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Search for neutral MSSM Higgs bosons decaying to $\tau^+\tau^-$ pairs in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

Discovering the mechanism responsible for electroweak symmetry breaking and the origin of mass for elementary particles is one of the major goals of the physics program at the Large Hadron Collider (LHC) [1]. In the Standard Model (SM) this mechanism requires the existence of a scalar particle, the Higgs boson [2–6]. In extensions of the Standard Model to the Minimal Supersymmetric Standard Model (MSSM) [7,8], two Higgs doublets of opposite hypercharge are required, resulting in five observable Higgs bosons. Three of these are electrically neutral ($h, H, A$) while two are charged ($H^\pm$). At tree level their properties such as masses, widths, and branching ratios can be predicted in terms of only two parameters, often chosen to be the mass of the $CP$-odd Higgs boson, $m_A$, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan \beta$. The Higgs boson production proceeds mainly via gluon fusion or in association with $b$ quarks, with the latter becoming more important for large $\tan \beta$.

In this Letter, a search for neutral MSSM Higgs bosons in the decay mode $A/H/h \to \tau^+\tau^-$ with the ATLAS detector [9] is presented. The decay into a $\tau^+\tau^-$ pair is a promising channel since the coupling of the Higgs bosons to third-generation fermions is strongly enhanced over large regions of the MSSM parameter space. The search considers Higgs boson decays to $e\mu 4\nu$, $e\tau_{had}3\nu$, and $\mu\tau_{had}3\nu$, where $\tau_{had}$ denotes a hadronically decaying $\tau$ lepton. These topologies have branching ratios of 6%, 23%, and 23%, respectively. This analysis is complementary to previous searches at the $e^+e^-$ collider LEP at CERN [10] and similar to those performed at the $p\bar{p}$ collider Tevatron at Fermilab [11,12], and extends to regions of the MSSM parameter space untested by these machines. The CMS Collaboration has recently published results of a similar analysis [13].

2. Event sample

The data used in this search were recorded with the ATLAS detector in proton–proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV during the 2010 LHC run. The ATLAS detector is described in detail elsewhere [9]. In the ATLAS coordinate system, polar angles $\theta$ are measured with respect to the LHC beamline and azimuthal angles $\phi$ are measured in the plane transverse to the beamline. Pseudorapidities $\eta$ are defined as $\eta = -\ln \tan \frac{\theta}{2}$. Transverse momenta are computed from the three-momenta $p$ as $p_T = |p| \sin \theta$. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were fully operational, is 36.1 ± 1.2 pb$^{-1}$ [14]. The data were collected using a single-electron trigger with $p_T$ threshold in the range 10–15 GeV for the $e\tau_{had}$ and $e\mu$ final states, and a single-muon trigger with $p_T$ threshold in the range 10–13 GeV for the $\mu\tau_{had}$ final state. With respect to the signal selection described below, the total trigger efficiencies are 99% and 82% for electrons and muons, respectively. Events that pass the trigger are selected if they have a reconstructed vertex that is formed by three or more tracks and lies within 15 cm of the nominal interaction point along the beam axis.

The cross sections for Higgs boson production have been calculated using HIGLU [15] and ggh@nnlo [16] for the gluon fusion
process. For the b-quark associated production, a matching scheme described in [17] is used to combine the next-to-leading order (NLO) calculation for gg → bbA/H/h in the 4-flavor scheme [18, 19] and the next-to-next-to-leading order (NNLO) calculation for bb → A/H/h in the 5-flavor scheme [20]. The masses, couplings, and branching ratios of the Higgs bosons are computed with FeynHiggs [21]. The ratio of the MSSM Yukawa couplings and their SM values have been used to derive the MSSM cross sections from the respective SM cross sections. Details of the calculations and associated σS, parton distribution function (PDF) and scale uncertainties can be found in Ref. [22]. The direct gg → A/H/h production is simulated with MC@NLO [23], and the associated bbA/H/h production with SHERPA [24]. Both gg → A and bbA samples are generated at 11 values of mA, in the range from 90 to 300 GeV. These samples are also used for the H and h bosons assuming the same kinematics of the decay products. For any given mA and tan β, the masses mH and mH of the H and h bosons are calculated in the mAzmax MSSM benchmark scenario [25] and A boson events with mA closest to mH and mH, respectively, are added to these samples with appropriately scaled cross sections to obtain a signal sample for A/H/h production. The increase of the Higgs boson natural width with mH is neglected as it is small compared with the experimental mass resolution. Table 1 shows the signal cross section times branching ratio for tan β = 40 and mH = 120 GeV.

