Higgs decays to invisible modes at the LHC and ILC

Heather Logan

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Outline

Motivation

Invisible Higgs at the LHC
Interlude: Invisible Higgs at the Tevatron?

Invisible Higgs at the ILC

Comparison
Future directions
Motivation

SM Higgs is very narrow for $m_H \lesssim 160$ GeV.

Any new decay mode with reasonable partial width can easily become the dominant BR.

If there is a neutral (quasi)stable particle with mass $< m_H/2$ and EW-strength coupling to $H$, then $H \rightarrow$ invisible can be the dominant decay.

- $H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ in MSSM, NMSSM
- $H \rightarrow SS$, scalar dark matter
- $H \rightarrow$ KK neutrinos in EDim
- $H \rightarrow$ Majorons
- etc.

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Higgs decays to invisible modes at the LHC and ILC

ALCPG'07
Invisible Higgs at LHC

\[ \text{VBF} \rightarrow H_{\text{inv}} \] [Eboli & Zeppenfeld (2000); Neukermans & Di Girolamo (2003)]

Signal is \(jjp_T\); jets are hard and forward

\[ Z + H_{\text{inv}} \] [Frederiksen, Johnson, Kane & Reid (1994); Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003); Davoudiasl, Han & H.L. (2004); Meisel, Dührssen, Heldmann & Jakobs (2006)]

Signal is \(\ell^+\ell^-p_T\), with \(m(\ell^+\ell^-) = m_Z\ (\ell = e, \mu)\)

\[ \bar{t}tH_{\text{inv}} \] [Gunion (1994); Kersevan, Malawski & Richter-Was (2002)]

Signal is \(bjj + b\ell + p_T\).

\[ W + H_{\text{inv}} \] [Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003)]

Signal is \(\ell p_T\); totally swamped by background.
95% CL exclusion limits with 30 fb$^{-1}$ at LHC

$\xi^2$ is a scaling factor: $\sigma \times \text{BR}(H \to \text{invis}) \equiv \xi^2\sigma_{\text{SM}}$

Comparison of the discovery potential for different channels

- $ZH_{\text{inv}}$ – uses $Z \to \ell^+\ell^-$
- VBF looks very good, but not clear how well events can be triggered.
- $ttH_{\text{inv}}$ – may be room for improvement?

ATLAS study in progress.

[Plot from ATL-PHYS-PUB-2006-009]
Naive extrapolation from the ATLAS plot for 30 (300) fb$^{-1}$:

Value of $\xi^2$ excluded at 95% CL:

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>120 GeV</th>
<th>140 GeV</th>
<th>160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $\rightarrow H_{inv}$</td>
<td>0.25 (0.08)</td>
<td>0.25 (0.08)</td>
<td>0.25 (0.08)</td>
</tr>
<tr>
<td>$Z + H_{inv}$</td>
<td>0.45 (0.15)</td>
<td>0.6 (0.2)</td>
<td>0.8 (0.25)</td>
</tr>
<tr>
<td>$t\bar{t}H_{inv}$</td>
<td>0.55 (0.17)</td>
<td>0.75 (0.25)</td>
<td>0.95 (0.3)</td>
</tr>
</tbody>
</table>

$1\sigma$ uncertainty on $\sigma \times \text{BR(inv)}$ for $\xi^2 = 1$:

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>120 GeV</th>
<th>140 GeV</th>
<th>160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $\rightarrow H_{inv}$</td>
<td>13% (4%)</td>
<td>13% (4%)</td>
<td>13% (4%)</td>
</tr>
<tr>
<td>$Z + H_{inv}$</td>
<td>23% (7%)</td>
<td>30% (10%)</td>
<td>40% (13%)</td>
</tr>
<tr>
<td>$t\bar{t}H_{inv}$</td>
<td>28% (9%)</td>
<td>38% (12%)</td>
<td>48% (15%)</td>
</tr>
</tbody>
</table>

Value of $\xi^2$ required for 5$\sigma$ discovery:

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>120 GeV</th>
<th>140 GeV</th>
<th>160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $\rightarrow H_{inv}$</td>
<td>0.63 (0.2)</td>
<td>0.63 (0.2)</td>
<td>0.63 (0.2)</td>
</tr>
<tr>
<td>$Z + H_{inv}$</td>
<td>1.1 (0.36)</td>
<td>1.5 (0.47)</td>
<td>2.0 (0.63)</td>
</tr>
<tr>
<td>$t\bar{t}H_{inv}$</td>
<td>1.4 (0.43)</td>
<td>1.9 (0.59)</td>
<td>2.4 (0.75)</td>
</tr>
</tbody>
</table>

Caveat: 300 fb$^{-1}$ numbers just scaled by $\mathcal{L}^{-1/2}$. Systematics, background normalization from data don’t scale this way!

