Searching for beyond-the-Standard Model Higgs bosons at ATLAS and CMS

11 December 2017

James Beacham [Ohio State/ATLAS]

SUSY17
Open questions before 4 July 2012

Electroweak symmetry breaking
- Does the Higgs boson exist?

Dark matter
- What is it? WIMP, sterile neutrino, axion, NLSP, other hidden sector particle?
- Only one type?
- Only gravitational or other interactions?
- Are we wrong about gravity? An emergent phenomenon?

Quarks and leptons
- Why three families?
- Why these masses and mixings?
- CP violation in the lepton sector
- Matter/anti-matter asymmetry
- Baryon and charged lepton number violation

Physics toward the Planck scale
- How does gravity play with the other forces?
- Are there more than three dimensions of space?
- Do all forces unify at high energy?
- Are there other forces?

Neutrinos
- Why do neutrinos have masses? And what are these masses?
- Majorana or Dirac?
- CP violation
- Are there more (sterile) neutrinos?

Two epochs of Universe’s accelerated expansion
- Primordial: Is inflationary model correct? Which (scalar) field? Role of quantum gravity?
- Today: Dark energy (why is $\Lambda$ so small?) or gravity modification?

Inspired by I. Shipsey
Open questions after 4 July 2012

Electroweak symmetry breaking
- Does the Higgs boson exist?
- Is $m_h$ natural or fine-tuned?
- If natural, what new physics/symmetry governs this?
- Does it regularize divergent $V_LV_L$ cross-section at high $m_{V_LV_L}$? Or new dynamics?
- Elementary or composite Higgs?
- Is it alone or does the Higgs have siblings and cousins?
- Origin of couplings to fermions?
- Coupling to dark matter?
- Connection to hidden sectors?
- Does it violate CP?
- Cosmological EW phase transition?

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Neutrinos
- Why do neutrinos have masses? And what are these masses?
- What’s the role of $h_{125}$?
- Majorana or Dirac?
- CP violation
- Are there more (sterile) neutrinos?

Two epochs of Universe’s accelerated expansion
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Inspired by I. Shipsey
Rediscovering the Higgs at 13 TeV

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV}, 13.3 \text{ fb}^{-1} \]

**CMS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV}, 12.9 \text{ fb}^{-1} (13 \text{ TeV}) \]

Data
- H(125)
- \( q\bar{q} \rightarrow ZZ, Z\gamma^* \)
- \( gg \rightarrow ZZ, Z\gamma^* \)
- \( Z + X \)

**Event Categories**
- Data
- Background
- Signal + Background
- Signal

S/B weighted sum of event categories

**Weights - bkg**

**Weights / GeV**

**Events / 4 GeV**

**Weights / GeV**

**Events / 4 GeV**
Is the Higgs alone?

Probability > 1 as center-of-mass energy grows.

\[ W_L \gamma/Z W_L \quad W_L \text{ as center-of-mass energy grows} \]
Is the Higgs alone?

- Probability > 1 as center-of-mass energy grows

The existence of a Standard Model Higgs yields meaningful predictions for vector boson scattering...
Is the Higgs alone?

...but are there other Higgs-like particles that help control these nonsense probabilities?
Exotic Higgs bosons

Two Higgs doublet models, Higgs triplet models, MSSM...

Our new Higgs with a mass of 125 GeV: h or H?

11 December 2017  
James Beacham [Ohio State]  
SUSY17 — TIFR — Mumbai

Exotic Higgs bosons

H^+  H^-
H^{++}  H^{--}
h  A  a

Our new Higgs with a mass of 125 GeV: h or H?
Extended scalar sectors appear in many extensions of the SM (SUSY, axion models, electroweak baryogenesis models, grand unification, etc.), but even the “repetition argument” is compelling enough to hypothesize siblings and cousins of $h_{125}$:
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Three repeated pairs of leptons and of quarks, without any a priori reason; why not in the scalar sector, as well?
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Nicely motivates a wealth of searches that can be done by adapting $h_{125}$ strategies to higher- and lower-mass scalars, in different production and decay modes.
Extended scalar sectors appear in many extensions of the SM (SUSY, axion models, electroweak baryogenesis models, grand unification, etc.), but even the “repetition argument” is compelling enough to hypothesize siblings and cousins of h125:

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Nicely motivates a wealth of searches that can be done by adapting h125 strategies to higher- and lower-mass scalars, in different production and decay modes.

