Higgs searches from CDF
(+ combination with D0)

New results: Low mass Higgs
New excitement: High mass Higgs
Some SUSY Higgs perspective

Ben Kilminster
Fermilab
CERN joint EP/PP seminar
Sept. 8, 2008
Basic theory of interactions does not provide for massive particles
Basic theory of interactions does not provide for massive particles.

The experimental problem (1)

Hierarchy of Standard Model particle masses

 Explicit mass terms cause Standard Model calculations to fail
The experimental problem (2)

Hierarchy of Standard Model particle masses

- **quarks**
- **bosons**
- **leptons**

Fundamental asymmetry between EM and weak force carrier mass

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<thead>
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<th>e^+</th>
<th>e^-</th>
<th>μ^-</th>
<th>τ^-</th>
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95% CL upper limit
Solution: Higgs mechanism

- Add field throughout the universe
  - Potential is symmetric
  - Ground state breaks symmetry
- Cleverly
  - $W$ and $Z$ bosons gain masses through degrees of freedom of Higgs field
  - Masses are generated for the fermions due to their interaction with this non-zero field
  - Theory preserves symmetry (gauge invariance)
  - Standard Model calculations no longer fail
  - A new particle is predicted: the Higgs boson

Finding the Higgs boson

- Means Higgs field exists
  - Means we confirm our theory for the origin of mass
What is the Higgs boson mass?

CDF and D0 may flip coins to decide talk order
What is the Higgs boson mass?

CDF and D0 may flip coins to decide talk order

... but we do use a likelihood to decide where to find the Higgs boson
What is the Higgs boson mass?

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CDF and D0 may flip coins to decide talk order

... but we do use a likelihood to decide where to find the Higgs boson

Electroweak observables constrain Higgs boson mass within SM
Where is the Higgs?

Direct searches at LEP:
\[ Z^* \rightarrow ZH \]

Indirect searches:
\~20 measurements from Tevatron, LEP, SLD

<table>
<thead>
<tr>
<th>Date</th>
<th>Direct</th>
<th>Indirect</th>
</tr>
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<tbody>
<tr>
<td>'98</td>
<td>&gt; 89</td>
<td>173.5 ( \pm ) 5.2</td>
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<td>'00</td>
<td>&gt; 108</td>
<td>174.3 ( \pm ) 5.1</td>
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<td>'04</td>
<td>&gt; 114.4</td>
<td>178.2 ( \pm ) 4.3</td>
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<tr>
<td>'06</td>
<td>&gt; 114.4</td>
<td>171.4 ( \pm ) 2.4</td>
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<tr>
<td>08</td>
<td>&gt; 114.4</td>
<td>172.4 ( \pm ) 1.2</td>
</tr>
</tbody>
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source: LEPEWWG as presented at Moriond 98 & 00, ICHEP 04, 06, 08
Revisiting global electroweak fit

- **Gfitter group includes**
  - Indirect electroweak constraints
  - LEP direct Higgs searches
  - Tevatron Higgs searches (only up to previous combo 2.4 fb⁻¹)

[CDF+D0: arXiv:0804.3423]
Revisiting global electroweak fit

Gfitter group includes
- Indirect electroweak constraints
- LEP direct Higgs searches
- Tevatron Higgs searches (only up to previous combo 2.4 fb$^{-1}$)

Fit finds $m_H = 120 \pm 15 -5$ GeV
2 $\sigma$ Interval : $[114.4, 144]$ GeV
SM Higgs at the Tevatron

Main decay modes

Events produced at CDF in 1 fb⁻¹

Higgs mass (GeV)

Higgs mass (GeV)

Events

Total

H → WW → lvlv
WH → lvbb
ZH → ννbb
ZH → llbb

Higgs mass (GeV)
SM Higgs at the Tevatron

Main decay modes

Events produced at CDF in 1 fb⁻¹

~6 months data

Higgs mass (GeV)

Events

10 20 30 40 50 60 70

Higgs mass (GeV)

110 120 130 140 150 160 170 180

Total

H → WW → l⁺l⁻νν
WH → lνbb
ZH → ννbb
ZH → l⁺l⁻bb
SM Higgs at the Tevatron

Main decay modes

Events produced at CDF in 1 fb⁻¹

~6 months data

Total (double including D0)

H → WW → llvv
WH → lνbb
ZH → ννbb
ZH → llbb

Higgs mass (GeV)
What if there is SUSY?

