Tevatron Combination of SM Higgs Searches and Fourth Generation Limits

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For the CDF and DØ Collaborations

19th International Conference on Supersymmetry and Unification Of Fundamental Interactions
Fits and Constraints

- Electroweak symmetry breaking is a cornerstone of the standard model
- Higgs mechanism provides mass for the W and Z
- A consequence of this is the Higgs boson
- Mass is not predicted

\[ M_H < 158 \text{ GeV (indirect constraints)} \]
\[ M_H < 185 \text{ GeV (include LEP search)} \]
Run II Integrated Luminosity

Delivered Recorded 11.7 fb⁻¹

Today: Up to 8.6 fb⁻¹

10.4 fb⁻¹
For $M_H \lesssim 135$ GeV, $H \rightarrow bb$ dominates

Control bg with leptons from associated $W/Z$
Higgs Production and Decay

- For $M_H \approx 135$ GeV, $H \rightarrow WW$ dominates
- Control bg with leptons from W decays
Leave No Higgs Behind

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity $(fb^{-1})$</th>
<th>$m_H$ range $(GeV/c^2)$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH \rightarrow \ell\nu bb$ 2-jet channels</td>
<td>4x(TDT,LDT,ST,LDTX)</td>
<td>7.5</td>
<td>100-150</td>
</tr>
<tr>
<td>$WH \rightarrow \ell\nu bb$ 3-jet channels</td>
<td>2x(TDT,LDT,ST)</td>
<td>5.6</td>
<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \nu\nu bb$ (TDT,LDT,ST)</td>
<td></td>
<td>7.8</td>
<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+\ell^- bb$</td>
<td>2x(TDT,LDT,ST)</td>
<td>7.7</td>
<td>100-150</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- 2x(0$ jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$)+(e-$\tau_{had}$)+(\mu-$\tau_{had}$)</td>
<td>8.2</td>
<td>110-200</td>
<td>[10]</td>
</tr>
<tr>
<td>$WH \rightarrow W^+W^-$(same-sign leptons)+(tri-leptons)</td>
<td></td>
<td>8.2</td>
<td>110-200</td>
</tr>
<tr>
<td>$ZH \rightarrow ZW^+W^-$(tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)</td>
<td></td>
<td>8.2</td>
<td>110-200</td>
</tr>
<tr>
<td>$H + X \rightarrow \tau^+\tau^-$ (1 jet)+(2 jets)</td>
<td></td>
<td>6.0</td>
<td>100-150</td>
</tr>
<tr>
<td>$WH \rightarrow \ell\nu\tau^+\tau^- /ZH \rightarrow \ell^+\ell^-\tau^+\tau^- (\ell-\ell\tau_{had})+(e-$\mu$-$\tau_{had}$)+(\ell-$\tau_{had}$-$\tau_{had}$)</td>
<td></td>
<td>6.2</td>
<td>110-150</td>
</tr>
<tr>
<td>$WH \rightarrow jbjj$ (GF,VBF) x(TDT,LDT)</td>
<td></td>
<td>4.0</td>
<td>100-150</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv)</td>
<td></td>
<td>7.0</td>
<td>100-150</td>
</tr>
<tr>
<td>$t\bar{t}H \rightarrow WWbbbb$ (lepton)</td>
<td>4jet,5jet x(TTT,TTL,TTL,TTT,LDT,LDT)</td>
<td>6.3</td>
<td>100-150</td>
</tr>
<tr>
<td>$t\bar{t}H \rightarrow WWbbbb$ (no lepton)</td>
<td>(low met,high met) x(2 tags,3 or more tags)</td>
<td>5.7</td>
<td>100-150</td>
</tr>
</tbody>
</table>

**TABLE III:** Luminosity, explored mass range and references for the different processes and final states ($\ell = e, \mu$) for the D0 analyses.

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<tr>
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<td>$WH \rightarrow \ell\nu bb$ (LST,LDT,2,3 jet)</td>
<td></td>
<td>8.5</td>
<td>100-150</td>
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<td>$ZH \rightarrow \nu\nu bb$ (LST,LDT)</td>
<td></td>
<td>8.4</td>
<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+\ell^- bb$ (TST,TLD,ee,ee$\mu\mu$,ee$\gamma\gamma$,$\mu\mu$,$\gamma\gamma$)</td>
<td></td>
<td>8.6</td>
<td>100-150</td>
</tr>
<tr>
<td>$H + X \rightarrow \ell^+\tau^-_{had}$</td>
<td></td>
<td>4.3</td>
<td>105-200</td>
</tr>
<tr>
<td>$VH \rightarrow \ell^+\ell^- + X$</td>
<td></td>
<td>5.3</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^+\nu$ (0,1,2+ jet)</td>
<td></td>
<td>8.1</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \mu\nu\tau_{had}$</td>
<td></td>
<td>7.3</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \ell\nu j\bar{j}$</td>
<td></td>
<td>5.4</td>
<td>130-200</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td></td>
<td>8.2</td>
<td>100-150</td>
</tr>
</tbody>
</table>
### Tevatron Combined SM and 4th Gen Higgs Limits

