Measurements of Higgs boson production with top quarks with the ATLAS detector

Nihal Brahimi

On behalf of the ATLAS collaboration

Higgs 2024 conference

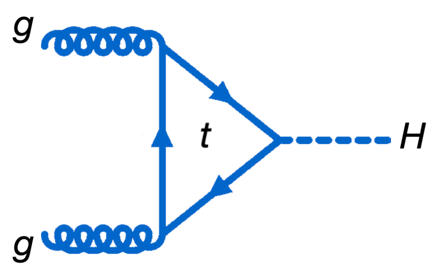
cnrs LAPP ATLAS EXPERIMENT

Funded by the European Union

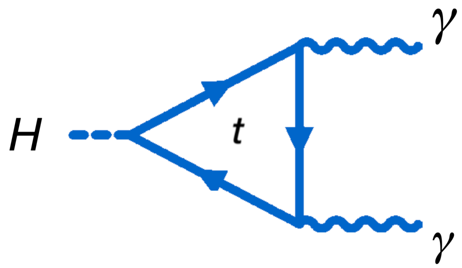
European Research Council
Established by the European Commission
DITTO - GA 101089007

Top Yukawa coupling: key interaction in the SM and BSM

- Higgs boson couples to fermions (**Yukawa interaction**) proportionally to their masses
  - ➡ Top quark is the **heaviest in the SM** ⇔ **Largest Yukawa coupling** ($\lambda_t = \frac{m_t\sqrt{2}}{v} \sim 1$)
  - ➡ **Sensitive probe** to New physics (BSM)
  - ➡ Gluon-gluon fusion and $H \to \gamma\gamma$ enable **indirect** access to λ_t in a model-dependent way

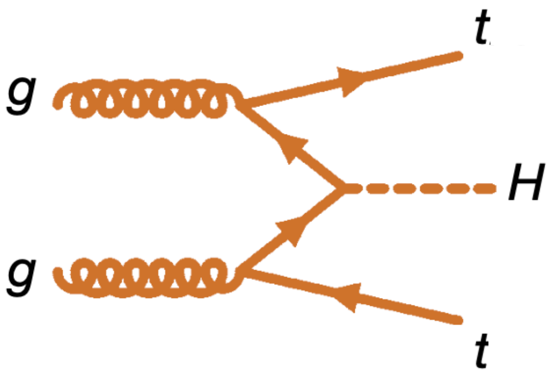


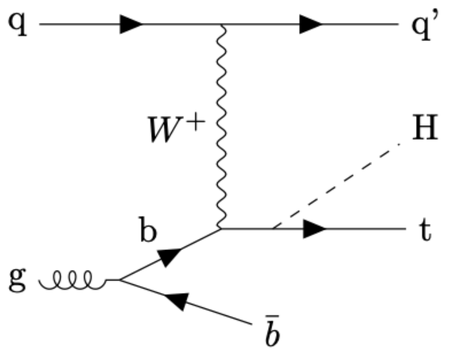
- **Top-associated** Higgs boson production provides a **direct access** to the top Yukawa
  - ➡ $\mathrm{t\bar{t}H}$: best way to measure λ_t (tree-level process), $\sigma_{ttH} \propto \lambda_t^2$
  - ➡ tH: lower cross-section in the SM (mainly tHqb production)
    - ★ Interference between top and W couplings → sensitive to the sign of λ_t and BSM effects

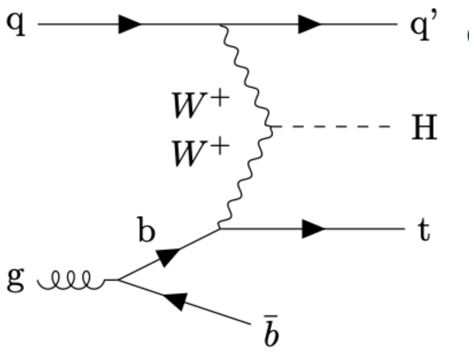


$\sigma_{SM}^{\mathrm{t\bar{t}H}} \sim 0.5$ pb

70k events produced in ATLAS during Run 2





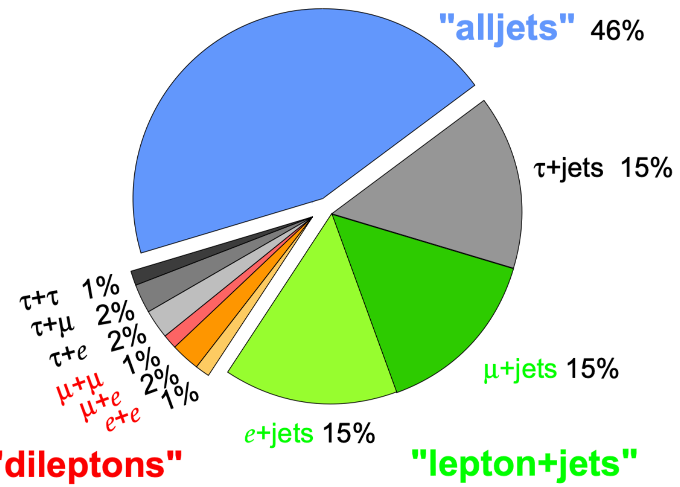


$\sigma_{SM}^{tH} \sim 0.09$ pb

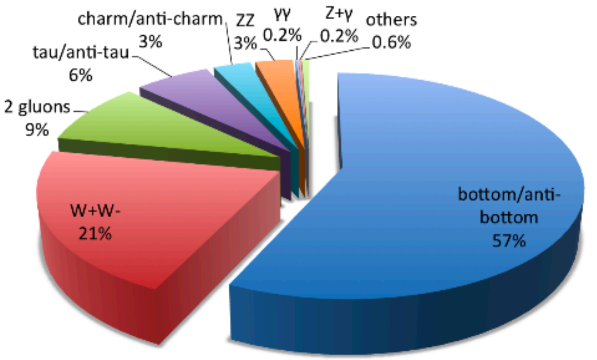
Top Yukawa coupling: measuring $t\bar{t}H/tH$ production

- Combination of top quarks and Higgs decays → **variety of complex final states**
  - ➡ Many objects: jets, b-jets, light leptons (ℓ), hadronic taus (τ_{had}) and photons
- $t\bar{t}H$ production **observed** combining several final states in ATLAS and CMS
  - ➡ established with > 5σ significance
  - ➡ tH production **not observed yet** given very small cross-section in SM

$t\bar{t}$ **pair BR**

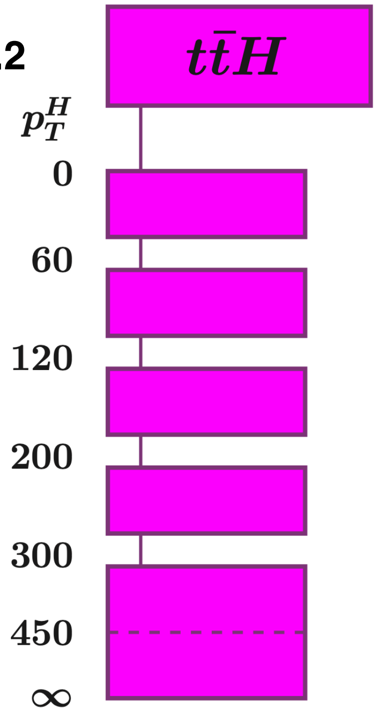


⊗



Higgs BR

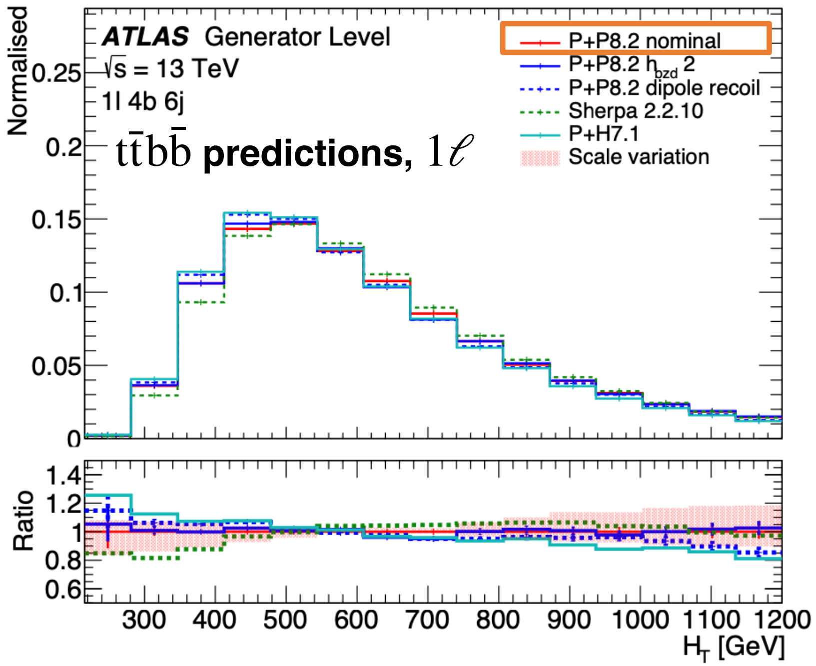
STXS Stage 1.2

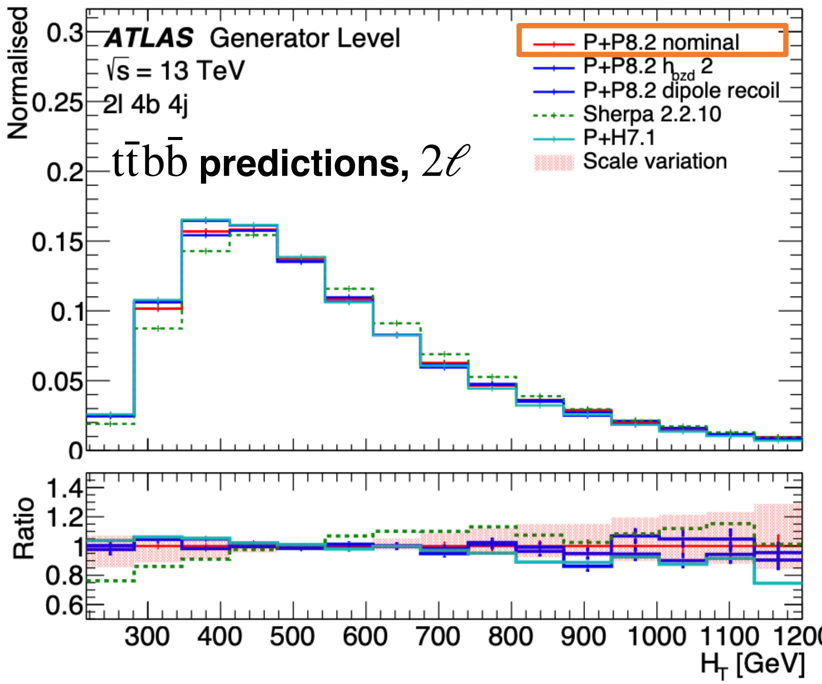


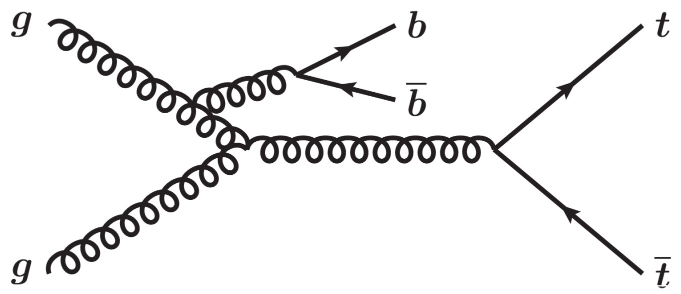
- Results of measured couplings expressed in terms of:
  - ➡ **Signal strengths** $\mu = \sigma/\sigma_{SM}$ or **coupling modifiers** k_t
- $t\bar{t}H$ part of the Simplified Template Cross-Section (STXS)
  - ➡ 5 or 6 bins in **Higgs boson** p_T

Couplings/STXS: $t\bar{t}H(H \to b\bar{b})$ w/ 140 fb^{-1} arXiv:2407.10904 (submitted to EPJC)

- **Re-analysis of the full Run 2 data** superseding the previous analysis JHEP 06 (2022) 97
- Targeting $H \to b\bar{b}$ mode with largest branching fraction ($\sim$ 58%) → valuable contribution to Higgs combination at higher p_T^H
  - ➡ Large and irreducible background from $t\bar{t} + b - \text{jets}$ → **leading source of uncertainty in the previous round**.
- Events categorised by $t\bar{t}$ decay ($1\ell/2\ell$) and p_T^H including 1ℓ boosted categories for $p_T^H > 300$ GeV
- Major improvements in this round:
  - ➡ advanced b-jet identification algorithm (DL1r), consolidated physics objects
  - ➡ Improved $t\bar{t} + \geq 1b$ modelling using a **new MC sample** with reduced associated systematics (ATL-PHYS-PUB-2022-006)



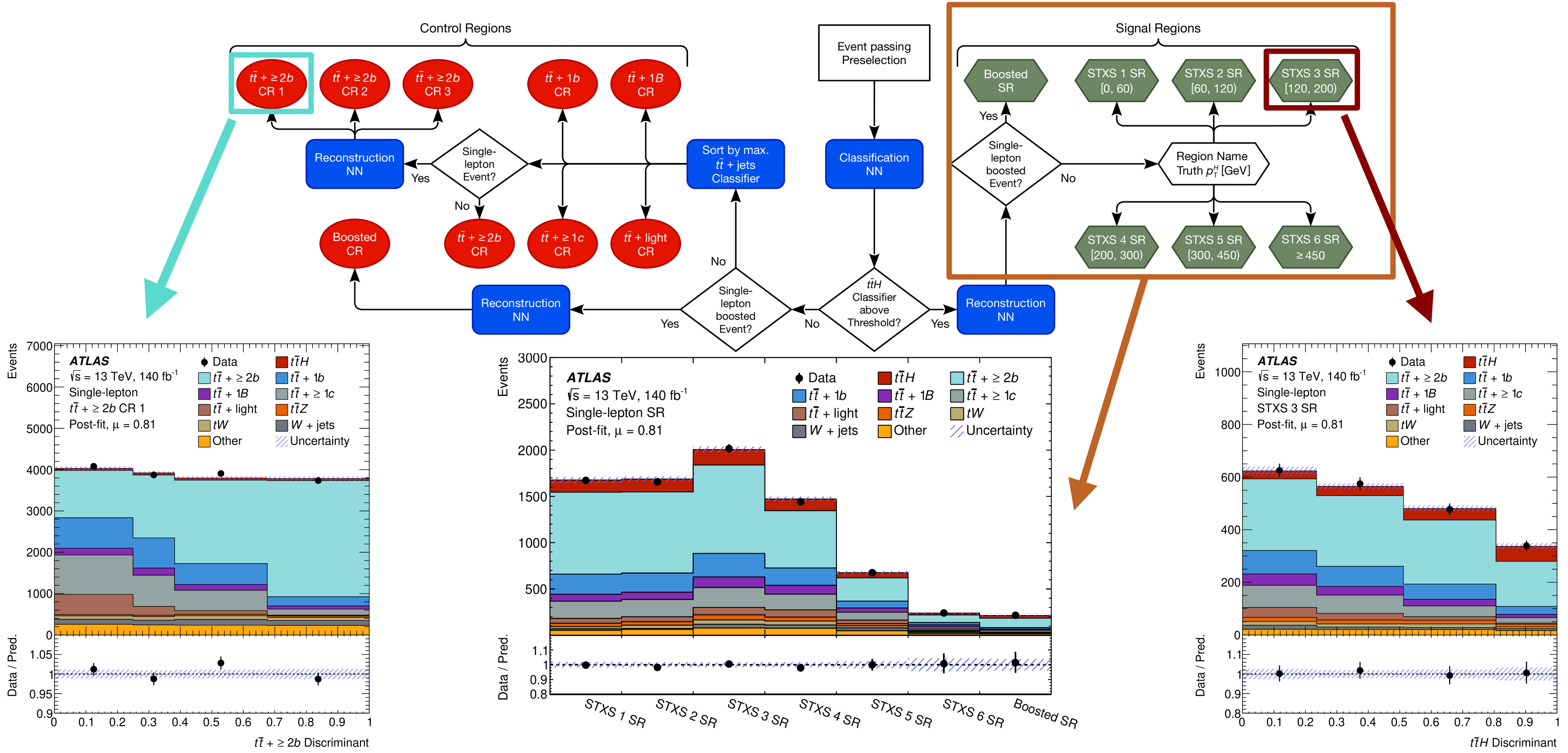




Couplings/STXS: $t\bar{t}H(H \rightarrow b\bar{b})$ w/ 140 fb^{-1} arXiv:2407.10904 (submitted to EPJC)

➡ Enhanced event **categorisation** and **reconstruction** using **transformer Neural Networks**

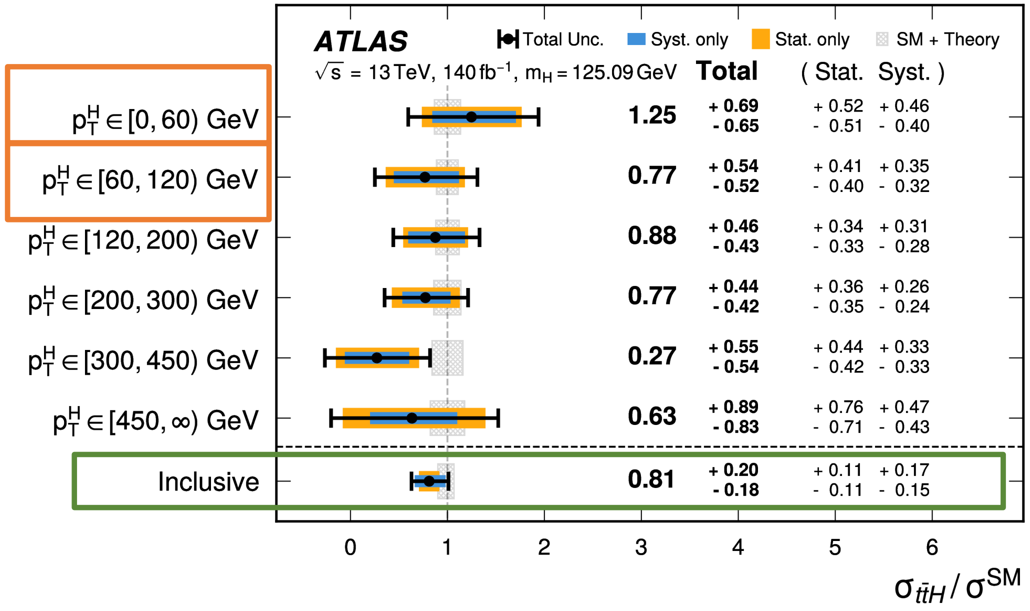
★ Allowed to **loosen kinematic preselection tripling signal events acceptance**

