Combined Limit on Standard Model Higgs Production at CDF

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- Introduction
- Brief Review Higgs Results with 1 fb$^{-1}$
- Combination Procedures and Systematics
- Combination Results
- Future Prospects
- Conclusions
Introduction

- The cornerstone of Standard Model is electroweak symmetry breaking (EWSB).
- SM predicts the existence of Higgs boson, but requires “new physics” to stabilize its mass (the hierarchy problem).
- Without it, the W, Z bosons would be massless.
- Precision tests of electroweak theory show no signs of deviation and predict a low mass Higgs boson.
- Possible source of new physics:
  - SUSY and its variants
  - Extra dimensions
  - Little Higgs ($m_h \approx m_t$, t’ and other Higgs at TeV scale)
  - Higgsless ...
- Experimental inputs are crucial for determining the future directions (Tevatron, LHC, ILC...)

Higgs Mass Limit

- Global fit to electroweak data with latest $M_{top} = 171.4 \pm 2.1$ GeV/c$^2$
- Best fit of $M_h = 85^{+39}_{-28}$, or $M_h < 166$ GeV/c$^2$ at 95% C.L.
- LEP excludes $M_h \leq 114.4$ GeV at 95% C.L.
- The Higgs boson remains elusive, but the data prefers a low mass Higgs that the discovery may be just in the corner.
Higgs Production and Search Strategies

- \( M_h < 130 \text{ GeV}: h \rightarrow b\bar{b} \)
  - \( Wh, Zh \) are most accessible, easy to trigger
  - Excellent b-tag efficiency and dijet mass resolution

- \( M_h > 130 \text{ GeV}: h \rightarrow WW^* \)
  - Exploit the large \( \sigma(gg \rightarrow h) \)
  - Identify clean final states with leptons

- Very Challenging...
Run2 Performance

- Tevatron are doing well. The record peak luminosity exceeded $2.3 \times 10^{32} cm^{-2}s^{-1}$

- CDF recorded $\geq 1.5 \text{ fb}^{-1}$ on tape, but results shown here mostly based on $\approx 1 \text{ fb}^{-1}$, up to Feb. 2006.

- Total expected int luminosity 4 - 8 fb$^{-1}$ in 2009
Recent CDF Run2 Higgs Results

- CDF have reported direct searches for SM Higgs production in many different final states with sufficient integrated luminosity ($\approx 1 fb^{-1}$)
  
  - Search for SM Higgs Boson in WH at CDF [360] (Yoshiaki Kusakabe)
  - Higgs Search in the $ZH \rightarrow l^+l^-bb$ at CDF [462] (Jonathan Efron)
  - Search for SM Higgs in $ZH \rightarrow b\bar{b} + E_T$ at CDF [365] (Viktor Veszpremi)
  - $gg \rightarrow H \rightarrow W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$: 360 pb$^{-1}$

- A combination limit would significantly improve the individual limits for CDF

- Apologized for not including $ttH \rightarrow ttbb$, $WH \rightarrow WWW$, $H \rightarrow \tau^+\tau^-$ this time. Will do next around for sure.
Selecting $P_T(\text{lepton}) > 20$, $E_T > 20$ GeV, 2jet

- Divide one NN b-tagged jets and double secvtx tagged jets
- Events agree with the expectation.
$Z H \rightarrow \nu \bar{\nu} b \bar{b}$

- Veto leptons, $E_T > 55$ GeV, $E_{j1(j2)} > 35(20)$ GeV, b-tagging.
- Significant contributions from $WH \rightarrow l \nu b \bar{b}$ where lepton is missing
- Events agree with the expectation.
$ZH \rightarrow l^+l^-b\bar{b}$

- Selecting $Z \rightarrow l^+l^-$ and $H \rightarrow b\bar{b}$

- Fully reconstructed events and neural network in 2-d to reject $Z+\text{jets}$ and $t\bar{t}$ backgrounds.

