Results of Beyond-the-Standard Model 2HDM Higgs Searches using the ATLAS detector in Run-I

Guillermo Nicolas Hamity
1 Jan Smuts Avenue, Braamfontein, Johannesburg, 2000, South Africa
E-mail: guillermo.nicolas.hamity@cern.ch

Abstract. One of the most alluring models used to probe Beyond the Standard Model physics in run-I at ATLAS stems from a simple extension of the Higgs sector. Models where the Higgs sector is assumed to have two Higgs doublets, known as two-Higgs-Doublet-Models (2HDMs), give rise to five Higgs bosons: two neutral CP-even ($h$, $H$) bosons, two charged ($H^\pm$) bosons, and one neutral CP-odd ($A$) boson. Direct searches for the additional Higgs bosons became an ever more promising prospect after the Higgs boson discovery, and various such searches have already been conducted in Run-I ATLAS data. The most recent 2HDM search is for the $A$ boson in the sensitive $Zh$ decay, where $h$ is assumed to be the LHC discovered Higgs boson, within the mass range of 220 – 1000 GeV. In such a search, upper limits on the cross section times branching ratio of the $A$ boson decaying to $Zh$ are set for various 2HDM scenarios. Where no excess is observed, exclusion limits are set on ranges of the 2HDM phase-space. In this note the search for $A \rightarrow Zh \rightarrow \ell\ell\tau\tau$ with fully hadronic tau decay is presented in detail, along with summaries from two of the most recent 2HDM searches in ATLAS.

1. Introduction
The Standard Model (SM) is the centrepiece describing the underlying principles of fundamental particle interactions at high energies. The model combines the fundamental electromagnetic, weak and strong forces, and is able to predict known particle interactions with great precision. The SM has withstood the test of multiple experimental observations, with it’s tour de force being the recent discovery of the Higgs boson which is predicted in the SM by the ATLAS and CMS experiments at the LHC in Geneva [1, 2]. The discovered Higgs boson was found with a mass around 125 GeV and is thus far consistent with the SM zero-spin and positive-parity hypothesis [3, 4]. It therefore comes as no surprise that present ambiguities with the SM are not phenomenological, but stem rather from the it’s ‘collage-type’ derivation [5]. The repetition of fermionic families and the un-quantification of quark charges suggest that the SM may be a low energy state of some underlying theory. More troublesome is that the SM gives no cause for the imbalance of matter over anti-matter, and excludes the gravitational force and dark matter. Models that describe Beyond the Standard Model (BSM) physics are generally aimed at answering some of these questions. In this light, searching for inconsistencies in the SM is crucial to searching for BSM phenomena.

One of the most basic extensions to the SM is by including an additional Higgs doublet in it’s derivation [6]. The SM Higgs sector is only comprised of a simple scalar structure. When considering that the fermionic structure has multiple families and mixings, this assumption need no be the case. The extended models with two Higgs doublets are intuitively referred
to as 2-Higgs-Doublet-Models (2HDMs). They include the Minimal Supersymmetric Standard Model (MSSM), an important candidate of Supersymmetry (SUSY), as well as axion [7] and baryogenesis [8] models. After including an additional Higgs doublet, as well as a few intuitive assumptions [6], 2HDMs give rise to five ‘Higgs’ bosons. There are two CP-even bosons, the light $h$ and heavy $H$, distinguishable only by their mass, where $m_h < m_H$. Then there are two charged Higgs bosons, denoted as $H^\pm$, and a single CP-odd pseudoscalar, the $A$ boson. One should note that the $h$ and $H$ bosons are candidates for the discovered boson, due to their zero-charge and even-parity nature. This allows for 2HDM searches where the mass of one of the CP-even bosons is that of the discovered Higgs. Generally in 2HDM searches one assumes that $m_h = 125$ GeV, although it is still feasible that the light Higgs lives somewhere in the $m_h < 125$ GeV range. Another common assumption made is that the remaining Higgs bosons have approximately equal masses $m_A \approx m_{H^\pm} \approx m_H$ [9]. With these assumptions the 2HDM phasespace is reduced considerably to three free parameters: the mass of one of the heavier Higgs bosons ($m_A$), the mixing angle of the two CP-even Higgs bosons, $\alpha$, and the ratio of the vacuum expectation values of the two Higgs doublets, $\beta$. The last two parameters are generally represented as $\tan \beta$ and $\cos(\beta - \alpha)$ for convenience. In direct searches for the 2HDM bosons, all thee parameters are allowed to vary. Furthermore the predicted couplings of the bosons to the vector bosons and fermions fluctuate in terms of $\tan \beta$ and $\cos(\beta - \alpha)$. An additional freedom in terms of the way that each Higgs doublet couples to vector bosons and fermions gives rise to four different 2HDM types. The ratio of the predicted coupling scale factors for the different 2HDM scenarios of the $h$ boson to the SM Higgs boson couplings is given in table 1. Coupling ratios to the vector bosons ($\kappa_V$), up-type quarks ($\kappa_u$), down-type quark ($\kappa_d$), and leptons ($\kappa_\ell$) are shown to vary as functions of $\beta$ and $\alpha$.

