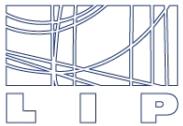
Measurements of Higgs boson production in association with top quarks at the ATLAS experiment

LHCP 2022

May 16th, Taipei University (online)

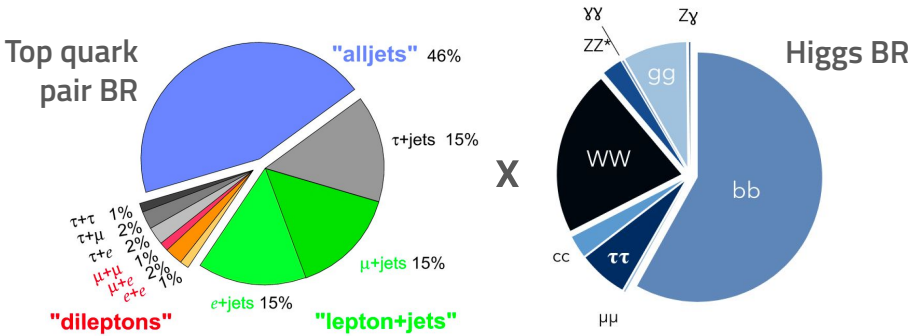
Ana Luísa Carvalho on behalf of the ATLAS Collaboration

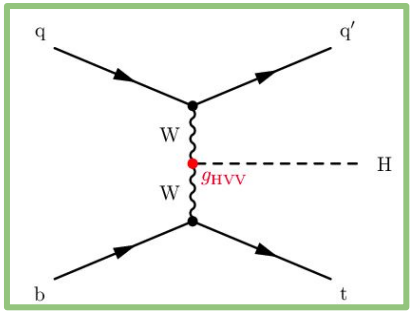


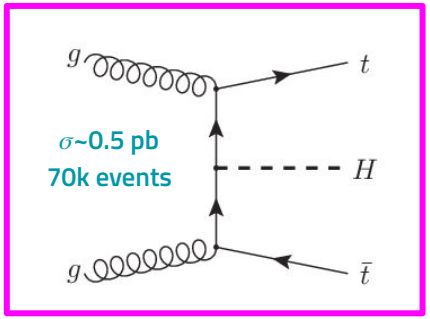
Motivation and outline

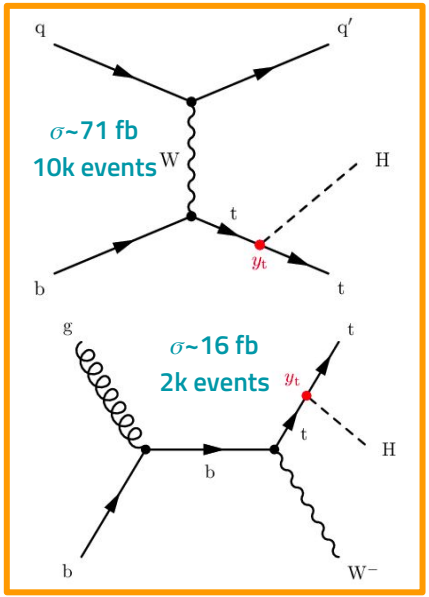
Higgs boson production in association with top quarks offers a direct probe of the top Yukawa coupling

- **Associated production with a pair of top quarks ($t\bar{t}H$)** observed in 2018 by ATLAS and CMS using a combination of decay channels
- **Associated production with a single top quark (tH)** not been observed yet (very small cross section in SM)
  - tH rate is particularly sensitive to deviations from SM due to destructive interference with **tWH diagram**









Cross sections @ 13 TeV
No. events in Run-2 prior to event selection

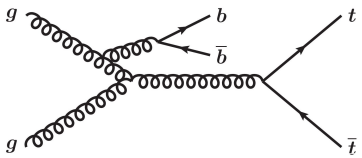
Where to look for ttH and tH

★ CP and STXS measurements included

$t\bar{t}H(H\to bb)$ ★

139 /fb

- Large irreducible background ttbb
- Final state with multiple b-jets



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

80 /fb, "multilepton"

- Irreducible ttZ/W backgrounds
- Large non-prompt leptons background

$t\bar{t}H(H\to\tau\tau)$ hadronic

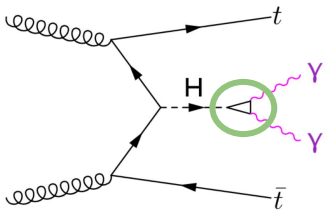
139 /fb

- Allows to exploit hadronic decays of Higgs and top
- Dominated by $Z\to\tau\tau$ and $t\bar{t}$ backgrounds

$t\bar{t}H(H\to\gamma\gamma)$ ★

$(H\to ZZ^*\to 4\ell)$ 139 /fb

- Clean signatures
- Low statistics
- Loop contribution in $H\to\gamma\gamma$ decay



Simpler background modelling

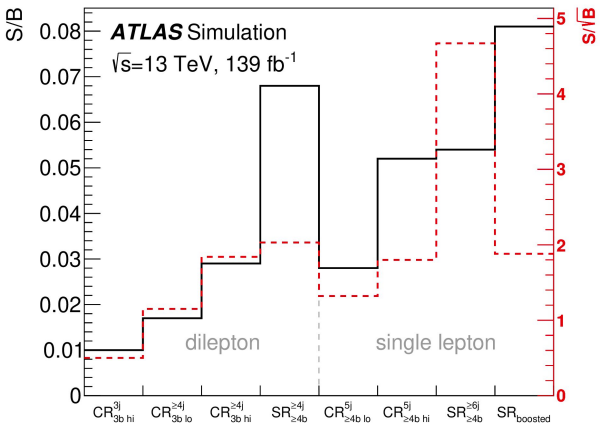
Larger branching ratio

Measurement of H→bb in associated production with a top-quark pair

$\mathcal{L}$ = 139 /fb at 13 TeV, 2111.06712 (submitted to JHEP)

