Seeking the Origin of Mass

Collider Searches for Higgs Bosons

Wade Fisher
Michigan State University

For the ATLAS, CDF, CMS & DØ collaborations
Today's Presentation

Higgs searches at colliders in a nutshell

- Brief history
- Context of modern Higgs searches
- Light overview of Tevatron and LHC experiments

Standard Model  Higgs Searches

Beyond the

Standard Model  Higgs Searches

A modest guess at things to come
“a rose by any other name”

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."
Higgs mechanism basics

**The idea:** our universe is filled with a quantum field, which we call the Higgs field.

Including this field in the EW Lagrangian gives rise to W/Z masses and preserves SU(2) gauge invariance.

The quanta of the Higgs field is the Higgs boson.

The mass of the Higgs boson is **not** predicted.

*If the Higgs does exist, its mass must be determined experimentally.*
What we know about the Higgs boson

DON'T KNOW
LEP 1989–2000
Direct searches have limited the potential places the Higgs can hide

LEP II direct search: $M_H > 114.4$ GeV at the 95% Confidence Level (C.L.)
**Indirect Experimental Evidence**

The interactions between SM particles and the Higgs provide indirect evidence through radiative corrections to particle masses.

The heaviest particles couple most strongly to the Higgs.

**Refinements of top-quark and W-boson masses can indicate Higgs mass**
Indirect Experimental Evidence

The interactions between SM particles and the Higgs provide indirect evidence through radiative corrections to particle masses.

The heaviest particles couple most strongly to the Higgs.

Refinements of top-quark and W-boson masses can indicate Higgs mass.

Mass of the Top Quark

<table>
<thead>
<tr>
<th>July 2011</th>
<th>(* preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 11.4 (±10.3 ± 4.9)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.4 ± 12.8 (±12.3 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II dilepton</td>
<td>170.6 ± 3.8 (± 2.2 ± 3.1)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.0 ± 3.1 (± 1.8 ± 2.5)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4 (± 5.1 ± 5.3)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3 (± 3.9 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>173.0 ± 1.2 (± 0.6 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.9 ± 1.5 (± 0.8 ± 1.2)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (±10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>172.5 ± 2.1 (± 1.4 ± 1.5)</td>
</tr>
<tr>
<td>CDF-II track</td>
<td>166.9 ± 9.5 (± 9.0 ± 2.9)</td>
</tr>
<tr>
<td>CDF-II MET+Jets *</td>
<td>172.3 ± 2.6 (± 1.8 ± 1.6)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>173.2 ± 0.9 (± 0.6 ± 0.8)</td>
</tr>
</tbody>
</table>

χ²/dof = 8.3/11 (68.5%)

\[ M_W = 80.4 \pm 0.023 \text{ GeV} \]

\[ M_{\text{top}} = 173.2 \pm 0.9 \text{ GeV} \]
Indirect Experimental Evidence

The interactions between SM particles and the Higgs provide indirect evidence through radiative corrections to particle masses.

A fit of precision electroweak data yields: $M_H < 158$ GeV at 95% CL

( $M_H < 185$ GeV including LEP II limit )
The Continued Higgs Search

Generations of physicists are eagerly awaiting the next chapter

Fermilab’s Tevatron collider ($\sqrt{s} = 1.96 \text{ TeV}$) is focusing large efforts on the Higgs search

The Large Hadron Collider ($\sqrt{s} = 7 \text{ TeV}$ for now) should be able to produce Higgs bosons for most theoretically preferred masses
Tevatron complex has performed very well
Proton-antiproton collisions at 1.96 TeV
10 year long Run II ending September 2011
Currently $>10 \text{ fb}^{-1}$ recorded per experiment
Tevatron Run I top quark discovery: ~50 pb$^{-1}$
First collisions in 2009 & now running smoothly

Proton-proton collisions at 7 TeV

New results appearing routinely

\[ \approx 1.3 \text{ fb}^{-1} \text{ delivered per experiment} \]
Standard Model  Higgs Searches
Higgs Production

Tevatron (p$\bar{p}$ @ 1.96 TeV)

\[
\sigma(p\bar{p} \rightarrow H + X) \quad [\text{pb}]
\]
\(\sqrt{s} = 1.96 \text{ TeV}\)
MSTW2008
m_t = 173.1 \text{ GeV}

