Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

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Introduction

- The coupling of the Higgs boson to the top quark is of particular importance as the top is the heaviest particle in the Standard Model.
- Indirect measurements of the top Yukawa coupling have been performed by probing gluon fusion production and diphoton decay loops.
- However, **Higgs production in association with a pair of top quarks ($t\bar{t}H$)** presents a **direct** tree-level test of the top Yukawa coupling.

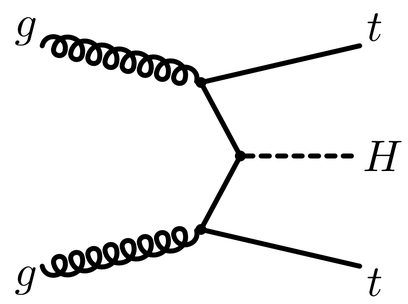

Figure 1: A representative diagram of the $t\bar{t}H$ production mode.

- $t\bar{t}H$ production is measured by the $\gamma\gamma$, four-lepton, multilepton, and $b\bar{b}$ analyses which target various Higgs decay channels using up to 79.8 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data collected by the ATLAS detector.
- The 13 TeV $\gamma\gamma$ and four-lepton analyses are **newly optimized**.
- The 13 TeV analyses are combined with previous analyses at 7 and 8 TeV.
- The combined results establish **observation** of the production of the Higgs boson in association with a top quark pair.

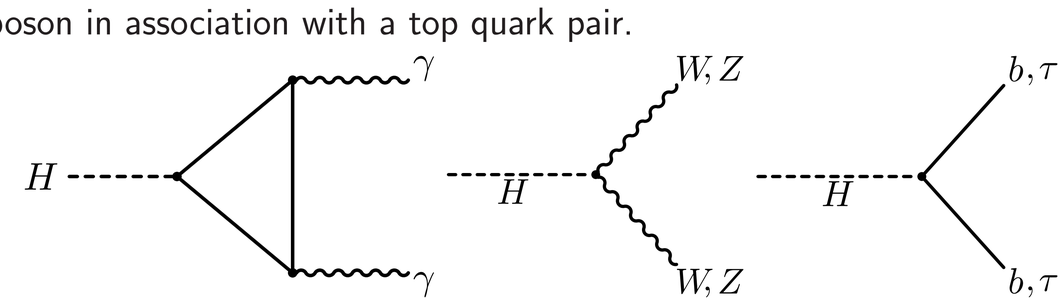

Figure 2: Representative diagrams for the Higgs decay modes targeted by the various analyses.

$t\bar{t}H(H \to \gamma\gamma)$ Analysis (79.8 fb^{-1} , 13 TeV)

- Events are selected requiring two photons, and split into two regions, **hadronic** and **leptonic**, based on the decay of the top quark.
- The main backgrounds include non-resonant $\gamma\gamma$ events with heavy flavor and $t\bar{t}\gamma\gamma$ production.
- Two boosted decision trees are trained using the **XGBoost** machine learning package.
- Excellent separation between signal and background is achieved by focusing on **object-level variables**, such as the p_T and η of the photons, jets, and leptons.

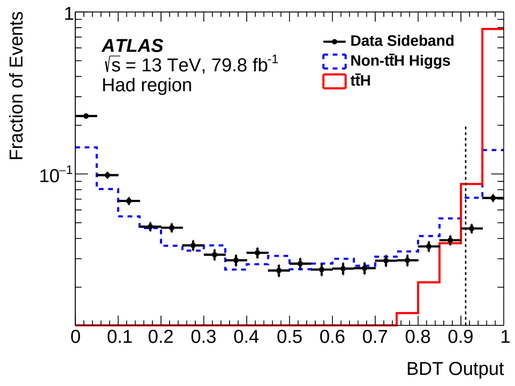

Figure 3: The BDT response curve in the hadronic region. Events to the left of the dashed line are rejected.

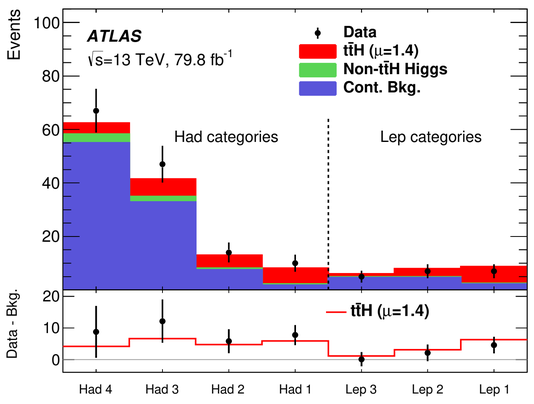

Figure 4: The observed data, expected background, and expected $t\bar{t}H$ signal in each category.

