Search for Exotic Higgs Decays with ATLAS Detector

Higgs Portal

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Outline

• Motivation
• Analyses at ATLAS
• Future challenges
• Summary
Could Higgs boson lead to another discovery?

Yes.

To see why, let’s look at its properties.
SM Higgs decay

\[ H \rightarrow b\bar{b} \]

57%

Other \[ H \rightarrow ff \]

\[ H \rightarrow gg, \gamma\gamma, Z\gamma \]

\[ H \rightarrow VV^* \]

24%

\[ B_H \rightarrow \chi\chi \]

Largest partial width is to \( \Gamma_{b\bar{b}} \)

Yet this has a tiny coupling of \( \sigma(0.01) \)

Suppressed by small mass

Suppressed by loop

Phase-space suppressed (\( m_H < 2 \cdot m_{W,Z} \))

Curtin et al. 1312.4992 (2014)

Exotic Higgs decay

\[ H \to BSM \]

- \[ H \to b\bar{b} \]
  - 57%
- Other \( H \to ff \)
- \( H \to gg, \gamma\gamma, Z\gamma \)
- \( H \to VV^* \)
  - 24%

\[ B_{H \to XX} \]

A new coupling of \( \sigma(0.01) \) can easily add \( B_{H \to BSM} = \sigma(10\%) \)

Curtin et al. 1312.4992 (2014)
Chang et al. 0801.4554 (2008)
Silveira & Zee, PL B 161 (1985) 136
+ many more
**Exotic Higgs decay**

- **$H \to BSM$**
  - $H \to b\bar{b}$
    - 57%
  - Other $H \to ff$
  - $H \to gg, \gamma\gamma, Z\gamma$
  - $H \to VV^*$
    - 24%

- **$B_H \to \chi\chi$**

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A new coupling of $\sigma(0.01)$ can easily add

$$B_{H \to BSM} = \sigma(10\%)$$

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**Portal** coupling

- c.f. LHC produced 2M Higgs events so far

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Curtin et al. 1312.4992 (2014)
Chang et al. 0801.4554 (2008)
Silveira & Zee, PL B 161 (1985) 136
+ many more
Exotic Higgs decay

Current limit is only at 34%

3 ab⁻¹ projection is ≈ 10%
i.e. 300M Higgs events

A new coupling of $\phi(0.01)$ can easily add
$B_{H \rightarrow BSM} = \phi(10\%)$

$H \rightarrow b\bar{b}$
57%

Other $H \rightarrow ff$

$H \rightarrow gg, \gamma\gamma, Z\gamma$

$H \rightarrow VV^*$
24%

$B_{H \rightarrow XX}$

$H \rightarrow BSM$

ATLAS+CMS combination 1606.02266
ATLAS projection ATL-PHYS-PUB-2014-016
Higgs “portal”

coined by Brian Patt, Frank Wilczek

\[ \zeta \ |H|^2 \ X^2 \]

“Portal” interaction

Higgs “portal” coined by Brian Patt, Frank Wilczek

\[ \zeta |H|^2 X^2 \]

“Portal” interaction

<table>
<thead>
<tr>
<th>SM charge</th>
<th>BSM charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Portal</td>
</tr>
<tr>
<td>z</td>
<td></td>
</tr>
<tr>
<td>w</td>
<td></td>
</tr>
<tr>
<td>light</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Higgs “portal” \[ \zeta |H|^2 X^2 \] 

“Portal” interaction

\[ \text{Mass} \]

\[ \text{SM charge} \quad \text{BSM charge} \]

\[ t \quad H \quad Z \quad W \quad light \]

Portal

Higgs “portal”

Can explore Hidden BSM structures via Higgs portal

**Case 1: Invisible Higgs decay**

- **H decays away to hidden sector**
- **Leaves missing energy**

- **Portal**

- **SM charge**
- **BSM charge**

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*H decays away to hidden sector*  
⇒ *leaves missing energy*

- e.g. Curtin et al. 1312.4992 (2014) + many more
Understanding Z → vv crucial (becoming the main limitation)

VBF H → inv analysis example

Probe missing energy spectrum

Understanding Z → vv crucial (becoming the main limitation)

No significant excess observed

Combining H→inv analyses constrain B_{H→inv} < 25% (95% CL)
Hidden sector particles decay back to visible but soft SM final states

\[ \sigma(M_H/4 = 30) \text{ GeV} \]

