Search for the Higgs in $VH \rightarrow VWWW \rightarrow \text{leptons} + X$

at the Tevatron

Michael Cooke

On behalf of the CDF and DØ Collaborations

2011 Meeting of the Division of Particles and Fields of the American Physical Society
The Life and Death of a Higgs

- Gluon fusion dominates production
  - Hard to tell $H \rightarrow b\bar{b}$ from multijet backgrounds

- Associated production ($H \rightarrow b\bar{b}$) most sensitive at low mass
  - Why $VH \rightarrow VWW$? ...

Michael Cooke <mpc@fnal.gov>  

VH→VWW→leptons+X at the Tevatron
Intermediate Importance

Higgs at

VH ⟶ VWW ⟶ leptons+X at the Tevatron

Tevatron Run II Preliminary, L ≤ 8.6 fb⁻¹

LEP Exclusion

Expected

SM=1

Tevatron Exclusion

July 17, 2011
Not many sources of same-sign leptons or trileptons in SM

Low bkgd leads to important contribution at intermediate $m_H$
The Tevatron produces $p\bar{p}$ collisions at CM energy ($\sqrt{s}$) 1.96 TeV.

Thanks to the Accelerator Division for providing excellent performance!

VH→VWW→leptons+X at the Tevatron

Michael Cooke <mpc@fnal.gov>
The CDF and DØ Detectors

- Silicon vertex detector
- Wire drift chamber tracking
- Pb/Fe-scintillator calorimeter
- Muon chambers

\[ \eta = -\ln\left(\tan \frac{\theta}{2}\right) \]

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VH→VWW→leptons+X at the Tevatron
Three channels ($ee, e\mu, \mu\mu$) considered:

- Central lepton within CFT, with SMT hits
  - $SS \ell'$'s $|\eta_e| < 1.1$, $|\eta_\mu| < 1.8$; Extra $\ell'$'s $|\eta_e| < 2.5$, $|\eta_\mu| < 2.0$

- Max $p_T \ell$, $m_{\ell\ell}$ cuts ensure good charge measurement
  - $SS \ell'$'s $15 < p_T \ell < 200$ GeV, $15 < m_{\ell\ell} < 250$ GeV

Instrumental bkgdsc dominate
- Charge-flip of OS pairs
- $W+$jet/$\gamma$
- Multijet
**Estimating Charge-Flip**

- **\( ee \):** Flip rate measured in \( Z \rightarrow ee \) control sample, then applied to unlike-sign data.
- **\( \mu\mu \):** Central tracking and muon system yield independent charge measurements.
  - Eff. of local muon charge assignment measured with \( Z \rightarrow \mu\mu \) as fn. of \( 1/p_T \).
  - Count of central vs. local muon charge discrepancy used to determine true same-sign lepton count.

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Michael Cooke  <mpc@fnal.gov>  VH\(\rightarrow\)VWW\(\rightarrow\)leptons+X at the Tevatron
Two Stage MVA Analysis

- First MVA trains against instrumental bkgd
  - Charge-flip and MJ for \(ee, \mu\mu; W+\text{jet/}\gamma\) and MJ for \(e\mu\)
  - Apply cut tuned to keep signal efficiency near 90%

- Final MVA trained against all backgrounds

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\[ VH \rightarrow VVV \rightarrow \text{leptons}+X \text{ at the Tevatron} \]
$VH \rightarrow VWW \rightarrow \ell^\pm \ell^\pm + X$ at DØ

$m_H = 130$
Expected: 12.5
Observed: 8.8
Both are subchannels to main $H \rightarrow WW^*$ result

Many lepton definitions used to increase acceptance

SS dilepton requires:
- 2 leptons, $p_T > 20$ GeV
- $e$ must be central and tight
- At least one $p_T > 15$ GeV jet

Trilepton requires:
- $p_T^{\ell_1} > 20$, $p_T^{\ell_2,3} > 10$ GeV
- Can’t all have same charge
Same-sign Dileptons at CDF

- Majority of background is instrumental
- Neural Network output used to set limits

