Richard E. Hughes
The Ohio State University
for
The CDF and D0 Collaborations

Tevatron Higgs Combination
Tevatron and Experiments

1.96 TeV

Booster

CDF

p

DØ

Tevatron

Main Injector & Recycler

p source

Chicago
Tevatron and Experiments
Tevatron and Experiments
Tevatron and Experiments

Run II Integrated Luminosity

19 April 2002 - 24 July 2011

Delivered
Recorded

11.57
10.36

Analyzed data for this combination: \( \leq 8.6 \text{ fb}^{-1} \)

Over 10 fb\(^{-1}\) on tape!
Constraints on the SM Higgs Boson

What we know:

• Direct search at LEPII:
  \[ M_h > 114 \text{ GeV/c}^2 @ 95\% \text{ CL} \]

• Precision EWK measurements (top mass, W mass, etc):
  \[ M_h = 89.0^{+35}_{-26} \text{ GeV/c}^2 \]
  \[ M_h < 158 \text{ GeV/c}^2 @ 95\% \text{ CL} \]
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

![Diagram showing SM Higgs production processes]

- $gg \rightarrow h$
- $qq \rightarrow Wh$
- $qq \rightarrow qqh$
- $bb \rightarrow h$
- $qq \rightarrow Zh$
- $gg,qq \rightarrow tth$

$\sigma [fb]$ vs. $\sqrt{s}$

Richard E, Hughes, The Ohio State University
### Higgs Search Challenges

**Expected number of events per fb⁻¹ per experiment**

<table>
<thead>
<tr>
<th>Higgs Mass (GeV/c²)</th>
<th>WH→lvbb</th>
<th>ZH→vvbb</th>
<th>ZH→llbb</th>
<th>H→WW→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→bb channels and ~25% in H→WW channels
Combining Channels

- **Our goal:** "No Higgs events left behind"

- **Best sensitivity** is obtained through the combination of many independent search channels

<table>
<thead>
<tr>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH \rightarrow lvbb$</td>
</tr>
<tr>
<td>$ZH \rightarrow vvbb$</td>
</tr>
<tr>
<td>$ZH \rightarrow llbb$</td>
</tr>
<tr>
<td>$WH/ZH \rightarrow jjbb$</td>
</tr>
<tr>
<td>$ttH \rightarrow WbWbbb$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
</tr>
<tr>
<td>$WH \rightarrow lv\tau\tau / ZH \rightarrow ll\tau\tau$</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow lvlv$</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow lvjj$</td>
</tr>
<tr>
<td>$WH \rightarrow WWW / ZH \rightarrow ZWW$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
</tr>
</tbody>
</table>
Combination Methods

- Two statistical approaches used
  - Bayesian: Flat signal prior, credibility intervals
  - Modified frequentist: Log-likelihood test statistic, \( CL_s = \frac{CL_s + b}{CL_b} \)

- Better than 10% agreement over whole mass range (~2% on average)

- Operate on binned, final discriminants
  - Poisson statistics assumed for each bin
Systematic Uncertainties

• Include systematic uncertainties on both signal and background
  • Normalization
  • Shape of final discriminations
• Systematics are incorporated in limit setting procedure as nuisance parameters
  • Correlations between different channels is taken into account

In this way, backgrounds can be further constrained by using information from different channels
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
Example Single Channel Result: ttH

- Search for events that are t-tbar like, but with higher jet multiplicity (>=4 jets) and more b-tags (>= 2 b-tags)

- Search for a Higgs boson in the range: 100 GeV/c$^2$ - 170 GeV/c$^2$, using neural networks optimized for each mass point independently.
- Search for events that are t-tbar like, but with higher jet multiplicity (>=4 jets) and more b-tags (>= 2 b-tags)

- Search for a Higgs boson in the range: 100 GeV/c^2 - 170 GeV/c^2, using neural networks optimized for each mass point independently.
Example Systematics: CDF $ttH$

**Systematics**

<table>
<thead>
<tr>
<th>5 jets</th>
<th>STSTST $tt$</th>
<th>STSTST $ttH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS$_{ttH}$</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>XS$_{ttbar}$</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>LUMI</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>CDFLUMI</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>BTAGSF</td>
<td>$+11$</td>
<td>$+9.9$</td>
</tr>
<tr>
<td>$-16$</td>
<td>$-13$</td>
<td></td>
</tr>
<tr>
<td>CDFMISTAG</td>
<td>$+8.1$</td>
<td>$+1.3$</td>
</tr>
<tr>
<td>$-3.4$</td>
<td>$-0.5$</td>
<td></td>
</tr>
<tr>
<td>CDFJES</td>
<td>$+15$</td>
<td>$-2.7$</td>
</tr>
<tr>
<td>$-15$</td>
<td>$-8.1$</td>
<td></td>
</tr>
<tr>
<td>ISRFSR</td>
<td>$+14$</td>
<td>$-1.9$</td>
</tr>
<tr>
<td>$-2.0$</td>
<td>$+1.9$</td>
<td></td>
</tr>
</tbody>
</table>

Systematics which can be correlated across the two experiments: signal/background cross sections, luminosity.

