Higgs production with top quarks at ATLAS

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on behalf of the
ATLAS Collaboration

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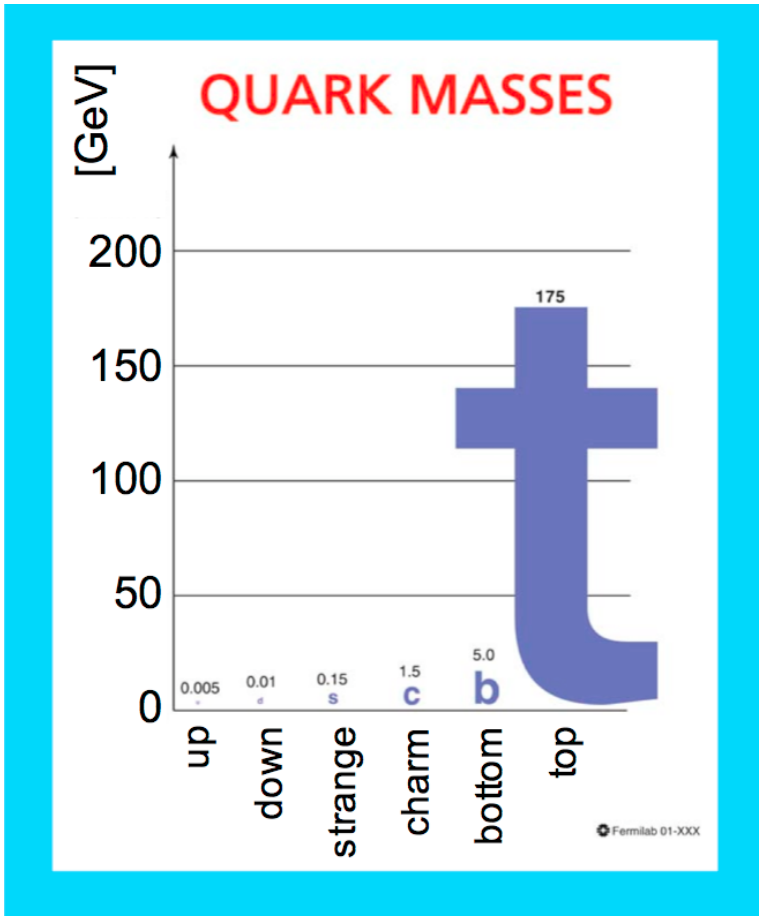
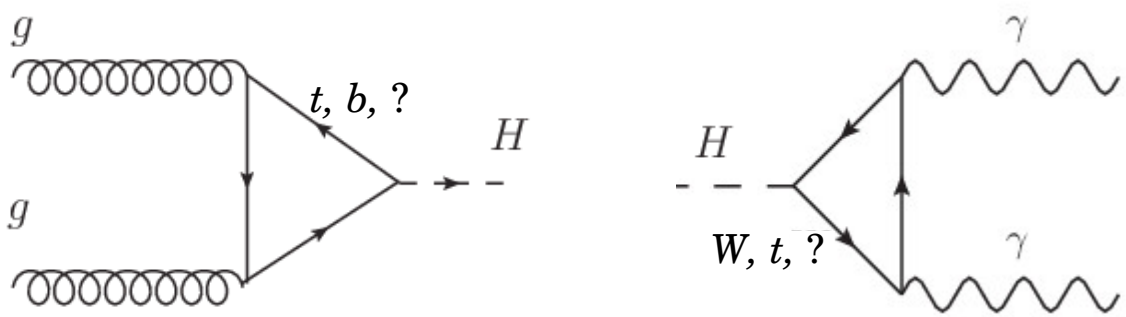
The top-Higgs Yukawa coupling

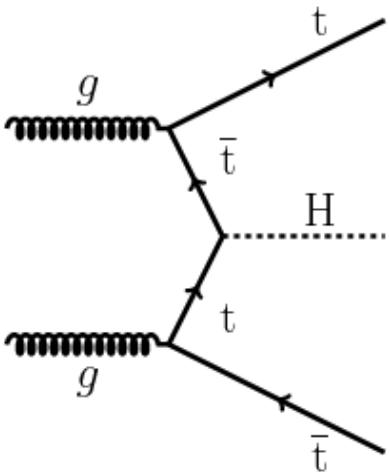
- Key prediction of the Standard Model: fermion masses come from Yukawa interaction with Higgs field → **coupling to Higgs boson is proportional to mass**.
- One fermion in particular stands out as a place to look for BSM effects.
- Top-Higgs coupling can be measured precisely via gluon fusion and γγ decay, but requires assumptions on BSM contributions to loops → **not ideal as test of BSM effects**.

