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CMS Physics Analysis Summary

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Projection of the Run 2 MSSM $\mathrm{H} \to \tau\tau$ limits for the High-Luminosity LHC

The CMS Collaboration

Abstract

A search for heavy Higgs bosons decaying to τ leptons was previously performed using data collected during Run 2 of the LHC, based on a data set of proton-proton collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 35.9 fb^{-1}. A projection of these results to a High-Luminosity LHC data set of 3000 fb^{-1} is described. For neutral Higgs boson masses above 1 TeV, an improvement by about one order of magnitude is expected in the 95% confidence level upper limits on the cross section. For the benchmark scenario $m_{\mathrm{h}}^{\mathrm{mod+}}$ of the minimal supersymmetric extension of the standard model, the expected lower limit on the mass of a heavy Higgs boson is extended from 1.25 to 2 TeV for $\tan\beta = 36$.

1 Introduction

Following the discovery of a Higgs boson by the ATLAS and CMS Collaborations in 2012 [1–3], a large number of measurements have established the compatibility of the new particle with standard model (SM) predictions. Nonetheless, there are many arguments in favor of theories that go beyond the SM. Many of these theories predict additional, heavy Higgs bosons. One such theory is supersymmetry [4, 5]. The minimal supersymmetric extension of the SM (MSSM) [6, 7] predicts two Higgs doublets, leading to five physical Higgs bosons: a light scalar (h), a heavy scalar (H), a pseudoscalar (A), and a charged pair ($H^{\pm}$).

Searches for MSSM Higgs bosons have been performed using the 2016 data from the LHC Run 2 [8–10]. So far, no significant evidence for physics beyond the SM has been found. However, the LHC to date has delivered only a small fraction of the integrated luminosity expected over its lifetime. Searches that are currently limited by statistical precision will see significant extensions in their reach as larger data sets are collected. Among the searches that will benefit are those for MSSM Higgs bosons.

Here, projections are presented for the reach that can be expected at higher luminosities in searches for heavy neutral Higgs bosons that decay to a pair of tau leptons. The projections are based on the most recent CMS publication for this search [10], performed using 35.9 fb^{-1} of data collected during 2016 at a center-of-mass energy of 13 TeV. All the details of the analysis, including the simulated event samples, background estimation methods, systematic uncertainties, and different interpretations are described in Ref. [10]. Only details of direct relevance to the projection are presented here.

The analysis is a direct search for a neutral resonance decaying to two tau leptons. The following tau lepton decay mode combinations are considered: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, and $e\mu$, where τ_h denotes a hadronically decaying tau lepton. In all these channels, events are separated into those that contain at least one b-tagged jet and those that do not contain any b-tagged jet. The goal of this categorization is to increase sensitivity to the dominant MSSM production modes: gluon fusion (ggH) and production in association with b quarks (bbH). The final discriminant is the total transverse mass, defined in Ref. [10]. The signal hypotheses considered consist of additional Higgs bosons in the mass range from 90 GeV to 3.2 TeV. The projection of the limits is performed by scaling all the signal and background processes to integrated luminosities of 300 and 3000 fb^{-1}, where the latter integrated luminosity corresponds to the total that is expected for the High-Luminosity LHC (HL-LHC).

