BSM Higgs Searches in ATLAS and CMS (part 2)

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On Behalf of the ATLAS and CMS Collaborations
Overview

• Vital question: **Is it in fact the discovered Higgs boson from the SM or part of an extended sector?**

• **Space to probe any non-SM property**

• **Additional Higgs bosons still a possibility**

• **Indirect searches** from observed Higgs couplings measurement (not in this talk)
Outline

- Talk focuses on results from ATLAS and CMS

Many new results from ICHEP and after:

**Non-SM property**
- Rare Higgs Decays
- Invisible Higgs Decays
- Higgs Decays to Long-Lived
- Lepton Flavour Violation

**Additional Higgs bosons**
- Additional Higgs in multilepton and photons channels
- MultiHiggs in cascade
- Di-Higgs production in diphoton and di b-jets channels
- New diphoton resonances
Rare decays

ATLAS: arXiv:1402.3051
CMS PAS HIG-14-003
Search for $H \rightarrow \gamma^* \gamma \rightarrow \mu\mu\gamma$

- **Rare Higgs decays** as probes of **new couplings** and **SM extensions**
- Loop and tree level processes contribute to $\mu\mu\gamma$ final state

$m_{\mu\mu} < 100$ GeV

Higher $m_{\mu\mu}$

- **First CMS search for Dalitz decays** with $\gamma^*$ internal conversion in $\mu\mu$
- $m_{\mu\mu} < 20$ GeV to separate $\gamma^* \gamma$ and $Z \gamma$

<table>
<thead>
<tr>
<th>@125 GeV</th>
<th><strong>CMS</strong></th>
<th><strong>ATLAS</strong></th>
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</thead>
<tbody>
<tr>
<td>$Z \gamma$</td>
<td>9.5X SM</td>
<td>11X SM</td>
</tr>
<tr>
<td>$\gamma^* \gamma$</td>
<td>10X SM</td>
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</table>

![CMS Preliminary](image_url)

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Invisible decays

ATLAS-CONF-2014-011
CMS PAPER HIG-13-030
Higgs decay to invisible particles

- What if Higgs couples to something invisible?

- One possibility: Higgs portal of DM interaction

  - Higgs mediator between SM and DM particles

- Search in the VBF and ZH (Z → ll; Z → b̄b) modes

- Large cross-section
- Large SM background reduced by VBF jet topology

- Lower cross-section
- Clear topology
- Sensitivity increase by the leptons an bs

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Results

- No evidence for signal observed in any of the three searches

- 95% CL Upper Limits on $\sigma \cdot B(H \rightarrow \text{inv})$

- CMS combination paper just accepted for publication.

- Results interpreted in the Higgs portal of DM interaction model

- Upper limit on BR($H \rightarrow \text{inv}$) : constrain the DM mass and its elastic cross section on nucleons

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<thead>
<tr>
<th>@125 GeV</th>
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<th>ATLAS</th>
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<tbody>
<tr>
<td>$Z(\rightarrow \ell \ell) H$</td>
<td>0.75XSM</td>
<td>0.75X SM</td>
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<tr>
<td>$Z(\rightarrow b \bar{b}) H$</td>
<td>1.82X SM</td>
<td>-</td>
</tr>
<tr>
<td>VBF</td>
<td>0.69X SM</td>
<td>-</td>
</tr>
<tr>
<td>COMB</td>
<td>0.58X SM</td>
<td>-</td>
</tr>
</tbody>
</table>

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Decays to long-lived particles

ATLAS-CONF-2014-041  NEW
Scalar boson decay to long-lived particles

- What if Higgs couples to **Long-Lived particles**?

