Search for Higgs Boson Produced in Association with a W Boson at CDF II

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Canadian Association of Physicists Congress,
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The Higgs Particle’s Territory

Higgs Particle (H)
Elementary particle as massive as heavy atoms
Tevatron, CDF

**Tevatron Accelerator**
- ppbar collisions at \( \sqrt{s} = 1.96 \text{ TeV} \)

**CDF Apparatus**
- Well understood
- General purpose detector

**Integrated Luminosity**
- 5.4 fb\(^{-1}\) delivered
- 3.2 fb\(^{-1}\) analyzed

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WH Analysis strategy

Event Selection

Estimate signal and backgrounds

Use multivariate techniques to separate signal and background

Perform a binned likelihood fit of the discriminant distribution

Set limits on the cross section times branching fraction as a function of Higgs boson mass

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WH Event Selection

3 Orthogonal Charged Lepton Categories

- **Central** (electron or muon), $|\eta|<1.1$
- **Forward** (electron), $1.1<|\eta|<2.0$
- **Isolated track** (muon, electron, tau) $|\eta|<1.2$
- For all: $P_T>20$ GeV

Missing Transverse Energy

- $MET > 20$ GeV for central and isolated track for 2 tag
- For 1 tag, also add a QCD veto
- $MET > 25$ GeV + QCD veto for forward

Jet Requirements

- Exactly 2 tight jets
- $E_T> 20$ GeV, $|\eta|<2.0$ for central and forward
- $E_T> 25$ GeV, $|\eta|<2.0$, one with $|\eta|<0.9$ and dR of jets $> 1$ for isolated track (dR is angular separation between the two jets)
- At least one jet is b-tagged

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b-tagging Principles

- B hadrons are long lived
- Look for displaced vertices
- Look at impact parameters of tracks from jets

3 Orthogonal b-tagging Categories

- **Tight 2 Tag**
  - Secondary Vertex + Secondary Vertex
- **Loose 2 Tag**
  - Secondary Vertex + Jet Probability
- **1 Tag**
  - Secondary Vertex

WH signal \( m_H = 120 \text{ GeV} \)
All charged lepton categories
Distribution of tag categories
Background Estimation

**Estimated from Data**
- QCD events that fake a $W$ boson signature
  - MET faked by jet energy mismeasurement
  - Charged Lepton faked by a jet
- $W$ boson + Light Flavour

**Estimated from Data and MC**
- $W$ boson + Heavy Flavour ($W+bb, W+cc, W+c$)

**Estimated from MC**
- Top quark events ($ttbar, single top$)
- Diboson events ($WW, WZ, ZZ$)
- $Z$ boson Events ($Z + jets$)

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Backgrounds example

CDF Run II Preliminary (3.2 fb⁻¹)

Signal region

• W boson + Heavy Flavour (HF: bb, cc)
• W boson + Light Flavour (LF: mistag)

Main backgrounds for 1 tag

• W boson + Heavy Flavour (HF: bb, cc)
• Top Quark (ttbar, also single top)

Main backgrounds for 2 tag

1.7±0.1

4.2±0.4

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Neural Network

- Most sensitive variable
- Also a third loose jet, if close to tight jets
- Invariant mass of two jets
  - + other kinematic variables
    - Sensitive to Top Quark Pair or to W+ HF

From 100 GeV to 150 GeV, with 5 GeV steps

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NN Result: $\sigma(p\bar{p} \to W^\mp H) \cdot BR(H \to b\bar{b})$

Upper limit on WH cross section times the branching fraction, as a ratio with the SM prediction (limit as a function of Higgs boson mass)

9 orthogonal categories combined in this result

11 Higgs boson mass points

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WH Search at CDF

Event Selection
3 orthogonal categories of charged lepton
3 orthogonal categories of b-tag

Neural Network
Discriminant (NN)

Matrix Element
+ Boosted Decision
Tree
Discriminant (MEBDT)

Super-Discriminant Combines NN and MEBDT

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NN and ME+BDT Combined: $\sigma(pp \rightarrow W^+H) \cdot BR(H \rightarrow b\bar{b})$

