Search for invisible decays of the 125 GeV Higgs boson using the CMS detector

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Nicholas Wardle - CERN
On behalf of the CMS collaboration
Introduction

Several BSM models predict additional contributions to Higgs boson width

Indirect constraints from off-shell $\leftrightarrow$ on-shell combination...

... and constraints on additional decay modes from Run-1 combined LHC couplings measurements (combined analysis of visible decay modes)
In SM, $B(H\rightarrow\text{Inv}) \sim 1.2 \times 10^{-3} (H\rightarrow 4\nu)$

$\rightarrow$ Invisible Higgs boson decays will be a hint of new physics

Search for invisible Higgs boson decays in several production modes, with different cross-sections and S/B ratios

See talk from Shin-Shan Yu for $bb/\tau\tau+\text{MET}$

Invisible decay channels

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Search for invisible Higgs boson decays in several production modes, with different cross-sections and S/B ratios

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Search for invisible Higgs boson decays in several production modes, with different cross-sections and S/B ratios

Today, will show results from 2.3 fb\(^{-1}\) 13 TeV data (including some with the full 12.9 fb\(^{-1}\)) and latest combination with Run-1 searches
Missing Energy at CMS

Common signature is visible system recoiling against large **missing energy**.

Well modelled missing energy response and resolution is key to invisible Higgs decay searches.

**Recoil (U)** used as proxy for missing energy in $Z\rightarrow ll + \text{jets}$, $W\rightarrow l\nu + \text{jets}$, and $\gamma + \text{jets}$ events for modelling $E_T^{\text{miss}}$ tails from SM backgrounds.
Vector-boson Fusion

Look for two jets with VBF topology:

Dedicated VBF trigger selects events with two jets with
- high rapidity gap
- large dijet mass

Offline selection driven by requirement to remain efficient wrt trigger

- $p_T^{j_1,j_2} > 80, 70$ GeV
- $m_{jj} > 1100$ GeV
- $E_T^{\text{miss}} > 200$ GeV
- $\Delta\phi(j, E_T^{\text{miss}}) > 2.3$ rad
- $\Delta\eta(j,j) > 3.6$

Upgrade in hardware trigger for 2016 data-taking will allow reduction of these thresholds *(see talk by A. Tapper)*
Dominant backgrounds due to SM W/Z+jets -> Use lepton control regions in data to normalize

- Assume common scale-factor between W/Z processes
- 30% systematic on ratio to account for HO corrections

### Process

<table>
<thead>
<tr>
<th>Process</th>
<th>Signal region</th>
<th>Control regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(μ⁺μ⁻)+jets</td>
<td>QCD</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>–</td>
</tr>
<tr>
<td>Z(νν)+jets</td>
<td>QCD</td>
<td>47 ± 12</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>21 ± 7</td>
</tr>
<tr>
<td>W(μν)+jets</td>
<td>QCD</td>
<td>13 ± 2</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>4.3 ± 0.8</td>
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<tr>
<td>W(eν)+jets</td>
<td>QCD</td>
<td>9.3 ± 1.5</td>
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<tr>
<td></td>
<td>EW</td>
<td>5.4 ± 1.1</td>
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<tr>
<td>W(τν)+jets</td>
<td>QCD</td>
<td>13 ± 2</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>5.5 ± 1.2</td>
</tr>
<tr>
<td>Top quark</td>
<td>QCD</td>
<td>2.3 ± 0.4</td>
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<tr>
<td></td>
<td>QCD multijet</td>
<td>3 ± 23</td>
</tr>
<tr>
<td>Dibosons</td>
<td>QCD</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>Total bkg.</td>
<td></td>
<td>125 ± 28</td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td>126</td>
</tr>
<tr>
<td>Signal</td>
<td>qqH</td>
<td>53.6 ± 4.9</td>
</tr>
<tr>
<td>m_H = 125 GeV</td>
<td>ggH</td>
<td>5.4 ± 3.6</td>
</tr>
</tbody>
</table>

