
- What do we know about Higgs CP properties?
  - In the SM, Higgs scalar is a CP eigenstate with $J^{CP} = 0^{++}$
  - Pure $J^P = 0^-$ hypothesis for observed Higgs boson was ruled out in Run 1[2]
  - But hypothesis of a CP-odd admixture is far from being constrained experimentally!

[1] See e.g. Mod.Phys.Lett.A 9 (1994) 795-810
[2] See e.g. Eur.Phys.J C75 (2015) 476

How to search for a CP-odd admixture?

- Effect of CP-odd components on **bosonic couplings** parametrized as expansion with higher order terms suppressed by powers of scale of new physics Λ
- Could explain why a CP-odd admixture has not been seen

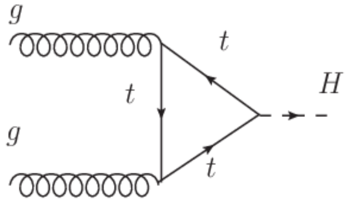


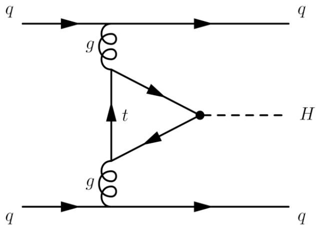
- **Fermionic couplings** are affected at tree level
- Mixing angle α between CP-even and CP-odd coupling components
- More notable for heavier fermions due to enhanced coupling

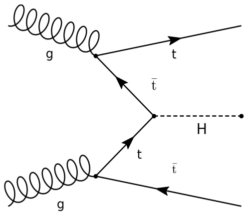
$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\, \phi \widetilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

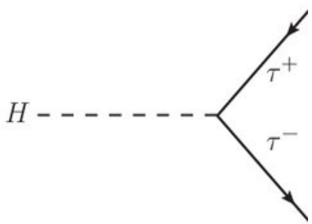
$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

Fermionic Higgs Couplings



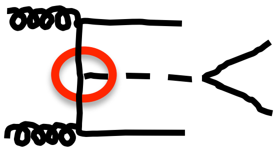






ATLAS-CONF-2022-016 (16 March 2022)

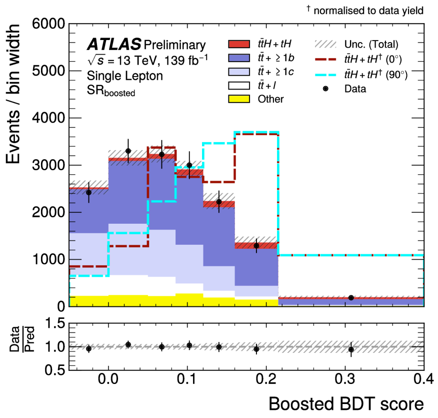
H-top Coupling in ttH/tH production

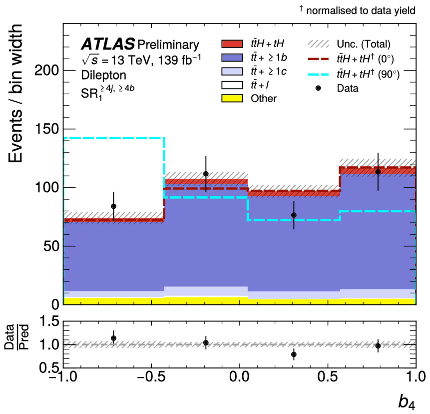


See talk by Neelam in YSF yesterday

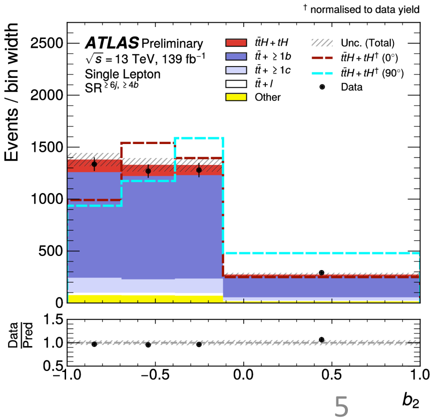
- Calculate CP-sensitive observables b_2 and b_4 from top-quark 3-momenta
- Use different observables in combined fit depending on region

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





Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton (PSR$^{\geq 4j, \geq 4b}$)	CR$^{\geq 4j, \geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	CR$^{\geq 4j, \geq 4b}$	BDT∈ [−1, −0.086)	b_4
	SR$_1^{\geq 4j, \geq 4b}$	BDT∈ [−0.086, 0.186)	b_4
	SR$_2^{\geq 4j, \geq 4b}$	BDT∈ [0.186, 1]	b_4
ℓ+jets (PSR$^{\geq 6j, \geq 4b}$)	CR$_1^{\geq 6j, \geq 4b}$	BDT∈ [−1, −0.128)	b_2
	CR$_2^{\geq 6j, \geq 4b}$	BDT∈ [−0.128, 0.249)	b_2
	SR$^{\geq 6j, \geq 4b}$	BDT∈ [0.249, 1]	b_2
ℓ+jets (PSR$_{\text{boosted}}$)	SR$_{\text{boosted}}$	BDT∈ [−0.05, 1]	Classification BDT score



