Study of top-Higgs CP properties in $t\bar{t}H$ and tH events with $H \to b\bar{b}$ decays in ATLAS

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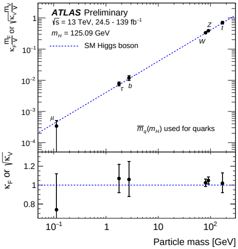
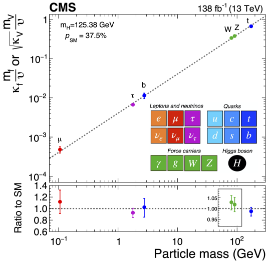
Introduction

- With LHC data we (try to) measure the coupling of each SM particle to the Higgs
- top-quark: fermion with the largest coupling to the Higgs boson in the SM
  - $\rightarrow$ do I need to explain why it matters for BSM searches?

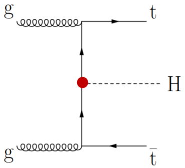


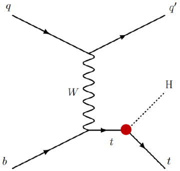


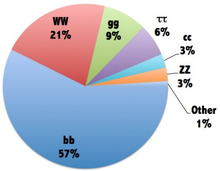
- Both CMS and ATLAS observed $t\bar{t}H$ with LHC run-2 data
  - $\rightarrow$ cross-section measurements are consistent with SM predictions: $\kappa_t \simeq 1$
  - $\rightarrow$ we are now performing differential measurements
  - $\rightarrow$ ...and probing top-Higgs coupling structure
- This talk: ATLAS latest measurements $t\bar{t}H$ measurements in the $H \rightarrow b\bar{b}$ channel
  - $\rightarrow$ especially focusing on the CP properties

$t(\bar{t})H$ production and decay

- $t\bar{t}H$ gives a direct access to the amplitude of the top Yukawa
  - → while loop-induced Higgs production or $H \to \gamma\gamma$ are indirect probes
  - → prediction (YR4): $\sigma_{t\bar{t}H} = 507.1^{+6.8}_{-9.9}\,\text{fb}$ CERN-2017-002
- tH gives access to the sign of the top Yukawa
  - → i.e. relative sign between top-Higgs and W-Higgs couplings
  - → prediction (YR4): $\sigma_{tH} = 74.3^{+7.5}_{-15.4}\,\text{fb}$ for t-channel (main production mode)







- Will focus in this talk on $H \to b\bar{b}$ Higgs decay channel
  - → largest branching ratio - larger statistics good for differential measurements
  - → caveat: dominant $t\bar{t}b\bar{b}$ background is very challenging

CPPM

$t\bar{t}H$ CP-odd and CP-even

- In the SM, $t\bar{t}H$ is handled by this term in the Lagrangian:

$$\mathcal{L}^{SM}_{t\bar{t}H} = -y_t \, \phi \, \bar{\psi}_t \, \psi_t$$

  - → $y_t = m_t / v$ is the top Yukawa coupling
  - → the produced top quark and anti-quark have the same chirality
- BSM physics may give a different coupling value:

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t \, y_t \, \phi \, \bar{\psi}_t \, \psi_t$$

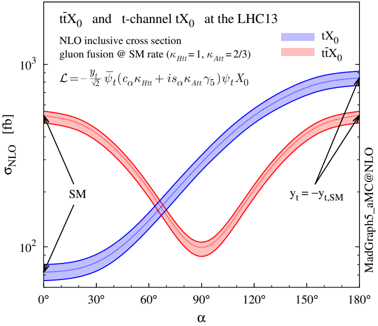
  - → parametrised with the coupling modifier κ_t
  - → this term is still CP-even: same coupling for the left- and right-handed $t\bar{t}$
- Even more BSM: introducing a CP-odd term in the Lagrangian

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

  - → pure CP-odd ($\alpha = 90^\circ$): left- and right-handed $t\bar{t}$ have opposite couplings
  - → nature may allow a CP-even/CP-odd admixture with α at any value $\Rightarrow$ CP violation