- One → Five Higgs bosons

- Are Tevatron **SM** Higgs searches still useful?
  - Consider CMSSM fits
    - Electroweak constraints
    - Anomalous magnetic moment \((g - 2)\)
    - Cosmology - relic neutralino abundance
    - Rare B decays
  - MSSM predicts a SM-like Higgs
    - 113 < \(m_H\) < 122 GeV @ 95% region
  - \(H^\pm, H^0, A^0\)
    - 0.2 TeV < m < 3.6 TeV @ 95% region
    - Likely out of reach for Tevatron

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JHEP 0704:084,2007

Roszkowski, Ruiz & Trotta (2006)
What if there is SUSY?

- One → Five Higgs bosons

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  - Consider CMSSM fits
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- Low mass SM Higgs searches may be first indication of MSSM
  - Though we wouldn’t know it from SM until LHC finds the others!

JHEP 0704:084,2007

Low mass SM Higgs searches may be first indication of MSSM

- Though we wouldn’t know it from SM until LHC finds the others!
Detectors

**ATHLAS**
- Diameter: 25 m
- Length: 46 m

**CMS**
- Diameter: 16 m
- Length: 21 m

**CDF**
- Diameter: 12 m
- Length: 21 m

**All-purpose:**
- Silicon vertex tracker
- Drift chamber tracker
- 1.4 T solenoid
- EM calorimeters
- Had calorimeters
- Muon detectors

**Performance:**
- 5 fb$^{-1}$ delivered
- 4 fb$^{-1}$ acquired
Detectors

diameter = 25 m
length = 46 m

d = 16 m
l = 21 m

d = 12 m
l = 12 m

ATLAS

Rutherford gold foil experiment 1911

CMS

CDF

All-purpose:
Silicon vertex tracker
Drift chamber tracker
1.4 T solenoid
EM calorimeters
Had calorimeters
Muon detectors
5 fb$^{-1}$ delivered
4 fb$^{-1}$ acquired

Ben Kilminster, CERN seminar '08
How to build an advanced Higgs analysis program

- Start with basic analysis
- Bootstrap special techniques to gain sensitivity
  - Improve acceptance
    - Loosen lepton ID & b-tag requirements
    - Add backup triggers
    - Relax kinematic selection
- But... backgrounds increase & become more difficult to model
  - Incorporate specialized background rejection techniques
  - Background modeling checks! Data must stay well modeled!
  - Separate out events into categories with better $S/\sqrt{B}$
    - High $S/\sqrt{B}$ gives best signal sensitivity
    - Low $S/\sqrt{B}$ gives best background constraints
  - Use multivariate techniques to distinguish signal events

Repeat for every Higgs discovery mode

Combine taking into account uncertainties correlated between correlated backgrounds
ZH $\rightarrow$ llbb story

- Smallest expected signal
  - Small $\sigma_{ZH}$ and BR($Z \rightarrow ll$)
- But, fully constrained = lower backgrounds
  - Two resonances $H \rightarrow bb$ and $Z \rightarrow ll$
- Baseline analysis
  - Start with inclusive high $P_T$ lepton trigger (Track + $E_T > 18$ GeV)
  - Select two leptons $E_T > 18, 10$ GeV, $\geq 2$ jets $E_T > 20, 15$ GeV
  - Fit dijet mass for an excess from $H \rightarrow bb$

for $m_H < 135$
ZH $\rightarrow llbb$ story

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  - Select two leptons $E_T > 18, 10$ GeV, $\geq 2$ jets $E_T > 20, 15$ GeV
  - Fit dijet mass for an excess from $H \rightarrow bb$
- Special techniques
  - Relax lepton requirements
    - Second muon does not require muon chamber confirmation
    - Second electron does not require track when forward in $\eta$
    - New: Dilepton categories from "no-track" trigger: two energy deposits in central or forward region
  - Use $b$-tagging to improve $S/\sqrt{B}$
  - Improve dijet mass resolution
  - Employ Artificial Neural Network for improved separation

for $m_H < 135$
B-tagging in $ZH \rightarrow llbb$

"B-tag" = Identify 2nd vertex

High $\eta$ $b$ quark
Low $\eta$ $b$ quark

Events
-3 -2 -1 0 1 2 3

SecVtx Tag Efficiency for Top $b$-Jets

Top MC scaled to match data
Only $b$-jets with $E_T > 15$ GeV

Tight SecVtx
Loose SecVtx
B-tagging in ZH → llbb

Divide into subsets and win
(ZH expectations shown here for 2.4 fb⁻¹)

