Final Combination of CDF’s Searches for the Higgs Boson

in the Standard Model and Extensions

Tom Junk
Fermilab

On behalf of the CDF Collaboration

Joint Experimental-Theoretical Physics Seminar
January 18, 2013
Tevatron Performance

Proton-antiproton collisions with
Run I: 1988 – 1996 : CDF Collects over 100 pb\(^{-1}\) of data at \(E_{\text{CM}} = 1.8\) TeV
Run II: 2001 – 2011 : CDF Collects 10.0 fb\(^{-1}\) of data at \(E_{\text{CM}} = 1.96\) TeV -- 12 fb\(^{-1}\) delivered.

Many thanks to the Beams Division for spectacular performance of the Tevatron
The CDF II Detector

First CDF p\bar p event: 1985
End of operations: 2011
**SM Higgs Boson Production and Decay Rates**

**Gluon Fusion**

**Associated Production**

**Vector Boson Fusion**

**ttH**

**Tevatron**
\[ \sqrt{s} = 1.96 \, \text{TeV} \]

Primary analysis modes:

- \( m_H < 130 \, \text{GeV} \): \( VH \rightarrow Vbb \)
- \( m_H > 130 \, \text{GeV} \): \( gg \rightarrow H \rightarrow WW \)

Additional modes:

- \( H \rightarrow \tau\tau, \ H \rightarrow yy, \ H \rightarrow ZZ \rightarrow 4l \)
- \( ttH \rightarrow ttbb \)
Talk Outline

• Updates to CDF’s METbb Search
• CDF’s H→bb combination
• Combined Results of all CDF SM Higgs boson searches
• Fourth-Generation and Fermiophobic Results
• Constraints on non-SM Couplings
The Main Associated Production Search Channels

Drawing Credit: CMS Higgs TWiki.
CDF also seeks qqH→qqbb and ttH→ttbb
The Status as of Summer 2012

CDF, D0, and Tevatron Publications:


At $m_H=125$ GeV/c$^2$, the measured rate is

$$\sigma(WH + ZH) \times Br(H \rightarrow b\bar{b}) = 291^{+118}_{-113} \text{ fb}$$

The SM prediction is

$$\sigma(WH + ZH) \times Br(H \rightarrow b\bar{b}) = 120 \pm 8 \text{ fb}$$

p-value using the cross section as test statistic: 2.7$\sigma$

Cross Sections: Baglio, Djouadi; Harlander, Mantler, Marzani, Ozeren
Branching Ratios: LHC Cross Section Working Group
Tevatron $H \rightarrow bb$ Results, Summer 2012


Cross section fit at $m_H = 125 \text{ GeV/c}^2$

$\left(\sigma_{WH} + \sigma_{ZH}\right) \times B(H \rightarrow b\bar{b}) = 230^{+0.090}_{-0.080} \text{ (stat+syst) fb}$

SM Prediction: $0.12 \pm 0.01 \text{ pb}$

Maximum local significance: $3.3\sigma$
at $m_H = 135 \text{ GeV/c}^2$

Global significance: $3.1\sigma$
Local significance at $m_H = 125 \text{ GeV/c}^2$ is $2.8\sigma$
Current Status from the LHC

A Higgs-like particle is firmly established, its mass looks to be between 125 and 126 GeV, and its properties are consistent with the SM Higgs boson.

Many more superb results are available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
CDF’s HOBIT b-tagger - Improved Sensitivity With Respect to the SECVTX, Roma, and BNess taggers

A neural-network b-tagger using inputs from other b-taggers, as well as lepton ID to include semileptonically decaying B hadrons.

HOBIT Tight and Loose operating points chosen to have similar mistag rates as older SECVTX operating points.

More signal
More b background
Similar LF background

<table>
<thead>
<tr>
<th>Operating Point</th>
<th>Mistag rate</th>
<th>SECVTX efficiency</th>
<th>HOBIT efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight</td>
<td>1.4%</td>
<td>39%</td>
<td>54%</td>
</tr>
<tr>
<td>Loose</td>
<td>2.9%</td>
<td>47%</td>
<td>59%</td>
</tr>
</tbody>
</table>

per-jet efficiencies shown

see also M. Stancari’s JETP Seminar, Mar. 7 2012
VH→METbb Analysis

Event Preselection

Select Events with 2 or 3 jets:
- \( 25 < E_{T,J1} < 200 \text{ GeV} \)
- \( 20 < E_{T,J2} < 120 \text{ GeV} \)
If a third jet is present,
- \( 15 < E_{T,J3} < 100 \text{ GeV} \)
- \( |\eta_{\text{jet}}| < 2 \) with at least one jet with \( |\eta| < 0.9 \)

