Search for High Mass SM Higgs at the Tevatron

Les Rencontres de Physique
de la Vallee D'Aoste
Mar. 6, 2009

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Fermilab
for the CDF and D0 Collaborations
SM Higgs Boson

- Direct Limit (LEP)
  \[ M_H > 114 \text{ GeV} \]

- Indirect Limit
  \[ M_H = 84^{+34}_{-26} \text{ GeV} \]

\[ M_H < 154 \text{ GeV @ 95\% CL} \]
Fermilab Tevatron

- $\bar{p}p$ collisions @ $\sqrt{s}=1.96$ TeV.
- CDF and D0 general purpose experiments.
Higgs Production and Decay at the Tevatron

- **Gluon Fusion**
- **Associated Production**
- **Vector Boson Fusion**

- $H \rightarrow WW$ dominant decay for $m_H > 135$ GeV (“high mass”).
- $H \rightarrow b\bar{b}$ dominant decay for $m_H < 135$ GeV (“low mass”).
Experimental Higgs Search Channels

High Mass

- $H \rightarrow WW \rightarrow \ell\ell$
- $WH \rightarrow WWW \rightarrow \ell^+\ell^+$
- $H \rightarrow \gamma\gamma$
- $WH \rightarrow \ell\nu\bar{b}b$
- $ZH \rightarrow \ell\ell\bar{b}b$
- $ZH \rightarrow \nu\nu\bar{b}b$
- $HX \rightarrow \tau\tau\bar{jj}$
- $VH \rightarrow b\bar{b}jj$
- $WH \rightarrow \tau\nu\bar{b}b$
- $ttH \rightarrow tt\bar{b}b$

Low Mass

Summer 2008 Tevatron
High Mass Combination

Winter 2008 Tevatron
Low + High Mass Combination
## Tevatron High Mass Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Integrated Luminosity (fb$^{-1}$)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer 2008</td>
<td>Winter 2009</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\ell$</td>
<td>CDF 3.0 D0 3.0</td>
<td>CDF 3.6 D0 3.0</td>
<td></td>
</tr>
<tr>
<td>$WH \rightarrow WWW \rightarrow \ell^+\ell^+$</td>
<td>CDF 1.9 D0 1.1</td>
<td>CDF 3.6 D0 1.1</td>
<td></td>
</tr>
</tbody>
</table>

- Additional results and new Tevatron combination expected soon.
$H \to WW$

- Most sensitive Higgs channel at the Tevatron.
  - Highest sensitivity around $M_H = 160$ GeV.

- Signature two high $p_T$ leptons ($\ell = e$ or $\mu$) and missing $E_T$.

- Backgrounds: $WW$, $WZ$, $ZZ$, $tt$, $W+\gamma$/jets, $Z \to \ell\ell$, $Z \to \tau\tau$, QCD.

- Strategies.
  - Good lepton id and missing $E_T$ resolution.
  - $WW$ is a fundamental physics background, and one of the largest backgrounds. Spin correlation ($\Delta\phi_{\ell\ell}$) is the best single variable for discriminating $H$ and $WW$.
  - All subchannels and both experiments make use of advanced multivariate techniques to get best possible signal / background discrimination.
$H \rightarrow WW$ Systematic Errors

- **Theoretical.**
  - Total cross sections ($H, WW, W+$jets).
  - Differential cross sections ($p_T(Z), p_T(W)$).
  - PDFs.

- **Simulation.**
  - Lepton / jet / missing $E_T$ energy scale & resolution.
  - Lepton id efficiencies.

- **Fake backgrounds / fake rates.**

- **Luminosity.**
Spin Correlation in $H \rightarrow WW$

- Leptons from $H \rightarrow WW \rightarrow \ell \ell$ tend to be emitted in the same direction (i.e. small $\Delta \phi(\ell, \ell)$).
Multivariate Analysis Techniques

- **Neural Networks (NN).**
  - Works well. Time-tested – have been used successfully for many years.

- **Boosted Decision Trees (BDT).**
  - Relatively recent. Popularity has grown enormously recently.