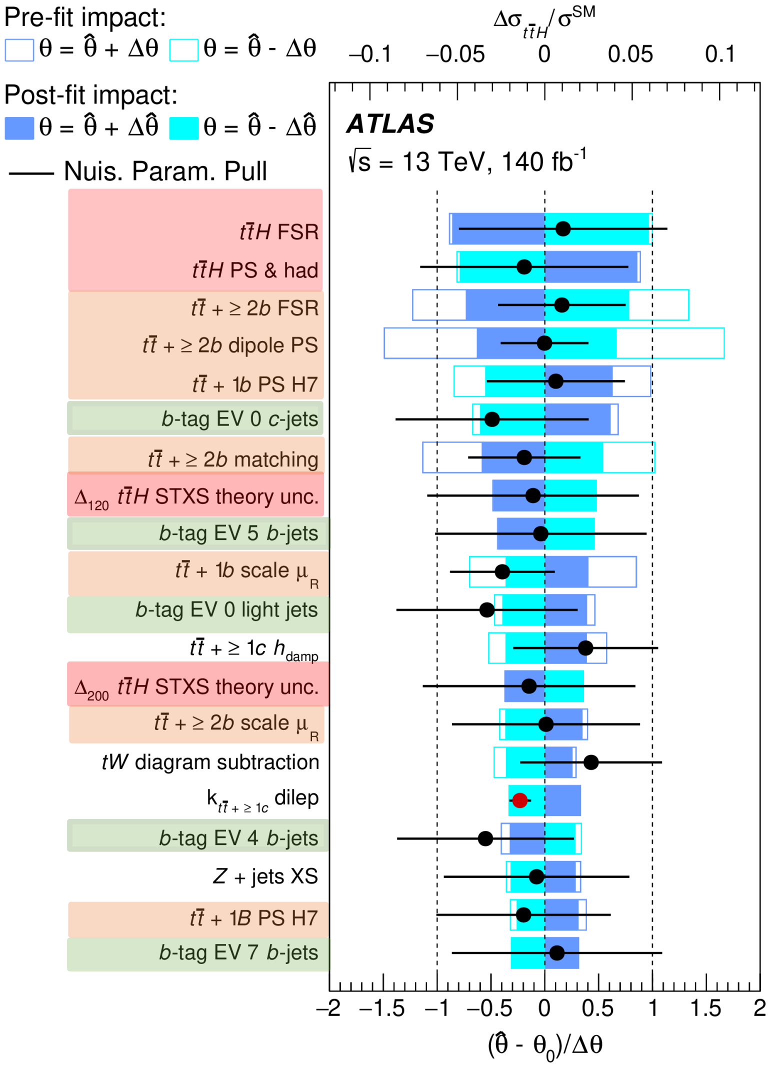


Couplings/STXS: $t\bar{t}H(H \rightarrow b\bar{b})$ w/ 140 fb^{-1}

arXiv:2407.10904 (submitted to EPJC)

- Simultaneous profile likelihood fit: 14 SRs/ 12 CRs
  - ➡ Signal cross-section and bkg normalisations free-floating
- Observed (expected) signal significance: **4.6 (5.4)** σ
  - ➡Compared to 1.0 (2.7) σ in previous round





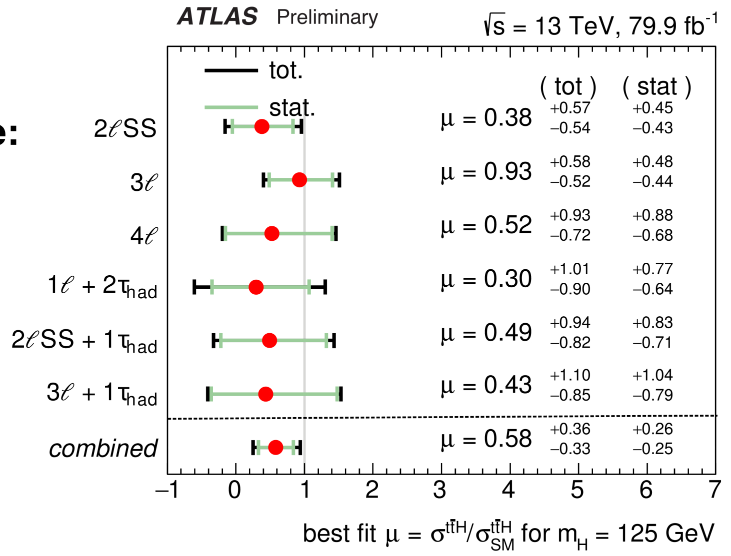
- **Full STXS stage 1.2 (6 Higgs p_T bins)**
  - ➡STXS Compatibility with SM: **89%**
- Sensitivity dominated by **signal modelling**, $t\bar{t} + \geq 1b$ **modelling** and **b-tagging**

Highest precision achieved in single channel $t\bar{t}H$ cross-section measurement to date, both inclusive and differential

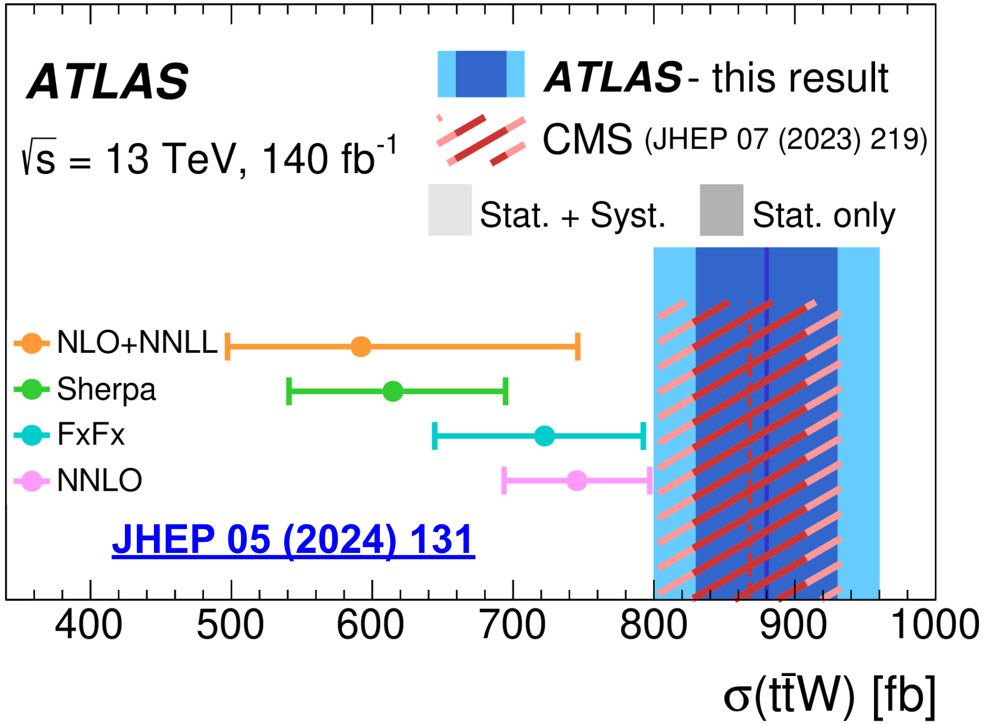
Couplings: $t\bar{t}H(H \rightarrow WW^*, ZZ^*, \tau\tau)$ w/ 80 fb^{-1} ATLAS-CONF-2019-045, JHEP 05 (2024) 131

- Relatively **large branching ratios** and low yet **challenging** backgrounds
- Targeting events with leptons in the H decay final states and **leptonic $t\bar{t}$ decays**
  - ➡ **6 channels** based on **number, flavour** and **charge** of lepton candidates
- Main backgrounds:
  - ➡ **Irreducible**: $t\bar{t}W$ (normalisation free-floated in the fit), $t\bar{t}Z$ and VV;
  - ➡ **Reducible**: non-prompt leptons, charge misID electrons and electrons from photon conversions

Observed significance: 1.8σ

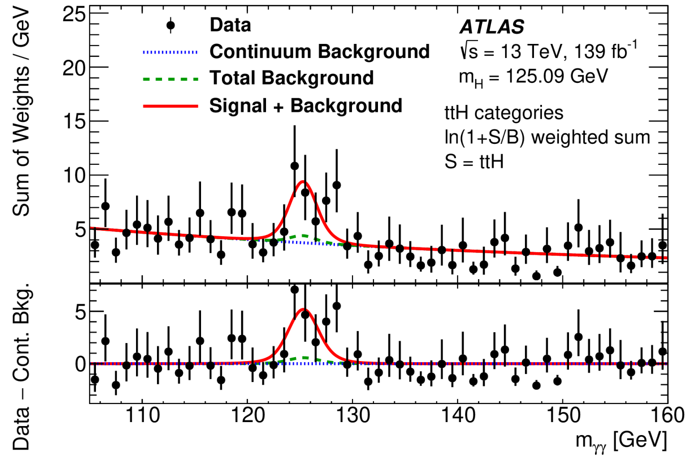


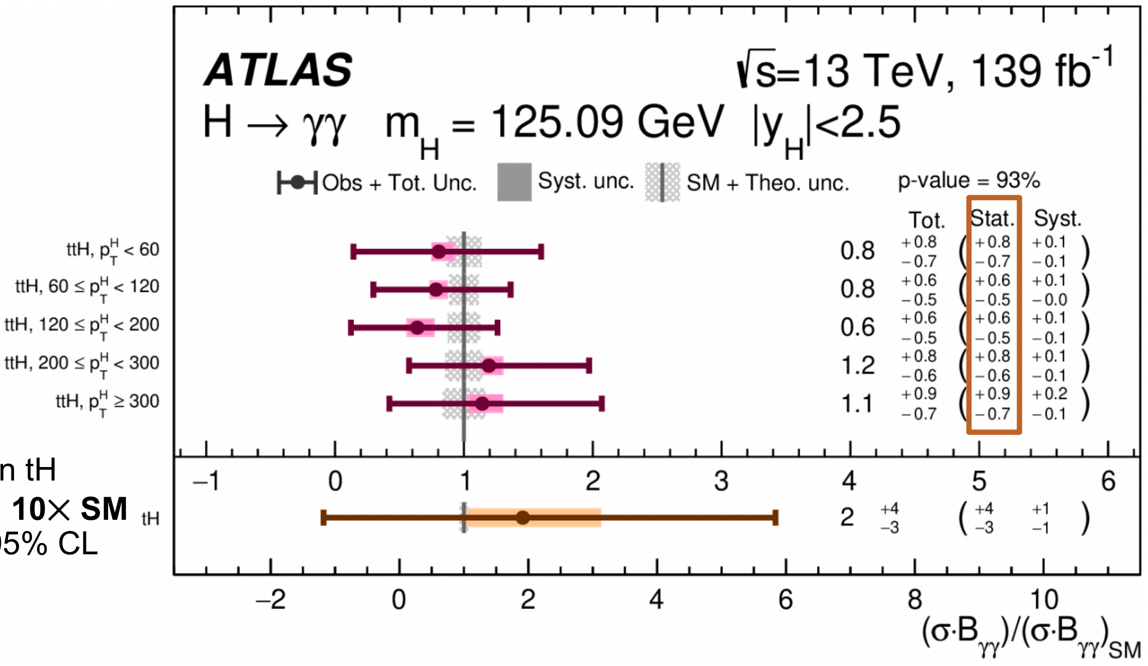
- $t\bar{t}W$ normalisation determined to be in the range ~ 1.3-1.7 w.r.t Sherpa 2.2.1-based prediction
  - ➡ $t\bar{t}W$ **modelling main limitation of analysis sensitivity**
- Dedicated $t\bar{t}W$ cross-sections measurements w/140 fb^{-1} performed:
  - ➡ tensions with predictions remain despite **improved theoretical calculations accounting for higher order QCD and EW corrections**
  - ➡ **Key input for the background modelling in the legacy $t\bar{t}H$-multilepton analysis.**



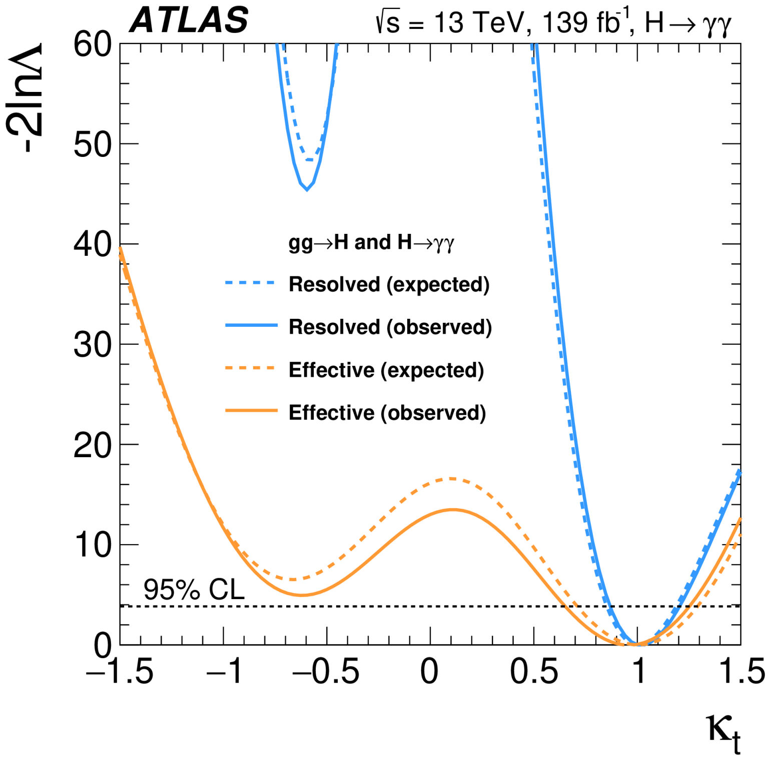
Couplings/STXS: $t\bar{t}H/tH(H \to \gamma\gamma)$ w/ 139 fb^{-1} [JHEP 07 (2023) 088]

- Analysis targets several **production modes** → **focussing on $t\bar{t}H/tH$ production** here
- **Small BR but clear signal peak and low background level**
- Refined event categorisation using **Multiclass and binary BDTs** → **13 dedicated to $t\bar{t}H/tH$**
  - ➡ **Using $m_{\gamma\gamma}$ as discriminant in the signal extraction fit**
- k_t probed with **two different configurations**:
  - ➡ **Resolved:** k_t in ggF and $H \to \gamma\gamma$ loops
  - ➡ **Effective :** effective coupling (**k_g and k_γ**) fixed to the **SM prediction**





Upper limit on tH cross-section: **10× SM** prediction @95% CL



negative k_t values excluded with $\geq 2.2\sigma$

values outside the range $0.65 < k_t < 1.25$ (expected $0.71 < k_t < 1.29$) excluded @ 95% CL

CP nature of top-Higgs interaction

- SM predicts the Higgs boson to be a **CP-even particle** ($J^{CP} = 0^{++}$, **scalar**)
- Signs of pure **CP-odd** or **CP-mixed** couplings to SM particles would hint at new physics beyond the SM

  ➡ **Additional sources of CP violation** (on top of CKM) needed to explain observed baryon asymmetry in the universe
- Effective Lagrangian describing top Yukawa coupling can be paramaterized as:

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

★k_t: coupling modifier parameter (SM: $\mathrm{k_t} = 1$) $\rightarrow \mathrm{k_t} \neq 1$ leads to variations in the cross-section

★α: CP-mixing angle (SM: $\alpha = 0°$; pure CP-odd: $\alpha = 90°$) $\rightarrow \alpha \neq 0°$ implies an admixture with pseudo-scalar coupling resulting in both cross-section and kinematics variations.