- Target decays of the top quark pair to 2 (**dilepton**) or ≥1 leptons (**single-lepton**)
- Events in which Higgs boson has a high transverse momentum (p_T>300 GeV) also included
- Analysis regions defined based on the number of jets and b-jets
- Signal enriched regions further split in bins of reconstructed Higgs boson p_T: [0-120], [120-200], [200-300], [300-450], [450-∞] (STXS formalism) ⇒ Total of **16 analysis regions**

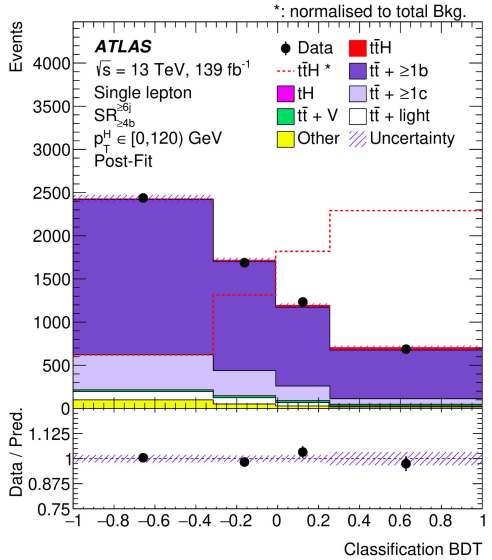
Region	Dilepton				Single-lepton			
	$SR^{\geq 4j}_{\geq 4b}$	$CR^{\geq 4j}_{3b\ hi}$	$CR^{\geq 4j}_{3b\ lo}$	$CR^{3j}_{3b\ hi}$	$SR^{\geq 6j}_{\geq 4b}$	$CR^{5j}_{\geq 4b\ hi}$	$CR^{5j}_{\geq 4b\ lo}$	$SR_{boosted}$
#leptons	= 2				= 1			
#jets	≥ 4			= 3	≥ 6	= 5		≥ 4
#b-tag @85%	–				≥ 4			
#b-tag @77%	–				–			≥ 2†
#b-tag @70%	≥ 4	= 3			≥ 4			–
#b-tag @60%	–	= 3	< 3	= 3	–	≥ 4	< 4	–
#boosted cand.	–				0			≥ 1
Fit input	BDT	Yield			BDT/Yield	ΔR^{avg}_{bb}		BDT

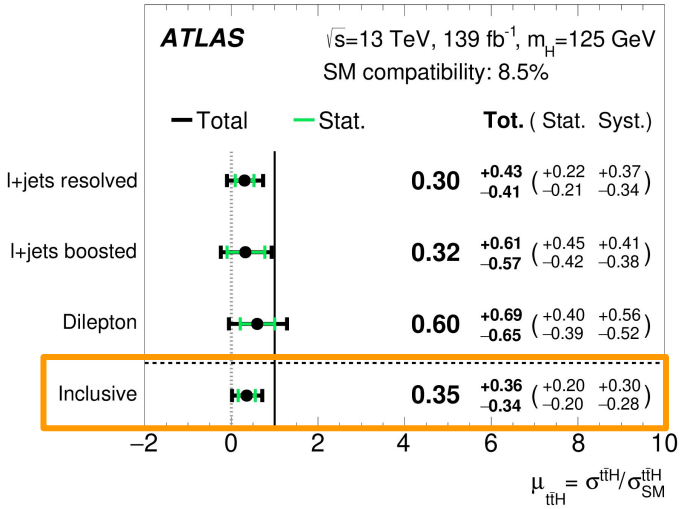


Measurement of H→bb in associated production with a top-quark pair

$\mathcal{L}$ = 139 /fb at 13 TeV, 2111.06712 (submitted to JHEP)

- BDT trained to distinguish between $t\bar{t}H$ and backgrounds used as discriminant in signal enriched regions
- **$t\bar{t}$+≥1b background** dominant in most analysis regions ⇒ **Normalization measured in data** 1.28 ± 0.08
- Maximum likelihood fit performed including all signal and control regions
- Measured **inclusive signal strength**: $\mu = 0.35^{+0.36}_{-0.34}$, dominated by $t\bar{t}$ modeling uncertainties





Study of CP properties of the top-Higgs interaction in H→bb decay channel

$\mathcal{L}$ = 139 /fb at 13 TeV, ATLAS-CONF-2022-016

- Follows closely strategy of $t\bar{t}H(H\to bb)$ STXS analysis: same control regions and background modeling
  - tH treated as signal: rate sensitive to coupling deviations from SM
- Higgs characterization model provides EFT framework to constrain 2D phase space given by (k_t, α)

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

CP-even (SM) CP-odd

- Signal regions split based on output of classification BDT
- CP-sensitive angular variables calculated **between the top quarks** used as discriminant in signal regions

