Higgs Searches at CDF

Michael Kirby, Fermilab
for the CDF Collaboration
incredible shrinking window

- improved limits from the LHC
- improved measurements in top mass and W mass
- provide strong motivation to focus on low-mass Higgs

### Mass of the W Boson

<table>
<thead>
<tr>
<th>Measurement</th>
<th>M_W [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-0/1</td>
<td>80432 ± 79</td>
</tr>
<tr>
<td>DØ-I</td>
<td>80478 ± 83</td>
</tr>
<tr>
<td>DØ-II (1.0 b')</td>
<td>80402 ± 43</td>
</tr>
<tr>
<td>CDF-II (2.2 b')</td>
<td>80387 ± 19</td>
</tr>
<tr>
<td>DØ-II (4.3 b')</td>
<td>80369 ± 26</td>
</tr>
<tr>
<td>Tevatron Run-0/II</td>
<td>80387 ± 16</td>
</tr>
<tr>
<td>LEP-2</td>
<td>80376 ± 33</td>
</tr>
<tr>
<td>World Average</td>
<td>80385 ± 15</td>
</tr>
</tbody>
</table>

New World Average
M_W = 80390 ± 16 MeV
CDF ± 19, DØ ± 23
The Tevatron at Fermilab

- Tevatron proton-antiproton collider at Fermilab
  - $\sqrt{s} = 1.96$ TeV
- EWK scale processes probe different region of parton distribution than LHC
- channel sensitivity differs from LHC
Tevatron Shutdown

September 30, 2011

photo courtesy of Bodhitha Jayatilika
Tevatron Integrated Luminosity

- delivered 11.9 fb⁻¹
- exceptionally efficient in final years

- recorded w/ ~90% eff
- final results ~10 fb⁻¹
CDF II detector

- Spectrometer: Outer tracker and Silicon Tracker in 1.4 Telsa Solenoid
- Energy Flow: Fine segmented Calorimeter and Preshower (Steel/Iron and Scintillator)
- Muons: multi layer scintillator and drift chamber systems
- Hermetic: Excellent coverage of Tracking, Calorimeter and Muon Systems

Detector coverage

- muons ~ 2
- tracking ~ 2.5
- EM/jet ~ 4
Gluon fusion dominates
Associated production
(WH, ZH)
Vector Boson fusion
Higgs Production at Tevatron

Gluon fusion dominates
Associated production (WH, ZH)
Vector Boson fusion

$M_H < 135$, $H \rightarrow bb$

$M_H > 135$, $H \rightarrow WW$
Higgs search at Tevatron

- Focus on the low Higgs mass region
- Re-evaluate current analysis tools to optimize signal acceptance
- Improve b-tagging strategy
- Jet energy resolution
- Develop new MVA discriminants
- Validation of search techniques in diboson measurements
Higgs search at Tevatron

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WH → lνbb Search

- Identification of b-quarks critical component
- Background rejection
- H→bb reconstruction

CDF Run II Preliminary (9.45fb⁻¹)

~112k evts
~600 evts
numerous b-taggers across several analyses
led to requirement for combined tagging channels

<table>
<thead>
<tr>
<th>OLD – Multiple Taggers</th>
<th>Tagging Category</th>
<th>S/√B</th>
</tr>
</thead>
<tbody>
<tr>
<td>SecVtx+SecVtx</td>
<td></td>
<td>0.228</td>
</tr>
<tr>
<td>SecVtx+JetProb</td>
<td></td>
<td>0.160</td>
</tr>
<tr>
<td>SecVtx+Roma</td>
<td></td>
<td>0.103</td>
</tr>
<tr>
<td>Single SecVtx</td>
<td></td>
<td>0.146</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td><strong>0.331</strong></td>
</tr>
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identifying b-quark jets

- previous taggers used in top quark, exotic, and QCD analyses
- utilize all features in single b-tagger
- displaced vertices
- high impact parameter single tracks
- soft charge muons from semi-leptonic decays

optimize tagger for Higgs kinematic region and tagging thresholds
Higgs optimized b-identification tagger

