The search for rare decays of the Higgs boson with ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

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ATLAS and CMS detectors and Datasets

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Rare Higgs decays in ATLAS and CMS

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SM Higgs Boson Production at the LHC

Gluon fusion:
- known at NNLO (theo. uncert. O(15%))

Vector boson fusion:
- known at NLO (theo. uncert. O(5%))
- distinctive exp. signature: 2 forward jets and rapidity gap

Associated $WH/ZH$:
- known at NNLO (theo. uncert. O(5%))
Higgs Boson Decays

Direct decay products:

Visible decay products in detector:

Focus of this talk on the rare Higgs boson decays:

- $H \rightarrow Z\gamma$ (ATLAS $4.6+20.7 \text{ fb}^{-1}$, CMS $5.0+19.6 \text{ fb}^{-1}$)
- $H \rightarrow \mu\mu$ (ATLAS $20.7 \text{ fb}^{-1}$)
- $ZH, H \rightarrow$ invisible (ATLAS $4.7+13.0 \text{ fb}^{-1}$, CMS $5.1+19.6 \text{ fb}^{-1}$)
Motivation:

- The $H \to Z\gamma$ decay proceeds via electroweak loop coupling to the Higgs boson, together with the $H \to \gamma\gamma$ channel can provide strong constraints on BSM particles in the loops.
- The $BR(H \to Z\gamma)$ is comparable to $BR(\to \gamma\gamma)$, but $BR(Z \to \ell\ell)$ reduces sensitivity (factor 15)
- Inclusive production

Event Selection:

- At least 2 isolated opp. charged high $p_T$ electrons or muons
- At least 1 high $p_T$ isolated photon
- $\Delta R(\gamma, \ell) > 0.3 \ (0.4)$ ATLAS (CMS)
- $m_{\ell\ell\gamma} > m_Z - 10 \text{ GeV}$ (ATLAS), $100 \text{ GeV} < m_{\ell\ell\gamma} < 180 \text{ GeV}$ (CMS)
**H → Zγ: Distributions**

### m_{llγ} Distribution for Electron and Muon Channel

- **Classes:** central γ & leptons, (un-)converted γ, endcap γ or lepton

### Δm(m_{llγ} − m_Z) Distribution for Electron Channel

- Insensitive to lepton energy uncert., reduced FSR H → μμ

**Backgrounds from Z + γ (both ISR and FSR) and Z+jets estimated from data driven methods, small contributions from top and WZ from MC**
\( H \rightarrow Z\gamma: \text{Fit and Uncertainties} \)

- Fit BG 3rd order polynomial to \( \Delta m \) in data
- Main systematic uncertainties: acceptance (5%), \( e/\gamma \) resolution (5%)


**H → Zγ: Results**

**Limits (CMS):**
- Observed: $3-31 \cdot \sigma_{SM}$
- Expected: $6-19 \cdot \sigma_{SM}$

**Limits (ATLAS):**
- Observed: $5.4-37 \cdot \sigma_{SM}$
- Expected: $7.3-22 \cdot \sigma_{SM}$

Any deviations from SM prediction will be indication of new electroweak particles coupling to Higgs boson.
ZH, $H \rightarrow \text{INVISIBLE}$

Motivation:

- Higgs couplings to non SM stable or long lived particles is excellent way to search for new physics, in particular Dark Matter through so called Higgs portal models. The search performed by looking for excess in events at high $E_T^{\text{miss}}$

Event Selection:

- 2 isolated high $p_T$ electrons or muons
- $|m_Z - m_{\ell\ell}| < 15$ GeV
- $E_T^{\text{miss}} > 90$ GeV (ATLAS), reduced $E_T^{\text{miss}} > 110$ GeV (CMS)
- $\Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 0.2$ (ATLAS)
- $\Delta \phi(E_T^{\text{miss}}, p_T^{\ell\ell}) > 2.6$
- $\Delta \phi(\ell\ell) < 1.7$ (ATLAS)
- $|E_T^{\text{miss}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$
- Jet veto
ZH, $H \rightarrow \text{invisible}: \text{Distributions}$

