The Tevatron Higgs Search
For the CDF & DØ collaborations
Wade Fisher
Michigan State University
Tevatron (1983–2011)
proton - antiproton collider
collision energy = 1.96 TeV
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Tevatron (1983-2011)
proton - antiproton collider
collision energy $= 1.96$ TeV
The Tevatron’s Higgs Legacy

**Higgs searches at the Tevatron**
- Production and decay modes
- Search strategies

**Studies of Higgs production at $M_H=125$ GeV**
- Signal significance
- Measurements of Higgs properties
Producing Higgs at the Tevatron
Producing Higgs at the Tevatron
Producing Higgs at the Tevatron

Tevatron
$\sqrt{s} = 1.96$ TeV

$\sigma(pp \to H+X)$ [fb]
Producing Higgs at the Tevatron

\[ \sigma(pp \to H + X) \] in [fb]

\[ \sqrt{s} = 1.96 \text{ TeV} \]

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

\[ M_H \text{ [GeV]} \]

\[ \sqrt{s} = 7 \text{ TeV} \]
Focusing the Search
Focusing the Search

- Main mode
- Supporting mode

LHC
Focusing the Search

Main mode
Supporting mode

LHC Tevatron
A Combination of Many Searches
Spring 2013

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

SM Higgs combination

95\% C.L. Limit/SM

- Observed
- Expected w/o Higgs
- Expected \( \pm 1 \text{ s.d.} \)
- Expected \( \pm 2 \text{ s.d.} \)
- Expected if \( m_H = 125 \text{ GeV/c}^2 \)

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

SM=1
Spring 2013

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

SM Higgs combination

95% C.L. Limit/SM

- Observed
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- Expected ± 1 s.d.
- Expected ± 2 s.d.
- Expected if $m_H=125 \text{ GeV/c}^2$

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

Expected Exclusion  Observed Exclusion
**p-value noun:**
probability of an outcome as extreme as that observed, assuming the null hypothesis is true.
Production Rates

$\mu_{125 \text{ GeV}} = 1.44^{+0.59}_{-0.56}$
Production Rates

\( \mu_{125 \text{ GeV}} = 1.44^{+0.59}_{-0.56} \)

\( \mu_{H \rightarrow b \bar{b}} = 1.59^{+0.69}_{-0.72} \)
But is it a Higgs boson??
But is it a Higgs boson??
But is it a Higgs boson??
<table>
<thead>
<tr>
<th>JP</th>
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<th>Comments</th>
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</thead>
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<td>$1^+$</td>
<td>Graviton-like tensor, or pseudo-tensor</td>
<td>Many assumptions to be made, depending on the model constructed</td>
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At the LHC, it’s all about the angles.
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At the LHC, it’s all about the angles.

\[ A_{00} = -\frac{M_x^2}{v} (a_1 \chi + a_2 \eta (\chi^2 - 1)) \]

\[ A_{\pm \pm} = \frac{M_x^2}{v} \left( a_1 \pm i a_3 \eta \sqrt{\chi^2 - 1} \right) \]

Vector boson helicity amplitudes
At the Tevatron, it's all about the threshold.
At the Tevatron, it's all about the threshold.

\[ A_{00} = -a_1 \frac{E_Z}{M_Z} \]
\[ A_{10} = -a_1 \]

\[ J^P: 0^+ \]

\[ A_{00} = 0 \]
\[ A_{10} = -ia_1 \beta s \]

\[ J^P: 0^- \]
At the Tevatron, it's all about the threshold.

\[ A_{00} = -a_1 E_Z / M_Z \]
\[ A_{10} = -a_1 \quad J^P: 0^+ \]
\[ A_{00} = 0 \quad J^P: 0^- \]
\[ A_{10} = -i a_1 \beta s \]

\[ \beta = 2p / \sqrt{s} \sim \sqrt{s - (M_H + M_Z)^2} \]
At the Tevatron, it’s all about the threshold.

\[
\beta = \frac{2p}{\sqrt{s}} \sim \sqrt{s} - (M_H + M_Z)^2
\]

\[
\sigma(V^* \rightarrow VH) \propto \beta \sum_{ij} |A_{ij}|^2
\]

\[
A_{00} = -a_1 \frac{E_Z}{M_Z}
\]

\[
A_{10} = -a_1 \text{ JP:0}^+
\]

\[
A_{00} = 0 \text{ JP:0}^-
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A_{10} = -ia_1 \beta s
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Threshold V+H production goes as:

- $\beta$ for $J^P=0^+$ (s-wave)
- $\beta^3$ for $J^P=0^-$ (p-wave)
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\[ WH \rightarrow \ell \nu b \bar{b}, \, 2\text{TT} \]

**DØ Preliminary, 9.7 fb\(^{-1}\):**
- Data
- Multijet
- \(V+lf\)
- \(V+hf\)
- \(t\bar{t}\)
- Single t
- \(VV\)
- \(0^+\) Signal
- \(0^-\) Signal
- \(2^+\) Signal

(Signals \(\times 25\))

\[ ZH \rightarrow \nu \nu b \bar{b}, \, 2\text{TT} \]

**DØ Preliminary, 9.5 fb\(^{-1}\):**
- Data
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- \(V+lf\)
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- \(0^+\) Signal
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- \(2^+\) Signal

(Signals \(\times 10\))

\[ WH \rightarrow \ell \nu b \bar{b}, \, 2\text{TT} \text{ HP} \]

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\[ ZH \rightarrow \nu \nu b \bar{b}, \, \text{TT HP} \]

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- \(0^+\) Signal
- \(0^-\) Signal
- \(2^+\) Signal

(Signals \(\times 10\))
DØ excludes $J^P$ models using $H \rightarrow bb$ decays
- $J^P=0^-$ excluded at the 99.6% C.L.
- $J^P=2^+$ excluded at the 99.9% C.L.

\[ \mu_{H \rightarrow b\bar{b}}^{\text{fit}} = 1.23 \]
Is nature more complicated?

Superposition?
Is nature more complicated?

\[ \phi = \cos \alpha \ H + \sin \alpha \ A \]

Eg, Two Higgs Doublet Model
Is nature more complicated?

\[ \phi = \cos \alpha \ H + \sin \alpha \ A \]

CP-Even  \hspace{1cm} CP-Odd

Eg, Two Higgs Doublet Model

Superposition?
Is nature more complicated?

\[ \phi = \cos \alpha \ H + \sin \alpha \ A \]

\[ \phi' = -\sin \alpha \ H + \cos \alpha \ A \]

Superposition?

Eg, Two Higgs Doublet Model

CP-Even

CP-Odd

What about this one??
Is nature more complicated?

\[ \phi = \cos \alpha H + \sin \alpha A \]

\[ \frac{\Gamma[\phi \rightarrow b\bar{b}]}{\Gamma_{SM}[H \rightarrow b\bar{b}]} = (y_d^H \cos \alpha)^2 + (y_d^A \sin \alpha)^2 \]

Superposition?

Yukawa Couplings
(1) \( \sigma_{\text{Tot}} = \sigma_A + \sigma_H \)

(2) \( f_A = \frac{\sigma_A}{\sigma_{\text{Tot}}} = \left( \frac{y_d^A}{y_d^{\text{SM}}} \sin \alpha \right)^2 \)
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(2) \[ f_A = \frac{\sigma_A}{\sigma_{\text{Tot}}} = \left( \frac{y_d^A}{y_d^\text{SM}} \sin \alpha \right)^2 \]

Scan the J^P=0^- Fraction

*Neglects Interference in Angular Variables*
(1) \( \sigma_{\text{Tot}} = \sigma_A + \sigma_H \)

(2) \( f_A = \frac{\sigma_A}{\sigma_{\text{Tot}}} = \left( \frac{y_d^A}{y_d^{\text{SM}}} \sin \alpha \right)^2 \)

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*Neglects Interference in Angular Variables*
Higgs couplings
\[ 2i \frac{m^2}{\nu} g_{\mu \nu} \]

\[ i \frac{m_f}{\nu} \delta_{ij} \]
\[ 2i \frac{m^2_W}{\nu} g_{\mu \nu} \times \kappa W \]

\[ i \frac{m_f}{\nu} \delta_{ij} \times \kappa f \]
$2i \frac{m^2_W}{v} g_{\mu \nu} \times \kappa W$

