Searches for High Mass Higgs at the Tevatron

$WW^*$ final states

Dean Andrew Hidas
Rutgers
On behalf of the CDF & D0 Collaborations

EPS 2009
Krakow, Poland
16 July 2009
CDF & D0 Detectors

Silicon tracking
Drift chamber/Fiber tracker
EM & Had Calorimetry
Muon Chambers

Tevatron: \( p \rightarrow \times \leftarrow \bar{p} \quad \sqrt{s} = 1.96 \text{ TeV} \)

Delivered luminosity to date: \( \approx 6.9 \text{ fb}^{-1} \)

Analysis shown here use up to \( 4.8 \text{ fb}^{-1} \)
Standard Model and the Higgs

The standard model needs a Higgs or Higgs-like mechanism

- To explain electroweak symmetry breaking
- And give particles mass

Direct searches at LEP tell us

\[ M_H > 114.4 \text{ GeV} \text{ @ 95\% C.L.} \]

Indirect constraints from EW data prefer a lighter higgs, but combined with the LEP lower limit gives an upper limit of

\[ M_H < 191 \text{ GeV} \]
Standard Model Higgs Production

- Four main production mechanisms
- Gluon fusion is the dominant process at the Tevatron
- Associated production (particularly useful for light Higgs for better S/B)

See talks by: Michele Giunta, Michael Mulhearn

Dean Andrew Hidas, Rutgers, 16 July 2009
Standard Model Higgs Decay

Higgs decay modes depend on $m_H$

- For $m_H < 135$ GeV
  - Higgs decays predominantly to $b\bar{b}$

- For $m_H > 135$ GeV
  - Higgs decays mainly to $W^+W^-$

$\sigma(gg \rightarrow H) \times Br(H \rightarrow WW)$

- For $gg \rightarrow H \rightarrow W^+W^- \sigma \times BR$
  - Peak sensitivity for $m_H = 165$ GeV
  - Comparable sensitivity to individual low mass analyses at 125 GeV
$H \rightarrow W^+W^-$ Final States

- **W Decay Modes**
  - Leptonically: 33% $(e, \mu, \tau)$
  - Hadronically: 67%

- **Dilepton** $(e, \mu)$: $BR = 5%$
  Very small BR, clean, easily triggerable
  Sensitive to $\tau \rightarrow (e, \mu)$

- **Lepton + $\tau_{had}$**: $BR = 4%$
  Of potential use at CDF and D0

- **Lepton + Jets**: $BR = 30%$
  Large BR, but large $W$ + multi-jets backgrounds

- **All Hadronic**: $BR = 45%$
  Largest BR, but huge QCD backgrounds
SM Backgrounds

The final state we are interested in is the Dilepton final state:
For $H \rightarrow WW \rightarrow l\nu l\nu$

- Largest background: $Z/\gamma^* \rightarrow \ell\ell$
- CDF & D0 suppress this by requiring significant $E_T$

After Drell-Yan suppression the main backgrounds are:
- Diboson production - $WW, WZ, ZZ$
- Top pair production - $t\bar{t}$
- $W+$ jets - where a jet is misidentified as a lepton
- $W\gamma$ - where the photon is misidentified as a lepton (typically an electron)

$\sigma_{WW}$ recently been measured by CDF and DØ and agrees well with SM
Analysis Strategy

In general terms, the analysis strategy for $H \rightarrow WW$ searches involving 2 leptons in the final state at the tevatron is:

▸ Reduce the otherwise overwhelming Drell-Yan contribution (Cut out events with low $\not{E}_T$)

▸ Maximize the signal acceptance
  • Extend lepton selection
  • Add signal production mechanisms

▸ Separate signal from remaining background using some advanced multivariate technique
  • NN, Matrix element calculations, likelihood discriminants

▸ When there is no excess observed
  • Set limits on SM Higgs production at 95% CL

In the analyses shown here D0 separates by lepton pair type ($ee, e\mu, \mu\mu$) whereas CDF separates by jet multiplicity.
DO $H \rightarrow WW$ ($ee$)

At pre-selection:
Requirement $2$ high-$P_T$ electrons $P_T > 15$ GeV and $M_{e^+e^-} > 15$ GeV $M_{\ell^+\ell^-}$ spectrum from $ee$ channel

