Search for additional Higgs bosons in ATLAS

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on behalf of the ATLAS Collaboration
Searches for BSM Higgs at the LHC

Extended Higgs sectors are present in models for Naturalness, Higgs portal models of dark matter, axions, Baryon asymmetry, etc

Searches for deviations from the SM in measurements of Higgs Boson properties
- Spin
- CP
- Couplings

See talk by Changqiao Li

Direct searches for BSM phenomena
\[ \rightarrow \] evidence of new physics

Additional Higgs-like scalars
- neutral or charged
- decays to SM particles and to Higgs bosons

BSM Higgs decays and couplings
- new light resonances
- invisible decays

See other ATLAS talks for other results, including
- Roberto Di Nardo
- John Stupak

Disclaimer: This is not a full list of analyzed channels.
Focus mainly on recent results with 13 TeV dataset
Extended Higgs Sector Benchmark Models

Cover a broad range of phenomenology & final states - benchmarks guide searches

Two Higgs doublet models (2HDM) such as MSSM

- Scalar fields: $\Phi_1$, $\Phi_2$ with vevs $v_1$, $v_2$
- Pseudo-scalar: $\Phi_{ps}$
- Charged states: $H^\pm$, $G^\pm$

Rotation to mass states:
- $\alpha \rightarrow h, H$
- $\beta \rightarrow A, G^0$
- $\beta \rightarrow H^\pm, G^\pm$

Mass matrices

Parameters $\alpha, \beta, m_h, m_H, m_A, m_{H^\pm}$

Commonly use $\tan(\beta) = \frac{v_2}{v_1}$ and $\cos(\beta - \alpha)$

Triplet models - predict double charged Higgs bosons $H^{++/-/-}$

Handbook of LHC Cross Sections: 4. Deciphering the Nature of the Higgs Sector
Handbook of LHC Cross Sections: 3. Higgs Properties
Neutral Higgs Production $A/H$

Charged Higgs Production $H^{\pm}$

Handbook of LHC Cross Sections: 4. Deciphering the Nature of the Higgs Sector
Handbook of LHC Cross Sections: 3. Higgs Properties
New Pseudo-Scalar Decay $BR(A)$

Rich phenomenology with several final states

Example benchmark hMSSM

$\tan \beta = 1$

$\tan \beta = 10$

$\tan \beta = 50$

Handbook of LHC Cross Sections: 4. Deciphering the Nature of the Higgs Sector
Handbook of LHC Cross Sections: 3. Higgs Properties
$A/H \rightarrow \tau\tau$

Target with b-veto

Target with b-tag

Two final states covered

\[ \tau_{\text{had}} \tau_{\text{had}} \]

\[ \tau_{\text{lep}} \tau_{\text{had}} \]

ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

Data

- Multijet
- $A/H (4000, \tan\beta=6)$
- $A/H (15000, \tan\beta=12)$
- $Z/\gamma \rightarrow \tau\tau$
- $W \rightarrow \tau\nu$
- $b$-tag
- Others
- Uncertainty

Events / GeV

Obs. / exp.

$\tau_{\text{had}} \tau_{\text{had}}$

$\tau_{\text{lep}} \tau_{\text{had}}$

ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

Data

- Top quarks
- Jet $\rightarrow \tau$ fake
- $A/H (4000, \tan\beta=6)$
- $A/H (15000, \tan\beta=12)$
- $Z/\gamma \rightarrow \tau\tau$
- Multijet
- Others
- Uncertainty

Events / GeV

Obs. / exp.

$\tau_{\text{had}} \tau_{\text{had}}$

$\tau_{\text{lep}} \tau_{\text{had}}$

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PRL 125 (2020) 051801
Key channel in several new physics scenarios such as 2HDM (MSSM) with large tanβ

Higher sensitivity due to increased luminosity, improved tau ID and optimization
A/H→γγ

Search for high mass resonance – excellent resolution of diphoton pair

$\gamma\gamma$ as final discriminant

Limits provided in terms of fiducial cross-section

Signal: double-sided crystal ball
Background: power-law functional form - choice of function & systematics from MC templates

Narrow & large widths also considered (up to $\Gamma_X/m_X = 10\%$)

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A→Zh, Z→2e/2μ or 2ν, h →bb

Two channels:
- Zh → 2e/2μ bb (2l) - single lepton trigger & two identified leptons
- Zh →νν bb (0l) - E_T^miss trigger & E_T^miss > 150 GeV

Categorization: Resolved or merged bb system with 1 or 2 b-tags

Invariant mass m_{Vh} (2l)

Transverse mass m_{T,Vh} (0l)

Important in several scenarios such as low tanβ MSSM
A → ZH, Z → 2e/2µ, H → bb

Scenario with different $m_H$ and $m_A$, motivated by 2HDM
Scanning $m_A$ (widths up to 20%) for different $m_H$ windows with $Z → 2e/2µ$ H→bb
A→ZH, Z→2e/2μ, H → WW → 4q

