Higgs to Invisible
at ATLAS

Elliot Lipeles
University of Pennsylvania
Outline

Physics
Motivation

Data Analyses

Vector Boson Fusion (VBF),
H→invisible

ZH, H→invisible

Summary: Other measurements, constraints, and interpretation
Higgs = Special Probe for Dark Matter

**Unique in SM**

$HH^\dagger$ is a dimension two operator with no quantum numbers

It is the only gauge invariant and Lorentz invariant operator that can couple to SU(3) x SU(2) x U(1) singlets at tree level

I.e. coupling to fermions or the gauge bosons would require a larger than dim 4 operator, which is not renormalizable and must have a cut-off scale

**Higgs Portal Concept**

General Idea: DM only couples to SM via Higgs

- Simplest one DM particle with WIMP miracle and no other particles already excluded
- Higgs would have been mostly invisible
  - Still order 50 papers with “Higgs Portal” in the title since the Higgs discovery with many variations
Relation to other DM searches

Production: Collider Searches

SM  DM  SM  DM

Annihilation: Indirect Detection, Early Universe

Scattering: Direct Detection
Relation to other DM searches

Production: Collider Searches

SM → DM

SM → DM

Scattering: Direct Detection

The rest of the talk is about this

Annihilation: Indirect Detection, Early Universe
Relation to other DM searches

Produced: Collider Searches

SM  DM  SM  DM

Annihilation: Indirect Detection, Early Universe

Scattering: Direct Detection

The rest of the talk is about this

Variety of Underground Experiments
Relation to other DM searches

Production: Collider Searches

SM  DM

SM  DM

Annihilation: Indirect Detection, Early Universe

Scattering: Direct Detection

The rest of the talk is about this

Variety of Underground Experiments

Gamma Ray (and Neutrino) Astronomy
Relation to other DM searches

Production: Collider Searches

SM

DM

SM

DM

Scattering: Direct Detection

The rest of the talk is about this

Annihilation: Indirect Detection, Early Universe

Variety of Underground Experiments

WIMP miracle

Gamma Ray (and Neutrino) Astronomy
Relation to other DM searches

Production: Collider Searches

Annihilation: Indirect Detection, Early Universe

Scattering: Direct Detection

The rest of the talk is about this

Variety of Underground Experiments

WIMP miracle

Gamma Ray (and Neutrino) Astronomy
Solid Lines are actual results

Dashed Lines are proposed experiments

Variety of Underground Experiments

We will be able to put a line on this plot under the assumptions that the DM couples to the nucleon via Higgs (and some other caveats)
Direct Dark Matter “Signals”

Shaded Areas at “Signals”

Obviously the signals are hotly debated.

Higgs to Invisible will limit the potential coupling of candidate models with masses below $m_H/2$. 
Indirect Dark Matter “Signals”

Indirect searches = looking for particles from DM annihilation in Galaxy or Galaxy Halos

Gamma Ray Sky (~300 MeV to 50 GeV)

Here again there are hotly debated signals
Indirect Dark Matter “Signals”

Indirect searches = looking for particles from DM annihilation in Galaxy or Galaxy Halos

Gamma Ray Sky (~300 MeV to 50 GeV)

Simulated DM addition to Gamma Ray Sky

Here again there are hotly debated signals

\( m_H/2 \)

\[
\langle \sigma v \rangle \quad (\text{cm}^3\text{s}^{-1})
\]

DM Mass (GeV/c^2)
ATLAS stuff...

pp collisions

Results are with Run 1 Data: 7 TeV (4.5 fb⁻¹) and 8 TeV (20.3 fb⁻¹)

I won’t further describe the ATLAS detector and data set
Higgs to Invisible

I’ll discuss these searches

But everyone knows that $ggH$ is much larger than VBF or ZH production

Why not use $ggH$?

