Higgs: Rare production and decay channels

Anthony Morley
on behalf of CMS and ATLAS Collaborations
The Higgs boson was discovered almost 5 years ago
- Initial studies of its properties have been inline with SM predictions
- Many rare decays have yet to be observed
  - May be sensitive to new physics if additional Higgs couplings exist
- Constraints on new particles coupling to the Higgs are still relatively loose
  - Room for beyond the standard model (BSM) physics: Run 1 limit $B(H \to \text{BSM}) < 34\%$
- New Higgs decay would definitively be a BSM signature
- Disclaimer: This is not a full list of analysed channels. Focus on recent results made public with the 13 TeV dataset.

Higgs pair production
$H \to \ell\ell\gamma$
$H \to \mu\mu$

Invisible decays
Lepton flavour violating (LFV) decays
Exotic Higgs boson decays

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The SM prediction for the cross section is $\sigma_{HH} = 33.4$ fb at 13 TeV
- SM: destructive interference between the two processes
- Trilinear self-coupling of the Higgs boson ($\lambda_{HHH}$) can be extracted from the measurement of the Higgs boson pair production cross section.
- Crucial to test shape of $V_H$ & thus test origin of electroweak symmetry breaking
- Enhanced HH production possible in many extensions of the SM
  - Non-resonant: Modify $\lambda_{HHH}$ or introduce new vertices
  - Resonant: Significant cross-section enhancement on resonance (up to pb) Exploit $m_X$ to reduce (and to model) backgrounds
Analysis Improvements

**High-mass:**
Increased signal acceptance including >=1 b-tagged jet matched to H-jet (instead of >=2 previously)

**Low mass & non-resonant**
Increase signal acceptance by loosening topological selection requirements

- Resolved regime: reconstruct 4 jets $R=0.4$ ($m_X <1000 \text{ GeV}$ & non-resonant production)

- Boosted regime: reconstruct 2 fat jets $R=1.0$ ($m_X >1000 \text{ GeV}$)

<table>
<thead>
<tr>
<th></th>
<th>95% CL UL expected</th>
<th>95% CL UL observed</th>
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<tbody>
<tr>
<td>$\sigma(pp \rightarrow HH \rightarrow bbbb)$</td>
<td>430 fb</td>
<td>330 fb</td>
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</table>

• corresponds to 29 times the SM prediction

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• Search for a resonant-like excess compatible with $m_H$ in $m_{bb}$ distribution

• Use deep neural network (DNN) to improve signal-to-background separation

<table>
<thead>
<tr>
<th>$\sigma(\text{pp} \rightarrow \text{HH} \rightarrow \text{bb} \ell \nu \ell \nu)$</th>
<th>95% CL UL expected</th>
<th>95% CL UL observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$81^{+42}_{-25}$ fb</td>
<td>72 fb</td>
<td></td>
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</table>

• The observed upper limit corresponds to approximately 79 times the SM prediction
• 3 $\tau\tau$ final states ($\tau_e\tau_h, \tau_\mu\tau_h, \tau_h\tau_h$)
  • $m_{\tau\tau}$ reconstructed using a likelihood technique

• Additional Categorisation based on b-jet candidates
  • 2b-tagged jet category
  • b-tagged jet + 1 untagged jet category
  • “boosted” category with a $R=0.8$ jet to improve reconstruction $H$ decays at high $m_X$

• The observed upper limit corresponds to approximately 28 times the SM prediction, while the expected one is about 25 times the SM prediction.
Higgs Pair production

Analyses @ 13 TeV

Original table from Luca Cadamuro

- Each analysis is complementarity and sensitive to different resonant mass ranges
- Analysis techniques are improving all of the time
- Experimental conditions are becoming more challenging
- A lot to be gained from a combination!

