

Search for $t\bar{t}H$ and tH production with $H \rightarrow b\bar{b}$

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The results from searches for a Standard Model Higgs boson decaying to a pair of bottom quarks and produced in association with top quarks at the Large Hadron Collider are presented. The analyses use a combination of data collected in proton-proton collisions at center-of-mass energies of 7 TeV and 8 TeV by the ATLAS and CMS detectors. No significant excess of events above the background expectation was found. Results are presented in terms of upper limits and best-fit values of the signal strength modifier relative to the Standard Model prediction.

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1. Introduction

Since the discovery of a new boson with mass around 125 GeV [1, 2] by the ATLAS [3] and CMS [4] collaborations, experimental studies have focused on the full characterization of the boson. Through measurements of the properties of the boson, particle physicists can determine the consistency of this particle with the Standard Model (SM) Higgs boson. One of the most striking properties of the SM Higgs boson is its strong coupling to the top quark.

Due to the large measured mass of the top quark, the top quark Yukawa coupling, y_t , is expected to be of order one. Although there have been indirect measurements of the top quark Yukawa coupling from measurements of the Higgs boson cross section via gluon fusion and the Higgs boson branching fraction to photons, these effective couplings occur at the loop level. Therefore, they can be affected by beyond Standard model (BSM) particles. The production of a Higgs boson in association with a top quark pair, $t\bar{t}H$, or a single top quark, tH , are the main modes directly sensitive to the top quark Yukawa coupling.

The analyses presented here share similar search strategies: select well-identified objects, categorize events based on the number of reconstructed objects, discriminate between signal and background using a multivariate discriminant, simultaneously fit all categories, and interpret the fit as an upper limit and/or a best-fit signal strength. In all cases, the major background is $t\bar{t}$ +jets. To extract the signal, the different analyses used boosted decision trees (BDTs), matrix element methods (MEMs), neural networks (NNs), or a combination of multiple methods.

2. ATLAS and CMS Search for $t\bar{t}H$, $H \rightarrow b\bar{b}$

For the ATLAS [5] and CMS [6] $t\bar{t}H$, $H \rightarrow b\bar{b}$ analyses, events are categorized based on the decay of the $t\bar{t}$ system: where one of the W bosons from the top quark decays to a charged lepton and a neutrino and the other W boson decays to a quark-antiquark pair (lepton + jets), or where both of the W bosons decay to charged leptons and neutrinos (dilepton). After requiring an initial event selection involving kinematics, object identification, and quality cuts, events are categorized based on the number of jets and the number of b -tagged jets they contain.

To further discriminate signal from background, CMS uses a BDT with inputs involving kinematics of the reconstructed objects, the event shape, and the b -tag discriminant. To characterize the strength of the $t\bar{t}H$ signal relative to the SM cross section ($\mu = \sigma/\sigma_{SM}$), a simultaneous fit of the BDTs across all categories is performed. The uncertainties involved in the background modeling are introduced into the fit as nuisance parameters. Figure 1 (left) shows the BDT output distribution in the most sensitive category: events with one lepton, ≥ 6 jets, and ≥ 4 b -tagged jets. The background distributions use the best-fit values of all nuisance parameters, with μ fixed at 1. Figure 1 (right) summarizes the post-fit event yields as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from all bins of the BDT output used in the fit.

ATLAS uses different strategies depending on whether the region is rich or depleted in signal with respect to the background expectation. In signal-depleted regions, a simple discriminator based on the scalar sum of the transverse momentum of jets and/or leptons is used. In signal-rich regions, a neural network is used. In events with one lepton, ≥ 6 jets, and ≥ 3 b -tagged jets, two variables involving matrix elements are used as inputs to the NNs. Figure 2 shows the NN

