Searches for the Standard Model Higgs Boson at the Tevatron

Thomas R. Junk
Fermilab

on behalf of the CDF and DØ Collaborations


- Context and Phenomenology
- The Experiments
- High Mass (130-200 GeV): Searches for $H \rightarrow WW$
- Low Mass (114-150 GeV): Searches for $H \rightarrow bb, \tau\tau$
- Combined Results
- Plans for the Future
The LEP2 and Tevatron, LEP1, SLD Precision EW Legacy

Direct searches for $\text{e}^+\text{e}^-\rightarrow\text{ZH}$: $m_{H}^{SM} > 114.4$ GeV/$c^2$

No evidence below

Precision $m_z$, $m_{W}$, $m_{t}$, Z-pole asymmetries, etc.

$m_{H}^{SM} = 90^{+36}_{-27}$ GeV/$c^2$ @95% CL, $m_{H} < 163$ GeV/$c^2$

(191 including LEP2 direct limit)
SM Higgs Boson Production Mechanisms


Tevatron SM Higgs Boson Searches / Thomas Junk / 23 June, 2009
Recent $gg\rightarrow H$ Production Cross Section Progress

• NLO corrections -- ~80% (almost double the cross section)!
• NNLO QCD corrections -- An additional 40% on top of that! Residual uncertainty ~10%. Catani, de Florian, Grazzini, Nason JHEP 0307, 028 (2003) hep-ph/0306211

Also resummed QCD corrections at NNLL

NLL,NNLL bands: $0.5m_H < \mu_F, \mu_R < 2M_H$.
Bands on LO and LL unreliable.

We take a ±12% uncertainty on $\sigma_{gg\rightarrow H}$ for scale and PDF
Recent \( gg \rightarrow H \) Production Cross Section Progress

- Two-loop EW corrections yield up to an 8% boost in cross section
- \( b \)-quark QCD corrections improved
- Total 14% bigger cross section at \( m_H = 160 \) GeV relative to NNLO

**2-Loop EW diagram:**

6 quark flavors contribute

\[ V = W \text{ or } Z \]


Anastasiou, Boughezal, Petriello, JHEP **0904**, 003 (2009)


Used by the Tevatron at ICHEP08

Used by the Tevatron at Moriond 2009
Parton Distribution Functions Are Important for $gg\rightarrow H$

• MSTW released a new PDF set on January 5, 2009 (“MSTW 2008”)
  Includes Tevatron Run II High-$E_t$ Jet Data
  (Less of an excess than Run I data)

• Effect: high-$x$ gluon PDF $x \alpha_s$ is less.

  Impact is ~15% **downward** shift in $gg\rightarrow H$ cross section

Included in Moriond 2009 Tevatron Higgs results
Standard Model Higgs Boson Decay Branching Fractions

HDECAY by M. Spira

114.4 < m_H < 135 GeV: 
H → bb dominates.

gg → H → bb drowned by 
gg → bb. Use WH, ZH.

135 < m_H < 200 GeV 
H → W^+W^- dominates

gg → H, WH, ZH, VBF all can be used
Tevatron Performance Constantly Improves

A partial list of improvements:

- Store antiprotons in recycler
- Faster transfers from pbar accumulator to recycler
- Electron cooling of pbars in recycler
- Efficiency and reliability of injection
- Faster shot setup
- Separation of orbits at parasitic crossings
- Replacement of 1200 He relief valves
- Faster beam aborts during quenches
- “cogging” pbars to prevent quenches during acceleration
The Detector

Lepton coverage:
- $|\eta| < 1.5$ (muons)
- $|\eta| < 2.0$ (electrons)

b-tagging with
- $|\eta| < \sim 1.4$

Jets to
- $|\eta| < 2.8$

Higgs analyses restrict to
- $|\eta| < 2.0$

Dijet mass resolution: $\sim 16\%$
The **Detector**

**Lepton coverage:**
- $|\eta| < 2$ (muons)
- $|\eta| < 2.6$ (electrons)

**b-tagging with**
- $|\eta| < \sim 2$

**Jets to**
- $|\eta| < 3$

Similar dijet mass resolution to CDF

New Innermost Silicon Layer added between Run IIa and Run IIb
H \rightarrow W^+W^-  Signal and Background

**gg→H Signal Process:**

Both CDF and D0 Select events with
- Two isolated, opposite-signed high-\(p_T\) leptons (e,\(\mu\))
- Missing transverse energy
- \(m_{ll} > \sim 15\) GeV

**Dominant difficult background:**
\(q\bar{q} \rightarrow W^+W^-\)

- **Higgs is a Scalar!** Angular correlations are different from SM \(W^+W^-\) bg
- **Signal leptons come out collinear**

\(\nu\) \quad \nu \quad W^+ \quad W^- \quad e^+ \quad e^-\)
WW Leptonic Decay Branching Ratios

$\text{Br}(W \rightarrow \text{hadrons}) \approx 68\%$

W+jets and multijet backgrounds prohibit using $W \rightarrow \text{hadron}$ decays

$\text{Br}(WW \rightarrow ee, e\mu, \mu\mu) \approx 6\%$

- Manageable background
- Lepton triggers are easier
- Missing $E_T$ (neutrinos) is an important signature too
- Includes some $W \rightarrow \tau$ decays
Four Years ago: 2005 H→WW Analysis

