

SEARCHING FOR BSM HIGGS AND GAUGE BOSONS
DECAYING TO TWO TAU LEPTONS USING 36 fb^{-1}
OF DATA COLLECTED AT $\sqrt{s} = 13 \text{ TeV}$
WITH THE ATLAS DETECTOR* **

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A search for additional heavy neutral Higgs bosons and Z' bosons decaying to two tau leptons is performed using data corresponding to an integrated luminosity of 36.1 fb^{-1} from proton–proton collisions at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the LHC during 2015 and 2016. The data are in good agreement with the Standard Model and results are interpreted in several benchmark scenarios.

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1. Introduction

The search presented in this report (see [1] for full analysis details) concentrates on additional neutral Higgs bosons H and A , while also investigating the presence of other BSM resonances decaying to two tau leptons, such as extra vector bosons Z' . The search was done using 36 fb^{-1} of proton–proton collision data at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector [2] at the LHC in the years 2015–2016. The analysis was divided into two channels based on tau-decay modes: $\tau_{\text{lep}}\tau_{\text{had}}$, where one tau lepton decays leptonically (to an electron or muon and two neutrinos) and one hadronically (to one or more hadrons and a neutrino) and $\tau_{\text{had}}\tau_{\text{had}}$, where both tau leptons decay hadronically. The $\tau_{\text{lep}}\tau_{\text{lep}}$ channel is not used, as it contributes little to the analysis sensitivity. Two Higgs production

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modes are considered: gluon–gluon fusion and b -associated production. To amplify the signal from these two production modes, two selection categories are defined, respectively: the b -veto category, which requires events to have no b -jets in the final state, and the b -tag category, which requires events to have at least one b -jet in the final state. For the Z' boson production, only the Drell–Yan process is considered, with an inclusive selection used in the analysis.

2. Event selection

The signal-region selection criteria for the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are listed below. The variable η refers to particle pseudorapidity, ϕ to the azimuthal angle measured with respect to the beam axis, p_{T} to transverse momentum, and $E_{\text{T}}^{\text{miss}}$ to missing transverse energy. Electrons and muons are collectively referred to as leptons ℓ , while hadronically-decaying tau jets, with neutrinos excluded, are called $\tau_{\text{had-vis}}$.

In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, events had to pass a single-lepton trigger with a p_{T} threshold in the 20–140 GeV range and varying isolation criteria depending on the data-taking period. Exactly one isolated lepton matching the trigger and at least one $\tau_{\text{had-vis}}$ candidate passing medium $\tau_{\text{had-vis}}$ identification (ID) criteria had to be present. The pseudorapidity requirement $|\eta^{\tau_{\text{had-vis}}}| < 2.3$ was introduced to reduce the background from misidentified electrons. The lepton and $\tau_{\text{had-vis}}$ candidate had to have opposite electric charges and be back-to-back in the detector, $|\Delta\phi(p_{\text{T}}^{\ell}, p_{\text{T}}^{\tau_{\text{had-vis}}})| > 2.4$. To reduce the background from W + jets production, a cut on transverse mass m_{T} was introduced: $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) \equiv \sqrt{2p_{\text{T}}^{\ell} E_{\text{T}}^{\text{miss}} [1 - \cos \Delta\phi(p_{\text{T}}^{\ell}, E_{\text{T}}^{\text{miss}})]} < 40$ GeV. Additionally, in the $\tau_e\tau_{\text{had}}$ channel, events where the invariant mass of the electron and $\tau_{\text{had-vis}}$ was between 80 and 110 GeV were vetoed to reduce the background from $Z \rightarrow ee$ production.

In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, events had to pass a single-tau trigger with a p_{T} threshold of 80, 125, or 160 GeV depending on the data-taking period and at least two oppositely-charged $\tau_{\text{had-vis}}$ candidates had to be present. The leading (highest- p_{T}) $\tau_{\text{had-vis}}$ had to be matched to the trigger, pass medium ID, and exceed the trigger p_{T} threshold by at least 5 GeV. The subleading (second-highest- p_{T}) $\tau_{\text{had-vis}}$ had to have a p_{T} of at least 65 GeV and pass loose ID. No electrons or muons could be present in events and the two leading $\tau_{\text{had-vis}}$ candidates had to fulfill the back-to-back requirement, $|\Delta\phi(p_{\text{T}}^{\tau_1}, p_{\text{T}}^{\tau_2})| > 2.7$.

