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Search for Neutral Minimal Supersymmetric Standard Model Higgs bosons H/A $\rightarrow \tau\tau$ produced in *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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This analysis corresponds to the search of a heavy neutral Higgs boson of the Minimal Supersymmetric extension of the Standard Model (MSSM) decaying to a pair of tau leptons using proton-proton collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 3.2 fb^{-1} recorded by the ATLAS detector for the Run II of the LHC. The analysis focuses on Higgs bosons produced in the mass range between 200 GeV and 1200 GeV by gluon-gluon fusion and associated production with a *b*-quark for which it defines two separated and optimized categories. The analysis is also split according to the tau decay modes, where at least one of the tau leptons decays to hadrons and a tau neutrino. The estimation of the backgrounds is done using data-driven techniques for leading backgrounds (multi-jet, W+jets) and MC models for other contributions.

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1. Motivation

The Minimal Supersymmetric Standard Model (MSSM) is the simplest extension of the Standard Model (SM) that includes the Supersymmetry theory (SUSY). In MSSM, five scalar bosons (h, H, A, H^+, H^-), arise from the two Higgs doublets after the breaking of the electroweak symmetry. The two neutral bosons, H and A (CP-even and CP-odd, respectively), have similar properties to the SM Higgs boson, h, which makes them susceptible to be found in the LHC experiments.
At tree level, the properties of the Higgs boson in the MSSM depend only on two parameters, that are usually chosen to be the mass of the CP-odd Higgs boson, m_A, and the ratio of the vacuum expectation of the doublets, $\tan\beta$. In the MSSM, the couplings of the heavy Higgs bosons to the down-type fermions is greatly enhanced for large $\tan\beta$ values and thus, the branching ratio of the decays to a pair of tau leptons (τ) and b-quarks, as well as the cross-section for the b-associated production of the Higgs boson (bbH) are increased. This property incentives the search of additional Higgs boson in the $\tau\tau$ channel as it could be a definite proof of the existence of new physics.

2. Analysis

The analysis is performed with the ATLAS detector [3], using the whole luminosity of Run II during the 2015 data-taking period, which accounts for an integrated luminosity of 3.2 fb^{-1} at an energy of the center of mass of $\sqrt{s} = 13$ TeV. The analysis was released in December 2015 [1]. Previous results of this search, with the LHC Run I dataset, are shown in [2].

In order to maximize the efficiency of the analysis, due to the different topology of the events, the dataset is divided in two different orthogonal channels, which are optimized independently. The channels are defined according to the decay of the τ leptons: the $\tau_{\text{had}}\tau_{\text{had}}$ channel, where both τ decay to hadrons and a τ neutrino (ν_τ); and the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, where one of the τ decays to hadrons and a ν_τ and the other τ is required to decay into leptons (ℓ), namely muon (μ) or electron (e), and the corresponding neutrinos (ν_τ, ν_ℓ). The $\tau_{\text{lep}}\tau_{\text{lep}}$ channel, where both τ decay into leptons (ℓ and ν_τ, ν_ℓ) is not considered at this stage.

The main background of the analysis, for both channels, is the multi-jet process, where jets are misidentified as τ_{had}. This contribution is estimated using a data-driven technique called Fake Factor: the rate of mis-identification is derived in a jet-enriched region and applied on the events passing the final selection except for a reversed τ identification. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the $W+$jets process is also a relevant background and it is estimated using a Fake Factor method derived in a different control region. The true τ backgrounds, such as $Z \to \tau\tau$, top and diboson, are estimated using MC simulation. In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, in order to model the probability of a jet being misidentifed as a τ_{had} in these processes, a Fake Rate derived in a $W \to \mu\nu$+jets data control region is used. The signal is modelled using MC samples at different mass values in the range 200 GeV - 1200 GeV for the b-associated production mode (bbH) and the gluon-fusion (ggH).

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In order to increase the sensitivity, an event selection is applied with the aim of reducing the background. This selection is optimized independently in each channel and the selection criteria are the following:

In the $\tau_{\rm lep}\tau_{\rm had}$ channel

- Single electron/muon trigger
- Lepton $p_{\rm T} > 30$ GeV and 'medium' identification
- $p_{\rm T}$ of $\tau_{\rm had} > 20$ GeV and 'medium' identification
- Opposite electric charge between lepton and $\tau_{\rm had}$
- $\Delta\phi(\ell, \tau_{\rm had}) > 2.4$
- $m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) < 40$ GeV or $m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) > 150$ GeV ($m_{\rm T}$ is defined below)
- only in $\tau_e\tau_{\rm had}$ sub-channel : $m_{\rm vis}(e, \tau_{\rm had}) < 80$ GeV or $m_{\rm vis}(e, \tau_{\rm had}) > 110$ GeV

