

Search for the decay of the Higgs boson into two nMSSM pseudo-scalar particles

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The next-to-minimal supersymmetric Standard Model (nMSSM) predicts the existence of a light pseudo-scalar boson "a" and the decay of the Higgs boson into a pair of such particles. This particle is searched for in several final states sensitive to different decay modes and mass ranges of the hypothetical pseudo-scalar, using ATLAS data amounting to either 20.3 fb^{-1} of p - p collisions at $\sqrt{s} = 8 \text{ TeV}$ or between 3.2 fb^{-1} and 36.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

The European Physical Society Conference on High Energy Physics

5-12 July, 2017

Venice

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1. Introduction

The discovery of a Higgs boson in 2012 [1],[2] raises an exciting question. Is it the Higgs boson of the Standard Model (SM) or is it part of an extended Higgs sector? So far, the observed Higgs boson seems consistent with the predictions for the single Higgs Boson included in the SM. But the current precision of measurements leaves room for new physics, e.g. the branching ratio (BR) into non-SM particles is only constrained to be 30% or less currently [3]. This is mainly due to the decays into light coloured particles being difficult to access in the LHC environment. Many models for new physics require an extended Higgs sector [4]. One well-motivated example is the next-to-minimal supersymmetric Standard Model (nMSSM), which contains two Higgs doublets and an additional electro-weak scalar. These mix to form two pseudo-scalar particles (a_1, a_2) and three scalar ones (h_1, h_2, h_3). If the lightest pseudo-scalar is significantly lighter than $m_h = 125$ GeV, the decay $h \rightarrow aa$ would be possible. Due to the different dominant decay modes that would result, three mass regions $m_a < 2m_\tau$, $2m_\tau < m_a < 2m_b$ and $m_a > 2m_b$ need to be considered, where m_a is the light pseudo-scalar mass and m_τ and m_b are the masses of the τ -lepton and the b -quark, respectively. In these proceedings searches at the ATLAS experiment for this decay in several final states are presented covering the range $3.7 < m_a < 62$ GeV. The considered final states include $\mu\mu\tau\tau$, 4γ , $4b$ and for the first time the 4 lepton final state. These searches were performed using the ATLAS [6] data of p - p collisions at the LHC amounting to either 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV (Secs. 2 and 3) or between 3.2 fb^{-1} (Sec. 4) and 36.1 fb^{-1} (Sec. 5) at $\sqrt{s} = 13$ TeV in the ATLAS data.

2. The $\mu\mu\tau\tau$ final state

In this search $m_h = 125$ GeV is assumed while the mass of the pseudo-scalar just needs to be above the τ -pair threshold $m_a = 3.7 - 50$ GeV. Subsequently one pseudo-scalar decays to τ -leptons and the second one to muons.

The signature searched for includes one leptonic τ decay and the second τ is identified by one or three high p_T tracks [5]. The most sensitive search range is $m_a < 10$ GeV. The decay to muons, although it has a much lower BR, allows for easy trigger selection and extraction of the signal as a narrow peak in the dimuon invariant mass spectrum $m_{\mu\mu}$. Dominant backgrounds comprise $t\bar{t}$, Drell-Yan, diboson production and low mass resonances ($J/\psi, Y$). The non-resonant background is estimated by fitting the mass sidebands with a 4th-order polynomial, while the signal and resonant backgrounds are fitted using double-sided crystal ball functions. Figure 1 shows one of the signal regions, where one τ decays to an electron. No excess over the SM background is observed here nor in the signal region with a muon. Therefore limits as function of m_a are set as shown in Fig. 1, under the assumption that the pseudo-scalar does not decay into quarks.

