Seeing an invisible Higgs at Tevatron and LHC

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Why an invisible Higgs?

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

If the Higgs couples with electroweak strength to a neutral (quasi)stable particle (e.g., dark matter) with mass $< \frac{m_h}{2}$, then $h \to$ invisible can be the dominant decay mode.
The Higgs *could* decay invisibly

- $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ in MSSM, NMSSM
- $h \rightarrow SS$ in simple models of scalar dark matter
- $h \rightarrow KK$ neutrinos in extra dimensions
- $h \rightarrow$ Majorons
- ...

→ Cover all our bases!
We shouldn’t just assume the Higgs will be SM-like – even small additions (such as scalar singlet dark matter) can make $\text{BR}(h \rightarrow \text{invis.})$ large.

“Invisible” Higgs is not that hard to “see”: $p_T$

$h \rightarrow jj$ is much harder.
Outline

• Motivation

• LHC

• Tevatron

• Mass extraction

• Conclusions
Search modes:

- **WBF** → $h_{inv}$ Eboli & Zeppenfeld (2000)
  Signal is $jj\not{p_T}$; jets are hard and forward

- **$Z + h_{inv}$** Frederiksen, Johnson, Kane & Reid (1994); Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003); Davoudiasl, Han & H.L. (2004)
  Signal is $\ell^+\ell^-\not{p_T}$, with $m(\ell^+\ell^-) = m_Z$ ($\ell = e, \mu$)

- **$W + h_{inv}$** Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003)
  Signal is $\ell\not{p_T}$; totally swamped by background.

- **$t\bar{t}h_{inv}$** Gunion (1994); Kersevan, Malawski & Richter-Was (2002)
  Signal is $bjj + b\ell + \not{p_T}$.
Associated $Z + h_{inv}$ production at LHC

Higgs decays invisibly; consider $Z$ decays to leptons.
→ Signal is $\ell^+\ell^- p_T$ ($\ell = e, \mu$)

Major backgrounds:
- $Z(\rightarrow \ell^+\ell^-)Z(\rightarrow \nu\bar{\nu})$
- $W(\rightarrow \ell^+\nu)W(\rightarrow \ell^-\bar{\nu})$
- $W(\rightarrow \ell\nu)Z(\rightarrow \ell^+\ell^-)$ with missed lepton
- $Z(\rightarrow \ell^+\ell^-) + j$ with fake $p_T$

We simulated the $Z + h_{inv}$ signal and the $ZZ$, $WW$, and $WZ$ backgrounds using Madgraph.

The $Z + j$ background with fake $p_T$ comes from $Z + j$ events in which the jet(s) are missed: either they are too soft or they go down the beampipe. We took results for this background from Frederiksen, Johnson, Kane & Reid.
Cuts:

We start with some “minimal cuts”:

\[ p_T(\ell^{\pm}) > 10 \text{ GeV}, \quad |\eta(\ell^{\pm})| < 2.5, \quad \Delta R(\ell^+\ell^-) > 0.4 \]

The leptons in the signal reconstruct to the \( Z \) mass. The \( WW \) background can be largely eliminated by a \( Z \) mass cut:

\[ |m_{\ell^+\ell^-} - m_Z| < 10 \text{ GeV} \]

This also removes Drell-Yan \( Z \rightarrow \tau\tau \).

The leptons from the \( WW \) background also tend to be back-to-back; this background can be further reduced with an angular cut:

\[ \Delta \phi_{\ell^+\ell^-} < 2.5 \]

This cut also eliminates Drell-Yan with mismeasured \( \ell^{\pm} \) energy.

To cut down the \( WZ \) background, we veto events with a third lepton with

\[ p_T > 10 \text{ GeV}, \quad |\eta| < 3.0 \quad \text{(lepton veto)} \]
Final cut is on $p_T$:

- $p_T$ of $WW$ background tends to be soft, since it comes from the neutrinos in two independent $W$ decays.
- $p_T$ of $ZZ$ background is softer than signal: $ZZ$ is t-channel while $Z + h_{inv}$ is s-channel.
- $p_T$ of Signal increases with $m_h$. 
$Z + j$ background with fake $p_T$:

Fake $p_T$ due to missed jets – too soft or too large rapidity
$\rightarrow$ escape the jet veto
Proper treatment for modern ATLAS/CMS design requires detector simulation – beyond the scope of our study.