Elliot Lipeles
Higgs to Invisible: Why not ggH?

ggH would need to be boosted by an extra gluon in the event

- VBF and ZH have some natural boost, but not that much

The real reason is over here

- Gluons and quarks in the proton don’t couple well to the Higgs
- \( qq \rightarrow Z \rightarrow \nu \nu \) background is much larger than ggH production

\[
\frac{\sigma(ggH)}{\sigma(Z) \times BR(Z \rightarrow \nu \nu)} = \frac{\approx 19 \text{ pb}}{\approx 6000 \text{ pb}}
\]

- Need to focus on processes where signal is on a more equal footing with background
- I.e. things that already have a W or Z in them (top also works ...see later...)

\[
\frac{\sigma(VBFH)}{\sigma(VBF - like \ Z) \times BR(Z \rightarrow \nu \nu)} = \frac{\approx 1.6 \text{ pb}}{\approx 0.6 \text{ pb}}
\]
Higgs to Invisible in ZH with Z→ll

Signal and Background Summary

**Basic Selection:** Exactly two charged leptons (e or μ, only same-flavor combinations)  
“Missing Transverse Energy” ($E_{T}^{miss}$) (actually momentum)

**Signal:**  
$ZH\rightarrow ll+\text{invisible}$

**“Irreducible” Background**  
$ZZ\rightarrow ll\nu\nu$

**WZ→llν**  
w/ lost lepton

$Z\rightarrow ll + \text{fake Missing Energy}$

**Additional Backgrounds:**  
$t\bar{t}$, $WW\rightarrow ll\nu\nu$,  
single top, $Z\rightarrow \tau\tau$
Higgs to Invisible in ZH with $Z \rightarrow ll$

Selection and Resulting Composition

$Z+\text{jets}$ is much much larger than signal

$E_T^{\text{miss}} > 90$ GeV

plus additional “cleaning”

$\phi(E_T^{\text{miss}}, p_T^{ll}) > 2.6$

$\phi(l, l) < 1.7$

$|E_T^{\text{miss}} - p_T^{ll}|/p_T^{ll} < 0.2$

$tt \rightarrow WWbb \rightarrow ll\nu\nu\nu\nu$ also larger than signal, so veto jets with $p_T > 25$ GeV

Signal here is normalized to a 100% Higgs branching fraction... limits will be a bit below this
Z + MET Event Topology

Candidate Event with a $Z \rightarrow \mu \mu$ and missing $E_T$

Run 167776, Event 129360643
Time 2010-10-28 10:41:18 CET
Higgs to Invisible in ZH with $Z \rightarrow l l$

Selection and Resulting Composition

After all cuts 100% BR signal would be comparable to total background (signal is stack on backgrounds)

Slightly better S/B at high $E_T^{miss}$

Signal is extracted from fit to this $E_T^{miss}$ distribution

<table>
<thead>
<tr>
<th>Data period</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ \rightarrow t\bar{t}jj$</td>
<td>$20.0 \pm 0.7 \pm 1.6$</td>
<td>$91 \pm 1 \pm 7$</td>
</tr>
<tr>
<td>$WZ \rightarrow t\ell jj$</td>
<td>$4.8 \pm 0.3 \pm 0.5$</td>
<td>$26 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>Dileptonic $\ell\ell$, $Wt$, $WW$, $Z \rightarrow \tau\tau$</td>
<td>$0.5 \pm 0.4 \pm 0.1$</td>
<td>$20 \pm 3 \pm 5$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$, $Z \rightarrow \mu\mu$</td>
<td>$0.13 \pm 0.12 \pm 0.07$</td>
<td>$0.9 \pm 0.3 \pm 0.5$</td>
</tr>
<tr>
<td>$W +$ jets, multijet, semileptonic top</td>
<td>$0.020 \pm 0.005 \pm 0.008$</td>
<td>$0.29 \pm 0.02 \pm 0.06$</td>
</tr>
<tr>
<td>Total background</td>
<td>$25.4 \pm 0.8 \pm 1.7$</td>
<td>$138 \pm 4 \pm 9$</td>
</tr>
<tr>
<td>Signal ($m_H = 125.5$ GeV, $\sigma_{ZH,SM}$, BR($H \rightarrow$ inv.) = 1)</td>
<td>$8.9 \pm 0.1 \pm 0.5$</td>
<td>$44 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>Observed</td>
<td>28</td>
<td>152</td>
</tr>
</tbody>
</table>
Higgs to Invisible in ZH with Z→ll

Background Modeling and Systematics

**Dominant ZZ background** is modeled with **MC simulation**

| Systematics included PDFs and scale (q^2) variations | 5% |
| Specified parton shower model uncertainty for jet-veto | 6% |
| Many detector response systematics (generally small) | 6% |
| Largest is jet energy scale for jet-veto |

**WZ background** and **Signal (ZH)** similar to **ZZ**

**WW, tt, Wt, and Z→ττ**: Use eμ combinations and extrapolate to ee/μμ

**Z+jets** with fake \( E_T^{\text{miss}} \) is modeled with “ABCD” method using \( \phi(E_T^{\text{miss}}, p_T^{ll}) \) and \( |E_T^{\text{miss}} - p_T^{ll}|/p_T^{ll} \)

\[
N_A = N_C \times \frac{N_C}{N_D}
\]

