Higgs SM and BSM at ATLAS

Elliot Lipeles

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Introduction

**Standard Model Channels @ 125 GeV**
- Rates ~ coupling strengths
- Higgs Properties (mass, spin)
- Differential distributions

**BSM decays @ 125 GeV**

**Searching for more Higgs Bosons**

**Pair Production**

**Outlook**

Still dominated by Run 1 results...

Run 1 produced more 125 GeV Higgs Bosons than Run 2 so far...

Still some new results in more modes and combinations

2015 Run 2 13 TeV results competitive with Run 1
Rates → Coupling Strengths @ 125 GeV

**ATLAS**

Individual analysis

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Production Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → γγ</td>
<td>gF: μ = 1.39 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>VBF: μ = 0.85 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>WH: μ = 1.0 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>ZH: μ = 0.6 ± 0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125.4</td>
</tr>
</tbody>
</table>

| H → ZZ*   | gF: μ = 1.44 ± 0.40 |
|          | gF+tH: μ = 1.7 ± 0.4 |
|          | VBF+VH: μ = 0.3 ± 0.6 |

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
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<tbody>
<tr>
<td>125.56</td>
</tr>
</tbody>
</table>

| H → WW*   | gF: μ = 0.98 ± 0.29 |
|          | VBF: μ = 1.23 ± 0.47 |
|          | VH: μ = 3 ± 1.6 |

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<tr>
<td>125.56</td>
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| H → ττ    | gF: μ = 2 ± 1.5 |
|          | VBF+VH: μ = 1.24 ± 0.39 |

<table>
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<tbody>
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<td>125.56</td>
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</table>

| VH → Vbb  | gF: μ = 0.53 ± 0.46 |
|           | WH: μ = 1.1 ± 0.61 |
|           | ZH: μ = 0.04 ± 0.47 |

<table>
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<tbody>
<tr>
<td>125.36</td>
</tr>
</tbody>
</table>

| H → μμ    | gF: μ = 0.73 ± 0.7 |

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
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</thead>
<tbody>
<tr>
<td>125.5</td>
</tr>
</tbody>
</table>

| H → Zγ    | gF: μ = 2.7 ± 4.5 |

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125.5</td>
</tr>
</tbody>
</table>

| tH        | gF: μ = 1.6 ± 1 |
|           | Multiplon: μ = 2.1 ± 1.2 |
|           | tH: μ = 1.3 ± 1.3 |

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
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<tr>
<td>125.4</td>
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</tbody>
</table>

**Input measurements ± 1σ on μ**

**Combined Fit(s)**

**Coupling Strengths**
**Test the Mass Generation Hypothesis**
**BSM constraints**

I’ll show a set of ATLAS plots...

There is now an ATLAS + CMS combination, see talk by Eric Feng

---

See talks by Carlo Enrico Pandini, Peter Kluit, and Ricardo Goncalo

Coupling Interpretation

**Simple model:** assign a multiplicative factor to each kind of vertex

- $\kappa_i=1$ is SM, $\kappa_i \neq 1$ is BSM
- Caveat: doesn’t account for shape changes with BSM physics

Both combined in a single $K_\gamma$
Simple model:

\[ \kappa_i = 1 \] is SM,
\[ \kappa_i \neq 1 \] is BSM

Caveat: doesn't account for shape changes with BSM physics

\[ \kappa_W = 0.91 \pm 0.14 \]
\[ \kappa_Z \in [-1.06, -0.82] \cup [0.84, 1.12] \]
\[ \kappa_t = 0.94 \pm 0.21 \]
\[ \kappa_b \in [-0.90, -0.33] \cup [0.28, 0.96] \]
\[ \kappa_f \in [-1.22, -0.80] \cup [0.80, 1.22] \]

(95% CL) \[ |\kappa_{\mu}| < 2.28 \]

\[ m_H = 125.36 \text{ GeV} \]

Testing the mass generation hypothesis

**ATLAS**

- $s = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1}$
- $s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

