ATLAS PUB Note

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Prospects for the search for additional Higgs bosons in the ditau final state with the ATLAS detector at HL-LHC

The ATLAS Collaboration

Estimates of the sensitivity of the search for a heavy neutral Higgs boson in the $\tau\tau$ final state with the full High-Luminosity LHC dataset of 3000 fb^{-1} proton–proton collisions at $\sqrt{s} = 14$ TeV are presented. These estimates are based on the extrapolation of current results obtained with the 36.1 fb^{-1} ATLAS dataset collected in 2015–2016 at $\sqrt{s} = 13$ TeV. The expected 95% CL upper exclusion limits or, in alternative, the expected 5 σ discovery reach are presented in terms of cross section times branching fraction of the gluon fusion production and b-associated production. In the hypothesis that no signal emerges, results are interpreted in the context of MSSM benchmark scenarios, e.g. in the hMSSM scenario $\tan\beta > 1$ is expected to be excluded for the mass range $250 < m_A < 350$ GeV. The parameter space with the expected 5 σ discovery reach is also shown. The impact of the systematic uncertainties is also discussed.

1 Introduction

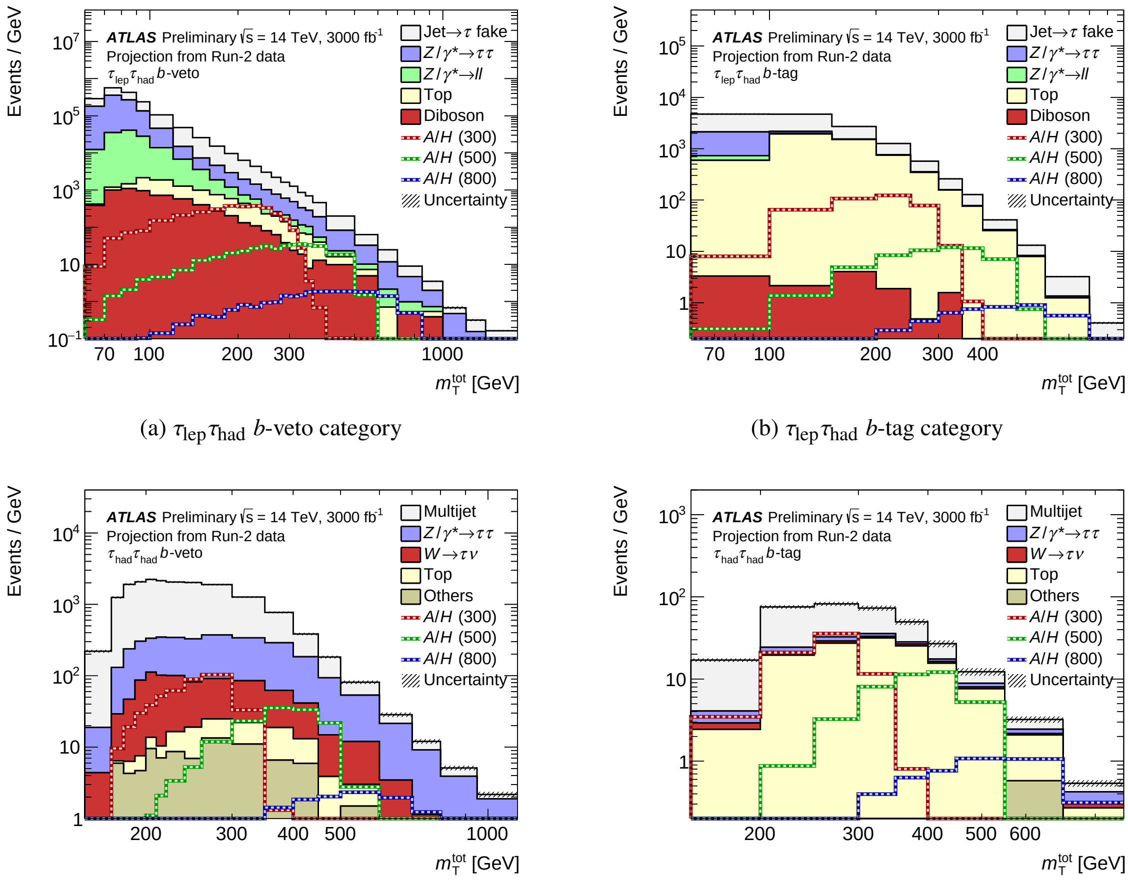
The discovery of a Standard Model (SM) like Higgs boson [1, 2] at the Large Hadron Collider (LHC) [3] has provided important insight into the mechanism of electroweak symmetry breaking. However, it remains possible that the discovered particle is part of an extended scalar sector, a scenario that is favored by a number of theoretical arguments [4, 5]. Searching for additional Higgs bosons is among the main goals of the High-Luminosity LHC (HL-LHC) programme [6]. The Minimal Supersymmetric Standard Model (MSSM) [4, 7, 8] is one of the well motivated extensions of the SM. Besides the SM-like Higgs boson, the MSSM requires two additional neutral Higgs bosons: one CP-odd (A) and one CP-even (H), which in the following are generically called ϕ. At tree level, the MSSM Higgs sector depends on only two non-SM parameters, which can be 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, $\tan\beta$. Beyond tree level, a number of additional parameters affect the Higgs sector, the choice of which defines various MSSM benchmark scenarios, such as $m_h^{\text{mod+}}$ [9] and hMSSM [10, 11]. The couplings of the additional MSSM Higgs bosons to down-type fermions are enhanced with respect to the SM Higgs boson for large $\tan\beta$ values, resulting in increased branching fractions to τ-leptons and b-quarks, as well as a higher cross section for Higgs boson production in association with b-quarks.

