Searches for Non-SM Higgs Bosons and for BSM Decays of the Higgs Boson at the ATLAS Experiment

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Introduction

- Discovery of a neutral scalar particle of mass $\sim 125$ GeV at the LHC confirmed the predicted electroweak symmetry breaking mechanism of the SM.

- Experimental results show consistency with the SM Higgs boson.

- Is there only one Higgs doublet (SM) or the Higgs sector is more complex?

- Various BSM models predict additional Higgs bosons:
  - Additional EW singlet: $h, H$
  - Two Higgs Doublet Model (2HDM): $h, H, A, H^\pm$
  - Two Higgs doublet + singlet Model
  - Higgs triplet models (SM doublet + triplet): $H^{\pm\pm}$

Strategies which use Higgs to find new physics:

Indirectly, by looking for non-standard properties of light Higgs (couplings, CP, LFV decays...)

Directly, by explicit search for BSM Higgs decaying to SM objects

Higgs decays to BSM states (light scalar resonances, invisible decays, LLP...
Heavy Neutral Higgs

- Heavy neutral Higgs in fermion final states
  - In the MSSM, the heavy Higgs boson couplings to down-type fermions ($\tau$, $b$) are strongly enhanced for a large part of the parameter space for large $\tan \beta$

- Heavy neutral Higgs in boson final states
  - In the EWS or 2HDM models heavy Higgs boson could decay into final states with Weak bosons

<table>
<thead>
<tr>
<th>Searches for heavy neutral Higgs in ATLAS</th>
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<tbody>
<tr>
<td>$A/H \rightarrow \tau\tau$</td>
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<tr>
<td>$A \rightarrow Zh \rightarrow \ell\ell b\bar{b}$</td>
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<td>$A \rightarrow ZH \rightarrow \ell\ell b\bar{b}$</td>
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<tr>
<td>$H \rightarrow WW \rightarrow \ell\nu qq$</td>
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<td>$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell/\ell\ell\nu\nu$</td>
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<td>$X \rightarrow Z\gamma$</td>
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Heavy Neutral Higgs

$A/H \rightarrow \tau\tau$ in 36.1 fb$^{-1}$ of $pp$ collisions at 13 TeV

- Two $\tau$ decay modes considered:
  - All hadronic final state ($\tau_{\text{had}}\tau_{\text{had}}$), 0 or $\geq 1$ $b$-jet
  - Semileptonic final state ($\tau_{\text{lep}}\tau_{\text{had}}$), 0 or $\geq 1$ $b$-jet

- Both channels have good sensitivity

- Discriminating variable:
  $$m_{T}^{\text{tot}} = \sqrt{(p_{T}^{\tau_1} + p_{T}^{\tau_2} + E_{T}^{\text{miss}})^2 - (p_{T}^{\tau_1} + p_{T}^{\tau_2} + E_{T}^{\text{miss}})^2}$$

- Main backgrounds:
  - Misidentified jet as $\tau$
Heavy Neutral Higgs

$A/H \to \tau\tau$ in 36.1 fb$^{-1}$ of $pp$ collisions at 13 TeV

- Set limits as a function of $\phi = h/A/H$ mass for $\sigma(pp \to [bb]\phi) \times BR(\phi \to \tau\tau)$:
  - $ggF$: 0.78 pb – 5.8 fb for $m_\phi$ range of 200 GeV – 2.25 TeV
  - $b$-associated: 0.7 pb – 3.7 fb for $m_\phi$ range of 200 GeV – 2.25 TeV

- Interpreted obtained results in context of hMSSM: $\tan\beta > 42$ for $m_\phi = 1.5$ TeV
Heavy Neutral Higgs

\[ A \rightarrow Zh \rightarrow \ell\ell b\bar{b}\] in 36.1 fb\(^{-1}\) of pp collisions at 13 TeV

- \(ggF\) and \(b\)-quark associated productions considered

- Two channels based on \(Z\) decays

- Main backgrounds:
  - \(t\bar{t}\) and single top events
  - \(Z/W +\)jets events