Was studied in Frederiksen, Johnson, Kane & Reid (1994) for various $p_T$ cuts and rapidity coverage of hadronic calorimeter
$\rightarrow$ we adapt their results for our study.

• With $\Delta R(\ell^+\ell^-) > 0.4$, we have larger lepton acceptance by a factor of 1.6 than Frederiksen, Johnson, Kane & Reid (who used $\Delta R(\ell^+\ell^-) > 0.7$)
$\rightarrow$ better statistics with same luminosity.

• We consider a range of $p_T$ cuts
Frederiksen, Johnson, Kane & Reid considered lower $p_T$, Godbole et al considered higher $\rightarrow$ optimize $p_T$ cut to improve signal significance
Comparison to Godbole et al (2003) study of $Z + h_{inv}$

They included hadronization using PYTHIA/HERWIG and detector simulation using CMSJET/GETJET (respectively).

No big surprises – our results are consistent with theirs.

- jet veto on ISR ↔ NLO K-factor
- $t\bar{t}$
- $WZ$ lepton veto
Results (LHC, ee + μμ)

Signal and background cross sections (after cuts):

<table>
<thead>
<tr>
<th>ψ_T cut</th>
<th>B(ZZ)</th>
<th>B(WW)</th>
<th>B(ZW)</th>
<th>B(Z + j)*</th>
<th>S(Z + h_{inv})</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 GeV</td>
<td>48.0 fb</td>
<td>10.6 fb</td>
<td>10.2 fb</td>
<td>22 fb</td>
<td>m_h = 120 GeV: 14.8 fb</td>
</tr>
<tr>
<td>75 GeV</td>
<td>38.5 fb</td>
<td>4.3 fb</td>
<td>7.4 fb</td>
<td>9 fb</td>
<td>m_h = 140 GeV: 12.8 fb</td>
</tr>
<tr>
<td>85 GeV</td>
<td>30.9 fb</td>
<td>1.8 fb</td>
<td>5.5 fb</td>
<td>11.1 fb</td>
<td>m_h = 160 GeV: 9.4 fb</td>
</tr>
<tr>
<td>100 GeV</td>
<td>22.1 fb</td>
<td>0.6 fb</td>
<td>3.6 fb</td>
<td>8.7 fb</td>
<td></td>
</tr>
</tbody>
</table>

*B(Z + j) extrapolated from Frederiksen, Johnson, Kane & Reid

Significance: (parentheses: includes Z + j)

<table>
<thead>
<tr>
<th>ψ_T cut</th>
<th>S/B</th>
<th>S/√B (10 fb^{-1})</th>
<th>S/√B (30 fb^{-1})</th>
<th>m_h = 140 GeV</th>
<th>m_h = 160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 GeV</td>
<td>0.22 (0.16)</td>
<td>5.6 (4.9)</td>
<td>9.8 (8.5)</td>
<td>7.3 (6.7)</td>
<td>5.4 (5.0)</td>
</tr>
<tr>
<td>75 GeV</td>
<td>0.25 (0.22)</td>
<td>5.7 (5.3)</td>
<td>9.9 (9.1)</td>
<td>7.4</td>
<td>5.6</td>
</tr>
<tr>
<td>85 GeV</td>
<td>0.29</td>
<td>5.7</td>
<td>9.8</td>
<td>7.3</td>
<td>5.7</td>
</tr>
<tr>
<td>100 GeV</td>
<td>0.33</td>
<td>5.4</td>
<td>9.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( m_h = 120 \text{ GeV}: >5\sigma \text{ signal with } 10 \text{ fb}^{-1}. \)

With 30 fb^{-1}, 5\sigma \text{ discovery extends out to } m_h = 160 \text{ GeV.}
• $Z + h_{inv}$: $S/\sqrt{B} \gtrsim 5$ for $m_h = 120$ GeV and $10$ fb$^{-1}$.

Comparison to WBF→$h_{inv}$ process
[Eboli & Zeppenfeld]

• WBF → $h_{inv}$ gives much better significance:
$S/\sqrt{B} \simeq 24$ for $m_h = 120$ GeV and $10$ fb$^{-1}$.