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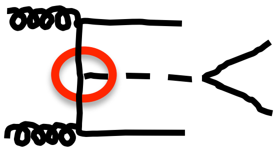
H-top Coupling in ttH/tH production



Simultaneous fit in all regions

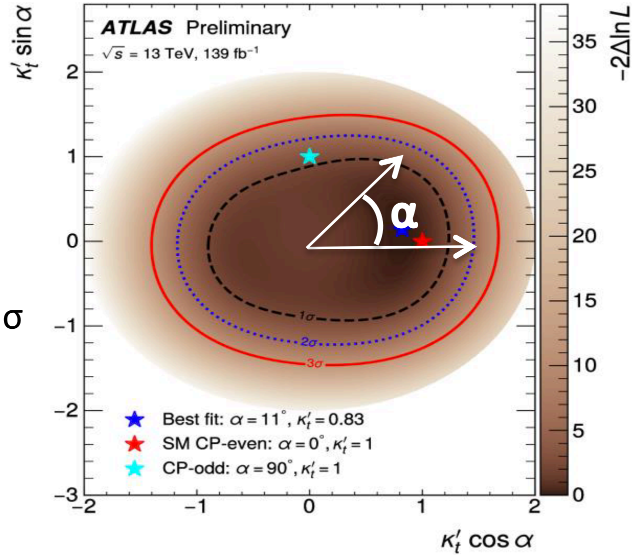
- $\mu = 0.83^{+0.30}_{-0.46}$
- $\alpha = 11° {}^{+55}_{-77}$

Expected:

- $\mu = 1.0^{+0.25}_{-0.27}$
- $\alpha = 0° {}^{+49}_{-50}$
- Pure CP-odd (α = 90°) disfavoured at 1.2 σ

Systematics-dominated analysis:

- Dominant uncertainties from tt+≥1b modelling: NLO matching, PS and hadronisation, flavour scheme



Uncertainty source	$\Delta\alpha$[°]	
Process modelling		
Signal modelling	+7.9	-13
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ 4V5 FS	+26	-40
$t\bar{t} + \geq 1b$ NLO matching	+24	-36
$t\bar{t} + \geq 1b$ fractions	+15	-23
$t\bar{t} + \geq 1b$ FSR	+5.2	-9.9
$t\bar{t} + \geq 1b$ PS & hadronisation	+17	-27
$t\bar{t} + \geq 1b$ $p_T^{b\bar{b}}$ shape	+5.7	-5.3
$t\bar{t} + \geq 1b$ ISR	+15	-26
$t\bar{t} + \geq 1c$ modelling	+7.4	-12
$t\bar{t}$ + light modelling	+2.7	-4.8
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+9.7	-17
c-mis-tag rates	+7.4	-12
l-mis-tag rates	+2.5	-3

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

ATLAS-CONF-2022-016 vs Phys. Rev. Lett. 125 (2020) 061802

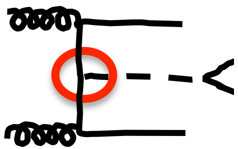
H-top Coupling in ttH/tH production

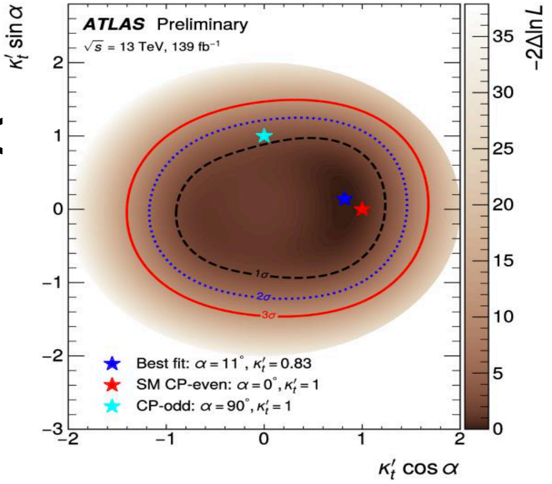
New analysis: ttH (H→bb):

