Recent results from Higgs physics at the LHC

Florencia Canelli - University of Zurich
On behalf of the ATLAS and CMS collaboration

ICHEP
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Introduction

• The first extended running period of the LHC at $\sqrt{s}$ 7 and 8 TeV brought the anticipated discovery of the Higgs boson by the CMS and ATLAS collaborations, the culmination of a decades-long effort.

• With these data ATLAS and CMS have measured nearly all its accessible properties — its production and decay rates, its mass, its couplings to most other SM particles — and set constraints on others.
Introduction

- Run II of the LHC at $\sqrt{s} = 13$ TeV is now making an even larger sample of Higgs boson events available for analysis.

- These data is increasing in precision and opening up new channels to study the interactions of Higgs bosons and SM particles.

- Higher collision energies is allowing us to direct probe for BSM physics by searching for additional Higgs bosons and for anomalous decays of the Higgs(125) boson.
Higgs Boson Production at 125 GeV

- **ggH (87.4%)**
- **VBF (7.1%)**
- **ttH (0.6%)**

**Observed production modes:** ggF, VBF

**Run I**
- 7/8 TeV (2011/2012)

**Run II**
Higgs Boson Decays at 125 GeV

H → γγ
Very rare (0.2%)
S/B < 1
ΔM/M ~ 1-2%

H → ZZ* → 4l
Rare (3%)
S/B >> 1
ΔM/M ~ 1-2%

H → bb
Abundant (58%)
S/B << 1
ΔM/M ~ 10-20%

H → ττ
Abundant (6%)
S/B < 1
ΔM/M ~ 10-20%

H → cc (2.9%)

H → WW* → 2l2ν
Very Abundant (22%)
S/B < 1
ΔM/M ~ 30%

Observed decay modes: γγ, ZZ, WW, ττ
Missing bb, cc, μμ, Zγ
CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Rates and couplings: arXiv:1606.02266

Precision test of Higgs boson coupling strengths

\[ \mu = \frac{\sigma}{\sigma_{SM}} \]
Higgs Profile in Run 1

CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Rates and couplings: arXiv:1606.02266

Gluon fusion measurements, starting to approach SM theory uncertainties: 15%

Mild excess in ttH and ZH production modes

Coupling strengths

$\mu = \frac{\sigma}{\sigma_{SM}}$
Higgs Profile in Run 1

CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

- Rates and couplings: arXiv:1606.02266

Mass has been measured to 0.2% precision $m_H = 125.09 \pm 0.24$ GeV

Angular distributions consistent with spin 0 and even parity

All couplings are consistent with SM within 2.5σ

Precision test of Higgs boson coupling strengths

Coupling strengths $\mu = \frac{\sigma}{\sigma_{SM}}$
Higgs Boson in Run 2

• LHC restarted in 2015 with a collision energy of 13 TeV

• Run 2 dataset per experiment as of ICHEP2016:
  – 2015: ~3 fb⁻¹
  – 2016: ~13 fb⁻¹
 Already produced more Higgs bosons than in Run 1!

• Most analyses in Run 2 follow closely methods and strategies developed during Run 1

• In this talk:
  – Only results with 13 TeV
  – Different luminosity per analysis
Higgs parallel sessions:
30 experimental talks
>30 new results
Higgs→γγ

• Narrow peak over falling background

• **Signature:** 2 isolated photons
  – All production modes targeted ggF, VBF, VH (only ATLAS), ttH events

• Signal extracted through fit of $m_{γγ}$ in different event categories
  – Main backgrounds: $γγ$ and $γ$-jet production

- Dominant systematic uncertainty: photon energy scale and resolution and background choice bias (smaller than statistical uncertainties)
Measurements of fiducial cross section

<table>
<thead>
<tr>
<th></th>
<th>Fiducial $\sigma$ (fb)</th>
<th>SM prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>43.2±14.9(stat)±4.9(syst)</td>
<td>62.8$^{+3.4}_{-4.4}$ (N$^3$LO+XH)</td>
</tr>
<tr>
<td>CMS</td>
<td>69$^{+16}<em>{-22}$(stat)$^{+8}</em>{-6}$(syst)</td>
<td>73.8±3.8</td>
</tr>
</tbody>
</table>