<table>
<thead>
<tr>
<th>Category</th>
<th>S</th>
<th>B</th>
<th>S/sqrt(B)</th>
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<td>High - 2 Loose b-tags</td>
<td>0.5</td>
<td>30</td>
<td>0.09</td>
</tr>
<tr>
<td>High - 1 Tight b-tag</td>
<td>0.9</td>
<td>200</td>
<td>0.06</td>
</tr>
<tr>
<td>Low - 2 Loose b-tags</td>
<td>0.1</td>
<td>7</td>
<td>0.04</td>
</tr>
<tr>
<td>Low - 1 Tight b-tag</td>
<td>0.1</td>
<td>70</td>
<td>0.01</td>
</tr>
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</table>

Sum in quadrature of S/sqrt(B)
(scales like 1 / Limit)

0.09 → 0.12

Dilepton categories
• “High” central Z purity
• “Low” central Z purity

“B-tag” = Identify 2nd vertex

Events

Top MC scaled to match data
Only b-jets with E_T > 15 GeV

H ——— b

b

Jet

Secondary vertex

Prompt tracks

Primary vertex

Displaced tracks

Decay lifetime

SecVtx Tag Efficiency for Top b-Jets

Tight SecVtx

Loose SecVtx

-3 -2 -1 0 1 2 3

-3 -2 -1 0 1 2 3

Events

b parton η

High η b quark

Low η b quark
ZH → llbb

Can improve Mjj resolution by correcting jets according to projection onto MET direction.
ZH → llbb

*Can improve Mjj resolution by correcting jets according to projection onto MET direction*

For events with two b-tags, dijet mass resolution improves from 18% to 11%
Multivariate techniques

- Multivariate analysis techniques
  - Used in all CDF Higgs analyses

- Functions which transform multiple inputs into single discriminant tuned for identifying a single process
  - NN = Neural Net
  - ME = Matrix Element
  - BDT = Boosted Decision Trees

- Validation
  - Inputs must be modeled correctly
  - Correlations of inputs and output discriminant tested vigorously in independent control samples with similar kinematics and backgrounds
Multivariate techniques

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Validation
- Inputs must be modeled correctly
- Correlations of inputs and output discriminant tested vigorously in independent control samples with similar kinematics and backgrounds

Pre b-tag NN Output for ZH
- Same object kinematics
- Statistics = 30 * tagged sample
- NN trained on:
  - Masses of combinations (j1, j2, e/μ)
  - P_T of combinations
  - Angular separations
**ZH → llbb**

- We use a 2D NN to distinguish ZH from tt and Z+jets.

- New “low” purity lepton types from no-track trigger improve limit by 10%.

---

**CDF Run II Preliminary (2.4 fb⁻¹)**

**Double Tag (High):**
- ZH × 15
- $M_H = 120 \text{ GeV/c}^2$

**Single Tag (Low):**
- ZH × 200
- $M_H = 120 \text{ GeV/c}^2$
ZH → llbb

We use a 2D NN to distinguish ZH from tt and Z+jets

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Have also done ME analysis with 2.1 fb⁻¹
In the process of merging the two...

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CDF Run II Preliminary (2.4 fb⁻¹)

\[ \mathcal{L} = 2.4 \text{ fb}^{-1}, \ m_H = 115 \text{ GeV} \]
Upper limit: 11.8*SM (expected 11.6*SM)
ZH $\rightarrow$ llbb

We use a 2D NN to distinguish ZH from tt and Z+jets

New “low” purity lepton types from no-track trigger improve limit by 10%

Have also done ME analysis with 2.1 fb$^{-1}$
In the process of merging the two ...