- **Hidden Valley Benchmark Model**: coupling via a heavy scalar particle, $\Phi_{HS}$

\[ \Phi_{HS} \rightarrow \pi^\nu \rightarrow f \overline{f} \]

- $\pi^\nu$ **neutral and long-lived**
- Lifetime of the $\pi^\nu$ is free parameter $\rightarrow \pi^\nu$ decays result as *displaced vertex*

Both $\pi^\nu$ decay in the **hadronic calorimeter** or near the **outer edge of the electromagnetic calorimeter**

CMS: search for displaced vertex using tracks

ATLAS: Decays in HCal/ECal

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Analysis Strategy

• Dedicated trigger:

At least one narrow jet with no charged tracks associated

Requirement on the $E_H/E_{EM}$

Average probability to fire the trigger $\sim 20\%$ in EB and $6\%$ in EE

• Non collision background: **Timing of the jet** used to discard out-of-time background

• 95% CL Upper Limits on **cross-section times BR vs $\pi_v$ proper decay length**

<table>
<thead>
<tr>
<th>MC sample $m_{\Phi}, m_{\pi_v}$ [GeV]</th>
<th>excluded range 30% BR $\Phi_{HS} \rightarrow \pi_v\pi_v$ [m]</th>
<th>excluded range 10% BR $\Phi_{HS} \rightarrow \pi_v\pi_v$ [m]</th>
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</thead>
<tbody>
<tr>
<td>126, 10</td>
<td>0.10 - 4.38</td>
<td>0.13 - 2.30</td>
</tr>
<tr>
<td>126, 25</td>
<td>0.27 - 10.01</td>
<td>0.37 - 5.12</td>
</tr>
<tr>
<td>126, 40</td>
<td>0.54 - 12.11</td>
<td>0.86 - 5.62</td>
</tr>
</tbody>
</table>
Lepton Flavor Violation

CMS PAS HIG-14-005  NEW
LFV at LHC

- What if we observe an unexpected decay of the new boson? $H \rightarrow \mu \tau$
  
  - LFV decays occur naturally in 2HDM, composite Higgs, models with flavor symmetries and Randall-Sundrum

- Constraints from indirect searches: $B(H \rightarrow \mu \tau) < \mathcal{O}(0.1)$, $B(H \rightarrow e \tau) < \mathcal{O}(0.1)$

- First dedicated search for $H \rightarrow \mu \tau e$ and $H \rightarrow \mu \tau_{had}$ at LHC

- W.r. t. $H \rightarrow \tau_{had} \mu$ and $H \rightarrow \tau_{had} \mu$:

![Harder muon p_T spectrum](image1)

![MET collinear with visible τ decay](image2)
Results

- **expected** upper limit: $B(H \rightarrow \mu \tau) < (0.75 \pm 0.38)\%$
- **observed** upper limit: $B(H \rightarrow \mu \tau) < 1.57\%$

Slight excess of observed number of events

Best fit: $B(H \rightarrow \mu \tau) = (0.89 \pm 0.40)\%$

Constraint on $B(H \rightarrow \mu \tau)$ interpreted in terms of LFV Higgs Yukawa couplings

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<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Dataset</th>
<th>Status</th>
<th>Results</th>
<th>Dataset</th>
<th>Status</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(ZZ)</td>
<td>CMS</td>
<td>5.1 + 19.7 fb⁻¹</td>
<td>HIG-14-009</td>
<td>ATLAS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(WW)</td>
<td>CMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(γγ)</td>
<td>CMS</td>
<td>19.7 fb⁻¹</td>
<td>HIG-14-003</td>
<td>ATLAS</td>
<td></td>
<td></td>
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<tr>
<td>H(tau tau)</td>
<td>CMS</td>
<td></td>
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<tr>
<td>V-H(bb)</td>
<td>CMS</td>
<td>19.0 fb⁻¹</td>
<td>HIG-13-011</td>
<td>ATLAS</td>
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<tr>
<td>ttH(bb)</td>
<td>CMS</td>
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<tr>
<td>VBF-H(bb)</td>
<td>CMS</td>
<td>19.0 fb⁻¹</td>
<td>HIG-13-011</td>
<td>ATLAS</td>
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</tr>
</tbody>
</table>