<table>
<thead>
<tr>
<th>Channel</th>
<th>Obs. (exp.) 95% C.L. limit on $\sigma/\sigma_{SM}$</th>
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<tbody>
<tr>
<td></td>
<td>ATLAS</td>
</tr>
<tr>
<td>bbbb</td>
<td>29 (38)</td>
</tr>
<tr>
<td></td>
<td>ATLAS-CONF-2016-049</td>
</tr>
<tr>
<td>bbWW</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
<tr>
<td>bbττ</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
<tr>
<td>bbγγ</td>
<td>117 (161)</td>
</tr>
<tr>
<td></td>
<td>ATLAS-CONF-2016-004</td>
</tr>
<tr>
<td>WWγγγ</td>
<td>747 (386)</td>
</tr>
<tr>
<td></td>
<td>ATLAS-CONF-2016-071</td>
</tr>
</tbody>
</table>

~2-3 fb$^{-1}$  ~13 fb$^{-1}$  ~36 fb$^{-1}$
H → invisible

- Really small BR in the SM: \( \text{BR}(H \to \text{invisible}) \sim 0.1\% \) (from \( H \to ZZ^* \to 4\nu \))
  - Any measurable rate will be a sign for new physics

- Need to tag Higgs event via production mode
  - \( ggF(gg \to gH), \) VBF, VH

- \( g \to H \to \text{invisible} \)

- \( \gamma \to \text{invisible} \)

- \( Z \to \ell \ell \): smallest \( \sigma \)
  - High \( S/B \)
  - Dijet system with large rapidity gap - \( \Delta \eta(j_1, j_2) \)
  - Large dijet mass - \( m_{jj} \)

- \( W/Z \to \ell \ell \): smallest \( \sigma \)
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  - Dijet system with large rapidity gap - \( \Delta \eta(j_1, j_2) \)
  - Large dijet mass - \( m_{jj} \)

- \( W/Z \to q\bar{q} \): moderate \( \sigma \)
  - Moderate \( S/B \)
  - 2 resolved or boosted jet with mass close to \( m_Z/m_W \)

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• Combined CMS: Run 1 + 2.3 fb$^{-1}$ at 13 TeV
  • no excess observed
  • BR(H→inv) < 0.24 (obs), 0.23 (exp)

• ATLAS similar results when combining run 1 results (JHEP 11 (2015) 206)
  • BR(H→inv) < 0.25 (obs), 0.27 (exp)

• ATLAS: generic Z→$\ell\ell + E_T$(miss) search using 13.3 fb$^{-1}$ of 13 TeV (ATLAS-CONF-2016-056)
  • BR(H→inv) < 0.98 (obs), 0.65 (exp)
H → Zγ decay proceeds via loop diagrams similar to those in γγ and has a similar branching ratio

- Due to the branching fraction of Z → ℓℓ sensitivity is much smaller

- Modifications of the H → Zγ branching ratio compared to the SM prediction are expected if:
  - H were a neutral scalar of different origin,
  - H is a composite state,
  - In models with additional colourless charged scalars, leptons or vector bosons coupled to the Higgs boson and exchanged in the H → Zγ loop

- Run 1
    \[ \text{BR}(H \rightarrow Z\gamma) < 9.5 \text{ BR}_{\text{SM}}(H \rightarrow Z\gamma) \]
    \[ \text{BR}(H \rightarrow Z\gamma) < 11 \text{ BR}_{\text{SM}}(H \rightarrow Z\gamma) \]
H→Zγ: Strategy

- Relies on the good mass resolution.
- 6 categories are used to enhance sensitivity
- Signal shape:
  - Modelled by double sided Crystal-Ball
- Background shape modelled on expected background from Z+γ (fast) simulation:
  - Bernstein polynomials used
  - Parameters extracted from fit to data
- The SM background composition (Z+jets, Z+γ) is estimated by data-driven method.
  - The reducible Z+jets < 20% of the events in all categories
H→Zγ: Results

<table>
<thead>
<tr>
<th>95% CL Upper limit</th>
<th>Expected without Higgs boson decays</th>
<th>Expected with SM Higgs boson</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ · BR / (σ · BR)_{SM}</td>
<td>4.4</td>
<td>5.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>
• Sensitivity to s-quark Yukawa couplings

• Reconstruct $\phi \rightarrow K^+K^-$
  • $\text{BR}(\phi \rightarrow K^+K^-) = 49\%$

• Two high-pT (20, 15 GeV) isolated collinear tracks ($\Delta R < 0.05$, $m_{KK} \sim m_{\phi}$) recoiling against $\gamma$ ($p_T > 35$ GeV)

• Dedicated trigger (~78% efficiency wrt. offline selection)

• Data-driven template modelling of background.