The CMS detector [11] will be substantially upgraded in order to fully exploit the physics potential offered by the increase in luminosity at the HL-LHC [12], and to cope with the demanding operational conditions at the HL-LHC [13–17]. The upgrade of the first level hardware trigger (L1) will allow for an increase of L1 rate and latency to about 750 kHz and 12.5 μs, respectively, and the high-level software trigger (HLT) is expected to reduce the rate by about a factor of 100 to 7.5 kHz. The entire pixel and strip tracker detectors will be replaced to increase the granularity, reduce the material budget in the tracking volume, improve the radiation hardness, and extend the geometrical coverage and provide efficient tracking up to pseudorapidities of about $|\eta| = 4$. The muon system will be enhanced by upgrading the electronics of the existing cathode strip chambers (CSC), resistive plate chambers (RPC) and drift tubes (DT). New muon detectors based on improved RPC and gas electron multiplier (GEM) technologies will be installed to add redundancy, increase the geometrical coverage up to about $|\eta| = 2.8$, and improve the trigger and reconstruction performance in the forward region. The barrel electromagnetic calorimeter (ECAL) will feature the upgraded front-end electronics that will be able to exploit the information from single crystals at the L1 trigger level, to accommodate trigger latency and bandwidth requirements, and to provide 160 MHz sampling allowing high precision timing capability for photons. The hadronic calorimeter (HCAL), consisting in the barrel region of brass absorber plates and plastic scintillator layers, will be read out by silicon photomultipliers (SiPMs). The endcap electromagnetic and hadron calorimeters will be replaced with a new combined sampling calorimeter (HGCal) that will provide highly-segmented spatial information in both transverse and longitudinal directions, as well as high-precision timing information. Finally, the addition of a new timing detector for minimum ionizing particles (MTD) in both barrel and endocap region is envisaged to provide capability for 4-dimensional reconstruction of interaction vertices that will allow to significantly offset the CMS performance degradation due to high PU rates. A detailed overview of the CMS detector upgrade program is presented in Ref. [13–17], while the expected performance of the reconstruction algorithms and pile-up mitigation with the CMS detector is summarised in Ref. [18].

A previous CMS projection of the sensitivity for MSSM Higgs boson decays to a pair of tau leptons at the HL-LHC is reported in Ref. [19]. The results are presented in terms of model independent limits on a heavy resonance (either H or A, generically referred to as H below) decaying to two tau leptons, and are also interpreted in the context of MSSM benchmark scenarios.

2 Projection methodology

The projection assumes that the CMS experiment will have a similar level of detector and triggering performance during the HL-LHC operation as it provided during the LHC Run 2 period [13–17]. Three scenarios are considered for the projection of the size of systematic uncertainties to the HL-LHC:

- statistical uncertainties only: all systematic uncertainties are neglected;
- Run 2 systematic uncertainties: all systematic uncertainties are held constant with respect to luminosity, i.e., they are assumed to be the same as for the 2016 analysis;
- YR18 systematic uncertainties: systematic uncertainties are assumed to decrease with integrated luminosity following a set of assumptions described below.

In the YR18 scenario, selected systematic uncertainties decrease as a function of luminosity until they reach a certain minimum value. Specifically, all pre-fit uncertainties of an experimental nature (including statistical uncertainties in control regions and in simulated event samples) are scaled proportionally to the square root of the integrated luminosity. The following minimum values are assumed:

- muon efficiency: 25% of the 2016 value, corresponding to an average absolute uncertainty of about 0.5%;
- electron, τ_h, and b-tagging efficiencies: 50% of the 2016 values, corresponding to average absolute uncertainties of about 0.5%, 2.5%, and 1.0%, respectively;
- jet energy scale: 1% precision for jets with $p_T > 30\,\text{GeV}$
- estimate of the background due to jets misreconstructed as τ_h [20], for the components that are not statistical in nature: 50% of the 2016 values;
- luminosity uncertainty: 1%;
- theory uncertainties: 50% of the 2016 values, independent of the luminosity for all projections.