The projections presented in this note are extrapolations of the recent results obtained by ATLAS using the 36.1 fb^{-1} Run 2 dataset [12]. The MSSM Higgs boson with masses of 0.2–2.25 TeV and $\tan\beta$ of 1–58 is searched for in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ decay modes, where τ_{lep} represents the leptonic decay of a τ-lepton, whereas τ_{had} represents the hadronic decay. The main production modes are gluon–gluon fusion and in association with b-quarks. To exploit the different production modes, events containing at least one b-tagged jet enter the b-tag category, while events containing no b-tagged jets enter the b-veto category. The total transverse mass ($m_{\text{T}}^{\text{tot}}$), as defined in Ref. [12], is used as the final discriminant between the signal and the background.

In making these extrapolations, the assumption is made that the planned upgrades to the ATLAS detector and improvements to reconstruction algorithms will mitigate the effects of the higher pileup which can reach up to 200 in-time pileup interactions, leading to the overall reconstruction performance matching that of the current detector. Furthermore, the assumption is made that the analysis will be unchanged in terms of selection and statistical analysis technique, though the current analysis has not been re-optimised for the HL-LHC datasets.

2 Extrapolation method

To account for the integrated luminosity increase at HL-LHC, signal and background distributions are scaled by a factor of 3000/36.1. Furthermore, to account for the increase in collision energy from 13 TeV to 14 TeV, the background distributions are further scaled by a factor 1.18 which assumes the same parton-luminosity increase for quarks as that for gluons. The cross section of signals in various scenarios at 14 TeV are given in Ref. [13]. Possible effects on the kinematics and the $m_{\text{T}}^{\text{tot}}$ shape due to the collision energy increase are neglected for this study. The scaled $m_{\text{T}}^{\text{tot}}$ distributions for the four signal categories and one for the top control region are shown in Figures 1 and 2. These distributions are used in the statistical analysis.



(a) $\tau_{\text{lep}}\tau_{\text{had}}$ b-veto category

(b) $\tau_{\text{lep}}\tau_{\text{had}}$ b-tag category

(c) $\tau_{\text{had}}\tau_{\text{had}}$ b-veto category

(d) $\tau_{\text{had}}\tau_{\text{had}}$ b-tag category

Figure 1: Distributions of $m_{\text{T}}^{\text{tot}}$ for each signal category. The predictions and uncertainties (including both statistical and systematic components) for the background processes are obtained from the fit under the hypothesis of no signal. The combined prediction for A and H bosons with masses of 300, 500 and 800 GeV and $\tan\beta = 10$ in the hMSSM scenario are superimposed.

