Property measurements of the Higgs boson production in association with top quark at the ATLAS detector

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on behalf of the ATLAS Collaboration

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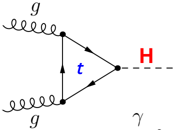
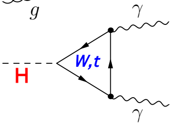
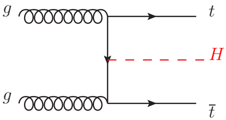
Introduction: Top quark Yukawa coupling

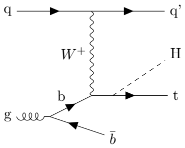


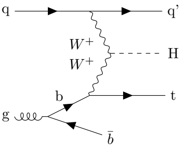


- Yukawa coupling of the Higgs boson and fermions (λ_f): proportional to fermion mass
  - Top quark is heaviest fermion in the SM $\rightarrow$ Largest Yukawa coupling: $\lambda_t \approx 1$
  - Only coupling that cannot be observed in Higgs decays
- Contributes to gluon-gluon fusion (ggF) and $H \rightarrow \gamma\gamma$ decays $\rightarrow$ Could be used to determine λ_t but under model assumptions

- ***$t\bar{t}H$* production:** best direct way to measure λ_t
  - Tree-level process, cross-section proportional to λ_t^2
  - Cross-section ($\sqrt{s} = 13$ TeV): 0.5 pb ($\sim 70 \times 10^3$ events in Run 2)



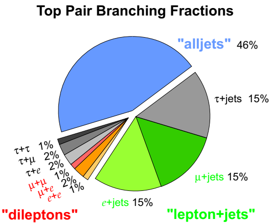




- **Single top+Higgs production:**
  - Lower cross-section: 0.09 pb at $\sqrt{s} = 13$ TeV in the SM (mainly *tHqb* production)
  - Interference between top and *W* couplings $\rightarrow$ Sensitive to the sign of λ_t and BSM effects

Measuring $t\bar{t}H$ production

- Combination of top quark and H decays $\rightarrow$ Complex final states, with many objects: jets, b-jets, light leptons (ℓ), hadronic taus (τ_{had}), photons



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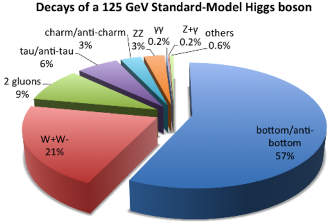
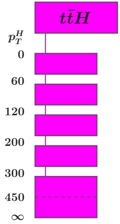


- Top quark Yukawa coupling measured in different analyses in ATLAS and established with $>5\sigma$ significance in PLB 784 (2018) 173
- Results of the measured couplings are usually expressed in terms of signal strength $\mu = \sigma/\sigma_{\text{SM}}$ or coupling modifier κ_t
- $t\bar{t}H$ also part of the Simplified Template Cross-Section (STXS) framework: 5 bins in Higgs boson p_T



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

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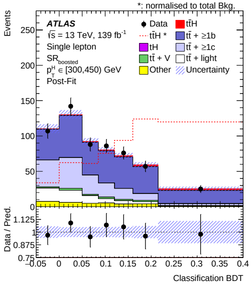
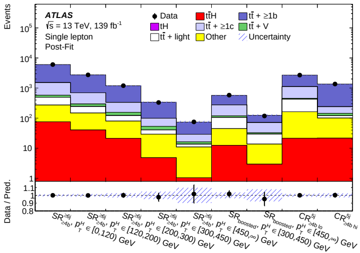
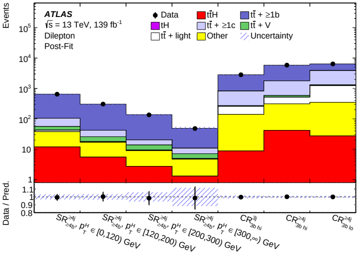
- **Large signal branching ratio but also large background from $t\bar{t}$+b-jet production ($\sim$15 pb)**
- Events categorized by $t\bar{t}$ decay ($1/2\ell$) and p_T^H, including 1ℓ boosted categories for $p_T^H > 300$ GeV
- Signal and control regions built using number of jets and various b-tagging requirements
- MVAs used for event reconstruction and classification
- Dedicated uncertainty covering pre-fit mismodelling for $p_T^{b\bar{b}}$ distribution







