Searches for rare and exotic Higgs decays with ATLAS

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Outline

Introduction

Rare Higgs decays
- Higgs decay to $\phi \gamma$
- Higgs decay to $J/\psi \gamma$ and $\Upsilon(nS)\gamma$
- **NEW** Higgs decay to $Z \gamma$

Beyond Standard Model Higgs decays
- Higgs to light resonances
- Lepton Flavour Violating decays of the Higgs boson
- Higgs to invisible particles

Conclusion and Outlook
Introduction

Higgs boson has been observed in several decay channels

Standard Model (SM) predicts more channels:

- Some of them with very small branching fraction
- An excess on these channels (or any) would be an indication of Beyond Standard Model (BSM) physics

Exotic Higgs decays and couplings

- New light resonances
- Flavour Violating decays
- Invisible decays

Predicted by many Beyond Standard Model (BSM):

- Models with an extended Higgs sector
  - 2HDM and NMSSM
- Higgs Portal models of dark matter
- Theories of Neutral Naturalness

$\text{m}_H = 125 \text{ GeV}$
Introduction

Current measurements constrain BSM decays to < 34% not only assuming SM branching ratio, but also the production cross section.

The constraints assumed compatible with a wide range of BSM physics:

- Loop-induced processes of $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ decay
- Potential deviations from the SM of the tree-level couplings to ordinary particles parameterised with their respective coupling modifiers
  - $K_Z$, $K_W$, $K_t$, $K_b$, $K_g$, $K_\gamma$, $K_{BSM}$

$B_{BSM}$ is the total branching fraction into BSM decays.

Applies to invisible decays into BSM particles and modifications of the decays into SM particles that are not directly measured by the experiments.
Rare Higgs decays

Higgs to $\phi\gamma$
- $13$ TeV
- $2.7$ fb$^{-1}$

Higgs to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$
- $8$ TeV
- $19.2$ fb$^{-1}$

Higgs to $Z\gamma$
- $13$ TeV
- $36.1$ fb$^{-1}$
Exotic Higgs decays

Higgs decays to new particles

Lepton flavour violating decays

Higgs to invisible

13 TeV 3.2 fb\(^{-1}\)

8 TeV 20.3 fb\(^{-1}\)

13 TeV 13.3 fb\(^{-1}\)
Rare Higgs decays
Higgs decay to $\phi\gamma$

SM predicts very small branching fraction - $10^{-6}$
- Larger values could come from new physics
- Sensitive to Higgs – strange quark couplings

Select events with:
- $\phi$ candidate reconstructed from tracks
- Photon $\gamma$

Main backgrounds:
- Multijet, $\gamma +$ jets

Background estimate is quite specific as the background shape is generated from the templated final state particles kinematics and correlations
- Estimated in region with relaxed $\gamma$ isolation requirement

Background model is validated with data in samples with relaxed kinematic and isolation criteria
Higgs decay to $\phi\gamma$

Total signal efficiency is 18%

Systematic uncertainties
- Track reconstruction efficiency 6%
- Shape of the background 3%
- Photon identification efficiency 2.4%

No significant excess is observed
- Set upper limit on Higgs branching ratio

SM prediction of $B(H\rightarrow\phi\gamma)=(2.3+/\mathbf{-}0.1)*10^{-6}$

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

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ATLAS
\(\sqrt{s}=13\) TeV, 2.7 fb\(^{-1}\)

LPC

13 TeV
2.7 fb\(^{-1}\)
Higgs decay to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$

Sensitive to both the magnitude and sign of the Yukawa couplings of the Higgs boson to quarks

Challenging because of large QCD background

Reconstruct $m(\mu\mu\gamma)$

Similar analysis technique as in $\phi\gamma$

Simultaneous unbinned maximum likelihood fit
  - performed to the selected events with $30 \text{ GeV} < m_{\mu\mu\gamma} < 230 \text{ GeV}$
  - separately in each of the analysis categories

Four exclusive categories, based upon the $\mu$ pseudorapidity and $\gamma$ reconstruction classification


8 TeV
19.2 fb$^{-1}$
Higgs decays to $J/\psi \gamma$ and $\Upsilon(nS)\gamma$

No significant excess of data over background is observed

SM calculation predicts:
- $B(H \to J/\psi \gamma) = (2.80 \pm 0.2) \times 10^{-6}$
- $B(H \to \Upsilon(nS)\gamma) \sim 10^{-10}$

