Search for rare decays of the Standard Model Higgs boson with the ATLAS detector

Aaron White on behalf of the ATLAS collaboration
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Higgs 2022
Outline

Four investigations of rare processes predicted by the SM
These results were covered in Giulio Umoret’s talk on Tuesday

► Higgs (or Z) to a quarkonium state ($D = J/\psi, \Upsilon$) and a photon 2208.03122
  ► $\mathcal{B}(H \rightarrow J/\psi \gamma) \approx 10^{-6}$
  ► $\mathcal{B}(H \rightarrow \Upsilon \gamma) \approx 10^{-9}$
  ► $\mathcal{B}(Z \rightarrow D \gamma) \approx 10^{-8}$

► Higgs to a Z and a photon 2005.05382
  ► $\mathcal{B}(H \rightarrow Z \gamma) = 1.5 \pm 0.1 \times 10^{-3}$

► Higgs to two muons 2007.07830
  ► $\mathcal{B}(H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$

► Higgs to two leptons and a photon 2103.10322
  ► $\mathcal{B}(H \rightarrow \ell\ell\gamma) \approx 10^{-5}$

Most of these analyses are $139\text{fb}^{-1}$ updates of partial Run-2 results
Search for $H(Z) \to \gamma \gamma$

- **Motivation:**
  - Indirect search for $H \to cc$, which may be sensitive to deviations of the quark Yukawa couplings
  - $\gamma \gamma$ final state is sensitive to the sign of the $Hbb$ coupling, making it complementary to direct $H \to bb$ measurements

- **Target:** Higgs decay to a photon and $\mathcal{O} = J/\psi, \psi(2S), \text{ or } \Upsilon(1S, 2S, 3S)$

- **Final state:** $\gamma + \mathcal{O}(\to \mu \mu)$

- **Previous limits on branching ratio:**
  - $\mathcal{B}(H \to J/\psi \gamma) < 3.5 \times 10^{-4}$
  - $\mathcal{B}(H \to \psi(2S)\gamma) < 2.0 \times 10^{-3}$ [1807.00802]
  - Results from CMS: [1810.10056]

- **Note:** this paper also studies the equivalent processes substituting a $Z$ for the Higgs
Analysis

Challenge

- Difficult to model “inclusive” multi-jet and $\gamma$+jet background with simulation due to its complex composition and misidentified objects

Strategy

- Selects photons with $p_T^\gamma > 35$ GeV, opposite charge muon pair, (sub)-leading $p_T > (3)18$ GeV
- The Drell-Yan background is modeled by a fit to simulation
- The “inclusive” background is modeled using toy events drawn from data distributions in a control region

Categorization of events

<table>
<thead>
<tr>
<th>Common event selection</th>
<th>$m_{\mu\mu} \in [2.4, 4.3]$ GeV for $J/\psi, \psi(2S)$</th>
<th>$m_{\mu\mu} \in [8.0, 12.0]$ GeV for $\Upsilon(1S, 2S, 3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$m_{\mu\mu} \in [2.4, 4.3]$ GeV for $J/\psi, \psi(2S)$</td>
<td>$m_{\mu\mu} \in [8.0, 12.0]$ GeV for $\Upsilon(1S, 2S, 3S)$</td>
</tr>
<tr>
<td>Barrel (all $\eta_{\mu} &lt; 1.05$)</td>
<td>$m_{\mu\mu} \in [2.4, 4.3]$ GeV for $J/\psi, \psi(2S)$</td>
<td>$m_{\mu\mu} \in [8.0, 12.0]$ GeV for $\Upsilon(1S, 2S, 3S)$</td>
</tr>
<tr>
<td>Endcap (any $\eta_{\mu} &gt; 1.05$)</td>
<td>$m_{\mu\mu} \in [2.4, 4.3]$ GeV for $J/\psi, \psi(2S)$</td>
<td>$m_{\mu\mu} \in [8.0, 12.0]$ GeV for $\Upsilon(1S, 2S, 3S)$</td>
</tr>
</tbody>
</table>

