Higgs Searches at the Tevatron

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on behalf of the CDF and D0 Collaborations

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EPS - HEP 2011
Higgs Boson in SM

- Higgs field is the SM mechanism for electroweak symmetry breaking
- The mass of Higgs boson is not predicted (must be determined experimentally)
- Combination of direct constraints from LEP and indirect constraints from precision EWK data indicates $m_H$ in range accessible to Tevatron

Excluded by direct searches at LEP
Potentially observable at Tevatron
Over 10 fb⁻¹ on tape!

- Expect > 10 fb⁻¹ analyzable data by end of September
Tevatron Detectors

CDF II Detector

DØ Detector
Higgs Decay

- Low Mass
  - Focus on $H \rightarrow bb$
  - Also $H \rightarrow \tau\tau$ and $H \rightarrow \gamma\gamma$
- High Mass
  - Focus on $H \rightarrow WW$
  - Also $H \rightarrow ZZ$

Cross-Over Point
$(m_H \sim 135 \text{ GeV})$
Higgs Production at Tevatron

SM Higgs production

<table>
<thead>
<tr>
<th>Process</th>
<th>σ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg → h</td>
<td>10^3</td>
</tr>
<tr>
<td>qq → Wh</td>
<td>10^2</td>
</tr>
<tr>
<td>qq → qqh</td>
<td>10^2</td>
</tr>
<tr>
<td>bb → h</td>
<td>10^2</td>
</tr>
<tr>
<td>gg,qq → tth</td>
<td>10</td>
</tr>
<tr>
<td>qq → Zh</td>
<td>1</td>
</tr>
</tbody>
</table>

TeV4LHC Higgs working group
## Higgs Search Challenge

Expected number of events per fb\(^{-1}\) per experiment

<table>
<thead>
<tr>
<th>Higgs Mass (GeV/c(^2))</th>
<th>WH(\rightarrow)lvbb</th>
<th>ZH(\rightarrow)vvbb</th>
<th>ZH(\rightarrow)llbb</th>
<th>H(\rightarrow)WW(\rightarrow)lvlv</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>25</td>
<td>12</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>135</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>150</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>32</td>
</tr>
</tbody>
</table>

reconstruction/selection/tagging efficiencies ~ 10% in H\(\rightarrow\)bb channels and ~25% in H\(\rightarrow\)WW channels
Higgs Search Strategy

• Select inclusive candidate samples that preserve the maximum possible acceptance to a potential Higgs signal
• Separate these samples into multiple analysis channels to isolate potential signal events in high S/B regions
• Carefully model all backgrounds and cross check using control regions in data
• Use advanced multivariate analysis tools to separate signal from background based on the full event kinematics
Event Selection

- Need to maximize signal acceptance
- Three main areas of focus:
  1. Increasing lepton reconstruction and selection efficiencies
  2. Improving the efficiency for tagging b-quark jets
  3. Optimizing dijet mass resolution

Pre-tagged events
Event Selection

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- Three main areas of focus:
  1. Increasing lepton reconstruction and selection efficiencies
  2. Improving the efficiency for tagging b-quark jets
  3. Optimizing dijet mass resolution

Single b-tagged events
Event Selection

- Need to maximize signal acceptance
- Three main areas of focus:
  1. Increasing lepton reconstruction and selection efficiencies
  2. Improving the efficiency for tagging b-quark jets
  3. Optimizing dijet mass resolution

Double b-tagged events
Maximizing Sensitivity

- We optimize search sensitivity by dividing events into multiple analysis channels.
- This allows us to use separate, optimized discriminants for each channel based on
  - specific signal contributions
  - specific background contributions
  - specific event kinematics

H\rightarrow WW\rightarrow l\nu l\nu

0 jet

1 jet

2+ jets
SM Backgrounds

- Need to separate small potential signal from large SM background contributions in our search channels
- For example, applying minimal selection criteria $S/B \sim 0.015$ in our most sensitive search channels
- Background modeling carefully checked in data control regions
Improving S/B

• In order to improve S/B need to utilize full kinematic event information
• Multi-variant techniques are used to maximize search sensitivities
  – Neural Networks
  – Boosted Decision Trees
  – Matrix Element Calculations
• Typically these add 10-20% in sensitivity beyond that obtained from optimized, cut-based analysis
Improving S/B