Table 1
<table>
<thead>
<tr>
<th>Signal process</th>
<th>σ × BR [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbA/H/h → τ + τ</td>
<td>30.8/1.08/32.3</td>
</tr>
<tr>
<td>gg → A/H/h → τ + τ</td>
<td>20.5/2.97/19.3</td>
</tr>
</tbody>
</table>

Process W → e + jets (e = μ, τ) and Z → e + τ + jets (mZ > 10 GeV) are added to these samples. The τ flavor is misidentified. Due to its large cross section, jet production in the range |η| < 2.5 and < 2.4 in the τ final states, respectively. Isolation requirements are imposed on electron (μon) candidates by requiring that the additional transverse energy in the calorimeter cells in a cone of radius ∆R = √(Δη)² + (Δφ)² < 0.3 (0.4) centered on the lepton direction is less than 10% (6%) of the electron (muon) transverse energy (momentum). In addition, the sum of the transverse momenta of all tracks with p_T > 1 GeV within ∆R = 0.4 around the lepton direction, excluding the lepton track, must be less than 6% of the lepton track transverse momentum. The reconstruction of candidates for hadronic τ decays is based on calorimeter jets reconstructed with the anti-kT algorithm [42,43] with a distance parameter R = 0.4, seeded using three-dimensional topological calorimeter energy clusters. Their identification, including vetoing electrons and muons, is based on observables that describe the shape of the calorimeter shower and on tracking information, which are combined in a likelihood discriminator [44]. A τ candidate must have a visible transverse momentum, p_T^{vis} > 20 GeV, a pseudorapidity in the range |η| < 2.5, 1 or 3 associated tracks (p_T > 1 GeV) and a total charge of ±1, computed from all tracks associated with the candidate. The efficiency for 1-prong (3-prong) τ candidates p_T^{vis} > 20 GeV is about 65% (60%) and the probability to misidentify a jet as a τ lepton, as determined from a di-jet control sample, is about 10% (5%). When candidates fulfilling the above criteria overlap with each other geometrically (within ∆R < 0.2), only one of them is selected. The overlap is resolved by selecting muons, electrons and τ candidates in this order of priority. The missing transverse momentum in the event, E_T^{miss} = (E_E^{miss})² + (E_μ^{miss})², is reconstructed as the vector sum of all topological calorimeter energy clusters in the region |η| < 4.5 and corrected for identified muons [41].

4. Event selection

The signatures of A/H/h → τ + τ → eμνν signal events are one isolated electron, one isolated muon and E_T^{miss} due to the undetected neutrinos from the two τ decays. Exactly one electron with p_T > 20 GeV and one muon with p_T > 10 GeV with opposite electric charge are required. In order to suppress backgrounds...
from $t\bar{t}$, single-top and di-boson production two additional requirements are applied. The scalar sum of the transverse momentum of the electron, the transverse momentum of the muon and the missing transverse momentum must be smaller than 120 GeV, and the azimuthal opening angle between the electron and the muon must be larger than 2.0 rad.