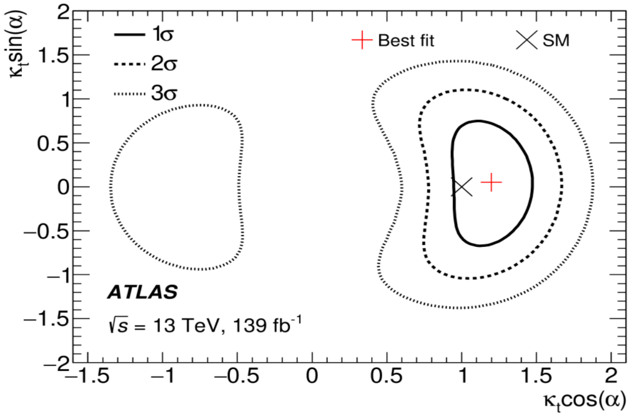
- $\mu = 0.83^{+0.30}_{-0.46}$ (exp. $\mu = 1.0^{+0.25}_{-0.27}$)
- $\alpha = 11°\ ^{+55}_{-77}$ (exp. $\alpha = 0°\ ^{+49}_{-50}$)
- Pure CP-odd (α = 90°) disfavoured at 1.2 σ

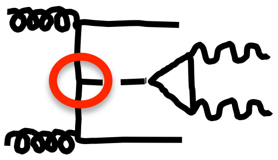
Complementary to previous ttH(H→γγ) analysis:

- Phys. Rev. Lett. 125 (2020) 061802
- Pure CP-odd (α = 90°) excluded at 3.9 σ
- Limit on $|\alpha| < 43°$ at 95% C.L.



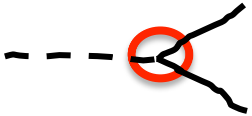


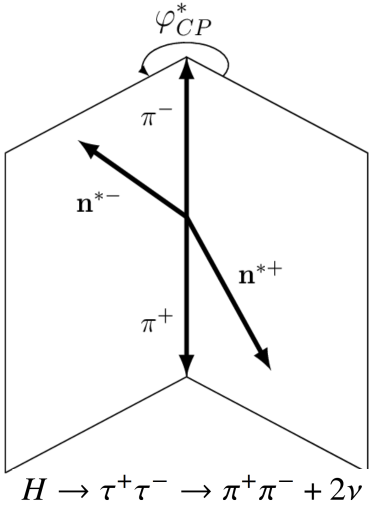


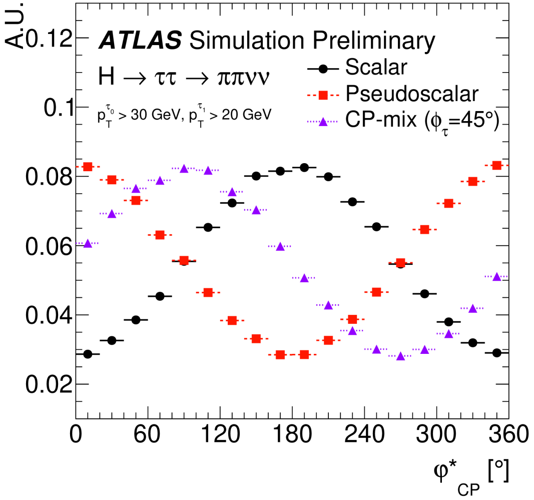


ATLAS-CONF-2022-032 (18 May 2022)

H-τ Coupling in inclusive production







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 %)

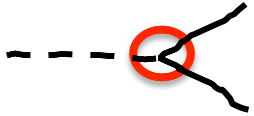
YpXn Y charged pions; X neutral pions

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

- Angle between τ decay planes in H rest frame sensitive to CP mixing angle ϕ_τ
- Due to neutrinos, use φ^{*CP} angle as proxy:
  - Acoplanarity angle between τ decay planes in Zero Momentum Frame of visible decay products
- φ^{*CP} reconstructed with dedicated methods for semi-exclusive decay modes
  - Total branching ratio in targeted decay modes: 68%

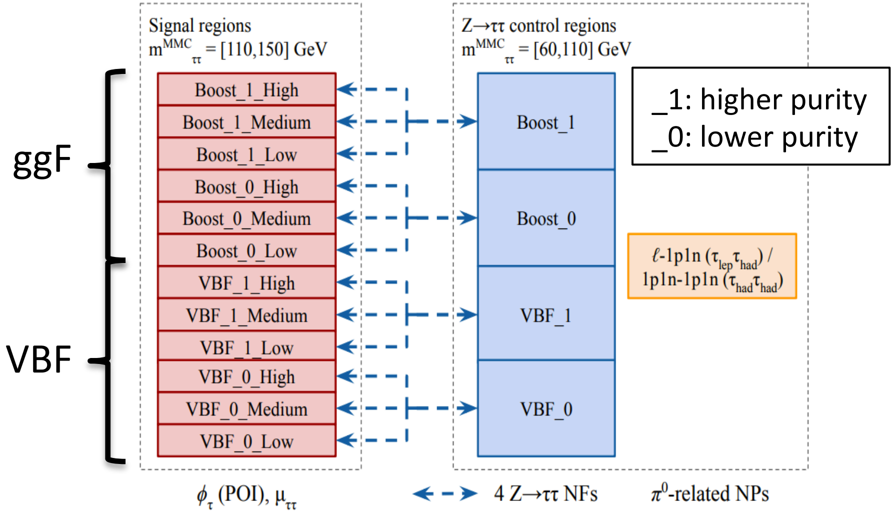
ATLAS-CONF-2022-032 (18 May 2022)