Full selection includes:
$E_T > 20$ GeV $E_T^{scaled} > 6$ $M_{Tmin}(e,E_T) > 20$ $\Delta \phi (e,e) < 2$\n
NN output for $ee$ channel (below)
At pre-selection:
Require 2 High-$P_T$ leptons
$P_T^e > 15$ GeV $P_T^\mu > 10$ GeV
and $M_{e\pm\mu\mp} > 15$ GeV
$E_T$ spectrum from $e\mu$ channel

Full selection:
Same as $ee$ channel
NN output for $e\mu$ channel (below)
DØ $H \rightarrow WW (\mu\mu)$

At pre-selection:
requiring 2 High-$p_T$ muons
$p_T^{1} > 15 \text{ GeV}, p_T^{2} > 10 \text{ and } M_{\mu^+\mu^-} > 15 \text{ GeV}$

$N_{\text{jet}} < 2 \text{ for } p_T^{\text{jet}} > 15 \text{ GeV}, \Delta R(\mu, \text{jet}) > 0.1$

$M_{\mu^+\mu^-}$ spectrum from $\mu\mu$ channel →

Full selection includes:

$N_{\text{jet}} = 0: p_T^{\mu\mu} > 20 \text{ GeV}$

$N_{\text{jet}} = 1: E_T > 20 \text{ GeV}$

NN output for $ee$ channel (below)
**D0 H → WW**

To better separate signal from background D0 uses neural networks

- Separate NNs for $ee$, $e\mu$, and $\mu\mu$ for each mass
- Trained against weighted sample of all BGs
- 12 to 14 inputs are used including
  - Lepton $P_T$, $E_T$, $M_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, and $\Delta\phi(E_T, \ell)$

95% C.L. ($M_H = 165$ GeV)

- **Expected/\sigma_{SM} = 1.7**
- **Observed/\sigma_{SM} = 1.3**
$WH \to WWW \to \ell^\pm \ell^\pm + X$

At pre-selection:
2 High-$p_T$ leptons same charge

Define a multidimensional likelihood

\textbullet Good separation of Signal and Multijet BG

$\ell^\pm \mu^\pm$ likelihood based discriminant

\begin{table}
<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit / Observed Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>0.18 / 23.6</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>0.35 / 39.2</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.18 / 12.3</td>
</tr>
</tbody>
</table>
\end{table}

← Limits for $WH \to WWW$
CDF $H \rightarrow WW : 0$-Jet

CDF requires 2 high-\(P_T\) leptons $P_T^1 > 20$, $P_T^2 > 10$ GeV and significant $E_T$

- Jet : $P_T > 15$ GeV and $|\eta| < 2.5$
- Makes use of leading order matrix element based likelihood ratios (LR) →
- Signal / BG : 11.8 / 858
- Final discriminant is NN (below)

CDF models 5 modes:
- $HWW$, $WW$, $ZZ$, $W\gamma$, $W$+jet

Use a Likelihood Ratio

$$LR_m = \frac{P_m(\vec{x}_{obs})}{P_m(\vec{x}_{obs}) + \sum_i k_i P_i(\vec{x}_{obs})}$$

PDF requires 2 high-P_{\text{lepton}} leptons $P_{\text{lepton}} > 2$ GeV and signifcant $E_{\text{T}}$

- Jet : $P_T > 15$ GeV and $|\eta| < 2.5$
- Makes use of leading order matrix element based likelihood ratios (LR) →
- Signal / BG : 11.8 / 858
- Final discriminant is NN (below)
CDF \( H \to WW : 1\)-Jet

For events containing 1 jet:

- VH and VBF become significant
- Makes use of kinematic variables such as \( M_{\ell\ell}, P_T(\ell) s, E(\ell_1) \)
  \( \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \)
- Final discriminant is NN (below)

\[ \int L = 4.8 \text{ fb}^{-1} \]
\[ M_H = 165 \text{ GeV/c}^2 \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Total Background</th>
<th>Total Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>383 ± 49</td>
<td>7.63 ± 0.99</td>
</tr>
<tr>
<td>( WZ )</td>
<td>115 ± 12</td>
<td>0.82 ± 0.11</td>
</tr>
<tr>
<td>( WZ )</td>
<td>55 ± 14</td>
<td>0.317 ± 0.041</td>
</tr>
<tr>
<td>( W\gamma )</td>
<td>17.5 ± 5.3</td>
<td>0.528 ± 0.084</td>
</tr>
<tr>
<td>( W+W)</td>
<td>123 ± 39</td>
<td>0.82 ± 0.11</td>
</tr>
<tr>
<td>( W+\text{jets} )</td>
<td>19.5 ± 2.7</td>
<td>0.317 ± 0.041</td>
</tr>
<tr>
<td>( Z\gamma )</td>
<td>7.5 ± 1.0</td>
<td>0.317 ± 0.041</td>
</tr>
<tr>
<td>( Z\gamma )</td>
<td>17.5 ± 5.3</td>
<td>0.528 ± 0.084</td>
</tr>
<tr>
<td>( g+\gamma )</td>
<td>1.5 ± 0.5</td>
<td>0.82 ± 0.11</td>
</tr>
<tr>
<td>( VBF )</td>
<td>383 ± 49</td>
<td>7.63 ± 0.99</td>
</tr>
</tbody>
</table>

