Tevatron Constraints on Models of the Higgs Boson with Exotic Spin and Parity Using Decays to $b\bar{b}$ Quark Pairs

Gavin Davies
On behalf of the CDF and DØ Collaborations
Outline

- Introduction
  - Tevatron
  - Higgs searches @ Tevatron
- Higgs Results
  - General
  - Spin-parity
- Conclusions

Reminder: Tevatron stopped fall 2011 ~ 10fb⁻¹ per expt after data quality
• Tevatron
  - Bridge between LEP search & LHC measurement era following discovery
  - 1\textsuperscript{st} exclusion after LEP in 2008
    • And then regularly updated
  - 2012: Evidence for coupling to fermions
  - Complementary as exploiting primarily $H \rightarrow bb$ decays

- ‘Higgs studies at Tevatron’
  • PRD 88, 052014 (2013)

- ‘Tevatron spin-parity constraints’
  • PRL 114, 151802 (2015)
• 'Low' mass $m_H < 135$ GeV
  - Dominated by:
    $qar{q}' \rightarrow WH \rightarrow \ell \nu b\bar{b}$
    $q\bar{q} \rightarrow ZH \rightarrow \ell\ell b\bar{b}$
    $q\bar{q} \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}$

• 'High' mass $m_H > 135$ GeV
  - Dominated by:
    $gg \rightarrow H \rightarrow WW(\ast) \rightarrow \ell \nu' \nu'$

• Less sensitive channels add overall sensitivity
• All channels sub-divided for sensitivity
• Exclusion cross section
  - Sensitivity over ~full mass range
  - 95% CL limit @ $m_H = 125$ GeV:
    - $1.06 \times \sigma$(SM) expected
    - $2.44 \times \sigma$(SM) observed

• Log-likelihood ratio (LLR)
  - Relative agreement of B-only and S+B hypotheses
  - Expected S+B shows good sensitivity up to ~185 GeV

~$3\sigma$ excess at 120-125 GeV
  - Consistent with SM Higgs
Quantifying the Excess

- **Compatibility with B-only prediction (left)**
  - Minimum local p-value at $m_H = 120$ GeV: $3.1\sigma$ (2.0$\sigma$ expected)
  - p-value at $m_H = 125$ GeV: $3.0\sigma$ (1.9$\sigma$ expected)

- **Compatibility with S+B prediction (right)**
  - Maximum likelihood fit with Higgs cross section as a free parameter
    - $\mu = \sigma/\sigma_{SM} = 1.4 \pm 0.6$ @ 125 GeV
**Tevatron cross section fits**

CDF

- $m_h = 125 \text{ GeV/c}^2$
- Green: Combined (68% C.L.)
- Red: Single channel

**PRD 88, 052013 (2013)**

- $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow \tau^+\tau^-$
- $VH \rightarrow Vb\bar{b}$

$D\bar{O}$, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$

- $M_H = 125 \text{ GeV}$
- Green: Combined (68%)
- Black: Single Channel

**PRD 88, 052011 (2013)**

- Green: Combined (68% C.L.)
- Black: Single channel

**PRD 88, 052014 (2013)**

- $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow \tau^+\tau^-$
- $VH \rightarrow Vb\bar{b}$

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

- $m_h = 125 \text{ GeV/c}^2$
- $\mu$
  - $5.97^{+3.39}_{-3.12}$
  - $0.94^{+0.85}_{-0.83}$
  - $1.68^{+2.28}_{-1.68}$
  - $1.59^{+0.69}_{-0.72}$

Best Fit $(\sigma \times \text{Br})/\text{SM}$
• Use LHCHXSWG framework (arXiv:1209:0040)

• 1D fits: Vary each of $\kappa_W$, $\kappa_Z$ or $\kappa_f$ independently in turn
  - Negative values for $\kappa_f$ ($\kappa_W$) preferred due to $H \rightarrow \gamma\gamma$ excess

• 2D fits: Probe custodial symmetry i.e. $\lambda_{WZ} = \kappa_W/\kappa_Z \approx 1$ (SM) or assume $\lambda_{WZ} = 1$

• All consistent with SM
Spin / Parity

- **Tevatron sensitive in $b\bar{b}$ final states**
  - VH cross section at threshold sensitive to $\beta$, & hence $J^P$ assignment
    
    e.g. Ellis et al., JHEP 1211 134 (2012)