H-τ Coupling in inclusive production



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%

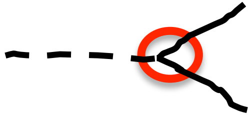
YpXn Y charged pions; X neutral pions



- 24 Signal categories and 10 Control Regions
  - **VBF** or **Boost** (ggF p_T^H > 100 GeV) × 2 **purity** regions × High/Medium/Low **sensitivity**
- Angle reconstruction requires excellent performance:
  - Particle flow based τ_{had} reconstruction
  - $\pi^0 \rightarrow \gamma\gamma$ and vertex / impact parameter reconstrucion
  - Both efficiency and purity around 80% for dominant decays

ATLAS-CONF-2022-032 (18 May 2022)

H-τ Coupling in inclusive production

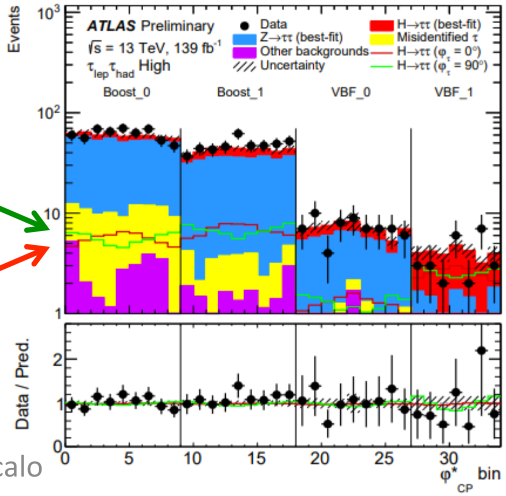


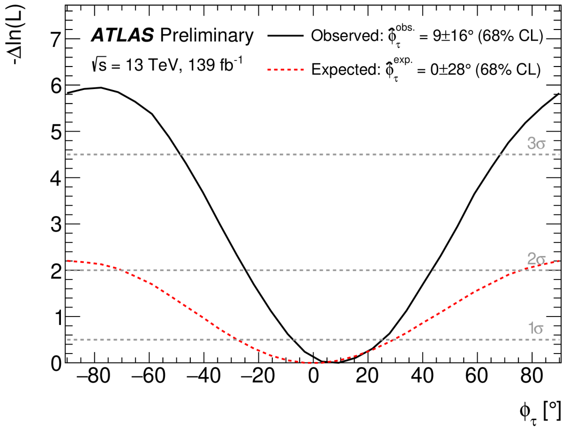
- Simultaneous fit in all regions
- Analysis leaves μ free to float − agnostic with respect to rate effects
- Best fit observed: $\phi_\tau = 9° \pm 16°$ (expected: $\phi_\tau = 0° \pm 28°$)
- Pure CP-odd (α = 90°) disfavoured at 3.4 σ
- Dominant background is $Z \rightarrow \tau\tau$: constrained from Control Regions
- Statistics-dominated analysis; dominant systematic uncertainty from jet calibration

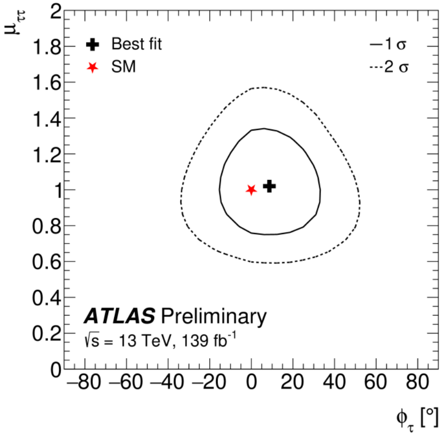
$$\boxed{\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H}$$

