Search for Standard Model Scalar Boson Decaying to Fermions at the LHC

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The results from searches for a Standard Model Higgs boson decaying to fermions at the LHC are presented. Using 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, new limits are set on the cross section times branching fractions of the Higgs boson decaying to bottom quarks, muons, and tau leptons for several production mechanisms.

1 Introduction

With the recent observation [1,2] of a new boson with a mass near 125 GeV/c^2 at the Large Hadron Collider (LHC), the focus of searches for the Standard Model (SM) Higgs boson has shifted to evaluating the consistency of this new particle with SM expectations. Both the ATLAS [3] and the CMS [4] collaborations presented preliminary results that the new particle is a Higgs boson [5,6,7,8,9]. These collaborations performed a number of measurements and found that the results prefer that the new particle have no spin and positive parity, consistent with the SM Higgs boson. In addition, the measurements of the branching ratios of the new particles to bosons ($H \to WW,\ ZZ,\ \gamma\gamma$) are consistent with SM expectation. In order to determine if this new particle is the Higgs boson of the SM, we need to precisely measure its branching ratio into all final states, including those with fermions.

2 Higgs decays to bottom quarks

At a mass of 125 GeV/c^2, the SM Higgs boson decays predominantly into a bottom-antibottom quark pair ($b\bar{b}$). Therefore, the observation of $H \to b\bar{b}$ is essential to characterize the nature of the new boson. However, the rate of $b\bar{b}$ production at the LHC from the QCD multi-jet background is many orders of magnitude larger than the rate of Higgs production. To reduce the backgrounds and investigate different

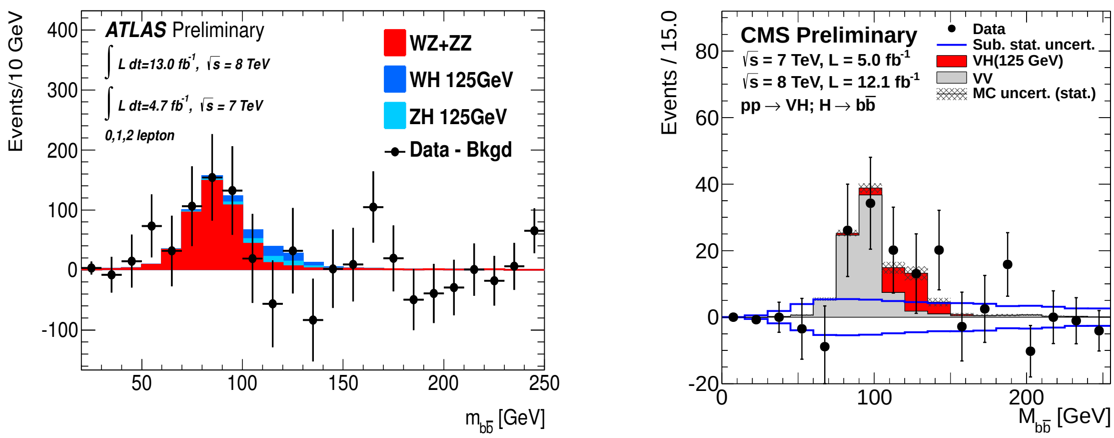

Figure 1: The distribution of $m_{b\bar{b}}$ in data after subtraction of all backgrounds except diboson backgrounds for ATLAS (left) and CMS (right). In both cases, the diboson background is visible and described well.

