Search for the Standard Model Higgs in the $ZH \rightarrow l^+l^- b\bar{b}$ Channel

Jonathan Efron
The Ohio State University
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Outline

- Why the Higgs?
- Tevatron and CDF II
- Event selection
- Improving signal-background separation
  - Neural network jet corrections
  - Neural network classification
- Results
- Prospects for future
Standard Model

- Excellent description of particle physics
  - All observable parameters within 3 $\sigma$ of expectations
- Combines weak, EM, and strong forces.
- Electrodynamics and weak forces combined into $SU(2) \times U(1)$ symmetry
- But . . . $W$ and $Z$ bosons required to be massless
Enter the Higgs Mechanism

- The Higgs field breaks electroweak symmetry and consequently adds masses to the gauge bosons
  - Mass is directly proportional to interaction with Higgs field
- Fermions similarly can attain mass with interaction with Higgs
- As a consequence of Higgs field, a new spin 0 boson is predicted
Constraints on the Higgs Boson

- Higgs searches ongoing for last 30 years
- **Direct search at LEP:**
  \[ M_{\text{Higgs}} > 114.4 \text{ GeV/c}^2 \] @ 95%
- **Indirect searches:** including new Tevatron precision measurements
  - \[ M_{\text{top}} = 170.9 \pm 1.8 \text{ GeV/c}^2 \]
  - \[ M_W = 80.398 \pm 0.025 \text{ GeV/c}^2 \]

\[ m_H = 76^{+33}_{-24} \text{ GeV/c}^2 \] @ 95% CL

\[ m_H < 144 \text{ GeV/c}^2 \] @ 95% CL
Higgs Boson at the Tevatron

- Higgs Boson interact with other particles proportionally to their mass
- At Higgs masses less than 135 GeV/c², $b\bar{b}$ is the primary Higgs decay
- Associated production (WH/ZH) of Higgs has much lower backgrounds than direct production
Higgs at the Tevatron

$ZH \rightarrow \ell\ell bb$

$BR(Z \rightarrow \ell^+\ell^-) \sim 7\%$
$
\sigma(ZH) \sim 0.1 \text{ pb}$

$ZH \rightarrow \nu\nu bb$

$BR(Z \rightarrow \nu\nu) \sim 20\%$
$
\sigma(ZH) \sim 0.1 \text{ pb}$

$WH \rightarrow \ell\nu bb$

$BR(W \rightarrow \ell\nu) \sim 22\%$
$
\sigma(WH) \sim 0.15 \text{ pb}$

$gg \rightarrow H \rightarrow WW \rightarrow \ell\ell\nu\nu$

$Events produced at CDF in 1 \text{ fb}^{-1}$

Total

Higgs mass (GeV)
Tevatron Run II 2000-2009 (est.)

- Proton-Antiproton collider
- Center of mass energy 1.96 TeV
- Current Peak Instantaneous Luminosity: $286 \times 10^{30} \text{ cm}^{-2}/\text{s}$
- Integrated Luminosity:
  - 3.0 fb$^{-1}$ Delivered
  - 2.5 fb$^{-1}$ on tape at CDF
- Projected total luminosity for Run II: 6-8 fb$^{-1}$
- This analysis 1 fb$^{-1}$
CDF II Detector

• Forward-background and radially symmetrical
• Multipurpose:
  Run II achievements
  - First observation of $B_s$ mixing -
    $17.77 \pm 0.10$ (stat.) $\pm 0.07$ (syst.) ps$^{-1}$
  - World’s most precise single measurement of the $W$ boson mass
    $(80413 \pm 34 \pm 34 \text{ MeV/c}^2)$
  - World’s most precise single measurements of top quark mass
    $(170.9 \pm 1.6 \pm 2.0 \text{ GeV/c}^2)$
  - Many other work in electroweak, QCD, b hadrons, top quark, and exotic physics
The signal is small
For $M_H = 120$ GeV/c$^2$
- $\sigma(ZH) \sim 0.1$ pb
  - ~100 events/1 fb$^{-1}$
- $BR(Z \rightarrow l^+l^-) = 6.8\%$
  - ~7 events/fb$^{-1}$ remaining
- $BR(H \rightarrow bb) \sim 70\%$
  - ~5 events/1fb$^{-1}$ remaining