#### Leave No Higgs Behind

Many different channels from both CDF and DØ

For more details, see talks by X. Bu, G. Facini, S. Shalhout, R. Nayyar

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<td>$WH \rightarrow \ell\nu b\bar{b}$ 2-jet channels</td>
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<tr>
<td>$WH \rightarrow \ell\nu b\bar{b}$ 3-jet channels</td>
<td>$2 \times (\text{TDT, LDT, ST})$</td>
<td>5.6</td>
<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+\ell^- b\bar{b}$</td>
<td>$(\text{TDT, LDT, ST})$</td>
<td>7.8</td>
<td>100-150</td>
</tr>
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<td>$ZH \rightarrow \ell^+\ell^- b\bar{b}$</td>
<td>$2 \times (\text{TDT, LDT, ST})$</td>
<td>7.7</td>
<td>100-150</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^-$</td>
<td>$2 \times (0 \text{ jets, 1 jet} + (2 \text{ or more leptons}))$</td>
<td>8.2</td>
<td>110-200</td>
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<td>$WH \rightarrow WW^+W^-$ (same-sign leptons)+(tri-leptons)</td>
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<td>110-200</td>
</tr>
<tr>
<td>$ZH \rightarrow ZW^+W^-$ (tri-leptons with 1 jet)</td>
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<td>8.2</td>
<td>110-200</td>
</tr>
<tr>
<td>$H + X \rightarrow \tau^+\tau^-$ (1 jet)+(2 jets)</td>
<td>6.0</td>
<td>100-150</td>
<td>13</td>
</tr>
<tr>
<td>$WH \rightarrow \ell\nu\tau^+\tau^-/ZH \rightarrow \ell^+\ell^+\tau^-\tau^-$ (1 jet)+(2 jets)</td>
<td>5.2</td>
<td>110-150</td>
<td>14</td>
</tr>
<tr>
<td>$WH + ZH \rightarrow jjbb$ (GF,VBF)×(TDT,LDT)</td>
<td>4.0</td>
<td>100-150</td>
<td>15</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv)</td>
<td>7.0</td>
<td>100-150</td>
<td>16</td>
</tr>
<tr>
<td>$ttH \rightarrow WWbbbb$ (lepton)</td>
<td>$(4\text{jet, 5jet}) \times (\text{TDT,LDT})$</td>
<td>6.3</td>
<td>100-150</td>
</tr>
<tr>
<td>$ttH \rightarrow WWbbbb$ (no lepton)</td>
<td>$(\text{low m_{tt}, high m_{tt}}) \times (2 \text{ tags, 3 or more tags})$</td>
<td>5.7</td>
<td>100-150</td>
</tr>
</tbody>
</table>

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**TABLE III:** Luminosity and $m_H$ range for different analyses of Higgs searches ($\ell = e, \mu$) for the DØ analyses.

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<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell\nu b\bar{b}$ (LST,LDT)</td>
<td>8.4</td>
<td>100-150</td>
<td>19</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+\ell^- b\bar{b}$</td>
<td>(TST,LDT,ee,ee,μμ,ee,μγ,μγ,μγ)</td>
<td>8.6</td>
<td>100-150</td>
</tr>
<tr>
<td>$H + X \rightarrow \ell^+\tau^\pm hj$</td>
<td>4.3</td>
<td>105-200</td>
<td>21</td>
</tr>
<tr>
<td>$VH \rightarrow \ell^+\ell^- + X$</td>
<td>5.3</td>
<td>115-200</td>
<td>22</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\nu$</td>
<td>$(0,1,2+ \text{ jet})$</td>
<td>8.1</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\nu$</td>
<td>7.3</td>
<td>115-200</td>
<td>24</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^- \rightarrow \ell^+\ell^-j$</td>
<td>5.4</td>
<td>130-200</td>
<td>25</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>8.2</td>
<td>100-150</td>
<td>26</td>
</tr>
</tbody>
</table>
Search for $H \rightarrow WW$ (example)

- Exploit low S/B regions without diluting more sensitive subsamples
- Selection defined by final state
- Train multivariate discriminants to extract more sensitivity
Combined Discriminants

\( M_H: 115 \text{ GeV} \)

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

\( m_H = 115 \text{ GeV/c}^2 \)

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

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

\( m_H = 115 \text{ GeV/c}^2 \)

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Combined Discriminants

\[ M_H : 165 \text{ GeV} \]