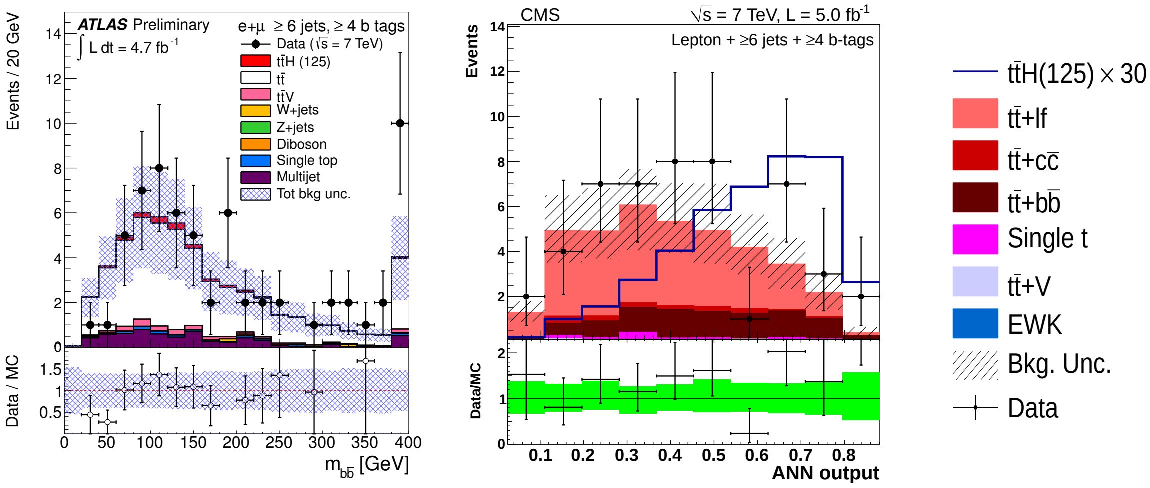

Figure 2: Signal discriminant distributions of the $t\bar{t}H$ analysis for ATLAS (left) and CMS (right) after requiring one well-identified lepton (electron or muon), $\geq$6 jets, and $\geq$4 b-tagged jets.

Higgs production mechanisms, the ATLAS and CMS experiments performed searches for the Higgs boson produced in association with a vector boson (WH or ZH) or a top quark pair ($t\bar{t}H$).

2.1 Higgs produced in association with vector bosons

The search for Higgs produced in association with a vector boson, W or Z, was performed in the decay channels $ZH \to \ell^+\ell^- b\bar{b}$, $WH \to \ell\nu b\bar{b}$, and $ZH \to \nu\nu b\bar{b}$, where ℓ refers to either an electron or a muon. Events must also possess two jets that are identified as originating from a b quark (b-tagged). After separating events based on the number of charged leptons, events are further sub-divided based on the transverse momentum of the vector boson and either the number of additional jets (ATLAS) or the tightness of the b-tag requirement (CMS). ATLAS used the $m_{b\bar{b}}$ distribution as its signal discriminator, while CMS used the output discriminant of a boosted-decision-tree (BDT) algorithm [10].

To show the validity of the Higgs search procedure, both experiments performed a fit of the $m_{b\bar{b}}$ distribution treating the diboson background as the signal of interest. Diboson production with a Z boson decaying to $b\bar{b}$ has a very similar signature to $H \to b\bar{b}$. Figure 1 shows the $m_{b\bar{b}}$ distribution in data after subtraction of all backgrounds except diboson backgrounds for ATLAS and CMS, and the data are consistent with the presence of a diboson signal with a rate approximately as expected from the SM [11,12].

The experiments both used 5 fb^{-1} of 7 TeV data and about half of the available 8 TeV data (12-13 fb^{-1}) in their search for VH production in the $b\bar{b}$ channel. For m_H = 125 GeV/c^2, ATLAS obtained an observed (expected) upper limit on the production cross section times branching ratio of 1.8 (1.9) times the SM prediction [11]. Similarly, CMS found an observed (expected) limit of 2.5 (1.2) times the SM prediction, corresponding to a local significance of 2.2σ [12].

2.2 Higgs produced in association with top quark pairs

The $t\bar{t}H$ mechanism is the only production mode directly sensitive to the top-Higgs Yukawa coupling. Furthermore, searching for $t\bar{t}H$ can also be used to probe new physics models that predict increased rates of $t\bar{t}H$ production without changing Higgs branching ratios [13,14].

Events were split 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 intitial event selection involving kinematics, object identification and quality cuts, events were categorized based on the number of jets and the number of b-tagged jets they contain. A signal discriminator is used to further improve signal sensitivity: ATLAS used either the scalar sum of the jet transverse momentum or the reconstructed $m_{b\bar{b}}$, depending on the category, and CMS used the output discriminant of an artificial neural network (ANN) algorithm [15]. Figure 2 shows the signal discriminators for the most sensitive categories of ATLAS and CMS.

Using 5 fb^{-1} of data at 7 TeV and focusing on the lepton+jets channel, ATLAS set an observed (expected) upper limit on $t\bar{t}H$ production in the $b\bar{b}$ channel of 13.1 (10.5) times the SM expectation [16] for