• $Z + h_{inv}$ provides an independent discovery channel:
  very different search with different systematics
  independent handle on $h_{inv}$ production

Comparison to $t\bar{t}h_{inv}$ process
[Gunion; Kersevan, Malawski & Richter-Was]

• $t\bar{t}h_{inv}$ is a complicated process – many particles in the final state and many backgrounds.
$S/\sqrt{B} \sim 4$ for $m_h = 120$ GeV and $10$ fb$^{-1}$. 
An invisible Higgs at the Tevatron

Search modes:

- $Z + h_{inv}$ Martin & Wells (1999)
  Signal is $\ell^+\ell^- p_T$, similar to LHC search.
  120 GeV Higgs, 10 fb$^{-1}$: $S/\sqrt{B} \simeq 1.9$

- WBF$\rightarrow h_{inv}$ Davoudiasl, Han & H.L. (2004)
  Signal is $jj p_T$; jets are hard and forward.
  120 GeV Higgs, 10 fb$^{-1}$: $S/\sqrt{B} \simeq 1.6$

Looks very depressing... but combining both channels and data from both detectors, can get $3\sigma$ with “only” 7 fb$^{-1}$ of delivered luminosity. Tevatron has a shot at this before the LHC!
$3\sigma$ requires $\sim 7 \text{ fb}^{-1}$ for $m_h = 120 \text{ GeV}$.

Comparable to SM Higgs sensitivity.
Weak boson fusion → $h_{inv}$ at the Tevatron

Higgs decays invisibly; signal is $jjp_T$

Major backgrounds:
- $Z(\rightarrow \nu \bar{\nu}) + 2j$, from QCD
- $Z(\rightarrow \nu \bar{\nu}) + 2j$, from EW (WBF) – kinematics similar to signal
- $W(\rightarrow \ell \nu) + 2j$, from QCD – with the lepton missed
- $jjp_T$ with fake $p_T$

We simulated the WBF signal and the $Z + 2j$ and $W + 2j$ backgrounds using Madgraph.

The $jjp_T$ background with fake $p_T$ comes from dijet events in which the jet(s) are mismeasured and from multijet events in which the extra jets are too soft or they go down the beampipe. We took a conservative upper limit for this background of 5 fb from a CDF study of $jjp_T$. 
Cuts:

We again start with some “minimal cuts”:

\[ p_T(j) > 10 \text{ GeV}, \quad |\eta(j)| < 3.0, \quad \Delta R(jj) > 0.4, \quad \not{p}_T > 90 \text{ GeV} \]

The \( \not{p}_T > 90 \text{ GeV} \) requirement serves as a trigger.

The jets in WBF tend to be separated by a large rapidity gap and reconstruct to a large invariant mass. The \( Z + 2j \) and \( W + 2j \) backgrounds from QCD can be significantly reduced by “WBF cuts”:

\[ \Delta \eta_{jj} > 2.8, \quad m_{jj} > 320, 340, 360, 400 \text{ GeV} \]

The \( W + 2j \) background can be further reduced by vetoing leptons with

\[ p_T(\ell) > 8 \text{ GeV}, \quad |\eta(\ell)| < 3.0 \quad \text{(lepton veto)} \]

To reduce the \( jj \not{p}_T \) background with fake \( \not{p}_T \) from jet energy mismeasurements, we require that the \( \not{p}_T \) is not aligned with either of the jets:

\[ \Delta \phi(j, \not{p}_T) > 30^\circ \]
Results (Tevatron Run II, $m_h = 120$ GeV)

Signal and background cross sections (after cuts):

<table>
<thead>
<tr>
<th>$m_{jj}$ cut</th>
<th>$S(h_{inv} + 2j)$</th>
<th>$B(Z + 2j,QCD)$</th>
<th>$B(Z + 2j,EW)$</th>
<th>$B(W + 2j,QCD)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>320 GeV</td>
<td>4.1 fb</td>
<td>55 fb</td>
<td>1.7 fb</td>
<td>7 fb</td>
</tr>
<tr>
<td>340 GeV</td>
<td>3.6 fb</td>
<td>43 fb</td>
<td>1.6 fb</td>
<td>5 fb</td>
</tr>
<tr>
<td>360 GeV</td>
<td>3.2 fb</td>
<td>34 fb</td>
<td>1.4 fb</td>
<td>5 fb</td>
</tr>
<tr>
<td>400 GeV</td>
<td>2.4 fb</td>
<td>21 fb</td>
<td>1.2 fb</td>
<td>2 fb</td>
</tr>
</tbody>
</table>