Systematics which can be correlated within one experiment: portion of luminosity, b-tagging, jet energy scale, etc.
Example Limit Plot: CDF $t\bar{t}H$

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

Observed limit (solid line) from data

Analysis repeated using different signal templates for each $m_H$ between 100 and 200 GeV in 5 GeV steps
## Combination Inputs

### CDF

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb⁻¹)</th>
<th>m_H range (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH → ℓνbb 2-jet channels</td>
<td>4× (TDT,LDT,ST,LDTX)</td>
<td>7.5</td>
</tr>
<tr>
<td>WH → ℓνbb 3-jet channels</td>
<td>2× (TDT,LDT,ST)</td>
<td>5.6</td>
</tr>
<tr>
<td>ZH → ννbb (TDT,LDT,ST)</td>
<td></td>
<td>7.8</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ⁻b̄b</td>
<td>2× (TDT,LDT,ST)</td>
<td>7.7</td>
</tr>
<tr>
<td>H → W⁺W⁻ 2× (0 jets, 1 jet) + (2 or more jets) + (low-m_ℓℓ) + (e−τHad) + (μ−τHad)</td>
<td>8.2</td>
<td>110-200</td>
</tr>
<tr>
<td>WH → W+W⁻ (same-sign leptons) + (tri-leptons)</td>
<td></td>
<td>8.2</td>
</tr>
<tr>
<td>ZH → ZW+W⁻ (tri-leptons with 1 jet) + (tri-leptons with 2 or more jets)</td>
<td></td>
<td>8.2</td>
</tr>
<tr>
<td>H + X → τ⁺τ⁻ (1 jet) + (2 jets)</td>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td>WH → ℓντ⁺τ⁻/ZH → ℓ⁺ℓ⁻τ⁺τ⁻ (ℓ−ℓ−τHad) + (e−μHad) + (μ−τHad) + (ℓ−τHad−τHad)</td>
<td>6.2</td>
<td>110-150</td>
</tr>
<tr>
<td>WH + ZH → jjbb (GF, VBF) × (TDT, LDT)</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>H → γγ (CC, CP, CC-Conv, CP-Conv)</td>
<td></td>
<td>7.0</td>
</tr>
<tr>
<td>tTH → WWb̄b̄b̄b̄ (lepton)</td>
<td>(4jet, 5jet) × (TTT, TTTL, TL, TTL, TDT, LDT)</td>
<td>6.3</td>
</tr>
<tr>
<td>tTH → WWb̄b̄b̄b̄ (no lepton)</td>
<td>(low met, high met) × (2 tags, 3 or more tags)</td>
<td>5.7</td>
</tr>
</tbody>
</table>

### DØ

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb⁻¹)</th>
<th>m_H range (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH → ℓνbb (LST, LDT, 2,3 jet)</td>
<td>8.5</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH → ννbb (LST, LDT)</td>
<td>8.4</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ−b̄b (TST, TLDT, ee, μμ, eeICR, μμtrk)</td>
<td>8.6</td>
<td>100-150</td>
</tr>
<tr>
<td>H + X → ℓ±τHadjj</td>
<td>4.3</td>
<td>105-200</td>
</tr>
<tr>
<td>VH → ℓ±ℓ± + X</td>
<td>5.3</td>
<td>115-200</td>
</tr>
<tr>
<td>H → W+W⁻ → ℓ±νℓ±ν (0, 1, 2+ jet)</td>
<td>8.1</td>
<td>115-200</td>
</tr>
<tr>
<td>H → W+W⁻ → μντHadν</td>
<td>7.3</td>
<td>115-200</td>
</tr>
<tr>
<td>H → W+W⁻ → ℓνjj</td>
<td>5.4</td>
<td>130-200</td>
</tr>
<tr>
<td>H → γγ</td>
<td>8.2</td>
<td>100-150</td>
</tr>
</tbody>
</table>

71 exclusive sub-channels

94 exclusive sub-channels
Example Channels

ZH → l⁺l⁻bb
(see M. Kirby’s talk Friday)

