Higgs boson searches at the Tevatron

Ben Kilminister
Fermilab
on behalf of
CDF & DO

MISSING PARTICLE:

Name: Higgs boson
Age: 13.7 billion years
Missing: 45 years
Birthday: Every few days at Fermilab
Favorite trait: Mass
Favorite particle: top quark
Favorite Hangout: Tevatron

ICH EP 2010
July 26, 2010
How to generate mass & break electroweak symmetry?

Higgs mechanism:
Non-zero field permeating the universe generates mass

- W and Z bosons gain mass through degrees of freedom of Higgs field
- Fermions gain mass interacting with the Higgs field
- New particle Higgs boson predicted

Finding the Higgs boson
- Means Higgs field exists
- Means we confirm our theory for the origin of mass
Recent headlines

“Higgs” or media favorite: “God particle”

Old faithful Tevatron collider leads race to Higgs

Has elusive God particle finally been discovered?

Did Someone Just Find the 'God Particle'? 

Higgs Boson Discovered? Not so fast.

Human buzz that God particle is found
2010 Sakurai Prize

... for “elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses.”

Brout  Englert  Higgs  Hagen  Guralnik  Kibble

PRL 13, 321-323 (1964)  PRL 13, 508-509 (1964)  PRL 13, 585-587 (1964)
2010 Sakurai Prize

... for “elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses.”

Brout, Englert
PRL 13, 321-323 (1964)

Higgs
PRL 13, 508-509 (1964)

Hagen
PRL 13, 585-587 (1964)

Guralnik

Kibble

So in honor of B-E-H-H-G-K authors ...
Re-energize newspaper headlines

“BEHHGK boson” alternative to “God particle”?

Discovery BEHHGK’ns
At Fermilab’s BEHHGK and call
Every last BEHHGK
Fermilab pulls BEHHGK from background
Mal BEHHGK evasif en France
Got BEHHGK?
What the BEHHGK?
Constraints on Higgs mass

Electroweak constraints
\[ \ln M_H \propto \Delta M_W \propto M_t^2 \]

Other precision electroweak observables

LEP direct searches
\[ m_H > 114.4 \text{ GeV} @ 95\% \text{ CL} \]

Tevatron direct searches ...

\[ m_H \text{[GeV]} \]
\[ 114 \quad 300 \quad 1900 \]
\[ m_t \text{[GeV]} \]
\[ 150 \quad 175 \quad 200 \]

July 2010

New \( M_{\text{top}} \)
CDF+D0 : 173.3 ± 1.1 GeV

68\% CL

LEP2 and Tevatron (prel.)

LEP1 and SLD
Constraints on Higgs mass

- **Electroweak constraints**
  \[ \ln M_H \propto \Delta M_W \propto M_t^2 \]

- **Other precision electroweak observables**

- **LEP direct searches**
  - \( m_H > 114.4 \text{ GeV} @ 95\% \text{ CL} \)

- **Tevatron direct searches**

Precision Fit finds
\[ m_H = 89.0^{+35}_{-26} \text{ GeV} \]
\[ m_H < 158 \text{ GeV} @ 95\% \text{ CL} \]
Tevatron

- 
  - \( p \bar{p} \) collisions with \( \sqrt{s} = 1.96 \text{ TeV} \)
  - Two collider experiments, CDF & DØ

![Luminosity graph](image)

- Integrated luminosity:
  - Delivered: 9.0 fb\(^{-1}\)
  - Acquired: up to 8.0 fb\(^{-1}\)
  - Analyzed: up to 6.7 fb\(^{-1}\)
Tevatron

- p $\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV
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![Luminosity Graph]

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Tevatron

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![Graph showing integrated luminosity](image)

Integrated luminosity

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**Tevatron**

- **p \overline{p}** collisions with √s = 1.96 TeV
- Two collider experiments, CDF & D0