No identified lepton
- \( \text{MET} > 35 \text{ GeV} \)
- \( \Delta\phi_{\text{MET,J2}}>0.4; \Delta\phi_{\text{MET,J3}}>0.4 \) if present

B-tagging:
- Double-tight HOBIT tag \((TT)\)
- Tight tag + Loose Tag \((TL)\)
- One tight tag \((1T)\)

Inversions of the event selection requirements define control samples
Signal (and b-tagged background) gain by using HOBIT compared with SECVTX and JetProb

<table>
<thead>
<tr>
<th>Tag category</th>
<th>$b$-tagging efficiency per event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref. [5]</td>
</tr>
<tr>
<td>Two tight $b$ tags</td>
<td>$13.7%$ (SS)</td>
</tr>
<tr>
<td>One tight and one loose $b$ tag</td>
<td>$13.1%$ (SJ)</td>
</tr>
<tr>
<td>Only one tight $b$ tag</td>
<td>$31.4%$ (1S)</td>
</tr>
<tr>
<td></td>
<td>This analysis</td>
</tr>
<tr>
<td>Two tight $b$ tags</td>
<td>$18.1%$ (TT)</td>
</tr>
<tr>
<td>One tight and one loose $b$ tag</td>
<td>$14.6%$ (TL)</td>
</tr>
<tr>
<td>Only one tight $b$ tag</td>
<td>$31.6%$ (1T)</td>
</tr>
</tbody>
</table>

Categories are non-overlapping.
The 1T category does not include TL or TT events
Data-Based Tagged QCD Multijet Prediction

Control Region: Same cuts as Preselection but:
- no b-tag required
- $35 \text{ GeV} < \text{MET} < 70 \text{ GeV}$
- $\Delta\phi(\text{MET},j2) < 0.4$

Nearly all events are QCD multijet events in this sample.

Measure tag fractions for TT, TL, 1T in this sample as functions of
- $H_T$
- missing $p_T$
- the fraction of charged energy in the cones of jets 1 and 2
- the number of reconstructed primary vertices
- The momentum-weighted sum of the sines of the angles between reconstructed muon candidates and jet axes

Result is three Tag Rate Matrices. Apply these to preselected data minus $W+jets$, $Z+jets$, $ttbar$, single top, and dibosons to model the tagged QCD multijet background
Validation of Key Variables in the Tagged Preselection Sample

Variables also checked in
- QCD-enriched region:
  low MET, low $\Delta\phi(MET,jet)$
- Electroweak control region
  Requires the presence of a high-$p_T$ isolated lepton ($e$ or $\mu$)
QCD-rejection Neural Network

**NN\textsubscript{QCD} Inputs**

- $M(\vec{E}_T, \vec{p}_T \not{E}_T)$
- $\vec{E}_T$
- $\vec{p}_T$
- $\vec{H}_T / \vec{E}_T$
- $\vec{E}_T / H_T$
- $\Delta \phi(\vec{E}_T, \vec{p}_T)$
- $\text{max}(\Delta R(\vec{j}_i, \vec{j}_j))$ where $i \neq j$
- $\text{max}(\Delta \phi(\vec{j}_i, \vec{j}_j))$ where $i \neq j$
- $\text{max}(\Delta \phi(\vec{E}_T, \vec{j}_i))$
- $\text{max}(\Delta \phi(\vec{p}_T, \vec{j}_i))$
- $\theta^*$ of jet in 2-jet rest frame
- Sphericity

**Signal Region:** $\text{NN}_{\text{QCD}} > 0.6$. Retains 87% of signal while rejecting 90% of QCD multijet backgrounds

0.1 < $\text{NN}_{\text{QCD}} < 0.6$ events used to normalize the QCD rate

Extrapolation uncertainties assessed in predicting rates for $\text{NN}_{\text{QCD}} > 0.6$. Larger uncertainties than Moriond 2012 analysis
### Predicted Yields in the Three Tagged Signal Samples