Phys. Rev. Lett. 76, 4468
arXiv:1909.00490

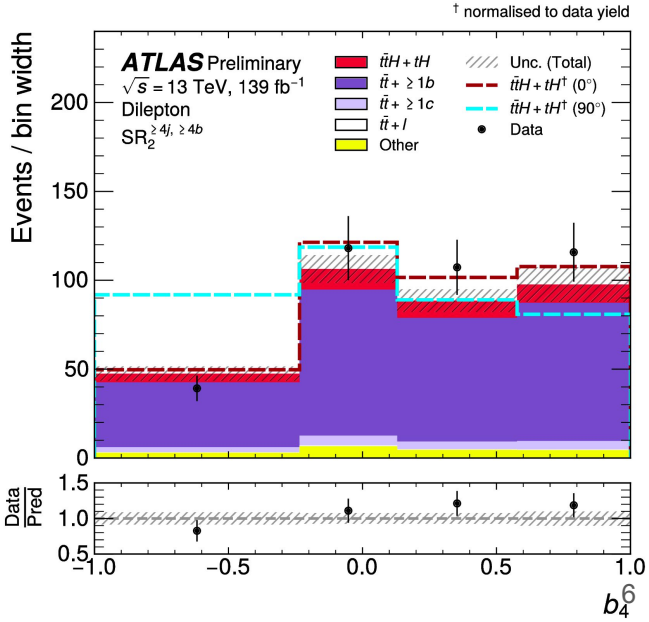
$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}$$

Single-lepton

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

Dilepton

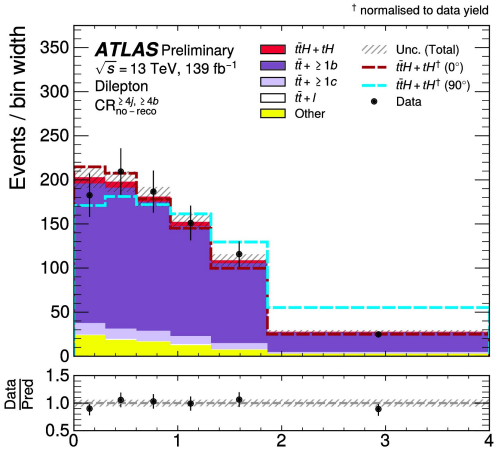
n̂ = z-axis



Study of CP properties of the top-Higgs interaction in H→bb decay channel

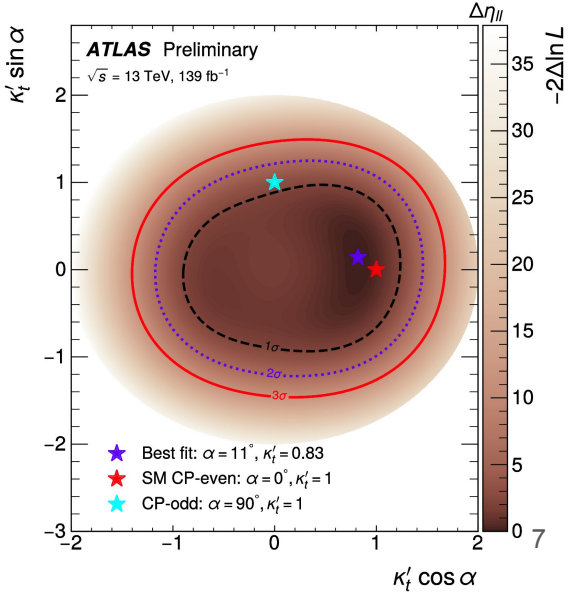
$\mathcal{L}$ = 139 /fb at 13 TeV, ATLAS-CONF-2022-016

- Dedicated dilepton control region containing events for which top-quark pair reconstruction is not possible
  - Fit $\Delta\eta$ **between leptons**
- Simultaneous maximum likelihood fit in all (12) analysis regions with free-floating $t\bar{t}$+≥1b normalization



