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Search for the decay of the Higgs boson into two NMSSM pseudoscalar particles

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The next to MSSM theory predicts the existence of a light pseudoscalar boson "a", and the decay of the Higgs boson into a pair of such particles. The search for this model in several final states relative to different decay modes of the "a" particle, is presented using 20.3 fb^{-1} and 3.2 fb^{-1} of data at the $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV, respectively, taken by the ATLAS detector at the LHC.

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1. Introduction

The discovery of a Higgs boson in 2012 [1, 2] completed the Standard Model (SM), but many phenomena remain unexplained. With present constraints and measurements [3], it is possible that 30% of the Higgs boson branching ratio (BR) goes to the decays to exotic particles that are predicted in many new models including those with extended Higgs sector like Next–to–Minimal–Super–Symmetric–Model (NMSSM) [4]. In NMSSM a singlet S is introduced and the μ–term from MSSM, $\mu \hat{H}_u \hat{H}_d$, is replaced with $\lambda \hat{S} \hat{H}_u \hat{H}_d$. The Higgs sector is extended, when compared to the MSSM, with an addition of one pseudoscalar and one scalar, and now it contains two pseudoscalars (a_1, a_2) and three scalars (h_1, h_2, h_3). Light pseudoscalar, with mass below $m_h/2$, where $m_h =$ 125 GeV is the mass of the SM Higgs boson, is motivated by many theories. Three distinct regions define dominant decays: (*i*) $m_a < 2m_\tau$, where m_a is the light pseudoscalar mass and m_τ is the mass of a τ–lepton; (*ii*) $2m_\tau < m_a < 2m_b$, where m_b is the mass of a b–quark; (*iii*) $m_a > 2m_b$.

We presented here the searches for pairs of light pseudoscalars in different final states covering the wide range in m_a between 3.7 and 62 GeV. The searches for pairs of pseudoscalars described in section 2 and 3 are performed using data corresponding to an integrated luminosity of 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV, while the search described in section 4 used 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector [5] at the LHC.

2. The 4γ final state

Inclusive three photon search is interpreted in an NMSSM context for $10 < m_a < 62$ GeV [6]. Events are selected if they contain at least three tight, where tight means that a rejection of 5000 is achieved for an efficiency of 85%, isolated photons with the $p_T > 22, 22, 17$ GeV, respectively. Photons are considered isolated if the transverse energy, E_T^{iso}, deposited in electromagnetic calorimeter within a cone $\Delta R < 0.4$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, is smaller than 4 GeV. The irreducible background consists of the prompt production of three or more photons, and reducible background includes events where electrons and jets, often produced together with photons, are misidentified as photons. Irreducible backgrounds and reducible component originating from the electroweak production, where electrons are misidentified as photons, are simulated with MC. Events where jets are misidentified as photons are obtained from data. A photon–like jet sample is defined using non–tight photon candidates. This sample is normalized in the tail of the E_T^{iso} (> 7 GeV) distribution. Events with all three photons passing tight criterion are divided into 160 categories based on kinematics (p_T, η) and if isolation **P**assed of **F**ailed. Then, PPP denotes signal region, and any F denotes control region. Inclusive in kinematics background composition for signal and control regions is shown in Fig. 1(left).

The invariant mass of a photon pair is used for a search for $H/h \to aa \to 4\gamma$ production. It was found that among the three p_T–ordered photons, the most often combination originating in a resonance is coming from the second and third leading photons. The invariant mass m_{23} of these two photons, as shown in Fig. 1(right), is used to search for excess.

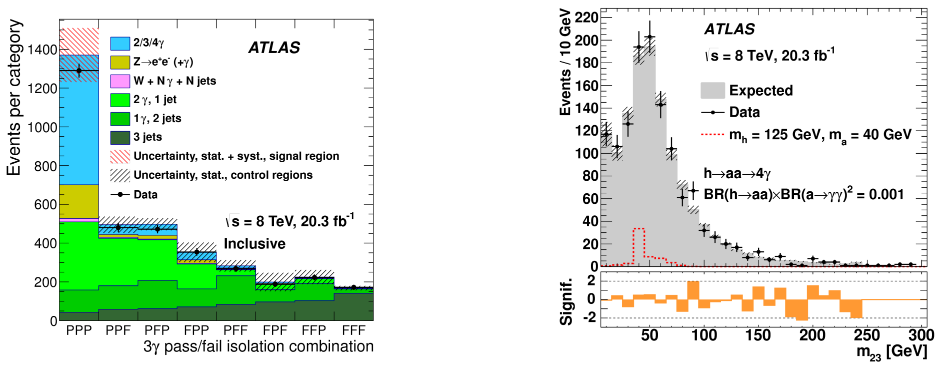

Figure 1: Observed and expected yields in signal and control regions for the full mass range (left). Observed spectra of m_{23} (right). Taken from [6].