3. The 4γ final state

An inclusive search in a final state with at least three photons can also be interpreted in the context of the nMSSM [7]. The photon p_T thresholds are kept as low as possible to allow sensitivity

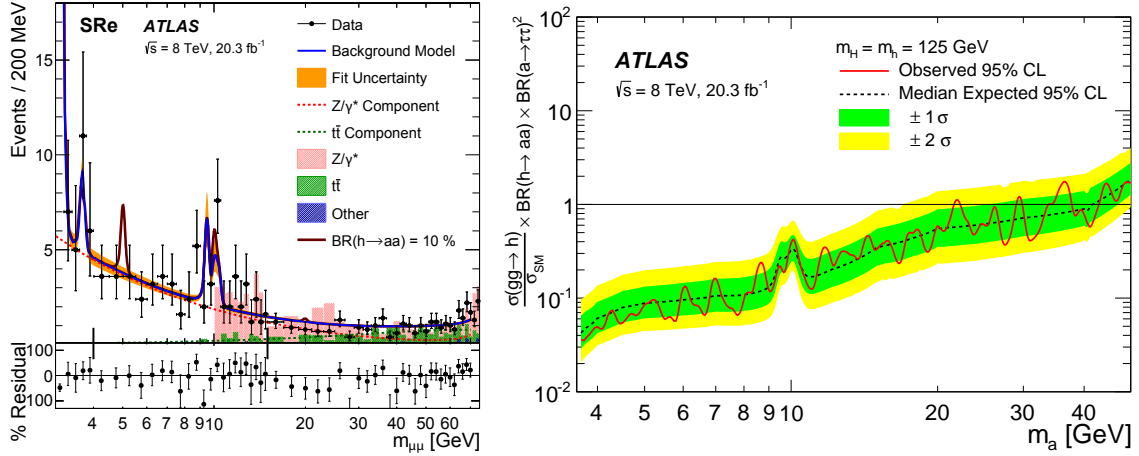


Figure 1: Distribution of the di-muon invariant mass in the signal region where one τ -lepton decays to an electron (left) and limit on production cross section and decay branching ratio as a function of m_a (right) [5].

39 to a mass range of $10 < m_a < 62$ GeV, while at the same time requiring very restrictive identification
 40 and isolation criteria to reduce backgrounds from electrons or jets reconstructed as photons. This
 41 background is modelled using data-driven methods to avoid large uncertainties from simulating the
 42 misidentification rate of the photon identification. Both signal models where the pair of pseudo-
 43 scalars result from the decay of the discovered Higgs particle as well as from a hypothetical heavier
 44 Higgs boson are considered. Depending on the signal model, the signal extraction is performed by
 45 a fit to the mass of the di-photon pairing that yields the smallest combinatorial error. The mass of
 46 the second and third leading p_T photon, which is used for the signal model with $m_h = 125$ GeV, is
 47 shown in Fig. 2 (left).

48

49 As can be seen, no excess of data above the SM background is observed and the resulting limits on
 50 the cross section times branching ratio versus m_a are shown in Fig. 2 (right).

51 4. The $4b$ final state

52 To reach sensitivity also to low pseudo-scalar masses ($m_a = 20 - 60$ GeV) in the decay to four
 53 b -quarks, the associated production of a Higgs boson with a W boson, where the W decays lepton-
 54 ically, is considered [8]. The lepton from the W decay allows for efficient trigger selection, while
 55 avoiding harsh p_T requirements on the b -jets. To maximize acceptance, events with at least three
 56 jets, two of which need to be tagged as b -jets, are selected. The dominant SM background consists
 57 of $t\bar{t}$ production in association with further heavy flavour quarks. Other backgrounds estimated
 58 from simulation include production of gauge bosons and single top quarks. The contribution from
 59 other multi-jet processes are estimated from data using the so-called matrix method applied to the
 60 lepton isolation criterion. Depending on the jet and b -jet multiplicity, events are categorized into
 61 signal and control regions. For the signal extraction, a boosted decision tree (BDT) is used, which