<table>
<thead>
<tr>
<th>Process</th>
<th>1T</th>
<th>TL</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD Multijet</td>
<td>5941 ± 178</td>
<td>637 ± 25</td>
<td>222 ± 16</td>
</tr>
<tr>
<td>Top</td>
<td>1174 ± 158</td>
<td>302 ± 40</td>
<td>271 ± 34</td>
</tr>
<tr>
<td>V+heavy flavor jets</td>
<td>3124 ± 718</td>
<td>286 ± 83</td>
<td>211 ± 65</td>
</tr>
<tr>
<td>Electroweak mistags</td>
<td>1070 ± 386</td>
<td>55 ± 21</td>
<td>13 ± 6</td>
</tr>
<tr>
<td>Diboson</td>
<td>305 ± 46</td>
<td>48 ± 6</td>
<td>41 ± 5</td>
</tr>
<tr>
<td>Total expected background</td>
<td>11612 ± 949</td>
<td>1329 ± 112</td>
<td>759 ± 86</td>
</tr>
<tr>
<td>Observed Data</td>
<td>11955</td>
<td>1443</td>
<td>692</td>
</tr>
<tr>
<td>ZH→vvbb, llbb (m_H=125 GeV)</td>
<td>9.7 ± 1.0</td>
<td>5.4 ± 0.5</td>
<td>5.4 ± 0.5</td>
</tr>
<tr>
<td>WH→lvbb</td>
<td>9.8 ± 1.0</td>
<td>5.3 ± 0.5</td>
<td>5.3 ± 0.5</td>
</tr>
</tbody>
</table>
Signal-Separation Neural Network Output Distributions for the Three b-tagged Signal Samples

**NN\textsubscript{SIG} Inputs**

\[
\begin{align*}
M(\vec{E}_T, \vec{j}_1, \vec{j}_2) \\
M(\vec{j}_1, \vec{j}_2) \\
H_T - \vec{E}_T \\
||\vec{H}_T - \vec{E}_T|| \\
\text{Output of TRACKMET neural network} \\
\text{Output of NN\textsubscript{QCD}} \\
\max(\Delta R(\vec{j}_i, \vec{j}_j)) \text{ where } i \neq j
\end{align*}
\]
Observed and Expected Limits


**This Result:**
HOBIT TT+TL+1T

<table>
<thead>
<tr>
<th></th>
<th>1s.d. expected</th>
<th>±2 s.d. expected</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At \(m_{H}=125\) GeV,
- \(\text{obs} = 3.06 \times \text{SM}\)
- \(\text{exp} = 3.33 \times \text{SM}\)

8% sensitivity improvement at \(m_{H}=125\) GeV/\(c^2\).

Average expected improvement over whole mass range: 14%.

Big change in observed result!
New limit is a drop of 55% relative to the published one at \(m_{H}=125\) GeV/\(c^2\)

**SECVTX+JP SS+SJ+1S**
At \(m_{H}=125\) GeV,
- \(\text{obs} = 6.7 \times \text{SM}\)
- \(\text{exp} = 3.6 \times \text{SM}\)
Discussion of METbb Results

Many cross-checks run to assess compatibility of the new HOBIT result and the published SECVTX+JetProb result:

1. Reanalysis of 1S, SJ, and SS tag categories using new framework, selection, and systematics
2. Validation of b-jet tagger modeling
3. Effects of Data Migration
4. P-value for the difference in observed limits using pseudoexperiments
5. Background modeling
Analysis Updates Besides Changing b-Taggers

• B-tag scale factor uncertainty handling improved – proper anticorrelations between exclusive samples evaluated.

• QCD Multijet uncertainties are larger, and improved methods for extrapolating from the control regions are used.

• Events with jets with $E_T > 200$ GeV and $E_T > 120$ GeV now rejected.

• Additional MET cut at 35 GeV in early stage of analysis to get away from trigger turn-on now applied.

• V+heavy flavor jets backgrounds now itemized separately with independent sources of uncertainty. The charm tag rate and gluon splitting rates are different depending on the sample.

• Z+jets with $Z \rightarrow bb$ background model included.

