Higgs Searches at the Tevatron

Aart Heijboer
(CERN, before: University of Pennsylvania/CDF)

for the DØ and CDF collaborations
Contents:

- Introduction & the Tevatron
- Beyond Standard Model Higgs
  - MSSM
  - fermiophobic Higgs
- Standard Model Higgs
  - low mass
  - high mass
- Combination
Introduction

Higgs mechanism is responsible for breaking is prime suspect for electroweak symmetry breaking and provides a way for the fermions to obtain mass.

If Higgs is Standard Model Higgs, Tevatron is looking in the right place.

But we should also look for Supersymmetric Higgs.
The Tevatron at Fermilab

Tevatron Run II p̅p collider at 1.96 TeV
Tevatron Run II pp collider at 1.96 TeV

Tevatron performing very well. Expect 6-8 fb\(^{-1}\) datasets by end of 2009 (possibly run in 2010)
The Tevatron at Fermilab: DØ and CDF

Two multipurpose detectors: D0 and CDF collecting data with high efficiency.

- excellent lepton ID
- muon systems
- EM cal and tracking.
- Good calorimeters for jet energy resolution
- Silicon detectors for identifying b-jets
The Challenge

Recently started to see the rarest of these:
- testing ground for analysis techniques: (single) top, observation of ZZ
- all processes are crucial for background modeling eg: Wb, Wbb, Zbb

First Trigger on:
- high $P_T$ leptons (also $\tau$)
- MET (+jets)
- Then, improve s/b by
  - efficient lepton ID
  - B-tagging
  - Advanced multivariate techniques

Higgs production very rare. Initial S/B < $10^{-10}$
Important tool: B-jet identification

B-tagging by finding secondary vertex
- **DØ**: powerful NN tagger
- **CDF**:
  - Secondary vertex tagger (SECVTX)
  - NN flavour separator to improve SECVTX output.
  - Jet probability tagger.
Beyond the Standard Model
Higgs Searches
Beyond SM Higgs Scenarios

**MSSM Higgs sector:**
2 charged Higgses
• $H^+ H^-$
3 neutral ones:
• A: CP-odd
• $h$ & $H$: cp even

• A has ~same mass as $h$ or $H$ and is SM-like.
• Coupling to down-type fermions enhanced for large tan $\beta$

• CDF and D0 looked for $H^+, H^-$ and $H^{++}, H^{--}$
  • direct production, e.g. decay into top
  • top decays into charged Higgs

• Several searches for SM-like Higgs in MSSM:
  • Sensitive to direct production in models with large tan $\beta$.
  • will discuss: $bbH \rightarrow bbbb$ and $H \rightarrow \tau\tau$

• Fermiophobic Higgs, decaying into $WW$ or $\gamma\gamma$
  will discuss: $H \rightarrow \gamma\gamma$ (DØ), $WH \rightarrow WWW$

![Diagram of Higgs production and decay](image)
$b\phi \rightarrow bbb$ searches

- High $E_T$ jets from $f$ decay: search for mass peak in 2 leading jets.
- require 3 $b$-jets for optimal S/B
- Understanding composition of $b$-tagged jets is key:
  - CDF: Vertex mass fits
  - DØ: multiple operating points of NN tagger
- DØ also has a $b\phi \rightarrow b\tau\tau$ search with similar sensitivity.
$\phi \rightarrow \tau\tau$ searches

- $\tau\tau$ signature pure enough to search for direct production
- Hadronic $\tau$ id capabilities developed and tested on large samples of W and Z events.

Similar limits across experiments and channels ($\tau\tau$ and $b\bar{b}b$) → Combining results will greatly improve the limits.
Fermiophobic Higgs:

DØ: H → γγ
• Photons selected with NN using calorimeter and track information.
• Look for mass peak
• Really a standard model search, with increased sensitivity if Higgs is fermiophobic
  • Branching ratio up to 10% in stead of SM value of 1e-3.

WH → WWW
• Look for two same-sign leptons
• Also sensitive to SM, at high mass where H → WW
• At low mass: more sensitive if H is fermiophobic.
• DØ has competitive result.
Standard Model Higgs Searches
SM Production and decay modes

High Mass
(M_H > ~135 GeV)

- H → WW → ll vv.
- backgrounds low enough to use gg → H
- signature: leptons and MET

Low Mass
(M_H <~135 GeV)

- Higgs goes to b's to τ's
- Identification of b-jets (or τ's)
- gg → H → bb swamped by background
- detect associated W or Z: leptons, MET
Low mass: WH → lνbb

- Signature: High $E_T$ lepton, MET, bjets
- Use isolated tracks as leptons and use forward electrons
- 2 bjets: require one or two tags, treated separately
- DØ: allow events with 3 jets.
- CDF: ME + BDT includes: NN b-tagger, and NN for jet corrections.