**Limits for WH Combination CDF Run II Preliminary 2.7 fb$^{-1}$**

- 95% of PE
- 68% of PE
- Median Expect WH Combination
- Observed WH Combination

**Discriminant** | **Expected Limit** | **Observed Limit**
---|---|---
NN | 5.8 x $\sigma_{SM}$ | 5.2 x $\sigma_{SM}$
ME+BDT | 5.2 x $\sigma_{SM}$ | 6.2 x $\sigma_{SM}$
COMBINED | 4.8 x $\sigma_{SM}$ | 5.6 x $\sigma_{SM}$

At $m_H=115$ GeV, sensitivity improves by 8% over the most sensitive multivariate technique.

**Higgs Mass (GeV/c$^2$)**

- **SM**

$\sqrt{s}=1960$ GeV

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Charged Lepton as Isolated Track

- High-$p_T$ track (> 20 GeV)
- Isolated from other tracks (Isol > 0.9)
- Is not Central or Forward charged lepton
- Is not required to match a calorimeter tower or a muon chamber
- **Fills in the gaps, adds 25% more acceptance!**
- 85% muon, 7% electron and 7% tau candidates
Latest Tevatron Higgs Combination

Tevatron Run II Preliminary, L=0.9-4.2 fb^{-1}

Excluded mass range!

First SM Higgs mass exclusion through direct searches at Tevatron

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Conclusion & Discussions

WH Search at CDF

- Super discriminant
  - 8% increase in sensitivity over best method

- ME+BDT

- Central Charged Lepton
- Forward Charged Lepton

Isolated Track

- Adds 25% WH acceptance (by filling in the gaps)
- Improves resolution by 10% on $\sigma(p\bar{p} \to W^+H) \cdot BR(H \to b\bar{b})$
- Will add new triggers for this channel
- Machinery already in place
- Expect 3.6 fb$^{-1}$ for Lepton Photon (3.0 fb$^{-1}$ now)

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Backup Slides
Improvements for Lepton-Photon 09

- Improve W boson acceptance
  - Add new trigger paths for isolated track

- Improve Higgs boson acceptance
  - Incorporate Roma tagger and KIT flavor separator to improve loose b-tagging categories

- Optimize event selection
  - Include 3-jet bin

- Dijet invariant mass distribution
  - Use b-quark specific jet corrections

- Optimize multivariate technique discriminants
  - NN, BDT, super-discriminant

- Optimize event selection
  - Reject events with extra isolated track
  - Optimize jet $E_T$ cuts

- Improve background modeling
  - Especially for QCD
Triggers for Isolated Track

No dedicated isolated track triggers at CDF

- MET + 2 Jets
- MET45
- MET + DIJET
- Muon Gap Triggers

Used for ICHEP 08: 25% improvement in acceptance over Central

To be added for Lepton Photon 09 & Estimate 25-30% acceptance improvement over MET + 2 Jets

Measure turnon curves for analysis and systematic uncertainties

Use turnon curves in data and MC

Evaluate trigger systematic uncertainty for isolated tracks

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**Measure turnon curves**

Select an orthogonal trigger

Select events that mimic WH

Cuts on the selection variables of the trigger, as to be in the plateau region, for them except for the parameterization variable

These events form the Denominator. The Numerator is formed by events that also fire our trigger

We divide numerator and denominator to get turnon curve

Keep in mind to correct each weight by the effective prescale

Multiply the three turnon curves to get the final one

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MET + 2 Jets turnon curves

3.0 fb^{-1}, Central muon trigger \( P_T > 20 \text{ GeV} \)
2 jets with \( E_T > 25 \text{ GeV}, |\eta|<2.0, dR>1 \), one with \( |\eta|<0.9 \)

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3.0 fb$^{-1}$, Central muon trigger $P_T$>20 GeV
2 jets with $E_T$>20 GeV, $|\eta|<$2.0, dR>0, one with $|\eta|<$0.9
Use Turnon Curves