### Data

- CMS PAS-HIG-16-009
- CMS Preliminary
- CMS PAS-HIG-16-009
- CMS Preliminary

- Events
- μ²
- ν²
- Events

- CMS
- PAS
- HIG
- 16-009
- 2.3 fb⁻¹ (13 TeV)

- Events
- μ²
- ν²
- Events

- CMS
- PAS
- HIG
- 16-009
- 2.3 fb⁻¹ (13 TeV)
Dominant backgrounds due to **SM W/Z+jets** -> Use lepton control regions in data to normalize
- Assume common scale-factor between W/Z processes
- 30% systematic on ratio to account for HO corrections

### Signal vs. Control Regions

<table>
<thead>
<tr>
<th>Process</th>
<th>Signal region</th>
<th>single e</th>
<th>single µ</th>
<th>single τ</th>
<th>µ⁺µ⁻</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(µ⁺µ⁻)+jets</td>
<td>QCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4.2±1.1</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>–</td>
<td>–</td>
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<td>–</td>
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<td>47±12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.0±0.7</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>21±7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>W(µν)+jets</td>
<td>QCD</td>
<td>13±2</td>
<td>53±5</td>
<td>0.40±0.19</td>
<td>–</td>
<td>45±5</td>
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<tr>
<td></td>
<td>EW</td>
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<td>–</td>
<td>6.0±0.9</td>
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<tr>
<td>W(νν)+jets</td>
<td>QCD</td>
<td>9.3±1.5</td>
<td>17±3</td>
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<td>0.2±2.2</td>
<td>39±4</td>
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<tr>
<td></td>
<td>EW</td>
<td>5.4±1.1</td>
<td>7.8±1.3</td>
<td>0.2±0.13</td>
<td>–</td>
<td>6.1±1.0</td>
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<tr>
<td>W(τν)+jets</td>
<td>QCD</td>
<td>13±2</td>
<td>0.06±0.06</td>
<td>–</td>
<td>12±2</td>
<td>74±9</td>
</tr>
<tr>
<td></td>
<td>EW</td>
<td>5.5±1.2</td>
<td>–</td>
<td>–</td>
<td>5.1±1.2</td>
<td>24±3</td>
</tr>
<tr>
<td>Top quark</td>
<td></td>
<td>2.3±0.4</td>
<td>1.5±0.3</td>
<td>6.8±0.9</td>
<td>7.1±1.0</td>
<td>0.22±0.06</td>
</tr>
<tr>
<td>QCD multijet</td>
<td></td>
<td>3.0±23</td>
<td>–</td>
<td>5.3</td>
<td>0.4±0.3</td>
<td>1200±170</td>
</tr>
<tr>
<td>Dibosons</td>
<td></td>
<td>0.7±0.3</td>
<td>0.4±0.4</td>
<td>0.8±0.4</td>
<td>–</td>
<td>0.02±0.02</td>
</tr>
<tr>
<td>Total bkg.</td>
<td></td>
<td>125±28</td>
<td>27±3</td>
<td>91±8</td>
<td>25±4</td>
<td>6.4±1.4</td>
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<tr>
<td>Data</td>
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<td>126</td>
<td>29</td>
<td>89</td>
<td>24</td>
<td>7</td>
</tr>
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<td>qqH</td>
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<td>–</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Simple counting experiment to extract potential signal

Backgrounds constrained *in-situ* via simultaneous fit across signal and control regions

8/5/16
Nicholas Wardle – LHC DM Searches 8
Limits on $\sigma \times \text{BR}$ of a scalar decaying invisibly as a function of hypothesised mass

-> Compare to “Higgs-like” scalar via VBF production

CMS-PAS-HIG-16-009

2.3 fb$^{-1}$ (13 TeV)

CMS

Preliminary

VBF $\Phi \rightarrow$ invisible

$g_\Phi = g_{\text{SM} H}$

Assuming SM Higgs XS

95% CL limits

- Observed limit
- Expected limit

Expected limit (1$\sigma$)