- Major background: Wbb, W+mistags, (modeled by a combination of data and MC)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lum (fb⁻¹)</th>
<th>Higgs Events</th>
<th>Exp. Limit</th>
<th>Obs. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF NN</td>
<td>2.7</td>
<td>8.3</td>
<td>5.8</td>
<td>5.0</td>
</tr>
<tr>
<td>CDF ME+BDT</td>
<td>2.7</td>
<td>7.8</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>DØ NN</td>
<td>1.7</td>
<td>7.5</td>
<td>8.5</td>
<td>9.3</td>
</tr>
</tbody>
</table>
Low mass: Missing $E_T + b$-jets

- Signature: Large MET and $b$-jets.
- Also sensitive to WH, where the lepton is undetected.
- Challenge: QCD events modeled from data

CDF NN analysis
- Allows 3-jet events, giving extra acceptance to $W \rightarrow W \rightarrow \tau\nu$. (D0 has dedicated $W \rightarrow \tau\nu$ search)
- 1 or 2 $b$-tags (or 2 mixed $b$-tags)
- Use H1 algorithm for $E_{jet}$ measurement

DØ BDT analysis
- Use NN $b$-tagger asymmetrically (one tight, one loose tag).
- 24 input variables.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lum (fb$^{-1}$)</th>
<th>Higgs Events</th>
<th>Exp. Limit</th>
<th>Obs. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF NN</td>
<td>2.1</td>
<td>7.3</td>
<td>6.3</td>
<td>7.9</td>
</tr>
<tr>
<td>DØ BDT</td>
<td>2.1</td>
<td>3.7</td>
<td>8.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Low mass: $l^+l^- + b$-jets

Very clean ($M_{ll} = M_Z$), but very rare → maximize acceptance:
- loose $b$-tagging (1 or 2 tags)
- extra leptons: isolated tracks, Calorimeter-only electrons. (CDF)
- CDF uses MET to constrain jet energies.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lum (fb$^{-1}$)</th>
<th>Higgs Events</th>
<th>Exp. Limit</th>
<th>Obs. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF NN</td>
<td>2.4</td>
<td>1.8</td>
<td>11.8</td>
<td>11.6</td>
</tr>
<tr>
<td>CDF ME(120)</td>
<td>2.0</td>
<td>1.4</td>
<td>15.2</td>
<td>11.8</td>
</tr>
<tr>
<td>DØ NN,BDT</td>
<td>2.3</td>
<td>2.0</td>
<td>12.3</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Low mass: additional channels:

- Hadronic τ + MET + 2 b jets
- Use DiJet mass to extract signal
- 0.9 fb\(^{-1}\)
- obs(exp)/sm: 35.4 (42.1) @\(M_H = 115\) GeV

\[\tau_{\text{had}} + \tau_{\text{lep}} + 2\text{ jets}\]

- Uses multiple NN's to reject Z, ttbar, QCD.
- 2.2 fb\(^{-1}\)
- obs(exp)/sm: 30.5 (24.8) @\(M_H = 115\) GeV

4 jets, at least 2 b jets
- Large BR for W/Z→qq
- Large QCD bkg, model from data
- ME technique
- obs(exp)/sm: 37.0 (36.6) @\(M_H = 115\) GeV

not as sensitive, but help in the combination.
Summary of low mass SM Higgs searches

<table>
<thead>
<tr>
<th>Channel</th>
<th>95% C.L. Limits (\sigma\cdot{\text{BR}}/\text{SM obs (exp)})</th>
<th>95% C.L. Limits (\sigma\cdot{\text{BR}}/\text{SM obs (exp)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH→lvbb</td>
<td>5.7 (5.6)* 2.7fb(^{-1})</td>
<td>9.3 (8.5) 1.7fb(^{-1})</td>
</tr>
<tr>
<td>WH→τvbb</td>
<td>-</td>
<td>35.4 (42.1) 0.9fb(^{-1})</td>
</tr>
<tr>
<td>VH→qqbb</td>
<td>37.0 (36.6) 2.0fb(^{-1})</td>
<td>-</td>
</tr>
<tr>
<td>ZH→llbb</td>
<td>11.6 (11.8) 2.4fb(^{-1})</td>
<td>11.0 (12.3) 2.3fb(^{-1})</td>
</tr>
<tr>
<td>VH→vv/(l)bb</td>
<td>7.9 (6.3)* 2.1fb(^{-1})</td>
<td>7.5 (8.4) 2.1fb(^{-1})</td>
</tr>
<tr>
<td>ttH→lvbbbbbbqq</td>
<td>-</td>
<td>63.9 (45.3) 2.1fb(^{-1})</td>
</tr>
<tr>
<td>H→γγ</td>
<td>-</td>
<td>30.8 (23.2) 2.7fb(^{-1})</td>
</tr>
<tr>
<td>H→ττ</td>
<td>30.5 (24.8) 2.2fb(^{-1})</td>
<td>-</td>
</tr>
</tbody>
</table>