BSM scalar decays

\[ H \rightarrow a b, \tau, \mu \]

Merged

Low transverse momentum final states

⇒ Trigger challenges

⇒ Relatively "Boosted" merged jets tagging

e.g. Curtin, Essig, Zhong 1412.4779 (2015) + many more
**ATLAS:** \( H \rightarrow aa \rightarrow b\bar{b}b\bar{b} \)

**Signal**

- \( q \) \( \rightarrow \) \( W \)
- \( \bar{q} \) \( \rightarrow \) \( W \)
- \( H \) \( \rightarrow \) \( t \rightarrow a \rightarrow b \bar{b} \)

**SM background**

- \( g \) \( \rightarrow \) \( t \rightarrow g \rightarrow b \bar{b} \)
- \( \bar{t} \rightarrow q \rightarrow t \rightarrow W \)

\( \sigma_{x\text{-sec}} \) much larger

*Use multivariate analysis*
ATLAS: $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$

- Sensitivity loss at low $m_{scalar}$ due to merged jet

More data being analyzed. Stay tuned.
Other channels

$95\%$ CL on $B_{H \to aa}$

- **Indirect constraint**
  - excludes this region

- **CMS Preliminary**

- **ATLAS**
  - $2\mu 2\tau$
  - $2\mu 2\tau$ overlaid

- **2HDM+S type-3**
  - $\tan\beta = 5.0$
  - $\sigma_{SM}$

- **$B_{H \to aa} = 34\%$ (indirect)**

- **Some channels reach beyond the indirect constraint**

- **Direct searches are constraining beyond indirect constraint for some parameter space**

This is CMS result to illustrate what other channels exist

*However, these are model dependent*

*Some channels reach beyond the indirect constraint*

*Direct searches are constraining beyond indirect constraint for some parameter space*
Lepton flavor violating Higgs decay

Many BSM models predict non-diagonal Yukawa couplings up to $\sigma(10\%)$ while satisfying experimental constraints.

$H \xrightarrow{e, \mu} \tau$

CMS reported 2.4$\sigma$ excess at Run 1 (13 TeV 2.3/fb shows no excess)

Diaz-Cruz, Toscano, PR D 62, 116005 (2000)
Blankenburg, Ellis, Isidori PL B 712 (2012) 386
Arhrib, Cheng, Kong PR D 87 015025 (2013)
Arana-Catania, Arganda, Herrero JHEP10 (2015) 192
+ many more
Mass reconstructions in $H \rightarrow l\tau$

Assume $v$'s are collinear

Relative orientations of $\bar{v}$ and $\rightarrow$ had consistent with $\tau$ decay

Well reconstructed $H \rightarrow l\tau$ peak
Focusing on $H \rightarrow \mu \tau$ results

One signal region reports 2.2$\sigma$
But combination shows no excess
Interesting challenges ahead

If $B_{H \rightarrow BSM} = \sigma(10\%)$, we already have 200k exotic higgs decay events.

They have topology different from typical analyses’ phase-space.

Key objects to study:
- low $P_T$ “merged” jets
- low $P_T$ b-tagging algorithms
- soft lepton final states
b-tagging efficiency

\[ \int L = 5 \text{ fb}^{-1} \]

- Data \( p_T^{\text{rel}} \) (stat)
- Data \( p_T^{\text{rel}} \) (stat+syst)
- Simulation \( p_T^{\text{rel}} \) (stat)

**Relevant region**

- \( M_X = 20 \text{ GeV} \)
- \( M_X = 30 \text{ GeV} \)
- \( M_X = 40 \text{ GeV} \)
Low $P_T$ b-tagging in SUSY
“Catch-all” analysis

Difficult topology is targeted with all hadronic channel

Soft b-jets tagging will be helpful in this area
Summary

A new coupling of $\mathcal{O}(0.01)$ can easily add $B_{H \rightarrow BSM} = \mathcal{O}(10\%)$

