$t\bar{t}H$+tH Production in ATLAS

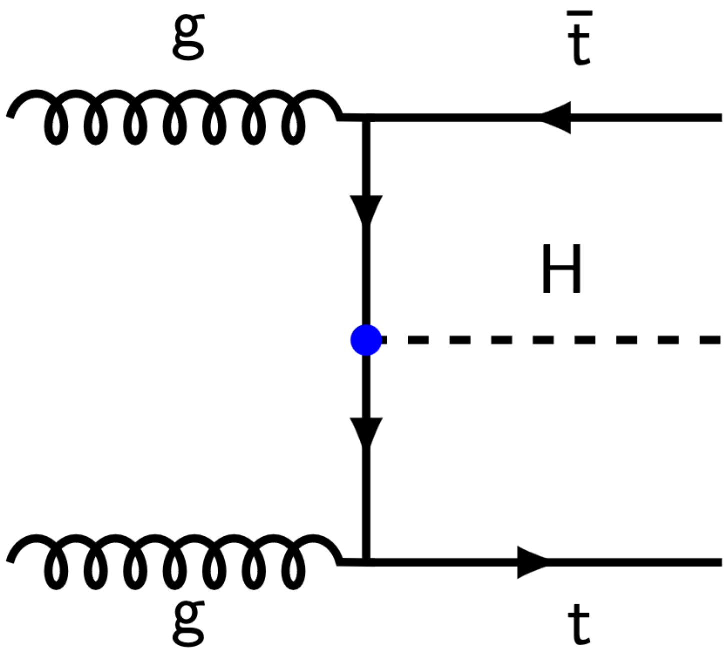
Anastasia Kotsokechagia (CERN)

on behalf of the ATLAS collaboration

LHCP, Boston

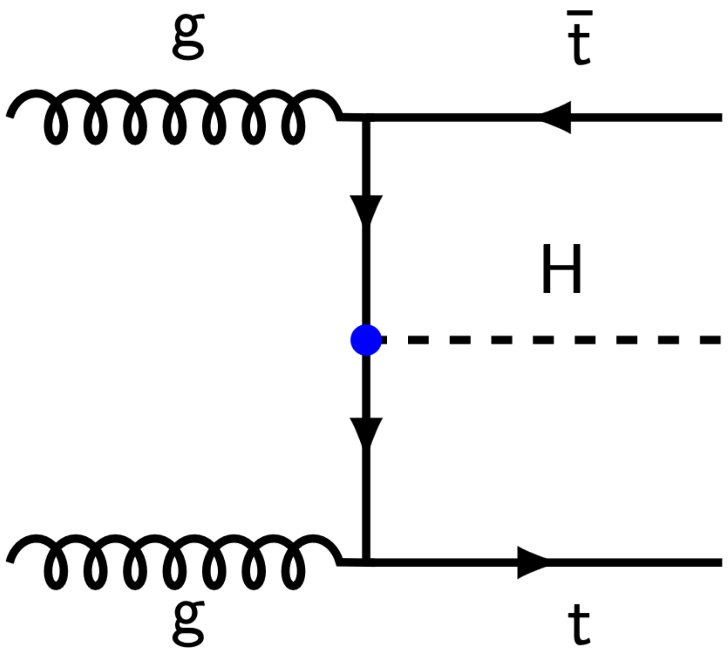
3-7 June 2024

Why $t\bar{t}H/tH$?



- Direct measurement of Higgs-top Yukawa coupling
- Coupling proportional to mass
  - ➡ Of the order of unity for top quark
  - ➡ Particularly sensitive to effects beyond the SM *i.e* *CP violation*

Why $t\bar{t}H$/tH?



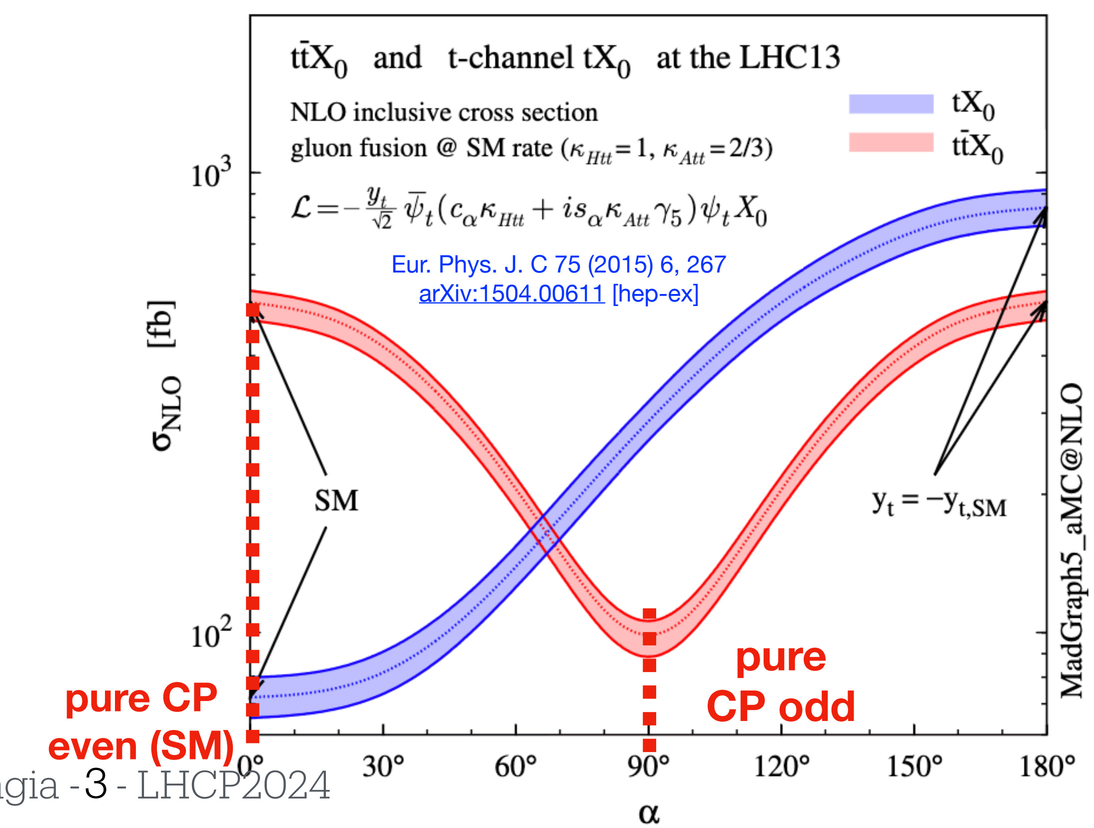
- Direct measurement of Higgs-top Yukawa coupling
- Coupling proportional to mass
  - ➡ Of the order of unity for top quark
  - ➡ Particularly sensitive to effects beyond the SM *i.e* *CP violation*

$$\mathcal{L} = -\kappa_t \bar{\psi} e^{i\alpha\gamma^5} \psi h$$
$$= -\kappa_t \bar{\psi}(\cos\alpha + i\gamma^5 \sin\alpha)\psi h$$
$$= \underbrace{-\kappa_t \cos\alpha \bar{\psi}\psi h}_{\text{CP-even part}} - \underbrace{i\kappa_t \sin\alpha \bar{\psi}\gamma^5\psi h}_{\text{CP-odd part}}$$

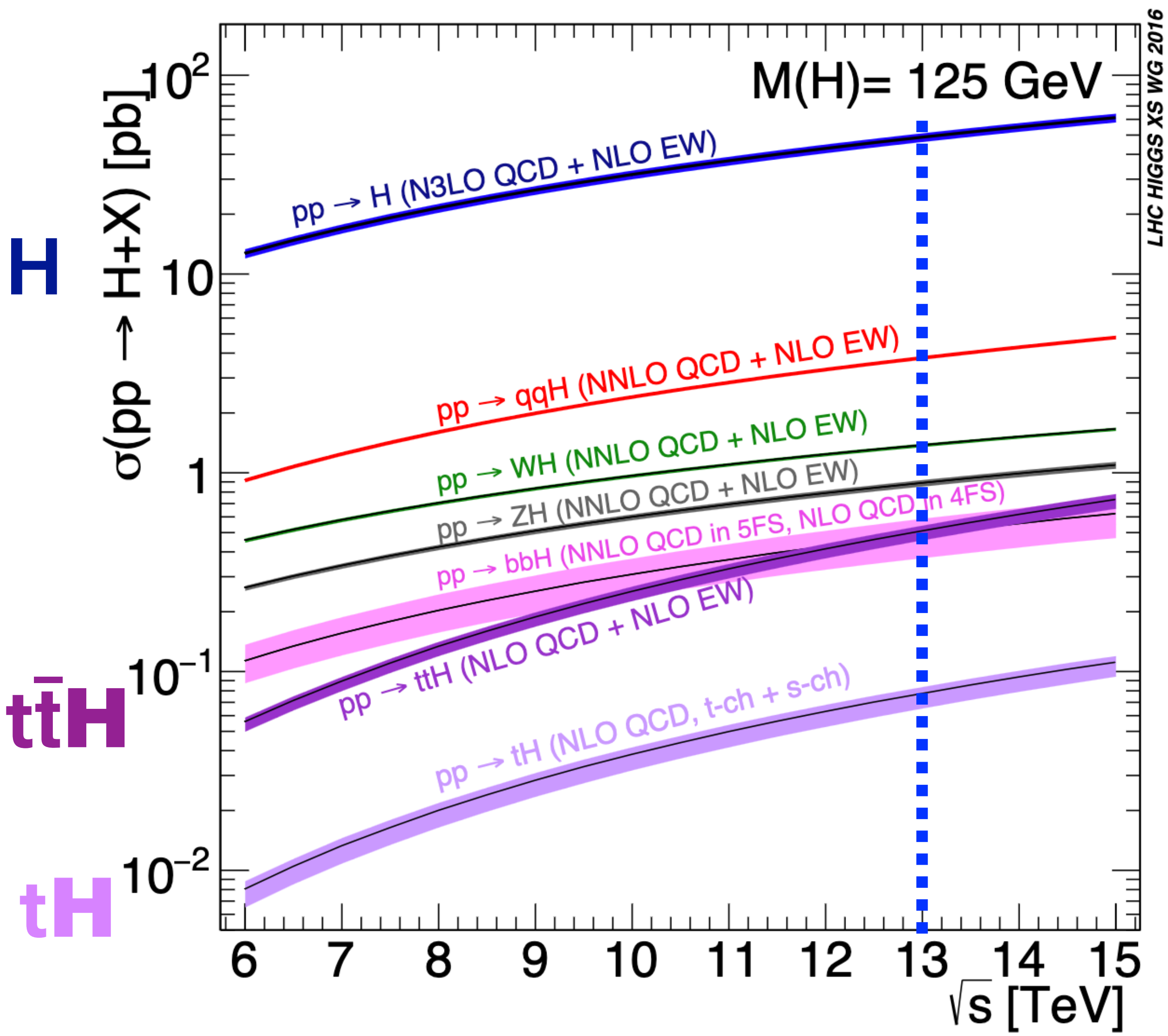
- Choice of α, κ_t → affects the cross section (XS) and kinematical properties of ttH/tH processes

CP Violation in the Higgs sector

- As an extra source to explain baryon asymmetry in the universe
- Added as a complex phase in the SM Lagrangian



Measuring tt̄H/tH



Not so easy…

- ttH cross-section: 0.5 pb at 13 TeV
- tH ~ an order of magnitude lower than ttH

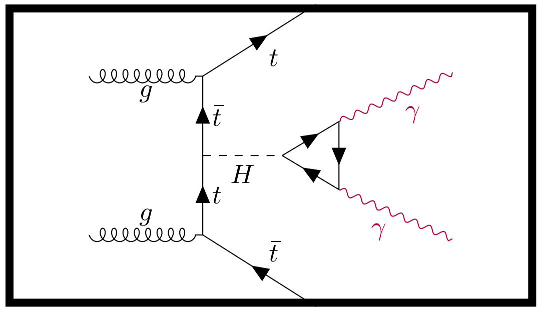
First observation by ATLAS and CMS of Higgs+top associated production in **2018** with partial Run 2 data

ATLAS: 6.3σ (5.1σ exp.)
(36.1 - 79.8 fb^{-1})

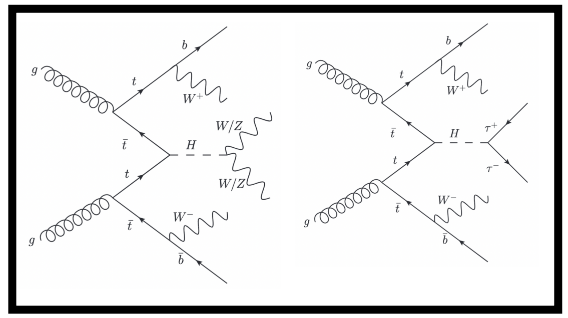
Phys.Lett.B784(2018)173

Since then..

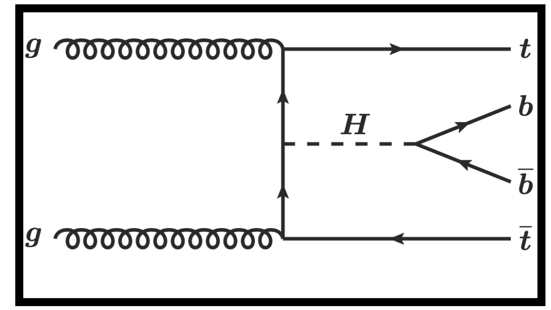
tt̄H (H→γγ)



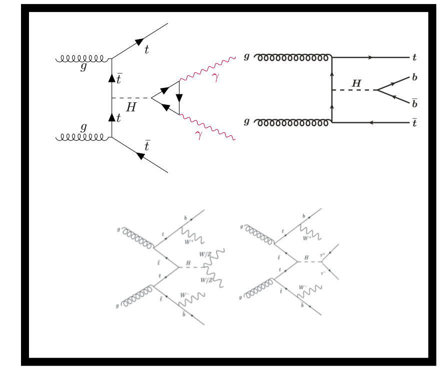
tt̄H (H→WW,ττ,ZZ)



tt̄H (H→bb)



Combination



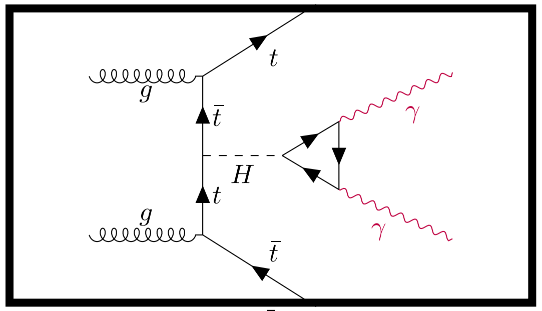
139 /fb
tH included

80 /fb

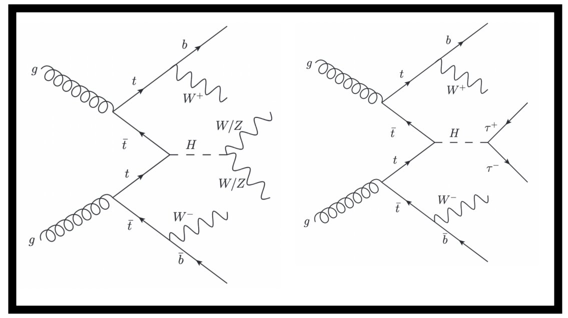
139 /fb
tH included

36 -139 /fb

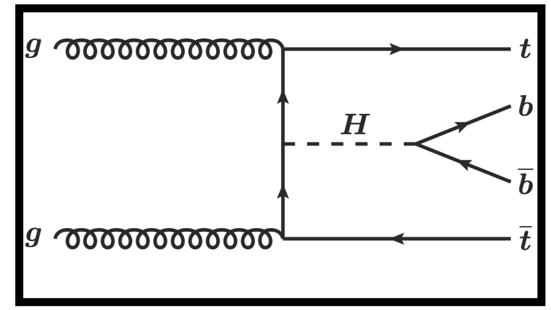
$t\bar{t}H$ ($H\to\gamma\gamma$)