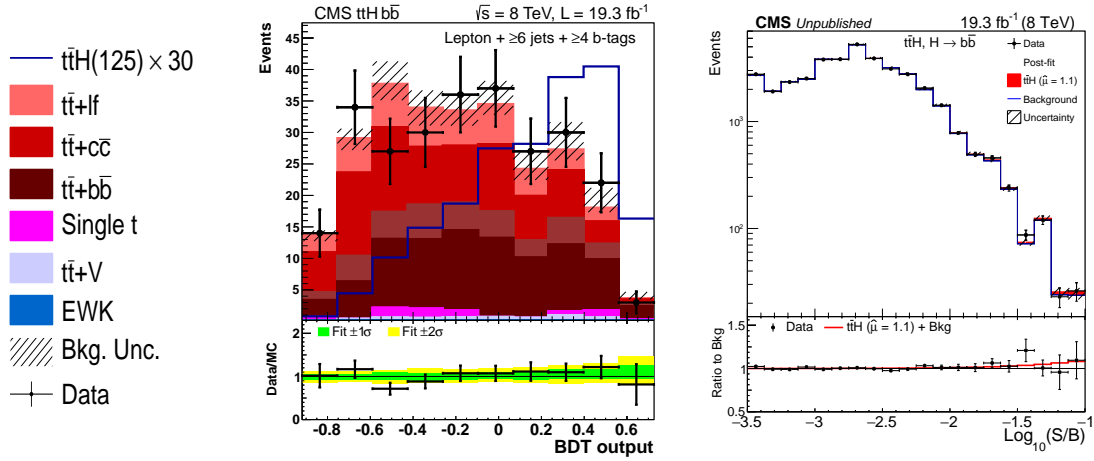


Figure 1: Left: Distribution of BDT discriminant of the CMS $t\bar{t}H$ analysis after requiring one well-identified lepton (electron or muon), ≥ 6 jets, and ≥ 4 b-tagged jets. Right: Event yields as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from all BDT output bins in the fitted regions [6].

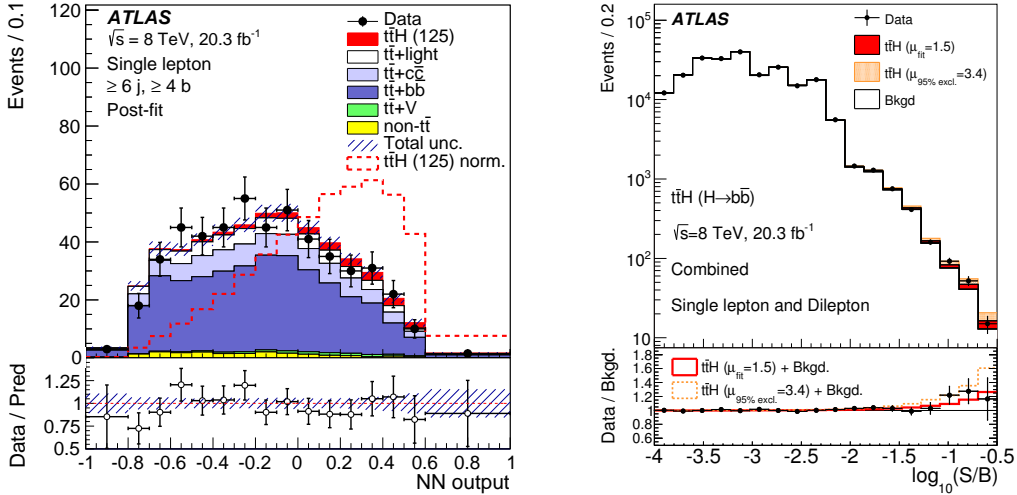


Figure 2: Left: Distribution of NN discriminant of the ATLAS $t\bar{t}H$ analysis after requiring one well-identified lepton (electron or muon), ≥ 6 jets, and ≥ 4 b-tagged jets. Right: Event yields as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from all NN output bins in the fitted regions [5].

distribution in the most sensitive single-lepton category (events with one lepton, ≥ 6 jets, and ≥ 4 b-tagged jets) and the post-fit event yields as a function of $\log_{10}(S/B)$ for all NN output bins used in the fit.