---

**Integrated luminosity**

- Delivered: 9.0 fb⁻¹
- Acquired: up to 8.0 fb⁻¹
- Analyzed: up to 6.7 fb⁻¹

---

**Multipurpose detectors**

- CDF
- DØ

---

Ben Kilminster, ICHEP 2010
SM Higgs at the Tevatron

Main decay modes

Events per experiment in 1 fb⁻¹

Total

H → WW → l+l−l−l−
WH → l+lvb
ZH → ννbb
ZH → llbb

Higgs mass (GeV)
SM Higgs at the Tevatron

Main decay modes

Events per experiment in 1 fb⁻¹

~6 months data

Higgs mass (GeV)

Total

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

Main decay modes

![Higgs decay modes](image)

Events per experiment in 1 fb⁻¹

- Total
- Doubled w/ CDF & D0

- H → WW → l⁺l⁻v lvlv
- WH → lvbb
- ZH → vvhbb
- ZH → llbb

~6 months data

Higgs mass (GeV)
Foundation of presentations

- ICHEP Tevatron Higgs talks
  - Covered variety of Higgs searches and analysis techniques

- Tevatron Higgs B.K.
  - CDF SM Higgs K. Potamianos
  - Tevatron BSM Higgs A. Patwa
  - DO SM Higgs M. Mulhearn

- H → bb
  - Y. Nagai
  - H → WW
    - Y. Enari
    - D. Lucchesi
    - B. Tuchming

- H → WW
  - K. Peters
  - γγ

Tevatron Higgs storyline

How to build an advanced Higgs analysis program

- Start with basic analysis for particular channel
- 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
    - Don’t cut, separate out events into categories with alike 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 from bkgd
    - Background modeling checks! Data must stay well modeled!

- Repeat for each Higgs topology per grad student
- Combine modes taking into account uncertainties correlated between backgrounds
Higgs acceptance

Higgs rate small, we reconstruct additional topologies

Production:

\( gg \rightarrow H \)
\( qq \rightarrow H + W \)
\( qq \rightarrow H + Z \)
\( qq \rightarrow H + qq \)

Decay:

\( H \rightarrow WW \)
\( H \rightarrow bb \)
\( H \rightarrow \tau\tau \)
\( H \rightarrow \gamma\gamma \)

W, Z decays:

\( W \rightarrow lv \)
\( Z \rightarrow ll \)
\( Z \rightarrow vv \)
\( W \rightarrow \tau\tau \)
\( W \rightarrow qq \)
Higgs acceptance

Higgs rate small, we reconstruct additional topologies

Production:
qq → H
qq → H + W
qq → H + Z
qq → H + qq

Decay:
H → WW
H → bb
H → TT
H → YY

W, Z decays:
W → lv
Z → ll
Z → vv
W → T v
W → qq

For example:
qq → HZ → WWZ → lvllqq

Select: electrons, muons, MET, jets
Low mass Higgs searches

Primary searches similar topology

Main backgrounds : W+jets, Z+jets

Goal: search for dijet resonance
Identifying $H \rightarrow bb$

- The “b-tag”
- Distinguishes $b$-quark jets from light $(u,d,s,g)$ jets
- Separates $W+bb/Z+bb$ from $W+light$ flavor / $Z+$ light flavor jets
Identifying $H \rightarrow bb$

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- Distinguishes b-quark jets from light (u,d,s, g) jets
- Separates $W+bb/Z+bb$ from $W+$light flavor / $Z+$ light flavor jets

Dijet mass is most sensitive variable to distinguish $H \rightarrow bb$ from falling background spectrum.
Identifying $H \rightarrow bb$

- The “b-tag”
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- Separates $W+bb/Z+bb$ from $W+$ light flavor / $Z+$ light flavor jets

Dijet mass is most sensitive variable to distinguish $H \rightarrow bb$ from falling background spectrum

1. Before $b$-tag, poor S/B
   - High statistics sample of $W+$jets/$Z+$jets to tests kinematic modeling of important variables (control region)
Identifying $H \rightarrow bb$