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Higgs mass measurement from $H \rightarrow$ invisible

Mass of $H_{inv}$ is accessible only through production process.

![Cross section graph](image)

Kinematic distributions?

![Kinematic distributions graph](image)

(needs more work)


Signal rate depends on $m_H$. Will use VBF and $Z + H_{inv}$. First pass: assume $\xi^2 = 1$. 

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Higgs decays to invisible modes at the LHC and ILC  
ALCPG'07
Higgs mass determination from $Z + H_{\text{inv}}$, with 10 (100) fb$^{-1}$:

<table>
<thead>
<tr>
<th>$m_h$ (GeV)</th>
<th>120</th>
<th>140</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(d\sigma_S/dm_h)/\sigma_S$ (1/GeV)</td>
<td>$-0.013$</td>
<td>$-0.015$</td>
<td>$-0.017$</td>
</tr>
<tr>
<td>Statistical uncert.</td>
<td>21% (6.6%)</td>
<td>28% (8.8%)</td>
<td>37% (12%)</td>
</tr>
<tr>
<td>Background normalization uncert.</td>
<td>33% (10%)</td>
<td>45% (14%)</td>
<td>60% (19%)</td>
</tr>
<tr>
<td>Total uncert.</td>
<td>40% (16%)</td>
<td>53% (19%)</td>
<td>71% (24%)</td>
</tr>
<tr>
<td>$\Delta m_h$ (GeV)</td>
<td>30 (12)</td>
<td>35 (12)</td>
<td>41 (14)</td>
</tr>
</tbody>
</table>


$Z + H_{\text{inv}}$: $\Delta m_H = 30/35/41$ (12/12/14) GeV with 10(100) fb$^{-1}$

Higgs mass determination from VBF$\rightarrow H_{\text{inv}}$, with 10 (100) fb$^{-1}$:

<table>
<thead>
<tr>
<th>$m_h$ (GeV)</th>
<th>120</th>
<th>130</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(d\sigma_S/dm_h)/\sigma_S$ (GeV$^{-1}$)</td>
<td>$-0.0026$</td>
<td>$-0.0026$</td>
<td>$-0.0028$</td>
<td>$-0.0029$</td>
</tr>
<tr>
<td>Statistical uncert.</td>
<td>5.3% (1.7%)</td>
<td>5.4% (1.7%)</td>
<td>5.7% (1.8%)</td>
<td>6.4% (2.0%)</td>
</tr>
<tr>
<td>Background norm.</td>
<td>5.2% (2.1%)</td>
<td>5.3% (2.1%)</td>
<td>5.6% (2.2%)</td>
<td>6.5% (2.6%)</td>
</tr>
<tr>
<td>Total uncert.</td>
<td>11% (8.6%)</td>
<td>11% (8.6%)</td>
<td>11% (8.6%)</td>
<td>12% (8.8%)</td>
</tr>
<tr>
<td>$\Delta m_h$ (GeV)</td>
<td>42 (32)</td>
<td>42 (33)</td>
<td>41 (31)</td>
<td>42 (30)</td>
</tr>
</tbody>
</table>


VBF: $\Delta m_H \approx 42$ (32) GeV with 10 (100) fb$^{-1}$

$Z + H_{\text{inv}}$ cross section falls faster with $m_H$ than VBF: more $m_H$ dependence but less statistics.

All numbers used here are from theorist parton-level MC studies.

Heather Logan Higgs decays to invisible modes at the LHC and ILC ALCPG'07
Getting $m_H$ from one cross section relies on assumption $\xi^2 = 1$.

Second pass: use ratio of $Z + H_{\text{inv}}$ and VBF rates.

$Z + H_{\text{inv}} \sim HZZ$ coupling; VBF $\sim HWW$, $HZZ$ couplings: related by custodial SU(2) in models with only Higgs doublets/singlets.