Reduced $E_T^{\text{miss}}$ in signal region

$E_T^{\text{miss}}$ in signal region after all cuts

Backgrounds:
- ZZ and WZ from MC
- WW and top from scaling signal free $e\mu$ decay channel distributions
- $Z+\text{jets}$ from $ABCD$ method with $\Delta\phi(E_T^{\text{miss}}, \vec{p_T}^{\text{miss}})$ and frac. $p_T$ diff. (ATLAS) or orthogonal reweighted $\gamma+\text{jets}$ sample (CMS)
- $W+\text{jets/multi-jet}$ from $4 \times 4$ matrix method loosened lepton-ID
**ZH, H → inv.: Uncertainties, Event yields**

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th></th>
<th>$\sqrt{s} = 8$ TeV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ee$</td>
<td>$\mu\mu$</td>
<td>$ee$</td>
<td>$\mu\mu$</td>
</tr>
<tr>
<td>$ZH(125)$</td>
<td>2.2 ± 0.3</td>
<td>3.3 ± 0.5</td>
<td>11.8 ± 1.9</td>
<td>16.7 ± 2.5</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell^+\ell^-$</td>
<td>0.3 ± 0.3</td>
<td>0.7 ± 0.7</td>
<td>1.0 ± 1.0</td>
<td>1.9 ± 1.9</td>
</tr>
<tr>
<td>$WZ \rightarrow 3\ell\nu$</td>
<td>2.0 ± 0.3</td>
<td>2.3 ± 0.3</td>
<td>11.0 ± 1.6</td>
<td>14.8 ± 2.1</td>
</tr>
<tr>
<td>$ZZ \rightarrow 2\ell2\nu$</td>
<td>5.1 ± 0.6</td>
<td>7.3 ± 0.8</td>
<td>29.8 ± 3.6</td>
<td>40.8 ± 4.5</td>
</tr>
<tr>
<td>$Top/WW/W + Jets$</td>
<td>0.4 ± 0.4</td>
<td>0.6 ± 0.6</td>
<td>1.3 ± 0.8</td>
<td>2.1 ± 1.3</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>7.8 ± 0.8</td>
<td>11.0 ± 1.3</td>
<td>43.1 ± 4.1</td>
<td>59.6 ± 5.5</td>
</tr>
</tbody>
</table>

| Data                        | 10 | 11 | 33 | 45 |

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**CMS:**

**Data Period**

<table>
<thead>
<tr>
<th>Process</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
</tr>
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<tbody>
<tr>
<td>$ZZ$</td>
<td>23.5 ± 0.8 ± 2.5</td>
<td>56.5 ± 1.2 ± 5.7</td>
</tr>
<tr>
<td>$WZ$</td>
<td>6.2 ± 0.4 ± 0.7</td>
<td>13.9 ± 1.2 ± 2.1</td>
</tr>
<tr>
<td>$WW$</td>
<td>1.1 ± 0.2 ± 0.2</td>
<td>used $e\mu$ data-driven</td>
</tr>
<tr>
<td>Top quark</td>
<td>0.4 ± 0.1 ± 0.4</td>
<td>used $e\mu$ data-driven</td>
</tr>
<tr>
<td>Top quark, $WW$ and $Z \rightarrow \tau\tau$ ($e\mu$ data-driven)</td>
<td></td>
<td>used MC</td>
</tr>
<tr>
<td>Z</td>
<td>0.16 ± 0.13 ± 0.09</td>
<td>1.4 ± 0.4 ± 0.7</td>
</tr>
<tr>
<td>$W$ + jets, multijet</td>
<td>1.3 ± 0.3 ± 0.2</td>
<td>1.4 ± 0.4 ± 0.3</td>
</tr>
<tr>
<td>Total BG</td>
<td>32.7 ± 1.0 ± 2.6</td>
<td>78.0 ± 2.0 ± 6.5</td>
</tr>
</tbody>
</table>

**Observed**

|                 | 27 | 71 |

**ATLAS**

**Dominant systematic uncertainties:**

- $ZZ, WZ$ 10-14 $\%$, $ZH$ Signal 6-7$\%$
**ZH, \( H \to \text{invisible} \): Results**

Two interpretations:

<table>
<thead>
<tr>
<th>GeV</th>
<th>fb</th>
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</thead>
<tbody>
<tr>
<td>105</td>
<td></td>
</tr>
<tr>
<td>110</td>
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</tr>
<tr>
<td>140</td>
<td></td>
</tr>
<tr>
<td>145</td>
<td></td>
</tr>
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</table>

**BR(\( H \to \text{inv} \)) > 71 (91) / 65 (84)%**

obs. (exp.) CMS/ATLAS excluded at 95% CL for SM Higgs boson with \( m_H = 125 \text{ GeV} \)