H → W⁺W⁻
(see B. Carls’ talk Wednesday)
Combining Regions of Similar s/b

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

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

July 17, 2011

Integrated Expected Signal vs. Cumulative Events

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

July 17, 2011
Combined Discriminants

\[ m_H = 115 \text{ GeV/c}^2 \]
What a 5\(\sigma\) Observation Looks Like

(a) SD + MJ Combination
- CDF Data
- Single Top
- Background

(b) SD + MJ Combination
- CDF Data
- Signal + Background
- Background

arXiv:1004.1181 Accepted by PRD

CDF Single Top, 3.2 fb\(^{-1}\)
Example Individual Channel Limits
CDF/D0 Combined Limits

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

- LEP Exclusion
- CDF Exclusion

95% CL Limit / SM

- SM = 1

CDF-only combination

D0 Preliminary, L=4.3-8.6 fb$^{-1}$

- Observed
- Expected
- Expected ±1σ
- Expected ±2σ

95% CL Limit / SM

- SM = 1.0

D0-only Combination

Richard E, Hughes, The Ohio State University
New Tevatron Combination

Observed Exclusion: 100-109 and 156-177 GeV/c^2

Expected Exclusion: 100-108 and 148-181 GeV/c^2
S+B versus B-only Hypotheses

\[ \text{LLR} = -2\ln Q \text{ where } Q = \frac{L_{s+b}}{L_b} \]

Larger separation = greater sensitivity
Other combinations: $H \rightarrow bb$

- Look at associated production & $H \rightarrow bb$ decay
- These channels provide 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

```
Observed and expected in good agreement
```
H→bb Compared to Expectations

Observed vs Expected with Injection of Higgs

CDF II x 2 Preliminary (5.7 fb⁻¹)

Expected Limits ± 1σ

Expected Limits ± 2σ

Expected with Injected M_H = 115 GeV/c²

Tevatron Run II Preliminary H→bb Combination, L ≤ 8.6 fb⁻¹

95% CL Limit/SM

Tevatron Exclusion

Higgs Mass (GeV/c²)

m_H (GeV/c²)
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.
- Look at $H \rightarrow WW/ZZ$ decays • Set limits on cross section x Br.
- Observed exclusion: $124 < m_H < 286$ GeV.
Fermiophobic Higgs

- “benchmark” Fermiophobic model
- No Higgs coupling to fermions
- SM Higgs coupling to bosons
- \( \text{Br}(h \rightarrow bb) \) suppressed by \( m_b = m_W^2 \)
- \( \text{Br}(h \rightarrow \Upsilon \Upsilon) \) high for low mass (\( m_h < 110 \text{ GeV/c}^2 \))
- Only WH, WZ, and VBF production (no gg → h)
- SM production cross section assumed

\[ m_H > 114.8 \text{ GeV/c}^2 \]
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.
• 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 10 fb\(^{-1}\) datasets that achieve our promised sensitivity goals.
Implies Tevatron 95% C.L. exclusion sensitivity over the entire Higgs mass range between 100 and 185 GeV/c² for next spring.

Better than 3σ for $m_H = 115$ GeV/c²

Only 2.4σ for $m_H = 130$ GeV/c²
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 bb Higgs decay mode

- We continue to improve our analyses: 5 new channels this summer, substantial improvement in existing channels
Updated Global EWK Fit

EPS 2011: $m_t = 173.2 \pm 0.9$ GeV, LEP & Tevatron Higgs Searches

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b}$$

**Tevatron RunII Preliminary**

L ≤ 8.6 fb⁻¹

- **CL_s Observed**
- **CL_s Expected**
- **Expected ±1 σ**
- **Expected ±2 σ**

**July 17, 2011**

**m_\text{H} (GeV/c^2)**
Confidence Levels

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

Limit/SM

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

July 17, 2011
Comparison with ATLAS
Event Display

Run, Event: 196170, 6577
Dijet Mass: 126.44 GeV/c^2
Z Mass: 97.94 GeV/c^2
N Jets: 2
MET: 10.12 GeV
ZH NN: 0.94, tt NN: 8.5 x 10^{-4}
S/B @ 115 GeV/c^2: 0.25

Jet 2
P_T 29.0 GeV/c

Jet 1
P_T 124.9 GeV/c

Lepton 2
P_T 54.8 GeV/c

Lepton 1
P_T 102.1 GeV/c
Recent History

Summer 2010

Tevatron Run II Preliminary, $<L> = 5.9$ fb$^{-1}$

95% CL Limit/SM

SM excluded:

158 < $m_H$ < 175 GeV  obs
156 < $m_H$ < 173 GeV  exp

Spring 2011

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

95% CL Limit/SM

SM excluded:

158 < $m_H$ < 173 GeV  obs
153 < $m_H$ < 179 GeV  exp