Effect of CP-odd coupling on $t\bar{t}H$ and tH cross-sections

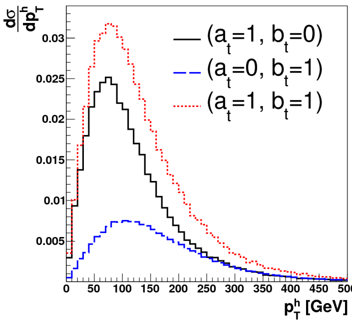
- Introducing a CP-odd term affects the $t\bar{t}H$ cross-section
  - → largest effect for pure CP-odd case $\alpha = 90^\circ$
  - → symmetric effect wrt. $\alpha = 90^\circ$: no distinction between 0 and 180°
- It affects the tH cross-section in a different way
  - → cross-section largest for $\alpha = 180^\circ$ (i.e. $\kappa_t = -1$)
  - → not symmetric $\alpha = 90^\circ$: tH is sensitive to the sign of the Yukawa
- NB: total cross-section affected by both κ_t' and α

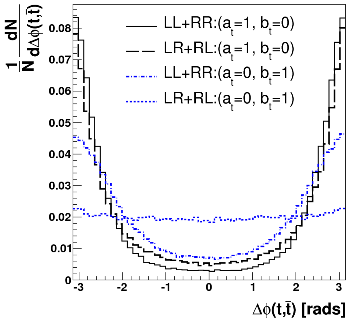


Eur. Phys. J. C **75** (2015) 6, 267

Effect of CP-odd coupling on $t\bar{t}H$ observables

- Impact of α on several observables, which one can exploit for analysis on data
- CP-odd scenario gives a smaller differential cross-section at low Higgs p_T
  - → at high top p_T: same amount of LL and RR helicity for $t\bar{t}$ no LR or RL
  - → at low top p_T: presence of LR or RL, but destructive interfecence in CP-odd case
  - → normalised Higgs p_T distribution has a maximum shifted at higher values
- Also: impact on angular variables due to different helicity admixtures
  - → many possible variables based on top or lepton kinematics, in $t\bar{t}H$ rest- or in lab-frame
  - → many phenomenology studies over the years to find the best variables

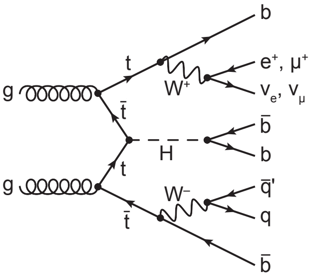


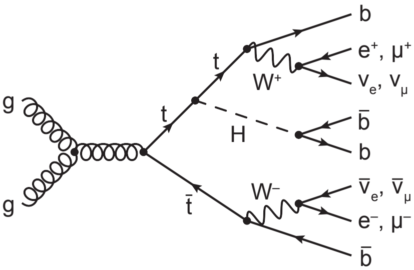


Phys. Rev. D **92** (2015) 1, 015019

ATLAS full run-2 $t\bar{t}H(H \to b\bar{b})$ analysis - JHEP **06** (2022) 97

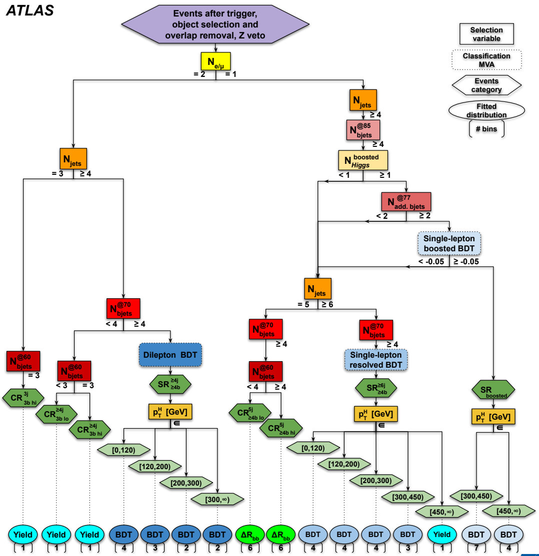
- ATLAS published a full run-2 $t\bar{t}H(H \to b\bar{b})$ analysis
- Measurement in the STXS framework
  - → first differential cross-section in this channel, as a function of $p_T(H)$
  - → also: $H \to \gamma\gamma$ channel arxiv:2207.00348
- The analysis uses final states with 1 or 2 leptons (e or μ) from $t\bar{t}$ decay
  - → use of large-R jets in ℓ+jets channel to better probe high $p_T(H)$ regime
  - → all-hadronic channel not used - additional challenge of multijets background