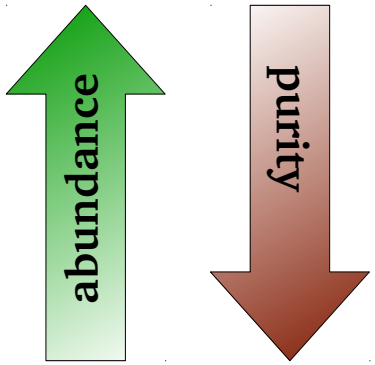


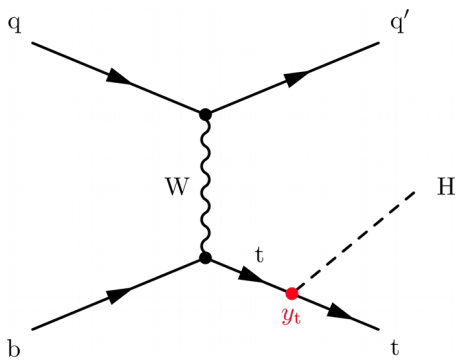


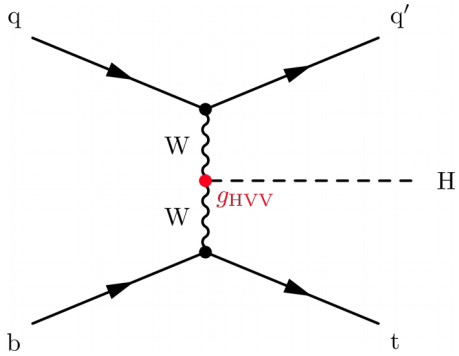
ttH and tH production

- **ttH production**: best chance for **direct observation** of top-Higgs coupling.
  - Represents ~1% of Higgs events at the 13 TeV LHC, but top quarks in final state provide clear signature.
- **tH production**: suppressed by negative interference between Higgs couplings to top and W, but strong senstivity to **non-standard couplings**.
- Analyses divided by **Higgs decay channel**:
  - H → bb
  - "Multilepton"
  - H → γγ
  - H → ZZ* → 4ℓ