### Favoured decay modes

- **H(ZZ)**: \( \mu = 1.00 \pm 0.09 \text{ (stat)} +0.08-0.07 \text{ (theo)} +/-0.07 \text{ (syst)} \)
- **H(WW)**: \( \mu = 1.30 \pm 0.12 \text{ (stat)} +0.14-0.11 \text{ (syst)} \)
- **H(γγ)**: \( \mu = 3.6(3.0) \)
- **H(tau tau)**: \( \mu = 4.1(3.4) \)
- **V-H(bb)**: \( \mu < 1.8(1.9) \)
- **ttH(bb)**: \( \mu < 5.8(4.6) \% \)
- **VBF-H(bb)**: \( \mu < 2.5(2.1) \% \)
- **Z(ll)-H(inv)**: \( \mu < 58(46) \% \)
- **Z(bb)-H(inv)**: \( \mu < 75(62) \% \)
- **H(tau mu)**: \( \mu < 1.57 \% \)
- **H(long-lived)**: \( \mu < 20.3 \text{ fb}⁻¹ \)

### Rare decay modes

- **H(mu mu)**: \( \mu < 7.4 \)
- **H(Z γ)**: \( \mu < 10 \)
- **H(γ* γ)**: \( \mu < 10 \)
- **Z(ll)-H(inv)**: \( \mu < 58(46) \% \)
- **Z(bb)-H(inv)**: \( \mu < 75(62) \% \)
- **H(tau mu)**: \( \mu < 1.57 \% \)
- **H(long-lived)**: \( \mu < 20.3 \text{ fb}⁻¹ \)

### Invisible decay modes

- **Z(ll)-H(inv)**: \( \mu < 58(46) \% \)
- **Z(bb)-H(inv)**: \( \mu < 75(62) \% \)
- **H(tau mu)**: \( \mu < 1.57 \% \)
- **H(long-lived)**: \( \mu < 20.3 \text{ fb}⁻¹ \)

### Exotic decay modes

- **H(tau mu)**: \( \mu < 1.57 \% \)
- **H(long-lived)**: \( \mu < 20.3 \text{ fb}⁻¹ \)

**Note:**
- 
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## Extended Higgs Sector Introduction

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS</th>
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<tbody>
<tr>
<td><strong>EWK Singlet Model</strong></td>
<td></td>
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<tr>
<td>MSSM $H(\tau \tau)$</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>MSSM $H(\bb)$</td>
<td>V</td>
<td>-</td>
</tr>
<tr>
<td>$H^+(\tau \nu)$</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>$H^+(\tau \text{jet})$</td>
<td>-</td>
<td>V</td>
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<tr>
<td>$H^+(\text{csbar})$</td>
<td>V</td>
<td>-</td>
</tr>
<tr>
<td>$\nu H(hh), A(Zh)$</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>$H(\text{multi } \gamma)$</td>
<td>-</td>
<td>Future</td>
</tr>
<tr>
<td>$H(\text{ttbar})$</td>
<td>Future</td>
<td>-</td>
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### 2HDM

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$h_1 \rightarrow a_1 \rightarrow 2\mu$</td>
<td>V</td>
<td>-</td>
</tr>
<tr>
<td>$h_1 \rightarrow a_1 a_1 \rightarrow 4\mu$</td>
<td>V</td>
<td>-</td>
</tr>
<tr>
<td>$h_2 \rightarrow h_1 h_1 \rightarrow 4\tau$</td>
<td>Future</td>
<td>-</td>
</tr>
<tr>
<td>$h_2 \rightarrow h_1 h_1 \rightarrow 2\tau 2\mu$</td>
<td>-</td>
<td>Future</td>
</tr>
<tr>
<td>$h_2 \rightarrow h_1 h_1 \rightarrow 2\tau 2b$</td>
<td>Future</td>
<td>-</td>
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<tr>
<td>$H^+ (Wa_1)$</td>
<td>-</td>
<td>Future</td>
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</table>

### NSSM

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<thead>
<tr>
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<tbody>
<tr>
<td>$Low \ Mass \ H(\gamma \gamma)$</td>
<td>-</td>
<td>V</td>
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<tr>
<td>$High \ Mass \ H(\gamma \gamma)$</td>
<td>V</td>
<td>V</td>
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<tr>
<td>$High \ Mass \ H(\gamma \gamma \bb)$</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>$High \ Mass \ H(bbbb)$</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>HighMass WW</td>
<td>V</td>
<td>V</td>
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<tr>
<td>HighMass ZZ</td>
<td>V</td>
<td>V</td>
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### Resonant searches

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Heavy Higgs
decays to h

CMS PAS HIG-13-025
2HDM Overview

- **Five physical Higgs sector particles** survive EWSB with **masses < TeV** and accessible at LHC ($h, H, A, H^+$)

- If $m_H$ and $m_A > 2m_h$ **$H \rightarrow hh$ and $A \rightarrow Zh$** promising avenues for discovery even when the couplings of the light Higgs within a few percent of SM predictions.