$i \frac{m_f}{v} \delta_{ij} \times \kappa f$

Standard Model = 1.0
For new particles with $M \sim 1$ TeV, this is a discovery measurement.
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<tr>
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<tr>
<td>Singlet Mixing</td>
<td>$\sim 6%$</td>
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<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
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<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.0013%$</td>
<td>$\sim 1.6%$</td>
<td>$\leq 1.5%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3 - 9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
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Standard Model = 1.0
Start with rates...
Start with rates...
Start with rates...

\[ \sigma \propto \left| (g_i \times \kappa_i) \cdot (g_j \times \kappa_j) \right|^2 \propto k_i^2 \cdot k_j^2 \]
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\[
\sigma \propto \left| (g_i \times \kappa_i) \cdot (g_j \times \kappa_j) \right|^2 \propto \kappa_i^2 \cdot \kappa_j^2
\]
No surprises, but the LHC will continue to improve here

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Standard Model = 1.0
Final Tevatron Higgs results
- Search channels using full RunII dataset & published.
  + tevnphwg.fnal.gov
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- Search channels using full RunII dataset & published.
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Achieved SM sensitivity over most of accessible mass range
- Excess near 125 GeV corresponds to $3.0\sigma$
  + Consistent with LHC results
Final Tevatron Higgs results
- Search channels using full RunII dataset & published.
  + [tevnphwg.fnal.gov](http://tevnphwg.fnal.gov)

Achieved SM sensitivity over most of accessible mass range
- Excess near 125 GeV corresponds to $3.0\sigma$
  + Consistent with LHC results

Sensitive to Higgs properties in Hbb mode
- $J^P$ & couplings measurements are a valuable contribution
  + Updated $J^P$ results coming from DØ, CDF & CDF+DØ
At $M_H = 125$ GeV:
Exp. limit: $1.5 \times \sigma_{(SM)}$
Obs. limit: $2.9 \times \sigma_{(SM)}$

At $M_H = 125$ GeV:
Exp. limit: $1.7 \times \sigma_{(SM)}$
Obs. limit: $2.9 \times \sigma_{(SM)}$
Higgs Mass
Higgs Mass

Tevatron Run II Preliminary

SM Higgs, $L_{\text{int}} \leq 10 \text{ fb}^{-1}$

Higgs Boson Mass (GeV/c$^2$)
$M_H^{\text{fit}} = 126.2^{+8.1}_{-7.8}$ GeV

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

SM Higgs Combination

Log-Likelihood Ratio

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

- \( \text{LLR}_b \pm 1 \text{ s.d.} \)
- \( \text{LLR}_b \pm 2 \text{ s.d.} \)
- \( \text{LLR}_{s+b} \)
- \( \text{LLR}_{m_H=125 \text{ GeV/c}^2} \)
At the Tevatron, it’s all about the threshold.

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} = \frac{3}{4A_{\text{Tot}}^2} \left( \sin^2 \theta [ |A_{00}|^2 + 2|A_{11}|^2] + (1 + \cos^2 \theta) [ |A_{01}|^2 + |A_{10}|^2 + |A_{12}|^2] \right)
\]

\[
A_{00} = -a_1 \frac{E_Z}{M_Z}
\]
\[
A_{10} = -a_1 \hspace{1cm} J^P: 0^+
\]
\[
A_{00} = 0 \hspace{1cm} J^P: 0^-
\]
\[
A_{10} = -i a_1 \beta s
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\( J^P = 0^+ \)

Isotropic near threshold

\[
A_{00} = -a_1 \frac{E_Z}{M_Z}
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\[
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\( J^P = 0^+ \)

Isotropic near threshold

\( J^P = 0^- \)

Strong angular dependence

\[
A_{00} = -a_1 \frac{E_Z}{M_Z}
\]

\[
A_{10} = -a_1
\]

\( J^P = 0^+ \)

\[
A_{00} = 0
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Threshold $V+H$ production goes as:

- $\beta$ for $J^P=0^+$ (s-wave)
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Quantifying the Excess: Sub Channels

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

**SM H\( \rightarrow \)bb Combination**

- LLR\(_b\) ± 1 s.d.
- LLR\(_b\) ± 2 s.d.
- LLR\(_{b}\)
- \( \sigma_H \times 1.0 \) (\( m_H = 125 \text{ GeV/c}^2 \))
- \( \sigma_H \times 1.5 \) (\( m_H = 125 \text{ GeV/c}^2 \))
- LLR\(_{\text{Obs}}\)