- gg \rightarrow H
- q\bar{q} \rightarrow WH
- q\bar{q} \rightarrow ZH
- qq \rightarrow q\bar{q}H

LHC (pp @ 7 TeV)

\[
\sigma(pp \rightarrow H + X) \quad [\text{pb}]
\]
\(\sqrt{s} = 7 \text{ TeV}\)

- pp \rightarrow t\bar{t}H
- pp \rightarrow t\bar{t}H (NLO QCD + NLO EW)
- pp \rightarrow q\bar{q}H (NNLO QCD + NLO EW)
- pp \rightarrow WH (NNLO QCD + NLO EW)
- pp \rightarrow ZZ (NNLO QCD + NLO EW)
Higgs Production

Tevatron (p\bar{p} @ 1.96 TeV)

- $\sigma(p\bar{p} \rightarrow H + X)$ [pb]
- $\sqrt{s} = 1.96$ TeV
- MSTW2008
- $m_t = 173.1$ GeV

LHC (pp @ 7 TeV)

Graph showing production cross-sections for Higgs bosons at different hadron colliders.
Higgs Production

Tevatron (pp @ 1.96 TeV)
\[ \sigma(p\bar{p} \rightarrow H + X) [pb] \]
\[ \sqrt{s} = 1.96 \text{ TeV} \]
\[ m_{t} = 173.1 \text{ GeV} \]

LHC (pp @ 7 TeV)
\[ \sqrt{s} = 7 \text{ TeV} \]
The Higgs decay determines what we see in the detector

Strong coupling to mass selects out most massive particles for each possible mass

Hadron colliders are quark/gluon factories: leptons/photons provide important handles for background reduction

At low mass ($M_H < 135$ GeV), the dominant Higgs decay is $H \rightarrow b \bar{b}$

Hard to distinguish $H \rightarrow b \bar{b}$ from huge jet background, easier when paired with associated particles ($W, Z, t\bar{t}$)

At higher masses $H \rightarrow WW$ and $H \rightarrow ZZ$ decays dominate

Efficient and accurate reconstruction of lepton momenta gives reasonable Higgs mass resolution
Higgs Search Strategies

The theory and detector environment together define our search strategies.

Each search defined by pairing production and decay modes.
**Higgs Search Strategies**

<table>
<thead>
<tr>
<th>H → b̅b</th>
<th>H → τ̅τ</th>
<th>H → γγ</th>
<th>H → WW</th>
<th>H → ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **H → b̅b**
  - ![Diagram](image6)
  - ![Diagram](image7)
  - ![Diagram](image8)

- **H → τ̅τ**
  - ![Diagram](image9)
  - ![Diagram](image10)
  - ![Diagram](image11)

- **H → γγ**
  - ![Diagram](image12)
  - ![Diagram](image13)
  - ![Diagram](image14)

- **H → WW**
  - ![Diagram](image15)

- **H → ZZ**
  - ![Diagram](image16)
Searching for $H \rightarrow bb$

Start with events consistent with W/Z decays

$W \rightarrow lv$ & $Z \rightarrow ll$: Select events with **electrons** or **muons**

$Z \rightarrow \nu\nu$: Select neutrino signature (**large missing transverse energy**) and 2 jets signature

Each final state poses a unique challenge

$W \rightarrow lv$: Invisible neutrino limits degree of constraint

$Z \rightarrow ll$: Despite full kinematic constraint, limited by small branching fraction

$Z \rightarrow \nu\nu$: Multijet background difficult to model/control

**W→lv Transverse Mass**

**Z→ll Mass**

**Z→vv Missing Momentum Signature**
$H \rightarrow bb$: Jets and b-Tagging

Background reduction enhanced by identifying heavy-flavor quark decays (b-Tagging)
Di-photon search depends strongly on mass resolution

Typical mass resolutions of 1-4%

Photons are categorized into regions of varying energy (→ mass) resolution

Irreducible di-photon background ultimately defines signal purity

Electron and jet fakes round out the remaining background
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Searching for $H \rightarrow W^+ W^-$

Selecting leptonic W-boson decays to reduce the very large multijet backgrounds

Use Z mass for normalization, veto region near peak

2 neutrinos: missing $E_t$ signature helps reject all but direct WW production

Capitalize on spin correlations to discriminate WW background ($H = \text{scalar}$, $W/Z = \text{vector}$)