Stringent limits on Higgs and Dark Matter coupling can be obtained in combination with mono-jet and mono-photon and VBF \( H \to \text{inv} \) searches
Motivation:
- $H \rightarrow \mu^+\mu^-$ directly probes SM Higgs Boson couplings to 2nd generation fermions
- $BR(H[125] \rightarrow \mu^+\mu^-) = 2.2 \times 10^{-4}$

Search strategy:
- Inclusive search
- Search for a small bump on top of continuous $m_{\mu\mu}$ background distribution
- „blinded” search of the SM resonance in 110-150 GeV $m_{\mu\mu}$ window
- Use parametrized functions to fit data for background rate and shape
- Dominant background is inclusive $Z/\gamma^*$ (small di-bosons and $t\bar{t}$)

Challenges:
- Irreducible $Z/\gamma^* \rightarrow \mu\mu$ background
- $\Gamma(H[125]) = 4.1$ MeV - signal width dominated by detector resolution
$H \rightarrow \mu^+ \mu^- : m_{\mu\mu}$ AND EVENT YIELDS

Event selection:
- 2 isolated opp. charged muons, $p_T^{\mu 1(2)} > 25 \ (15) \text{ GeV}$
- $p_T^{\mu\mu} > 15 \text{ GeV}$
- Muon resolution categories: $|\eta_\mu| < 1, |\eta_\mu| > 1$

Event yields:

| Source            | $|m_H - m_{\mu\mu}| \leq 5 \text{ GeV}$ |
|-------------------|------------------------------------------|
| Signal [125 GeV]  | 37.7 ± 0.2                                |
| $WW$              | 250 ± 4                                   |
| $WZ/ZZ/W\gamma$   | 30 ± 1                                    |
| $t\bar{t}$        | 1374 ± 13                                 |
| Single Top        | 151 ± 5                                   |
| $Z$ + jets        | 15810 ± 130                               |
| $W$ + jets        | 88 ± 6                                    |
| Total BG          | 17700 ± 130                               |
| Observed          | 17442                                     |
$H \rightarrow \mu^+\mu^-$: **Fit procedure**

**Background model:**
Breit-Wigner + exponential function

**Signal model:**
Crystal ball + Gaussian function

Background fit validated in MC and data control regions

**ATLAS Preliminary**
$\sqrt{s} = 8$ TeV
\[ \int L dt = 20.7 \text{ fb}^{-1} \]

![Graph showing di-muon mass distribution](image)

![Graph showing fit model comparison](image)
$H \rightarrow \mu^+ \mu^-$: Results

Limits at $m_H=125$ GeV:
- Observed: $9.5 \cdot \sigma_{SM}$
- Expected: $8.2 \cdot \sigma_{SM}$

Dominant systematic uncertainties (all at percent level):
- Theory: cross section and branching ratio, ISR
- Experimental: Luminosity, muon reconstruction
$H \rightarrow \mu^+\mu^-$: Future perspectives

HL-LHC substantially improved statistical precision for already established channels, allows to study rare Higgs boson production and decay modes ATLAS and CMS with $3000 \text{ fb}^{-1}$:

- Inclusive analysis expected significance $> 6\sigma$ (ATLAS) and $\approx 5\sigma$ for gluon-gluon fusion and VBF (CMS)
- Expected measurement precision better than 20% (ATLAS) or than 10% on $H\mu\mu$ coupling (CMS)
Summary and Conclusions

- Presented the analysis by ATLAS and CMS with LHC data from 2011 and 2012 for rare SM Higgs boson decays in:
  - $H \rightarrow Z\gamma$
  - $H \rightarrow \mu\mu$
  - $ZH, H \rightarrow$ invisible

- No deviations from SM Higgs boson expectations and set upper limits on the various $\sigma \cdot BR$
  - further indication that it is a SM Higgs boson

- Establish signal of rare decay latest with HL-LHC data
Documentation

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/

\[ H \rightarrow Z\gamma \quad \text{ATLAS-CONF-2013-009} \]
\[ H \rightarrow \mu\mu \quad \text{ATLAS-CONF-2013-010} \]
\[ ZH \text{ (Invisible decays)} \quad \text{ATLAS-CONF-2013-011} \]

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

HL-LHC physics \quad \text{ATL-PHYS-PUB-2012-004}

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

\[ H \rightarrow Z\gamma \quad \text{CMS-PAS-HIG-13-006} \]
\[ ZH \text{ (Invisible decays)} \quad \text{CMS-PAS-HIG-13-018} \]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