$\sigma_i = \frac{\nu_i^{sig}}{c_i \int L dt}$

Fiducial $\sigma$:
Event yields corrected for detector inefficiency and resolution for minimal theoretical modeling

Differential cross section measurements

Important to improve MC generators and calculations $\Rightarrow$ reduce systematic uncertainties
Production cross section and signal strength

- Events are split into orthogonal categories that exploit topological differences between production mechanisms

Extract strength of production processes in a 2-parameter fit

- Achieved similar precision to Run 1
- Measurements compatible with SM
- Results still dominated by statistical uncertainty
**Higgs → ZZ**

- **Narrow peak over a flat background**

- **Signature:** two pairs of same flavor, opposite sign, isolated leptons
  - All production modes targeted ggF, VBF, VH, ttH events

- Extraction of signal through fit of $m_{4l}$
  - Also uses kinematic discriminant (e.g. $M_{Z_1}$, $M_{Z_2}$, 5 angles from decay chain, matrix element) used to enhance the signal purity of different production modes

- **Dominant systematic uncertainty:** luminosity and lepton SF (smaller than statistical uncertainty)
**Measurements of fiducial cross section**

<table>
<thead>
<tr>
<th>13 TeV</th>
<th>Fiducial $\sigma$ (fb)</th>
<th>SM prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (14.8 fb$^{-1}$)</td>
<td>4.54$^{+1.02}_{-0.90}$</td>
<td>3.07$^{+0.21}_{-0.25}$</td>
</tr>
<tr>
<td>CMS (12.9 fb$^{-1}$)</td>
<td>2.29$^{+0.74}<em>{-0.64}$ (stat) $^{+0.30}</em>{-0.23}$ (syst)</td>
<td>2.53$^{\pm 0.13}$</td>
</tr>
</tbody>
</table>

**Differential cross section measurements**

- **CMS Preliminary**
  - Data (stat. & sys. unc.)
  - Systematic uncertainty
  - Model dependence

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Combination of $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^*$

- Combine $H \rightarrow \gamma \gamma$ and $H \rightarrow Z \rightarrow 4l$ inclusive samples, with no categorization
- Higgs production is observed with $10\sigma$ significance ($8.6\sigma$ expected) with 13 TeV data in agreement with SM expectations

<table>
<thead>
<tr>
<th>Measurement at 13 TeV</th>
<th>SM prediction at 13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (pb)</td>
<td>$59.0^{+9.7}<em>{-9.2}$ (stat) $^{+4.4}</em>{-3.5}$ (syst)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$1.13^{+0.18}_{-0.17}$</td>
</tr>
</tbody>
</table>

Comparable precision to Run 1
Towards Discovery - ttH

- Probing the Yukawa coupling between top and Higgs at LHC:
  - via gluon fusion cross section, assumes no BSM particles running in the loop
  - directly at tree level, via associated production:

  \[
  \begin{array}{c}
  g \\
  t \quad H \\
  g \\
  \bar{t}
  \end{array}
  \]

  - **ttH(\(\rightarrow bb\))**: Uses \(H \rightarrow bb\) with one or two W bosons decaying to e or \(\mu\) (and ttH (hadronic) with both W bosons decaying hadronically)

  - **ttH(multileptons)**: targets \(H \rightarrow WW, ZZ, \tau \tau\) (\(\tau\) decaying leptonically and hadronically), and additional leptons from top quark decays

  - **ttH(\(\gamma\gamma\))**: included in \(H \rightarrow \gamma\gamma\) analyses

<table>
<thead>
<tr>
<th>Higgs decay mode</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow bb)</td>
<td>58.1</td>
</tr>
<tr>
<td>(H \rightarrow WW)</td>
<td>21.5</td>
</tr>
<tr>
<td>(H \rightarrow \tau\tau)</td>
<td>6.3</td>
</tr>
<tr>
<td>(H \rightarrow ZZ)</td>
<td>2.6</td>
</tr>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>0.23</td>
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</tbody>
</table>
• Largest branching ratio and large background, also offers sensitivity to the Higgs-Bottom Yukawa coupling