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Di-lepton Invariant Mass

Di-lepton Angular Separation

CDF Run II Preliminary

$M_H = 160$ GeV/c²

OS 0 Jets

$L = 8.2$ fb$^{-1}$
Searching for $H \to W^+ W^-$

Selecting leptonic W-boson decays to reduce the very large multijet backgrounds

Use Z mass for normalization, veto region near peak

2 neutrinos: missing $E_T$ signature helps reject all but direct WW production

Capitalize on spin correlations to discriminate WW background ($H = \text{scalar, } W/Z = \text{vector}$)

Particle spin (helicity) & momentum constrained to satisfy spin-0 Higgs decay
**Searching for $H \rightarrow W^+ W^-$**

Two-neutrino final state precludes mass reconstruction

With appropriate cuts, can use transverse WW mass to isolate backgrounds

Or rely upon Multi-Variable Analysis filters to provide final event classification

Typically achieve S/B ratios of ~1/3 or greater
Searching for $H \rightarrow ZZ$

$H \rightarrow ZZ \rightarrow 4l$ is a “golden mode” for $M_H > 140$ GeV

Low rate due to $H \rightarrow ZZ$ and $Z \rightarrow ll$ branching fractions

Balanced by narrow 4-lepton mass resolution

CMS & ATLAS have excellent mass resolution & trigger efficiency

Though rate limited at the Tevatron, still a useful contribution
Adding $H \rightarrow ZZ \rightarrow 2l + 2j / 2\nu$ boosts rate significantly

$H \rightarrow ZZ \rightarrow llqq$:

No neutrinos! All 4 decay particles reconstructed.

$H \rightarrow ZZ \rightarrow ll\nu\nu$:

No Higgs peak, but signal lies in the tails of missing energy distributions.

Benefits come at the cost of larger $Z + \text{jets}$ background
Confirming agreement with “standard candles” provides essential validation for search results

Example: SM WW cross section

Similar selections should yield similar results

MVA should behave similarly for WW = signal and WW = background

\[
\sigma(p\bar{p}\rightarrow WW)^{EXPT} = 12.1 \pm 0.9 \text{(stat)} \pm 1.6 \text{(syst)} \text{ [pb]}
\]

\[
\sigma(p\bar{p}\rightarrow WW)^{THEORY} = 12.4 \pm 0.8 \text{ [pb]}
\]
Upper limits on cross section are derived at the 95% C.L.  

Reported in units of the SM prediction:  **Ratio = 1 is exclusion condition**  

Limits derived for a combination of all contributing search channels  

Limits include consideration of:  

- Limited MC statistics  
- Poisson sampling uncertainty  
- Systematic sources of uncertainty
Limits on SM Higgs Production

Tevatron Run II Preliminary, $L \leq 8.6 \text{ fb}^{-1}$

**LEP Exclusion**

- Expected
- Observed
- $\pm 1\sigma$ Expected
- $\pm 2\sigma$ Expected

**Tevatron Exclusion**

**SM Higgs excluded at 95% C.L.**

- $M_H < 108 \text{ GeV}$
- $156 < M_H < 177 \text{ GeV}$
Limits on SM Higgs Production

ATLAS Preliminary

Observed CLs
Expected

\[ \int Ldt = 1.0 - 1.2 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

95% CL Limit on \( \sigma / \sigma_{\text{SM}} \)

SM Higgs excluded at 95% C.L.

\[ 155 < M_H < 190 \text{ GeV} \]
\[ 295 < M_H < 450 \text{ GeV} \]
Limits on SM Higgs Production

CMS Preliminary, $\sqrt{s} = 7$ TeV
Combined, $L_{\text{int}} = 1.1$ fb$^{-1}$

SM Higgs excluded at 95% C.L.

$149 < M_H < 206$ GeV
$300 < M_H < 440$ GeV
Limits on SM Higgs Production

Summary of Collider SM Higgs Exclusions

- LEP
- FNAL
- ATLAS
- CMS

Simple OR of exclusions
Limits on SM Higgs Production

Summary of Collider SM Higgs Exclusions

LEP
FNAL
ATLAS
CMS
All

95% C.L. region preferred by fit to precision EW data
Beyond the Standard Model

Higgs Searches
Limits on 4\textsuperscript{th} Generation Models

An additional generation of quarks/leptons could drastically alter the Higgs landscape.

2 extra heavy quarks adds 2 more gg→H diagrams

- Boost of ~9x in gg→H rate. No change in VH, VBF, ttH rates.