A 7% correlation between these variables is found in MC
Higgs to Invisible in ZH with $Z \rightarrow \ell\ell$

Statistical Interpretation and Results

Scan a variety of Higgs masses

ATLAS

$\sigma = 7$ TeV, $\int L dt = 4.5$ fb$^{-1}$
$\sigma = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$
$ZH \rightarrow \ell\ell + \text{inv.}$

At $m_H = 125$ GeV

Observed BR limit
75% at 95% C.L.

Expected BR limit
62% at 95% C.L.
VBF Higgs to Invisible

Signal and Background Summary

VBF = vector boson fusion

Signal: VBF, H→invisible

Irreducible Z→νν background:
VBF, Z→νν ~ “Weak”, Z→νν

“Weak” has 4+ ewk vertices

Plus “multijet QCD” (i.e. no actual weak bosons)

“Reducible” Z→νν background:
“Strong” Z→νν

W background:
Both Strong and Weak W→lν (with lost lepton)

“Strong” has 2 ewk vertices

“Strong” has 2 ewk vertices

+ many other diagrams
VBF Higgs to Invisible

How do you tell VBF from non-VBF?

**Signal:** VBF, $H \rightarrow \text{invisible}$

```
q   q
q   q
W, Z H
```

**Irreducible background:**

```
q   q
W, Z \chi
```

**“Reducible” background:**

```
q   q
W, Z \chi
```

$Z \rightarrow \nu \nu$

Less Signal-like

More Signal-like

VBF has two jets separated in aligned along the beam directions

**“Strong” $Z \rightarrow \nu \nu$**

```
q   q
Z \nu
```

ATLAS

$20.3 \text{ fb}^{-1}, 8 \text{ TeV}$

**ATLAS**

$20.3 \text{ fb}^{-1}, 8 \text{ TeV}$
VBF Event Display

Actually $H \rightarrow WW \rightarrow ll\nu\nu$ but illustrative anyway

$H \rightarrow WW^* \rightarrow e\nu\nu$ candidate and two jets with VBF topology

**Longitudinal view**

**Projected $\eta$-$\varphi$ view**

Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET
VBF Event Display

Actually $H \rightarrow WW \rightarrow ll\nu\nu$ but illustrative anyway

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology

*Longitudinal view*

*Projected $\eta$-$\varphi$ view*

Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET

http://atlas.ch
VBF Higgs to Invisible

Second handle for VBF: Central Jet Veto

VBF-like topologies: Signal and Weak \(Z \rightarrow \nu \nu\) background

"Reducible" background: "Strong" \(Z \rightarrow \nu \nu\)

\(\alpha_s\) already at hard scale

\(\alpha_s\) at hard scale to get to central region

now two \(\alpha_s\) both at lower scales
VBF Higgs to Invisible

Second handle for VBF: Central Jet Veto

VBF-like topologies:

Signal and Weak

\[ \text{Z or H} \]

\[ \text{EW Z}_{ij} \text{ (blue)} \]

\[ \text{Background (red)} \]

ATLAS graph showing normalized counts for different jet gap sizes.

Reducible background: "Strong" Z → νν

VBF-like topologies:

Signal and Weak

\[ \text{Z or H} \]

\[ \text{EW Z}_{ij} \text{ (blue)} \]

\[ \text{Background (red)} \]

ATLAS graph showing normalized counts for different jet gap sizes.

Second handle for VBF: Central Jet Veto

\[ \alpha_s \] already at hard scale

Now two \( \alpha_s \) both at lower scales.
VBF Higgs to Invisible

Selection

Basic 2-jet+MET Selection

Jet 1: \( p_T > 75 \text{ GeV} \)
Jet 2: \( p_T > 50 \text{ GeV} \)
\( E_T^{\text{miss}} > 150 \text{ GeV} \)

MET Cleaning

\( |\Delta \varphi (j, E_T^{\text{miss}})| > 1.6 \) for jet 1
\( > 1.0 \) otherwise

\( |\Delta \varphi (j,j)| < 2.5 \)

VBF Selection

\( m_{jj} > 1 \text{ TeV} \)
\( \Delta \eta_{jj} > 4.8 \)
No addition jets, \( p_T > 30 \text{ GeV} \)
### Paper actually has three signal regions