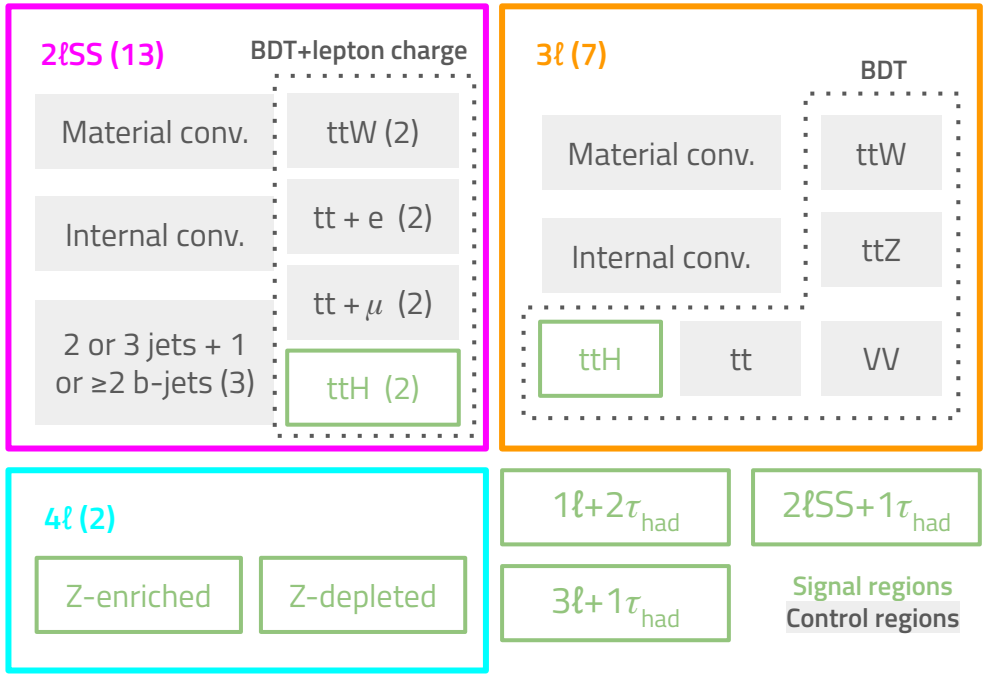
Top-Yukawa coupling results

- Measured value of CP-mixing angle: $\alpha = 11^{\circ}{}^{+56^{\circ}}_{-77^{\circ}}$ (stat contribution $^{+34^{\circ}}_{-51^{\circ}}$)
- Overall coupling strength: $\kappa_t' = 0.83^{+0.30}_{-0.46}$
- Pure CP-odd hypothesis disfavoured at 1.2 σ
- ttH signal strength compatible with STXS measurement within 1σ
- Dominated by systematic uncertainties in **modeling of $t\bar{t}$+≥1b background**

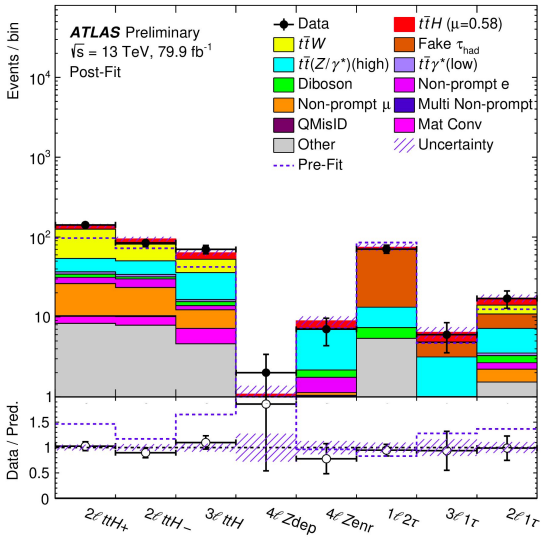


Analysis of ttH and ttW production in multilepton final states (H→WW*, $\tau\tau$, ZZ*)

$\mathcal{L}$ = 80 /fb at 13 TeV, ATLAS-CONF-2019-045



- Targets events with leptons in the final state and leptonic decays of $t\bar{t}$ pair
- 6 channels based on number and flavor of lepton candidates: **2ℓ same-sign (SS)**, 3ℓ, 4ℓ, $1\ell+2\tau_{had}$, $2\ell SS+1\tau_{had}$, $3\ell+1\tau_{had}$



- Main irreducible backgrounds: ttZ/W, VV
- Reducible backgrounds: non-prompt ℓ, charge misID electrons, electrons from photon conversions

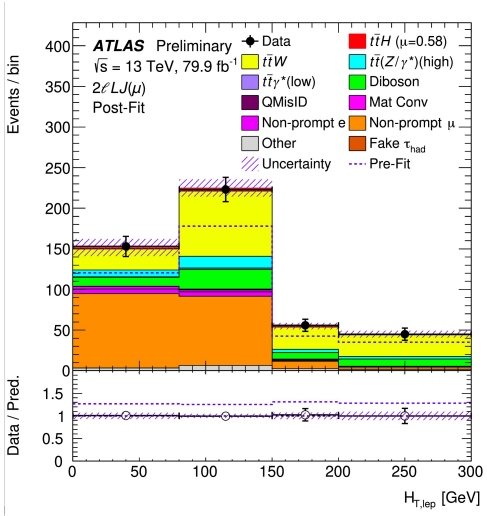
Analysis of ttH and ttW production in multilepton final states

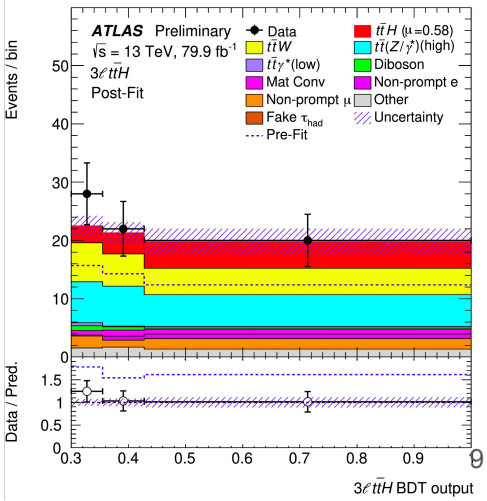
$\mathcal{L}$ = 80 /fb at 13 TeV, ATLAS-CONF-2019-045

- Simultaneous maximum likelihood fit in all analysis regions with 7 independent normalization factors
  - 3 ttW: measured in **2ℓSS high/low no. jets regions** and **3ℓ channel**
  - 1 internal conversions: measured by fitting yield 3ℓ ttZ, VV CR's
  - 3 non-prompt leptons: e, μ and material conversion candidates): measured in 2ℓSS and 3ℓ regions, $H_{T,lep}$ and **ΔR(ℓ,ℓ)** provide separation against ttW and internal conversion candidates
- BDT discriminant used in signal regions of 2ℓSS, 3ℓ and 1ℓ+2τ_{had} channels
- Event yield fitted in remaining regions