The 95% C.L. upper limit on the $B(H \to J/\psi \gamma)$ corresponds to about 540 times the expected SM branching fraction

![Graph showing the 95% CL upper limit on Branching Fraction for various Higgs decays](Image)


8 TeV
19.2 fb$^{-1}$
Higgs decays to $Z\gamma$

Events are split into 6 exclusive event categories
- optimised to improve the sensitivity of both the $\rightarrow Z\gamma$ and high-mass resonance searches

Reoptimisation of the categories brings a 20% improvement in sensitivity wrt the Run1 categories

VBF-enriched:
- Events with at least two jets
- Uses BDT to separate VBF events from other Higgs boson production modes and non-Higgs backgrounds

High relative $p_T$

Low and high $ee$ $p_Tt$ regions

Low and high $\mu\mu$ low $p_Tt$

$$p_{Tt} = 2 \frac{|p_x^Z p_y^\gamma - p_x^\gamma p_y^Z|}{p_T^Z}$$

$P_{Tt}$ - orthogonal component of the transverse momentum of the Z system when projected on the axis given by the difference of the 3-momenta of the Z boson and the photon candidate
Higgs decays to Zγ

**NEW**
Background-only fit performed in the range of $115 < m_{Z\gamma} < 150$ GeV

No evidence of a localized excess is visible near Higgs mass $m_H = 125.09$ GeV

<table>
<thead>
<tr>
<th>$m_H = 125.09$ GeV</th>
<th>p-value</th>
<th>local significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected</td>
<td>0.33</td>
<td>0.5 $\sigma$</td>
</tr>
<tr>
<td>observed</td>
<td>0.16</td>
<td>1.0 $\sigma$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_H = 125.09$ GeV</th>
<th>no Higgs boson decay into Z</th>
<th>a SM Higgs boson decay into Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected 95% CL</td>
<td>4.4 SM expectation</td>
<td>5.2 SM expectation</td>
</tr>
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</table>

Assuming SM Higgs boson production a limit on the $\text{BR}(H \rightarrow Z)$ is 0.01
Higgs decays to $Z\gamma$

The largest deviation observed around $m_X = 960$ GeV corresponding to a local (global) significance of 2.7 (0.8)
Exotic Higgs decays
Higgs to Light Scalars

Many different models predicting different branching fractions
- In many of them, $a \rightarrow b\bar{b}$ is the preferred decay when $m(a) > 2m(b)$

Higgs production in association with a $W$ boson, decaying leptonically
- Charged lepton from $W$ decay important to efficiently trigger and identify these events against strong production of $b$-jets

Large background mainly top quark pairs

Use multivariate technique used to improve sensitivity

Simultaneous fit in control and signal regions based on number of jets and $b$-jets
- Estimate the main backgrounds in control regions

\[ \text{ATLAS} \]
\[ s = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \]
4 jets, 4 $b$-tags
$H \rightarrow 2a \rightarrow 4b$, $m_a = 60 \text{ GeV}$

\[ \text{Data 2015} \]
- WH
- $t\bar{t} + \text{light}$
- $t\bar{t} + c\bar{c}$
- $t\bar{t} + b\bar{b}$
- Non-$t\bar{t}$

\[ \text{BDT output (4j, 4b)} \]
Higgs to Light Scalars

Loss in sensitivity at low mass due to overlapping b-jets

Main uncertainty is statistics
- Large improvement expected with more data


13 TeV
3.2 fb⁻¹
Search for the LFV signal by fitting $m_{MMC}$
- Aim to reconstruct the Higgs mass

Missing mass calculator (MMC):
- version of the collinear approximation
- relative orientations of the neutrino and other $\tau$-lepton decay products are consistent with the mass and kinematics of a $\tau$-lepton decay.

$$m_{\text{coll}} = \sqrt{2p_T^{\ell_1}(p_T^{\ell_2} + E_T^{\text{miss}})} (\cosh \Delta \eta - \cos \Delta \phi)$$

Template fits to the collinear mass distribution
A simultaneous fit is performed in signal and control regions

- Uncorrelated systematics uncertainties as background estimation techniques are different

Set 95% CL upper limits:

- Computed under assumption that either BR($H \rightarrow \mu\tau$)=0 or BR($H \rightarrow e\tau$)=0

### ATLAS

**$t_s = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$**

- **$\eta_{\text{had}}$, SR1**
- **$\eta_{\text{had}}$, SR2**
- **$\eta_{\text{had}}$, Comb**
- **$\eta_{\text{lep}}$, SR$^\text{noJ}$**
- **$\eta_{\text{lep}}$, SR$^\text{withJ}$**
- **$\eta_{\text{lep}}$, Comb**

**95% CL upper limit on Br($H \rightarrow e\tau$), %**

### ATLAS

**$t_s = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$**

- **$\mu_\tau$, SR1**
- **$\mu_\tau$, SR2**
- **$\mu_\tau$, Comb**
- **$\mu_\tau$, SR$^\text{noJ}$**
- **$\mu_\tau$, SR$^\text{withJ}$**

**95% CL upper limit on Br($H \rightarrow \mu\tau$), %**

CMS saw small excess in $H \rightarrow \mu\tau$ channel corresponding to 2.4 $\sigma$
Higgs invisible decays

Searching for an excess over SM in the ZZ transverse mass distribution and in the $E_T^{\text{miss}}$ distribution.

Final state
- two high-$p_T$ leptons from a Z boson decay
- Large $E_T^{\text{miss}}$

Main backgrounds
- ZZ, WZ

$$ (m_{\text{ZZ}}^2)^2 = \left( \sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2} \right)^2 - |\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}}|^2 $$
Higgs invisible decays

Results are compatible with SM expectation

Small BF to invisible particles
- \( \sim 0.1\% \) in the \( H \rightarrow ZZ \rightarrow \nu\nu\nu\nu \) channel
- far below the experimental sensitivity

Interpreted in many different models
Conclusion and Outlook

Searches for rare and exotic Higgs decays with the ATLAS detector with 8 TeV and 13 TeV

- Increase of sensitivity with more data
- More possibilities to explore to cover full spectrum

No significant deviations from the Standard Model found

- Limits on different models extended or set for the first time
Back up
Back up

\[ m_T = \sqrt{2p_T^{\ell\ell} E_{T}^{\text{miss}} \left[ 1 - \cos \Delta \phi \left( p_T^{\ell\ell}, E_{T}^{\text{miss}} \right) \right]} \]
Higgs decays to $J/\psi \gamma$

Motivation:
- May have sensitivity to magnitude and sign of Yukawa couplings to quarks
  - These are challenging through $H \rightarrow qq\bar{q}$ decays b/c of large QCD background
- Light Yukawa couplings - proposed channels:
  - $J/\psi$ or $\Upsilon(nS)$ (denoted as $Q$) is most readily accessible
  - $J/\psi \gamma$ may represent a viable probe of $Hc\bar{c}$ coupling (sensitive to Beyond Standard Model physics)
- Theory calculations
  - $\mathcal{B}(H \rightarrow J/\psi\gamma) = (2.8 \pm 0.2) \times 10^{-6}$
  - $\mathcal{B}[H \rightarrow \Upsilon(nS)] = (6.1, 2.0, 2.4) \times 10^{-10}$
- No experimental evidence yet
- These decays are a source of background and potential control sample for the nonresonant decays $H \rightarrow \mu^+\mu^-\gamma$ sensitive to new physics
Higgs decays to $Z\gamma$

No significant excess is observed.
Higgs decays to $Z\gamma$
Higgs decays to $Z\gamma$

p0 distribution for the individual ee and $\mu\mu$ and combined categories

- using a spin-0 resonance produced via gluon-gluon fusion as signal model

The largest deviation observed around $m_X = 960$ GeV corresponding to a local (global) significance of 2.7 (0.8)
Higgs decays to $Z\gamma$

- p0 distribution for the individual ee and $\mu\mu$ and combined categories
  - using a spin-0 resonance produced via gluon-gluon fusion as signal model

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**ATLAS** Internal

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$gg \rightarrow X \rightarrow Z\gamma$

$J_X = 0$, $\Gamma_X = 4$ MeV

95% CL Upper Limit on $\sigma \times B$ (fb)

Local $p_0$

Global significance of $p_0$ at $m_X = 960$ GeV: 0.8$\sigma$