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Measurement of fermionic couplings of the Standard Model Higgs boson using the $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$ decay channels with the ATLAS detector

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In this report we present the latest results from the ATLAS experiment on the measurements of fermionic couplings of the Standard Model Higgs boson via the searches of the Higgs boson in the $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$ decay channels. The searches are performed on proton-proton collisions produced by the Large Hadron Collider during Run 1 and the first two years of Run 2 data taking by ATLAS. These results also include the most recent measurements where ATLAS observed evidence of $H \to b\bar{b}$ decay in the WH and ZH associated production channels.

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1. Introduction

A Standard Model (SM) like Higgs boson was discovered by the ATLAS and CMS experiments in 2012 through the channels where the Higgs boson decays into a pair of gauge bosons ($H \to \gamma\gamma, W^+W^-, ZZ$). Many measurements that came after the discovery further strengthen the hypothesis that the new particle is the SM Higgs boson. Nevertheless it is essential to study whether the new particle also decays directly into fermions, and to establish the mass generation mechanism for fermions as predicted in the SM by measuring whether the coupling strengths of the Higgs boson to fermions are proportional to the fermion masses. For a Higgs boson mass of $m_H = 125$ GeV, SM predicts the Higgs boson decays predominantly into a pair of b-quarks ($BR(H \to b\bar{b}) \sim 58\%$). The predicted decay rates to $\tau^+\tau^-$ and $\mu^+\mu^-$ are much smaller at $\sim 6.3\%$ and $\sim 0.02\%$, respectively.

ATLAS experiment has searched for the Higgs boson in these three ferimonic decay modes via several production channels. The gluon fusion (ggH) channel has the largest production rate among all the production processes, and it is suitable for leptonic decay searches (e.g. $\mu^+\mu^-$ and $\tau^+\tau^-$) which have smaller decay branching ratios but cleaner final state signatures. The vector boson fusion (VBF) channel, which has a unique final state signature that consists of two forward jets and low hadronic activities in between them (excluding contributions from the Higgs boson decays), is considered in all Higgs fermionic decay searches. For the WH and ZH associated production channel, the leptons (electrons, muons and neutrinos) from the W and Z boson decays are useful for triggering the signal and to suppress the background. This production channel is considered in the $H \to \tau^+\tau^-$ and $H \to b\bar{b}$ decay searches. The $t\bar{t}$ signature in the ttH associated production is used for triggering the signal events and for background suppression. The decay modes that are searched for with this production channel are $H \to \tau^+\tau^-$ and $H \to b\bar{b}$.

The Run 1 proton-proton collisions produced by the Large Hadron Collider (LHC) were at $\sqrt{s} = 7$ and 8 TeV. The center-of-mass energy is increased to 13 TeV for Run 2 data taking. The limits on production cross section times branching ratio ($\sigma \times BR$) at 95% confidence level, and the signal strength μ (ratio of the measured signal rate with respect to the SM predicted rate) that are presented in this report, are determined for a Higgs boson mass of $m_H = 125$ GeV.

2. $H \to \mu^+\mu^-$

The search in $H \to \mu^+\mu^-$ allows ATLAS to probe the Higgs boson coupling to second generation fermions. Since the final state, which consists of a pair of oppositely charged muon, is relatively clean of background, ATLAS choose to conduct the search in the two leading production channels (ggF and VBF). This helps to make up for the small $H \to \mu^+\mu^-$ decay rate. The signal is searched in a Run 2 data sample, collected with the ATLAS detector [1], with an integrated luminosity of 36.1 fb^{-1} [2].

The analysis select events with exactly two opposite charged muons and classify them into categories that are sensitive to signal events produced in VBF and ggF processes. The signal event selection priority is first given to the VBF production by requiring two high transverse momentum jets in opposite detector hemisphere. These events then undergo a multivariate analysis (MVA) where Boosted Decision Tree (BDT) algorithm is trained on several kinematic variables to enrich the VBF signal in the high region of the BDT output distribution, which is defined to be the VBF signal region and is divided into "loose" and "tight" categories. The events that fall outside the VBF signal region in the BDT distribution, or fail the two-jet requirement, are then optimised for the search in the ggF channel. These events are grouped into different categories based on the transverse momentum ($p_{\mathrm{T}}^{\mu\mu}$) and pseudo rapidity ($\eta^{\mu\mu}$) of the $\mu^+\mu^-$ system. The signal is searched in the di-muon invariant mass ($m_{\mu\mu}$) distributions of the selected events by performing simultaneous fits to the $m_{\mu\mu}$ distributions from all the VBF and ggF categories. The $m_{\mu\mu}$ distribution of the "tight" VBF category is shown in Figure 1(a). The extracted signal strength value is $\mu = -0.1 \pm 1.5$ and the observed (expected) upper limit at 95% confidence level (CL) on the production cross section times branching fraction is 3.0 (3.1) times the SM prediction. When combining with Run 1 search results [3], the combined signal strength value is $\mu = -0.1 \pm 1.4$ and the observed (expected) upper limit on $\sigma \times BR$ is 2.8 (2.9) times the SM prediction. The sensitivity of this search is currently limited by the data statistical uncertainty.