**Multilepton signature with unusual kinematics characteristics**

- **$h$** has a nominal mass of **126 GeV** and **Brs to WW, ZZ, $\tau \tau$, bb and $\gamma\gamma$ channels appropriate to SM**

\[
H \rightarrow hh \quad A \rightarrow Zh
\]

<table>
<thead>
<tr>
<th>$h \rightarrow WW^*$</th>
<th>$h \rightarrow ZZ^*$</th>
<th>$h \rightarrow \tau\tau$</th>
<th>$h \rightarrow bb$</th>
<th>$h \rightarrow \gamma\gamma$</th>
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</thead>
<tbody>
<tr>
<td>$h \rightarrow WW^*$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$X$</td>
</tr>
<tr>
<td>$h \rightarrow ZZ^*$</td>
<td>$-$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
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<tr>
<td>$h \rightarrow \tau\tau$</td>
<td>$-$</td>
<td>$-$</td>
<td>$\checkmark$</td>
<td>$X$</td>
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<tr>
<td>$h \rightarrow bb$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$X$</td>
</tr>
<tr>
<td>$h \rightarrow \gamma\gamma$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
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<table>
<thead>
<tr>
<th>$h \rightarrow WW^*$</th>
<th>$h \rightarrow ZZ^*$</th>
<th>$h \rightarrow \tau\tau$</th>
<th>$h \rightarrow \gamma\gamma$</th>
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<tbody>
<tr>
<td>$Z \rightarrow ll$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
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<tr>
<td>$Z \rightarrow qq$</td>
<td>$X$</td>
<td>$\checkmark$</td>
<td>$X$</td>
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<tr>
<td>$Z \rightarrow $νν</td>
<td>$X$</td>
<td>$\checkmark$</td>
<td>$X$</td>
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Interpretation in 2HDM

• Search procedure in exclusive channels depending upon the number of flavor of leptons, hadronic taus, photons, jet flavors and missing energy.

• Observed and expected limits in the 2HDM for masses in the range $[260-360]$ GeV

• $\alpha$ and $\beta$ determine cross-section and BRs for H and A production and decays

\[ \cos(\beta - \alpha) = 0 : \text{Decoupling limit: } h \text{ behaves exactly like in SM} \]
**ATLAS search for multi-Higgs sector**

- Single heavy neutral $H$ decays to charged $H^\pm$ and a $W$. $H^\pm$ decaying to $W$ and $h$ and $h$ to $b\bar{b}$ pair.

- One $W$ assumed to decay **hadronically** and the other **leptonically**

- **MultiHiggs Cascade** relevant for $m_H > 800 \text{ GeV}$

- **Signal topology:**
  
  1. One lepton + MET
  2. At least 4 jets - 2 b-tagged

- **Main background contributions:**
  
  1. $tt\bar{t}$ (~90%) Estimated from simulation and validated in control regions
  2. $V+$ jets
  3. Multi-jets Small. Estimated from data
Results

• **Multivariate analysis** to discriminate signal and main bkg ttbar

• **Counting experiment** with events passing the BDT output threshold

• Observed and expected 95% CL model independent upper limits on cross-section

• Analysis performed for any combination of $m_H$ and $m_{H^+}$.