• Just used gg→H signal
  acceptance: 0.7% of ggH, or about 0.55% of all H at m_H=160 GeV
• Final discriminant: Δφ_{ll}
• Jet vetoes to suppress ttbar

CDF Run II Preliminary, L_{int} = 360 pb^{-1}

Expected limit: ~15 x SM at m_H=160 GeV
Lepton Acceptance Gains

10% gain in CDF electron acceptance

30% gain in CDF single-muon acceptance

Inter-calorimeter electrons
-- 10% gain in D0 electron acceptance

These Leptons don’t all trigger!
Use another lepton, or MET+Jets triggers.
Splitting up the $H \rightarrow WW$ Sample

- Three final states, each gets a separate channel

$ee, e\mu, \mu\mu$

Different signal and background rates and systematics. Split and combine at the end.

Preselection:

Two oppositely-signed leptons:
- $p_{T,e} > 15 \text{ GeV}$, $p_{T,\mu} > 10 \text{ GeV}$ (15 GeV for leading muon)
- $m_{ll} > 15 \text{ GeV}$
- $n_{\text{jet}} < 2$ in the $\mu\mu$ channel
ee, $e\mu$ Samples: Preselection Level

Data
- $Z\rightarrow ee$
- Diboson
- W+jets/γ
- Multijet
- ttbar
- $H_{165} \times 10$

$ee$

$e\mu$

$ee$

$e\mu$

$ee$

$e\mu$
μμ Sample at Preselection Level

Missing-\(E_T\) resolution not as good. Cut MET on it only in 1-jet case for selection.

\[\text{ee and } e\mu \text{ Selection requirements} \]
\[\text{MET} > 20 \text{ GeV, } \text{MET}_{\text{scaled}} > 6 \]
\[M_{T,\text{min}}(l,\text{MET}) > 20 \text{ GeV} \]
\[\Delta \phi_{ll} < 2.0.\]
• Different amounts of DY background in different channels due to different MET cuts

• Neural networks derived from $p_t$ of leptons, MET, $\Delta \phi(l,l)$, $R_\phi(l,l)$, $\Delta \phi$(MET,l), M(l,l), $H_T$
Splitting up $H \to WW$ Into Subsamples

- Original analysis vetoed on extra jets
- But We can analyze these events one category at a time
  - $WW+0$ jets: $gg \to H$ signal
  - $WW+1$ jet: add in WH, ZH, VBF signals
    (20% more signal)
  - $WW+2$ jets (or more) 60% more signal from WH, ZH and VBF. Main background is $t\bar{t}$
  - Total CDF acceptance: 1.1%: **DOUBLE the 2005 acceptance**.

Better MET resolution -- lepton categories treated more symmetrically

- Same-sign dileptons + one or more jets: Mostly sensitive to WH and ZH, with leptonic $W$, $Z$ decay.

Each major background has a dedicated control sample
Checking Control Regions

Low MET significance control region -- events with fake MET

Same Sign Dileptons

$W\gamma$, $W$+jets backgrounds
Checking The Signal Region
Matrix Element Basics

Predictions given by QM matrix element and phase space.

Many processes (signal and background) give the same observable quantities in the detector -- cannot assign an event to be signal or background (if we could, we would!)

Instead, ask what the ratio of chances of getting an event from signal or background processes. Need to incorporate experimental resolution effects.
Imperfect Reconstruction

- Missing neutrinos!  Missing $E_T$ resolution not perfect.

- Jet energies not perfectly measured.  Directions are pretty good, and leptons are measured well.

- What parton 4-vectors could have given us the measured events?

\[
P(x) = \frac{1}{\sigma} \int 2\pi^4 |M|^2 \frac{f(y_1)}{|E_{q_1}|} \frac{f(y_2)}{|E_{q_2}|} W(y, x) d\Phi_4 dE_{q_1} dE_{q_2}
\]

\[y=\text{parton (or neutrino momenta)}, \ x=\text{measured jet quantities.}\]

Do this for each physics process -- form a likelihood ratio from them.
WW Cross Section Measurement

Checks Matrix
Element discriminant
shape of dominant
background in the
signal sample

Same as Higgs search
but reverse roles of
signal and background

\[\sigma(p\bar{p} \rightarrow W^+W^-) = 12.1 \pm 0.9 \text{ (stat)} \pm^{+1.6}_{-1.4} \text{ (syst)} \text{ [pb]}\]

SM: 12.4 \pm 0.7 \text{ pb (MCFM)}
## H→WW -- Event Kinematics Separating Signal from Background

### Channel | Signal | Primary background | Primary discriminants
--- | --- | --- | ---
0 Jets | gg→H | WW, DY | $\Delta\phi/R,\text{MET,ME}$
1 Jet | gg→H, VH, VBF | WW, DY | $\Delta\phi/R,\text{MET,} m_{TH}$
2+ Jets | gg→H, VH, VBF | Top dilepton | MET, HT, $m_{TH}$
1+ Jets SS lepton | VH | W+Jets | Good lepton ID, MET

### Graphs
- CDF Run II Preliminary
  - SS 1 Jets
    - $M_H = 160 \text{ GeV/c}^2$
  - OS 2 Jets
    - $M_H = 160 \text{ GeV/c}^2$
  - OS 1 Jets
    - $M_H = 160 \text{ GeV/c}^2$

### Tevatron Site: Higgs Boson Search
- Thomas Junk
- 23 June, 2009
Discriminant Outputs: $m_H = 165$ GeV

Signal x 1.0

Tevatron SM Higgs Boson Searches / Thomas Junk / 23 June, 2009
CDF and DØ limits for $H \to WW$ Channels

At $m_H = 165$ GeV, at 95% CL

CDF: obs 1.3 x SM  
    exp 1.5 x SM

DØ: obs 1.3 x SM  
    exp 1.7 x SM
CMSSM Favors $m_H < 120$ GeV

- Bayesian scan over CMSSM parameter space.