CP-odd

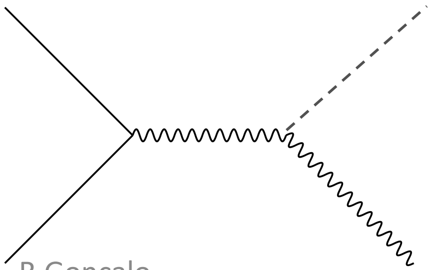
CP-even

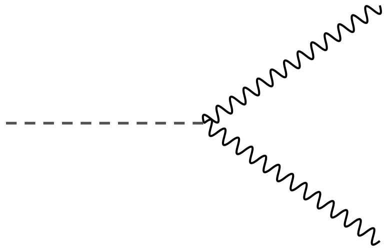


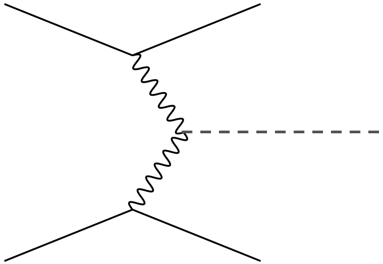




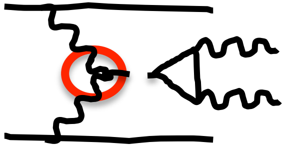
Bosonic Higgs Couplings







HVV Coupling in Vector Boson Fusion



- New analysis: VBF H→γγ
- Consider effective HVV Lagrangian augmented with dimension six **CP-odd** observables
- Strength of CP violation in VBF matrix element can be described by a single parameter(*) giving:

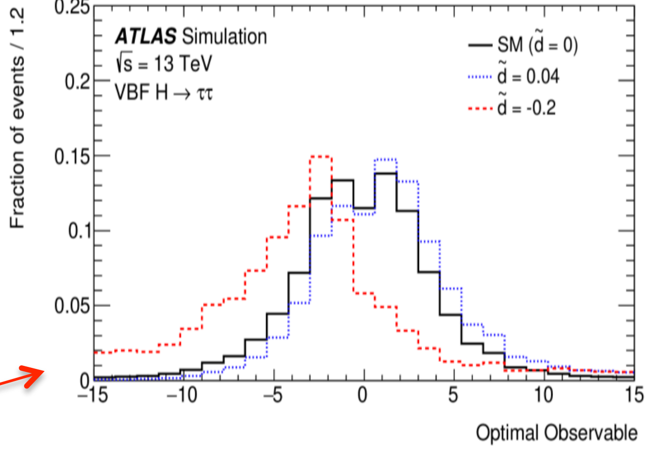
$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

- Calculate LO matrix elements using 4-momenta of Higgs and VBF jets
  - Extract initial-state parton momentum fractions from jet momenta
- Use to calculate Optimal Observable (OO):
  - Expected to be symmetric with mean value of zero if no CP-violation

$$\boxed{OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}}$$

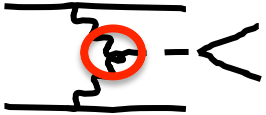
Phys. Lett. B 805 (2020) 135426



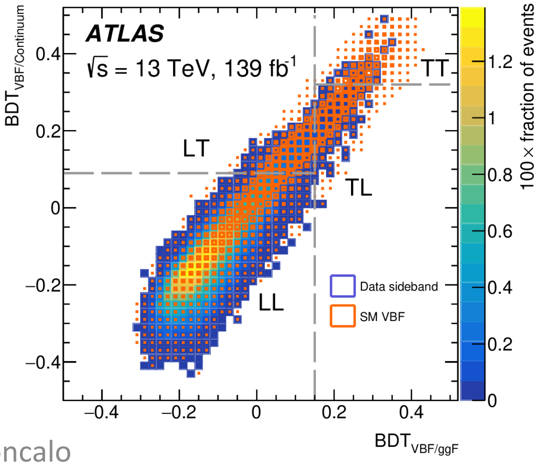
 (*) Slightly simplified scenario: see Phys. Lett. B 805 (2020) 135426 , set: $\tilde{d} = \tilde{d}_B$

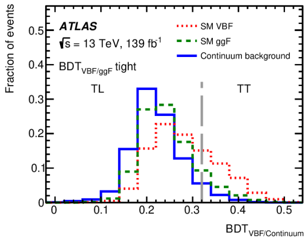
CERN-EP-2022-134 (3 August 2022)

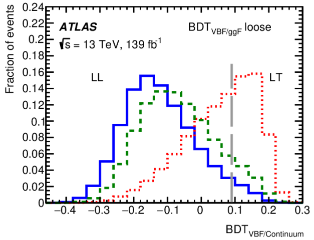
HVV Coupling in Vector Boson Fusion

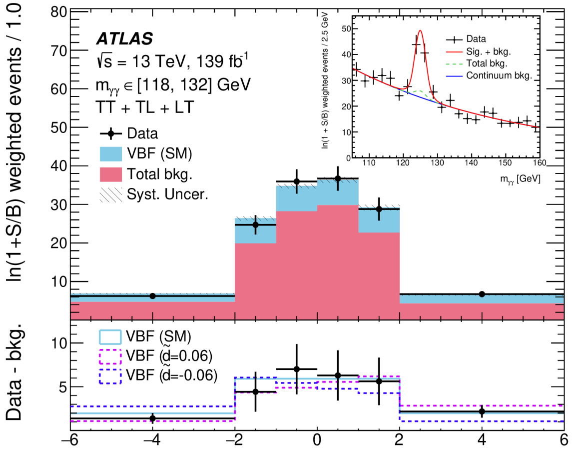


- Select events with ≥2 photons and ≥2 tag jets (energy flow)
- Increase signal purity with 2 BDTs:
  - $BDT_{VBF/ggF}$: separate VBF signal from gluon-fusion Higgs production
  - BDTVBF/Continuum: separate VBF signal from continuum diphoton background
- Split into signal regions using BDT output: Tight-Tight; Loose-Tight; Tight-Loose
- In each OO bin extract signal yield from a fit to the di-photon mass spectrum
- Fit shape of Optimal Observable to extract the coefficient of the interference term $\tilde{d}$
  - Pure **shape analysis** – signal normalisation is left floating in the fit to depend only on interference term