- Additional \(b\)-jets from the associated \(b\)-quarks in the production process

- As \(m_A\) gets larger, \(h\) is boosted (higher momentum), resolved and merged categories

\[ R = 0.4 \quad \text{Resolved} \quad \begin{aligned} b \quad & \quad \text{Merged} \quad b \quad R = 1 \end{aligned} \]
Heavy Neutral Higgs

$A \rightarrow Zh \rightarrow \ell\ell b\bar{b}$ in 36.1 fb$^{-1}$ of $pp$ collisions at 13 TeV

- No significant excess over SM predictions
- Set limits as a function of $m_A$ for:
  - $\sigma(pp \rightarrow A \rightarrow Zh) \times BR(h \rightarrow b\bar{b})$ for ggF
  - $\sigma(pp \rightarrow b\bar{b}A \rightarrow Zh) \times BR(h \rightarrow b\bar{b})$ for $b\bar{b}A$: excess at 440 GeV, 3.6 $\sigma$ local and 2.4 $\sigma$ global significance, arises mostly from 2-lepton $\geq 3$ $b$-tag channel
- Interpreted results in context of 2HDM Type II ($\cos(\beta - \alpha) = 0.1$)
Heavy Neutral Higgs

$A \rightarrow ZH \rightarrow \ell\ell b\bar{b}$ in 36.1 fb$^{-1}$ of $pp$ collisions at 13 TeV

- Electroweak baryogenesis scenarios in 2HDM require that $m_A > m_H$

- Two channels for different production modes:
  - $= 2$ $b$-tag: ggF production
  - $\geq 3$ $b$-tag: $b$-associated production

- The discriminant variable $m_{\ell\ell bb}$ from different $m_{bb}$ windows scanned for excesses beyond the background expectations
  - steps of 10 GeV
  - $230 < m_A < 800$ and $130 < m_H < 700$ GeV
  - $m_A - m_H > 100$ GeV

- Main backgrounds:
  - $t\bar{t}$ and single top events
  - $W/Z$+jets events
Heavy Neutral Higgs

$A \to ZH \to \ell\ell b\bar{b}$ in 36.1 fb$^{-1}$ of $pp$ collisions at 13 TeV

- Set limits as a function of $H$ mass for $\sigma(pp \to A) \times B(A \to ZH) \times B(H \to bb)$
  - for ggF production: 14 – 830 fb
  - for $b$-associated production: 26 – 570 fb
- Interpreted results in context of 2HDM Type II: $m_H \leq 600$ GeV excluded at high tan $\beta$

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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Observed 95% CL upper limits on $\sigma \times B(A \to ZH) \times B(H \to bb)$
- Gluon-gluon fusion
- $b$-associated production
Charged Higgs

- Any extension to the Higgs sector, beyond adding a singlet scalar, implies existence of charged scalars (2HDM, NMSSM, Triplet...)

- Dominant production in association with top quarks in benchmark models

- At high mass $H^\pm \rightarrow tb$ is the dominant decay mode in type-II 2HDM

- $H^\pm \rightarrow \tau \nu$ remains significant for a large range of masses for high $\tan \beta$ in type-II 2HDM

- Addition of a Higgs triplet to SM gives doubly charged Higgs bosons $H^{\pm\pm}$

Charged Higgs searches in ATLAS

$H^\pm \rightarrow \tau \nu$  \hspace{1cm} arXiv:1807.07915
$H^\pm \rightarrow tb$  \hspace{1cm} arXiv:1808.03599
$H^{++} H^{--} \rightarrow W^+ W^+ W^- W^-$  \hspace{1cm} arXiv:1808.01899
$H^{++} H^{--} \rightarrow \ell^+ \ell^+ \ell^- \ell^-$  \hspace{1cm} Eur. Phys. J. C 78 (2018) 199
Charged Higgs