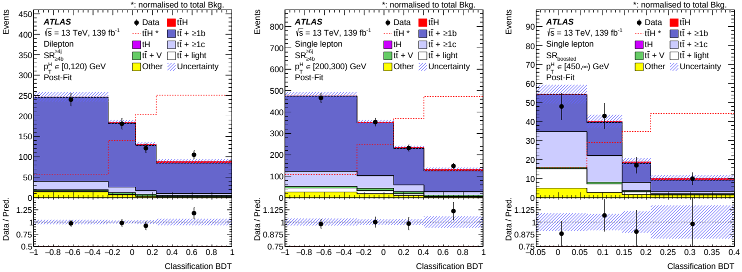
Analysis workflow

- Event selection based on targetted topology
- Top and Higgs kinematics reconstructed with MVA
- Several analysis regions
  - $\rightarrow$ CRs to constrain backrounds
  - $\rightarrow$ SRs to measure signal
- Signal regions split according to reconstructed $p_T(H)$
  - $\rightarrow$ up to $p_T(H) > 450$ GeV



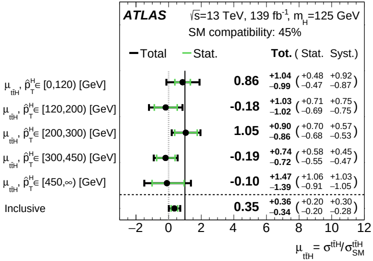
Multivariate analysis

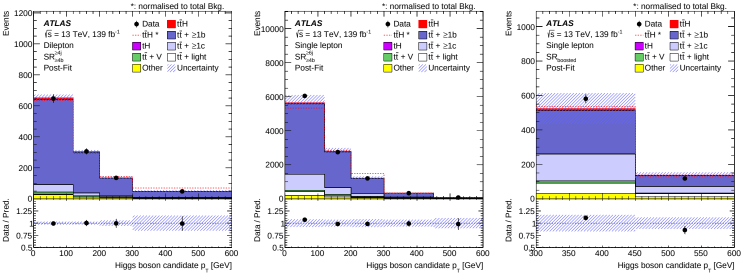
- MVA to reconstruct Higgs and top topology
  - → DNN to tag the large-R jet from $H \to b\bar{b}$ in ℓ+jets boosted channel
  - → "reconstruction" BDTs to reconstruct Higgs and top kinematics in resolved channels
- This allows to:
  - → reconstruct the Higgs p_T we want to measure
  - → build discriminating variables to separate $t\bar{t}H$ from backgrounds
- "Classification" BDTs trained to separate signal from backgrounds, one per channel
  - → topological variables, top and Higgs kinematics, B-tagging
  - → BDT distribution used in each $p_T(H)$-dependent signal region (except one)



Results

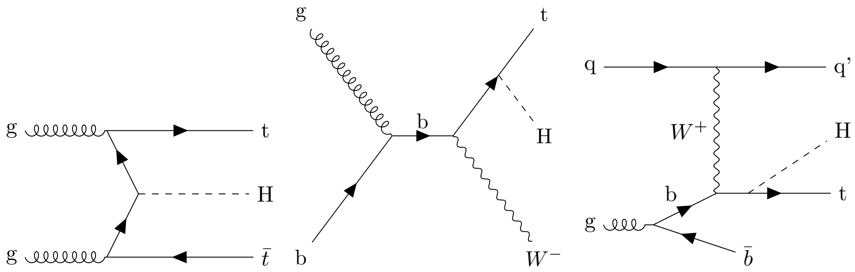
- $t\bar{t}H$ signal split at truth level vs. $\hat{p}_T(H)$
  - $\rightarrow$ simultaneous fit of the 5 signal categories
  - $\rightarrow$ $\hat{p}_T(H) > 450$ GeV category accessible
- Result compatible with SM predictions
- Lowest $\hat{p}_T(H)$ category dominated by systs
  - $\rightarrow$ especially those related to $t\bar{t}b\bar{b}$ modelling