- 25 input variables drawn from other taggers
- vertex: $L3D$, $\sigma(L3D)$, vertex inv mass, pseudo-ct,
- tracks: b-like track score (10), track multiplicity, track inv mass, total track $p_T$
- soft muon kinematics
- two operating points optimized for use in $H \rightarrow bb$
### HOBIT Performance

<table>
<thead>
<tr>
<th>Tagger</th>
<th>Eff</th>
<th>HOBIT</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV T</td>
<td>0.39</td>
<td>0.54</td>
<td>38%</td>
</tr>
<tr>
<td>SV L</td>
<td>0.47</td>
<td>0.59</td>
<td>25%</td>
</tr>
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HOBIT validation

- compare performance in simulation with data
- previous taggers utilized resolution effects to measure corrections
- no longer available in MVA tagger, but now have large orthogonal datasets
- measure correction scale factors using two techniques
- combine the two measurements to reduce the b-tag efficiency uncertainty

σ(tt) method

- previously measure σ(tt) and b-tag eff simultaneously
- select tt-bar enhanced data
  - W+3,4,5+ jet sample with large $H_T$
  - W+1 jet sample
- fluctuate the b-tag eff and light-jet mistag efficiency
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soft-electron method

- use known efficiency of SecVtx tagger to generate tag-probe sample
- enhance b-content in the probe jets with soft-electron tagging
- all variables orthogonal to HOBIT inputs
- correct HF content based upon identifying photon conversions

SecVtx

soft electron
**HOBIT validation**

- Combine the two measurements to reduce the b-tag efficiency uncertainty.
- Give access to full kinematic range of jets from tt-bar and dijet events.

<table>
<thead>
<tr>
<th>HOBIT</th>
<th>eff SF</th>
<th>uncert</th>
</tr>
</thead>
<tbody>
<tr>
<td>tight</td>
<td>0.993</td>
<td>±0.032</td>
</tr>
<tr>
<td>loose</td>
<td>0.937</td>
<td>±0.037</td>
</tr>
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**tt-bar sample**

**soft-electron jet sample**
HOBIT in low-mass Higgs

- excellent agreement in HOBIT tagged samples
- single Tight tag control
- HOBIT has been incorporated into most CDF low-mass analyses
- each analysis optimized operating points for best signal to background
- use Tight and Loose points
- up to 5 tag categories TT, TL, Tx, LL, Lx
HOBIT in low-mass Higgs

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<td>SecVtx+Roma</td>
<td>0.103</td>
<td>0.143</td>
</tr>
<tr>
<td>Single SecVtx</td>
<td>0.146</td>
<td>0.053</td>
</tr>
<tr>
<td>Sum</td>
<td>0.331</td>
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<table>
<thead>
<tr>
<th>Tag Category</th>
<th>b-jet eff</th>
<th>light jet fake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight</td>
<td>42%</td>
<td>0.89%</td>
</tr>
<tr>
<td>Loose</td>
<td>70%</td>
<td>8.9%</td>
</tr>
</tbody>
</table>

increase > 10% in S/√B for WH→lvbb
increase > 15% in S/√B for ZH→llbb
b-jet calorimeter deposits have sizable differences from light-jets

develop specialized NN and corrections for b-jets to improve H → bb mass resolution
ZH → $llbb$ Signature

- lepton $E_T$ resolution is excellent and provides constraint
- attribute missing-$E_T$ to measurement of jets
- trained Neural Network to balance jets against missing-$E_T$

CDF Run II Preliminary 9.45/fb

**Graphs:**
- [Dijet Mass (GeV/c^2)]
- [Corrected Dijet Mass (GeV/c^2)]
ZH $\rightarrow \nu\nu bb$ Signature

- NN based b-jet corrections
- better signal/background separation
- RMS/mean improves in Met+bb
- 0.195 $\rightarrow$ 0.156
- b-jet corrections now included in all $H\rightarrow bb$ analysis

