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Searches for neutral and charged Higgs bosons in the context of the MSSM and more general 2HDMs at ATLAS and CMS

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A review of the searches for charged and neutral Higgs bosons, h, H, A, H^+, in the context of the minimal supersymmetric standard model and more general two-Higgs doublet models, is given. The results of the ATLAS and the CMS experiments are discussed. They are based on the full LHC Run I dataset. In particular, new results from the CMS Collaboration in the search for additional neutral Higgs bosons decaying to a pair of tau leptons are presented.

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1. Introduction

Experimental data collected over the last decades at high energy experiments are in astonishing agreement with the Standard Model (SM) of particle physics [1, 2, 3]. The Higgs mechanism [4, 5] allows for elementary particles to gain mass. It also predicts the existence of a physical scalar Higgs boson, which couples to massive particles. The discovery of a Higgs boson of mass 125 GeV by the ATLAS and CMS experiments [6, 7] at the CERN LHC is an historical success for the experimentalists as well as a confirmation of the predictions made by the SM [8, 9]. Measurements of the new resonance properties, such as its spin-parity [10, 11], width [12] and couplings to known particles [13], are in good agreement with the SM. However, given the present large uncertainties, those measurements are also compatible with the possibility that the 125 GeV state is one of multiple Higgs bosons, as predicted by models with an extended Higgs sector.

The two-Higgs doublet model (2HDM) is an effective extension of the SM where two Higgs doublets are introduced, leading to five physical Higgs bosons: two scalar and neutral (one light h and one heavy H), one neutral pseudoscalar (A) and two charged ($H^{\pm}$) Higgs bosons.

Supersymmetry (SUSY) is a fundamental symmetry between fermions and bosons. Along with SM superpartners, SUSY predicts an extended scalar sector which, contrary to the SM, is strongly constrained: the mass of the lightest Higgs boson is protected by the model symmetries against divergent radiative corrections. The minimal supersymmetric extension of the Standard Model (MSSM) is a 2HDM with a SUSY sector. At tree level, the corresponding scalar sector is fully controlled by two parameters chosen to be the mass of the pseudoscalar m_A (or sometimes $m_{H^{\pm}}$) and the ratio of the two vacuum expectation values $\tan\beta$. The additional parameters are used to define MSSM benchmark scenarios [14]. Constraints in the MSSM ($\tan\beta$,m_A) phase space have been set by the LHC experiments, using direct searches and indirect measurements, as can be seen in Fig. 1 in the case of ATLAS.

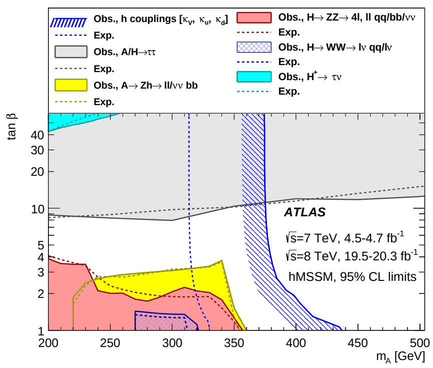

Figure 1: Expected and observed 95% Confidence Level (CL) exclusion limits set in the ($\tan\beta, m_A$) plane, using direct searches and indirect constraints from the 125 GeV boson couplings measurements. The results, taken from Ref. [16], are based on the full Run I dataset, and are interpreted in the context of the hMSSM benchmark scenario as defined in Ref. [17].

At the LHC, the neutral Higgs bosons h, H, A, are generically called ϕ. In this paper, we report for the Run I search of additional neutral Higgs bosons by the ATLAS and CMS experiments at the

CERN LHC, in the $\phi \to \tau^+\tau^-$ channel. A CMS $\phi \to b\bar{b}$ search [18] was presented for the first time at this conference. The interested reader can refer to the proceedings in Ref. [19] for details. In this paper, we also concentrate on the searches for $H^\pm \to \tau\nu$ based on the Run I datasets. The results of the search for $H^\pm \to tb$ are not documented here, but can be found in Ref. [20]. Similarly, in the case of the searches for $H^\pm \to cs$, one may refer to Refs. [21] (ATLAS) and [22] (CMS).