The signatures of $A/H/\gamma\gamma \rightarrow \tau^+\tau^-$ signal events, where one $\tau$ lepton decays leptonically and the other hadronically, are an isolated electron or muon, $\ell$, a $\tau$ candidate, $e_{\text{had}}$, and $E_{T}^{\text{miss}}$ due to the undetected neutrinos from the two $\tau$ decays. Exactly one electron or muon with $p_{T}^{\ell} > 20$ GeV or $p_{T}^{\ell} > 15$ GeV and one oppositely-charged $\tau$ candidate with $p_{T}^{\tau\text{vis}} > 20$ GeV are required in the event. Events with more than one electron or muon, using the lepton $p_{T}$ thresholds from the object definition given in Section 3, are rejected to suppress events from $Z/\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) decays and from $t\bar{t}$ and single-top production. A missing transverse momentum above 20 GeV is required to reject events with jets from QCD processes as well as $Z/\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) decays. Events with real leptons from $W \rightarrow \ell\nu$ decays are suppressed by requiring the transverse mass of the $\ell-E_{T}^{\text{miss}}$ system, defined as

$$m_{T} = \sqrt{2p_{T}E_{T}^{\text{miss}}(1 - \cos \Delta\phi)}, \quad (1)$$

to be below 30 GeV. Here $p_{T}$ is the transverse momentum of the electron or muon and $\Delta\phi$ is the angle between the electron or muon and the $E_{T}^{\text{miss}}$ vector in the plane perpendicular to the beam direction.

Table 2 compares the number of selected events in data with those expected from the simulation of various background processes, not including QCD jet production. After the full selection, 70, 74, and 132 data events are observed in the $e\mu$, $e_{\text{had}}$, and $\mu_{\text{had}}$ channels, respectively. The estimation of backgrounds based on data control samples used for the final results of the analysis is discussed in Section 5. The signal efficiency amounts to 7 (3)% for $m_{t} = 120$ GeV and 9 (8)% for $m_{t} = 200$ GeV in the $e\mu$ ($\ell_{\text{had}}$) final states.

After the selection of signal candidates in the $e\mu$ final state, the effective mass, $m_{\tau\tau}^{\text{effective}}$, is used as the discriminating variable to search for a potential Higgs boson signal. Here, $m_{\tau\tau}^{\text{effective}}$ is calculated as the invariant mass of the electron, muon and $E_{T}^{\text{miss}}$ system according to

$$m_{\tau\tau}^{\text{effective}} = \sqrt{(p_{e} + p_{\mu} + p_{\text{miss}})^{2}}, \quad (2)$$

where $p_{e}$ and $p_{\mu}$ denote the four-vectors of the electron and muon, respectively, and the missing momentum four-vector is defined by $p_{\text{miss}} = (E_{T}^{\text{miss}}, x_{\text{miss}}, y_{\text{miss}}, 0)$.

In the $e_{\text{had}}$ and $\mu_{\text{had}}$ final states, the visible $\tau^+\tau^-$ mass, $m_{\tau\tau}^{\text{visible}}$, defined as the invariant mass of the electron or muon from the leptonic $\tau$ decay and the hadron(s) from the hadronic $\tau$ decay, is used as the discriminating variable.

Fig. 1 shows distributions of $m_{\tau\tau}^{\text{effective}}$ and $m_{\tau\tau}^{\text{visible}}$ for the data, compared to the background expectations described in Section 5.

5. Background estimation

In the search for a Higgs boson signal the normalization and shape of the $m_{\tau\tau}^{\text{visible}}$ and $m_{\tau\tau}^{\text{effective}}$ distributions for the sum of all background contributions have to be determined. Data control samples are used, where possible, to estimate or validate the most
relevant background sources: $Z/\gamma^* \rightarrow \tau^+\tau^-$ and QCD jet production in the $e\mu$ final state, and $W + \text{jets}$, $Z/\gamma^* \rightarrow \tau^+\tau^-$, and QCD jet production in the $\ell_\tau\text{had}$ final state. The remaining backgrounds given in Table 2 are estimated solely from simulation.