- Inputs
  - Direct LEP2 Higgs searches
  - Precision EW
  - Muon $g-2$
  - WMAP assuming CDM=neutralinos: $\Omega_\chi h^2$
  - $B_s$ Mixing Rate: $\Delta M_{B_s}$
  - $\text{Br}(B \rightarrow s\gamma)$
  - $\text{Br}(B_s \rightarrow \mu^+\mu^-)$

- Markov Chain Monte Carlo search through high-dimensional parameter space

- CMSSM parameters (flat prior)
  - $50 \text{ GeV} < m_0 < 4 \text{ TeV}$
  - $50 \text{ GeV} < m_{1/2} < 4 \text{ TEV}$
  - $|A_0| < 7 \text{ TeV}$
  - $2 < \tan\beta < 62$

MSSM $h$ is SM-like for these models (production, decay)

B-Tagging

**L00 single-sided silicon + 5-layer double-sided silicon+ 2-layer ISL**

Impact parameter resolution for high-\(p_T\) tracks \(\sim 18 \mu\text{m}\)

B-tagging relies on displaced vertex reconstruction: high mass, long lifetime

**Mistag rates typically \(\sim 1\%\) for light-flavor jets**

**Example candidate event (lvbb)**

**D0 B-tagging per-jet efficiency = 50-70\% (of taggable jets) for 1-5\% Mistag rate**
Neural Networks for Better B-tagging

CDF: Train a NN to separate b’s from charm and light flavor jets in vertex-tagged jets

D0: Use the NN as the b-tagging tool from the start. Choice of operating points.

Some of the inputs:
- Displaced vertex mass
- # tracks in displaced vertex
- Decay flight distance and significance
- Identified leptons in and near jets
- Secondary vertex fit $\chi^2$
- Jet $E_T$

CDF and D0: Efficiency and Mistags and NN’s Calibrated with Data
Low-Mass Search Channel 1: WH→lνbb: Matrix Element + Boosted Decision Tree

• Select events with:
  • A high-\(P_T\) lepton (\(\geq 20\) GeV), e or \(\mu\) isolated track category -- gave an extra PhD thesis
  • Missing \(E_T\) \(\geq 20\) GeV
  • Two jets (cone=0.4, |\(\eta|\)<2.0, \(E_T\)>20 GeV)
  • One or two b-tags (different s/b so split these categories)
  • Veto Z’s, cosmics, conversions

• Two teams -- ME+BDT and NN then collaborated with a superdiscriminant combination
### Backgrounds are Ferocious

### Preliminary, 2.7 fb\(^{-1}\)

<table>
<thead>
<tr>
<th>Process</th>
<th>1 Tag</th>
<th>2 Tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>56.2 ± 6.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>WZ</td>
<td>23.0 ± 1.7</td>
<td>4.8 ± 0.5</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.8 ± 0.1</td>
<td>0.2 ± 0.0</td>
</tr>
<tr>
<td>TopLJ</td>
<td>121.3 ± 17.1</td>
<td>23.8 ± 3.9</td>
</tr>
<tr>
<td>TopDil</td>
<td>48.8 ± 6.8</td>
<td>14.1 ± 2.3</td>
</tr>
<tr>
<td>Stop T</td>
<td>64.0 ± 9.3</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>Stop S</td>
<td>40.6 ± 5.7</td>
<td>12.8 ± 2.1</td>
</tr>
<tr>
<td>Z+jets</td>
<td>37.4 ± 5.5</td>
<td>2.1 ± 0.3</td>
</tr>
<tr>
<td>Wbb</td>
<td>538.7 ± 162.5</td>
<td>70.3 ± 22.5</td>
</tr>
<tr>
<td>Wcc/Wc</td>
<td>489.1 ± 150.9</td>
<td>6.8 ± 2.3</td>
</tr>
<tr>
<td>W+LF</td>
<td>458.0 ± 57.9</td>
<td>2.2 ± 0.6</td>
</tr>
<tr>
<td>QCD</td>
<td>135.5 ± 54.2</td>
<td>9.0 ± 3.6</td>
</tr>
<tr>
<td>Total Bg</td>
<td>2013.3 ± 324.1</td>
<td>148.2 ± 26.1</td>
</tr>
<tr>
<td>WH115</td>
<td>6.3 ± 0.5</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>Data</td>
<td>1998</td>
<td>156</td>
</tr>
</tbody>
</table>
Matrix Element Analysis Optimization

• Not every process has a matrix element
  -- e.g. fake leptons
  -- need to have a discriminant for separating signal from background that we can test the distribution of using data-based models