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

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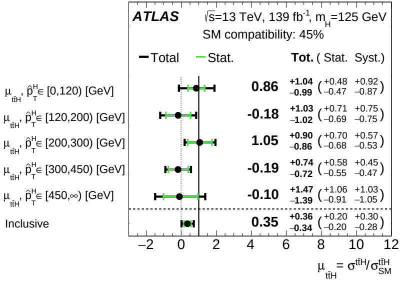
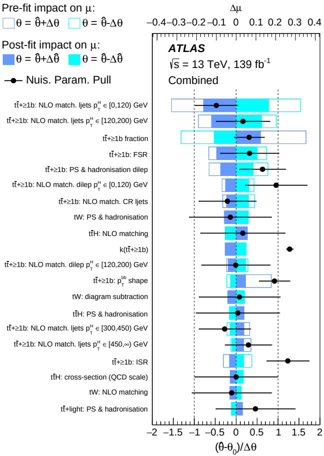
- Inclusive results: $\mu_{t\bar{t}H} = \mathbf{0.35^{+0.36}_{-0.34}}$, 1.0$\sigma$ observed significance (2.7σ expected)
- Measured μ for five separate p_T^H STXS bins





- Sensitivity dominated by uncertainties on $t\bar{t}+\geq 1b$ background modeling (despite significant improvement relative to previous measurements)
- Most relevant uncertainties: $t\bar{t}$ NLO matching (MadGraph5 vs. Powheg), $t\bar{t}+\geq 1b$ fractions (Powheg+Herwig7/Pythia8) and FSR variations

Couplings/STXS: $t\bar{t}H$, tH with $H \to \gamma\gamma$

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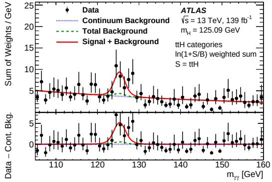
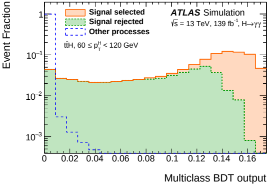
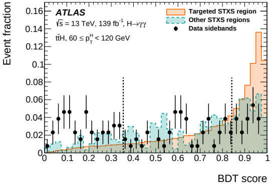




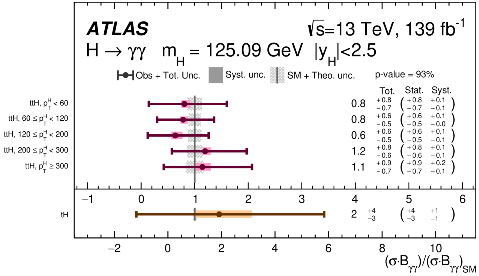


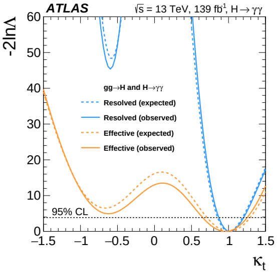
- **Relatively low signal yields but clear signal peak and low background level**
- Multiclass BDT to separate signal events in 45 different STXS analysis regions $\to$ Different categories for $t\bar{t}H$, *tHqb* and *tHW*
  - BDT inputs: photon kinematics, $E_{\mathrm{T}}^{\mathrm{miss}}$, number of jets, *b*-jets, reconstructed top quarks, etc.
- Each class is further divided into multiple categories using a binary MVA classifier
- ***$t\bar{t}H$* and *tHW*:** binary BDT classifier separating signal and the continuum $\gamma\gamma$ background
- ***tHqb***: two sub-classes with a neural-network (NN) binary classifier separating $\kappa_t = 1$ vs. $\kappa_t = -1$, then NN separating *tHqb* from continuum background and other Higgs production modes.

Couplings/STXS: $t\bar{t}H$, tH with $H \to \gamma\gamma$

JHEP 07 (2023) 088

- Results: $\mu_{t\bar{t}H} = \mathbf{0.89^{+0.32}_{-0.30}}$ and $\mu_{tH} = \mathbf{2^{+4}_{-3}}$ (both statistically dominated)
- Measured five STXS $t\bar{t}H$ bins as a function of p_T^H
- Probing κ_t with two different models:
  - **Resolved:** using κ_t in the ggF and $H \to \gamma\gamma$ loops
  - **Effective:** effective coupling (κ_g and κ_γ) fixed to the SM prediction $\to$ Sensitivity to the sign of κ_t mostly from tH production
- Effective approach: excluding negative κ_t values by $\geq 2.2\sigma$ and values outside the $0.65 < \kappa_t < 1.25$ range (expected: $0.71 < \kappa_t < 1.29$) at 95% CL