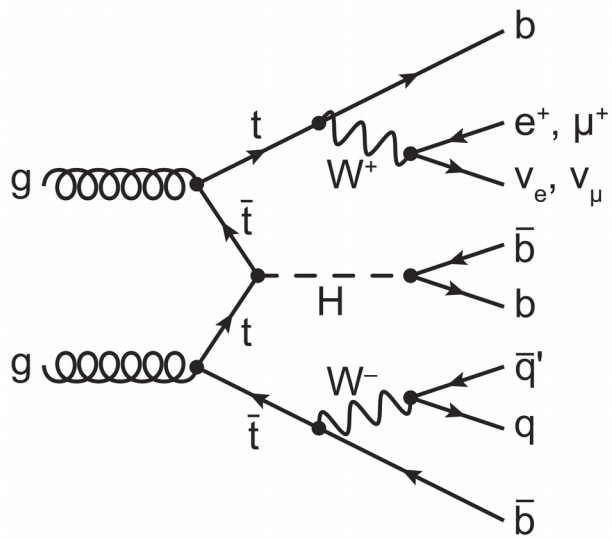


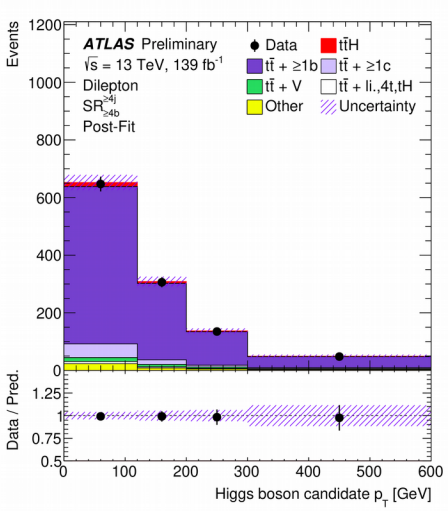


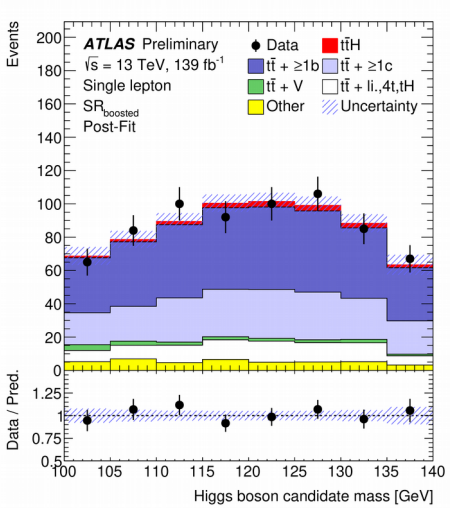
ttH (H→bb): Strategy

ATLAS-CONF-2020-058

- Most common decay mode, but challenging final state:
  - Combinatorics from **many b-jets** makes reconstruction ambiguous.
  - **Large background** from $t\bar{t}$+HF jets.
- Events categorized by $t\bar{t}$ decay mode (dilepton, single-lepton) and candidate Higgs boson p_T.
  - Dedicated **boosted category** in single-lepton targets high-p_T events.
- Sophisticated **multivariate techniques** to separate signal from background, including Jet-assignment BDTs, Deep Neural Network, classification BDT.

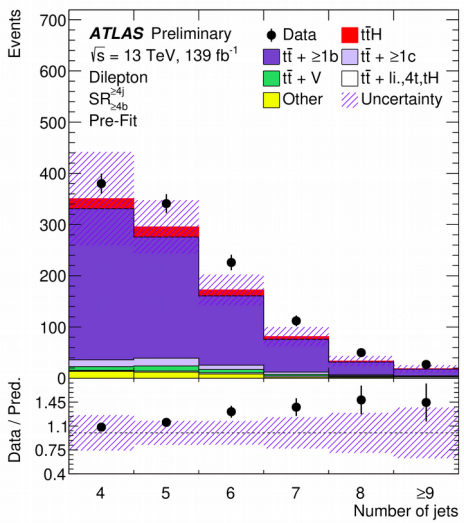


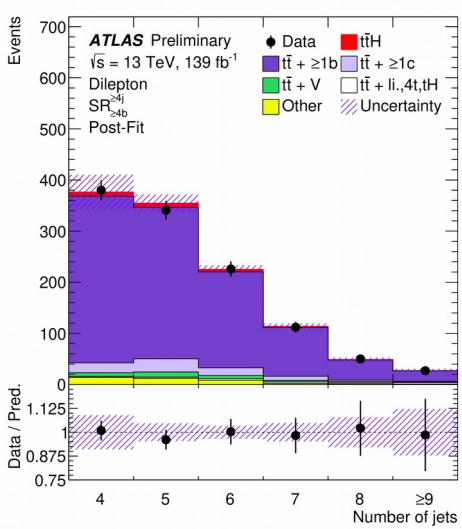


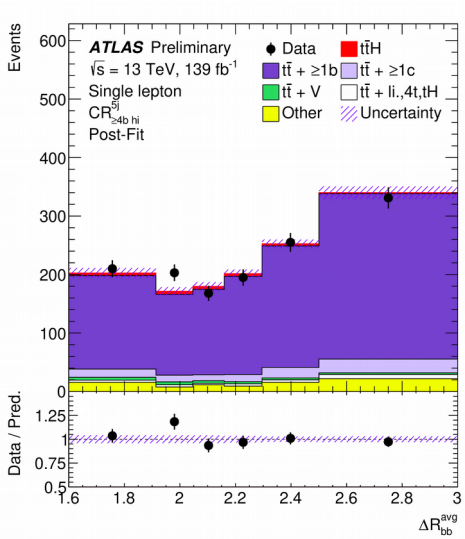


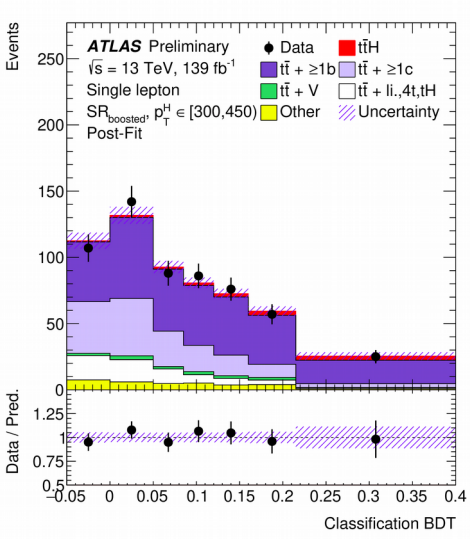
ttH (H→bb): Modelling

- Dominant background from $t\bar{t}$ events with one or more b-jets.
- Modelled using **$t\bar{t}$+$b\bar{b}$ NLO Monte Carlo** in the 4-flavor scheme from Powheg+Pythia8.