But so are the backgrounds
And all final products are measurable
- Find two leptons that form a Z boson
- Find two or more jets from b-hadrons
Guiding Goals of this Analysis

- Try to push the limits of basic event selection
  - Increase lepton acceptance
- Use innovative techniques to separate signal from backgrounds
Steps of the Analysis

- Find events with a Z and b-tagged jets
- Separate events into two loose and exclusive single tight b-tags
- Correct jet energy using a neural network (NN jet corrections)
- Use event kinematics in an optimized 8 input 2 output artificial neural network (NN classification)
- Fit neural network output shape to find expected and measured upper limit
Event Criteria

- "Tight" lepton is required for event to be triggered
  - $|\eta| < 1$
  - $E_T (P_T) > 18 \text{ GeV}(/c)$ for electrons (muons)
  - Other fiducial requirements
    - Isolation
    - Had/Em of electrons
    - Calorimeter energy deposition of muons
- "Loose" lepton Selection
  - Lower $E_T (P_T)$ requirement
  - Looser requirements
- Reconstruction as Z
  - Same flavor opposite sign leptons
  - $76 < M_{ll} < 106 \text{ GeV}/c^2$
- Looser lepton criteria yields ~70% signal events

- 2 or more jets
  - 1st Jet $E_T > 25 \text{ GeV}$
  - Other jets $E_T > 15 \text{ GeV}$
  - $|\eta| < 2$
  - B-tagging requirement

Electrons
- $E_T$ (Ele 1) = 64 GeV
- $E_T$ (Ele 2) = 62 GeV

Jets
- $E_T$ (Jet 1) = 100 GeV
- $E_T$ (Jet 2) = 39 GeV

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B-tagging

- Secondary Vertex Algorithm at CDF
  - 40 - 50 % efficient (tight, loose)
  - 0.5 - 1.5 % fake rate from light jets
- Can take advantage of the Higgs decaying to bb
  - from ~1:1000
  - to ~1:100
- A separate channel for events with 2 b-tags
  - Most fake b-jets removed
Background Contributions

- $Z \rightarrow l^+l^- + \text{jets}$
  - $Z \rightarrow l^+l^- + bb$ (MC)
  - $Z \rightarrow l^+l^- + cc$ (MC)
  - $Z \rightarrow l^+l^- + \text{other jets ("mistags"-data simulated)}$

- $tt \rightarrow WbWb \rightarrow l\nu b l\nu b$
  - Dilepton events within $Z$ mass window (MC)

- Diboson - (2 leptons + 2 jets - MC)
  - $ZZ, ZW, WW+2p$

- QCD background - “fake” leptons
  - Muons modeled by same-sign data
  - Electrons – estimated using jet data
Mistag Modeling

Basic Idea

• $L_{xy}$ is the distance between vertex and primary in $x$-$y$ plane
• Positive Tags: $L_{xy} > 0$
• Light flavor jets: slightly more likely to have positive than negative $L_{xy}$
• CDF has made a function based on jet properties to estimate likelihood of jets being “mistagged”
  • Higher energy Jets are more likely to be mistagged
Fake Electron Estimations

- **Jet → Electron fake rate function for loose electrons**
  - Use jet only data
  - Calculated as a function of Jet $E_T$
  - Separate functions for Central and Plug electrons
- **Steps to eliminate possible real electron contributions**
  - Real electron in jet data would greatly inflate our electron fake rate
  - Do not use trigger jet to calculate error function
    - Eliminates biggest source of electrons from $W \rightarrow e\nu$
    - Missing $E_T$ cut < 15 GeV
# Events Expected in 1 fb$^{-1}$