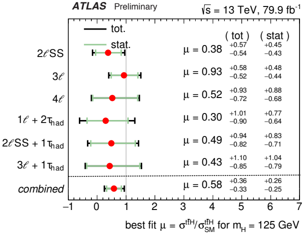


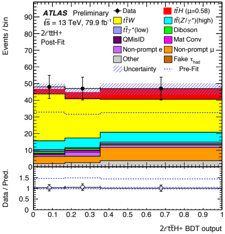


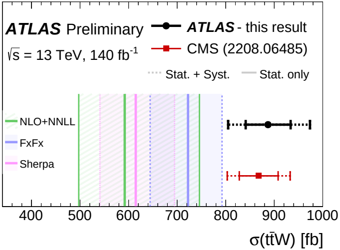
Couplings/STXS: $t\bar{t}H(WW^*, \tau\tau, ZZ^*)$ multi-lepton

ATLAS-CONF-2019-045 (80 fb^{-1})

- **Combination of relative large signal yields and low (despite challenging) background**
- Targeting $H \to WW^*, \tau\tau, ZZ^*$ decays, with leptonic $t\bar{t}$
- Main background: $t\bar{t} \Rightarrow \ell^\pm\ell^\pm$ or $>3\ell +$ b-jets



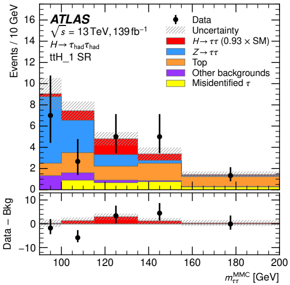


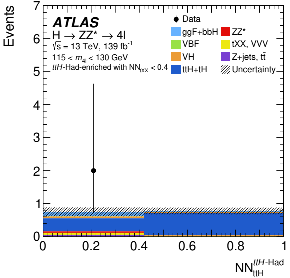


- Results (80 fb^{-1}): $\mu_{t\bar{t}H} = \mathbf{0.58^{+0.36}_{-0.33}}$
- Normalization for $t\bar{t}W$ a factor 1.3-1.7 above the theoretical predictions available at the time
- Recent $t\bar{t}W$ cross-section measurement (ATLAS-CONF-2023-019, full Run 2 data) confirmed tensions even with updated theoretical predictions (now incorporating higher order QCD and EWK corrections)

Couplings/STXS: $t\bar{t}H(\tau\tau, ZZ^*)$ resonant

EPJC 80 (2020) 957, JHEP 08 (2022) 175



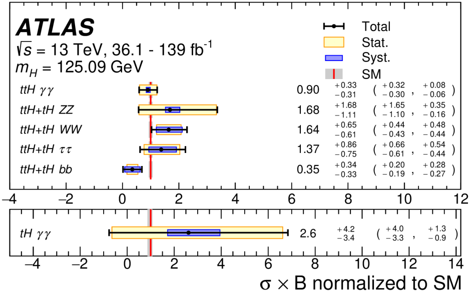


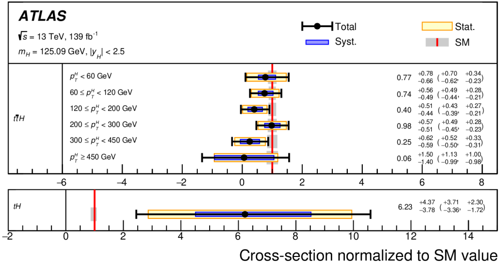
- $t\bar{t}H$ production also explored in leptonic resonant Higgs decays using full Run 2 dataset
- Very good separation from other production modes achieved with jet and *b*-jets requirements, although low signal yields expected
- $t\bar{t}H(\tau_{had}\tau_{had})$ with fully hadronic tau-lepton and top quark decays:
  - Two BDTs employed to separate signal from $Z\to\tau\tau$ and top backgrounds
  - Results: $\mu_{t\bar{t}H} = \mathbf{1.06}^{+1.07}_{-0.94}(\text{stat})^{+0.70}_{-0.53}(\text{syst})$
- $t\bar{t}H(ZZ^*\to 4\ell)$ targeting hadronic and leptonic top quark decays:
  - Neural network to separate $t\bar{t}H$ from t+XX processes in the hadronic channel
  - Results: $\mu_{t\bar{t}H} = \mathbf{1.7}^{+1.7}_{-1.2}(\text{stat})^{+0.3}_{-0.2}(\text{syst})$

Couplings/STXS: $t\bar{t}H$ combination

Nature 607, 52 (2022)

- Detailed $t\bar{t}H$ and tH combination for the 10th anniversary of the discovery
- Split of $t\bar{t}H$ measurements for different decay modes ($\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, $b\bar{b}$)
- Including $t\bar{t}H$ multilepton results from PRD 97 (2018) 072003 (36 fb^{-1})