• Gain sensitivity for Very High Masses

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$X \rightarrow hh$

CMS PAS HIG-13-032  NEW
ATLAS: CERN-PH-EP-2014-113
ATLAS-CONF-2014-005  NEW
Overview

- **Heavy H resonant** search performed in channels which allow **full reconstruction of the decay chain**

\[ X \rightarrow hh \rightarrow ? \]

- **Non Resonant SM Higgs pair production not expected to be observable at LHC 8 TeV**

<table>
<thead>
<tr>
<th>CMS</th>
<th>ATLAS</th>
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</thead>
<tbody>
<tr>
<td>$\gamma \gamma bb$</td>
<td>V</td>
</tr>
<tr>
<td>$\gamma \gamma bb$ non resonant</td>
<td>V</td>
</tr>
<tr>
<td>$bbbb$</td>
<td>V</td>
</tr>
</tbody>
</table>

- **Model independent** analyses: Results interpreted in terms of **Graviscalars or Radion** production

- **$\gamma \gamma bb$:** Large BR of the $H \rightarrow b\bar{b}$ and the low background and good resolution of the $H \rightarrow \gamma\gamma$ channel

- **$bbbb$:** More sensitive at high mass

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Analysis Strategy

- **CMS [260-1100] GeV:** Analysis performed in **two ranges:** $m_X < 400$ GeV and $m_X > 400$ GeV
  - **Low mass:** signal extracted from a fit to the $m_{\gamma\gamma}$ data spectrum
  - **High mass:** similar procedure with a fit to the $m_{\gamma\gamma jj}$

Not possible to fit a bump in the $m_{\gamma\gamma jj}$ below 400 GeV
$m_{\gamma\gamma jj}$ has kinematic peak ≈ 300 GeV

- **ATLAS [260-550] GeV:**
  - **Non resonant search:**
    - Fit to the unbinned $m_{\gamma\gamma}$ spectrum
  - **Resonant production search:**
    - **Counting experiment** due to small number of expected events
**Analysis Strategy**

- **4-tag selection:** 4 b-tagged high energy jets
- Kinematics requirement on dijet system to **veto ttbar events**
- Elliptical cut in the plane of the leading and the subleading dijet invariant mass
- >90% background in the signal region from **multijet events** + 10% **ttbar**

![Graph](image)

**Multijet:** $m_{4j}$ shape and normalization from data

**ttbar:** $m_{4j}$ shape from MC and normalization from data

$$X_{HH} = \sqrt{\left(\frac{m_{jj} - \tilde{m}_{jj}}{\sigma_{m_{jj}}}\right)^{2} + \left(\frac{m_{jj} - \tilde{m}_{jj}}{\sigma_{m_{jj}}}\right)^{2}}$$
Results

- 95% CL Upper Limits set on the cross-section times BR of the process
- Non Resonant Search assuming SM BR(hh): \textbf{Exp (Obs) 1.0 (2.2) pb}

- Resonant Searches: Results interpreted in terms of KK-graviton, radion and 2HDM models

\[ \gamma \gamma \rightarrow HH \rightarrow \gamma \gamma b\bar{b} \]

\[ \sigma(pp \rightarrow X) \times \text{BR}(X \rightarrow \gamma\gamma b\bar{b}) \text{ (fb)} \]

\[ m_X \text{ (GeV)} \]

\[ \text{Expected Limit (95% CL)} \]
\[ \text{Expected } \pm 1\sigma \]
\[ \text{Expected } \pm 2\sigma \]

\[ \text{Observed Limit (95% CL)} \]

\[ \text{ATLAS Preliminary} \]
\[ \sqrt{s} = 8 \text{ TeV}; \int Ldt = 19.5 \text{ fb}^{-1} \]

\[ \text{Expected Limit (95% CL)} \]
\[ \text{Expected } \pm 1\sigma \]
\[ \text{Expected } \pm 2\sigma \]

\[ \text{ATLAS} \]
\[ \int Ldt = 20 \text{ fb}^{-1} \text{ at } \sqrt{s} = 8 \text{ TeV} \]

\[ \text{Observed 95\% upper limit} \]
\[ \text{Expected 95\% upper limit} \]

\[ \gamma \gamma \rightarrow HH \rightarrow \gamma \gamma b\bar{b} \]

\[ \text{Observed 95\% upper limit} \]
\[ \text{Expected 95\% upper limit} \]
X → YY