Since data describes background prediction well, upper 95% C.L. limits are set on a production cross section as a function m_a for the SM–like Higgs boson with $m_h = 125$ GeV (Fig. 2, left) and for $m_H = 600$ GeV (Fig. 2, right).

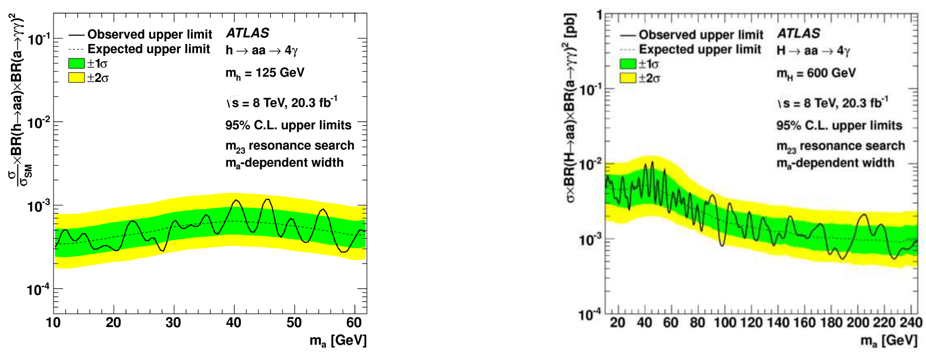

Figure 2: Expected and observed 95% C.L upper limits on $(\sigma/\sigma_{SM}) \times BR(h \to aa) \times BR(a \to \gamma\gamma)^2$ (left), and $\sigma_H \times BR(h \to aa) \times BR(a \to \gamma\gamma)^2$ (right). Taken from [6].

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

The ATLAS experiment searched for a SM–like Higgs boson with $m_h = 125$ GeV decaying to a pair of pseudoscalars with $m_a = 3.7 - 50$ GeV, and for heavy scalar with $m_H = 100 - 500$ GeV decaying to a pair of pseudoscalars with $m_a = 5$ GeV [7]. It is assumed that couplings of a pseudoscalar to quarks are suppressed, and only a case where one a boson decays to two muons and the other decays to a pair of τ–leptons with at least one decaying to an electron or muon is considered. The other τ–lepton is identified by selecting one to three additional tracks. The search is optimized for $m_a < 10$ GeV. Requiring that one boson decays to a pair of muons instead to another pair of τ–leptons reduces the total signal production rate by a factor of $\sim$100, but it provides higher trigger efficiency, and a larger signal to background ratio. The decay to muons shows as a narrow resonance in dimuon invariant mass, $m_{\mu\mu}$, which is used as a discriminant between signal and background.

Standard model background is composed from non–resonant processes ($t\bar{t}$, Drell–Yan, diboson production) and low mass resonances (J/ψ,Υ). Non–resonant SM background processes are constrained with data in the two control regions, light and heavy flavor dominated. Signal and resonant SM background processes are modeled with a double–sided Crystal Ball function. Invariant mass of the dimuon system for SM background processes in light flavor dominated control region is shown in Fig. 3(left).

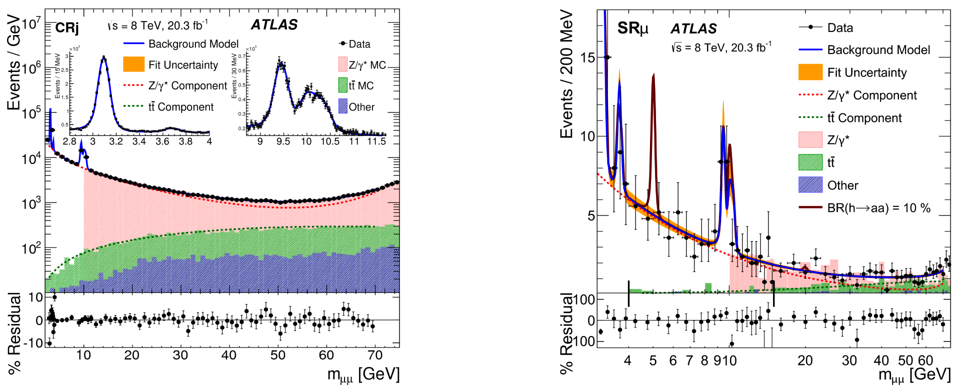

Figure 3: The observed and expected from SM backgrounds distribution of the $m_{\mu\mu}$ in light flavor jet control region (left), and, together with a signal expectation, in the muon signal region (right). Taken from [7].