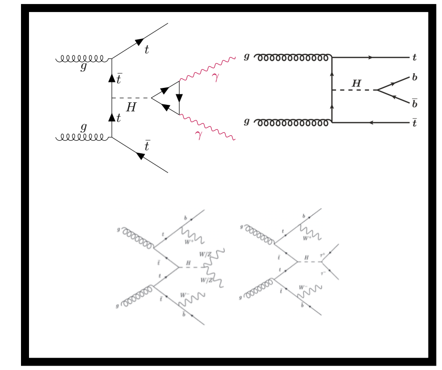
$t\bar{t}H$ ($H\to WW,\tau\tau,ZZ$)



$t\bar{t}H$ ($H\to bb$)



Combination



139 /fb
tH included

80 /fb

139 /fb
tH included

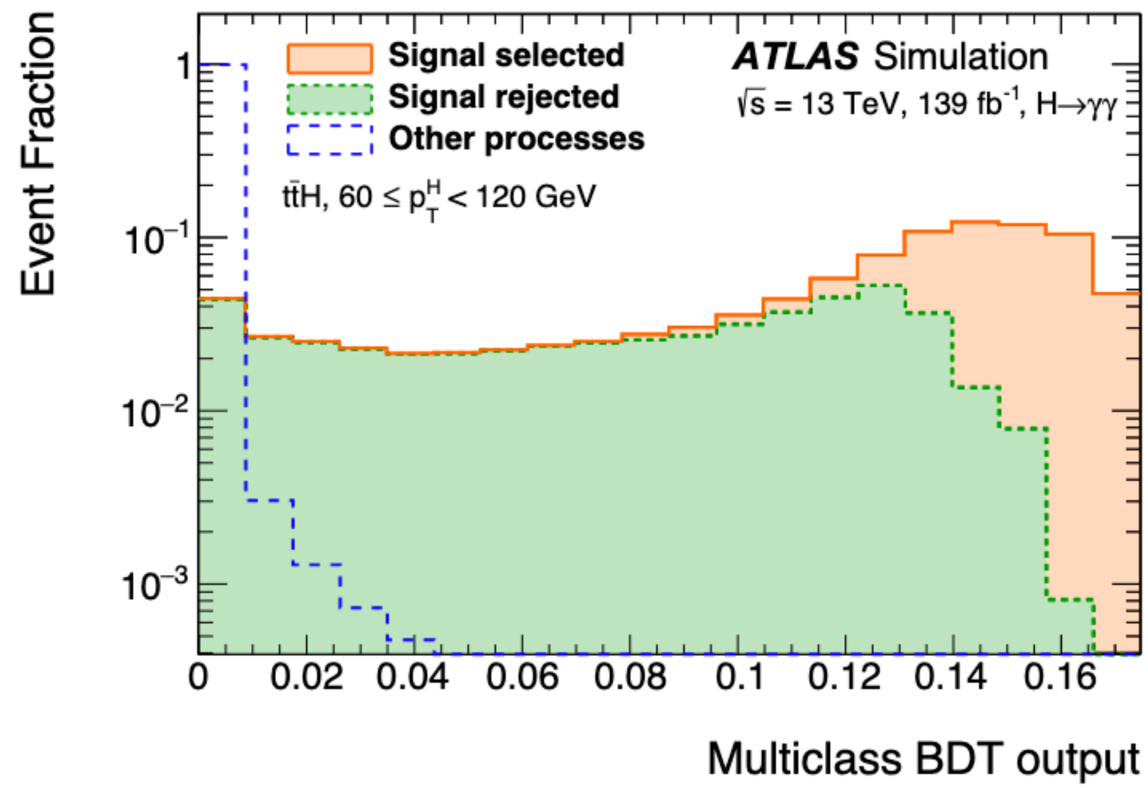
36 -139 /fb

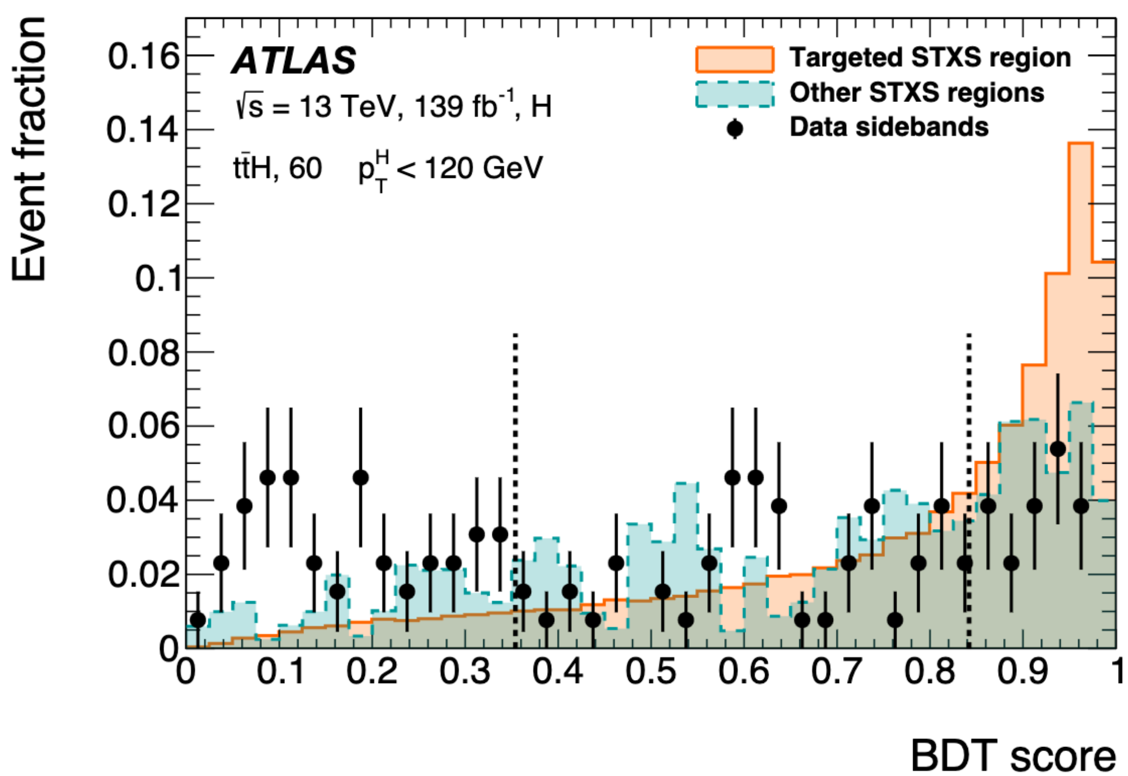
- Very clean signature, Good S/B :)
- Low branching ratio :(

$t\bar{t}H/tH$ ($H\rightarrow\gamma\gamma$)

Analysis Strategy (at 139 fb-1)

- targets $t\bar{t}H/tH$ production along w/other Higgs productions through **Simplified Template Cross Sections (STXS)** formalism where cross-section is measured as a function of truth p_{TH}
- In total 45 STXS regions defined
  - based on targeted production, Higgs p_T and number of jets





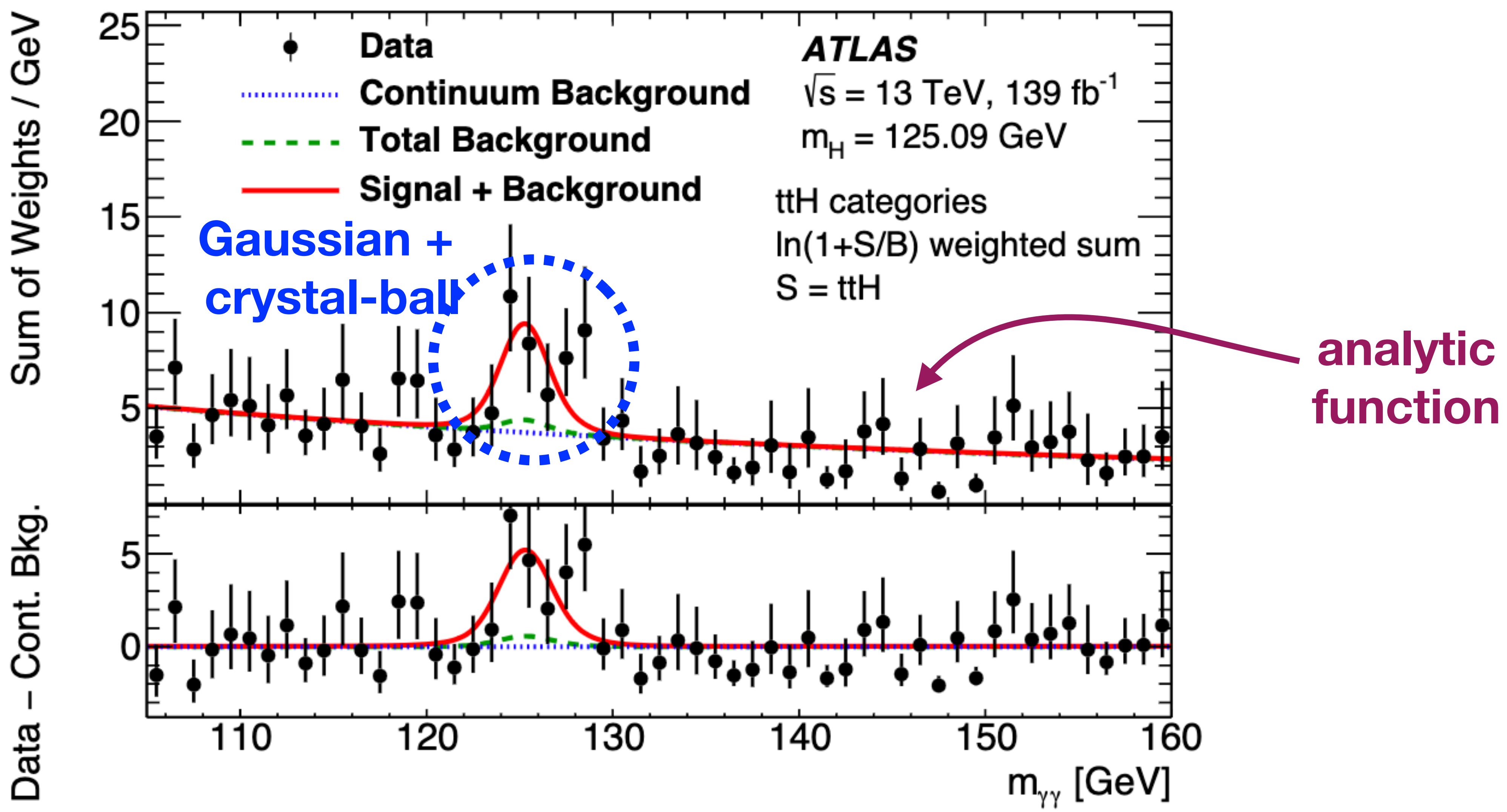
STXS category assignment:

- Multi-classifier BDT sensitive to particular STXS regions + additional binary BDT trained to distinguish signal from background
- $tHqb$ class divided into two sub-classes using a neural network to distinguish between κ_t = 1 and κ_t = -1, and further categorization done to separate signal from background events

JHEP 07 (2023) 088

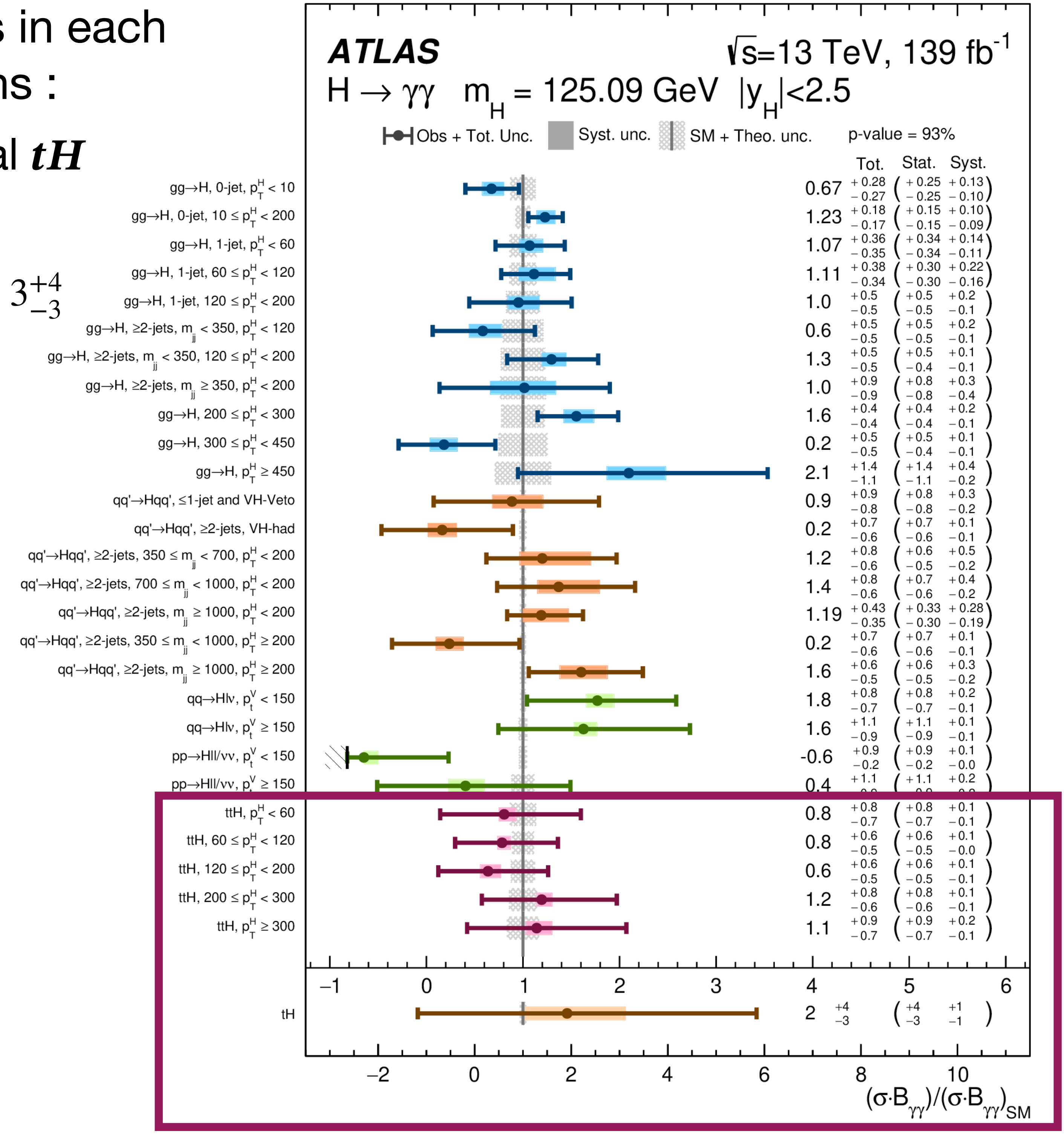
$t\bar{t}H/tH$ ($H\rightarrow\gamma\gamma$)