3. $H \to \tau^+\tau^-$

The search of the Higgs boson decaying into a pair of tau leptons has been performed by ATLAS on data samples collected in Run 1 (4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV) [4]. The search is optimised for Higgs boson produced through the VBF and ggF processes. The leptonic (LEP) and hadronic (HAD) tau decay modes are considered in the search and the selected events are grouped into "$\tau_{\mathrm{LEP}}\tau_{\mathrm{LEP}}$", "$\tau_{\mathrm{LEP}}\tau_{\mathrm{HAD}}$" and "$\tau_{\mathrm{HAD}}\tau_{\mathrm{HAD}}$" categories. MVA technique is applied in this search with separate BDT trainings for each di-tau category of the VBF and ggF production channels. The BDT output distribution from each category is used as the final discriminant variable. The di-tau invariant mass ($M_{\tau\tau}^{\mathrm{MMC}}$) is a powerful discriminating variable that is included as one of the training variables for all search categories. The $M_{\tau\tau}^{\mathrm{MMC}}$ is constructed using the Missing Mass Calculator (MMC) method [5] which reconstructs mass from most probable kinematic configuration of neutrinos using matrix element probability.

The main background sources are from $Z(\tau\tau)$+jets production, W+jets production, $t\bar{t}$ production and background from jets faking taus. The $Z(\tau\tau)$+jets background is estimated by using the $Z(\mu\mu)$+jets data events and replace the reconstructed muons with simulated taus.

The BDT output distribution for VBF "$\tau_{\mathrm{HAD}}\tau_{\mathrm{HAD}}$" category is shown in Figure 1(b). A maximum likelihood fit is performed on the BDT output distributions of all the categories to extract a signal strength value of $\mu = 1.43^{+0.43}_{-0.37}$, and with an observed (expected) signal significance of 4.5 (3.4) standard deviations for a Higgs mass at $m_H = 125.36$ GeV. This ATLAS results clearly show the evidence of detecting the $H \to \tau^+\tau^-$ decay. By combining with CMS Run 1 results on similar search, an observed 5.5 standard deviations discovery significance is obtained [6].

4. $H \to b\bar{b}$ in VBF plus γ production

ATLAS has searched for the SM Higgs boson in the $H \to b\bar{b}$ decay mode via several production channels. One recent analysis, which is performed on 12.6 fb^{-1} of Run 2 data sample, is carried out in the VBF production channel with an associated photon [7]. The photon may be radiated from an internal W boson or from an incoming or outgoing quark. The extra photon in the

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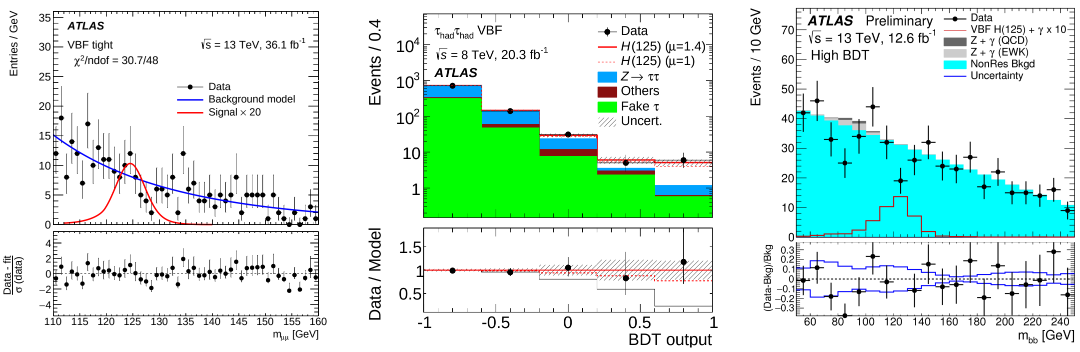
final state helps to reduce the dominant multi-jet background, and it also provides an extra handle to trigger on the signal.