The larger dataset at HL-LHC will give the opportunity to reduce the systematic uncertainties. The “Baseline” scenario for the systematic uncertainty reduction compared to current Run 2 values follows the recommendation of Ref. [14], according to which the systematic uncertainties associated with b-tagging, τ_{had} (hadronic τ decay) and theoretical uncertainties due to the missing higher order, the PDF uncertainty, etc., are reduced. The systematic uncertainties associated with the reconstruction and identification of the high-p_{T} τ_{had} is reduced by a factor of 2 and becomes the leading systematic uncertainty for a heavy Higgs boson with mass $m_\phi > 1$ TeV. The systematic uncertainty associated with the modeling of the jet to τ_{had} fake background is assumed to be the same as in the current analysis. For the jet to τ_{had} fake background from multijet in $\tau_{\text{had}}\tau_{\text{had}}$ channel, the modeling uncertainty is mainly due to the limited data size in the control region and is reduced by a factor of 2. The statistical uncertainties on the predicted signal and background distributions, defined as the “template stat. uncertainty”, is determined by the size of the MC samples and of the data sample in the control region where the τ_{had} fake factor is applied. The impact of the template stat. uncertainty is negligible in the Run 2 analysis. Assuming large enough MC samples will be generated for HL-LHC and sufficient data will be collected at HL-LHC, the uncertainties

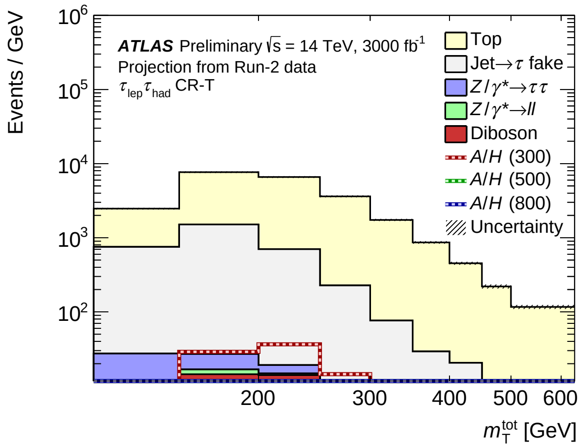


Figure 2: Distribution of m_T^{tot} distributions in the top quark enriched control region of the $\tau_{lep}\tau_{had}$ channel.

due to the sample size is ignored in this extrapolation study. To quantify the importance of the reduction of systematic uncertainties compared to current Run 2 values, results (labeled as "Unreduced") will also be given with current Run 2 values except for ignoring the template stat. uncertainty.

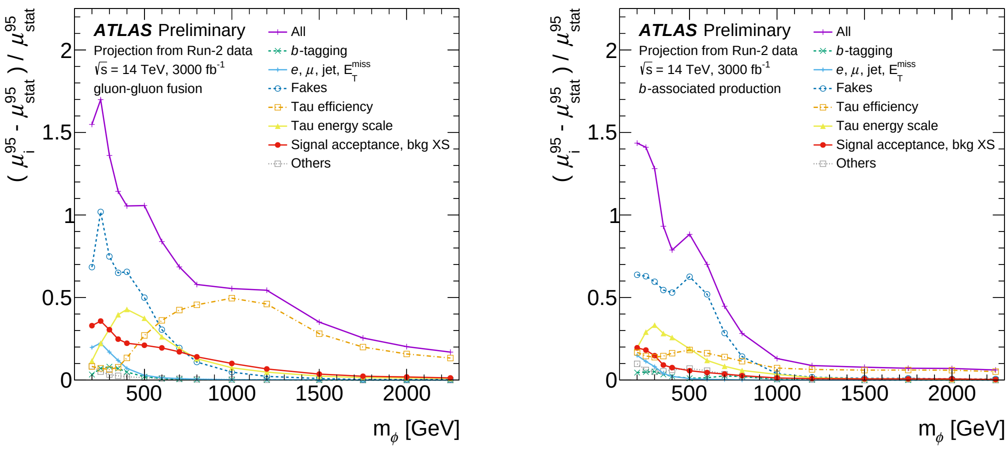
3 Results

The m_T^{tot} distributions from the $\tau_{lep}\tau_{had}$ (separately in the electron and muon channels) and $\tau_{had}\tau_{had}$ signal regions, as well as the top control region, are used in the final combined fit to extract the signal. The statistical framework used to produce the Run 2 results is documented in Ref. [12] and is adapted for this HL-LHC projection study. The results are given in terms of exclusion limits [15], as well as the 5 σ discovery reach for gluon–gluon fusion and b-quarks association production modes.

3.1 Impact of systematic uncertainties

The impact of systematic uncertainties on the upper limit of the cross section times branching ratio ($\sigma \times BR(\phi \to \tau\tau)$) in Baseline scenario are calculated by comparing the expected 95% CL upper limit in case of no systematic uncertainties, μ^{95}_{stat}, with a limit calculated by introducing a group of systematic uncertainties, μ^{95}_{i}, as described in Ref. [12]. The systematic uncertainty impacts are shown in Figure 3(a) for gluon–gluon fusion production and Figure 3(b) for b-quarks association production as a function of the scalar boson mass. The major uncertainties are grouped according to their origin, while minor ones are collected as "Others" as detailed in Ref. [12].