- Main background from random tracks and γ combinations in multi-jet and γ+jet
  - Background modelled with non-parametric data-driven approach
- Events from a loose selection are used to build templates for the kinematic distributions of the φ candidate and photon
  - Distributions are then sampled (retaining correlations with $p_T$) and used to build pseudo-candidates
- Large samples of pseudo-candidates are used to build background model templates
- Model validated in control regions with looser selection.
- Model shape uncertainty estimated from modifications to modelling procedure (e.g. shifting $p_T^{KK}$ and neglecting the weakest correlation included in the model)
• Unbinned maximum likelihood fit on $m_{KK\gamma}$

<table>
<thead>
<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(H \rightarrow \phi\gamma) [10^{-3}]$</td>
<td>$1.5^{+0.7}_{-0.4}$</td>
<td>1.4</td>
</tr>
<tr>
<td>$B(Z \rightarrow \phi\gamma) [10^{-6}]$</td>
<td>$4.4^{+2.0}_{-1.2}$</td>
<td>8.3</td>
</tr>
</tbody>
</table>

• Predicted SM values:
  • $BR(H \rightarrow \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$
  • $BR(Z \rightarrow \phi\gamma) = (1.17 \pm 0.08) \times 10^{-8}$

• First limits on these rare exclusive processes ($\sim 600/700$ times the expected SM branching fraction)

H → X(→ ll)γ

- ATLAS perform a search using the same method as for H → Φγ search
  - BR(H → J/ψγ) < 0.15%
  - BR(H → Y(1S,2S,3S)γ) < (0.13%, 0.19%, 0.13%)
- CMS performed the search using low di-lepton mass very similar to the H → Zγ analysis but with m_ll < 20 GeV
  - BR(H → γ*γ) < 6.7 x BR_{SM}(H → γ*γ)
  - BR(H → J/ψγ) < 0.15%

• $H \rightarrow \mu\mu$ is the cleanest channel to observe Higgs coupling to second generation fermions.

• The branching fraction in this channel for a 125 GeV SM Higgs boson is $2.2 \times 10^{-4}$, about ten times smaller than that for $H \rightarrow \gamma\gamma$.

• The dominant and irreducible background arises from the $Z/\gamma^* \rightarrow \mu\mu$ process which has a rate several orders of magnitude larger than that from the SM Higgs boson signal.

• Analysis follow a similar path to $H \rightarrow Z\gamma$
**H → μμ**

- **ATLAS Run 2**
  - $m_H = 125$ GeV, 95% CL upper limits $< 3.0$ (3.1) observed (expected) x SM prediction

- **ATLAS Run 1 + Run 2**
  - $< 2.8$ (2.9) observed (expected) x SM prediction.


- **CMS Run 1: H → μμ**
  - $m_H = 125$ GeV, 95% CL upper limits $< 7.4$ (6.5) x $\sigma_{SM}$ observed (expected)

- **CMS Run 1: H → ee**
  - $m_H = 125$ GeV, 95% CL upper limits $\sigma(H)\times BR < 0.041$ (0.052) pb observed (expected)
  - BR$<0.0019$ or $\sim 3.7 \times 10^5$ x SM BR