• **Analysis strategy:** categorize events according to amount of leptons, jets, b-jets
  – Main background \( tt + \text{heavy flavour} \) production: very challenging theoretical description

• **Dominant systematic uncertainty:** signal and background modeling and normalization (larger than statistical uncertainty)

**CMS includes now a boosted category and 2D matrix-element and BDT**

**ATLAS uses BDT to reconstruct Higgs and separate signal and background for each category**
**ttH(→bb)**

- Largest branching ratio and large background, also offers sensitivity to the Higgs-Bottom Yukawa coupling

- **Analysis strategy:** categorize events according to amount of leptons, jets, b-jets
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- **Dominant systematic uncertainty:** signal and background modeling and normalization (larger than statistical uncertainty)
**ttH(multileptons)**

- Targets Higgs decays and focus on final states with clean signatures and low backgrounds

- **Signature:** 2-4 leptons, 2 or more jets, and at least 1 b-tagged jet. Allows at least one $\tau_{\text{had}}$

- **Dominant systematic uncertainty:** fake-rate measurements and non-prompt background estimates

---

**ATLAS cut and count analysis in main different category regions**

**CMS BDT based discriminants including matrix element weights**

And also $H\rightarrow ZZ$, $H\rightarrow \tau\tau$
**ttH(multileptons)**

- Targets Higgs decays and focus on final states with clean signatures and low backgrounds

- **Signature:** 2-4 leptons, 2 or more jets, and at least 1 b-tagged jet. Allows at least one $\tau_{had}$

- **Dominant systematic uncertainty:** fake-rate measurements and non-prompt background estimates
tH(→bb)

- Smallest SM production cross section
  - Diagrams are interfering in SM
  - While it is constructive for inverted top coupling (ITC) \( \kappa_{\text{top}} = -1 \)

<table>
<thead>
<tr>
<th>CMS</th>
<th>Upper limit x SM (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>113.7 (98.6)</td>
</tr>
<tr>
<td>ITC</td>
<td>6.0 (6.4)</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
& \text{CMS Preliminary} \\
& pp \rightarrow tH, H \rightarrow b\bar{b}, t \rightarrow b'\nu_Y \\
& M(H) = 125 \text{ GeV}
\end{align*}
\]
Higgs $\rightarrow bb$

- Important to establish coupling of Higgs to b quarks
  - Inclusive $H \rightarrow bb$ search extremely challenging: overwhelming background from QCD multi-jet production

- Exploit associated production modes:
  - $t\bar{t}H$ as previously shown
  - VH with lepton/MET provides clean signature
  - VBF with tagging of forward jets
**Analysis strategy:** utilize leptonic decays of Z/W events
- Multivariate techniques necessary to achieve good S/B
- Dominant backgrounds, depend on channel: Z+b, tt
- Most discrimination from $m_{bb}$ and $\Delta R(b_1,b_2)$

**Systematic and statistical uncertainties of the same size**
• **Analysis strategy:** utilize leptonic decays of Z/\W events
  – Multivariate techniques necessary to achieve good S/B
  – Dominant backgrounds, depend on channel: Z+b, tt
  – Most discrimination from \( m_{bb} \) and \( \Delta R(b_1, b_2) \)

• Systematic and statistical uncertainties of the same size

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**ATLAS** Preliminary \( \sqrt{s}=13 \text{ TeV}, \int L \, \text{dt}=13.2 \, \text{fb}^{-1} \)

<table>
<thead>
<tr>
<th></th>
<th>Total (Stat. Syst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH</td>
<td>0.15±0.67 (0.49, 0.45)</td>
</tr>
<tr>
<td>WH</td>
<td>0.33±0.95 (0.68, 0.68)</td>
</tr>
</tbody>
</table>

\( \mu = 0.21^{+0.51}_{-0.50} \)

Best fit \( \mu = \sigma / \sigma_{SM} \) for \( m_{H}=125 \text{ GeV} \)