In addition, each channel was divided into a b -veto category, with zero b -jets in the final state, and a b -tag category, with at least one b -jet in the final state.

3. Data-driven background estimation

3.1. $\tau_{\text{lep}}\tau_{\text{had}}$ channel

Two background contributions are estimated using data-driven methods: the background where the lepton is faked by a jet, which corresponds mainly to multijet (QCD) events, and the background where the $\tau_{\text{had-vis}}$ is faked by a jet, which corresponds mainly to W + jets events in the b -veto category and $t\bar{t}$ events in the b -tag category. A scheme showing the background estimation process is shown in figure 1. Two control regions are constructed: CR-1, where $\tau_{\text{had-vis}}$ candidates fail the medium ID criteria, and CR-2, where events fail both the τ -lepton ID and the lepton isolation criteria. Additionally, three fake factor regions are defined: the lepton fake region L-FR, where $\tau_{\text{had-vis}}$ candidates fail loose ID; the multijet fake region MJ-FR, where the lepton fails the isolation criterion; and the W + jets/ $t\bar{t}$ fake region W-FR, where $m_T > 60$ GeV. Fake factors (f_X , $X = \text{L, MJ, W}$) are calculated in these regions by subtracting non-multijet Monte Carlo background (denoted as MC background hereafter) from data, then taking the ratio of remaining data events in two sub-regions: in L-FR, the ratio of events passing/failing lepton isolation criteria; in MJ-FR and W-FR, the ratio of events passing/failing the medium $\tau_{\text{had-vis}}$ ID requirement. The lepton and multijet fake factors are binned in p_T^ℓ , while the W + jets/ $t\bar{t}$ fake factor is binned in $p_T^{\tau_{\text{had-vis}}}$ and $\tau_{\text{had-vis}}$ track multiplicity.

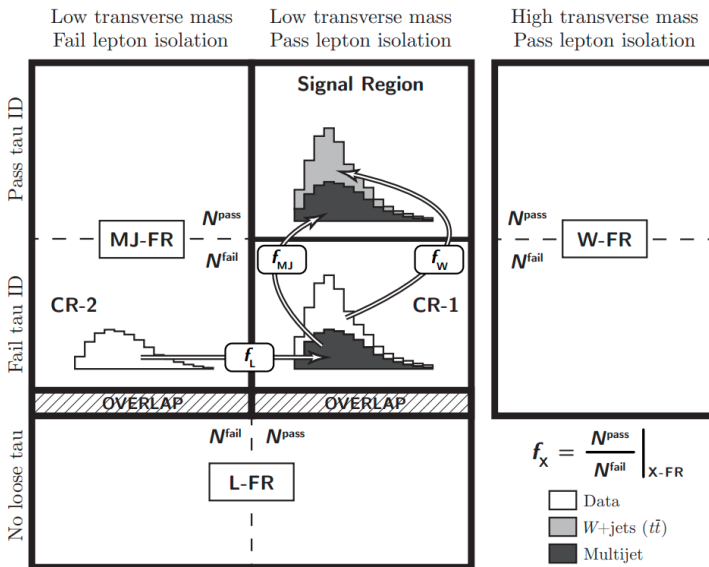


Fig. 1. A scheme of data-driven background estimation in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel [1].

The fake factors are then used for propagating events with fakes from CR-1 and CR-2 to the signal region. First, MC background, including simulated $W + \text{jets}$ events, is subtracted from data in CR-2; the remaining events are assumed to constitute QCD background and are propagated to CR-1. In CR-2, MC background and QCD background is again subtracted from data; the remaining events are considered to be $W + \text{jets}$ or $t\bar{t}$ fakes. QCD and $W + \text{jets}/t\bar{t}$ fakes are then propagated to the signal from CR-1 region using the multijet and $W + \text{jets}/t\bar{t}$ fake factors, respectively. This can be summarised with the following formulas: $N_{\text{QCD}}^{\text{SR}} = f_{\text{MJ}} \times f_{\text{L}} \times (N_{\text{data}}^{\text{CR-2}} - N_{\text{MC}}^{\text{CR-2}})$ and $N_{W+\text{jets}/t\bar{t}}^{\text{SR}} = f_{\text{W}} \times (N_{\text{data}}^{\text{CR-1}} - N_{\text{QCD}}^{\text{CR-1}} - N_{\text{MC}}^{\text{CR-1}})$.