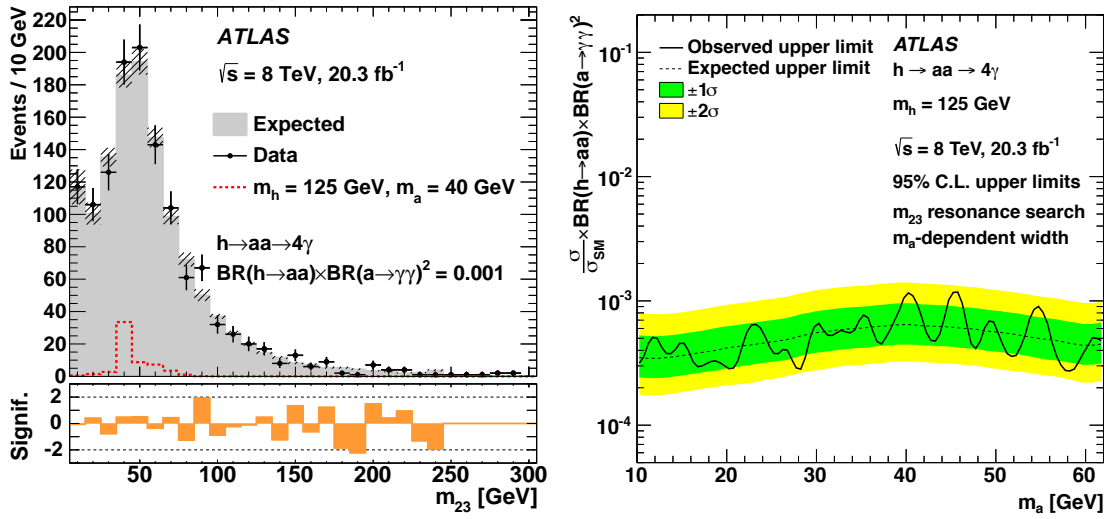


Figure 2: Distribution of the invariant mass of the second- and third-leading photons m_{23} in the 4γ final state (left) and limit on production cross section and decay branching ratio as a function of m_a (right) [7].

62 exploits characteristic kinematic variables like masses and angles between b-jets and the lepton. In
 63 the control regions the scalar sum of jet momenta H_T is fitted simultaneously to constrain the back-
 64 grounds normalizations and uncertainties. Figure 3 shows example distributions of H_T in the ≥ 4
 65 jet and 3 b-jet control region (left) and of the BDT in the 4 jet and 4 b-jet signal region (middle).
 66 Since none of the signal regions show an excess over the SM background, 95% confidence level
 67 limits are set on production cross section times branching ratio for the full m_a range and displayed
 68 in Fig. 3 (right).

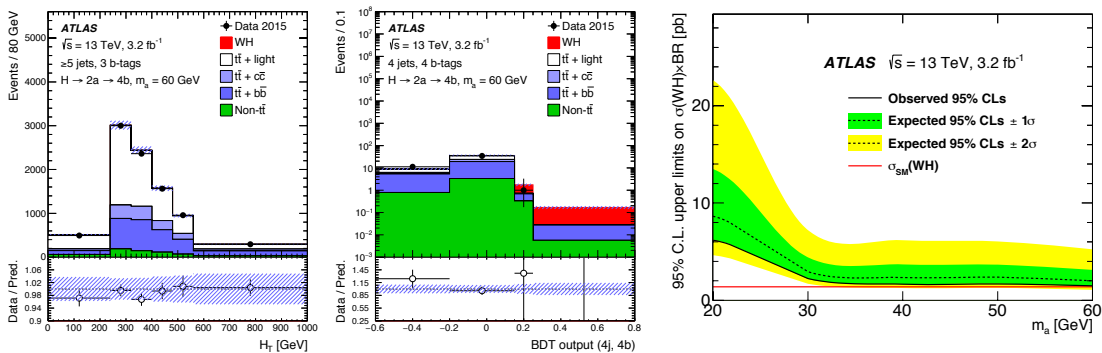


Figure 3: The scalar sum of jet momenta H_T in one of fitted control regions (left) and BDT distribution in one signal region (right) as well as the resulting limits on the production cross section and decay branching ratio as a function of m_a (middle) [8].

