Search for non-standard, rare or invisible decays of the Higgs boson with the ATLAS detector

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On behalf of the ATLAS Collaboration
Rare Higgs Decays

- **Higgs Boson** discovered 5 years ago. Initial measurements in line with Standard Model (SM) predictions.
- Many rare decays yet to be measured. Sensitive to new physics Beyond the Standard Model (BSM) if additional Higgs couplings exist.
- Run 1 ATLAS limit $B(H \rightarrow \text{Inv}) < 23(24)\%$ observed (expected).
- New Higgs decay would be a signature of BSM Physics!

**Focus here on** latest ATLAS results at 13 TeV:
- $H \rightarrow \text{Invisible}$
- $H \rightarrow ZZ$
- $H \rightarrow \phi \gamma, H \rightarrow \rho \gamma$
- Lepton Flavour Violating Decays (Run 1 – see backup)
- Decays to nMSSM pseudo scalars $h \rightarrow aa$ (see talk from Michel Janus on Friday).
Latest ATLAS Results

Many ATLAS analyses producing results using full 2015+2016 data of around 36 fb⁻¹:

- **$H \rightarrow \text{Invisible}$**
  
  *New preliminary results* $pp \rightarrow ZH \rightarrow ll + E_T^{\text{miss}}$ *using 36 fb⁻¹ of 2015+2016 data* [ATLAS-CONF-2017-040]

  Supercedes preliminary results on 13.2 fb⁻¹ of 2015+2016 data: [ATLAS-CONF-2016-056]


- **$H \rightarrow Z\gamma$**
  
  *Preliminary results using 36 fb⁻¹ of 2015+2016 data.*

  Previous Run 2 results with high mass search: [CONF-2016-044]

  Previous result on SM $H \rightarrow Z\gamma$ was using Run 1 data: [Phys. Lett. B 732C (2014) 8-27]

- **$H \rightarrow \phi\gamma, H \rightarrow \rho\gamma$**
  
  *New preliminary results using 36 fb⁻¹ of 2015+2016 data* [ATLAS-CONF-2017-057]

  Previous results: $H \rightarrow \phi\gamma$ using 2.7 fb⁻¹ of 2015 data: [Phys. Rev. Lett. 117, 111802 (2016)]

  Other $H \rightarrow \gamma\gamma$ results, Run-1: $H \rightarrow J/\psi\gamma, H \rightarrow \Upsilon\gamma$: [Phys. Rev. Lett. 114, 121801 (2015)]
H→Invisible

- Look for $pp \rightarrow ZH \rightarrow ll + E_T^{\text{miss}}$. Clear signature of $Z\rightarrow ee$ or $Z\rightarrow \mu\mu$ plus missing energy from invisible Higgs decay.
- In the SM, the invisible decay ($H \rightarrow ZZ \rightarrow \nu\nu\nu\nu$) of the Higgs boson has $B(H\rightarrow \text{inv}) = 1.06 \times 10^{-3}$.
- Use to place upper limit on $B(H\rightarrow \text{inv})$ assuming SM ZH production.
- Also interpret in DM models with BSM axial-vector mediator and decay to WIMP pair.
H → Invisible: $E_T^{\text{miss}}$

- $E_T^{\text{miss}}$ distribution shown for pairs of electrons (left) and muons (right).
- Similar sensitivity for $ee$ and $\mu\mu$.
- Signal yields shown for SM ZH and DM model with example settings.
- No significant excess wrt SM background (mainly $ZZ$, $WZ$ at high $E_T^{\text{miss}}$).
- Small excess in $\mu\mu$ (2.2σ) and 1.5σ for combined $ee+\mu\mu$. 

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**H→Invisible: Results**

- **Exclusion limit on** $B(H\rightarrow\text{inv.})$ **assuming SM ZH cross section.** Observed (Expected) limit of 67% (39%). Run 1 results were 75% (62%)

- **Best fit** $B(H\rightarrow\text{inv})$ **is found to be** $30\% \pm 20\%$ **, where the data statistical and systematic uncertainties are about 13% and 16%**

- **95% CL exclusion limit in 2D $m_\chi$ and $m_{\text{med}}$.** DM model assumes an axial-vector mediator, fermionic WIMPs, and a specific scenario of the coupling parameters ($g_\chi = 1, g_q = 0.25$).