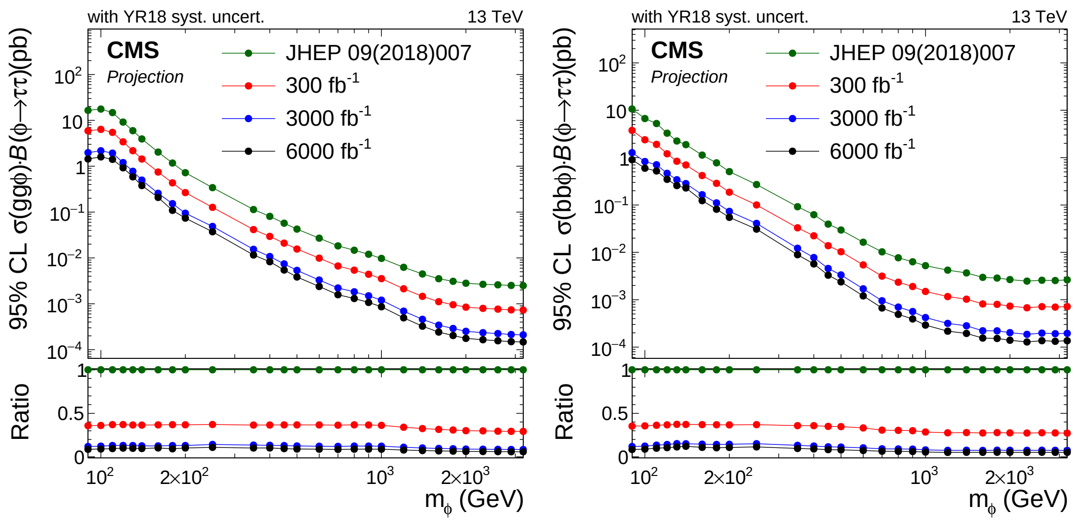
Note that for limits in which the Higgs boson mass is larger than about 1 TeV, the statistical uncertainties dominate and the difference between the systematic uncertainties found from the different methods has a negligible impact on the results.

The lightest Higgs boson h is excluded from the SM versus MSSM hypothesis test for the following reason: With increasing luminosity, the search will become sensitive to this boson. However, the current benchmark scenarios do not incorporate the properties of the h boson with the accuracy required at the time of the HL-LHC. Certainly the benchmark scenarios will evolve with time in this respect. Therefore the signal hypothesis includes only the heavy A and H bosons, to demonstrate the search potential only for these.

3 Projection results

3.1 Model independent limits

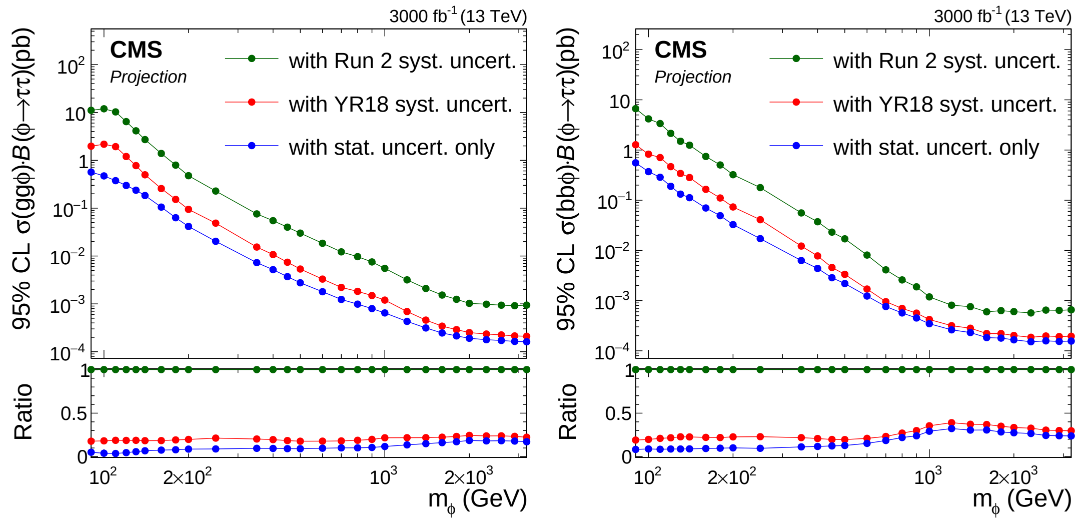
The model independent 95% confidence level (CL) upper limit on the cross sections for the ggH and bbH production modes, with the subsequent decays $H \to \tau\tau$, are shown in Figs. 1 and Fig. 2 for integrated luminosities of 300, 3000 and 6000 fb^{-1}. The 6000 fb^{-1} limit is an approximation of the sensitivity with the complete HL-LHC dataset to be collected by the ATLAS and CMS experiments, corresponding to an integrated luminosity of 3000 fb^{-1} each. The approximation assumes that the results of the two experiments are uncorrelated and that their sensitivity is similar. The first assumption is fulfilled to a high degree because the results are statistically limited; the validity of the second assumption is evident by comparing previous limits and projections.



