Higgs boson decay into a pair of leptons: signal and backgrounds

Edmond L. Berger
Argonne National Laboratory
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Higgs boson decay to $W^+ W^-$ to $l^+ l^-$ plus missing energy and the standard model backgrounds

Search for the Higgs Boson

• Discover/understand the mechanism for electroweak symmetry breaking: a clear goal of Tevatron, LHC, and ILC experiments during the next decade

• Experimental plans:
  • Thorough search for Higgs bosons
  • Measure their properties and determine their couplings

• Focus on the $l^+l^-$ final state:
  • At LHC, examine signal $h \rightarrow W^+W^- \rightarrow l^+l^- X$ and backgrounds from a cocktail of standard model processes; including leptons from decays of heavy flavors produced in hard scattering subprocesses, e.g., $gg \rightarrow b\bar{b}X$
  • Comments on $h \rightarrow W^+W^- \rightarrow l^+l^- X$ at the ILC
$h \rightarrow W^+W^-$ branching fraction takes over when $m_h > 135$ GeV
Higgs boson production and decay at the LHC $pp \rightarrow hX; h \rightarrow WW$

- glue-glue fusion is the dominant production mechanism; lowest order triangle graph with $X = t, b, \tilde{q}$

- Decay modes of the $W$ include $W \rightarrow q\bar{q}$ and $W \rightarrow l\nu$

- Signals of $h \rightarrow WW \rightarrow 4$ jets and $h \rightarrow WW \rightarrow l\nu + 2$ jets are buried in the hadronic backgrounds at Tevatron and LHC energies

- Try to look at $WW \rightarrow l\bar{l}\nu\bar{\nu}$

- Information on the coupling $g_{hhWW}$ can be gained from the weak boson fusion process, $qq \rightarrow qqh$
Higgs boson decay $h \rightarrow W^+W^- \rightarrow l\bar{l}\nu\bar{\nu}$

- $h \rightarrow W^+W^-$ branching fraction dominant when $m_h > 135$ GeV;
at $m_h = 170$ GeV, $BR(h \rightarrow WW^* \rightarrow l^+l^-\nu\bar{\nu}) \sim 100BR(h \rightarrow ZZ^* \rightarrow 4l)$

- The `signal' is an excess of events above backgrounds from processes that provide $l^+l^-$ plus missing transverse energy ($\not{E}_T$)

- Standard model backgrounds:
  - `irreducible' backgrounds have at least two `isolated' leptons plus missing energy: continuum $WW^* \rightarrow l^+l^-\nu\bar{\nu}$; $WZ/ZZ \rightarrow l^+l^-\nu X$; $t\bar{t} \rightarrow WWb\bar{b}$; `single top' $qg \rightarrow Wt \rightarrow WWb$;...
  - `reducible' backgrounds in which the (second) lepton(s) and the missing energy arise from heavy flavor decay: $Wb\bar{b} \rightarrow l\nu b\bar{b}$; $Wc\bar{c}$, $Wc$, ..., and inclusive $b\bar{b}/c\bar{c}$

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**Dφ study of** $h \rightarrow W^+W^- \rightarrow l\bar{l} + E_T$

- Taken from a 1/3 fb$^{-1}$ study of $e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$ pairs

  PRL 96, 011801 (2006)

- Table lists the number of expected signal and background events, after all cuts have been applied. Statistical uncertainties only

<table>
<thead>
<tr>
<th>$M_H$(GeV)</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>0.007 ± 0.001</td>
<td>0.125 ± 0.002</td>
<td>0.398 ± 0.008</td>
<td>0.68 ± 0.01</td>
<td>0.463 ± 0.009</td>
<td>0.210 ± 0.004</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>7.9 ± 1.1</td>
<td>7.5 ± 1.0</td>
<td>3.8 ± 0.6</td>
<td>4.0 ± 0.7</td>
<td>6.6 ± 0.9</td>
<td>9.9 ± 1.1</td>
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<tr>
<td>Diboson</td>
<td>4.4 ± 0.2</td>
<td>8.1 ± 0.2</td>
<td>11.7 ± 0.3</td>
<td>12.3 ± 0.3</td>
<td>11.6 ± 0.3</td>
<td>9.6 ± 0.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.03 ± 0.01</td>
<td>0.11 ± 0.02</td>
<td>0.29 ± 0.02</td>
<td>0.47 ± 0.03</td>
<td>0.66 ± 0.05</td>
<td>0.72 ± 0.05</td>
</tr>
<tr>
<td>$W^+\text{jet}/\gamma$</td>
<td>16.9 ± 2.2</td>
<td>14.2 ± 2.1</td>
<td>5.8 ± 1.2</td>
<td>2.8 ± 0.9</td>
<td>0.7 ± 0.5</td>
<td>0.7 ± 0.5</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>0.6 ± 0.3</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Background sum</td>
<td>29.9 ± 2.5</td>
<td>30.1 ± 2.3</td>
<td>21.8 ± 1.4</td>
<td>19.7 ± 1.2</td>
<td>19.8 ± 1.1</td>
<td>21.2 ± 1.2</td>
</tr>
<tr>
<td>Data</td>
<td>27</td>
<td>21</td>
<td>20</td>
<td>19</td>
<td>19</td>
<td>14</td>
</tr>
</tbody>
</table>