## Backgrounds

<table>
<thead>
<tr>
<th>Background</th>
<th>2 Tags</th>
<th>1 Tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>2.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Diboson</td>
<td>1.5</td>
<td>5.2</td>
</tr>
<tr>
<td>fakes</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>$Z + bb$</td>
<td>6.3</td>
<td>35</td>
</tr>
<tr>
<td>$Z + cc$</td>
<td>1.0</td>
<td>22</td>
</tr>
<tr>
<td>Mistags</td>
<td>1.0</td>
<td>32</td>
</tr>
<tr>
<td><strong>Total bkg.</strong></td>
<td><strong>12.8</strong></td>
<td><strong>101</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>11</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

## Signal

<table>
<thead>
<tr>
<th>Higgs Mass (GeV/c$^2$)</th>
<th>$\sigma$(ZH)$\times$BR $\times$BR (H $\rightarrow$ $bb$)</th>
<th>2 Tags</th>
<th>exclusive 1 Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.14 pb</td>
<td>0.41</td>
<td>0.87</td>
</tr>
<tr>
<td>110</td>
<td>0.092 pb</td>
<td>0.32</td>
<td>0.65</td>
</tr>
<tr>
<td>115</td>
<td>0.080 pb</td>
<td>0.28</td>
<td>0.56</td>
</tr>
<tr>
<td>120</td>
<td>0.061 pb</td>
<td>0.23</td>
<td>0.45</td>
</tr>
<tr>
<td>130</td>
<td>0.037 pb</td>
<td>0.15</td>
<td>0.27</td>
</tr>
<tr>
<td>140</td>
<td>0.017 pb</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
<td>150</td>
<td>0.007 pb</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Introduction to Artificial Neural Networks

- Designed to mimic a brain
  - Interconnected nodes
  - Connections “learned” based on experience
  - Each node “fires” based on incoming information
- Has been shown to be able to reproduce any non-linear function

Sample 1-D NN

Train neural networks toward target outputs.
- Look to reduce error
- \[ E = \frac{1}{N_p} \sum (\hat{T} - \hat{O})^2 \]
- Repeat based on previous performance

Adjustable parameters
- Weight of each node’s inputs
- Threshold for “firing” of each node
NN Jet Corrections

- Training to match corrected jet energies to generator level parton energies
- Input Variables from 2 b-quark jets
  - 1 Corrected Jet $E_t$
  - 2 Detector $\eta$
  - 3 Jet $\phi$
  - 4 MET projected on axis of individual jet
- Total event MET and MET $\phi$
- Two output nodes - corrected jet energies
- Create single NN for all masses
  - $H_{mass}$ from 60-180 GeV used in training
  - ttbar used in training as well
NN Jet Energy
Correction Comparison

- Jet energy resolution is better using the NN
- More accurate and precise measurement of Higgs Boson mass
- Rule of thumb for fitting $M_{jj}$
  1% improvement mass resolution
  ~ 10% luminosity

<table>
<thead>
<tr>
<th>$M_{jj}$</th>
<th>2-tag</th>
<th>1-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave Std.</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>NN JetCorr</td>
<td>18%</td>
<td>22%</td>
</tr>
</tbody>
</table>
A separate neural network from NN jet corrections

Dijet mass still has large backgrounds

A NN takes advantage of correlations between different variables

With a 1-D NN that separated Z+jets from ZH, $tt$ remains prominent in most Higgs like region

Therefore a 2-D network is used

NN estimated to improve search by a factor of 2.5x more luminosity versus dijet mass alone
Classification Artificial Neural Network with 2-D output

- Develop NN classification after NN jet corrections
- Training
  - Neural net output determined by exposure to training data
    Iteratively adjust parameters to minimize error
  - Training accomplished through JETNET program (Peterson et al. CERN-TH/7135-94)
- Will fit resulting shape from data against signal background shapes to measure upper limit of ZH cross-section

2D Neural Net Discriminant

Training on: TT, ZH, Z+jets
Allow other shapes to fall in place:
Fakes, ZZ, ZW
Kinematic Input Variables in Neural Network Classification

- $H_t$ (Sum of 2 leptons, Missing $E_t$, and top two jets)
- Missing $E_t$
- Mass of top two jets
- $\Delta R$ of Jet 1 and Z candidate
  - $(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2})$
- $\Delta R$ of Jet 2 and Z candidate
- $\Delta R$ of Jet 1 and Jet 2
- Sphericity
- Jet 2 $\eta$
Input Kinematic Variables