Expected limit (2$\sigma$)

$\sigma_{\text{VBF}}$ (SM)

$B(H \rightarrow \text{inv}) < 69\% (62\%)$

obs (exp)

@ 125 GeV
Limits on $\sigma \times B(\Phi \rightarrow \text{inv})$ of a scalar decaying invisibly as a function of hypothesised mass

$\rightarrow$ Compare to “Higgs-like” scalar via VBF production

See talk from Bjoern Penning

Largest systematic due to $W/Z$ ratio, however sensitivity is statistics limited

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td></td>
</tr>
<tr>
<td>$W$ to $Z$ ratio in QCD produced $V+$jets</td>
<td>13%</td>
</tr>
<tr>
<td>$W$ to $Z$ ratio in EW produced $V+$jets</td>
<td>6.3%</td>
</tr>
<tr>
<td>Jet energy scale+resolution</td>
<td>6.0%</td>
</tr>
<tr>
<td>QCD multijet normalisation</td>
<td>4.3%</td>
</tr>
<tr>
<td>PU mis-modelling</td>
<td>4.2%</td>
</tr>
<tr>
<td>Lepton efficiencies</td>
<td>2.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.2%</td>
</tr>
<tr>
<td>Signal specific</td>
<td></td>
</tr>
<tr>
<td>$ggH$ acceptance</td>
<td>3.8%</td>
</tr>
<tr>
<td>QCD scale + PDF ($ggH$)</td>
<td>1.8%</td>
</tr>
<tr>
<td>QCD scale + PDF ($ggH$)</td>
<td>$&lt;0.2%$</td>
</tr>
<tr>
<td>Total statistical only</td>
<td>$-27/ +28%$</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>$-33/ +32%$</td>
</tr>
</tbody>
</table>

Assuming SM Higgs XS $\sigma_{VBF} (\text{SM})$

B(H->inv) $< 69\% (62\%)$ obs (exp) @ 125 GeV

CMS-PAS-HIG-16-009

2.3 fb$^{-1}$ (13 TeV)
Leptonic Z decay offers clean final state
look for $E_T^{miss} + 2$ well isolated opposite sign, $e/\mu$
- $p_T > 20$ GeV, $76 < m_{ll} < 106$ GeV
- $\Delta\phi(Z, E_T^{miss}) > 2.8$
- $\Delta\phi(j, E_T^{miss}) > 0.5$ - kills $Z$+jets background

Fit transverse mass ($m_T$) distributions in electron/muon channels, separated into 0 and 1 jet categories

CMS-PAS-HIG-16-016

Backgrounds dominated by diboson processes

$ZZ(2l2v)$ (70%)
$WZ(lvll)$ (25%)
- Estimated from simulation @NLO
Z(II) H

CMS-PAS-HIG-16-008

2.3 fb⁻¹ (13 TeV)

CMS Preliminary
ZH → 2l+E_{T}^{miss} +0/1-jets

Systematic uncertainty dominated by theory in ZZ backgrounds

Sensitivity statistics limited

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ background theory</td>
<td>16%</td>
</tr>
<tr>
<td>luminosity</td>
<td>8.4%</td>
</tr>
<tr>
<td>b jet tag efficiency</td>
<td>6.2%</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>6.2%</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>6.2%</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>3.2%</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>3.2%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.2%</td>
</tr>
<tr>
<td>Diboson normalisation</td>
<td>5.3%</td>
</tr>
<tr>
<td>eμ region extrapolation</td>
<td>4.0%</td>
</tr>
<tr>
<td>Z(l⁺l⁻) normalisation</td>
<td>4.8%</td>
</tr>
</tbody>
</table>

Signal specific

| QCD scale + PDF (qqZH)                                  | 7.4%   |
| QCD scale + PDF (ggZH)                                  | 4.0%   |
| Total statistical only                                  | -50/ + 56% |
| Total uncertainty                                       | -55/ + 62% |