- Signal extraction by a simultaneous fit to mass of the two photons m(γγ)

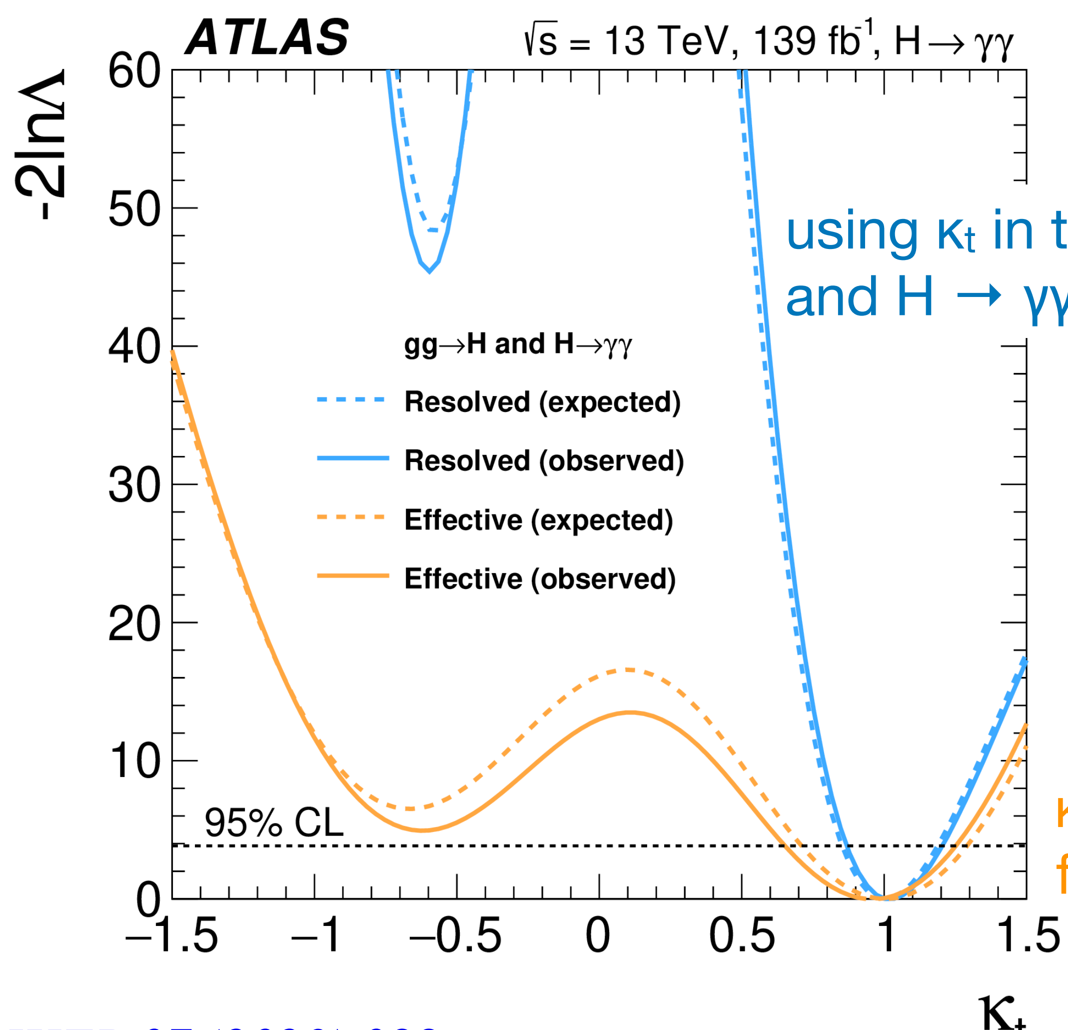


$t\bar{t}H/tH$ ($H \to \gamma\gamma$)

- Results for **STXS** parameters in each of the 28 phase-space regions :
  - 5 **$t\bar{t}H$** p_T bins and additional ***tH*** category (p_T inclusive)
- **Inclusive:** $\mu_{t\bar{t}H} = 0.89^{+0.32}_{-0.30}, \quad \mu_{tH} = 3^{+4}_{-3}$



- Interpretation of the results in **κ-framework**; sensitivity to sign of κ_t thanks to tH categories → **$\kappa_t < 0$** excluded at **2.2σ**

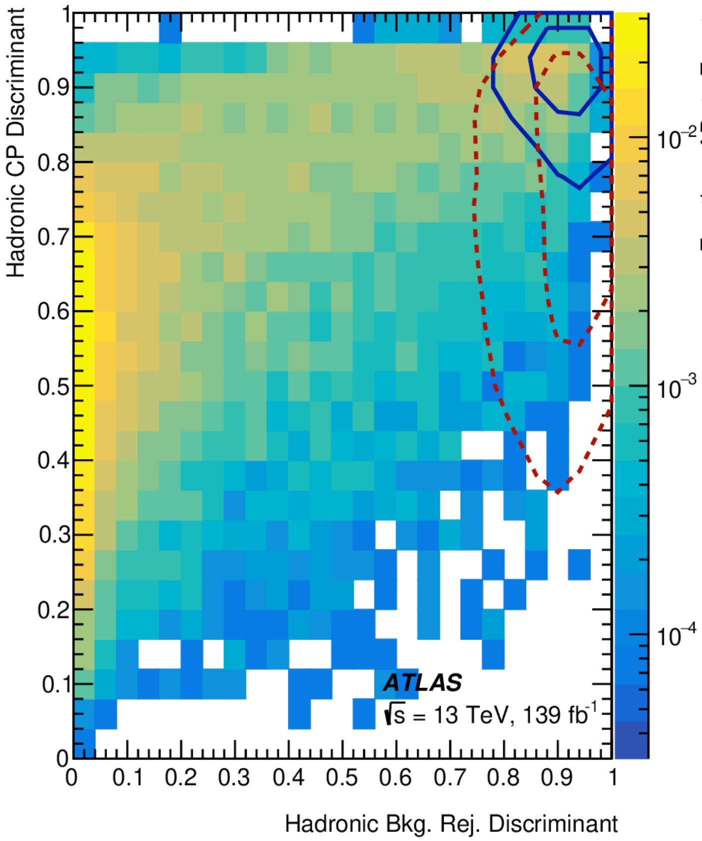


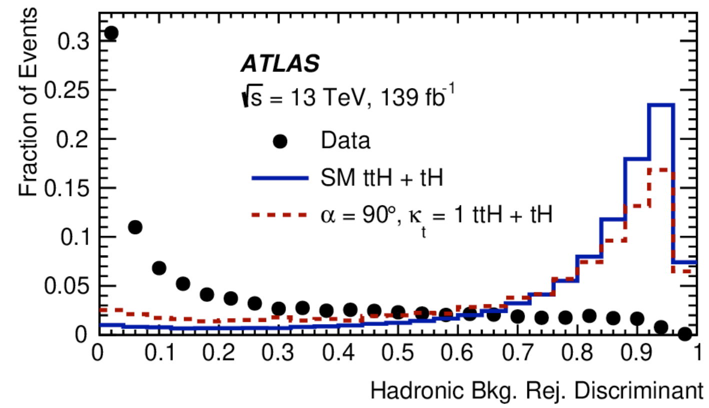
using κ_t in the ggF and H → γγ loops

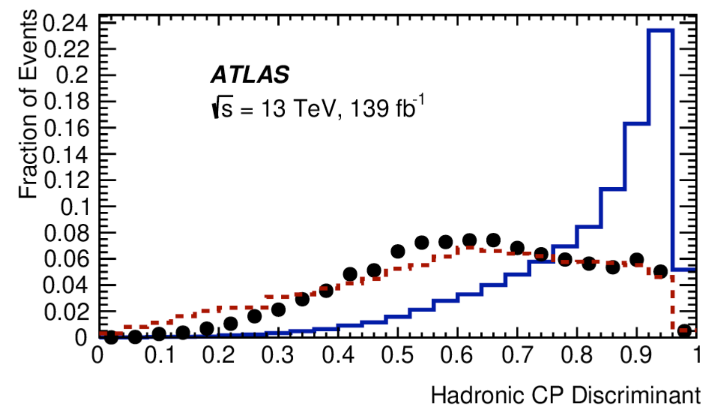
κ_g and κ_γ fixed to the SM prediction

[JHEP 07 (2023) 088]

$t\bar{t}H/tH$ ($H\rightarrow\gamma\gamma$) CP Analysis



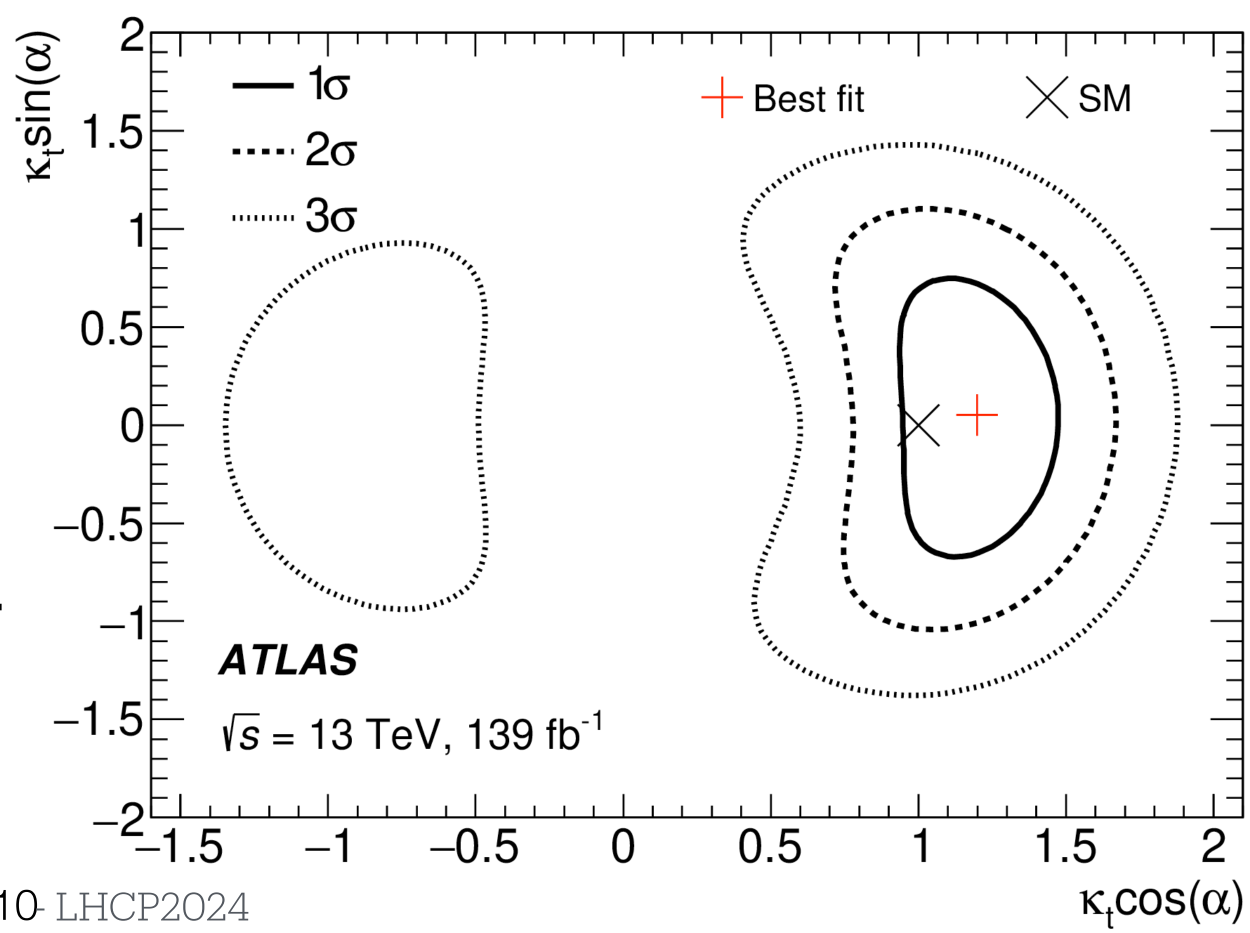




- **Two channels:** Leptonic or Hadronic based on type of top decay
- Event categorization in two steps:
  - First train BDT to separate $t\bar{t}H$ from non resonant background (***Bkg. Rej. Discriminant***)
  - Second BDT trained to separate CP-even from CP-odd couplings (***CP Discriminant***)
  - Events are categorized using partitions of two-dimensional BDT space

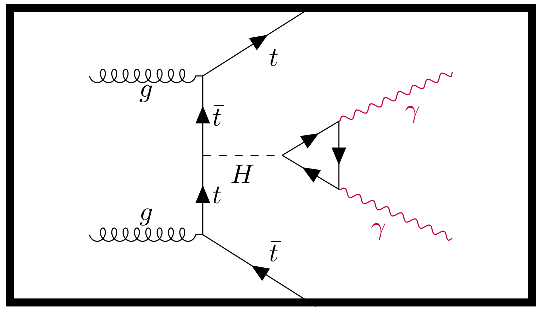
In total **12** Hadronic categories and **8** Leptonic

- Results from a simultaneous fit to m(γγ) across all categories
  - Higgs couplings to photons and gluons constrained by the Run 2 combination results [Phys. Rev. D 101 (2020) 012002]
- Results strongly support CP even hypothesis
  - Pure CP-odd (α=90) excluded with **3.9σ**
  - **|α|>43** excluded at 95% CL

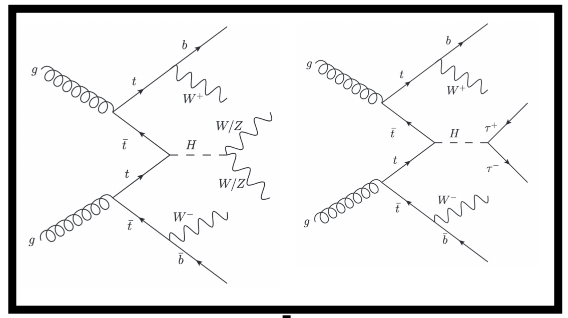


Phys. Rev. Lett. 125 (2020) 061802

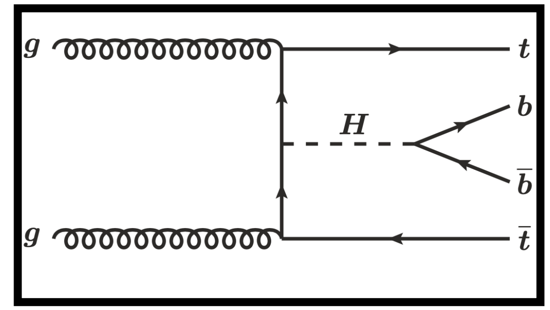
$t\bar{t}H$ ($H \to \gamma\gamma$)



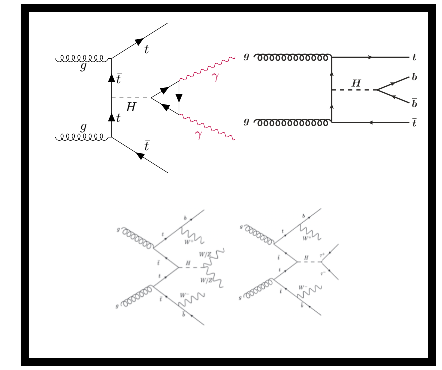
$t\bar{t}H$ ($H \to WW,\tau\tau,ZZ$)