5.1. QCD jet background in the $e\mu$ final state

For the estimation of the QCD jet background, four independent samples are selected by using selection criteria on two variables: the isolation of the electron and muon and their charge product. The signal region A is defined by the selection criteria defined above, i.e. opposite-sign isolated leptons. Region B contains same-sign isolated leptons, region C opposite-sign anti-isolated leptons, and region D same-sign anti-isolated leptons. Anti-isolated leptons are obtained by inverting the isolation criteria described in Section 3. The shape of the $m_{\text{eff}}^{\text{effective}}$ distribution in the signal region A is taken from control region C and the normalization is derived by $n_A = r_{C/D} \times n_B$. Here, $n_A$ and $n_B$ denote the event yields in regions A and B and $r_{C/D}$ the ratio of the event yields in regions C and D after subtracting the contribution from non-QCD jet backgrounds estimated from simulation. This method relies on the assumption that the two variables used to define the four regions are uncorrelated and that the shape of the $m_{\text{eff}}^{\text{effective}}$ distribution does not depend on the isolation or charge product requirement. This has been verified by comparing the event yields and shapes of the $m_{\text{eff}}^{\text{effective}}$ distribution in data for regions C and D and in further control regions defined by the requirement of one isolated and one non-isolated lepton.

After subtracting the contribution from non-QCD jet backgrounds, estimated from simulation, the QCD jet event yield in region B is found to be $n_B = 1.07 \pm 1.57 \text{(stat.)}$ and the ratio $r_{C/D}$ is determined to be $r_{C/D} = 1.97 \pm 0.12 \text{(stat.)}$. The QCD jet event yield in the signal region is therefore estimated to be $n_A = 2.11 \pm 0.17 \text{(stat.)}$. Systematic uncertainties are discussed in Section 6.

5.2. Background in the $\ell_\tau\text{had}$ final states

The method to estimate the QCD and $W + \text{jets}$ backgrounds [45] is based on both data and simulation and uses events with same-sign charges of the electron/muon and the $\tau_\text{had}$ candidate. It relies on the assumptions that the shape of the $m_{\text{vis}}^{\text{visible}}$ distribution for these backgrounds is the same for opposite-sign (OS) and same-sign (SS) events and that their ratio is the same in the signal region, defined by the nominal selection, and in background-enhanced QCD and $W + \text{jets}$ control regions. These assumptions have been verified with simulated events. The method is referred to as the baseline method and is used to derive the results for the $\ell_\tau\text{had}$ channel. It is cross-checked with an alternative background estimation method.

The total number of opposite-sign background events in the signal region, $n_{B_{\text{OS}}}^{\text{Bkg}}$, can be expressed as

$$n_{B_{\text{OS}}}^{\text{Bkg}} = n_{B_{\text{SS}}}^{\text{Bkg}} + n_{B_{\text{OS}}^{\text{QCD}}} + n_{B_{\text{OS}}^{\text{SS}}} + n_{B_{\text{OS}}^{\text{other}}} + n_{B_{\text{SS}}^{\text{QCD}}} + n_{B_{\text{SS}}^{\text{SS}}} + n_{B_{\text{SS}}^{\text{other}}},$$

where $n_{B_{\text{OS}}}^{\text{Bkg}}$ is the sum of all same-sign backgrounds in the signal region and the remaining terms are the differences between opposite-sign and same-sign events for the QCD, $W + \text{jets}$, $Z/\gamma^* \rightarrow \tau^+\tau^-$, and other backgrounds. The ratio of opposite-sign and same-sign events for the QCD background, $r_{\text{QCD}}^{\text{OS/SS}}$, is expected to be close to unity. For $W + \text{jets}$, a significant deviation of the ratio $r_{\text{SS}}^{W}$ from unity is expected since $W + \text{jets}$ production is dominated by $g/\gamma d$-processes that often give rise to a jet originating from a quark whose charge is anti-correlated with the $W$ charge. From simulation, the ratio $r_{\text{SS}}^{W}$ is $2.24 \pm 0.13 \text{(stat.)}$ obtained.