UL of 1.1 (1.1) pb obs (exp) @ 125 GeV
NEW with 12.9 fb⁻¹

Assuming SM x-section

B(H→inv) < 86% (70%) obs (exp)

See talk from Shin-Shan Yu
Gluon-fusion production tagged via ISR jet(s)

Look for high $p_T$, central jet(s) + large missing energy

- $p_T > 100$ GeV
- $|\eta| < 2.5$
- $E_T^{miss} > 200$ GeV

Signal extraction from fit to $E_T^{miss}$ spectrum (sizeable theory systematics on ggH $p_T$ spectrum)

Dominant backgrounds from $W/Z$+jets

-> Constrain shape and normalization with lepton and photon control regions

Analysis also used for generic DM searches

See talk from Shin-Shan Yu

8/5/16
Nicholas Wardle – LHC DM Searches
“Recoil” in control regions defined as
\[ |\vec{E}_{T}^{\text{miss}} + \sum \vec{p}_{T}^{ll/\gamma}| \]

For each bin of \( E_{T}^{\text{miss}} \) equivalent recoil bin in Z->\( \mu\mu/ee \), \( \gamma+\text{jets} \) and W->E\( \nu/\mu\nu \) translated to signal region via transfer factors.
Simultaneous fit across all regions allowing for sys.
• lepton/photon efficiency/purity
• W/Z and \( \gamma/Z \) ratios theory
V(jj) H

Boosted (high $p_T$) vector bosons decaying to jets will form a single "fat"-jet

Use jet substructure techniques to identify hadronically decaying V-bosons:
• Look for high-$p_T$ "fat" jet with $m_J$ close to $m_W$ or $m_Z$
  • $65 < m_J < 105$ GeV
  • N-subjettiness ($\tau_N$) (likelihood for N-daughter hypotheses)
    • $\tau_2/\tau_1 < 0.6$

Additionally require
• $p_T^J > 250$ GeV
• $E_T^{miss} > 250$ GeV
• $\Delta\phi(J,E_T^{miss}) > 0.5$ rad

Events selected in this analysis are removed from gluon-fusion tag
Signal extracted from fit to $E_T^{\text{miss}}$ spectrum

Dominant backgrounds from SM $V$+jets

- Use leptonic $W/Z$ and $\gamma$ + jets events in data to constrain backgrounds
- Independent scale factors per bin
- Systematics due to $\gamma/Z$ and $W/Z$ HO electroweak and QCD effects as in ggH
Gluon-fusion and V(jj)H

Upper limits on $\sigma x BR / \sigma_{SM}$ for Higgs decaying invisibly @ 125 GeV

Assume SM values for ratios of production cross-sections

<table>
<thead>
<tr>
<th></th>
<th>Limits with 2.3fb$^{-1}$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH - tag</td>
<td>1.11</td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>V(jj) H - tag</td>
<td>1.43</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Comb.</td>
<td>0.84</td>
<td>0.85</td>
<td></td>
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</tbody>
</table>

Systematic uncertainty dominated by W/Z and $\gamma/Z$ theory systematics, JES and lepton ID

-> All related to transfer from CR to SR to constrain W/Z+jets backgrounds

Systematic uncertainty

<table>
<thead>
<tr>
<th>Common</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$+jets/Z(\nu)+jets ratio theory</td>
<td>32%</td>
</tr>
<tr>
<td>$W(\nu)$+jets/Z(\nu)+jets ratio theory</td>
<td>21%</td>
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<tr>
<td>Jet energy scale+resolution</td>
<td>12%</td>
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<tr>
<td>V-tagging efficiency</td>
<td>12%</td>
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<tr>
<td>Lepton veto efficiency</td>
<td>13%</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>13%</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>8.6%</td>
</tr>
<tr>
<td>b jet tag efficiency</td>
<td>5.7%</td>
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<tr>
<td>Photon efficiency</td>
<td>3.1%</td>
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<tr>
<td>$E_{T}^{miss}$ scale</td>
<td>4.6%</td>
</tr>
<tr>
<td>Top quark background normalisation</td>
<td>6.0%</td>
</tr>
<tr>
<td>Diboson background normalisation</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