Two signal and two corresponding validation regions are identified based on the flavor of the lepton from the τ–lepton decay. In the signal region, the third lepton is required to have opposite sign from the accompanying tracks, while in the validation region, the requirement for the same sign is imposed. To search for the presence of a signal a simultaneous fit of the full background model is performed in signal regions, and predicted from the background and observed $m_{\mu\mu}$ distribution in the muon signal region is shown in Fig. 3(right). Since the data is well described by the background only fit, 95% C.L. upper limits are set as function of m_a (Fig. 4, left) and as a function of m_H (Fig. 4, right).

4. The 4b final state

A search for the Higgs boson, $m_h = 125$ GeV, decaying to a pair of new spin zero particles, $H \to aa$, $m_a = 20 - 60$ GeV, where $a \to b\bar{b}$ is performed in associated production with a W boson, where $W \to \ell\nu$ [8]. While gluon–gluon fusion production would have led to higher signal cross section, the leptonic decay of the associated W boson is providing efficient triggering. This analysis presents the first search for the final state with two pairs of b–quarks coming from low mass resonances. Events with one isolated lepton and at least three jets, with at least two tagged as b–jets, are selected, where b–tagging efficiency of 77% with a rejection of light jets of 126 is requested. Dominant background processes are $t\bar{t}$ production with additional light or heavy flavor jets. Other

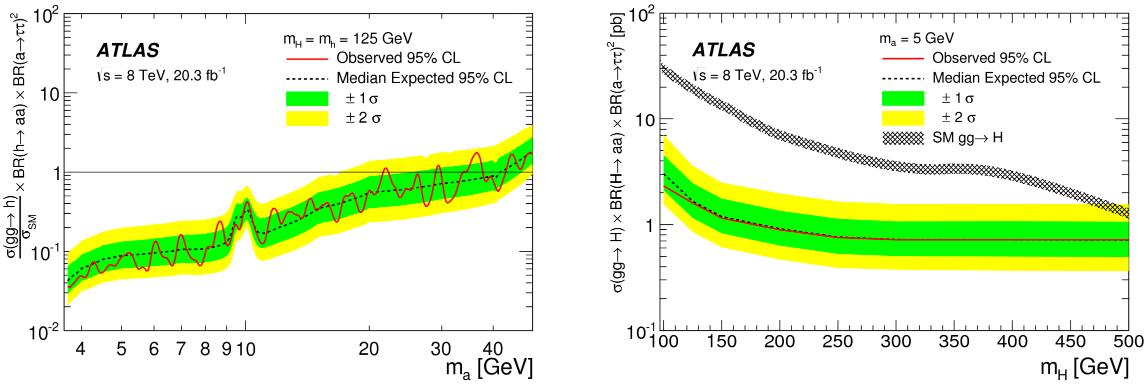

Figure 4: Expected and observed 95% C.L upper limits on $(\sigma/\sigma_{SM}) \times BR(h \to aa) \times BR(a \to \tau\tau)^2$ as a function of m_a and for SM–like Higgs boson with $m_h = 125$ GeV (left), and $\sigma_H \times BR(h \to aa) \times BR(a \to \tau\tau)^2$ as a function of m_H and for $m_a = 5$ GeV (right). Taken from [7].

Region		m_{bbb}	m_{bbbb}	Δm^{bb}_{min}	H_T	p^W_T	ΔR^{bb}_{av}	ΔR^{lb}_{min}	m_{bbj}	m_{T2}
	(3j,3b)	√			√	√	√	√		
Signal	(4j,3b)	√			√	√	√		√	
	(4j,3b)		√	√	√		√			√
Control					√					

Table 1: Input variables for BDT for three signal regions. Shown also is H_T used as a discriminant for all control regions. Taken from [8].

backgrounds include single top, boson+jets and diboson production. Signal and control regions are defined from eight categories, three for signal, and five for control, based on the number of jets ($n = 3,4,5$) and b–tagged jets ($m = 2,3,4$). These regions are denoted as (nj,mb). Signal regions are $(3j,3b),(4j,3b),(4j,4b)$, events belonging to $(nj,2b)$ and $(\geq 5j,3b)$ are mostly $t\bar{t}$ + light jets, and those in $(\geq 5j, \geq 4b)$ are mostly from $t\bar{t}$ + heavy flavor jets.