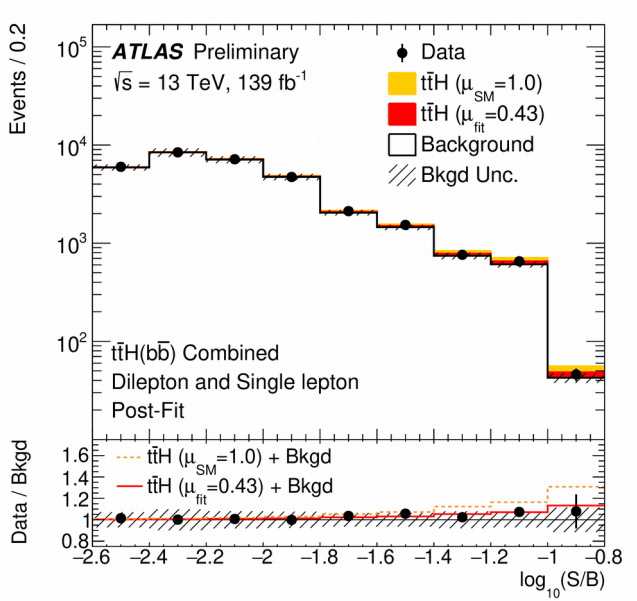


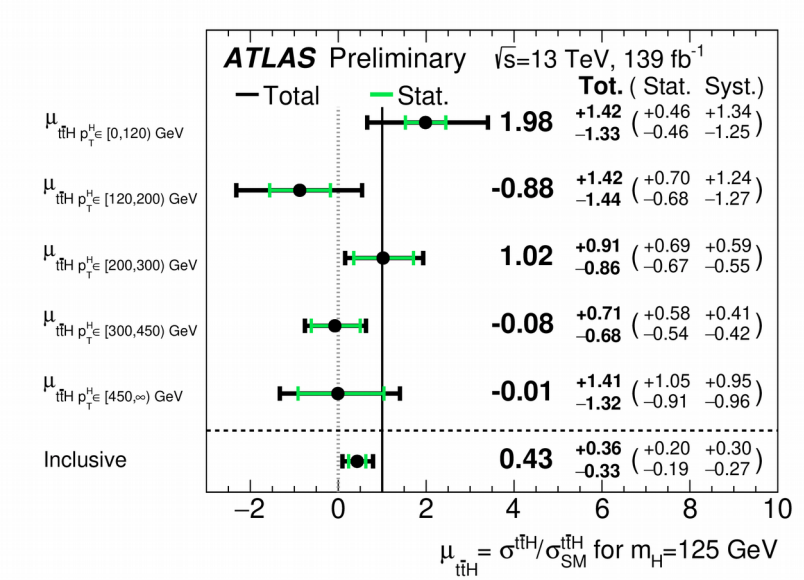




- Clear differences between data and MC in several observables: **profile likelihood fit** to data including background-enriched control regions.
- **Excellent agreement** observed post-fit in all regions.

ttH (H→bb): Results



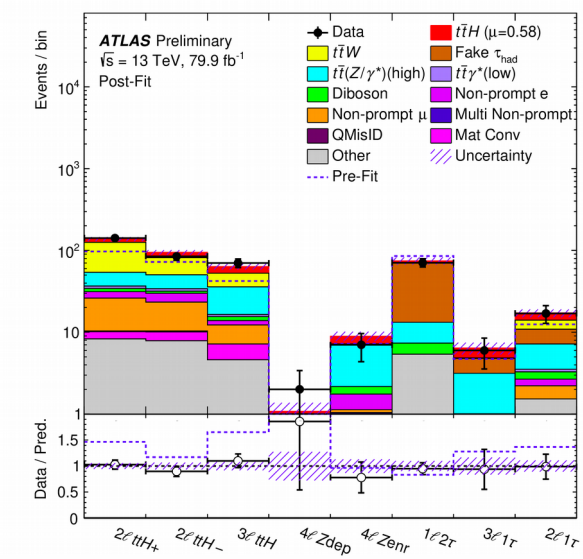


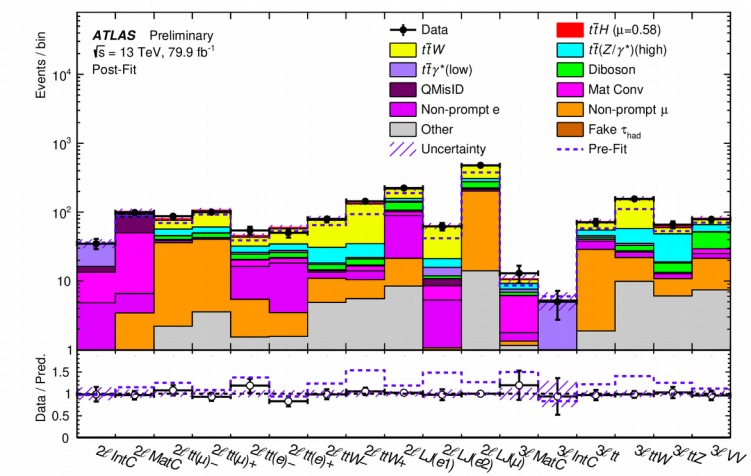
- Measured signal strength $\mu_{ttH} = \sigma/\sigma_{SM}$ of $\mathbf{0.43}^{+0.36}_{-0.33}$; observed/expected significance of **1.3σ**/3.0σ.
- Measurement performed in **STXS bins** of Higgs boson p_T.
  - High statistics and boosted category allow probe of high-p_T regime.
- Results limited by **theoretical uncertainty** on $t\bar{t}$ background as well as data statistics.