2. After 1 or 2 b-tags

- Signal region with enhanced signal / background

![Diagram showing dijet mass distributions for different signal regions and b-tagging scenarios](image-url)
Multivariate techniques

- Multivariate analysis techniques
  - Used in all TeV Higgs analyses
  - Functions transform multiple inputs into single discriminant tuned for identifying a single process
  - Algorithms have similar performance:
    - NN = Neural Net
    - ME = Matrix Element
    - BDT = Boosted Decision Trees
      - RF = “random forest” of decision trees

- Improve analyses by ~20% with respect to leading two variables
  - Correlations useful
    - ie, if $M_{jj}$ is consistent with Higgs, so better be sum $E_T$ and missing transverse energy
  - Caveat: our primary sensitivity gains in recent years don’t come from multivariate techniques
    - Mainly from improved signal acceptance
      - Looser lepton ID
      - Better b-tagging, etc.
Gaining faith in multivariate methods

Single top observation

\( t+q \rightarrow lvjj \) (with b-tag)

Similar to WH \( \rightarrow lvbb \)

Neural Network:

Us: \( \sigma(t) = 4.70 \pm 0.93 \) pb

SM: \( \sigma = 3.46 \pm 1.8 \) pb

Diboson observation:

\( WW + WZ \rightarrow lvjj \)

Similar to WH \( \rightarrow lvbb \)

Matrix Element:

Us: \( \sigma(WW+WZ) = 16.6^{+3.5}_{-3.0} \) pb

SM: \( \sigma = 15.1 \pm 0.8 \) pb

WH sample before b-tag

Similar to WH \( \rightarrow lvbb \)

Actual control region for WH

Same object kinematics

Statistics = 30 \* tagged sample

Random Forest trained on:

- Masses of jets
- \( P_T \) of combinations
- Angular separations

W + 2 jet

Data

W+jet

Multi Jet
c/cbWb
tts-top
Diboson

WH

115 GeV (x10)

Preliminary

D -1

L = 5.3 fb

W + 2 jet

WH \( \rightarrow lvbb \) search

Ben Kilminster, ICHEP 2010
High Mass Higgs search

\( m_H > 125 \text{ GeV} \)

\( H \rightarrow WW \) most important channel
We make use of well-motivated and state of the art gluon fusion cross-section calculations and uncertainties

- $gg \rightarrow H$ uses NNLL + NNLO calculations
  - “Next to Next to Leading Log/Order”
  - Soft-gluon resummation treatment
  - MSTW2008 Parton Density Function
- Anastasiou, Boughezal, Petriello (JHEP:0904:003, 2009)
  - Proper treatment of b-quarks at NLO
  - Inclusion of two-loop electroweak effects

For those interested in a detailed explanation of our choices and comparison with more extreme approaches:


Consider same variations for dominant WW bkg
Basic $H \rightarrow WW$ analysis

Signature: Opposite charge leptons, high MET, no jets

<table>
<thead>
<tr>
<th>Main Signal</th>
<th>Main BKGs</th>
<th>Key discriminant</th>
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<td>$gg \rightarrow H$</td>
<td>$WW, W\gamma$</td>
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Spin 0 $H \rightarrow WW$
Spin 1 $Z \rightarrow WW$
**Basic $H \rightarrow WW$ analysis**

**Signature:** Opposite charge leptons, high MET, no jets

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**Spin 0 $H \rightarrow WW$**

**Spin 1 $Z \rightarrow WW$**

**Fakes & conversions:** Can check Same Sign modeling
Validating background models

\( \text{H} \to \text{WW} \) topologies have different main backgrounds:
- Isolate control regions to test rate & shape of dominant backgrounds