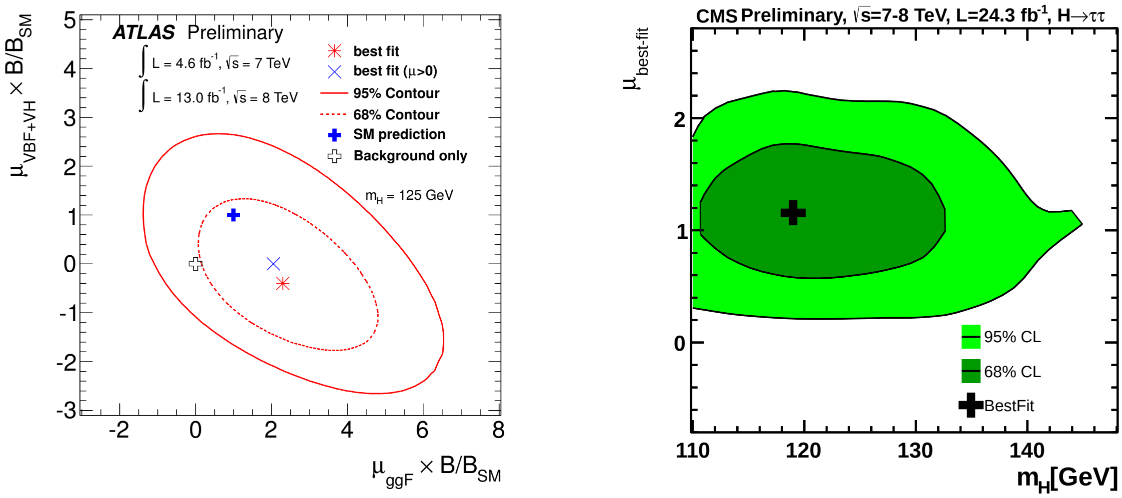

Figure 3: Left: ATLAS result showing the best fit of the signal strength for vector boson fusion and associated production of $H \to \tau\tau$ versus gluon fusion. Right: CMS result on the best fit of signal strength for total $H \to \tau\tau$ production compared to the SM expectation as a function of the Higgs mass.

$m_H = 125$ GeV$/c^2$. CMS combined 5 fb^{-1} of 8 TeV data with 5 fb^{-1} of 7 TeV data to set an observed (expected) limit of 5.8 (5.2) times SM expectation [17] for the same mass.

3 Higgs decays to leptons

In addition to Higgs decaying to $b\bar{b}$, the other experimentally accessible channels at the LHC for investigating Higgs decaying to fermions are $H \to \mu\mu$ and $H \to \tau\tau$.

3.1 Higgs decays to muons

The $H \to \mu\mu$ decay provides an experimentally clean final-state signature with a good resolution on the mass of the Higgs boson. It is also the best channel to investigate the Higgs coupling to second generation fermions at the LHC. One of the difficulties of this channel is that there is a large background from $Z/\gamma^* \to \mu\mu$. ATLAS performed a search in this channel by selecting events with two muons, where the di-muon system was boosted, and then performed a fit on the invariant mass of the di-muon system to extract a signal. Seeing no excess in 20 fb^{-1} of data at 8 TeV, the observed (expected) limit for $m_H = 125$ GeV$/c^2$ was 9.8 (8.2) times the SM prediction [18].

3.2 Higgs decays to tau leptons

The branching ratios for Higgs decaying to fermions are proportional to the square of the fermion mass. Due to the large m_τ, the $H \to \tau\tau$ decay is important for testing Yukawa couplings in the case of leptons.

The search strategies for $H \to \tau\tau$ were similar for ATLAS [19] and CMS [20,21]. Events were categorized based on the number of jets, the boost of the system, the transverse momentum of the leptons (e, μ, τ_h), and the final-state signature ($e\mu$, $\mu\mu$, $e\tau_\mathrm{h}$, $\mu\tau_\mathrm{h}$, $\tau_\mathrm{h}\tau_\mathrm{h}$). Selections on the event topology were made to suppress background. The dominant background in this search was $Z \to \tau\tau$, which was estimated by taking $Z \to \mu\mu$ events from data and replacing the muons by simulated τ decays.

Due to the neutrinos resulting from the tau decays, the invariant mass of the di-tau system ($m_{\tau\tau}$) is not fully constrained. In order to get the best estimate for $m_{\tau\tau}$, ATLAS used the Missing Mass Calculator method [22], and CMS used a maximum likelihood method (SVFit algorithm) [20]. A simultaneous fit of $m_{\tau\tau}$ across the different categories and channels was used to extract the signal.

The ATLAS experiment used 5 fb^{-1} of data at 7 TeV and 13 fb^{-1} of data at 8 TeV, and the observed (expected) limit on SM $H \to \tau\tau$ was found to be 1.9 (1.2) times the SM prediction [19]. Using 5 fb^{-1} of data recorded at 7 TeV and 19 fb^{-1} of data at 8 TeV, an excess of events was observed by the CMS experiment, with a maximum local significance of 2.9σ [20] at $m_H = 120$ GeV$/c^2$. Figure 3 shows the best fit of the signal strength for different $H \to \tau\tau$ production modes and as a function of m_H.

4 Summary

ATLAS and CMS have performed searches for a Standard Model Higgs boson decaying to fermions. Limits were set on the cross section times branching fraction of Higgs decaying to bottom quarks, muons, and tau leptons. Excesses in the $b\bar{b}$ and $\tau\tau$ channels are consistent with SM Higgs expectations with local significances 2.2σ and 2.9σ, respectively.

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