Dedicated analysis for CP properties - arxiv:2303.05974

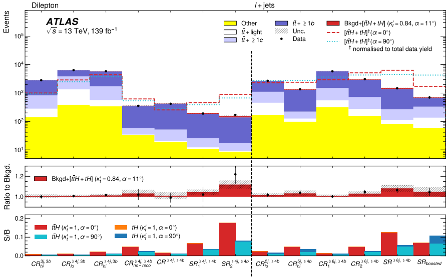
- Dedicated paper to study CP properties in $t\bar{t}H(H \to b\bar{b})$
- Based on the same analysis, with several modifications
  - $\to$ *tH* (both *tWH* and *tHjb*) considered as signal
  - $\to$ reconstruction of top kinematics in the dilepton channel (neutrino weighting technique)
  - $\to$ different choice of signal and control regions
  - $\to$ different variables used for the fit
  - $\to$ additional systematics on $t\bar{t}b\bar{b}$



$t\bar{t}H(H \to b\bar{b})$ CP: analysis regions

- Training regions (TRs) are defined based on topology
  - $\rightarrow$ where MVAs are trained - called SRs in the previous analysis
- SRs are defined within the TRs
  - $\rightarrow$ cut on classification BDT to select events enriched in $t\bar{t}H$
- CP-sensitive observables used in the fit in each region within the TRs

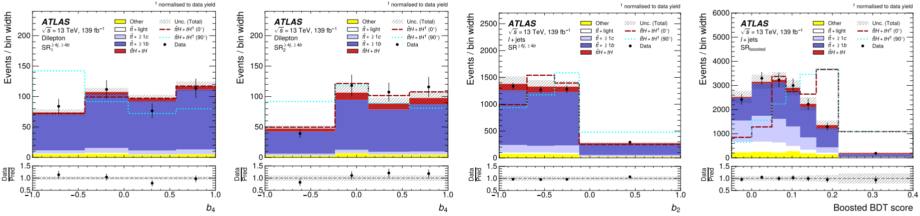
Region	Dilepton				ℓ+jets			
	$\mathrm{TR}^{\geq 4j,\geq 4b}$	$\mathrm{CR}^{\geq 4j,3b}_{\mathrm{hi}}$	$\mathrm{CR}^{\geq 4j,3b}_{\mathrm{lo}}$	$\mathrm{CR}^{3j,3b}_{\mathrm{hi}}$	$\mathrm{TR}^{\geq 6j,\geq 4b}$	$\mathrm{CR}^{5j,\geq 4b}_{\mathrm{hi}}$	$\mathrm{CR}^{5j,\geq 4b}_{\mathrm{lo}}$	$\mathrm{TR}_{\mathrm{boosted}}$
N_{jets}	≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b\text{-tag}}$ @85%	–				≥ 4			
$N_{b\text{-tag}}$ @77%	–				–			$\geq 2^{\dagger}$
$N_{b\text{-tag}}$ @70%	≥ 4	$= 3$			≥ 4			–
$N_{b\text{-tag}}$ @60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\mathrm{boosted\ cand.}}$	–				0			≥ 1
Fit observable	–	Yield			–	$\Delta R^{\mathrm{avg}}_{bb}$		–