$t\bar{t}H$ ($H \to bb$)



Combination



$t\bar{t}H$ ($H \to \gamma\gamma$)	$t\bar{t}H$ ($H \to WW,\tau\tau,ZZ$)	$t\bar{t}H$ ($H \to bb$)	Combination
139 /fb tH included	80 /fb	139 /fb tH included	36 -139 /fb

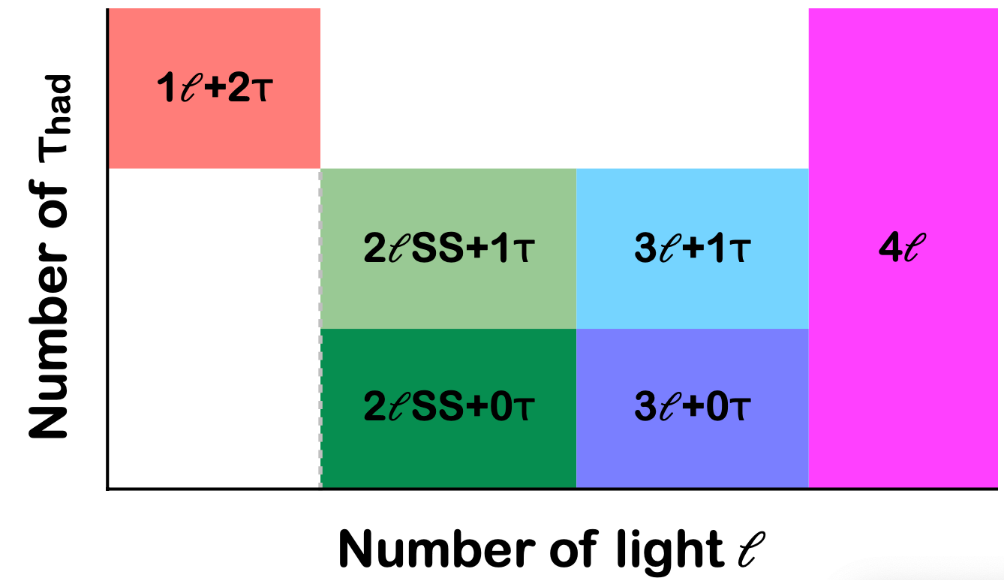
- Clean final state with leptons, low irreducible backgrounds (S/B~1) :)
- Challenging reducible backgrounds w/ non-prompt leptons + jets faking τ_{had} :(
- Higgs reconstruction also challenging (several decay modes in final state, MET…)

$t\bar{t}H$ Multi-Lepton

ATLAS-CONF-2019-045

Analysis Strategy (at 80 fb-1)

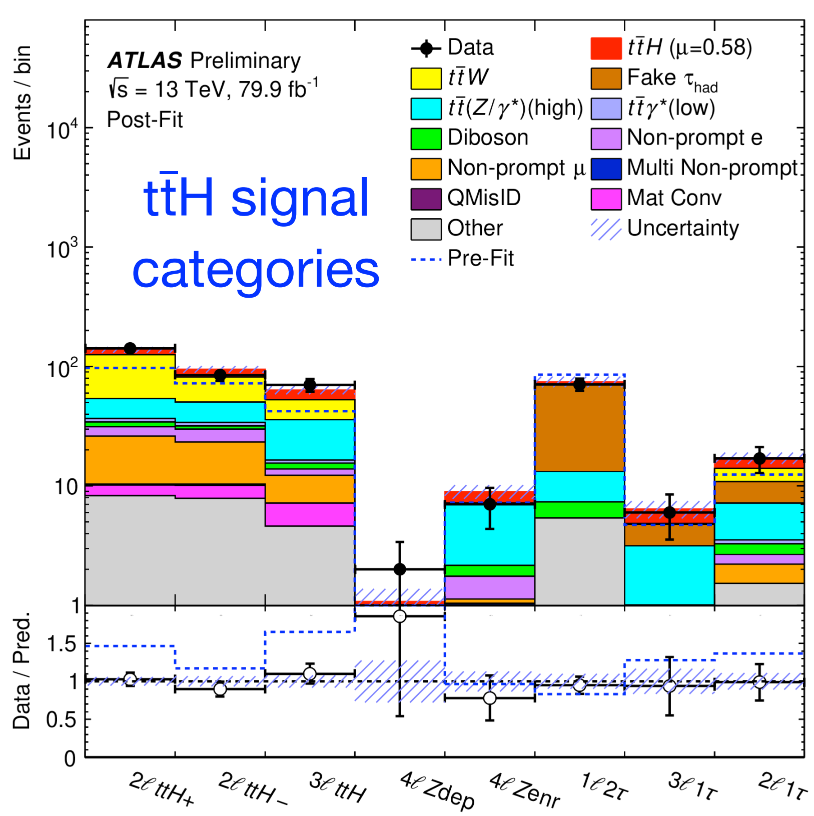
- Targets several Higgs decay modes (H→WW*/ZZ* and H →ττ)
- In total **6 orthogonal channels** distinguished by number of light leptons and hadronic taus

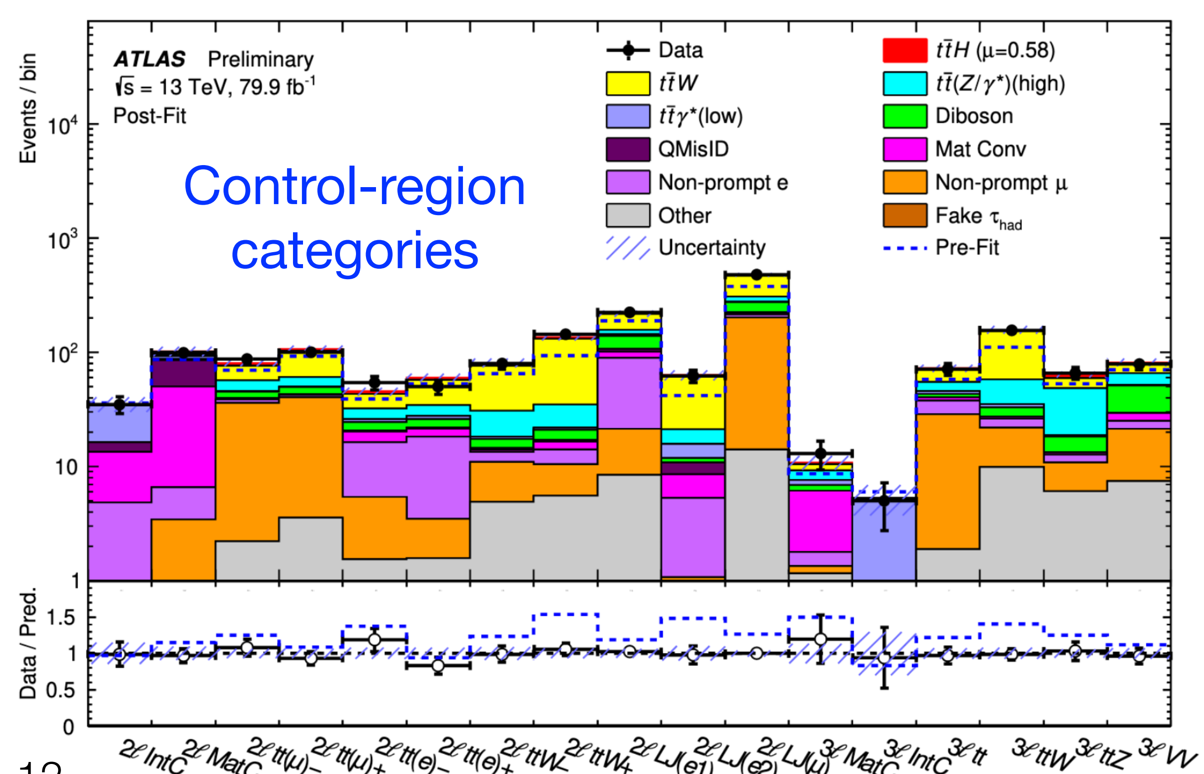


Two main sources of background:

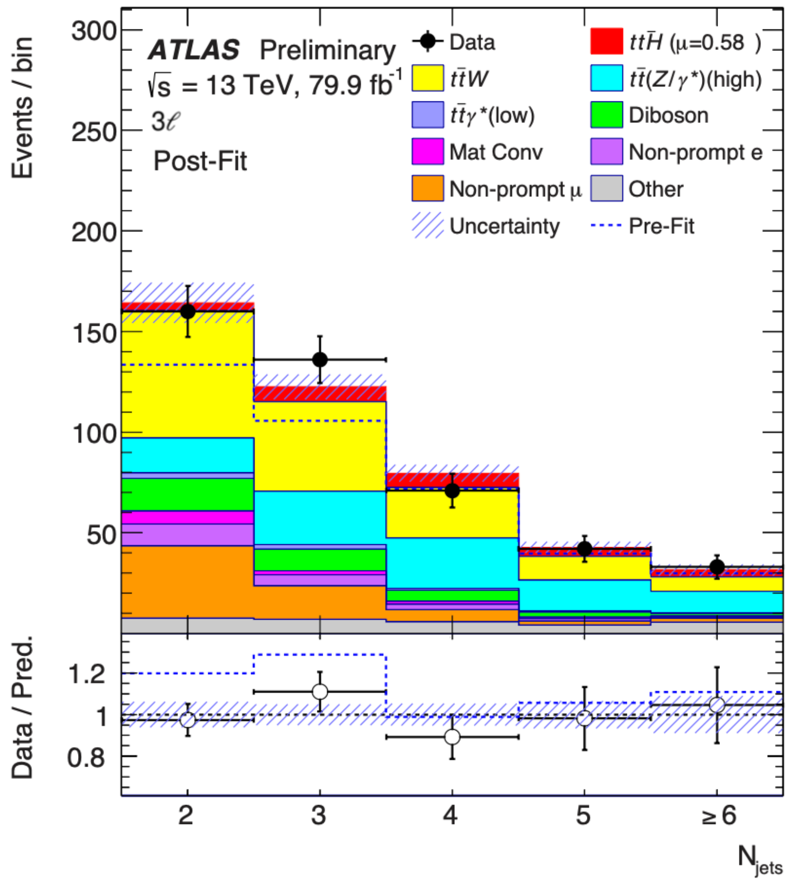
- **Reducible:** from non-prompt/fake light leptons, charge mis-ID, fake τ_{had}
- **Irreducible:** $t\bar{t}W$, $t\bar{t}Z$ and Diboson processes

- In total 25 event categories defined!
  - 8 $t\bar{t}H$ categories
  - 17 control-regions





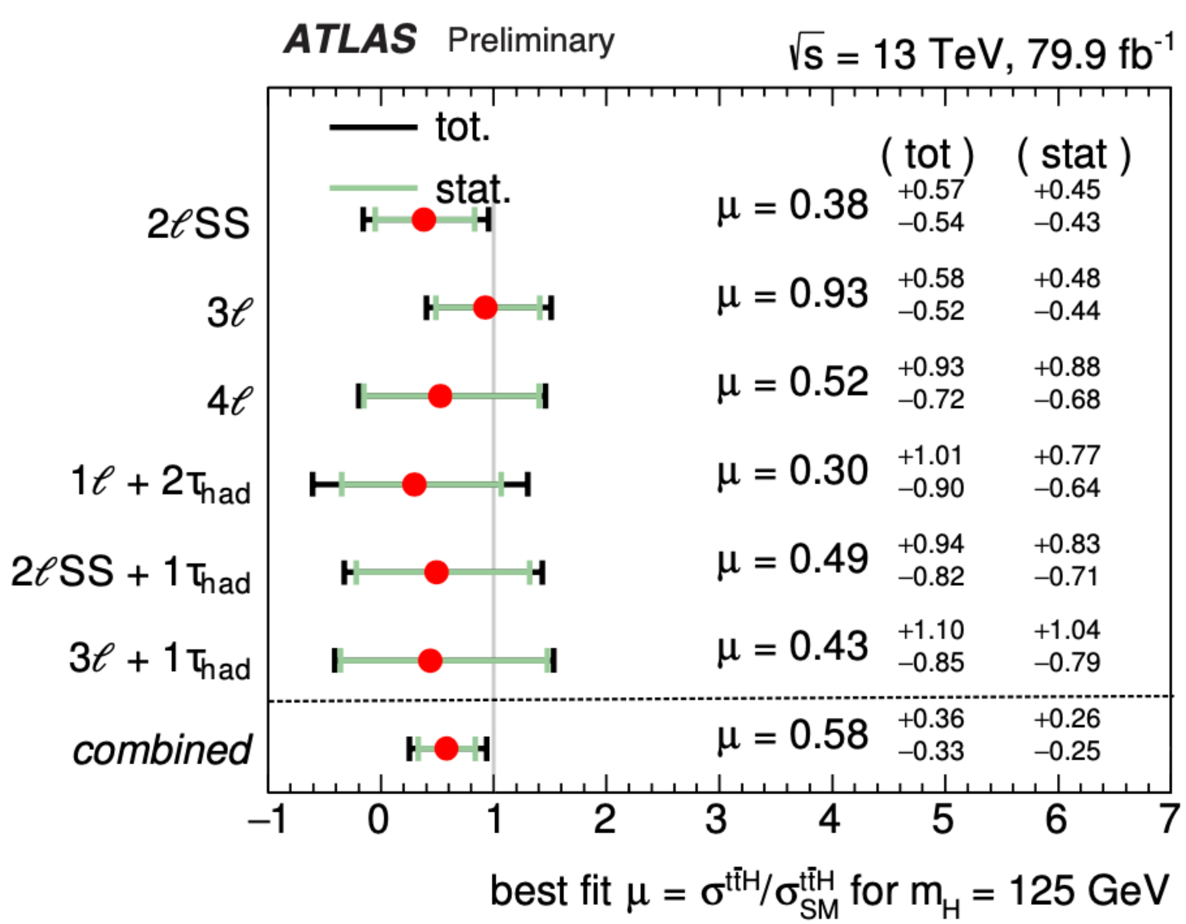
$t\bar{t}H$ Multi-Lepton



$t\bar{t}W$ within $t\bar{t}H$ analysis

- Constrained by 3 dedicated norm factors
- Found to be largely under-estimated in MC
- Significant mis-modelling of $t\bar{t}W$ background vs. N_{jets}, N_{bjets} and total (lepton) charge

Recent **$t\bar{t}W$ cross-section measurement**; show discrepancies even when compared to latest theoretical predictions, w/ higher-order QCD and electroweak (EWK) corrections included JHEP 05 (2024) 131



Results (at 80 fb^{-1})

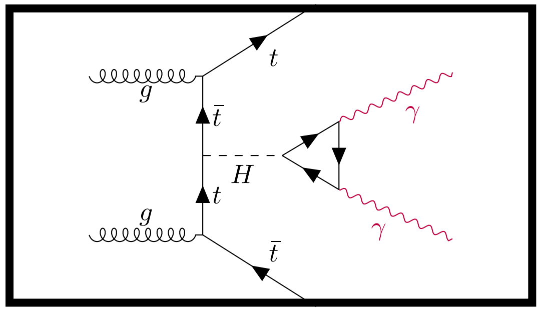
- Simultaneous fit to all signal and control regions to extract signal strength μ
- Measured signal strength:

$$\hat{\mu} = 0.58^{+0.26}_{-0.25}\,(\text{stat.})^{+0.19}_{-0.15}\,(\text{exp.})^{+0.13}_{-0.11}\,(\text{bkg. th.})^{+0.08}_{-0.07}\,(\text{sig. th.})$$