- **Dφ** included as relevant backgrounds: continuum $WW, t\bar{t}$, Drell-Yan, small rate from jets faking $e^\pm$, ....

  Note: Continuum WW is the largest background for $m_h = 160$ GeV

- Data consistent with the backgound estimate

- Not the end of the story. What about leptons from semi-leptonic decays of heavy flavors: $b$ and $c$ quarks?
Higgs boson decay $h \rightarrow W^+W^- \rightarrow l\bar{l}\nu\bar{\nu}$

- Heavy flavor backgrounds: issue is the extent to which lepton isolation and subsequent kinematic physics cuts can suppress them
- The problem: at the LHC energy,
  \[ \sigma B(h \rightarrow WW^* \rightarrow ll\nu\bar{\nu}) \sim 0.7 \text{ pb} \text{ for } m_h = 150 \text{ to } 190 \text{ GeV} \]
  \[ \sigma_{b\bar{b}}^{\text{inclusive}} \sim 5 \times 10^8 \text{ pb} \]
- ‘Isolation’ in $b \rightarrow lX (\Delta R, E_T^{\text{iso}})$ even at the 0.5 % level leaves $l^+l^-E_T$ background that is $10^4$ greater than the signal
- Questions of both magnitude and shape of the backgrounds
- Thorough (re)evaluation of the signal and backgrounds for $h \rightarrow WW^* \rightarrow ll\nu\bar{\nu}$:
- Independent study of the DØ and ATLAS analysis chains but with all heavy flavor processes included
Detailed simulations for Tevatron and LHC

- DØ (PRL 96, 011801 (2006)) and CDF (PRL 97, 081802 (2006)) have data and ongoing analyses, with $S/B \sim 1/30$
- ATLAS has done simulations and expects $S/B \sim 1$

Two classes of backgrounds with heavy-flavor leptons:

1. $W_c, W_b\bar{b}, W_c\bar{c}, W_b$, single-top — All have 1 real $W$ plus 1 HFL
2. $b\bar{b}, c\bar{c}$ — have 2 HFL.
   Both have mb cross sections, w/ only $10^4$ suppression from isolation

How our simulations were done

- $h \rightarrow WW$ and $WW$ start with PYTHIA normalized with NLO $K$ factors
- $W_c/W_b$ use MadEvent fed through PYTHIA with NLO $K$ factors
- Single-top, $W_b\bar{b}, W_c\bar{c}$, normalized to ZTOP/MCFM differential NLO

PYTHIA output is fed through modified PGS simulation that reproduces DØ and ATLAS full detector results to 10%
**Dφ-like search (μ⁺μ⁻), m_h = 160 GeV; σ(fb)**

<table>
<thead>
<tr>
<th>Cut level</th>
<th>WW</th>
<th>b̅b</th>
<th>c̅c</th>
<th>Wc</th>
<th>Wb̅b</th>
<th>Wc̅c̅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>1.3 × 10⁴</td>
<td>2.7 × 10⁹</td>
<td>3.3 × 10⁹</td>
<td>1.2 × 10⁵</td>
<td>5.0 × 10⁴</td>
<td>5.0 × 10⁴</td>
</tr>
<tr>
<td>Isolated μ⁺μ⁻</td>
<td>62</td>
<td>7.8 × 10⁶</td>
<td>5.3 × 10⁴</td>
<td>85</td>
<td>36</td>
<td>16</td>
</tr>
<tr>
<td>p_Tμ₁ &gt; 15 GeV</td>
<td>61</td>
<td>5.8 × 10⁶</td>
<td>3.9 × 10⁴</td>
<td>82</td>
<td>34</td>
<td>15</td>
</tr>
<tr>
<td>E_T &gt; 20 GeV</td>
<td>49</td>
<td>208</td>
<td>5</td>
<td>51</td>
<td>19</td>
<td>7.5</td>
</tr>
<tr>
<td>E_Tscaled &gt; 15</td>
<td>42</td>
<td>24</td>
<td>&lt; 0.1</td>
<td>38</td>
<td>7.7</td>
<td>4.4</td>
</tr>
<tr>
<td>H_T &lt; 100 GeV</td>
<td>42</td>
<td>24</td>
<td>&lt; 0.1</td>
<td>38</td>
<td>7.7</td>
<td>4.3</td>
</tr>
<tr>
<td>Δφll &lt; 2.0</td>
<td>19</td>
<td>24</td>
<td>&lt; 0.1</td>
<td>12</td>
<td>3.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Interval cuts</td>
<td>9.3</td>
<td>24</td>
<td>&lt; 0.1</td>
<td>3.1</td>
<td>2.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