$H^\pm \rightarrow \tau \nu$ in 36.1 $fb^{-1}$ of $pp$ collisions at 13 TeV

- Search for $H^\pm$ over wide mass range
  - Low mass range (90-160 GeV)
  - Intermediate mass range ($m_{H^\pm} \approx m_t$) never probed experimentally
  - High mass range (200-2000 GeV)

- Two channels depending on associated $t$ decay
  - 1 hadronic $\tau$, veto events with $\ell$, $\geq 3$ jets ($\geq 1$ $b$-jet), $E_T^{\text{miss}}$
  - 1 hadronic $\tau$, 1 $\ell$, $\geq 1$ jets ($\geq 1$ $b$-jet), $E_T^{\text{miss}}$

- Events classified with BDT from kinematic variables. BDT score used in statistical analysis

- Main backgrounds:
  - Misidentified jet as $\tau$
  - $t\bar{t}$ and single top events
Charged Higgs

$H^\pm \rightarrow \tau \nu$ in 36.1 fb$^{-1}$ of $pp$ collisions at 13 TeV

- No significant excess over SM predictions observed
- Set limits as a function of $H^\pm$ mass for:
  - $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau \nu)$ for full $H^\pm$ mass (bottom): 4.2 pb – 2.5 fb
  - $\text{BR}(t \rightarrow bH^\pm) \times \text{BR}(H^\pm \rightarrow \tau \nu)$ for low $H^\pm$ mass (top): 0.25% – 0.031%
- Compared the limits with
  - 2015 results for high $H^\pm$ mass
  - Run 1 results for low $H^\pm$ mass
- Significant gain with respect to previous results

$H^\pm$ intermediate mass probed experimentally for a first time

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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Observed (95% CL)
- $\pm 1\sigma$
- $\pm 2\sigma$
- Expected (95% CL)

- 2015 result
- Run-1 result

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Charged Higgs

$H^\pm \rightarrow tb$ in 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV

- Search in the 200-2000 GeV mass range
- Multiple regions based on $N(\text{jets})$ and $N(b\text{-jets})$ to constrain the $t\bar{t} + \geq 1b$ and $tt + \geq 1c$ backgrounds
- Events classified with BDT from kinematic variables
- Fit simultaneously in all regions
- Main backgrounds:
  - $t\bar{t} + \text{jets}$ dominated by $t\bar{t} + \geq 1b$
Charged Higgs

\[ H^\pm \rightarrow tb \] in 36.1 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 13 \) TeV

- No significant excess over SM predictions observed
- Set limits as a function of \( H^\pm \) mass for \( \sigma(pp \rightarrow tbH^\pm) \times \text{BR}(H^\pm \rightarrow tb) \):
  - 2.9 pb – 70 fb
- Interpreted obtained results in context of hMSSM and \( m^\text{mod-} \) scenario:
  - \( 0.5 < \tan\beta < 1.95 \) excluded for \( m_{H^\pm} = 200 \) GeV
  - \( \tan\beta > 36 \) excluded for \( 220 < m_{H^\pm} = 540 \) GeV
Common $H^\pm \rightarrow \tau\nu$ and $H^\pm \rightarrow tb$ Results

- Superposition of the $H^\pm \rightarrow \tau\nu$ and $H^\pm \rightarrow tb$ exclusion limits in context of hMSSM and $m^\text{mod-}h$ scenario:
  - $m_{H^\pm} < 1100$ GeV excluded for $\tan \beta > 60$
  - All $\tan \beta$ values excluded for $m_{H^\pm} < 160$ GeV

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ATLAS

$H^+ \rightarrow \tau\nu, tb$

hMSSM

$\sqrt{s} = 13$ TeV

36.1 fb$^{-1}$

95% CL$_s$ exclusions

- Observed, $\tau\nu$
- Expected, $\tau\nu$
- Observed, $tb$
- Expected, $tb$

ATLAS

$H^+ \rightarrow \tau\nu, tb$

$m^\text{mod-}h$

$\sqrt{s} = 13$ TeV

36.1 fb$^{-1}$

95% CL$_s$ exclusions

- Observed, $\tau\nu$
- Expected, $\tau\nu$
- Observed, $tb$
- Expected, $tb$
Beyond Standard Model Decays of the Higgs Boson