*arXiv:1705.04582*
LFV decays

- Direct searches for LFV Higgs decays, in the three decay channels: $\mu\tau$, $\mu e$, $e\tau$, have been performed
  - Complementary to the SM $H\to\tau\tau$ and $H\to\mu\mu$ searches
- BSM models (e.g. with an additional Higgs doublet) allow LFV decays of $H$
  - Only loose indirect limits prior to LHC for $H\to\mu\tau$ and $H\to e\tau$
- Slight excess of the CMS 8 TeV result not confirmed (but not excluded) by the first preliminary 13 TeV results
- No deviation from the background-only hypothesis is observed for the $e\tau$ channel or $\mu e$ channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Experiment</th>
<th>95% CL obs (exp) limit</th>
<th>Best fit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\to\mu e$</td>
<td>CMS 8 TeV</td>
<td>0.036% (0.048%)</td>
<td></td>
<td>Phys. Lett. B 763C (2016) 472</td>
</tr>
<tr>
<td>$H\to e\tau$</td>
<td>ATLAS 8 TeV</td>
<td>1.04% (1.21%)</td>
<td></td>
<td>Eur. Phys. J. C 77 (2017) 70</td>
</tr>
<tr>
<td></td>
<td>CMS 8 TeV</td>
<td>0.69% (0.75%)</td>
<td></td>
<td>Phys. Lett. B 763C (2016) 472</td>
</tr>
<tr>
<td>$H\to\mu\tau$</td>
<td>ATLAS 8 TeV</td>
<td>1.43% (1.01%)</td>
<td>$0.53^{+0.51}_{-0.51}$%</td>
<td>Eur. Phys. J. C 77 (2017) 70</td>
</tr>
<tr>
<td></td>
<td>CMS 8 TeV</td>
<td>1.51% (0.75%)</td>
<td>$0.84^{+0.39}_{-0.37}$%</td>
<td>Phys. Lett. B 749 (2015) 337</td>
</tr>
<tr>
<td></td>
<td>CMS 13 TeV</td>
<td>1.20% (1.62%)</td>
<td>$0.76^{+0.81}_{-0.84}$%</td>
<td>CMS-PAS-HIG-16-005</td>
</tr>
</tbody>
</table>
**LFV decays**

- Updated analysis using full 2015 +2016 dataset and improve analysis methods
  - Collinear mass-fit expected 95% CL < 0.49%
  - BDT-fit expected 95% CL < 0.25%

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<th>95% CL obs (exp.) limit</th>
<th>Best fit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow \text{ee})</td>
<td>CMS 8 TeV</td>
<td>0.72 (0.56)</td>
<td>0.23 ± 0.24 %</td>
<td>CMS-PAS-HIG-17-001</td>
</tr>
<tr>
<td>(H \rightarrow \mu\tau)</td>
<td>CMS 13 TeV</td>
<td>0.25% (0.25%)</td>
<td>0.00 ± 0.12 %</td>
<td>CMS-PAS-HIG-17-001</td>
</tr>
</tbody>
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Exotic decays

CMS-PAS-HIG-16-035

- Background dominated by $b\bar{b}$ and $J/\Psi$ events
  - Data driven determination of backgrounds
- Target $2m_\mu \leq m_a \leq 2m_\tau$ as $\text{BR}(a \rightarrow \mu\mu)$ can be large in this regime
- Covers very low mass range: 0.25-3.55 GeV expect improved sensitivity with the full 13 TeV dataset interpretation in terms of models with dark photons also available
Exotic decays

- Trigger events using leptons from the W decays
- Major background tt + X
- Target $m_a > 2m_b$ as $\text{BR}(a \rightarrow bb)$ can be large in this regime
- Categories based on the number of jets and b-jets are in the event
- Use multivariate technique and detailed background modelling to improve sensitivity
- Loss in sensitivity at low $m_a$ due to merged jets


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Summary

• The SM-like Higgs boson discovery opens a new era of precision physics
• A wide variety of measurement have been performed at ATLAS & CMS
  • This will continue to be broadened during Run II
• Many rare decays have not been observed yet but may become observable in the next few years
• Unfortunately still no evidence for BSM Higgs decays
  • Small fluctuation LFV decay $H \rightarrow \mu \tau$ from 8 TeV data neither has now been excluded from using 13 TeV data.
• More details in:

Exotic and Rare Decays - Tuesday Morning:
• Marija Marjanovic (ATLAS) & Cecile Caillol (CMS)

Di-Higgs production - Wednesday Morning
• Harald Fox (ATLAS) & David Morse (CMS)

BSM decays - Wednesday Morning:
• Gianni Masetti (CMS) & Arno Straessner (ATLAS)
• Many posters to explore as well
• Qi Li (HH→WWγγ) & Shuo Han (H→Zγ)