Several kinematic variables, as shown in Table 1, which discriminate between signal and background are combined into a boosted decision tree (BDT), which is then trained for a signal with $m_a = 60$ GeV and $t\bar{t}$ background. The training is performed separately for each signal region. The H_T distribution is used in five control regions. These distributions of the final discriminants in all eight channels are combined to test for the presence of the signal. The invariant mass of the four b–jets is shown in Fig. 5(top left), the BDT output in $(4j,4b)$ region in Fig. 5(top middle), and the H_T distribution in $(4j,2b)$ in Fig. 5(top right) and in $(\geq 5j, \geq 4b)$ in Fig. 5(bottom left). Since no excess is seen, the 95% CL upper limits are set as shown in Fig. 5(bottom right).

5. Summary

In summary, we presented searches for light pseudoscalars from the Higgs boson sector in the range $3.7 < m_a < 62$ GeV for a variety of decay modes. No excess is observed and decays of the Higgs boson to light pseudoscalars are further constrained.

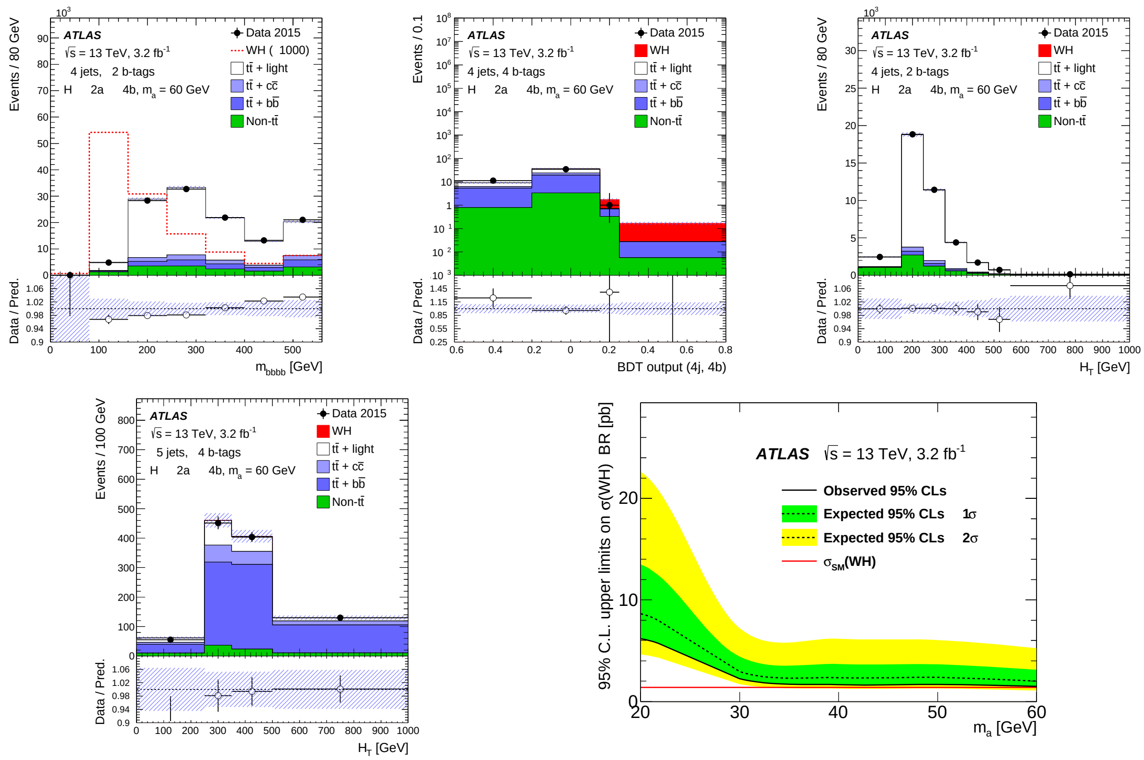

Figure 5: The m_{bbbb} distribution for the signal, expected backgrounds and observed in data for inclusive, in number of jets and b–tagged jets, sample (top left), the BDT output in $(4j, 4b)$ signal region (top middle), and the H_T distribution in $4j, 2b)$ region (top right) and in $(\geq 5j, \geq 4b)$ (bottom left). Expected and observed 95% C.L. upper limit as a function of m_a on $\sigma(WH) \times BR(H \to aa) \times BR(a \to bb)^2$ (bottom left). Taken from [8].

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