- Four hadronic categories and three leptonic categories are defined based on the BDT discriminant.
- The $t\bar{t}H$ signal strength is obtained from a simultaneous fit to the diphoton mass spectrum $m_{\gamma\gamma}$ across all categories.
- The observed (expected) significance is $\mathbf{4.1\sigma}$ $(\mathbf{3.7\sigma})$.

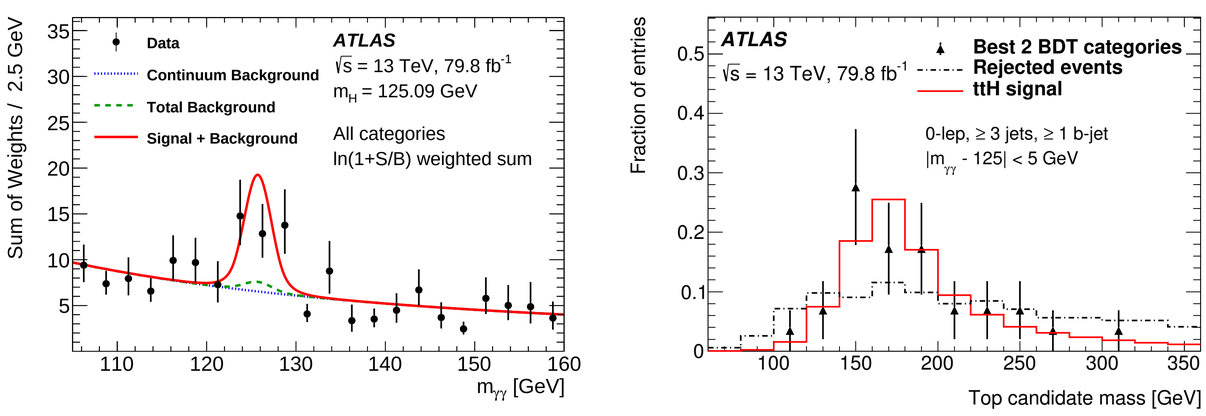

Figure 5: The diphoton mass spectrum of the selected events in all seven categories, weighted by ln(1+S/B) of each category (Left), and a reconstructed top mass for the best selected events, rejected events, and $t\bar{t}H$ signal (Right). The top mass variable is not used in the BDT training.

$t\bar{t}H(H \to \mathit{Four\text{-}Lepton})$ Analysis (79.8 fb^{-1} , 13 TeV)

- The four-lepton analysis targets the $ZZ^* \to 4\ell$ decay of the Higgs, selecting events with four electrons, four muons, or two electrons and two muons.
- The main backgrounds include $t\bar{t}W$, $t\bar{t}Z$, and non-$t\bar{t}H$ Higgs boson production, which are estimated from simulation.
- No events are observed. The observed (expected) significance is $\mathbf{0\sigma}$ $(\mathbf{1.2\sigma})$.

$t\bar{t}H$ Multilepton Analysis (36.1 fb^{-1} , 13 TeV)

- The multilepton analysis targets Higgs decays into the WW^*, $\tau\tau$, and ZZ^* (excluding $ZZ^* \to 4\ell$) final states.
- Events are categorized into eight signal regions based on the number and flavor of charged leptons, including hadronically decaying τs.
- The main backgrounds include $t\bar{t}V$ production and events with non-prompt leptons or fake hadronic τs.
- The observed (expected) significance is $\mathbf{4.1\sigma}$ $(\mathbf{2.8\sigma})$.

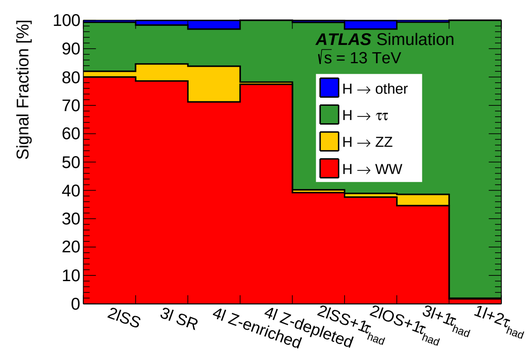

Figure 6: The fraction of expected $t\bar{t}H$ signal from each targeted decay mode.