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Combining Channels

- Our goal is to leave no Higgs events behind
- Best sensitivity is obtained through the combination of many independent search channels

| WH → lvbb |
| ZH → vvbb |
| ZH → llbb |
| WH/ZH → jjbb |
| ttH → WbWbbb |
| H → γγ |
| H → ττ |
| WH → lvττ / ZH → llττ |
| H → WW → lvlv |
| H → WW → lvjj |
| WH → WWW / ZH → ZWW |
| H → ZZ |
Combining Channels

- Our goal is to leave no Higgs events behind
- Best sensitivity is obtained through the combination of many independent search channels
Validation of Search Techniques

- Diboson cross section measurements based on the same tools and data samples used for the $H \rightarrow WW \rightarrow l\nu l\nu$ search provide an important cross check on our background modeling and analysis techniques.

$$\text{WW} \rightarrow l\nu l\nu : \sigma(\text{WW}) = 12.1^{+1.8}_{-1.7} \text{ pb}$$
Validation of Search Techniques

- Diboson cross section measurements based on the same tools and data samples used for the $H \rightarrow WW \rightarrow l\nu l\nu$ search provide an important cross check on our background modeling and analysis techniques.

$$ZZ \rightarrow l\nu l\nu : \sigma(ZZ) = 1.45^{+0.60}_{-0.51} \text{ pb}$$

CDF Run II Preliminary

FIT RESULT

<table>
<thead>
<tr>
<th>Events</th>
<th>220</th>
<th>200</th>
<th>180</th>
<th>160</th>
<th>140</th>
<th>120</th>
<th>100</th>
<th>80</th>
<th>60</th>
<th>40</th>
<th>20</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN Output</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td>0</td>
<td>-0.2</td>
<td>-0.4</td>
<td>-0.6</td>
<td>-0.8</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

$L dt = 5.9 \text{ fb}^{-1}$
Validation of Search Techniques

- Similarly, search for semi-leptonic diboson production in the $l\nu bb$, $\nu\nu bb$, and $l\nu bb$ final states to validate our $H\rightarrow bb$ analysis techniques.

- Final test is to observe $WZ/ZZ (Z\rightarrow bb)$ production by combining CDF and D0 searches in all three final states.

$$\sigma(WW/WZ\rightarrow l\nu cs/l\nu bb) = 1.08^{+0.26}_{-0.40} \times SM (3.0\sigma)$$
Validation of Search Techniques

- Similarly, search for semi-leptonic diboson production in the $l\nu bb$, $\nu\nu bb$, and $ll bb$ final states to validate our $H\rightarrow bb$ analysis techniques
- Final test is to observe $WZ/ZZ (Z\rightarrow bb)$ production by combining CDF and D0 searches in all three final states

$$\sigma(WZ/ZZ\rightarrow \nu\nu bb) = 1.5 \pm 0.5 \times \text{SM (2.8}\sigma)$$
Systematic Uncertainties

- We consider uncertainties both on the overall normalization of each signal/background process and on the shapes of the final discriminant templates for each signal/background process.
- In the limit-setting procedure systematics are included as nuisance parameters, taking into account the correlations between different channels.

Using this approach we are able to further constrain our background uncertainties directly from the data.
Theoretical Uncertainties

• Since we combine searches focusing on different Higgs production and decay modes, cross section limits are given with respect to nominal SM predictions
• This forces us to incorporate theoretical predictions and uncertainties for signal cross sections and branching ratios
• Changed in each iteration to reflect recent theoretical developments

<table>
<thead>
<tr>
<th>channel</th>
<th>scale 0</th>
<th>scale 1</th>
<th>scale 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 jet</td>
<td>13.4%</td>
<td>-23.0%</td>
<td>-</td>
</tr>
<tr>
<td>1 jet</td>
<td>-</td>
<td>35.0%</td>
<td>-12.7%</td>
</tr>
<tr>
<td>2+ jets</td>
<td>-</td>
<td></td>
<td>33.0%</td>
</tr>
</tbody>
</table>

Berger et al., arXiv:1012.4480v2

Stewart and Tackmann, arXiv:1107.2117v1
Combined Discriminants

**Tevatron Run II Preliminary, \( L \leq 8.6 \text{ fb}^{-1} \)**

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

\[ \log_{10}(s/b) \]

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

7/27/11
Combined Discriminants

Tevatron Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

$\mathbf{m_H = 140 \text{ GeV/c}^2}$

CDF + D0 Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

$\mathbf{m_H = 140 \text{ GeV/c}^2}$

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Combined Discriminants

Tevatron Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

$\mu_H = 115$ GeV/c$^2$

CDF + D0 Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

$m_H = 115$ GeV/c$^2$

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Limit Plot Example

Upper cross section limit for Higgs production relative to SM prediction

Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

Analysis repeated using different signal templates for each $m_H$ between 100 and 200 GeV in 5 GeV steps
CDF/D0 Limits