The impact of systematic uncertainties is significant, as they degrade the expected limits by about 10–150 percent. In the low mass range, the leading uncertainties arise from the estimation of the dominant jet to τ_{had} fake background. At high masses, the leading uncertainty is from the reconstruction and identification of high-p_T τ_{had}. Because μ^{95}_{stat} is mainly determined by the data statistical uncertainty. In Figure 3(a) the impact of the τ_{had} related systematic uncertainties decreases after 1 TeV is due to the fact that the results at the higher mass regime are more limited by the data statistical uncertainty, while in Figure 3(b) the data statistical uncertainty in the b-tag category dominates in the high mass regime which leads the high-p_T τ_{had} systematic uncertainty less outstanding.



(a) gluon–gluon fusion production

(b) b-associated production

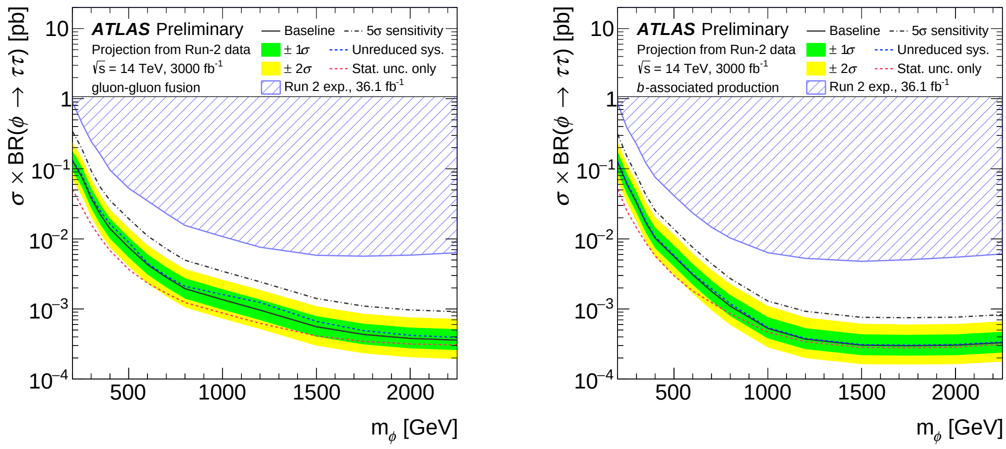
Figure 3: Impact of major groups of systematic uncertainties (Baseline) on the $\phi \to \tau\tau$ 95% CL cross section upper limits as a function of the scalar boson mass, separately for the (a) gluon–gluon fusion and (b) b-associated production mechanisms.

3.2 Cross section limits and discovery reach

Figure 4 shows the upper limits on the gluon–gluon fusion and b-quark associated production cross section times the branching fraction for $\phi \to \tau\tau$. To demonstrate the impact of systematics, the expected exclusion limits with different systematic uncertainty scenarios are shown, as well as the Run 2 expected results [12]. The peaking structure around $m_\phi = 1$ TeV in figure 4(a) is due to the impact of the high-p_T τ_{had} systematic uncertainty. The 5 σ sensitivity line in the same figure illustrates the smallest values of the cross section times the branching fraction for which discovery level can be reached at HL-LHC: as clearly shown, the region where discovery is expected at HL-LHC extends significantly below the currently expected Run 2 exclusion region.