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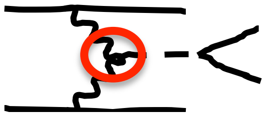
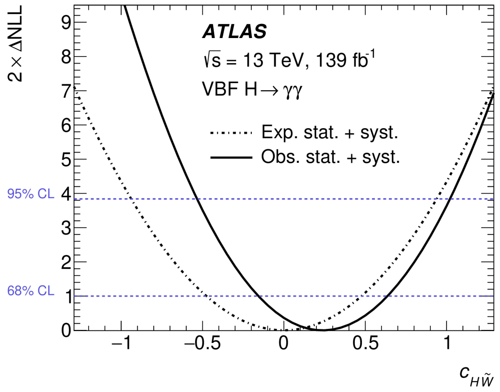
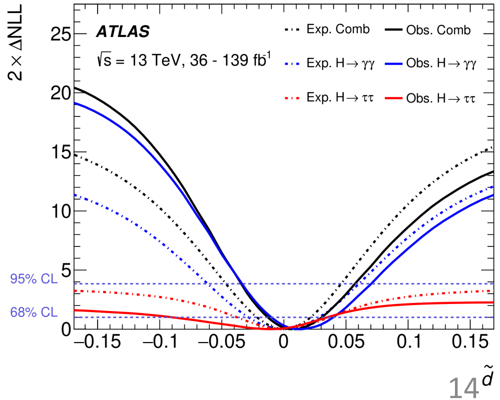


- Result interpretation with $\tilde{d}$ (HISZ EFT operator basis) but also $c_{H\tilde{W}}$ (Warsaw basis)
  - No improvement from using quadratic term – sensitivity driven by interference
- Results are the **strongest existing bounds** on CP violation in HVV
- Combination with previous analysis of VBF H→ττ (36 fb^{-1})
  - Phys. Lett. B 805 (2020) 135426
  - Confidence intervals further improved



	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]



Summary & Outlook

- The search for a CP structure of Higgs boson couplings is being very actively pursued in ATLAS
  - Still much space for CP odd admixture, potential source for CP violation
  - Would be clear evidence for deeper theory, beyond the SM and might address fundamental question of baryon asymmetry

- Results generally in agreement with Standard Model CP-even hypothesis

- Several Run 2 measurements using 139 fb^{-1}
  - Produced about 8 M Higgs bosons in Run 2!
  - A lot to expect from Run 3 and later!

- Today: showed only latest results in this presentation:
  - H-top Coupling in ttH/tH production with H → γγ, H → bb
  - H-τ Coupling in VBF + hhF production
  - HVV Coupling in VBF , H → γγ
  - More Run 2 analyses reaching results soon

Pure CP-odd ttH coupling excluded at 3.9 σ
Pure CP-odd Hττ coupling excluded at 3.4 σ
Strongest existing bounds on $\tilde{d}$ and $c_{H\tilde{W}}$

Backup slides

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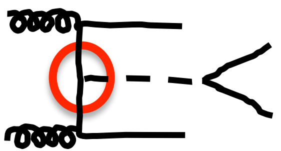
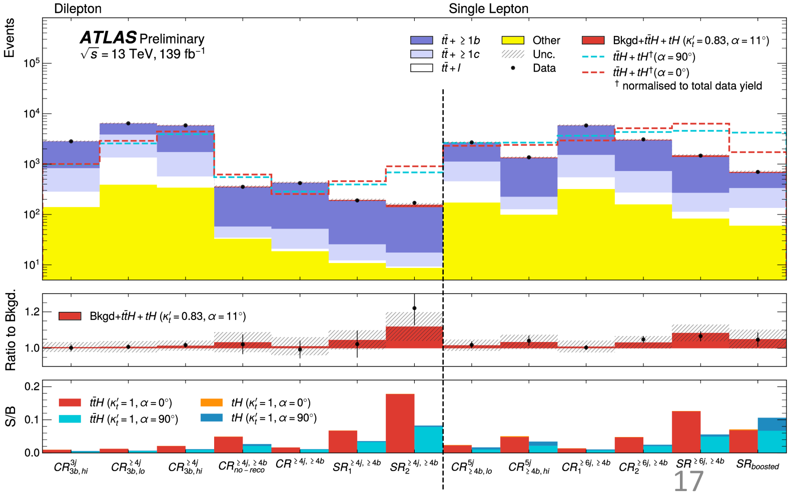