- Combined measurements for six STXS p_T^H bins
- Low p_T^H limited by statistics ($H \to \gamma\gamma$) and higher p_T^H more affected by systematics
- **Very good agreement with the SM predictions**

CP properties of top-Higgs interactions

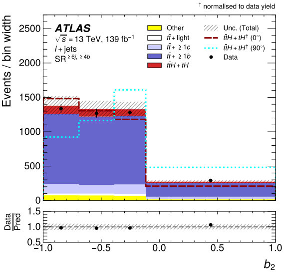
- In the SM, the Higgs boson is CP-even ($J^{CP} = 0^{++}$, scalar)
- Signs of a CP-odd ($J^{CP} = 0^{+-}$, pseudoscalar) couplings to SM particles (or an CP-odd/even admixture) would be a indication of BSM physics
  - Motivation: New sources of CP violation needed to explain baryon asymmetry in the university (besides the CKM matrix)
- Effective Lagrangian describing the top quark Yukawa coupling can be parametrized as:

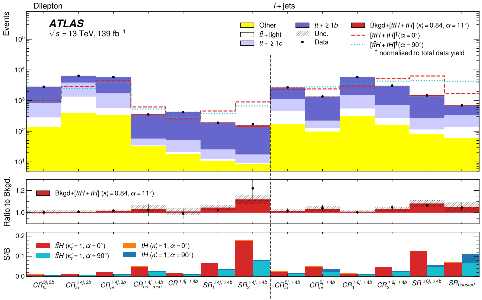
$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

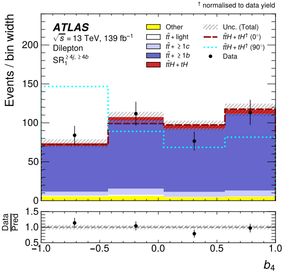
- $\boldsymbol{\kappa_t}$: coupling modifier parameter (SM: $\kappa_t = 1$)
  - Values of $\kappa_t \neq 1$ would induce changes in the total cross-section
- $\boldsymbol{\alpha}$: CP mixing angle (SM: $\alpha = 0$; pure CP-odd: $\alpha = 90^o$)
  - Values of $\alpha \neq 0$ would imply an admixture with pseudoscalar coupling $\rightarrow$ Changes in cross-section and kinematics
- Dedicated analyses exploring the CP properties of the top-Higgs interaction exploiting $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$ decays

CP properties: $t\bar{t}H/tH$, $H \to b\bar{b}$

arXiv:2303.05974





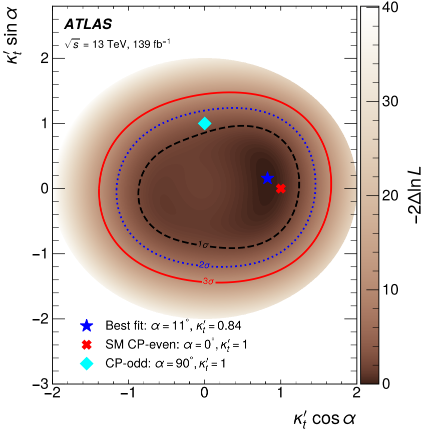


- Similar strategy as couplings/STXS analysis but now also considering *tH* signal
- Dedicated *CP*-sensitive variables built with angular distance between top quarks or lepton candidates:
  - b_2: enhanced for top quarks in opposite directions and closer to the beam pipe $\quad b_2 = \dfrac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$
  - b_4: narrower azimuthal separation of top quarks for *CP*-odd case $\quad b_4 = \dfrac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$

CP properties: $t\bar{t}H/tH$, $H \to b\bar{b}$

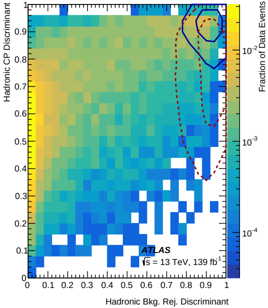
arXiv:2303.05974

- Most relevant systematic uncertainties:
  - $t\bar{t}+\geq 1b$ 4 flavour scheme (massive b-quarks, only from $g \to b\bar{b}$) vs. 5 flavour scheme (massless b-quarks, in the PDF)
  - NLO matching (PowhegBox vs. MadGraph5_aMC@NLO)
  - Relative fractions of $t\bar{t}+1b$ and $t\bar{t}+\geq 2b$
- Best-fit value:
  $\alpha = 11^{+56}_{-77}$ degrees
  $\kappa_t = 0.84^{+0.30}_{-0.46}$
- In agreement with the SM expectations of $\kappa_t = 1$ and $\alpha = 0$
- *CP*-odd hypothesis ($\alpha = 90^o$) excluded at 1.2σ significance