**SM H\( \rightarrow \)WW Combination**

- LLR\(_b\) ± 1 s.d.
- LLR\(_b\) ± 2 s.d.
- LLR\(_{b}\)
- \( \sigma_H \times 1.0 \) (\( m_H = 125 \text{ GeV/c}^2 \))
- \( \sigma_H \times 1.5 \) (\( m_H = 125 \text{ GeV/c}^2 \))

---

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

**SM H\( \rightarrow \)bb combination**

- Measured
- \( \pm 1 \) s.d.
- \( \pm 2 \) s.d.
- Predicted
- \( \sigma_H \times 1.0 \) (\( m_H = 125 \text{ GeV/c}^2 \))
- \( \sigma_H \times 1.5 \) (\( m_H = 125 \text{ GeV/c}^2 \))

**SM H\( \rightarrow \)WW combination**

- Observed
- \( \pm 1 \) s.d.
- \( \pm 2 \) s.d.
- \( \sigma_H \times 1.0 \) (\( m_H = 125 \text{ GeV/c}^2 \))
- \( \sigma_H \times 1.5 \) (\( m_H = 125 \text{ GeV/c}^2 \))
Display all input histogram bins ordered according to S/B in one plot.

- The background model has been constrained by the data.
Search Validation?
Search Validation?
\[ \sigma(VX \rightarrow Vbb) \]

- \( Z \rightarrow \ell \ell \)
- \( Z \rightarrow \nu \nu \)
- \( W \rightarrow l \nu \)

Charm
Low Mass Search
Low Mass Search

\[ \begin{aligned} W(e^\nu + 2 \text{jets}, \text{Single and Double Tags}) \end{aligned} \]

\[ \begin{aligned} DØ, 9.7 \text{ fb}^{-1} \end{aligned} \]

- Data
- Multijet
- V+lf
- V+hf
- t\bar{t}
- single t
- VV

\[ M_H = 125 \text{ GeV} \times 100 \]
Low Mass Search

**W(→ℓν)+2 jets, Single and Double Tags**

DØ, 9.7 fb⁻¹

- Data
- Multijet
- V+/lf
- V+/hf
- tt
- single t
- VV
- M_H = 125 GeV (×100)

**Tevatron Run II, L_{int} ≤ 10 fb⁻¹**

1+2 b-Tagged Jets

- Data — Bkgd
- WZ
- ZZ
- Higgs Signal
  - m_H = 125 GeV/c²

**Dijet Mass (GeV)**

**Events (20 GeV/c²)**
Low Mass Search

\[
\frac{\sigma(WZ + ZZ)}{\sigma^{SM}} = 0.7 \pm 0.2
\]
High Mass Search

![Graph showing events vs. log_{10}(s/b) for DØ, 9.7 fb^{-1}, ll + E_T. The graph compares Data - Bkgd, Signal (WW), and ±1 s.d. on Bkgd.](image)
High Mass Search

**VALIDATED**

\[ \text{Events} \]

**DØ, 9.7 fb}^{-1}, ll + E_T**

- Data - Bkgd
- Signal (WW)
- ±1 s.d. on Bkgd

\[ \log_{10}(s/b) \]

**Cross Section (pb)**

- \[ \sigma_{ee} \]
- \[ \sigma_{WW} \]
- \[ \sigma_{WW}^{\text{LH}} \]
- \[ \sigma_{WW}^{\text{combined}} \]
- \[ \sigma_{WW}^{\text{NLO}} \]

\[ 13.3 \pm 1.1 \text{ (stat)} \pm 1.1 \text{ (syst)} \]

\[ 11.1 \pm 0.6 \text{ (stat)} \pm 0.6 \text{ (syst)} \]

\[ 11.5 \pm 0.9 \text{ (stat)} \pm 0.7 \text{ (syst)} \]

\[ 11.6 \pm 0.4 \text{ (stat)} \pm 0.6 \text{ (syst)} \]

\[ 11.3 \pm 0.7 \]

(Campbell and Ellis, PRD 60, 113006 (1999))