A curated selection of ATLAS/CMS results presented here; we have a multitude of dedicated parallel talks at this conference for more details!

Exhaustive results are available at

**CMS**

**ATLAS**
Neutral scalars $h/A/H$

$\phi = h/A/H \rightarrow \tau^+\tau^-$

Categorize events based on hadronic / leptonic tau decays & lepton flavor

Search for excesses in total transverse mass spectrum

Background estimate from a combination of data-driven and simulation based methods

ATLAS: arXiv:1709.07242
CMS-PAS-HIG-16-037
Neutral scalars $h/A/H$

Associated production with $b$-jets

Low-mass di-muon search at 8 TeV

Mass range inspired by 2HDM for a pseudoscalar with $12 \text{ GeV} < m_A < m_{h_{125}}/2$

CMS: JHEP 11 (2017) 010

James Beacham [Ohio State]
Neutral scalars $h/A/H$

$h/A/H \rightarrow t\bar{t}$

2HDM:
$tan\beta = \text{ratio of vevs of the two scalar doublets}$

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$, all limits at 95% CL

**ATLAS: PRL 119 (2017) 191803**

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Small branching ratio of $h_{125} \rightarrow Z\gamma$ in SM, but can be enhanced in some scenarios with higher-mass scalars.
$H \rightarrow \gamma\gamma$

**High mass**


**Low mass**

ATLAS (8 TeV): [PRL 113 171801](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.171801)

CMS (8 & 13 TeV): [CMS-PAS-HIG-17-013](https://cds.cern.ch/record/2188023)

$m_{\gamma\gamma} = 750$ GeV
Charged Higgses with hadronic tau final states

$H^{+/−} → τν$

ATLAS-CONF-2016-088

CMS-PAS-HIG-16-031

$\sqrt{s} = 13$ TeV, 14.7 fb$^{-1}$

Data / SM

Uncertainty

Events / bin
Doubly-charged Higgses can arise in, e.g., Higgs triplet models.

**ATLAS search for $H^{++/-}$ focusing on same-sign lepton pairs in 4-lepton events**

**CMS search for $H^{++/-}$ focusing on same-sign lepton pairs in 3-lepton events**

Doubly-charged Higgses can arise in, e.g., Higgs triplet models.

**CMS-PAS-HIG-16-036**

**arXiv:1710.09748**
**Vh resonances**

\[ Z' / A \rightarrow Zh \rightarrow (ll/vv)bb \]

\[ W' \rightarrow Wh \rightarrow lvbb \]

ATLAS search with 2015+2016 dataset at 13 TeV focusing on h125 \( \rightarrow bb \)

ATLAS-CONF-2017-055

CMS search at 8 TeV with h125 \( \rightarrow \tau\tau \)

PLB 755 (2016) 217

A \( \rightarrow Zh \rightarrow ll/\tau\tau \)
**Di-Higgs resonances**

\[ X \rightarrow hh \rightarrow 4SM \]

Di-Higgs production is extremely rare in the SM, but new particles can yield di-Higgs resonances

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**ATLAS**  \( \sqrt{s} = 8 \) TeV, 20.3 fb\(^{-1} \)

- **Observed**
- **Expected**
- **\( \pm 1 \sigma \) expected**
- **\( \pm 2 \sigma \) expected**

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**CMS 4b channel with 2015+2016 13 TeV dataset**

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**PRD 92, 092004 (2015)**

ATLAS combination of four channels at 8 TeV

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**CMS-PAS-HIG-17-009**

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Comparing searches — e.g., in the hMSSM

hMSSM

• MSSM framework constrained by h125 measurements

ATLAS Preliminary
hMSSM, 95% CL limits

- - - Expected

ATLAS Higgs summary plots

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How standard is $h_{125}$?
Plenty of room for new physics

How can we find evidence of this possible new physics?

