Searches for Exotic and Rare Higgs Decays
(ATLAS+CMS)

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Higgs discovery gives a new opportunity: study it in detail and look for RARE or EXOTIC decays

Non-SM couplings?
- $H \rightarrow Z\gamma, \ell\ell\gamma$
- $1^{\text{st}}$ and $2^{\text{nd}}$ generation couplings?
  - $H \rightarrow \mu\mu$
  - $H \rightarrow \text{meson} + \gamma$
  - $Z + H \rightarrow c\bar{c}$
  - $H \rightarrow \eta\tau, \mu\tau$

Decays to new particles?
- $h \rightarrow \text{invisible}$
- $h \rightarrow \gamma + \text{MET}$
- $h \rightarrow \text{other bosons (a, } Z_D)$

| $H \rightarrow a^0 a^0 \rightarrow \mu\mu\tau\tau$ | BR $\sim (3.5 - 100)\%$ | arXiv:1505.01609 |
| $H \rightarrow a^0 a^0 \rightarrow \gamma\gamma\gamma\gamma$ | BR $\sim (0.02 - 0.2)\%$ | arXiv:1509.05051 |
| $H \rightarrow a^0 a^0 \rightarrow 4\mu$ | BR $\sim (0.02 - 100)\%$ |
| $H \rightarrow Z_D Z_D \rightarrow 4\ell$ | BR $\sim (5 - 30) \times 10^{-5}$ | arXiv:1802.03388 |
| $H \rightarrow ZZ_D \rightarrow 4\ell$ | BR $\sim 0.1\%$ |
| $H \rightarrow a^0 a^0 \rightarrow \gamma\gamma jj$ | BR $\sim 10\%$ | arXiv:1803.11145 |
| $WH \rightarrow \ell\nu a^0 a^0 \rightarrow \ell\nu 4b$ | (1.5-6.2) pb | arXiv:1606.08391 |

$h \rightarrow aa \rightarrow 2X2Y$  CMS HIG-17-029
$H \rightarrow Z\gamma, H \rightarrow \ell\ell\gamma$

Present in the SM, but very small rate

Loop-induced decay, sensitive to new physics

Multiple event categories used to enhance signal sensitivity by 11-18%
H→Zγ, H→llγ

First hint of decay seen?

ATLAS limit: H→Zγ < 6.6 (5.2) xSM - arXiv:1708.00212

- observed (expected) upper limit for σ/σ_{SM} is 3.9 (2.0)
- corresponding to an observed (expected) p-value of ~2σ (~1σ)
$H \rightarrow \mu\mu$

Very rare decay, BR=2.18E-4

Clean and narrow peak, but huge background

Only SM H decay to 2$^{nd}$ generation expected to be seen at LHC

Could be enhanced by new physics

BDT and 15 event categories (based on BDT and mass resolution) used to enhance sensitivity
Combining Run1 and 2015/16 data, limit less than a factor of 3 away from SM rate!

First tiny hint of the decay being seen already?!

<table>
<thead>
<tr>
<th>Dataset</th>
<th>95% CL limit on $\sigma/\sigma_{SM}$ observed (expected)</th>
<th>Significance observed (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 TeV (35.9/fb)</td>
<td>2.64 (2.08)</td>
<td>0.74 (0.98)$\sigma$</td>
</tr>
<tr>
<td>7 TeV + 8 TeV + 13 TeV</td>
<td>2.64 (1.89)</td>
<td>0.98 (1.09)$\sigma$</td>
</tr>
</tbody>
</table>

- upper limit on BR($H\rightarrow\mu\mu$) is $5.7 \times 10^{-4}$
H→mumu

ATLAS also has an advanced analysis, with 8 event categories and a BDT for VBF for enhanced sensitivity.

Combining Run1 + 2015/16 data: BR<2.8 (2.9) x SM rate

Mass resolution here is driven by the inner-tracker momentum resolution... higher B-field helps!

To improve sensitivity by x3, need ~9 times more data

9 x 40/fb = ~400 /fb

Good chance of seeing hints of this decay in Run3!

Innovative set of ATLAS searches using meson decays

Search for enhanced Higgs couplings to 1\textsuperscript{st} and/or 2\textsuperscript{nd} generation quarks

Uses triggers and background estimate techniques from B-physics group!