Example: MSSM or 2HDM

$$ZZH \text{ coup } = \left( \frac{g m_Z}{\cos \theta_W} \right) \sin(\beta - \alpha)$$

$$WWH \text{ coup } = g m_W \sin(\beta - \alpha)$$

Higgs mass determination from ratio method with 10 (100) fb$^{-1}$:

<table>
<thead>
<tr>
<th>$m_h$ (GeV)</th>
<th>120</th>
<th>140</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r = \sigma_S(Zh)/\sigma_S(WBF)$</td>
<td>0.132</td>
<td>0.102</td>
<td>0.0807</td>
</tr>
<tr>
<td>$(dr/dm_h)/r$ (1/GeV)</td>
<td>$-0.011$</td>
<td>$-0.013$</td>
<td>$-0.013$</td>
</tr>
<tr>
<td>Total uncert., $\Delta r/r$</td>
<td>41% (16%)</td>
<td>54% (20%)</td>
<td>72% (25%)</td>
</tr>
<tr>
<td>$\Delta m_h$ (GeV)</td>
<td>36 (14)</td>
<td>43 (16)</td>
<td>53 (18)</td>
</tr>
</tbody>
</table>


Ratio method:

$\Delta m_H = 36/43/53$ (14/16/18) GeV with 10 (100) fb$^{-1}$

Assumed $\xi^2 = 1$ for signal statistics.
Summary of $m_H$ extraction 1σ uncertainty with 100 fb$^{-1}$:

<table>
<thead>
<tr>
<th></th>
<th>$m_H = 120$ GeV</th>
<th>140 GeV</th>
<th>160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + H_{inv}$, $\xi^2 = 1$</td>
<td>12 GeV</td>
<td>12 GeV</td>
<td>14 GeV</td>
</tr>
<tr>
<td>VBF, $\xi^2 = 1$</td>
<td>32 GeV</td>
<td>32 GeV</td>
<td>31 GeV</td>
</tr>
<tr>
<td>Ratio method</td>
<td>14 GeV</td>
<td>16 GeV</td>
<td>18 GeV</td>
</tr>
</tbody>
</table>

Comments:

- All numbers used come from theorist parton-level MC studies.

- VBF numbers are from Eboli & Zeppenfeld and include a central jet veto – this degrades at higher luminosity LHC running.

- Precisions do not scale with $\mathcal{L}^{-1/2}$ because of systematics and background normalization from data.

- With $Z + H_{inv}$, VBF, and $t\bar{t}H_{inv}$ channels, together with assumption of Higgs doublets/singlets only, we should be able to simultaneously fit for $m_H$, $\xi_V$, and $g_{Htt}^2/g_{HVV}^2$.
Interlude: Invisible Higgs at the Tevatron?

Pheno studies for $m_H = 120$ GeV:

$Z + H_{\text{inv}}$ [Martin & Wells, hep-ph/9903259]
- $1.9\sigma$ with 10 fb$^{-1}$
- $3\sigma$ requires 12 fb$^{-1} \times 2$ detectors

$\text{VBF} \rightarrow H_{\text{inv}}$ [Davoudiasl, Han, & H.L., hep-ph/0412269]
- $1.6\sigma$ with 10 fb$^{-1}$
- $3\sigma$ requires 18 fb$^{-1} \times 2$ detectors
- No central jet veto used: room for improvement.
Combining these 2 channels: $3\sigma$ requires $7 \text{ fb}^{-1} \times 2$ detectors.

Comparable to SM Higgs sensitivity?

$m_H = 120 \text{ GeV}$: above LEP limit.

Could extend LEP exclusion before LHC data is analyzed.

No central jet veto used: room for improvement.

LHC: central jet veto improves $S/B$ by factor of 3


If central jet veto works this well for Tevatron, can get $3\sigma$ in VBF channel alone with $6 \text{ fb}^{-1} \times 2$ detectors.
Invisible Higgs at ILC

Relevant production modes:

\[ e^+e^- \rightarrow ZH \]

\[ e^+e^- \rightarrow e^+e^-H \]
(\textit{ZZ fusion})

\[ e^+e^- \rightarrow \nu\bar{\nu}H \] – invisible for \( H_{\text{inv}} \)

\[ e^+e^- \rightarrow t\bar{t}H \] – cross section too small at 500 GeV
Use recoil mass technique to find (missing) mass bump.

\begin{center}
\begin{tikzpicture}
\begin{axis}[
width=\textwidth,
height=0.5\textwidth,
xlabel={Recoil Mass [GeV]},
ylabel={Number of Events / 1.5 GeV},
]
\addplot[mark=*,mark options={solid}] table [y index=2] {data.csv};
\addplot[mark=x,mark options={solid}] table [y index=2] {data.csv};
\addplot[red,fill=red,draw=red,mark=+] table [y index=2] {data.csv};
\end{axis}
\end{tikzpicture}
\end{center}

\[m_H = 120 \text{ GeV}\]

[TESLA TDR] \(m_H = 120 \text{ GeV}, \sqrt{s} = 350 \text{ GeV}, \int \mathcal{L} = 500 \text{ fb}^{-1}, \mu\mu \text{ only}\)

Measure \(m_H\) and \(e^+e^- \to ZH\) total cross section.