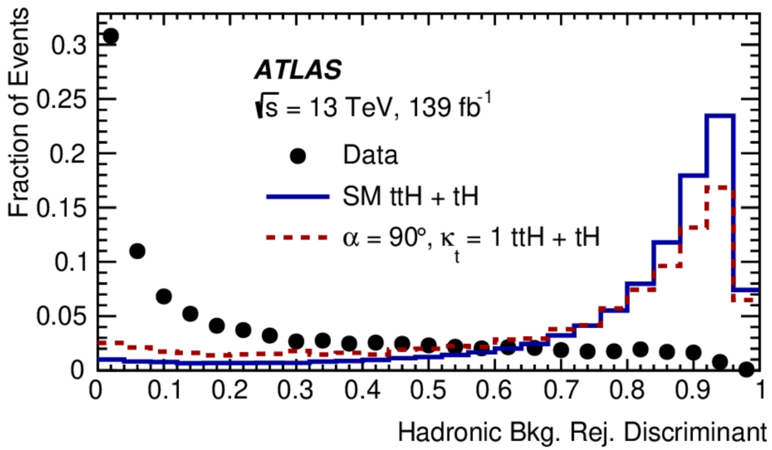
- **CP properties** of the top Yukawa coupling can be directly probed through $\mathrm{t\bar{t}H/tH}$ processes

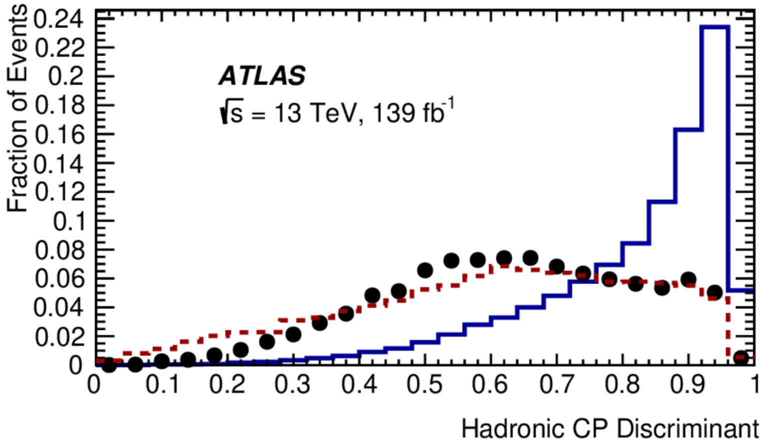
  ➡ exploiting $\mathrm{H} \rightarrow \gamma\gamma$ and $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$

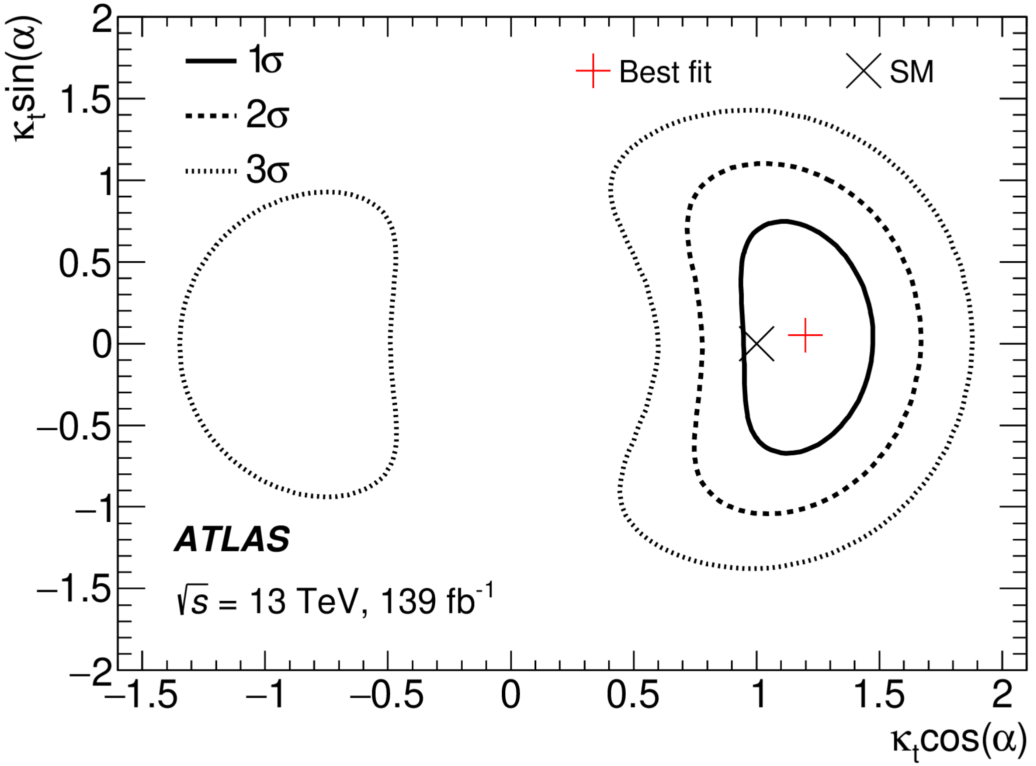
CP properties: $t\bar{t}H/tH(H \rightarrow \gamma\gamma)$ w/ 139 fb^{-1}

PRL 125 (2020) 061802

- Sharing similarities w/ the STXS analysis e.g signal and background modelling, discriminant variable $m_{\gamma\gamma}$
- Events categorisation using **2 BDTs**: **Background rejection BDT and CP BDT (CP-even vs CP-odd)** → **20 categories**







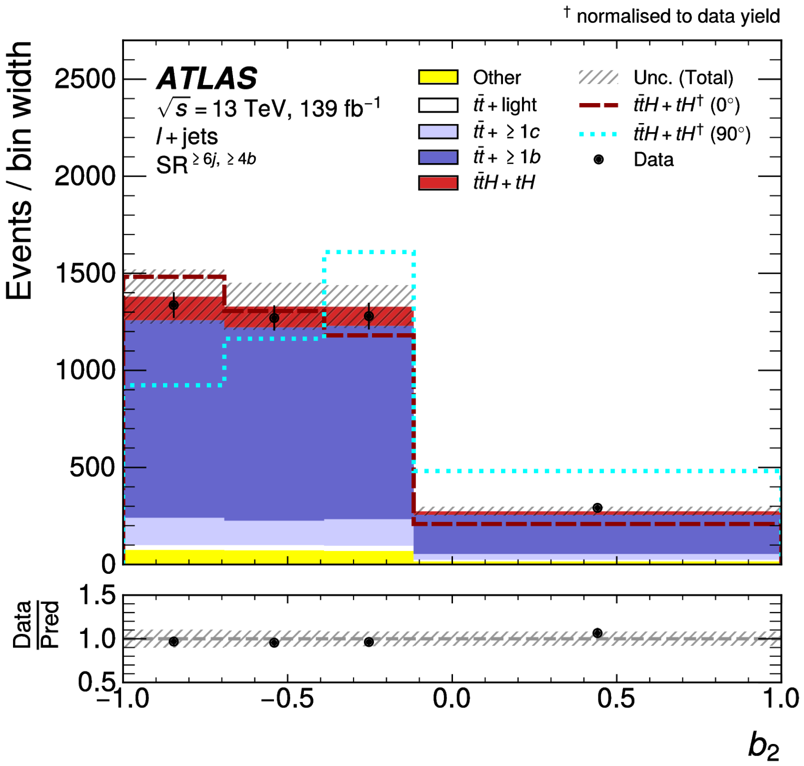
- **Statistically dominated** measurement
- Data **strongly favours the CP even** hypothesis:
  - ➡ $|\alpha| > 43^{\circ}$ excluded @ 95% CL
  - ➡ **Pure CP-odd coupling excluded at 3.9σ**

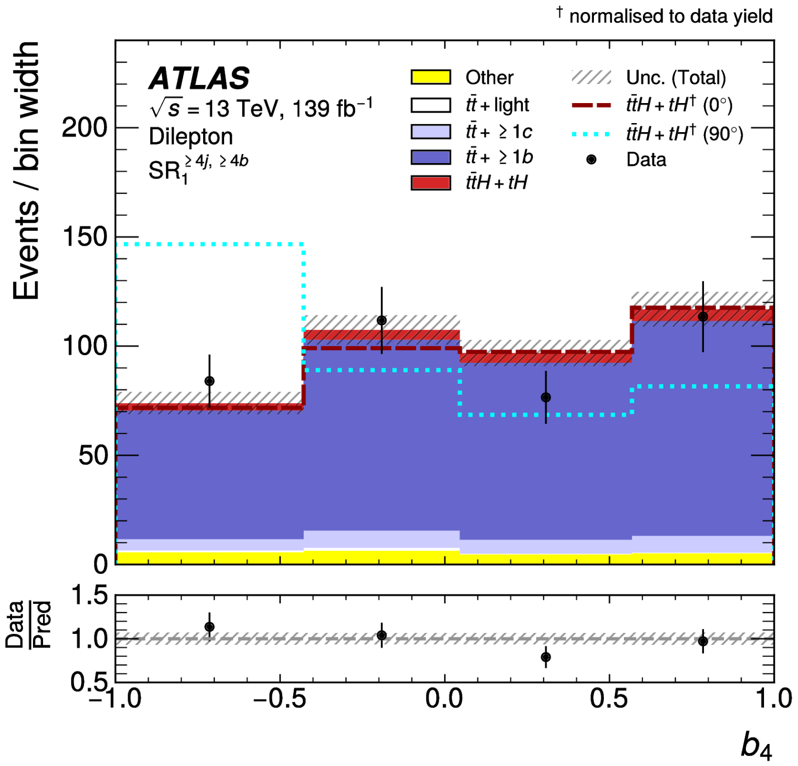
CP properties: $t\bar{t}H/tH(H \to b\bar{b})$ w/ 139 fb^{-1}

PLB 849 (2024) 138469

- Similar strategy to previous iteration of $t\bar{t}H(H \to b\bar{b})$ cross-section analysis with full Run 2 data JHEP 06 (2022) 97
  - ➡ **BDTs used for event reconstruction and event classification** (optimised for SM $t\bar{t}H$)
  - ➡ Considering both $t\bar{t}H$ and tH as signals
- **Dedicated CP sensitive observables** are built relying on angular separation between reconstructed top quarks
  - ➡ **b2**: enhanced for narrower azimuthal separation of top quarks in CP-odd case
  - ➡ **b4**: enhanced for top quarks in opposite directions and closer to the beamline
  - ❖ used as **fitting observables** in the signal regions

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

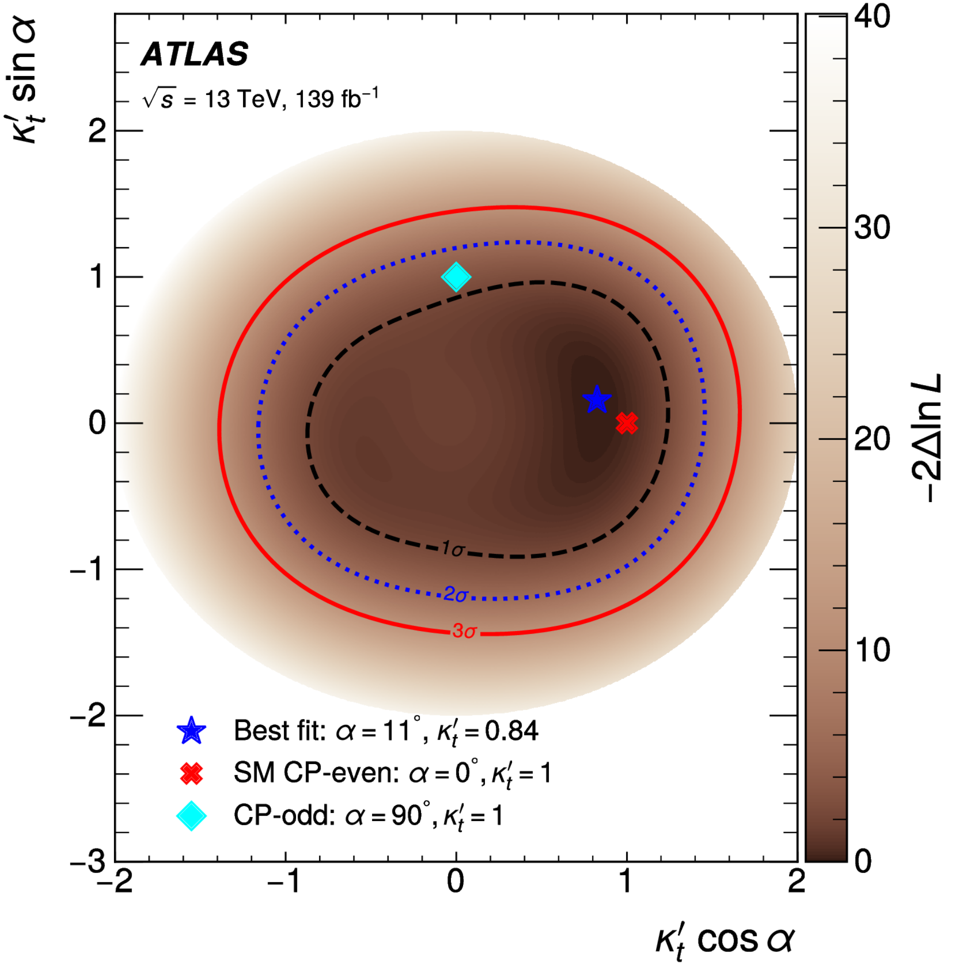




$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

CP properties: $t\bar{t}H/tH(H \to b\bar{b})$ w/ 139 fb^{-1}

PLB 849 (2024) 138469



- Best fit values:
  - ➡ CP-mixing angle $\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$
  - ➡ coupling strength $k_t' = 0.84^{+0.30}_{-0.46}$
  - ★ Compatible with both $\alpha = 0^{\circ}$ and $\alpha = 90^{\circ}$
  - ★Data prefers SM and disfavours CP-odd hypothesis at **1.2 σ significance.**

- Sensitivity driven by the $t\bar{t} + \geq 1b$ modelling uncertainties:
  - ➡ Same as in previous round of $t\bar{t}H(H \to b\bar{b})$ analysis
  - ➡ would benefit greatly from the improved modelling

Can enhance CP measurement precision when combined with $H \to \gamma\gamma$ measurement

Summary

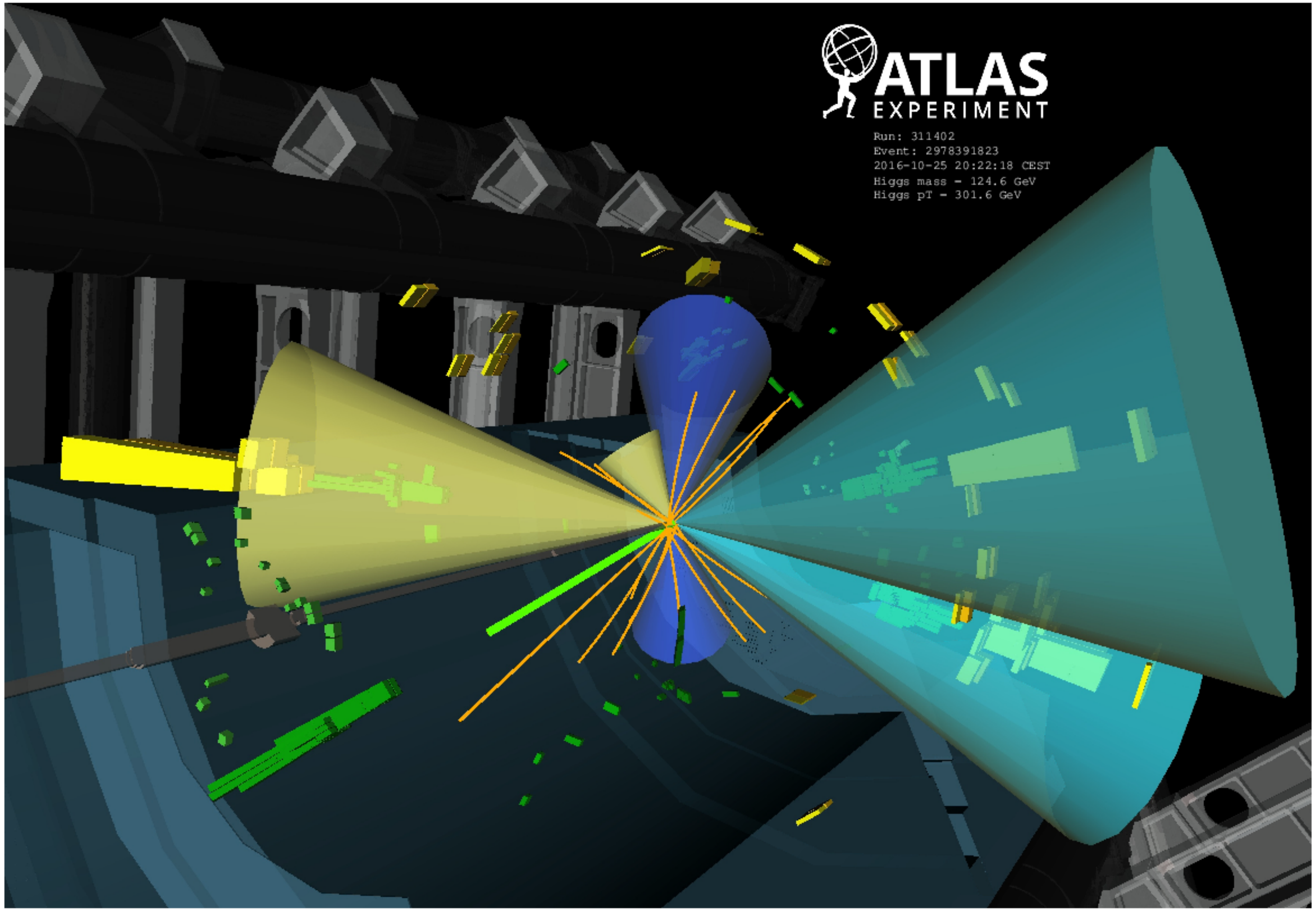
- An overview of the **latest** $t\bar{t}H/tH$ **ATLAS measurements with full Run 2 data** given
  - ➡ targeting $H \rightarrow b\bar{b}, \gamma\gamma, ZZ^*, WW^*, \tau\tau$ decay modes with complex final states
  - ➡ $H \rightarrow \tau\tau$ resonant leptonic decay with fully hadronic top decays covered in Enrique's talk
- **Largest ever dataset available** allowing to evolve from individual coupling measurements to the **STXS approach**
  - ➡ detailed $t\bar{t}H$ measurements as a function of the **Higgs boson** p_T
- Several analyses also exploring the **CP nature of the Higgs-top interaction**: $H \rightarrow b\bar{b}, \gamma\gamma$
- All measurements are **remarkably consistent with the predictions of the SM predictions**
  - ➡ some **limited by statistics** $(\gamma\gamma)$ while others by the **understanding of the background modelling** $(b\bar{b},$ multilepton$)$
- With Run 3 and beyond an unprecedented amount of data awaits!
  - ➡ would drive the precision of $t\bar{t}H/tH$ analyses even higher…**stay tuned**!