- **mediator mass** $m_{\text{med}}$ **is excluded up to 560 GeV for a light WIMP**

- **WIMP mass** $m_\chi$ **is excluded up to 130 GeV for** $m_{\text{med}} = 400$ GeV.
H→Zγ

- H→Zγ proceeds by loop diagrams similar to those in H→γγ and has a similar branching ratio. Due to the branching fraction of Z→ll sensitivity is lower.

- Modifications of the H→Zγ branching ratio compared to the SM prediction are expected if:
  - H is 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 result
  - Observed upper limit at the 95% confidence level 11 times Standard Model.
• Signal extracted by signal+background fit to $m(Z\gamma)$
  - Relies on good mass resolution.
    - Kinematic Z fit improves the $m_{\mu\nu}$ ($m_{ee\gamma}$) resolution by 7% (13%) and recovering FSR in muon channel improves by 3%
• 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 using looser isolation requirements
  - The reducible Z+jets < 20% of the events in all categories
H→Zγ: Results

**ATLAS Preliminary**

- **Data**
  - s=13 TeV, 36.1 fb⁻¹
  - VBF-enriched
  - m_H = 125 GeV

- **Background fit**
  - Signal × 20

<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>
H→φγ, H→ργ

- H→φγ, H→ργ sensitivity to s-quark, ud-quark Yukawa couplings. First study of H→ργ
- The expected SM: \( B(H \rightarrow \phi\gamma) = (2.31\pm0.11) \times 10^{-6} \) and \( B(H \rightarrow \rho\gamma) = (1.68\pm0.08) \times 10^{-5} \)

- Reconstruct \( \phi \rightarrow K^+K^-\gamma \) and \( \rho \rightarrow \pi^+\pi^-\gamma \)
- \( \phi \rightarrow K^+K^- \) is \((48.9\pm0.5)\%\) while the decay \( \rho \rightarrow \pi^+\pi^- \) is \(~100\%\)
- Two high-\( p_T \) (20, 15 GeV) isolated tracks consistent with \( \phi, \rho \) mass hypothesis recoiling against \( \gamma \) (\( p_T > 35 \) GeV)
- Cut on transverse momentum of \( \phi, \rho \) dependent on three body invariant mass
- Dedicated triggers (\(~75\%\) efficiency wrt. offline selection)
- Data-driven template modelling of background.
$H \rightarrow \phi \gamma, \ H \rightarrow \rho \gamma$

- Main background from random tracks and $\gamma$ combinations in multi-jet and $\gamma$+jet
- Events from a loose selection are used to generate pseudo-candidates for the kinematic distributions of the $\phi/\rho$ candidate and photon retaining correlations
- Large samples of pseudo-candidates are used to construct background model templates
- Model validated in validation regions by adding: the $p_T$ requirement (VR1), the photon isolation (VR2), and the meson isolation requirement (VR3).

- Model shape uncertainty estimated from modifications to modelling procedure (scale variations on the $p_T^\gamma$ distribution, linear distortions of the shape of the $\Delta\phi(M, \gamma)$, and a global tilt of the three body mass distribution around a central pivot point)
- Further validation in mass sidebands. Background model describes data within uncertainties
No significant excess above bkg for either H or Z
Unbinned maximum likelihood fit used to extract limits

<table>
<thead>
<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
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<tbody>
<tr>
<td>$\mathcal{B}(H \to \phi\gamma) [10^{-4}]$</td>
<td>4.2$^{+1.8}_{-1.2}$</td>
<td>4.8</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \phi\gamma) [10^{-6}]$</td>
<td>1.3$^{+0.6}_{-0.4}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \rho\gamma) [10^{-4}]$</td>
<td>8.4$^{+4.1}_{-2.4}$</td>
<td>8.8</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \rho\gamma) [10^{-6}]$</td>
<td>33$^{+13}_{-9}$</td>
<td>25</td>
</tr>
</tbody>
</table>