Indirect constraint is 34%

Various direct searches have put stringent constraints

Low $P_T$ objects are very important

Stay tuned for more updates
Back Up
FIG. 1: Sensitivity of a 125 GeV Higgs to light weakly coupled particles. **Left:** Exotic Higgs branching fraction to a singlet scalar $s$ versus the singlet’s mass $m_s$, assuming the interaction Eq. (1) is solely responsible for the $h \rightarrow ss$ decay. If the interaction in Eq. (1) generates the $s$ mass, the result is the orange curve; the other curves are for fixed and independent values of $\zeta$ and $m_s$. **Right:** Exotic Higgs branching fraction to a new fermion $\psi$ interacting with the Higgs as in Eq. (2) to illustrate the sensitivity of exotic Higgs decay searches to high scales, here $\Lambda$. We take here $\mu = m_\psi$. 
FIG. 3: Size of the cubic coupling $\mu_v$ in units of Higgs expectation value $v$ to yield the indicated $h \to ss$ branching fraction as a function of singlet mass, as given by Eq. (8).

The partial width for exotic Higgs decays is given by

$$\Gamma(h \to ss) = \frac{1}{32\pi m_h} \frac{\mu_v^2}{m_h} \sqrt{1 - \frac{4m_s^2}{m_h^2}} \approx \left(\frac{\mu_v/v}{0.03}\right)^2 \Gamma(h \to \text{SM}),$$  \hspace{1cm} \text{(8)}
$H \rightarrow \text{invisible decay}$

Missing energy spectrum in two production modes are studied

- **VH**: $B_{H \rightarrow \text{inv}} < 75\%$

- **VBF**: $B_{H \rightarrow \text{inv}} < 28\%$
VBF $H\rightarrow$invisible

Figure 6. Data and MC distributions after all the requirements in SR1 for (a) $E_T^{\text{miss}}$ and (b) the dijet invariant mass $m_{jj}$. The background histograms are normalized to the values in table 8. The VBF signal (red histogram) is normalized to the SM VBF Higgs boson production cross section with BF($H \rightarrow$invisible) = 100%.
Invisible Higgs decay

**Figure 6.** Data and MC distributions after all the requirements in SR1 for (a) $E_{\text{miss}}$ and (b) the dijet invariant mass $m_{jj}$. The background histograms are normalized to the values in table 8. The VBF signal (red histogram) is normalized to the SM VBF Higgs boson production cross section with $\text{BF}(H \to \text{invisible}) = 100\%$.

**Figure 7.** Data and MC distributions after all the requirements in SR2 for (a) $E_{\text{miss}}$ and (b) the dijet invariant mass $m_{jj}$. The background histograms are normalized to the values in table 8. The VBF signal is normalized to the SM VBF Higgs boson production cross section with $\text{BF}(H \to \text{invisible}) = 100\%$.

- Uncertainty in the luminosity measurements. This impacts the predicted rates of the signals and the backgrounds that are estimated using MC simulation, namely ggF and VBF signals, and $t\bar{t}$, single top, and diboson backgrounds.
- Uncertainties in the absolute scale and resolution of the reconstructed jet energy.
- Uncertainties in the modelling of the parton shower.
- Uncertainties in renormalization and factorization scales.
VBF $H \rightarrow \text{invisible}$

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**Figure 6.** Data and MC distributions after all the requirements in SR1 for (a) $E_T^{\text{miss}}$ and (b) the dijet invariant mass $m_{jj}$. The background histograms are normalized to the values in table 8. The VBF signal is normalized to the SM VBF Higgs boson production cross section with $\text{BF}(H \rightarrow \text{invisible}) = 100\%$.

**Figure 7.** Data and MC distributions after all the requirements in SR2 for (a) $E_T^{\text{miss}}$ and (b) the dijet invariant mass $m_{jj}$. The background histograms are normalized to the values in table 8. The VBF signal is normalized to the SM VBF Higgs boson production cross section with $\text{BF}(H \rightarrow \text{invisible}) = 100\%$.
### Table 8.