    $J^P = 0^+$; $\sigma \sim \beta$
    $J^P = 0^-$; $\sigma \sim \beta^3$
    $J^P = 2^+$; $\sigma \sim \beta^5$

- **Strategy**
  - Models tested
    - $0^-$: Model of Ellis et al.
      i.e. Basic dim. 5 effective coupling
    - $2^+$: Standard RS graviton model
  - Re-use published VH $\rightarrow$ V$b\bar{b}$ analyses, assume $m_X = 125$GeV
  - Main discriminating variable
    - Invariant or transverse mass
• Published event selection, b-tag, jet multiplicity & lepton categories
• DØ [Phys. Rev. Lett. 113, 161802 (2014)]
  - Split into high (HP) & low purity (LP) samples
  - Final discriminant: invariant or transverse mass

Spin / Parity
Published event selection, b-tag, jet multiplicity & lepton categories

- Final discriminant:
  - MVA approach, combination of NNs trained against SM and BSM signals
  - Information on mass of VX system included
**Spin / Parity**

- **LLR** = \(-2\log[L(H1)/L(H0)]\) with $H1=(2^+ + \text{bkg})$ or $(0^- + \text{bkg})$ & $H0=(0^+ + \text{bkg})$
  - $CL_s = CL_{H1}/CL_{H0}$

  - **CDF**
    - $0^-$ signal excluded at 99.99% CL (99.92% exp)
    - $2^+$ signal excluded at 99.1% CL (99.3% exp)

  - **DØ**
    - $0^-$ signal excluded at 97.6% CL (99.9% exp)
    - $2^+$ signal excluded at 99.0% CL (99.9% exp)
- Assuming production rate x BR of X same as for SM (i.e. $\mu = 1$)
  - $0^-$ signal excluded at $5.0\sigma$ ($4.8\sigma$ exp)
  - $2^+$ signal excluded at $4.9\sigma$ ($4.6\sigma$ exp)
- Other values of $\mu$ tested
Consider admixture of $0^+$ & $0^-$ (or $2^+$)

Limits on $0^-$ (or $2^+$) fraction

$-\mu_{SM}=0$, exclude at 95%CL

- $f_{0^-} > 0.36$ (0.32 exp)
- $f_{2^+} > 0.36$ (0.33 exp)

'Exotic fraction' vs total rate

$\mu = \mu_{exotic} + \mu_{SM}$
• Tevatron
  - Sensitivity over most of accessible mass range
  - Excess from $115 < m_H < 140$ GeV
    - $\sim 3\sigma$ significance at 125 GeV
  - Coupling & spin results consistent with SM Higgs

• Tevatron: Continued to provide valuable information on nature of observed boson
  - Look forward to Tevatron + LHC $H \rightarrow bb$ combination

• Testament to Tevatron’s legacy: Making of a new generation of physicists
  - Many moved to LHC
The CDF and DØ Collaborations
• ~12fb$^{-1}$ delivered, ~11fb$^{-1}$ recorded, ~10fb$^{-1}$ after data quality per expt
  - with $L_{\text{inst}} \leq 4 \times 10^{32}$

**Integrated Luminosity 11871.03 (1/pb)**

Primary Higgs analyses: 9.5-10fb$^{-1}$

Many thanks to Accelerator Division
• Proton-antiproton
  - Unlikely to be repeated
  - Dominantly $qq$ collisions not $gg$ as at LHC
    • Gives enhanced xsect for some processes eg VH
  - Initial CP eigenstate (and DØ’S ability to reverse magnetic field)
    • Enable incisive asymmetry and CP measurements eg $A_{fb}$ in $tt$
• Relative cleanliness (low pileup) facilitates precision measurements
  - e.g. W mass, top quark mass
• e.g. looking at DØ publications