**Significance (expected)**

<table>
<thead>
<tr>
<th></th>
<th>ATLAS (13 TeV)</th>
<th>ATLAS+CMS (8 TeV)</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4(\sigma) (1.94(\sigma))</td>
<td>2.6(\sigma) (3.7(\sigma))</td>
<td>2.8(\sigma)</td>
</tr>
</tbody>
</table>

**W(Z)Z(\rightarrow bb)**

<table>
<thead>
<tr>
<th></th>
<th>Observed ( \mu )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.91±0.17(stat) +0.32-0.27(syst)</td>
<td>3.0(\sigma) (expected 3.2(\sigma))</td>
</tr>
</tbody>
</table>
**VBF Higgs → bb**

- VBF \(H \rightarrow bb\) more difficult to exploit VBF than VH signature for \(H \rightarrow bb\) but larger production cross-section
  - Forward jets are used to trigger and discriminate against multi-jet background
  - Signal extracted via a fit to the \(m_{bb}\) spectrum

---

**ATLAS result with 12.6 fb\(^{-1}\) requiring a high \(p_T\) photon to provide a clean signature for efficient triggering**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>(H(\rightarrow bb) + \gamma j)</th>
<th>(Z(\rightarrow bb) + \gamma j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit at 95% CL</td>
<td>4 x SM (expected 6 x SM)</td>
<td>2 x SM (expected 1.8 x SM)</td>
</tr>
</tbody>
</table>

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**CMS**

<table>
<thead>
<tr>
<th>Run</th>
<th>Upper limit x SM (expected)</th>
<th>Signal strength (\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>5.5 (2.5)</td>
<td>2.8(^{+1.6}_{-1.4})</td>
</tr>
<tr>
<td>Run 2</td>
<td>3.4 (2.3)</td>
<td>1.3(^{+1.2}_{-1.1})</td>
</tr>
</tbody>
</table>

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**ATLAS-CONF-2016-063**

**CMS-PAS-HIG-16-003**
Higgs$\rightarrow\mu\mu$

- **A very rare decay** in the SM
  - Probe Yukawa-coupling to 2nd-generation fermions and mass dependence
  - Test of the Higgs coupling to leptons

- **Signature:** Very clean signature from dimuon final state but $Z/\gamma^*\rightarrow\mu\mu$ overwhelming irreducible background

- **Analysis strategy:**
  Search for peak in $m_{\mu\mu}$ spectrum over smoothly falling background
  - Categorize events according to VBF and ggF signature enriched
Higgs → μμ

- A very rare decay in the SM
  - Probe Yukawa-coupling to 2nd-generation fermions and mass dependence
  - Test of the Higgs coupling to leptons

- Signature: Very clean signature from dimuon final state but Z/γ* → μμ overwhelming irreducible background

- Analysis strategy:
  Search for peak in m_{μμ} spectrum over smoothly falling background
  - Categorize events according to VBF and ggF signature enriched
**Higgs → µµ**

- **A very rare decay** in the SM
  - Probe Yukawa-coupling to 2nd-generation fermions and mass dependence
  - Test of the Higgs coupling to leptons

- **Signature:** Very clean signature from dimuon final state but \(Z/\gamma^* \rightarrow \mu\mu\) overwhelming irreducible background

- **Analysis strategy:**
  Search for peak in \(m_{\mu\mu}\) spectrum over smoothly falling background
  - Categorize events according to VBF and ggF signature enriched

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**ATLAS**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>Upper limit x SM (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>7.1 (7.2)</td>
</tr>
<tr>
<td>Run 2</td>
<td>4.4 (5.5)</td>
</tr>
<tr>
<td>Combined Run 1 and Run 2</td>
<td>3.5 (4.5)</td>
</tr>
</tbody>
</table>

**Florencia Canelli - University of Zurich**

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Beyond the SM

- The 125 GeV Higgs is so far consistent with the SM prediction

- Extensions of the standard model often include an extended Higgs sector

- Numerous models introduce additional Higgses. Many BSM theories require two or more Higgs doublets
  - Heavy Higgs (H),
  - Charged Higgs (H±),
  - Pseudo-scalar Higgs (A)

