$A \rightarrow Zh \rightarrow \ell^+\ell^- \tau^+\tau^-$

Analysis overview and motivation for the search of the pseudoscalar Higgs with the ATLAS experiment

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SM Higgs discovered (125 GeV) → is the Higgs sector minimal? is it extended?

- SM Higgs sector has experimental constrain:
  \[ \rho \equiv \frac{m_W}{m_Z \cos \theta_W} \to 1 \]

- 2HDM: Simple extension by adding complex Higgs doublet, SU(2), satisfying
  \[ \rho \to 1 \]

- **Assumptions:**
  - CP-conservation
  - Softly broken $\mathbb{Z}_2$ symmetry ($\Phi_1 = -\Phi_1$)
  - Electroweak symmetry breaking, and $\nu_1 \nu_2 \neq 0$

- Resulting 8 fields:
  3 give mass to $W^\pm$ and $Z$ bosons,

  5 physical **scalar** ("Higgs") fields

  \[ \begin{align*}
  &\text{CP-odd pseudoscalar} \quad \to \quad A \\
  &\text{h (light)} \quad \to \quad m_h < m_H \\
  &\text{2 CP-even} \\
  &\text{H (Heavy)} \\
  &\text{2 scalar charged} \quad \to \quad H^\pm
  \end{align*} \]
Motivation for 2HDM search at High-Lumi with ATLAS

- ATLAS Note motivates 2HDM searches at high luminosity: Beyond-the-Standard-Model Higgs boson searches at a High-Luminosity LHC with ATLAS. 
  ATL-PHYS-PUB-2013-016

- Sensitivity study done for high Luminosity (300 and 3000 fb$^{-1}$ pp, $\sqrt{s} = 14$ TeV)
  - $A \rightarrow Zh \rightarrow \ell\ell bb$
  - $H \rightarrow \mu\mu$
  - $H \rightarrow ZZ' \rightarrow 4\ell$

- Assumptions that are made:
  - $m_h = 125$ GeV.
  - $m_A = m_H = m_{H^\pm}$
    Mass splitting disfavoured by considering potential parameters and changes in $\rho$.

- Degrees of freedom:
  $$m_A \quad tan\beta \quad cos(\beta - \alpha) \rightarrow 0$$

Generally $A \rightarrow Zh$ is dominant decay mode of $A$ in any 2HDM for $m_h + m_Z < m_A < 2m_{top}$.

Figure: Constraints in the 2HDM
95% CL upper limits for $m_A \in 220-900$ GeV for $3000 \text{ fb}^{-1}$.


Complimentary limits set by constraints on New Phenomena via Higgs Coupling Measurements with the ATLAS Detector

ATLAS-CONF-2014-010.
Results from CMS search for extended Higgs sectors

CMS Note on BSM search results: Search for extended Higgs sectors in the $H \rightarrow hh$ and $A \rightarrow Zh$ channels in $\sqrt{s} = 8$ TeV pp collisions with multileptons and photons final states
CMS-PAS-HIG-13-025

- Search for $H \rightarrow hh$ and $A \rightarrow Zh$: 19.5 fb$^{-1}$; $\sqrt{s} = 8$ TeV.
- CL limits in the range 260-360 GeV $\rightarrow$ consistent with the SM.
- Significant portions of 2HDMs parameter excluded.
- Final states considered:

<table>
<thead>
<tr>
<th>$Z \rightarrow h \rightarrow$</th>
<th>WW$^*$</th>
<th>ZZ$^*$</th>
<th>$\tau\tau$</th>
<th>$\gamma\gamma$</th>
<th>$bb$</th>
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<td>X</td>
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</tbody>
</table>

$A \rightarrow Zh$ ATLAS search: ☐

- CMS inclusive search strategy vs ATLAS fully reconstructed.

Observed and expected limits with 1 and 2-$\sigma$ bands for $H \rightarrow hh$ (left) and $A \rightarrow Zh$ (right) in terms of $\sigma \times Br$ based on multilepton and diphoton channels.

Observed and expected limits with 1 and 2-$\sigma$ bands on combined signal for $H$ and $A$ in Type-I (left), and Type-II (right) 2HDMs ($m_H = m_A = 300$ GeV). Regions below limits are excluded.
Introducing the $A \rightarrow Zh$ analysis

- $A \rightarrow Zh$ analysis searching for $m_A \in (220, 1000)$ GeV at 8TeV $pp$ collisions with 20 fb$^{-1}$.