2. Searches for $\phi \to \tau^+\tau^-$

Both ATLAS and CMS performed a search for additional neutral Higgs bosons in the $\phi \to \tau^+\tau^-$ channel. The experiments analyzed their respective Run I datasets. The $\phi \to \tau^+\tau^-$ branching ratio depends on $\tan\beta$, is typically around 10%, and is relatively stable with m_A. The $\phi \to \tau^+\tau^-$ channel benefits from a much better signal to background ratio than $\phi \to b\bar{b}$. The search probes a large region of the MSSM phase space.

As the τ lepton can either decay to hadrons (τ_h) or to e or μ leptons, accompanied by one or two neutrinos, the search is performed in the following decay channels: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$ and $\mu\mu$[1]. The decay channels are characterized by different levels and types of backgrounds. The estimation of the di-τ mass is also a challenge, due to the presence of missing transverse energy attributed to the neutrinos. Both ATLAS and CMS developed refined techniques to reconstruct the di-τ mass, which is then used as the final discriminant variable to extract the signal[2].

The background templates are estimated in a similar way for both experiments. The normalization of the $Z/\gamma^* \to \tau\tau$ template is taken from simulation, while its shape is taken from $Z \to \mu\mu$ data, where the muons are replaced by simulated taus ("embedding" technique). The W+jets normalization and the QCD multijets backgrounds normalization and shape are estimated from data-driven techniques; the W+jets shape is taken from simulation. The other backgrounds ($t\bar{t}$+jets, $Z \to \mu\mu/ee$, di-boson, etc.) are estimated using simulation. The signals templates are predicted by Monte Carlo (MC) generators for masses going from about 100 to 1000 GeV and normalized to theoretical computations.

The statistical procedures are described in the referred documents. They look for the simultaneous apparition of three resonances, one of which being identified with the 125 GeV boson. The leading uncertainties for both experiments are the one associated to the τ_h energy scale, and the one associated with the particle identification efficiencies and fake rates.

ATLAS result [23]

The result exploits the 19.5-20.3 fb^{-1} of 8 TeV data. Each decay channel is used in the mass range for which it is most sensitive. For example, the $\tau_h\tau_h$ channel is only used at high masses, because it is overwhelmed by QCD background at low masses. The events selection strongly depends on the channel under consideration. The events are categorized according to the number of b-tagged jets in the $e\mu$, $e\tau_h$ and $\mu\tau_h$ channels. In the latter two, the events are further categorized based on kinematic cuts that are different for the low- and high-m_A regions. Finally, the $\phi \to \tau_h\tau_h$ candidates are separated according to the trigger that took the decision to record the event.

The data show no excess of events with respect to the background-only hypothesis, so 95 % CL

[1] $\mu\mu$ was only analyzed in the CMS result.

[2] ATLAS implements a different variable in the $\tau_h\tau_h$ channel: the total transverse mass.

limits are set on the expected cross sections times branching ratio for the ggϕ and $bb\phi$ processes[3]. The results are also interpreted in a model-dependent way, in the $(\tan\beta, m_A)$ plane, and are shown in the case of the $m_h^{\text{mod}+}$ benchmark scenario in Fig. 2 (left).