- And current constraints still allow for Higgs to couple to new particles or new couplings to particle
  - Higgs to invisible
  - Lepton flavour violating decays
  - H(125) decays to pseudo-scalars

- An extensive range of BSM searches are performed at the LHC
# Heavy Higgs Searches @ 13 TeV

<table>
<thead>
<tr>
<th>Higgs to fermions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ττ</td>
<td>2.3 fb⁻¹ (CMS-PAS-HIG-16-006)</td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-085)</td>
</tr>
<tr>
<td>H → bb</td>
<td>2.7 fb⁻¹ (CMS-PAS-HIG-16-025)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Higgs to vector bosons</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ → 4l</td>
<td>12.9 fb⁻¹ (CMS-PAS-HIG-16-033)</td>
<td>14.8 fb⁻¹ (ATLAS-CONF-2016-079)</td>
</tr>
<tr>
<td>H → ZZ → lννν</td>
<td>2.3 fb⁻¹ (CMS-PAS-HIG-16-001)</td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-056)</td>
</tr>
<tr>
<td>H → ZZ → llqq</td>
<td>included exotica/B2G</td>
<td>13.2 fb⁻¹ (ATLAS-CONF-2016-082)</td>
</tr>
<tr>
<td>H → ZZ → qqνν</td>
<td>included exotica/B2G</td>
<td>13.2 fb⁻¹ (ATLAS-CONF-2016-082)</td>
</tr>
<tr>
<td>H → WW → lνlν</td>
<td>2.3 fb⁻¹ (CMS-PAS-HIG-16-023)</td>
<td>13.2 fb⁻¹ (ATLAS-CONF-2016-074)</td>
</tr>
<tr>
<td>H → WW → lνqq</td>
<td>included exotica/B2G</td>
<td>13.2 fb⁻¹ (ATLAS-CONF-2016-062)</td>
</tr>
<tr>
<td>H → Zγ</td>
<td></td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-044)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Higgs to Higgs (diHiggs)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H → hh → bbb</td>
<td>2.3 fb⁻¹ (CMS-PAS-HIG-16-002)</td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-049)</td>
</tr>
<tr>
<td>H → hh → bbττ</td>
<td>12.9 fb⁻¹ (CMS-PAS-HIG-16-029)</td>
<td></td>
</tr>
<tr>
<td>H → hh → bbWW</td>
<td>2.3 fb⁻¹ (CMS-PAS-HIG-16-011)</td>
<td></td>
</tr>
<tr>
<td>H → hh → γγWW</td>
<td></td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-071)</td>
</tr>
<tr>
<td>H → hh → γγbb</td>
<td></td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-004)</td>
</tr>
</tbody>
</table>

Some of these in Exotica talk
## Heavy Higgs Searches @ 13 TeV

### Higgs to fermions

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS Lumi fb⁻¹ (CMS-PAS-HIG-16-006)</th>
<th>ATLAS Lumi fb⁻¹ (ATLAS-CONF-2016-085)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>2.3 fb⁻¹</td>
<td>13.3 fb⁻¹</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>2.7 fb⁻¹</td>
<td></td>
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</table>

### Higgs to vector bosons

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</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>12.9 fb⁻¹</td>
<td>14.8 fb⁻¹</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow ll\nu\nu$</td>
<td>2.3 fb⁻¹</td>
<td>13.3 fb⁻¹</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow llqq$</td>
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</tr>
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<td>$H \rightarrow WW \rightarrow l\nu l\nu$</td>
<td>2.3 fb⁻¹</td>
<td>13.2 fb⁻¹</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow l\nu qq$</td>
<td>included exotica/B2G</td>
<td>13.2 fb⁻¹</td>
</tr>
</tbody>
</table>