Results

- Measured signal strength: $\mu = 0.58^{+0.36}_{-0.33}$
- Observed excess above background-only hypothesis: 1.8 σ
- ttW normalization factors: $1.56^{+0.30}_{-0.28}, 1.26^{+0.19}_{-0.18}$ $1.68^{+0.30}_{-0.28}$
- Similar contributions from statistical and systematic uncertainties





Higgs boson production cross-section measurement in the H→ττ decay channel

$\mathcal{L}$ = 139 /fb at 13 TeV, 2201.08269 (submitted to JHEP)

Includes multiple Higgs production modes, focus on $t\bar{t}H$ part only

- Targets **hadronic** decays of **top quark pair** and **τ leptons from Higgs decay**
- Hadronic τ candidates (τ_{had}) reconstructed from jets and identified by RNN

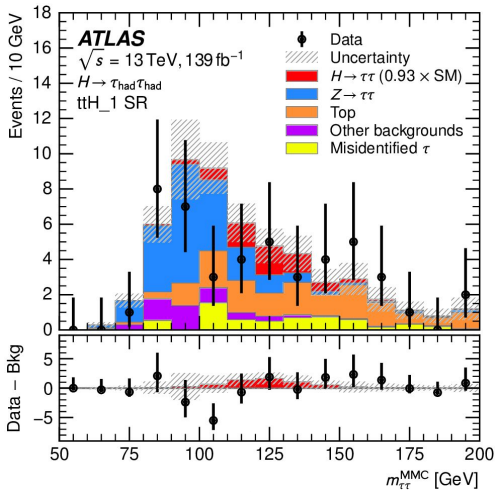
H→ττ selection

≥2 τ_{had} p_T>40, 30 GeV
Opposite sign
Angular requirements (ΔR, Δη)

Hadronic $t\bar{t}$ selection

≥6 jets ≥1 b-jet or
≥5 jets ≥2 b-jet

2 BDT's to separate ttH from Z→ττ and $t\bar{t}$



2 ttH signal regions (signal enriched and depleted)

- **Dominant backgrounds:** Z→ττ, $t\bar{t}$ (independent normalization factors)
- Simultaneous maximum likelihood fit to 32 signal regions and 36 control regions
- Measured $t\bar{t}H(0\ell)$ signal strength: $\mu = 1.06^{+1.28}_{-1.08}$
- Signal and Z+jets and $t\bar{t}$ background modelling are the leading systematic uncertainties

Measurement of Higgs boson production in H→$\gamma\gamma$ decay channel

$\mathcal{L}$ = 139 /fb at 13 TeV, ATLAS-CONF-2020-026

- Targets $t\bar{t}H$ and tH processes in the STXS framework

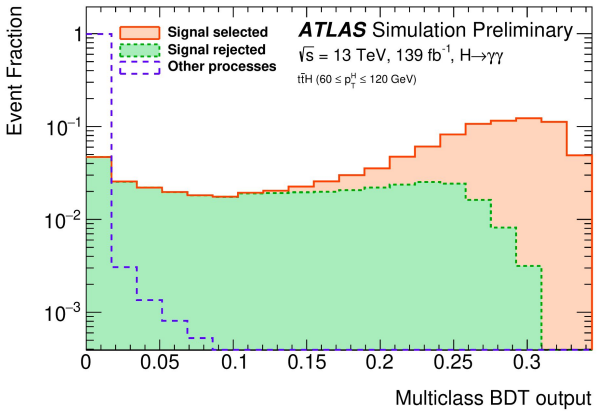
≥2 loose photons + reconstructed vertices

Diphoton selection
NN to identify production vertex
(Sub-)leading photon p_T>(0.25)0.35$m_{\gamma\gamma}$

Binary BDT trained to separate signal from backgrounds and further subdivide STXS classes

Multiclass BDT trained on Higgs events from multiple production processes

0-60 (2)	60-120 (2)	120-200 (2)	tHW	tHqb
200-300	300-∞	$t\bar{t}H$		

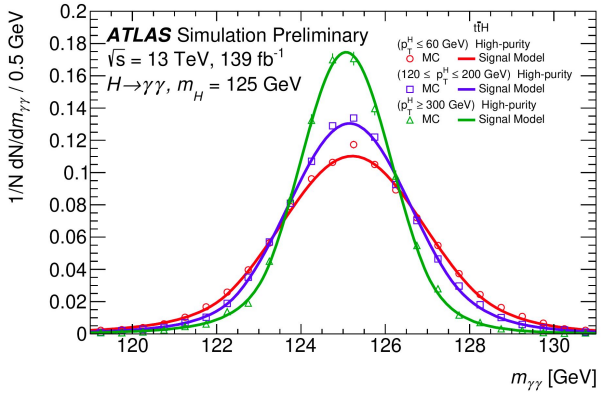


- BDT's trained using multiplicity and kinematic properties of photons, jets and leptons and event-level quantities
- Variables with a correlation with $m_{\gamma\gamma}$ above 5% are removed

Measurement of Higgs boson production in H→$\gamma\gamma$ decay channel

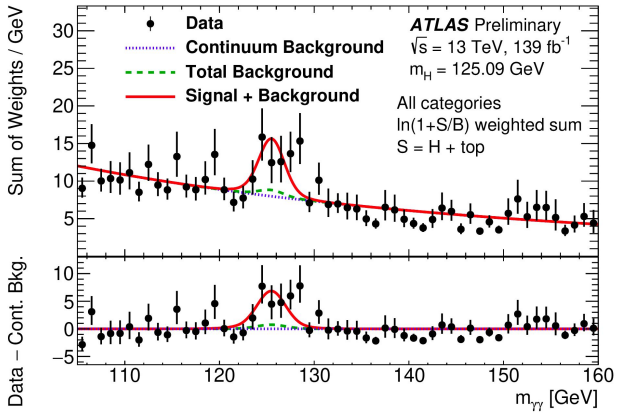
$\mathcal{L}$ = 139 /fb at 13 TeV, ATLAS-CONF-2020-026