3.3 MSSM interpretation

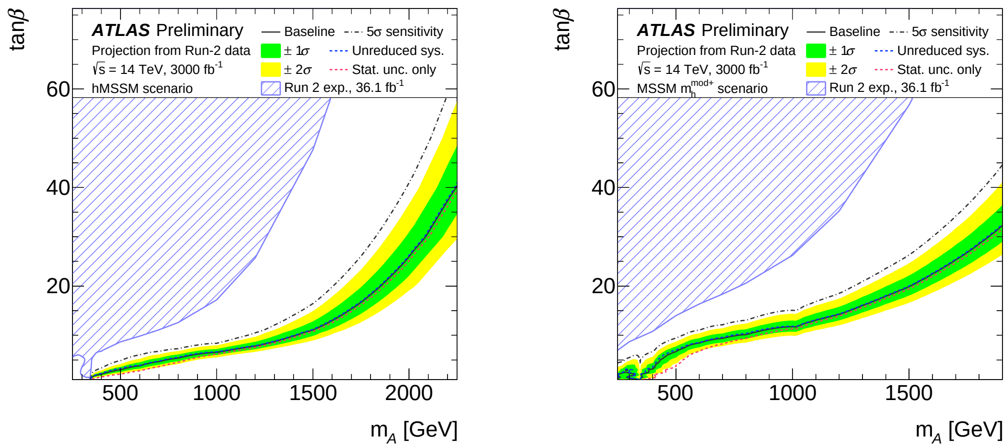
Results are interpreted in terms of the MSSM. The cross section calculations follow the exact procedure used in Ref. [12], apart from the centre of mass energy is switched to 14 TeV. Figure 5 shows regions in the m_A–$\tan\beta$ plane excluded at 95% CL or discovered with 5 σ significance in the hMSSM and $m_h^{\text{mod+}}$ scenarios. In the hMSSM scenario, $\tan\beta > 1.0$ for $250 < m_A < 350$ GeV and $\tan\beta > 10$ for $m_A = 1.5$ TeV could be excluded at 95% CL. When m_A is above the $A/H \to t\bar{t}$ threshold, this additional decay mode reduces the sensitivity of the $A/H \to \tau\tau$ search for low $\tan\beta$. In the MSSM $m_h^{\text{mod+}}$ scenario, the expected 95% CL upper limits exclude $\tan\beta > 2$ for $250 < m_A < 350$ GeV and $\tan\beta > 20$ for $m_A = 1.5$ TeV.



(a) gluon–gluon fusion production

(b) b-associated production

Figure 4: Projected 95% CL upper limits on the production cross section times the $\phi \to \tau\tau$ branching fraction for a scalar boson ϕ produced via (a) gluon–gluon fusion and (b) b-associated production, as a function of scalar boson mass. The limits are calculated from a statistical combination of the $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. "Baseline" uses the reduced systematic uncertainties scenario described in the text. "Unreduced sys." uses the same systematic uncertainties as the Run 2 analysis while ignoring the template stat. uncertainty. "Stat. unc. only" represents the expected limit without considering any systematic uncertainty. "5 σ sensitivity" shows the region with the potential of 5 σ significance in the Baseline scenario.



(a) hMSSM scenario

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

Figure 5: Projected 95% CL limits on $\tan\beta$ as a function of m_ϕ in the MSSM (a) hMSSM and (b) $m_h^{\text{mod+}}$ scenarios. The limits are calculated from a statistical combination of the $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. "Baseline" uses the reduced systematic uncertainties scenario described in the text. "Unreduced sys." uses the same systematic uncertainties as the Run 2 analysis while ignoring the template stat. uncertainty. "Stat. unc. only" represents the expected limit without considering any systematic uncertainty. "5 σ sensitivity" shows the region with the potential of 5 σ significance in the Baseline scenario.

4 Conclusion

The $H/A \to \tau\tau$ analysis documented in [12] has been extrapolated to estimate the sensitivity with $3000\,\text{fb}^{-1}$ of the HL-LHC dataset. The expected upper limits at 95% CL or, in alternative, the $5\,\sigma$ discovery reach in terms of cross section for the production of scalar bosons times the branching fraction to ditau final states have been estimated. The region with $5\,\sigma$ discovery potential at HL-LHC extends significantly below the currently expected Run 2 exclusion region. The expected limits are in the range 130–0.4 fb (130–0.3 fb) for gluon–gluon fusion (b-associated) production of scalar bosons with masses of 0.2–2.25 TeV. A factor of 6 to 18 increase in the sensitivity compared to the searches with the $36.1\,\text{fb}^{-1}$ Run 2 data [12] is projected. In the context of the hMSSM scenario, in the absence of a signal, the most stringent limits expected for the combined search exclude $\tan\beta > 1.0$ for $250 < m_A < 350$ GeV and $\tan\beta > 10$ for $m_A = 1.5$ TeV at 95% CL. The systematic uncertainties degrade the exclusion limit on $\sigma \times BR(\phi \to \tau\tau)$ by more than a factor of 2 for $m_\phi < 500$ GeV and about 10%–20% for $m_\phi = 2$ TeV. While the uncertainty on the estimate of fake τ_{had} dominates at low m_ϕ, the uncertainty on high-p_{T} τ_{had} reconstruction and identification is the leading systematic uncertainty at $m_\phi > 1.0$ TeV.

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