In the $\tau_{\rm had}\tau_{\rm had}$ channel

- Single τ trigger
- At least one 'medium ID' $\tau_{\rm had}$ with $p_{\rm T} > 135$ GeV
- At least one 'loose ID' $\tau_{\rm had}$ with $p_{\rm T} > 55$ GeV
- Opposite electric charge between both $\tau_{\rm had}$
- Electron and muon veto
- $\Delta\phi(\tau_{\rm had}, \tau_{\rm had}) > 2.7$

The di-tau mass reconstruction is crucial for the discrimination between signal and background, but a precise reconstruction is challenging due to the several neutrinos involved in the τ decay. The algorithm which has the best discrimination power is the "Total transverse mass", defined as:

$$m_{\rm T}^{\rm tot} = \sqrt{m_{\rm T}^2(E_{\rm T}^{\rm miss}, \tau_1) + m_{\rm T}^2(E_{\rm T}^{\rm miss}, \tau_2) + m_{\rm T}^2(\tau_1, \tau_2)}, \tag{2.1}$$

where $m_{\rm T}(a,b)$ is defined as

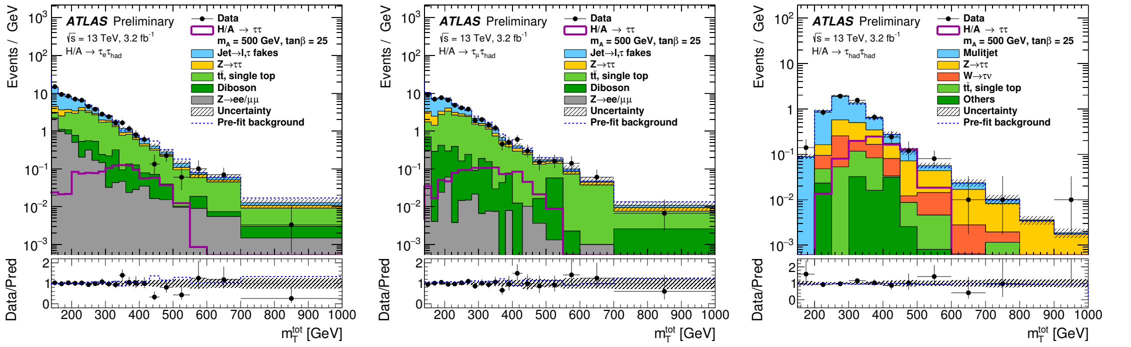
$$m_{\rm T}(a,b) = \sqrt{2p_{\rm T}(a)p_{\rm T}(b)[1-\cos(\Delta\phi_{ab})]} \tag{2.2}$$

and τ refers to the visible decay of the τ lepton (ℓ or $\tau_{\rm had}$).

3. Results

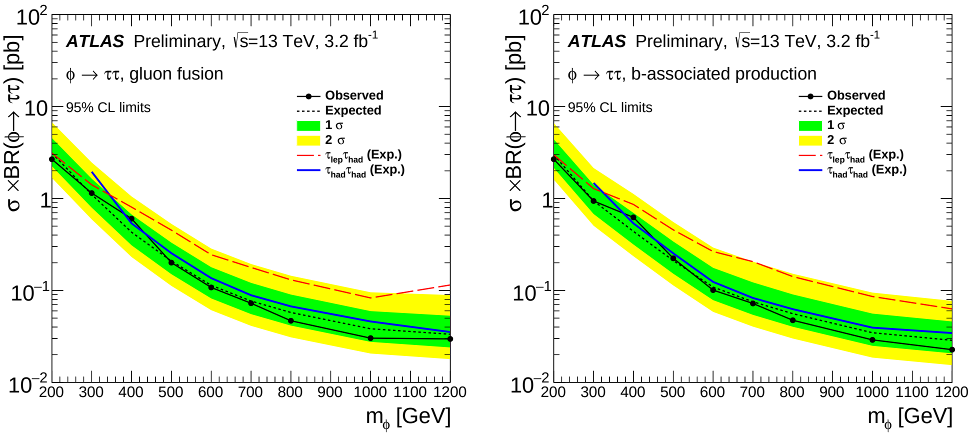
A maximum-likelihood fit is performed on the discriminant variable $m_{\rm T}^{\rm tot}$. The data is found to be compatible with the expectations for the SM prediction, as shown in Figure 1 and so, the results are given in terms of exclusion limits for model-dependent or model-independent scenarios.
Observed and expected 95% confidence level upper limits on the cross section times the branching fraction ($\sigma \times BR$) of a single scalar boson ϕ decaying to $\tau\tau$ as a function of the mass of the boson m_ϕ for ggH and bbH are given in Figure 2. The excluded $\sigma \times BR$ values range from $\sigma \times BR > 2.7$ pb at $m_\phi = 200$ GeV to $\sigma \times BR > 0.030$ pb at $m_\phi = 1200$ GeV for the ggH production mode. The values for the bbH production mode range from $\sigma \times BR > 2.7$ pb at $m_\phi = 200$ GeV to $\sigma \times BR > 0.023$ pb at $m_\phi = 1200$ TeV.