| Coupling scale factor | Type-I | Type-II | Type-III | Type-IV |
|-----------------------|--------|---------|----------|---------|
| $\kappa_V$            | $\sin(\beta - \alpha)$ | $\sin(\beta - \alpha)$ | $\sin(\beta - \alpha)$ | $\sin(\beta - \alpha)$ |
| $\kappa_u$            | $\cos(\beta)/\sin(\alpha)$ | $\cos(\beta)/\sin(\alpha)$ | $\cos(\beta)/\sin(\alpha)$ | $\cos(\beta)/\sin(\alpha)$ |
| $\kappa_d$            | $\cos(\beta)/\sin(\alpha)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\beta)/\sin(\alpha)$ | $-\sin(\alpha)/\cos(\beta)$ |
| $\kappa_\ell$         | $\cos(\beta)/\sin(\alpha)$ | $-\sin(\alpha)/\cos(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ |

Direct searches for 2HDM boson set upper limits on the cross section times decay branching ratio of a specific final state channel. In this way we are able to search for the existence of the 2HDM bosons and subsequent traces of BSM physics. As a bi-product of these studies one is able to exclude the existence of 2HDMs from certain areas of the $m_A$, $\tan \beta$, and $\cos(\beta - \alpha)$ phasespace if no sufficient excess above the upper limits is observed. Various searches have already been conducted, including the CMS searches for $H \rightarrow hh$ and $A \rightarrow Zh$ between $260 - 360$ GeV [10], and an independent search for $A \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ [11]; and the $A \rightarrow \tau\tau$ search with ATLAS [12]. No excess was measured in the studies and large sections of the 2HDM phasespace were excluded. Indirect exclusion limits have also been placed on 2HDMs in the $(\tan \beta, \cos(\beta - \alpha))$ plane by interpreting the observed couplings of the discovered Higgs boson to other particles [13]. The $(\tan \beta, \cos(\beta - \alpha))$ phasespace is scanned for points where the measured Higgs couplings disagree with the 2HDM predictions, at 95% CL or greater, so as to exclude regions in $(\tan \beta, \cos(\beta - \alpha))$. There are however areas of phasespace for 2HDMs which have not been probed due to the low branching ratios of the various topologies, a task set for higher luminosity searches in Run-II.
2. The ATLAS detector