- Exotic Higgs boson decays are a powerful probe for BSM physics

- Very narrow Higgs decay width provides the sensitivity to small couplings to non-SM particles

- Current measurements at the LHC constrain non-SM BR of the Higgs boson to less than 34% at 95% CL

- Exotic decays of the Higgs boson are predicted by NMSSM

- Searches for decay of the Higgs boson to a pair of spin-zero particles \(a\) or spin-1 \(Z_d\) decaying into a pair of SM particles

Searches for BSM decays of the Higgs boson in ATLAS

\[
\begin{align*}
    h \rightarrow a a &\rightarrow b b \mu \mu & \text{arXiv:1807.00539} \\
    h \rightarrow a a &\rightarrow \gamma \gamma j j & \text{Phys. Lett. B 782 (2018) 750} \\
    h \rightarrow a a &\rightarrow b b b b & \text{arXiv:1806.07355} \\
    h \rightarrow a a / Z Z_d / Z_d Z_d &\rightarrow \ell \ell \ell \ell & \text{JHEP 06 (2018) 166}
\end{align*}
\]
BSM decays of the Higgs Boson

$h \rightarrow aa \rightarrow bb\mu\mu$

- Signature: 2 $\mu$, 2 jets, Higgs mass window, upper cut on $E_T^{\text{miss}}$

- $m_{\mu\mu}$ mass resolution is 10x better than $m_{bb}$

- Kinematic fit exploiting the symmetry of $h \rightarrow aa$ decays to test the compatibility of an event with the $m_{\mu\mu} \simeq m_{bb}$. Fit finds the energies of the $b$-jets that maximize the likelihood

- 2x improvement in $m_{\mu\mu bb}$ resolution

- Main backgrounds
  - Drell-Yan dimuon events
  - Top events
BSM decays of the Higgs Boson

\[ h \rightarrow aa \rightarrow bb\mu\mu \]

- No significant excess over SM predictions observed

- Limits set for:
  - \( \text{BR}(h \rightarrow aa \rightarrow bb\mu\mu) \) given the SM Higgs boson production cross section in the ggF, VBF and VH modes as a function of \( m_a \): \( 10^{-4} - 10^{-3} \) for \( m_a \) range 20 – 60 GeV
  - Visible cross section for new physics times branching ratio to the \( bb\mu\mu \) final state: \( 0.1 - 0.73 \) fb for \( m_{\mu\mu} \) between 18 and 62 GeV
BSM decays of the Higgs Boson

\[ h \rightarrow aa \rightarrow \gamma\gamma jj \]

- Final state relevant in models where the fermionic decays are suppressed. The \( a \) boson only decays to photons or gluons

- VBF production mode provides experimental handles to suppress backgrounds

- \( \geq 4 \) jets, \( p_T^{j_1}, m_{jj}^{VBF}, m_{\gamma\gamma jj}, |m_{jj} - m_{\gamma\gamma}| \)

- Main backgrounds:
  - \( \gamma\gamma \) + jets events estimated using data driven method
BSM decays of the Higgs Boson

$h \rightarrow aa \rightarrow \gamma\gamma jj$

- No significant excess over SM predictions observed
- Set limits as a function of $m_a$ for $\sigma(pp \rightarrow H) \times \text{BR}(H \rightarrow aa \rightarrow \gamma\gamma gg)$ normalized to the SM inclusive $\sigma(pp \rightarrow H)$: 3.1 – 9.0 pb
Conclusions & Summary

- ATLAS is highly active in searching for BSM phenomena in the Higgs sector. Effort to cover maximum topologies.

- The Run 2 data are being analyzed. A lot of new results released this Summer.

- Shown selection of recent beyond Standard Model Higgs results

- No sign of additional Higgs boson seen in the LHC data yet. Therefore, exclusion limits are set.

- Looking forward to analyze data being collected this year