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Search for the Standard Model Higgs boson decaying into $b\bar{b}$ produced in association with hadronically decaying top quarks in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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A search for Higgs boson production in association with a pair of top quarks ($t\bar{t}H$) is presented, where the Higgs boson decays to $b\bar{b}$, and both top quarks decay hadronically. The data used correspond to an integrated luminosity of 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$TeV collected with the ATLAS detector at the Large Hadron Collider. The search selects events with at least six energetic jets and uses a boosted decision tree algorithm to discriminate between signal and Standard Model background. For a Higgs boson mass of 125 GeV, an upper limit of 6.4 (5.4) times the Standard Model cross section is observed (expected) at 95% confidence level. The best fit value for the signal strength is $\mu = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} = 1.6 \pm 2.6$ for $m_H = 125$ GeV. Combining all $t\bar{t}H$ searches carried out by ATLAS at $\sqrt{s} = 7$ and 8 TeV, an observed (expected) upper limit of 3.1 (1.4) times the Standard Model expectation is obtained at 95% confidence level, with a signal strength $\mu = 1.7 \pm 0.8$.

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1. Why should we care about the top Yukawa coupling?

The top quark has the largest Yukawa coupling ($y_t \simeq 1$) in the Standard Model (SM) and is the main responsible for the instability of the Higgs mass m_H. The top Yukawa coupling also affects the instability of the Higgs effective potential $V(\Phi)$, together with m_H: because of the renormalisation evolution of some coupling constants (in particular the Higgs self-coupling constant λ), additional minima of $V(\Phi)$ develop at large values of the Higgs field, changing the vacuum structure. Defining y_{crit} as the critical value at which our electroweak vacuum is degenerate with the new one at a certain energy scale Λ, three scenarios are possible [1]:

- $y_t < y_{\text{crit}} - \varepsilon$, the most cosmologically safe case, as our electroweak vacuum is unique;
- $y_t > y_{\text{crit}} - \varepsilon$, a new minimum develops at large values of the Higgs field;
- $y_t > y_{\text{crit}}$, the new minimum is deeper than ours, meaning that our vacuum is metastable;
- $y_t > y_{\text{crit}} + \eta$, the life-time of our vacuum is smaller than the age of the Universe, which becomes unstable,

where ε and η strongly depend on the accuracy of loop corrections to $V(\Phi)$.
In practice, if the measurement of the top Yukawa coupling will give $y_t < y_{\text{crit}} + \eta$, the embedding of the SM with New Physics in cosmology does not lead to any troubles and thus no information on the scale of New Physics can be derived. If $y_t > y_{\text{crit}} + \eta$ the Higgs self-coupling λ becomes negative, indicating an instability at the scale Λ: to make it positive for all energies, something new should intervene at the scale around or below Λ.

2. How to hunt for $t\bar{t}H$?

The coupling y_t is experimentally accessible by measuring the gluon fusion (ggF) production process or the $H \to \gamma\gamma$ decay, where a sizeable contribution derives from a top quark loop. However this case requires the assumption that no New Physics contributes with additional induced loops in order to measure y_t. Currently, the only process where y_t can be accessed directly is the production of a top quark pair in association with a Higgs boson ($t\bar{t}H$).
The results of the searches for the Higgs boson are usually expressed in terms of the signal strength parameter μ, which is defined as the ratio of the observed to the expected number of signal events. The latter is calculated assuming the SM cross section. The ATLAS Collaboration has searched for a $t\bar{t}H$ signal in events enriched in Higgs boson decays to two massive vector bosons or τ leptons in the multilepton channel [2], finding $\mu = 2.1^{+1.4}_{-1.2}$. For $t\bar{t}H(H \to b\bar{b})$ [3] in final states with at least one lepton ATLAS measured $\mu = 1.4 \pm 1.0$, and for $t\bar{t}H(H \to \gamma\gamma)$ [4] $\mu = 1.3^{+2.6}_{-1.7}$.

3. The $t\bar{t}H$ fully hadronic channel

This search [5] is based on data collected using a multijet trigger, which requires at least five jets passing the Event Filter stage, each having $p_{\text{T}} > 55$ GeV and $|\eta| < 2.5$. All other jets are required to have $p_{\text{T}} > 25$ GeV and $|\eta| < 2.5$. The selected events are required to have at least six jets, of which at least two must be b-tagged with a 60% efficiency operating point. Events with well-identified isolated muons or electrons with $p_{\mathrm{T}} > 25$ GeV are discarded to avoid overlap with other $t\bar{t}H$ analyses. To enhance the sensitivity, the selected events are categorised into six analysis regions, according to their jet and b-tag multiplicities (nj, mb): two Control Regions ($6j$, $3b$) and ($6j$, $\geq 4b$); four Signal Regions ($7j$, $3b$), ($7j$, $\geq 4b$), ($\geq 8j$, $3b$) and ($\geq 8j$, $\geq 4b$).