World's best exp. limit in this channel!
Selection \((l + \text{MET} + \geq 2 \text{jets} + \geq 1 \text{b-tag})\):
- one lepton, e or \(\mu\), \(P_T > 20\) GeV
- \(\text{MET} = \text{Missing transverse energy} > 20\) GeV
- \(\geq 2\) jets from bs, \(E_T > 15\) GeV
- Require jet to be b-tagged

Lots of Tevatron experience:
- Same as single top - CDF had 2006 evidence
- Similar to golden analysis for studying top quark pairs
  - \(l + \text{MET} + \geq 4 \text{jets} + \text{b-tag}\)

Basic analysis:
- Use central high \(P_T\) lepton trigger
- Search for resonance in dijet mass

\(\text{WH} \rightarrow l\nu bb: \text{the golden channel for } m_H < 135\)
**WH → lvbb**

**Improving lepton acceptance**

**Forward (plug) electrons**
- Plug electron trigger rate is too high since we have little tracking to reject jets
- Use plug electron + MET trigger

**New: Incomplete muons**
- Central muon trigger requirements are stringent because trigger rate is high
- Use jets + MET trigger
- Select muons offline with looser criteria

**Diagram**
- Dijet mass in plug WH candidates
- New events passing “isolated track” lepton requirements

**Data vs. Mistag vs. Non-W**
- Brown is non-W (QCD)
- Blue is real W’s

**CDF Run II Preliminary (1.9 fb⁻¹)**

**CDF Run II Preliminary 2.7 fb⁻¹**

**Graphs**
- 10% more WH
- 20% more WH
- Number of Events vs. Transverse Mass
WH → lνbb results

- Several iterations to optimize NN analysis
- Newer parallel effort with matrix elements (from single-top evidence group)

Uses 2 b-tagging categories for final result (this is one)
WH → ℓνbb results

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CDF Run II Preliminary 2.7 fb⁻¹

Upper limit: 5.0*SM (expected 5.8*SM)

CDF Run II Preliminary, L=2.7 fb⁻¹

Upper limit: 5.8*SM (expected 5.6*SM)
WH → ℓνbb results

Several iterations to optimize NN analysis

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Uses 2 b-tagging categories for final result (this is one)

CDF Run II Preliminary 2.7 fb⁻¹

Neural Network Output (M=110)

L = 2.7 fb⁻¹, m_H = 115 GeV
Upper limit: 5.0*SM (expected 5.8*SM)

World's best low mass Higgs limits!
**VH → MET+jets**

**Signature**
- MET > 50 GeV, >= 2 jets, >= 1 b-tag

**Large total signal**
- 7.3 Higgs events in 2.1 fb⁻¹

**Baseline analysis**
- Uses MET + multi-jet trigger
- Fit of $M_{jj}$ in 2-jet data, >= 1 b-tag

**Challenge**
- Large QCD background from mismeasured jets
- Peak in $M_{jj}$ where signal

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<thead>
<tr>
<th>Process</th>
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<tr>
<td>QCD</td>
<td>80 ± 15</td>
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<tr>
<td>Total Bkg</td>
<td>149 ± 20</td>
</tr>
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<td>ZH Signal</td>
<td>0.8</td>
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**CDF Run II Preliminary, 2.1 fb⁻¹**

- Invariant Mass of all jets, Signal Region, ST+ST

**QCD**
VH $\rightarrow$ MET+jets

Using tracking in 2 ways
- Tracks have excellent momentum resolution
- 2/3 of particles in jets are charged

Missing $P_T$ of tracks = TMET
- Provides confirmation of high MET measured in calorimeter
- Helpful for reducing QCD

Improving jet resolution
- H1 algorithm
  - New: 1st time in CDF analysis
- Correct calorimeter towers with matched higher $P_T$ tracks
VH $\rightarrow$ MET+jets result

- First stage NN
  - Trained to remove QCD

- Cut here
  - Removes 65% of Multijet
  - Removes only 5% of signal
VH $\rightarrow$ MET+jets result

**First stage NN**
- Trained to remove QCD

**Second stage NN**
- Removes W/Z+jets and top

**Cut here**
- Removes 65% of Multijet
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Uses 3 b-tagging categories for final result (this is one)
**VH → MET+jets result**

- **First stage NN**
  - Trained to remove QCD
  - Removes 65% of Multijet
  - Removes only 5% of signal

- **Second stage NN**
  - Removes W/Z+jets and top
  - Uses 3 b-tagging categories for final result (this is one)

\[ \int L = 2.1 \text{ fb}^{-1} \]

Upper limit: \[ 7.9 \times \text{SM} \text{ (exp. 6.3 \times \text{SM})} \]