Limits on neutrino mass set a lower bound, but a large phase space remains with heavy quarks.

Typical mass of down-type 4\textsuperscript{th} Gen quark for models tested:
- Tevatron: 300-400 GeV
- LHC: 600 GeV

\[ +2 \text{ new quarks} = 9x \text{ in rate!} \]
Some multi-doublet Higgs models predict Higgses with zero fermion couplings.

Similar search strategies as SM search, but the $gg \rightarrow H$ diagram doesn't contribute.
**MSSM Higgs**

**Minimal SUSY Model (MSSM):** Two doublets of scalar fields (only one in SM)

Total of 8 degrees of freedom results in 5 Higgs bosons:

- **3 Neutral:** h, H, A
- **2 Charged:** H⁺

In the Minimal SUSY Model:

Need at least 2 parameters to calculate all Higgs masses and couplings at tree level:

- $M_A$ and $\tan(\beta) = \text{ratio of vacuum expect'n values for the two Higgs doublets}$

Coupling of neutral Higgs bosons to bottom quarks is enhanced by $\tan(\beta)$, production enhanced by $\tan^2(\beta)$

**Neutral MSSM Higgs decays**

- $\phi \rightarrow bb \sim 90\%$
- Large background
- $\phi \rightarrow \tau\tau \sim 10\%$
- More distinct signature

*Diagrams showing Higgs decays and production processes.*
**bH→bbb Search**

Challenging 3 b-quark final state only possible with very efficient b-tagging

Theory predictions for background rates have large uncertainties

Fit of templates to data provides normalization

Much care to be taken to ensure signal isn’t “fitted away”
Challenging 3 b-quark final state only possible with very efficient b-tagging

Theory predictions for background rates have large uncertainties

Fit of templates to data provides normalization

Much care to be taken to ensure signal isn’t “fitted away”

Signal mass resolution ultimately limits high mass search potential
Limits are derived in the same manner as with SM searches

Data are compatible with the background predictions

But both CDF & DØ see ~2σ excesses around $M_H = 120-150$ GeV.

Combination of search results is being investigated
The presence of charged Higgs bosons could manifest in non-SM top production rate. Not necessarily obvious in a regular top quark measurement. Presence of final state taus and/or resonant dijet mass (H⁺→cs) would be the evidence.
The presence of charged Higgs bosons could manifest in non-SM top production rate

Not necessarily obvious in a regular top quark measurement

Presence of final state taus and/or resonant dijet mass ($H^+\rightarrow cs$) would be the evidence

Limits from LHC & Tevatron thus far consistent with SM predictions
Di-tau searches contribute to both the MSSM and SM search efforts

Both gluon-fusion and associated production diagrams contribute

→Analyses are separated into b-tagged and non-tagged final states

Di-tau “visible mass” is one of the most powerful search criteria
(b)H→(b)ττ Search

Powerful exclusions in tanB/M_A plane

CMS observes a broad excess for all M_A.

→Tevatron searches in similar final state exhibit excess at low M_A, but are less powerful.
Glimpses into a possible future of Higgs searches
What do today's results tell us?

We now have the most extensive SM Higgs exclusions ever produced.

- A null result is nearly as powerful an indicator as discovery.
- But we have not excluded the region most favored by EW precision data.

**Summary of Collider SM Higgs Exclusions**

- **LEP**
- **FNAL**
- **ATLAS**
- **CMS**
- **All**

95% C.L. region preferred by fit to precision EW data.
What do today's results tell us?

We now have the most extensive SM Higgs exclusions ever produced

A null result is nearly as powerful an indicator as discovery

But we have not excluded the region most favored by EW precision data

Is there already emerging evidence of an excess?

Inside the EW preferred region: searches dominated by gg→H production seem to have common features near $M_H = 140$ GeV

Excess doesn't seem compatible with 4th Generation predictions. There may still be a twist to the story
Tevatron experiments will collect data through Sept 30 2011
Current results based on \( \sim 8.0 \text{ fb}^{-1} \) on average, will have \( \geq 10 \text{ fb}^{-1} \) in the end.
Including ongoing analysis improvements, could exclude \( M_H < 190 \text{ GeV} \)

The LHC should have \( \sim 4 \text{ fb}^{-1} \) on the timescale of Winter 2012 (\textit{4x in statistics})
Broad discovery potential for \( M_H > 130 \text{ GeV} \)
More difficult for \( M_H < 130 \text{, reliant largely upon } H \rightarrow \tau\tau \text{ and } H \rightarrow \gamma\gamma \)
**Conclusions**

We stand at the precipice of understanding for the mass generation mechanism

Is the most successful theory in the history of particle physics complete?