- Signal modeled as **double-sided Crystal ball** function
- Background modelled as power law, Bernstein polynomials or exponential function of polynomial
  - Chosen by spurious signal test
- Simultaneous maximum likelihood fit performed in 88 analysis categories (10 dedicated to $t\bar{t}H$/tH) to $m_{\gamma\gamma}$



Results

- Observed significance of $t\bar{t}H$+tH processes: 4.7σ
- Measured $t\bar{t}H$+tH signal strength: $\mu = 0.92^{+0.27}_{-0.24}$
- **Upper limit for tH** at 95% CL: **8 x SM** (most stringent to date)
- Dominated by statistical uncertainty
- Leading experimental uncertainty is photon energy resolution



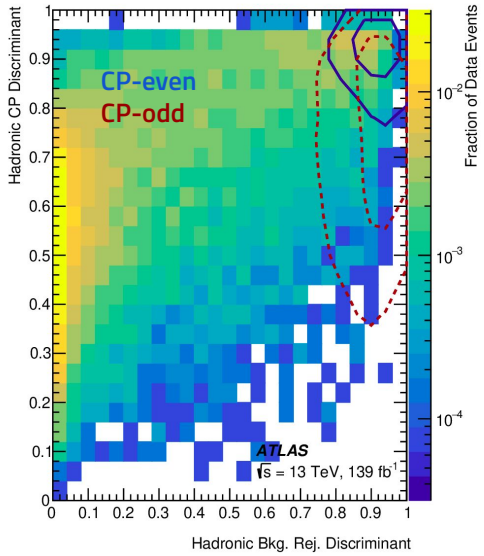
CP properties of Higgs boson interaction with top quarks in H→$\gamma\gamma$

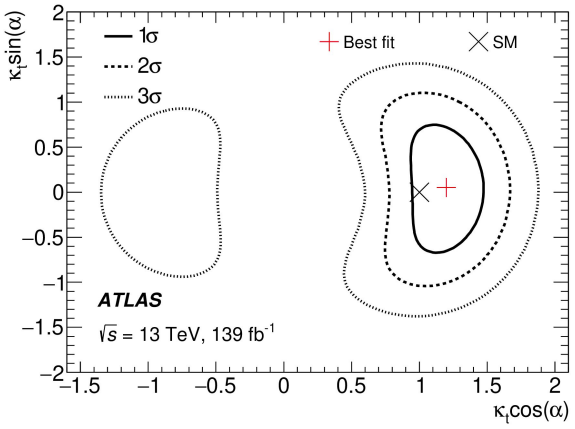
$\mathcal{L}$ = 139 /fb at 13 TeV, Phys. Rev. Lett. 125 (2020) 061802

- Shares some similarities with STXS analysis: diphoton vertex, signal modelling and discriminant variable ($m_{\gamma\gamma}$)
- Targets **leptonic** and fully **hadronic** of the $t\bar{t}$ pair: defined based on number of jets and leptons
- 2 sets of BDT's to discriminate **$t\bar{t}H$ from backgrounds** and **CP-even/odd $t\bar{t}H$+tH** production
  - Trained separately in the hadronic and leptonic channels
- Categories defined in 2D BDT space ⇒ Total of 20 analysis categories (12 hadronic and 8 leptonic)
- Simultaneous maximum likelihood fit in all categories

Top-Yukawa coupling results

- $|\alpha| > 43°$ is excluded at 95% CL
- Pure CP-odd coupling (α=90°) is excluded at 3.9σ





Higgs boson production cross-section measurement in the H→ZZ*→4ℓ decay channel

$\mathcal{L}$ = 139 /fb at 13 TeV, Eur. Phys. J. C 80 (2020) 957

- Targets **leptonic** and fully **hadronic** of the $t\bar{t}$ pair and events consistent with a 4ℓ vertex

≥2 same-flavour, opposite charge lepton pairs

Quadruplet: m_{12}, m_{34}

Higgs candidates selection

$50<m_{12}<106$ GeV, $m_{min}<m_{34}<115$ GeV

$\Delta R(\ell,\ell)>0.1$ and lepton isolation

Impact parameter and common vertex

Leptonic

≥1 add. ℓ, ≥2 b-jets (@85%)

≥5 jets, ≥1 b-jet (@85%)

≥2 jets, ≥1 b-jet (@60%)