Number of signal events, S/B, and significance:

<table>
<thead>
<tr>
<th>$m_{jj}$ cut</th>
<th>S ($10 \text{ fb}^{-1}$)</th>
<th>S/B</th>
<th>S/$\sqrt{B}$ ($10 \text{ fb}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320 GeV</td>
<td>41 evts</td>
<td>0.060</td>
<td>1.6</td>
</tr>
<tr>
<td>340 GeV</td>
<td>36 evts</td>
<td>0.066</td>
<td>1.5</td>
</tr>
<tr>
<td>360 GeV</td>
<td>32 evts</td>
<td>0.070</td>
<td>1.5</td>
</tr>
<tr>
<td>400 GeV</td>
<td>24 evts</td>
<td>0.082</td>
<td>1.4</td>
</tr>
</tbody>
</table>

$m_h = 120$ GeV: 1.6$\sigma$ signal with 10 fb$^{-1}$.

Background must be understood at < 10% level.

This could be improved...
Central jet veto

The LHC study of $\text{WBF}\rightarrow h_{inv}$ uses a central jet veto to reduce the background. Takes advantage of different color structures of signal and background.

**WBF:** no color flow between forward/backward jets: expect little jet activity in central region.

**QCD $Z + 2j$:** final-state jets are color-connected: expect additional jet radiation in central region.

Eboli & Zeppenfeld applied a central jet veto (from Rainwater) – improves S/B by a factor of three without significantly reducing signal rate.

We have not imposed a central jet veto. If similar background reduction could be achieved at Tevatron, $\text{WBF}\rightarrow h_{inv}$ channel alone could give a $3\sigma$ observation with “only” 6 fb$^{-1}$ per detector, with S/B $\simeq 1/5$. 
Extracting the mass of an invisible Higgs

- Mass of $h_{inv}$ accessible only through production process:

  **Kinematic distributions**

  ![Kinematic distribution graph]

  **Cross sections (LHC)**

  ![Cross sections graph]

  (future direction)

- Measure signal rate
- Assume SM production cross section, 100% invisible decay.*
  \[ \rightarrow \] Higgs mass.

*Will remove these assumptions later!
Uncertainties:

- **Statistical uncertainty:**
  \[
  \Delta \sigma_S / \sigma_S = \sqrt{S + B} / S
  \]

- **Background normalization:**
  Backgrounds for \(Z + h_{inv}\) and WBF are dominated by \(Z \rightarrow \nu\nu\). Can measure background rates/shapes in \(Z \rightarrow \ell\ell\) channel!
  Less statistics: \(\text{BR}(Z \rightarrow \ell\ell) / \text{BR}(Z \rightarrow \nu\nu) \approx 0.28\).
  \[
  \Delta \sigma_S / \sigma_S = \sqrt{B \times \text{BR}(\ell\ell) / \text{BR}(\nu\nu)} / S
  \]

- **Theory uncertainty:** QCD + PDFs
  4% for WBF, 7% for \(Z + h_{inv}\)

- **Uncertainty on experimental efficiencies:**
  5% for WBF forward-jet tag / central-jet veto
  4% dilepton tagging (2% per lepton)

- **Luminosity normalization:** 5%
Higgs mass determination from $Z + h_{inv}$, 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>

$Z + h_{inv}$: $\Delta m_h = 30–40 (12–14)$ GeV with 10 (100) fb$^{-1}$

Higgs mass determination from $WBF \rightarrow h_{inv}$, 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>

$WBF$: $\Delta m_h \simeq 40 (30)$ GeV with 10 (100) fb$^{-1}$

$Z + h_{inv}$ cross section falls faster with $m_h$ than WBF – more $m_h$ dependence but less statistics.
Extracting \( m_h \) from a single cross section relies on SM assumption for production couplings.