<table>
<thead>
<tr>
<th>Requirement</th>
<th>SR1</th>
<th>SR2a</th>
<th>SR2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading Jet $p_T$</td>
<td>$&gt;75$ GeV</td>
<td>$&gt;120$ GeV</td>
<td>$&gt;120$ GeV</td>
</tr>
<tr>
<td>Leading Jet Charge Fraction</td>
<td>N/A</td>
<td>$&gt;10%$</td>
<td>$&gt;10%$</td>
</tr>
<tr>
<td>Second Jet $p_T$</td>
<td>$&gt;50$ GeV</td>
<td>$&gt;35$ GeV</td>
<td>$&gt;35$ GeV</td>
</tr>
<tr>
<td>$m_{jj}$</td>
<td>$&gt;1$ TeV</td>
<td>$0.5 &lt; m_{jj} &lt; 1$ TeV</td>
<td>$&gt;1$ TeV</td>
</tr>
<tr>
<td>$\eta_{j1} \times \eta_{j2}$</td>
<td></td>
<td>$&lt;0$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>$</td>
<td>$&gt;4.8$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi_{jj}</td>
<td>$</td>
<td>$&lt;2.5$</td>
</tr>
<tr>
<td>Third Jet Veto $p_T$ Threshold</td>
<td></td>
<td>$30$ GeV</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi_{j,E_{\text{miss}}}</td>
<td>$</td>
<td>$&gt;1.6$ for $j_1$, $&gt;1$ otherwise</td>
</tr>
<tr>
<td>$E_{\text{miss}}$</td>
<td>$&gt;150$ GeV</td>
<td></td>
<td>$&gt;200$ GeV</td>
</tr>
</tbody>
</table>

Almost all the sensitivity comes from SR1 which is what I described
### VBF Higgs to Invisible

**Resulting Selection**

<table>
<thead>
<tr>
<th>Signal region</th>
<th>Process</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SR1</td>
<td></td>
</tr>
<tr>
<td>ggF signal</td>
<td>20±15</td>
<td></td>
</tr>
<tr>
<td>VBF signal</td>
<td>286±57</td>
<td></td>
</tr>
<tr>
<td>Z(→ νν)+jets</td>
<td>339±37</td>
<td></td>
</tr>
<tr>
<td>W(→ ℓν)+jets</td>
<td>235±42</td>
<td></td>
</tr>
<tr>
<td>Multijet</td>
<td>2±2</td>
<td></td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>1±0.4</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>577±62</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>539</td>
<td></td>
</tr>
</tbody>
</table>

W and Z backgrounds are ~50/50 strong and weak production (background estimation next slide...)

Small top and diboson backgrounds from MC

Mulitjet from similar procedure to ZH analysis: |Δφ(j,j)| and |Δφ(j, E_T^{miss})|
# VBF Higgs to Invisible

## Background Modeling

**MC systematics are just too large to exploit the full statistics!**

### W and Z systematics from MC modeling

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Z or W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>SR1 17–33 SR2 0–11</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>Negligible 0.2–7.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8</td>
</tr>
<tr>
<td>QCD scale</td>
<td>5–36   7.5–21</td>
</tr>
<tr>
<td>PDF</td>
<td>3–5    0.1–2.6</td>
</tr>
<tr>
<td>Parton shower</td>
<td>9–10</td>
</tr>
</tbody>
</table>

Detector Response to Jets: How well does a generator level jet energy agree with a reconstructed jet energy. (Forward jets are less well calibrated)

Modeling of Underlying Physics of the Z or W + 2-jet process

Structure of Proton

How partons (gluon or quark) hadronize

Numbers at in %

Background yield will have a $1/\sqrt{577 \text{ events}} \sim 4\%$ statistical error

Systematic Uncertainty on W and Z MC yield $\sim 50\%$
VBF Higgs to Invisible

Background Modeling

Solution: Use $Z\rightarrow ll$ and $W\rightarrow lv$ data with found leptons to model $Z\rightarrow \nu\nu$ and $W\rightarrow lv$ (with a lost lepton)

Define Control Regions:

- $Z$ CR = 2-leptons, use ll-system in place of $E_{T}^{\text{miss}}$ wherever it occurs
- $W$ CR = 1-lepton+MET and use l+MET-system in place of $E_{T}^{\text{miss}}$ wherever it occurs

There are two yields to predict in the signal region:

- $Z\rightarrow \nu\nu$
- $W\rightarrow lv$ where the lepton is lost

Naively you would use $W$ to model $W$ and $Z$ to model $Z$, but there is a problem

- $Z\rightarrow ll$ statistics is really poor b/c small $Z\rightarrow ll$ branching fraction
- $\text{BR}(Z\rightarrow ee+\mu\mu) \approx 0.066$
- $\text{BR}(Z\rightarrow \nu\nu) \approx 0.2$

<table>
<thead>
<tr>
<th>Background</th>
<th>SR1 Z Control Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z(\rightarrow ee)+$jets</td>
</tr>
<tr>
<td>QCD $Z \rightarrow \ell\ell$</td>
<td>$10.4 \pm 1.5$</td>
</tr>
<tr>
<td>EW $Z \rightarrow \ell\ell$</td>
<td>$7.4 \pm 0.8$</td>
</tr>
<tr>
<td>Other Backgrounds</td>
<td>$0.3 \pm 0.2$</td>
</tr>
<tr>
<td>Total</td>
<td>$18.1 \pm 1.7$</td>
</tr>
<tr>
<td>Data</td>
<td>22</td>
</tr>
</tbody>
</table>

We don’t want to use $\sim 50$ $Z\rightarrow ll$ events to model $\sim 340$ $Z\rightarrow \nu\nu$ events
VBF Higgs to Invisible
Background Modeling

**Solution:** Allow $W \rightarrow l\nu$ to model $Z \rightarrow \nu\nu$

- processes are similar enough to account for difference with MC

**Caveats to similarity**
- Mass
- V and A structure of coupling different
- Flavor Differences in couplings
  - Quark flavors are symmetric except for mass
  - Big effect if top is involved in a diagram, but that is rare

*Use MC to model all these*
VBF Higgs to Invisible

Background Modeling

**Solution:**
- Allow $W \to l \nu$ to model $Z \to \nu \nu$ processes are similar enough to account for difference with MC

**Caveats to similarity:**
- Mass
- $V$ and $A$ structure of coupling different
- Flavor Differences in couplings
- Quark flavors are symmetric except for mass
- Big effect if top is involved in a diagram, but that is rare

But we now have $\sim 650 W \to l \nu$ events to model $\sim 340 Z \to \nu \nu$ events... no longer the limiting factor in the analysis

<table>
<thead>
<tr>
<th>Background</th>
<th>$W^+ \to e \nu$</th>
<th>$W^- \to e \nu$</th>
<th>$W^+ \to \mu \nu$</th>
<th>$W^- \to \mu \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD $W \to \ell \nu$</td>
<td>$92.3 \pm 7.2$</td>
<td>$55.1 \pm 5.3$</td>
<td>$85.5 \pm 7.0$</td>
<td>$43.8 \pm 4.6$</td>
</tr>
<tr>
<td>EW $W \to \ell \nu$</td>
<td>$99.4 \pm 4.0$</td>
<td>$52.5 \pm 2.9$</td>
<td>$81.9 \pm 3.7$</td>
<td>$39.1 \pm 2.5$</td>
</tr>
<tr>
<td>QCD $Z \to \ell \ell$</td>
<td>$3.4 \pm 0.6$</td>
<td>$4.4 \pm 0.9$</td>
<td>$6.4 \pm 1.1$</td>
<td>$5.0 \pm 0.9$</td>
</tr>
<tr>
<td>EW $Z \to \ell \ell$</td>
<td>$2.5 \pm 0.3$</td>
<td>$2.9 \pm 0.3$</td>
<td>$2.7 \pm 0.3$</td>
<td>$3.2 \pm 0.3$</td>
</tr>
<tr>
<td>Multijet</td>
<td>$28.0 \pm 6.8$</td>
<td>$28.0 \pm 6.8$</td>
<td>$1.6 \pm 2.6$</td>
<td>$1.6 \pm 2.6$</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>$4.0 \pm 0.7$</td>
<td>$1.8 \pm 0.4$</td>
<td>$3.2 \pm 0.7$</td>
<td>$1.0 \pm 0.3$</td>
</tr>
<tr>
<td>Total</td>
<td>$230 \pm 11$</td>
<td>$145 \pm 9$</td>
<td>$181 \pm 8$</td>
<td>$93.7 \pm 5.9$</td>
</tr>
<tr>
<td>Data</td>
<td>$225$</td>
<td>$141$</td>
<td>$182$</td>
<td>$98$</td>
</tr>
</tbody>
</table>