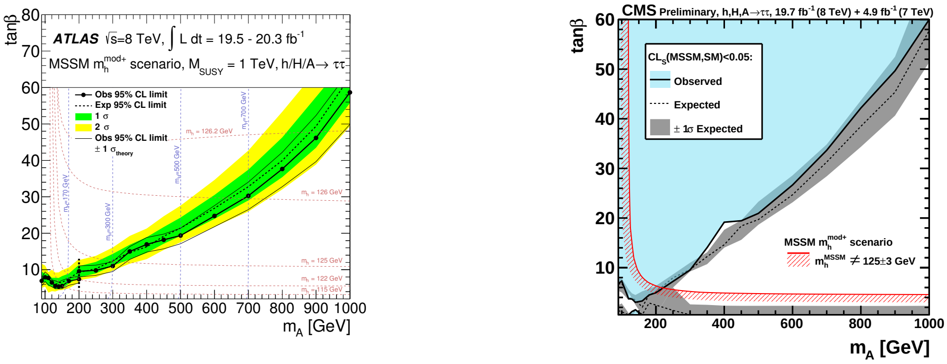

Figure 2: Expected and observed 95% CL limits in the $(\tan\beta, m_A)$ plane in the MSSM $m_h^{\text{mod}+}$ benchmark scenario for (left) the ATLAS experiment [23] and (right) the CMS experiment [24].

CMS result [24]

This new result, presented for the first time at this conference, exploits the 7 and 8 TeV datasets, with 4.9 and 19.7 fb^{-1} of integrated luminosity, respectively. The analysis described here is an update of the previous CMS published result [25]. Both use the same strategy built on categorizing the events based on the presence or not of a b-tagged jet (b-tag and no-b-tag categories). The new analysis however implements two significant changes:

- A refined categorization of the $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ events at 8 TeV. The original no-b-tag (b-tag) category is subdivided into 3 (2) exclusive categories, based on the hadronic τ p_T. The new splitting has the advantage of targeting the varied MSSM kinematic regimes.
- An updated hadronic τ identification, based on a multivariate technique using isolation related variables and τ-lifetime information as inputs. This refined method significantly reduces the jet-to-τ_h fake rate at constant signal efficiency, especially for high p_T objects [26].

Both aspects, combined, significantly improve the analysis sensitivity, as is shown in terms of expected limits on the cross sections times branching ratio in Fig. 3. Depending on the mass, the sensitivity to an additional resonance decaying to a di-τ pair is increased by 20 to 50%.

As the data show no significant excess of events with respect to the background-only hypothesis, limits are set on the production cross sections times branching ratio (see Ref. [24]), and in the $(\tan\beta, m_A)$ plane, as shown in Fig. 2 (right).

3. Searches for $H^\pm \to \tau\nu$

ATLAS and CMS use similar strategies to look for $H^\pm \to \tau\nu$, for which the respective results can be found in Refs. [27] and [28]. The $H^\pm \to \tau\nu$ branching ratio is dominant for $m_{H^\pm}$ below

[3]Which is a model-independent interpretation, except the assumptions on the width of the Higgs bosons, which is assumed to be dominated by the experimental resolution.

PoS(EPS-HEP2015)119

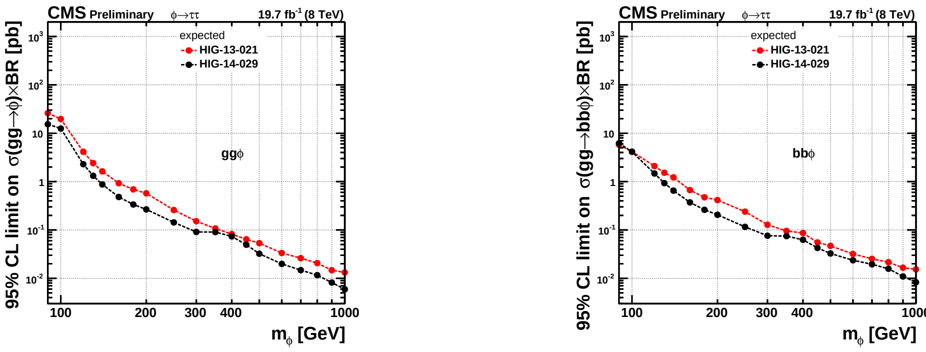

Figure 3: Comparison between the HIG-13-021 and HIG-14-029 (updated analysis) expected 95% CL limits on (left) $\sigma(gg \to \phi) \times \mathscr{B}(\phi \to \tau\tau)$ and (right) $\sigma(gg \to b\bar{b}\phi) \times \mathscr{B}(\phi \to \tau\tau)$ [24].