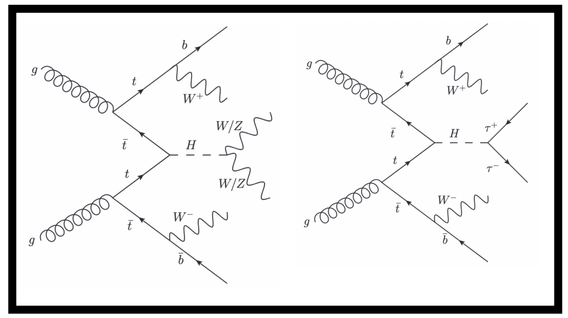
$$= 0.58^{+0.36}_{-0.33}$$

Z= 1.8σ (3.1σ exp.)
(79.9 fb^{-1})

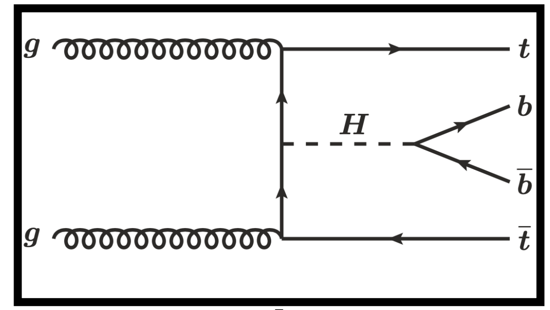
$t\bar{t}H$ ($H\rightarrow\gamma\gamma$)



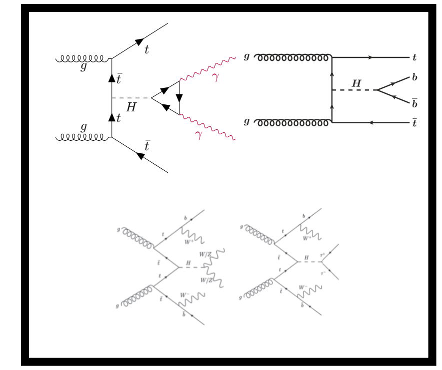
$t\bar{t}H$ ($H\rightarrow WW,\tau\tau,ZZ$)



$t\bar{t}H$ ($H\rightarrow bb$)



Combination



139 /fb
tH included

80 /fb

139 /fb
tH included

36 -139 /fb

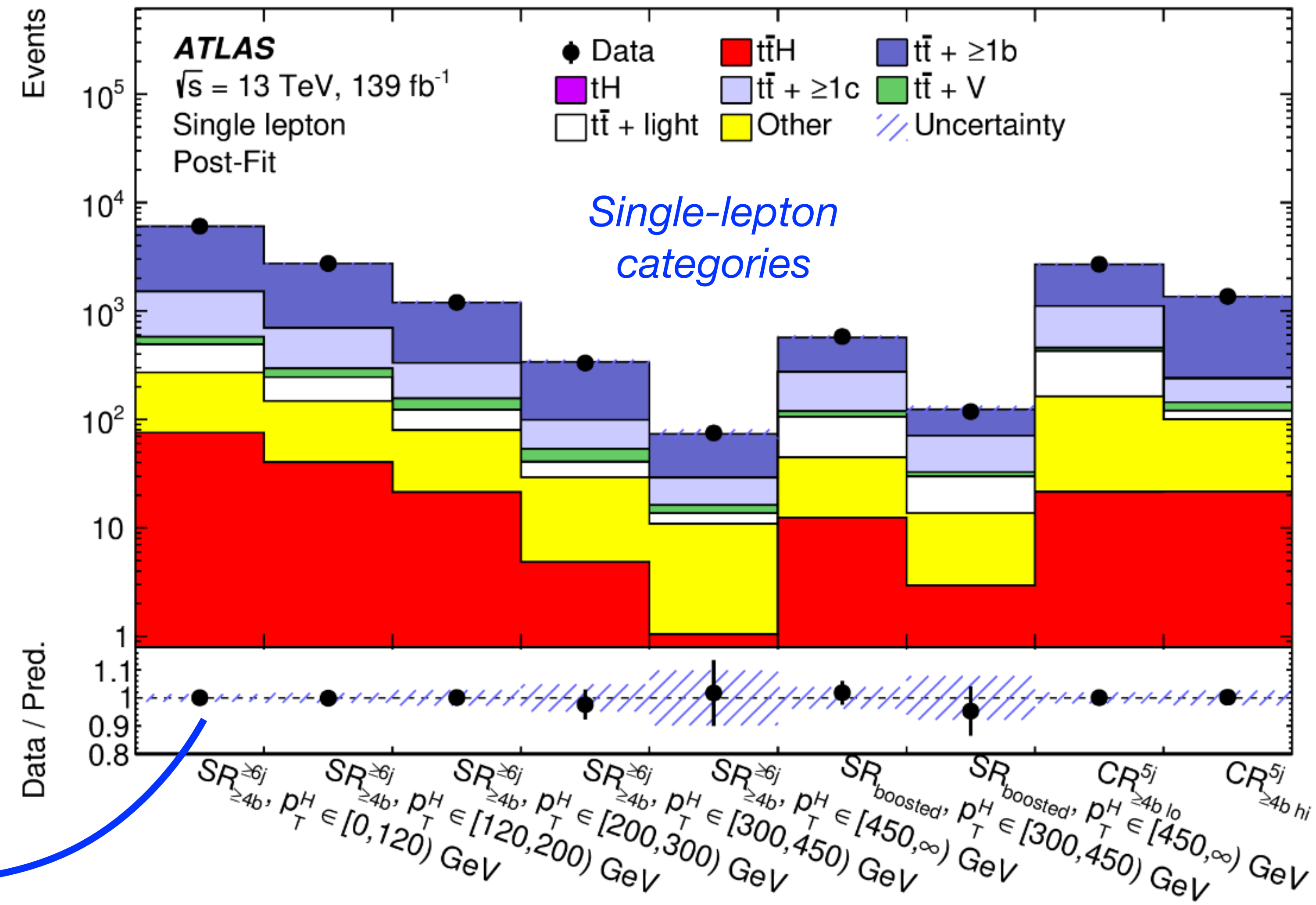
- Large branching ratio :)
- Low S/B, large theoretical uncertainties on irreducible $t\bar{t}$+bb :(
- Higgs reconstruction challenging due to combinatorics

$t\bar{t}H$ ($H \rightarrow bb$)

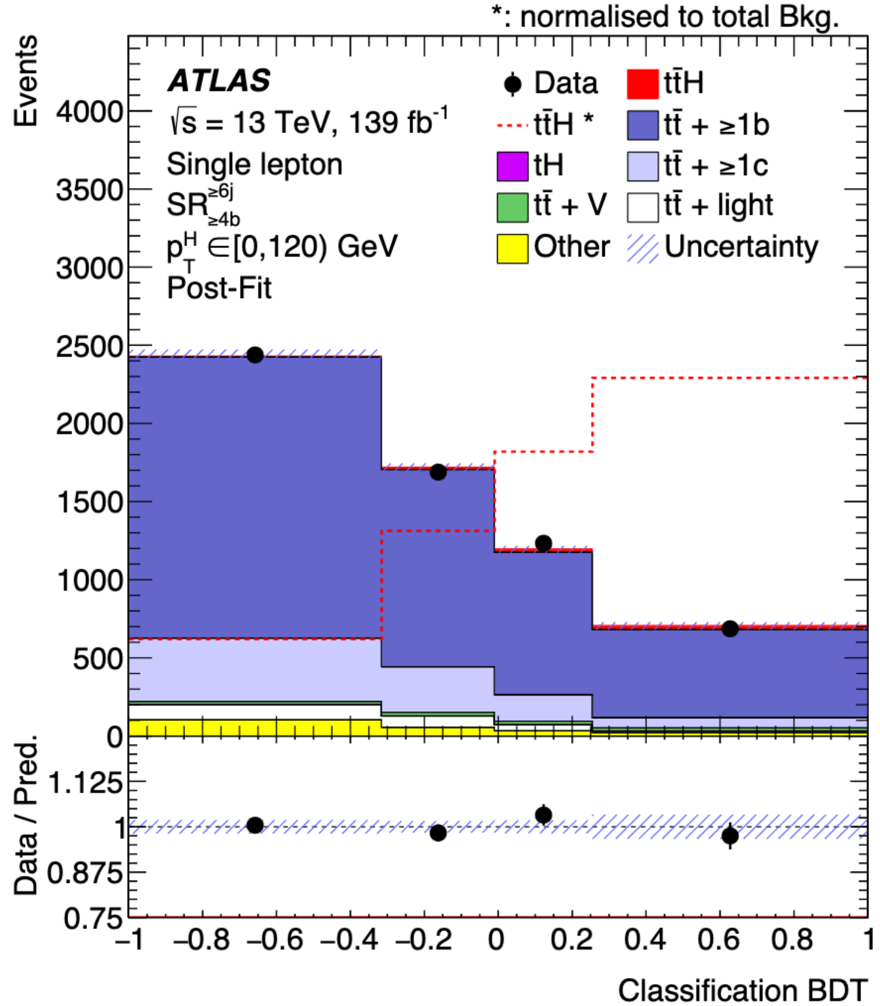
[JHEP 06 (2022) 97]

Analysis Strategy (at 139 fb^{-1})

- Results in the STXS formalism; **5 STXS Higgs p_T bins**
- Two main analysis channels; **single-lepton** or **dilepton**
- Signal/control regions defined by number of jets, b-tagged jets
  - Additional **boosted Higgs** categories for single-lepton



*: normalised to total Bkg.



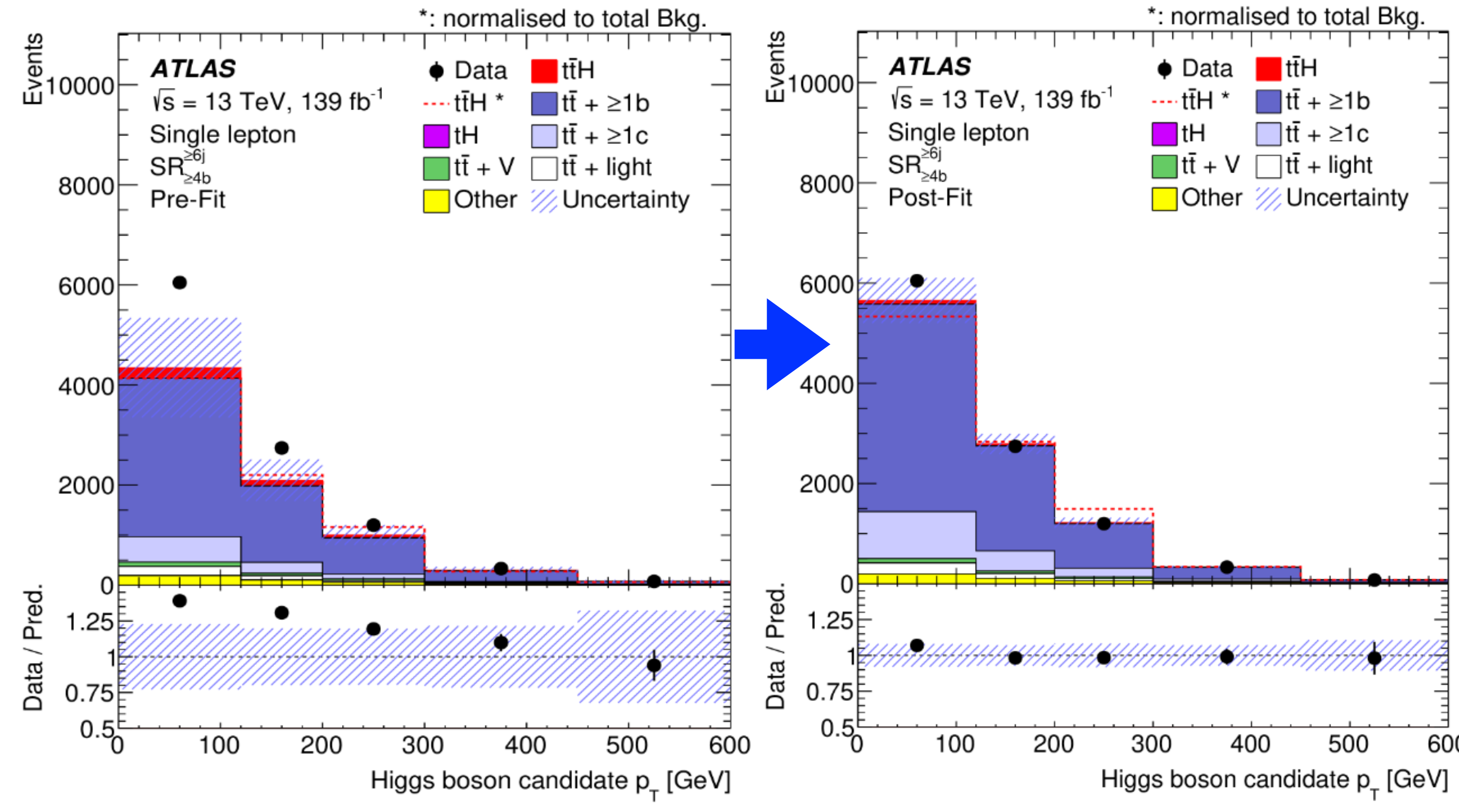
- Different MVAs used for reconstructing Higgs boson candidate and event classification
- Large irreducible background mainly from **tt+≥1b** constrained by dedicated Control regions (CRs)