CMS PAS HIG-14-006
ATLAS-CONF-2014-031

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Overview

- Model Independent search for local excesses in the diphoton spectrum exploiting a fit technique

\[ H \rightarrow \gamma\gamma \] interesting in 2HDM in the decoupling limit

- Method developed for the SM \( H \rightarrow \gamma\gamma \) channel extended to search for diphoton resonances in a wider mass range

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width Range [GeV]</td>
<td>0-85</td>
<td>0</td>
</tr>
<tr>
<td>Spin</td>
<td>0,2</td>
<td>0</td>
</tr>
</tbody>
</table>
CMS Analysis

- **High Mass** analysis performed in **four classes** according to the two photons kinematics properties to increase the search sensitivity

- **Parametrized signal** model through analytic function with **two free parameters**: $m_X$ and $\Gamma_X$

- **Background** estimated **fitting directly data** assuming negligible signal

  Sliding window fit range

  Bias Study to validate the fit technique
ATLAS Analysis


- **Low-mass**: Main background from Drell-Yan production estimated from data. Events categorized according to the number of converted photons

- **High-mass**: Sliding window fit range using analytic function SM-Higgs production as background

- Parametrized narrow signal model with \( m_X \) parameter

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Results

- No excess observed over the full mass range. 95% CL limits set on the fiducial cross-section times BR.
Conclusions

• Search for BMS physics in the Higgs sector:

Directly from decays of neutral and charged Higgses

Indirectly by interpreting measured properties of the light Higgs

• Many analyses completed at ATLAS + CMS on full 8 and 7 TeV data:

No significant excess observed and various cross-section limits and exclusion regions for the parameter space of several models have been provided.

• 2015 and sqrt(s)=13 TeV will greatly enhance our sensitivity

BSM Higgses might be just around the corner...
Invisible: Search in VBF and ZH channels

- **VBF Signal topology:**
  1. Two final state quarks separated by a **large rapidity gap** and with **high invariant mass**
  2. Large **missing energy**

- **ZH Signal topology:**
  1. **Z(ll)H**(inv): Pair of **isolated leptons** and **High MET** - Limited jet activity
  2. **Z(bbar)H**(inv): **B-tagged jet pair** and **High MET** (same as Z(νν)H(bbar))

Angular separation MET-Z system
• Signal topology:
  1. Two final state quarks separated by a large rapidity gap and with high invariant mass
  2. Large missing energy

• Main background from V+jets estimated from control regions in data

• Signal region defined: MET > 130 GeV & m_{jj} > 1100 GeV & |Δη|>4.2

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(νν)+jets</td>
<td>99 ± 29 (stat.) ± 25 (syst.)</td>
</tr>
<tr>
<td>W(μν)+jets</td>
<td>67 ± 5 (stat.) ± 16 (syst.)</td>
</tr>
<tr>
<td>W(τν)+jets</td>
<td>63 ± 9 (stat.) ± 18 (syst.)</td>
</tr>
<tr>
<td>W(τν)+jets</td>
<td>53 ± 18 (stat.) ± 18 (syst.)</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>31 ± 2 (stat.) ± 23 (syst.)</td>
</tr>
<tr>
<td>Sum (t¯t, single top quark, VV, DY)</td>
<td>20.0 ± 8.2 (syst.)</td>
</tr>
<tr>
<td>Total background</td>
<td>332 ± 36 (stat.) ± 46 (syst.)</td>
</tr>
<tr>
<td>VBF H(inv.)</td>
<td>210 ± 30 (syst.)</td>
</tr>
<tr>
<td>ggF H(inv.)</td>
<td>14 ± 11 (syst.)</td>
</tr>
<tr>
<td>Observed data</td>
<td>390</td>
</tr>
<tr>
<td>S/B (%)</td>
<td>70</td>
</tr>
</tbody>
</table>

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Signal topology:

1. \(Z(\ell\ell)H(\text{inv})\): Pair of isolated leptons and High MET - Limited jet activity

2. \(Z(b\bar{b})H(\text{inv})\): B-tagged jet pair and High MET

Dominant background from boson and diboson production w/o jets estimated from control regions.