3.2. $\tau_{\text{had}}\tau_{\text{had}}$ channel

In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, only QCD events are estimated using a data-driven method analogous to the one used in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. One control region, CR-1, is defined by inverting the cut on subleading $\tau_{\text{had-vis}}$ ID. The fake factor is calculated in the DJ-FR fake region, where events are selected using a single-jet rather than a single-tau trigger. No $\tau_{\text{had-vis}}$ ID criteria are used, and p_{T} of the subleading $\tau_{\text{had-vis}}$ must be at least 30% of the p_{T} of the leading $\tau_{\text{had-vis}}$. The fake factor f_{DJ} is calculated by subtracting MC (non-multijet) events from the DJ-FR, then taking the ratio of events passing/failing the loose ID requirement. This fake factor is parameterised in subleading $\tau_{\text{had-vis}}$ p_{T} and subleading $\tau_{\text{had-vis}}$ track multiplicity. QCD events are propagated from CR-1 to the control region using the formula $N_{\text{multijet}}^{\text{SR}} = f_{\text{DJ}} \times (N_{\text{data}}^{\text{CR-1}} - N_{\text{MC}}^{\text{CR-1}})$.

Additionally, MC events which include jets misidentified as tau leptons are weighted by fake rates calculated in the $W + \text{jets}/t\bar{t}$ fake regions W/T-FR, where a single-muon rather than a single-tau trigger is used, no $\tau_{\text{had-vis}}$ ID criteria are used, $|\Delta\phi(p_{\text{T}}^{\mu}, p_{\text{T}}^{\tau_{\text{had-vis}}})| > 2.4$, and $m_{\text{T}}(\mu, E_{\text{T}}^{\text{miss}}) > 40$ GeV. Events in W-FR pass the b -veto requirement, while events in T-FR pass the b -tag requirement. Fake rates are calculated by taking the ratio of events passing/failing the medium $\tau_{\text{had-vis}}$ ID criterion and are binned in p_{T}^{τ} and $\tau_{\text{had-vis}}$ track multiplicity.

4. Results

4.1. Fit model

The parameter of interest in the analysis is the signal strength μ defined as the ratio of the observed value of the resonance production cross section times the resonance branching ratio to the predicted value. Predicted values are calculated for specific theoretical models, called benchmark scenarios. The parameter of interest is estimated using a likelihood function

constructed as the product of Poisson probability terms, with one term derived from each bin of discriminating variable distributions in the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels and b -veto and b -tag categories. The discriminating variable is the total transverse mass $m_{\text{T}}^{\text{tot}}$, which is defined as follows:

$m_{\text{T}}^{\text{tot}} = \sqrt{m_{\text{T}}^2(E_{\text{T}}^{\text{miss}}, \tau_1) + m_{\text{T}}^2(E_{\text{T}}^{\text{miss}}, \tau_2) + m_{\text{T}}^2(\tau_1, \tau_2)}$, where τ_1 and τ_2 can be either τ_{lep} or $\tau_{\text{had-vis}}$. Sample post-fit distributions of $m_{\text{T}}^{\text{tot}}$ are shown in figure 2.