- Selections on $m_{\mu\mu}$ target $J/\psi, \psi(2S), \Upsilon(1S, 2S, 3S)$
- The categories targeting $\Upsilon$ events are divided by muon $\eta$ to separate events based on $\Upsilon$ resolution
Results

- Two dimensional fits are performed in $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$
- One fit is performed for each meson (5) boson (2) combination
  - For each limit, the other meson/boson signal strengths are treated as nuisance parameters
- These plots show the signal corresponding to $H \rightarrow 2\gamma$ in green, and $Z \rightarrow 2\gamma$ in red
  - Fit shown is background-only
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Results

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<tr>
<th>Decay channel</th>
<th>Higgs boson $[10^{-3}]$</th>
<th>$\sigma \times B$</th>
<th>Z boson $[10^{-6}]$</th>
<th>Higgs boson [fb]</th>
<th>Z boson [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ γ</td>
<td>$1.9^{+0.8}_{-0.5}$</td>
<td>2.1</td>
<td>$0.6^{+0.3}_{-0.2}$</td>
<td>1.2</td>
<td>12</td>
</tr>
<tr>
<td>$\psi(2S)$ γ</td>
<td>$8.5^{+3.8}_{-2.4}$</td>
<td>10.9</td>
<td>$2.9^{+3.0}_{-0.8}$</td>
<td>2.3</td>
<td>61</td>
</tr>
<tr>
<td>$\Upsilon(1S)$ γ</td>
<td>$2.8^{+1.3}_{-0.8}$</td>
<td>2.6</td>
<td>$1.5^{+0.6}_{-0.4}$</td>
<td>1.0</td>
<td>14</td>
</tr>
<tr>
<td>$\Upsilon(2S)$ γ</td>
<td>$3.5^{+1.6}_{-1.0}$</td>
<td>4.4</td>
<td>$2.0^{+0.8}_{-0.6}$</td>
<td>1.2</td>
<td>24</td>
</tr>
<tr>
<td>$\Upsilon(3S)$ γ</td>
<td>$3.1^{+1.4}_{-0.9}$</td>
<td>3.5</td>
<td>$1.9^{+0.8}_{-0.5}$</td>
<td>2.3</td>
<td>19</td>
</tr>
</tbody>
</table>

- The result is statistically limited
- The observations are compatible with the expected background
- Limits are set, in particular:
  - $\mathcal{B}(H \rightarrow J/\psi \gamma) < 2.1 \times 10^{-4}$
  - This is interpreted as a limit on the ratio of coupling modifiers ($\kappa^2 = \sigma / \sigma_{SM}$)
    - $\frac{\kappa_c}{\kappa_{\gamma}} \in (-136, 178)$, an indirect constraint on the Higgs coupling to charm quarks
    - For comparison, $\kappa_c < 8.5(12.4)$ from the direct search

- Overview of the limits set in this paper
- Note: $\phi$ and $\rho$ results are from 1712.02758

ATLAS = 13 TeV

95% CL upper limit on Branching Fraction

$\sqrt{s}=13$ TeV

95% CL upper limits

- Branching fraction $\sigma_B$
- Decay Higgs boson $\rightarrow Z$ boson $\rightarrow Higgs boson [fb]$ $Z$ boson $[fb]$
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Limits are set, in particular:

\[ \mathcal{B}(H \rightarrow J/\psi \gamma) < 2.1 \times 10^{-4} \]

This is interpreted as a limit on the ratio of coupling modifiers \( \kappa^2 = \sigma / \sigma_{SM} \)

\[ \frac{\kappa_c}{\kappa_Y} \in (-136, 178), \] an indirect constraint on the Higgs coupling to charm quarks