Signal region 1: \(\text{MET} > 120 \text{ GeV}, \Delta \phi(\ell\ell, \text{MET}) > 2.7, |\text{MET}-p_T,\ell\ell|/p_T,\ell\ell\)

Signal extracted with a 2-dimensional fit of \(\Delta \phi\) and \(m_T\) of the dilepton-MET system

For the \(Z(b\bar{b})H(\text{inv})\) a BDT technique is used to select the signal.
LFV: Analysis strategy

- $M_{\text{collinear}}$ between decay products as estimator of the Higgs mass

Exploit the kinematics of the boosted $\tau$ from H decay

$$M_H = M_{\text{collinear}} = \frac{M_{\text{vis}}}{\sqrt{x_{\tau_{\text{vis}}}}}$$

- Events divided into categories according to the number of jets in the event

- $Z \rightarrow \tau\tau$ and misidentified leptons from W+jets and QCD multi-jet from data

Data, $\mu\tau$, Bckg Uncertainty

SM Higgs
$Z+\tau\tau$ (embedded)
$Z+\tau\tau$
Single top quark
$t\bar{t}$
VV
$W_1$, $W_1^*$
Fakes (leptons)
LFV GG Higgs (Br=100%)
LFV VBF Higgs (Br=100%)

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LFV: Mass spectra

Data, µ/
Bckg Uncertainty
SM Higgs
Z+\gamma (embedded)
Z+/\gamma
Single top quark
W+ / W-/
LFV GG Higgs (Br=100%)
LFV VBF Higgs (Br=100%)
2HDM: Background estimation

- Multilepton searches allow probing regions of parameter space inaccessible to hadronic searches.

- Main reducible contributions:
  
  1. Z+jets, W+jets with bosons decay leptonically and additional fake lepton
     
     Estimated from data
  
  2. ttbar with W’s leptonically decays
     
     Evaluated in control regions

- Irreducible contributions:
  
  1. VV+jets with >=3 real leptons
  
  2. Drell-Yan processes with internal asymmetric conversions

- Diphoton plus lepton searches:
  
  Main background reduced by the diphoton mass cut around the SM-Higgs observed value
  
  Estimated with sidebands
2HDM: Results

• Most sensitive search channels for a Heavy Higgs search

<table>
<thead>
<tr>
<th>Events</th>
<th>0-50</th>
<th>50-100</th>
<th>100-150</th>
<th>150-200</th>
<th>&gt;200</th>
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<td>tt</td>
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<tr>
<td>WZ</td>
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<td>ZZ</td>
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<td>tW</td>
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<tr>
<td>tZ</td>
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<td>H→hh 300 GeV</td>
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<td>Bkg Uncertainties</td>
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• 95% CL limits on cross-section times Br

<table>
<thead>
<tr>
<th>m_H [GeV]</th>
<th>260</th>
<th>280</th>
<th>300</th>
<th>320</th>
<th>340</th>
<th>360</th>
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<tbody>
<tr>
<td>B×σ [pb]</td>
<td>8</td>
<td>6.5</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
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<table>
<thead>
<tr>
<th>m_A [GeV]</th>
<th>260</th>
<th>280</th>
<th>300</th>
<th>320</th>
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<tr>
<td>B×σ [pb]</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

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MultiHiggs: Event Reconstruction

- Identification of the leptonically decaying W
- \( h \) candidate reconstructed with the two b-tagged jets
- Hadronically decaying W reconstructed from the remaining jets.
- \( H^+ \) reconstructed from \( h \) and the W which gives the highest mass
- \( H \) formed with the bbarWW system reconstructed

\[ m_{h^0} = 125 \text{ GeV} \]
\[ m_{H^0} = 325 \text{ GeV} \]
\[ m_{H^0} = 525 \text{ GeV} \]
\[ m_{H^0} = 825 \text{ GeV} \]
\[ m_{H^0} = 125 \text{ GeV} \]
\[ m_{H^0} = 725 \text{ GeV} \]
\[ m_{H^0} = 1025 \text{ GeV} \]

(\( \ell^+ \ell^- \) reconstructed from \( h \) and the W which gives the highest mass)
bbgg: Signal Reconstruction

- Di-Higgs system reconstructed from a pair of photons and a pair of jets originating from b-quarks

