The search for the Standard Model Higgs boson decaying to a pair of W bosons in the fully leptonic final state by ATLAS

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A search for the Higgs boson decaying to a pair of W bosons is performed in the fully leptonic final state with the ATLAS experiment at the LHC. The full 2011 dataset comprising 4.7 fb^{-1} of data is used. Backgrounds are determined from data-driven estimates as well as from simulation where applicable. The large branching fraction to W pairs makes this a viable search channel over a large range of possible Higgs masses. The expected exclusion range at 95% confidence level is between 127 GeV and 234 GeV while observed limits are between 130 GeV and 260 GeV.

1 The Higgs Boson

The Higgs Mechanism was posited by Higgs, Englert, Brout, Guralnik, Kibble, and Hagen [1, 2, 3] to provide mass to the weak gauge bosons predicted by the theory of weak interactions. The discovery of the Higgs boson will complete the description of the electroweak theory and will provide insights into physics beyond the standard model. Searches for the Higgs boson have been carried out at LEP, the Tevatron, and now at the LHC. Experiments at LEP placed an upper limit on the Higgs mass of 114 GeV and the CDF and D0 experiments at the Tevatron have ruled out masses between 147 GeV and 179 GeV. This note will describe the search for the Higgs in the WW channel with the ATLAS experiment using the full 2011 data set of 4.7 fb^{-1} taken with a center of mass energy of $\sqrt{s} = 7$ TeV [4].

The theory of electroweak interactions predicts the existence of a charged W bosons and a neutral Z boson. To preserve gauge invariance in the theory, these particles must be massless, which is contravened by experimental observations. The Higgs theory predicts the existence of a scalar field that has a non-zero vacuum expectation value. The observed mass of the weak boson arises from interactions with the Higgs field and so the coupling to the Higgs particle is proportional to its mass. This scenario is generally extended so that the Higgs contributes to the masses of the quarks and leptons as well.

The spectrum of possible Higgs decay particles depends on the mass of the Higgs. A Higgs boson having a mass above 140 GeV decays primarily to a pair of W or Z bosons. For masses between 100 GeV and 140 GeV the decays to weak bosons become suppressed and decays to gluons, bottom quarks, and tau leptons are favored. Although the WW channel is most sensitive above 140 GeV and up to 230 GeV, the exclusion sensitivity extends down to approximately 125 GeV with the full 2011 dataset. This large range of exclusion sensitivity makes the WW channel a valuable search mode.

There are a number of possible decay modes in which to search for the decay of a Higgs boson to WW. The fully leptonic final state has the lowest branching fraction, but the presence of two electrons, muons, or taus and two neutrinos provides a clean event signature. This analysis focuses on events having two electrons (ee), two muons ($\mu\mu$), or one electron and one muon ($e\mu$) and large transverse missing momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the escaping neutrinos. At the LHC the Higgs boson is produced predominantly via gluon-gluon fusion. Higgs boson production also occurs via vector boson fusion (VBF) which results in a unique detector signature. Therefore the presence of zero or one hadronic jet is required to select gluon-gluon fusion production and for VBF production, two jets having a topology consistent with VBF production are required.

2 The ATLAS Experiment

The ATLAS detector is a general purpose particle detector situated at one collision point of the LHC. ATLAS is comprised of a fine granularity tracking system, an electromagnetic and hadronic calorimeter, and a muon system. The combined performance of these detectors allows for good identification of electrons, photons, muons, and jets. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated by summing the p_T vectors of all identified objects and all calorimeter energy deposits. The detector is described in more detail elsewhere [5].

3 Event Selection

This section outlines the basic event selection for this analysis. A complete description can be found in [4]. Events are selected with at least one triggered electron or muon having $p_T > 25$ GeV. The second lepton p_T requirement is lowered to 15 GeV to improve sensitivity to lower mass Higgs bosons. The requirement of two well identified leptons reduces the di-jet and W+jet backgrounds significantly. A variable derived from $E_{\mathrm{T}}^{\mathrm{miss}}$ called relative $E_{\mathrm{T}}^{\mathrm{miss}}$ ($E_{\mathrm{T}}^{\mathrm{miss,Rel}}$) is used to identify events having real $E_{\mathrm{T}}^{\mathrm{miss}}$ while reducing the sensitivity to mis-measured leptons or jets. The $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ variable is defined as

