Tevatron Higgs Sensitivity

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On behalf of the Tevatron Higgs Sensitivity Group
Invitation

✗ Tevatron Higgs search studies have gathered a lot of attention
  ✓ SUSY/Higgs Working Group (1998)
✗ But the speculation is that they are too optimistic to make searches worthwhile

✗ I want to demonstrate that
  ✓ Higgs searches at the Tevatron are realistic and exciting
  ✓ The two estimates are good benchmarks
  ✓ We really need a combination between CDF & DØ
    ✓ Sooner is much better!
SHWG covered most of the Higgs production and decay channels
Used parameterized simulations for an average FNAL detector performance
Very complete study using the resources available
Evolution
1998-2004

Combined LEP2 SM Higgs Result

J. Erler, hep-ph/0310202
In a Nutshell...

hep-ph/0407097

\[ M_H \text{ [GeV]} \]

\[ m_t \text{ [GeV]} \]

- $\Gamma_Z, \sigma_{\text{had}}, R_f, R_q$
- Asymmetries
- Low-energy
- $M_W$
- $m_t$

Excluded by all data at 90% CL
What else changed since 1998?

**Things that help:**
- Full simulation of Run II detectors (GEANT)
- Real measurements of trigger rates and efficiencies
- Greater understanding of physics processes
- Lots of data to make comparisons with
- More advanced analysis techniques

**Things that don't help:**
- Tevatron bunch crossing time will not be 132ns
- Larger rate of multiple interactions
- Changes in expected cross sections

### Select Cross Sections (pb)

<table>
<thead>
<tr>
<th>Process</th>
<th>New</th>
<th>SHWG</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH(\nu\nu)$, $m_H = 120$ GeV</td>
<td>0.013</td>
<td>0.016</td>
<td>0.79</td>
</tr>
<tr>
<td>Wbb</td>
<td>3.40</td>
<td>2.53</td>
<td>1.34</td>
</tr>
<tr>
<td>WZ</td>
<td>3.20</td>
<td>2.81</td>
<td>1.14</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.70</td>
<td>1.24</td>
<td>1.38</td>
</tr>
</tbody>
</table>
The Stage is Set...

✗ The DoE requested a new estimate for Higgs search sensitivity in Run II

✗ Message from LEP is clear – no individual experiment will succeed alone

✗ **Prescription:** Split the task between collaborations

✗ **CDF:** $W^+ \gamma \to \nu \nu \bar{b} \bar{b}$  
   **DØ:** $ZH \to \nu \nu \bar{b} \bar{b}$

✗ Assume equal sensitivity for each expt, combine results

✗ Good opportunity to force the experiments to work together and convince ourselves we can succeed
Three Important Ingredients

**Dijet Mass Resolution**
- Determines ultimate separation of signal and background
- Current data ~15%
  - SHWG used 10%
- What is achievable?
  - What can advanced techniques buy us?

**b-quark Tagging**
- Essential for reduction of non-b backgrounds
- Methodology determines overall signal rate
- Care must be taken to properly handle fake rate

**Estimation of Search Sensitivity**
- Shape estimation vs counting expt can change result by 30%
- Choice of final variable and/or shape estimator can vary result by 10%
Outline of the Study

1) Start with Run IIA detector simulation
2) Add additional min-bias events for higher Run IIB lumi ($2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$)
3) Add b-tag parameterizations
4) Introduce trigger efficiencies
5) Determine achievable dijet mass resolution and scale to this operating point
6) Calculate expected QCD background contribution from data
7) Optimize analysis for maximal sensitivity
8) Extract luminosity thresholds based on final variable distributions
Needle in a Pile of Needles

Cross Section $\times$ BR ($WH \rightarrow l\nu bb$):

\[
\begin{align*}
\sigma \times \text{BR}(m_H = 110) &= 0.22 \text{ pb} \times 0.254 = 55 \text{ fb} \\
\sigma \times \text{BR}(m_H = 120) &= 0.16 \text{ pb} \times 0.224 = 36 \text{ fb} \\
\sigma \times \text{BR}(m_H = 130) &= 0.12 \text{ pb} \times 0.174 = 21 \text{ fb}
\end{align*}
\]
Needle in a Pile of Needles