HL-LHC physics \quad \text{CMS-NOTE-2012-006}
BACKUP
Background is directly fitted from data mass spectrum

ATLAS: 2D sideband fit method: $\gamma$-ID and $\gamma$-Isolation in $Z$+jets enriched region to determine $Z$+jets and $Z + \gamma$ fraction after $t\bar{t}$ and $WZ$ subtraction

Backgrounds are:
- SM $Z + \gamma$ ($\sim 82\%$)
- SM $Z$+jets ($\sim 17\%$)
- $t\bar{t}$ and $WZ$ ($\sim 1\%$)
ZH, $H \rightarrow$ invisible: Background determination

- ZZ and WZ from MC
- WW and top from scaling signal free $e\mu$ decay channel distributions
- $Z+\text{jets}$ from $ABCD$ method with $\Delta \phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$ and frac. $p_T$ diff.
- $W+\text{jets}$ and multi-jet BG from $4 \times 4$ matrix method with loosened lepton-ID

\[
\begin{pmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{pmatrix} =
\begin{pmatrix}
r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\
r_1 (1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\
(1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\
(1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2)
\end{pmatrix}
\times
\begin{pmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{pmatrix}
\]

\[
N_{W+\text{jets}} = \sum_i N_{RF}^i \times r_1^i \times f_2^i + N_{FR}^i \times f_1^i \times r_2^i,
\]
\[
N_{\text{multijet}} = \sum_i N_{FF}^i \times f_1^i \times f_2^i.
\]

$r_1, r_2, f_1, f_2$ lepton efficiencies and fake rates for first lepton and second lepton
ZH, $H \rightarrow$ invisible: Background determination

- ZZ and WZ from MC (MCFM)
- WW and top from scaling signal free $e\mu$ decay channel distributions
- $Z +$jets from $\gamma +$jets sample reweighted for trigger, pile-up and selection differences

- Define 2 axis $i$: parallel and orthogonal to di-lepton system
- reduced $E_T^{\text{miss}} = p_T^{\ell\ell} - \min(R_{\text{clust}}^i, R_{\text{uncl}}^i)$
- $R_{\text{clust}}^i$: clustered recoil, $R_{\text{uncl}}^i$: unclustered recoil
### CMS:

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Uncertainty(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>PDF</td>
<td>4-5</td>
</tr>
<tr>
<td></td>
<td>QCD scale variation (ZH)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>QCD scale variation (VV)</td>
<td>7-10</td>
</tr>
<tr>
<td></td>
<td>Luminosity</td>
<td>2.2-4.4</td>
</tr>
<tr>
<td></td>
<td>Lepton Trigger, Reco., Isolation</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>$Z/\gamma^* \rightarrow \ell^+\ell^-$ normalization</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Top, WW &amp; W + jets normalization</td>
<td>25-100</td>
</tr>
<tr>
<td>Shape</td>
<td>MC statistics: ZH, ZZ, WZ</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>Control sample statistics $Z/\gamma^* \rightarrow \ell^+\ell^-$</td>
<td>12-24</td>
</tr>
<tr>
<td></td>
<td>Control sample statistics NRB</td>
<td>53-100</td>
</tr>
<tr>
<td></td>
<td>Pile Up</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td></td>
<td>b-tagging Efficiency</td>
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<td>Lepton Momentum Scale</td>
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<td>Jet Energy Scale, Resolution</td>
<td>1-3</td>
</tr>
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<td>Unclustered energy</td>
<td>1-4</td>
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</tbody>
</table>

### ATLAS:

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimation method</th>
<th>Uncertainty (%)</th>
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<tbody>
<tr>
<td><strong>ZH Signal</strong></td>
<td>MC</td>
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<tr>
<td><strong>ZZ</strong></td>
<td>MC</td>
<td>11</td>
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<tr>
<td><strong>WZ</strong></td>
<td>MC</td>
<td>12</td>
</tr>
<tr>
<td><strong>WW</strong></td>
<td>MC</td>
<td>14</td>
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<tr>
<td><strong>Top quark</strong></td>
<td>MC</td>
<td>90</td>
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<tr>
<td><strong>Top quark, WW and Z → ττ</strong></td>
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<td>$Z$</td>
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<td>56</td>
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<td>$W +$ jets, multijet</td>
<td>Matrix method</td>
<td>15</td>
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