$t\bar{t}H(H\to b\bar{b})$ CP: observables used in the fit

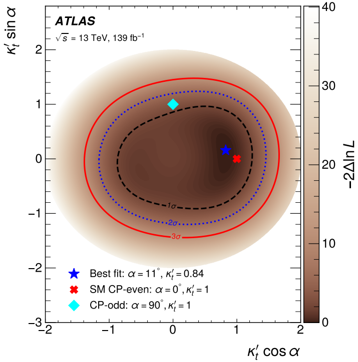
- In the dilepton channel: $b_4 = \frac{(\vec{p}_1\cdot\hat{z})(\vec{p}_2\cdot\hat{z})}{|\vec{p}_1||\vec{p}_2|}$
  - $\rightarrow$ except when top kinematics can't be reconstructed, in which case $\Delta\eta_{\ell\ell}$ is used
- In the ℓ+jets resolved: $b_2 = \frac{(\vec{p}_1\times\hat{z})\cdot(\vec{p}_2\times\hat{z})}{|\vec{p}_1||\vec{p}_2|}$
- In the ℓ+jets boosted: classification BDT, to exploit the $p_T(H)$ spectrum

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



$t\bar{t}H(H \to b\bar{b})$ CP: results

- Likelihood contour in the $(\kappa_t' \cdot \cos\alpha, \kappa_t' \cdot \sin\alpha)$ plane
- Best-fit: $\alpha = 11^\circ {}^{+52^\circ}_{-73^\circ}$ and $\kappa_t' = 0.84^{+0.30}_{-0.46}$
  - $\to$ well compatible with SM hypothesis $\alpha = 0^\circ$ and $\kappa_t = 1$
- Sensitivity to exclude pure CP-odd hypothesis: 1.2σ
  - $\to$ excluded at 3.9σ by $H \to \gamma\gamma$ ($|\alpha| < 43^\circ$ at 95% CL) - Phys. Rev. Lett. **125** (2020) 061802
- Dominant effect of systs: ${}^{+41^\circ}_{-54^\circ}$ on α and ${}^{+0.29}_{-0.45}$ on κ_t'
  - $\to$ especially $t\bar{t}b\bar{b}$ modelling: ${}^{+37^\circ}_{-51^\circ}$ on α, compared to ${}^{+32^\circ}_{-49^\circ}$ for stat



Conclusion

- Possible SM extension with top-Higgs CP-odd interaction
- Can be tested on data with dedicated $t(\bar{t})H$ analyses
- Pure CP-odd scenario excluded by LHC run-2 data thanks to $H \to \gamma\gamma$
- ...but CP violating CP-even/CP-odd mixture still possible
- $H \to b\bar{b}$ analysis helps especially in the high $p_T(H)$ regime
- However, sensitivity limited by systs on the $t\bar{t}b\bar{b}$ background modelling

Backup

Uncertainties, $t\bar{t}H(H \to b\bar{b})$ STXS JHEP **06** (2022) 97

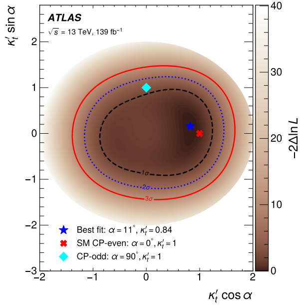
Uncertainty source	$\Delta\mu$	
Process modelling		
$t\bar{t}H$ modelling	+0.13	−0.05
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ NLO matching	+0.21	−0.20
$t\bar{t} + \geq 1b$ fractions	+0.12	−0.12
$t\bar{t} + \geq 1b$ FSR	+0.10	−0.11
$t\bar{t} + \geq 1b$ PS & hadronisation	+0.09	−0.08
$t\bar{t} + \geq 1b$ p_{T}^{bb} shape	+0.04	−0.04
$t\bar{t} + \geq 1b$ ISR	+0.04	−0.04
$t\bar{t} + \geq 1c$ modelling	+0.03	−0.04
$t\bar{t}$ + light modelling	+0.03	−0.03
tW modelling	+0.08	−0.07
Background-model statistical uncertainty	+0.04	−0.05
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.03	−0.02
c-mis-tag rates	+0.03	−0.03
l-mis-tag rates	+0.02	−0.02
Jet energy scale and resolution		
b-jet energy scale	+0.00	−0.01
Jet energy scale (flavour)	+0.01	−0.01
Jet energy scale (pile-up)	+0.00	−0.01
Jet energy scale (remaining)	+0.01	−0.01
Jet energy resolution	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.28
$t\bar{t} + \geq 1b$ normalisation	+0.04	−0.07
Total statistical uncertainty	+0.20	−0.20
Total uncertainty	+0.36	−0.34