*Use MC to model all these*
VBF Higgs to Invisible

Systematics Reduction with Ratio Method

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Z or W</th>
<th>$Z_{SR}/W_{CR}$ or $W_{SR}/W_{CR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>17–33</td>
<td>3–5</td>
</tr>
<tr>
<td></td>
<td>0–11</td>
<td>1–4</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td></td>
<td>0.2–7.6</td>
<td>0.5–5.8</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8</td>
<td>Irrelevant</td>
</tr>
<tr>
<td>QCD scale</td>
<td>5–36</td>
<td>7.8–12</td>
</tr>
<tr>
<td></td>
<td>7.5–21</td>
<td>1–2</td>
</tr>
<tr>
<td>PDF</td>
<td>3–5</td>
<td>1–2</td>
</tr>
<tr>
<td></td>
<td>0.1–2.6</td>
<td></td>
</tr>
<tr>
<td>Parton shower</td>
<td>9–10</td>
<td>5</td>
</tr>
</tbody>
</table>

QCD scale variations are treated as correlated for W and Z processes

Assumption validated using $Z \rightarrow ll/W \rightarrow l\nu$ in a sample with loosened VBF selection

Effect of Systematics Significantly Reduced
- Uncertainty on absolute yields is order 30-50% total
- Uncertainty on ratios is order 10%
  - many uncertainties are actually now MC stat limited :(
VBF Higgs to Invisible
Statistical Interpretation and Results

Global likelihood fit using 1-bin for each SR and CR
- Total 9 bins (SR, W-CR, Z-CR) x (SR1, SR2a, SR2b)
- Free parameters are
  - 3 scale factors for the W and Z in each of (SR1, SR2a, SR2b)
  - 1 signal yield correlated across all bins
- Systematics implemented as correlated Gaussian constrained nuisance parameters

Postfit yields and uncertainties

<table>
<thead>
<tr>
<th>Signal region Process</th>
<th>SR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF signal</td>
<td>20±15</td>
</tr>
<tr>
<td>VBF signal</td>
<td>286±57</td>
</tr>
<tr>
<td>Z(→ νν)+jets</td>
<td>339±37</td>
</tr>
<tr>
<td>W(→ ℓν)+jets</td>
<td>235±42</td>
</tr>
<tr>
<td>Multijet</td>
<td>2±2</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>1±0.4</td>
</tr>
<tr>
<td>Total background</td>
<td>577±62</td>
</tr>
<tr>
<td>Data</td>
<td>539</td>
</tr>
</tbody>
</table>

Final Results = Limits on Invisible Higgs BR !!!

<table>
<thead>
<tr>
<th>Results</th>
<th>Expected</th>
<th>+1σ</th>
<th>−1σ</th>
<th>+2σ</th>
<th>−2σ</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1</td>
<td>0.35</td>
<td>0.49</td>
<td>0.25</td>
<td>0.67</td>
<td>0.19</td>
<td>0.30</td>
</tr>
<tr>
<td>SR2</td>
<td>0.60</td>
<td>0.85</td>
<td>0.43</td>
<td>1.18</td>
<td>0.32</td>
<td>0.83</td>
</tr>
<tr>
<td>Combined</td>
<td>0.31</td>
<td>0.44</td>
<td>0.23</td>
<td>0.60</td>
<td>0.17</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Recall ZH, Z→ll limit was 75% observed with 65% expected
## Other Higgs to Invisible Limits

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>ZH, Z→ll</td>
<td>75%</td>
<td>62%</td>
</tr>
<tr>
<td>VBF H</td>
<td>28%</td>
<td>31%</td>
</tr>
<tr>
<td>WH+ZH with W/Z→jj</td>
<td>78%</td>
<td>86%</td>
</tr>
<tr>
<td>ZH with W/Z→bb</td>
<td>182%</td>
<td>199%</td>
</tr>
</tbody>
</table>

These signals will all largely systematics limited,
If a signal is observed then it will have to be multiple places to be believed

Interestingly a CMS search for tt+MET can be reinterpreted as a ttH, H→invisible limit giving 40% observed (65% expected)  

PRL 113, 151801 (2014)
Limits from Global Fits

There is an entirely different way to constrain Higgs to Invisible

We have a huge array of measurements of visible Higgs decays

All of these would be suppressed if the Higgs had an additional decay mode

\[ \sigma(ggH) \times BR(H \rightarrow WW) = \sigma(ggH) \frac{\Gamma_{WW}}{\Gamma_{\text{total}}} \]

\[ \Gamma_{\text{total}} = \Gamma_{bb} + \Gamma_{WW} + \Gamma_{ZZ} + \ldots + \Gamma_{\text{BSM}} \]