Signal specific

| ggH $p_T$-spectrum | 12% |
| QCD scale + PDF (ggH) | 3.0% |
| QCD scale + PDF (VH)  | 1.4% |

Total statistical only

-46% ± 50%

Total uncertainty

-69% ± 74%
Gluon-fusion and V(jj)H

Upper limits on $\sigma x \text{BR}/\sigma_{\text{SM}}$ for Higgs decaying invisibly @ 125 GeV

<table>
<thead>
<tr>
<th></th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH - tag</td>
<td>0.85</td>
<td>0.48</td>
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<tr>
<td>V(jj) H - tag</td>
<td>0.72</td>
<td>1.17</td>
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<tr>
<td>Comb.</td>
<td>0.56</td>
<td>0.44</td>
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</tbody>
</table>

CMS-PAS-EXO-16-037

NEW with 12.9 fb$^{-1}$

See talk from Shin-Shan Yu
Combination
Run-1 + 2015 data
Combination of H-$\rightarrow$invisible searches performed using **Run-1** dataset and **2.3 fb$^{-1}$ of 13 TeV** (2015) data

<table>
<thead>
<tr>
<th>Analysis Tag</th>
<th>$\int \mathcal{L}$ (fb$^{-1}$)</th>
<th>Expected Signal Composition (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>7 TeV</td>
<td>8 TeV</td>
</tr>
<tr>
<td>qqH-tagged</td>
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<tr>
<td>VBF</td>
<td>–</td>
<td>19.2 [16]</td>
</tr>
<tr>
<td>$Z(l^+l^-)$</td>
<td>4.9 [16]</td>
<td>19.7 [16]</td>
</tr>
<tr>
<td>$Z(bb)^*$</td>
<td>–</td>
<td>18.9 [16]</td>
</tr>
<tr>
<td>VH-tagged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V(jj)$-tagged</td>
<td>–</td>
<td>19.7 [56]</td>
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<tr>
<td>ggH-tagged</td>
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<td></td>
</tr>
<tr>
<td>monojet</td>
<td>–</td>
<td>19.7 [56]</td>
</tr>
</tbody>
</table>

**CMS-PAS-HIG-16-016**

- Latest SM x-sections + uncertainties from LHC-HXSWG used as theory inputs
- Explicit event selection vetos allow for combination of searches
  - VBF tagged events removed from ggH/V(jj)H-tagged searches)

*Also include 8TeV Z(bb) channel (not discussed today)*

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[56] arXiv:1607.05764 (sub JHEP)
Combined

95% CL Upper limits on $\sigma x \text{BR}$ relative to SM production

$4.9 \text{ fb}^{-1} (7 \text{ TeV}) + \leq 19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 2.3 \text{ fb}^{-1} (13 \text{ TeV})$

**CMS Preliminary**

$\sigma x B(H \rightarrow \text{inv})$ - Upper limit 95% CL

**Observed**

**Median expected**

- **68% expected**
- **95% expected**

**m_H=125 GeV**

VH includes $Z(\ell\ell)$, $Z(bb)$ and $V(jj)H$ channels

Expected sensitivity dominated by vector-boson fusion channel

$\sigma x B(H\rightarrow\text{inv}) < 24\%$ observed (23% expected)

Assume SM values for ratios of production cross-sections
95% Upper limit on $B(H \rightarrow \text{inv})$ expressed as for different assumptions on production

Vary coupling modifiers of Higgs boson to SM fermions ($\kappa_F$) and vector bosons ($\kappa_V$)

- Non trivial scaling for $gg \rightarrow ZH$ component
- $ZH(H \rightarrow bb)$ background in $Z(bb)$ channel also modified

95% upper limit on $B(H \rightarrow \text{inv})$ varies between 20-30% within LHC couplings constraints
DM interpretation

B(H→inv.) translated into DM-nucleon spin-independent cross section limits as a function of DM mass

