Properties of a Higgs-like particle of mass 125 GeV

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On behalf of the DØ collaboration

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Overview

- Introduction/Motivation
  - The Higgs
  - The Tevatron
- DØ Higgs results
  - Cross Section
- Tevatron Higgs results
  - Cross Section
  - Couplings
- Higgs Spin and Parity in \( VH \rightarrow Vb\bar{b} \)
- Summary
• July 2012 was an exciting time for particle physics!
• LHC experiments discovered new particle at 125 GeV in $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ final states consistent with SM Higgs
• Tevatron provided $3\sigma$ evidence of particle in $b\bar{b}$ final state, also consistent with SM Higgs
• Focus now is shifting to measure this new particle’s properties
The Higgs at the Tevatron

- Primary search modes at LHC:
  \( H \rightarrow ZZ, \ H \rightarrow \gamma\gamma, \ H \rightarrow WW \)

- Primary search modes at the Tevatron:
  \( VH \rightarrow Vbb, \ H \rightarrow WW \).

![Graph showing branching ratios for different decay modes of the Higgs boson.](image)
The Tevatron was a $p\bar{p}$ collider operating at $\sqrt{s} = 1.96$ TeV.
• General strategy:
  • Select events based on final state topology
  • Categorize events
  • Separate signal from background using multivariate techniques
  • Perform statistical analysis
Example: \( VH \rightarrow Vbb \)

- Require large missing transverse energy and two jets
- Includes contribution from \( WH \rightarrow ℓνbb \), where the lepton was not identified
- Dedicated MVA to reject multijet background

- Require exactly one lepton (\( e \) or \( µ \)), missing transverse energy and two or three jets
- Dedicated MVA to reject multijet background

- Require two isolated charged leptons (\( e \) or \( µ \)), and at least two jets
- Able to fully reconstruct final state
- Dedicated MVA to reject \( t\bar{t} \) background
Classifying events: b-tagging

- Tag events coming from decay of a B meson
  - Use secondary vertex and tracking information to build an MVA to separate out light jets from b-jets.
Separate signal from specific backgrounds, or all backgrounds together.

- **Multivariate Analysis Example: ZH→ℓℓbb**

- **RF Output**

- **Events / 0.05 Data**
  - Z+LF
  - Z+b\bar{b}
  - Z+c\bar{c}
  - Top
  - Diboson
  - Multijet

- **ZH x 40 = 125 GeV Higgs**

- **RF < 0.5t**
  - **Double Tag**
  - DØ, 9.7 fb⁻¹

- **Events / 0.05 Global RF Output**

- **tt̄ RF < 0.5**

- **tt̄ RF ≥ 0.5**

- **tt̄ enriched**

- **tt̄ depleted**
Combining all DØ Higgs searches

- Combine searches in $H \rightarrow bb$, $H \rightarrow WW$, $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$
- Observe a broad excess over background only prediction

![Graph showing SM Higgs Combination](image-url)
Combining all Tevatron Higgs searches

- Combine DØ and CDF Higgs searches
- Observe a broad excess over background only prediction
Best Fit Cross Section

Higgs Decay Mode

<table>
<thead>
<tr>
<th>Higgs Decay Mode</th>
<th>$\frac{(\sigma \times BR)}{(\sigma \times BR)_{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>$1.40^{+0.92}_{-0.88}$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$4.20^{+4.60}_{-4.20}$</td>
</tr>
<tr>
<td>$H \rightarrow W^{+}W^{-}$</td>
<td>$1.90^{+1.63}_{-1.52}$</td>
</tr>
<tr>
<td>$H \rightarrow \tau^{+}\tau^{-}$</td>
<td>$3.96^{+4.11}_{-3.38}$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$1.23^{+1.24}_{-1.17}$</td>
</tr>
</tbody>
</table>

Higgs Properties DPF 2013

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<th>Higgs Decay Mode</th>
<th>$\frac{(\sigma \times BR)}{(\sigma \times BR)_{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>$1.44^{+0.59}_{-0.56}$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$5.97^{+3.39}_{-3.12}$</td>
</tr>
<tr>
<td>$H \rightarrow W^{+}W^{-}$</td>
<td>$0.94^{+0.85}_{-0.83}$</td>
</tr>
<tr>
<td>$H \rightarrow \tau^{+}\tau^{-}$</td>
<td>$1.68^{+2.28}_{-1.68}$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$1.59^{+0.69}_{-0.72}$</td>
</tr>
</tbody>
</table>
• Introduce multiplicative scaling factors on Higgs coupling to fermions, W bosons, Z bosons, and general vector bosons: $\kappa_f, \kappa_W, \kappa_Z, \kappa_V$
  • Search for deviations from SM expectation of 1
• Also measure the ratio $\lambda_{WZ} = \kappa_W / \kappa_Z$
  • For custodial symmetry to hold $\lambda_{WZ} = 1$
Couplins 1-D

(a) $\kappa_f$

- $\kappa_f = -2.64^{+1.59}_{-1.30}$
  - Negative sign from excess in $H \rightarrow \gamma\gamma$ ($\Gamma_{\gamma\gamma} \propto |1.28\kappa_V - 0.28\kappa_f|^2$)