World's best in this channel
VH → MET+jets result

First stage NN
- Trained to remove QCD

Second stage NN
- Removes W/Z+jets and top

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\[ \mathcal{L} = 2.1 \text{ fb}^{-1} \]
Upper limit: \( 7.9 \times \text{SM} \) (exp. \( 6.3 \times \text{SM} \))
World's best in this channel

With more \( \mathcal{L} \) as good as WH "golden channel"
"Diamond in the Rough" Channel
Getting every last Higgs event at low mass

Analyses become more challenging

- $H \rightarrow \tau\tau$ decay modes
  - BR ($H \rightarrow \tau\tau$) ten times smaller than $H \rightarrow bb$

- $Z/W + H \rightarrow qq + bb$
  - More signal than lepton modes but enormous QCD backgrounds
Selection: $H \rightarrow \tau\tau + 2$ jets

Signal: $gg \rightarrow H \rightarrow \tau\tau$, $VH \rightarrow q\bar{q}\tau\tau$, V.B.F. $H \rightarrow \tau\tau qq$

NN’s trained for each of main backgrounds

- $Z \rightarrow \tau\tau$, Top, QCD
- Final discriminant is minimum of all

KS prob = 68.4%

CDF Run II Preliminary

$\mathcal{L} = 2.0$ fb$^{-1}$, $m_H = 115$ GeV

Upper limit: 26*SM (expected 30*SM)
QCD backgrounds enormous

- Challenge to pull out signal
- Matrix element analysis used

\[ \mathcal{L} = 2.0 \text{ fb}^{-1}, \ m_H = 115 \text{ GeV} \]

Upper limit: 37*SM  
(expected 35*SM)
High Mass Higgs search

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

\[ H \rightarrow WW \text{ most important channel} \]
High mass $H \rightarrow WW$

$m_H = 160$ GeV

New: dedicated analyses in different 0, 1, 2 jet bins

<table>
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<tr>
<th>Process</th>
<th>$H \rightarrow WW + \geq 2j$ Evts, $L = 3$fb$^{-1}$</th>
</tr>
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<td>$gg \rightarrow H \rightarrow WW$</td>
<td>$1.52 \pm 0.26$</td>
</tr>
<tr>
<td>$WH \rightarrow WWW$</td>
<td>$1.18 \pm 0.16$</td>
</tr>
<tr>
<td>$ZH \rightarrow WWW$</td>
<td>$0.59 \pm 0.08$</td>
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<tr>
<td>V.B.F. $H \rightarrow WW$</td>
<td>$0.61 \pm 0.1$</td>
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High mass $H \rightarrow WW$

New: dedicated analyses in different 0, 1, 2 jet bins

Divide and conquer

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$m_H = 160$ GeV
High mass $H \rightarrow WW$

New: dedicated analyses in different 0, 1, 2 jet bins

Divide and conquer

<table>
<thead>
<tr>
<th># jets</th>
<th>$H \rightarrow WW$ events</th>
<th>Total Bkg events</th>
<th>% WW</th>
<th>% Drell-Yan</th>
<th>% $tt$</th>
<th>% fakes &amp; conversions</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>540</td>
<td>52</td>
<td>12</td>
<td>0.2</td>
<td>30</td>
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<td>1</td>
<td>5</td>
<td>230</td>
<td>32</td>
<td>31</td>
<td>11</td>
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</tr>
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<td>2</td>
<td>4</td>
<td>130</td>
<td>12</td>
<td>22</td>
<td>54</td>
<td>8</td>
</tr>
</tbody>
</table>

Different background compositions

Analyses optimized for each jet bin

$m_H = 160$ GeV

Process

- $H \rightarrow WW + \geq 2j$
  - Evts, $L = 3fb^{-1}$
- $gg \rightarrow H \rightarrow WW$ $1.52 \pm 0.26$
- $WH \rightarrow WWW$ $1.18 \pm 0.16$
- $ZH \rightarrow WWW$ $0.59 \pm 0.08$
- V.B.F. $H \rightarrow WW$ $0.61 \pm 0.1$
\( H \rightarrow WW : 0 \) jets

- **WW background**
  - Primarily distinguished by spin correlation of leptons
- **Fakes and conversions**
  - Difficult to model, require data validation

\[ \begin{align*}
\Delta R (\text{lep 1, lep 2}) & \\
\text{Spin 0 } H & \rightarrow WW \\
\text{Spin 1 } Z & \rightarrow WW
\end{align*} \]