Re-Doing the SECVTX+JetProb analysis with these changes measures the impact of the changes and provides a cross check of the Winter/Summer 2012 METbb analysis.
Results of SECVTX+JetProb Redo Cross Check

At $m_H = 125 \text{ GeV}/c^2$, the observed HOBIT limit is 47% lower than the Re-Done SECVTX+JP observed limit. (Was 55% lower than published.)
Combine the Redone SECVTX+JetProb METbb with llbb+lvbb

CDF Combined VH→Vbb limits/SM

- Red Curve: Published llbb, lvbb, and the Redone SECVTX+JetProb crosscheck
  - P-value remains unchanged. at 2.7σ at m_H=125 GeV/c^2

CDF finds no significant issues with the previous version of the METbb analysis and stands firmly behind last summer’s published results.
B-Tag Modeling Validation: Electroweak Control Region

Preselection requirements, but require a high-$p_T$ isolated lepton (e or $\mu$)

Look for mismodeled correlations between $NN_{SIG}$ and b-tagging

No modeling issues seen with either b-tag algorithm as a function of $NN_{SIG}$
Studying the Effects of Event Migration

We do not see problems in modeling: Suspect statistical fluctuations.

Data Event Overlap Fractions: $NN_{SIG}>0.8$

<table>
<thead>
<tr>
<th></th>
<th>1T</th>
<th>TL</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S</td>
<td>55%</td>
<td>35%</td>
<td>15%</td>
</tr>
<tr>
<td>SJ</td>
<td>4%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>SS</td>
<td>1%</td>
<td>14%</td>
<td>51%</td>
</tr>
</tbody>
</table>

Denominator: HOBIT analysis events

HOBIT Tagger is more efficient: Expect promotion of signal events to higher tag categories.
Event Rate Summaries - HOBIT analysis vs. SECVTX+JP

<table>
<thead>
<tr>
<th>Tag category</th>
<th>Background (fit)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>39.5 ± 4.6</td>
<td>33</td>
</tr>
<tr>
<td>SS</td>
<td>37.6 ± 4.6</td>
<td>37</td>
</tr>
<tr>
<td>TL</td>
<td>67.4 ± 6.8</td>
<td>80</td>
</tr>
<tr>
<td>SJ</td>
<td>45.6 ± 5.1</td>
<td>62</td>
</tr>
</tbody>
</table>

High Score: $\text{NN}_{\text{SIG}} > 0.8$ Observed Event Counts

Now: 6.5 events deficit at high score. Was: spot on

Excesses seen in both old and new tight-loose categories
Events Gained and Lost: TL and SJ

Top three NN_{SIG} score events in the SJ analysis are no longer selected.

Two are now LL and one is 1L.

Bin has high s/b and a large weight in the result.

A test: We added these three events by hand to TL.

SECVTX+JP(redo) vs. HOBIT limit discrepancy changes from 47% to 31% with the events added back.

The NN_{SIG} function is unchanged since Moriond 2012. Selected, tagged events receive the same NN_{SIG} scores they always did.
Events Gained and Lost: TT and SS

Lost More Events than Gained in the high-$\text{NN}_{\text{SIG}}$ region.

Studied adding 5 extra candidates to the TT data by hand, following the background shape (not just the last bin).

Change in limit discrepancy: from $47\%$ to $33\%$

Combined effect of TT and TL candidates: reduces discrepancy from $47\%$ to $19\%$

Improvement in sensitivity is $8\%$ at $m_{H}=125$ GeV
How Likely is it?

Compare CDF METbb HOBIT analysis with the re-done SECVTX+JP analysis

**Paired pseudoexperiments:**
- HOBIT channels TT, TL, 1T
- SECVTX channels SS, SJ, 1S
- Use expected overlaps in the $NN_{\text{SIG}} < 0.8$ and $NN_{\text{SIG}} > 0.8$ regions to generate independent samples of events in 15 categories:
  - TTSS, TTSJ, TT1S, TTnone
  - TLSS, TLSJ, TL1S, TLnone
  - 1TSS, 1TSJ, 1T1S, 1Tnone
  - noneSS, noneSJ, none1S

Calculate limit for each pair of pseudoexperiments & compare

P-value for $|\text{Limit difference}|$ to be as big as observed: 7%
Highly correlated over $m_H$ range: P-value for all limits to be low: 3-5%
How Correlated are the Searches at Each $m_H$?

Limited resolution on input variables to $\text{NN}_{\text{SIG}}$ correlates results of searches at nearby masses.

Between 2 and 3 independent search results over the mass range $90 < m_H < 150 \text{ GeV/c}^2$
Studying Backgrounds in the Intermediate $NN_{SIG}$ Score Region

Intermediate Score: $0.48 < NN_{SIG} < 0.8$

Background fits dominated by events at even lower $NN_{SIG}$ score

Limits on Higgs boson signal fairly insensitive to these bins.