$\sim$ 200 GeV, after which $\mathscr{B}(H^{\pm} \to tb)$ takes over. The $H^{\pm} \to \tau\nu$ searches focus on two distinct production channels, targeting different masses for the charged Higgs boson. The low mass search ($m_{H^{\pm}} < m_t - m_b$) looks for an increase in $t \to b\tau\nu$ branching ratio due to the $t \to bH^{\pm}$ process. The parameter of interest is $\mathscr{B}(t \to bH^{\pm}) \times \mathscr{B}(H^{\pm} \to \tau\nu)$. The high mass analysis ($m_{H^{\pm}} > m_t - m_b$) looks for the associated production of a Higgs boson with a top quark (and possibly a bottom quark). In this case, the relevant measurement is $\sigma(pp \to t(b)H^{\pm}) \times \mathscr{B}(H^{\pm} \to \tau\nu)$. In both analyses, the final state which is sought for is the presence of a hadronically-decaying τ, at least three jets (including at least one b-jet), large missing transverse energy ($\not{E}_T$), and no additional leptons. A challenging τ_h+$\not{E}_T$ trigger is used to select the events. Another difficulty is the control of the dominant backgrounds from $t\bar{t}$ production and QCD multijets. Both experiments then look for an excess of events in the transverse mass distribution.

Since no significant excess of events is found, limits are set on the parameters of interest and interpreted in the context of the MSSM benchmark scenarios. The model-dependent results for ATLAS are shown in Fig. 4.

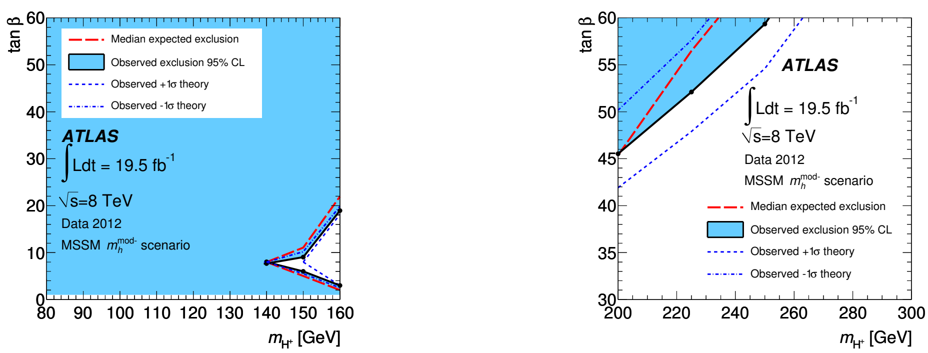

Figure 4: Expected and observed 95% CL limits in the $(\tan\beta, m_{H^{\pm}})$ plane in the MSSM $m_h^{\text{mod+}}$ benchmark scenario for (left) the low mass and (right) high mass $H^{\pm} \to \tau\nu$ analyses [27].

4. Conclusion

Results obtained by the ATLAS and CMS experiments in the searches for additional Higgs bosons, as predicted by the 2HDM and the MSSM, were presented. The analyses of the $\phi \to \tau^+\tau^-$ and $H^\pm \to \tau\nu$ channels were performed based on the full Run I datasets. The searches find no indication of signal; therefore, limits are set on the production cross sections times branching ratio, and, using benchmark scenarios, in the MSSM parameter space. The $\phi \to \tau^+\tau^-$ channel is the most sensitive at high masses, excluding values of $\tan\beta > 5$ around $m_A = 150$ GeV and $\tan\beta > 60$ around $m_A = 1000$. The $H^\pm \to \tau\nu$ search is very sensitive at low masses, excluding most of the $(\tan\beta, m_{H^\pm})$ plane for $m_{H^\pm} < 150$ GeV.

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