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Elliot Lipeles

_Top 68% error bar_

A General BSM fit

Tree Level

New Physics in Loops

“Invisible” decays

Non-SM width

A BSM fit

Various 2 Higgs Doublet Models

<table>
<thead>
<tr>
<th>Coupling scale factor</th>
<th>Type I</th>
<th>Type II</th>
<th>Lepton-specific</th>
<th>Flipped</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{V}$</td>
<td>$\sin(\beta - \alpha)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_{U}$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_{d}$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
</tr>
<tr>
<td>$\kappa_{l}$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
</tr>
</tbody>
</table>

SUSY-like

Set limits on BSM specific models

ATLAS

JHEP11(2015)206
New constraints on $H \rightarrow bb$ (Run 1 data)

$WH$ or $ZH$ with $H \rightarrow bb$ is the main constraint on the $H \rightarrow bb$ decay rate

$\mu = 0.52 \pm 0.4$ (observed)

Now other options are being explored:

VBF with $H \rightarrow bb$

$\mu = -0.8 \pm 2.3$ (observed)

$ttH$ decaying hadronically with $H \rightarrow bb$

$\mu = 1.7 \pm 0.8$ (observed)

arXiv:1606.02181

JHEP 05 (2016) 160
Rates Measurements at 13 TeV

Sensitivity has not yet reached 7+8 TeV sensitivity

Yields consistent with expectations

\[ \sigma_{pp \rightarrow H} \text{ [pb]} \]

**ATLAS** Preliminary

- $H \rightarrow \gamma \gamma$
- $H \rightarrow ZZ^* \rightarrow 4l$

- comb. data
- syst. unc.

- $\sqrt{s} = 7 \text{ TeV}, \ 4.5 \ \text{fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}, \ 20.3 \ \text{fb}^{-1}$
- $\sqrt{s} = 13 \text{ TeV}, \ 3.2 \ \text{fb}^{-1}$

\[ m_H = 125.09 \ \text{GeV} \]

- $\sigma_{pp \rightarrow H}$

- QCD scale uncertainty

- Tot. uncert. (scale $\oplus$ PDF+$\alpha_s$)

**ATLAS-CONF-2015-060**
Spin, Parity, and Mass @ 125 GeV

Spin and Parity constraints using angular distributions in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and $H \rightarrow WW$

- Effective field theory modifications of tensor structure in diboson production
- Test of CP structure in VBF $H \rightarrow \tau\tau$
  - arXiv:1602.04516
- Mass measurement (combines $ZZ$ and $\gamma\gamma$)
  - $m_H = 125.36 \pm 0.37\text{(stat)} \pm 0.18\text{(syst)}$ GeV

Distributions of test statistic expectations for SM and non-SM
Differential Distributions @ 125 GeV

- Different distributions are sensitive to different modeling aspects...
  - Perturbative QCD: $N_{\text{jets}}$, Higgs $p_T$, leading-jet $p_T$,
  - Soft Gluon Resummations: Higgs $p_T$
  - PDFs: Higgs rapidity
  - ... or sensitive to new physics
- Tests agreement of shapes with theoretical predictions
- First Example: $ZZ$ and $\gamma\gamma$ combined

**Quantify Agreement = p-values**

|          | $p_T^H$ | $|y^H|$ | $p_T^{\text{jet}}$ |
|----------|---------|---------|-------------------|
| HRES     | 15%     | 64%     | -                 |
| NNLOPS   | 10%     | 64%     | 64%               |
| SHERPA 2.1.1 | 22%   | 63%     | 88%               |
| MG5_aMC@NLO | 8%     | 60%     | 88%               |

Differential Distributions @ 125 GeV

Recently extend to used $H\rightarrow WW$ also

Complicated because of need for a jet veto to suppress large top background

Dedicated measurement of jet-veto efficiency

**ATLAS** $gg\rightarrow H$

- data, tot. unc.
- sys. unc.

- $\sigma_{\text{LHC-XS}} \times A\text{NNLOPS-PY8}$
- $\sigma_{\text{LHC-XS}} \times A\text{MG5_aMC@NLO+PY8}$
- $\sigma_{\text{LHC-XS}} \times A\text{SHERPA 2.1.1}$

$p_T^H$ [GeV]

$\int s = 8 \text{ TeV}$, $20.3 \text{ fb}^{-1}$

$H\rightarrow WW^*\rightarrow e\nu\mu\nu$

**ATLAS** $gg\rightarrow H$

- data, tot. unc.
- sys. unc.