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

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

Events

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

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

Cumulative Events

Integrated Expected Signal

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

CDF + D0 Run II Preliminary, \( L \leq 8.6 \text{ fb}^{-1} \)
Systematic Uncertainties

- Limits extracted using shape comparisons of final discriminant
  - Important to consider
    - Normalization uncertainties
    - Shape uncertainties
  - Track correlations across channel and experiment

<table>
<thead>
<tr>
<th>Source</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>2%</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>1-3%</td>
</tr>
<tr>
<td>Jet Identification</td>
<td>2%</td>
</tr>
<tr>
<td>Multijet Estimate</td>
<td>0-25%</td>
</tr>
<tr>
<td>b-tagging Efficiency</td>
<td>1-6%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6%</td>
</tr>
<tr>
<td>Cross Sections</td>
<td>6-20%</td>
</tr>
</tbody>
</table>
Getting the Results

- Use Bayesian method
- Use CLs as cross check
- Agree within 2% on average (at worst 10% depending on $M_H$)

Bayesian Method

\[ \prod_{i} \text{Poisson} \left( x_i \mid B_i(\theta) + RS(\theta) \right) \]

\[
0.95 = \frac{\int_{0}^{\text{limit}} dR \int L(RS, B, x, \theta) d\theta}{\int_{0}^{\infty} dR \int L(RS, B, x, \theta) d\theta}
\]
The Log Likelihood Ratio

Tevatron RunII Preliminary

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

LLR from CLs method

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Tevatron Combined SM and 4th Gen Higgs Limits

Excluded Regions:
- Observed: 100-109 and 156-177 GeV
- Expected: 100-108 and 148-181 GeV

Limits at $M_H = 115$ GeV:
- Observed: $1.16 \times \sigma_{SM}$
- Expected: $1.17 \times \sigma_{SM}$
Fourth Generation Models

- Additional quark loops enhance $\sigma(gg\rightarrow H)$ by factor of 9
- Higgs mass up to 300 GeV allowed by indirect constraints

- Two scenarios based on mass of extra leptons
  - Low mass exclusion: 124 – 286 GeV
  - High mass exclusion: 124 – 300 GeV
Looking to the Future

Already recorded more than 10 fb^{-1}

2xCDF Preliminary Projection, m_H=115 GeV

Projected Improvements
Summary

- We already exclude a significant part of the $M_H$ range allowed by electroweak fits
- Tevatron reaching sensitivity in dominant decay modes in the most interesting region
- Look forward to an exciting set of results in 2012

http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
http://www-cdf.fnal.gov/physics/new/hdg/hdg.html
Summary

- We already exclude a significant part of the $M_H$ range allowed by electroweak fits
- Tevatron reaching sensitivity in dominant decay modes in the most interesting region
- Look forward to an exciting set of results in 2012

Stay Tuned!!!

http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
http://www-cdf.fnal.gov/physics/new/hdg/hdg.html
Between the High and the Low

Tevatron Combined SM and 4th Gen Higgs Limits

High mass channels from Moriond 2011

Sensitivity at $M_H = 135$ GeV:
$2.2 \times \sigma_{SM}$

Sensitivity at $M_H = 135$ GeV:
$2.? \times \sigma_{SM}$
The Big Picture

Tevatron Combined SM and 4th Gen Higgs Limits

**Tevatron Run II Preliminary, L ≤ 8.6 fb⁻¹**

- **LEP Exclusion**
- **Tevatron Exclusion**

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**ATLAS Preliminary**

- **Observed**
- **Expected**

∫ L dt = 1.0-2.3 fb⁻¹

**CMS Preliminary, √s = 7 TeV**

- **Combined observed**
- **Combined expected**

Experimental Results

- **H → bb**
- **H → WW**
- **H → ZZ → 4l**
- **H → ZZ → 2l 2τ**
- **H → ZZ → 2l 2q**

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

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

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**SM = 1**

**Tevatron Exclusion**

Higgs boson mass (GeV/c²)

100 110 120 130 140 150 160 170 180 190 200

m_H (GeV/c²)

10 1 1 200 180 160 140 120 100

95% CL Limit/SM

10 1 1

Higgs boson mass (GeV/c²)

100 200 300 400 500 600

100 110 120 130 140 150

m_H (GeV/c²)

10 1 1

95% CL Limit/SM

10 1 1
1-CLs

Tevatron RunII Preliminary

L ≤ 8.6 fb⁻¹

95% C.L.

Tevatron Combined SM and 4th Gen Higgs Limits
Tevatron RunII Preliminary

CLs

L ≤ 8.6 fb⁻¹

CLs Observed

CLs Expected

Expected ±1 σ

Expected ±2 σ

1-CLs:

68%

95%

99.5%

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m_H (GeV/c²)