For comparison, \( \kappa_c < 8.5(12.4) \) from the direct search 2201.11428

Overview of the limits set in this paper

Note: \( \phi \) and \( \rho \) results are from 1712.02758

Note:

\[ \phi \text{ and } \rho \text{ results are from 1712.02758} \]
Search for $H \rightarrow Z\gamma$

- **Motivation:** The $H \rightarrow Z\gamma$ cross section can be modified by new particles coupled to the Higgs, contributing loop corrections
- **Target:** Higgs decay into $Z\gamma$ via a loop
- **Final state:** $\gamma + \ell\ell$
- **Previous limits on cross-section times $\mathcal{B}$:**
  - ATLAS: $6.6(5.2) \times \text{SM}$ [1708.00212]
  - CMS: $7.4(6.0) \times \text{SM}$ [1806.05996]

- Candidate $\gamma + \mu\mu$ event with **two electrons** (closely spaced green) identified as a photon conversion, and **two muons** (red) from a Z candidate
Analysis

Backgrounds

- Non-resonant production of $Z\gamma$
- $Z+$jets with a jet identified as a photon

Strategy

- Select $\gamma$ and a same-flavor opposite charge lepton pair ($p_T > 10$ GeV)
- $m_{\ell\ell} \in [81, 101]$ GeV to select a Z
- $m_{\ell\ell\gamma} \in [105, 160]$ GeV to select a Higgs

Six categories:

- VBF-enriched, based on a BDT cut
- High relative $p_T^\gamma$, if $p_T^\gamma/m_{\ell\ell\gamma} > 0.4$
- Four categories: $(ee/\mu\mu) \times$ (high/low $p_{Tt}$)
  - $p_{Tt}$ is the component of $p_T^{Z\gamma} \perp (\vec{p}_Z - \vec{p}_\gamma)$
  - Divided by $p_{Tt} = 40$ GeV

The VBF BDT distribution separates VBF from both $ggF$ and backgrounds
Results

- Uncertainty is primarily statistical, with a subleading spurious signal uncertainty
- Observed signal strength: \( \mu = 2.0 \pm 0.9\) (stat) \(\pm 0.4\) (syst)
- Observed (expected) significance: \(2.2\sigma (1.2\sigma)\)
- Limit on \(\sigma \times \mathcal{B}\): \(3.6(2.6) \times\) SM
- 20\% of the improvement compared to the previous result is due to changes in the analysis
  - Event categorization
  - Optimized \(\ell/\gamma\) identification
Search for $H \rightarrow \mu\mu$

- **Motivation**: measure Higgs coupling with second generation fermions
- **Target**: direct decay of $H \rightarrow \mu\mu$
  
  $H \rightarrow \mu\mu$

- **Final state**: two oppositely charged muons, and additional leptons/jets depending on the production mechanism

- **Previous limits on signal strength**:
  - **ATLAS**: $\mu < 2.8(2.9) \times SM$ [1705.04582]
  - **CMS**: $\mu < 2.9(2.2) \times SM$ [1807.06325]

- **Signal width**: 2.6-3.2 GeV depending on category
- **Note**: the simulated events are used to illustrate signal and background composition, while an analytic background estimate is used for the measurement
Analysis

Challenge
- Large Drell-Yan (DY) background
- Significant diboson and top backgrounds

Strategy
- Target \( ttH \) using b-tagged jets and an additional lepton
- Target \( VH \) using additional leptons to remove DY
- Target VBF production with a 2-jet selection
- 0, 1, 2 jet categories target \( ggF \)
- All categories use xgboost BDTs to enhance sensitivity
- 20 categories in total with different signal, background composition