$t\bar{t}H$	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow WW^*, ZZ^*, \tau\tau$
$\mu_{t\bar{t}H}$	$0.81^{+0.20}_{-0.18}$	$0.89^{+0.32}_{-0.30}$	$0.58^{+0.36}_{-0.33}$
α(**CP**)	$11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$	$\lvert\alpha\rvert > 43^{\circ}$ excl. @95 CL	—

Backup

Couplings/STXS: $\mathrm{t\bar{t}H(H \rightarrow b\bar{b})}$ w/ 140 fb^{-1}

Couplings/STXS: $t\bar{t}H(H \rightarrow b\bar{b})$



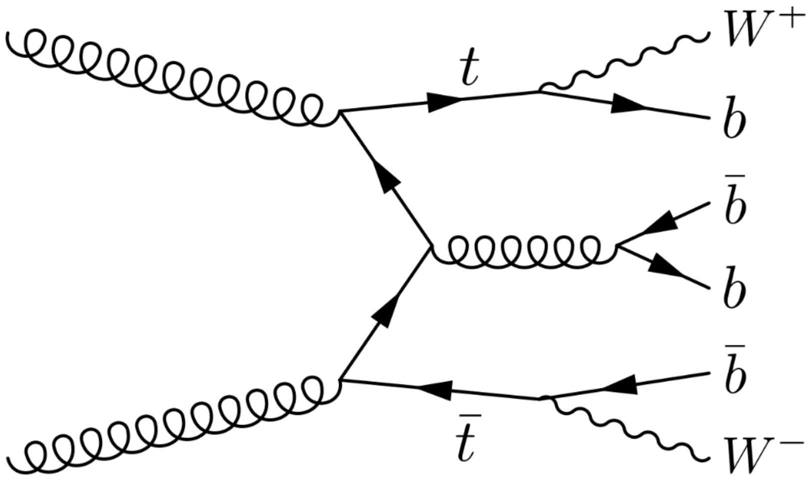
Preselection

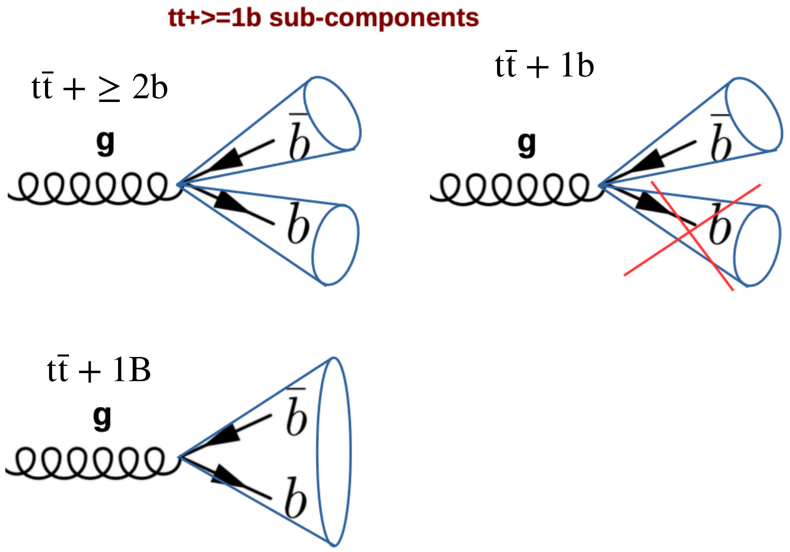
Channel	# Jets	# DL1r b-Tags @ 70 %	@ 77 %	@ 85 %	# e/μ	# τ_{had}	# Boosted Higgs Candidates
Dilepton	≥ 3	≥ 2	–	≥ 3	2	0	n/a
ℓ + Jets Resolved	≥ 5	≥ 3	–	–	1	≤ 1	–
ℓ + Jets Boosted	≥ 4	–	≥ 2	≥ 4	1	≤ 1	≥ 1

Chris Scheulen

$t\bar{t}$ + jets classification

- $t\bar{t}$ + jets events classified based on the flavour of additional non-$t\bar{t}$ jets: determined via matching particle jets to p_T>5 GeV b/c-hadrons with $\Delta R < 0.4$
- 4FS $t\bar{t}bb$ component split into 3 categories





- 5FS $t\bar{t}$ components classified into
  - $t\bar{t} + \geq 1c$: one or more non-$t\bar{t}$ jets matched to c-hadrons, no non-$t\bar{t}$ jets matched to b-hadrons
  - $t\bar{t}$ + light: no non-$t\bar{t}$ jets matched to b/c-hadrons

$t\bar{t}$ + jets modeling

- Nominal $t\bar{t}b\bar{b}$ 4FS sample generated based on the PowhegBoxRes+Pythia8 setup
- $t\bar{t} + \geq 1c$ and $t\bar{t} + \mathrm{light}$ 5FS samples generated based on the PowhegBox+Pythia8 setup

Optimised ttbb setup w.r.t previous round

Parameter	previous value	new default value
PDF	NNPDF3.0 nnlo Nf4	NNPDF3.1 nnlo Nf4
Scale choice[a] [b]	$\mu_R^{def} = \sqrt[4]{\prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}}$ $\mu_F^{def} = \frac{1}{2}[\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}]$	$\mu_R = 0.5 \cdot \mu_R^{def}$ $\mu_F = \mu_F^{def}$
h_{bzd}	2	5
h_{damp}	$H_T/2$	$H_T/2$
Decay handling	MadSpin	POWHEG
PYTHIA8 POWHEG:$pTdef$	2	1
PYTHIA8 SpaceShower:dipoleRecoil	off (global recoil)	off (global recoil)

ATL-PHYS-PUB-2022-006

$t\bar{t} + \text{jets}$ systematic model

- $t\bar{t} + \text{jets}$ components normalisation free-floating in the fit (only inclusive $t\bar{t} + \geq 1b$ normalisation floating in previous round)

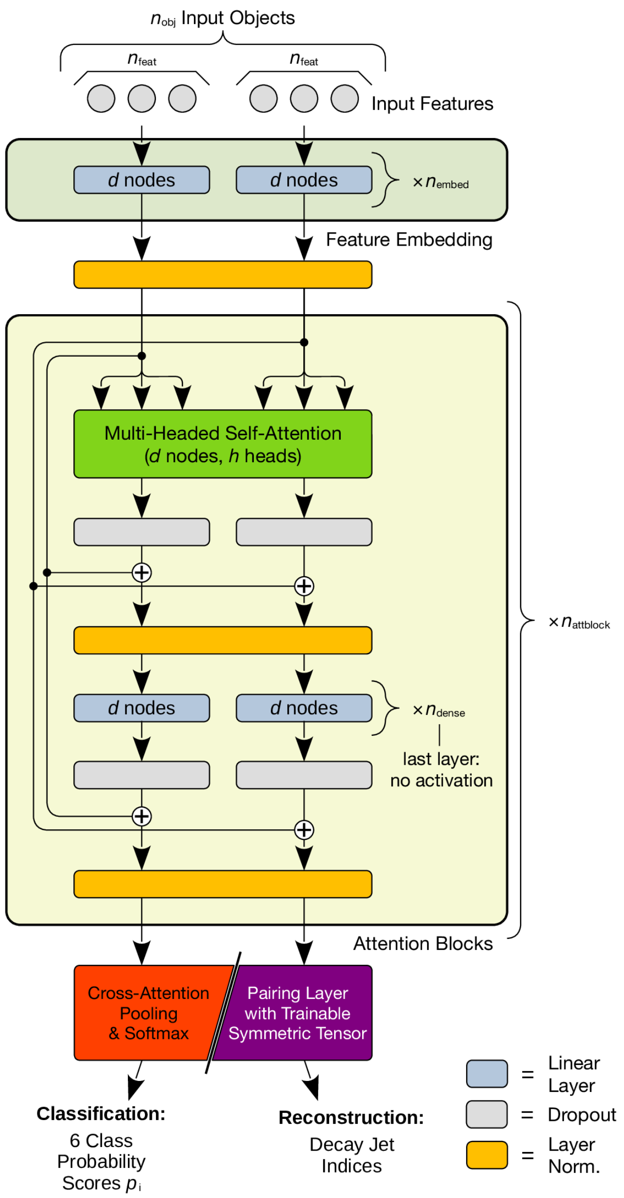
Systematic	ATLAS First Full Run 2	ATLAS Run 2 Legacy
ME Scale	–	independent ME μ_R, μ_F variations
ISR	Var3c and ME μ_R, μ_F variations	A14 tune Var3c variations
FSR	PS FSR μ_R variations	
Parton Shower & Hadronisation	Powheg + Herwig7 alternative (5FS only)	Powheg + Herwig7 alternative (5FS and 4FS)
NLO Matching	MG5_aMC@NLO + Pythia8 (5FS only)	PP8 p_T-hard = 1 alternative (5FS and 4FS)
ISR Recoil	–	PP8 dipole recoil alternative ($t\bar{t} + \geq 1b$ only)
h_{damp} variation	–	h_{damp} up-variation alternative ($t\bar{t}$ + c/light only)

Chris Scheulen

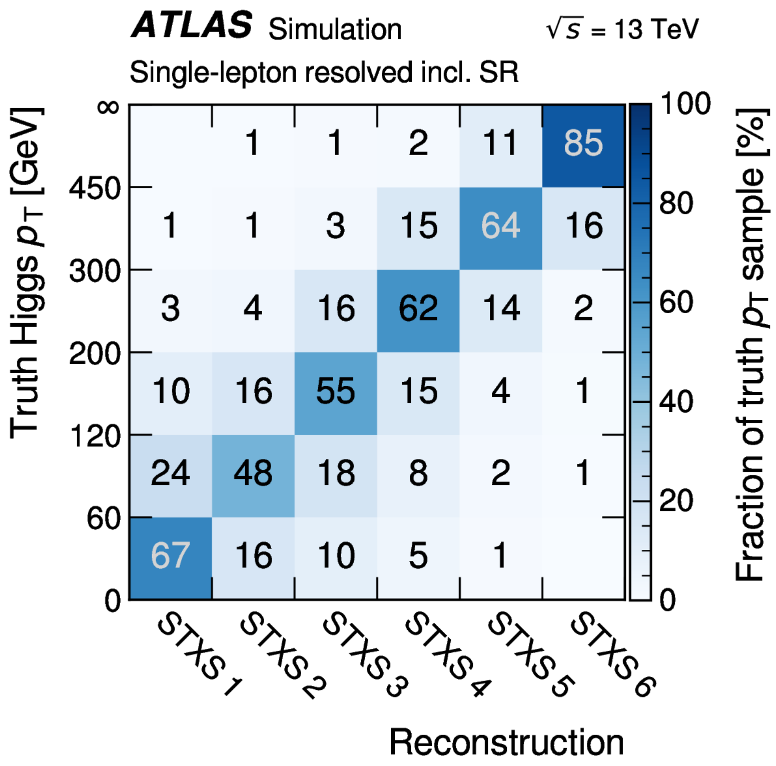
Transformers architecture (classification/reconstruction)

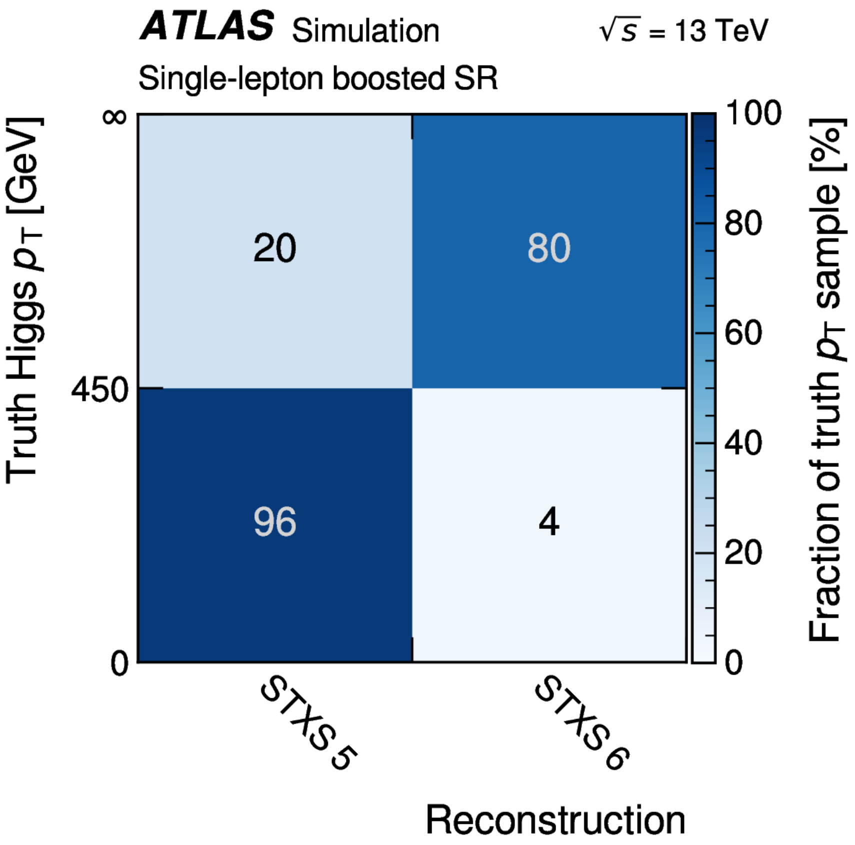
Feature	Description	Feature Transformations
p_x	Object momentum in x-direction.	Re-scaled to $\mu = 0, \sigma = 1$.
p_y	Object momentum in y-direction.	Re-scaled to $\mu = 0, \sigma = 1$.
p_z	Object momentum in z-direction.	Re-scaled to $\mu = 0, \sigma = 1$.
energy	Object energy.	Re-scaled to $\mu = 0, \sigma = 1$.
p_T	Object transverse momentum.	Re-scaled to $\mu = 0, \sigma = 1$.
mass	Object mass.	Re-scaled to $\mu = 0, \sigma = 1$.
η	Object pseudo-rapidity.	Re-scaled to $\mu = 0, \sigma = 1$.
ϕ	Object azimuthal angle.	Re-scaled to $\mu = 0, \sigma = 1$.
$\cos\phi$	Sine of object azimuthal angle.	Re-scaled to $\mu = 0, \sigma = 1$.
$\sin\phi$	Cosine of object azimuthal angle.	Re-scaled to $\mu = 0, \sigma = 1$.
PCBT bin	DL1r pseudo-continuous b-tagging bin assigned to jets in the following manner. Set to 0 for leptons and E_T^{miss}. $\text{feature} = \begin{cases} 1, & \text{if un-tagged} \\ 2, & \text{if tagged at } [85\%, 77\%) \\ 3, & \text{if tagged at } [77\%, 70\%) \\ 4, & \text{if tagged at } [70\%, 60\%) \\ 5, & \text{if tagged at } 60\%. \end{cases}$	None.
lepton type	Lepton type of input objects. Set to 1 for electrons, 2 for muons, and 0 for jets and E_T^{miss}.	None.
lepton charge	Charge of lepton objects in units of e. Set to 0 for jets and E_T^{miss}.	Re-scaled to $\mu = 0, \sigma = 1$.
E_T^{miss} flag	Whether input object is E_T^{miss} (value of 1) or not (value of 0).	None.