<table>
<thead>
<tr>
<th>Tag category</th>
<th>Background (fit)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>$264.8 \pm 25.1$</td>
<td>265</td>
</tr>
<tr>
<td>SS</td>
<td>$228.8 \pm 21.0$</td>
<td>217</td>
</tr>
<tr>
<td>TL</td>
<td>$506.1 \pm 38.8$</td>
<td>506</td>
</tr>
<tr>
<td>SJ</td>
<td>$312.5 \pm 22.6$</td>
<td>291</td>
</tr>
</tbody>
</table>

No evidence for mismodeling in this region
Final CDF Combined VH→Vbb Cross Section Measurements

At $m_H=125$ GeV/c$^2$ the previous measurement is

$$\sigma(WH + ZH) \times Br(H \rightarrow b\bar{b}) = 291^{+118}_{-113} \text{ fb}$$

The SM prediction is

$$\sigma(WH + ZH) \times Br(H \rightarrow b\bar{b}) = 120 \pm 8 \text{ fb}$$

At $m_H=125$ GeV/c$^2$, the final measurement is

$$\sigma(WH + ZH) \times Br(H \rightarrow b\bar{b}) = 206^{+110}_{-104} \text{ fb}$$
Summary of the H→bb Updates and Investigations

• Previous METbb (SECVTX+JetProb) analysis is still valid
  • Analysis redone with new framework, cuts, and systematic uncertainty handling
  • Previous METbb result reproduced with small shifts in limits
  • No change in combined limits or p-values

• Switching to a new b-tagger reclassified events – only 50% overlap with events in the old analysis in the highest-weight region.

• New best-fit cross sections are lower.

• We must choose the more sensitive analysis:
  HOBIT METbb is 8% more sensitive than the previous version at m_H=125 GeV/c^2, and 14% stronger on average in 90 < m_H < 150 GeV
Combining the SECVTX+JetProb Analysis and HOBIT Analysis?

**Reasons to do it:**
- More statistical power
- Observed results may be intermediate between published and new results

**Reasons not to do it:**
- Expected sensitivity gain is very small – signal events are expected to remain tagged, merely shuffled from one category to another
- More exclusive tag categories (15 instead of 3). Smaller data control samples mean higher systematic uncertainties
- HOBIT uses SECVTX variables as inputs, among others. It’s already a combination.
- Combining HOBIT and SECVTX+JetProb was not on our original menu of analysis improvements, for the above reasons. We made the decision to switch all analyses from SECVTX+JetProb to HOBIT without knowledge of the data outcome.Switching *a posteriori* would bias the final result.

**Predicted Event Overlap Fractions, signal MC**

<table>
<thead>
<tr>
<th></th>
<th>0T</th>
<th>1T</th>
<th>TL</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>—</td>
<td>22%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1S</td>
<td>17%</td>
<td>63%</td>
<td>15%</td>
<td>6%</td>
</tr>
<tr>
<td>SJ</td>
<td>12%</td>
<td>20%</td>
<td>37%</td>
<td>32%</td>
</tr>
<tr>
<td>SS</td>
<td>5%</td>
<td>3%</td>
<td>15%</td>
<td>77%</td>
</tr>
</tbody>
</table>

Roman font – normalized to HOBIT yields. Italics: Normalized to SECVTX+JP yields
Updates Since the last full CDF SM Higgs Combination

• Revert to the published 6.0 fb\(^{-1}\) H\(\rightarrow\tau\tau\) Search.  
  8.3 fb\(^{-1}\) preliminary result not published.

• Update the ttH search: train MVA’s at each m\(_H\).

• Improve correlations/anticorrelations in b-tag uncertainties in l\(\ell\)bb / lvbb analyses

• Upgraded the Central-Central H\(\rightarrow\gamma\gamma\) search to use an MVA instead of m\(_{\gamma\gamma}\).  
  Searches including plug photons and conversions still use m\(_{\gamma\gamma}\).