Using 5.1 fb^{-1} of data at 7 TeV and 19.5 fb^{-1} of data at 8 TeV, CMS set an observed (expected) upper limit of $\mu < 4.1$ (3.5) at the 95% confidence level, corresponding to a best-fit value of $\hat{\mu} = 0.7 \pm 1.9$ for a Higgs boson mass of 125.6 GeV. ATLAS used 19.5 fb^{-1} of data at 8 TeV and set an observed (expected) upper limit of $\mu < 3.4$ (2.2) at the 95% confidence level, corresponding to a best-fit value of $\hat{\mu} = 1.5 \pm 1.1$ for a Higgs boson mass of 125 GeV. The ATLAS result is a significant improvement over previous analyses. Some of the sources of improvement include:

more efficient b-tagging for the same mis-tag rate, looser object selection, NLO $t\bar{t} + b\bar{b}$ corrections, and combining event interpretation MEM discriminators with NNs.

3. CMS Search for $t\bar{t}H$, $H \rightarrow b\bar{b}$ with MEMs

For the CMS MEM analysis [7], events are assigned a b-tag likelihood based on the b-tag value of the jets in the event. This b-tag likelihood is used to separate events into low- and high-purity regions. Events are further categorized based on the number of reconstructed objects and the event interpretation, e.g., all quarks are reconstructed v.s. missing one of the W boson daughters.

To separate the signal from the larger $t\bar{t}$ +jets background, this analysis used a matrix element method that assigns a probability density value to each reconstructed event under the signal ($t\bar{t}H$) or background ($t\bar{t} + b\bar{b}$) hypothesis. The ratio between these two values is used to construct the event discriminant $P_{s/b}$, which encodes information from the event kinematics and dynamics. The event discriminant $P_{h/l}$ is defined using the b-tag likelihood information to separate between the heavy- and light-flavor components of the $t\bar{t}$ +jets background. Figure 3 shows the $P_{s/b}$ distribution in the single-lepton, high-purity region and the post-fit event yields as a function of $\log_{10}(S/B)$ for all $P_{s/b}$ bins used in the fit.

Using 19.5 fb^{-1} of data at 8 TeV, CMS set an observed (expected) upper limit of $\mu < 4.2$ (3.3) at the 95% confidence level, corresponding to a best-fit value of $\hat{\mu} = 1.2^{+1.6}_{-1.5}$ for a Higgs boson mass of 125 GeV. Comparing to the CMS BDT result using only 8 TeV data, the MEM result corresponds to about a 15% improvement in the expected limit.

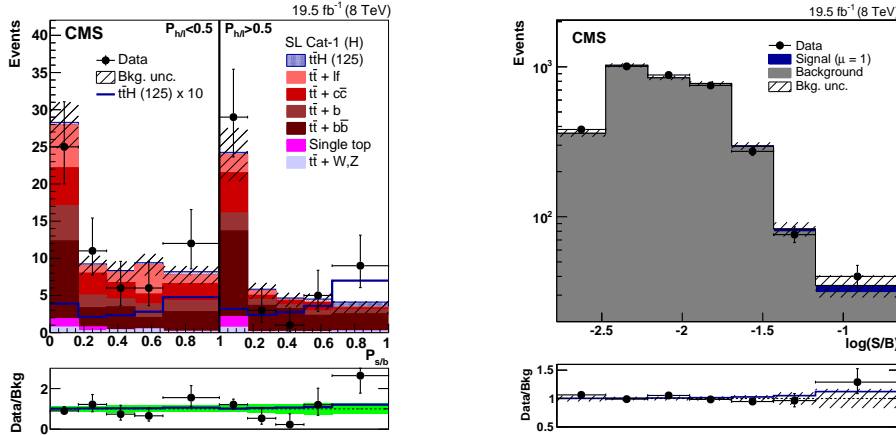


Figure 3: Left: Distribution of the MEM-based $P_{s/b}$ discriminant of the CMS $t\bar{t}H$ analysis in the single lepton, high-purity category. Right: Event yields as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from all $P_{s/b}$ output bins in the fitted regions [7].