**Signal region**

**Control region using**

**Same-sign**

**Fakes & conversions:**

- **Control region using**
  - Same-sign
- **Fakes & conversions:**
  - Control region using

---

**CDF Run II Preliminary**

\[ \int L dt = 3.0 \text{ fb}^{-1} \]

**Region: Base**

- Data
- \( t\bar{t} \)
- \( WW \)
- \( W_3 \)
- \( WZ \)
- \( W+\text{jets} \)
- \( ZZ \)

**Events / 0.2**

- \( t\bar{t} \times m_H (160) \)
- CL = 16.0%
- KS CL = 19.7%

**Region: Base**

\[ \begin{align*}
\Delta R (\text{lep 1, lep 2}) & \\
\text{Spin 0 } H & \rightarrow WW \\
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\end{align*} \]

- Data
- \( t\bar{t} \)
- \( WW \)
- \( W_3 \)
- \( WZ \)
- \( W+\text{jets} \)
- \( ZZ \)
- DY

**Events / 0.2**

- \( t\bar{t} \times m_H (160) \)
- CL = 17.3%
- KS CL = 45.6%
**H → WW : 1 jet**

- Drell-Yan & WW bkgs contribute equally
  - Check Drell-Yan has proper dilepton & MET correlations
  - DY can be cleaned up with special MET calculations

\[ \Delta R (\text{lep } 1, \text{lep } 2) \]
- in low MET region dominated by DY
- MET crossed with nearest lepton or jet modeled well both in DY and WW regions

**CDF Run II Preliminary**

- Region: DY
- \( \int L \, dt = 3.0 \text{ fb}^{-1} \)

**CDF Run II Preliminary**

- Region: Base
- \( \int L \, dt = 3.0 \text{ fb}^{-1} \)

---

Ben Kilminster, CERN seminar ’08
**H → WW : 2 jet**

- Top pairs biggest bkg ($tt \rightarrow WbWb \rightarrow l\nu l\nu bb$)
  - Analysis requires anti-b tag to get rid of top
  - Can also examine b-tagged control region to test model

<table>
<thead>
<tr>
<th></th>
<th>$tt$</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>observed</strong></td>
<td>98</td>
<td>91 ± 17, 2.3 ± 0.3</td>
</tr>
</tbody>
</table>

$\Delta R$ (lep 1, lep 2) in b-tagged control region

$\Delta R$ (lep 1, lep 2) in anti b-tagged signal region
### $H \rightarrow WW$ analyses results

<table>
<thead>
<tr>
<th></th>
<th>0 J</th>
<th>1 J</th>
<th>2 J</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>552</td>
<td>227</td>
<td>139</td>
</tr>
<tr>
<td>expected</td>
<td>$540 \pm 65$</td>
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**0 J**

NN using LO matrix elements
probabilities, sum transverse energies,
$d\Phi(l_1,l_2)$, $dR(l_1,l_2)$

**CDF Run II Preliminary**

$\int L = 3.0 \text{ fb}^{-1}$

$m_H = 170 \text{ GeV}$
**H → WW analyses results**

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**0 J**

NN similar to 0J NN: adds in special MET cut, lepton $P_T$s, removes LO matrix elements because of extra jets

**1 J**

NN using LO matrix elements, probabilities, sum transverse energies, $d\Phi(l_1,l_2)$, $d\mathcal{R}(l_1,l_2)$

---

$m_H = 170$ GeV
H → WW analyses results

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<td>129 ± 20</td>
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</table>

2 J
NN similar to 1J NN: adds in P_T of dijet system

1 J
NN similar to 0J NN: adds in special MET cut, lepton P_Ts, removes LO matrix elements because of extra jets

m_H = 170 GeV
H ➞ WW Combination at CDF

Lots of systematics uncertainties:
Correlated between backgrounds, signal processes, and between 0J, 1J, 2J channels

Leading systematics:

- WW, tt, H ➞ WW
  - 10-15% cross-section
- W+jets, W+γ
  - 20-30% jet fakes and conversions
- Drell-Yan
  - 20% MET modeling

List of systematics and background correlations (Don't try to read)
$H \rightarrow WW$ Combination at CDF

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![Graph showing CDF Run II Preliminary Results](image)