5. The 4 lepton final state

For the first time ATLAS presented the results from a search for the decay $h \rightarrow aa \rightarrow 4$ leptons [9]. In this search the experimental signature consists of two opposite-sign, same flavour, light lepton pairs. In the case where all four leptons are of the same type, the pairing that results in the smallest mass difference between pairs is chosen and pairs are ordered by closeness to the Z boson mass. Two sets of selection criteria are optimized separately for low (1-15 GeV) and high (15-60 GeV) pseudo-scalar masses. The low mass selection only considers the four muon final state. Also, the four-lepton mass is required to be consistent with the observed Higgs mass. Vetoes on di-lepton mass are used to reject backgrounds from quarkonia. In the high mass selection, a Z -mass veto and angular separation between leptons is required in addition. The dominant backgrounds that contribute to both signal regions are di- Z production from SM Higgs decays and from the continuum. Leptonic heavy flavour decays become important in the low mass selection. Signs of potential signal are extracted by a profile maximum likelihood fit to the average di-lepton pair mass distribution $\langle m_{ll} \rangle$ as shown in Fig. 4 (left). Although one event is observed at $\langle m_{ll} \rangle \approx 20$ GeV over the very small SM background, the significance of this is below 3σ once the look-elsewhere effect is taken into account. Since no clear sign of a signal is observed, limits on $BR(h \rightarrow aa)$ are set accordingly, which are shown in Fig. 4 (right). The additional interpretation under the signal hypothesis of the Higgs decaying to dark Z bosons is also shown.

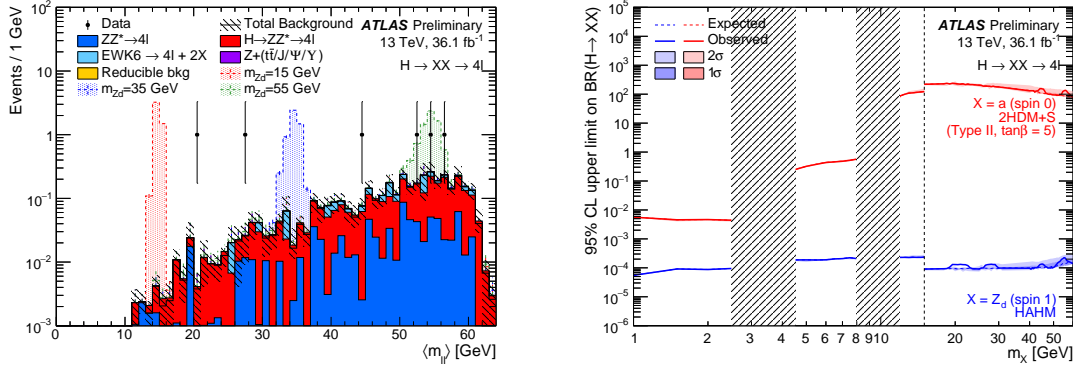


Figure 4: Distribution of the average invariant di-lepton mass in the low mass signal region (left) and limit on the decay branching ratio $h \rightarrow aa/Z_d Z_d$ as a function of m_a (right) [9].

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6. Summary

Four different searches, including the $\mu\mu\tau\tau$, 4γ , $4b$ and 4 lepton final states, for the decay of the newly discovered Higgs boson to a pair of light pseudo-scalars (a) in a mass range $3.7 < m_a < 62$ GeV were presented. The dominant decay modes vary according to the mass of the pseudo-scalar, depending on whether it is over the di- τ - or di- b -mass threshold. No excess over the background expectations in the different search modes is observed and therefore the branching ratio for the decays of the Higgs boson to light pseudo-scalars as a function of pseudo-scalar mass

96 are further constrained. With the existing datasets, these limits however do not completely exclude
97 many well-motivated extensions to the SM Higgs sector and this topic will remain relevant for the
98 duration of the LHC and high luminosity LHC projects.

99 **References**

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