**Most sensitive kinematic variable**
\( \Delta R(l_1, l_2) \)

- **Test W+jets**
- **Test W+γ**
- **Test tt**
- **Test Drell-Yan**
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<th>Expt</th>
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<tr>
<td>$H \to WW$</td>
<td>DO</td>
<td>6.7</td>
<td>24%</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>CDF</td>
<td>5.9</td>
<td>23%</td>
</tr>
<tr>
<td>$WH \to lvbb$</td>
<td>CDF</td>
<td>5.7</td>
<td>30%</td>
</tr>
<tr>
<td>$WH \to lvbb$</td>
<td>DO</td>
<td>5.3</td>
<td>6%</td>
</tr>
<tr>
<td>$ZH/WH \to METbb$</td>
<td>CDF</td>
<td>5.7</td>
<td>60%</td>
</tr>
<tr>
<td>$ZH/WH \to METbb$</td>
<td>DO</td>
<td>6.4</td>
<td>23%</td>
</tr>
<tr>
<td>$ZH \to llbb$</td>
<td>CDF</td>
<td>5.7</td>
<td>40%</td>
</tr>
<tr>
<td>$ZH \to llbb$</td>
<td>DO</td>
<td>6.2</td>
<td>45%</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>CDF</td>
<td>5.4</td>
<td>New!</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>DO</td>
<td>4.2</td>
<td>0%</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>CDF</td>
<td>2.3</td>
<td>15%</td>
</tr>
<tr>
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<td>DO</td>
<td>4.9</td>
<td>0%</td>
</tr>
<tr>
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<td>CDF</td>
<td>4</td>
<td>100%</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>DO</td>
<td>2.1</td>
<td>0%</td>
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## Summary of low & high mass results

Each channel represents several "sub-channels"

### H→WW Sub-channels
- opposite sign leptons + 0-jets
- opposite sign leptons + 1-jets
- opposite sign leptons + 2-jets
- opposite sign leptons, low $M_{ll}$
- same sign leptons
- trileptons, no Z candidate
- trileptons, Z candidate, 1-jet
- trileptons, Z candidate, 2-jet
- electron + hadronic tau
- muon + hadronic tau
- leptons + jets

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<td>$t\bar{t}H$</td>
<td>DO</td>
<td>2.1</td>
<td>0%</td>
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**New**
CDF & DO Combinations

Each experiment combines all its searches to produce one set of limits
CDF & DO combinations

Shown first on July 23, 2010

CDF’s limits

- CDF Run II Preliminary, \( <L> = 5.6-5.9 \text{ fb}^{-1} \)
- LEP Exclusion

DO’s limits

- SM Higgs Combination
- Observed
- Expected
- Expected ±1\sigma
- Expected ±2\sigma
- Standard Model = 1.0

CDF Run II Preliminary, \( <L> = 5.6-5.9 \text{ fb}^{-1} \)

DO Preliminary, \( <L> = 6.1 \text{ fb}^{-1} \)

July 19, 2010
CDF & DO combinations
Shown first on July 23, 2010

CDF’s limits

DO’s limits

CDF achieves expected exclusion at 165 GeV

@ \( m_H = 100 \) GeV, both set observed limits below expected

Closing in on low mass LEP exclusion

Ben Kilminster, ICHEP 2010
What goes into the combination?

CDF Run II Preliminary, $\langle L \rangle = 5.6-5.9 \text{ fb}^{-1}$

- WH$+ZH+VBF \rightarrow jjbb \ 4.0 \text{ fb}^{-1}$ Obs
- WH$+ZH+VBF \rightarrow jjbb \ 4.0 \text{ fb}^{-1}$ Exp
- $H \rightarrow \tau\tau \ 2.3 \text{ fb}^{-1}$ Obs
- $H \rightarrow \tau\tau \ 2.3 \text{ fb}^{-1}$ Exp
- $ZH \rightarrow llbb \ 5.7 \text{ fb}^{-1}$ Obs
- $ZH \rightarrow llbb \ 5.7 \text{ fb}^{-1}$ Exp
- $H \rightarrow \gamma\gamma \ 5.4 \text{ fb}^{-1}$ Obs
- $H \rightarrow \gamma\gamma \ 5.4 \text{ fb}^{-1}$ Exp
- $WH \rightarrow llbb \ 5.6 \text{ fb}^{-1}$ Obs
- $WH \rightarrow llbb \ 5.6 \text{ fb}^{-1}$ Exp
- $WH \rightarrow llbb \ 5.6 \text{ fb}^{-1}$ Exp
- $H \rightarrow WW \ 5.9 \text{ fb}^{-1}$ Obs
- $H \rightarrow WW \ 5.9 \text{ fb}^{-1}$ Exp
- Combined Obs
- Combined Exp

LEP Excl.