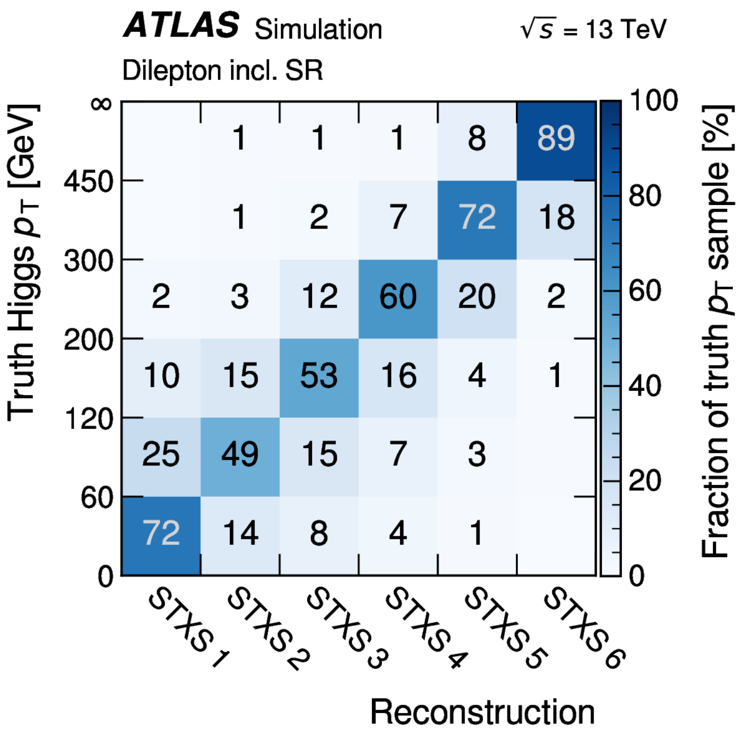
Chris Scheulen



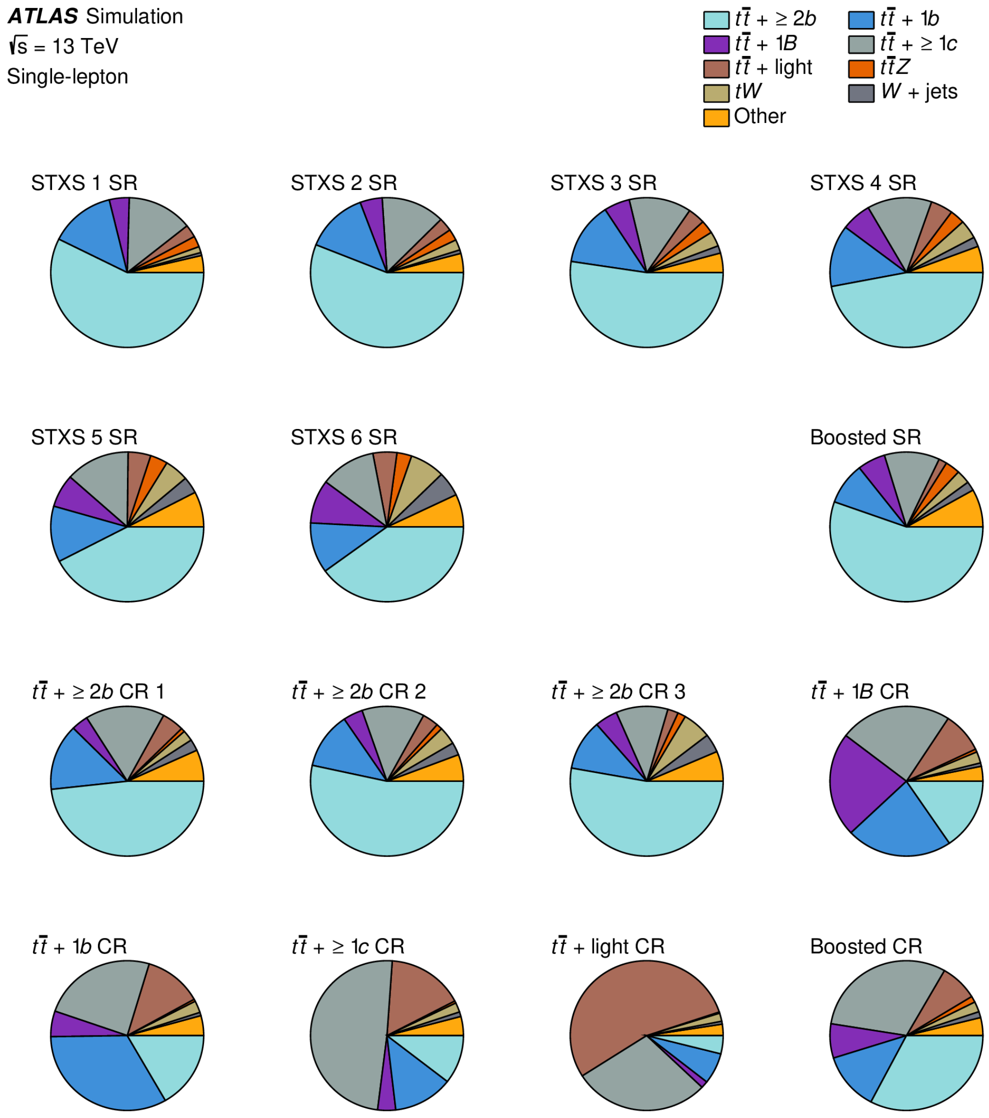
STXS migration matrices

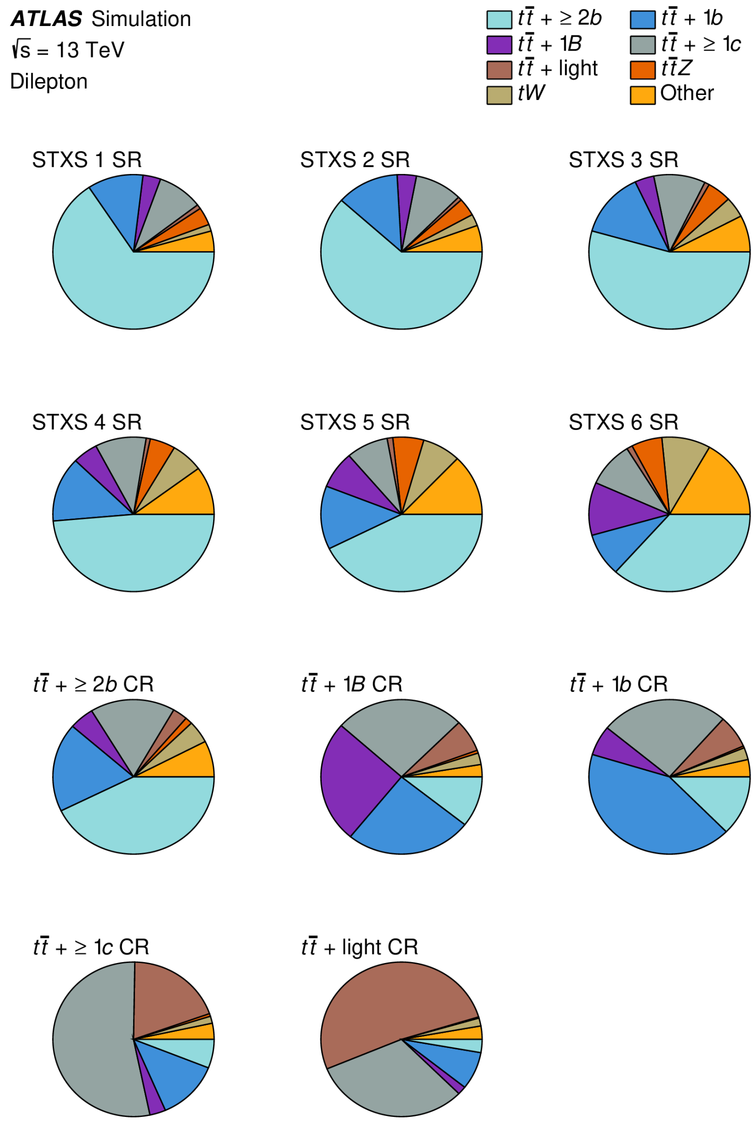






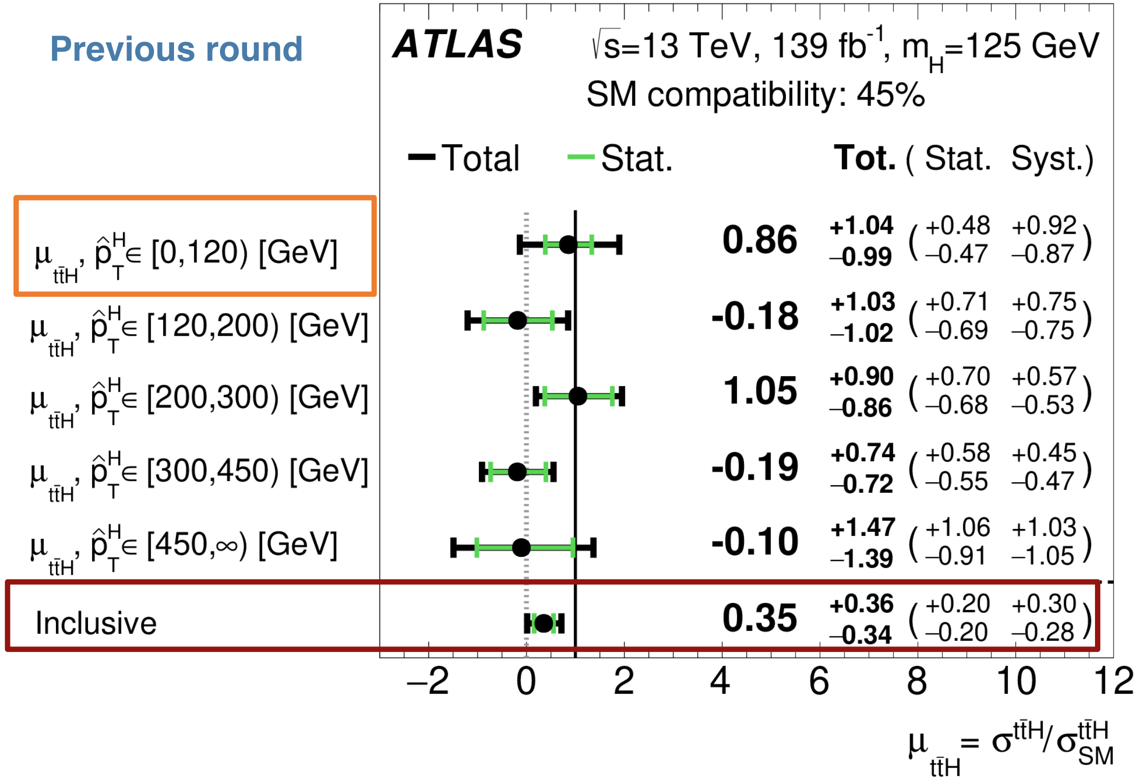
Background composition

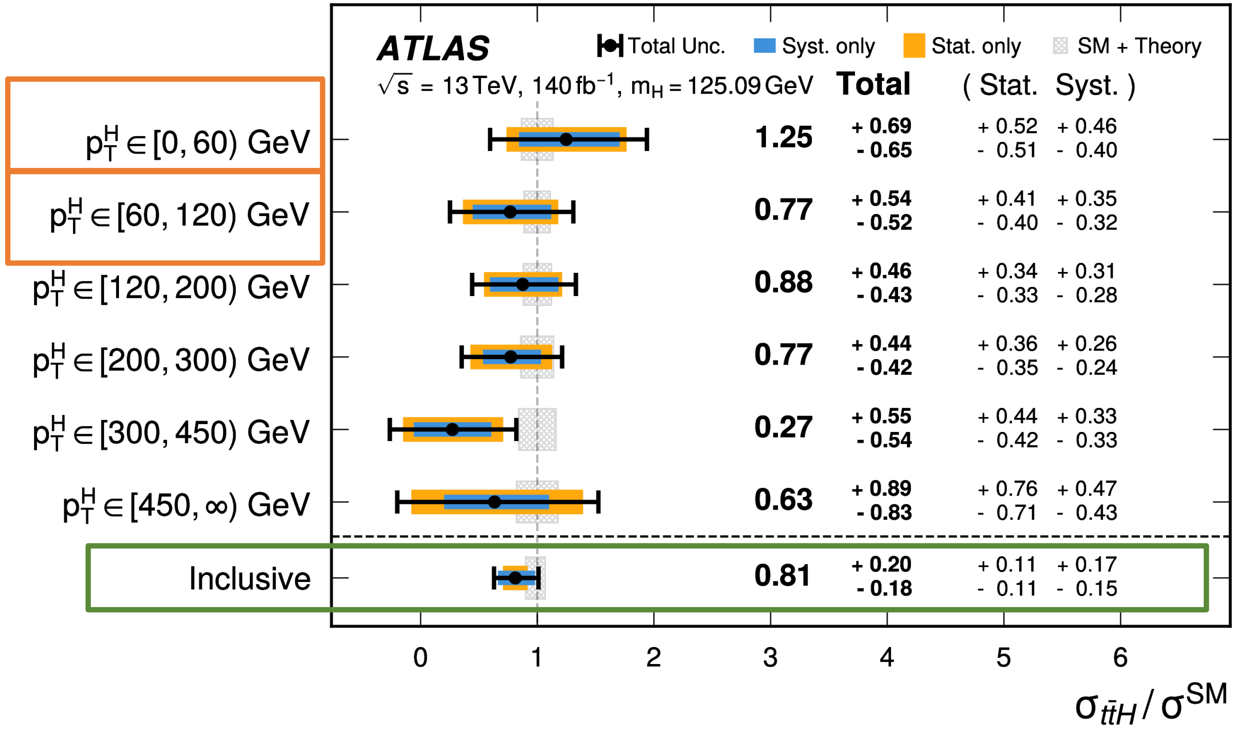




STXS measurements comparison w/ previous round

Previous round

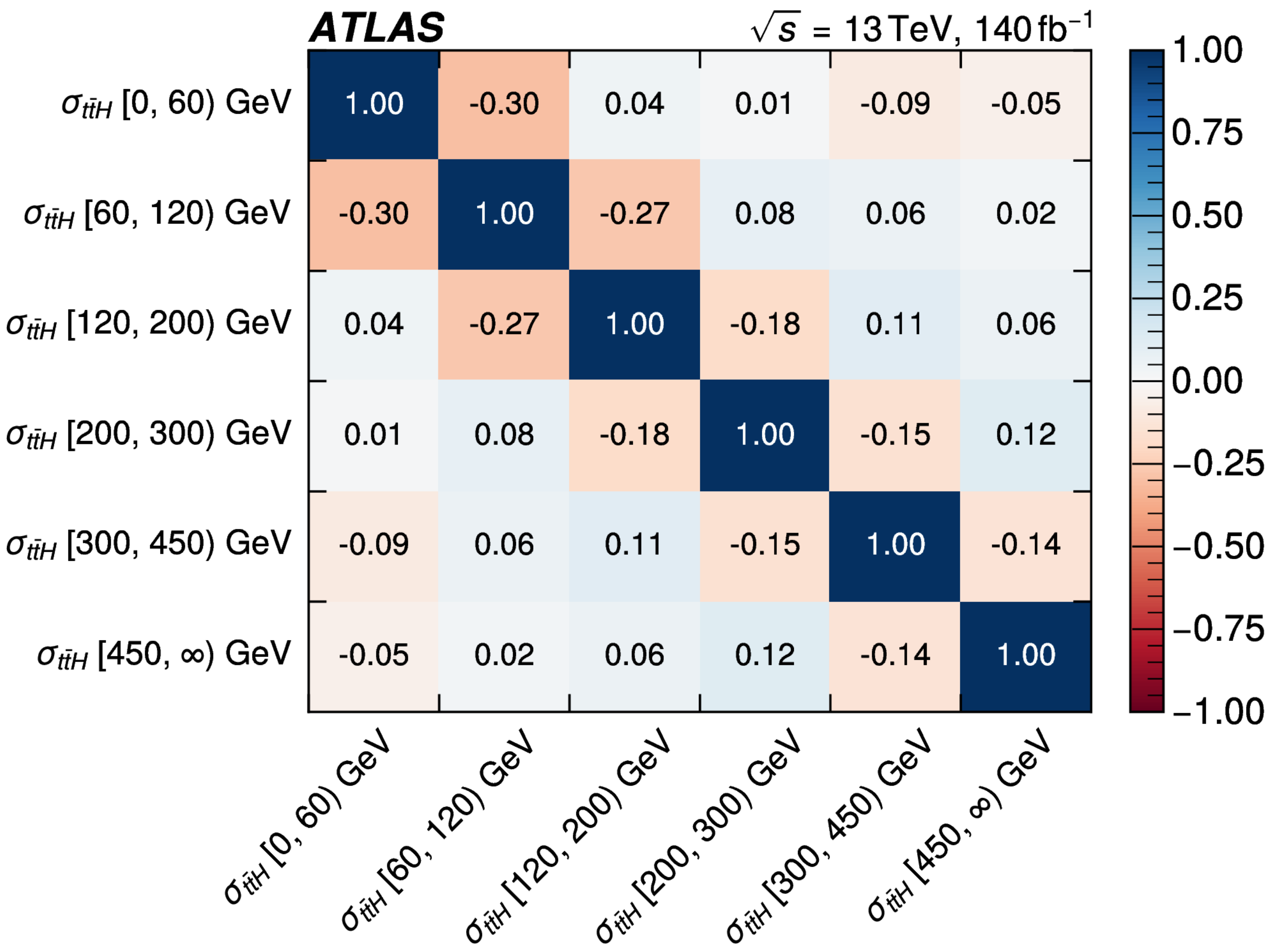




Background normalisation

Normalisation factor	$t\bar{t}$ + light	$t\bar{t} + \geq 1c$	$t\bar{t} + 1b$	$t\bar{t} + 1B$	$t\bar{t} + \geq 2b$
Single-lepton	$0.78^{+0.08}_{-0.08}$	$1.51^{+0.19}_{-0.18}$	$1.06^{+0.10}_{-0.10}$	$1.15^{+0.15}_{-0.14}$	$0.94^{+0.08}_{-0.08}$
Dilepton	$0.88^{+0.11}_{-0.10}$	$1.36^{+0.10}_{-0.10}$	$1.24^{+0.09}_{-0.09}$		

STXS correlations



Systematics grouped impact

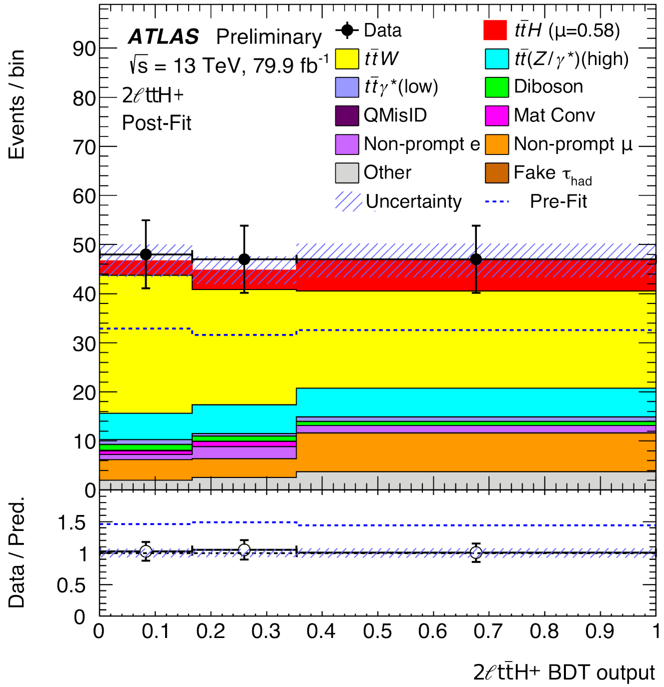
Uncertainty source	$\Delta\sigma_{t\bar{t}H}$ (fb)		$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ (%)	
Process modelling				
$t\bar{t}H$ modelling				
$t\bar{t}H$ radiation	+35	−21	+9	−5
$t\bar{t}H$ parton shower	+32	−19	+8	−5
$t\bar{t}H$ matching	<0.1	−0.3	<0.1	−0.1
$t\bar{t}H$ theory	+25	−17	+6	−4
$t\bar{t} + \geq 1b$ modelling				
$t\bar{t} + \geq 1b$ radiation	±31		±8	
$t\bar{t} + \geq 1b$ parton shower	±29		±7	
$t\bar{t} + \geq 1b$ matching	±19		±5	
$t\bar{t} + \geq 1c$ modelling	±18		±4	
$t\bar{t}$ + light modelling	±5		±1	
tW modelling	±16		±4	
Minor background modelling	±19		±5	
Flavour tagging	±36		±9	
Jet modelling	±22		±5	
Monte-Carlo statistics	±17		±4	
Other instrumental	±10		±2	
Total systematic uncertainty	+85	−75	+21	−18
Normalisation factors	±21		±5	
Total statistical uncertainty	±54		±13	
Total uncertainty	+101	−92	+25	−22

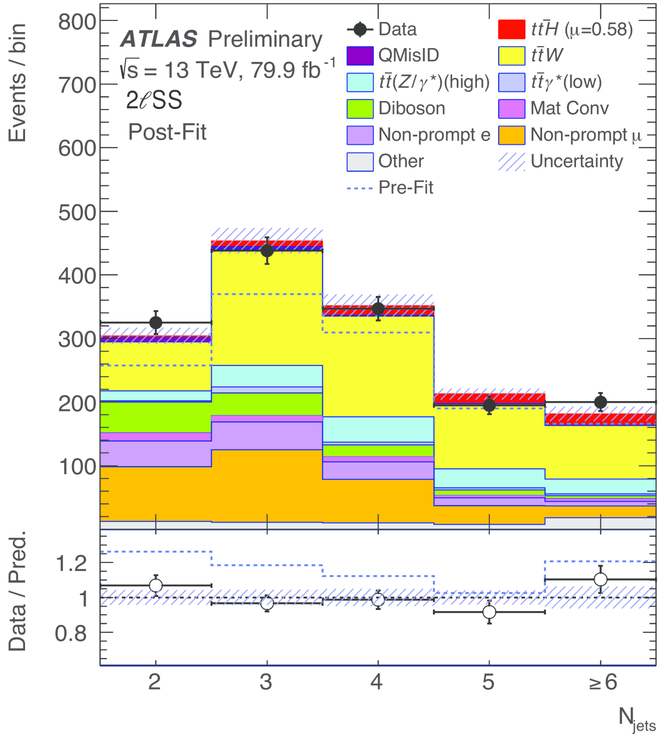
Couplings: $t\bar{t}H(H \rightarrow WW^*, ZZ^*, \tau\tau)$ w/ 80 fb^{-1}