4. Background estimate via Tag Rate Functions

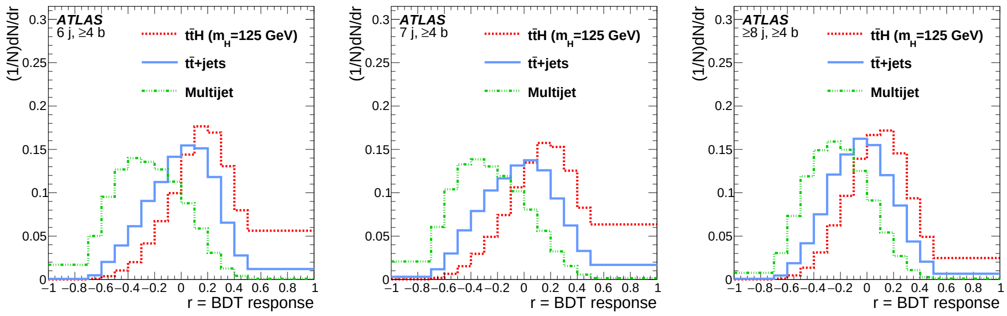
The dominant background is multijet production, followed by $t\bar{t}$+jets. Small background contributions come from the production of single top quark and $t\bar{t}V$ ($V = W, Z$) processes. Selecting a large number of b-jets, based on the b-tagging algorithm, would reduce significantly the number of simulated events with a high b-tag multiplicity. Therefore, a Tag Rate Function (TRF) method is applied: the probability of a jet with a given flavour, p_{T}, and η to be b-tagged is calculated and then applied as event weight in order to predict normalisations and shapes. The method is validated by verifying that the predictions reproduce the normalisation and shape obtained for a given working point of the b-tagging algorithm. The method is applied to all simulated signal and background samples. A similar data-driven $\mathrm{TRF_{MJ}}$ method is used to extract the multijet contribution: after measuring $\varepsilon_{\mathrm{MJ}}$, the probability of b-tagging a third jet in a sample of events with at least two b-tagged jets, the $\mathrm{TRF_{MJ}}$ method uses $\varepsilon_{\mathrm{MJ}}$ to extrapolate the multijet background from the regions with lower b-tag multiplicity to the analysis regions with higher b-tag multiplicity but otherwise with an identical event selection.

5. Analysis strategy

A dedicated Boosted Decision Tree (BDT) is defined and optimised in each of the six analysis regions. It exploits event-shape variables such as the scalar sum of the p_{T} of jets divided by their invariant mass, global event variables such as the modulus of the vector sum of the p_{T} of jets and the smallest invariant mass of all dijet combinations. Other variables are calculated from pairs of objects: the ΔR between the two b-tagged jets with highest vector sum p_{T}, the invariant mass of the two b-tagged jets with the smallest ΔR and the invariant mass of the two b-tagged jets which are selected by requiring that the invariant mass of all the remaining jets is maximal. Finally, a "Pseudo Matrix Element" variable, P, is used; it is a measure of the probability of an event to be signal-like rather than multijet-like. The P variable is defined as the sum of the logarithms of ratios of relative probability densities for W boson, top quark and Higgs boson resonances reconstructed in the event. For a given resonance X decaying to two jets, the P_X component is built as $P_X(m_{jj}) = \ln \frac{P_{\mathrm{sig}}(m_{jj})}{P_{\mathrm{bkg}}(m_{jj})}$ within a mass window $w_X = \pm 30$ GeV around the given particle mass. $P_{\mathrm{sig}}(m_{jj})$ and $P_{\mathrm{bkg}}(m_{jj})$ are signal and background mass probability density functions, respectively, modelled by a Gaussian $G(m_{jj}|m_X, \sigma_X)$ and a uniform distribution $\mathrm{Rect}(m_X, w_X)$ between $m_X - w_X$ and $m_X + w_X$. The expression for the complete event is:

$$P(m_{jj}, m_{jjb}, m_{bb}) = P_W(m_{jj}|m_W, \sigma_X) + P_{\mathrm{top}}(p_{\mathrm{T},jjb}, m_{jjb}|m_{\mathrm{top}}, \sigma_X) + P_H(p_{\mathrm{T},bb}, m_{bb}|m_H, \sigma_X).$$

For top and Higgs probability densities, the transverse momenta of the resonance candidates are also considered: the ratio of the signal and background p_{T} distributions is used. P is computed for all possible jet combinations and the maximum P of the event is chosen. Figure 1 shows the BDT response for signal, $t\bar{t}$+jets background and multijet background events.