The signal events are selected by requiring two identified b-jets, two forward jets and a central photon. The other major background source is from $Z(bb)$+jets production. A BDT is trained to separate the signal against the multi-jet background, and the BDT output distribution is divided into three regions (low, medium, high) of varying signal sensitivities. The signal is searched in the di-b-jet invariant mass (m_{bb}) distribution of each BDT region. Figure 1(c) shows the m_{bb} distribution in the high BDT region. The multi-jet background contribution is estimated by fitting the low and high side-band regions of the m_{bb} distribution in the data, and the $Z(bb)$+jets background is estimated from simulation. In the absence of observing the $H \to b\bar{b}$ signal, the analysis set a preliminary observed (expected) 95% CL upper limit on the Higgs production cross section times branching ratio of 4.0 ($6.0^{+2.3}_{-1.7}$) times the SM expectation.



(a) (b) (c)

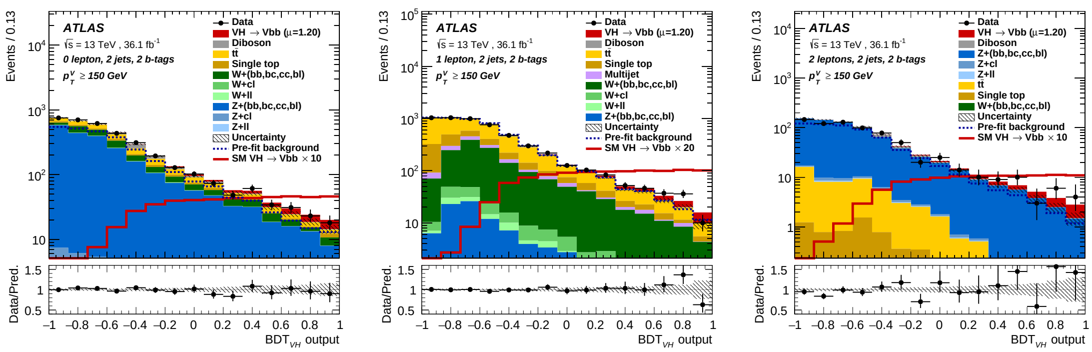
Figure 1: Plots of SM Higgs search in different fermionic decay channels. (a) $m_{\mu\mu}$ distribution of the “tight” VBF category in the $H \to \mu^+\mu^-$ decay channel [2]. (b) BDT output distribution for VBF “$\tau_{\mathrm{HAD}}\tau_{\mathrm{HAD}}$” category in the $H \to \tau^+\tau^-$ decay channel [4]. (c) m_{bb} distribution in the high BDT region of the $H \to b\bar{b}$ decay for the search in the VBF plus γ production channel [7].

5. $H \to b\bar{b}$ in WH and ZH associated production

The other recent analysis from ATLAS on the SM Higgs boson search in the $H \to b\bar{b}$ decay mode is performed in the production channels where the Higgs boson is produced in association with a W or Z boson. The search analysed a Run 2 data sample with an integrated luminosity of 36.1 fb^{-1} [8]. The signal event selection requires two identified b-jets and that the final state contains 0, 1 and 2 charged leptons (electrons or muons), which correspondingly target the decays $Z \to \nu\nu$, $W \to l\nu$ and $Z \to ll$. The search is conducted at the high transverse momentum region of the vector boson $p_{\mathrm{T}}^{V} > 150$ GeV (75 GeV for 2-lepton channel) where the signal purity is higher. The main analysis separates the signal from the background by constructing a multivariate discriminant that makes use of a BDT that is trained separately for each leptonic decay channel on several kinematic variables that are tailored for that channel. The BDT output distribution is used as the main discriminant. The m_{bb} mass distribution of the two b-tagged-jet system is one of the key discriminating variable. Several corrections are applied to improve its mass resolution and the mean value. These corrections include “muon-in-jet”, “b-jet energy respond correction” and “kinematic likelihood fit". Details of these corrections are described in Ref. [8]. These corrections improve the m_{bb} resolution by $\sim 18-40\%$ (shown in Figure 3(a)).