Using $n_{B_{\text{OS}}}^{W} = (r_{\text{OS/SS}}^{W} - 1) \times n_{B_{\text{SS}}}^{W}$ and assuming $r_{\text{QCD}}^{\text{OS/SS}} = 1$, Eq. (3) can be approximated by

$$n_{B_{\text{OS}}}^{\text{Bkg}} = n_{B_{\text{SS}}}^{\text{Bkg}} + (r_{\text{OS/SS}}^{W} - 1) \times n_{B_{\text{SS}}}^{W} + n_{B_{\text{OS}}^{\text{SS}}} + n_{B_{\text{SS}}^{\text{other}}}.$$  (4)

Each of the terms in Eq. (4) is estimated separately and for each bin in the $m_{\text{vis}}^{\text{visible}}$ distribution, thus not only an estimation of the background normalization but also of the $m_{\text{vis}}^{\text{visible}}$ shape is obtained. The total number of same-sign events $n_{B_{\text{OS}}}^{SS}$ is determined for the nominal selection except for changing the opposite-sign charge requirement to same-sign. In the full $m_{\text{vis}}^{\text{visible}}$ range, 36 same-sign events are selected in data. The contributions from $Z/\gamma^* \rightarrow \tau^+\tau^-$ and other backgrounds are taken from simulation: $n_{B_{\text{OS}}^{SS}} = 112 \pm 4 \text{(stat.)}$ and $n_{B_{\text{SS}}^{\text{other}}} = 26 \pm 2 \text{(stat.)}$. The $W + \text{jets}$ term in Eq. (4) is estimated to be $(r_{\text{OS/SS}}^{W} - 1) \times n_{B_{\text{SS}}}^{W} = 31 \pm 2 \text{(stat.)}$. Here, the number of same-sign $W + \text{jets}$ events in the signal region, $n_{B_{\text{SS}}}^{W}$, and the ratio $r_{\text{SS}}^{W}$ are determined in a $W + \text{jets}$-dominated data control region selected by replacing the $m_{\text{vis}} < 30 \text{ GeV}$ requirement in the nominal selection by $m_{\text{vis}} > 50 \text{ GeV}$. The small contribution from backgrounds other than $W + \text{jets}$ is subtracted based on simulation. A value of $r_{\text{OS/SS}}^{W} = 2.41 \pm 0.15 \text{(stat.)}$ is obtained. It has been checked in simulation that this ratio is approximately independent of the $m_{\text{vis}}$ range and can thus be used for the signal region. $n_{B_{\text{OS}}}^{SS}$ is obtained by scaling the number of events in the $W + \text{jets}$ control region by the ratio of events in the signal and control regions determined from simulation. The shape of the $m_{\text{vis}}^{\text{visible}}$ distribution for this contribution is taken from simulation.

The assumption $r_{\text{QCD}}^{\text{OS/SS}} \approx 1$ used in Eq. (4) is checked with a data control sample that is dominated by relatively low-$E_T$ jets from QCD processes, as expected in the signal region. This sample is selected by replacing the requirement $E_T^{\text{miss}} > 20 \text{ GeV}$ with $E_T^{\text{miss}} < 15 \text{ GeV}$ and relaxing the isolation of the electron/muon candidate. After subtraction of the other backgrounds using simulation, a value of $r_{\text{QCD}}^{\text{OS/SS}} = 1.16 \pm 0.04 \text{(stat.)}$ is obtained. The observed deviation of $r_{\text{QCD}}^{\text{OS/SS}}$ from unity is taken into account in the determination of systematic uncertainties for the final result, leading to a total systematic uncertainty of 19% on $n_{B_{\text{OS}}}^{\text{QCD}}$. This uncertainty also includes an uncertainty associated with the dependence of $r_{\text{QCD}}^{\text{OS/SS}}$ on the lepton isolation and detector effects.