Or will the data point in a completely different direction?

HEP collider programs have been very successful in assembling a Higgs search program

The Tevatron was never expected (or designed) to be able to perform a Higgs search

The LHC machine and experiments have worked as well as one could hope, with a bright future

With a broad search program ongoing, some real answers are likely very close

*Please stay tuned!*
Backup Slides
Test of “fake” data made by injecting $M_H = 140$ GeV signal into bkgd MC

Gives an indication of effective mass resolution
Test of “fake” data made by injecting $M_H = 135$ GeV signal into bkgd MC

Gives an indication of effective mass resolution
Tevatron Comparison with ATLAS

Tevatron Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

- **LEP Exclusion**
  - Expected
  - Observed
- **Tevatron Exclusion**
  - $1\sigma$ Expected
  - $2\sigma$ Expected

$95\%$ CL Limit/SM

$m_H$(GeV/c$^2$)

July 17, 2011
Tevatron Impact to Global Fit

EPS 2011: $m = 173.2 \pm 0.9$ GeV

Theory uncertainty
- Fit including theory errors
- Fit excluding theory errors

LEP 95% CL
Tevatron 95% CL
Tevatron $H\rightarrow bb$ vs $H\rightarrow WW$

Tevatron Run II Preliminary $H\rightarrow bb$ Combination, $L \leq 8.6$ fb$^{-1}$

Tevatron Run II Preliminary $H\rightarrow WW$ Combination, $L \leq 8.6$ fb$^{-1}$
Tevatron Signal to Noise

CDF + D0 Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

$m_{h}=165$ GeV/c$^2$
July 17, 2011

$m_{h}=115$ GeV/c$^2$
July 17, 2011
**Minimal SUSY Model (MSSM):** Two doublets of scalar fields (only one in SM)

Total of 8 degrees of freedom results in 5 Higgs bosons:

- **3 Neutral:** h, H, A
- **2 Charged:** H±

In the Minimal SUSY Model:

- Need at least 2 parameters to calculate all Higgs masses and couplings at tree level: $M_A$ and $\tan(\beta)$ (ratio of vacuum expectation values for the two Higgs doublets)
- All three neutral Higgs bosons can have same final states: extra 2x in effective rate
Semi-leptonic $H \to WW \to l\nu qq$ decays can contribute a lot. Signal is boosted by 4x over fully leptonic decays. $W/Z+\text{jets}$ rate also grows significantly. Additional handle in kinematic rejection opens many doors for data analysis. Guess at longitudinal neutrino momentum allows for estimate of $M(l\nu qq)$. Angular correlations of signal provide further handle for background rejection.

![Graph](image)

- **Data**
- **$V+\text{jets}$**
- **MJ**
- **Top**
- **Diboson**
- **Signal}$\times 200$

**ATLAS Preliminary**

- **Signal** (x 100)
- $m_W = 400 \text{ GeV}/c^2$
- $\int L dt = 1.04 \text{ fb}^{-1}$
- $\sqrt{s} = 7 \text{ TeV}$

**$\mu$ channel, $M_H = 160 \text{ GeV}$**

- DØ $5.4 \text{ fb}^{-1}$
- angle($j_1, j_2$) in Higgs rest frame: 0 to 3
Confirming agreement with “standard candles” provides essential validation for search results

Eg, SM WW cross section

Similar selections should yield similar results

\[
\sigma(p \bar{p} \to WW)^{\text{EXPT}} = 48.2 \pm 4.0 \,(\text{stat}) \pm 6.4 \,(\text{syst}) \, [\,pb]\]

\[
\sigma(p \bar{p} \to WW)^{\text{THEORY}} = 46 \pm 3 \, [\,pb]\]
Dijet invariant mass is not the only discriminating variable

Scalar Higgs spin information

MET significance

Bottom vs Charm flavor discrimination
$H\rightarrow bb$: Multivariate Analysis

Multivariate techniques are used to improve signal to background ratios

- Boosted Decision Trees
- Neural Networks
- Matrix Element Discriminants

Typically achieve S/B of ~1/5-1/25

$S/B \sim 1/100$ for dijet mass alone