4. CMS Search for tHq , $H \rightarrow b\bar{b}$ with $y_t = -1$

Although current coupling constraints from the combination of ATLAS and CMS results disfavor negative values of the top quark Yukawa coupling [8], the result assumes only SM contributions to the total width. The production of a Higgs boson in association with a single top quark through

t -channel diagrams, tHq , is sensitive to other modifications of the SM. Negative y_t are still tolerated if BSM contributions to loop $H \rightarrow gg$ and $H \rightarrow \gamma\gamma$ diagrams are allowed [9]. The CMS analysis is optimized to search for anomalous tHq with a negative coupling of the Higgs boson to the top quark ($y_t = -1$) [10]. In this model, the tHq cross section would be increased by a factor of ≈ 15 [11].

After requiring one isolated lepton, missing transverse momentum, and one forward, light jet, events are categorized based on lepton flavor (electron or muon) and the number of b -tagged jets (three or four). Two NNs are trained to assign jets to partons in the hard process under either the signal (tHq) hypothesis or the background ($t\bar{t}$ +jets) hypothesis. A third, dedicated NN is trained to separate between signal and background. Input variables for the final event NN include global variables (e.g. lepton charge), variables under the signal hypothesis (e.g. transverse momentum of the Higgs boson candidate), and variables under the background hypothesis (e.g. mass of the top candidate). Figure 4 shows the NN distribution for events with four b -tagged jets in the muon channel and the post-fit signal-to-background event yields for all NN output bins used in the fit.

Using 19.7 fb^{-1} of data at 8 TeV, CMS set an observed (expected) upper limit on anomalous tHq production of $\mu = \sigma/\sigma_{y_t=-1} < 7.57$ (5.14) at the 95% confidence level for a Higgs boson mass of 125 GeV.

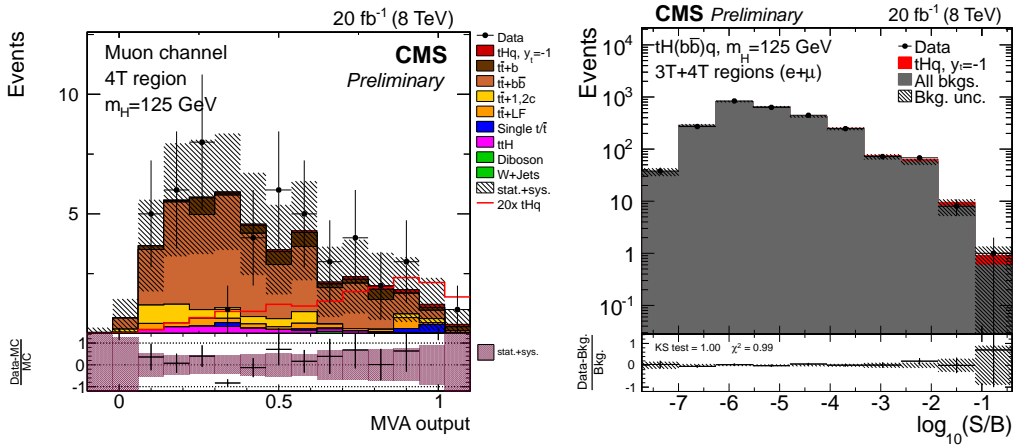


Figure 4: Left: Distribution of the NN output of the CMS tHq analysis for events with four b -tagged jets in the muon channel. Right: Event yields as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from all NN output bins in the fitted regions [10].

5. Summary

ATLAS and CMS have performed searches for a SM Higgs boson produced in association with top quarks. Limits were set on the cross section times branching fraction of Higgs boson decaying to bottom quarks. Over time, the combination of more sophisticated multivariate techniques and improved modeling of the backgrounds has resulted in increased sensitivity to these small signals.

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