$$E_{\mathrm{T}}^{\mathrm{miss,Rel}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \sin\Delta\phi & \text{if } \Delta\phi \leq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi > \pi/2 \end{cases}$$

where $\Delta\phi$ is the angular separation, in the transverse plane, between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the nearest lepton or jet. $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ is required to be greater than 45 GeV in the ee and $\mu\mu$ channels to suppress Drell-Yan events and to further suppress the di-jet background. These backgrounds are smaller in $e\mu$ events, so the cut is applied at 25 GeV. For events having no jets a cut is applied on the p_{T} of the dilepton system ($p_{\mathrm{T}}^{\ell\ell}$) to further reject Drell-Yan events. This cut requires events to have $p_T^{\ell\ell} > 45$ GeV for the ee and $\mu\mu$ channels and $p_T^{\ell\ell} > 25$ GeV for the $e\mu$ channel. Jet requirements are made to suppress the background from top events. Jets are required to have $p_{\mathrm{T}} > 25$ GeV and must pass a cut that limits the fraction of momentum from tracks associated to the jet that originate from pileup collisions. To reduce the contamination of background from top events the analysis is separated into three jet categories – no jets, one jet, and two jets having a VBF topology. Events having no jets have little top background, and so these events contribute most of the sensitivity to the Higgs signal. Events having one jet are included to improve the combined sensitivity, but this category of events contributes less than the no jet category because of the larger top background. Events having two jets are only selected with a VBF topology to reduce the top background in two jet events. The two jets must be on opposite sides of the detector in pseudorapidity (η) and also have $M_{jj} > 500$ GeV and $|\eta(j_1) - \eta(j_2)| > 3.8$.

After the basic lepton, $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$, and jet requirements are applied, continuum WW production is the dominant background. Differences in the topology of continuum WW and the decay from a Higgs boson are exploited to reduce this background. The spins of the two W bosons must be anti-aligned because they decay from a scalar particle. The V-A coupling of the weak interaction correlates the direction of the decay products to the spin of the W boson. Depending on the charge of the W the decaying neutrinos are preferentially emitted either along or opposite to the direction of the W spin with the charged leptons emitted in the opposite direction of the neutrinos. The two W particles must have opposite charge and opposite spin, so the charged leptons tend to be emitted in the same direction. Therefore the initial state spin of the Higgs Boson is transmitted to the topology of the final state leptons. The most discriminating effect of the spin correlation is that the two leptons tend to be close in ϕ whereas the leptons are preferentially back-to-back for continuum WW production. A cut requiring $\Delta\phi_{\ell\ell} < 1.8$ suppresses approximately half of the continuum WW background while keeping most of the Higgs signal. The invariant mass of the dilepton system ($M_{\ell\ell}$) is required to be greater than 12 GeV in the ee and $\mu\mu$ channels to avoid Υ production. This requirement is lowered to 10 GeV for $e\mu$ events. The $M_{\ell\ell}$ must also be smaller than 50 GeV for a Higgs mass hypothesis below 200 GeV. This cut is correlated with $\Delta\phi_{\ell\ell}$, but provides additional rejection.

4 Background estimation

Events originating from a number of Standard Model processes can enter the signal region and constitute a non-negligible background. The most notable backgrounds are from the production of W bosons, Z/γ* , top quark pairs as well as single top, and continuum WW. These backgrounds must be well understood to be confident in a possible Higgs signal. To this end, a dedicated background estimate is performed for each of these backgrounds which use the data to constrain the background when feasible.

4.1 Method of estimating the W background

Events where a W boson is produced are kept as signal if the W decays leptonically and a jet produced with the W fakes an electron or muon. Although the rate at which jets fake leptons is small, the relatively large cross section for W production makes this an important background. The mechanism by which a jet can fake a lepton differs between electrons and muons. Electron fakes result mainly from fluctuations in jet fragmentation while muons are mostly faked by real muons produced within heavy flavor jets. The physics that causes fakes to occur may not be well modeled in Monte Carlo. Therefore this method extracts the W background directly from data.

The background estimate is separated into two stages. First the fake factor is extracted from data rich in di-jets. Second the fake factor is applied to a control region defined by reversing lepton identification variables and isolation. Leptons that fall into the control region are labeled as denominators while fully identified leptons are labeled as numerators. Denominators are defined separately for muons and electron because they are faked by different sources. This definition is the same that is used in extracting the fake factor in the first step.