JHEP08 (2016) 045
How standard is h125?
Plenty of room for new physics

How can we find evidence of this possible new physics?

One way: Wait for the HL-LHC to measure the couplings to ~5/10% and then wait for an e+e- Higgs factory to measure them to <1% by the 2040s or beyond.

JHEP08 (2016) 045
How standard is $h_{125}$?

Another way: Make some basic BSM assumptions and look directly for a new particle that can take up a non-negligible fraction of the total Higgs width

$\begin{align*}
\text{ATLAS and CMS} \\
\text{LHC Run 1}
\end{align*}$

$-2 \ln \Lambda$ vs. $B_{BSM}$

$\begin{align*}
\text{Observed} \\
\text{SM expected}
\end{align*}$

$\text{JHEP08 (2016) 045}$
Non-standard decays of h125

Basic BSM assumptions: Extensions to the SM gauge group that include new light (pseudo)scalars or vectors ($Z_{\text{dark}},$ dark photons) that couple (in some way) to both the Higgs and SM particles

Yields a rich set of resonant decay topologies that can be actively searched for!

Example:
2HDM+S with Type 1 Yukawa couplings

Another example: Models with dark Higgses that mix with h125 and decay to $Z_{\text{dark}}$/dark photons

Exotic Decays of the 125 GeV Higgs Boson
arXiv:1312.4992
ATLAS search for very challenging signature

Even with only 3.2 fb at 13 TeV start to approach SM WH x-sec

CMS search at 8 TeV

JHEP 10 (2017) 076
\[ h_{125} \rightarrow aa \rightarrow \mu^+\mu^-\tau^+\tau^- \]

**ATLAS**

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

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

**CMS**

\[ 19.7 \text{ fb}^{-1} (8 \text{ TeV}) \]

Events / (6.5 GeV)

- Signal model
- Bkg. model
- ZZ component
- Red. component
- Bkg. uncertainty
- Observed

**JHEP 10 (2017) 076**

- ATLAS
  - $\sigma = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$
- BR\((h \rightarrow 2\gamma_d + X)\)

**PRD 92 (2015) 052002**

\[ h_{125} \rightarrow xx \rightarrow 4\ell \]

**ATLAS-CONF-2017-042**

- ATLAS Preliminary
- $13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
- $H \rightarrow XX \rightarrow 4\ell$

- Expected
- Observed

**CMS-PAS-HIG-16-035**

- $pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_d + 2n_0 \rightarrow 4\mu + X$
- $BR(h \rightarrow 2\gamma_d + X)$

- Kinetic mixing parameter $\epsilon$

- CMS Preliminary
  - $2.8 \text{ fb}^{-1} (13 \text{ TeV})$

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General search for new phenomena in inclusive three-photon events at 8 TeV with ATLAS

H/h125 → 4γ one of the main benchmarks

Also sensitive to resonant three-photon final state with an intermediate BSM pseudoscalar
Comparing searches for non-standard decays of $h_{125}$

Improvements and expansions in the pipeline:

- Challenging low-$m_a$ regime for many final states
- Other channel combinations
- Expansion to higher-mass parent scalars
What are we overlooking?
h125 -> long-lived particles

We have a wide range of particle lifetimes in the SM; this means we should include LLPs in any BSM search — non-negligible lifetimes can generically appear!

- Lifetime is best treated as a free parameter
- Rich and challenging set of decay topologies often requiring significantly customized analysis methods

\[ h \rightarrow LLP \rightarrow jets \]

\[ h \rightarrow LLP \rightarrow leptons \]

**ATLAS**

<table>
<thead>
<tr>
<th>95% CL Upper Limit on ( \sigma / \sigma_{SM} ) ( \times 10^{2} )</th>
<th>( \pi_{\tau} ) proper lifetime (( \tau )) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-2}</td>
<td>10^{-1}</td>
</tr>
</tbody>
</table>

\[ \text{Observed limits} \]