• Not all information we know about goes into the matrix element
  -- e.g., the neural network flavor separator $P(b\text{-quark}) \equiv b$

\[
\text{EPD} = \frac{b \times P_{WH}}{b \times \left( P_{WH} + P_{\text{singletop}} + P_{Wb\bar{b}} + P_{t\bar{t}} \right) + (1 - b) \times \left( P_{Wc\bar{c}} + P_{Wc} + P_{\text{Mistag}} + P_{\text{Diboson}} \right)}
\]
Some of the Important Distributions

**No b-tags control sample**

**One b-tag**

**Two b-tags**

- MC scaled to data for all plots

**Tevatron SM Higgs Boson Searches / Thomas Junk / 23 June, 2009**
A boosted decision tree with ME inputs

21 inputs. Important ones:
- matrix element EPD
- $m_{jj}$
- jet energies
- event $H_T$ (scalar sum of object energies)
- NN flavor separator (b-tag improvement)

A standard machine-learning technique
Find the variable to cut on that gives the best improvement in $Gini = p(1-p)$.
Boosting: Reweight misclassified events and retrain a DT.
One- and Two-Tag ME+BDT Outputs

Signal systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Single Tag</th>
<th>Double Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>2.0 %</td>
<td>2.0 %</td>
</tr>
<tr>
<td>ISR/FSR + PDF</td>
<td>3.1 %</td>
<td>5.6 %</td>
</tr>
<tr>
<td>Lepton ID</td>
<td>~2.0 %</td>
<td>~2.0 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.0 %</td>
<td>6.0 %</td>
</tr>
<tr>
<td>b-tagging SF</td>
<td>3.5 %</td>
<td>8.4 %</td>
</tr>
</tbody>
</table>

Background Systematic uncertainties

- $W^+HF$ yield: $\pm 30\%$
- $W^+LF$ yield: $\pm 13\%$
- non-$W$ yield: $\pm 40\%$
- $t\bar{t}W$ yield: $\pm 14\%$

(other backgrounds smaller)
Add in a Neural Network

- Separate Analysis Team,
  Same selected data events!
  Same Monte Carlo samples!
  Same Systematic Uncertainties!
  Not 100% correlated however

- Six NN input variables:
  \( m_{jj} \)
  Total system \( p_T \)
  \( p_T \) imbalance (scalar sum of
  lepton+jet \( p_T \) - Missing \( E_T \))
  \( \Sigma E_T \) (loose jets)
  \( M_{\min}(\text{lepton}+\nu+\text{jet}) \)
  \( \Delta R(\text{lepton},\nu) \)

Different choice of variables -- orthogonal information

CDF Run II Preliminary 2.7 fb\(^{-1}\)

one b-tag

CDF Run II Preliminary 2.7 fb\(^{-1}\)

two b-tags
Combining the Work of Two Teams Analyzing the Same Set of Events

• How do we get the most out of our work?
• Typical NN error function is not something we care about:
  \[ E = \sum_{\text{events}} (\text{meas} - \text{desired})^2 \]
• But it is easy to back-propagate for efficient training
• Instead we want
  • Discovery
    • failing that, exclusion
• This figure of merit works better:
  \[ F = \sum_{\text{bins}} s^2 / b \]
• But how do you train to optimize that?
Neuro-Evolution to the Rescue!


• Figure of merit difficult to calculate
• Test one configuration, set of weights against others, pick features from the best performers
• Handles to optimize:
  • Network topology
  • Network weights
  • Output binning
• Inputs MEBDT, NN outputs for each event.

• Sensitivity improvement -- 9% in expected limit
WH→lνbb Limits in Combination

CDF Run II Preliminary, L = 2.7 fb⁻¹

D0 @ m_H=115: 6.4 expected, 6.7 observed also with 2.7 fb⁻¹ NN with ME

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
<th>Expected (σ/SM)</th>
<th>Observed (σ/SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>105</td>
<td>3.8</td>
<td>3.6</td>
</tr>
<tr>
<td>110</td>
<td>4.1</td>
<td>4.9</td>
</tr>
<tr>
<td>115</td>
<td>4.8</td>
<td>5.6</td>
</tr>
<tr>
<td>120</td>
<td>5.9</td>
<td>5.9</td>
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<tr>
<td>125</td>
<td>7.2</td>
<td>8.0</td>
</tr>
<tr>
<td>130</td>
<td>8.7</td>
<td>8.9</td>
</tr>
<tr>
<td>135</td>
<td>12.2</td>
<td>13.2</td>
</tr>
<tr>
<td>140</td>
<td>17.5</td>
<td>26.5</td>
</tr>
<tr>
<td>145</td>
<td>25.6</td>
<td>42.1</td>
</tr>
<tr>
<td>150</td>
<td>40.5</td>
<td>75.5</td>
</tr>
</tbody>
</table>
Low Mass II: WH+ZH→MET+Jets

• Large Br(Z→νν); Picks up signal with W→νl_{missing}

• Multijet background with instrumental (fake) MET an issue -- Fake MET usually points along a jet!