The LHC is currently the largest man-made particle accelerator in the world, capable of proton-proton (pp), heavy ion (lead-proton (Pb-p) and lead-lead (Pb-Pb)) collisions. It has a circumference of 27 km, a design center-of-mass energy of 14 TeV, and peak instantaneous luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for pp collisions. The ATLAS detector is one of the two general-purpose detectors at the LHC [14]. It was designed to accommodate a wide spectrum of different physics signatures and explore processes stemming from the TeV mass scale, where groundbreaking discoveries are expected. The ATLAS detector is a multi-purpose particle detector with approximately forward-backward symmetric cylindrical geometry. ATLAS uses a right handed coordinate system with the origin at the interaction point. The $z$-axis is along the beam pipe, $x$-axis points towards the center of the LHC ring and the $y$-axis points up. Polar coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined as $\eta = -\ln(\tan(\theta/2))$ where $\theta$ is the angle between the particle momentum 3-vector and the beam axis. The inner detector (ID) covers $|\eta| < 2.5$. It consists of silicon pixels, silicon micro-strips and a transition radiation tracker. The ID is surrounded by a superconducting solenoid providing a 2 T magnetic field. Surrounding the ID are two calorimeters, the inner electromagnetic (EM) and the outer hadron calorimeters. The EM calorimeter measures the energy and the position of EM showers within $|\eta| < 3.2$ as well as hadronic showers in the end-cap ($1.5 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) regions. The hadronic calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The muon spectrometer surrounds the calorimeters and consists of three subsystems: eight superconducting air-core toroid magnets, a system of tracking chambers and a fast tracking chamber for triggering. A three-level trigger system selects events to be recorded for offline analysis.

3. The $A \rightarrow Z h \rightarrow \ell\ell\tau_{\text{had}}\tau_{\text{had}}$ analysis

The $A \rightarrow Z h$ channel with the $h$ decaying to $\tau\tau$ and $Z$ to $\ell\ell$ is a new search that promises good sensitivity. In particular this channel probes areas of the Type-II and Type-IV 2HDMs which have not been accessible in previous searches. In this topology three orthogonal final states are available, depending on the either leptonic or hadronic decay of each tau lepton. They are $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$. The production of the pseudoscalar $A$ boson is predominantly driven by gluon-fusion. Contributions from $b$-associated production only become relevant for Type-II and Type-IV 2HDMs at high values of $\tan\beta$, dominating over gluon-fusion at around $\tan\beta = 10$ [9]. In most cases the ratio of $b$-associated $A$ boson production to that of gluon-fusion is restricted to $<3\%$. Two leading order Feynman diagrams of the gluon-fusion and $b$-associated $A$ productions are shown in figure 4.

![Figure 1. Feynman diagrams for (a) gluon-fusion and (b) $b$-associated $A$ boson production.](image-url)
Generally speaking, \( A \rightarrow Zh \) is the dominant decay mode of \( A \) in any 2HDM when the mass of the \( A \) is less than two times the mass of the top-quark \( (m_h + m_Z < m_A < 2m_t) \). This makes the \( A \rightarrow Zh \) channel a very promising search. At masses of \( m_A > 2m_h \) the branching ratio \( \text{BR}(A \rightarrow Zh) \) drops drastically due to the exposed \( t\bar{t} \) kinematic region. In this paper the results from the search of the gluon-produced \( A \) boson decaying to \( Zh \rightarrow \ell\ell\tau_{\text{had}}\tau_{\text{had}} \) are presented in the range of \( 220 < m_A < 1000 \) GeV. The results are combined with the \( \tau_{\text{lep}}\tau_{\text{lep}} \) and \( \tau_{\text{lep}}\tau_{\text{had}} \) channels and finally interpreted in the various 2HDM scenarios in conjunction with a complementary \( A \rightarrow Zh \rightarrow fffbb \) analysis, where \( f = \ell, \) or \( \nu \).