<table>
<thead>
<tr>
<th>Process</th>
<th>SR1</th>
<th>SR2a</th>
<th>SR2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF signal</td>
<td>20±15</td>
<td>58±22</td>
<td>19±8</td>
</tr>
<tr>
<td>VBF signal</td>
<td>286±57</td>
<td>182±19</td>
<td>105±15</td>
</tr>
<tr>
<td>$Z(\rightarrow \nu\nu)$+jets</td>
<td>339±37</td>
<td>1580±90</td>
<td>335±23</td>
</tr>
<tr>
<td>$W(\rightarrow \ell\nu)$+jets</td>
<td>235±42</td>
<td>1010±50</td>
<td>225±16</td>
</tr>
<tr>
<td>Multijet</td>
<td>2±2</td>
<td>20±20</td>
<td>4±4</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>1±0.4</td>
<td>64±9</td>
<td>19±6</td>
</tr>
<tr>
<td>Total background</td>
<td>577±62</td>
<td>2680±130</td>
<td>583±34</td>
</tr>
<tr>
<td>Data</td>
<td>539</td>
<td>2654</td>
<td>636</td>
</tr>
</tbody>
</table>

Estimates of the expected yields and their total uncertainties for SR1 and SR2 in 20.3 fb$^{-1}$ of 2012 data. The $Z(\rightarrow \nu\nu)$+jets, $W(\rightarrow \ell\nu)$+jets, and multijet background estimates are data-driven. The other backgrounds and the ggF and VBF signals are determined from MC simulation. The expected signal yields are shown for $m_H = 125$ GeV and are normalized to BF($H \rightarrow \text{invisible}$) = 100%. The $W$+jets and $Z$+jets statistical uncertainties result from the number of MC events in each signal and corresponding control region, and from the number of data events in the control region.

### Table 9.

<table>
<thead>
<tr>
<th>Results</th>
<th>Expected</th>
<th>+1$\sigma$</th>
<th>-1$\sigma$</th>
<th>+2$\sigma$</th>
<th>-2$\sigma$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1</td>
<td>0.35</td>
<td>0.49</td>
<td>0.25</td>
<td>0.67</td>
<td>0.19</td>
<td>0.30</td>
</tr>
<tr>
<td>SR2</td>
<td>0.60</td>
<td>0.85</td>
<td>0.43</td>
<td>1.18</td>
<td>0.32</td>
<td>0.83</td>
</tr>
<tr>
<td>Combined Results</td>
<td>0.31</td>
<td>0.44</td>
<td>0.23</td>
<td>0.60</td>
<td>0.17</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Summary of limits on BF($H \rightarrow \text{invisible}$) for 20.3 fb$^{-1}$ of 8 TeV data in the individual search regions and their combination, assuming the SM cross section for $m_H = 125$ GeV.
for the scalar, vector and Majorana-fermion dark matter, respectively. The parameters \(\lambda_{HSS}, \lambda_{HV}, \lambda_{Hff}/\Lambda\) are the corresponding coupling constants, \(v\) is the vacuum expectation value of the SM Higgs doublet, \(\beta_\chi = \sqrt{1 - 4m_\chi^2/m_H^2}\) (\(\chi = S, V, f\)), and \(m_\chi\) is the WIMP mass. In the Higgs-portal model, the Higgs boson is assumed to be the only mediator in the WIMP-nucleon scattering, and the WIMP-nucleon cross section can be written in a general spin-independent form. Inserting the couplings and masses for each spin scenario gives:

\[
\sigma^{SI}_{SN} = \frac{\lambda_{HSS}^2}{16\pi m_H^4} \frac{m_N^4 f_N^2}{(m_S + m_N)^2},
\]

Table 11. Parameters in the Higgs-portal dark-matter model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum expectation value</td>
<td>(v/\sqrt{2}) 174 GeV</td>
</tr>
<tr>
<td>Higgs boson mass</td>
<td>(m_H) 125 GeV</td>
</tr>
<tr>
<td>Higgs boson width</td>
<td>(\Gamma_H) 4.07 MeV</td>
</tr>
<tr>
<td>Nucleon mass</td>
<td>(m_N) 939 MeV</td>
</tr>
<tr>
<td>Higgs-nucleon coupling form factor</td>
<td>(f_N) 0.33 (^{+0.30}_{-0.07})</td>
</tr>
</tbody>
</table>

\[
\sigma^{SI}_{VN} = \frac{\lambda_{HV}^2}{16\pi m_H^4} \frac{m_N^4 f_N^2}{(m_V + m_N)^2},
\]

\[
\sigma^{SI}_{fN} = \frac{\lambda_{Hff}^2}{4\pi \Lambda^2 m_H^4} \frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2},
\]