### Higgs to Higgs (diHiggs)

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS Lumi fb⁻¹ (CMS-PAS-HIG-16-002)</th>
<th>ATLAS Lumi fb⁻¹ (ATLAS-CONF-2016-049)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow hh \rightarrow bbb\bar{b}$</td>
<td>2.3 fb⁻¹</td>
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<tr>
<td>$H \rightarrow hh \rightarrow bb\tau\tau$</td>
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<td></td>
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<td>$H \rightarrow hh \rightarrow bbWW$</td>
<td>2.3 fb⁻¹ (CMS-PAS-HIG-16-011)</td>
<td></td>
</tr>
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<td>$H \rightarrow hh \rightarrow \gamma\gamma WW$</td>
<td></td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-071)</td>
</tr>
<tr>
<td>$H \rightarrow hh \rightarrow \gamma\gamma bb$</td>
<td></td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-004)</td>
</tr>
</tbody>
</table>

Some of these in Exotica talk
Heavy Higgs $\rightarrow$ ZZ $\rightarrow$ 4l

• Search for an additional heavy scalar
  – Assumed to be produced via the ggF and VBF processes

• Extension of the $H \rightarrow ZZ$ measurement and fits the $m_{4l}$ distribution

• No signal seen we set limits for different decay width $\Gamma_X$ assumptions
Heavy Higgs $\rightarrow \tau\tau$

- In 2HDMs a heavy Higgs boson can have enhanced couplings to down-type fermions
  - Increased heavy Higgs production decaying mainly to $b$ quarks and $\tau$ leptons

- New ATLAS analysis includes new triggers and event categories
  - Combine all categories but separate limits for production mechanism
Higgs → hh → bbττ

- **Resonance search**
  - generally one h(125) → bb [BR=58%]
  - resonance searches benchmark models: spin-0 (radion) and spin-2 (G)

- **Non-resonance search**
  - BSM can be enhanced by resonance or particle in the loop and can be modeled in EFT adding dim-6 operators to the SM Lagrangian
  - can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g
Higgs $\rightarrow hh \rightarrow bb\tau\tau$

- **Resonant search**
  - Fit to the invariant mass of $\tau\tau$ and $bb$
  - At high $m_H$→boosted regime, uses substructure information for jets, b-tag

- **Non-resonant search**
  - Limits as a function of the ratio of the anomalous trilinear coupling to the SM trilinear coupling ($\kappa_\lambda = \lambda_{hhh}/\lambda_{SM}^{hhh}$)
  - At $\kappa_\lambda=1$ value corresponds to $\sim 200$ $(170) \times$ SM prediction
### Charged Higgs Searches @ 13 TeV

<table>
<thead>
<tr>
<th>Charged Higgs</th>
<th>cross-section (fb⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^+ \rightarrow \tau\nu$</td>
<td>14.7</td>
<td>ATLAS-CONF-2016-088</td>
</tr>
<tr>
<td>$H^+ \rightarrow tb$</td>
<td>13.2</td>
<td>ATLAS-CONF-2016-089</td>
</tr>
<tr>
<td>$H^+ \rightarrow WZ$</td>
<td>15.2</td>
<td>CMS-PAS-HIG-16-025</td>
</tr>
</tbody>
</table>
Charged Higgs bosons appear in many extensions of the SM.

**Search for $H^±\rightarrow tb$**

$300 < m_{H^±} < 1000$ GeV

**Search for $H^±\rightarrow \tau\nu$**

$200 < m_{H^±} < 2000$ GeV

**Search for $H^±WZ$**

$15.2$ fb$^{-1}$ (13 TeV)
Exotic decays of the Higgs boson

- Fit of Run-1 SM Higgs measurements/searches provides indirect constraint:
  - $B(H \rightarrow BSM) < 34\%$ at 95\% CL

- Search for BSM decays directly, e.g.
  - $H \rightarrow$ invisible
  - LFV decays, e.g. $e\mu, \mu\tau, e\tau$
  - $H \rightarrow aa$ in nMSSM
### Exotic decays at 13 TeV

| Higgs to invisible |  
|-------------------|----------------------|
| ggF + VH          | 12.9 fb⁻¹ (CMS-PAS-HIG-16-037) |
| combination       | Run 1 + Run 2 (2.3 fb⁻¹) (CMS-PAS-HIG-16-016) |
| ZH                | 12.9 fb⁻¹ (CMS-PAS-HIG-16-038) 13.3 fb⁻¹ (ATLAS-CONF-2016-056) |