Measure weight for all desired triggers
- Measure weight given by each trigger for that event
- Correct for effective prescale of that trigger
- If jet selection fails for that trigger, return weight of zero

Pick the correct trigger
- Pick the trigger that returns the largest weight.
- Check the trigger bits for that trigger.
- If it passed, keep the event in data and assign it its weight in MC
- Can not do OR for the 3 MET-based triggers as there is overlap
- However, once the weight is measured, it can be OR-ed with the weight from the muon gap triggers
Measure trigger systematic

Measure turnon curves for systematic

- Besides turnon curve for the entire dataset, divide the dataset in bins of various variables and for each bin measure the turnon curve
- Variables: jet quantities, number of event, fully corrected MET, etc

Measure systematic uncertainty

- For signal, have event selection and count the acceptance using turnon curve for the entire dataset
- Then count acceptance for a given variation quantity (check this quantity in which bin it is, pick its turnon curve and get the weight)
- Compare acceptance of central and for all variations
- Add percentages of difference in quadrature

Result

- Systematic uncertainty < 3% for MET + 2 Jets and for MET 45

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(MET+2 Jets) + (MET45)

WH120 MC, isolated track with $P_T>20$ GeV and 2 jets with $E_T>20$ and full analysis selection

Effect of turnon curve on jets-corrected met in WH120 MC

<table>
<thead>
<tr>
<th>Triggers (1 tag)</th>
<th>Acc.</th>
<th>Syst.</th>
<th>Impr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET2J (PS=0.93)</td>
<td>603</td>
<td>2.4%</td>
<td>0%</td>
</tr>
<tr>
<td>MET2J (PS=0.93) + MET45 (PS=1.00)</td>
<td>756</td>
<td>2.3%</td>
<td>25%</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Triggers (2 tag)</th>
<th>Acc.</th>
<th>Syst.</th>
<th>Impr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET2J (PS=0.93)</td>
<td>170</td>
<td>2.3%</td>
<td>0%</td>
</tr>
<tr>
<td>MET2J (PS=0.93) + MET45 (PS=1.00)</td>
<td>200</td>
<td>2.6%</td>
<td>17%</td>
</tr>
</tbody>
</table>

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Use Boosted Decision Tree (BDT)

- S/B too small
- Counting experiments are hopeless
- Use BDT as multivariate technique

Choose kinematic variables as inputs to the BDT

- Matrix Element values – most sensitive
- Variables sensitive to specific backgrounds
- Dijet invariant mass – next to most sensitive
Use Neural Network (NN)
• S/B too small
• Counting experiments are hopeless
• Use Neural Network as multivariate technique

Choose kinematic variables as inputs to the NN
• Variables sensitive to specific backgrounds
• Most sensitive is dijet invariant mass

Train the Neural Network
• Using signal and background

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NN and ME+BDT Combination Output

Super-discriminant (NEAT)
Neuro-evolution of augmented topologies

CDF Run II Preliminary, $L = 2.7 \text{ fb}^{-1}$

- $W + b\bar{b}$
- $W + b\bar{c}$, $W + c$
- $W + j$
- Top
- Other

From 100 GeV to 150 GeV, with 5 GeV steps

Different Higgs mass points

Tight 2 tag

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Winter Tevatron Higgs Combination

Search for the Higgs Particle
Status as of March 2009

90% confidence level
95% confidence level

Excluded by LEP Experiments
95% confidence level

Excluded by Tevatron Experiments

Excluded by Indirect Measurements
95% confidence level

Periodic Table of the Elements

H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Actinide series

Lanthide series

Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71

Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

82 Se 92 Se 92 Sr 92 Y 92 Zr 92 Nb 92 Mo 92 Tc 92 Ru 92 Rh 92 Pd 92 Ag 92 Cd 92 In 92 Sn 92 Sb 92 Te 92 I 92 Xe 92 Cs 92 Ba 92 La 92 Ce 92 Pr 92 Nd 92 Pm 92 Sm 92 Eu 92 Gd 92 T b 92 Dy 92 Ho 92 Er 92 Tm 92 Yb 92 Lu 92