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$\sigma \times \text{BR}(m_H = 110) = 0.22 \text{ pb} \times 0.254 = 55 \text{ fb}$
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Cross Section $\times$ BR (ZH $\rightarrow$ $\nu\nu$bb):

$\sigma \times \text{BR}(m_H = 110) = 0.12 \text{ pb} \times 0.154 = 19 \text{ fb}$
$\sigma \times \text{BR}(m_H = 120) = 0.09 \text{ pb} \times 0.136 = 13 \text{ fb}$
$\sigma \times \text{BR}(m_H = 130) = 0.07 \text{ pb} \times 0.106 = 7.5 \text{ fb}$
Needle in a Pile of Needles

Cross Section $\times$ BR (WH $\rightarrow$ l$\nu$bb):

$\sigma \times \text{BR}(m_H = 110) = 0.22 \text{ pb} \times 0.254 = 55 \text{ fb}$

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Backgrounds:

- QCD heavy-flavor
  $\sigma \sim 1-10 \mu\text{b}$

- W/Z + LF
  $\sigma \sim 100-200 \text{ pb}$

- W/Z + HF
  $\sigma \sim 7-15 \text{ pb}$

- tt, single-top
  $\sigma \sim 6-10 \text{ pb}$

- WZ/ZZ
  $\sigma \sim 1-2 \text{ pb}$

Gives an estimate of the uncertainty!
b-Quark Tagging: SHWG

- SHWG used several different b-tagging parameterizations
  - MCFAST (shown here)
  - CDF Run I performance
  - Assumed flat $\eta$ efficiency
- We used two approaches
  - **D0**: Full GEANT simulations of the Run IIB silicon
  - **CDF**: Parameterizations based on current silicon performance with extended $\eta$ coverage

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SHWG MCFAST b-Tagging

![Graph showing b-jet pT vs. tag efficiency per b jet]
b-Quark Tagging:
DØ/CDF

**DØ**

![Graph 1](image1)

**CDF**

![Graph 2](image2)

**Graph 1:**
- Tagging efficiency vs $\eta$
- $\chi^2/\text{ndf} = 0.8694 / 5$
- $p_0 = 0.6873 \pm 0.01493$
- $p_2 = -0.04579 \pm 0.04903$
- $p_3 = 0.03122 \pm 0.02798$

**Graph 2:**
- Per Jet Tagging Efficiency
- Jet $E_T$
- Eta Dependence
- 10$<E_T<$20
- 20$<E_T<$30
- 30$<E_T<$40
- 40$<E_T$
- Tight OR Loose: for Central Jets
- Tight for Central Jets
b-Quark Tagging: What's Realistic?

Average Double b-Tagging Efficiencies (%)

<table>
<thead>
<tr>
<th></th>
<th>H → bb</th>
<th>non – b sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ RIIB</td>
<td>32.0</td>
<td>0.0024</td>
</tr>
<tr>
<td>CDF RIIB</td>
<td>30.0</td>
<td>0.20</td>
</tr>
<tr>
<td>DØ RIIA Current</td>
<td>19.0</td>
<td>0.20</td>
</tr>
<tr>
<td>DØ RIIA Future</td>
<td>25.0</td>
<td>0.10</td>
</tr>
</tbody>
</table>

✗ Are these numbers realistic?

✗ Quick answer: yes

✗ We used simple estimates, nothing complicated

✗ No fancy b-Tag combinations

✗ No SLT

✗ Bottom line: It won't be easy, but we can achieve this
Changes In Trigger Strategy

✗ SHWG assumed 100% efficiency after offline cuts
   ✗ Realistically, we hope for $\epsilon_{\text{trigger}} \geq 90\%$
✗ Need to know trigger efficiencies for all ZH and WH decays to include cross efficiencies
✗ Need electron and muon triggers as well as calorimeter triggers

