The Search for Invisible Higgs Boson Production
With the CMS Detector at the LHC

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For the CMS Collaboration
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Outline

**Experimental Apparatus**
- The CMS Detector

**Intro To Invisible Higgs Boson**
- Invisible Higgs and ZZ Production

**Samples and Modeling**
- Monte Carlo and DataSets

**The Search Strategy**
- Utilizing Missing Energy

**Event Selection**
- Background Estimation with Data

**Uncertainties**
- Systematics

**Results**
- Final Yields
- Limit Results

**Conclusion**
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The Compact Muon Solenoid (CMS) Detector

- **Inner silicon tracker**
  - determines tracks and vertices of charged particles
  - electron, muon, jet
- **PbWO₄ ECAL**
  - measures energy and location of electrons
- **Brass-scintillator HCAL**
  - measures energy of jets
- **Muon chambers**
  - measures location and momentum of muons
- **Combine information from subdetectors to measure missing transverse energy**
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Invisible Higgs and ZZ Production

Signal: Invisible Decay Modes

- Z boson Higgs-strahlung
- Higgs decay products invisible to detector
  - Not a Standard Model phenomenon
  - Model-independent search
- Some theorized decay modes:
  - Decay into pair of Stable neutral Lightest SUSY Particles (LSP)
    - neutralinos (1)
  - Large extra dimensions
    - Higgs oscillates into a graviscalar and disappears from our brane (2)
  - Decay into pair of graviscalars (3)
  - Decay into light neutrino and heavy neutrino (4)
- Explore range of Higgs masses
  - 105-145 GeV
Invisible Higgs and ZZ Production

Main Background: ZZ Production

- Same final state as $ZH \rightarrow \ell^+\ell^- + H(\text{inv})$
  - Two leptons from Z decay
  - Large $E_T$
- Irreducible Background
  - Comprises $\sim 70\%$ of total background at final selection
- Some kinematic differences between ZZ and ZH
  - Mass difference between Z and Higgs
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Monte Carlo and Datasets

MC Samples For Signal And Background, and Datasets

Calculations

- NLO $\sigma(ZZ)$, $\sigma(WZ)$ computed using MCFM
- $\sigma(ZH)$ computed at NNLO in QCD, and NLO in EW (5)

Datasets

- full 2011 and 2012 data samples at 7 TeV and 8 TeV
- Integrated luminosity at $\sqrt{s} = 7$ TeV: 5.1 $fb^{-1}$
- Integrated luminosity at $\sqrt{s} = 8$ TeV: 19.6 $fb^{-1}$
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Hadronic Recoil

- \( ZH \rightarrow \ell^+ \ell^- + H(\text{inv}) \) and \( ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu} \) characterized by large \( \not{E}_T \) from neutrinos and/or non-standard particles
- Dominant background: \( Z + \text{jets} \) with mis-measured large \( \not{E}_T \)
  - \( \sigma(Z + \text{jets}) > 10^5 \cdot \sigma(ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}) \)
- The goal is to reduce \( \not{E}_T \) of imbalanced events to effectively subtract the hadronic recoil and suppresses \( Z + \text{jets} \) (6)
- \( \text{red-} \not{E}_T \) variable:
  - \( \text{red-} \not{E}^i_T = p_T^{\ell \ell i} + \min(R_{cl}^i, R_{uncl}^i) \)
    - \( i = \perp, \parallel \) to dilepton \( p_T \)
  - \( R_{cl} \rightarrow N_{\text{jets}} \sum_{\text{jet}} p_T^{\text{jet}} \)
  - \( R_{uncl} \rightarrow - \not{E}_T - p_T^{\ell \ell} \)
  - \( \text{red-} \not{E}_T = |\text{red-} \not{E}_T| \)
### Event Selection

#### Discriminating Variables

<table>
<thead>
<tr>
<th>Main selection cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ Two leptons:</td>
</tr>
<tr>
<td>▶ well-identified, isolated, same flavor leptons</td>
</tr>
<tr>
<td>▶ $p_T^\ell &gt; 20$ GeV</td>
</tr>
<tr>
<td>▶ Reject events with jets if:</td>
</tr>
<tr>
<td>▶ $E_T &gt; 30$ GeV</td>
</tr>
<tr>
<td>▶ bjet:</td>
</tr>
<tr>
<td>▶ soft-muon ($p_T &gt; 3$ GeV)</td>
</tr>
<tr>
<td>▶ b-tag and ($p_T &gt; 20$ GeV and $</td>
</tr>
<tr>
<td>▶ Reject events with additional leptons if $p_T &gt; 10$ GeV</td>
</tr>
<tr>
<td>▶ $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>+ Optimized cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ $\Delta \phi_{\ell\ell} - \not{E_T} &gt; 2.6$</td>
</tr>
<tr>
<td>▶ $0.8 &lt; \frac{\not{E_T}}{p_T^{\ell\ell}} &lt; 1.2$</td>
</tr>
<tr>
<td>▶ $red\cdot \not{E_T} &gt; 110$ GeV</td>
</tr>
</tbody>
</table>
Event Selection

Reduced Missing Energy

Preference of red-$E_T$ over $E_T$

- Performs better in signal efficiency and Drell-Yan background suppression
- Found to be more stable under pile-up condition and jet energy scale variations
Other Optimization Variables

- Both used in ZH optimization along with \( \text{red-}\slashed{E}_T \)
  - Optimized to obtain best expected exclusion limits at 95% C.L.
- Suppress Drell-Yan and Top processes
Non-Resonant Background Estimation