(a) ggH (b) bbH

Figure 1: Projection of expected model independent 95% CL upper limits based on 2016 CMS data [10] for ggH and bbH production with subsequent $H \to \tau\tau$ decays, with YR18 systematic uncertainties. The limit shown for 6000 fb^{-1} is an approximation of the sensitivity with the complete HL-LHC dataset to be collected by the ATLAS and CMS experiments, corresponding to an integrated luminosity of 3000 fb^{-1} each. The limits are compared to the CMS result using 2016 data [10].

For both production modes, the improvement in the limits at high mass values scales similarly to the square root of the integrated luminosity, as expected from the increase in statistical precision. The improvement at very low mass is almost entirely a consequence of reduced systematic uncertainties and not the additional data in the signal region. The difference between the Run 2 and YR18 scenarios is mostly because of the treatment of two kinds of systematic uncertainty of a statistical nature: the uncertainty related to the number of simulated events and that related to the number of events in the data control regions.



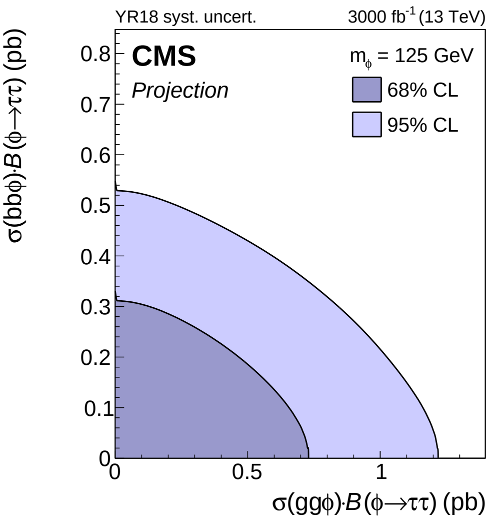
(a) ggH (b) bbH

Figure 2: Projection of expected model-independent limits based on 2016 CMS data [10] for ggH and bbH production with subsequent $H \to \tau\tau$ decays, comparing different scenarios for systematic uncertainties for an integrated luminosity of 3000 fb^{-1}.

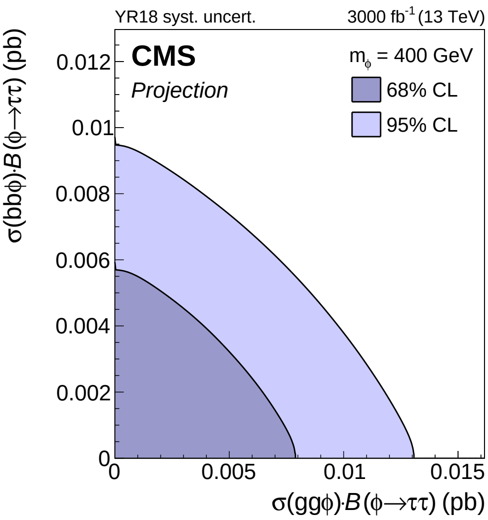
3.2 Model dependent limits

At the tree level, the Higgs sector of the MSSM can be specified by suitable choices for two variables, often chosen to be the mass m_A of the pseudoscalar Higgs boson and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. The typically large radiative corrections are fixed based on experimentally and phenomenologically sensible choices for the supersymmetric parameters, each choice defining a particular benchmark scenario [21]. Generally, MSSM scenarios assume that the 125 GeV Higgs boson is the lighter scalar h, an assumption that is compatible with the current experimental constraints for at least a significant portion of the m_A–$\tan\beta$ parameter space. The di-tau lepton final state provides the most sensitive direct search for additional Higgs bosons predicted by the MSSM for intermediate and high values of $\tan\beta$, because of the enhanced coupling to down-type fermions.