<table>
<thead>
<tr>
<th>mH</th>
<th>120</th>
<th>130</th>
<th>160</th>
<th>165</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected</td>
<td>13</td>
<td>6</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>observed</td>
<td>14</td>
<td>6</td>
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*σ_{SM}
H → WW Combination at CDF

Lots of systematics uncertainties:
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- WW, tt, H → WW
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List of systematics and background correlations (Don’t try to read)

![Graph showing world’s best high mass limits](image)

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*σ_{SM}
CDF Combination

Low and high mass Higgs channels combined for CDF

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limit @ 115 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH</td>
<td>5 (6)</td>
</tr>
<tr>
<td>VH → MET+bb</td>
<td>8 (6)</td>
</tr>
<tr>
<td>ZH → llbb</td>
<td>12 (12)</td>
</tr>
<tr>
<td>H → ττ + jets</td>
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CDF combined upper limits:
- $m_H = 115$ GeV $3.6\times$SM expected
- $m_H = 165$ GeV $1.6\times$SM expected
For $m_H = 160$ GeV

- Baseline analysis (2004) would require 36 fb$^{-1}$ for 2$\sigma$ sensitivity
- Advanced analysis now sensitive with < 5 fb$^{-1}$
- CDF only limit is 1.6*SM
- Goal is bottom of yellow band
- Expect to exclude significant region around $m_H = 160$ GeV with more data
CDF results - Past and Future

For $m_H = 160$ GeV
- Baseline analysis (2004) would require $36 \text{ fb}^{-1}$ for $2\sigma$ sensitivity
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- CDF only limit is $1.6 \times \text{SM}$
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For $m_H = 115$ GeV
- Ongoing improvements
  - B-tagging
  - Lepton acceptance
  - Jet / Met resolution
  - Complementary triggers
  - Signal/Bkg separation techniques
- Nearing yellow band steadily

---

CDF Run II Preliminary, $m_H=160$ GeV

![Graph showing expected limit/SM versus integrated luminosity/ Experiment (fb$^{-1}$)]

- **2004 analyses** with more data

---

Ben Kilminster, CERN seminar '08
CDF results - Past and Future

For $m_H = 160$ GeV

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CDF Run II Preliminary, $m_H=160$ GeV

<table>
<thead>
<tr>
<th>Integrated luminosity/Experiment (fb$^{-1}$)</th>
<th>Expected Limit/SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary, $m_H=115$ GeV

<table>
<thead>
<tr>
<th>Integrated luminosity/Experiment (fb$^{-1}$)</th>
<th>Expected Limit/SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>22.5</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>17.5</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
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<td>7.5</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

2004 analyses with more data
2005 analyses with more data
More on SUSY

If SUSY is the correct theory

- Some Higgs production mechanisms enhanced by $(\tan \beta)^2$
- Direct $gg \rightarrow H \rightarrow bb$ and $H \rightarrow \tau\tau$ modes become viable searches for neutral SUSY Higgs mass $< \sim 200$ GeV

Between CDF and D0

- $H \rightarrow bb$, $H \rightarrow \tau\tau$, $H \rightarrow \tau\tau + b$
- Will have 6 channels with comparable sensitivity
- Plan to combine for MSSM tan $\beta$ limits
CDF Conclusions

- Searching for every available Higgs boson

**Low mass Higgs**
- World’s best limits in $ZH \rightarrow llbb, WH \rightarrow lvbb, VH \rightarrow MET+bb$
  - Additional all-jets and $\tau\tau$ modes improve total sensitivity
  - Combined limit $3.6 \times$ SM expected with $3 \text{ fb}^{-1}$
  - Steady improvements since 2005
  - Near sensitivity for low mass exclusion with full dataset & D0

**High mass Higgs**
- World’s best limits in $H \rightarrow WW$
  - $1.6 \times$ SM expected with $3 \text{ fb}^{-1}$
  - Goal is single-experiment exclusion for range of masses

**MSSM Higgs**
- Low mass ZH/WH Higgs searches may be best way to find CMSSM
  - SUSY searches for $H \rightarrow bb$ and $H \rightarrow \tau\tau$ extend limits on $\tan \beta$
CDF + D0 Combination

We use two different methods (done by different people on different experiments) to verify accuracy

- Method 1: CLs
- Method 2: Bayesian - expected to be more conservative (coverage is greater than 95%)
CDF + DO Combination