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*Higgs decays to invisible modes at the LHC and ILC*  
*ALCPG’07*
Study: search for $e^+e^- \rightarrow ZH_{\text{inv}}$ with $Z \rightarrow q\bar{q}$.

[M. Schumacher, LC-PHSM-2003-096]

First discover $H$ and measure mass (via recoil mass?)
Measure total $e^+e^- \rightarrow ZH$ cross section from recoil technique.

Then look at $e^+e^- \rightarrow ZH_{\text{inv}}$ with $Z \rightarrow q\bar{q}$.

- Force event to 2 jets

- Cuts on $E_{\text{vis}}, p_T^{\text{tot}}, \cos \theta_{\text{dijet}}$

- Require $jj$ reconstruct $Z$ mass: $|M_{\text{vis}} - M_Z| < 7.5$ GeV

- Require missing mass near $H$ mass: $|M_{\text{miss}} - M_H| < 15$ GeV
Discovery reach: \(500 \text{ fb}^{-1} \) at \( \sqrt{s} = 350 \text{ GeV} \)

\[ [\text{M. Schumacher, LC-PHSM-2003-096}] \]

\[
\begin{align*}
\text{BR}(H \rightarrow \text{inv.}) & \text{ vs. BR}(H \rightarrow \text{inv.}) \\
\text{significance} & \text{ vs. BR}(H \rightarrow \text{inv.})
\end{align*}
\]

- \( M_H = 160 \text{ GeV} \)
- \( M_H = 140 \text{ GeV} \)
- \( M_H = 120 \text{ GeV} \)

5\(\sigma\) discovery for \( \text{BR}_{\text{inv}} \) down to

- \( \sim 2.5\% \) for \( m_H = 120 \text{ GeV} \)
- \( \sim 1.5\% \) for \( m_H = 140, 160 \text{ GeV} \)

Heather Logan \hspace{1cm} Higgs decays to invisible modes at the LHC and ILC \hspace{1cm} ALCPG’07
Measurement precision: \(500 \text{ fb}^{-1} \text{ at } \sqrt{s} = 350 \text{ GeV}\)

Precision on large BR(inv) limited by uncertainty on \(\sigma(ZH)\) measurement.

Heather Logan \(Higgs\) decays to invisible modes at the LHC and ILC \(ALCPG'07\)
Measurement precision: \( 500 \text{ fb}^{-1} \) at \( \sqrt{s} = 350 \text{ GeV} \)

Indirect method:
Look in recoil mass peak, count up visible final states.
\( \text{BR} \text{(inv)} \) is what is left over. Better for \( \text{BR} \text{(inv)} \gtrsim 0.7 \).

[M. Schumacher, LC-PHSM-2003-096]

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Higgs decays to invisible modes at the LHC and ILC  
ALCPG’07
Study: $e^+e^- \rightarrow ZH$ near threshold

Motivation:

1) Cross section is larger near threshold.

Falls like $1/(s - m_Z^2)^2$ well above threshold due to $Z$ propagator.

2) Better energy/momentum resolution for less-boosted visible particles: sharper Higgs recoil mass peak.

Luminosity to reach 30 MeV precision on Higgs mass for $m_H = 120$ GeV

<table>
<thead>
<tr>
<th>$E_{CM}$ (GeV)</th>
<th>$\sigma(H\mu\mu)$ (no ISR)</th>
<th>Single event $m_H$ (MeV)</th>
<th>$\mathcal{L}$ for 30 MeV resolution ($\mu\mu + ee$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>4.6 fb</td>
<td>900</td>
<td>780 fb$^{-1}$</td>
</tr>
<tr>
<td>230</td>
<td>9.1 fb</td>
<td>200</td>
<td>20 fb$^{-1}$</td>
</tr>
</tbody>
</table>

[Richard & Bambade, hep-ph/0703173]
\[ e^+e^- \rightarrow ZH_{\text{inv}} \text{ with } Z \rightarrow q\bar{q} : \text{running near threshold} \]

Higher cross section and less background under Higgs recoil peak. Much less lumi needed for comparable precision.