Single Tag Histograms

CDF II Preliminary

ΔR of 1st Jet and Z Candidate

ΔR of 2nd Jet and Z Candidate

H_T (GeV)

Sphericity

Missing E_T (GeV)

ΔR between jets

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25
Neural Network Shapes

Normalized to single tag expectations
“Pretag” Data Output

With no b-tag requirements
~95% Z+jets
Use as NN validation

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Projections and Slices

- Looking at projections
  - Z+jets vs ZH axis
    - 0 → 1 increasing energy
    - Most energetic corner (1) has tt and ZH
    - Slice
      - Separates Z+jets v ZH
      - Excludes tt
  - ZH vs tt
    - 0 → 1 increasing Met
    - 0 contains Z+jets and ZH, most events
    - Slice
      - Separates: ZH v tt
      - Most Z+jets excluded
Pretag Output Projections
Pretag Output Projections

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Single Tag Output
Single Tag Output Projections

CDF II Preliminary $\int L dt = 0.97 - 1.02 \text{ fb}^{-1}$

- Data - Single Tag
- Standard Model Backgrounds
- ZH $\rightarrow$ llbb X50($M_{ll} \approx 120 \text{ GeV/c}^2$)

Z+jets  ZH

NN Projection (Z+jets vs ZH)

Z+jets  ZH

NN Projected Slice (Z+jets vs. ZH)

Z+jets  ZH

NN Projection (ZH vs $t\bar{t}$)

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Double Tag Output
Double Tag Output Projections

CDF II Preliminary $L_{dt} = 0.97 - 1.02$ fb$^{-1}$

- Data - Double Tag
- Standard Model Backgrounds
  - $Z\rightarrow\tau\tau X 10$ ($M_{\tau\tau} = 120$ GeV/c$^2$)

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Run 196170 Event 6577

NN output = 0.958, 0.009
$M_{JJ} = 120 \text{ GeV/c}^2$

$S/B = 1/4.2$

2 SecVtx tagged Jets
Jet 1 Et(NN corrected) = 126.6 GeV
Jet 2 Et(NN corrected) = 37.1 GeV

April 5, 2005
~8:09 am
Inst.Lumi
~$28 \times 10^{30}$

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Zbb</td>
<td>0.11</td>
</tr>
<tr>
<td>$tt$</td>
<td>0.019</td>
</tr>
<tr>
<td>Zcc</td>
<td>0.017</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.016</td>
</tr>
<tr>
<td>Mistag</td>
<td>0.010</td>
</tr>
<tr>
<td>Total bkg</td>
<td>0.18</td>
</tr>
<tr>
<td>ZH(120)</td>
<td>0.042</td>
</tr>
</tbody>
</table>
Setting a Limit

- Fit data using background (b) only template and signal + background (s+b) template
  - Vary signal cross-section
  - Systematics are included in a possible model of the fit
  - Takes advantage of sidebands to determine background rates
- Run many pseudo-experiments based on nominal expectations
  - Randomly “create” data from templates
  - Fit “pseudo-data” just like real data
- Find likelihood ratio (Q) of the s+b model versus b only
- Exclude values of \( \sigma_{ZH} \) where Q is less than 5% likely from s+b hypothesis
Systematics

All Systematics errors increase the expected limit by 14%

Main culprits (>5% affect on expected limit)

- 8% B hadron b-tagging efficiency (per tag): – worsens limit 12%
- 6% Luminosity uncertainty: - worsens limit 7%
- 40% error on Z+heavy flavor production : - worsens limit 6%

Other systematics

- Jet Energy : +/- 1 sigma fluctuations (shape and counting)
- Z+l.f. mistag error (and shapes): 17%
- Alpgen vs Pythia for Z+jets NN Output Shapes
- C hadron b-tagging efficiency: 16% per tag
- Lepton scale factors : 1% each
- PDF : 2%
- Diboson cross-section normalization: 20%
- \(tt\) cross-section: 20%
- QCD fake rate error: 50%
- Initial State Radiation/Final State Radiation : for signal ZH signal
B-tagging Efficiency