Focus here: Higgs

Wealth of other results reported elsewhere
@ $m_H = 125 \text{ GeV}$

LHC

Tevatron

Main mode

Supporting mode
### Details: Final Full Combination

<table>
<thead>
<tr>
<th>CDF Channel ($V = W, Z$ and $\ell = e, \mu$)</th>
<th>Luminosity (fb$^{-1}$)</th>
<th>$M_H$ (GeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH \rightarrow \ell \nu b \bar{b}$</td>
<td>9.45</td>
<td>90–150</td>
<td>PRL 109, 111804 (2012)</td>
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<td>90–150</td>
<td>PRD 87, 052008 (2013)</td>
</tr>
<tr>
<td>$WH + ZH \rightarrow jj b \bar{b}$</td>
<td>9.45</td>
<td>100–150</td>
<td>JHEP 02, 004 (2013)</td>
</tr>
<tr>
<td>$t\bar{t}H \rightarrow W^+ bW^- b\bar{b}$</td>
<td>9.45</td>
<td>100–150</td>
<td>PRL 109, 181802 (2012)</td>
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<tr>
<td>$H \rightarrow W_+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$</td>
<td>9.7</td>
<td>110–200</td>
<td>PRD 88, 052012 (2013)</td>
</tr>
<tr>
<td>$H \rightarrow W_+ W^- \rightarrow \ell \tau_\nu$</td>
<td>9.7</td>
<td>110–200</td>
<td>PRD 88, 052012 (2013)</td>
</tr>
<tr>
<td>$WH \rightarrow WW^- \rightarrow \ell \ell, \ell^\pm \ell^\pm$</td>
<td>9.7</td>
<td>130–200</td>
<td>PRD 88, 052012 (2013)</td>
</tr>
<tr>
<td>$WH \rightarrow WW^- \rightarrow \ell \ell, \ell^\pm \ell^\pm$</td>
<td>9.7</td>
<td>130–200</td>
<td>PRD 88, 052012 (2013)</td>
</tr>
<tr>
<td>$ZH \rightarrow ZW^- \rightarrow \ell \ell + jet(s)$</td>
<td>9.7</td>
<td>110–200</td>
<td>PRD 88, 052012 (2013)</td>
</tr>
<tr>
<td>$H + X \rightarrow \tau^+ \tau^- + jet(s)$</td>
<td>9.7</td>
<td>100–150</td>
<td>PRL 108, 181804 (2012)</td>
</tr>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>10.0</td>
<td>100–150</td>
<td>PLB 717, 173 (2012)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>9.7</td>
<td>120–200</td>
<td>PRD 86, 072012 (2012)</td>
</tr>
</tbody>
</table>

### CDF grand combination
| all CDF | 6.0–10.0 | 90–200 | PRD 88, 052013 (2013) |

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<tr>
<th>DØ Channel ($V = W, Z$ and $\ell = e, \mu$)</th>
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<td>PRD 88, 052008 (2013)</td>
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<td>$ZH \rightarrow \ell \nu b \bar{b}$</td>
<td>9.7</td>
<td>90–150</td>
<td>PRD 88, 052010 (2013)</td>
</tr>
<tr>
<td>$ZH \rightarrow \nu \nu b \bar{b}$</td>
<td>9.5</td>
<td>100–150</td>
<td>PLB 716, 285 (2012)</td>
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<tr>
<td>$H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$</td>
<td>9.7</td>
<td>100–200</td>
<td>PRD 88, 052006 (2013)</td>
</tr>
<tr>
<td>$H + X \rightarrow W^+ W^- \rightarrow \mu^\pm \tau^\mp + \leq 1$ jet</td>
<td>7.3</td>
<td>155–200</td>
<td>PLB 714, 237 (2012)</td>
</tr>
<tr>
<td>$H \rightarrow W^+ W^- \rightarrow \ell \nu q \bar{q}$</td>
<td>9.7</td>
<td>100–200</td>
<td>PRD 88, 052008 (2013)</td>
</tr>
<tr>
<td>$VH \rightarrow e e \mu/\mu e + X$</td>
<td>9.7</td>
<td>100–200</td>
<td>PRD 88, 052009 (2013)</td>
</tr>
<tr>
<td>$VH \rightarrow e^\pm \mu^\pm + X$</td>
<td>9.7</td>
<td>100–200</td>
<td>PRD 88, 052009 (2013)</td>
</tr>
<tr>
<td>$VH \rightarrow \nu q q \bar{q}$</td>
<td>9.7</td>
<td>100–200</td>
<td>PRD 88, 052008 (2013)</td>
</tr>
<tr>
<td>$VH \rightarrow \tau_h \tau_h \mu + X$</td>
<td>8.6</td>
<td>100–150</td>
<td>PRD 88, 052009 (2013)</td>
</tr>
<tr>
<td>$H + X \rightarrow \ell \tau_h j j$</td>
<td>9.7</td>
<td>105–150</td>
<td>PRD 88, 052005 (2013)</td>
</tr>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>9.7</td>
<td>100–150</td>
<td>PRD 88, 052007 (2013)</td>
</tr>
</tbody>
</table>