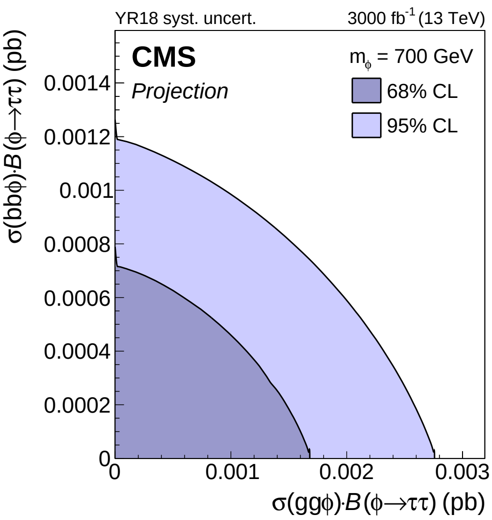
The analysis results are interpreted in terms of these benchmark scenarios based on the profile likelihood ratio of the background-only and the tested signal-plus-background hypotheses. For this purpose, the predictions from both production modes and both heavy neutral Higgs bosons are combined. Figure 4 shows the results for three different benchmark scenarios: the m_h^{mod+}, the hMSSM, and the tau-phobic scenarios [10]. The sensitivity reaches up to Higgs boson masses of 2 TeV for values of $\tan\beta$ of 36, 26, and 28 for the m_h^{mod+}, the hMSSM, and the tau-phobic scenarios, respectively. Even at low mass, improvements are expected but in this case they are mostly a consequence of reduced systematic uncertainties and not the additional data in the signal region.