where \(m_N\) is the nucleon mass, and \(f_N\) is the form factor associated to the Higgs boson-nucleon coupling and computed using lattice QCD \[10\]. The numerical values for all the parameters in the equations above are given in table 11.
FIG. 2 (color online). Distribution of $E_T^{\text{miss}}$ after the full selection in the 8 TeV data (dots). The filled stacked histograms represent the background expectations. The signal expectation for a Higgs boson with $m_H = 125.5$ GeV, a SM $ZH$ production rate and $\text{BR}(H \rightarrow \text{inv.}) = 1$ is stacked on top of the background expectations. The inset at the bottom of the figure shows the ratio of the data to the combined background expectations. The hashed area shows the systematic uncertainty on the combined background expectation.
FIG. 3 (color online). Upper limits on $\sigma_{ZH} \times \text{BR}(H \to \text{inv.})$ at 95% C.L. for a Higgs boson with $110 < m_H < 400$ GeV, for the combined 7 and 8 TeV data. The full and dashed lines show the observed and expected limits, respectively.
TABLE I. Number of events observed in data and expected from the signal and from each background source for the 7 and 8 TeV data-taking periods. Uncertainties on the signal and background expectations are presented with statistical uncertainties first and systematic uncertainties second.

<table>
<thead>
<tr>
<th>Data period</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ → ℓℓνν</td>
<td>20.0 ± 0.7 ± 1.6</td>
<td>91 ± 1 ± 7</td>
</tr>
<tr>
<td>WZ → ℓνℓℓ</td>
<td>4.8 ± 0.3 ± 0.5</td>
<td>26 ± 1 ± 3</td>
</tr>
<tr>
<td>Dileptonic ℓℓ, Wt, WW, Z → ττ</td>
<td>0.5 ± 0.4 ± 0.1</td>
<td>20 ± 3 ± 5</td>
</tr>
<tr>
<td>Z → ee, Z → μμ</td>
<td>0.13 ± 0.12 ± 0.07</td>
<td>0.9 ± 0.3 ± 0.5</td>
</tr>
<tr>
<td>W + jets, multijet, semileptonic top</td>
<td>0.020 ± 0.005 ± 0.008</td>
<td>0.29 ± 0.02 ± 0.06</td>
</tr>
<tr>
<td>Total background</td>
<td>25.4 ± 0.8 ± 1.7</td>
<td>138 ± 4 ± 9</td>
</tr>
<tr>
<td>Signal (m_H = 125.5 GeV, σ_{ZH,SM}, BR(H → inv.) = 1)</td>
<td>8.9 ± 0.1 ± 0.5</td>
<td>44 ± 1 ± 3</td>
</tr>
<tr>
<td>Observed</td>
<td>28</td>
<td>152</td>
</tr>
</tbody>
</table>
Table 4 Predicted and observed numbers of events for the six categories in the signal region. The yields and uncertainties of the backgrounds are shown after the profile likelihood fit to the data. In this fit all categories share the same signal-strength parameter. The quoted uncertainties combine the statistical and systematic contributions. These can be smaller for the total background than for individual components due to anti-correlations. The yields and uncertainties of the signals are shown as expected before the fit for $m_H = 125$ GeV and BR$(H \to \text{inv}) = 100\%$. Signal contributions from VBF and $t\bar{t}H$ production are estimated to be negligible.