Analysis strategy

- Relatively **large branching ratios** and low yet **challenging** backgrounds
- Targeting events with leptons in the H decay final states and **leptonic $t\bar{t}$ decays**
  - ➡ **6 channels** based on **number, flavour** and **charge** of lepton candidates: $2\ell SS$, 3ℓ, 4ℓ, $2\ell SS + 1\tau_{had}$, $3\ell + 1\tau_{had}$ and $1\ell + 2\tau_{had}$
  - ➡ MVA discriminants used in the $2\ell SS$, 3ℓ, 4ℓ and $1\ell + 2\tau_{had}$ for event classification (signal and control regions)
    - ❖ also used in signal extraction fit for signal regions (except for 4ℓ)

$\lambda_{ttW}^{2\ell LJ}$	$\lambda_{ttW}^{2\ell HJ}$	$\lambda_{ttW}^{3\ell}$
$1.56^{+0.30}_{-0.28}$	$1.26^{+0.19}_{-0.18}$	$1.68^{+0.30}_{-0.28}$





State-of-the-art ttW predictions

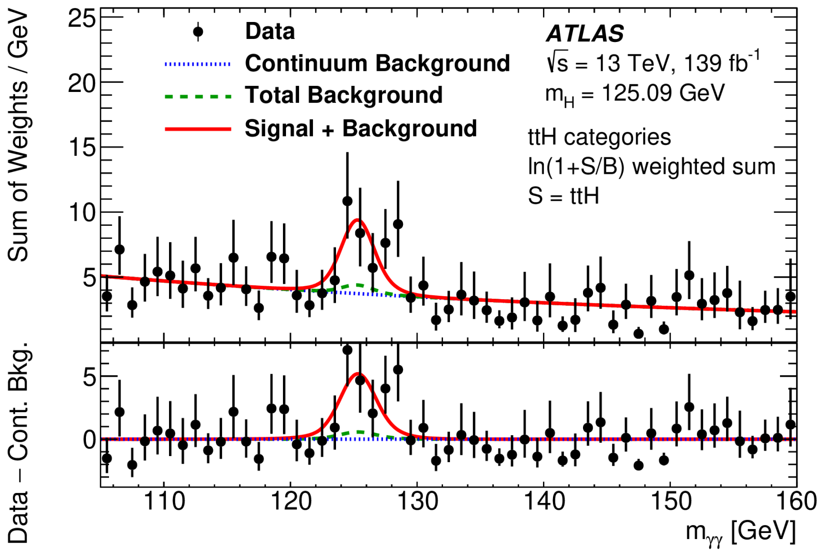
NNLO [15]		FxFx [27]	
Order	σ [fb]	Order	σ [fb]
LO QCD: $\alpha_s^2\alpha$	$420\ ^{+106}_{-79}$		
NLO QCD: $+\alpha_s^3\alpha$	$622\ ^{+79}_{-72}$	$t\bar{t}W$+0,1,2j@NLO	$691\ ^{+66}_{-74}$
NNLO QCD: $+\alpha_s^4\alpha$	$711\ ^{+35}_{-46} \pm 14$		
NLO EWK: $+\alpha_s\alpha^3 + \alpha_s^2\alpha^2 + \alpha^4$	$745 \pm 50 \pm 13$	$+\alpha_s\alpha^3$	$739\ ^{+75}_{-81}$
		$+\alpha_s^2\alpha^2 + \alpha^4$	$722\ ^{+70}_{-78}$

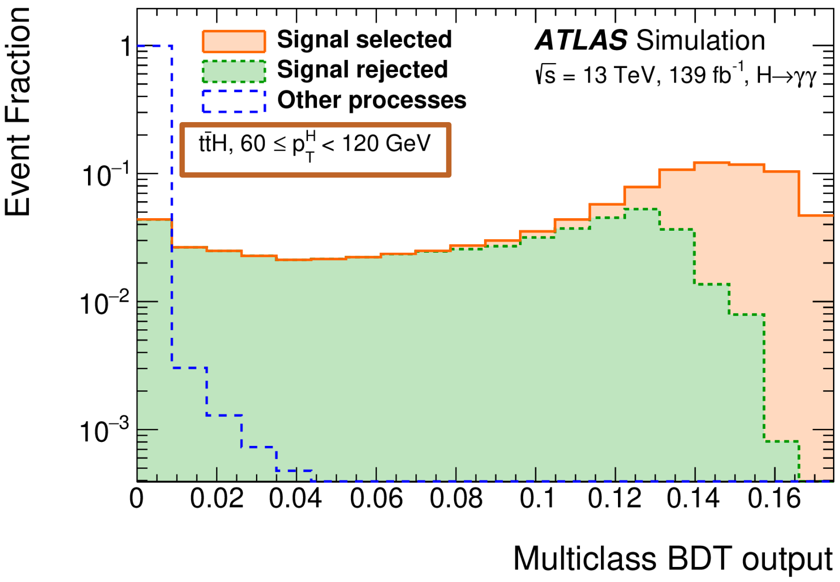
Table 1. Summary of theoretical predictions with NNLO precision in the strong coupling [15] and using FxFx NLO multijet merging [27], both including NLO EWK corrections. The first uncertainty is due to variations of the chosen renormalisation and factorisation scales. Where there is a second contribution to the uncertainty, this corresponds to the approximation used in the 2-loop calculation. Uncertainties due to the choice of PDF and α_s are omitted.

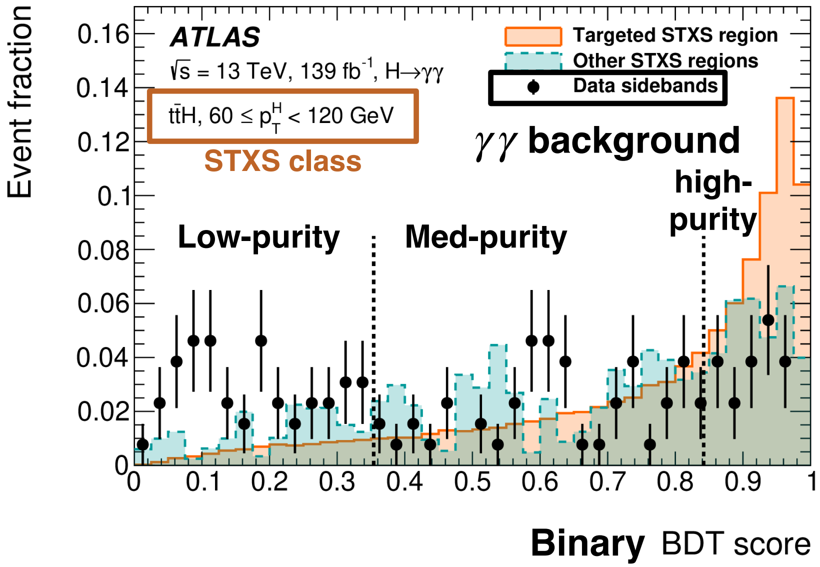
Couplings/STXS: $\mathrm{t\bar{t}H(H \rightarrow \gamma\gamma)}$ w/ 139 fb^{-1}

Analysis strategy

- **Small BR but clear signal peak and low background level**
  - ➡ excellent performance of **photon reconstruction/identification** in ATLAS.
- Event categorisation using a **Multiclass BDT** classifying signal events into **45 different STXS analysis regions**
  - ➡ **7 STXS regions** dedicated to $\mathrm{t\bar{t}H/tH}$ (5 Higgs boson $\mathrm{p_T}$ regions for $\mathrm{t\bar{t}H}$, tWH, tHqb)
- Each STXS class is further **subdivided into categories** based on **binary MVA classifiers**
  - ➡ $\mathrm{t\bar{t}H/tWH}$: binary BDT **separating signal from continuum $\gamma\gamma$ background**
  - ➡ **tHqb: two-stages NN binary classification** to reduce background and separate $k_t = 1$ **vs** $k_t = -1$







- Signal modelled as **double-sided Crystal Ball** function
- Background modelled as **power law, Bernstein polynomial or exponential function of polynomials**
  - ➡ chosen based on a spurious signal test
- Simultaneous **Maximum Likelihood fit to $m_{\gamma\gamma}$** performed in 101 analysis categories (**13 dedicated to $\mathrm{t\bar{t}H/tH}$**)

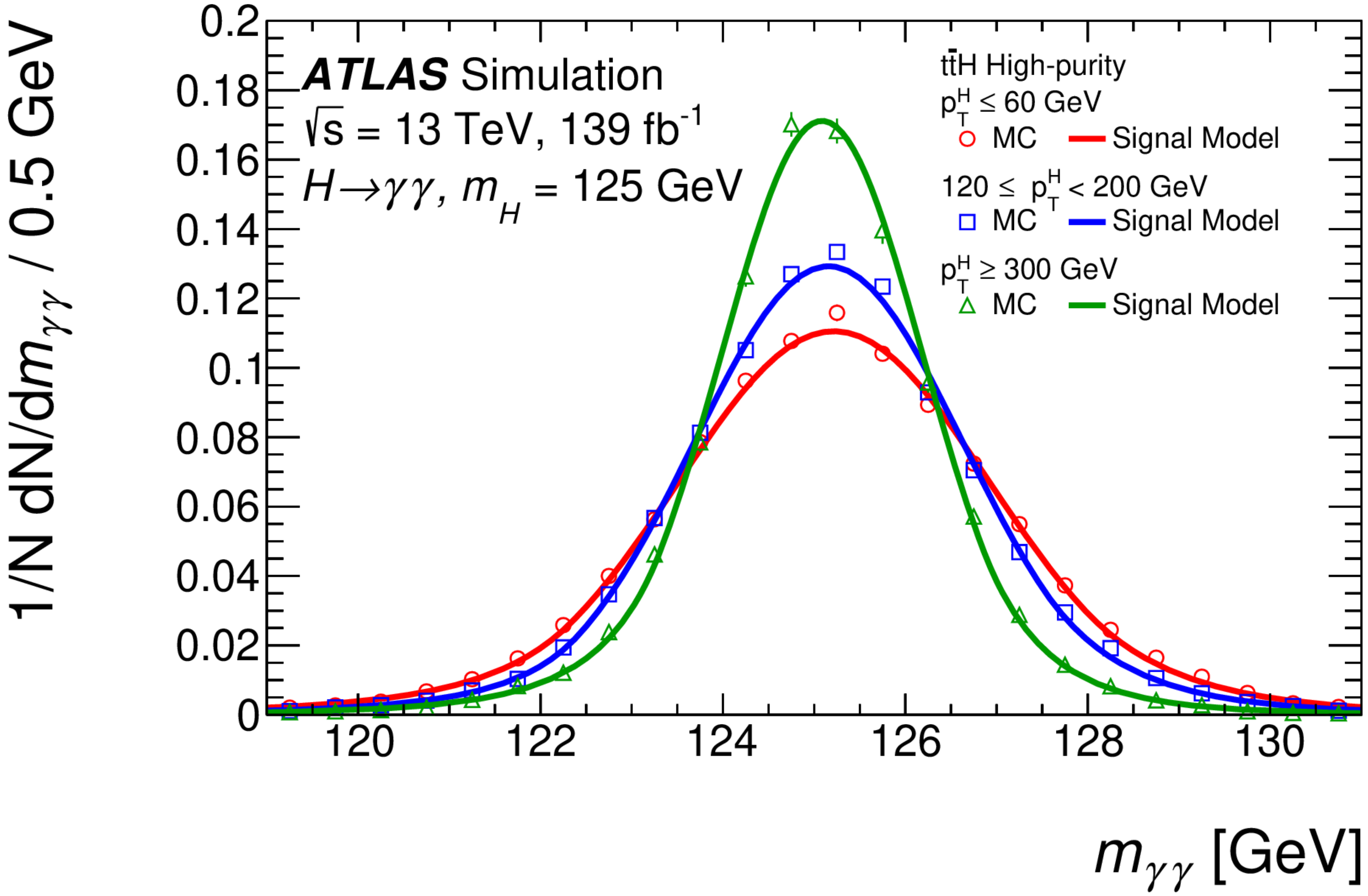
Multiclass BDT input features

$\eta_{\gamma_1}, \eta_{\gamma_2}, p_{\mathrm{T}}^{\gamma\gamma}, y_{\gamma\gamma}$,
$p_{\mathrm{T},jj}^{\dagger}$, m_{jj}, and Δy, $\Delta\phi$, $\Delta\eta$ between j_1 and j_2,
$p_{\mathrm{T},\gamma\gamma j_1}$, $m_{\gamma\gamma j_1}$, $p_{\mathrm{T},\gamma\gamma jj}\dagger$, $m_{\gamma\gamma jj}$
Δy, $\Delta\phi$ between the $\gamma\gamma$ and jj systems,
minimum ΔR between jets and photons,
invariant mass of the system comprising all jets in the event,
dilepton p_{T}, di-e or di-μ invariant mass (leptons are required to be oppositely charged),
$E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T} and transverse mass of the lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ system,
p_{T}, η, ϕ of top-quark candidates, $m_{t_1 t_2}$
Number of jets†, of central jets ($|\eta| < 2.5$)†, of b-jets† and of leptons,
p_{T} of the highest-p_{T} jet, scalar sum of the p_{T} of all jets,
scalar sum of the transverse energies of all particles ($\sum E_{\mathrm{T}}$), $E_{\mathrm{T}}^{\mathrm{miss}}$ significance,
$\left|E_{\mathrm{T}}^{\mathrm{miss}} - E_{\mathrm{T}}^{\mathrm{miss}}(\text{primary vertex with the highest } \sum p_{\mathrm{T,track}}^2)\right| > 30\,\mathrm{GeV}$
Top reconstruction BDT of the top-quark candidates,
$\Delta R(W, b)$ of t_2,
η_{j_F}, $m_{\gamma\gamma j_F}$
Average number of interactions per bunch crossing.

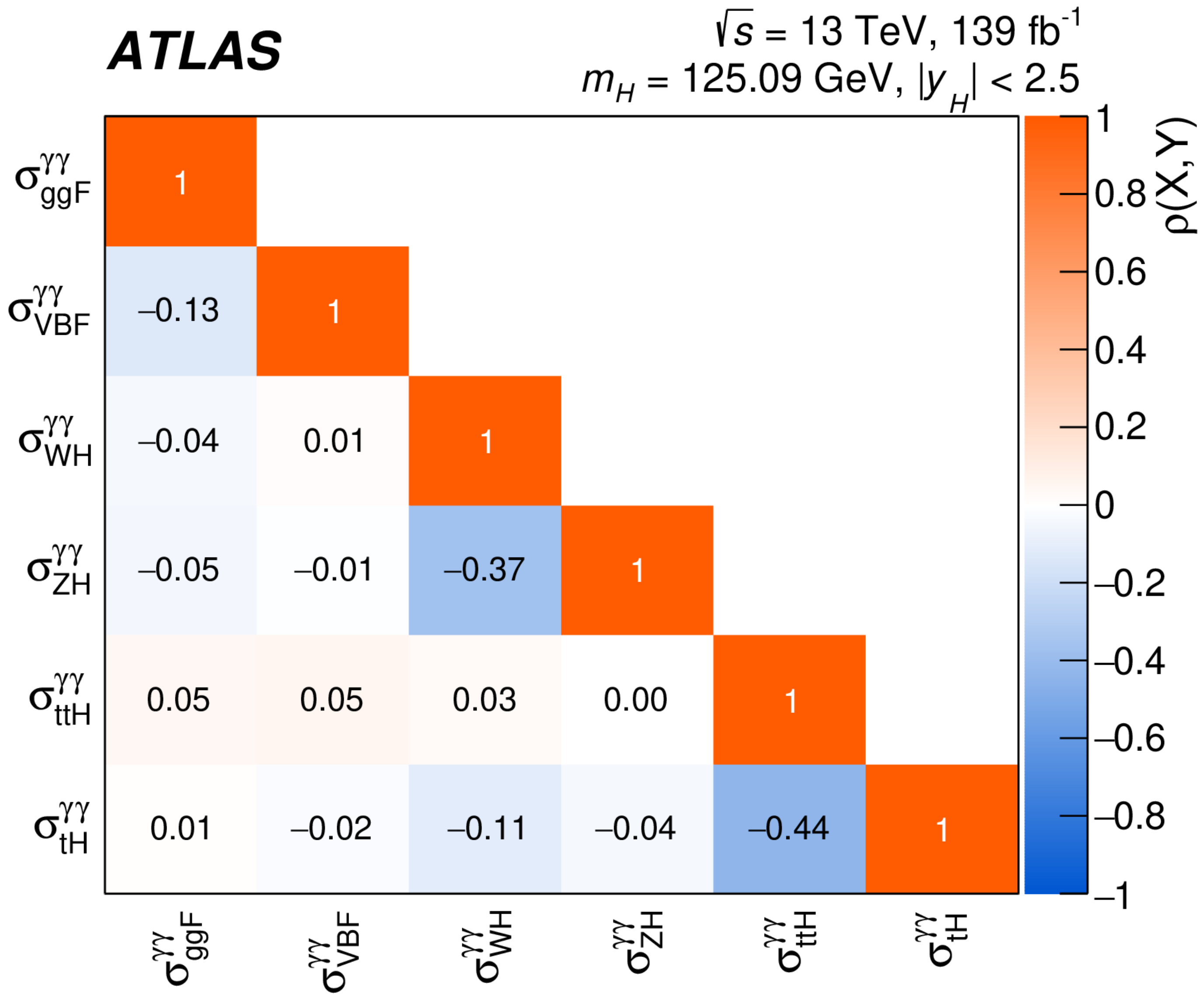
Binary classifiers input features

STXS classes	Variables
Individual STXS classes from $gg \to H$, $qq' \to Hqq'$, $qq \to H\ell\nu$, $pp \to H\ell\ell$, $pp \to H\nu\bar{\nu}$	All multiclass BDT variables, $\boldsymbol{p}_{\mathrm{T}}^{\gamma\gamma}$ projected to the thrust axis of the $\gamma\gamma$ system ($p_{\mathrm{Tt}}^{\gamma\gamma}$), $\Delta\eta_{\gamma\gamma}$, $\eta^{\mathrm{Zepp}} = \frac{\eta_{\gamma\gamma}-\eta_{jj}}{2}$, $\phi^*_{\gamma\gamma} = \tan\left(\frac{\pi-\lvert\Delta\phi_{\gamma\gamma}\rvert}{2}\right)\sqrt{1-\tanh^2\left(\frac{\Delta\eta_{\gamma\gamma}}{2}\right)}$, $\cos\theta^*_{\gamma\gamma} = \left\lvert\frac{(E^{\gamma_1}+p_z^{\gamma_1})\cdot(E^{\gamma_2}-p_z^{\gamma_2})-(E^{\gamma_1}-p_z^{\gamma_1})\cdot(E^{\gamma_2}+p_z^{\gamma_2})}{m_{\gamma\gamma}+\sqrt{m_{\gamma\gamma}^2+(p_{\mathrm{T}}^{\gamma\gamma})^2}}\right\rvert$ Number of electrons and muons.
all $t\bar{t}H$ and tHW STXS classes combined	p_{T}, η, ϕ of γ_1 and γ_2, p_{T}, η, ϕ and b-tagging scores of the six highest-p_{T} jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance, $E_{\mathrm{T}}^{\mathrm{miss}}$ azimuthal angle, Top reconstruction BDT scores of the top-quark candidates, p_{T}, η, ϕ of the two highest-p_{T} leptons.
$tHqb$	$p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma}$, $\eta_{\gamma\gamma}$, p_{T}, invariant mass, BDT score and $\Delta R(W,b)$ of t_1, p_{T}, η of t_2, p_{T}, η of j_F, Angular variables: $\Delta\eta_{\gamma\gamma t_1}$, $\Delta\theta_{\gamma\gamma t_2}$, $\Delta\theta_{t_1 j_F}$, $\Delta\theta_{t_2 j_F}$, $\Delta\theta_{\gamma\gamma j_F}$ Invariant mass variables: $m_{\gamma\gamma j_F}$, $m_{t_1 j_F}$, $m_{t_2 j_F}$, $m_{\gamma\gamma t_1}$ Number of jets with $p_{\mathrm{T}} > 25$ GeV, Number of b-jets with $p_{\mathrm{T}} > 25$ GeV*; Number of leptons*, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance*