$m_H (\text{GeV/c}^2)$

July 19, 2010
What would a signal look like?

CDF test:
* Inject $m_H = 115$ GeV signal into pseudoexperiments (just CDF $ZH\rightarrow llbb$, $WH\rightarrow lvbb$, $ZH\rightarrow vvbb$)

1 sigma high effect would get more pronounced with other channels and DO as well
And now, here is the Tevatron (CDF + DO) combination
... Please scroll down ...
Tevatron combination

Expected sensitivity

$95\% \text{ CL Limit/SM}$

LEP Exclusion

Tevatron Exclusion

SM=1

Tevatron Exclusion

LEP Exclusion

Expected

Observed

$\pm 1 \sigma$ Expected

$\pm 2 \sigma$ Expected

July 19, 2010

$M_H (GeV/c^2)$

Tevatron Run II Preliminary, $L \leq 6.7 \text{ fb}^{-1}$
High mass 95% CL exclusion:

- $158 < m_H < 175$ GeV

- 4 times previous (162 – 166 GeV)

- Expected ($156 < m_H < 175$ GeV)
Tevatron combination

Low mass sensitivity approaching LEP exclusion:

- Expected 1.45*SM @ 115 GeV
- Expected 1.24*SM @ 105 GeV

High mass 95% CL exclusion:

- 158 < \( m_H \) < 175 GeV
  - 4 times previous (162 - 166 GeV)
  - Expected (156 < \( m_H \) < 175 GeV)
Hypothesis: $m_H = 165$ GeV

All bins of all sub-channels of all channels

CDF + D0 Run II Preliminary

Data - Background shown compared to signal in red
Hypothesis: $m_H = 165$ GeV

Excellent modeling, consistent with no signal: Exclusion at 165 GeV
Hypothesis: $m_H = 115$ GeV

Events vs. $\log_{10}(s/b)$

- Tevatron Data
  - Background
  - Signal

Tevatron Run II Preliminary, $L \approx 6.7$ fb$^{-1}$

July 19, 2010

All bins of all sub-channels of all channels

Data - Background shown compared to signal in red
Hypothesis: $m_H = 115$ GeV

All bins of all sub-channels of all channels

Fluctuations: Excess and deficit average out:

Expected limit $1.45 \times SM$

Observed limit $1.56 \times SM$
Hypothesis: $m_H = 115$ GeV

Data: 5 events, Expectation 0.8 events  
$S:B \sim 1:2$

Candidate event

CDF Run II Preliminary Dimuon Event

Run, Event: 229879, 3787664
Dijet Mass: 113.06 GeV/c$^2$
Z Mass: 86.22 GeV/c$^2$
N Jets: 2
MET: 8.52 GeV
ZH NN: 0.95, $t\bar{t}$ NN: $8.6 \times 10^{-4}$
$S/B @ 115$ GeV/c$^2$: 0.42
2 b-tags
Beyond SM Higgs
Search for Supersymmetric Higgs boson

- Supersymmetric models extend Higgs sector
  - \( \Phi = (H^0, A^0, h^0) \), and \( H^\pm \)
  - Introduces \( \tan \beta = \frac{<H_u>}{<H_d>} \) parameter
    - \( \sigma(\Phi) \) enhanced by \( (\tan \beta)^2 \sim 1000 \) over SM

- Branching ratio
  - \( \sim 90\% \) bb, 10\% \( \tau \tau \)

- Tevatron has comprehensive MSSM Higgs program
  - \( \Phi \rightarrow \tau \tau \)
  - \( \Phi + b \rightarrow bb+b \)
  - \( \Phi + b \rightarrow \tau \tau + b \)