<table>
<thead>
<tr>
<th>$b$-tag category</th>
<th>0-tag</th>
<th>1-tag</th>
<th>2-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>2-jet events</td>
<td>3-jet events</td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>24400 ± 1100</td>
<td>1960 ± 200</td>
<td>164 ± 13</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>20900 ± 770</td>
<td>1160 ± 130</td>
<td>47 ± 7</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>403 ± 74</td>
<td>343 ± 65</td>
<td>57 ± 10</td>
</tr>
<tr>
<td>Single top</td>
<td>149 ± 16</td>
<td>107 ± 14</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>Diboson</td>
<td>1670 ± 180</td>
<td>227 ± 25</td>
<td>64 ± 7</td>
</tr>
<tr>
<td>SM VH$(bb)$</td>
<td>1.5 ± 0.5</td>
<td>6 ± 2</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>Multijet</td>
<td>26 ± 43</td>
<td>8 ± 7</td>
<td>0.7 ± 0.9</td>
</tr>
<tr>
<td>Total</td>
<td>47560 ± 490</td>
<td>3804 ± 64</td>
<td>347 ± 15</td>
</tr>
<tr>
<td>Signal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$gg \to H$</td>
<td>403 ± 95</td>
<td>25 ± 6</td>
<td>2.1 ± 0.5</td>
</tr>
<tr>
<td>$W(\to jj)H$</td>
<td>425 ± 45</td>
<td>44 ± 6</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>$Z(\to jj)H$</td>
<td>217 ± 19</td>
<td>42 ± 4</td>
<td>26 ± 2</td>
</tr>
<tr>
<td>Data</td>
<td>47404</td>
<td>3831</td>
<td>344</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>3-jet events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>9610 ± 580</td>
<td>795 ± 93</td>
<td>53 ± 7</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>7940 ± 510</td>
<td>479 ± 70</td>
<td>21 ± 4</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>443 ± 53</td>
<td>437 ± 53</td>
<td>63 ± 7</td>
</tr>
<tr>
<td>Single top</td>
<td>97 ± 14</td>
<td>66 ± 9</td>
<td>6.4 ± 0.9</td>
</tr>
<tr>
<td>Diboson</td>
<td>473 ± 54</td>
<td>55 ± 6</td>
<td>13 ± 2</td>
</tr>
<tr>
<td>SM VH$(bb)$</td>
<td>0.8 ± 0.3</td>
<td>2.6 ± 0.9</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>Multijet</td>
<td>22 ± 29</td>
<td>4 ± 4</td>
<td>0.6 ± 0.6</td>
</tr>
<tr>
<td>Total</td>
<td>18580 ± 200</td>
<td>1840 ± 40</td>
<td>158 ± 7</td>
</tr>
<tr>
<td>Signal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$gg \to H$</td>
<td>224 ± 55</td>
<td>15 ± 4</td>
<td>1.2 ± 0.5</td>
</tr>
<tr>
<td>$W(\to jj)H$</td>
<td>110 ± 16</td>
<td>11 ± 1</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>$Z(\to jj)H$</td>
<td>65 ± 7</td>
<td>12 ± 1</td>
<td>6.1 ± 0.7</td>
</tr>
<tr>
<td>Data</td>
<td>18442</td>
<td>1842</td>
<td>159</td>
</tr>
</tbody>
</table>
VH→Invisible

\[ \text{in} \rightarrow \text{inv.} \]

Invisible particles are at the level of the particles' true identities. Their efficiency uncertainties arise from jets matched to invisible particles.

The JER and JES uncertainties are also propagated to the total background.

The signal expectation for \( m_H = 125 \) GeV and BR(\( H \rightarrow \text{inv.} \)) = 100% is shown on top of the background and additionally as an overlay line, scaled by the factor indicated in the legend. The total background before the fit is shown as a dashed line. The hatched bands represent the total uncertainty on the background.
**Fig. 2** The missing transverse momentum ($E_T^{\text{miss}}$) distributions of the 3-jet events in the signal region for the a 0-tag, b 1-tag and c 2-tag categories. The data are compared with the background model after the likelihood fit. The bottom plots show the ratio of the data to the total background. The signal expectation for $m_H = 125$ GeV is shown on top of the background and additionally as an overlay line, scaled by the factor indicated in the legend. The total background before the fit is shown as a dashed line. The hatched bands represent the total uncertainty on the background.
Dark Matter interpretation

Recasting $B_{H \rightarrow \text{inv}}$ limit on DM model

Direct detection Expt. limits

LHC limit dominates for $m_{\text{WIMP}} < m_H/2$
Higgs decaying to a light “hidden” sector is well motivated

Larger the mass, larger the BR

\[ \Delta R \approx \frac{2m}{P_T} \]

Low \( P_T \) merged jet tagging is an interesting area of research
Kinematics of $X \rightarrow YY$

$H_{125} \rightarrow XX \rightarrow YYYY$  

Final states carry $125 \text{ GeV}/4 \approx O(30) \text{ GeV}$

Interesting experimental challenges of low $P_T$
Not-so-boosted merged jets

\[ H_{125} \rightarrow XX \]

\( X \)'s carry \( 125 \text{ GeV}/2 \approx O(60) \text{ GeV} \)

\( \Delta R \approx 2M \cdot P_T \)

Rule-of-thumb for opening angle

If \( M_X = 24 \text{ GeV} \), \( \Delta R \approx 0.8 \)

New area to develop a low \( P_T \) merged jet tagger + b-tagging
Natural SUSY

FIG. 1: Natural electroweak symmetry breaking constrains the superpartners on the left to be light. Meanwhile, the superpartners on the right can be heavy, $M_{1,2} \lesssim 1 \text{ TeV}$, without spoiling naturalness. In this paper, we focus on determining how the LHC data constrains the masses of the superpartners on the left.