### Lepton Flavor Violating Decays

| H → µτ      | 2.3 fb⁻¹ (CMS-PAS-HIG-16-005) |

### h(125) to pseudo-scalars

| h → aa → 2µ2b | Run I full dataset summary of results (CMS-PAS-HIG-16-007) |
| h → aa → 4µ   |                                             |
| h → aa → 2µ2τ |                                             |
| h → aa → 4τ   |                                             |
| W(h → aa → bτ) | 3.2 fb⁻¹ (arXiv:1606.08391) |

### Rare decays

| H/Z → φγ | 2.7 fb⁻¹ (arXiv:1607.03400) |
# Exotic decays at 13 TeV

<table>
<thead>
<tr>
<th>Higgs to invisible</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF + VH</td>
<td>12.9 fb$^{-1}$ (CMS-PAS-HIG-16-037)</td>
</tr>
<tr>
<td>combination</td>
<td>Run 1 + Run 2 (2.3 fb$^{-1}$) (CMS-PAS-HIG-16-016)</td>
</tr>
<tr>
<td>ZH</td>
<td>12.9 fb$^{-1}$ (CMS-PAS-HIG-16-038)</td>
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## Lepton Flavor Violating Decays

<table>
<thead>
<tr>
<th>LNV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \mu \tau$</td>
<td>2.3 fb$^{-1}$ (CMS-PAS-HIG-16-005)</td>
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</table>

## h(125) to pseudo-scalars

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<tbody>
<tr>
<td>$h \rightarrow a \rightarrow 2\mu 2b$</td>
<td>Run I full dataset summary of results (CMS-PAS-HIG-16-007)</td>
</tr>
<tr>
<td>$h \rightarrow a \rightarrow 4\mu$</td>
<td></td>
</tr>
<tr>
<td>$h \rightarrow a \rightarrow 2\mu 2\tau$</td>
<td></td>
</tr>
<tr>
<td>$h \rightarrow a \rightarrow 4\tau$</td>
<td></td>
</tr>
<tr>
<td>$W(h \rightarrow a \rightarrow b\tau)$</td>
<td>3.2 fb$^{-1}$ (arXiv:1606.08391)</td>
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</table>

## Rare decays

<table>
<thead>
<tr>
<th>Rare decays</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H/Z \rightarrow \varphi \gamma$</td>
<td>2.7 fb$^{-1}$ (arXiv:1607.03400)</td>
</tr>
</tbody>
</table>
Many final states explored by ATLAS and CMS
- Many searches depending on m(a) and decay, e.g. a→γγ,μμ,ττ,bb
- No significant deviation from SM expectation in any search
- BR limits range from 0.1% to 100% depending on m(a)
Higgs → invisible

- Search for invisible Higgs boson decays in several production modes, with different cross-sections and S/B ratios

- Assume SM values for ratios of production cross sections

VH includes Z(\(\ell\ell\)), Z(\(bb\)), and V(\(jj\))H channels

Expected sensitivity dominated by vector-boson fusion channel

\[ \sigma x B(\text{H} \rightarrow \text{invisible}) < 24\% \quad (23\% \text{ expected}) \]
Lepton Flavor Violating Higgs

- In the 8 TeV data, CMS found a small excess searching for lepton-flavor violating Higgs couplings in $H \rightarrow \mu \tau$

With 13 TeV, we searched again:

- 0 Jets
  - $\mu \tau$ had: 4.17% (exp.)
  - $\mu \tau$ e: 2.24% (exp.)
- 1 Jet
  - $\mu \tau$ had: 4.89% (exp.)
  - $\mu \tau$ e: 4.36% (exp.)
- 2 Jets
  - $\mu \tau$ had: 6.41% (exp.)
  - $\mu \tau$ e: 7.31% (exp.)