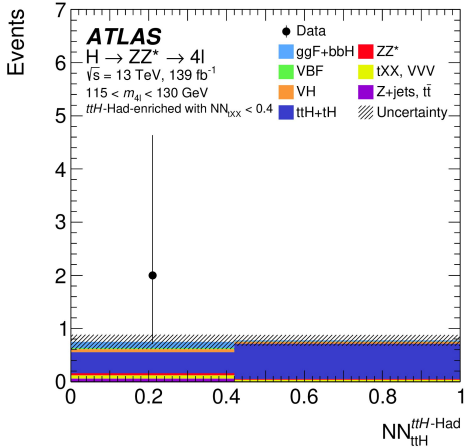
Taken inclusively due to low stats

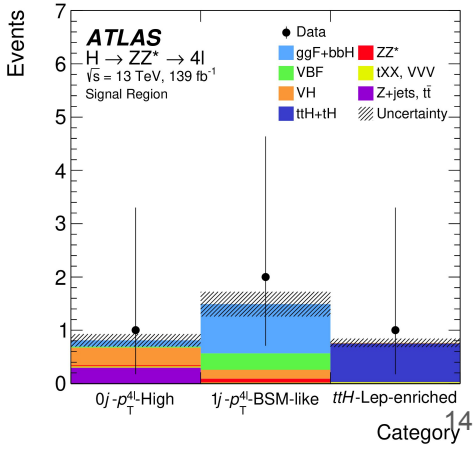
Hadronic

≥5 jets, ≥2 b-jet (@85%)

≥4 jets, ≥1 b-jet (@60%)

NN trained to separate $t\bar{t}H$ from ttV and ggF

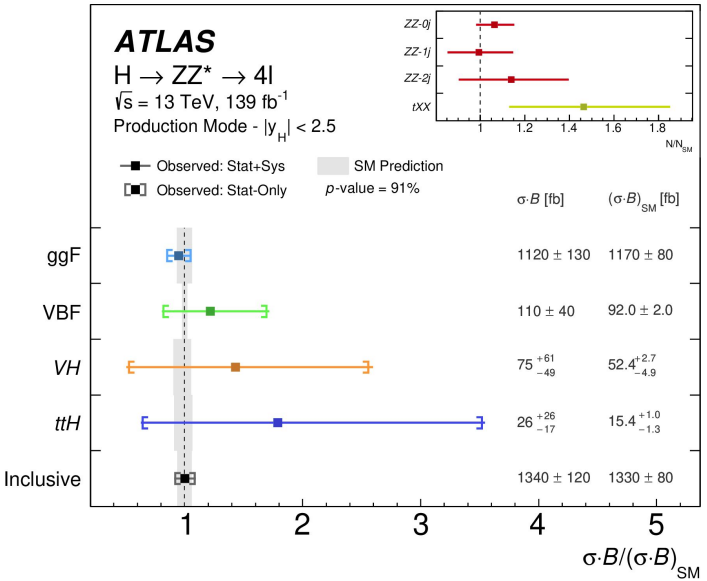




Higgs boson production cross-section measurement in the H→ZZ*→4ℓ decay channel

$\mathcal{L}$ = 139 /fb at 13 TeV, Eur. Phys. J. C 80 (2020) 957

- In $t\bar{t}H$ enriched regions backgrounds containing top quarks and electroweak bosons are dominant
- In the remaining regions, non-resonant ZZ* production is the dominant background
- Backgrounds with non-prompt leptons are significantly smaller



- Simultaneous maximum likelihood fit to regions enriched in different Higgs production modes

Results

- Measured $t\bar{t}H$ signal strength: $\mu = 1.7^{+1.7}_{-1.2}$
- Largely statistically limited
- Significantly less precise than other production modes

Highlights challenges and opportunities in $t\bar{t}H$ production

Conclusions

- Presented new measurements of $t\bar{t}H$ and tH with the ATLAS experiment
  - Analyses targeting H→bb, $\gamma\gamma$, ZZ(→4ℓ), $\tau_{had}\tau_{had}$ already updated with full Run-2 dataset (139 /fb)
- Higgs boson associated production with top quarks leads to complex final states
  - Sensitivity enhanced by multivariate analysis techniques and precise background modeling
- Largest ever dataset allows for measurements of the structure of the top Yukawa coupling
  - Charge-parity measurements performed in H→bb, $\gamma\gamma$
- All measurement compatible with the SM expectations
- Better (theoretical and experimental) understanding of ttbb, ttW and ttZ backgrounds is crucial
  - Limiting factor in H→bb and multilepton analyses

Thank you

Backup

Measurement of Higgs boson production in association with tt pair in H→$\gamma\gamma$ decay channel

$\mathcal{L}$ = 139 /fb at 13 TeV, ATLAS-CONF-2019-004

- Targets **leptonic** and fully **hadronic** of the $t\bar{t}$ pair and events with a primary diphoton vertex