### DØ grand combination
| all DØ | 7.3–9.7 | 90–200 | PRD 88, 052011 (2013) |

### CDF+DØ grand combination
| all CDF+DØ | 6.0–10.0 | 90–200 | PRD 88, 052014 (2013) |
Observed exclusion: $90 < m_H < 109 \text{ GeV}, \quad 149 < m_H < 182 \text{ GeV}$

Expected exclusion: $90 < m_H < 120 \text{ GeV}, \quad 140 < m_H < 184 \text{ GeV}$

95% CL limit @ $m_H = 125 \text{ GeV}: 1.06 \times \sigma(\text{SM}) \text{ expected}, 2.44 \times \sigma(\text{SM}) \text{ observed}$
Quantifying the Excess: LLR

- Log-likelihood ratio (LLR)
  - Relative agreement of B-only and S+B hypotheses
  - Throw pseudo-data to populate B-only and S+B models
    - Compare to observed
  - Expected S+B shows good sensitivity up to ~185 GeV
  - ~3σ excess at 120-125 GeV
    - Consistent with SM Higgs
Tevatron: $H \rightarrow bb$ Results

![Log-Likelihood Ratio vs. $m_H$](image1)

![Expected Standard Model $H \rightarrow bb$ Cross Section](image2)
• Measure deviations of couplings from SM prediction using LHCHXSWG framework (arXiv:1209:0040)

\[ \sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2} \]

- Assume all signals near 126 GeV from single resonance of zero width, with SM-like coupling structure

- Additionally: no additional invisible or undetected Higgs decay modes

  - e.g.

  \[ \sigma(WH) \cdot BR(H \rightarrow bb) = \sigma(WH)_{SM} \cdot BR(H \rightarrow bb)_{SM} \frac{\kappa_W^2 \cdot \kappa_b^2}{\kappa_H^2} \]

  \[ \kappa_{\gamma} = 1.28 \kappa_W - 0.28 \kappa_f \]

- Study fermion coupling, \( \kappa_f \) and boson couplings \( \kappa_W, \kappa_Z \) and \( \kappa_V \)
Couplings: 1D

- 1D fits: Vary each of $\kappa_W$, $\kappa_Z$ and $\kappa_f$ independently in turn

For $\kappa_Z = \kappa_f = 1$,

$$\kappa_w = \kappa_Z = 1$$

$$k_z = \pm (1.05^{+0.45}_{-0.55})$$

$$k_f = -2.64^{+1.59}_{-1.30}$$

$$k_w = -1.27^{+0.46}_{-0.29}$$ or $1.04 < k_w < 1.51$

Negative values for $\kappa_w$ and $\kappa_f$ preferred due to $H \rightarrow \gamma\gamma$ excess

All consistent with SM
• Probe custodial symmetry
  
  \[ \lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} \approx 1 (\text{SM}) \]
  
  - Preferred region
  \[ (\kappa_W, \kappa_Z) = (1.25, \pm 0.90) \]

  • Assume \( \lambda_{WZ} = 1 \)
    
    - Preferred regions
  \[ (\kappa_V, \kappa_f) = (1.05, -2.40) \& \]
  \[ (\kappa_V, \kappa_f) = (1.05, 2.30) \]

  All consistent with SM
Tevatron: Couplings

- Posterior probability densities

![Graphs showing posterior probability densities for Tevatron Run II, $L_{int} \leq 10$ fb$^{-1}$]
Spin / Parity

- Posterior probability density functions
• Consider admixture of $0^+$ & $0^-$ (or $2^+$), set limits on $0^-$ (or $2^+$) fraction

Exclude at 95% CL

- $f_{0^-} > 0.32$ & $f_{2^+} > 0.35$ (no SM Higgs present)
- $f_{2^+} > 0.28$ & $f_{2^+} > 0.31$ (SM Higgs present)

Exclude at 95% CL

- $f_{0^-} > 0.80$
- $f_{2^+} > 0.67$
Spin / Parity

- Consider admixture of $0^+ \& 0^-$ (or $2^+)$, set limits on $0^-$ (or $2^+$) fraction