ttH Multilepton: Strategy

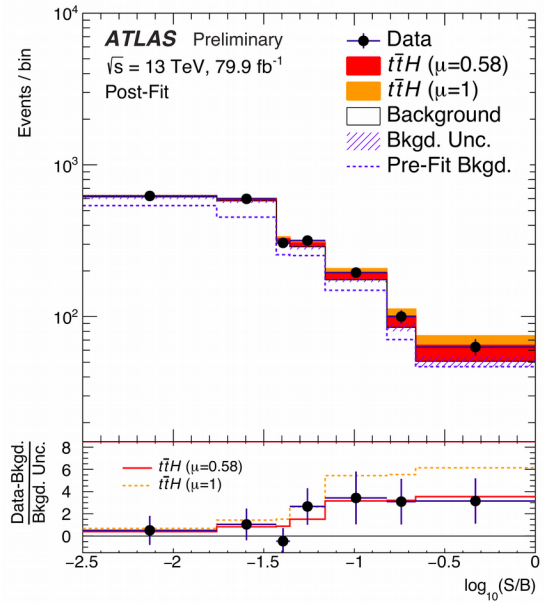
ATLAS-CONF-2019-045

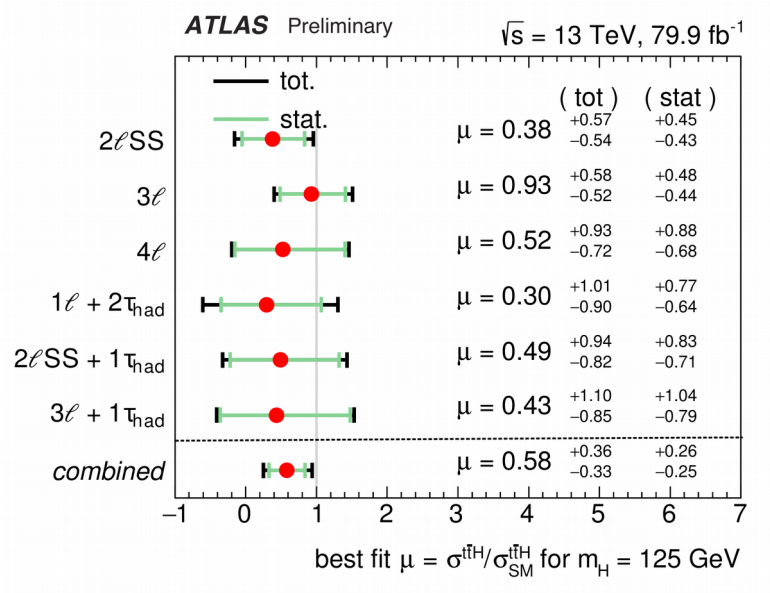
- **H → WW*, ττ, ZZ***: Many decay paths possible. Divide by final state, with focus on those with **high S/B**.
- In most categories, **boosted decision trees** used to enhance signal and define control regions.
- Simultaneous fit of 25 regions.
- Rates of electron charge flip and mis-ID τ_{had} **measured in data**; non-prompt leptons from simulation with data-driven corrections.
- Three normalization factors for $t\bar{t}W$ based on lepton and jet multiplicity.