≥2 loose photons + reconstructed vertices

Diphoton selection

NN to identify production vertex

(Sub-)leading photon p_T>(0.25)0.35$m_{\gamma\gamma}$

105<$m_{\gamma\gamma}$<160 GeV

Leptonic

≥1 isolated lepton

≥1 b-jet, p_T>25 GeV

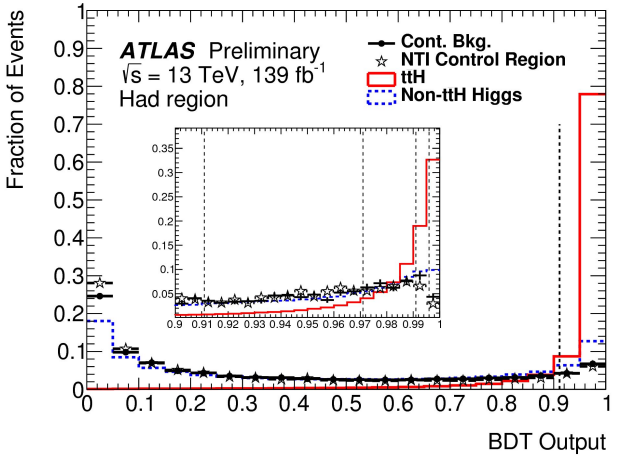
BDT: 3 categories

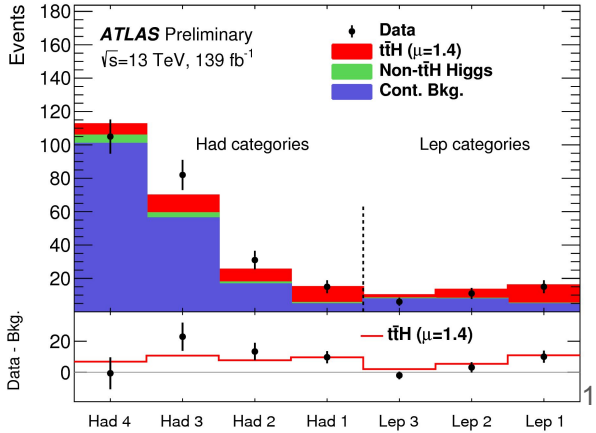
Hadronic

No reconstructed leptons

≥1 b-jet, ≥2 jets, p_T>25 GeV

BDT: 4 categories

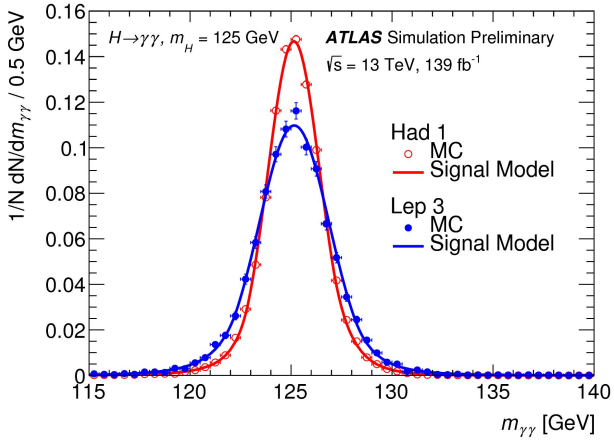




Measurement of Higgs boson production in association with tt pair in H→$\gamma\gamma$ decay channel

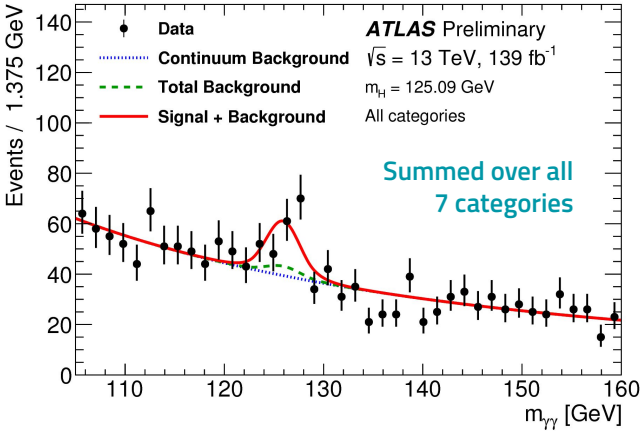
$\mathcal{L}$ = 139 /fb at 13 TeV, ATLAS-CONF-2019-004

- Signal modeled as **double-sided Crystal ball** function
- Background modelled as **power law** or **exponential**
  - Chosen by spurious signal test
  - Single-parameter functions chosen due to low stats
- Simultaneous maximum likelihood fit performed in the 7 analysis categories



Results

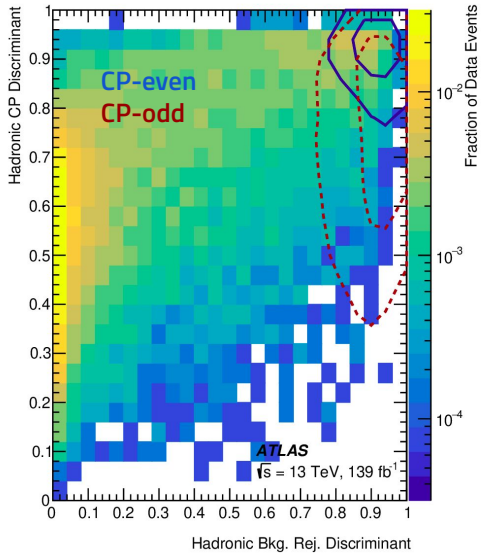
- Observed significance: 4.9 σ
- Observed signal strength: $\mu = 1.43^{+0.33}_{-0.31}(\text{stat})^{+0.21}_{-0.15}(\text{sys})$
- Upper limit for tH at 95% CL: 12 x SM
- Dominated by statistical uncertainty
- Photon energy scale and resolution are the leading experimental uncertainties



CP properties of Higgs boson interaction with top quarks in H→$\gamma\gamma$

$\mathcal{L}$ = 139 /fb at 13 TeV, [Phys. Rev. Lett. 125 (2020) 061802]

- Follows closely strategy of rate analysis, with tH included as signal
- CP-odd contribution parameterized as a function of (k_t, α)
- **Additional BDT's to discriminate CP-even/odd ttH+tH production**
  - Trained separately in the hadronic and leptonic channels
- Categories defined in 2D BDT space ⇒ Total of 20 analysis categories (12 hadronic and 8 leptonic)
- Simultaneous maximum likelihood fit in all categories



Top-Yukawa coupling results

- $|\alpha| > 43°$ is excluded at 95% CL
- Pure CP-odd coupling (α=90°) is excluded at 3.9σ
- Signal strength and cross section also extracted ⇒ Compatible with cross-section analysis