A search for \( A \rightarrow Zh(\tau\tau) \) is conducted with the 2012 ATLAS data at 8 TeV center of mass energy, where the light \( h \) boson is assumed to have a mass of \( m_A = 125 \) GeV. Signal Monte Carlo (MC) samples are produced with Pythia8 [15] for \( A \) masses at fixed working points: \( m_A = 220, 240, 260, 300, 340, 350, 400, 500, 800, 1000 \) GeV. As mentioned in the introduction, each tau in the analysis can decay leptonically (35\%) or hadronically (65\%). Since tau leptons are massive particles, they decay quickly in the detector and are never observed directly in ATLAS, but can only be reconstructed from their decay products. This makes differentiating light-leptons originating from leptonic-tau-decays to light-leptons originating from other processes virtually impossible. As such, tau leptons in the ATLAS detector are considered to be hadronically decaying taus. Tau leptons decay hadronically into either 1− or 3−charged pions, with a \( \nu_\tau \) and possibly a neutral pion. Since the BR(\( A \rightarrow Zh \)) is already relitavely small, and since the SM branching ratio BR(\( h \rightarrow \tau\tau \)) is around 1000 times larger that BR(\( h \rightarrow \mu\mu \)), searches in the \( \tau_{\text{lep}}\tau_{\text{lep}} \) and \( \tau_{\text{lep}}\tau_{\text{had}} \) channels can be conducted in \( \tau\tau \) without worrying about contamination from \( h \rightarrow \ell\ell \,(\ell \neq \tau) \). In all three analysis strategies, the reconstructed \( A \) boson mass, \( m_A \), is considered as the parameter of interest.

The fully hadronic final state is a particularly challenging analysis since it contains a large amount of missing transverse energy, \( E_T^{\text{miss}} \), from the two neutrinos. In the case of \( \tau_{\text{had}}\tau_{\text{had}} \), full reconstruction of the event topology requires solving a system of equations with 6 unknowns. This system is under-constrained and an exact solution is not possible. Therefore, the full event reconstruction, as well as the full reconstruction of the \( m_{\tau\tau} \) mass, are impossible. The Missing Mass Calculator (MMC) method is therefore used to reconstruct \( m_{\tau\tau} \) [16]. This method scans for the most likely \( m_{\tau\tau} \) solution given the known conditions of the event, i.e. the visible taus and \( E_T^{\text{miss}} \) kinematics. The MMC is compared to alternate \( m_{\tau\tau} \) reconstruction methods: the transverse mass and collinear approximation (CLA) methods [16], performing at a better efficiency and resolution than the CLA method.

The event selection in the \( \tau_{\text{had}}\tau_{\text{had}} \) channel focuses on selecting a clean signal with exactly two leptons (\( e, \) or \( \mu \)) and two visible tau jets. Events are triggered by single lepton triggers. The events are required to have exactly two same flavour opposite charge loose leptons with a combined invariant mass of \( 80 < m_{\ell\ell} < 100 \) GeV, which corresponds to \( m_Z = 90 \) GeV. Track and calorimeter track isolation requirements are also imposed on the leptons. The event must also have exactly two opposite charge loose tau leptons, which need to pass electron and muon vetos, and have a MMC combined invariant mass of \( 75 < m_{\tau\tau}^{\text{MMC}} < 175 \) GeV, corresponding to \( m_h = 125 \) GeV. The large window here compensates for the resolution of the MMC algorithm. Two additional selection conditions are applied after an optimization study performed on different kinematic variables. The first of these is that the tau lepton with highest \( p_T \) should have a transverse energy of \( E_T > 35 \) GeV. Finally, events where the reconstructed di-lepton \( p_T \) is smaller than 0.64 \times m_A - 131 GeV are discarded. This selection is applied to all events with a reconstructed \( A \) mass less than 400 GeV.

After the full event selection, the \( \tau_{\text{had}}\tau_{\text{had}} \) analysis has a few surviving background processes, the most prominent of which is the \( Z+\)jets background. This background contains jets which are mis-identified as tau leptons. A small contribution from \( WZ \) di-boson processes also contributes to the fake background. Other important backgrounds include di-boson ZZ and
SM $Z\ell\ell$ production, which are comprised of true tau signatures, and are estimated from MC. All backgrounds caused by mis-identified jets are estimated via a data-driven template method prediction. This method is performed by constructing three orthogonal control regions. The first region is defined identically to the full signal selection, except that the leading tau is forced to fail the loose tau selection. The second region requires that the tau leptons have the same charge. The third region combines both the inverted loose tau and same tau charge requirements. When looking at data in these regions, the control regions are completely populated by fake tau jets. Data distributions in the control regions are extrapolated into the signal region and used to estimate the mis-identified tau background. The distribution is normalized using $m_A$ sidebands.