ttH Multilepton: Results



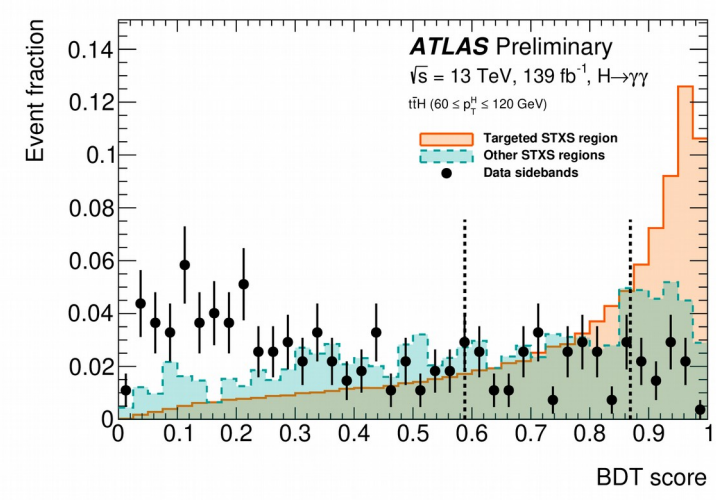


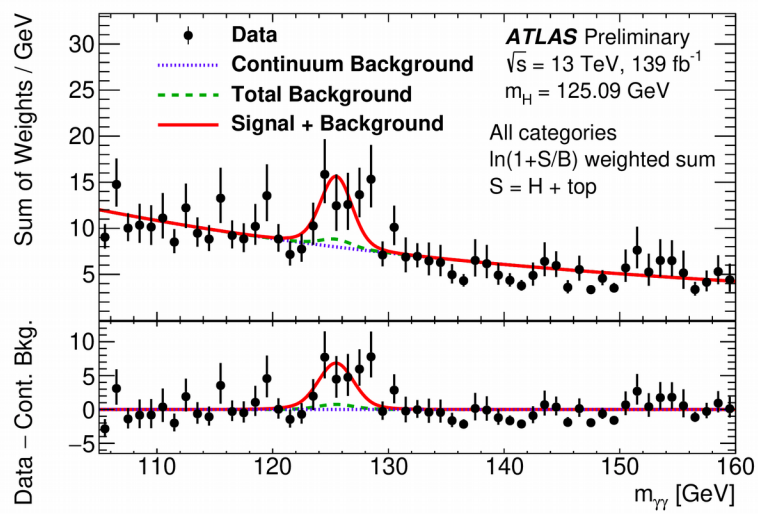
- Best fit signal strength $\mu_{\mathrm{ttH}} = \mathbf{0.58}^{+0.36}_{-0.33}$; observed/expected significance of **1.8σ**/3.1σ.
- $t\bar{t}W$ normalization pulled higher than SM prediction, consistent among regions and other ATLAS analyses.
- Largest uncertainty from data statistics.

ttH/tH (H → γγ) STXS: Strategy

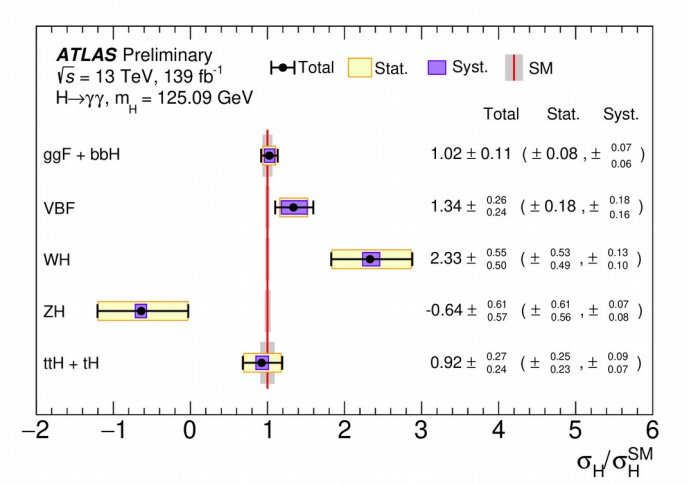
ATLAS-CONF-2020-026

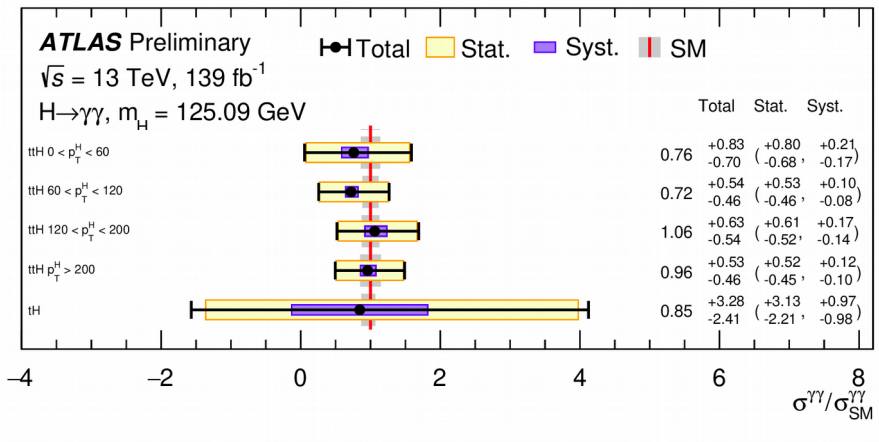
- **H → γγ**: Rare decay (0.2%), but clean final state and fully reconstructable Higgs.
- ttH/tH class distinguished from other production modes using **multi-class BDT**; further categories defined within STXS regions using binary BDTs.
- Dominant continuum di-photon background modelled with exponential function.
- Signal extracted by combined **fit to data** across all categories.