- CDF & DO combined search for \( \Phi \rightarrow \tau \tau \) with 2 fb\(^{-1}\)
  - Probes interesting value of \( \tan \beta \sim m_t/m_b \sim 30 \)
Search for Supersymmetric Higgs boson

- MSSM Higgs 3b search \((\Phi+b\rightarrow bb+b)\)
  - Complements MSSM \(H \rightarrow \tau\tau\) search
  - Relies on CDF’s trigger-level b-tagging used in b physics
  - New version of analysis 2x more acceptance
    - \(m_H = 140\) GeV most significant excess
    - \(P\)-value = 0.9\% (5.7\% with trials factor)

![Graph showing dijet mass distribution and 95\% C.L. upper limits](image-url)
Search for Supersymmetric Higgs boson

- MSSM Higgs 3b search ($\Phi+b\rightarrow bb+b$)
  - Complements MSSM $H \rightarrow \tau\tau$ search
  - Relies on CDF's trigger-level $b$-tagging used in $b$ physics
  - New version of analysis 2x more acceptance
    - $m_H = 140$ GeV most significant excess
    - $P$-value = 0.9% (5.7% with trials factor)

Sorry! This 2 $\sigma$ excess is the closest we have to a discovery :(  
but let's keep an eye on it as we add new data :)
New MSSM Higgs search

- **D0's $\Phi \rightarrow \tau \tau + b$**
  - Does not suffer radiative corrections which increase Higgs width as in $\Phi \rightarrow bb + b$
  - Exclusive from $\Phi \rightarrow \tau \tau$
  - Provides similar sensitivity

**Signal:** \[ \tan \beta = 40 \]
SM Higgs Projections
Prospects for Higgs evidence

2xCDF Preliminary Projection

with Projected Improvements

Expected Sensitivity $\sigma$

$\text{m}_H \ (\text{GeV}/c^2)$

Analyzed Lumi/Exp. (fb$^{-1}$)
Prospects for Higgs evidence

End of 2011:
- $> 2.4 \sigma$ expected sensitivity across mass range
- $3 \sigma$ at 115 GeV
Prospects for Higgs evidence

~16 fb^{-1}:*

> 3 \sigma expected sensitivity from 100 - 185 GeV
4 \sigma @ 115 GeV

End of 2011:

> 2.4 \sigma expected sensitivity across mass range
3 \sigma at 115 GeV

* 16 fb^{-1}: based on “Run III” proposal to run 3 more years
You’ve got mail
To: TEV Higgs working group

“Nice new results! We just ran this for you ...”

minimum:

$m_H = 125.029$ GeV

1 sigma range(s):

[115.752, 118.411]
[121.342, 128.053]

2 sigma range(s):

[114.577, 151.804]

3 sigma range(s):

[113.81, 159.307]
[178.124, 205.285]

95 % CL upper Limit is 151.537 GeV !!!
99 % CL upper Limit is 155.988 GeV !!!
Conclusions

Higgs has no place to hide!

- Squeezing allowed mass from both sides
  - 95% CL Exclusion $158 < m_\text{H} < 175$ GeV (about expected)
  - Limit $1.5*\text{SM} @ 115$ GeV

- BSM searches: consistent with SM
  - 2 sigma is largest discrepancy in CDF MSSM $H \rightarrow bb$ (so far)
BACKUPS
Tevatron Higgs production modes

Gluon fusion
\[ \sigma(gg \rightarrow H) = 0.2 - 1 \text{ pb} \]

Production with W or Z
\[ \sigma(gg \rightarrow H) = 0.01 - 0.3 \text{ pb} \]

Vector boson fusion
\[ \sigma(gg \rightarrow H) = 0.02 - 0.1 \text{ pb} \]
Search for Higgs with 4 quark generations

- 4th quark generation popular theory to resolve SM discrepancies and produce new CP violation