Scenario with different m_H and m_A, motivated by 2HDM

Scanning m_A (widths up to 20%) for different m_H windows with Z → 2e/2μ in H→WW→4q final state

Interpretations in the context of 2HDM vs m_A, m_H and tanβ, in / near weak coupling limit
New Scalar Decay $BR(H)$

Rich phenomenology with several final states

Example benchmark hMSSM

- $\tan \beta = 1$
- $\tan \beta = 10$
- $\tan \beta = 50$

Handbook of LHC Cross Sections: 4. Deciphering the Nature of the Higgs Sector
Handbook of LHC Cross Sections: 3. Higgs Properties
\( H \rightarrow ZZ \rightarrow 4l \text{ and } 2l2v \)

ggF production of new heavy scalar decaying to ZZ

Considers narrow and large widths, VBF included for narrow width

Large width search includes interference effects with background

Invariant mass \( m_{4l} \) (4l)

Transverse mass \( m_T \) (2l2v)

\[
m_T = \sqrt{m_Z^2 + (p_T^l)^2 + m^2 + (E_T^{miss})^2} - |p_T^l + E_T^{miss}|^2
\]
H → WW and H → ZZ

Searches for new heavy scalar decaying to ZZ and WW - leptonic & hadronic decays

Higher mass range, above 2 TeV, covered by ZZ → llqq/vvqq and WW → lvqq channels
Search for high mass resonance – boosted hadronically decaying Z boson reconstructed as a large-radius jet in association with a photon

$m_{\gamma J}$ as final discriminant

Limits include ggF and qq production modes

Analysis also searches for a new heavy charged boson decaying to $W\gamma$
Search for new heavy scalar decaying to higgs boson pairs
Includes three channels $bb\gamma\gamma$, $bb\tau\tau$ and $bbbb$

Different channels contribute most sensitive to complementary mass ranges
$bb\gamma\gamma$ at the lowest masses, $bb\tau\tau$ in the intermediate range &
$bbbb$ at the highest masses
New Charged Higgs Decay $BR(H^{\pm})$

Rich phenomenology with several final states

Example benchmark hMSSM

$\tan \beta = 10$

$\tan \beta = 50$

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Key channel in several new physics scenarios such as 2HDM (MSSM) at high $H^+$ mass.

Events 1 e/µ (trigger), ≥ 5 jets (≥3 b-jets)
Categories based on number of jets & b-jets
Parameterized Neural Network as final discriminant

Higher sensitivity due to larger dataset and improved analysis.
Interesting channel in new physics scenarios such as 3HDM at low $H^+$ mass.

Events 1 e/μ (trigger), ≥ 4 jets (≥3 b-jets)

Categories based on number of jets & b-jets

Parameterized Neural Network as final discriminant

Largest excess at $m_{H^+} = 130$ GeV

local sig. ~3σ
$H^+ \rightarrow W^+ A, \ A \rightarrow 2\mu$

Scenario with different $m_{H^+}$ and $m_A$, low $H^+$ and $A$ masses in $t\bar{t}$ decays

Scanning $m_A$ with $A \rightarrow 2\mu$ for different $m_{H^+}$ windows in the $e\mu\mu$ final state

Interpretations in the context of 2HDM vs $m_A$, $m_{H^+}$
Double Charged Higgs

$H^+ H^- \rightarrow 4l$ candidate event

$m_{e^+_1} = 228 \text{ GeV}$

$m_{e^-_2} = 207 \text{ GeV}$

Run: 304128
Event: 2657756788
2016-07-20 5:44:41 CEST
Pair Production of $H^{++} \rightarrow W^+ W^+$

Pair production of double charged Higgs bosons

Multivariate analysis in three channels:
2 same-sign charge, 3 or 4 leptons

Prompt lepton backgrounds from MC, non-prompt leptons from data

Sensitive to triplet vev $v_t \sim 100$ MeV
Associated production of single charged & double charged Higgs bosons

Multivariate analysis in three channels: 2 same-sign charge, 3 or 4 leptons

Prompt lepton backgrounds from MC, non-prompt leptons from data

Sensitive to triplet vev $v_t \sim 100$ MeV

Targets range $|m_{H^{\pm\pm}} - m_{H^\pm}| < 5$ GeV

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Summary of Heavy Higgs Boson Results

Direct searches for heavy Higgs bosons and fits to observed Higgs boson production & decay rates constrain scenarios with extended Higgs sectors

Note: not all updated results included in summary plot
Combined Higgs Measurements

Reinterpretation of combination of Higgs measurements in several MSSM benchmark scenarios