Systematic uncertainties due to the fake background normalization are considered by taking into account the fluctuations in normalization values when choosing alternate control regions. This uncertainty constitutes the largest uncertainty, approximately 25%. Uncertainties due to detector calibration effects, and theoretical uncertainties are also included. The $m_A$ distribution of the $\tau_{\text{had}}\tau_{\text{had}}$ channel after full event selection is given in figure 2, showing the predicted backgrounds, the 340 GeV mass signal signal with a cross section times branching ratio of 50 fb, and the observed data.

A binned likelihood ratio test, along with an asymptotic approximation, is used in order to plot the 95% CL upper limits on the cross section times branching ratio of $\ell\ell\tau\tau$. Figure 3 shows the expected and observed upper limits of gluon-fusion $\sigma \times \text{BR}(A \rightarrow Zh) \times \text{BR}(h \rightarrow \tau\tau)$ for the combined $A \rightarrow Zh \rightarrow \ell\ell\tau\tau$ analysis. No assumptions are made on the branching ratio of $h \rightarrow \tau\tau$ in order to maintain the result model independent. The observed combined upper limit is within $2\sigma$ of the expected limit. The expected 95% CL for the $\tau_{\ell\ell\tau_{\text{lep}}}$, $\tau_{\ell\ell\tau_{\text{had}}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ are shown in dashed lines. The drop in the limits at higher values are from the lack of data observed in the highest $m_A$ bins. The 95% CL upper limits on the gluon-fusion $\sigma \times \text{BR}(A \rightarrow Zh) \times \text{BR}(h \rightarrow \ell\ell\tau)$ range from 0.098–0.013 pb in a range of $220 \leq m_A \leq 1000$ GeV. No excess is observed outside the 2$\sigma$. The low observed limits at the higher mass points is caused by a lack of events in the final 315-2000 GeV $m_{\ell\ell}^{\text{rec}}$ bin.

The final limits are combined with limits from a complementary $A \rightarrow Zh \rightarrow f\bar{f}bb$ analysis, where $f = \ell, \nu$ [17]. The results are presented as model independent limits on the $A \rightarrow Zh$ cross section times branching ration and no excess is observed outside of the uncertainties. They are interpreted in the context of the four 2HDM scenarios us in order to exclude sections of

**Figure 2.** The reconstructed $A$ boson mass, $m_A$ of the $\tau_{\text{had}}\tau_{\text{had}}$ channel after full event selection [17].

**Figure 3.** Expected and observed 95% CL upper limits of the gluon-fusion cross section times branching ratio of the combined $A \rightarrow Zh \rightarrow \ell\ell\tau\tau$ [17].
the phase space. The final paper includes the first published search for an $A$ boson in the $\ell\ell\tau\tau$ channel.

4. Other recent 2HDM searches with ATLAS in Run-I

4.1. $H^{\pm}$ to $\tau^{\pm}$-jets

A search for a charged Higgs boson decaying via $H^{\pm} \rightarrow \tau^{\pm}\nu$ is conducted in the hadronic final state at 8TeV center of mass energy $pp$ collisions with an integrated luminosity of 19.5$fb^{-1}$ [18]. The search is conducted between the mass intervals of $m_{H^+} \in (80\,\text{GeV},\,160\,\text{GeV})$ and $m_{H^+} \in (180\,\text{GeV},\,1\,\text{TeV})$, split by the top quark mass ($m_t \approx 173.3$ GeV) around which the physics processes are not well understood by MC. In the low mass region ($m_{H^+} < m_{\ell\nu}$) the $H^+$ production is dominated by di-top production via gluon-fusion, where one $t$-quark decays to $H^+$ and a $b$-quark jet, while the other decays to $W^-b$ producing additional jets in the final state. In the high mass region ($m_{H^+} > m_{\ell\nu}$) $H^+$ is produced via $t$-quark associated production, with at least one $b$-quark jet in the final state.