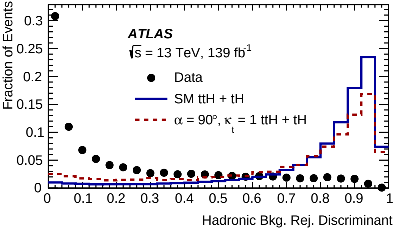


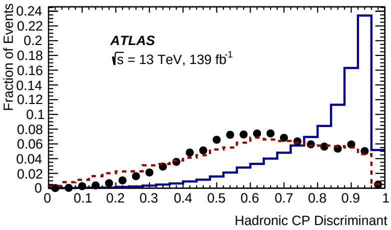
CP properties: $t\bar{t}H/tH$, $H \to \gamma\gamma$

PRL 125 (2020) 061802



- Two separate channels (0/$\geq$1 leptons)
- Categories defined using two BDTs:
  - Background rejection: $t\bar{t}H$ vs. main backgrounds ($\gamma\gamma$+jets, $t\bar{t}\gamma\gamma$)
  - *CP* BDT: separate ***CP*-odd** and ***CP*-even** couplings in the signal
- 12 categories for hadronic top decays and 8 for leptonically top decays





CP properties: $t\bar{t}H/tH$, $H \to \gamma\gamma$

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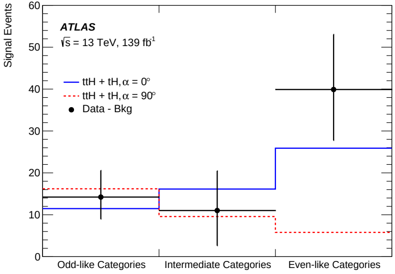
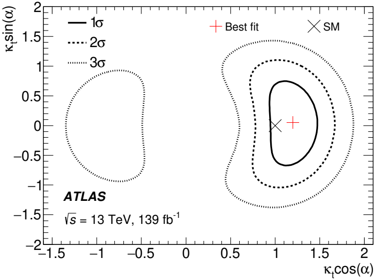
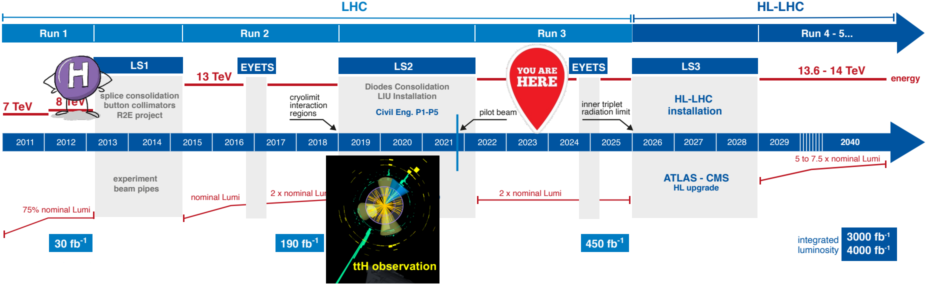




- Simultaneous fit to $m_{\gamma\gamma}$ in all categories
  - Higgs couplings to photons and gluons constrained by the Run 2 combination results in PRD 101 (2020) 012002 (up to 80 fb^{-1})
  - Dominated by statistical uncertainties
- Results strongly favouring the *CP*-even hypothesis:
  - Exclusion of $|\alpha| > 43^o$ at 95% CL
  - Pure *CP*-odd coupling excluded at 3.9σ

Summary

- More than 11 years after the discovery of the Higgs boson,
- ... and 5 since the top quark Yukawa coupling was observed
- Going beyond single coupling measurement $\rightarrow$ Exploiting STXS approach with measurements of $t\bar{t}H$ as a function of the Higgs boson p_T
- Several analyses exploring *CP* violation in Higgs-top interactions
- Some of these measurements limited by statistics, others by background understanding ($t\bar{t}W$, $t\bar{t}b\bar{b}$; see talk by Tomáš Ježo on Monday) $\rightarrow$ Stay tuned
- Still a factor 10 more data to be acquired at the LHC!



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Backup Slides

BACKUP: $t\bar{t}H(b\bar{b})$ p_{T}^{H} modelling

- Reweighting pre-fit p_{T}^{H} distribution to match data used as correlated uncertainty between channels $\rightarrow$ 1σ pull in the fit corresponds to correcting the distribution