“Inclusive” b̅b, c̅c already have some cuts applied: E_T > 10 GeV, |η| < 3.25
Isolated μ⁺μ⁻ means 2 reconstructed OS muons, p_T > 10 GeV

- **W + X** is chipped away and finally reduced by “interval cuts”
  (the most effective of which is 20 GeV < Mll < m_h/2)

- b̅b, c̅c are reduced primarily by the E_T cuts

- reason for Δφll cut: spin correlations in h decay:

  Once E_T cut is applied, b̅b is already in a configuration that passes the rest of the cuts; **background doubled**
**ATLAS-like search, $m_h = 160$ GeV**

Series of isolation and physics cuts on reconstructed objects

(Table shows $\sigma$(fb) from our analysis.) ‘Isolated’ means $p^l_T > 10$ GeV, $\eta^l < 2.5$, plus generic ATLAS cone $\Delta R$ and $E^\text{iso}_T$ choices

<table>
<thead>
<tr>
<th>Cut level</th>
<th>$h \to WW$</th>
<th>WW</th>
<th>$bbj^*$</th>
<th>$Wc$</th>
<th>single-top</th>
<th>$Wb\bar{b}$</th>
<th>$Wc\bar{c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated $l^+l^- &gt; 10$ GeV</td>
<td>336</td>
<td>1270</td>
<td>&gt; 35700</td>
<td>12200</td>
<td>3010</td>
<td>1500</td>
<td>1110</td>
</tr>
<tr>
<td>$E_T l_1 &gt; 20$ GeV</td>
<td>324</td>
<td>1210</td>
<td>&gt; 5650</td>
<td>11300</td>
<td>2550</td>
<td>1270</td>
<td>963</td>
</tr>
<tr>
<td>$E_T &gt; 40$ GeV</td>
<td>244</td>
<td>661</td>
<td>&gt; 3280</td>
<td>2710</td>
<td>726</td>
<td>364</td>
<td>468</td>
</tr>
<tr>
<td>$M_{ll} &lt; 80$ GeV</td>
<td>240</td>
<td>376</td>
<td>&gt; 3270</td>
<td>2450</td>
<td>692</td>
<td>320</td>
<td>461</td>
</tr>
<tr>
<td>$\Delta \phi &lt; 1.0$</td>
<td>136</td>
<td>124</td>
<td>&gt; 1670</td>
<td>609</td>
<td>115</td>
<td>94</td>
<td>131</td>
</tr>
<tr>
<td>$</td>
<td>\theta_{ll}</td>
<td>&lt; 0.9$</td>
<td>81</td>
<td>83</td>
<td>&gt; 1290</td>
<td>393</td>
<td>68</td>
</tr>
<tr>
<td>$</td>
<td>\eta_1 - \eta_2</td>
<td>&lt; 1.5$</td>
<td>76</td>
<td>71</td>
<td>&gt; 678</td>
<td>320</td>
<td>48</td>
</tr>
<tr>
<td>Jet veto</td>
<td>41</td>
<td>43</td>
<td>&gt; 557</td>
<td>175</td>
<td>11</td>
<td>12</td>
<td>7.4</td>
</tr>
<tr>
<td>$130 &lt; M_{ll}^{\text{T}} &lt; 160$ GeV</td>
<td>18</td>
<td>11</td>
<td>—</td>
<td>0.21</td>
<td>1.3</td>
<td>0.04</td>
<td>0.09</td>
</tr>
</tbody>
</table>

- $bbj^*$ ME is preselected to pass $E_T$ cut
  Looser cuts indicate that “>” is at least a factor of 5
  This method allowed us to demand 2 reconstructed isolated leptons!
- After the $E_T$ cut, real power comes from the transverse mass $M_{ll}^{\text{T}}$ cut
Transverse mass distribution after cuts