Higgs Trigger Menu

<table>
<thead>
<tr>
<th>Process</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Total:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH→ννbb:</td>
<td>94</td>
<td>94</td>
<td>90%</td>
</tr>
<tr>
<td>ZH→eebb:</td>
<td>99</td>
<td>98</td>
<td>98%</td>
</tr>
<tr>
<td>ZH→μμbb:</td>
<td>94</td>
<td>99</td>
<td>94%</td>
</tr>
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</table>

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<thead>
<tr>
<th>Process</th>
<th>Level 1</th>
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</tr>
</thead>
<tbody>
<tr>
<td>WH→eνbb:</td>
<td>97</td>
<td>97</td>
<td>94%</td>
</tr>
<tr>
<td>WH→μνbb:</td>
<td>90</td>
<td>98</td>
<td>89%</td>
</tr>
<tr>
<td>WH→τνbb:</td>
<td>93</td>
<td>96</td>
<td>90%</td>
</tr>
</tbody>
</table>
Di-Jet Mass Resolutions

✗ SHWG used flat 10%

✗ Too optimistic?

✗ Rule of thumb: ±1% in DMR gives ±10% in sensitivity

✗ We compare two experiments

✗ CDF: 10.4% with central jets

✗ D0: 11% with central jets

✗ With more time and effort we can do even better!

CDF Measurement of Higgs Mass resolutions
QCD Estimation

✗ For ZH→ννbb, SHWG estimated QCD background contribution as equal to the sum of all other backgrounds: \( QCD = \sum (\text{bkgd})_i \)

✗ Underestimation (or overestimation)?

✗ QCD background for WH→ℓνbb assumed to be small (and it is)

✗ We can actually measure this today in three steps

1) Get relative light quark and b quark rates from MC
2) Measure cross section and acceptances from data
3) Combine efficiencies to find total contribution

✗ We find SHWG estimate twice too large: \( QCD \sim \frac{1}{2} \sum (\text{bkgd})_i \)

✗ But we didn't spend any time trying to reduce this contribution!
Optimization Strategy

✗ SHWG cuts weren't optimal
  ✗ Must soften them to maximize signal acceptances
✗ Apply loose kinematic cuts to remove “obvious” backgrounds
✗ All acceptances measured using full simulation
  ✗ Includes lepton-ID, jet-ID, etc.
✗ Let Neural Networks (NN) do the heavy lifting

Expected Events in 1 fb⁻¹

<table>
<thead>
<tr>
<th>m_H = 115 GeV</th>
<th>ZH → γγbb</th>
<th>WH → lνbb</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH</td>
<td>3.11</td>
<td>0.2</td>
</tr>
<tr>
<td>WH</td>
<td>3.04</td>
<td>3.2</td>
</tr>
<tr>
<td>Wbb/Zbb</td>
<td>35.25</td>
<td>69.7</td>
</tr>
<tr>
<td>WZ/ZZ</td>
<td>26.03</td>
<td>11.0</td>
</tr>
<tr>
<td>tt</td>
<td>58.74</td>
<td>52.1</td>
</tr>
<tr>
<td>QCD</td>
<td>102.0</td>
<td>-</td>
</tr>
<tr>
<td>Total Signal</td>
<td>6.15</td>
<td>3.4</td>
</tr>
<tr>
<td>Total Background</td>
<td>223.25</td>
<td>101.1</td>
</tr>
</tbody>
</table>

No NN or bb mass window cuts applied!

W. Fisher, Princeton
Optimization Strategy

- Train NN using WH/ZH signal and top backgrounds
- Input variables:
  - MET/JET (+lepton for WH) $p_T$ balance
  - Fox-Wolfram moments (modified for the transverse plane)
  - $H_T$, Aplanarity
- Use $S/B^{1/2}$ estimator to find optimal NN cut

![Graph with $s/\sqrt{b}$ vs. NN Output](image1)