CDF’s SM combination last done for Winter 2012 conferences.
# All CDF SM Search Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity $^{(fb^{-1})}$</th>
<th>$m_H$ range $^{(GeV/c^2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH \to \ell\nu\bar{b}b$ 2-jet channels</td>
<td>4×(5 b-tag categories)</td>
<td>9.45</td>
</tr>
<tr>
<td>$WH \to \ell\nu b\bar{b}$ 3-jet channels</td>
<td>3×(2 b-tag categories)</td>
<td>9.45</td>
</tr>
<tr>
<td>$ZH \to \nu\bar{b}b$ (3 b-tag categories)</td>
<td>9.45</td>
<td>90-150</td>
</tr>
<tr>
<td>$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels</td>
<td>2×(4 b-tag categories)</td>
<td>9.45</td>
</tr>
<tr>
<td>$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels</td>
<td>2×(4 b-tag categories)</td>
<td>9.45</td>
</tr>
<tr>
<td>$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(2 or more jets)+1×(low-$m_{\ell\ell}$)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>$H \to W^+W^-$ ($e^{-}\tau_{had})+(\mu^{-}\tau_{had}$</td>
<td>9.7</td>
<td>130-200</td>
</tr>
<tr>
<td>$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>$WH \to WW^+W^-$ (tri-leptons with 1 $\tau_{had}$)</td>
<td>9.7</td>
<td>130-200</td>
</tr>
<tr>
<td>$ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>$H \to ZZ$ (four leptons)</td>
<td>9.7</td>
<td>120-300</td>
</tr>
<tr>
<td>$H \to \tau^+\tau^-$ (1 jet)+(2 or more jets)</td>
<td>6.0</td>
<td>100-150</td>
</tr>
<tr>
<td>$WH+ZH \to jjb\bar{b}$ (2 b-tag categories)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$ 1×(0 jet)+1×(1 or more jets)+3×(all jets)</td>
<td>10.0</td>
<td>100-150</td>
</tr>
<tr>
<td>$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (4 jet, 5 jet, ≥ 6 jet)×(5 b-tag categories)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
</tbody>
</table>
Sensitivity Evolution over Time

We collected data, and we also learned how to get more out of the data.

- Better MVA’s
- Better Event Selection
- Better lepton ID
- Better jet energy resolution
- More triggers
- More analysis categories
- Sharing improvements between analyses
SM Combined Data Summaries at $m_H=125$ and 165 GeV/c$^2$

Background Hypothesis fit to data
Bins of similar s/b added together
SM Combined Data Summaries at $m_H=125$ and 165 GeV/c^2

Same as before, but fitted background subtracted from the data.

Data error bars are $\sqrt{s+b_{\text{fit}}}$
Sensitivity of the Main Search Channels

![Graph showing the sensitivity of different Higgs search channels as a function of Higgs boson mass. The graph plots the ratio of observed to expected signal strength, $R_{95}$, against the Higgs boson mass, $m_H$, in GeV/c$^2$. The channels include Higgs decays to $\tau^+\tau^-$, $\gamma\gamma$, $t\bar{t}H\rightarrow t\bar{t}b$, $VH\rightarrow Vbb$, $H\rightarrow ZZ\rightarrow 4l$, and $H\rightarrow W^+W^-$. The combined sensitivity is also shown.]
CDF’s Final SM Higgs Rate Limits

Excluded regions: 90 < m_H < 102 GeV/c^2 and 149 < m_H < 172 GeV/c^2
Expect to exclude if no Higgs: 90 < m_H < 94 GeV/c^2, 96 < m_H < 106 GeV/c^2, and 153 < m_H < 175 GeV/c^2
Best-Fit Cross Sections at $m_H=125$ GeV/c$^2$

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$: $9.49^{+6.60}_{-6.28} \times \text{SM}$

$H \rightarrow \gamma\gamma$: $7.81^{+4.61}_{-4.42} \times \text{SM}$

$H \rightarrow W^+W^-$: $0.00^{+1.78}_{-0.00} \times \text{SM}$

$H \rightarrow \tau^+\tau^-$: $0.00^{+8.44}_{-0.00} \times \text{SM}$

$VH \rightarrow Vb\bar{b}$: $1.72^{+0.92}_{-0.87} \times \text{SM}$

Combined: $1.54^{+0.77}_{-0.73} \times \text{SM}$
CDF’s Combined SM Higgs Boson Search p-value

Observed local significance at $m_H=125$ GeV/c$^2$ is $2.0\sigma$.

Expected significance at $m_H=125$ GeV/c$^2$ is $1.6\sigma$ assuming a signal is present.

2.5\sigma local significance at $m_H=120$ GeV/c$^2$.