In a natural theory of EWSB the various contributions to the quadratic terms of the Higgs potential should be comparable in size and of the order of the electroweak scale $v \sim 246 \text{ GeV}$. The relevant terms are actually those determining the curvature of the potential in the direction of the Higgs vacuum expectation value. Therefore the discussion of naturalness...

Fine mass splitting predicted for natural SUSY $\Rightarrow$ Soft lepton important
FIG. 4: **Left:** Branching ratios of a CP-even scalar singlet to SM particles, as function of $m_s$.

**Right:** Branching ratios of exotic decays of the 125 GeV Higgs boson as function of $m_s$, in the $SM + Scalar$ model described in the text, scaled to $\text{Br}(h \rightarrow ss) = 1$. Hadronization effects likely invalidate our simple calculation in the shaded regions.
FIG. 6: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type I Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions. For $\tan\beta < 1$, decays to quarks are enhanced over decays to leptons. Type IV (Fig. 9): The branching ratios are $\tan\beta$-dependent. For $\tan\beta < 1$ and compared to the NMSSM, the pseudoscalar decays to up-type quarks and leptons can be enhanced with respect to down-type quarks, so that branching ratios to $b\bar{b}$, $c\bar{c}$, and $\tau^+\tau^-$ can be similar. This opens up the possibility of detecting this model in the $2b\tau\tau$ or $2c\tau\tau$ final state. Note that the branching ratios are only independent of $\tan\beta$ for Type I, and all types reduce to Type I for $\tan\beta = 1$. A sizable $\mathcal{B}(h \to Za)$ would open up additional exciting search channels with leptons that reconstruct the $Z$-boson. This is discussed in §10. For $3m\pi < m_a < 1$ GeV the decay rate calculations suffer large theoretical uncertainties but the dominant decay channels will likely be muons and hadrons. Below the pion, muon, and electron thresholds, the pseudoscalar decays dominantly to muons, electrons, and photons.
FIG. 7: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.
FIG. 8: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type III Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.
FIG. 9: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type IV Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.
FIG. 10: Singlet scalar branching ratios in the 2HDM+S for different $\tan \beta$, $\alpha'$ and Yukawa coupling type. These examples illustrate the possible qualitative differences to the pseudoscalar case, such as dominance of $s \rightarrow c\bar{c}$ decay above $b\bar{b}$-threshold; democratic decay to $b\bar{b}$ and $\tau^+\tau^-$; and democratic decay to $c\bar{c}$ and $\tau^+\tau^-$. Hadronization effects likely invalidate our simple calculations in the shaded regions.
ATLAS $\mu\mu\tau\tau$ analysis

PRD 92, 052002 (2015)

$H \rightarrow \mu \mu \tau \tau$

$\sigma_{1} \pm \sigma_{2}$

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

$H = m_{H} = 125$ GeV

$\text{Observed 95\% CL}$

$\text{Median Expected 95\% CL}$

$m_{H} = m_{h} = 125$ GeV

• Run 2 results will come

• $B_{H \rightarrow 4\tau} = 100\%$ line

• $B_{H \rightarrow 4\tau} = 10\%$ line
**LFV: CMS 8 TeV v. 13 TeV**

<table>
<thead>
<tr>
<th>Category</th>
<th>95% CL Limit on B(H→μτ), %</th>
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<tbody>
<tr>
<td>μτ_e, 0 Jets</td>
<td>1.32% (exp.)</td>
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<td>2.04% (obs.)</td>
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<td>3.68% (obs.)</td>
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<td>H→μτ</td>
<td>0.75% (exp.)</td>
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<td>1.51% (obs.)</td>
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</table>

**Expected Values**

- \(1.51\%\) (obs.)
- \(0.75\%\) (exp.)
- \(3.68\%\) (obs.)
- \(2.31\%\) (obs.)
- \(0.75\%\) (obs.)

**Observed Values**

- \(1.20\%\) (obs.)
- \(1.62\%\) (exp.)
- \(3.04\%\) (obs.)
- \(4.36\%\) (exp.)
- \(7.71\%\) (obs.)