Event selection in the $H^{\pm}$ to $\tau^{\pm}$-jets search optimizes on events with the following criteria: one hadronically decaying tau; a large amount of $E_T^{miss}$; two quark jets from hadronic $W^-$ decay; and at least one(two) $b$-jets for the high(low) mass case. The backgrounds originate from processes with either a true or a mis-identified tau lepton. The true tau background is predicted by using an embedding method in $\mu$+jets data, and replacing the $\mu$ leptons with true MC tau leptons which are allowed to decay hadronically through the detector. The amount of background originating from mis-identified jets is predicted by calculating the identification efficiency of taus in control regions. A small amount ($1\%-2\%$) of background from mis-identified $e$ and $\mu$ leptons is taken from MC. The final discriminating variable is chosen to be the $H^{\pm}$ transverse mass.

The 95% CL expected limits on the cross section and/or branching ratios of $H^+ \rightarrow \tau^{\pm}\nu$ are derived using an asymptotic approximation. Limits in the low mass region on $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau^{\pm}\nu)$ via di-top production are found to be between 0.23% and 1.3%. For the high mass range the limits on the cross section times branching ratio, $\sigma(pp \rightarrow tH^+ + X) \times B(H^+ \rightarrow \tau^{\pm}\nu)$, are between 0.76 pb and 4.5 fb. No Excess is observed and the observed limits agree with the SM predictions within systematic uncertainties.

4.2. Di-Higgs resonant searches

In the SM, direct di-Higgs production and the Higgs self coupling to di-Higgs have very low cross sections. In the best case, gluon-fusion produced di-Higgs has a predicted cross section of around 10 fb at 8TeV [19]. These processes where therefore not accessible during the Run-I data taking period at ATLAS. The measurement of the di-Higgs production cross section will be one of the main tasks in Run-II at higher center of mass energy. However, in the light of 2HDMs the cross section of di-Higgs production may be significantly boosted [20]. Depending on the chosen 2HDM parameters, two light Higgs may originate from a heavy Higgs boson with a cross section times branching ratio of up to a few pb. This gave rise to various searches in ATLAS during Run-I for $hh$ production. One such search is a model independent non-resonant/resonant search for $hh \rightarrow bb\gamma\gamma$ [21]. The search observed 5 events from an expected 1.5 events, 1.3±0.5 of which came from fitted background predictions, while 0.17 ± 0.04 came from SM Higgs production. Figure 4 shows the expected and observed 95% CL limits on the resonant cross section times branching ratio, $\sigma_X \times \text{BR}(X \rightarrow hh)$. The expected cross section times branching ratio of a Type-I 2HDM with $\tan\beta = 1$ and $\cos(\beta - \alpha) = -0.05$ is superimposed for comparison. The fluctuation at $m_X = 300$ GeV corresponds to a fluctuation of 3$\sigma$. When considering the look elsewhere effect this is brought down to 2.1$\sigma$. Currently the di-Higgs production can not be excluded around the $m_X = 300$ GeV mass, and a $\sigma_X \times \text{BR}(X \rightarrow hh)$ analysis will be conducted at a higher center of mass energy when the LHC reopens in Run-II.
5. Conclusion

A few 2HDM searches which were conducted during Run-I data taking at ATLAS where summarized. The focus is place on the most recent search of the pseudoscalar Higgs in the $A \rightarrow Zh$ channel. The analysis techniques in the fully hadronic channel are presented in detail. Further 2HDM motivated searches for the charged ($H^+ \rightarrow \tau^+ \nu$) and heavy Higgs ($X \rightarrow hh$) bosons are also presented, none of which show any conclusive evidence for the existence of the bosons. The analysis strategies include placing 95% CL upper limits on their cross sections and/or branching ratios. Where no excess is observed, regions of the 2HDM phase-space are excluded. The list of 2HDM searches in ATLAS is not exhausted here and readers are encouraged to visit results from $h/A/H \rightarrow \tau\tau$ [22] and $hh \rightarrow bbbb$ [23] searches, to name but a few. These ATLAS searches will continue at higher center of mass energies in Run-II in order to place greater restrictions on the 2HDM phase-space, or alternitavely reveal some BSM physics phenomena.