Look-Elsewhere Effect:

- $m_H \sim 125$ GeV has been firmly established by the LHC.
- CDF’s mass resolution is not very sharp -- $\sim 2$ independent search results in $H \rightarrow bb$, $\sim 2$ in $H \rightarrow WW$.
- Technical challenge – MVA’s trained at each $m_H$ separately. Histograms of predictions exchanged. Would need to exchange correlated pseudoexperiments to compute LEE exactly.
A heavy fourth generation of quarks would scale the $gg\to H$ production rate at colliders by a factor of $\sim 9$. But watch out for $H\to \nu_4\nu_4$ decays.


Searches for $gg\rightarrow H\rightarrow WW$ - Model Independent and SM4 interpretation

Searches optimized specifically for $gg\rightarrow H$ (NN’s not trained with WH, ZH, or VBF).

Limit on cross section times b.r. shown along with SM4 model predictions.

Low-Mass scenario: $m_{l_4}=100$ GeV, $m_{v_4}=80$ GeV
High-Mass scenario: $m_{l_4}=m_{v_4}=1$ TeV
Both Scenarios: $m_{d_4}=400$ GeV, $m_{u_4}=450$ GeV

SM4 Cross Sections computed at NNLO in QCD by Anastasiou, Boughezal, and Furlan

Low-mass scenario exclusions:
Expected exclusion: $123 < m_H < 231$ GeV/c$^2$
Observed exclusion: $124 < m_H < 203$ GeV/c$^2$
A Test of the Fermiophobic Higgs Model

Model tested: Assume SM-like behavior for the Higgs boson, except switch off all couplings to fermions.

Decays for $H \rightarrow bb$, $H \rightarrow \tau\tau$, and $H \rightarrow gg$ are highly suppressed. $gg \rightarrow H$ production is negligibly small.

WH, ZH, VBF production cross sections are as predicted by the SM

$H \rightarrow WW$, ZZ partial widths are as predicted by the SM.

$H \rightarrow \gamma\gamma$ is modified – loss of the fermion loop increases the decay rate.

$H \rightarrow \gamma\gamma$ search is re-optimized for this search because the $p_T$ spectrum of the $H$ is harder in WH and ZH than for $gg \rightarrow H$

Branching ratios recomputed using the modified decay widths.

Included channels: $H \rightarrow \gamma\gamma$, $H \rightarrow WW$, $H \rightarrow ZZ \rightarrow 4l$

Observed exclusion: $100 < m_H < 113$ GeV/c$^2$

Expected exclusion: $100 < m_H < 122$ GeV/c$^2$
Constraining the Couplings of the Higgs Boson to Fermions and Gauge Bosons

We follow the procedures and notation of the LHC Higgs Cross Section WG A. David et al., arXiv:1209.0040

The model: SM-like, but

Hff couplings are scaled together by $\kappa_f$

HWW coupling is scaled by $\kappa_W$

HZZ coupling is scaled by $\kappa_Z$

For some studies, we scale the HWW and HZZ couplings by $\kappa_W = \kappa_Z = \kappa_V$

Standard Model is recovered if $\kappa_f = \kappa_W = \kappa_Z = 1$
Constraining Couplings

**Step 1:** Scale cross sections for each process according to couplings

\[ \sigma(gg \rightarrow H) = \sigma_{SM}(gg \rightarrow H)(0.95\kappa_f^2 + 0.05\kappa_f\kappa_V) \]

\[ \sigma(WH) = \sigma_{SM}(WH)\kappa_V^2 \]

\[ \sigma(ZH) = \sigma_{SM}(ZH)\kappa_V^2 \]

- LO relations, but mostly true at higher order (most QCD affects the colored initial-state particles. There is \(gg\rightarrow WH\) at higher order, however.)

\[ \sigma(VBF) = \sigma_{SM}(VBF)\kappa_V^2 \]

- Pretty much by definition! Unless NNLO VBF includes the EW ggH piece. From Bolzoni, Moch, Maltoni, and Zaro’s papers, it seems as if the EW ggH piece is not in the NNLO VBF calculation.