ttH/tH (H → γγ) STXS: Results





- Observed/expected significance of **4.7σ**/5.0σ for top+Higgs production; best fit signal strength $\mu_{\mathrm{ttH+tH}} = \mathbf{0.92}^{+0.27}_{-0.24}$.
- ttH cross-section in 4 bins of Higgs p_T show good agreement with SM.
- tH cross-section higher than **8x SM** is excluded at 95% C.L.
- All results limited by data statistics.

ttH/tH (H → γγ) CP: Strategy

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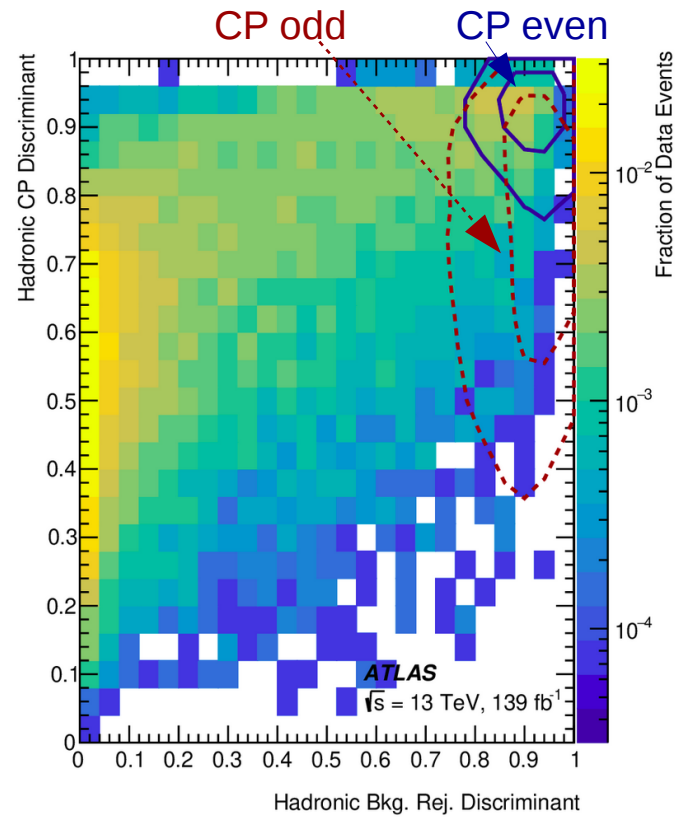
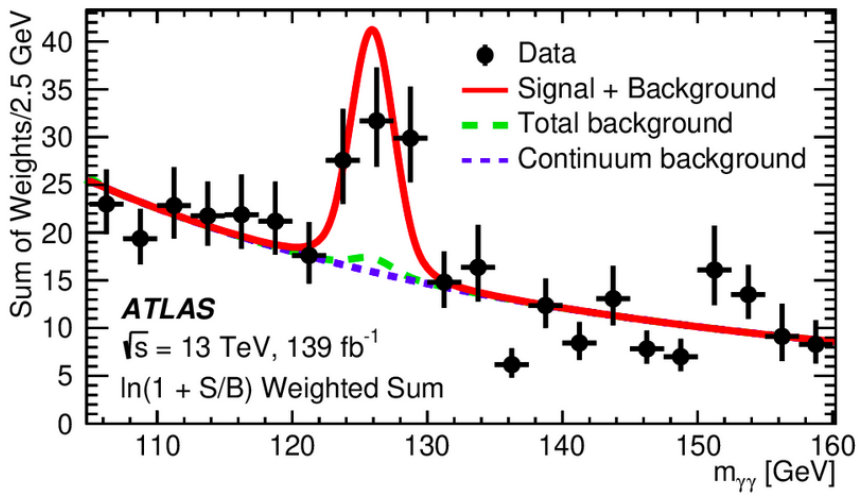
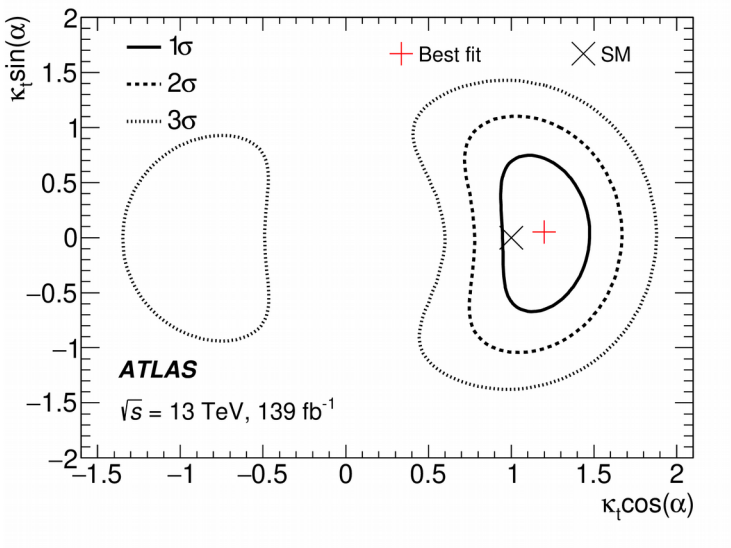
- Clear signal allows for a measurement of the **CP nature** of the top-Higgs interaction.
- Leptonic and hadronic top quark decays are used, and **two BDTs** are trained to distinguish signal from background and CP-odd from CP-even.
- 20 categories defined based on these BDTs, and the signal is extracted by fitting analytical functions to $m_{\gamma\gamma}$ spectra.