Uncertainties, $t\bar{t}H(H \rightarrow b\bar{b})$ CP arxiv:2303.05974

Uncertainty source	$\Delta\alpha\,[^\circ]$	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ 4V5 FS	+23	-37
$t\bar{t} + \geq 1b$ NLO matching	+22	-33
$t\bar{t} + \geq 1b$ fractions	+14	-21
$t\bar{t} + \geq 1b$ FSR	+5.2	-9.9
$t\bar{t} + \geq 1b$ PS & hadronisation	+16	-24
$t\bar{t} + \geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t} + \geq 1b$ ISR	+14	-24
$t\bar{t} + \geq 1c$ modelling	+6.6	-11
$t\bar{t}$ + light modelling	+2.5	-4.7
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+8.7	-15
c-mis-tag rates	+6.7	-11
l-mis-tag rates	+2.3	-2.7
Jet energy scale and resolution		
b-jet energy scale	+1.6	-3.8
Jet energy scale (flavour)	+7.8	-11
Jet energy scale (pileup)	+5.2	-7.9
Jet energy scale (remaining)	+8.1	-13
Jet energy resolution	+5.7	-9.3
Luminosity	$\leq \pm 1$	
Other sources	+4.9	-8
Total systematic uncertainty	+41	-54
$t\bar{t} + \geq 1b$ normalisation	+8.2	-13
κ_t'	+17	-33
Total statistical uncertainty	+32	-49
Total uncertainty	+52	-73

Uncertainty source	$\Delta\kappa_t'$	
Process modelling		
Signal modelling	+0.10	-0.10
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ 4V5 FS	+0.08	-0.23
$t\bar{t} + \geq 1b$ NLO matching	+0.15	-0.30
$t\bar{t} + \geq 1b$ fractions	+0.09	-0.21
$t\bar{t} + \geq 1b$ FSR	+0.01	-0.02
$t\bar{t} + \geq 1b$ PS & hadronisation	+0.09	-0.20
$t\bar{t} + \geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+0.07	-0.11
$t\bar{t} + \geq 1b$ ISR	+0.07	-0.17
$t\bar{t} + \geq 1c$ modelling	+0.04	-0.10
$t\bar{t}$ + light modelling	+0.00	-0.01
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.06	-0.12
c-mis-tag rates	+0.03	-0.07
l-mis-tag rates	+0.01	-0.03
Jet energy scale and resolution		
b-jet energy scale	+0.02	-0.02
Jet energy scale (flavour)	+0.01	-0.05
Jet energy scale (pileup)	+0.02	-0.05
Jet energy scale (remaining)	+0.04	-0.08
Jet energy resolution	+0.03	-0.09
Luminosity	$\leq \pm 0.01$	
Other sources	+0.03	-0.07
Total systematic uncertainty	+0.29	-0.45
$t\bar{t} + \geq 1b$ normalisation	+0.05	-0.15
α	+0.08	-0.07
Total statistical uncertainty	+0.09	-0.10
Total uncertainty	+0.30	-0.46

CP properties - comparison with $H \to \gamma\gamma$ result



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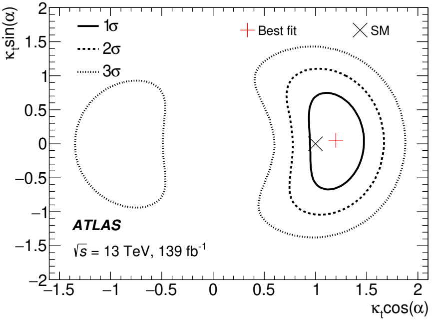

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