Of course there can be conspiracies where e.g. an extra \( \Gamma_{\text{BSM}} \) is hidden by a suppressed \( \Gamma_{bb} \) ... until \( H \rightarrow bb \) is well measured
Global Higgs Fits

General Idea: for each Higgs coupling add a parameter $\kappa$ which describes it’s deviation from the SM (SM is when all $\kappa_x = 1$)

$\kappa_{\tau}$

$\kappa_Z$

$\kappa_W$

$\kappa_g$ used to describe sum of loops

$\kappa_\gamma$ used to describe sum of loops
Limits from Global Fits

Each measurement here can then be described in terms of this model:

$$\mu = \frac{\sigma \times \text{BR}}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}} = \frac{k_g^2 \cdot k_Z^2}{k_h^2}$$

where

$$k_h^2 = \sum_{jj} \frac{k_j^2 \Gamma_{jj}^{\text{SM}}}{\Gamma_h^{\text{SM}}}$$

Numerator here is calculation this:

$$\Gamma_{\text{total}} = \Gamma_{bb} + \Gamma_{WW} + \Gamma_{ZZ} + \ldots + \Gamma_{\text{BSM}}$$

Then do a global fit using all the measurements to get limits on the $k_x$ parameters

### ATLAS

<table>
<thead>
<tr>
<th>Individual analysis</th>
<th>Input measurements</th>
<th>$\pm$ 1σ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>Overall: $\mu = 1.17^{+0.27}_{-0.27}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>ggF; $\mu = 1.32^{+0.36}_{-0.30}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>VBF; $\mu = 0.6^{+0.7}_{-0.6}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>WH; $\mu = 1.0^{+1.0}_{-1.0}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>ZH; $\mu = 0.3^{+0.3}_{-0.3}$</td>
<td>125.4</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>Overall: $\mu = 1.44^{+0.40}_{-0.43}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>ggF+tth; $\mu = 1.2^{+0.1}_{-0.1}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VBF+VH; $\mu = 0.3^{+0.2}_{-0.2}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>Overall: $\mu = 1.16^{+0.24}_{-0.24}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>ggF; $\mu = 0.96^{+0.20}_{-0.20}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VBF; $\mu = 1.28^{+0.50}_{-0.47}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VH; $\mu = 3.0^{+1.5}_{-1.3}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>Overall: $\mu = 1.43^{+0.43}_{-0.43}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>ggF; $\mu = 2.0^{+1.2}_{-1.2}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VBF+VH; $\mu = 1.24^{+0.50}_{-0.47}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$VH \rightarrow Vbb$</td>
<td>Overall: $\mu = 0.52^{+0.40}_{-0.40}$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>WH; $\mu = 1.11^{+0.61}_{-0.61}$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>ZH; $\mu = 0.05^{+0.50}_{-0.50}$</td>
<td>125</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>Overall: $\mu = -0.7^{+3.7}_{-2.7}$</td>
<td>125.5</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>Overall: $\mu = 2.7^{+4.5}_{-4.3}$</td>
<td>125.5</td>
</tr>
<tr>
<td>ttH</td>
<td>bb; $\mu = 1.5^{+1.1}_{-1.1}$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Multilepton; $\mu = 2.1^{+1.4}_{-1.2}$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma$; $\mu = 1.3^{+1.7}_{-1.5}$</td>
<td>125.4</td>
</tr>
</tbody>
</table>