(a) (b) (c)

Figure 1: BDT response for signal (dashed red) $t\bar{t}$+jets background (solid blue) and multijet background (dotted green) events in the regions with ≥ 4 b-tags (a) 6, (b) 7 and (c) ≥ 8 jets [5].

6. Fully hadronic results

The BDT discriminants for each of the six analysis regions are combined as inputs to a test statistic to search for the presence of a signal. The analysis uses a maximum-likelihood fit to measure the compatibility of the observed data with the background-only hypothesis ($\mu = 0$) and to make statistical inferences about the signal strength, such as upper limits, using the CL_S method. The signal strength in the all-hadronic $t\bar{t}H$ decay mode is measured to be 1.6 ± 2.6, for $m_H =$ 125 GeV. The observed (expected) significance of the signal is 0.6 (0.4) standard deviations, corresponding to an observed (expected) p-value of 27% (34%). A $t\bar{t}H$ signal 6.4 times larger than predicted by the SM is excluded at 95% CL (Figure 2).

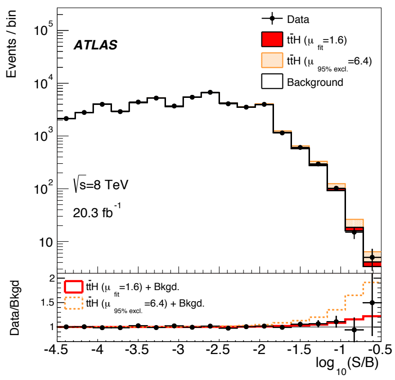
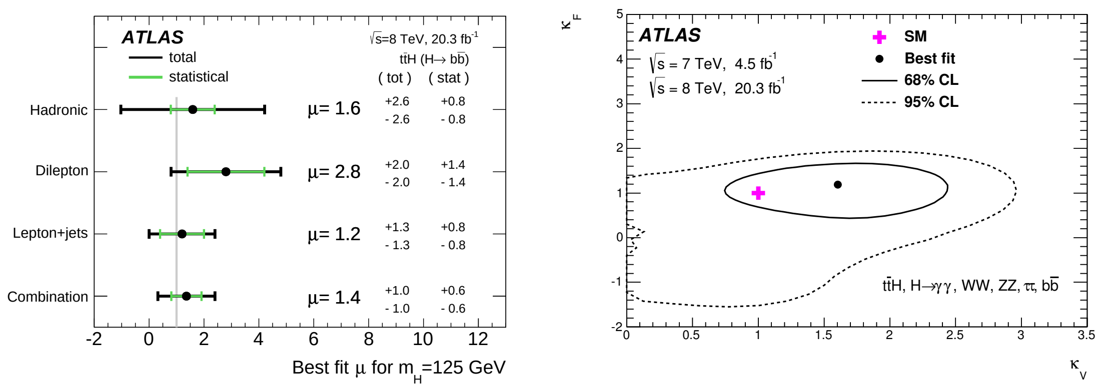


Figure 2: Event yields from all fitted regions as a function of $\log_{10}(S/B)$, where S (expected signal yield) and B (expected background yield) are taken from the corresponding BDT bin [5]. In the lower plot the ratio between observed and expected events is shown.

7. Combination with other $t\bar{t}H$ analyses

Combining all the $t\bar{t}H(H \to b\bar{b})$ searches gives a signal strength $\mu = 1.4 \pm 1.0$. The observed signal strengths for the individual $t\bar{t}H(H \to b\bar{b})$ channels and for their combination are summarised in Figure 3. The observed (expected) significance of the combined $t\bar{t}H$ result is 2.3σ (1.5σ). The combination of all $t\bar{t}H$ analyses yields an observed (expected) 95% CL upper limit of 3.1 (1.4) times the SM cross section while the result for the best-fit value is $\mu = 1.7 \pm 0.8$.
A two-parameter fit is also performed, assuming that all Higgs boson couplings scale with a common modifier κ_V, while all Higgs fermion couplings scale with a common modifier κ_F: the values of κ_V and κ_F obtained by the fit agree with the SM expectation within the 68% CL.



(a) (b)

Figure 3: (a) Summary of the measurements of the signal strength μ for $t\bar{t}H(H \to b\bar{b})$ production for the individual $H \to b\bar{b}$ channels and for their combination. (b) Contours of constant log-likelihood in the κ_V-κ_F plane for the combined $t\bar{t}H$ fit. κ_V is constrained to be positive [5].

References

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