- Analysis:
  - $gg \to H$ production enhanced if new 4th generation quarks more massive than top
  - $m_H < 300$ GeV electroweak precision fits @ 68%C.L.
  - Use existing $H \to WW$ analysis framework

Excess could signal both evidence for Higgs boson, and evidence for 4th generation of quarks

CDF + D0 combination: $131 < m_H < 204$ GeV excluded
Hypothesis: $m_H = 100$ GeV

All bins of all sub-channels of all channels

Decent modeling, clear deficit of signal: Exclusion at 100 GeV
Increasing Higgs acceptance

- Originally: tight triggers & lepton ID
- Now: suite of triggers and loose lepton ID
  - Challenge: Model important kinematics for increasingly poorly reconstructed events

- For instance, CDF WH→lνbb analysis:

<table>
<thead>
<tr>
<th>Standard central lepton triggers</th>
<th>Partially reconstructed muons from missing transverse energy (MET) triggers</th>
<th>Partially reconstructed electrons from MET triggers</th>
</tr>
</thead>
</table>

*For instance, CDF WH→lνbb analysis:*
Removing difficult backgrounds

- Higgs signals can have large MET
  - $ZH \rightarrow \nu\nu bb$, $WH \rightarrow l\nu bb$ (lepton missed)
  - Large QCD multijet with mismeasured jets
  - Peaks near where signal expected in $M_{jj}$

- Multijet removal techniques save this channel
  - MET significance
  - Missing track $P_T$ (MPT)
  - Topological requirements

![DiJet Invariant Mass (GeV)](image)

<table>
<thead>
<tr>
<th>Events / 20 GeV</th>
<th>Data</th>
<th>Multijet</th>
<th>Diboson</th>
<th>$W+\text{jets}(l.f.)$</th>
<th>$W+\text{b/c-jets}$</th>
<th>$Z+\text{jets}(l.f.)$</th>
<th>$Z+\text{b/c-jets}$</th>
<th>Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>DiJet Invariant Mass (GeV)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Improving $M_{bb}$ resolution

- $H \rightarrow bb$ signal significance enhanced by improving $M_{jj}$ resolution

Apply MET constraint to correct jet energies

$Z + tt$ uncertainty

CDF Run II Preliminary (4.1 fb$^{-1}$)
Improving $M_{bb}$ resolution

- $H \rightarrow bb$ signal significance enhanced by improving $M_{jj}$ resolution

Apply MET constraint to correct jet energies

$ZH \rightarrow llbb$ MET likely from Jet 1

- $M_{jj}$ resolution improvements in other analyses:
  - Track momenta within jets additional constraint (~"particle flow")
  - Displaced vertex info to determine boost of $b$-hadron

CDF Run II Preliminary (4.1 fb$^{-1}$)

$Z \rightarrow l^+l^-b\bar{b}$

$H \rightarrow llbb$

- $M_H = 120$ GeV/c$^2 \times 1500$ After NN Corr.
- $M_H = 120$ GeV/c$^2 \times 1500$ Before NN Corr.

PreTag

- data
- WW, WZ, ZZ
- $Z + \text{lf jets}$
- $Z + bb$
- $t\bar{t}$
- $Z + cc$
- uncertainty

Number of Events

$M_{jj}$ (GeV/c$^2$)
Every last Higgs event at low mass

Analyses become more challenging

- $H \rightarrow \tau\tau$ decay modes
  - BR ($H \rightarrow \tau\tau$) 10 times smaller than $H \rightarrow bb$
  - Jets from vector boson & associated production reduce background

- $H \rightarrow \gamma\gamma$ decay modes
  - BR ($H \rightarrow \gamma\gamma$) 300 times smaller than $H \rightarrow bb$
  - Narrow resonance 3 GeV compared to 16 GeV $H \rightarrow bb$

- $Z/W + H \rightarrow qq + bb$
  - All-jets final state means enormous multijet backgrounds
  - Largest expected signal

- $WH \rightarrow \tau\nu bb$
  - Low selection efficiency, due to large QCD backgrounds
  - Exclusive trigger improves WH selection efficiency