Unfortunately, right on the SM
Summary

• Run II of the LHC at $\sqrt{s} = 13$ TeV is now making an even larger sample of Higgs boson events available for analysis
  – Higgs physics is moving at full speed

• These data are increasing in precision and opening up new channels to study the interactions of Higgs bosons and SM particles
  – Run 2 is surpassing Run 1 precision

• Higher collision energies is allowing us to direct probe for BSM physics by searching for additional Higgs bosons and for anomalous decays of the Higgs(125) boson
  – Many BSM searches presented, more to come soon!
EXTRA MATERIAL
Fiducial Cross Sections

• Differences in the fiducial selections for $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$

• Taken from the links:
  – ATLAS $H \rightarrow \gamma\gamma$ http://cds.cern.ch/record/2206210/files/ATLAS-CONF-2016-067.pdf
  – CMS $H \rightarrow \gamma\gamma$ http://cds.cern.ch/record/2205275/files/HIG-16-020-pas.pdf

• $\gamma\gamma$ differences in fiducial selection:
  – CMS: both photons $|\eta| < 2.5$, excluding $1.44 < |\eta| < 1.57$, 1st $p_T > 30$ GeV, 2nd $p_T > 20$ GeV
  – ATLAS: both photons $|\eta| < 2.37$ (excluding $1.37 < |\eta| < 1.52$), both with $E_T > 25$ GeV and

• $ZZ$ differences in fiducial selection:
  – CMS: 1st lepton $P_T > 20$ GeV, 2nd $P_T > 10$ GeV, other mu $P_T > 5$, ele $P_T > 7$ GeV
  – ATLAS: 1st $P_T > 20$ GeV, 2nd $P_T > 15$, 3rd $P_T > 10$ GeV, 4th mu $P_T > 5$, 4th ele $P_T > 7$ GeV
  – $Z_1$ and $Z_2$ mass cuts also slightly different between experiments

• For both, additional cuts to remove various backgrounds - too hard to tabulate
  • Additional cuts on jets, b-jets, leptons to enrich ttH, VH, VBF categories
Heavy Higgs $\rightarrow$ WW $\rightarrow$ lνlνlνlν

- Extraction of signal done via a fit to the $M_T$ of the 2 leptons and MET
  - Events are categorized according to the jet multiplicity
  - Divided in ggF and VBF

- Limits set for different hypothesis of the signal width
  - ATLAS: low mass limits than previously combined limits
Heavy Higgs $\rightarrow$ WW $\rightarrow$ lνlν

- Extraction of signal done via a fit to the $M_T$ of the 2 leptons and MET
  - Events are categorized according to the jet multiplicity
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- Limits set for different hypothesis of the signal width
  - ATLAS: low mass limits than previously combined limits

Higher masses in Exotic talk
Heavy Higgs → bb

• Narrow heavy neutral boson resonance decaying to b quarks
  – Motivated by excess of data in diphoton (750 GeV)
  – Two benchmark scenarios: a spin-0 resonance produced in gluon-gluon fusion, and a spin-2 Randall-Sundrum graviton, both with a negligible width-over-mass ratio

• Peak in dijet mass spectrum to smoothly falling background
### VBF

<table>
<thead>
<tr>
<th>8 TeV</th>
<th>Upper limit x SM (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>4.4 (5.4)</td>
</tr>
<tr>
<td>CMS</td>
<td>5.5 (2.5)</td>
</tr>
</tbody>
</table>

### VH

<table>
<thead>
<tr>
<th>8 TeV</th>
<th>Observed (expected) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>1.4σ (2.6σ)</td>
</tr>
<tr>
<td>CMS</td>
<td>2.1σ (2.1σ)</td>
</tr>
<tr>
<td>ATLAS+CMS</td>
<td>2.6σ (3.7σ)</td>
</tr>
<tr>
<td>Tevatron</td>
<td>2.8σ</td>
</tr>
</tbody>
</table>
ttH(combination)

- ttH(→bb), tt(multileptons), and ttH(γγ) combined

- Observed significance with respect to background only hypothesis 2.8σ (1.8σ expected)
Heavy Higgs $\rightarrow$ ZZ $\rightarrow$ 4l

- Search for an additional heavy scalar
  - Assumed to be produced via the ggF and VBF processes

- Extension of the H $\rightarrow$ ZZ measurement and fits the $m_{4l}$ distribution

- Decay width $\Gamma_X$ free parameter in the limit, different assumptions considered