- \( m_{\chi} = 20 \text{ GeV/c}^{2} \)
- \( m_{\chi} = 50 \text{ GeV/c}^{2} \)
- Expected limits (\( \pm 1\sigma \))
- \( m_{\chi} = 20 \text{ GeV/c}^{2} \)

**CMS**

\[ \text{Search for displaced vertex in CMS tracker} \]

- 19.6 fb^{-1} (8 TeV)

**References**

- PRD 92 012010 (2015)
- PLB 743 (2015) 15-34
**h125 —> displaced lepton-jets**

Dark / hidden sector coupled to SM Higgs and leptons via very light dark fermions radiating low-mass dark photons

Very weak interaction —> displaced decay

Very light, highly boosted dark photon —> highly collimated groupings of leptons, or lepton-jets

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**Higher-mass H —> Lepton-jets**

ATLAS Preliminary
3.4 fb⁻¹ √s = 13 TeV
FRVZ 2γ model
mₜ = 800 GeV mₙ = 400 MeV

95% CL limit on αx BR(H → 2γd + X) [pb]

- Observed limit
- Expected ± 2σ
- Expected ± 1σ

13 TeV: ATLAS-CONF-2016-042

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**JHEP 11 (2014) 088**

**JHEP 1602 (2016) 062**

**BR(h → 2γd + X)**

ATLAS
20.3 fb⁻¹ √s = 8 TeV

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James Beacham [Ohio State]  SUSY17 — TIFR — Mumbai  11 December 2017  26
Higher-mass scalars $\rightarrow$ long-lived particles

$H \rightarrow LLPs \rightarrow$ jets

CMS search at 8 TeV for displaced jet pairs

ATLAS search at 13 TeV for displaced jets in the hadronic calorimeter

$\sigma(H \rightarrow XX) \times B^2(X \rightarrow q\bar{q})$ [pb]

95% CL limits:
- $m_H = 1000$ GeV

$m_\chi = 150$ GeV
$m_\chi = 350$ GeV
Exp. limits ($\pm 1\sigma$)

$X ct$ [cm]

ATLAS-CONF-2016-103

PRD 91 (2015) 012007
Higher-mass scalars $\rightarrow$ long-lived particles

$H \rightarrow LLPs \rightarrow jets$

CMS search at 8 TeV for displaced jet pairs

ATLAS search at 13 TeV for displaced jets in the hadronic calorimeter

Mapping the lifetime frontier ongoing right now in the LHC LLP Community initiative; white paper, workshops — join us!
Summary

Neutral scalars h/H/A decaying resonantly to leptons and tops

\[ A/H \rightarrow Z\gamma \]

\[ H \rightarrow \gamma\gamma \]

Charged Higgses with hadronic tau final states

Charged Higgses to leptons

Vh resonances

Di-Higgs (h125) resonances

Comparing searches — e.g., in the hMSSM

Non-standard decays of h125 to new, light resonances

The lifetime frontier for h125 and beyond-the-SM scalars
Is $h_{125}$ alone?

Conclusions
Is $h_{125}$ alone?

Is $h_{125}$ the SM Higgs?

Conclusions
Robust program of BSM Higgs searches at ATLAS and CMS to answer these questions.

8 TeV results being updated and expanded now with our first look at 13 TeV.

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Impressive agreement with SM expectations thus far, but we’re just getting started

If h_{125} has cousins kinematically accessible at the LHC, we’ll find them

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See the parallel talks for more details!
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Reserve slides
Lepton flavor-violating h decays

\[ h_{125} \rightarrow e\tau / \mu\tau \]

LFV decays of h125 can appear generically in 2HDMs, RPV SUSY, etc., and would be an instant sign of BSM physics

CMS search with 2015+2016 dataset at 13 TeV → Limits on BR(h125 LFV) < 1%

EPJC 77 (2017) 70

ATLAS search at 8 TeV, example of reconstructing \( m_h \) as invariant mass of electron, hadronic tau, and \( E_T^{\text{miss}} \)

EPJC 77 (2017) 70

ATLAS search at 8 TeV, example of reconstructing \( m_h \) as invariant mass of electron, hadronic tau, and \( E_T^{\text{miss}} \)