- Non-resonant backgrounds are mainly leptonic W decays
  - WW, tW, t\bar{t}, single top, Z → \tau\tau
- Calculate scale factors from data control region of $e^\pm \mu^\mp$ and $\ell^+\ell^-$ ($e^+e^-$ or $\mu^+\mu^-$) events that pass selection cuts
  - Z-peak sidebands $40 < m_{\ell\ell} < 70$ GeV and $110 < m_{\ell\ell} < 200$ GeV
- Apply scale factors $\alpha_{\ell\ell} = \frac{N_{SB}^{e\mu}}{N_{e\mu}^{SB}}$
  - $N_{\ell\ell}^{peak} = \alpha_{\ell\ell} \cdot N_{e\mu}^{peak}$
- Checked with closure test
Background Estimation with Data

**Z + jets Background Estimation**

- Normalized to $Z + jets$
- Reweighting factors as function of $p_T^Z$ and number of reconstructed vertices
- Subtract EW processes with photons and neutrinos (MC)
- Modeling is improved for $\text{red-}E_T$ distribution for $Z + jet$

- Modeled from orthogonal $\gamma + jets$ control sample
  - Larger statistics and topologically equivalent
  - MC may not fully model detector and pile-up effects in tail of $\text{red-}E_T$

![Graph showing background estimation with data](image-url)
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## Systematic Uncertainties of ZH Analysis

<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., Iso.</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, W+jets normalization</td>
<td>25-100</td>
</tr>
<tr>
<td>Shape and Rate</td>
<td>MC statistics ZH,ZZ,WW</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>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Lepton Momentum Scale</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Jet Energy Scale, Resolution</td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td>Unclustered energy</td>
<td>1-4</td>
</tr>
</tbody>
</table>

- Combined relative signal efficiency uncertainty 12%
  - Theoretical uncertainty
  - PDF uncertainties
- Total relative uncertainty on background estimation 15%
  - Theoretical uncertainty (ZZ, WZ)
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## Final Yields of ZH Analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH(m_H = 125$ GeV)</td>
<td>$2.2 \pm 0.3$</td>
<td>$11.8 \pm 1.9$</td>
</tr>
<tr>
<td>$Z/\gamma^* \to \ell^+\ell^-$</td>
<td>$0.3 \pm 0.3$</td>
<td>$1.0 \pm 1.0$</td>
</tr>
<tr>
<td>Top/WW/ $W + jets$</td>
<td>$0.4 \pm 0.4$</td>
<td>$1.3 \pm 0.8$</td>
</tr>
<tr>
<td>$WZ \to 3\ell\nu$</td>
<td>$2.0 \pm 0.3$</td>
<td>$11.0 \pm 1.6$</td>
</tr>
<tr>
<td>$ZZ \to \ell^+\ell^-\nu\bar{\nu}$</td>
<td>$5.1 \pm 0.6$</td>
<td>$29.8 \pm 3.6$</td>
</tr>
<tr>
<td>total bkgd</td>
<td>$7.8 \pm 0.8$</td>
<td>$43.1 \pm 4.1$</td>
</tr>
<tr>
<td>Data</td>
<td>10</td>
<td>33</td>
</tr>
</tbody>
</table>

![7 TeV Background Yields](image1.png)

![8 TeV Background Yields](image2.png)
Shape Analysis for Invisible Higgs

\[ m_T^2 = \left( \sqrt{p_{T}^{\ell\ell} + m_{\ell\ell}^2} + \sqrt{E_T^2 + m_{\ell\ell}^2} \right)^2 - \left( p_{T}^{\ell\ell} + E_T^* \right)^2 \]

Exploit differences in kinematics

\[ ZZ \rightarrow \ell^+\ell^- \nu\bar{\nu} \quad \text{and} \quad ZH \rightarrow \ell^+\ell^- + H(\text{inv}) \] both have missing energy, but mass of missing particle is different

Shape used for all Higgs masses

\[ 105, 115, 125, 135, 145 \text{ GeV} \]
Limits on Invisible Higgs Decay

- Upper limit on $BR(H \to \text{invisible})$
  - Assume SM production rate
- Use modified frequentist construction $CL_s$
- Use Shape of Transverse Mass of Z and H

For Higgs with $m_H = 125$ GeV
- Observed 95% C.L. upper limit 75%
- Expected 95% C.L. upper limit 91%

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>105</th>
<th>115</th>
<th>125</th>
<th>135</th>
<th>145</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs Lim(%)</td>
<td>60</td>
<td>63</td>
<td>75</td>
<td>82</td>
<td>85</td>
</tr>
<tr>
<td>Exp Lim(%)</td>
<td>73</td>
<td>79</td>
<td>91</td>
<td>97</td>
<td>105</td>
</tr>
</tbody>
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Conclusions and looking forward.

- Set limits on invisible higgs branching fraction for SM-range masses
  - $m_H = 105$ GeV: Observed limit: $= 60\%$, Expected limit: $= 73\%$
  - $m_H = 115$ GeV: Observed limit: $= 63\%$, Expected limit: $= 79\%$
  - $m_H = 125$ GeV: Observed limit: $= 75\%$, Expected limit: $= 91\%$
  - $m_H = 135$ GeV: Observed limit: $= 82\%$, Expected limit: $= 97\%$
  - $m_H = 145$ GeV: Observed limit: $= 85\%$, Expected limit: $= 105\%$

- Comparable results to CMS and ATLAS indirect and direct searches (7) (8) (9)

- Continue analysis to explore Higgs masses beyond 150 GeV

- CMS-PAS-HIG-13-018 (10)
References