CDF Run II Preliminary $\int L = 8.2 ~{\text{fb}}^{-1}$

<table>
<thead>
<tr>
<th>$M_H = 165 ~{\text{GeV/c}}^2$</th>
<th>$t\bar{t}$</th>
<th>$DY$</th>
<th>$WW$</th>
<th>$WZ$</th>
<th>$ZZ$</th>
<th>$W + \text{jets}$</th>
<th>$W\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>$2.08 \pm 0.30$</td>
<td>$79 \pm 34$</td>
<td>$0.169 \pm 0.075$</td>
<td>$14.8 \pm 2.0$</td>
<td>$2.80 \pm 0.39$</td>
<td>$92 \pm 35$</td>
<td>$6.7 \pm 1.1$</td>
</tr>
<tr>
<td>$WH$</td>
<td>$2.73 \pm 0.36$</td>
<td>$0.404 \pm 0.054$</td>
<td>$3.13 \pm 0.42$</td>
<td>$224$</td>
<td></td>
<td></td>
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Michael Cooke <mpc@fnal.gov>
Same-sign Dileptons at CDF

\[ \text{VH} \rightarrow \text{VWW} \rightarrow \text{leptons} + \text{X} \text{ at the Tevatron} \]

Expected: 9.0
Observed: 10.9

\[ m_H = 130 \]

Higgs Mass (GeV)

CDF Run II Preliminary

\[ \int L = 8.2 \text{ fb}^{-1} \]
Trileptons at CDF

- Divided into subchannels to optimize analysis
- Two opposite-sign like-flavor leptons near Z mass
- One or more jets required, events form separate channels
- All events not in other categories are WH candidates
- Additionally require missing $E_T > 20$ GeV

### ZH 1 jet

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<tr>
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<tr>
<td>$t\bar{t}$</td>
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<td>$WZ$</td>
<td>12.1 ± 2.0</td>
<td>3.65 ± 0.84</td>
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<tr>
<td>$ZZ$</td>
<td>4.98 ± 0.71</td>
<td>1.91 ± 0.38</td>
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<tr>
<td>$Z + \text{jets}$</td>
<td>7.9 ± 1.9</td>
<td>6.4 ± 1.6</td>
</tr>
<tr>
<td>$Z_{\gamma}$</td>
<td>6.5 ± 1.4</td>
<td>2.55 ± 0.66</td>
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<tr>
<td>Total Background</td>
<td>31.6 ± 3.8</td>
<td>14.6 ± 2.4</td>
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<tr>
<td>$WH$</td>
<td>0.0380 ± 0.0058</td>
<td>0.0133 ± 0.0034</td>
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<td>$ZH$</td>
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<td>Total Signal</td>
<td>0.308 ± 0.046</td>
<td>0.74 ± 0.11</td>
</tr>
<tr>
<td>Data</td>
<td>35</td>
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### ZH 2+ jet

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Trileptons at CDF

**ZH 1 jet**

**ZH 2+ jet**

**WH**

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Trileptons at CDF

$VH \rightarrow VWW \rightarrow \text{leptons} + X$ at the Tevatron

$m_H = 130$

Expected: $10.9$

Observed: $11.6$

$m_H = 130$

Expected: $20.3$

Observed: $21.5$
Higgs search for $m_H \approx 130$ will be very interesting

Same-sign dilepton and trilepton channels are important here!

<table>
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<th>Channel</th>
<th>$\int L$ (fb$^{-1}$)</th>
<th>$m_H=130$ Exp Lim</th>
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<td>DØ $\ell^+\ell^-$</td>
<td>5.3</td>
<td>12.5</td>
</tr>
<tr>
<td>CDF $\ell^+\ell^-$</td>
<td>8.2</td>
<td>9.01</td>
</tr>
<tr>
<td>CDF $\ell\ell\ell$ (ZH, 1j)</td>
<td>8.2</td>
<td>36.8</td>
</tr>
<tr>
<td>CDF $\ell\ell\ell$ (ZH, 2j)</td>
<td>8.2</td>
<td>20.3</td>
</tr>
<tr>
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Search for the Higgs in 

\[ VH \rightarrow VWWW \rightarrow \text{leptons} + X \]

at the Tevatron

Thank you!