- ST
- JetVeto
- NNLOPS+PY8
- STWIZ
- $N^S_{\text{LO+NNLL+LLR}}$

$\epsilon_0$

Ratio to JetVeto

$\rho_{\text{jet}}$ threshold [GeV]

arXiv:1604.02997
Differential distributions can also be used to limit BSM contributions

For example, limits on an extended Effective Lagrangian using $H \rightarrow \gamma \gamma$

$$\mathcal{L}_{\text{eff}} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB}$$

Changes in differential distributions

Limits on Wilson coefficients

*Physics Letters B 753 (2016) 69-85*
BSM decays @ 125 GeV

Higgs is a narrow resonance

- all decay modes are suppressed by
  - small Yukawa couplings (bb, ττ, cc)
  - off-shell vector bosons (WW*, ZZ*)
  - loop couplings (γγ, gg)

This makes Higgs decay especially sensitive to potential BSM decay modes

- Also easy to couple Higgs to new physics for model building (Higgs “portal”)

Example ATLAS searches:

- Lepton Flavor Violating decays (hep-ex/1604.07730)
- Additional light weakly coupled scalars (a) or vectors (Z_d)
  - H to aa to 4 gamma (hep-ex/1509.05051)
  - H to aa to 4b (hep-ex/1606.08391)
- Decay to SUSY particles (ATLAS-CONF-2015-001)
- Direct coupling to dark matter (aka Higgs to Invisible)

See talk by Philip Chang:
Search for non-standard and rare decays of the Higgs boson
BSM decays @ 125 GeV

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• Additional light weakly coupled scalars (a) or vectors (Z_d)
  • H to aa to 4 gamma (hep-ex/1509.05051)
  • H to aa to μμττ (Phys. Rev. D92 (2015) 052002)
  • H to aa to 4b (hep-ex/1606.08391)
  • H to Z_dZ_d to 4 e/μ leptons (Phys. Rev. D 92 (2015) 092001)
• Decay to SUSY particles (ATLAS-CONF-2015-001)
• Direct coupling to dark matter (aka Higgs to Invisible)

See talk by Philip Chang:
Search for non-standard and rare decays of the Higgs boson
Lepton Flavor Violating Decays

Various models exist in which lepton flavor violation could happen:
- Multiple Higgs doublets, composite Higgs, and many more...
- $H \rightarrow e\mu$ tightly constrained from $\mu \rightarrow e\gamma$, but $H \rightarrow \mu\tau$ allowed

CMS has a small excess in $H \rightarrow \mu\tau$:
- $2.4\sigma$ significance
- $\text{BR}(H \rightarrow \mu\tau) = 0.84^{+0.39}_{-0.37}\%$
- CMS Limit $\text{BR}(H \rightarrow \mu\tau) < 1.51\%$

ATLAS search combines:
- leptonic $\tau$ decay (focus on $e\mu$)
- hadronic $\tau$ decay ("$\tau_{\text{had}}$")

ATLAS Limit $\text{BR}(H \rightarrow \mu\tau) < 1.43\%$

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### Higgs to Invisible: Direct Searches

**Table:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching Fraction Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td><strong>ZH with Z→ll</strong></td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WH or ZH with W/Z→jj</strong></td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vector Boson Fusion</strong></td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Assume SM production rate**

**Example signal diagram (for VBF)**

```
Example signal diagram (for VBF)
```

- Modeling Z→νν is the key challenge
- VBF analysis uses W→lν as constraint

**Graph:**

- **ATLAS**
  - 20.3 fb⁻¹, 8 TeV
  - SR1
- **Data/ MC**
  - Events/0.5 TeV
  - m_{H}[TeV]

**References:**

- JHEP 01 (2016) 172
Higgs to Invisible: Indirect Constraints

Higgs to invisible can also be limited by indirect constraints from the coupling fit.

Limits are then model dependent, results below are least model dependent option.