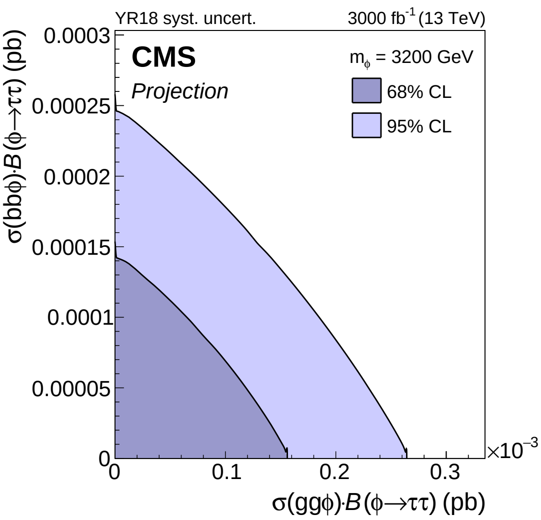
(a) ggH



(b) ggH

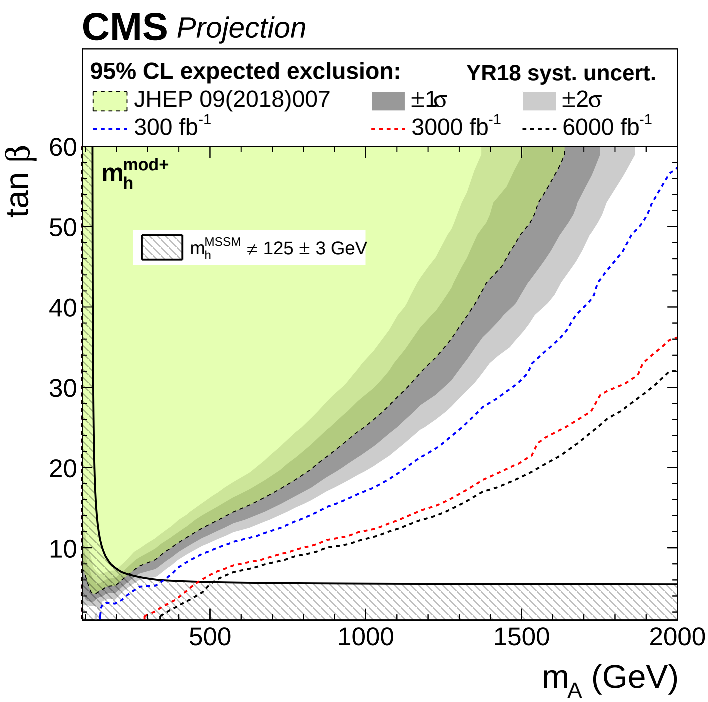


(c) ggH

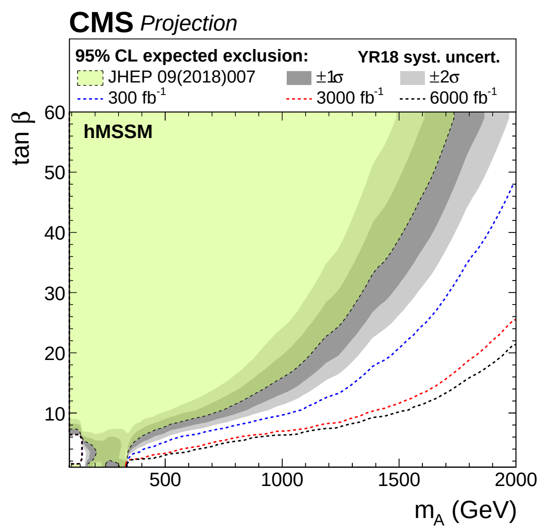


(d) ggH

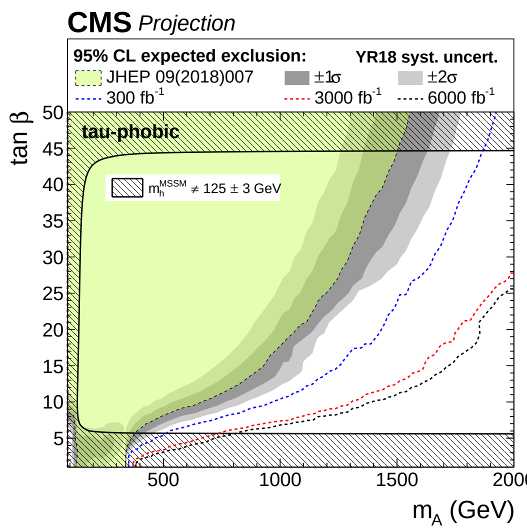
Figure 3: Projection of expected model-independent limits based on 2016 CMS data [10] for a simultaneous fit to the ggH and bbH production cross sections with subsequent $H \rightarrow \tau\tau$ decays, for an integrated luminosity of $3000\,fb^{-1}$ and with YR18 systematic uncertainties.



(a) $m_{\mathrm{h}}^{\mathrm{mod+}}$



(b) hMSSM



(c) tau-phobic

Figure 4: Projection of expected MSSM $\mathrm{H} \to \tau\tau$ 95% CL upper limits based on 2016 data [10] for different benchmark scenarios, with YR18 systematic uncertainties. The limit shown for $6000\,\mathrm{fb}^{-1}$ is an approximation of the sensitivity with the complete HL-LHC dataset to be collected by the ATLAS and CMS experiments, corresponding to an integrated luminosity of $3000\,\mathrm{fb}^{-1}$ each. The limits are compared to the CMS result using 2016 data [10]; for the tau-phobic scenario, it is a new interpretation of the information given in this reference.

4 Conclusions

The HL-LHC projections of the most recent results on searches for neutral MSSM Higgs bosons decaying to τ leptons have been shown, based on a data set of proton-proton collisions at $\sqrt{s} = 13$ TeV collected in 2016, corresponding to a total integrated luminosity of 35.9 fb^{-1}. The assumed integrated luminosity for the HL-LHC is 3000 fb^{-1}. In terms of cross section, an order-of-magnitude improvement in sensitivity is expected for neutral Higgs boson masses above 1 TeV since here the current analysis is statistically limited by the available integrated luminosity. For lower masses, an improvement of approximately a factor of five is expected for realistic assumptions on the evolution of the systematic uncertainties. For the MSSM benchmarks, the sensitivity will reach up to Higgs boson masses of 2 TeV for values of $\tan\beta$ of 36, 26, and 28 for the $m_{\mathrm{h}}^{\mathrm{mod+}}$, the hMSSM, and the tau-phobic scenarios, respectively.

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