$t\bar{t}H(H \to b\bar{b})$ Analysis (36.1 fb^{-1} , 13 TeV)

- Events are selected requiring leptons from top quark decays, and are then categorized by the number of jets and b-tagging discriminants.
- The main backgrounds include $t\bar{t}$ + jets events.
- The observed (expected) significance is $\mathbf{1.4\sigma}$ $(\mathbf{1.6\sigma})$.

Combination and Results

- The following analyses are included in the combination:
  - The $\gamma\gamma$ and four-lepton analyses using 79.8 fb^{-1} of 13 TeV data
  - The multilepton and $b\bar{b}$ analyses using 36.1 fb^{-1} of 13 TeV data
  - The $\gamma\gamma$, multilepton, and $b\bar{b}$ analyses using 20.3 fb^{-1} of 8 TeV data
  - The $\gamma\gamma$ analysis using 4.5 fb^{-1} of 7 TeV data
- All branching ratios and non-$t\bar{t}H$ production cross sections are fixed to Standard Model values.
- The relevant systematic uncertainties are **correlated** between the various analyses, and the robustness of the correlation scheme is checked.
- A **simultaneous fit** to the signal and control regions of the individual analyses is performed to extract the combined significance and cross section.

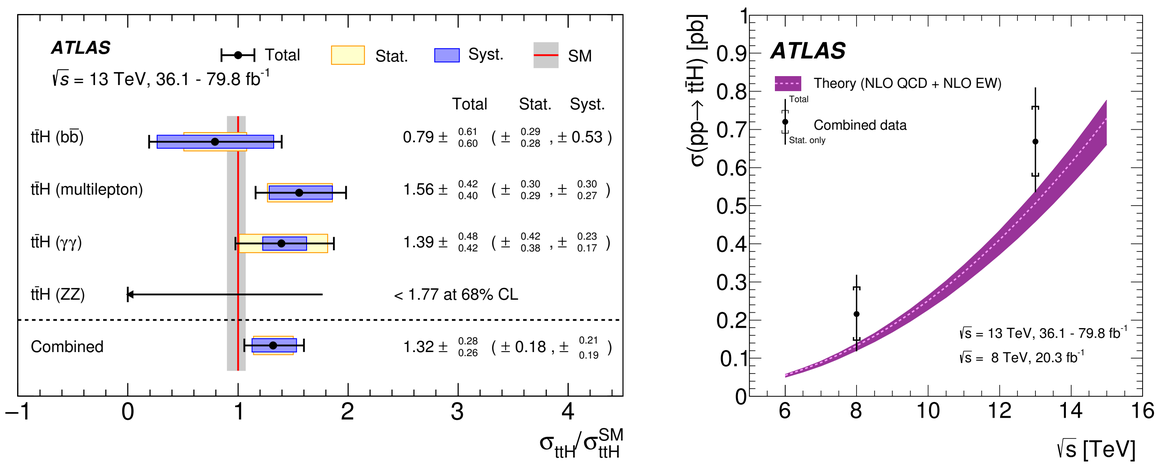

Figure 7: The ratio of the measured $t\bar{t}H$ cross sections to the predicted cross section at 13 TeV, by analysis (Left), and the measured $t\bar{t}H$ cross sections at 8 and 13 TeV, compared to predictions (Right).

- Combining the 13 TeV $t\bar{t}H$ analyses, the observed (expected) significance is $\mathbf{5.8\sigma}$ $(\mathbf{4.9\sigma})$ over the background-only hypothesis.
- Combining the 7, 8, and 13 TeV $t\bar{t}H$ analyses, the observed (expected) significance is $\mathbf{6.3\sigma}$ $(\mathbf{5.1\sigma})$ over the background-only hypothesis.
- The $t\bar{t}H$ production cross section at 13 TeV is measured to be $\mathbf{670 \pm 90\ (stat)\ ^{+110}_{-100}\ (sys)}$ fb, consistent with the predicted value of $\mathbf{507^{+35}_{-50}}$ fb.
- These results establish a direct **observation** of the Higgs boson Yukawa coupling to the top quark.