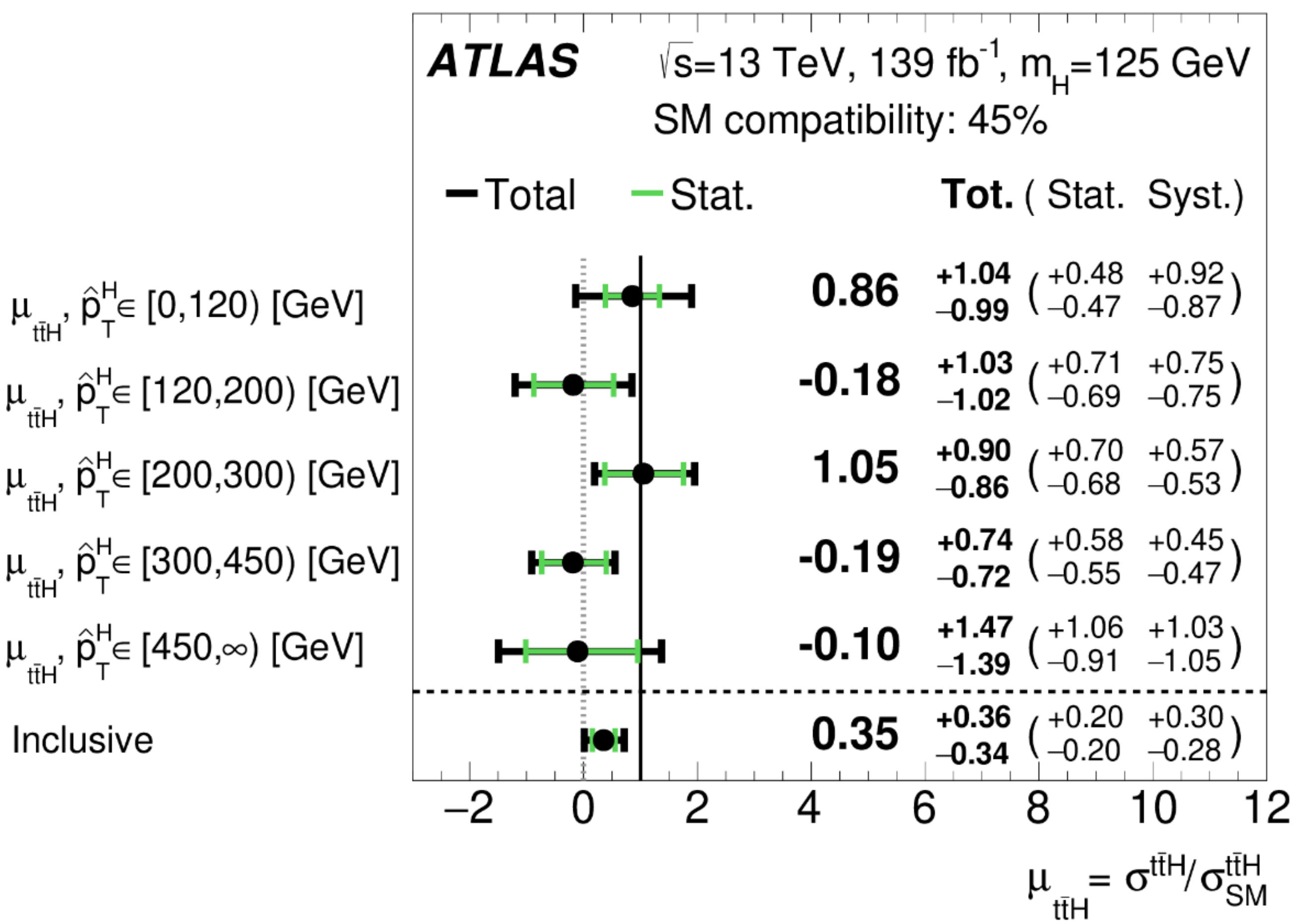
$t\bar{t}H$ ($H \rightarrow bb$)

JHEP 06 (2022) 97

Background modeling

- **tt+bb** background modelled with 4 flavour-scheme NLO QCD accuracy
- Main shape systematic uncertainties: Initial and final state radiation, parton shower, NLO matching, relative fractions of tt+heavy flavor components
  - Additional uncertainty to account for mis-modeling observed in reconstructed $p_{T,higgs}$





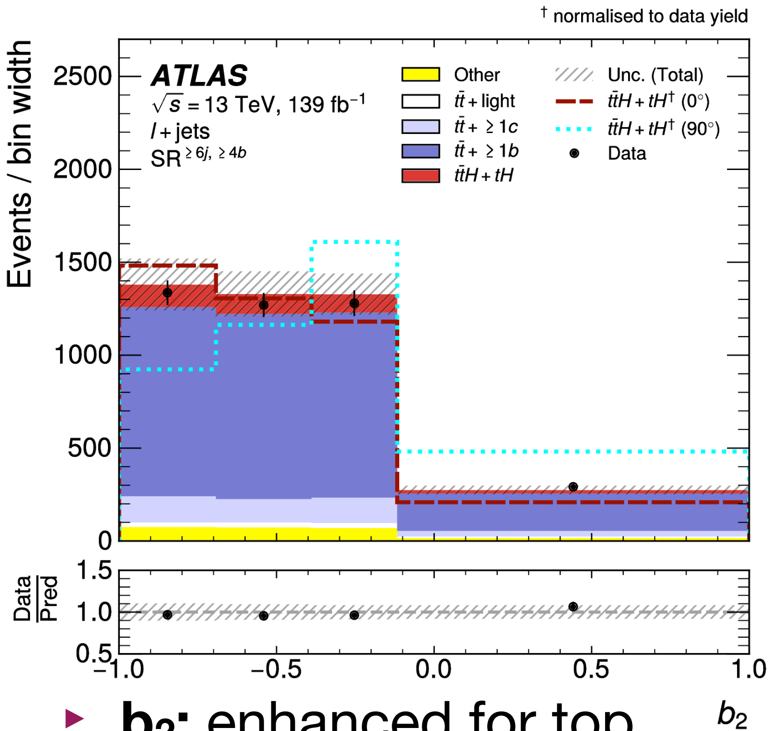
- **Inclusive results:**

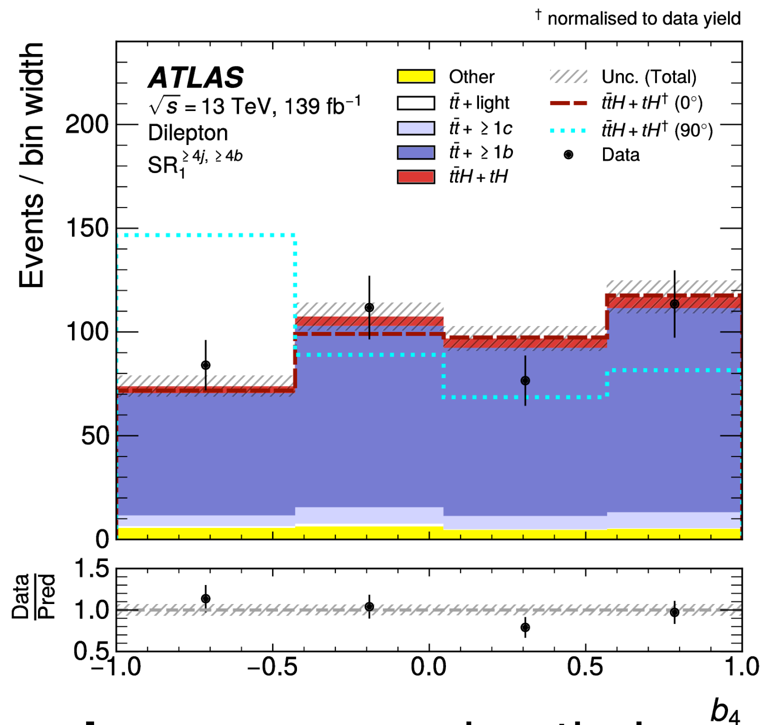
$$\mu = 0.35 \pm 0.20\,(\text{stat.})\,^{+0.30}_{-0.28}\,(\text{syst.}) = 0.35^{+0.36}_{-0.34}$$

Z= 1.0σ (2.7σ exp.)
(139 fb^{-1})

- Measured μ for five separate $p_{T,higgs}$ bins
- Sensitivity dominated by large theoretical uncertainties on irreducible tt+≥1b background

$t\bar{t}H$ ($H\rightarrow bb$) CP Analysis





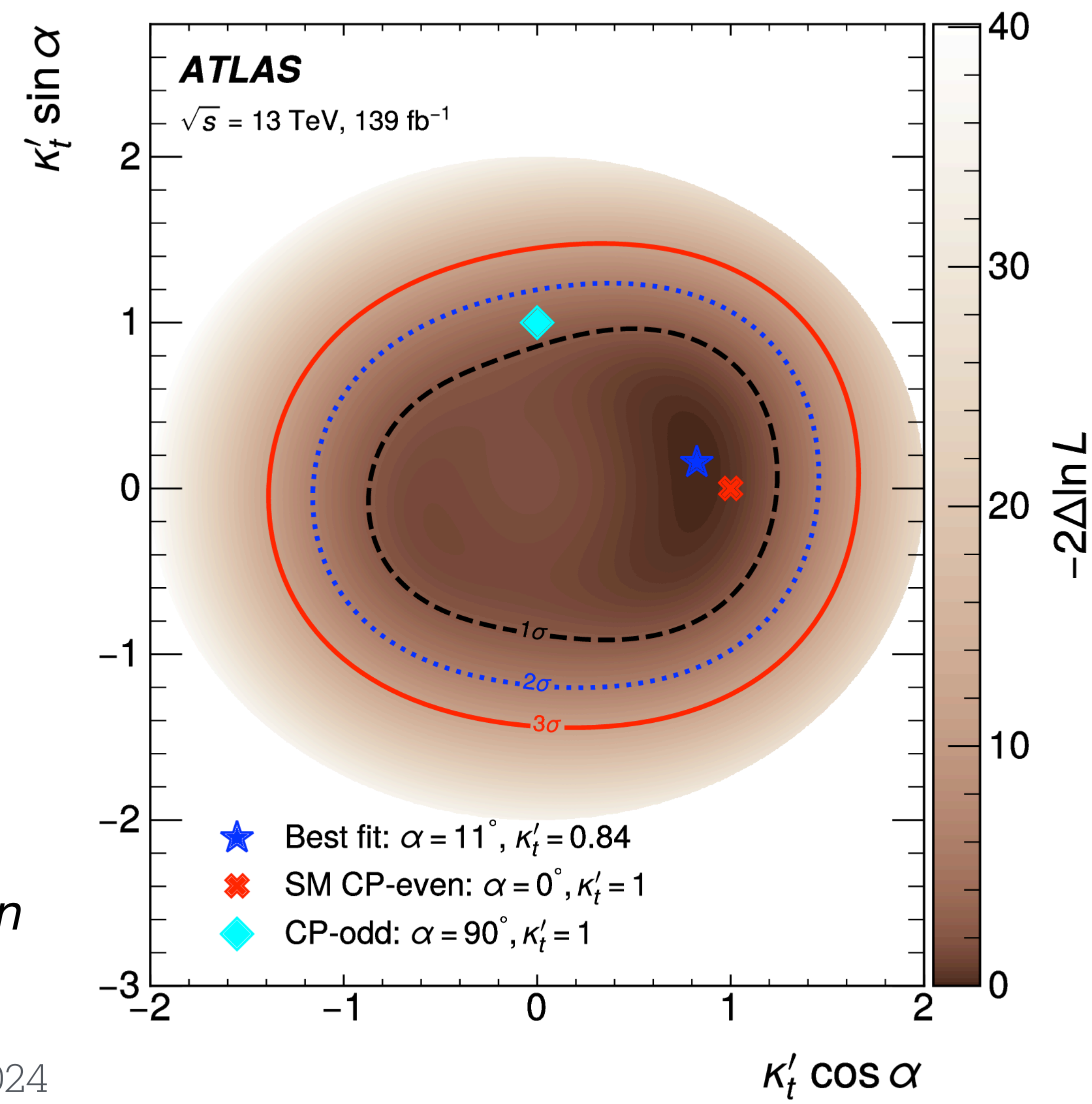
- Similar strategy to STXS analysis, now including the tH signal
- Dedicated **CP-sensitive** variables, **b_2** and **b_4**, designed to take into account spin correlations of tops
  - Choice of rest frame matters; b_2 computed in $t\bar{t}H$ rest frame

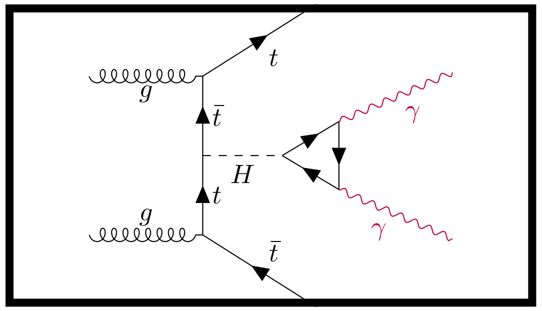
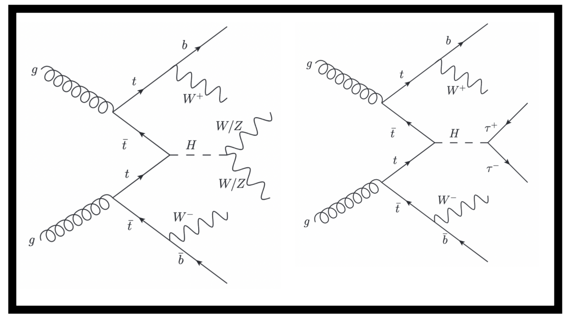
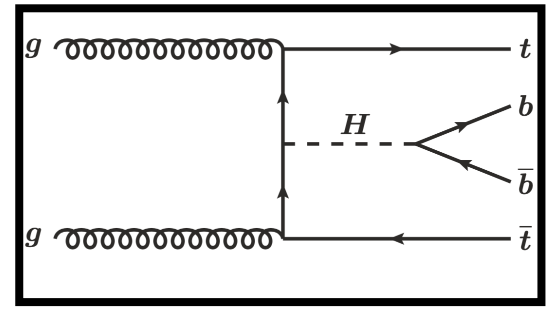
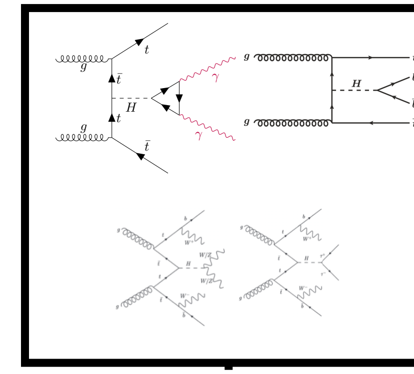
- **b_2:** enhanced for top quarks in opposite directions and closer to the beam line in CP-odd $t\bar{t}H$ $$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$
- **b_4:** narrower azimuthal separation of top quarks for CP-odd case $$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

- **Results** support CP-even hypothesis:
  - Pure CP-odd excluded at 1.2σ
  - **Best fit values:**

$$\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}},\ \kappa_t' = 0.84^{+0.30}_{-0.46}$$

In agreement with the SM expectation of $\alpha = 0$ and $k_t = 1$

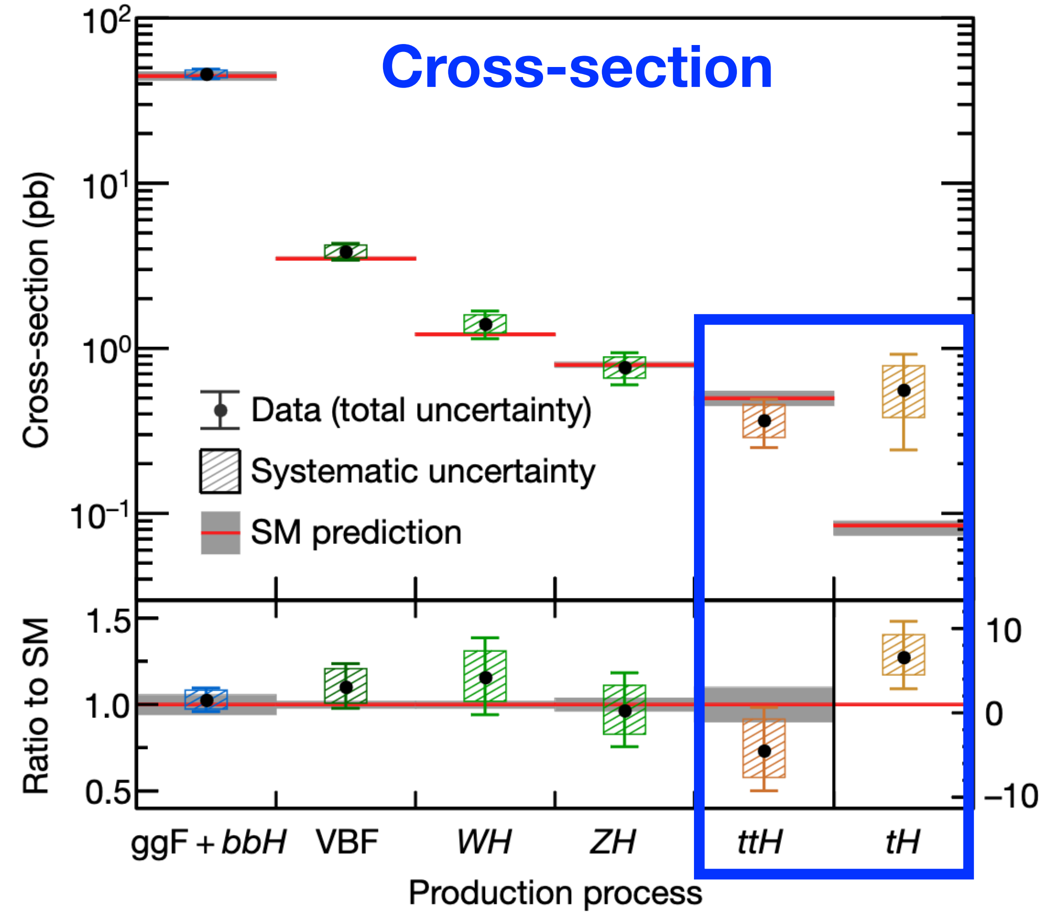


$t\bar{t}H$ ($H \rightarrow \gamma\gamma$)	$t\bar{t}H$ ($H \rightarrow WW,\tau\tau,ZZ$)	$t\bar{t}H$ ($H \rightarrow bb$)	Combination
			