**95% CL Limit on Br(H→μτ), %**

- \(1.20\%\) (obs.)
- \(1.62\%\) (exp.)
- \(3.04\%\) (obs.)
- \(4.36\%\) (exp.)
- \(7.71\%\) (obs.)


- \(19.7\) fb
- \(19.7\) fb

**13 TeV**

- \(4.17\%\) (exp.)
- \(4.24\%\) (obs.)
- \(4.89\%\) (exp.)
- \(6.35\%\) (obs.)
- \(6.41\%\) (exp.)
- \(7.71\%\) (obs.)

**Expected Values**

- \(4.17\%\) (exp.)
- \(4.24\%\) (obs.)
- \(4.89\%\) (exp.)
- \(6.35\%\) (obs.)
- \(6.41\%\) (exp.)
- \(7.71\%\) (obs.)

**Observed Values**

- \(4.36\%\) (exp.)
- \(3.04\%\) (obs.)
- \(7.31\%\) (exp.)
- \(8.99\%\) (obs.)

**Expected Values**

- \(1.20\%\) (exp.)
- \(1.62\%\) (exp.)
- \(3.04\%\) (exp.)
- \(4.36\%\) (exp.)
- \(7.71\%\) (obs.)

**Observed Values**

- \(3.04\%\) (obs.)
- \(4.36\%\) (exp.)
- \(7.71\%\) (obs.)

**95% CL Limit on Br(H→μτ), %**

- \(1.20\%\) (obs.)
- \(1.62\%\) (exp.)
- \(3.04\%\) (obs.)
- \(4.36\%\) (exp.)
- \(7.71\%\) (obs.)
Lepton flavor violating Higgs decay

Many BSM models predict non-diagonal Yukawa couplings

CMS reported 2σ excess at Run 1

Curtin et al. 1312.4992 (2014)
Chang et al. 0801.4554 (2008)
Silveira & Zee, PL B 161,136 (1985)
+ many more
$H \rightarrow J/\Psi \gamma$

The process is very rare

If $H c\bar{c}$ coupling is larger it can increase the rate (possibly more than 100%)

Searching for $J/\Psi + \gamma$ probes the loop

Perhaps $H c\bar{c}$ is larger?

Higgs decay branching fraction

Bodwin, Petriello, Stoynev, Velasco PR D 88, 053003 (2013)
Bodwin, Chung, Ee, Lee, Petriello et al. PR D 90, 113010 (2014)
The process is very rare

$H \rightarrow Z \gamma$

BSM particle can contribute in the loop

Searching for $Z\gamma$ probes the loop
quickly systematic dominated (more work needed!)
**ATLAS and CMS combination**

### ATLAS and CMS

**LHC Run 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS+CMS</th>
<th>ATLAS</th>
<th>CMS</th>
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<td>$</td>
<td>\kappa_t</td>
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</tr>
<tr>
<td>$B_{BSM}$</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

- $B_{BSM} \geq 0$
- $|\kappa_t| \leq 1$
- $B_{BSM} = 0$

- **Parameter value**

![Graph](image.png)

Figure 15: Fit results for two parameterisations allowing BSM loop couplings discussed in the text: the first one assumes that $B_{BSM} = 0$ and that $|\kappa_V| \leq 1$, where $\kappa_V$ denotes $\kappa_Z$ or $\kappa_W$, and the second one assumes that there are no additional BSM contributions to the Higgs boson width, i.e. $B_{BSM} = 0$. The measured results for the combination of ATLAS and CMS are reported together with their uncertainties, as well as the individual results from each experiment. The hatched areas show the non-allowed regions for the $\kappa_t$ parameter, which is assumed to be positive without loss of generality. The error bars indicate the 1 (thick lines) and 2 (thin lines) intervals. When a parameter is constrained and reaches a boundary, namely $|\kappa_V| = 1$ or $B_{BSM} = 0$, the uncertainty is not defined beyond this boundary. For those parameters with no sensitivity to the sign, only the absolute values are shown.

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1606.02266
Why 0.5 million?

20pb · 25/fb = 500k
50pb · 10/fb = 500k
(500k + 500k) · 2 expt = 2 million Higgs events
2 million Higgs events · (B_{H→BSM} = 25%) = 0.5 million