\( \int L = 4.8 \text{ fb}^{-1} \)

\[ M_H = 165 \text{ GeV/c}^2 \]
**CDF** \( H \rightarrow WW : \geq 2\)-Jet

For events containing \( \geq 2 \) jets:

- VH and VBF significant
- Veto events with secondary vertices → Reduce \( t\bar{t} \)
- Makes use of kinematic variables such as \( M_{\ell\ell}, P_T(\ell)s, \Delta R, \Delta \phi_{\ell\ell} \)
- Final discriminant is NN (below)

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**CDF Run II Preliminary**

<table>
<thead>
<tr>
<th>Processes</th>
<th>( M_H = 165 \text{ GeV}/c^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W+\text{jets} )</td>
<td>2.29 ± 0.39</td>
</tr>
<tr>
<td>( Wt )</td>
<td>2.98 ± 0.98</td>
</tr>
<tr>
<td>( W\gamma )</td>
<td>0.97 ± 0.16</td>
</tr>
<tr>
<td>( ZH )</td>
<td>0.93 ± 0.12</td>
</tr>
<tr>
<td>( VBF )</td>
<td>1.76 ± 0.23</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>2.22 ± 0.30</td>
</tr>
<tr>
<td>( WW )</td>
<td>5.13 ± 0.71</td>
</tr>
<tr>
<td>( WZ )</td>
<td>24.0 ± 5.4</td>
</tr>
<tr>
<td>( DY )</td>
<td>46 ± 15</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>137 ± 23</td>
</tr>
</tbody>
</table>

Total Background 237 ± 31

Total Signal 5.96 ± 0.68

Data 214

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For events containing \( \geq 2 \) jets:

- VH and VBF significant
- Veto events with secondary vertices → Reduce \( t\bar{t} \)
- Makes use of kinematic variables such as \( M_{\ell\ell}, P_T(\ell)s, \Delta R, \Delta \phi_{\ell\ell} \)
- Final discriminant is NN (below)
CDF $H \rightarrow WW : $ Like Charge $\geq 1$-Jet

For events containing $\geq 1$ jet:

- 2 like charge leptons $P_T > 20$ GeV
- VH and VBF significant
- Dominant backgrounds is from $W$+jets
- Makes use of kinematic variables such as $M_{\ell\ell}, P_T(\ell)s, \Delta \phi_{\ell\ell}, \sum E_T^{jets}$
- Final discriminant is NN (below)
CDF $H \rightarrow WW$

Using up to 4.8 fb$^{-1}$ of data CDF sets limits on SM Higgs production at 95% CL

- Separate NNs for each channel for each mass
- Using all relevant production mechanisms
- Combine all channels (below)

CDF Run II Preliminary $\int L = 4.8$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected/σ$_{SM}$</th>
<th>Observed/σ$_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>185 ± 30</td>
<td>185 ± 30</td>
</tr>
<tr>
<td>$DY$</td>
<td>304 ± 55</td>
<td>304 ± 55</td>
</tr>
<tr>
<td>$WW$</td>
<td>563 ± 59</td>
<td>563 ± 59</td>
</tr>
<tr>
<td>$WZ$</td>
<td>52.4 ± 7.2</td>
<td>52.4 ± 7.2</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>39.8 ± 5.4</td>
<td>39.8 ± 5.4</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>249 ± 63</td>
<td>249 ± 63</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>147 ± 39</td>
<td>147 ± 39</td>
</tr>
<tr>
<td>Total Background</td>
<td>1541 ± 148</td>
<td>1541 ± 148</td>
</tr>
<tr>
<td>Total Signal</td>
<td>27.1 ± 3.2</td>
<td>27.1 ± 3.2</td>
</tr>
<tr>
<td>Data</td>
<td>1531</td>
<td>1531</td>
</tr>
</tbody>
</table>