$M_h^{125}$ Scenario

$M_h^{125}$ (alignment) Scenario

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated lumi (fb$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$ (all production modes)</td>
<td>139</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$ (all production modes)</td>
<td>139</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (VH)</td>
<td>139</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$ (ggH, VBF)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (ggH, VBF)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (VBF)</td>
<td>24.5 - 30.6</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (#tH)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \rightarrow multilepton$ (#tH)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ (all production modes)</td>
<td>139</td>
</tr>
</tbody>
</table>
Exotic Higgs Boson Decays
Exotic Higgs Decays

Higgs boson branching ratios in the SM

Available measurements are only able constrain BSM decays to \( \lesssim 20\% \)

\[
\begin{align*}
\text{bb} & : 58\% \\
\text{WW}^* & : 21\% \\
\text{ZZ}^* & : 3\% \\
\text{W} & : 0.2\% \\
\text{gg} & : 8\% \\
\text{cc} & : 3\% \\
\text{other} & : 12\%
\end{align*}
\]

Higgs decays in the SM are suppressed by small Yukawa couplings, loops, or multi-body phase space even a small coupling to another light state can open up additional sizable decay modes

Simple example: one new scalar

\[ \zeta = \frac{m_a^2}{v^2} \]
Phenomenological Models

New scalars have very rich phenomenology with many final states, mass regimes and lifetime ranges.

Exotic higgs decays in SM+scalar model. Yukawa coupling favors heavy particles in final state.

Models with new U(1)\textsubscript{D} gauge symmetry predict new vector field that can mix with the hypercharge boson. Sizeable decays to electrons and muons.

See recent review here
Exotic decays of the higgs boson to a pair of new scalars or pseudo-scalars

Target events with a pair of muons and b-jets

Search for excess in dimuon spectrum

Significant gains in sensitivity by using a BDT multivariate discriminator

Largest excess at $m_a = 52$ GeV local sig. $\sim 3.3\sigma$
Search for cascade decay $h \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow (a \rightarrow bb) \tilde{\chi}_1^0 \tilde{\chi}_1^0$ where $\tilde{\chi}_1^0$ is an invisible particle

Search for excess in dijet spectrum

Challenging semi-visible signatures

Interesting for models of dark matter
Search for decays in final states with $4e, 2e2\mu, 4\mu$

Analysis targets different mass ranges

No events observed
Search for decays in final states with $4e, 2e2\mu, 4\mu$

Analysis targets different mass ranges
\( h \rightarrow ZZ_d/Za \rightarrow 4\ell \)

Search for decays in final states with \( 4e, 2e2\mu, 4\mu \)

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**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**ZX Signal Region**

- VVV, t\( t \bar{t} + Z \)
- Reducible (Z+Jets, WZ, t\( t \bar{t} \))
- \( ZZ \rightarrow 4\ell \)
- \( H \rightarrow ZZ \rightarrow 4\ell \)
- \( ZZ_d, m_{Z_d} = 20 \text{ GeV} \)
- \( ZZ_d, m_{Z_d} = 35 \text{ GeV} \)
- \( ZZ_d, m_{Z_d} = 55 \text{ GeV} \)
- Uncertainty
- Data

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\( h \rightarrow ZZ_d \)

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\( h \rightarrow Za \)

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Submitted to JHEP
Summary of Exotic Higgs Decay Results

Interpret searches for exotic Higgs decays as limits on $h \rightarrow aa$ branching ratio in the context of specific 2HDM+S benchmark scenarios

**Note:** not all updated results included in summary plot
### Summary and Conclusions

- Extensive program of searches for BSM Higgs at the LHC
  - Recent results shown here including several with full Run 2 dataset
- Searches extend the sensitivity to new regimes
  - Uncovered kinematics, both highest and lowest masses, new channels
  - Benefit from large dataset, improved reconstruction and analysis techniques that are increasingly sophisticated

#### Neutral Higgs
- $H/A \rightarrow \tau\tau$
- $H/A \rightarrow bb$
- $H/A \rightarrow tt$
- $H/A \rightarrow \gamma\gamma$
- $A \rightarrow Zh$
- $A \rightarrow ZH$
- $H \rightarrow WW$
- $H \rightarrow ZZ$
- $H \rightarrow hh$
- $H \rightarrow ZA$

#### Charged Higgs
- $H^+ \rightarrow \tau\nu$
- $H^+ \rightarrow tb$
- $H^+ \rightarrow cs$
- $H^+ \rightarrow bc$
- $H^+ \rightarrow WZ$

#### Double Charged Higgs
- $H^{++} \rightarrow W^+W^+$
- $H^{++} \rightarrow \ell^+\ell^+$

#### Exotic Higgs Decays
- $h \rightarrow aa/ss$
- $h \rightarrow Z_dZ_d$
- $h \rightarrow Za$
- $h \rightarrow ZZ_d$
- $h \rightarrow a/s + E_T^{miss}$
- $h \rightarrow E_T^{miss}$

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Stay tuned for many more results!