* in case of multiple analyses, showing result with best expected limit

on to high mass....
High Mass Standard Model Higgs Searches.

Signature
- Two leptons in ~same direction due to spin correlation
- 1 or 2 additional jets (associated production, VBF)
- key issue: maximize lepton acceptance.

CDF:
- analyze in 0,1 and >1 jet events bins
- 0 jets: NN with ME likelihood as one of the inputs.
- Separate high S/B and low S/B leptons.
- 1,2 extra jets: NN analysis. Adds signal from Associated production and VBF.

D0: NN analysis.
- allow for jets to be present.
- 14 variables,
- separate ee, eμ, μμ channels
High Mass Standard Model Higgs Searches.

Results at $m_H = 165\text{GeV}$: 95% CL Limits/SM

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lum (fb$^{-1}$)</th>
<th>Higgs Events</th>
<th>Exp. Limit</th>
<th>Obs. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF ME+NN</td>
<td>3.0</td>
<td>17.2</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>DØ NN</td>
<td>3.0</td>
<td>15.6</td>
<td>1.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

NB: Also contributes at lower MH!
Combined SM Higgs results
Combined full mass range results, per experiment

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$M_H = 115$ GeV</th>
<th>$M_H = 165$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF NN</td>
<td>3.6 exp 4.2 obs</td>
<td>1.6 exp 1.6 obs</td>
</tr>
<tr>
<td>DØ BDT</td>
<td>4.6 exp 5.3 obs</td>
<td>1.9 exp 2.0 obs</td>
</tr>
</tbody>
</table>

Tevatron-wide low-mass (>70 channels) difficult. Full range combination coming soon. Expect $\sim 3 \times \sigma(sm)$ at 115 GeV.
Tevatron combined results: High mass SM Higgs

We exclude, at 95% CLs, $M_H=170$ GeV. First direct exclusion since LEP!

- Bayesian and Modified frequentist approaches used. (agree well).
- Systematics and their correlations between channels and experiments taken into account.
Conclusions:

- Both SM and Susy Higgs searches are being fiercely pursued
  - Tevatron performing well: Luminosity still increasing fast
  - Many improvements in the analysis techniques too.

- MH=170 GeV Mass point now excluded and 95% Cls!
- Larger exclusion zone around 170 GeV will follow soon... or see first hints of excess.
- Many results still to come soon – e.g. combined Tevatron result for low masses. (expect factor of 3 above SM).

all results available from [http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm](http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm) and [http://www-cdf.fnal.gov/physics/new/hdg/hdg.html](http://www-cdf.fnal.gov/physics/new/hdg/hdg.html)
“Motivation”

In a race, the quickest runner can never overtake the slowest, since the pursuer must first reach the point whence the pursued started, so that the slower must always hold a lead.

—Aristotle, Physics
Tevatron Run II Preliminary, L=3 fb^{-1}

<table>
<thead>
<tr>
<th>M Higgs (GeV)</th>
<th>160</th>
<th>165</th>
<th>170</th>
<th>175</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1: Exp</td>
<td>1.3</td>
<td>1.2</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Method 1: Obs</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Method 2: Exp</td>
<td>1.2</td>
<td>1.1</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Method 2: Obs</td>
<td>1.3</td>
<td>1.1</td>
<td>0.95</td>
<td>1.2</td>
</tr>
</tbody>
</table>
MSSM charged Higgses to and from top
Sensitivity projections

\[ m_H = 115 \text{ GeV} \]

Winter 2008 = old
(Analyses updated since this)

\[ m_H = 160 \text{ GeV} \]

CDF Run II Preliminary

- Observed \((L = 2.0 \text{ fb}^{-1})\)
- Jet \(\rightarrow \tau\) (QCD+Wjets)
- Top
- Diboson/Z \(\rightarrow \tau\)
- \(Z \rightarrow \tau \tau + \text{jets}\)
- \(\text{Higgs}(M_H = 120)\)

Expected Limit/SM

Integrated luminosity/Experiment (fb\(^{-1}\))