References

[1] ATLAS Collaboration, 2013 Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC Phys.Lett. B 726 88
[2] CMS Collaboration, 2013 Combination of standard model Higgs boson searches and measurements CMS-PAS-HIG-13-005
[3] ATLAS Collaboration, 2013 Evidence for the spin-0 nature of the Higgs boson using ATLAS data Phys.Lett. B 726 120
[4] CMS Collaboration, 2013 Study of the Mass and Spin-Parity of the Higgs Boson Candidate Via Its Decays to Z Boson Pairs Phys.Rev.Lett. 110 081803
[5] Langacker P, 1981 Grand unified theories and proton decays Phys.Rev.Lett. 72 185
[6] Branco G C, et al., 2012 Theory and phenomenology of two-Higgs-doublet models Phys.Rept. 516 1
[7] Kim J E, 1987 Light Pseudoscalars, Particle Physics and Cosmology Phys.Rept. 150 1
[8] Joyce M, Prokopec T and Turok N, 1994 Nonlocal electroweak baryogenesis. Part 2: The Classical regime Phys.Rev. D53 2958
[9] ATLAS Collaboration, 2013 Beyond-the-Standard-Model Higgs boson searches at a High-Luminosity LHC with ATLAS ATLAS-PUB-2013-016
[10] CMS Collaboration, 2013 Search for extended Higgs sectors in the $H$ to $hh$ and $A$ to $Zh$ channels in $\sqrt{s} = 8$ TeV $pp$ collisions with multileptons and photons final states *CMS-PAS-HIG-13-025*

[11] CMS Collaboration, 2014 Search for a pseudoscalar boson $A$ decaying into a $Z$ and an $h$ boson in the $llbb$ final state *CMS-PAS-HIG-14-011*

[12] ATLAS Collaboration, 2014 Search for neutral Higgs bosons of the minimal supersymmetric standard model in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector *J. High Energy Phys.* JHEP11(2014)056

[13] ATLAS Collaboration, 2014 Constraints on New Phenomena via Higgs Coupling Measurements with the ATLAS Detector *ATLAS-CONF-2014-010*

[14] CERN, 1999 ATLAS: Detector and physics performance technical design report. Volume 1 *CERN-LHCC-99-14*

[15] Sjostrand T, Mrenna S and Skands P, 2006 PYTHIA 6.4 Physics and Manual *JHEP* 0605 026

[16] Elagin A, Murat P, Pranko A and Safonov A, 2011 A New Mass Reconstruction Technique for Resonances Decaying to di-tau *Nucl.Instrum.Meth.* A654 481

[17] ATLAS Collaboration, 2015 Search for a CP-odd Higgs boson decaying to $Zh$ in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector *CERN-PH-EP-2015-013*

[18] ATLAS Collaboration, 2014 Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu$ in hadronic final states using $pp$ collision data at $\sqrt{s} = 8$ TeV with the ATLAS *ATLAS-CONF-2014-050*

[19] Baglio J, and Djouadi A, Grober R, et al., 2013 The measurement of the Higgs self-coupling at the LHC *JHEP* 1304 (2013) 151

[20] Nathaniel C, and Jamison G, and Scott T, 2013 Searching for Signs of the Second Higgs Doublet *RU-NHETC-2013-07*

[21] ATLAS Collaboration, 2014 Search For Higgs Boson Pair Production in the $\gamma\gamma bb$ Final State using $pp$ Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector *HIGG-2013-29*

[22] ATLAS Collaboration, 2014 Search for neutral Higgs bosons of the minimal supersymmetric standard model in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector *JHEP11(2014)056*

[23] ATLAS Collaboration, 2014 A search for resonant Higgs-pair production in the $bbbb$ final state in $pp$ collisions at $\sqrt{s} = 8$ TeV *ATLAS-CONF-2014-005*