- **Matrix Element (ME).**
  - Highly efficient for specific signals / backgrounds.
  - Computationally costly.
  - Can be used as input to other techniques.
# $H \rightarrow WW$ Event Selection

<table>
<thead>
<tr>
<th>Leptons (preselection)</th>
<th>ee</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\mu) &gt; 10\text{ GeV}, p_T(e) &gt; 15\text{ GeV}, M_{\ell\ell} &gt; 15\text{ GeV}$</td>
<td>$E_T^T (\text{GeV})$</td>
<td>&gt;20</td>
<td>&gt;20</td>
</tr>
<tr>
<td>$E_T^T (\text{GeV})$</td>
<td>$E_T^{\text{Scaled}}$</td>
<td>&gt;7</td>
<td>&gt;6</td>
</tr>
<tr>
<td>$M_{T\min} (\ell, E_T) (\text{GeV})$</td>
<td>&gt;20</td>
<td>&gt;30</td>
<td>&gt;20</td>
</tr>
<tr>
<td>$\Delta \phi(\ell, \ell)$</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
<td>&lt;2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$e\mu$ pre-selection</th>
<th>$e\mu$ final</th>
<th>ee pre-selection</th>
<th>ee final</th>
<th>$\mu\mu$ pre-selection</th>
<th>$\mu\mu$ final</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ee$</td>
<td>209.0 ± 3.0</td>
<td>0.72 ± 0.16</td>
<td>160463 ± 264</td>
<td>73.6 ± 5.1</td>
<td>-</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>151.1 ± 0.6</td>
<td>2.14 ± 0.06</td>
<td>-</td>
<td>-</td>
<td>256432 ± 230</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>2312 ± 2</td>
<td>2.45 ± 0.05</td>
<td>835 ± 8</td>
<td>1.0 ± 0.3</td>
<td>1968 ± 11</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>187.5 ± 0.2</td>
<td>54.2 ± 0.1</td>
<td>96.9 ± 0.2</td>
<td>28.5 ± 0.1</td>
<td>19.4 ± 0.1</td>
</tr>
<tr>
<td>$W + jets$</td>
<td>163.4 ± 5.3</td>
<td>60.1 ± 3.2</td>
<td>174 ± 7</td>
<td>72.0 ± 4.3</td>
<td>149 ± 3</td>
</tr>
<tr>
<td>$WW$</td>
<td>285.6 ± 0.1</td>
<td>108.0 ± 0.1</td>
<td>127.5 ± 0.4</td>
<td>45.7 ± 0.2</td>
<td>162.9 ± 0.5</td>
</tr>
<tr>
<td>$WZ$</td>
<td>14.8 ± 0.1</td>
<td>4.9 ± 0.1</td>
<td>89.6 ± 0.8</td>
<td>7.6 ± 0.2</td>
<td>51.6 ± 0.5</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>3.47 ± 0.01</td>
<td>0.49 ± 0.01</td>
<td>73.5 ± 0.3</td>
<td>5.4 ± 0.1</td>
<td>43.0 ± 0.2</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>190 ± 168</td>
<td>1 ± 8</td>
<td>2322 ± 193</td>
<td>4.3 ± 8.3</td>
<td>945 ± 31</td>
</tr>
<tr>
<td>Signal ($m_H = 160\text{ GeV}$)</td>
<td>9.0 ± 0.1</td>
<td>6.9 ± 0.1</td>
<td>4.40 ± 0.01</td>
<td>3.49 ± 0.01</td>
<td>4.7 ± 0.1</td>
</tr>
<tr>
<td>Total Background</td>
<td>3516 ± 168</td>
<td>234 ± 9</td>
<td>164181 ± 327</td>
<td>238 ± 11</td>
<td>259770 ± 232</td>
</tr>
<tr>
<td>Data</td>
<td>3706</td>
<td>234</td>
<td>164290</td>
<td>236</td>
<td>263743</td>
</tr>
</tbody>
</table>
Neural network analysis makes use of 14 input variables.
$H \rightarrow WW$ Result

- Upper limit on $\sigma \times$BR set using entire NN output distribution for all channels using modified frequentist method (CLs method).