$s = 7$ TeV, 4.5-4.7 fb$^{-1}$

$s = 8$ TeV, 20.3 fb$^{-1}$
Global Higgs Fits

Invisible Limits

Here is the set parameters included in the fit

<table>
<thead>
<tr>
<th>Higgs portal (Baseline config. of vis. &amp; inv.)</th>
<th>Higgs boson decay channels: general coupling param., no assumption about $\kappa_{W,Z}$</th>
<th>$\kappa_Z$ (Z boson coupling s.f.)</th>
<th>$0.99 \pm 0.15$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\kappa_W$ (W boson coupling s.f.)</td>
<td>$0.92 \pm 0.14$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_t$ ($t$-quark coupling s.f.)</td>
<td>$1.26^{+0.32}_{-0.34}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_b$ ($b$-quark coupling s.f.)</td>
<td>$0.61 \pm 0.28$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_T$ (Tau lepton coupling s.f.)</td>
<td>$0.98^{+0.20}_{-0.18}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_{\mu}$ (Muon coupling s.f.)</td>
<td>$&lt; 2.25$ at 95% CL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_g$ (Gluon coupling s.f.)</td>
<td>$0.92^{+0.18}_{-0.15}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_\gamma$ (Photon coupling s.f.)</td>
<td>$0.90^{+0.16}_{-0.14}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_{Z\gamma}$ ($Z\gamma$ coupling s.f.)</td>
<td>$&lt; 3.15$ at 95% CL</td>
</tr>
</tbody>
</table>

$+ BR_{\text{inv}}$ which is the key parameter for Higgs to invisible limits!

<table>
<thead>
<tr>
<th>Decay channels</th>
<th>$\kappa_i$ assumption</th>
<th>Upper limit on $BR_{\text{inv}}$ (Obs.</th>
<th>Exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invisible decays</td>
<td>$\kappa_{W,Z,g} = 1$</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>Visible decays</td>
<td>$\kappa_{W,Z} \leq 1$</td>
<td>0.49</td>
<td>0.48</td>
</tr>
<tr>
<td>In. &amp; vis. decays</td>
<td>None</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>Inv. &amp; vis. decays</td>
<td>$\kappa_{W,Z} \leq 1$</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Combination of direct limits

Indirect limit from visible processes

Combination of everything under two assumptions
Higgs Portal Interpretation

Remember this relation...

Production: Collider Searches

\[ \text{SM} \rightarrow \text{H} \rightarrow \text{DM} \]

Scattering: Direct Detection

Annihilation: Indirect Detection, Early Universe

Limits depend on the particle assumption (scalar, Majorana fermion, vector)

Comparable sensitivity to direct dark matter searches without the loss of sensitivity at low WIMP mass

Assuming DM couples to SM via Higgs only and other caveats.... (next slide)
Caveats on the Portal Models

Here are the Lagrangians...

\[ \mathcal{L}_{\text{SSDM}} = \frac{1}{2} \partial_{\mu} S \partial^{\mu} S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \]
\[ \mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi)\psi - \frac{\lambda_{\psi H}}{\Lambda} \bar{\psi} \psi H^\dagger H \]
\[ \mathcal{L}_{\text{VDM}} = -\frac{1}{4} V_{\mu \nu} V^{\mu \nu} + \frac{1}{2} m_V^2 V_\mu V^\mu - \frac{\lambda_{V H}}{2} V_\mu V^\mu H^\dagger H - \frac{\lambda_V}{4} (V_\mu V^\mu)^2 \]

Problems

- Masses inserted by hand
- Vector mass given by hand is not renormalizable
- Fermion is an effective field theory and if the mediator that has been integrated out is too light it can effect the relationship between scattering cross-section and BR_{inv}

On going theory work on this topic

- Next slide example impact of fixing these problems in the context of a model
Caveats on the Portal Models

Add an additional scalar to generate fermion and vector masses (and couple the fermion to the Higgs)  

\[ m_s = 10^{-2} \text{ GeV} \]
\[ m_s = 1 \text{ GeV} \]
\[ m_s = 10 \text{ GeV} \]
\[ m_s = 50 \text{ GeV} \]
\[ m_s = 70 \text{ GeV} \]

\[ m_s = 1000 \text{ GeV} \]
\[ m_s = 500 \text{ GeV} \]
\[ m_s = 200 \text{ GeV} \]
\[ m_s = 100 \text{ GeV} \]

Dashed line is the simple Higgs Portal model result
Higgs to Invisible Summary

Provides strong constraint on Dark Matter model building for $m_{DM} < m_H/2$

Strongly complementary to the direct dark matter searches
• H to invisible not sensitive above $m_H/2$
• Direct dark matter not sensitive below $\sim m_{DM} 10$ GeV
• Overlap in $\sim 10$-60 GeV

Various hints in direct and indirect searches are in the overlap range

Getting ready for Run 2 VBF Higgs to Invisible

My other work you can ask me about later...
• H to WW (Run 1 only)
• SUSY compressed spectra trilepton (Run 2 only)
• ATLAS Phase-1/2 trigger (jets, track trigger, and menus/architecture)
• ATLAS Upgrade strips tracker readout
• Fast timing detectors (just starting)