95% C.L. ($M_H = 165$ GeV)

- Expected/σ$_{SM}$ = 1.28
- Observed/σ$_{SM}$ = 1.25
Systematic Uncertainties

Many systematic uncertainties are considered and evaluated by both experiments. The dominant uncertainties are typically

- Theoretical cross section uncertainties for signal and background
  - Range from 5-12%
- Acceptance uncertainty from limited order MC (5-10%)
- $W$+jets, uncertainty in how often a jet is misidentified as a lepton (20-30%)
- Jet modeling (5-20%)
- Luminosity $\approx 6\%$

Uncertainties are correlated, uncorrelated, and anti-correlated appropriately

Several shape systematics are investigated including jet energy scale, jet reconstruction, $P_{T}^{WW}$, $P_{T}^{H}$, $P_{T}^{Z}$
Tevatron Combination

Have had great success combining the results from CDF and D0 over the past several years

For Tevatron combination results please see the next talk by Bjoern Penning

(New CDF result will be incorporated in the next Tevatron combination for Lepton-Photon)
Conclusions

- CDF & D0 both making rapid progress in high mass Higgs searches
- Many improvements added over the last few years are bringing each experiment closer and closer to SM sensitivity
- Expecting an updated combination for Lepton-Photon

The Tevatron has reached standard model exclusion in the most sensitive mass region
Backup
CDF Matrix Elements

\[ P(\vec{x}_{\text{obs}}) = \frac{1}{\langle \sigma \rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}_{\text{obs}}, \vec{y}) d\vec{y} \]

- \( \vec{x}_{\text{obs}} \) Observed leptons and \( E_T \)
- \( \vec{y} \) True lepton 4-vectors \((l, \nu)\)
- \( \sigma_{th} \) Leading order theoretical cross-section
- \( \epsilon(\vec{y}) \) Efficiency & acceptance
- \( G(\vec{x}_{\text{obs}}, \vec{y}) \) Resolution effects
- \( 1/\langle \sigma \rangle \) Normalization

CDF models 5 modes:
- \( HWW, WW, ZZ, W\gamma, W+\text{jet} \)

Use a Likelihood Ratio

\[ LR_m = \frac{P_m(\vec{x}_{\text{obs}})}{P_m(\vec{x}_{\text{obs}}) + \sum k_i P_i(\vec{x}_{\text{obs}})} \]
At pre-selection:
Require 2 High-$P_T$ leptons ($e$ or $\mu$)

\[ P_T > 15 \text{ GeV} \ (e), \ 10 \text{ GeV} \ (\mu) \]

- $M_{\ell^+\ell^-} > 15 \text{ GeV}$
- $\mu\mu$: $N_{jets} < 2$, where $P_T^{jet} > 15 \text{ GeV}$ & $\Delta R(\mu, \text{jet}) > 0.1$

$M_{\ell^+\ell^-}$ spectrum from $ee$ channel →

<table>
<thead>
<tr>
<th>Pre-Selection</th>
<th>$ee$</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ee$</td>
<td>218695 ± 704</td>
<td>280.6 ± 3.3</td>
<td>-</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>-</td>
<td>274.6 ± 0.9</td>
<td>4235670 ± 158</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>1135 ± 16</td>
<td>3260 ± 3</td>
<td>1735 ± 10</td>
</tr>
<tr>
<td>$\text{tt}$</td>
<td>131.4 ± 1.4</td>
<td>272.0 ± 0.3</td>
<td>19.93 ± 0.05</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>241 ± 5</td>
<td>183 ± 4</td>
<td>214 ± 7</td>
</tr>
<tr>
<td>$WW$</td>
<td>172.2 ± 2.6</td>
<td>421.2 ± 0.1</td>
<td>159.0 ± 0.3</td>
</tr>
<tr>
<td>$WZ$</td>
<td>112.5 ± 0.2</td>
<td>20.5 ± 0.1</td>
<td>47.3 ± 0.5</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>98.2 ± 0.2</td>
<td>5.3 ± 0.1</td>
<td>40.5 ± 0.2</td>
</tr>
<tr>
<td>Signal ($M_H = 165 \text{ GeV}$)</td>
<td>9.45 ± 0.01</td>
<td>17.1 ± 0.01</td>
<td>5.43 ± 0.01</td>
</tr>
<tr>
<td>Total Background</td>
<td>221937 ± 707</td>
<td>4995 ± 168</td>
<td>238272 ± 159</td>
</tr>
<tr>
<td>Data</td>
<td>221530</td>
<td>4995</td>
<td>239923</td>
</tr>
</tbody>
</table>
DO $H \rightarrow WW$