- Cannot reconstruct a Higgs boson mass peak from $h \rightarrow WW^* \rightarrow l^+l^-\nu\bar{\nu}$; use ‘transverse mass’ as an estimator;

$$M_T^{ll} = \sqrt{2p_T^{ll}E_T^{miss}(1 - \cos(\Delta\phi))}$$

Missing backgrounds for $H \rightarrow WW$ at ATLAS

- Heavy flavor background is more than 10 times previous estimates of backgrounds when $M_T^{ll} < 110$ GeV; a tail extends into the signal region

Edmond Berger, Argonne – p.11/20
The HF background starts off $50 \times$ the signal

The $M_{ll}^{TH}$ peak is $\sim 2/3 \, b\bar{b}j^*$, $\sim 1/4 \, Wc$

$Wb\bar{b}$, $Wc\bar{c}$, single-top all are larger than continuum $WW$

The leading edge in $M_{ll}^{TH}$ covers $m_h = 140$ GeV, and bisects larger Higgs masses
Transverse mass distribution at ATLAS

The HF background starts off $50 \times$ the signal

The $M_{ll}^{T}$ peak is $\sim \frac{2}{3} b\bar{b}j^{*}, \sim \frac{1}{4} Wc$

$Wb\bar{b}, Wc\bar{c}$, single-top all are larger than continuum $WW$

The leading edge in $M_{ll}^{T}$ covers $m_{h} = 140$ GeV, and bisects larger Higgs masses

ATLAS makes a very tight cut:

$m_{h} - 30(40)$ GeV $< M_{ll}^{T} < m_{h}$

in an attempt to extract the upper shoulder of $h \rightarrow WW$ from the upper shoulder of continuum $WW$

Since the shapes for $m_{h} > 160$ GeV are so similar, everything relies on counting events in the tails.
The HF background starts off 50× the signal

The $M_{T}^{ll}$ peak is $\sim 2/3 \bar{b}bj^*, \sim 1/4 Wc$

$W\bar{b}$, $Wc\bar{c}$, single-top all are larger than continuum $WW$

The leading edge in $M_{T}^{ll}$ covers $m_h = 140$ GeV, and bisects larger Higgs masses

ATLAS makes a very tight cut:

$m_h - 30(40)$ GeV < $M_{T}^{ll}$ < $m_h$

in an attempt to extract the upper shoulder of $h \rightarrow WW$ from the upper shoulder of continuum $WW$

Since the shapes for $m_h > 160$ GeV are so similar, everything relies on counting events in the tails

If $WW$ were the only background, this might work

Cannot predict to 10–20 GeV the the position of HF leading edge

However, can measure the HF background . . . and maybe cut it
Harder cut on the $p_T$ of the second lepton suppresses the heavy flavor background, by a factor of about 20, but has only a small effect on the $h \rightarrow WW$ and continuum WW contributions.

The leading edge of the heavy flavor contribution drops to lower $M^{ll}_{T}$. 

Edmond Berger, Argonne – p.13/20
Summary for $h \rightarrow W^+W^- \rightarrow l\bar{l}\nu\bar{\nu}$ at LHC

- Previously omitted heavy flavor backgrounds are potentially huge: not killed by isolation
- Raising the $p_T^l$ cut on the non-leading lepton appears essential
- Lepton identification criteria and isolation cuts will change once data are in-hand and real detector response is known
- Shape of the background is a limiting factor – not clear we can simulate tails well – could be worse
- ‘Measure’ the background in the transverse mass distribution?
- Can do a study now with a good sample of $b\bar{b}$ events in Tevatron data to measure what fraction of leptons from $b$ decay pass isolation cuts
- Heavy flavor backgrounds are an issue for all BSM signals with leptons in the final state; e.g., requirement to raise the $p_T^l$ cut will affect SUSY studies with multi-lepton final state signatures
$h \rightarrow W^+W^- \rightarrow l\bar{l}\nu\bar{\nu}$ at the ILC

**Higgs production mechanisms (Higgs-strahlung and $WW$ fusion)**

- **Higgs boson mass is well determined** ($\delta m/m \sim 100$ MeV), independently of decays, via the recoil mass from the $Z$ from Tesla TDR

![Diagram of Higgs production mechanisms](image)

Also $ZZ$ fusion
\( h \to W^+W^- \) final states at the ILC

- \( h \to W^+W^- \) decays dominate for \( m_h > 150 \text{ GeV} \)
  
  Higgs boson decay can be fully reconstructed from hadronic \( W \) decays in \( e^+e^- \to hZ \to W^+W^-Z \), with \( Z \to q\bar{q} \) or \( Z \to l\bar{l} \)

\[ \begin{array}{c}
\text{(c)} \quad Z \to q\bar{q}; \quad \text{(d)} \quad Z \to l\bar{l}; \quad \sqrt{s} = 350 \text{ GeV and } \int Ldt = 500 \text{ fb}^{-1} \\
\end{array} \]