CDF II Preliminary
multivariate methods

- develop MVA for specific backgrounds
- multi-stage classification of events
- separate easiest background first
- train final discriminant after
search for $WZ/ZZ \rightarrow X+bb$

- identical final state as $WH/ZH \rightarrow X+bb$
- $\sigma(VZ) \approx 5 \times \sigma_{SM}(VH)$
- use same search strategy
- critical test of analysis

$\sigma(VZ) = 4.47 \pm 0.64_{(\text{stat})} \pm 0.73_{(\text{syst})} \text{ pb}$

approximately $4.6\sigma$ significance

$\sigma_{SM}(VZ) = 4.4 \pm 0.3 \text{ pb}$
Expected CDF Sensitivity

CDF Run II Preliminary, $m_H = 115$ GeV

- Summer 2005
- December 2008
- Summer 2006
- November 2009
- Summer 2007
- July 2010
- January 2008
- July 2011
- Projected Improvements

Expected Limit/SM vs. Integrated Luminosity (fb$^{-1}$)
Expected CDF Sensitivity

CDF Run II Preliminary, $m_H=115$ GeV

Expected Limit/SM

- Summer 2005
- Summer 2006
- Summer 2007
- Summer 2008
- November 2009
- July 2010
- July 2011
- January 2008
- February 2012
- December 2008
- Sensitivity Goal

$1.16 \times \sigma_{SM}(H)$
CDF Full Combination

Exclude SM Higgs at 95% C.L.: $147 < m_H < 175$ GeV/c$^2$

Expect to exclude: $100 < m_H < 106$ GeV/c$^2$ & $154 < m_H < 176$ GeV/c$^2$
Global significance of excess

- Highest local p-value at $m_H = 120$ GeV/c$^2$
- Mass resolution of searches, dominated by $b\bar{b}$ at low mass and $WW$ at high mass, is broad
- Estimate LEE of 4 for our entire SM search range from 100 to 200 GeV/c$^2$
Compatible with SM Higgs?

Consistent with SM Higgs at 1 $\sigma$ level for mass range between 107 and 142 GeV/c$^2$. 

CDF Run II Preliminary

$\sigma_{/SM}$

$\sigma < 10$ fb$^{-1}$

Fitted Higgs cross section

$m_H$ (GeV)
how much did things change?

A $\sim 0.5\sigma$ excess in mass range from 115 to 135 GeV/c$^2$ has become a $\sim 2\sigma$ excess. How can this happen?
- 18% additional data
- Small signal acceptance improvements (0.1 < \( \Delta R_{ll} \) < 0.2)
- No appreciable change in behavior of limits

\[ \mathcal{H} \rightarrow \text{WW} \]
ZH → ννbb

- 21% additional luminosity
- Small improvements in background rejection
- same basic behavior w/ 0.5 to 1.0σ increases in significance of excess

Summer 2011

Winter 2012
WH→lvbb

- 26% (69%) additional luminosity for 2-jet (3-jet) channels
- 5-10% level lepton acceptance/trigger efficiency improvements
- New HOBIT b-tagger equivalent to adding another 20% in additional luminosity
- Limits show same basic behavior with 1.0 to 1.5σ increases in significance of excess

Summer 2011

Winter 2012
23% additional luminosity
More gain from HOBIT in this analysis than WH (original tagging not as sophisticated)
56% of data events in current analysis were not included in previous analysis!
37% sensitivity improvement (4.67\(^{+2.95}_{-1.34}\) at \(m_H = 120\) GeV/c\(^2\))
Tevatron strength: $H \rightarrow bb$

- Combine our three primary low mass search channels
  - $WH \rightarrow l\nu bb$
  - $ZH \rightarrow \nu\nu bb$
  - $ZH \rightarrow llbb$
- Allows for a quasi-model independent search for associated Higgs production with $H \rightarrow bb$
Global Significance of $H\rightarrow bb$