Expected limit is $2.1$ times SM at $M_H = 160$ GeV
$H \rightarrow WW$ Event Selection

<table>
<thead>
<tr>
<th>Leptons</th>
<th>$ee$</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{T1} &gt; 20$ GeV, $p_{T2} &gt; 10$ GeV, $M_{\ell\ell} &gt; 16$ GeV</td>
<td>$&gt; 25$</td>
<td>$&gt; 15$</td>
<td>$&gt; 25$</td>
</tr>
<tr>
<td>$E_{T\text{spec}}$ (GeV)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$E_{T\text{spec}} = E_T \sin\{\min[\pi/2, \Delta\phi(E_T, \ell j)]\}$

- Separate NN analysis for 0, 1, and $\geq 2$ jets.
- 1 and 2 jets includes VBF and VH contributions to signal.
- Also separate NN analysis for high and low S/B events based on lepton quality for 0 and 1 jets.
**H→WW 0 jets NN Analysis**

- Neural network analysis makes use of 5 input variables, including $\Delta\phi_{\ell\ell}$ and $H$ vs. $WW$ matrix element likelihood ratio (LRHWW).
- Separate NN for high and low S/B lepton id.
$H\rightarrow WW$ 1 jets NN Analysis

- Neural network analysis makes use of 8 input variables (LRHWW not included for $>0$ jets).
- Separate NN for high and low S/B lepton id.
**$H \rightarrow WW$ 2+ jets NN Analysis**

- Neural network analysis makes use of 8 input variables.
- High and low S/B lepton id not used for $\geq 2$ jets.

<table>
<thead>
<tr>
<th>CDF Run II Preliminary $\int L = 3.6 \text{ fb}^{-1}$</th>
<th>$M_H = 160 \text{ GeV/c}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$100 \pm 17$</td>
</tr>
<tr>
<td>$DY$</td>
<td>$33 \pm 11$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$17.6 \pm 4.0$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$3.76 \pm 0.52$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$1.62 \pm 0.22$</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>$14.7 \pm 4.0$</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$2.12 \pm 0.70$</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td><strong>$173 \pm 23$</strong></td>
</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td>$1.75 \pm 0.30$</td>
</tr>
<tr>
<td>$WH$</td>
<td>$1.39 \pm 0.18$</td>
</tr>
<tr>
<td>$ZH$</td>
<td>$0.693 \pm 0.090$</td>
</tr>
<tr>
<td>$VBF$</td>
<td>$0.70 \pm 0.11$</td>
</tr>
<tr>
<td><strong>Total Signal</strong></td>
<td><strong>$4.53 \pm 0.52$</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>169</strong></td>
</tr>
</tbody>
</table>
H → WW Result

- Upper limit on $\sigma \times$BR obtained likelihood fit of all five NN output distributions.

Expected limit is 1.48 times SM at $M_H = 160$ GeV
\[ WH \rightarrow WWW \rightarrow \ell^+ \ell^+ \]

- Signature two like-sign high \( p_T \) leptons (\( \ell = e \) or \( \mu \)).
- Smaller \( \sigma \times \text{BR} \) than \( H \rightarrow WW \) but very low SM background.
- Backgrounds: \( WZ, ZZ, W^+\gamma/\text{jets}, \text{QCD}, \) charge flips.
  - Instrumental backgrounds (fakes and charge flips) are dominant.
**WH → WWW → ℓ⁺ ℓ⁺**

- Event selection: $p_T(e) > 15$ GeV, $p_T(μ) > 15$ GeV.

- Upper limit on $σ×BR$ from 2D multivariate likelihood fit.
  - Expected limit is 17 times SM at $M_H = 160$ GeV.
$WH \rightarrow WWW \rightarrow \ell^+ \ell^+$

- Event selection: $p_T^{l_1} > 20$ GeV, $p_T^{l_2} > 20$ GeV.
- Multivariate analysis using 13-variable NN.
  - Expected limit is 7.2 times SM at $M_H = 160$ GeV.
Tevatron High Mass Combination

- CDF and D0 results from $WW$ and $WWW$ channels are combined into single Higgs limit.
  - Bayesian and modified frequentist (CLs) methods using LLR test statistic.
    \[
    LLR(M_H) = -2 \ln \frac{p(data|M_H)}{p(data|Null)}
    \]
  - Correlated systematic errors taken into account.

- Most recent high mass combination includes results from summer 2008.
Tevatron High Mass Combination Result

SM Higgs excluded at 95% CL for $M_H = 170$ GeV
Updated High Mass Combination Preview

2xCDF Run II Preliminary, L=3.6 fb$^{-1}$

95% CL Limit/SM

$\mu_{H}(\text{GeV}/c^2)$

February 26, 2009
\[ H \rightarrow \gamma\gamma \]

- Low branching ratio, but sensitive in intermediate mass range.
  - Flat sensitivity for intermediate mass \( M_H \sim 120–130 \text{ GeV} \).
  - Sensitive to gluon fusion production for low \( M_H \).
  - Fermiphobic interpretation also available.