- Recent analysis with H→bb decay
  - High branching ratio, but challenging backgrounds
  - Complementary to previous ttH(H→γγ) analysis
- Two channels:
  - Lepton+jets: target 1 semi-leptonic top decay – dedicated boosted region targets p_T^H>200 GeV using large-R jets (R=1, m_j > 50 GeV)
  - Dilepton: target 2 semi-leptonic top decays
- Reconstruct top and Higgs candidates in regions
  - "Reconstruction" BDT selects jet combinations to build top and Higgs candidates
  - "Classification" BDT separates signal (trained on ttH) from background

See talk by Neelam in YSF yesterday

PSR: Preliminary Signal Region (before classification BDT)

Region		Dilepton				ℓ+jets			
		$PSR^{\geq 4j,\geq 4b}$	$CR^{\geq 4j,3b}_{hi}$	$CR^{\geq 4j,3b}_{lo}$	$CR^{3j,3b}_{hi}$	$PSR^{\geq 6j,\geq 4b}$	$CR^{5j,\geq 4b}_{hi}$	$CR^{5j,\geq 4b}_{lo}$	$PSR_{boosted}$
N_{jets}		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
N_{b-tag}	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{boosted\ cand.}$		–				0			≥ 1



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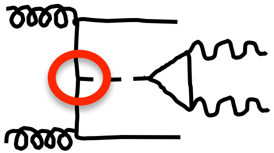
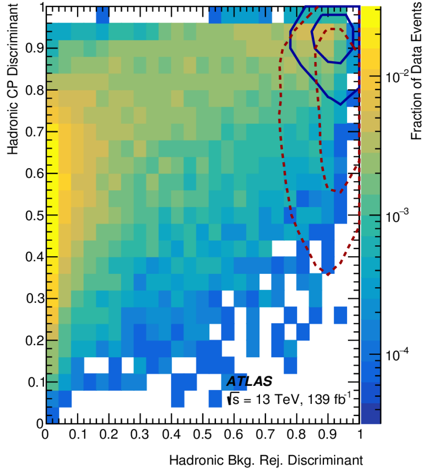
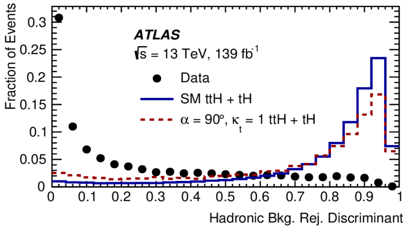
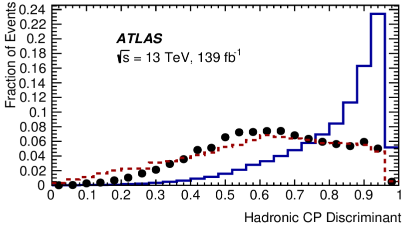
H-top Coupling in ttH/tH production



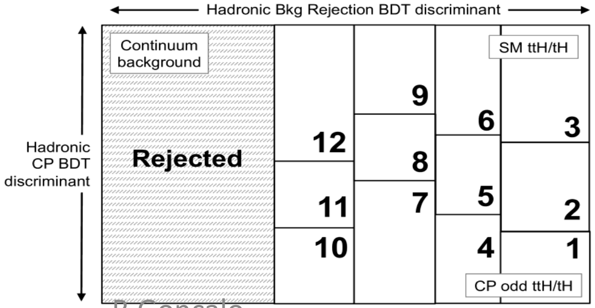
- Reconstruct Leptonic or Hadronic **γγ + top** events
- Two BDTs to define 2D space:
  - Reject **continuum background** and
  - Enrich **in CP-odd-like** events (kinematic and angular variables)
- Simultaneous fit to $\mathbf{m_{\gamma\gamma}}$ in 2D regions defined by BDT outputs
  - Established **5σ** observation of **ttH(γγ)**
  - Assuming SM decay get $\mu = 1.43^{+0.33}_{-0.31}(\text{stat})^{+0.17}_{-0.14}(\text{sys})$
  - Set upper limit of 12×SM for **tH** production
  - Pure **CP-odd** (α = 90°) excluded at **3.9 σ** and **|α|>43°** at 95% C.L.
  - Statistics-dominated analysis