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</tr>
<tr>
<td>Vector Boson Fusion</td>
<td>0.31</td>
</tr>
<tr>
<td>Combination of Direct Limits</td>
<td>0.27</td>
</tr>
<tr>
<td>Indirect limit from fit to visible rates</td>
<td>0.48</td>
</tr>
<tr>
<td>Combination of Direct and Indirect Limits</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Assume SM production rate

JHEP11(2015)206
Higgs Portal Interpretation

Production: Collider Searches

SM → H → DM

Annihilation: Indirect Detection, Early Universe

SM → H → DM

Limits depend on the particle assumption (scalar, Majorana fermion, vector)

Comparable sensitivity to direct dark matter searches (if $m_\chi < m_H/2$) without the loss of sensitivity at low WIMP mass

JHEP11(2015)206

Assuming DM couples to SM via Higgs only and other caveats.... (in back-up)
More Higgses

Numerous models introduce additional Higgses (MSSM and beyond)
- Heavy Higgs (H),
- Charged Higgs (H±),
- Pseudo-scalar Higgs (A)

Wide variety of ATLAS searches

- Heavy Higgs (H)
  - Heavy dibosons (WW, ZZ): llqq, ννqq, lνqq, qqqq,
  - ZZ → 4l, ZZ → ννll, WW → lνlν
  - Diphoton
  - Dihiggs: 4b, bbγγ, bbττ, γγWW
  - A/H → ττ
- Charged Higgs (H±)
  - tH± with H± → τν and hadronic top decay
  - H± → tb, H± → WZ, H± → cs, H± → τν in top decay
- Pseudo-scalar Higgs (A)
  - A → Zγ → llγ, A → ZH → llbb or ννbb, A → ττ

Also see talks by Dmitri Tsybychev and Blake Burghgrave
More Higgses

Numerous models introduce additional Higgses (MSSM and beyond)

- Heavy Higgs (H),
- Charged Higgs ($H^\pm$),
- Pseudo-scalar Higgs (A)

Wide variety of ATLAS searches

- Heavy Higgs (H)
  - Heavy dibosons ($WW, ZZ$) : $llqq, \nu\nuqq, lvqq, qqqq$,
    - $ZZ \rightarrow 4l, ZZ \rightarrow \nu\nu llll, WW \rightarrow l\nu l\nu$
  - Diphoton
  - Dihiggs: $4b, bb\gamma\gamma, bb\tau\tau, \gamma\gamma WW$
  - $A/H \rightarrow \tau\tau$
- Charged Higgs ($H^\pm$)
  - $tH^+ \text{ with } H^+ \rightarrow \tau\nu \text{ and hadronic top decay}$
  - $H^+ \rightarrow tb, H^+ \rightarrow WZ, H^+ \rightarrow cs, H^+ \rightarrow \tau\nu \text{ in top decay}$
- Pseudo-scalar Higgs (A)
  - $A \rightarrow Z\gamma \rightarrow ll\gamma, A \rightarrow ZH \rightarrow llbb \text{ or } \nu\nu bb, A \rightarrow \tau\tau$

I3 TeV results for items in red

Also see talks by
Dmitri Tsybychev and
Blake Burghgrave
**H^+ → τV in tH^+ with hadronic top**

**New 13 TeV result!**

Targets $m_{H^+} > m_{\text{top}}$

- Select 3 jets, at least one b-tagged
- Hadronic $\tau$ candidate
- Large $E_T^{\text{miss}} (> 150 \text{ GeV})$

**Estimator of mass…**

\[
m_T = \sqrt{p_T^\tau E_T^{\text{miss}} (1 - \cos \Delta \phi_{p_T^\tau, E_T^{\text{miss}}})}
\]

*Phys. Lett. B759 (2016) 555*
$H^+ \rightarrow \tau V$ in $tH^+$ with hadronic top

New 13 TeV result!

**Resulting Limits**

- **b-tagged**
- Hadronic $\tau$ candidate
- Large $E_T^{\text{miss}} (> 150 \text{ GeV})$

$$m_T = \sqrt{p_T^\tau E_T^{\text{miss}} (1 - \cos \Delta \phi_{p_T^\tau, E_T^{\text{miss}}})}$$

**In hMSSM parameter space**

$\tan \beta = 60$

Another example of Run 2 vs Run 1

Combination of $\tau_{\text{lep}}$ $\tau_{\text{had}}$ and $\tau_{\text{had}}$ $\tau_{\text{had}}$