Use Higgs-Portal* models assuming scalar/fermion DM

90% CL to compare to direct detection experiments

CMS limits more stringent for small DM masses

Summary

Presented searches for Higgs decaying to invisibles at CMS

- Run-2 data @ 13 TeV, including some new results with 12.9 fb⁻¹
- Search channels include VBF, Z(H)H, V(jj)H and gluon-fusion tags
- Combination of searches between Run-1 and 2015 data provide direct constraint on B(H→Inv)

B(H→inv) < 24% observed (23% expected) @ 95% CL

- Non SM-production scenarios and DM interpretations presented
- Sensitivity is statistics dominated but systematics are becoming more important

Look forward to additional data from 2016!

4.9 fb⁻¹ (7 TeV) + ≤ 19.7 fb⁻¹ (8 TeV) + 2.3 fb⁻¹ (13 TeV)

CMS Preliminary

B(H → inv.)<0.20

90% CL limits

DM mass [GeV]

DM-nucleon cross section [cm²]

LUX (2015)
CDMSlite (2015)
XENON100 (2016)
CMS detector

Hermetic design of CMS provides good coverage of interaction

→ Vital for searches with missing energy

Triggers reduce 40 MHz (LHC) → O(100) Hz

High multiplicity from multiple, pile-up interactions (PU)

→ Upgrade Trigger for 2016 data taking performs PU subtraction at L1

**Tracker**

Pixel + Silicon strip

~50% of Photons convert

**EM Calorimeter**

Lead tungstate (PbWO₄) crystals

61 200 (EB) / 7 324 (EE)

**Hadron Calorimeter**

Scintillating Brass

Exploit jets from VBF production
Combined $13$ TeV

- Observed
- Expected
- 7+8 TeV

CMS Preliminary

Observed $\leq 19.7$ fb$^{-1}$ (8 TeV) $+ 2.3$ fb$^{-1}$ (13 TeV)

$4.9$ fb$^{-1}$ (7 TeV)
$E_T^{\text{miss}}$ Resolution

![Graphs showing $E_T^{\text{miss}}$ resolution with data points for $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, and $\gamma + \text{jets}$ compared to MC predictions.](image)

CMS Preliminary, 0.8 fb$^{-1}$ (13 TeV, 2016)

$U = \text{MET} - p_T^z$

Recoil, $U$

MET
Dedicated noise filters remove events with spurious missing energy

$\rightarrow$ Remove $E_T^{\text{miss}}$ Resolution fake contributions in high tails.
Backgrounds dominated by **diboson processes**: $ZZ(2l2\nu)$ (70%), $WZ(l\nu ll)$ (25%)

$->$ Estimated from simulation NLO with POWHEG+MCFM

<table>
<thead>
<tr>
<th>Process</th>
<th>0 jets $\mu^+\mu^-$</th>
<th>0 jets $e^+e^-$</th>
<th>1 jet $\mu^+\mu^-$</th>
<th>1 jet $e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH$, $m_H = 125$ GeV</td>
<td>$5.97 \pm 0.55$</td>
<td>$4.27 \pm 0.39$</td>
<td>$1.29 \pm 0.20$</td>
<td>$0.98 \pm 0.15$</td>
</tr>
<tr>
<td>$Z(l^+l^-)$+jets</td>
<td>$0.45 \pm 0.45$</td>
<td>$0.30 \pm 0.30$</td>
<td>$0.45 \pm 0.45$</td>
<td>$0.30 \pm 0.30$</td>
</tr>
<tr>
<td>$ZZ \rightarrow ll\nu\nu$</td>
<td>$10.4 \pm 1.14$</td>
<td>$7.46 \pm 0.81$</td>
<td>$2.04 \pm 0.31$</td>
<td>$1.49 \pm 0.23$</td>
</tr>
<tr>
<td>$WZ \rightarrow l\nu ll$</td>
<td>$3.42 \pm 0.28$</td>
<td>$2.40 \pm 0.19$</td>
<td>$1.04 \pm 0.10$</td>
<td>$1.00 \pm 0.10$</td>
</tr>
<tr>
<td>Top/WW/\tau\tau</td>
<td>$0.69 \pm 0.23$</td>
<td>$0.88 \pm 0.29$</td>
<td>$0.44 \pm 0.22$</td>
<td>$0.26 \pm 0.13$</td>
</tr>
<tr>
<td>VVV</td>
<td>-</td>
<td>-</td>
<td>$0.13 \pm 0.06$</td>
<td>$0.07 \pm 0.03$</td>
</tr>
<tr>
<td>Total background</td>
<td>$15.0 \pm 1.28$</td>
<td>$11.0 \pm 0.93$</td>
<td>$4.10 \pm 0.60$</td>
<td>$3.12 \pm 0.41$</td>
</tr>
<tr>
<td>Data</td>
<td>18</td>
<td>8</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
Event balance variables
Likelihood Model