The total background estimate obtained from Eq. (4) is $r_{\text{OS}}^{\text{Bkg}} = 206 \pm 7 \text{(stat.)}$, to be compared with 206 events observed in data. An alternative background estimation is performed, which provides separate estimates of the QCD and $W + \text{jets}$ background contributions and is used to cross-check the results of the baseline method discussed before. For the QCD jet background the same method and assumptions as described in Section 5.1 for the $e\mu$ final state are used, but replacing one of the leptons ($e$ or $\mu$) by the $\tau_\text{had}$ candidate and using the $m_{\text{vis}}^{\text{visible}}$ distribution instead of $m_{\text{vis}}^{\text{effective}}$. The shape of the $m_{\text{vis}}^{\text{visible}}$ distribution is taken from region B and scaled by the ratio of event yields in regions C and D: $r_{C/D} = 1.12 \pm 0.04 \text{(stat.)}$. The resulting estimate of the QCD jet background in the signal region is $n_{B_{\text{OS}}}^{\text{QCD}} = r_{C/D} \times n_B = 7.8 \pm 7.0 \text{(stat.)}$. The estimate of the $W + \text{jets}$ background is obtained by deriving a scale factor of $0.83 \pm 0.04 \text{(stat.)}$ for the normalization of the simulated $m_{\text{vis}}^{\text{visible}}$ distribution in a $W$-dominated data control sample. This control region is defined by replacing the $m_{\text{vis}} < 30 \text{ GeV}$ requirement in the nominal selection by $m_{\text{vis}} > 120 \text{ GeV}$. The shape of the $W + \text{jets}$ background is taken from simulation. The estimated number of $W + \text{jets}$ events for the nominal selection amounts to $54.8 \pm 2.1 \text{(stat.)}$ events. Adding the expected number of events for $Z/\gamma^* \rightarrow \tau^+\tau^-$ and the other backgrounds from simulation (see Table 2) to the sum of the estimated QCD jet and $W + \text{jets}$ yields, a total background contribution of...
211 ± 8(stat.) events is obtained, which agrees well with the 206 events observed in data. The $m_{\tau\tau}^{\text{visible}}$ shapes predicted by the two methods are found to agree as well.

5.3. Validation of the $Z/\gamma^* \rightarrow \tau^+\tau^-$ background shape

The shape of the $m_{\tau\tau}^{\text{visible}}$ and $m_{\tau\tau}^{\text{effective}}$ distributions for the irreducible $Z/\gamma^* \rightarrow \tau^+\tau^-$ background can be determined from a high-purity data sample of $Z/\gamma^* \rightarrow \mu^+\mu^-$ events in which the muons are removed and replaced by simulated $\tau$ leptons. Thus, only the $\tau$ decays and the corresponding detector response are taken from simulation, whereas the underlying $Z/\gamma^*$ kinematics and all other properties of the event are obtained from the $Z/\gamma^* \rightarrow \mu^+\mu^-$ data. Fig. 2 compares the $m_{\tau\tau}^{\text{visible}}$ and $m_{\tau\tau}^{\text{effective}}$ distributions of the $\tau$-embedded sample with simulated $Z/\gamma^* \rightarrow \tau^+\tau^-$ events. A good agreement is observed within the sizable statistical uncertainties, justifying the use of the simulation for the determination of the $Z/\gamma^* \rightarrow \tau^+\tau^-$ background. This background is normalized according to the theoretical cross section in Table 1, which agrees with the ATLAS $Z/\gamma^* \rightarrow \tau^+\tau^-$ cross section measurement [41].

6. Systematic uncertainties

Systematic effects on the signal efficiency and the estimated number of background events are evaluated. The uncertainties can be grouped in four categories: theoretical inclusive cross sections, acceptance, knowledge of detector performance and systematic uncertainties of the data-driven approaches to estimate the background contribution.

The uncertainty on the theoretical inclusive cross section for each individual signal and background process is obtained from variations of the renormalization and factorization scales ($\mu_R, \mu_F$) by factors 1/2 and 2 and a variation of the strong coupling constant and the PDF sets within their uncertainties. The uncertainty on the acceptance is estimated by varying $\mu_R, \mu_F$, matching parameters in ALPGEN and the choice of the PDF in the generation of simulated event samples. The uncertainty on the trigger efficiencies for electrons and muons is 1%. The uncertainties due to the limited knowledge of the detector performance are evaluated by varying the trigger, reconstruction and identification efficiencies for electrons, muons and $\tau$ candidates, and by varying the energy resolution and energy scale of electrons, muons, $\tau$ candidates, and energy deposits outside of these objects. These are propagated in a fully correlated way into the $E_T^{\text{miss}}$ scale and resolution. For the probability to misidentify electrons as $\tau$ candidates, a 20% uncertainty is assumed, resulting in a 20% uncertainty on the $Z/\gamma^* \rightarrow e^+e^-$ background.