- Highest local p-value is found at $m_H = 135$ GeV/c$^2$
- These searches are performed in the mass range between 100 to 150 GeV/c$^2$
- Estimate LEE of 2

**Single Channel Searches**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channel</th>
<th>Local P-value</th>
<th>Global P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>H-&gt;bb</td>
<td>2.9σ</td>
<td>2.7σ</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary
SM $H\rightarrow b\bar{b}$, $L_{int} < 9.5$ fb$^{-1}$

February 2012
Data are most consistent with SM in mass range from $105 < m_H < 120$ GeV/c$^2$

Behavior at higher $m_H$ values is consistent with the expectation from a lower mass Higgs
CDF Conclusions

- CDF has significantly increased the sensitivity of its Higgs searches by incorporating the full 10 fb⁻¹ dataset and a wide range of analysis improvements.
- All SM searches combined:
  - excess of Higgs-like events observed consistent with SM Higgs production in the mass range from 107 to 142 GeV/c².
  - global significance of 2.1σ.
- Associated Higgs production in the decay mode $H \rightarrow bb$:
  - excess of Higgs-like events observed, again consistent with SM Higgs production.
  - global significance of 2.7σ.
Backup
Tevatron Higgs Summary

- Tevatron delivered a spectacular dataset
- CDF and D0 incorporated full dataset into Higgs searches
- added considerable improvements to Higgs searches beyond luminosity
- measure $VZ \rightarrow X+bb$ at $4.6\sigma$ significance and consistent with SM
- Observe an excess of Higgs like event consistent with SM Higgs production
- global significance of excess is $2.2\sigma$
- consistent with SM Higgs production

Tevatron Exclusion

$147 < m_H < 179$ GeV/c$^2$
optimal b-quark tagger for Higgs

- start with yields from previous taggers
- scale efficiencies and fake rates
- run pseudo experiments
- c-quark discrimination had minimal effect
- can afford an increase in fake rate

<table>
<thead>
<tr>
<th>$WH \rightarrow \ell\nu bb$, 2jets</th>
<th>CDF Run II Preliminary 7.5 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>Pretag Events</td>
<td>184050</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>142±22</td>
</tr>
<tr>
<td>Single top(s-ch)</td>
<td>45.0±6.7</td>
</tr>
<tr>
<td>Single top(t-ch)</td>
<td>13.9±2.4</td>
</tr>
<tr>
<td>WW</td>
<td>1.67±0.42</td>
</tr>
<tr>
<td>WZ</td>
<td>12.9±2.0</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.62±0.09</td>
</tr>
<tr>
<td>$Z + jets$</td>
<td>9.64±1.40</td>
</tr>
<tr>
<td>$W\bar{b}b$</td>
<td>257±104</td>
</tr>
<tr>
<td>$Wc\bar{c}/c$</td>
<td>31.0±12.6</td>
</tr>
<tr>
<td>Mistag</td>
<td>12.1±2.9</td>
</tr>
<tr>
<td>non-W QCD</td>
<td>57.9±23.6</td>
</tr>
<tr>
<td>Total background</td>
<td>584±169</td>
</tr>
<tr>
<td>Observed Events</td>
<td>519</td>
</tr>
<tr>
<td>$WH$ and $ZH$ signal (115 GeV)</td>
<td>7.28±0.98</td>
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use select variables from older taggers

combine into a single Higgs optimized Neural Network

provide multiple operating points

training with Higgs decay jets improves
HOBIT validation

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Soft-electron method

- enhance b-content in a dijet sample with soft-electron tagging in away jet
- correct the heavy flavor content based upon identifying photon conversions

Measurements using two newly developed techniques combine to reduce the b-tag efficiency uncertainty.
Examine top 20 events in both channels based on S/B of the discriminant bin in which it’s located.

The electron channel contains 12 new candidates within this high score region, while muon channel has 5.