Ratio of \( Z + h_{inv} \) and WBF rates → more model-independent \( m_h \) extraction!

\[ Z + h_{inv} \sim h_{ZZ} \text{ coupling; WBF } \sim h_{WW}, h_{ZZ} \text{ couplings} - \text{ related by SU}(2) \text{ in models with only Higgs doublets/singlets.} \]

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**Example: MSSM (or 2HDM)**

\[
\begin{align*}
    ZZh \text{ coup} &= \left( \frac{g m_Z}{\cos \theta_W} \right) \sin(\beta - \alpha) \\
    WWh \text{ coup} &= g m_W \sin(\beta - \alpha)
\end{align*}
\]

---

**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 = \frac{\sigma_S(Zh)}{\sigma_S(WBF)} )</td>
<td>0.132</td>
<td>0.102</td>
<td>0.0807</td>
</tr>
<tr>
<td>( \frac{dr/dm_h}{r} ) (1 GeV(^{-1}))</td>
<td>(-0.011)</td>
<td>(-0.013)</td>
<td>(-0.013)</td>
</tr>
<tr>
<td>Total uncert., ( \frac{\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>
Can now learn more about the Higgs!

**Test 100% invisible decay:**
- Look for visible decays in all detectable channels $\rightarrow$ upper bounds on BRs
  - $\sum \text{BR}_i = 1 \longrightarrow \text{BR}_{\text{inv}} = 1 - \sum \text{BR}_{\text{other}}$
  - Cannot exclude certain decays, e.g. $h \rightarrow$ light quarks, $h \rightarrow gg$: background is overwhelming

Assume SU(2) doublets and/or singlets only
(same assumption as we made for ratio method $m_h$ extraction):
$hWW$ and $hZZ$ couplings $\leq$ SM values.
$Z + h$ and WBF *production* cross sections bounded from above by SM values.
$\longrightarrow$ Relatively model-independent *lower bound* on $\text{BR}_{\text{inv}}$ to produce observed rates in $Z + h_{\text{inv}}$ and WBF$\rightarrow h_{\text{inv}}$. 
Test the assumption of SM production cross section:
- Measure $m_h$ using ratio method
- Compute SM prediction for $\sigma_{S}(Z + h)$ and $\sigma_{S}(WBF)$
- Compare to measured $\sigma_{S}(Z + h_{inv})$ and $\sigma_{S}(WBF)$
→ Probe $hZZ$, $hWW$ couplings! (modulo BR$_{inv}$)

If we assume no significant branching fraction for $h \rightarrow gg, jj$ (so that BR$_{inv} +$ BR$_{SM \ decays} \simeq 1$), then:
- Compute $\Gamma(h \rightarrow WW)$ from $hWW$ coupling and $m_h$
- Add upper bound on BR($h \rightarrow WW$) from non-observation in WBF→ $h \rightarrow WW$
→ lower bound on total Higgs width $\Gamma_{tot}$
→ lower bound on $\Gamma(h \rightarrow invis)$.
→ Test models of invisibly-decaying Higgs.

Test the top quark Yukawa coupling:
- Compute SM prediction for $\sigma_{S}(t\bar{t}h)$
- Compare to measured $\sigma_{S}(t\bar{t}h_{inv})$
→ Probe $htt$ coupling! (again modulo BR$_{inv}$)
Conclusions

• SM Higgs width very small below $WW$ threshold: unexpected decay modes could have large BRs.
  The Higgs could decay invisibly!

• LHC:
  - WBF well studied, good significance
  - $Z + h_{inv}$ is a promising second channel
  - $t\bar{t}h_{inv}$ offers access to top Yukawa

• Tevatron:
  - $Z + h_{inv}$, WBF both depressingly small
  - Combining two channels and two detectors gives Tevatron a chance with 7 fb$^{-1}$
    - Central jet veto could improve WBF significantly at the Tevatron

• Relatively model-independent $m_h$ measurement by combining WBF and $Z + h_{inv}$ at LHC:
  $\Delta m_h \simeq 15$–20 GeV with 100 fb$^{-1}$.
  Compare with measured cross sections to test Higgs couplings.