Further cuts are then applied including cuts on

$$M_T^{\min}(\ell, \not{E_T}), E_T, M_{\ell\ell}, \Delta \phi_{\ell\ell}, N_{jets}(\mu\mu)$$

These cuts are optimized by individual channel for difference $m_H$

Dilepton azimuthal separation $\rightarrow$

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>(e\mu)</th>
<th>(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ee$</td>
<td>108 ± 14</td>
<td>0.0 ± 0.1</td>
<td>-</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>-</td>
<td>5.8 ± 0.1</td>
<td>3921 ± 22</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>1.4 ± 0.5</td>
<td>7.3 ± 0.1</td>
<td>66 ± 2</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>39.9 ± 0.8</td>
<td>272.0 ± 0.3</td>
<td>12.55 ± 0.04</td>
</tr>
<tr>
<td>$W + jets$</td>
<td>98.3 ± 3</td>
<td>78.6 ± 2.8</td>
<td>134 ± 5</td>
</tr>
<tr>
<td>$WW$</td>
<td>66.8 ± 1.6</td>
<td>154.7 ± 0.1</td>
<td>92.8 ± 0.3</td>
</tr>
<tr>
<td>$WZ$</td>
<td>9.68 ± 0.05</td>
<td>6.6 ± 0.1</td>
<td>19.4 ± 0.3</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>7.68 ± 0.07</td>
<td>0.60 ± 0.01</td>
<td>15.1 ± 0.1</td>
</tr>
<tr>
<td>Signal ($M_H = 165$ GeV)</td>
<td>6.13 ± 0.01</td>
<td>12.2 ± 0.1</td>
<td>4.85 ± 0.01</td>
</tr>
<tr>
<td>Total Background</td>
<td>332 ± 15</td>
<td>337 ± 10</td>
<td>4325 ± 24</td>
</tr>
<tr>
<td>Data</td>
<td>336</td>
<td>329</td>
<td>4084</td>
</tr>
</tbody>
</table>

Signal / Background

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>(e\mu)</th>
<th>(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>6.13 / 332</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e\mu)</td>
<td>12.2 / 337</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\mu\mu)</td>
<td>4.85 / 4325</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CDF $H \rightarrow WW$

CDF requires 2 high-$P_T$ leptons $P_T^1 > 20$, $P_T^2 > 10$ GeV and significant $E_T$

- Opposite and same charge $\ell$
- Separated by jet multiplicity
- Makes use of leading order matrix element based likelihood ratios (LR)

CDF Run II Preliminary

 Like Charge Leptons 0 Jets

Events / 5.0 GeV/c²

Dilepton Mass [GeV/c²]

OS 0 Jets

$M_H = 160$ GeV/c²

Cross checks (Same charge leptons)

- One of many orthogonal “regions”
- A good measure of $W\gamma$, $W+$jet predictions, and charge mis-ID

Several channels used: 0, 1, $\geq 2$ Jets, Same Charge
(Above: example from 0-Jet)
CDF \( H \rightarrow WW \)

1-jet Channel (right)
- In the 1-jet channel \( VH \) and \( VBF \) are more significant
- “Significant” \( E_T \) for 1-jet channel

\( \geq 2 \) jet channel (below)
- Veto events with secondary vertices to reduce \( t\bar{t} \)

**All Channels Combined**

CDF Run II Preliminary \( \int \mathcal{L} = 4.8 \text{ fb}^{-1} \)

\( M_H = 165 \text{ GeV}/c^2 \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Background</td>
<td>1541 ± 148</td>
</tr>
<tr>
<td>( gg \rightarrow H )</td>
<td>20.0 ± 2.9</td>
</tr>
<tr>
<td>( WH )</td>
<td>4.06 ± 0.53</td>
</tr>
<tr>
<td>( ZH )</td>
<td>1.50 ± 0.19</td>
</tr>
<tr>
<td>( VBF )</td>
<td>1.50 ± 0.24</td>
</tr>
<tr>
<td>Total Signal</td>
<td>27.1 ± 3.2</td>
</tr>
<tr>
<td>Data</td>
<td>1531</td>
</tr>
</tbody>
</table>

Dean Andrew Hidas, Rutgers, 16 July 2009