• Require, for signal region:
  • MET>50 GeV
  • MET > 80 - 40 x min Δφ(MET, any jet)
  • 2 or 3 jets with |η|<2.5 and E_T>20 GeV
  • Δφ(j_1,j_2)<165°
  • -0.1 < (MET-Missing H_t)/(MET+Missing H_t)<0.2
  • Δφ(MET,Track-MET)<π/2 rejects events with fake MET
  • Reject isolated e, μ

Event Yields, before and after b-tagging

<table>
<thead>
<tr>
<th>Sample</th>
<th>HZ</th>
<th>HW</th>
<th>W+jets</th>
<th>Z+jets</th>
<th>top</th>
<th>VV</th>
<th>multijet</th>
<th>Total</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>6.15 ± 0.03</td>
<td>5.20 ± 0.04</td>
<td>24357</td>
<td>8199</td>
<td>532</td>
<td>814</td>
<td>6438</td>
<td>40340</td>
<td>40340</td>
</tr>
<tr>
<td>after</td>
<td>2.12 ± 0.01</td>
<td>1.58 ± 0.01</td>
<td>174.0</td>
<td>127.3</td>
<td>95.2</td>
<td>12.5</td>
<td>33.8</td>
<td>442.8 ± 1.1</td>
<td>439</td>
</tr>
</tbody>
</table>
MET+Jets: Control Samples

Require a lepton: check W+jets modeling

Analysis sample before b-tagging
Some variables:
MET, $\Sigma E_T$, Missing $H_T$, $H_T$, Missing $H_T/H_T$,
$(MET - \text{Missing } H_T)/(MET + \text{Missing } H_T)$
$\Delta R_{JJ}$, $\min \Delta \phi (\text{MET, any jet})$
Track-MET (missing-$P_T$)
Observed and Expected Limits: METbb

CDF @m_H=115 GeV
Expects 5.6*SM, Observes 6.9*SM
also with 2.1 fb^{-1}
Low-Mass Searches III: $ZH\to eebb$ and $ZH\to \mu \mu bb$

- Clean events -- $Z\to ll$ has almost no multijet or $W$ background
- No real MET! Can use $\Sigma p_T$ constraint to sharpen $m_{jj}$ resolution with a kinematic fit ($D\emptyset$) or NN (CDF)
- Low $B(Z\to ll)$ (3% per lepton): low signal acceptance
- $D\emptyset$: electrons with $|\eta|<2.5$, muons with $|\eta|<2.0$

Select events with two isolated, high-$p_T$ leptons and two or more jets

Multijet background estimated from data: electron candidates which fail shower-shape requirements ($e$) or isolation ($\mu$)
Low-Mass Searches III: ZH→eebb and ZH→μμbb

Split sample into 1, 2 b-tags (looser tags for double-tagged events) and by lepton category

<table>
<thead>
<tr>
<th></th>
<th>pre-selection</th>
<th>70 &lt; M_{ee} &lt; 110 GeV</th>
<th>1 tight b-tag</th>
<th>2 loose b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>12747</td>
<td>7610</td>
<td>201</td>
<td>131</td>
</tr>
<tr>
<td>Bkg</td>
<td>12926 ± 73</td>
<td>7900 ± 44</td>
<td>198.3 ± 1.3</td>
<td>119.0 ± 0.9</td>
</tr>
<tr>
<td>ZH(115)</td>
<td>2.09 ± 0.02</td>
<td>1.98 ± 0.02</td>
<td>0.52 ± 0.005</td>
<td>0.69 ± 0.007</td>
</tr>
<tr>
<td>Multijet</td>
<td>5303 ± 62</td>
<td>1368 ± 25</td>
<td>32.1 ± 0.6</td>
<td>16.6 ± 0.3</td>
</tr>
<tr>
<td>Zjj</td>
<td>6301 ± 37</td>
<td>5458 ± 35</td>
<td>29.6 ± 0.2</td>
<td>21.8 ± 0.1</td>
</tr>
<tr>
<td>Zb̅b̅</td>
<td>352.6 ± 3.5</td>
<td>308.3 ± 3.3</td>
<td>80.4 ± 1.0</td>
<td>45.7 ± 0.8</td>
</tr>
<tr>
<td>Zc̅c̅</td>
<td>798.0 ± 7.3</td>
<td>663.7 ± 6.6</td>
<td>45.5 ± 0.5</td>
<td>22.5 ± 0.3</td>
</tr>
<tr>
<td>ZZ</td>
<td>36.4 ± 0.6</td>
<td>32.6 ± 0.5</td>
<td>2.46 ± 0.08</td>
<td>2.47 ± 0.10</td>
</tr>
<tr>
<td>WZ</td>
<td>43.8 ± 0.9</td>
<td>40.7 ± 0.9</td>
<td>1.53 ± 0.05</td>
<td>0.61 ± 0.02</td>
</tr>
<tr>
<td>WW</td>
<td>9.42 ± 0.74</td>
<td>2.97 ± 0.40</td>
<td>0.096 ± 0.035</td>
<td>0.028 ± 0.007</td>
</tr>
<tr>
<td>tt̅</td>
<td>81.9 ± 0.5</td>
<td>25.5 ± 0.3</td>
<td>6.58 ± 0.08</td>
<td>9.21 ± 0.12</td>
</tr>
</tbody>
</table>

Also: Muons and Inter-cryostat electrons similar tables
More than just the Dijet Mass is Important!