For the model-dependent scenario, many different possibilities are considered in [1], from where two examples have been extracted and are shown in Figure 3. Figure 3(a) corresponds to



(a) $\tau_e \tau_{\rm had}$ channel (b) $\tau_\mu \tau_{\rm had}$ channel (c) $\tau_{\rm had} \tau_{\rm had}$ channel

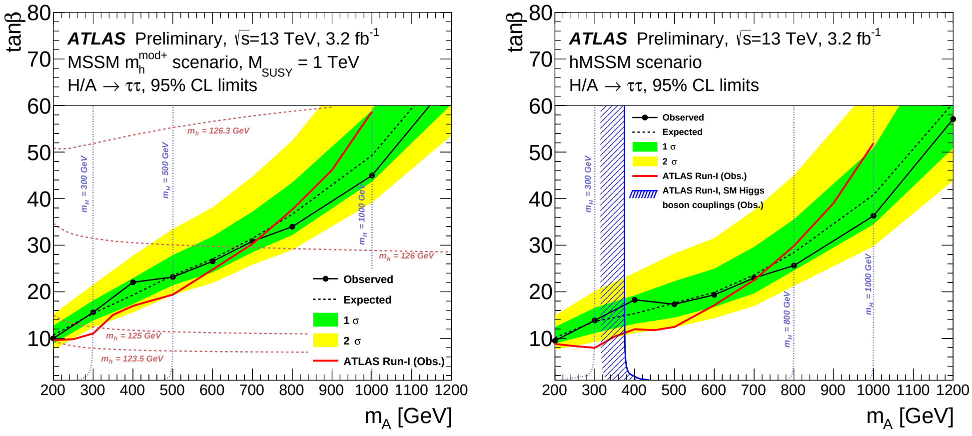
Figure 1: Post-fit distributions of $m_{\rm T}^{\rm tot}$ in the different channels. Below each plot, the ratio between the data and the model prediction is shown. A signal with $m_A = 500$ GeV and $\tan\beta = 25$ is draw for comparison purpose. The background uncertainty includes systematic and statistical uncertainties. Figures have been extracted from [1].



(a) *ggH* production mode (b) *bbH* production mode

Figure 2: Expected and observed 95% upper limits on the production cross section times branching ratio of $\phi \to \tau\tau$ for the combination of $\tau_{\rm lep}\tau_{\rm had}$ and $\tau_{\rm had}\tau_{\rm had}$. Data corresponding to an integrated luminosity of 3.2 fb^{-1} at $\sqrt{s} = 7$ TeV are used. The production mechanism is assumed to be gluon fusion (a) or *b*-associated production (b). Figures have been extracted from [1].

the $m_h^{\rm mod+}$scenario [4] and Figure 3(b) corresponds to the *hMSSM* scenario [5, 6]. All scenarios show similar $\tan\beta$ constraint apart from the hMSSM in which the limits are stronger. In the $m_h^{\rm mod+}$scenario the most stringent constraint on $\tan\beta$ excludes $\tan\beta > 10$ for $m_A = 200$ GeV and $\tan\beta > 45$ for $m_A = 1000$ GeV.



(a) MSSM $m_h^{\text{mod}+}$scenario (b) hMSSM scenario

Figure 3: Expected and observed 95% upper limits on the production cross section times branching ratio of $H/A \to \tau\tau$ for the combination of $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ for two different scenarios and for data corresponding to an integrated luminosity of 3.2 fb^{-1} at $\sqrt{s} = 7$ TeV. Subfigure (a) corresponds to the $m_h^{\text{mod}+}$scenario, where dashed lines of constant m_h and m_H are shown in red and blue colour, respectively. Subfigure (b) corresponds to the *hMSSM* scenario, where dashed lines of constant m_H are shown in blue colour. For comparison, the observed limits from the ATLAS Run-I analysis from Ref. [2] are shown as a continuous red line in both plots. Figures have been extracted from [1].

4. Conclusions

The analysis at the present luminosity shows no evidence of an excess above the SM predictions in the channels considered. However, the analysis proved to perform very well with the Run II data, improving the exclusion limits of the Run I for the high mass range ($m_A > 700$ GeV).

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