Garcia-Abia, Lohmann, Raspereza, LC-PHSM-2000-062

- Branching fraction \( BR(h \to WW^*) \) can be measured to \( \sim 4\% \) in \( e^+e^- \to hZ \to WW^*Z \), with \( WW^* \to 4 \text{ jets or } WW^* \to l\nu + 2 \text{ jets} \)
- Can also use the Higgs-strahlung process to determine \( g_{hZZ} \) and the \( WW \) fusion process (plus a known branching fraction) for \( g_{hWW} \)

Edmond Berger, Argonne – p.16/20
Anything (e.g., $J^{PC}$) to learn from 
$h \rightarrow W^+ W^- \rightarrow l^+ l^- + E_{\text{miss}}$ at the ILC?

- $e^+ e^- \rightarrow hZ$, with $Z \rightarrow l^+ l^-$, with $h \rightarrow W^+ W^- \rightarrow l^+ l^- + E_{\text{miss}}$, has interesting kinematic signatures in the 4 charged lepton final state, especially near threshold.

- In $W \rightarrow l \nu$ (unlike $W \rightarrow q \bar{q} \rightarrow 2 \text{ jets}$), we can identify the electric charge of the lepton, whether $l^+$ or $l^-$. The electric charge tells us the helicity (right- or left-handed). In $W^- \rightarrow l^- \nu$, the decay $l^-$ goes in the direction opposite to the spin orientation of the $W$.

- Determination of the charges of the two leptons in 
$h \rightarrow W^+ W^- \rightarrow l^+ l^- + E_{\text{miss}}$ tells us the spin orientations of each of the $W$'s.

- Work in progress

- Request to the audience: if anyone knows of studies of 
$h \rightarrow W^+ W^- \rightarrow l^+ l^- + E_{\text{miss}}$ at the ILC, please let me know
BACKUPS
### Breakdown of LS/OS leptons at DØ

<table>
<thead>
<tr>
<th>$\sigma_{ll}$ (fb):</th>
<th>$ee$</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LS</td>
<td>OS</td>
<td>LS</td>
</tr>
<tr>
<td>$h \rightarrow WW$</td>
<td>—</td>
<td>$0.73 \pm 0.04$</td>
<td>—</td>
</tr>
<tr>
<td>$WW$</td>
<td>—</td>
<td>$12 \pm 1$</td>
<td>—</td>
</tr>
<tr>
<td>$b\bar{b}(j)$</td>
<td>—</td>
<td>$2.1$</td>
<td>—</td>
</tr>
<tr>
<td>$WC$</td>
<td>$0.8 \pm 0.4$</td>
<td>$2.3 \pm 1.1$</td>
<td>$1.1 \pm 0.4$</td>
</tr>
<tr>
<td>$Wb\bar{b}$</td>
<td>$0.4 \pm 0.2$</td>
<td>$0.4 \pm 0.1$</td>
<td>$2.1 \pm 1.6$</td>
</tr>
<tr>
<td>$WCc$</td>
<td>$1.4 \pm 0.5$</td>
<td>$1.1 \pm 0.4$</td>
<td>$1.0 \pm 0.2$</td>
</tr>
<tr>
<td>all else</td>
<td>$0.1$</td>
<td>$1.6$</td>
<td>$0.3$</td>
</tr>
</tbody>
</table>

$b\bar{b}$ contribution more than doubles the background to $\mu^+\mu^-$

Other channels see 50% increases

Is this consistent with the DØ result? Yes, to within 1–2σ

Should you trust this result as an absolute prediction? No

To understand all of the physical processes at play, we must try to measure the backgrounds...
Why does varying isolation cuts have such a small impact?

Essentially, all experiments have tuned their isolation cuts to have high lepton acceptance, with reasonable rejection vs. jets faking leptons. It is possible to get factors of 2–3 suppression of the heavy-flavor background by using tighter cuts.

• CDF did this in Note 7152 to get a very pure $WW$ cross section.
• They got purity by sacrificing real signal leptons, and killing $H \rightarrow WW$.

The only question is whether the hadron remnant is seen.

Our simulations suggest:

• $\sim 1/2$ of the events pass the usual isolation cuts, because the remnant is just outside whatever cone is used for tracking/energy cuts.
• $\sim 1/2$ of the events pass because the lepton took nearly all of the energy. Hence, there is nothing left to reject on.

These events are not good candidates to reject with impact parameter cuts — they tend to point back to the primary vertex.