CDF Run II Preliminary, $L \leq 8.2 \text{ fb}^{-1}$

95% CL Limit/SM

CDF Exclusion

LEP Exclusion

Expected

Observed

$\pm 1\sigma$ Expected

$\pm 2\sigma$ Expected

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

100 110 120 130 140 150 160 170 180 190 200

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DØ Preliminary, $L=4.3-8.6 \text{ fb}^{-1}$

SM Higgs Combination

95% CL Limit/SM

Expected

Observed

$\pm 1\sigma$ Expected

$\pm 2\sigma$ Expected

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

100 110 120 130 140 150 160 170 180 190 200

SM = 1.0

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CDF

D0
New Tevatron Combination

Observed Exclusion: 100-109 and 156-177 GeV/c²
Expected Exclusion: 100-108 and 148-181 GeV/c²
S+B versus B-only Hypotheses

Tevatron RunII Preliminary
L=4.3-8.6 fb^{-1}

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Fourth Generation Interpretation

- We also interpret our high mass search results in terms of a fourth generation model.
- Presence of additional quarks enhances $gg \rightarrow H$ production by as much as a factor of nine - also modifies Higgs branching ratios.
- Observed exclusion: $124 < m_H < 286$ GeV.
Final Steps

- We continue to obtain large improvements in search sensitivity beyond that expected from simply adding more data.
- Tevatron is on track to deliver Higgs search results next spring based on the full 10fb$^{-1}$ datasets that achieve our expected sensitivity goals.
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Final Steps

- This implies Tevatron 95% C.L. exclusion sensitivity over the entire Higgs mass range between 100 and 185 GeV/c² for next spring
• This channel provides best sensitivity in the mass region just above the LEP bounds

• Observation of this decay mode is important for establishing that a Higgs-like signal found in other channels is in fact the SM Higgs
Fermiophobic Higgs

- Fermiophobic Higgs is not accessible though the dominant gluon fusion production mode
- CDF sets world-best lower mass limit of 114.8 GeV/c² pending soon to be completed combination with D0
Pursuing interesting broad excesses observed by both CDF and D0 in $b\Phi \rightarrow bbb$ search channel
Conclusions and Outlook

• Expect to collect over 10 fb$^{-1}$ of analyzable data by the end of September 2011
• On track to reach 95% C.L. exclusion sensitivity over entire $m_H$ range from 100 to 185 GeV/c$^2$ by next spring
• Best current sensitivity to $b\bar{b}$ Higgs decay mode
• Looking forward to a very interesting next six months
Updated Global EWK Fit

CL$_S$ Plot

Tevatron RunII Preliminary

$L \leq 8.6$ fb$^{-1}$

CL$_S$ Observed

CL$_S$ Expected

Expected ±1 $\sigma$

Expected ±2 $\sigma$

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$m_H$ (GeV/c$^2$)

1$\sigma$

2$\sigma$

3$\sigma$
Confidence Levels

Tevatron Run II Preliminary, $L \leq 8.6 \text{ fb}^{-1}$

Limit/SM vs. $m_H$ (GeV/c$^2$)

- 99.5% CL
- 99% CL
- 95% CL
- 90% CL
- 68% CL

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Comparison with ATLAS
Current Exclusions

Summary of Collider SM Higgs Exclusions

LEP
FNAL
ATLAS
CMS
All

$M_H$ (GeV)

7/27/11
Run, Event: 196170, 6577
Dijet Mass: 126.44 GeV/c²
Z Mass: 97.94 GeV/c²
N Jets: 2
MET: 10.12 GeV
ZH NN: 0.94, tt NN: 8.5 x 10⁻⁴
S/B @ 115 GeV/c²: 0.25

Jet 1
$P_T$ 124.9 GeV/c

Jet 2
$P_T$ 29.0 GeV/c

Lepton 1
$P_T$ 102.1 GeV/c

Lepton 2
$P_T$ 54.8 GeV/c
Z-Jet Balancing: Jet QG Value

CDF Run II Preliminary, ∫L = 6.6 fb⁻¹

- Data - Fakes
- MC, JES 0
- MC, JES -2σ (Gluons)
- MC, JES -1σ (All)

Jet QG Value

Gluon-like

Quark-like