- Events agree with the expectation.
$WW \rightarrow l^+l^- \nu \bar{\nu}$

- Take full advantage of large $\sigma(gg \rightarrow h)$
- Two high pt isolated lepton (e or $\mu$) + large $E_T$
- Major background: $W^+W^-$ production
- Exploit spin correlations of $h \rightarrow W^+W^-$
Summary of Tevatron Higgs Results

- What we measure: the ratio of 95% upper limit on Xsec times branching ratio to SM.
- Assume the ratio the same for different channels, so we can combine them statistically.
- 10% is assigned to $g \rightarrow H \rightarrow W^+W^-$ cross section (NNLO).
# Systematic Uncertainties for Combination

<table>
<thead>
<tr>
<th>Channels</th>
<th>$l\nu\bar{b}b$</th>
<th>$\nu\bar{b}b$</th>
<th>$l^+l^-\bar{b}b$</th>
<th>$W^+W^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single</td>
<td>Double</td>
<td>Single</td>
<td>Double</td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Luminosity (%)</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
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<tr>
<td>$b$tag SF (%)</td>
<td>5.3</td>
<td>16.0</td>
<td>8.0</td>
<td>16.0</td>
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<tr>
<td>Lepton ID (%)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>JES (%)</td>
<td>3.0</td>
<td>3.0</td>
<td>(1-20)</td>
<td>(1.6-20)</td>
</tr>
<tr>
<td>MC modeling (%)</td>
<td>4.0</td>
<td>10.0</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Trigger (%)</td>
<td>0.0</td>
<td>0.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Shapes (%)</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td><strong>Backgrounds</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mistag (%)</td>
<td>22</td>
<td>15</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>QCD (%)</td>
<td>17</td>
<td>20</td>
<td>-10</td>
<td>-44</td>
</tr>
<tr>
<td>$W/Z+HF(I)$ (%)</td>
<td>33</td>
<td>34</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>$W+HF(II)$ (%)</td>
<td>0</td>
<td>0</td>
<td>-10</td>
<td>-42</td>
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<tr>
<td>$Z+HF(II)$ (%)</td>
<td>0</td>
<td>0</td>
<td>-6</td>
<td>-19</td>
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<tr>
<td>Top(I) (%)</td>
<td>13.5</td>
<td>20</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Top(II) (%)</td>
<td>0.</td>
<td>0.</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>Diboson(I) (%)</td>
<td>16</td>
<td>25</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Diboson(II) (%)</td>
<td>0</td>
<td>0</td>
<td>-5</td>
<td>-10</td>
</tr>
<tr>
<td>Other (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- The positive value means correlated, the negative value means uncorrelated
- The results seems insensitive to these correlations changing from 100% to 0%
Special Treatment Shape Uncertainties

- For $ZH \rightarrow l^+ l^- b\bar{b}$ with neural network analysis, there is additional systematic uncertainties due to the background shape.

- Estimated the limit change using pseudo-experiment with one shape against another.

- Either implemented as additional systematic on the signal or random sampling two shapes ($alpgen*\text{random} + (1-\text{random})*\text{pytha}$).

- Both give almost identical upper limit.
Technique for Limit Combination

- Bayesian framework
  - Use Bayesian posterior probability
  - Assume flat prior density for the number of Higgs events

- Combined Binned Poisson Likelihood:
  \[
  \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) = \prod_{i=1}^{N_C} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} / n_{ij}!
  \]

- Combined Posterior Density Function:
  \[
  p(R|\vec{n}) = \int d\vec{s} \int d\vec{b} \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) \times s_{tot} / \int dR \int d\vec{s} \int d\vec{b} \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) \times s_{tot}
  \]

- 95% Credibility Upper Limit \( R_{95} \):
  \[
  \int_0^{R_{95}} p(R|\vec{n})dR = 0.95.
  \]
Likelihood of Combined Fit

- Likelihood vs R as $M_H$ (red line: 95% upper limit).
Pseudo-experiments

- The observed upper limit shown as in arrow in red, consistent with expectation.
- There are some excesses in both $WH \rightarrow l\nu b\bar{b}$ and $ZH \rightarrow \nu\bar{\nu} b\bar{b}$ single tags near 100 GeV, but not statistical significant yet.
Effect of the Correlation