Two-Loop Electroweak Contributions to the ggH Coupling

- Approximately a 5% contribution to the gg\(\rightarrow H\) production cross section at \(m_H=125\) GeV/c\(^2\). Main contribution is from interference with the LO process.
- Contribution not included in VBF calculation (HAWK: Denner, Dittmaier, Mück)


Anastasiou, Boughezal, Petriello, JHEP 0904 003 (2009)

Actis, Passarino, Sturm, Uccirati PLB 670, 12 (2008)

Grazzini and de Florian PLB 674, 291 (2009)
Constraining Couplings

Step 2: Recompute all Higgs boson decay branching ratios from scaled partial widths

\[
\begin{align*}
\Gamma(H \to gg) &= \Gamma_{\text{SM}}(H \to gg)(0.95k_f^2 + 0.05k_fk_V) \\
\Gamma(H \to W^+W^-) &= \Gamma_{\text{SM}}(H \to W^+W^-)k_V^2 \\
\Gamma(H \to b\bar{b}) &= \Gamma_{\text{SM}}(H \to b\bar{b})k_f^2 \\
\Gamma(H \to \tau^+\tau^-) &= \Gamma_{\text{SM}}(H \to \tau^+\tau^-)k_f^2 \\
\Gamma(H \to c\bar{c}) &= \Gamma_{\text{SM}}(H \to c\bar{c})k_f^2 \\
\Gamma(H \to ZZ) &= \Gamma_{\text{SM}}(H \to ZZ)k_V^2 \\
\Gamma(H \to \gamma\gamma) &= \Gamma_{\text{SM}}(H \to \gamma\gamma)|\alpha k_V + \beta k_f|^2
\end{align*}
\]

\(\alpha\) and \(\beta\) come from Spira et al., arXiv:hep-ph/9504378
\(\alpha = 1.28\quad \beta = -0.21\)

Other modes, like \(H \to \mu^+\mu^-\) and \(H \to Z\gamma\) have very small widths.
Some work from theorists


\[ a = \kappa_V, \quad c = \kappa_F \]
More Complete Treatment of Signal Scalings

Example: HWW Search. All Signals have $H \rightarrow WW$, but different mixtures of production mechanisms in each search channel.

Each signal contribution should be scaled by the appropriate factor

Pie charts show relative contributions.
Signal Rate Enhancement Factors for $gg \rightarrow H \rightarrow WW$ and $WH \rightarrow lvbb$
Signal Rate Enhancement Factors for $ttH \rightarrow ttbb$ and $WH \rightarrow WWW$
Posterior Constraint on the Hff Coupling Factor $\kappa_f$

- Uniform prior assumed
- $\kappa_W = \kappa_Z = 1$ assumed

Excess in the $H \rightarrow \gamma\gamma$ searches drives the asymmetry from positive and negative coupling scale factors
Posterior Constraint on the HWW Coupling Factor $\kappa_W$

- Uniform prior assumed
- $\kappa_f = \kappa_Z = 1$ assumed

Excess in the $H \rightarrow \gamma\gamma$ searches drives the asymmetry from positive and negative coupling scale factors
Posterior Constraint on the HWW Coupling Factor $\kappa_Z$

- Uniform prior assumed
- $\kappa_f = \kappa_W = 1$ assumed
Two-Dimensional Constraints: Bosons vs. Fermions

Uniform prior assumed

Large $\kappa_V$ with small $\kappa_f$ constrained by trileptons, same-sign dileptons

Large $\kappa_f$ and small $\kappa_V$ constrained by $ttH \rightarrow ttbb$
Two-Dimensional Constraints: W vs. Z Couplings

Uniform prior assumed

$\kappa_f$ integrated over ("marginalized")

Less constraint on HZZ than on HWW

All couplings consistent with SM predictions
Summary (1)

- CDF’s Searches for the Higgs boson in the SM, SM4, and Fermiophobic models are now finalized.

- Publications on the final METbb (HOBIT) search plus the combination are being submitted.

- Previous METbb (SECVTX+JP) analysis is still valid – no mistakes affecting the Summer 2012 result were found.

- Switching to a new b-tagger reclassified events – only 50% overlap with events in the old METbb analysis in the highest-NN$_{SIG}$ region.

- New best-fit cross sections are somewhat lower.

- We must choose the more sensitive analysis: HOBIT METbb is 8% more sensitive than the previous version at m$_{H}$=125 GeV/c$^2$. 

Summary (2)

Excess of events persists in the SM Higgs search near $m_H=125$ GeV/c$^2$.

Higgs boson does not look like those of the FP model, or SM4.

Couplings to W, Z, and fermions are consistent with SM predictions.

Extracting coupling information from the data requires full predictions of signal rates and shapes in all channels.

Channels that contribute little to the total SM sensitivity can have outsized impacts on exotic coupling scenario tests.