- Signature two high \( p_T \gamma \)'s.

- Backgrounds: \( Z/\gamma^* \rightarrow ee, \gamma + \text{jets, dijet, nonresonant } \gamma\gamma \).
  - Nonresonant \( \gamma\gamma \) is irreducible physics background.

- Strategies.
  - Good photon id.
    - Need best possible rejection of \( e \rightarrow \gamma \) and jet \( \rightarrow \gamma \) fake photons.
  - Look for narrow invariant mass peak.
$H \rightarrow \gamma\gamma$ Event Selection

- Require tight photon id and $p_T > 25$ GeV and $|\eta| < 1.1$. 

![Graph](image1)

![Graph](image2)
\[ H \to \gamma\gamma \text{ Result} \]

- Limit extracted using expected lineshape.
  - Use sidebands around \( M_H \pm 15 \text{ GeV} \) to fix background normalization.

- Expected limit is 18.3 times SM at \( M_H = 130 \text{ GeV} \).
- Observed limit is 13.1 times SM at \( M_H = 130 \text{ GeV} \).
Prospects

- Tevatron and experiments are running well.
- Experiments have ~6 fb\(^{-1}\) delivered today (~5.3 fb\(^{-1}\) recorded).
- Expect 8-9 fb\(^{-1}\) of integrated luminosity per experiment delivered (7-8 fb\(^{-1}\) recorded) by end of FY10 (more if Tevatron runs in 2011).
- Analysis improvements will likely improve Higgs sensitivity faster than luminosity scaling.
Summary

- SM Higgs excluded at 95% CL at $M_H=170$ GeV.
- Updated results with up to 4 fb$^{-1}$ and updated Tevatron combination are expected soon.
- Tevatron and experiments are continuing to run well.
  - CDF and D0 currently have recorded about 5 fb$^{-1}$ of data.
  - Expect 7–8 fb$^{-1}$ or more of analyzed data eventually.
Backup Slides
CDF Detector

Tracking
Solenoid magnet
Silicon vertex detector
Wire drift chamber
$|\eta| < 2.5$

Calorimeter
$|\eta| < 4$

Muon system
$|\eta| < 1.5$
D0 Detector

- **Tracking**
  - Solenoid magnet
  - Silicon vertex detector
  - Scintillating fiber tracker
  - $|\eta| < 3$

- **LAr-U Calorimeter**
  - $|\eta| < 4$

- **Muon system**
  - $|\eta| < 2$

- 5000 tons

H. Greenlee  
LaThuile 2009
### $H\to WW$ Systematic Errors

<table>
<thead>
<tr>
<th>Systematic Error</th>
<th>Signal (%)</th>
<th>Background (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale &amp; Resolution</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Lepton ID Efficiency</td>
<td>5.7–8</td>
<td>5.7–8</td>
</tr>
<tr>
<td>Jet ID Efficiency</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Theory $\sigma'$s</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>$p_T(Z)$</td>
<td></td>
<td>1–5</td>
</tr>
<tr>
<td>$p_T(W)$</td>
<td>6.8</td>
<td>3</td>
</tr>
<tr>
<td>PDFs</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Fake backgrounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>
### $H \rightarrow WW$ Systematic Errors

<table>
<thead>
<tr>
<th>Systematic Error</th>
<th>Signal (%)</th>
<th>Background (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>4.6–8.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Lepton Energy Scale</td>
<td>2.5–3.1</td>
<td></td>
</tr>
<tr>
<td>Lepton ID &amp; trigger efficiency</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Missing $E_T$ modeling</td>
<td>1</td>
<td>1–5</td>
</tr>
<tr>
<td>$\gamma$ Conversion modeling</td>
<td>20 ($W\gamma$)</td>
<td></td>
</tr>
<tr>
<td>Theory $\sigma$'s</td>
<td>12</td>
<td>5–10</td>
</tr>
<tr>
<td>PDFs</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Fake backgrounds</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>5.9</td>
<td>5.9</td>
</tr>
</tbody>
</table>
Tevatron High Mass Combination
90% and 95% CL Exclusions