  • **Resonant signal topology:**

    1. **Peak around** \( m_H \) (125 GeV) **in** diphoton and dijet spectra

    2. **Peak around** \( m_X \) (unknown) **in the 4-body spectrum**

- \( m_X \) mass range: ATLAS [260-500] GeV
  CMS [260-1100] GeV

- Narrow resonance signal hypothesis

- **Dominant Background:** non resonant production of photons and jets (QCD)
  SM-Higgs considered as resonant background
Summary on decay modes

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Status</th>
<th>Results</th>
<th>Dataset</th>
<th>Status</th>
<th>Results</th>
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<tbody>
<tr>
<td><strong>Favoured decay modes</strong></td>
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<tr>
<td>H(ZZ)</td>
<td>5.1 + 19.6 fb⁻¹</td>
<td>arXiv:1312.5353</td>
<td>μ = 0.93</td>
<td>4.8 + 20.3 fb⁻¹</td>
<td>ATLAS-CONF-2014-009</td>
</tr>
<tr>
<td>H(WW)</td>
<td>5.1 + 19.4 fb⁻¹</td>
<td>arXiv:1312.1129</td>
<td>μ = 0.72</td>
<td>4.8 + 20.3 fb⁻¹</td>
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<tr>
<td>H(γ γ)</td>
<td>5.1 + 19.7 fb⁻¹</td>
<td>arXiv:1407.0558</td>
<td>μ = 1.14</td>
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<td>ATLAS-CONF-2014-009</td>
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<tr>
<td>H(tau tau)</td>
<td>4.9 + 19.7 fb⁻¹</td>
<td>arXiv:1401.5041</td>
<td>μ = 0.78</td>
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<td>V-H(bb)</td>
<td>5.1 + 18.9 fb⁻¹</td>
<td>arXiv:1310.3687</td>
<td>μ &lt; 1.89(0.95)</td>
<td>4.7 + 20.3 fb⁻¹</td>
<td>ATLAS-CONF-2013-079</td>
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<td>VBF-H(bb)</td>
<td>19.0 fb⁻¹</td>
<td>HIG-13-011</td>
<td>μ &lt; 3.6(3.0)</td>
<td>4.7 + 13.0 fb⁻¹</td>
<td>ATLAS-CONF-2012-161</td>
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<td>ttH(bb)</td>
<td>19.5 fb⁻¹</td>
<td>HIG-14-010</td>
<td>μ &lt; 2.9(3.3)</td>
<td>20.3 fb⁻¹</td>
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<td><strong>Rare decay modes</strong></td>
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<td>H(mu mu )</td>
<td>5.0+ 19.7 fb⁻¹</td>
<td>HIG-13-007</td>
<td>μ &lt; 7.4</td>
<td>24.8 fb⁻¹</td>
<td>arXiv:1406.7663</td>
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<tr>
<td>H(Z γ)</td>
<td>5.0+ 19.6 fb⁻¹</td>
<td>arXiv:1307.5515</td>
<td>μ &lt; 10</td>
<td>4.5 + 20.3 fb⁻¹</td>
<td>arXiv:1402.3051</td>
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<td>H(γ* γ)</td>
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<td>μ &lt; 10</td>
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<td><strong>Invisible decay modes</strong></td>
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<tr>
<td>Z(ll)-H(inv)</td>
<td>4.9 + 19.7 fb⁻¹</td>
<td>arXiv:1402.1344</td>
<td>BR &lt; 58(46)%</td>
<td>4.5 + 20.3 fb⁻¹</td>
<td>arXiv:1402.3244</td>
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<tr>
<td>Z(bb)-H(inv)</td>
<td>4.9 + 19.7 fb⁻¹</td>
<td>arXiv:1404.1344</td>
<td>BR &lt; 58(46)%</td>
<td>-</td>
<td>-</td>
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<td>arXiv:1404.1344</td>
<td>BR &lt; 58(46)%</td>
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<td>H(tau mu)</td>
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<td>H(long-lived)</td>
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<td>-</td>
<td>-</td>
<td>20.3 fb⁻¹</td>
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</tr>
</tbody>
</table>

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| = preliminary |