139 /fb tH included	80 /fb	139 /fb tH included	36 -139 /fb

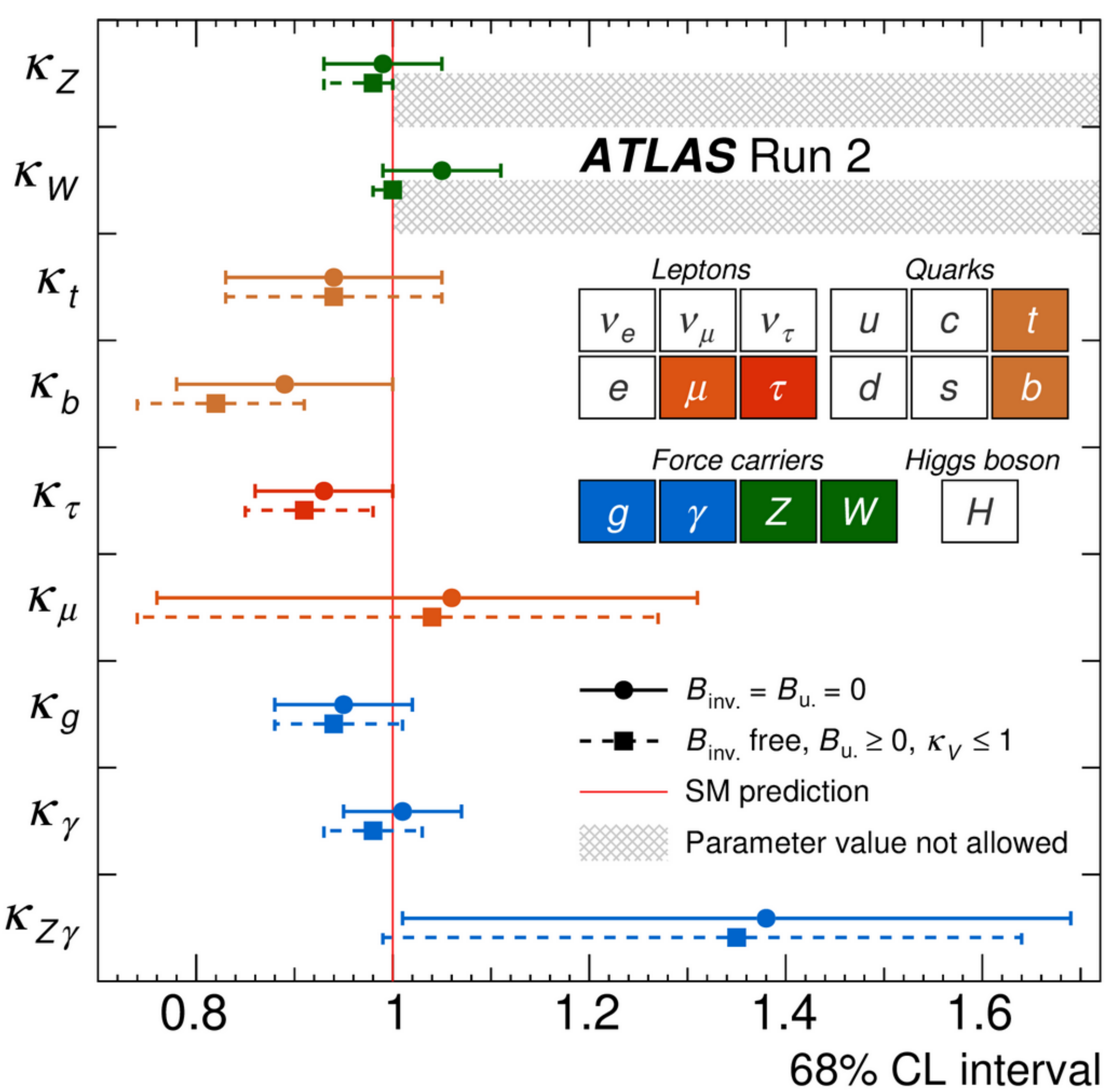
- Individually we gather insights, but combined we achieve clarity

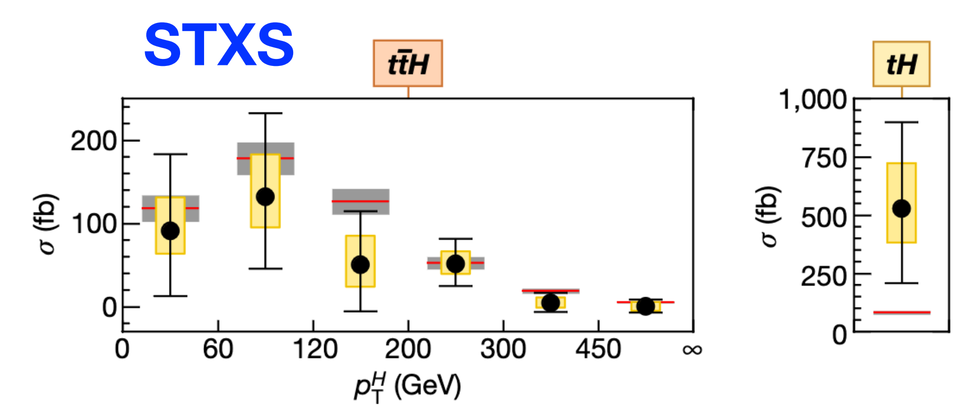
Combination

- Combination of **all Run 2 Higgs analyses** available at time**: inclusive cross-section + STXS measurements :
  - ➡ Combined ttH + tH sensitivity **6.4σ (exp. 6.6σ)**
  - ➡ STXS results in good agreement with SM



Reduced coupling strength modifiers





- Sensitivity to κ_t from ttH categories *(under hypothesis with independent effective κ_g and κ_γ)*

*** ttH→ML(at 36/fb), $t\bar{t}H$→γγ and $t\bar{t}H$→bb (at 139/fb)*

[Nature 607 (2022)]

Summary

- Six years after the first observation of Higgs+top associated production in $t\bar{t}H$ final states
- Going beyond inclusive cross-section measurements
  - First differential measurements of $t\bar{t}H$ through STXS framework
- Background modelling very challenging in some channels ($t\bar{t}$+bb, $t\bar{t}W$)
  - Better understanding of these processes necessary in order to improve sensitivity for future analyses
- Multiple analyses investigating CP violation within the Higgs-top coupling
  - opens path for future CP combinations
- Still a long way to go; Combination with full Run 2 data, tH process yet to be observed…

Stay tuned and stay curious

Back Up

$t\bar{t}H$ ($H\to\gamma\gamma$)

- Uncertainty breakdown

	ggF + $b\bar{b}$H	VBF	WH	ZH	$t\bar{t}H$	tH
Uncertainty source	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]
Theory uncertainties						
Higher-order QCD terms	±1.4	±4.1	±4.1	±12	±2.8	±16
Underlying event and parton shower	±2.5	±16	±2.5	±4.0	±3.6	±48
PDF and α_s	$<\pm1$	±2.0	±1.4	±2.3	$<\pm1$	±5.8
Matrix element	$<\pm1$	±3.2	$<\pm1$	±1.2	±2.5	±8.2
Heavy-flavour jet modelling in non-$t\bar{t}H$ processes	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	±13
Experimental uncertainties						
Photon energy resolution	±3.0	±3.0	±3.8	±4.8	±3.0	±12
Photon efficiency	±2.7	±2.7	±3.3	±3.6	±2.9	±9.3
Luminosity	±1.8	±2.0	±2.4	±2.7	±2.2	±6.6
Pile-up	±1.4	±2.2	±2.0	±2.3	±1.4	±7.3
Background modelling	±2.0	±4.6	±3.6	±7.2	±2.5	±63
Photon energy scale	$<\pm1$	$<\pm1$	$<\pm1$	±1.3	$<\pm1$	±5.6
Jet/E_T^{miss}	$<\pm1$	±6.8	$<\pm1$	±2.2	±3.5	±22
Flavour tagging	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	±1.5	±3.4
Leptons	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	±1.8
Higgs boson mass	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$	$<\pm1$

Table 7. Expected contributions from the main sources of systematic uncertainty to the total uncertainty in the measurement of the cross-section times $H\to\gamma\gamma$ branching ratio for each of the main Higgs boson production processes. The uncertainty from each source ($\Delta\sigma$) is shown as a fraction of the total expected cross-section (σ).

$t\bar{t}H$ ($H\rightarrow\gamma\gamma$)

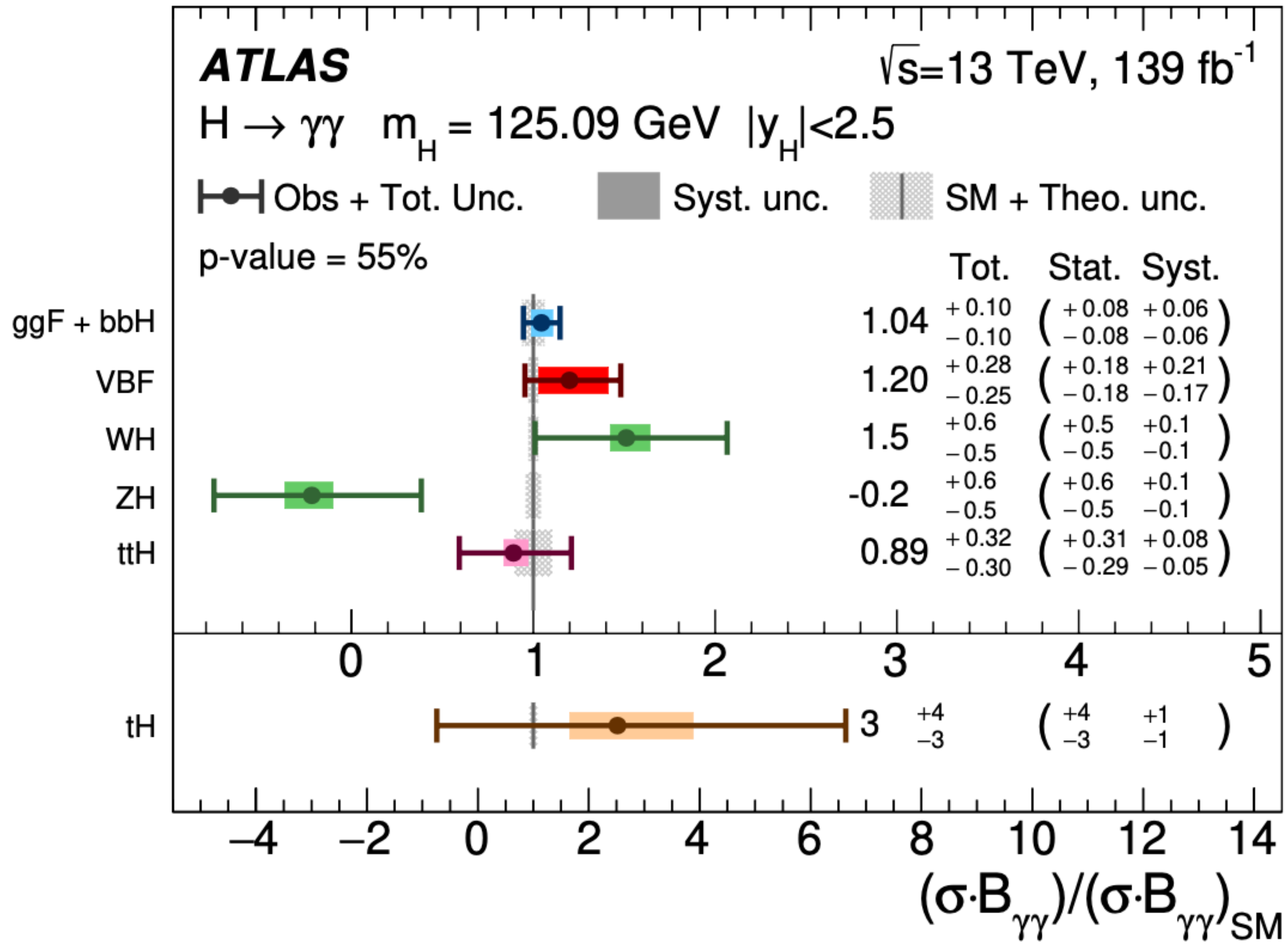


Figure 9. Cross-sections times $H \rightarrow \gamma\gamma$ branching ratio for ggF + $b\bar{b}H$, VBF, VH, $t\bar{t}H$, and tH production, normalized to their SM predictions. The values are obtained from a simultaneous fit to all categories. The error bars and shaded areas show respectively the total and systematic uncertainties in the measurements. The grey bands show the theory uncertainties in the predictions, including uncertainties due to missing higher-order terms in the perturbative QCD calculations, the PDFs and the value of α_s, as well as the $H \rightarrow \gamma\gamma$ branching ratio uncertainty.