- Measured in dijet sample
  - One jet with soft lepton
  - Second jet with a SecVtx tag
  - Very pure sample of heavy flavor jets
- Efficiency measured using soft lepton-tagged jet
  - Parameterized for Jet $E_T$, eta, etc.
- Source of uncertainty
  - Statistical
  - Heavy flavor fraction
  - Mistag uncertainty

Is there a 2nd SecVtx Tag?
40% systematic motivated by error on error from $Z + b$-jet measurement

- Measurement fit mass of SecVtx tags to templates of $Z+b$, $Z+c$ and $Z+1f$

- $\sigma_{Z+b\text{-jet}} = 0.93 \pm 0.32 \text{ (stat.)} \pm 0.14 \text{ (syst.)} \text{ pb}$

Jet Energy Scale

- Determine parton energy from measurements in calorimeter
- Correct for
  - Detector effects
  - Fragmentation/Hadronization
  - Underlying event
- Energy scale determined from data and MC
- Uncertainties in jet energy scale directly affect kinematic uncertainties
  - Allow uncertainties to change acceptance
  - Allow uncertainties to change kinematic shape of NN output
  - Correlated errors between MC modeling
Mistag Shape Errors

- Adjust all bins by their bin error to get alternative shapes
  - Contributions to shape errors
    - Pretag statistical errors
    - Ratio of negative tags to mistags
    - Errors of mistag matrix

Single Tag Mistag shape
BLACK nominal shape
BLUE shifted up and down mistagged shape
ZH → $l^+l^- bb$ with 1 fb$^{-1}$
Upper Limit at 95% CL

<table>
<thead>
<tr>
<th>Mass (GeV/c$^2$)</th>
<th>1-tag $\sigma_{ZH}/$SM</th>
<th>2-tags $\sigma_{ZH}/$SM</th>
<th>Combined $\sigma_{ZH}/$SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>23 (23)</td>
<td>15 (16)</td>
<td>12 (13)</td>
</tr>
<tr>
<td>110</td>
<td>25 (24)</td>
<td>20 (19)</td>
<td>14 (14)</td>
</tr>
<tr>
<td>115</td>
<td>28 (27)</td>
<td>23 (22)</td>
<td>16 (16)</td>
</tr>
<tr>
<td>120</td>
<td>30 (31)</td>
<td>28 (26)</td>
<td>18 (18)</td>
</tr>
<tr>
<td>130</td>
<td>48 (49)</td>
<td>43 (39)</td>
<td>29 (28)</td>
</tr>
<tr>
<td>140</td>
<td>110 (96)</td>
<td>86 (75)</td>
<td>65 (54)</td>
</tr>
<tr>
<td>150</td>
<td>260 (250)</td>
<td>220 (200)</td>
<td>160 (140)</td>
</tr>
</tbody>
</table>

115 GeV/c$^2$ limit corresponds to 1.3 pb for $\sigma_{ZH} \times \text{BR}(H \rightarrow bb)$
Higgs at CDF II with 1 fb⁻¹

- Expected limits similar to other SM low-mass Higgs searches
- Despite lowest cross-section
- Despite lowest branching ratio

CDF collectively, expected limit is 8.0 times SM at $M_H = 115$ GeV/c²

Observed = 11 x SM
Step One to Discovery

- Scaling current analysis with 8 fb\(^{-1}\) of data, expected upper limit is 5.2 times SM at \(M_H = 120\) GeV/c\(^2\)
- Improvements in the works
  - Greater event acceptance
  - Improve b-taggers
    - Higher efficiency
    - Wider eta range
  - Lower systematics
  - Mix in other advanced selection techniques
Conclusions

- Standard Model adds a Higgs sector to explain electroweak symmetry breaking, resulting in Higgs Boson

- Designed an analysis using the CDF detector to search for $ZH \rightarrow l^+l^- b\bar{b}$
  - Use different artificial neural networks to signal to background

- Set an upper limit on production of ZH to 16 times the SM expectation and a Higgs mass of 115 GeV/c$^2$

- Opportunity for discovery at the Tevatron exists
  - Combination within CDF and with D0 necessary