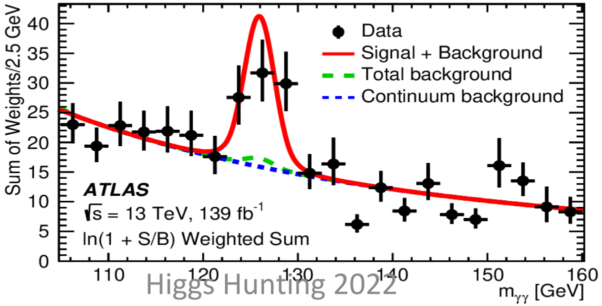


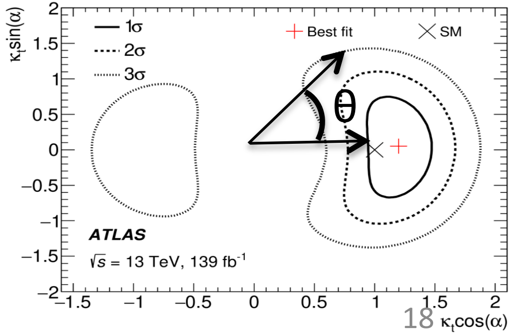




$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$







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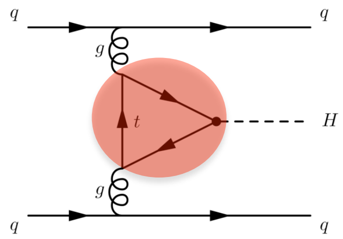
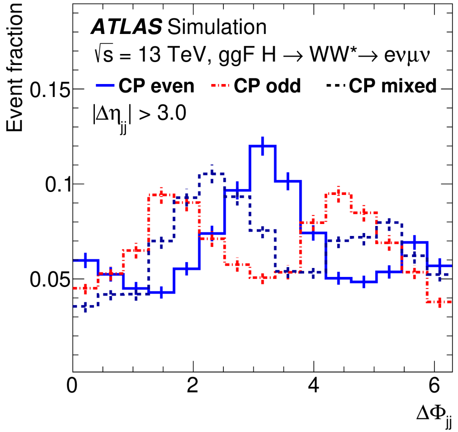
Hgg Effective Coupling

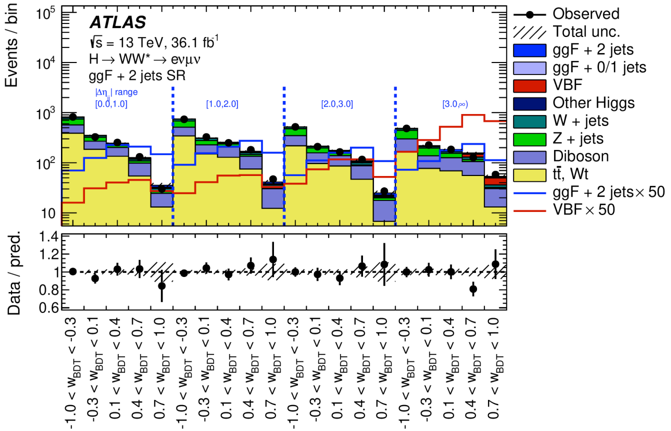
- Depending on the production mode, H+2 jets probse CP violation (for ggF) or W/Z polarization (for VBF)
- In gluon fusion:
  - Effective vertex either or top Yukawa coupling or BSM particles in loop
  - Use BDT to separate signal and background (no CP sensitivity)
  - Classify H+2jets into 4x5 categories according to |Δη| and BDT score

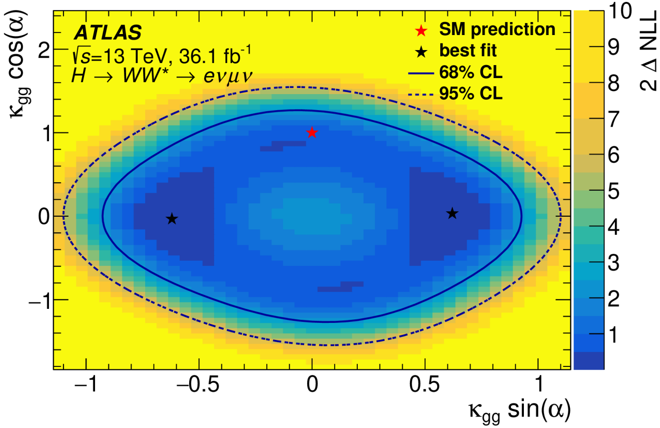


$$\boxed{\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H}$$

$$\tan(\alpha) = 0.0 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.})$$







- Search for changed **shapes** of differential cross sections due to CP-odd observables (2^{nd} term)
- Or on process **rates** (cross sections) from 3^{rd} term − but other BSM scenarios can change rates

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2 \cdot c_i \cdot \mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}} \mathcal{M}_{\mathrm{CP\text{-}odd}}) + c_i^2 \cdot |\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2 .$$

See e.g. arXiv:2208.02338 [hep-ex], arXiv:1008.3869v3 [hep-ph], or C.Grefe, ICHEP'22