Run 2 more sensitive at high mass,
• But not yet at low mass
• That will change soon
Heavy Scalars Decaying to WW and ZZ

Moving to higher mass

• Complete search for $llqq$, $\nu\nu qq$, $l\nu qq$, $qqqq$ with $Z$ or $W \rightarrow qq$ merged into one large-R jet

• Each final state has a resonance mass estimator

• Same analysis used to constrain
  • Heavy Scalar
  • Graviton
  • $W'$ and $Z'$
Heavy Scalars Decaying to WW and ZZ

Moving to higher mass

- Complete search for $llqq, ννqq$ with $Z \rightarrow qq$ merged into one large-$R$ jet
- Each final state has a resonance mass estimator
- Same analysis used to constrain
  - Heavy Scalar
  - Graviton
  - $W'$ and $Z'$

Resulting Limits

![Graph showing limits for different scenarios.](image)
Search for Heavy Higgs to Diphoton

Obviously important
You’ve probably heard about the result

See talk by Eilam Gross:
Search for a high mass diphoton resonance using the ATLAS detector

Local Significance: $3.9 \sigma$
Global Significance: $2.1 \sigma$

Needs more data to know one way or the other
Higgs Pair Production

Higgs pair production is a direct probe of the Higgs self-coupling (i.e. the Higgs potential)

Analyses generally combine heavy resonance and non-resonant searches

Example HH→4b analysis (13 TeV analysis)

Analysis divided into resolved (lower dihiggs mass) and boosted jet regimes

Yields in resolved region

<table>
<thead>
<tr>
<th>Sample</th>
<th>Signal Region Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multijet</td>
<td>43.3 ± 2.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>4.3 ± 3.0</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>–</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>47.6 ± 3.8</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>46</td>
</tr>
<tr>
<td>SM $hh$</td>
<td>0.22 ± 0.05</td>
</tr>
<tr>
<td>$G^*_K K (800)$</td>
<td>$k/M_{Pl} = 1$</td>
</tr>
<tr>
<td></td>
<td>5.7 ± 1.5</td>
</tr>
</tbody>
</table>

SM non-resonant challenging

8 TeV analyses in 4b, $bb\tau\tau$, $bb\gamma\gamma$, $WW\tau\tau$

Combination expected limit is 48 x SM non-resonant cross-section

BSM sensitivity comes sooner...
The Future

Run 1:  5 fb$^{-1}$ 7 TeV + 20 fb$^{-1}$ 8 TeV
Run 2 (until end 2018):
  ~3 fb$^{-1}$ 13 TeV from 2015
  ~7 fb$^{-1}$ 13 TeV so far in 2016
  ~100 fb$^{-1}$ expected
Run 3 (2020-2023): ~ 300 fb$^{-1}$
HL-LHC (2026-2035): ~ 3000 fb$^{-1}$

Precision Higgs Measurement is a big part of that program
  • ~5% achievable in several channels
  • Great theory program to match this, e.g. N$^3$LO ggH prediction

Big reach on rare decays (e.g. $H \rightarrow \mu\mu$)
  • and possible BSM decays

Challenging goal to observe Higgs self-coupling

hashed area indicates theory uncertainty
Summary

Four years ago today, a particle discovery was announced by ATLAS and CMS

We now know this particle strongly resembles the SM Higgs boson

But there are still many things to test and possibilities to explore
  • Precision rates and shapes, BSM decays, more Higgses, pair production

And much more data to come!
  • LHC performance in 2016 is great so far, with 7 fb\(^{-1}\) already recorded
Back-up
Caveats on the Portal Models

Complete instead of effective field theory can move result...

Example: Add an additional scalar to generate fermion and vector masses (and couple the fermion to the Higgs)  

\[
\begin{align*}
    m_s &= 10^{-2} \text{ GeV} \\
    m_s &= 1 \text{ GeV} \\
    m_s &= 10 \text{ GeV} \\
    m_s &= 50 \text{ GeV} \\
    m_s &= 70 \text{ GeV} \\
    m_s &= 1000 \text{ GeV} \\
    m_s &= 500 \text{ GeV} \\
    m_s &= 200 \text{ GeV} \\
    m_s &= 100 \text{ GeV}
\end{align*}
\]

Dashed line is the simple Higgs Portal model result