- **m_{jj}, muons, two b-tags**

- **BDT Input variables:**
  - m_{ll}, m_{bb}, transverse versions,
  - Δφ(Z,dijet), Δη(ll), η(Z), η(bb)

- **BDT, electron sample, two b-tags**

- **Helicity angle of dijets, electron sample two b-tags**
### ZH→llbb Limits

CDF @m_H=115 GeV
Expects 9.9*SM, Observes 7.1*SM with 2.7 fb^{-1}

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
<th>Observed Limit/SM</th>
<th>Expected Limit/SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>4.3</td>
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</tr>
<tr>
<td>150</td>
<td>67.6</td>
<td>58.3</td>
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L=4.2 fb^{-1}
## Data Used for the Moriond 2009 Combinations

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF Lumi [fb⁻¹]</th>
<th>D0 Lumi [fb⁻¹]</th>
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</thead>
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<tr>
<td>WH→lνbb</td>
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<td>2.7</td>
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<tr>
<td>ZH→llbb</td>
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<tr>
<td>jjbb</td>
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<tr>
<td>H→WW Opposite-Sign dileptons</td>
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<td>3.0 - 4.2</td>
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<tr>
<td>WH→WWW Same-Sign dileptons</td>
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<td>1.1</td>
</tr>
<tr>
<td>H→ττ</td>
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<td>1.0</td>
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<tr>
<td>H→γγ</td>
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<td>4.2</td>
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<tr>
<td>ttH→ttbb</td>
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<td>2.1</td>
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</table>
Steps Required for Combination

- Histories and named rate \textit{and shape} errors exchanged
- Check stacked histograms and systematic tables with analysis documentation total counts:
  - data, signal, background
  - look for bins with \(b=0\) and have data events (bad!)
- Repeat individual channel limits -- compare against approved results.
- Assess correlations on systematics

CDF and D0 teams each do three combinations, using Bayesian and CL\(_{s}\) techniques.

CDF
D0
Tevatron
Consistency at the better than 10% level required for all combinations at all test masses. \textbf{Take the weaker limits.}
Combinations as done by CDF and D0

\[ m_H = 115 \text{ GeV}: \quad \text{CDF/D0} \quad 3.6/3.7 \ (3.2/3.6) \quad \text{observed (expected)} \]

\[ m_H = 165 \text{ GeV}: \quad \text{CDF/D0} \quad 1.5/1.3 \ (1.6/1.7) \quad \text{observed (expected)} \]
Tevatron Correlated Systematic Errors I

Total Systematic error count: 109 (not counting bin-by-bin errors)

Note: correlation in errors on backgrounds between experiments helps sensitivity! One experiment is another experiment’s control sample.

Luminosity: 3.8% Correlated CDF and D0 $\sigma_{\text{inel}}(\text{ppbar})$
4.4% detector-specific

Diboson Cross Sections: WW, WZ and ZZ
Cross sections used (6% relative uncertainty)
\[
\sigma_{\text{WW}} = 12.4 \pm 0.7 \text{ pb} \\
\sigma_{\text{WZ}} = 3.7 \pm 0.2 \text{ pb} \\
\sigma_{\text{ZZ}} = 3.8 \pm 0.2 \text{ pb}
\]

ttbar Cross Section: Moch and Uwer, evaluated at 
\[m_t = 172.4 \pm 1.2 \text{ GeV}\] $\sigma_{\text{tt}} = 7.794$ with a 10% syst. assigned
Tevatron Correlated Systematic Errors II

Signal Cross Section uncertainties:
- WH, ZH: ± 5%
- gg→H: ± 12%
- VBF: ± 10%

Applied to SM interpretations, but taken off for cross-section times branching ratio limits.

CDF-D0 Uncorrelated errors:
- K-factors (data driven)
- trigger efficiency
- b-tag efficiency and mistags
- jet energy scale
- lepton ID, fakes and conversions
- MET modeling

Correlated within CDF and D0 where appropriate
Any Hint of a Higgs Boson?

Neyman-Pearson Lemma says the Likelihood Ratio is uniformly most powerful test statistic

$$-2 \ln Q \equiv LLR \equiv -2 \ln \left( \frac{L(data \mid s + b, \hat{\theta})}{L(data \mid b, \hat{\theta})} \right)$$

Negative values: signal-like outcomes, Positive values: background-like outcomes.

No obvious hint of a signal.

Getting sensitive, though!
Tevatron Higgs Limits

CDF Run II Preliminary, L=2.0-3.6 fb^{-1}

95% CL Limit/SM

10

LEP Limit

Expected
Observed
±1σ Expected
±2σ Expected

1

SM=1

100 110 120 130 140 150 160 170 180 190 200

m_{H} (GeV/c^2)

March 5, 2009

Bayesian

Tevatron Run II Preliminary, L=0.9-4.2 fb^{-1}

95% CL Limit/SM

10

LEP Exclusion

Tevatron Exclusion

1

SM

100 110 120 130 140 150 160 170 180 190 200

m_{H} (GeV/c^2)

March 5, 2009

Modified Frequentist

SM Higgs Combination

DØ Preliminary, L=0.9-4.2 fb^{-1}

95% CL Limit/SM

10

Expected Limit

Standard Model = 1.0

1

100 110 120 130 140 150 160 170 180 190 200

m_{H} (GeV/c^2)

March 5, 2009

1-CLs

Tevatron RunII Preliminary

L=0.9-4.2 fb^{-1}

1-CLs Observed

1-CLs Expected

Expected ±1-σ

Expected ±2-σ

95% C.L.