- $\lambda_{WZ} = 1.24^{+2.34}_{-0.42}$
Couplings 2-D

(a) $\kappa_W$ vs $\kappa_Z$

- $(\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$
- $(\kappa_f, \kappa_V) = (1.05, -2.04)$

(b) $\kappa_f$ vs $\kappa_V$
• The Standard model Higgs is predicted to have $J^P = 0^+$
• Could have non-SM scenarios with $J^P = 0^-, 2^+$. 
• LHC experiments studying spin and parity in bosonic final states
• Tevatron experiments sensitive to $b\bar{b}$ final state.
• Total visible mass of the Vbb system shows good separating power between different $J^P$ assignments
  • arXiv:1208.6002 [hep-ph].
Signal Generation

- Non-SM signals generated with MADGRAPH5, then interfaced with PYTHIA for showering
- Will only be considering $2^+ \text{ vs } 0^+$ today (work on $0^-$ result is ongoing)
  - $2^+$ signal is generated using Randall-Sundrum graviton model
- After full reconstruction and detector simulation, we see good separation as predicted

(a) $ZH \to \ell\ell bb$

(b) $ZH \to \nu\nu bb$
Discriminating Further

- Can use the knowledge of mass to split our samples into regions of high and low signal purity
- ZH→Zbb analyses split into regions based on dijet mass, while WH→Wbb analysis split based on MVA output
Final Variable

(a) $ZH \rightarrow \nu \nu bb$

(b) $WH \rightarrow \ell \nu bb$

(c) $ZH \rightarrow \ell \ell bb$
Statistical Analysis

- Use LLR as a test statistic: \( LLR = -2 \log \left( \frac{H_1}{H_0} \right) \)
  - \( H_0 = 0^+ + \text{background} \)
  - \( H_1 = 2^+ + \text{background} \)
- Do computation under two different assumptions:
  - \( \sigma \times \text{BR} = 1.0 \) SM
  - \( \sigma \times \text{BR} = 1.23 \) SM (best cross section fit value)
  - \( \mu = \frac{\sigma}{\sigma_{SM}} \)

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(a) \( \mu = 1.00 \)

(b) \( \mu = 1.23 \)
To quantify model preference, use \( CL_S = \frac{CL_{H_1}}{CL_{H_0}} \)

- \( CL_X = P(\text{LLR} \geq \text{LLL}^{\text{observed}} | X) \).
- Can interpret \( 1-CL_S \) as the confidence level for exclusion of \( 2^+ \) model in favour of \( 0^+ \) model.

| \( \mu = 1.00 \), Expected | 0.9995 |
| \( \mu = 1.00 \), Observed | 0.992 |
| \( \mu = 1.23 \), Expected | 0.9999 |
| \( \mu = 1.23 \), Observed | 0.999 |
Summary

- Tevatron sees broad excess in data that is consistent with SM Higgs boson.
- Tevatron primarily sensitive to $H \rightarrow b \bar{b}$, provides information complimentary to LHC $H \rightarrow$ bosons.
- Prefer $J^P = 0^+$ over $2^+$, and reject $2^+$ (with graviton like couplings) at $> 99.2\%$ confidence level in $VH \rightarrow Vb\bar{b}$.
- Spin and parity studies on $0^-$ in $VH \rightarrow Vb\bar{b}$ coming soon!
For more information:

- Tevatron New Phenomena and Higgs Working Group:
  - http://tevnphwg.fnal.gov/

- DØ Higgs results:
  - http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
Run II Integrated Luminosity

19 April 2002 - 30 September 2011

Delivered
Recorded

Luminosity (fb⁻¹)

0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0

Apr-02 Apr-03 Apr-04 Apr-05 Apr-06 Apr-07 Apr-08 Apr-09 Apr-10 Apr-11

Delivered
Recorded

11.9
10.7
Background p-values

(a) DØ

(b) Tevatron
$H \rightarrow bb$

(a) D0

(b) Tevatron
H → WW

(a) D0

DØ, \( L_{\text{int}} \leq 9.7 \text{ fb}^{-1} \)

SM \( H \to W^+W^- \) Combination

(b) Tevatron

Tevatron Run II, \( L_{\text{int}} \leq 10 \text{ fb}^{-1} \)

SM \( H \to WW \) Combination

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

Log-Likelihood Ratio

9.7 fb \( \leq \text{int} \ DØ, \ L_{\text{int}} \leq 9.7 \text{ fb}^{-1} \)

Combination

125 GeV/c²

Savanna Shaw (MSU/DØ)
95 % C.L. Limits

(a) D0

(b) Tevatron

DØ, $L_{int} \leq 9.7 \text{ fb}^{-1}$

SM Higgs Combination

$95\%$ C.L. Limit on $\sigma_H / \sigma_{SM}$

$M_H$ (GeV)

Expected if $m_H=125$ GeV

Expected $\pm 1$ s.d.

Expected $\pm 2$ s.d.

DØ Exclusion

Tevatron Run II, $L_{int} \leq 10 \text{ fb}^{-1}$

SM Higgs combination

Observed

Expected w/o Higgs

Expected w/$m_H=125$ GeV

Expected $\pm 1$ s.d.

Expected $\pm 2$ s.d.

Expected if $m_H=125$ GeV

$95\%$ C.L. Limit/SM

$M_H$ (GeV/c$^2$)
Couplings

(a) $\kappa_W$

(b) $\kappa_Z$