\textbf{Direct} \hspace{2cm} \textbf{Indirect}

- Window to 1\textsuperscript{st} and 2\textsuperscript{nd} generation Yukawa couplings
- Distinctive topology to trigger and select events
- Target mesons:
  - $\rho$: $\text{BR}_{\text{SM}}(H \to \rho \gamma) = 1.7 \times 10^{-5}$ $\dagger$, $\rho \to \pi^+\pi^-$
  - $\phi$: $\text{BR}_{\text{SM}}(H \to \phi \gamma) = 2.3 \times 10^{-6}$ $\dagger$, $\phi \to K^+K^-$
  - $J/\psi$: $\text{BR}_{\text{SM}}(H \to J/\psi \gamma) = 2.8 \times 10^{-6}$ $\ddagger$, $J/\psi \to \mu^+\mu^-$
  - $\Upsilon$: $\text{BR}_{\text{SM}}(H \to \Upsilon(1S, 2S, 3S) \gamma) = (6.1, 2.0, 2.4) \times 10^{-10}$ $\ddagger$, $\Upsilon \to \mu^+\mu^-$

$H \rightarrow \text{meson} + \gamma$

Not close to SM, but would see enhanced decay

- $\text{BR}(H \rightarrow \rho\gamma) < 8.8 \times 10^{-4}$ (52xSM)
- $\text{BR}(H \rightarrow \phi\gamma) < 4.8 \times 10^{-4}$ (208xSM)

Unbinned maximum likelihood fits extract 95% CL limits of:

- $\text{BR}(H \rightarrow J/\psi\gamma) < 1.5 \times 10^{-3}$
- $\text{BR}(H \rightarrow \Upsilon(1S, 2S, 3S)\gamma) < (1.3, 1.9, 1.3) \times 10^{-6}$
**H→ZH→ll cc**

**ATLAS also looks for direct H→cc decays**

Use associated production with Z for triggering and to enhance S/sqrt(B)

Use charm-jet tagging!

Split into low and high Z pT categories

BR $H \rightarrow cc < 110 \ (150^{+80}_{-40})$ times SM

arXiv:1802.04329
$H \to e^{\pm}\tau$ / $\mu^{\pm}\tau$

Lepton flavor violating – clearly would be new physics

Use multiple tau-decay channels, Higgs production categories, and BDT fits to improve sensitivity
H → invisible

\[ \text{BR}(H \rightarrow ZZ \rightarrow 4\nu) = 0.1\% \text{ in SM} \]

Many possible extensions of the SM would allow enhance the rate: decays to dark matter, hidden valleys / portals, ...

CMS use combination of VBF-tagged, associated W/Z (including boosted W/Z → quarks!), and ISR/mono-jet

\[ \text{BR}(H \rightarrow \text{invisible})<24 \ (18) \% \text{ (at 95\% CL)} \]

ATLAS ZH search: \[ \text{BR}(H \rightarrow \text{invisible})<67 \ (39) \% \text{ (at 95\% CL)} \]
H → ZZ_D or Z_DZ_D

Reuse technology of H→4l measurement to search for new “hidden sector” decays

Dual range analysis:
- Low mass: 1 < m_{a_o} & Z_D < 15 GeV, 4μ only
- High mass: 15 < m_{a_o} & Z_D < 60 GeV, 4μ + 2μ2e + 4e

Select quadruplet with min: Δm = |m_{12} − m_{34}|
Observable: ⟨m⟩ = (m_{12} + m_{34})/2

Set limits in the range of BR(H→Z_DZ_D) < ~10^{-4} − E^{-3} and BR(H→ZZ_D) < ~E^{-3}
Summary

Large range of rare and exotic Higgs decays considered by ATLAS/CMS!

• $H \rightarrow Z\gamma$, $l\ell\gamma$
• $H \rightarrow \text{mumu}$
• $H \rightarrow \text{meson} + \gamma$
• $Z + H \rightarrow cc$
• $H \rightarrow \text{etau, mutau}$
• $h \rightarrow \text{invisible}$
• $h \rightarrow \gamma + \text{MET}$
• $h \rightarrow \text{other bosons (a, Z}_D)$

Sensitive to many new-physics scenarios

Closing in on some rare SM Higgs decays

Run3 (and HL-LHC) will be critical for these statistics-limited searches... stay tuned!