$A \rightarrow Zh(\tau\tau)$

- $\tau \ell \ell$ (leplep)
- $\tau \ell \tau$ (lephad)
- $\tau \tau$ (hadhad)

$\tau$ Decays:

- $3\pi^\pm 1\pi^0_\nu$: 14%
- $3\pi^\pm$: 8%
- $1\pi^\pm 2\pi^0_\nu$: 14%
- $1\pi^\pm 1\pi^0_\nu$: 8%
- $1\pi^\pm$: 35%
- $1\pi^\pm$ (hadhad)
- $3\pi^\pm$ (hadhad)
- $3\pi^\pm$ (leptonic mode)
- $1\pi^\pm$ (hadronic mode)

Documentation: HSG6/notes/HiggsToHiggs/AZh/Internal_AZh_lltautau
The Fake Tau Problem

Different decays in ATLAS detector:

- Photons
- $e^\pm$
- Muons
- $\pi^\pm, \rho$
- $n$

Taus never make the inner-detector (can only look at decays)

Non-Tau Jet

- Narrow cone jet
- 1- or 3-prong jet

Tau Jet
Processes with $2\ell$ and 2 taus (had)

Processes with $2\ell$ and 2 jets serve as irreducible background
Event Preselection for hadronic channel:

- Single lepton triggers.
- Leptons: 2 loose $\ell$ SF, OS
  - Z mass window: $80 < m_{ll} < 100$ GeV
  - Isolation ($p_{T\text{cone}40}/p_T < 0.2$ and $\text{etcone}20/p_T < 0.2$)
- Taus: 2 loose $\tau_{\text{had}}$
  - Muon and electron vetos
  - H mass window: $75 < m_{ll} < 175$ GeV.
- Events with additional light leptons or $\tau_{\text{had−vis}}$ are discarded.

Background Monte Carlo:

- Z+jets (DY)
- Diboson: ZZ, WZ, WW
- Tribozon: WWW*, ZWW*, ZZZ*
- Top: $t\bar{t}$, $tW$, $t\ell$, $t\bar{t}Z$
- SM associated Higgs production: ZH

10 Signal Mass points (in GeV):

220, 240, 260, 300, 340, 350, 400, 500, 800, 1000
Had-had optimization

Discriminating variables are shown below after pre-selection. Further optimization done by maximising signal significance at every mass point.

Performed a scan of the significance defined as

\[
Sig = \sqrt{2 \cdot (S + B) \cdot \ln\left(1 + \frac{S}{B}\right) - S}
\]
Backgrounds with fakes

are due to jets faking taus
Full selection for Hadhad channel

Full Selection

- The leading $\tau_{\text{had-vis}}$ is required to have $E_t > 35$ GeV
- For events with $m_A \leq 400$ GeV, $Z p_T > (0.64 m_A - 131)$ GeV.
- For events with $m_A > 400$ GeV, $Z p_T > 125$ GeV.

Pre-selection

Full-selection
Data estimated background

- Blind in signal region.
- Data can boost BKG predictions.
- Bkgs with fake taus estimated using template.

**Template Method**
- Define 3 control regions populated with fakes:
  - **OS — loose \( \tau \)**
  - **SS — loose \( \tau \)**
  - **OS — !loose \( \tau \)**
  - **SS — !loose \( \tau \)**
- Bkg shape extrapolated from CR to SR
- Bkg normalized using \( m_A \) sideband

**Important assumptions:**
- Template \( m_A \) shape is good in SR.
- Normalisation in \( h \)-sideband describes \( m_h \) window

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**Guillermo Hamity**
Had-had final signal acceptance

Signal acceptance increases with $m_A$, except at the highest mass point, where high $p_T$ leptons failing the isolation requirements result in a lower acceptance.

Figure: The signal acceptance for simulated signal samples, for all $m_A$ available mass points.
Experimental systematics negligible when compared to template systematics.

- **Experimental**
  - Electron, muon, tauID
  - Pile-up and Luminosity
  - Jet Energy Scale
  - Tau Energy Scale
  - Tau Energy Resolution
  - Tau Energy Scale
  - Missing Transverse Energy
  - Jet Vertex Fraction

- **Theoretical systematics being considered**

- **Template method systematics:**
  - Changes in normalization and template due to different CR
    - Region 1 (R1): events with 2 loose $\tau$ that are of same sign charge,
    - Region 2 (R2): events with 2 $\tau$, where one fails the loose $\tau$ ID, of opposite sign charge.
    - Region 3 (R3): events with 2 $\tau$ that fail the loose $\tau$ ID, of opposite sign charge.
    - Region 4 (R2): events with 2 $\tau$, where one fails the loose $\tau$ ID, of same sign charge.
    - Region 5 (R3): events with 2 $\tau$ that fail the loose $\tau$ ID, of same sign charge.
Currently blind. Hoping to look at data in the coming months Planning to combine in a note with:

- $A \rightarrow Zh(bb)$
  - $\rightarrow \ell\ell bb$
  - $\rightarrow \nu\nu bb$
- Similar VH(bb) [ATLAS-CONF-2013-079]