$$\mathcal{L}_c(\mu, \mu_{Z\to\nu\nu}, \theta) = \prod_i \text{Poisson} \left( d_i^\gamma | B_i(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^\gamma(\theta)} \right)$$

$$\times \prod_i \text{Poisson} \left( d_i^Z | B_i^Z(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^Z(\theta)} \right)$$

$$\times \prod_i \text{Poisson} \left( d_i^W | B_i^W(\theta) + \frac{f_i(\theta) \cdot \mu_i^{Z\to\nu\nu}}{R_i^W(\theta)} \right)$$

$$\times \prod_i \text{Poisson} \left( d_i^{Zee} | B_i^{Zee}(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Zee}(\theta)} \right)$$

$$\times \prod_i \text{Poisson} \left( d_i^{W\mu\mu} | B_i^{W\mu\mu}(\theta) + \frac{f_i(\theta) \cdot \mu_i^{Z\to\nu\nu}}{R_i^{W\mu\mu}(\theta)} \right)$$

$$\times \prod_i \text{Poisson} \left( d_i | B_i(\theta) + (1 + f_i(\theta)) \mu_i^{Z\to\nu\nu} + \mu S_i(\theta) \right)$$

- Number of observed events
- Expected ‘other background’ contamination in CR
- Expectation of number of Z/W/\gamma given TF (R)

\( f_i \rightarrow \text{ratio of } W\to\ell\nu / Z\to\nu\nu \text{ in the signal region}:

- Relies on theoretical prediction for differential cross-sections and lepton acceptance!
- Transfer factors (R) are unchanged (easy to switch back and forth between this and old likelihood definition)
V+jets theory systematics

EWK corrections at High pT are large! → 100% of correction as uncertainty

arXiv:1505:05704
DM Scalar + mixing with 125

arXiv:1607.06680

If DM is light, H(125) will dominate kinematics when mixing is allowed
-> Rescale B(H→Inv) constraints to constrain generic scalar DM models

“Heavy Higgs” (no mixing)
ttH(125) (no mixing)
Combination

Assuming SM values for production cross sections

→ Interpret potential signal as Invisible Higgs branching ratio

Profile likelihood ratio

\[ q = -2\ln \frac{L(data|B(H \rightarrow \text{inv.}), \hat{\theta})}{L(data|\hat{B}(H \rightarrow \text{inv.}), \hat{\theta})} \]

Expected sensitivity dominated by VBF but small excess (<1σ) results in less stringent limit

Deficit of events in VH tagged channels yields stronger observed limit

4.9 fb\(^{-1}\) (7 TeV) + ≤ 19.7 fb\(^{-1}\) (8 TeV) + 2.3 fb\(^{-1}\) (13 TeV)

Combination

VH-tagged

Observed

VBF-tagged

Expected

ggH-tagged

Combined

CMS Preliminary
Sensitivity dominated by Run-1 analyses

Excess in VBF at 8 TeV yields slightly worse improvement in observed limit

Systematic uncertainties play a large role
-> Large impacts from CR<->SR transfer
theory uncertainties to constrain backgrounds
1D projections