<table>
<thead>
<tr>
<th>Mass (GeV/c^2)</th>
<th>Combined Limits (pb)</th>
<th>Expected Limits (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlated</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>110</td>
<td>14.2</td>
<td>13.8</td>
</tr>
<tr>
<td>115</td>
<td>12.8</td>
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<td>120</td>
<td>11.8</td>
<td>11.8</td>
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<td>130</td>
<td>11.8</td>
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<td>140</td>
<td>14.8</td>
<td>14.8</td>
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<tr>
<td>150</td>
<td>11.2</td>
<td>11.2</td>
</tr>
<tr>
<td>160</td>
<td>10.2</td>
<td>10.2</td>
</tr>
<tr>
<td>170</td>
<td>12.2</td>
<td>12.2</td>
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<tr>
<td>180</td>
<td>18.2</td>
<td>18.2</td>
</tr>
<tr>
<td>200</td>
<td>40.8</td>
<td>40.8</td>
</tr>
</tbody>
</table>

- There are small effects on the limit due to the correlations.
CDF Combined Limit

CDF II Preliminary

95% CL Limit/SM

CDF Combined: 0.4-1 fb-1

Expected CDF ± 1σ

D0 combined: 0.3-1 fb-1

Higgs Mass (GeV/c²)

CDF Combined Limit

WH->lvbb: 1 fb-1

Expected WH->lvbb

ZH->vvbb: 1 fb-1

Expected ZH->vvbb

ZH->llbb: 1 fb-1

Expected ZH->llbb

H->WW->llvv: 0.4 fb-1

Expected H->WW->llvv

H->WW->llvv: 1 fb-1

Expected H->WW->llvv

0.4 fb-1

1 fb-1

10

100

1000
Future Prospects

- The combined limit is very close to what we expected from the Higgs sensitivity report

- **Future improvements**
  - Including lepton acceptance with forward electron and muons
  - Including $\tau$-leptons with isolated track
  - Improved tracking and $b$-tagging in the large $\eta$ region
  - Improving jet resolution with tracking
  - Improving analysis techniques
    * Neural Network, Matrix-elements …
    * better Monte Carlo modeling and better optimization
  - Of course, there will be lots of data on the way

- Recent top mass measurements and observation of $B_s$ mixing are few success stories of CDF

- With some luck, the Higgs discovery may be the next…
We are One Step Closer… !

Tevatron Run II Preliminary

\[ \int_{Ldt=0.3-1.0 \text{ fb}^{-1}} \]

- LEP Excluded
- Run1 CDF Expected
- Run1 CDF Observed (0.1 fb\(^{-1}\))
- D0 Expected
- CDF Expected
- Tevatron Expected
- Tevatron Observed

95\% CL Limit/SM

Higgs Mass (GeV/c\(^2\))
Conclusion

- We obtain a combined Higgs limit from cdf with a data sample of 1 fb$^{-1}$ using Bayesian method.
  
  - $WH \rightarrow l\nu b\bar{b}$
  - $ZH \rightarrow \nu\bar{\nu} b\bar{b}$
  - $ZH \rightarrow l^+ l^- b\bar{b}$
  - $gg \rightarrow H \rightarrow WW \rightarrow l^+ l^- \nu\bar{\nu}$

- Observed limits are mostly consistent with the expectation of Pseudo-experiments, except at $m_h=110$, which seems there are some excess of events in both $WH \rightarrow l\nu b\bar{b}$ and $ZH \rightarrow \nu\bar{\nu} b\bar{b}$ single tag channel.

- The 95% CL upper observed (expected) limits are a factor of 12.8(9.1) and 10.2(11.4) away from the Standard Model cross section for Higgs mass at 115 and 160 GeV/c$^2$

- The future looks very promising and it’s up to us how far we want to push before LHC.