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



ttH/tH (H → γγ) CP: Results





- Pure CP-odd interaction (α=90°) **excluded at 3.9σ**, while negative coupling (α=180°) **excluded at 2.5σ**.
- Values of **|α| > 43° excluded** at 95% CL.
- These constraints do not assume κ_t fixed to the SM.

ttH/tH (H → ZZ* → 4ℓ)

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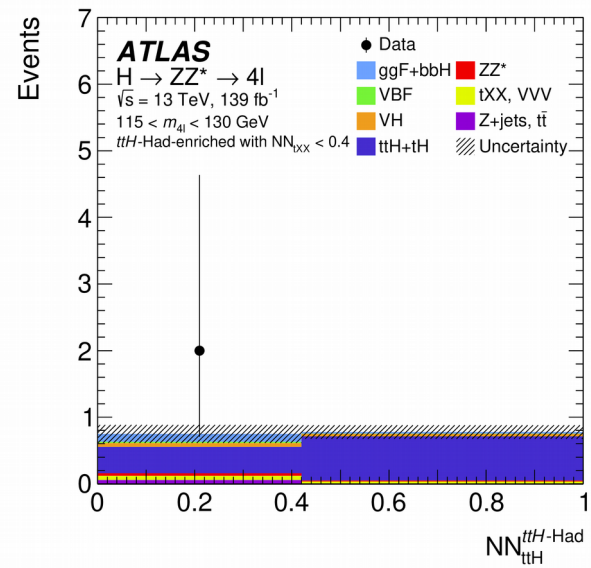
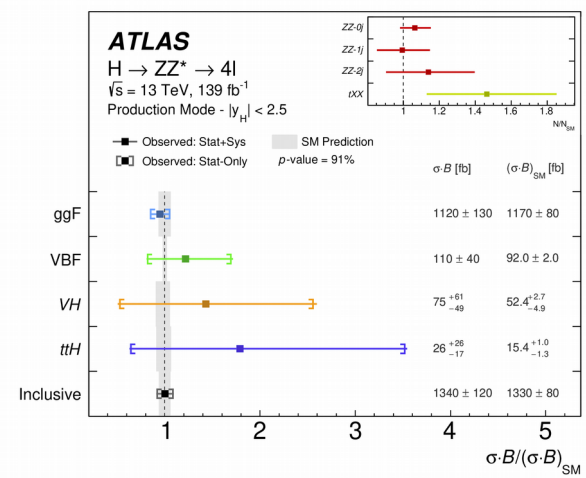
- Events selected with 4 leptons consistent with Higgs boson, and ttH-enriched **hadronic & leptonic categories** defined from additional leptons and b-jets.
  - Neural network used in ttH-Had category.
- 2 (1) events observed in Had (Lep) category, compared to 1.45 (0.44) expected.
- Best fit signal strength $\mu_{\mathrm{tH+ttH}} = \mathbf{1.7}^{+1.7}_{-1.2}$.
- Sensitivity limited by data statistics, but very high purity offers promise for the future.





Summary

- **Observation of ttH production** has fulfilled one of the main goals of the ATLAS Run-II physics program, and has begun to allow detailed studies of the top-Higgs interaction.
- In addition to increasingly precise cross-section values, measurements of the Higgs boson **p_T spectrum** and **CP nature** of the interaction have been performed.
- Limits on **tH production** constrain non-standard coupling scenarios.
- Further precision will come from Run 3 data, as well as improved modelling of the main background sources.

Backup slides