Di-jet events are selected using a prescaled trigger that accepts lepton-like objects, but is un-biased towards the lepton shower shapes and isolation. The fake factor is the ratio of the number of identified denominators to the number of identified numerators. The fake factor is binned in p_T because the probability for a jet to fake a lepton depends on its p_T. Small contributions to these events from electroweak events are subtracted using Monte Carlo.

To apply the fake factor, events are selected to have one fully identified lepton and one denominator lepton. The fake factor is applied to the denominator object to determine the background from W events.

4.2 Method of estimating the Z/γ^* background

Events where a single Z or γ^* is produced ideally have no $E_{\mathrm{T}}^{\mathrm{miss}}$. However detector resolution causes these events to be measured with non-zero $E_{\mathrm{T}}^{\mathrm{miss}}$. These effects are not necessarily well modeled in simulation, so a data-driven method is used to extract the background. A control region is defined with events selected to have a Z boson candidate. The processes that cause fake $E_{\mathrm{T}}^{\mathrm{miss}}$ in Drell-Yan events passing the signal invariant mass selection are expected to be the same for Z boson events. An ABCD method is used to extrapolate the $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ modelling in the control region to the signal region. The ratio of Z boson events in the $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ tail to events at moderate $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ is applied to the signal $M_{\ell\ell}$ region at moderate $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ to extract the background contribution to the signal. This method assumes that the $E_{\mathrm{T}}^{\mathrm{miss,Rel}}$ distribution is uncorrelated to the $M_{\ell\ell}$. Studies using simulation show that there is a small correlation between the distributions. A correction factor is derived from the simulation to correct for this effect.

4.3 Method of estimating the Top background

Events that include a pair of top quarks can enter as a background when both W bosons decay leptonically and the jet kinematics are such that 0 or 1 jets are reconstructed. A similar background results from single top production with a W boson and is treated together with top pair production. Top pair events tend to have two jets that originate from b quarks plus any number of additional jets from initial or final state radiation. In order to be reconstructed as a 0 or 1 jet event the jets must fall below the jet p_T threshold of 25 GeV, or be out of the detector acceptance. Separate methods are used to determine the background in the 0 and 1 jet channels.

In 1 jet events the Monte Carlo prediction is normalized to a control region that requires an additional b-tagged jet. This control region is fairly pure in top events and the remaining small background from other events is subtracted using the Monte Carlo prediction. This normalization factor is applied to simulated Top events that pass the signal selection.

The method to estimate the top background reconstructed with no jets is obtained by scaling the observed number of top events with a jet veto efficiency. The jet veto efficiency is determined in a control region that requires at least one b-tagged jet. A Monte Carlo scale factor is determined from the ratio of events between Data and Monte Carlo in the control region having no additional jet. This scale factor is applied to the number of top events in Monte Carlo having 0 jets to estimate the number of these events in data.

4.4 Method of estimating the WW background

The continuum WW background is the largest. These events enter the signal region simply because of the overlap between the signal kinematics and those of the continuum WW. These kinematic distributions are expected to be well modeled in Monte Carlo. A scale factor is determined from data to account for any mis-modellings of the rate of continuum WW production. The scale factor is determined from the ratio of data events to Monte Carlo events in a control region of $M_{\ell\ell} > 106$ GeV – above the Z boson mass. For the $e\mu$ channel the $M_{\ell\ell}$ cut is lowered to 80 GeV. In the two jet channel such a control region does not exist and this background is estimated from the simulation.

5 Results

No significant excess is observed over the background prediction. Therefore a maximum likelihood estimator is used to extract limits on the Higgs boson mass. The presence of two neutrinos in the final state prevents a full reconstruction of the mass of the initial state particle. Instead the transverse mass (m_T), which calculates the mass using the transverse lepton vector and the

$E_{\mathrm{T}}^{\mathrm{miss}}$, is used as the final discriminator between signal and background. To take advantage of the different m_T shape between signal and background, this distribution is fit in five bins. The three lepton channels together with three jet channels are fit simultaneously. Systematic uncertainties determined for each background contribution and the expected signal are propagated through the fitting procedure to the final limit results.

With all channels combined a Standard Model Higgs boson having a mass between 130 GeV and 260 GeV is excluded at 95% confidence. The expected 95% confidence level exclusion is between 127 GeV and 234 GeV. This result enters into the full ATLAS combination which reports the combined Higgs sensitivity for all search channels [6].

References

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