ATLAS, \( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}, H \rightarrow \mu\mu \)

\[
\begin{array}{c|c|c|c|c}
\hline
\text{Signal composition} & \text{ttH} & \text{VH} & \text{VBF} & \text{ggF} \\
\hline
\text{Bkg. composition} & Z/\gamma^* & \text{Diboson} & \text{Top} \\
\hline
\end{array}
\]
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- 0, 1, 2 jet categories target $ggF$
- All categories use xgboost BDTs to enhance sensitivity
- 20 categories in total with different signal, background composition
Result is limited by statistical uncertainty
- Observed signal strength: \( \mu = 1.2 \pm 0.6 \)
- 95% CL upper limit on signal strength (expected): \( \mu < 2.2(1.1) \times SM \)
- Observed (expected) significance: 2.2\(\sigma\)(1.7\(\sigma\))

Note on category definitions
- ttH additional lepton, at least one b-jet
- WH one additional lepton, no b-jets
- ZH at least two additional leptons, no b-jets
- VBF no additional muons, no b-jets, two jets
- ggH no additional muons, no b-jets, 0, 1, or 2 jets
Search for $H \rightarrow \ell\ell\gamma$ with a low $\ell\ell$ mass

- **Motivation:** probe for coupling modifications to the SM
- **Target:** Higgs decays to low-mass ($m_{\ell\ell} < 30$ GeV) dilepton pairs and a photon
- **Final state:** $\gamma + \ell\ell$
  - $ee$ may be merged or unmerged
- **Previous results:** CMS
  $\mu < 4.0(2.2) \times SM$ \[1806.05996\]
- **Event display showing** two muons and a photon
Analysis

**Challenges**
- Using $\gamma^* \rightarrow ee$ when ee pairs are merged in the calorimeter
- Dominant background: non-resonant $\ell\ell\gamma$

**Strategy**
- Cuts on $m_{\ell\ell}$ remove $Z, J/\psi, \Upsilon$
  - $m_{\ell\ell} < 30$ GeV, $m_{\mu\mu} \in [2.9,3.3]$ GeV, $m_{ee} \in [2.5,3.5]$ GeV
- A $\Delta R(\gamma, \ell) > 0.4$ separation helps remove FSR
- A multivariate discriminant is trained to select merged-ee pairs
- Three selections ($\mu\mu$, $ee$, merged-ee) are each divided:
  - VBF defined by kinematics (Jet $p_T$, $\Delta\eta$ and $\Delta R$)
  - High $p_T > 100$ GeV
  - Low $p_T \leq 100$ GeV

![Graph showing ratio of reconstructed/true energy for merged-ee pairs](image)
Results

- Result is statistically limited
- Observed signal strength: $\mu = 1.5 \pm 0.5 (\text{stat})^{+0.2}_{-0.1} (\text{syst})$
- Evidence of $H \rightarrow \ell \ell \gamma$ with observed (expected) significance: $3.2\sigma (2.2\sigma)$
- The $H \rightarrow \ell \ell \gamma$ crosssection times branching ratio in this region is:
  - $8.7 \pm 2.7 (\text{stat})^{+0.7}_{-0.6} (\text{syst})$ fb
Summary: Four Results

\( H(Z) \rightarrow \gamma \gamma \) \hspace{1cm} \( H \rightarrow Z \gamma \) \hspace{1cm} \( H \rightarrow \mu \mu \) \hspace{1cm} \( H \rightarrow \gamma \gamma^* (\rightarrow \ell \ell) \)

- Limit on \( \mathcal{B}(H \rightarrow J/\psi \gamma) \) lowered from \( 3.5 \times 10^{-4} \) to \( 2.1 \times 10^{-4} \)
- Limit on \( \sigma \mathcal{B} \) lowered from \( 6.6(5.2) \times \text{SM} \) to \( 3.6(2.6) \times \text{SM} \)
- A factor of 2.5 improvement in expected sensitivity
- New measurement from ATLAS

In general

- Each of these studies (except \( H \rightarrow \ell \ell \gamma) \) report a significant improvement over their partial Run-2 predecessor
- Due in large part to the increased luminosity, and also to improvements in the analysis
- Each result is statistically limited, and will benefit from the addition of data from Run-3