90% C.L.

March 5, 2009

150 155 160 165 170 175 180 185 190 195 200

m_{H} (GeV/c^2)
Tevatron Combination at $m_H=165$ GeV

<table>
<thead>
<tr>
<th></th>
<th>observed</th>
<th>expected</th>
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<tbody>
<tr>
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<td>1.33</td>
<td>1.50</td>
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<tr>
<td>DØ</td>
<td>1.74</td>
<td>1.87</td>
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<tr>
<td>Tevatron</td>
<td>0.86</td>
<td>1.15</td>
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A Close-Up in the Highest s/b bins at $m_H=165$ GeV

The Last Few Bins’ Contents:

<table>
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<th>Signal yield (events)</th>
<th>Background yield (events)</th>
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<tr>
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<td>3.14</td>
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<td>1.38</td>
<td>5.38</td>
<td>3</td>
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<tr>
<td>4.61</td>
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</table>
Tevatron Combination at $m_H=115$ GeV

<table>
<thead>
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<tr>
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<td>3.64</td>
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<tr>
<td>DØ</td>
<td>3.70</td>
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</tr>
<tr>
<td>Tevatron</td>
<td>2.54</td>
<td>2.36</td>
</tr>
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</table>

Tevatron Run II Preliminary, $L=0.9-4.2$ fb$^{-1}$

$m_H=115$ GeV

Tevatron SM Higgs Boson Searches / Thomas Junk / 23 June, 2009
SM Fit From Gfitter

M. Baak et al., http://gfitter.desy.de/GSM/
Sensitivity and Projections -- $m_H=115$ GeV

Tevatron sensitivity approximated by 2xCDF

Steady improvement in analysis technique and better understanding of systematic uncertainties
Sensitivity and Projections -- $m_H=160$ GeV

CDF Run II Preliminary, $m_H=160$ GeV

Integrated Luminosity (fb$^{-1}$)

Expected Limit/SM

2xCDF Preliminary Projection, $m_H=160$ GeV

Integrated Luminosity/Experiment (fb$^{-1}$)

Expected Limit/SM
A Priori Chances of Seeing Something If It’s There

2xCDF Preliminary Projection

Median sensitivity: 50% more lucky, 50% less lucky
Summary

• The Tevatron is running very well

• We will run in 2010; planning for 2011

• Higgs boson search efforts on CDF and DØ are vigorous

• We are finding more acceptance and improving our analysis techniques as we collect more data

• Our hard work is bearing fruit! The combined sensitivity is now at 2.36*SM (m_H=115 GeV), and 1.15*SM at m_H=165 GeV. A 1σ deficit of candidates provides exclusion of 160<m_H<170 GeV.

• Another factor of two to four in data sample size is coming.
Backup Material
## Higgs Boson Production Cross Sections and Branching Ratios

<table>
<thead>
<tr>
<th>$m_H$ (GeV/$c^2$)</th>
<th>$\sigma_{gg\rightarrow H}$ (fb)</th>
<th>$\sigma_{WH}$ (fb)</th>
<th>$\sigma_{ZH}$ (fb)</th>
<th>$\sigma_{VBF}$ (fb)</th>
<th>$B(H \rightarrow bb)$ (%)</th>
<th>$B(H \rightarrow \tau^+\tau^-)$ (%)</th>
<th>$B(H \rightarrow W^+W^-)$ (%)</th>
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<td>100</td>
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<td>286.1</td>
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</table>

$gg\rightarrow H$ from Grazzini and de Florian, similar to those of other authors
### Tevatron Combined Limits

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<tr>
<th>mass</th>
<th>obs</th>
<th>-2σ</th>
<th>-1σ</th>
<th>exp</th>
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<td>7.83</td>
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# CDF Higgs Combination Limits

<table>
<thead>
<tr>
<th>$m_H$ (GeV/c²)</th>
<th>Observed limit/SM</th>
<th>$-2\sigma$ expected</th>
<th>$-1\sigma$ expected</th>
<th>median expected</th>
<th>$+1\sigma$ expected</th>
<th>$+2\sigma$ expected</th>
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Higgs Boson Couplings to Gluons

Lowest order: Fermion Loops

Mostly top contributes in SM

Heavier 4\textsuperscript{th} generation quarks contribute as much as top quark, almost independent of $m_Q$.

A heavy 4\textsuperscript{th} generation would scale the $gg \rightarrow H$ production rate at colliders by a factor of $\sim 9$. But watch out for $H \rightarrow \nu_4 \nu_4$ decays.