The MVA analysis technique is first validated by performing a search for $WZ \to l\nu bb$ and $ZZ \to llbb, \nu\nu bb$, with one of the Z boson decays into a pair of b-quarks. The reason for choosing these production and decay channels is because they have similar final state signatures as the Higgs signal, and their total production cross section is about an order of magnitude larger than the Higgs signal that we are searching for. Global fits are performed on the BDT output distributions of eight signal regions and on other kinematic distributions of six control regions, and the extracted observed (expected) significance for WZ and ZZ signal is 5.8 (5.3) standard deviations. The measured signal strengths for WZ, ZZ and combined $(WZ+ZZ)$ are $\mu_{WZ} = 1.02^{+0.80}_{-0.57}$, $\mu_{ZZ} = 1.13^{+0.29}_{-0.26}$ and $\mu_{WZ+ZZ} = 1.11^{+0.25}_{-0.22}$, respectively. They agree well with the SM prediction.

After validating the MVA analysis technique, this method is applied to the WH and ZH search. The BDT output distributions of the signal regions in the 2-jet final state, after performing the global fits, are shown in Figure 2 for the 0-, 1- and 2-lepton channels. In the plots there are excesses in the data over the predicted background yield at the high BDT region. The expected significances for 0-, 1- and 2-lepton channels, respectively, are 1.7, 1.8 and 1.9 standard deviations. Whereas the observed significances for 0-, 1- and 2-lepton channels are 0.5, 2.3 and 3.6 standard deviations, respectively. The combined observed (expected) significance of the $WH+ZH$ signal is 3.5 (3.0) standard deviations. The measured signal strengths are shown in Figure 3(b). The compatibility among the three leptonic channels is $\sim 10\%$.



(a) (b) (c)

Figure 2: BDT output distributions of the signal regions in the 2-jet final state for the WH and ZH search in $H \to b\bar{b}$ decay mode [8]. (a) 0-lepton, (b) 1-lepton and (c) 2-lepton channels.

To cross check this search result, a second analysis is performed by using the m_{bb} distribution as the main discriminant. Additional selection cuts are applied to optimise the signal sensitivity. The combined m_{bb} distribution, from the three leptonic channels, after subtracting all predicted background contributions except the diboson WZ and ZZ productions, is shown in Figure 3(c). The contributions are weighted by their respective values of S/B, where S (B) is the fitted signal (background) yield. The contributions from WH and ZH signals are scaled by the measured combined signal strength value. A clear peak of the diboson can be seen around $m_{bb} \sim 90$ GeV, and the shoulder around $m_{bb} \sim 120$ GeV indicates the presence of the Higgs signal. For this second analysis, the observed (expected) significance is 3.5 (2.8) standard deviations.

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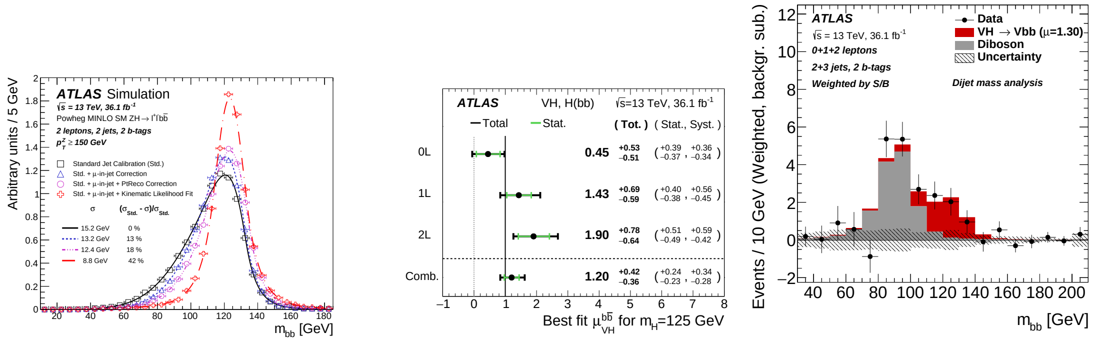
These Run 2 search results, based on the MVA technique, are combined with ATLAS Run 1 search results [9]. The combined signal strength is $\mu_{Run1+Run2} = 0.90^{+0.28}_{-0.26}$. The compatibility of the signal strengths between Run 1 and Run 2 is 21%. The combined observed (expected) signal significance is 3.6 (4.0) standard deviations.

This latest search results from ATLAS shows evidence for a SM Higgs boson produced in WH and ZH associated channel, and with the Higgs boson decaying into a pair of b-quarks.



(a) (b) (c)

Figure 3: Plots of WH and ZH search in $H \to b\bar{b}$ decay mode [8]. (a) m_{bb} distributions with additional corrections applied to improve the mass resolution. (b) Signal strength parameters of each leptonic and combined channels from the MVA analysis. (c) m_{bb} distribution of the cross check analysis that uses the m_{bb} distribution as the main discriminant.

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