$t\bar{t}H$ ($H \rightarrow \gamma\gamma$) CP Analysis

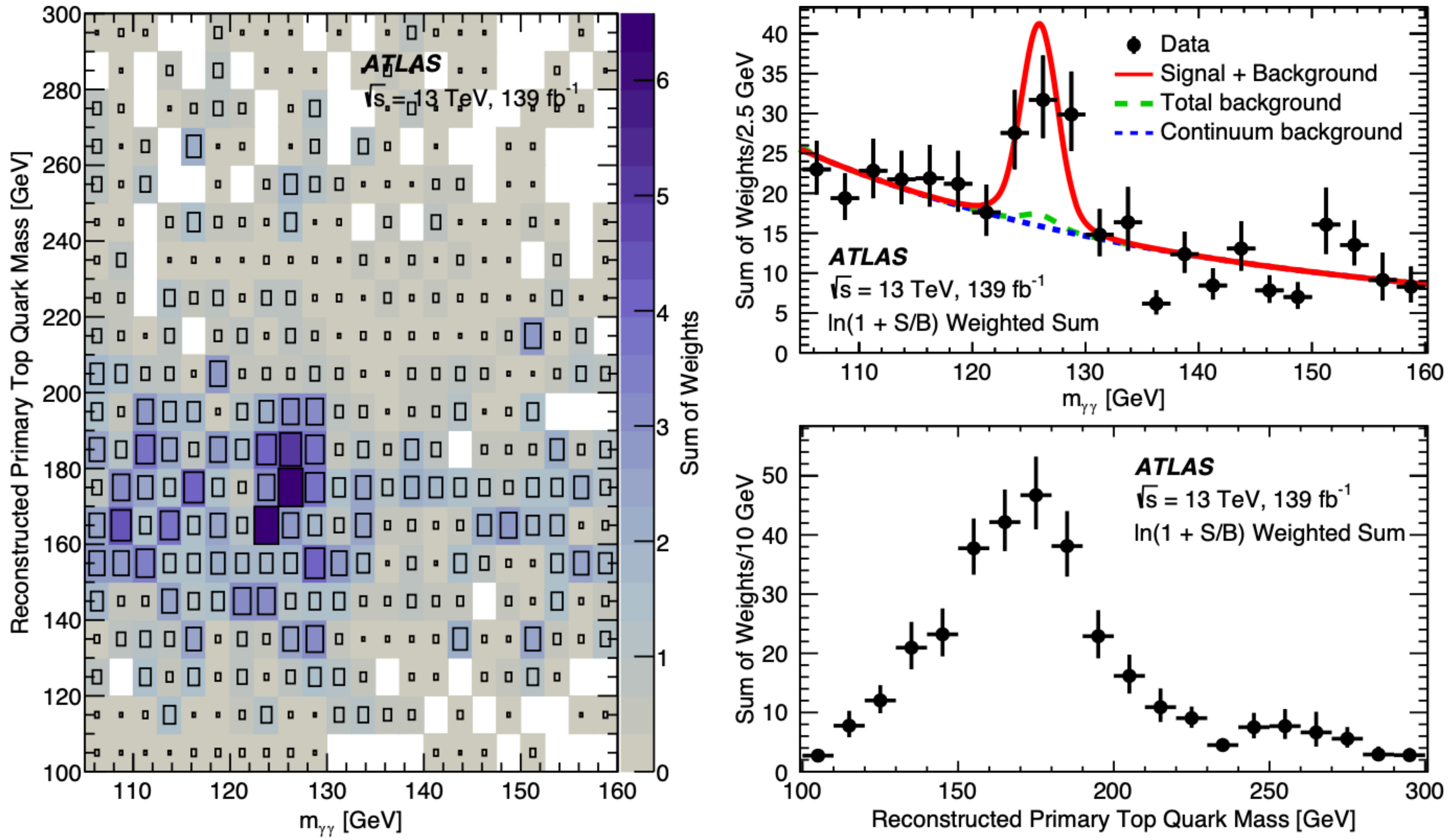


FIG. 2. Distribution of reconstructed primary top quark mass versus reconstructed Higgs boson mass in the data events. The right panels show the projections onto the Higgs boson mass and primary top quark mass axes. In the upper panel, the fitted continuum background (blue), the total background including non-$t\bar{t}H/tH$ Higgs boson production (green), and the total fitted signal plus background (red) are shown. The error bars on data are statistical.

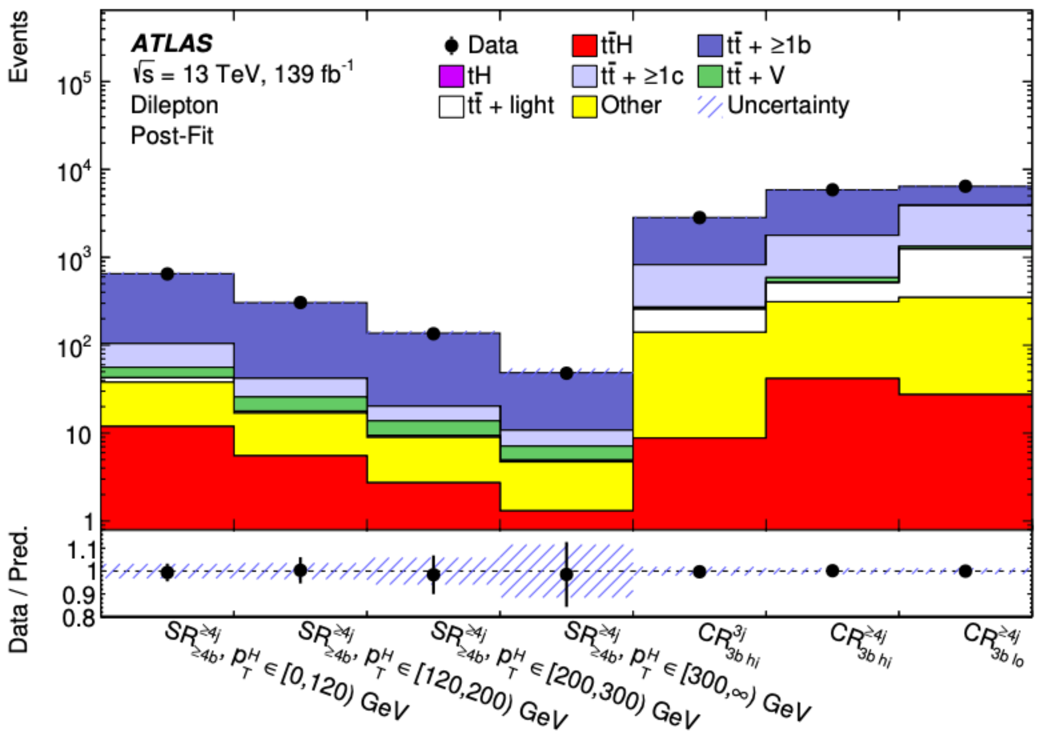
$t\bar{t}$H Multi-Lepton

ATLAS-CONF-2019-045

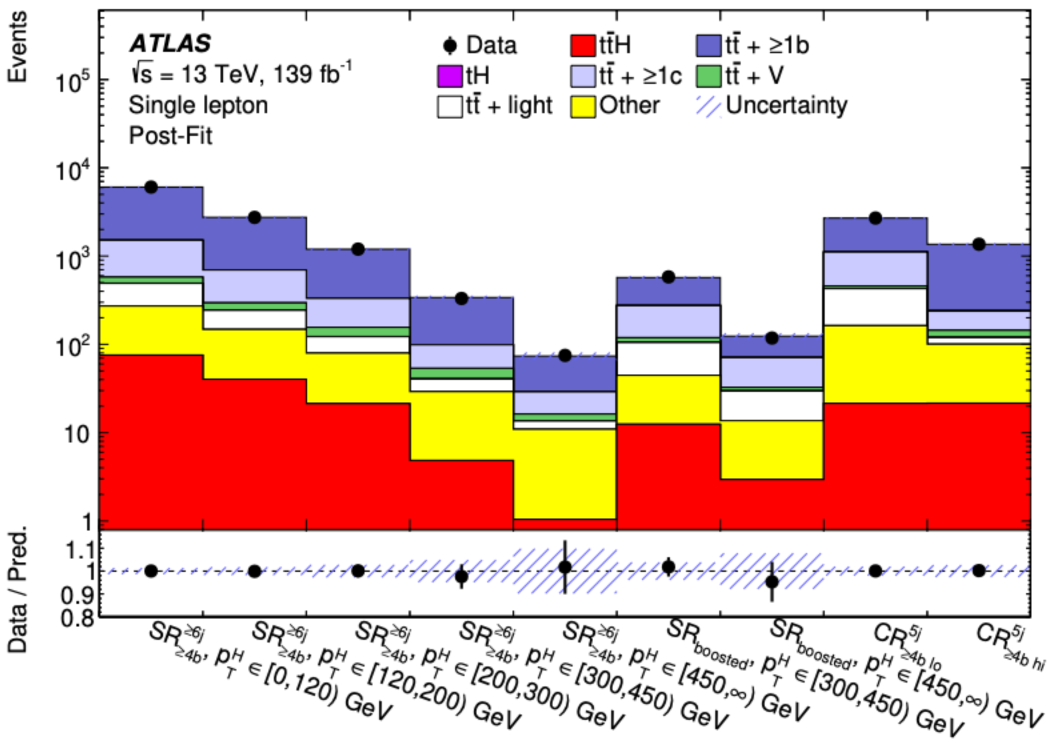
- Uncertainty breakdown

Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	−0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	−0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	−0.08
Fake τ_{had} background estimate	+0.07	−0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	−0.05
$t\bar{t}H$ cross section	+0.05	−0.05
Simulation sample size	+0.05	−0.05
$t\bar{t}H$ modelling	+0.04	−0.04
Other background modelling	+0.04	−0.04
Jet flavour tagging and τ_{had} identification	+0.04	−0.04
Other experimental uncertainties	+0.03	−0.03
Luminosity	+0.03	−0.03
Diboson modelling	+0.01	−0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	−0.01
Charge misassignment	+0.01	−0.01
Template fit (non-prompt leptons)	+0.01	−0.01
Total systematic uncertainty	+0.25	−0.22
Intrinsic statistical uncertainty	+0.23	−0.22
$t\bar{t}W$ normalisation factors	+0.10	−0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	−0.05
Total statistical uncertainty	+0.26	−0.25
Total uncertainty	+0.36	−0.33

$t\bar{t}H$ ($H \to bb$)



(a)



(b)

Figure 5. Comparison of predicted and observed event yields in each of the control and signal regions in the (a) dilepton and (b) single-lepton channels after the fit to the data. The uncertainty band includes all uncertainties and their correlations.

$t\bar{t}H$ (H→bb)

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

Table 6. Breakdown of the contributions to the uncertainties in μ. The contributions from the different sources of uncertainty are evaluated after the fit. The $\Delta\mu$ values are obtained by repeating the fit after having fixed a certain set of nuisance parameters corresponding to a group of systematic uncertainties, and then evaluating $(\Delta\mu)^2$ by subtracting the resulting squared uncertainty of μ from its squared uncertainty found in the full fit. The same procedure is followed when quoting the effect of the $t\bar{t}+\geq 1b$ normalisation. The total uncertainty is different from the sum in quadrature of the different components due to correlations between nuisance parameters existing in the fit.

$t\bar{t}H$ ($H \rightarrow bb$) CP Analysis

Table 2: Summary of the selections used to define SRs and CRs from the TRs, based on the classification BDT score. In the boosted region, the selection requirement is applied and rejected events are removed entirely from further analysis. In the dilepton channel, events with failed reconstruction due to absence of a real solution from the neutrino weighting are categorised into an additional region known as $\mathrm{CR}^{\geq 4j,\geq 4b}_{\text{no-reco}}$. The fitted discriminating variable in each region is indicated in the last column.

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 ($\mathrm{TR}_{\text{boosted}}$)	$\mathrm{SR}_{\text{boosted}}$	$\mathrm{BDT}^{\text{boosted}} \in [-0.05, 1]$	$\mathrm{BDT}^{\text{boosted}}$

$t\bar{t}H$ ($H\to bb$) CP Analysis

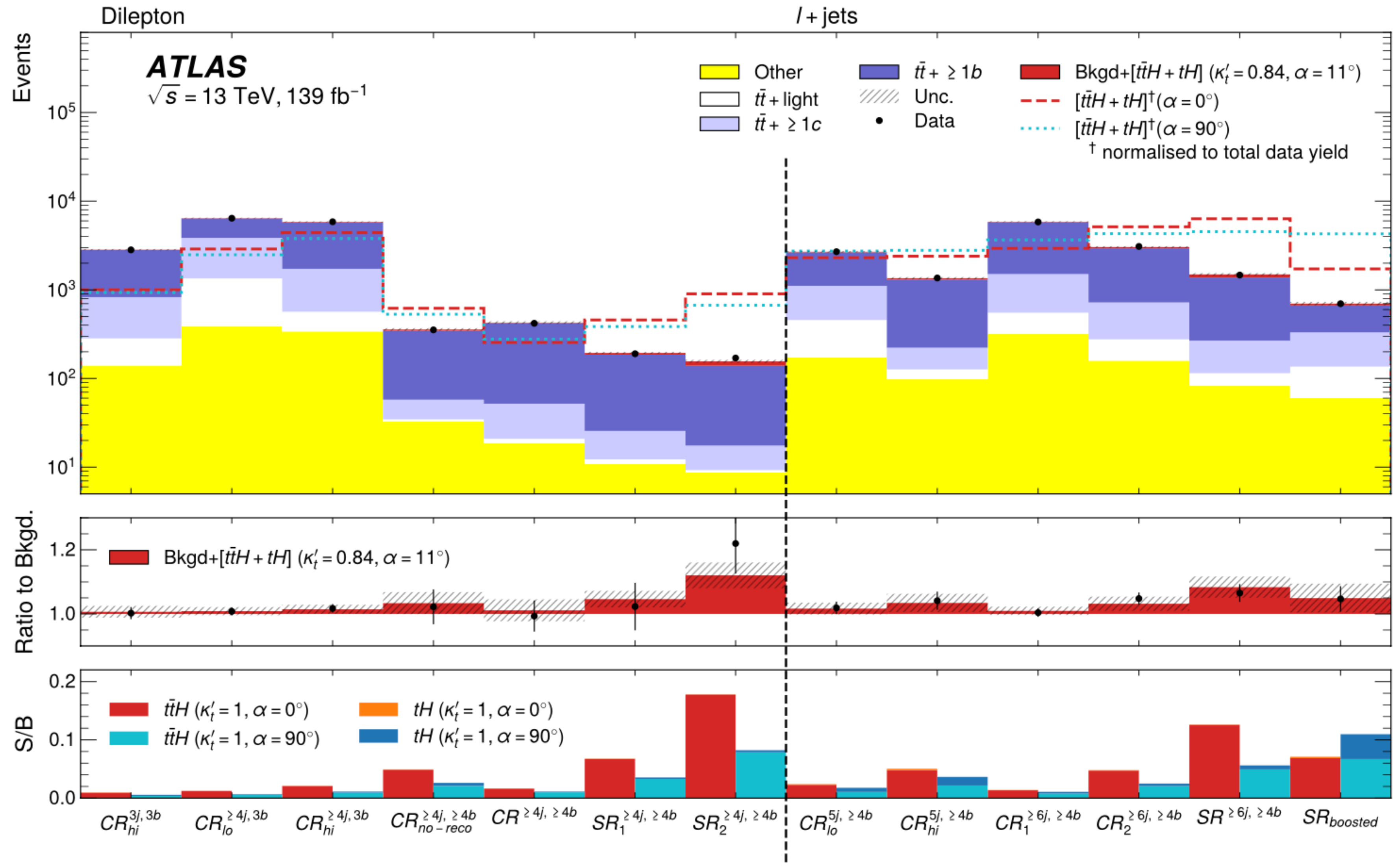


Figure 1: Yields calculated following a fit with κ_t' and α as free parameters, compared to the observed data in all analysis regions. The different backgrounds and the signal are shown in coloured stack. The background component labelled "other" corresponds to the production of W+ jets, Z+ jets, $t\bar{t}W$, $t\bar{t}Z$, tZq, tWZ, $t\bar{t}t\bar{t}$ and $WW/WZ/ZZ$ events, as in Ref. [29]. The dashed and dotted lines show the sum of $t\bar{t}H + tH$ signals for pure CP-even and CP-odd hypotheses normalised to the total data yields including all regions. The hashed area around the prediction illustrates the total post-fit uncertainties. In the middle panel, the best-fit model is compared with the data by showing ratios of its value to the post-fit background prediction. The histogram represents the total post-fit model including the best-fit signals. The hashed band represents the total post-fit uncertainty as a ratio to the background. In the bottom panel, the S/B is shown for pure CP-even and CP-odd signals, separately. The histograms are shown as a stack of $t\bar{t}H$ and tH.