Signal modeling



STXS correlations



κ parametrisation

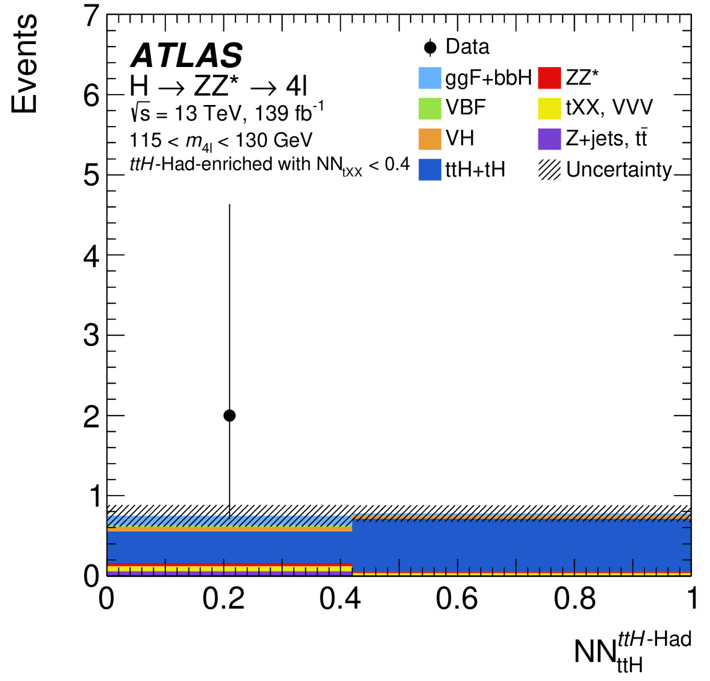
Table 1: Parameterization of Higgs boson production cross-sections σ_i, the partial decay widths $\Gamma_{\gamma\gamma}$, Γ_{gg} and $\Gamma_{Z\gamma}$ of the $H\to\gamma\gamma$, $H\to gg$ and $H\to Z\gamma$ decays, respectively, and the total width Γ_H, normalized to their SM values, as functions of the coupling-strength modifiers κ. The coefficients for $\sigma(tHW)$ and $\sigma(tHqb)$ include acceptance effects that differ between analysis categories as described in the text. Other coefficients are derived following the methodology in Refs. .

Production cross-section	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(q\bar{q}\to ZH)$	-	-	κ_Z^2
$\sigma(gg\to ZH)$	t–Z	-	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	κ_t^2
$\sigma(tHW)$	t–W	-	$A\,\kappa_t^2 + B\,\kappa_W^2 + C\,\kappa_t\kappa_W$, category-dependent
$\sigma(tHqb)$	t–W	-	$A\,\kappa_t^2 + B\,\kappa_W^2 + C\,\kappa_t\kappa_W$, category-dependent
$\sigma(b\bar{b}H)$	-	-	κ_b^2
Partial and total decay widths			
$\Gamma_{\gamma\gamma}$	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t + 0.009\,\kappa_W\kappa_\tau$ $+ 0.008\,\kappa_W\kappa_b - 0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
Γ_{gg}	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma_{Z\gamma}$	t–W		$1.118\,\kappa_W^2 + 0.004\,\kappa_t^2 - 0.125\,\kappa_W\kappa_t + 0.003\,\kappa_W\kappa_b$
Γ_H	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.063\,\kappa_\tau^2$ $+ 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2 + 0.0023\,\kappa_\gamma^2$ $+ 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$ $+ 0.082\,(\Gamma_{gg}/\Gamma_{gg}^{\text{SM}})$ $+ 0.0015\,(\Gamma_{Z\gamma}/\Gamma_{Z\gamma}^{\text{SM}})$

Couplings/STXS: $t\bar{t}H(H \rightarrow ZZ^{*})$ res. w/ 139 fb^{-1}

Couplings/STXS: $t\bar{t}H(H \to \tau\tau, ZZ^*)$ w/ 139 fb^{-1} EPJC 80 (2020) 957

- $t\bar{t}H$ production also explored in **resonant** leptonic Higgs decays (orthogonal to $t\bar{t}H$ multilepton)
  - ➡ very good separation from other production modes achieved with (b)-jets requirements
  - ➡ Low signal yields expected
- $t\bar{t}H(ZZ^* \to 4\ell)$ targets leptonic and fully hadronic top quarks decays
  - ➡ NN used to separate signal from $t\bar{t}V$ and ggF Higgs production in the hadronic channel
    - ❖ also used as observable in the fit
  - ➡ **Results:** $\mu_{t\bar{t}H} = 1.6^{+1.7}_{-1.1}$ (stat) $^{+0.3}_{-0.2}$ (syst)
  - ➡ Largely **statistically limited** and to date less precise than other production modes for $H \to ZZ^* \to 4\ell$ final state.

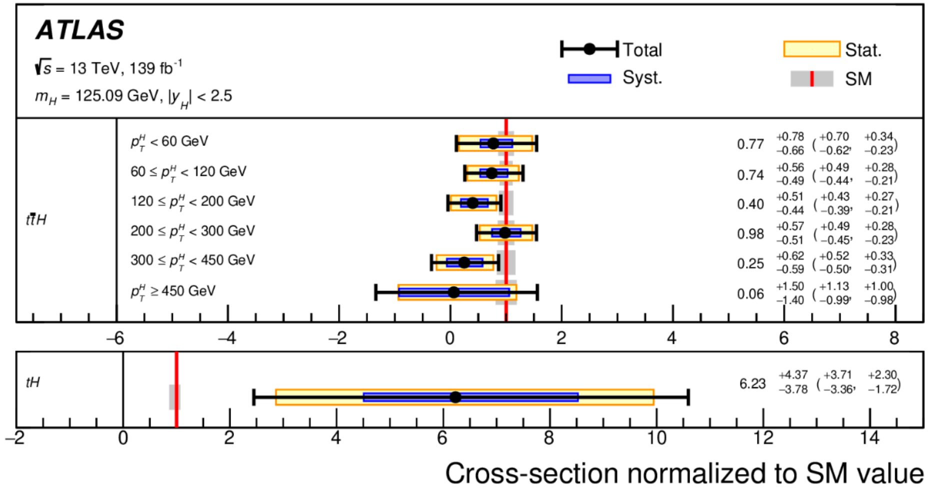


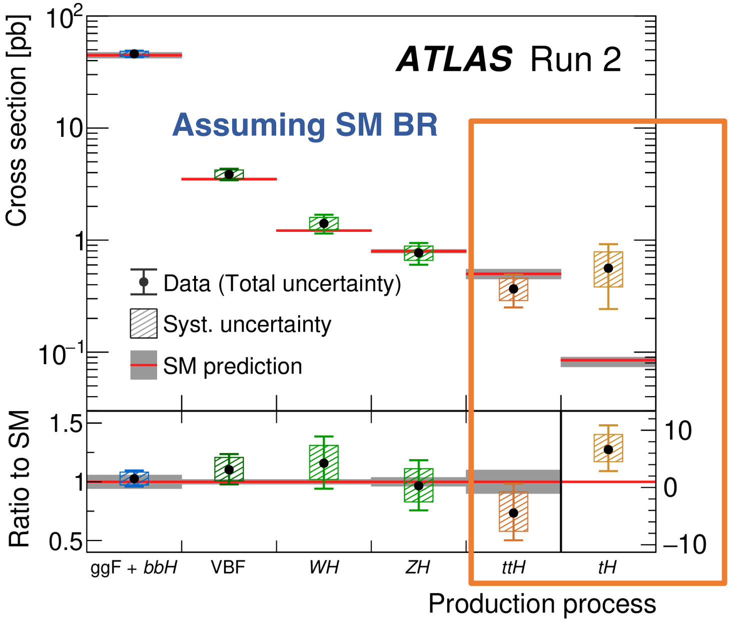
$t\bar{t}H$ combination

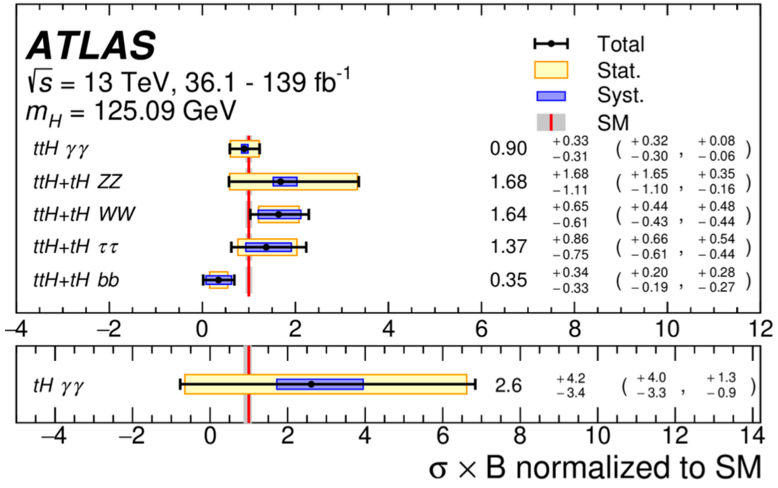
$t\bar{t}H$ combination

[Nature 607 52 (2022)]

- Detailed $t\bar{t}H/tH$ combination for the Higgs boson 10th discovery anniversary
  - ➡ Considering individual measurements targeting the various decay modes
  - ➡ Including $t\bar{t}H$ multilepton measurement from [PRD 97 (2018) 072003]
- Splitting $t\bar{t}H$ measurement for different decay channels
  - ➡ $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, $b\bar{b}$
  - ➡ free floating $\sigma_{t\bar{t}H}(\sigma_{t\bar{t}H+tH}) \times BR_i$







- Combined measurements for six Higgs boson p_T
  - ➡ Low p_T statistically limited $(H \rightarrow \gamma\gamma)$
  - ➡ Higher p_T systematically dominated

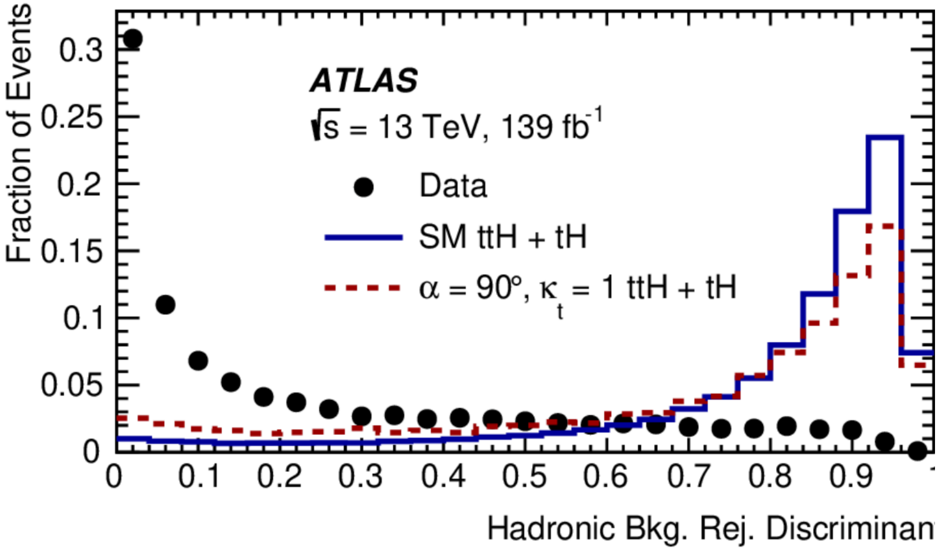
Measurements agree very well with the SM predictions

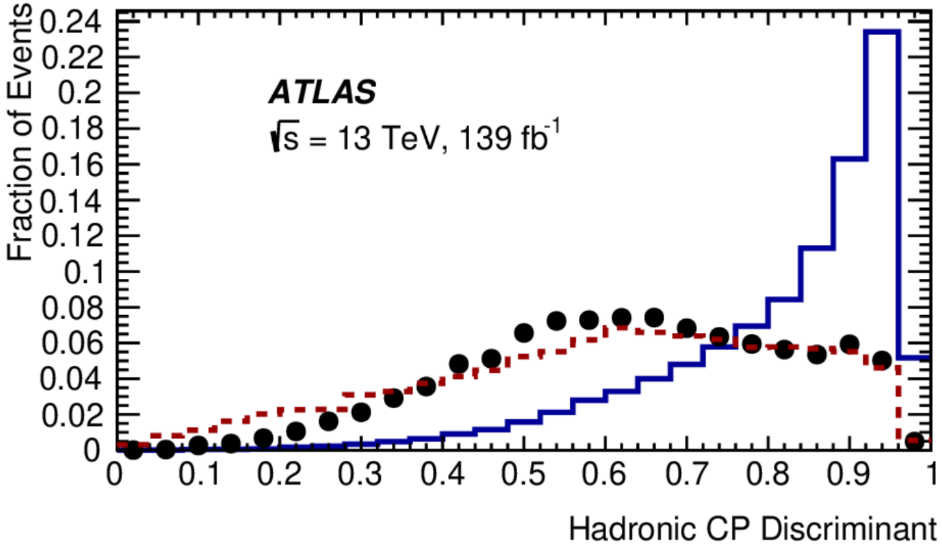
CP properties: $t\bar{t}H/tH(H \to \gamma\gamma)$ w/ 139 fb^{-1}

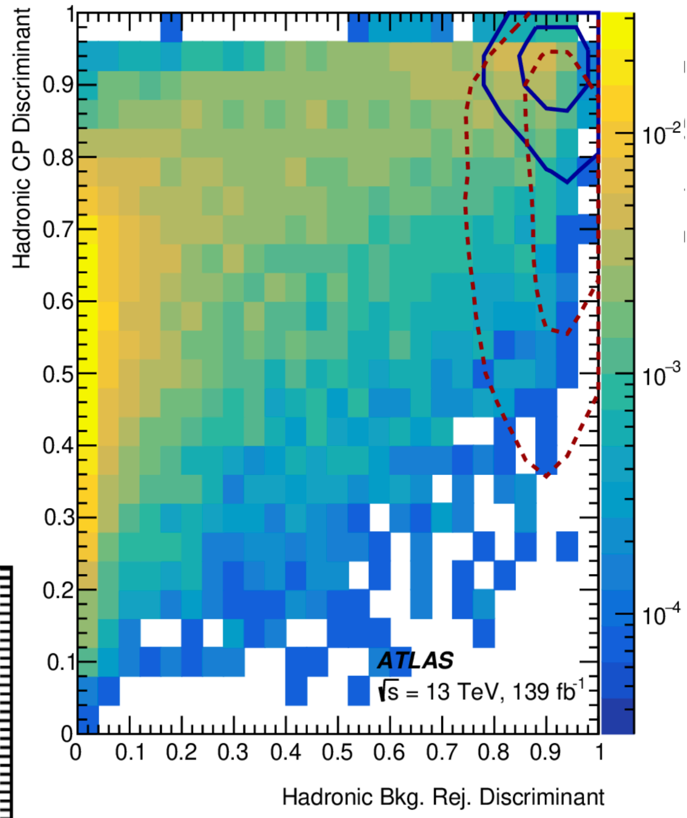
CP properties: $t\bar{t}H/tH(H \rightarrow \gamma\gamma)$ w/ 139 fb^{-1}

PRL 125 (2020) 061802

- Sharing similarities with the STXS analysis e.g signal and background modelling, discriminant variable $m_{\gamma\gamma}$
- Events split into two $t\bar{t}H$-enriched channels: **Lep** ($\geq 1\ell$: leptonic tops), **Had** (0ℓ: hadronic tops)
- Events further categorised in each channel using **2 BDTs**:
  - ➡ **Background rejection BDT**: $t\bar{t}H$ vs main backgrounds ($\gamma\gamma + \text{jets}, t\bar{t} + \gamma\gamma$)
  - ➡ **CP BDT**: separate **CP-even** and **CP-odd** in the signal
- **20 categories** defined in 2D BDT space optimising $t\bar{t}H$ significance and **CP-odd** vs **CP-even** separation
  - ➡ 12 **hadronic** and 8 **leptonic**