For \( m_H = 120 \text{ GeV} \):

<table>
<thead>
<tr>
<th>( E_{CM} )</th>
<th>( \sigma(HZ_{\text{had}}) ) (34% eff)</th>
<th>( \Delta M_H ) (hadronic)</th>
<th>( Z_{\text{had}}Z_{\text{inv}}\gamma ) BG in ( \pm 2\Delta m_H )</th>
<th>( \int \mathcal{L} ) for 95% excl of ( \text{BR}_{\text{inv}} &gt; 2% )</th>
<th>( \int \mathcal{L} ) for ( \text{BR}_{\text{inv}} = (2 \pm 0.5)% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 GeV</td>
<td>30 fb</td>
<td>7.3 GeV</td>
<td>10 fb</td>
<td>85 fb(^{-1})</td>
<td>500 fb(^{-1})</td>
</tr>
<tr>
<td>230 GeV</td>
<td>60 fb</td>
<td>2.3 GeV</td>
<td>4 fb</td>
<td>8 fb(^{-1})</td>
<td>50 fb(^{-1})</td>
</tr>
</tbody>
</table>

[Richard & Bambade, hep-ph/0703173]
Better recoil mass resolution: direct access to Higgs width (!)

SM Higgs recoil spectrum, 

\( m_H = 175 \ \text{GeV} \) and \( \sqrt{s} = 290 \ \text{GeV} \).

Plotted without and with \( \Gamma_H = 500 \ \text{MeV} \) Breit-Wigner.

[Richard & Bambade, hep-ph/0703173]

Invisibly-decaying Higgs:

BR(fermions) remains measurable down to fraction of a %. Visible BR(fermions) allows ratio of partial widths between SM mode and invisible.

No BR(fermions) means \( \Gamma_{\text{tot}} \) larger by 2 orders of magnitude. Total width becomes measurable for \( m_H = 120 \ \text{GeV} \)!
Comparison of ILC to LHC

Higgs mass:

LHC indirect from ratio of rates. $\Delta M_H \sim 14$–18 GeV; relies on SU(2) doublets/singlets assumption.

ILC direct from recoil spectrum. $\Delta M_H \sim 30$ MeV; model independent.

BR(inv) discovery reach:

LHC from VBF. $5\sigma$ reach for $\xi^2 \gtrsim 0.65$ with $30$ fb$^{-1}$; better for $300$ fb$^{-1}$. Maybe 0.2?

ILC from $Z(\to qq)H_{\text{inv}}$. $5\sigma$ reach for $\xi^2 \gtrsim 0.02$.

BR(inv) measurement precision:

LHC from VBF. 13% assuming cross section $= \text{SM}$ with $30$ fb$^{-1}$; better for $300$ fb$^{-1}$. Maybe 4%?

ILC from indirect method. 2%, model independent.

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ALCPG'07
Future directions

Existing ILC studies are for $\sqrt{s} = 350$ GeV and $\sqrt{s} = 230$ GeV. But if we start with 500 GeV, we won’t turn it down for a while!

Should quantify how well can be done at $\sqrt{s} = 500$ GeV.
- Start with $e^+e^- \rightarrow ZH_{\text{inv}}$ with $Z \rightarrow ee, \mu\mu$.
- Reconstruct recoil spectrum.
- Add $ZZ$ fusion! Final state is $e^+e^-H_{\text{inv}}$: can be used to reconstruct recoil mass.

Cross section increases with $\sqrt{s}$.
No $Z \rightarrow \ell^+\ell^-$ BR to fold in:
2x more $ZZ$ fusion evts than $Z(\rightarrow ee, \mu\mu)H$ at $\sqrt{s} = 500$ GeV and $m_H = 120$ GeV.

- Add $Z \rightarrow q\bar{q}$ later for statistics: mass resolution is worse.
- At higher $\sqrt{s}$, add $t\bar{t}H_{\text{inv}}$ for access to top Yukawa.

Heather Logan Higgs decays to invisible modes at the LHC and ILC ALCPG’07
Backup slides
Uncertainties for LHC $H_{inv}$ mass extraction:

Statistical uncertainty on signal rate:

$$\frac{\Delta \sigma_S}{\sigma_S} = \sqrt{\frac{S + B}{S}}$$

Background normalization uncertainty:

Backgrounds for $Z + H_{inv}$ and VBF are dominated by $Z \rightarrow \nu \nu$. Can measure background rates/shapes in $Z \rightarrow \ell \ell$ channel!

Less statistics: $\frac{\text{BR}(Z \rightarrow \ell \ell)}{\text{BR}(Z \rightarrow \nu \nu)} \simeq 0.28$.

$$\frac{\Delta \sigma_S}{\sigma_S} = \sqrt{B \times \frac{\text{BR}(\ell \ell)}{\text{BR}(\nu \nu)}}/S$$

Theory uncertainty: QCD + PDFs

4% for VBF, 7% for $Z + h_{inv}$

Uncertainty on experimental efficiencies:

5% for VBF forward-jet tag / central-jet veto

4% dilepton tagging (2% per lepton)

Luminosity normalization: 5%