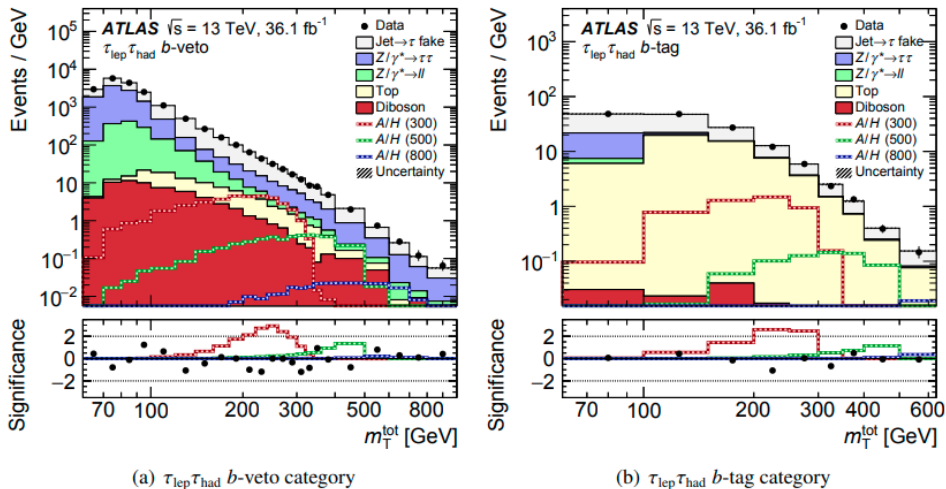


Fig. 2. Post-fit distributions of $m_{\text{T}}^{\text{tot}}$ in the b -veto and b -tag categories of the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. The superimposed signal histograms correspond to the combined predictions for H and A bosons in the hMSSM benchmark scenario with $\tan\beta = 10$ [1].

4.2. Model-independent limits

Observed and expected 95% confidence level (C.L.) limits for gluon-gluon fusion and b -associated resonance production modes are shown in figures 3(a) and 3(b), respectively. No excess over the expected Standard Model background is seen, but limits are significantly improved in comparison to limits from the previous ATLAS paper [3], which used 3.2 fb^{-1} of data collected in 2015.

4.3. Model-dependent limits

Results were analysed in terms of two MSSM benchmark models, $m_h^{\text{mod}+}$ [4] and hMSSM [5], and two Z' models, the Sequential Standard Model (SSM) and the non-universal G(221) model [6]. MSSM limits are set on the

m_A – $\tan\beta$ phase space, where m_A is the mass of the CP-odd neutral Higgs boson and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. In the $m_h^{\text{mod+}}$ scenario, the observed (expected) 95% C.L. upper limits exclude $\tan\beta > 5.1$ (7.0) for $m_A = 250$ GeV and $\tan\beta > 51$ (57) for $m_A = 1.5$ TeV. In the hMSSM scenario (figure 3(c)), the corresponding limits exclude $\tan\beta > 1.0$ (5.5) for $m_A = 250$ GeV and $\tan\beta > 42$ (48) for $m_A = 1.5$ TeV.

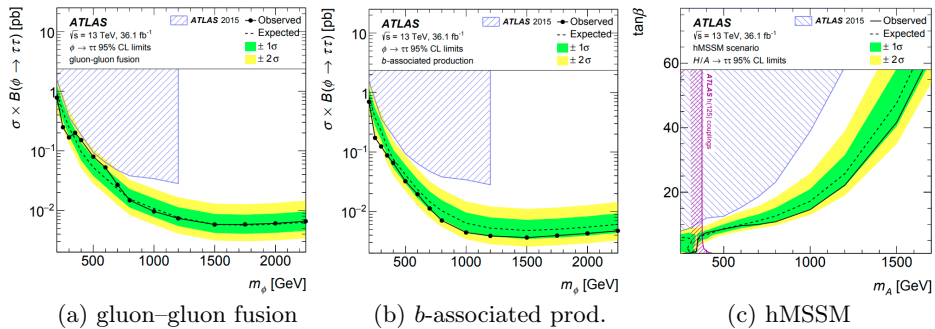


Fig. 3. (Colour on-line) Observed and expected 95% C.L. limits [1]. The hatched blue area corresponds to limits set by the 2015 ATLAS analysis [3].

In the Sequential Standard Model scenario, the observed (expected) 95% C.L. lower limit on the Z' mass is 2.42 (2.47) TeV. Limits on Z' bosons in the non-universal G(221) model are set in the $m_{Z'}$ – $\sin^2\phi$ phase space, where $m_{Z'}$ is the mass of the Z' boson and ϕ is the mixing angle between the heavy and light SU(2) gauge groups. Masses below 2.25–2.60 TeV are excluded for the $0.03 < \sin^2\phi < 0.5$ range, assuming no μ – τ mixing.

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