The size of the uncertainties from the different sources on the various background processes which are at least partially estimated from simulated events are summarized in Table 3. The luminosity uncertainty is 3.4%.

The dominant systematic uncertainty in the $\ell\tau_{\text{had}}$ final states is due to the variation of the jet and $\tau$ energy scales, which are dependent on transverse momentum and pseudorapidity, by typically 7% and 5%, respectively. The difference in the impact on the $E_T^{\text{miss}}$ and resolution uncertainty on the expected event yields in the $\ell\tau_{\text{had}}$ and $e\mu$ final states is caused by requiring a hadronic $\tau$ decay with $p_T^{\tau} > 20$ GeV and a lower threshold $E_T^{\tau} > 20$ GeV in the $\ell\tau_{\text{had}}$ final states, whereas in the $e\mu$ final state only an upper threshold of $p_T^\tau + E_T^{\text{miss}} < 120$ GeV is required. The uncertainties, apart from the ones related to the data-driven techniques, are treated as fully correlated between the three final states.

The systematic uncertainty from the data-driven estimate of the QCD jet background in the $e\mu$ final state corresponds to 0.8 events. It includes the systematic uncertainty on the subtracted non-QCD background (0.2 events) and on the assumption of identical $m_{\tau\tau}^{\text{effective}}$ shapes in the different control regions (uncertainty on $r_{C/D}$ of 0.78). The final estimate for the QCD jet yield in the signal region is therefore $n_A = 2.1^{+3.1}_{-2.1}\,(\text{stat.}) \pm 0.8\,(\text{syst.}) = 2.1^{+3.2}_{-2.1}$. The total uncertainty is dominated by the small event yield in control region B.

For the $\ell\tau_{\text{had}}$ channels, the most important uncertainties for the data-driven estimation of the QCD jet and $W +$ jets backgrounds (see Eq. (4)) are the statistical uncertainty on the number of same-sign events in the signal region (17%) and the uncertainty on the ratios $r_{QCD}^{\text{SS}}$ (19%) and $r_{W/SS}^{\text{OS}}$ (11%). An additional uncertainty of 10% is derived from the $m_{\tau}$ dependence of $r_{W}^{\text{OS/SS}}$, i.e. for the extrapolation from control to signal region. The final estimate for the total background yield is $n_{W}^{\text{mis}} = 206 \pm 7\,(\text{stat.}) \pm 34\,(\text{syst.}) = 206 \pm 35$. 

![Fig. 2. Effective mass distribution for the $e\mu$ final state (top) and visible mass distribution for the $e\tau_{\text{had}}$ final states (bottom) for simulated $Z/\gamma^* \rightarrow \tau^+\tau^-$ events (boxes) and $\tau$-embedded $Z/\gamma^* \rightarrow \mu^+\mu^-$ events (points) passing the signal selection. The size of the boxes and the length of the error bars indicate the statistical uncertainty on the simulated and $\tau$-embedded sample, respectively.](figure)
Table 3
Uncertainties on the number of selected events for those background contributions that are at least partially estimated from simulation and for a hypothetical signal ($m_A = 120$ GeV). All numbers are given in %. When two numbers are given the first refers to the $\ell\mu$ final state and the second to the $\ell\tau_{had}$ final states. If an uncertainty does not apply for a certain background, this is indicated by a `--'.