![Graphs showing distributions](image2)
Applying the NN

<table>
<thead>
<tr>
<th></th>
<th>$m_H = 115$ GeV</th>
<th>No NN</th>
<th>NN</th>
</tr>
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<tbody>
<tr>
<td><strong>ZH→ννbb</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>3.1</td>
<td>2.5</td>
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<td></td>
</tr>
<tr>
<td>tt</td>
<td>58.7</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>QCD</td>
<td>112.0</td>
<td>61.2</td>
<td></td>
</tr>
<tr>
<td><strong>Total Signal</strong></td>
<td>6.1</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>233.3</td>
<td>112.2</td>
<td></td>
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</tbody>
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<tr>
<td><strong>WH→eνbb</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>0.2</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>WH</td>
<td>3.2</td>
<td>3.0</td>
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<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Total Signal</strong></td>
<td>3.4</td>
<td>3.1</td>
<td></td>
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<tr>
<td><strong>Total Background</strong></td>
<td>152.0</td>
<td>79.7</td>
<td></td>
</tr>
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</table>

No bb mass window cuts applied!
Combination

× To evaluate sensitivity, calculate how much luminosity is needed to:
  × Exclude (95% CL) the SM Higgs at a given mass
    × ie, consistent with background-only expectation
  × 3σ evidence of SM Higgs production
    × signified by an excess of events
  × 5σ observation of SM Higgs production

× Start with full bb mass distributions for each bkgd and signal
  × Allows us to capitalize on the shape of the distributions

× To evaluate these requirements, we use two similar methods:
  × $CL_s$ frequentistic method (used by LEP Higgs Group)
  × Bayesian integration with a flat prior (similar to SHWG)
CDF provides $WH \rightarrow l\nu bb$ and DØ provides $ZH \rightarrow \nu \nu bb$

$ZH \rightarrow llbb$ contribution added by scaling $ZH \rightarrow \nu \nu bb$ by 1.33

Consistent with current searches and SHWG

CDF: $WH \rightarrow l\nu bb$  DØ: $ZH \rightarrow \nu \nu bb$
Combined Results

✗ Combined DØ/CDF result
  ✗ Assumes luminosity from two experiments
✗ 10% dijet mass resolution
✗ Run IIB silicon
✗ Width of HSG bands determined by method uncertainty
✗ No systematics included
✗ Width of SHWG bands given by analysis uncertainty
✗ SHWG included $H \rightarrow WW$
  ✗ contributes at high $m_H$
Is this the best we can do??

✗ For full sensitivity, we need:
  ✗ Optimized b-Tagging techniques
  ✗ Multivariable taggers will help a LOT, but take time and effort
  ✗ Constrained fitting techniques
  ✗ Already used in some analyses
  ✗ Matrix Element ratio techniques
  ✗ Effective factor of $\times 2$ in lumi for DØ top mass. Expect $\sim 20\%$ for Higgs.
  ✗ Expanded NN optimization
  ✗ For this study, not enough time to grind things out
  ✗ But we really need to have a CDF/DØ combination

✗ Still open to competition, but we can't ignore each other if we want to discover!
What could we do right now?

✗ Measurement of $WZ/ZZ$ mass distribution
  ✗ A combination would be sensitive to this with $\sim 250$ pb$^{-1}$ per expt
  ✗ Standard candle for dijet mass resolution studies
  ✗ “Dry run” for a Higgs search (also a nice result in itself!)
✗ Full measurements of systematic errors
  ✗ One of the largest complaints about the SHWG and HSG studies
  ✗ Timescale is good for understanding these issues
  ✗ Can be a huge factor in reducing luminosity requirements!
✗ Studies of final variable techniques
  ✗ Learn from LEP (b-Tag, constrained fits, etc...)
  ✗ Give this many smart people enough time, a lot can be thought up
Conclusions

× 6 years ago, the SHWG study set the standard for Higgs searches at the Tevatron
  × Many believed this was much too optimistic

× Complete studies of realistic detector performance now allow us to stand on solid ground
  × b-tagging, trigger, dijet mass resolution, QCD background

× We now see that the SHWG was not over-optimistic
  × In fact, we exceed their expectations
  × Will get even better as we get smarter

× Time is ripe to encourage a CDF/DØ combination for this study

× Please read the full report at FERMILAB--PUB-03/320-E