Another Interesting Candidate Event

Jet$_1$ \( E_T = 84.7 \) GeV
Jet$_2$ \( E_T = 71.9 \) GeV -- Tagged

\[ m_{jj} = 129 \text{ GeV} \]

Missing \( E_T = 98 \text{ GeV} \)
Standard Model Higgs Boson Decay Branching Fractions

HDECAY by M. Spira
Discovery with p-Values

Example: CDF’s single top observation

\[ -2\ln Q = LLR \equiv -2\ln \left( \frac{L(\text{data} | s + b, \hat{\theta})}{L(\text{data} | b, \hat{\theta})} \right) \]

100 M s+b and b-only pseudoexperiments, each with fluctuated nuisance parameters, and fit twice.

- 5\(\sigma\): p-value of 2.77x10^{-7} or less.
- 3\(\sigma\): p-value of 1.35x10^{-3} or less
- 2\(\sigma\): p-value of 2.28% or less

Systematics varied in each pseudoexperiment
Tevatron Combination at 160 GeV

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Tevatron Combination at $m_H=115$ GeV

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Tevatron Combination at $m_H=165$ GeV

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Tevatron Run II Preliminary, $L=3.6-4.2$ fb$^{-1}$

Mean 1.223
RMS 0.401
$\chi^2$/ndf 199.3/73
Prob 0.603801

$p_0 \pm 2.346\times10^4 = 17918$
p1 $0.4248\pm 0.0515$
p2 $3.067\pm 0.653$
p3 $5.052\pm 0.554$
NNLO+EW K-factor (vs. LO) At Tevatron Energies

We assume 12% uncertainty in the total cross section

Markov Chain Monte Carlo Integration

- Monte Carlo integration method
- improvement on scattershot MC
- faster and more stable results

- problem: most integration points contribute little
- would like to sample only the peaks of the distribution
- problem: we throw nuisance parameters, not likelihood

- solution: we slowly walk along the peaks taking care not to step into the valley
  › Markov Chain Monte Carlo
Mini-Review: CL$_s$ Limits

p-values:
Yellow area = 1-CL$_b$ = 1-P(-2\ln Q>-2\ln Q_{\text{obs}} | b only)
Green area = CL$_{s+b}$ = P(-2\ln Q>-2\ln Q_{\text{obs}} | s+b)

CL$_s$ $\equiv$ CL$_{s+b}$/CL$_b$ $\geq$ CL$_{s+b}$
Exclude if CL$_s$<$0.05$
Vary r until CL$_s$=0.05 to get $r_{\text{lim}}$

• Advantages:
  • Exclusion and Discovery p-values are consistent.
    Example -- a 2\sigma upward fluctuation of the data with respect to the background prediction appears both in the limit and the p-value as such
  • Does not exclude where there is no sensitivity (big enough search region with small enough resolution and you get a 5% dusting of random exclusions with CL$_{s+b}$)
Mini-Review: Bayesian Limits

\[ L(r, \theta) = \prod_{\text{channels}} \prod_{\text{bins}} P_{\text{Poiss}}(\text{data} \mid r, \theta) \]

Where \( r \) is an overall signal scale factor, and \( \theta \) represents all nuisance parameters.

\[ P_{\text{Poiss}}(\text{data} \mid r, \theta) = \frac{(r s_i(\theta) + b_i(\theta))^{n_i} e^{-(r s_i(\theta) + b_i(\theta))}}{n_i!} \]

where \( n_i \) is observed in each bin \( i \), \( s_i \) is the predicted signal for a fiducial model (SM), and \( b_i \) is the predicted background. Dependence of \( s_i \) and \( b_i \) on \( \theta \) includes rate, shape, and bin-by-bin independent uncertainties.
Mini-Review: Bayesian Limits

Including uncertainties on nuisance parameters $\theta$

$$L'(data \mid r) = \int L(data \mid r, \theta)\pi(\theta)d\theta$$

where $\pi(\theta)$ encodes our prior belief in the values of the uncertain parameters. Usually Gaussian centered on the best estimate and with a width given by the systematic. Includes rate uncertainties, shape uncertainties, MC statistics in each bin.

$$0.95 = \int_{0}^{r_{\text{lim}}} L'(data \mid r)\pi(r)dr$$

Sensitivity = Median Expected Limit

- Run simulated background-only MC pseudoexperiments (fluctuate all systematics)
- Compute $r_{\text{lim}}$ for each one; find median and $\pm 1,2\sigma$ variations.
Tevatron Combined Higgs Limits -- By the Numbers

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For details, see arXiv:0903.4001 [hep-ex]
ATLAS’s Projections

EW corrections to $\sigma(gg\rightarrow H)$

Recent \textit{gg}→H Production Cross Section Progress

- NLO corrections -- \(\sim 80\%\) (almost double the cross section)!
- NNLO QCD corrections -- An additional 40\% on top of that!
  Residual uncertainty \(\sim 10\%\). Catani, de Florian, Grazzini, Nason

NLO,NNLO bands: \(0.5m_H<\mu_F,\mu_R<2M_H\). Bands on LO unreliable.
Templates For Matrix Element WH Search
Evolutionarily Trained Neural Networks

Starting Configuration...

Evolved into this!

Approximately a 9% improvement in expected limit over the best input
 Amount of DY background left after cuts different.
WW not so different between channels
Tevatron SM Higgs Boson Searches / Thomas Junk / 23 June, 2009

Tevatron Run II Projection

Tevatron Run II Projection

Tevatron SM Higgs Boson Searches / Thomas Junk / 23 June, 2009

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WW and WZ and ZZ Production at Hadron Colliders

Campbell and Ellis
e-Print: hep-ph/9905386
## H→WW Selection Requirements

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<td>$\mu\mu$: $n_{jet} &lt; 2$ for $p_T^{jet} &gt; 15$ GeV, $\Delta R(\mu, \text{jet}) &gt; 0.1$ and $p_T^{\mu} &gt; 15$ GeV for the leading $\mu$</td>
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