<table>
<thead>
<tr>
<th></th>
<th>$W + \text{jets}$</th>
<th>$t\bar{t}$-boson</th>
<th>$tt + \text{single-top}$</th>
<th>$Z/\gamma^* \rightarrow e\mu$, $\mu\mu$</th>
<th>$Z/\gamma^* \rightarrow \tau^+\tau^-$</th>
<th>Signal ($m_A = 120$ GeV, tan $\beta = 40$)</th>
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<td>5/--</td>
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<td>11/38</td>
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</tbody>
</table>

The impact of the energy scale uncertainties of the electron, muon, $\tau$ candidate, and $E_{\text{Tmiss}}$ on the shapes of the discriminating mass variables are included as an additional correlated uncertainty in the derivation of the Higgs boson exclusion limits in Section 7. All other systematic uncertainties have no significant effect on the mass shape.

Combining the estimated contribution from the various background processes and their uncertainties results in the final background estimate shown in Table 4.

7. Results

No significant excess of events is observed in the data, compared to the SM expectation. Exclusion limits at the 95% confidence level are set on the production cross section times branching ratio of a generic Higgs boson $\phi$ as a function of its mass and for MSSM Higgs boson $A/H/h$ production as a function of the parameters $m_A$ and $\tan \beta$. The exclusion limits are derived with the profile likelihood method [46] from an analysis of the $m_\text{effective}$ distribution for the $\ell\mu$ final state and the $m_\text{visible}$ distribution for the $\ell\tau_{had}$ final states.

Systematic uncertainties are separated into common, fully correlated (energy scale, acceptence, luminosity) and channel-specific, and are included as nuisance parameters. The $m_\text{effective}$ and $m_\text{visible}$ shape uncertainties due to variation of the energy scales of leptons and $E_{\text{Tmiss}}$ for the backgrounds obtained from simulation are taken into account.

The $p$-values for the consistency of the observed data with the background-only hypothesis range from 3% for a mass of 300 GeV to 59% for a mass of 110 GeV for the combination of the $\ell\mu$ and $\ell\tau_{had}$ channels.

Background-only toy MC experiments are generated to find the median expected limit along with the $\pm 1\sigma$ and $\pm 2\sigma$ error bands. As a protection against excluding the signal hypothesis in cases of downward fluctuations of the background, the observed limit is not allowed to fluctuate below $-1\sigma$ of the expected limit, i.e. a power-constrained limit [PCL [47]], with the power required to be larger than 16%, is given.

Fig. 3 shows the resulting exclusion limits. The cross section limit is evaluated for signal acceptances of two different production processes, $gg \rightarrow \phi$ and $b$-quark associated production, where $\phi$ denotes a generic neutral Higgs boson. Differences in the observed limits for the two processes are small compared to the $1\sigma$ error and occur due to differences in the signal shapes used in the extraction of the limits. The limit on the production cross section times branching ratio into a pair of $\tau$ leptons for a generic Higgs boson $\phi$ is in the range between approximately 300 pb for a Higgs boson mass of 90 GeV and approximately 10 pb for a Higgs boson mass of 300 GeV, with a small dependence on the production mode considered. The limit on the production of neutral MSSM Higgs bosons $A/H/h$ in the $\tan \beta$-$m_A$ plane, also shown in Fig. 3, uses the $m_{\text{mass}}$ scenario and Higgsino mass parameter $\mu > 0$.

8. Conclusions

In this Letter, a search for neutral MSSM Higgs bosons $A/H/h$ with the ATLAS detector in proton–proton collisions corresponding to an integrated luminosity of 36 pb$^{-1}$ at a center-of-mass energy of 7 TeV is presented. Candidates for $A/H/h \rightarrow \tau^+\tau^-$ decays are selected in the three final states $\ell\mu$, $\ell\tau_{had}$, and $\mu\tau_{had}$. No evidence for a Higgs boson signal is observed in the reconstructed mass spectra. Exclusion limits on both the cross section for the production of a generic Higgs boson $\phi$ as a function of its mass and on MSSM Higgs boson production $A/H/h$ as a function of $m_A$ and $\tan \beta$ are derived. These results exclude regions of parameters space beyond the existing limits from previous experiments at LEP and the Tevatron and are similar to those recently obtained by the CMS Collaboration.

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