Michael Cooke

Fermilab
The Standard Model

- Describes the interactions between quarks & leptons
  - Mediated by gauge bosons
- The EM ($\gamma$) and weak ($W^\pm, Z$) forces are unified under a broken symmetry
  - The Higgs field is introduced to cause EWSB & generate $W, Z$ mass
  - Either a SM Higgs particle exists or there is new physics that causes EWSB
Where to Look for a Higgs

- Indirect limits from EW precision measurements

- Direct exclusion from LEP & Tevatron
  - $m_H > 114.4$ GeV (LEP)
  - $m_H$ not in [156,177] (TeV)
  - Indirect + LEP: $m_H < 185$ GeV

95% C.L. as of July 2011
Higgs Events in 1 fb\(^{-1}\)

Higgs	

\begin{align*}
\text{VH} & \rightarrow \text{VWW} \\
& \rightarrow \text{leptons} + X
\end{align*}

at the Tevatron

\begin{align*}
\text{Total} \\
H \rightarrow \text{WW} \rightarrow \ell\nu\ell\nu \\
WH \rightarrow \ell\nu\text{bb} \\
ZH \rightarrow \nu\nu\text{bb} \\
ZH \rightarrow \ell\ell\text{bb}
\end{align*}
Gains in trigger efficiency and lepton acceptance are key to increasing our sensitivity.

Michael Cooke <mpc@fnal.gov>

VH→VWW→leptons+X at the Tevatron
Gain sensitivity by combining many variables into one powerful discriminant

- Use full discriminant output to set limit

- Neural Networks

- Matrix Element Method
  - Use differential cross sections of signal and major backgrounds to estimate signal likelihood

- Decision Trees
  - Recover events that fail a normal cut-based analysis

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Decision Trees

- Start by making best cut to optimize signal purity
- Continue placing cuts on each subsample
- Enhancing purity with each step
- Each final leaf produces a purity weight

\[ m_{jj} > 120 \]
\[ H_T > 100 \]
\[ \Delta \phi(\ell, j_1) > 0.5 \]

- \( S/B \)
Advanced Decision Trees

Boost a tree by retraining, giving more weight to misclassified events

Final output for event is a combination of all tree classifications

Random Forest

Random subset of inputs and training samples make many trees

m_{jj} > 120

H_T > 100

\Delta \phi(\ell,j_1) > 0.5

m_{jj} > 120

H_T > 100

\Delta \phi(\ell,j_1) > 0.5

Pass

Fail

F

P

F

P

F

P

S/B

VH \xrightarrow{VWW} \text{leptons} + X \text{ at the Tevatron}
Sample Two Variable Decision Tree

VH $\rightarrow$ VWW $\rightarrow$ leptons+X at the Tevatron

- Variable A
- Variable B

- B > 3
  - Fail
  - Pass
- A > 2.8
- B < 7
- A > 8

Signal / Background

F - Fail
P - Pass
S/B - Signal to Background Ratio
**Systematics**

- Can be flat or shaped, asymmetric, correlated...
  - Inelastic $pp$ cross section, top & diboson production cross sections correlated between CDF & DØ
  - Within each collaboration, lepton ID, $b$-ID, jet energy scale & resolution are correlated

**WH→ℓvjj**
- 2 jet, 1 $b$-tag
  - $e$-channel: $t\bar{t}$ electron ID
  - $μ$-channel: single-$t$ $b$-jet ID
Each final output bin is treated independently
- Adding analysis channels is as easy as adding bins!

Two ensembles are created: B only and S+B
- Poisson seeded by nominal S and B expectation
- Systematic uncertainties are used to vary the nominal S and B predictions for each “experiment”
  - Correlated systematics share the same shift in all bins

Every pseudo-experiment contributes to the expected distribution of our test statistic

Michael Cooke  <mpc@fnal.gov>  VH→VWW→leptons+X at the Tevatron
Start with a “normal” Log Likelihood Ratio

Can integrate over systematics as nuisance pars...

\[ \Gamma = -2 \cdot \log \left( \frac{P(x|H_{S+B})}{P(x|H_B)} \right) \]

Instead of integrating over nuisance pars., perform a fit to maximize each \( P(x|H_\alpha) \)

\[ \theta_\alpha \] are best fit nuisance parameter values

\[ \Gamma = -2 \cdot \log \left( \frac{P(x|H_{S+B}, \theta_{S+B})}{P(x|H_B, \theta_B)} \right) \]
Evaluating a Limit: 
The CL$_S$ Method

Knowing the expected test statistic distribution for $H_{S+B}$ could let us set limits

- Poor B modeling not accounted for

\[
CL_S = \frac{CL_{S+B}}{CL_B}
\]

- As $CL_B$ approaches 1, reduces to $CL_{S+B}$
The Tevatron Combined LLR Distribution

VH $\rightarrow$ VWV $\rightarrow$ leptons+X at the Tevatron

$<L> = 5.9 \text{ fb}^{-1}$
How Would a Higgs Appear Today?

If a 125 GeV mass Higgs is injected into our current Tevatron combination, the result is consistent with our current observations.