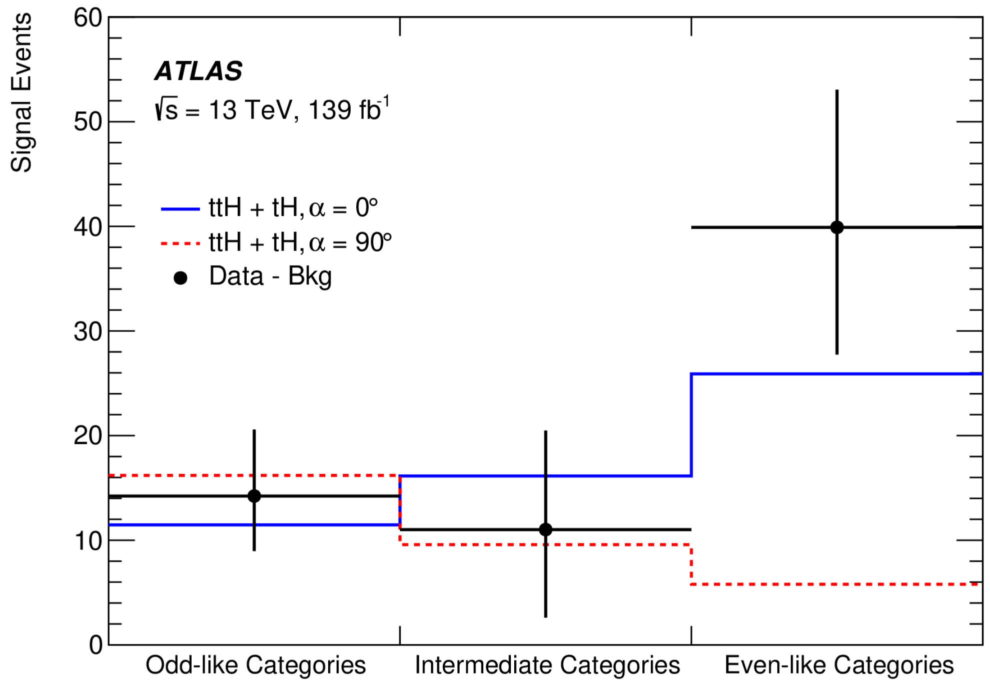


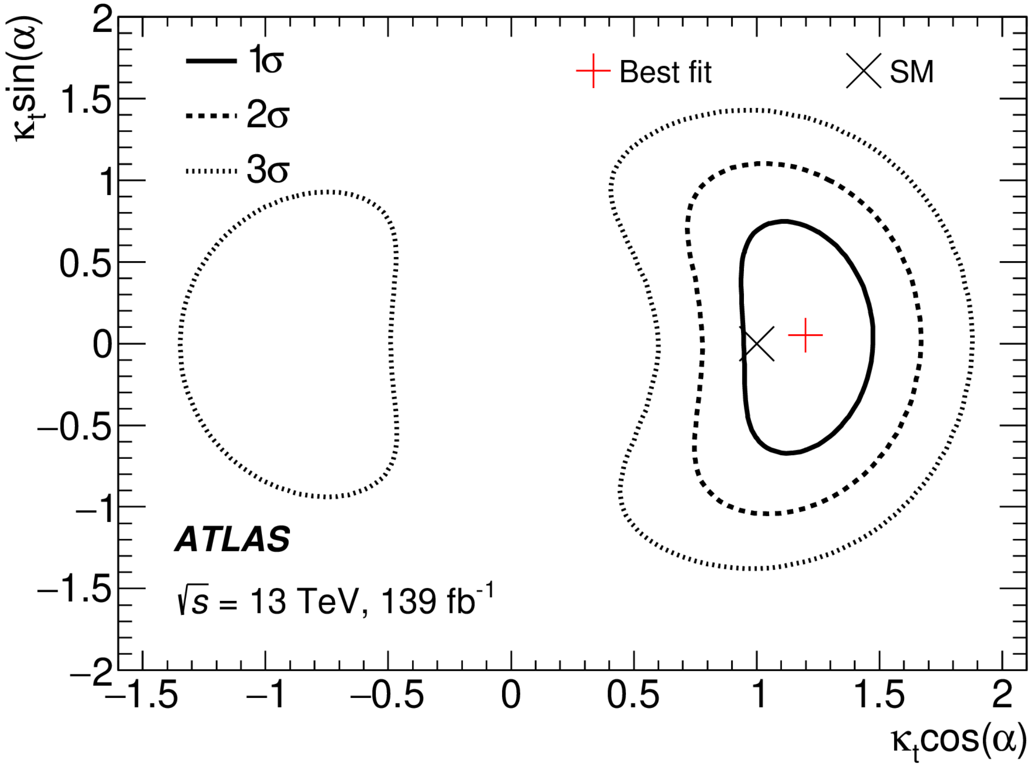




CP properties: $t\bar{t}H/tH(H \rightarrow \gamma\gamma)$ w/ 139 fb^{-1}

PRL 125 (2020) 061802





- Simultaneous maximum likelihood fit in all categories to $m_{\gamma\gamma}$
  - ➡ Higgs couplings to photons and gluons constrained by the Run 2 combination results in Phys. Rev. D 101 (2020) 012002
  - ➡ **Statistically dominated** measurement
- Data **strongly favours the CP even** hypothesis:
  - ➡ Exclusion of $|\alpha| > 43^{\circ}$ @ 95% CL
  - ➡ **Pure CP-odd coupling excluded at 3.9σ**

CP properties: $t\bar{t}H/tH(H \rightarrow bb)$ w/ 139 fb^{-1}

CP properties: $\mathrm{t\bar{t}H/tH(H \rightarrow b\bar{b})}$ w/ 139 fb^{-1}

PLB 849 (2024) 138469

- Dedicated CP sensitive observables are built relying on angular separation between reconstructed top quarks
  - ➡ b2: enhanced for narrower azimuthal separation of top quarks in CP-odd case
  - ➡ b4: enhanced for top quarks in opposite directions and closer to the beamline

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

- $\vec{p}_i$ with $i = 1,2$ correspond to the three-vectors of the two top quarks, $\hat{z}$: unit vector in the direction of the beam line, defines the z-axis.
- b2 calculation is performed in ttH rest frame to enhance discrimination

Input features for reconstruction BDTs

Single lepton

Variables
Topological information from $t\bar{t}$
Mass of top$_{\text{lep}}$
Mass of top$_{\text{had}}$
Mass of W_{had}
Mass of W_{had} and b from top$_{\text{lep}}$
Mass of W_{lep} and b from top$_{\text{had}}$
$\Delta R(W_{\text{had}}, b$ from top$_{\text{had}})$
$\Delta R(W_{\text{had}}, b$ from top$_{\text{lep}})$
$\Delta R(\ell, b$ from top$_{\text{lep}})$
$\Delta R(\ell, b$ from top$_{\text{had}})$
$\Delta R(b$ from top$_{\text{lep}}, b$ from top$_{\text{had}})$
$\Delta R(q_1$ from W_{had}, q_2 from $W_{\text{had}})$
$\Delta R(b$ from t_{had}, q_1 from $W_{\text{had}})$
$\Delta R(b$ from t_{had}, q_2 from $W_{\text{had}})$
Min. $\Delta R(b$ from top$_{\text{had}}, q_i$ from $W_{\text{had}})$
$\Delta R($lep, b from top$_{\text{lep}})$ − min. $\Delta R(b$ from top$_{\text{had}}, q_i$ from $W_{\text{had}})$
Topological information from the Higgs boson candidate
Mass of Higgs
Mass of Higgs and q_1 from W_{had}
$\Delta R(b_1$ from Higgs, b_2 from Higgs$)$
$\Delta R(b_1$ from Higgs, lepton$)$

Dilepton lepton

Variables	BDT w/ Higgs	BDT w/o Higgs
Topological information from $t\bar{t}$		
Mass of top	✓	✓
Mass of anti-top	✓	✓
Mass difference between top and anti-top	✓	✓
$\Delta R(\ell, b)$ from top	✓	✓
$\Delta R(\ell, b)$ from anti-top	✓	✓
—$\Delta R(\ell, b)$ from top − $\Delta R(\ell, b)$ from anti-top—	–	✓
$\Delta R(b$ from top, b from anti-top$)$	✓	–
$\Delta\phi(b$ from top, b from anti-top$)$	–	✓
p_{T} b from top	–	✓
p_{T} b from anti-top	–	✓
Min. $\Delta\eta(\ell, b$ from top or anti-top$)$	–	✓
Topological information from the Higgs boson candidate		
Max. $\Delta R($Higgs, b from top or anti-top$)$	✓	–
Mass of Higgs	✓	–
$\Delta R($Higgs, $t\bar{t})$	✓	–
$\Delta R(b_1$ from Higgs, b_2 from Higgs$)$	✓	–

Input features for classification BDTs

Single lepton

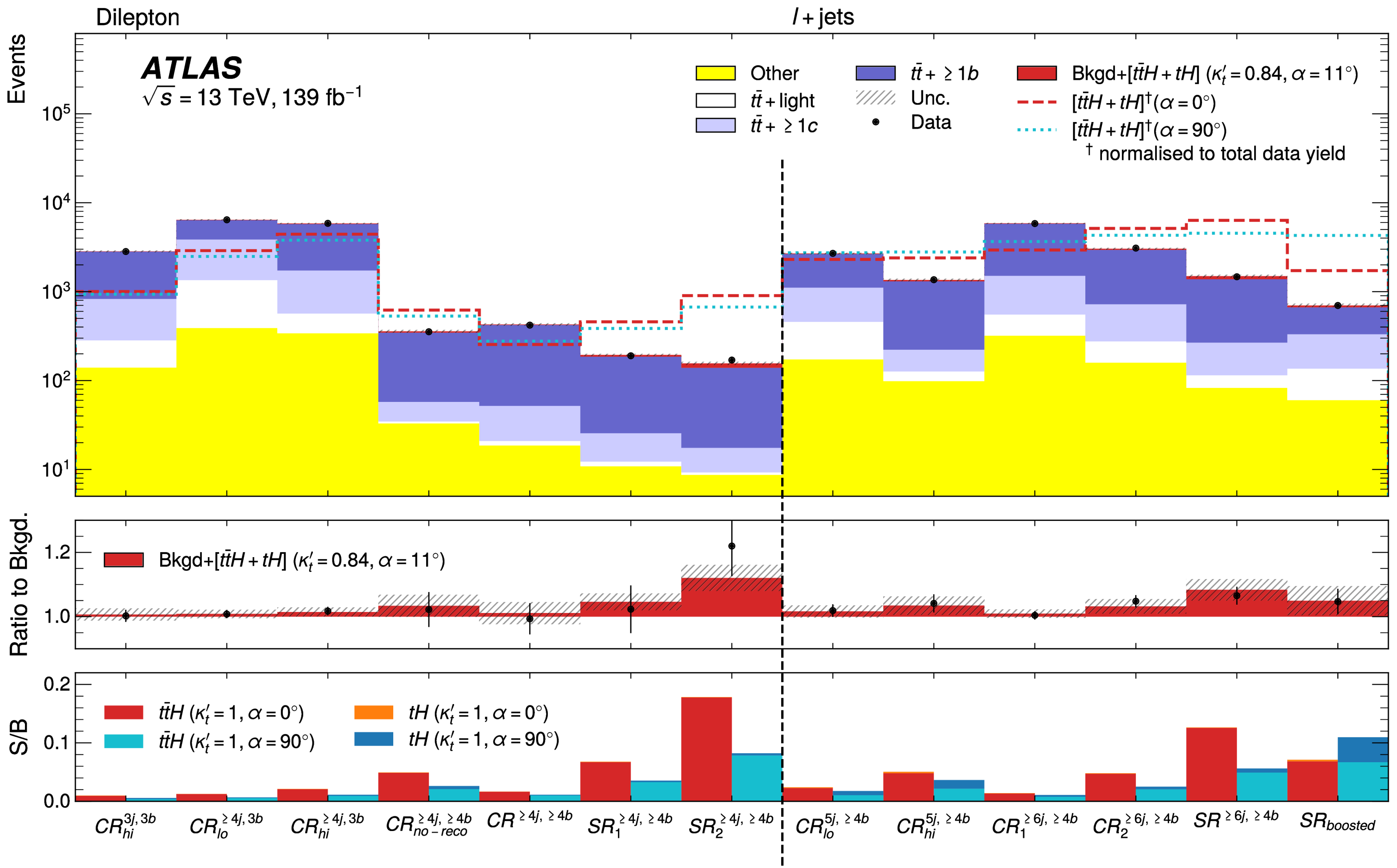
Variable	Definition	
General kinematic variables		
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b-tagged jet pairs	
$\Delta R_{bb}^{\text{max } p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	
$\Delta \eta_{jj}^{\text{max}}$	Maximum $\Delta\eta$ between any two jets	
$m_{bb}^{\text{min } \Delta R}$	Mass of the combination of two b-tagged jets with the smallest ΔR	
$N_{bb}^{\text{Higgs } 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs boson mass	
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [Phys. Rev. D **48** (1993) R3953] built with all jets	
H_1	Second Fox–Wolfram moment computed using all jets and the lepton	
Variables from reconstruction BDT		
BDT output	Output of the reconstruction BDT	†
m_{bb}^{Higgs}	Higgs candidate mass	
$m_{H,b_{\text{lep top}}}$	Mass of Higgs candidate and b-jet from leptonic top candidate	
$\Delta R_{bb}^{\text{Higgs}}$	ΔR between b-jets from the Higgs candidate	
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	†
$\Delta R_{H,\text{lep top}}$	ΔR between Higgs candidate and leptonic top candidate	
Variables from likelihood calculations		
LHD	Likelihood discriminant	
Variables from b-tagging		
$w_{b\text{-tag}}^{\text{Higgs}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	
B_{jet}^{3}	3^{rd} largest jet b-tagging discriminant	
B_{jet}^{4}	4^{th} largest jet b-tagging discriminant	
B_{jet}^{5}	5^{th} largest jet b-tagging discriminant	

Dilepton lepton

Variable	Definition	
General kinematic variables		
m_{bb}^{min}	Minimum invariant mass of a b-tagged jet pair	
$m_{bb}^{\text{min } \Delta R}$	Invariant mass of the b-tagged jet pair with minimum ΔR	
$m_{jj}^{\text{max } p_T}$	Invariant mass of the jet pair with maximum p_T	
$m_{bb}^{\text{max } p_T}$	Invariant mass of the b-tagged jet pair with maximum p_T	
$\Delta \eta_{bb}^{\text{avg}}$	Average $\Delta\eta$ for all b-tagged jet pairs	
$N_{bb}^{\text{Higgs } 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs boson mass	
Variables from reconstruction BDT		
BDT outputs	Output of the reco. BDT w/ Higgs info. for the combination selected by the reco. BDTs w/ or w/o Higgs info.	‡
m_{bb}^{Higgs}	Higgs candidate mass	
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	†
$\Delta R_{H,\ell}^{\text{min}}$	Minimum ΔR between Higgs candidate and lepton	
$\Delta R_{H,b}^{\text{min}}$	Minimum ΔR between Higgs candidate and b-jet from top	

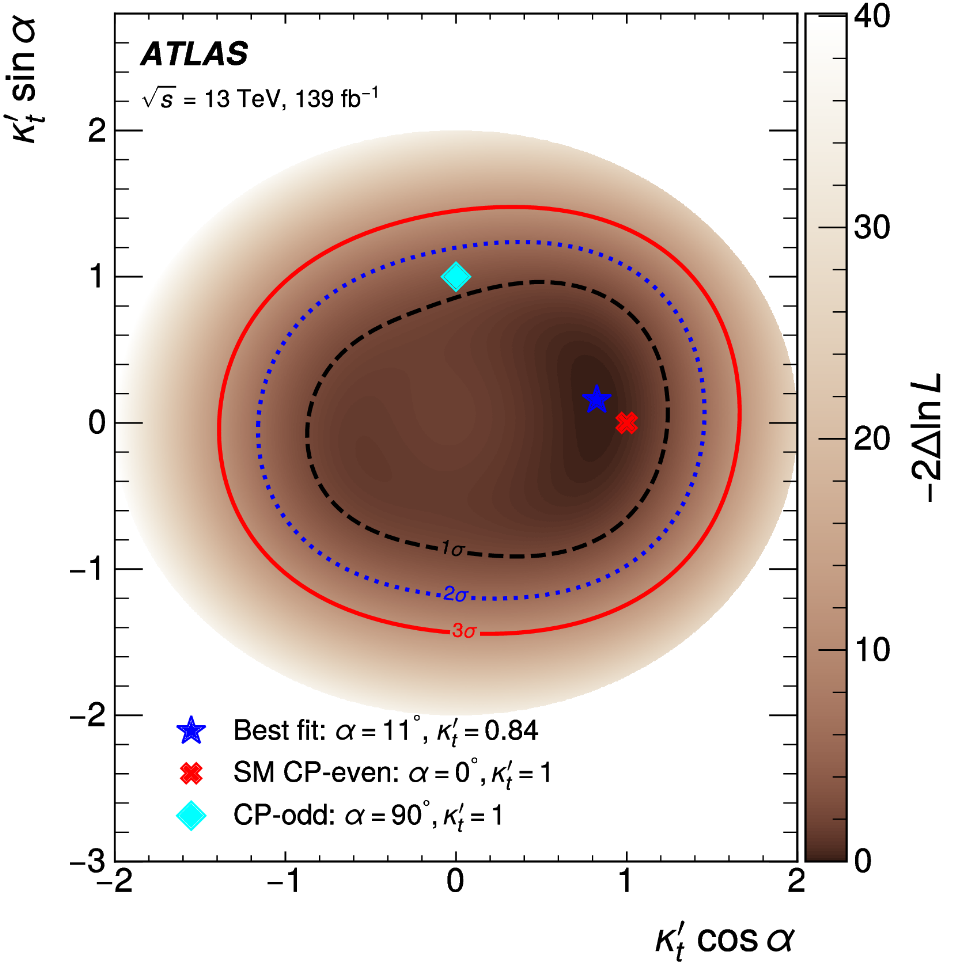
CP properties: $t\bar{t}H/tH(H \to b\bar{b})$ w/ 139 fb^{-1}

PLB 849 (2024) 138469



CP properties: $t\bar{t}H/tH(H \to b\bar{b})$ w/ 139 fb^{-1}

PLB 849 (2024) 138469



- Best fit values:
  - ➡ CP-mixing angle $\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$
  - ➡ coupling strength $k_t^{\prime} = 0.84^{+0.30}_{-0.46}$
  - ★ Compatible with both $\alpha = 0^{\circ}$ and $\alpha = 90^{\circ}$
  - ★Data prefers SM and disfavours CP-odd hypothesis at **1.2 σ significance**.

- Sensitivity driven by the $t\bar{t} + \geq 1b$ modelling uncertainties:
  - ➡ Same as in previous round of $t\bar{t}H(H \to b\bar{b})$ analysis
  - ➡ NLO matching (PowhegBox vs. MadGraph5_aMC@NLO)
  - ➡ Choice of 4 flavour scheme (with massive b-quarks from ME) vs 5FS with massless b-quarks in the PDF)
  - ➡ Parton Shower and Hadronisation (Pythia 8 vs Herwig7)