Improvement over previous Run 2 result

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<tr>
<td>$\mathcal{B}(H \to \phi\gamma) [10^{-3}]$</td>
<td>1.5$^{+0.7}_{-0.4}$</td>
<td>1.4</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \phi\gamma) [10^{-6}]$</td>
<td>4.4$^{+2.0}_{-1.2}$</td>
<td>8.3</td>
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The observed 95% confidence level (CL) upper limits on the branching fractions for $H \to \phi\gamma$ and $Z \to \phi\gamma$ decays are around 208 and 87 times the expected SM
For the $\rho\gamma$ decays: 52 and 597 times the expected SM
Summary

- The SM-like Higgs boson discovery opens a new era of precision physics
- Many rare decays have not been observed yet but may become observable in the next few years
- A wide variety of measurements have been performed at ATLAS
- Showed the most recent ATLAS results on analysis of 2015+2016 13 TeV data:

<table>
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<th>Limit on</th>
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<th>Observed</th>
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<tr>
<td>$pp \rightarrow ZH \rightarrow ll + E_{T}^{\text{miss}}$</td>
<td>$B(H \rightarrow \text{Inv})$</td>
<td>39%</td>
<td>67%</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$B(H \rightarrow Z\gamma)/B(H \rightarrow Z\gamma)_{SM}$</td>
<td>5.2</td>
<td>6.6</td>
</tr>
<tr>
<td>$H \rightarrow \phi\gamma$</td>
<td>$B(H \rightarrow \phi\gamma) [10^{-4}]$</td>
<td>4.2</td>
<td>4.8</td>
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<td>$B(H \rightarrow \rho\gamma) [10^{-4}]$</td>
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- Unfortunately still no evidence for BSM Higgs decays
- Looking forward to analysing the Run 2 data to come in 2017+2018 to see what we can find!

More details on ATLAS $H \rightarrow \phi\gamma$, $H \rightarrow \rho\gamma$ in Poster by Rhys Owen
Back-up
Lepton Flavour Violating (LFV) Decays

- Using 20.3 fb\(^{-1}\) of Run 1 8TeV data \textit{Eur. Phys. J. C 77 (2017) 70}
- Search for the LFV signal by fitting reconstructed Higgs mass for each of the decays \(H\to e\tau_{\text{had}}\), \(H\to e\tau_{\text{lep}}\) and \(H\to \mu\tau_{\text{had}}\)
- Set 95% CL upper limits: Computed under assumption that Br\((H\to\mu\tau)\)=0 or Br\((H\to e\tau)\)=0
H→Invisible: Results ee, μμ

\[ \text{Observed} \pm 1 \sigma \]

\[ \text{Expected} \pm 2 \sigma \]

\[ 95\% \text{ CL} \]

\[ \tilde{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

\[ \text{ATLAS Preliminary} \]

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H→Invisible: High $m_H$ and WIMP Limits

**ATLAS Preliminary**

- Observed
- Expected Median
- Expected ±1 $\sigma$
- Expected ±2 $\sigma$

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

$ZH(Z\rightarrow ee+\mu\mu; H\rightarrow \text{inv})$

95% Limit on $\sigma_{SD} \times \text{BR}(Z\rightarrow ee+\mu\mu; H\rightarrow \text{inv})$ [fb]

$\sigma_{SD}$ (v-proton) [cm$^2$]

- Observed 90% CL
- LUX 2013+2014-16
- PICO-2L 2016
- PICO-60 2017

Axial-vector, Dirac

$g_q = 0.25$, $g_\chi = 1.0$

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H→Zγ @ High Mass

**ATLAS Preliminary**

- Observed
- Expected

95% CL Upper Limit on σ × BR [fb]

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

- gg→X→Zγ
- \( J_X = 0, \Gamma_X = 4 \text{ MeV} \)

Events / 20 GeV

Significance

Local \( P_0 \)

- ee + μμ
- ee
- μμ

Global significance of largest deviation for ee+μμ: 0.8σ

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