We use two different methods (done by different people on different experiments) to verify accuracy:

- Method 1: CLs
- Method 2: Bayesian - expected to be more conservative (coverage is greater than 95%)
Combination with D0

CLs combination plot

<table>
<thead>
<tr>
<th>95%CL Limits/SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Higgs (GeV)</td>
</tr>
<tr>
<td>160 165 170 175</td>
</tr>
<tr>
<td>Method 1: Exp</td>
</tr>
<tr>
<td>1.3 1.2 1.4 1.7</td>
</tr>
<tr>
<td>Method 1: Obs</td>
</tr>
<tr>
<td>1.4 1.2 1.0 1.3</td>
</tr>
<tr>
<td>Method 2: Exp</td>
</tr>
<tr>
<td>1.2 1.1 1.3 1.7</td>
</tr>
<tr>
<td>Method 2: Obs</td>
</tr>
<tr>
<td>1.3 1.1 0.95 1.2</td>
</tr>
</tbody>
</table>
Combination with D0

CLs combination plot

Results are consistent:

\( m_H \) at 170 GeV ruled out at 95% CL

| Method 1: Exp | 1.3 | 1.2 | 1.4 | 1.7 |
| Method 1: Obs | 1.4 | 1.2 | 1.0 | 1.3 |
| Method 2: Exp | 1.2 | 1.1 | 1.3 | 1.7 |
| Method 2: Obs | 1.3 | 1.1 | 0.95 | 1.2 |

95%CL Limits/SM

M Higgs(GeV)  160 165 170 175

Ben Kilminster, CERN seminar ’08
CDF + DO Conclusions

- Searching for every available Higgs boson
  - Using up to 3 fb\(^{-1}\) of data per experiment
  - Current full dataset is \(\sim 4\) fb\(^{-1}\)
  - Expect 6 – 8 fb\(^{-1}\) total per experiment

- MSSM Higgs
  - Low mass ZH/WH Higgs searches may be best way to find CMSSM
  - SUSY searches for H \(\rightarrow bb\) and H \(\rightarrow \tau\tau\) extend limits on tan \(\beta\)

- Low mass Higgs
  - Steady improvements since 2005
  - Near sensitivity for low mass exclusion with full dataset & DO

- High mass Higgs
  - Excluded \(m_H\) at 170 GeV !!
  - Goal is combined exclusion for wide range of high mass Higgs
Backups
B-tagging jets in WH $\rightarrow l\nu bb$

Algorithms:
- SVX Tag “ST”
- Loose SVX Tag
- Jet probability Tag “JP”
- NN flavor separator

Divide into subsets and win
(WH expectations shown here)

<table>
<thead>
<tr>
<th>B-tags</th>
<th>S</th>
<th>B</th>
<th>S/sqrt(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 ST</td>
<td>1.6</td>
<td>150</td>
<td>0.13</td>
</tr>
<tr>
<td>ST+JP</td>
<td>1.1</td>
<td>160</td>
<td>0.09</td>
</tr>
<tr>
<td>1 ST</td>
<td>3.6</td>
<td>1750</td>
<td>0.09</td>
</tr>
</tbody>
</table>

sum in quadrature of S/sqrt(B)
good figure of merit for sensitivity

0.14 $\rightarrow$ 0.18
WH $\rightarrow l\nu bb$ backup

- Test of NN in WH analysis
  - Control region with same kinematic selection
  - Using high statistics pretagged events

New category: Isolated track leptons only

CDF Run II Preliminary 2.7 fb$^{-1}$

- All lepton types

<table>
<thead>
<tr>
<th>Category</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+bottom</td>
<td>Light green</td>
</tr>
<tr>
<td>W+charm</td>
<td>Light blue</td>
</tr>
<tr>
<td>W+LF</td>
<td>Light pink</td>
</tr>
<tr>
<td>Top</td>
<td>Medium red</td>
</tr>
<tr>
<td>Diboson</td>
<td>Medium yellow</td>
</tr>
<tr>
<td>Z+jets</td>
<td>Medium brown</td>
</tr>
<tr>
<td>Non-W</td>
<td>Dark brown</td>
</tr>
<tr>
<td>WH (115 GeV) (x 200)</td>
<td>Red</td>
</tr>
</tbody>
</table>

Data